MEASUREMENT OF THE ISOLATED PHOTON CROSS SECTION WITH
CONVERSIONS IN $pp$ COLLISIONS AT $\sqrt{s} = 7$ TeV

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MEASUREMENT OF THE ISOLATED PHOTON CROSS SECTION WITH CONVERSIONS IN $pp$ COLLISIONS AT $\sqrt{s} = 7$ TeV

Abstract

by

Ted R. Kolberg

We present a measurement of the isolated direct photon cross section using 36.1 pb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 7$ TeV collected with the Compact Muon Solenoid (CMS) experiment during the 2010 physics run of the CERN Large Hadron Collider (LHC). The measurement is performed on events where the photon candidate converts into an $e^+e^-$ pair in the material of the inner tracking system. The transverse momentum of the conversion track pair is compared with the transverse energy measured in the CMS electromagnetic calorimeter (ECAL), and is then used to subtract the background due to e.g. $\pi^0 \rightarrow \gamma\gamma$ decays. We measure the photon cross section over a range of photon transverse momentum and pseudorapidity and find that it agrees with the predictions of perturbative quantum chromodynamics (QCD) calculations.
CONTENTS

FIGURES ........................................................................ iv
TABLES ........................................................................ ix
ACKNOWLEDGMENTS ...................................................... xi

CHAPTER 1: INTRODUCTION ........................................... 1

CHAPTER 2: PROMPT PHOTON THEORY AND PREVIOUS MEASUREMENTS .................................................. 5
  2.1 Quantum Chromodynamics ........................................ 5
  2.2 Computing the photon cross section ............................ 15
  2.3 History of experimental measurements ....................... 17

CHAPTER 3: THE LHC ACCELERATOR AND THE CMS DETECTOR .................................................. 22
  3.1 The Large Hadron Collider ......................................... 22
    3.1.1 LHC physics reach ........................................... 22
    3.1.2 LHC design and parameters ............................... 25
  3.2 The Compact Muon Solenoid detector ......................... 29
    3.2.1 Magnet system ............................................... 31
    3.2.2 Inner tracking detector .................................... 32
      3.2.2.1 Pixel detector ........................................... 39
      3.2.2.2 Silicon strip tracker ................................... 42
    3.2.3 Electromagnetic calorimeter ............................... 45
      3.2.3.1 Mechanical design .................................... 46
      3.2.3.2 Photodetectors ........................................ 50
      3.2.3.3 Readout electronics ................................... 51
      3.2.3.4 ECAL preshower detector ......................... 55
    3.2.4 Hadronic calorimeter ........................................ 56
    3.2.5 Muon system .................................................. 59
    3.2.6 Level-1 trigger ............................................... 63
<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.7 Data acquisition and High Level Trigger</td>
<td>64</td>
</tr>
<tr>
<td>3.3 CMSSW software</td>
<td>66</td>
</tr>
<tr>
<td>CHAPTER 4: PHOTON RECONSTRUCTION AND SELECTION</td>
<td>68</td>
</tr>
<tr>
<td>4.1 Superclustering</td>
<td>68</td>
</tr>
<tr>
<td>4.2 Energy corrections</td>
<td>69</td>
</tr>
<tr>
<td>4.3 Photon candidate reconstruction and selection</td>
<td>70</td>
</tr>
<tr>
<td>4.4 Photon conversion reconstruction and identification</td>
<td>72</td>
</tr>
<tr>
<td>4.4.1 Photon conversion kinematics</td>
<td>73</td>
</tr>
<tr>
<td>4.4.2 ECAL seeded conversion reconstruction</td>
<td>74</td>
</tr>
<tr>
<td>4.4.3 Conversion pair ambiguity solving</td>
<td>77</td>
</tr>
<tr>
<td>4.4.4 Conversion identification selection</td>
<td>82</td>
</tr>
<tr>
<td>CHAPTER 5: DATA AND SIMULATION SAMPLES</td>
<td>83</td>
</tr>
<tr>
<td>5.1 PYTHIA simulated events</td>
<td>83</td>
</tr>
<tr>
<td>5.2 Event selection in data</td>
<td>86</td>
</tr>
<tr>
<td>5.3 Binning in transverse momentum and pseudorapidity</td>
<td>88</td>
</tr>
<tr>
<td>CHAPTER 6: SIGNAL EFFICIENCY AND BACKGROUND SUBTRACTION</td>
<td>90</td>
</tr>
<tr>
<td>6.1 Isolation efficiency $\epsilon_{\text{iso}}$</td>
<td>91</td>
</tr>
<tr>
<td>6.2 Efficiency of the conversion selection</td>
<td>92</td>
</tr>
<tr>
<td>6.3 Photon signal extraction</td>
<td>95</td>
</tr>
<tr>
<td>6.3.1 Signal template</td>
<td>101</td>
</tr>
<tr>
<td>6.3.2 Background template</td>
<td>102</td>
</tr>
<tr>
<td>CHAPTER 7: SYSTEMATIC UNCERTAINTIES</td>
<td>127</td>
</tr>
<tr>
<td>7.1 Isolation efficiency</td>
<td>127</td>
</tr>
<tr>
<td>7.2 Conversion selection efficiency</td>
<td>128</td>
</tr>
<tr>
<td>7.3 Signal shape</td>
<td>130</td>
</tr>
<tr>
<td>7.4 Background shape</td>
<td>131</td>
</tr>
<tr>
<td>7.5 Fitting</td>
<td>133</td>
</tr>
<tr>
<td>7.6 Prompt electrons</td>
<td>136</td>
</tr>
<tr>
<td>7.7 Energy scale</td>
<td>136</td>
</tr>
<tr>
<td>7.8 Unfolding</td>
<td>139</td>
</tr>
<tr>
<td>CHAPTER 8: RESULTS AND CONCLUSION</td>
<td>147</td>
</tr>
<tr>
<td>8.1 Final cross section results</td>
<td>147</td>
</tr>
<tr>
<td>8.2 Conclusions</td>
<td>149</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>154</td>
</tr>
</tbody>
</table>
FIGURES

2.1 Values of the coupling constant $\alpha_s$ for increasing probe momentum $Q$. The source of each data point is shown in the legend and the value of the coupling constant at the typical mass scale $M_Z$ is shown at bottom \[23\].

2.2 The regions of $x$ and $Q^2$ probed by various colliders and fixed-target experiments at the beginning of the LHC era \[23\].

2.3 Distributions of $x$ times the parton fraction $f(x)$ for the constituents of the proton at $\mu^2 = Q^2 = 20 \text{ GeV}^2$ and $10,000 \text{ GeV}^2$. Results are from the MRST2006 set \[23\].

2.4 Feynman diagrams for prompt photon production at leading order.

2.5 Fragmentation processes which contribute to the isolated photon cross section. On the left is the perturbatively calculable pointlike emission of a high momentum photon by an outgoing quark. On the right the photon is produced by the non-perturbative fragmentation of a gluon.

2.6 Previous prompt photon cross section measurements with proton beams \[6\]. The more recent measurements not included in this figure agree with NLO theory within their experimental uncertainties.

3.1 The CERN accelerator complex.

3.2 Schematic of the CMS detector \[5\]. The coordinate system definitions are overlaid at right.

3.3 Schematic of the CMS magnet, showing the five cold mass modules and the supporting tie rods \[5\].

3.4 The material budget of the inner tracking system in units of radiation length $X_0$ as a function of the pseudorapidity $\eta$ \[5\].

3.5 The number of hits per track as a function of the pseudorapidity $\eta$ \[5\]. The closed circles show the total number of hits, while the open squares show the number of hits on the stereo layers.
3.6 Transverse momentum resolution for muons with $p_T$ of 1, 10, and 100 GeV as a function of $\eta$ [5].

3.7 Transverse impact parameter resolution for muons with $p_T$ of 1, 10, and 100 GeV as a function of $\eta$ [5].

3.8 Longitudinal impact parameter resolution for muons with $p_T$ of 1, 10, and 100 GeV as a function of $\eta$ [5].

3.9 The layout of the inner detector system [5].

3.10 The layout of the pixel detector showing the pseudorapidity coverage of the barrel and forward pixel detector (top), and hit coverage vs. $\eta$ (bottom) [5].

3.11 The 15 different sensor geometries used in the silicon strip tracker [5].

3.12 ECAL barrel energy resolution measured with test beam electrons [5]. Stochastic (S), constant (C) and noise (N) terms are extracted from a fit to the data.

3.13 The layout of the ECAL [5].

3.14 The on-detector readout electronics of ECAL [5]. The EB readout of the APDs is presented in the figure but the EE chain is equivalent.

3.15 The off-detector electronics of ECAL [5].

3.16 The layout of the CMS HCAL and its subcomponents: HB (barrel HCAL), HE (endcap HCAL), HF (forward HCAL) and HO (outer barrel HCAL) are labeled in the figure [5].

3.17 Jet energy resolutions for the barrel, endcap, and forward HCAL. Jets shown are reconstructed with an iterative cone algorithm with radius $\delta R = 0.5$ [5].

3.18 Muon $p_T$ resolution ($\delta(p_T)/p_T$) as a function of $p_T$ for the barrel and endcap muon systems. [5].

3.19 Schematic view of the Level-1 trigger system [5].

3.20 Schematic view of the data acquisition and High Level Trigger system [5].

4.1 Cross sections for photon interactions with a light element (C, $Z = 6$, top) and a heavy element (lead, $Z = 82$, bottom). At lower energies the photoelectric effect $\sigma_{p.e}$, Rayleigh scattering, and Compton scattering dominate the cross sections. At higher energy pair production from the nuclear ($\kappa_{\text{NUC}}$) and electron ($\kappa_e$) electric fields dominate [23].
4.2 Normalized pair production cross sections versus the fractional $e^{-}$ energy for various values of the initial photon energy. Energies less than 1 TeV are well approximated by the 1 TeV curve [23].

4.3 The three possible hit arrangements in the outermost tracker layers which can seed the inward conversion track reconstruction. Reproduced with modifications from [22].

4.4 The inward track (1) is seeded from a basic cluster in the ECAL supercluster (blue) and hits in the outermost three tracker layers. The outward track (2) is then built using the innermost hit of the inward track as a hypothesis for the conversion vertex. Reproduced with modifications from [22].

4.5 $\Delta \cot \theta$ for matched and unmatched track pairs.

4.6 $\Delta \phi$ for matched and unmatched track pairs.

4.7 $E_{sc}/P_{tracks}$ for matched and unmatched track pairs.

4.8 The $\chi^2$ of the highest-$P_T$ track for matched and unmatched track pairs.

4.9 The $\chi^2$ of the lowest-$P_T$ track for matched and unmatched track pairs.

4.10 The output of the likelihood discriminant for matched and unmatched track pairs in simulation [22].

6.1 The results of the A/B statistical independence test. For each eta bin of the analysis, the ratio between the total efficiency-corrected result is shown when using half A for the signal extraction and half B for the $f_{conv}$ measurement and vice versa. The errors include the statistical error from the split samples as well as the systematic error quoted on the efficiency measurement.

6.2 Efficiencies calculated in Monte Carlo simulation.

6.3 Fit results for the combined isolation signal extraction technique. These are the fit results before applying the conversion selection. Black points are data, the red line is the background template, the blue dotted line is the signal fit, and the solid blue line is the sum of the fitted components.

6.4 Fit results for the combined isolation signal extraction technique. These are the fit results after applying the conversion selection. Black points are data, the red line is the background template, the blue dotted line is the signal fit, and the solid blue line is the sum of the fitted components.
6.5 Efficiencies extracted from data for each \( \eta \) bin. Error bars are those computed according to the procedure described in Section 7.2.  

6.6 Schematic diagram of the two-dimensional sideband used as the control region. In order to accumulate enough statistics in data to perform the fit while keeping the shape systematic under control, we take a narrow window in shower shape and in track isolation to obtain the QCD background enriched sample for the background templates. Diagrams are separate for Barrel (left) and Endcap (right).  

6.7 Fit results for candidates with \( p_T \) between 25 and 30.  
6.8 Fit results for candidates with \( p_T \) between 30 and 35.  
6.9 Fit results for candidates with \( p_T \) between 35 and 40.  
6.10 Fit results for candidates with \( p_T \) between 40 and 45.  
6.11 Fit results for candidates with \( p_T \) between 45 and 50.  
6.12 Fit results for candidates with \( p_T \) between 50 and 55.  
6.13 Fit results for candidates with \( p_T \) between 55 and 60.  
6.14 Fit results for candidates with \( p_T \) between 60 and 65.  
6.15 Fit results for candidates with \( p_T \) between 65 and 70.  
6.16 Fit results for candidates with \( p_T \) between 70 and 80.  
6.17 Fit results for candidates with \( p_T \) between 80 and 100.  
6.18 Fit results for candidates with \( p_T \) between 100 and 120.  
6.19 Fit results for candidates with \( p_T \) between 120 and 200.  
6.20 Purity measured in the conversion sample for each bin of pseudo-rapidity.  

7.1 Plots of \( P(\chi^2) \) for each energy shift considered for the signal shape systematic.  
7.2 Plots of background shapes summed over transverse momentum for each \( \eta \) obtained from MC truth and data control region.  
7.3 Linear fit of the background shape systematic vs. \( p_T \) bin.  
7.4 Distributions of the mean pulls for the fitting systematic.  
7.5 Distributions of the RMS pulls for the fitting systematic.  
7.6 P values for the conversion vertex fit used in the ID step. The MC bkg. (red) and signal (blue) are summed according to the purity in data. Overflow entries are shown in the last bin.
7.7 $Z \to e^+e^-$ peaks for unconverted legs (blue) and converted legs (red). The contribution of converted legs beneath the $Z$ peak is used to estimate the fake rate for prompt electrons.

7.8 Relative systematic uncertainties on the photon cross section measured with the photon conversion method in the four $\eta$ regions. Systematic uncertainties due to the uncertainties on the fit bias, energy scale, selection efficiency, unfolding corrections, and signal and background shapes are shown, as well as their total quadrature sum (upper curve).

8.1 Fully corrected cross section, binned in $p_T$ for the four $\eta$ bins used in the analysis. The JETPHOX prediction is also shown for comparison.

8.2 Fully corrected cross section, binned in $p_T$ for the four $\eta$ bins used in the analysis. The ratio of data to the JETPHOX prediction is shown.
TABLES

4.1 ISOLATED PHOTON SELECTION .................................................. 73
5.1 HLT PATHS USED AND THE ACCOMPANYING RUN RANGES
AND LUMINOSITIES .............................................................. 87
6.1 CONTROL REGION SELECTION .................................................. 103
6.2 RAW SIGNAL YIELDS AND PURITIES FOR THE FIRST EB
η BIN ...................................................................................... 105
6.3 RAW SIGNAL YIELDS AND PURITIES FOR THE SECOND EB
η BIN ...................................................................................... 106
6.4 RAW SIGNAL YIELDS AND PURITIES FOR THE FIRST EE η
BIN ...................................................................................... 107
6.5 RAW SIGNAL YIELDS AND PURITIES FOR THE SECOND EE
η BIN ...................................................................................... 108
6.6 EFFICIENCY FOR THE FIRST EB BIN ......................................... 109
6.7 EFFICIENCY FOR THE SECOND EB BIN ..................................... 110
6.8 EFFICIENCY FOR THE FIRST EE BIN ......................................... 111
6.9 EFFICIENCY FOR THE SECOND EE BIN ..................................... 112
7.1 DIFFERENCE BETWEEN THE EFFICIENCY MEASURED WITH
DATA-DRIVEN AND MC TRUTH BACKGROUND TEMPLATES
FOR THE ISOLATION VARIABLE ............................................... 129
7.2 RATIO BETWEEN THE CROSS SECTION VALUES OBTAINED
WITH THE COMBINED ISOLATION SELECTION AND THE
SELECTION FROM TABLE 4.1 ...................................................... 129
7.3 SYSTEMATIC ERRORS IN PERCENT FOR THE FIRST EB BIN 142
7.4 SYSTEMATIC ERRORS IN PERCENT FOR THE SECOND EB
BIN ........................................................................................... 143
7.5 SYSTEMATIC ERRORS IN PERCENT FOR THE FIRST EB BIN 144
7.6 SYSTEMATIC ERRORS IN PERCENT FOR THE SECOND EE BIN ................................. 146
8.1 DIFFERENTIAL CROSS SECTION WITH STATISTICAL AND SYSTEMATIC ERRORS, EB BINS ................................. 151
8.2 DIFFERENTIAL CROSS SECTION WITH STATISTICAL AND SYSTEMATIC ERRORS, EE BINS ................................. 152
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CHAPTER 1

INTRODUCTION

The Large Hadron Collider (LHC) is built to study particle physics at the highest center of mass energies yet achieved. It is primarily intended to produce new discoveries about the nature of the matter and forces which make up our universe. Important topics to be investigated at the LHC include the Higgs mechanism, thought to be responsible for the breaking of the symmetry between the electromagnetic and weak forces, and new physics beyond the Standard Model of particle physics, including the possible existence of new symmetries of nature like supersymmetry (SUSY). The CMS detector is constructed to fully explore the range of physics topics which the LHC opens up. It leverages significant technological advances in many techniques of experimental particle physics in order to meet the demanding requirements for particle physics at the TeV scale. In particular, this thesis is one of the early LHC measurements to exploit the capabilities of the CMS electromagnetic calorimeter (ECAL), a device which greatly enhances the experiment’s physics capabilities due to its excellent performance characteristics.

This thesis presents a measurement of the isolated direct photon cross section using 36.1 pb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 7$ TeV collected with the CMS experiment during the 2010 physics run of the CERN LHC. Measuring the photon cross section is an important early measurement for the LHC physics program. First, the photon cross section is one of the classical tests of perturbative quantum
chromodynamics (QCD) theory [18]. QCD is the theory which governs the interactions of the quarks and gluons which interact during LHC collisions, so these interactions must be well understood in order to do any other physics analysis. In addition, QCD interactions are the most common background for most searches for new physics at the LHC and so a complete picture of QCD at LHC energies is essential to carry out the physics goals of the experiment. Probing QCD with photons rather than hadronic jets offers some experimental advantages: the energy resolution for photons is typically better than for jets, and measurements of jet production depend on the jet clustering algorithm chosen for the measurement. Since the most important production processes for direct photons involve gluons in the initial state, the photon cross section measurement can constrain the gluon parton distribution functions (PDFs) for protons in $\sqrt{s} = 7$ TeV collisions. Since many of the production processes for other measurements and searches at the LHC also involve gluons in the initial state, this is a essential early measurement to the physics program. Secondly, the reconstruction and identification of photons, and techniques to measure the purity of a selected photon candidate sample, are important for studying a variety of physics signatures which include photons in the final state. These include, but are not limited to, the $H \rightarrow \gamma\gamma$ decay mode, certain SUSY models, and models with compactified extra dimensions. In addition, the production of isolated photons from QCD forms a cornerstone of the strategy for measuring the jet energy scale at the LHC, which is a limiting factor for the precision of measurements using hadronic jets.

The main difficulty in making a measurement with direct photons lies in the fact that, at a hadron collider, QCD jets outnumber real photons by more than three orders of magnitude. Most of this background can be eliminated by requiring
them to be isolated in the calorimeters and tracking system, and by exploiting the fine segmentation of the CMS ECAL to require a photon-like shower shape. However, highly boosted decays like $\pi^0 \to \gamma\gamma$ and $\eta^0 \to \gamma\gamma$ can mimic the photon signal if they have a large fraction of the total jet energy. In this case, the measured isolation of the photon candidate may be similar to a direct photon, and the shower shape at high transverse momentum ($p_T$) will also resemble that of a single photon, since the photons from the decay are nearly coincident at their impact with the ECAL.

Another complementary method to identify single isolated photons is to use photons which convert into $e^+e^-$ pairs. The calorimetric energy of the photon candidate can be compared with the momentum of the conversion tracks. For isolated converted photons the ratio of the energy to the momentum is expected to be near one, whereas it should be larger than one if multiple photons from neutral meson decays are clustered into a single photon candidate. The CDF collaboration used this method to measure the isolated photon cross section using Tevatron Run I data [4]. The large amount of material in the CMS tracking system (about one radiation length $X_0$ on average between the primary vertex and the ECAL face) causes a large fraction of photons to convert before they reach ECAL. For this reason the CMS experiment is an ideal setting for using conversions to measure the photon cross section; the large conversion probability increases the statistical power of the method.

In Chapter 2 we present a brief review of the theory behind the cross section measurement and summarize previous measurements made at fixed-target and collider experiments. In Chapter 3 we present the experimental setup used to perform the measurement: the LHC accelerator and the CMS detector. In
Chapter 4 we describe the CMS photon (and photon conversion) reconstruction software. Chapter 5 presents the data and simulation samples used to perform the measurement. Chapter 6 describes the measurement of the signal efficiency and the results of the background subtraction technique. Chapter 7 contains estimates of the systematic uncertainties which affect the measurement of the cross section. The final cross section results and conclusions are presented in Chapter 8.
CHAPTER 2

PROMPT PHOTON THEORY AND PREVIOUS MEASUREMENTS

In this chapter, we present the general framework of Quantum Chromodynamics (QCD), the theory of the strong interaction, first in the general case and then in the specific case of the inclusive photon production cross-section. We also present a survey of the previous experimental measurements of this process.

2.1 Quantum Chromodynamics

QCD is the theory of strong interactions within the framework of the Standard Model of particle physics. QCD is a quantum field theory which describes the interactions of the quarks and gluons which make up hadronic matter. In contrast to other quantum field theories, QCD is remarkable because it describes a system with very different properties in different energy regimes. At low energies, quarks are confined, meaning that the force between them increases with their separation. QCD therefore predicts the failure of experimental searches for free quarks at low energy. At high energies, QCD predicts that quarks and gluons interact weakly, a phenomenon known as asymptotic freedom, which successfully describes the behavior of these partons in high-energy collisions. QCD successfully explains the organization of hadrons into $q\bar{q}$, $qq$, and $q\bar{q}\bar{q}$ states as a consequence of the quantum number called color. Color has an exact $SU(3)$ symmetry and hadrons
are invariant under this symmetry, that is, they carry no net color charge. QCD is also a non-Abelian gauge theory where the gluon itself carries color charge. This means that three interactions are possible: a quark may emit or absorb a gluon, a gluon may emit or absorb a gluon, and two gluons may interact with each other. This contrasts with Abelian field theories, for example QED where interactions of the first type are the only ones possible. It is the non-Abelian nature of the field which gives rise to the properties of asymptotic freedom and confinement.

The QCD Lagrangian is as follows [23]:

\[
\mathcal{L}_{QCD} = -\frac{1}{4} F^{(a)}_{\mu\nu} F^{(a)}_{\mu\nu} + i \sum_q \bar{\psi}_q \gamma^\mu (D_\mu)_{ij} \psi^j_q - \sum_q m_q \bar{\psi}^i_q \psi^i_q \tag{2.1}
\]

where

\[
F^{(a)}_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f^{abc} A^b_\mu A^c_\nu \tag{2.2}
\]

and

\[
(D_\mu)_{ij} = \delta_{ij} \partial_\mu + ig_s \sum_a \frac{\lambda^a_{ij}}{2} A^a_\mu. \tag{2.3}
\]

In these equations the following notation is used:

- The \( \lambda \)s are the Gell-Mann matrices, which play an analogous role in \( SU(3) \) to the familiar Pauli spin matrices in \( SU(2) \).

- \( f^{abc} \) are the structure constants of the \( SU(3) \) algebra, defined by the commutators of the Gell-Mann matrices, \( [\lambda^a, \lambda^b] = 2i f^{abc} \lambda^c \).

- \( \psi \) is the 4-component Dirac spinor for the quark field. Indices run over the colors \( i \) and the flavors \( q \).

- \( A^a_\mu \) are the gluon fields.
• $g_s$ is the QCD coupling constant. It is related to the effective QCD coupling

$\alpha_s$ by $\alpha_s = g_s^2/4\pi$.

In Equation [2.1] the three terms each represent a different component of the QCD interaction.

The first term represents the free gluon field. The gluon field tensors $F$ can be thought of as analogous to the free field term in QED with two major differences. First, the more complicated gauge group $SU(3)$ means that there are eight gluon fields instead of a single photon field. The second, even more fundamental difference is that Equation [2.2] contains a third term which represents the self-interaction of the gluon field due to the fact that gluons carry a color charge.

The second term describes the interaction of the quarks with the gluon field. The important feature to note here is that the quarks couple to the component of the gluon field which carries the same value of the color charge. The typical interaction of a quark with a gluon field changes the color charge of the quark with the gluon carrying off the difference.

The third term describes the free quarks with mass $m_q$. However, free quarks cannot exist in nature due to confinement, and furthermore, the mass of hadrons is dominated not by the mass of the quark, but by the binding energy carried by the gluons. For the proton, the masses of the valence quarks (11 MeV) contribute only about 1% of the overall mass (938 MeV).

In QCD as in other quantum field theories, a renormalization procedure must be used in order to avoid divergences in the calculation. This must be done in such a way that the physical observables are independent of the renormalization scheme used and the scale chosen. In QCD, it is not convenient to renormalize at the mass scale of the quarks since they are strongly interacting particles and
their mass is small compared to the energy of their interactions. Instead, we impose the renormalization conditions at some higher momentum scale where the coupling is small and observables can be more easily measured. The contribution of higher order terms can then be absorbed into a coupling constant which changes depending on the momentum scale of the process being calculated. The running of the coupling constant $\alpha_s$ with the momentum $Q$ of the probe is given by the renormalization group equation, which describes the change in the strength of the interaction at different energy scales:

$$Q^2 \frac{d\alpha_s}{dQ^2} = \beta(\alpha_s(Q^2))$$  \hspace{1cm} (2.4)

and it can be solved to yield

$$\alpha_s(Q^2) = \frac{1}{\beta_0 \log Q^2/\Lambda^2}.$$  \hspace{1cm} (2.5)

We see that $\Lambda$ must have dimensions which match $Q$. $\Lambda$ is experimentally determined to be about 200 MeV; this sets the typical scale for low-energy QCD interactions, for example, the masses of the hadrons are of order $\Lambda$. The running of the coupling constant with the probe energy is illustrated in Figure 2.1.

Problems in QCD can generally be factorized into a perturbative part and non-perturbative effects. Perturbative QCD covers the high-energy regime where $\alpha_s$ is small and the quarks and gluons are asymptotically free. Because the coupling is weak at high energy the techniques of perturbation theory can be applied to make precise predictions. The classic example of perturbative QCD is the calculation of $R = \frac{e^+e^- \rightarrow \text{hadrons}}{e^+e^- \rightarrow \mu^+\mu^-}$, where the sum over all hadrons cancels out the dependence on individual hadron types. At lower energies, the coupling is stronger, and the
Figure 2.1. Values of the coupling constant $\alpha_s$ for increasing probe momentum $Q$. The source of each data point is shown in the legend and the value of the coupling constant at the typical mass scale $M_Z$ is shown at bottom [23].
number of terms required to make a precise calculation is large or infinite. Thus phenomena that occur near the energy scale $\Lambda$ can not be calculated using perturbation theory. One example of non-perturbative QCD is the binding of quarks and gluons into hadrons. Lattice QCD can be used to estimate non-perturbative effects numerically by defining the field values on a discrete lattice of points in space and time. Extrapolating the results to a lattice spacing of zero yields estimates of the behavior of continuum QCD. Lattice QCD can successfully predict the phenomenon of confinement and yield estimates of some hadron masses, though the computations are extremely demanding.

In practice, experiments must usually account for both perturbative and non-perturbative effects when comparing with QCD. One example is the typical dijet structure of $2 \to 2$ quark scattering events at high $Q^2$. In the hard scattering process the quarks are asymptotically free, so their outgoing kinematics can be calculated perturbatively. However, since the quarks must be confined into hadrons, they undergo a process of hadronization into collimated jets of final state hadrons. This hadronization process cannot be treated perturbatively, so the number and type of particles in the jets are instead described by empirical models. When computing the cross section for a given production process, the calculation can be factorized into three distinct parts \cite{13}: the parton distribution function (PDF), fragmentation, and the parton-parton cross section. Here we briefly review each of the parts.

The LHC collides two protons but the cross section must be calculated at the parton level. At a qualitative level, the proton can be thought of as consisting of three valence quarks ($uud$) and a “sea” of quarks and gluons produced by continual splitting and recombination of gluons, the splitting of gluons into $q\bar{q}$ pairs, and the
annihilation of these pairs. As the proton is probed at larger momentum, the sea particles come to dominate the interactions, such that at LHC energies collisions between the gluons are the dominant production mechanism. The PDFs describe the probability of finding a parton with a given type and longitudinal momentum fraction $x$ at a given probe momentum $Q$. PDFs are not currently calculable from theory so they must be fit to experimental data, in particular data from deep-inelastic electron-proton scattering. Figure 2.2 illustrates the region of parameter space which has so far been probed by experiment.

Various techniques are used to fit PDFs for the proton from the experimental data. Here we give the example of the CT10 PDF set [20] which will be used later in the thesis to compute a prediction of the isolated prompt photon cross section at NLO. Experimental results from the following processes (and experiments) are used as ingredients: combined neutral and charged current deep-inelastic scattering (HERA), the nucleon structure functions $F_2$ (BCDMS, NMC, CDHSW, CCFR, H1, ZEUS) and $F_3$ (CDHSW, CCFR), di-muon production in neutrino scattering (NuTeV, CCFR), the differential Drell-Yan cross sections (E605, E866), W decay lepton asymmetry (CDF-I, CDF-II, DØ-II), jet production cross sections (CDF-I, CDF-II, DØ-II), and Z rapidity distributions (DØ-II, CDF-II). Each experiment is given an equal weight in the combination. Systematic errors are assumed to be uncorrelated between experiments since carrying out a global systematic study across so many different experimental setups would be impractical. The QCD differential (when appropriate) cross section calculation is carried out for each process at NLO, excepting the convolution with the PDFs. The PDFs are varied and a central value is obtained which gives the best (minimum) $\chi^2$ with the data sets. In addition to the central value, a set of eigenvectors is provided.
which represent a 90% confidence level with respect to the data, in order to allow
the uncertainty on the PDF to be computed.

LHC measurements are beginning to add to our understanding of the PDFs
at high $Q^2$ and the inclusive photon cross section measurement is an example of
one that could constrain the PDFs, though inclusive photon data are currently
not used in the PDF fitting process due to difficulties in the experimental data at
large $x$ (See Section 2.3). An example of fitted PDFs for two different values of $Q^2$
is shown in Figure 2.3. Two features stand out. First, as the probe momentum
increases, the fraction of the total momentum carried by the valence $u_v$ and $d_v$
quarks decreases with respect to the fraction carried by the virtual “sea” of other
particles inside the proton. Secondly, the high $Q^2$ PDF is dominated by the gluon
(which is much larger than the others even when divided by a factor 10). The
implication for LHC physics is that the most dominant production processes will
be those with gluons in the initial state, and therefore, constraining the gluon part
of the PDF is important to a broad range of physics analysis.

Fragmentation functions are used to describe the final state distribution of
single particles given an initial state. They are used to parameterize the results
of the fragmentation process by which an outgoing parton from the QCD hard
scattering can fragment into the observed particles in the final state. Since this
fragmentation process is non-perturbative, it cannot be calculated and must in-
stead come from experimental data. Typically, $e^+e^-$ collider data are used to
obtain the fragmentation functions for a given final state particle. For example,
in the case of photons, $e^+e^- \rightarrow qq\gamma$ events are used in the framework of the Vector
Meson Dominance model to obtain the photon fragmentation functions [10].

12
Figure 2.2. The regions of $x$ and $Q^2$ probed by various colliders and fixed-target experiments at the beginning of the LHC era \cite{23}.
Figure 2.3. Distributions of $x$ times the parton fraction $f(x)$ for the constituents of the proton at $\mu^2 = Q^2 = 20 \text{ GeV}^2$ and 10,000 GeV$^2$. Results are from the MRST2006 set [23].
2.2 Computing the photon cross section

At leading order (LO) in perturbative QCD, direct photons are produced by the so-called “Compton” process $qg \rightarrow q\gamma$ and the “annihilation” process $q\bar{q} \rightarrow q\gamma$. The Feynman diagrams for these LO processes are shown in Figure 2.4. Additionally, prompt photons can be created during the fragmentation of a high momentum parton, examples of which are shown if Figure 2.5. This distinction between direct and fragmentation processes is not physically meaningful past leading order.

At leading order, we can write down the differential photon cross section as the sum of the direct and fragmentation components:

$$\frac{d^2\sigma}{dp_T^2 d\eta} = \frac{d^2\sigma^D}{dp_T^2 d\eta} + \sum_{k=q,\bar{q},g} \frac{d^2\sigma^F_k}{dp_T^2 d\eta} \otimes D_{\gamma/k}(\mu_F). \quad (2.6)$$

Here we use $\sigma^D$ for the direct part of the cross section and $\sigma^F$ for the fragmentation part. The fragmentation part depends on the parton type $k$, the fragmentation function $D_{\gamma/k}$ for parton $k$ into the photon, and the choice of the renormalization

Figure 2.4. Feynman diagrams for prompt photon production at leading order.
Figure 2.5. Fragmentation processes which contribute to the isolated photon cross section. On the left is the perturbatively calculable pointlike emission of a high momentum photon by an outgoing quark. On the right the photon is produced by the non-perturbative fragmentation of a gluon.

\(\mu_R\), factorization \(\mu_F\), and fragmentation \(\mu_f\) scales in the calculation. These three scales are conventionally chosen to be the \(p_T\) of the photon:

\[
\mu_R = \mu_F = \mu_f = p_T^\gamma.
\]  

(2.7)

The renormalization scale represents the cutoff introduced in the perturbative QCD calculation of the direct photon cross section in order to avoid the UV singularities which appear after leading order. The factorization scale likewise absorbs singularities introduced by low energy phenomena like collinear radiation which cannot be treated perturbatively in the determination of the PDFs, and the fragmentation scale performs the same purpose for the fragmentation functions.

In practice the cross section measured in collider experiments is necessarily that for isolated photon production. Experimentally, photons inside of high-\(p_T\) jets are extremely difficult to identify, and theoretically, the fragmentation processes which produce photons in or near hadronic jets are not well understood. By introducing an isolation cut on the total momentum of other final state particles in an annular region around the photon, we can minimize the dependence of the
final result on these problematic issues. In order to make a direct comparison, the isolation cut applied at the experimental level must also be introduced into the theoretical calculation in order to compare data with theory. A Monte Carlo cross section calculator can be used to make the full NLO cross section estimate, including modeling of the isolation cut at the parton level. For this thesis, we use the program JETPHOX [11] to compute the cross section. JETPHOX is a cross section integrator which uses Monte Carlo integration over the requested phase space of photon $p_T$ and rapidity in order to compute the cross section binned by both variables. It performs the computation of the parton-parton cross section for direct photon events and uses the BFG set of fragmentation functions to compute the cross section for fragmentation events. It interfaces to the standard sets of PDFs in order to allow the user to evaluate the dependence of the computed cross section on the PDF set chosen. The results of the JETPHOX program version 1.2.2 were checked against an independent calculation of the photon cross section using different integration techniques and found to be within the statistical uncertainties due to the number of points used in the integration.

2.3 History of experimental measurements

During the 1970s and 1980s, the first direct photon measurements were made at fixed target experiments and at the ISR $pp$ collider. Jet identification was difficult and controversial, especially at the relatively low center of mass energies which produced jets that were not well collimated. In contrast, photons offered a method to probe the scattering subprocesses directly without relying on jet definition algorithms. At this point in the development of QCD, the hard scattering formalism had not yet been fully confirmed and the theory faced competition from
the Consituent Interchange Model (CIM). The $\gamma/\pi^0$ ratio offered a test of QCD vs. CIM \cite{15} and the $qg \rightarrow q\gamma$ process was viewed as a test of QCD’s validity for describing strong interactions \cite{16}.

Starting in the 1980s, the development of the $SpS$ collider at CERN and the Tevatron at Fermilab enabled the study of QCD processes at higher center of mass energies and therefore over a larger reach of final state transverse momenta. At the same time, the measurement and characterization of processes involving jets was standardized. As the predictions of the QCD hard scattering formalism were confirmed and experiments turned to measuring increasingly rare processes, the focus of QCD measurements shifted away from testing the theory itself and towards using QCD to constrain the parton distributions in the initial state hadrons. Prompt photon production is sensitive to the gluon distribution inside the proton because of the initial state gluon present in the Compton subprocess. A comparison of previous measurements of direct photon production from proton beams with NLO QCD is shown in Figure 2.6.

Except for the results of the E706 Tevatron fixed-target experiment with proton and pion beams on beryllium and hydrogen targets, the results of experiments across several orders of magnitude of $x$ are in good agreement with the results of NLO QCD. It has been suggested that intrinsic transverse momentum $k_T$ of the initial partons can be introduced in the calculation to obtain better agreement with the experimental data at large $x$ \cite{19}. The intrinsic $k_T$ hypothesis leads to a smearing of the transverse momentum spectrum of the final state photons because the initial state transverse momentum is not zero. Since the photon spectrum falls approximately exponentially with the photon $p_T$, the result of this smearing would be an observed excess of low $p_T$ photons with respect to theoretical calculations.
order of the theoretical uncertainty when varying the common scale from $p_T = 2$ to $2p_T$. However, the standard choice $p_T = 2$ reproduces the data extremely well over the whole $p_T$ range in which the cross section varies by a factor $10^3$.

B. Previous world data in the light of the new data from D0 and PHENIX

As there is some overlap in $x_T$ between these new data and some of the previous ones, in particular, in the controversial 0.2 to 0.3 range previously covered by the ISR and E706 experiments, it is interesting to reconsider how the "world data" is described by theory.

We consider now the inclusive $pp$ and $p/p$ data coming from the fixed target experiments from WA70, UA6, E706, ISR, R110, R806, AFS and the isolated data from CDF. The collider data will be discussed separately. Below we shall also compare the $pBe$ data from the E706 experiment with the more recent $pp$ data of the same experiment. The comparison is done with the scales $p_T = 2$ in terms of ratios data/theory. As explained in section II A, such a scale is motivated for the fixed target and ISR range by the recent resummed calculations.

The results are shown in Fig. 6 which exhibits the striking agreement between theory and data in the whole $x_T$ range, with the exception of the E706 data. This last point has been already discussed at length for $pBe$ data in ref. [45]. Here the new features are the new D0 and PHENIX data which confirm the "world" agreement between theory and data. We emphasize the very good agreement between theory and the PHENIX inclusive data which confirms that already shown in Fig. 2.6. Previous prompt photon cross section measurements with proton beams [6]. The more recent measurements not included in this figure agree with NLO theory within their experimental uncertainties.

without $k_T$. However, other studies have argued that there is no need to introduce this complication for other experiments' data, and that the effect should anyways be too small to account for the observed difference between data and theory [6]. Overall the intrinsic $k_T$ hypothesis remains difficult to judge because there is no generally accepted method for computing the smearing effects on the observed photon $p_T$. The lack of consensus on this point has led to the exclusion of photon cross section data in the PDF fits since 1998. The results of this thesis can potentially improve our understanding of these issues in the high $p_T$, low $x$ range.
For photons with low transverse momentum ($p_T < 10$ GeV), the experimental measurements of the production cross section have typically been done at fixed target experiments. In these experiments, the electromagnetic decays of netural mesons such as $\pi^0$ and $\eta^0$ to two photons can be separated from prompt photon production on an event-by-event basis because the two photons can be detected separately and the invariant mass of the photon pair can be used to identify the photon candidates that come from neutral meson decay. However, in hadron collider experiments at higher energies, the opening angle between the two photons from meson decay is typically too small to reliably measure the invariant mass of the pair. Instead, a statistical background subtraction method is used, based on one or more template variables whose shapes differ between the prompt photon signal and the netural meson background.

Previous measurements of the isolated photon cross section at hadron colliders have used a variety of techniques to accomplish the background subtraction. Most of the recent measurements at hadron colliders have used either the EM shower shape (broader for netural meson decays than for isolated single photons) or the surrounding isolation energy in an annulus about the photon candidate (on average less for single photons) as the variables over which the background subtraction is performed. In 2009, the CDF collaboration used the measured isolation sum to subtract the background [2]. In the same year, the ZEUS collaboration used the shape of the EM shower as the handle for photon purity [12]. The DØ collaboration has used a neural net with both charged track isolation and shower shape variables to measure the photon plus $n$-jet cross sections and their ratios [3]. This thesis uses the ratio of photon conversion track momentum to the calorimeter energy of the photon candidate as the discriminating variable. In 2004 the CDF collaboration
used a similar method to measure the isolated photon cross section [4]. The main difference between that measurement and this one is that the conversion probability at CDF is of order one percent, while here the conversion probability times reconstruction efficiency is an order of magnitude higher.
CHAPTER 3

THE LHC ACCELERATOR AND THE CMS DETECTOR

In this chapter, we present the relevant features of the accelerator and the detector. We put special emphasis on the CMS ECAL and inner tracking detector since they are the most important subdetectors for the inclusive photon cross section measurement.

3.1 The Large Hadron Collider

The Large Hadron Collider is designed to investigate particle physics at the highest collision energies ever achieved, starting with the 7 TeV collision run in 2010 which provided the data used in this thesis. First, we review the physics questions which the LHC will attempt to answer. Then, we review the properties of the machine design which allow it to investigate these questions.

3.1.1 LHC physics reach

The design of the LHC is prompted by a wide range of physics topics which can be studied at a TeV-scale collider.

Investigations of QCD are a fundamental part of the physics program, and they lay the groundwork for all other measurements, since QCD is the theory which describes the initial state protons which the LHC collides. High energy jets and
photons are copiously produced by LHC collisions and they can give insight into the perturbative regime of QCD, in addition to providing tests for new phenomena like quark compositeness. The behavior of protons and their remnants in the far forward rapidities in elastic and diffractive events is an example of a topic in QCD which cannot be treated perturbatively and therefore must be investigated experimentally. The properties of strong matter can also be investigated through the analysis of LHC heavy ion collisions, where the hypothesized quark-gluon plasma is likely to be created and phenomena such as jet quenching in the dense “fireball” of quarks and gluons can be studied in detail.

Hadrons containing the $b$ quark are the heaviest known bound states and give a range of interesting phenomenology with which we can probe the parameters of the Standard Model as well as look for physics beyond it. The large cross section for $b$ production at the LHC allows a detailed investigation of this phenomenology. As the highest mass and most recently discovered Standard Model particle, the $t$ quark gives a unique perspective on Standard Model physics and shares many properties with hypothetical models for physics beyond the Standard Model, e.g. the presence of high energy leptons, jets, and large missing energy. Thus $t$ quark physics is a laboratory for the development of experimental techniques necessary to fully explore the TeV scale. Furthermore, precision measurements of the top quark mass and cross section will be possible at the LHC where the large production rate creates a top quark “factory.” The $t$ mass also gives indirect information on the mass of a Standard Model Higgs boson.

The weak vector bosons $W$ and $Z$ also give rise to a variety of interesting phenomena. Precision measurements of their properties using the very large sample produced by the LHC can test the Standard Model and can also give indirect clues
as to the nature of the electroweak symmetry breaking (EWSB). For example, the mass of the $W$ is an input to indirect limits on the Standard Model Higgs mass, and the cross section of $WW$ scattering events at high invariant mass provides a model-independent test of the scale of the EWSB. Of course, the most anticipated data on EWSB will come from direct searches for the Higgs particle, which can be discovered or excluded over the whole allowed mass range up to about 1 TeV. A number of different final states for Higgs decays will be explored, including $\gamma\gamma$, $bb$ and $\tau\tau$ at low mass, and $WW$ and $ZZ$ decay modes at high mass.

The final major piece of the physics program revolves around direct searches for new particles beyond the Standard Model. Supersymmetry (SUSY) is a popular choice for an extension of the SM, since it offers the solution to a number of outstanding theoretical problems in an elegant way. SUSY works by introducing an additional symmetry of nature, where each boson has a fermion partner and each fermion has a boson partner. SUSY, if it exists, must be a broken symmetry, since none of the superpartners have yet been observed, and therefore they must be at a much larger mass than the corresponding SM particles. SUSY can provide a candidate for the dark matter which we know makes up much of the visible universe, since the lightest superpartner could be stable. It can also offer a solution to the so-called “hierarchy problem” with the Standard Model, where the mass of the Higgs is subject to very large corrections which happen to cancel, by introducing a natural cancellation between the quantum corrections to the Higgs mass between SM particles and their SUSY partners. SUSY has a large number of free parameters and there are many different models of how the symmetry is broken. There are a correspondingly large number of ways to search for SUSY at the LHC but most of them have in common the presence of missing transverse
energy from the escaping superpartners. Next to SUSY there are a broad range of other theories for physics beyond the SM which generally try to answer the same difficulties. Examples of more exotic phenomena which may appear at LHC energies include extra spatial dimensions, Randall-Sundrum gravitons, black holes, technicolor, leptoquarks, magnetic monopoles, and many others. What all these theories have in common are relatively high mass particles, due to the fact that experiments at lower energies place lower limits on the mass scale of new physics. A high center-of-mass energy is required to probe past these limits.

3.1.2 LHC design and parameters

The LHC is a proton-proton collider located at the CERN laboratory near Geneva, Switzerland. Nominally, the LHC is designed to collide protons at 14 TeV center-of-mass energy with an instantaneous luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$. However, during the 2010 physics run, the LHC machine commissioning was still in its relatively early stages. Due to concerns about the number of training quenches required to achieve the full 14 TeV energy, the accelerator operated at an energy of 7 TeV (3.5 TeV per beam) during 2010.

In order to provide the energy and luminosity to carry out the physics program, the design of the collider must meet certain requirements. Because many of the physics processes described above are extremely rare, the luminosity must be as high as possible in order to provide large enough data samples for study. The luminosity for colliding bunches is given by

$$\mathcal{L} = f \frac{n_1 n_2}{4 \pi \epsilon \beta^*} \quad (3.1)$$

The $n_1$ and $n_2$ in the numerator represent the number of particles in the colliding...
bunches. In order to achieve the highest luminosity, it is better to collide two beams of protons instead of the proton-antiproton design used by e.g. the Tevatron collider, where the difficulty of producing and storing antiprotons places an upper limit on the achievable bunch intensities. This decision is reinforced by the large increase in the amount of momentum carried by the gluons at high $Q^2$, illustrated in Section 2.1. Because it collides particles of the same charge, the LHC cannot use the convenient beam geometry of a particle-antiparticle collider, where both beams share the same vacuum and magnet system. Instead, the LHC uses dual bore magnets in the bending sections which carry two independent sets of magnet coils and beam channels [14].

In order to exert the tremendous magnetic fields required to steer particles at energies of 7 TeV, the LHC design pushes the boundaries of magnet technology. There are a total of 1232 main dipole magnets used to steer the beam around the nearly 27 km LHC ring. Most extant accelerators use fields of less than 5 T and can therefore operate above 4.2 K, but the NbTi cables used in LHC magnet coils must be operated at more than 8 T and therefore must be cooled to superfluid helium temperatures of around 2 K. The use of superfluid helium results in a substantial loss of heat capacity, so the system must be carefully engineered to avoid magnet quenches due to beam losses [14].

The $f$ in Equation 3.1 represents the collision frequency. The LHC beam is captured and accelerated by a 400 MHz superconducting cavity section which is also responsible for damping any longitudinal oscillations resulting from the injection. Each of the two beams requires its own RF system. The LEP approach of using niobium sputtered RF cavities has been adopted, but the power requirements are substantially larger than for previous superconducting cavity systems.
Each cavity is driven by an independent klystron in order to avoid coupling between the cavities [14]. The RF system captures the beam in bunches with a minimum time separation of 24.95 ns, and the bunch length is about 7.5 cm.

The vacuum system must meet stringent requirements in order to limit both the amount of beam losses into the superconducting magnets, and the amount of beam gas background suffered by the experiments. Gas densities must be below $10^{15}$ equivalent hydrogen molecules per cubic meter in the main part of the vacuum system for the first purpose, and below $10^{13}$ in the areas near the experiments for the second. The vacuum coatings must be resilient to the dose of synchrotron radiation received in the bending sections, and they must also be treated with circulating beams to limit the number of free electrons migrating out of the bulk beam pipe material along the potential introduced by the presence of the proton beam. Dedicated “scrubbing” runs are used to accomplish this goal [14].

The $\epsilon$ in Equation 3.1 represents the emittance, a measure of the transverse size of the beam. Beam focusing is accomplished primarily by the 506 quadrupole magnets. In addition to the quadrupoles, there are a variety of other corrector magnets which make higher order corrections to the beam orbit and focusing. At nominal luminosity, the focusing system is capable of maintaining beam emittances of 3.75 $\mu$m in both transverse directions. The $\beta^*$ in Equation 3.1 represents the amplitude function at the collision point, which must be made as small as possible to increase the instantaneous luminosity. The final focusing of the beam at the two high-luminosity interaction points at ATLAS and CMS is performed by a quadrupole triplet structure capable of focusing the beam down to $\beta^* = 0.5$ m.

During the 2010 run, the LHC machine parameters were constantly evolving to increase the luminosity. The majority of the data used in this analysis was
collected at the final 2010 instantaneous luminosity of about $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$, where the bunch intensity was $1.22 \times 10^{11}$ protons, there were 368 bunches per beam (348 colliding in CMS), $\epsilon$ of 2.4 $\mu$m, and $\beta^*$ = 3.5 m.

Protons are delivered to the LHC by an injection chain consisting of most of CERN’s major accelerators. The protons begin in the Linac 2, which provides 1 Hz pulses of up to 175 mA at 50 MeV energy. From there they are injected into the PS Booster, which consists of four stacked identical rings. There they are accelerated to 1.4 GeV. At this stage, the (nearly) final transverse and longitudinal bunch characteristics have already been achieved. From the PS Booster, the beams are then sent to the Proton Synchrotron (PS) and then to the Super Proton

Figure 3.1. The CERN accelerator complex.
Synchrotron (SPS) for acceleration to LHC injection energy, 450 GeV. The full accelerator complex is displayed in Figure 3.1.

3.2 The Compact Muon Solenoid detector

CMS is a multipurpose apparatus for analyzing the particles produced in LHC collisions. Its experimental scope includes all of the physics topics listed in Section 3.1.1. This ambitious physics program and experimental environment at the LHC imply that the detector should have:

- Muon identification, momentum measurement, and accurate charge measurement up to muon momenta of about 1 TeV.
- Charged particle momentum measurement and efficient track reconstruction, including triggering on and tagging of displaced vertices from e.g. $b$ and $\tau$ decays.
- Excellent electron and photon energy resolution and efficient reconstruction and isolation of electrons and photons even at high luminosities.
- Good missing transverse energy (MET) and dijet-mass resolution.

The CMS detector is designed to meet these requirements [5]. In this section we will review the components of the CMS detector which are used in the photon cross section measurement.

The coordinate system used in CMS is as follows (neglecting the small tilt of the LHC plane):

- The $x$ axis is horizontal, and points south towards the center of the LHC.
- The $y$ axis is vertical, and points upwards.
Figure 3.2. Schematic of the CMS detector [5]. The coordinate system definitions are overlaid at right.

- The $z$ axis is horizontal, and points west along the beam direction towards the Jura mountains.
- The origin of the coordinate system is at the center of the CMS detector, at the nominal collision point.
- The polar angle $\theta$ is measured with respect to the $z$ axis: $\theta = 0$ is the positive $z$ axis, and $\theta = \pi$ is the negative $z$ axis.
- The azimuthal angle $\phi$ is measured in the $xy$ plane: $\phi = 0$ is the positive $x$ axis, $\phi = \frac{\pi}{2}$ is the positive $y$ axis, and $\phi = \text{atan2}(y, x)$.
- The pseudorapidity $\eta$ is defined as $\eta = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right]$. The pseudorapidity closely approximates the true rapidity $y = \frac{1}{2} \ln \frac{E+\not{p}_t}{E-\not{p}_t}$. The sign of $\eta$ is the same as the sign of $z$.

A schematic view of the detector with overlaid coordinate system definitions is presented in Figure 3.2.
Figure 3.3. Schematic of the CMS magnet, showing the five cold mass modules and the supporting tie rods [5].

3.2.1 Magnet system

The CMS superconducting magnet provides a strong magnetic field of 3.8 Tesla with a free bore of 6 meters. This strong field allows the experiment to maintain good transverse momentum measurement and charge identification up to high $p_T$ in a relatively compact volume.

The CMS magnet, shown in Figure 3.3 differs from magnets in previous HEP experiments in three main ways:

- The very high field value requires a winding in four layers, as opposed to the single or double layers used in other experiments.
- Because of the large stresses on the coil, the conductor cable is co-extruded
with an aluminum insert for mechanical reinforcement.

- The solenoid is very large: 6 m free bore, 12.5 m length, and 220 T weight.

The inner tracking detector and calorimeters are situated inside the bore of the magnet. Outside the magnet, a 10000 T iron return yoke contains the magnetic field. The muon detectors are embedded in this return yoke. In this analysis, the magnet provides the magnetic field that is used to measure the transverse momentum of charged tracks, including the tracks of the $e^+e^-$ pair and the charged tracks of hadronic activity in the isolation annulus.

3.2.2 Inner tracking detector

The CMS inner tracking detector is designed to perform a precise and efficient measurement of the position and momentum of charged tracks as well as to measure the location of secondary vertices from particles which decay in flight. Taken as a whole, the system surrounds the interaction point in a cylindrical volume with 5.8 m length and a radius of 1.25 m. Within this volume, the magnetic field provided by the CMS solenoid is a homogeneous 3.8 T [5]. The harsh LHC experimental environment (order $\times 10^3$ tracks every 25 ns) places demanding performance requirements on the tracking system, namely, a high granularity and a fast time response. The tracking system must also be sufficiently radiation-hard to survive the integrated dose accumulated over years of LHC operation (more than $3 \times 10^{15}$ cm$^{-2}$ fast hadron fluence at the innermost layers for 500 fb$^{-1}$ of integrated luminosity). Unfortunately, these attributes imply a high power density, which in turn requires a powerful cooling system. This increases the amount of material inside the detector, and this material is a medium for multiple scattering, nuclear interactions, bremsstrahlung, and photon conversion. The total tracker material

32
Figure 3.4. The material budget of the inner tracking system in units of radiation length \(X_0\) as a function of the pseudorapidity \(\eta\) [5].

The design chosen by CMS to satisfy the experimental requirements is an all-silicon inner tracking detector, consisting of cylindrical layers of pixels at small radius \((4.4 < R < 10.2\,\text{cm})\) and strips at larger radius, extending up to a radius of 1.1 m. The cylindrical barrel layers are complemented by endcap disks for both the strips and pixels, which extend the pseudorapidity coverage of the tracking system up to \(|\eta| < 2.5\). In total the system is composed of over 200 m\(^2\) of active silicon area, and it is the largest such device ever constructed.
Figure 3.5. The number of hits per track as a function of the pseudorapidity $\eta$ [5]. The closed circles show the total number of hits, while the open squares show the number of hits on the stereo layers.
Figure 3.6. Transverse momentum resolution for muons with $p_T$ of 1, 10, and 100 GeV as a function of $\eta$ [5].
Figure 3.7. Transverse impact parameter resolution for muons with $p_T$ of 1, 10, and 100 GeV as a function of $\eta$. 

[Diagram showing the transverse impact parameter resolution with legend indicating different $p_T$ values for muons.]
Figure 3.8. Longitudinal impact parameter resolution for muons with $p_T$ of 1, 10, and 100 GeV as a function of $\eta$ [5].
In order to achieve the desired performance, it is necessary to keep the occupancy of the silicon detectors at or below about 1% at design luminosity. For the pixel detector, the physics requirements on impact parameter resolution dictate a pixel size of about $100 \times 150 \mu m^2$ and this results in an occupancy of about $x \times 10^{-4}$ per bunch crossing. For $20 < R < 55$ cm, silicon microstrips can be used, and with a typical cell size of $10 \text{ cm} \times 80 \mu m$, the occupancy is at the 2-3% level. This part of the detector is referred to as the Tracker Inner Barrel (TIB) in the barrel region and Tracker Inner Disks (TID) in the forward region as shown in Figure 3.9. For $R > 55$ cm, even larger strips can be used, up to a cell size of about $25 \text{ cm} \times 180 \mu m$ with an occupancy of about 1%. This part of the detector is called the Tracker Outer Barrel (TOB) in the barrel region and the Tracker End Cap (TEC) in the forward region as shown in Figure 3.9. The strip size choices driven by occupancy considerations also yield a position hit resolution which is sufficient for the physics goals of the experiment [5]. The modules in the first two layers of TIB and TOB, the first two rings of TID, and the rings 1, 2, and 5 of TEC have a second layer of sensors mounted at an angle of 100 mrad to the first. These stereo layers allow a measurement along $z$ in the barrel and $r$ in the endcap with resolution on the order of a few hundred microns. The increased three-dimensional precision of the hits in the stereo layers improves the overall track parameter resolution. The number of hits per track as a function of $\eta$ is shown in Figure 3.5. The $p_T$ resolution, transverse impact parameter $d_0$ resolution, and longitudinal impact parameter $dz_0$ resolution are shown in Figures 3.6-3.8.
3.2.2.1 Pixel detector

The primary purpose of the CMS pixel detector is to provide highly precise secondary vertex position resolution, for example to reconstruct the displaced secondary vertex from the decay of a $B$-hadron. To achieve this goal, the hit position must be well measured in both the $r - \phi$ and $z$ directions. The pixel cell size of $100 \times 150 \mu\text{m}^2$ has been chosen to provide the necessary resolution. The pixel system covers the pseudorapidity range $-2.5 < \eta < 2.5$. It has three cylindrical barrel layers (BPIX) and two endcap disks (FPIX). The arrangement of the barrel layers and endcap disks is shown in Figure 3.10 along with the efficiency for a track to leave at least two hits in the pixel detector as a function of pseudorapidity. Because of the large radiation flux through the pixel detector, the mechanical support and service cabling are designed for yearly access if needed. It is envisioned that the pixel detector should stay operational and reasonably...
efficient for about two years of operation at full LHC luminosity before it must be replaced [5].

The CMS pixel detector uses “n-on-n” sensor technology, which consists of a high dose n-implant in a high resistance n-substrate. The pn-junction is placed on the back of the sensor, surrounded by multiple guard rings which keeps the sensor edges at ground. This structure was chosen to maintain a large signal at a reasonable bias voltage even after a large dose of radiation [5].

The pixel sensors are read out in several steps. First, the sensor signals are read out by a Read Out Chip (ROC) which is bump bonded to the sensors themselves. It is a full custom ASIC and serves 52 × 80 pixels. It simultaneously performs several jobs: amplification and buffering of the charge signals from the sensors, zero suppression of signals below a certain noise threshold, Level-1 trigger verification (hit information is thrown out without a corresponding Level-1 accept from the trigger system at this point), sending the hit information upstream to the Token Bit Manager (TBM) chip, and controlling the voltage, current, and offset values to compensate for chip-to-chip variations in the performance parameters. Next, the data arrives at the TBM, which is responsible for the read-out of a group of ROCs. The TBM is located on-detector near the ROCs. The TBM performs several functions. It initiates data collection from the ROCs upon receipt of a Level-1 trigger, writes data headers and trailers to the data stream (containing event number and error status), and transmits the Level-1 information and clock information to the ROCs. In the second step of the readout, triggered data are sent to the front-ends (FEDs) of the CMS data acquisition (DAQ) system. The data are converted into optical signals by the analog optical hybrid (AOH) system. These signals are sent along optical cables to the FEDs, 9U VME modules which
Figure 3.10. The layout of the pixel detector showing the pseudorapidity coverage of the barrel and forward pixel detector (top), and hit coverage vs. $\eta$ (bottom) [5].
are located approximately 100 m off the detector in the off-detector electronics room. Once they reach the FED, the analog optical signals are digitized and stored in a FIFO awaiting readout by the CMS DAQ via an S-Link connection [5].

3.2.2.2 Silicon strip tracker

The active elements of the silicon strip tracker are single sided $p$-on-$n$ silicon microstrips. Strip shaped diodes are formed by $p^+$ implants into the $n$ bulk. Sensors are either ‘thin’ (320 $\mu$m, used in TIB/TID/inner TEC) or ‘thick’ (500 $\mu$m, used in TOB and outer TEC). There are a total of 15,148 detector modules with either a single thin or two thick sensors for a total of 24,244 sensors. These modules are supported by carbon fiber or graphite frames depending on their position within the tracker. In order to cover the available space fifteen different sensor geometries are used, as depicted in Figure 3.11. Each sensor has either 512 or 768 strips depending on its size, reflecting the read-out unit size of 256 strips [5].

The signals from the strips are amplified and shaped by a custom integrated circuit and then stored on the detector waiting for an accept from the Level-1 trigger system. When an accept is received, the analog signals are multiplexed and then transmitted via optical fiber to the tracker FEDs, located off-detector in the CMS service cavern. Clock and control signals are also sent by optical fiber from the off-detector control module (CCU). Once they arrive at the FED, the signals are digitized and processing such as pedestal subtraction and noise suppression is performed. Performing these steps off-detector allows for improved monitoring of the analog to digital conversion step, and also reduces the need for additional custom radiation-hardened electronics installed on the detector itself [5].
In order to obtain the best performance, the tracker must be operated below -10 °C, while the total power dissipated by the system during operation is around 60 kW. In order to cool the detector, a single-phase C₆F₁₄ cooling system is used to carry the heat off the detector. C₆F₁₄ is chosen because its properties match the requirements for the cooling system. It has sufficiently low viscosity down to the lowest temperatures required in the system (-35 °C). It is extremely volatile, and therefore the amount of residue left by accidental leaks is minimal. Additionally, it does not exhibit any undesirable behavior under irradiation. In total the cooling system moves about 77 cubic meters of C₆F₁₄ through the detector each hour, with a cooling capacity of up to 128 kW. In addition to the cooling system, the detector volume is flushed with dry nitrogen gas at a rate of one volume per hour. Finally, in order to thermally isolate the very cold tracker volume from the rest of the experiment, an active thermal screen is installed between the outer surface of the tracker and the inner surface of ECAL. This screen consists of cold C₆F₁₄.
circulated inside a thin aluminum plate on the inner surface, polyimide-insulated resistive heating elements on the outer surface, and 8 mm of Rohacell foam forming a thermal barrier in between. 64 temperature sensors spread over the surface of the screen provide feedback which controls the operation of the system to maintain constant temperatures on both sides [5].

Since good spatial alignment is important to the physics performance of the tracking detector, several methods are used to confirm the position and orientation of the detector elements. During detector assembly, the relative positions of the detector elements were carefully measured. However, effects such as magnetic field stresses, mechanical stresses during detector access, cooling-induced deformations, and outgassing of tracker components in the dry nitrogen environment all contribute to time-dependent fluctuations in the tracker alignment. A laser alignment system is used to track these changes. It uses infrared beams with \( \lambda = 1075 \) nm to monitor the position of some modules. It generates alignment information on the position of the different mechanical substructures of the tracker (TIB, TOB, and TEC) continuously. Selected modules are penetrated by a 10 mm hole in the backside metallization, coated with an anti-reflective coating to allow the infrared beams to penetrate the sensor. The location and intensity of the laser-induced signals can be used to determine the relative alignments of the various tracker components. Finally, the most accurate and detailed alignment is done using tracks in data. Various computational approaches are used to solve the system of \( O(100,000) \) alignment equations using tracks in collision data. Tracks in collision data are supplemented by collision runs with the CMS magnet turned off, and by cosmic ray data both with and without magnetic field [5].
3.2.3 Electromagnetic calorimeter

The CMS electromagnetic calorimeter is the most important subdetector for measuring the photon cross section. It is a hermetic and homogeneous total absorption calorimeter. It consists of a cylindrical barrel component made up of 61,200 lead tungstate crystals (PbWO$_4$) and two endcaps each consisting of 7,324 crystals. Lead tungstate is chosen for its unique properties, which are well suited to electromagnetic calorimetry with good energy resolution in the challenging LHC environment. The primary characteristics of lead tungstate that are important to the CMS physics goals are as follows:

- High density (8.28 g/cm$^3$) and consequently short radiation length (0.89 cm) allow the calorimeter to be compact along the direction of the shower axis, allowing for the compact design of CMS without sacrificing ECAL performance.

- Small Molière radius (2.2 cm) allows for fine granularity of the crystals, especially useful for pattern recognition at high luminosity.

- Optical clarity of the crystals allows for efficient collection of the relatively low light yield of lead tungstate.

- Fast scintillation decay time is similar to the 25 ns bunch spacing at nominal LHC luminosity; 80% of scintillation light is emitted inside of 25 ns.

- Radiation hardness to cope with the challenging radiation doses from LHC operation.

However, along with its desirable properties, lead tungstate also imposes some difficulties:
• Low light output (about 4.5 photoelectrons per MeV) means that optical properties of the crystals must be tightly controlled in order to maximize the internal reflection of scintillation light while minimizing non-uniformities due to shower location within the crystal.

• Lead tungstate scintillation light yield is highly temperature-sensitive (the yield varies by approximately 2% per degree Celsius of temperature change) so the temperature of the crystal bulk must be carefully controlled.

• Though the crystals are mostly resistant to permanent radiation damage, they tend to temporarily lose transparency under irradiation by the formation of color centers in the crystal matrix which absorb some of the scintillation light output. The transparency change and the annealing process by which the color centers disappear both occur on the timescale of a single LHC fill (typically eight hours or more) and so the transparency of the crystals must be carefully monitored during running to maintain the best possible performance.

The ECAL energy resolution is shown in Figure 3.12. It is about 0.5% at 50 GeV. The excellent energy resolution is useful especially for the $H \rightarrow \gamma\gamma$ decay mode, where a small resonance must be observed above a large continuous background. The ECAL energy resolution directly determines the sensitivity of this analysis. In the following sections we examine the design of the ECAL in detail to observe how this performance is achieved.

3.2.3.1 Mechanical design

The ECAL is organized into three major components: the barrel ECAL (EB), the ECAL endcap (EE) and the ECAL preshower detector (ES). The overall layout
Figure 3.12. ECAL barrel energy resolution measured with test beam electrons [5]. Stochastic (S), constant (C) and noise (N) terms are extracted from a fit to the data.

\[
\begin{align*}
S &= 2.8 \text{ (\% (GeV)}^{\frac{1}{2}} \\
N &= 0.12 \text{ (GeV)} \\
C &= 0.3 \text{ (\%)}
\end{align*}
\]
of these components is shown in cutaway view in Figure 3.13.

The barrel ECAL covers the pseudorapidity range $|\eta| < 1.479$. Each crystal subtends $1^\circ$ in $\phi$ and $1.479/85$ in $\eta$ yielding 61,200 total barrel crystals. Each crystal is slightly tapered with the degree of taper dependent on the $\eta$ position of the crystal. The crystals are arranged in a quasi-projective geometry where the crystal axis makes a $3^\circ$ angle with respect to the nominal interaction vertex at $(0, 0, 0)$ in the CMS coordinate system. This off-pointing is chosen to minimize the amount of showering which occurs in the small gaps between the crystals. The inner radius is at 1.29 meters from the beam line and the crystals themselves are about 23 cm long, corresponding to 26 $X_0$. In total the crystals take up 8.14 m$^3$ of volume. In the trasverse dimension, the crystal size is similar to the Molière radius ($22 \times 22$ mm$^2$) at the front face, broadening to 26 mm at the back. The crystals are held in place by 0.1 mm thick alveolar structures, formed from a
aluminum layer covered in glass fiber epoxy resin [5]. Groups of either 400 or 500 crystals, depending on the $\eta$ coordinate, are grouped into modules. Four modules are combined into a supermodule of 1,700 crystals, and each half of the barrel consists of 18 such supermodules [5].

The endcap ECAL covers the pseudorapidity range between $1.479 < |\eta| < 3.0$. The distance between the plane at $z = 0$ and the front face of the EE is approximately 3.15 m. EE crystals are slightly larger than their counterparts in the EB, with front face dimensions of $28.62 \times 28.62 \text{mm}^2$ broadening to 30 mm at the rear. They have a length of 22 cm ($24.7 \times 0$). The EE crystals are arranged into $5 \times 5$ groups, contained within a carbon fiber support structure. Each endcap consists of two semicircular “Dees” holding 3,662 crystals each. Unlike the $\eta - \phi$ geometry of the barrel crystals, the endcap crystals are arranged in an $x - y$ grid. Like the off-pointing introduced in the barrel, the endcap crystals point to a focus 1.3 m beyond the interaction point as seen from that endcap [5].

The relatively large variation in light output of lead tungstate under changing temperature conditions imposes a strict limit on the temperature stability needed to achieve the best energy resolution. The crystals must be kept within $\pm 0.05^\circ C$ of 18$^\circ C$ to attain the design performance. The ECAL must both carry away the heat generated by its own on-detector electronics and protect against changes in the ambient temperature. This is accomplished with a water cooling system which delivers water at 18 $^\circ C$ to a thermal screen between the crystals and the tracker. This water is then returned through aluminum bars placed alongside the front end electronics on the outer surface of the ECAL. In the EB, the cooling is provided to each supermodule independently, whereas in the EE the cooling is provided separately to each Dee [5].
In addition to temperature stability, the variation of crystal transparency under irradiation must be tracked in real time during ECAL physics operation. In order to accomplish this, laser pulses from off-detector lasers are sent to each region of ECAL in turn. Two wavelengths are used in order to monitor the different loss of transparency at different wavelengths. Since the laser pulse amplitude is not necessarily constant, PN diodes are used to measure the intensity of the laser light. Laser data are taken during the LHC abort gap and can then be used to compute corrections to the light measured by the photodetectors [5].

3.2.3.2 Photodetectors

The operating environment and physics goals for the ECAL place strict requirements on the performance characteristics of the photodetectors used to detect the scintillation light produced by the ECAL crystals: they must be fast, radiation hard, and functional in a 4 T magnetic field. Because of the relatively low light yield of lead tungstate crystals, they must also be highly efficient. Because of the different orientation of the crystals relative to the CMS magnetic field in EB and EE, different amplification technologies were chosen for the barrel and endcap.

In EB, the photodetectors are Hamamatsu S8148 avalanche photodiodes (APDs). They are built with so-called “reverse structure,” that is, the bulk n-type silicon is located behind the p-n junction. These APDs were specifically developed for use in the CMS ECAL. Each APD measures 5 × 5 mm and two are mounted on each crystal. The amplification uses a gain of 50 and the two APDs are read out in parallel as a single unit. They are operated at a voltage of approximately 400 V and have an effective thickness of about 6 µm. This thickness determines the size of the nuclear counter effect from minimum ionizing particles traversing the
silicon; the resulting signal corresponds to about 100 MeV of energy deposited into the crystal. Since the APD gain is highly dependent on the bias voltage (about 3%/V at gain 50) the voltage supplied must be carefully regulated at the level of tens of mV in order to get the best performance [5].

In EE, the photodetectors are vacuum phototriodes (VPTs) type PMT188 manufactured by NRIE St. Petersburg. VPTs are essentially photomultiplier tubes with a single gain stage, accomplished with an anode of fine copper mesh which allows them to operate in the 4 T magnetic field. The mean gain decreases by only about 10% when at a 15° angle to the magnetic field. The active area of the VPT is about 280 mm². The VPT sensitivity can change depending on the anode current (count rate) in tests outside of a magnetic field. Though the CMS magnetic field is expected to suppress any resulting change in the VPT gain, the VPTs are pulsed with LED light corresponding to about 50 GeV equivalent energy in the crystals at 100 Hz during operation to maintain a minimum anode current for VPT stability [5].

3.2.3.3 Readout electronics

The ECAL readout electronics chain consists of two major parts: the on-detector chain shown in Figure 3.14 and the off-detector chain shown in Figure 3.15.

The on-detector electronics are designed to acquire, amplify, and digitize the data, and then send it to the off-detector electronics. At the same time, they are also responsible for generating the trigger primitives which are used in the Level-1 trigger decision. Each electronics unit is designed to handle a 5 × 5 array of ECAL crystals. There are five Very Front End (VFE) boards, one Front End
Figure 3.14: The on-detector readout electronics of ECAL [5]. The EB readout of the APDs is presented in the figure but the EE chain is equivalent.
Figure 3.15. The off-detector electronics of ECAL [5].

(FE) board, two or six (EB or EE) Gigabit Optical Hybrids (GOH), a single Low Voltage Regulator (LVR) and a motherboard. The motherboard is connected to to 25 of the relevant photodetectors and to the temperature sensors used to monitor the temperature stability of the ECAL. In EB the motherboard also distributes the high voltage to the APDs while in the EE a separate HV card is used for this task. The LVR uses LHC specific radiation hard electronics to regulate the low voltage supply. Three Detector Control Unit (DCU) ASICs, interfaced to the FE card, provide data on all input and output voltages [5].

Signals from the photodetectors are shaped and amplified with variable gain by the Multi Gain Pre Amplifier (MGPA), which contains an RC-CR network with time constant 40 ns. It additionally contains a test-pulse generator which is used during operation to verify correct operation of the electronics. The MGPA digitizes the signals in parallel with three gains (1, 6, or 12) and the highest non-saturated gain is chosen by an integrated logic circuit. The chosen gain path is
then digitized and reported by the ADC. Once the MGPA has switched to a higher
gain it is not allowed to fall back to a lower gain during the fall time of the pulse.
The FE card then stores the digitized signals during the Level-1 trigger latency.
At the same time, an ASIC called FENIX is used to sum the signals of five-crystal
strips along the $\phi$ coordinate for triggering purposes. In EE these sums are sent
off detector to the Trigger Concentrator Card (TCC) while in EB the five strips
are summed and a fine-grain veto bit (FGVB) is calculated by comparing the
five-crystal sums to the total. The energy sum and the FGVB are then sent to
the TCC via GOH. Upon receipt of a Level-1 trigger signal, ten 40 MHz signals
are sent off detector to the Data Concentrator Card (DCC) using another GOH.
The VFE and FE boards are controlled via signals sent optically from the off-
detector Clock and Control System (CCS) boards. Fast control signals send the
Level-1 decisions along with the 40 MHz clock, while the slow control signals carry
configuration information for the FE and VFE as well as the readout of electronics
status, voltages, currents, and temperatures [5].

The off-detector electronics are located on boards sitting off-detector in VME
crates in the CMS service cavern. Both the DAQ and trigger paths are served
by this part of the system. The CCS board distributes clock, trigger, and control
signals to the on-detector electronics. The TCC board collects the trigger prim-
itives on-detector and then transmits them to the Level-1 trigger system via the
Synchronization and Link Boards (SLBs). It also transmits the trigger signals to
the Selective Readout Processor (SRP), and stores the trigger signals for reading
by the DCC. The SRP uses programmable thresholds to determine the readout
type for each trigger tower. There are two thresholds, the lower of which forces all
crystals in the trigger tower of interest to be read out without zero suppression,
and the higher of which forces that trigger tower and each of the eight surrounding towers to be read out without zero suppression. The remaining crystals are only read out if their energy exceeds a programmable zero suppression threshold. The SRP system thus allows a large reduction in the total data volume, while maintaining full read out without zero suppression in areas that will be used to reconstruct physics objects. The DCC collects the crystal data from up to 68 FE boards and also collects the trigger information from the TCC, the selective read-out decision from the SRP, and the laser intensity data from the PN diodes. The DCC then applies the zero suppression to the data according to the SRP flags and the zero suppression settings [5].

3.2.3.4 ECAL preshower detector

In front of the EE in the range $1.653 < |\eta| < 2.6$ there is an ECAL preshower detector (ES). The primary goal of the ES is to provide additional background rejection power for e.g. $\pi^0 \rightarrow \gamma\gamma$ decays which can fake the signature of an isolated photon. The high granularity of the sensors can also provide handles for distinguishing between electrons and minimum ionizing particles, and adds additional position resolution for the location of endcap EM showers. The ES is a sampling calorimeter with two layers. Each layer consists of a lead radiator to induce incoming EM particles to shower, and a set of silicon strip detectors which measure both the energy and the shower shape. The total thickness of the assembly is about 20 cm. The total material thickness corresponds to about 3 $X_0$ at the outer edge. The silicon sensors in each of the two preshower layers are oriented orthogonally to each other so as to provide precise determination of the shower location and extent along the CMS $x$ and $y$ coordinates. The silicon
layers are divided into sensors with size $6.3 \times 6.3 \text{ cm}^2$, divided into 32 strips with 1.9 mm pitch. In total there are about 137,000 individual strips to be read out. The data from the silicon strips are digitized on detector and then sent via GOH to the off-detector preshower DCC for readout. The preshower DCC is a variant design of the ECAL DCC and performs the functions data deserialization, pedestal subtraction, noise suppression, and time alignment of the signals in preparation for sending the data to the CMS DAQ [5]. In this thesis the ES is primarily used to provide energy corrections to photon candidates falling inside its coverage range.

3.2.4 Hadronic calorimeter

The CMS hadronic calorimeter (HCAL) is used to measure the energy of hadronic jets and complements the ECAL in the calculation of the missing transverse energy in each event. A schematic of the overall layout of the HCAL and its components is shown in Figure 3.16 In this thesis the HCAL is used to compute the sum of the hadronic activity around the photon candidate and to discriminate between photon candidates and hadronic jets.

The barrel HCAL (HB) covers the range $|\eta| < 1.3$. It consists of two half-barrels, each divided into 18 identical azimuthal wedges each covering 20° of $\phi$. It is a sampling calorimeter with alternating layers of metal absorber and scintillating tiles. The absorber consists of an initial 4 cm of steel plate before the first active layer, and then eight 5.05 cm thick brass plates, six 5.65 cm thick brass plates, and a 7.5 cm thick steel backplate. In total the HB is about 5.8 hadronic interaction lengths ($\lambda_I$) at 90°, increasing to 10.6 interaction lengths at the end of the barrel. The ECAL provides about one hadronic interaction length of additional material. The endcap HCAL (HE) covers the range $1.3 < |\eta| < 3$. The absorber material
Figure 3.16. The layout of the CMS HCAL and its subcomponents: HB (barrel HCAL), HE (endcap HCAL), HF (forward HCAL) and HO (outer barrel HCAL) are labeled in the figure [5].

in HE is provided by 7.9 cm thick layers of brass. Including the EE in front of it, the total depth of the endcap calorimeter system is about 10 interaction lengths. The scintillating tiles of both HB and HE are arranged in a staggered geometry to ensure that there are no projective gaps in coverage within each azimuthal wedge. These tiles are arranged into readout towers with dimensions $0.087 \times 0.087$ in $\eta - \phi$ space, except in the forward region ($|\eta| > 1.6$) where the segmentation decreases to $0.17 \times 0.17$ [5].

Scintillation light is brought out of the detector volume by wavelength shifting fibers. The fibers absorb the scintillation light from the surrounding scintillator and then shift the wavelength of the light to avoid re-absorption of the light by the scintillating material. In total there are approximately 70,000 scintillating tiles to be read out. The scintillating material in HB is 3.7 mm thick layers of Kuraray SCSN81 plastic scintillator, chosen for its chemical stability and radiation hard-
ness. The light from each tile is collected by a double-cladded wavelength shifting fiber (Kuraray Y-11) which is laid into a machined groove in the scintillator tile. After exiting the tile, the light is transmitted into a clear fiber and then into an optical cable. The light from all tiles in an HCAL readout tower is brought to an optical decoder unit which delivers the light to a hybrid photodiode for readout. Additional fibers are used to deliver laser light for HPD calibration. In general there is no longitudinal segmentation of the readout, except in the last two towers of HB, where there are two separately read out layers. The HE functions in the same way, except that most towers have two layers of longitudinal segmentation in the readout, and the last two rows of towers have three layers [5].

Analog signals output from the HPDs are collected and converted to a digital signal by a charge integrator and encoder, and combined with detector monitoring data to form 32-bit words. These words are sent at 40 MHz to a GOL which converts them into optical data and sends them off-detector to the service cavern. There, a HTR (HCAL Trigger and Readout) board receives the data, produces HCAL trigger primitives for transmission to the Level-1 trigger system, and stores the data during the Level-1 trigger latency. When the HTR receives a Level-1 trigger from the CMS TTC system, it prepares a programmable number of time samples of HCAL readout for transmission to the CMS DAQ and sends them to the HCAL Data Concentrator Card (DCC). The DCC collects information from up to 36 read out channels and then transmits them to the DAQ [5].

The forward hadron calorimeter (HF) is used in this thesis primarily to monitor the instantaneous luminosity delivered by the LHC to CMS. The HF consists of a steel absorber structure with longitudinal quartz fibers as the active material. These materials were chosen to withstand the tremendous radiation dose expected
in HF (about 10 MGy after 10 years of nominal LHC operation). HF is a cylindrical structure with an outer radius of 130 cm and covers approximately $3 < |\eta| < 5$. HF uses the Cherenkov light induced by shower particles to measure the energy of showers. High energy charged particles emit Cherenkov light in quartz when above the Cherenkov threshold, and since this threshold is lower for electrons than for heavier particles with the same energy, HF is mainly sensitive to the EM component of showers. Long fibers (which extend over all 165 cm or 10 $\lambda_I$ of the detector) alternate with short fibers (which are 22 cm shorter). Since electrons and photons tend to shower in the first 22 cm, the difference between the light collected with the long and short fibers provides some discrimination between EM and hadronic showers. Individual fibers are collected into calorimeter towers of $20^\circ$ in $\phi$ and variable size in $\eta$ and read out by PMTs situated in a shielded area behind the HF for transmission to the HCAL DAQ system \cite{5}.

The jet $p_T$ resolution as a function of the jet transverse energy is shown in Figure 3.17. The resolution is about 20% at 50 GeV and reaches 10% by 300 GeV.

3.2.5 Muon system

The CMS muon system is not used in the inclusive photon cross section measurement. However, since it was a driving feature of the overall CMS design we briefly mention its most important aspects here. Muon detection is critical for the experiment since the backgrounds to interesting physics signatures are much lower relative to processes containing electrons, photons, jets, or missing energy in the final state. In addition the invariant mass resolution for signatures containing multiple muons (e.g. $Z' \rightarrow \mu\mu$ or $H \rightarrow ZZ \rightarrow 4\mu$) is better than the
Figure 3.17. Jet energy resolutions for the barrel, endcap, and forward HCAL. Jets shown are reconstructed with an iterative cone algorithm with radius $\delta R = 0.5$ \[5\].
corresponding electron signatures because muons interact relatively little with the detector material. The system is designed using three complementary technologies to meet the challenge of muon identification, momentum measurement, and triggering. The high magnetic field in the CMS return yoke aids the momentum determination and triggering capabilities. Like the other CMS subdetectors, the magnetic field geometry implies a cylindrical barrel element supplemented by two endcap disks. In total there are about 25,000 square meters of active detection plane spread through the return yokes [5].

In the barrel region $|\eta| < 1.2$, drift chambers with rectangular cells (DTs) are used. They consist of four stations at increasing radial distance from the beam line. The first three stations have sets of drift tubes along $\phi$ and $z$ while the final station does not measure the $z$ coordinate. In addition to the fine spatial resolution, the DTs provide excellent time resolution in order to correctly assign the muons to the correct LHC bunch crossing. In the endcap region $0.9 < |\eta| < 2.4$, cathode strip chambers (CSCs) are used. They have the fine segmentation, radiation hardness, and fast response necessary to measure muons with good resolution in the forward region where backgrounds are higher and radiation damage is of more concern. The cathode strips run radially outward and provide measurement in the bending plane while the anode wires run perpendicular to the strips and provide measurements along the $\eta$ coordinate as well as good time resolution. There are four stations of six layers each in both of the CMS endcaps. Since there are over 16 hadronic interaction lengths of material in front of the muon system, there is relatively little hadronic punch-through [5].

The DT and CSC systems are complemented by a dedicated system of resistive plate chambers (RPCs) which form an independent triggering system with good
spatial and $p_T$ resolution. They offer independent and redundant coverage of the barrel and part of the endcap region, $|\eta| < 1.6$. The RPCs are double-gap chambers run in the avalanche mode. Their presence is also helpful in the resolution of ambiguities in muon reconstruction due to multiple hits in a chamber. Six RPC stations are present in the barrel yoke and three in each endcap disk [5].

The muon system $p_T$ resolution is shown in Figure 3.18 both separately and combined with inner tracker measurements. In the central region the $p_T$ resolution ranges from less than 1% at 10 GeV up to about 5% at 1 TeV. In the endcap region the resolution ranges from about 2% at 10 GeV up to about 10% at 1 TeV.

Figure 3.18. Muon $p_T$ resolution ($\delta(p_T)/p_T$) as a function of $p_T$ for the barrel and endcap muon systems. [5].
3.2.6 Level-1 trigger

Due to the high (40 MHz) rate of $pp$ interactions delivered by the LHC, one of the most difficult experimental challenges is the triggering of the CMS detector. In order to store and process the data a drastic reduction in the event rate must be achieved online during operation. The CMS trigger system solves this challenges with a two-tiered structure, consisting of the Level-1 trigger and the High Level Trigger (HLT).

The Level-1 trigger consists of programmable, custom-designed electronics which reduce the rate of incoming events from 40 MHz to about 100 kHz. In general, the approach is to use coarse information from the calorimeters and the muon system to identify potentially interesting events which are then passed on to the HLT. During the latency of the Level-1 trigger, the full event data are held...
in buffers awaiting the trigger decision. At the most basic level, the calorimeters and muon detectors produce trigger primitives (TPs) which correspond to energy deposits in the calorimeter towers and track segments in the muon system. The TPs are then sent to a regional trigger processing, where trigger primitives are combined using pattern recognition algorithms to produce Level-1 trigger objects like $e/\gamma$, jet, or muon candidates. The trigger objects of each type are sorted according to energy/momentum and object quality in limited spatial regions, and then they are sent to the global calorimeter trigger (GCT) or global muon trigger (GMT) for the final sorting. These global triggers determine the overall rank for each trigger object and send the top candidates to the global trigger (GT) for the final Level-1 decision. A schematic view of the Level-1 trigger logic is shown in Figure 3.19. The GT is responsible for determining the final Level-1 trigger decision based on the trigger information as well as feedback from the CMS DAQ on its state of readiness to accept additional events. The total time allotted for each decision is only 3.2 $\mu$s so the processing is pipelined to achieve fast and nearly deadtime-free operation [5].

3.2.7 Data acquisition and High Level Trigger

The DAQ system is responsible for accepting the incoming data at up to 100 kHz. Since individual events are approximately 1 MB in size, and the output rate of the DAQ system is a few hundred Hz, the system must be capable of processing and filtering up to 100 GB/s of incoming data to achieve a rate reduction of an additional 1000 times relative to the Level-1 system. A schematic view of the architecture which accomplishes this task is shown in Figure 3.20. When a Level-1 accept is transmitted to the subdetectors, the data are extracted from
Figure 3.20. Schematic view of the data acquisition and High Level Trigger system [5].

the FEDs of the individual subsystems. Nearly 650 FEDs are needed to read out all subsystems. Individual data fragments from each FED are aligned in bunch crossing number and combined by an event builder and then transmitted to the Event Filter for processing. In order to avoid overfilling the buffers of the individual FEDs because of variations in event content and processing time, the DAQ is capable of exerting backpressure on the system by throttling the rate of Level-1 triggers if necessary.

The main purpose of the Event Filter is to perform nearly offline-quality reconstruction of selected parts of the event content in order to select the events which will be permanently stored. This functionality, performed entirely in software, makes up the High-Level Trigger (HLT). One advantage of using a software-only HLT is that commercial CPUs can be used to build the system, which minimizes the cost of the system while allowing it to evolve along with the capabilities of commercially available parts. Another is that the algorithms have access to the full event data, so any selection which can be performed offline can also be programmed into the HLT. There is no limitation to the sophistication of the se-
lections which can be performed. The main challenge of such a system is that the CPU time of HLT processes must be carefully monitored and controlled to avoid overwhelming the system, especially given the high Level-1 input rate. Though it functions as a single system, the HLT has some internal substructure. The so-called “Level-2” trigger has access to the calorimeters and muon systems only, while “Level-2.5” includes matching between these and the pixel system. Only at “Level-3” is the full tracking made available. This division allows the trigger to function more efficiently by only unpacking the full event if the previous levels accept the event. Regional and conditional unpacking of the event reduces the CPU time needed to generate an accept.

The Event Filter performs a number of other crucial tasks, including a basic consistency check on the data, the generation and collection of data quality information, routing a subset of events to local storage for calibration and related purposes, and finally transferring the data away from the CMS site for offline reconstruction elsewhere. To make the system more robust, the DAQ is organized into up to eight autonomous “slices” which run more or less independently, and the number and size of the slices can be scaled up to meet the increased computing needs of higher LHC luminosities. On top of the main event processing path, the DAQ system also includes a variety of control and monitoring systems which allow human operators to steer and troubleshoot the operation of the system.

3.3 CMSSW software

The CMSSW software is used for a large variety of tasks inside the experiment. It is used online in the High Level Trigger to process and select events, to produce data quality monitoring information as the data are taken, to process calibration
and alignment data for the experiment, to perform offline reconstruction of the data, to produce simulated data samples, and for physics analysis of the data. In addition to performing these diverse roles, the software must be modular enough to be maintained by a widely dispersed network of collaborators. The design of the software is defined by a common framework which can be used for the various tasks, with individual modules which utilize a common interface to the framework. Here we describe the reconstruction workflow which is used to convert raw data from the detector into useable physics objects for analysis.

Data from the detector is recorded in RAW format. RAW data are also used to store the output of simulated events. RAW data are recorded by the HLT if the event is accepted and moved to offline storage for processing. In order to keep the datasets of manageable size, the data are segmented into a number of different “streams” depending on the HLT path(s) that passed the event. The RAW data are then reconstructed by the offline software into the RECO format. This processing involves a number of steps: filtering and correction of the data from the detector, clustering and track finding in the individual subdetectors, the linking of detector objects into cross-detector physics objects, and the production of various identification variables used in analysis. The resulting RECO files contain the physics objects as well as the lower-level hits, clusters, and tracks which are used to produce them. Periodic re-reconstructions of the data are undertaken in order to make use of improvements in the detector calibration and alignment, as well as improvements in the pattern recognition used to produce physics objects [5].
CHAPTER 4

PHOTON RECONSTRUCTION AND SELECTION

The CMS photon reconstruction algorithm is designed to meet several objectives. Since photons can convert before reaching the ECAL, and since the conversion electrons can lose energy by bremsstrahlung while moving through the tracker material, the photon reconstruction must be able to collect the full energy of the original photon. In addition, since a photon candidate without selection is much more likely to be a fake caused by hadronic activity than a real direct photon, it must provide the discriminating variables necessary to distinguish signal from background. In this chapter we will describe the photon reconstruction algorithm, the conversion reconstruction algorithm, and the isolation variables used to select the sample of isolated photon candidates.

4.1 Superclustering

The material of the inner tracking detector provides a medium for photon conversion and electron bremsstrahlung. Since the magnetic field inside the CMS solenoid points along the $z$-axis, conversion electrons and their bremsstrahlung photons are spread along the $\phi$ coordinate but stay contained in a narrow band of $\eta$. The so-called “superclustering” algorithm used to reconstruct EM objects in CMS is designed to cope with this characteristic shape.
The first step of superclustering is the formation of so-called “basic clusters”. Basic cluster formation begins by sorting the list of reconstructed hits in each ECAL channel by transverse energy. Each hit above an energy threshold of 0.5 GeV is considered as a seed for a basic cluster. Then, the algorithm begins to scan for crystals to add to the cluster, first along \( \phi \) and then along \( \eta \). Crystals are added along each line until a rise in energy is encountered, or until the crystal in question was not read out in that event [7]. In the ECAL endcap, dynamic clustering is not used. Instead the basic cluster is a fixed \( 5 \times 5 \) array centered on the seed crystal. To recover the energy deposited in the endcap preshower detector (ES), the position of endcap clusters is projected forward into the ES and ES clusters are built. The total energy of the endcap basic clusters includes the corresponding cluster energy in ES.

Once the list of basic clusters has been obtained, the superclustering can proceed. Starting from the highest energy seed basic cluster, the superclustering attempts to add additional basic clusters within a narrow (5 crystals) \( \eta \) window but wide (17 crystals) \( \phi \) window to the cluster. In the endcap region, the \( 5 \times 5 \) basic clusters are joined together similarly.

4.2 Energy corrections

Energy corrections are applied to the supercluster object to account for unclustered or otherwise lost energy. The energy corrections are determined on the basis of the Monte Carlo simulation, and they typically change the energy of the supercluster by \( \lesssim 1\% \). First, clusters are corrected for the \( \eta \) dependence of the lateral shower leakage, which arises because of the 3\(^\circ\) tilt of the crystals with respect to the nominal primary vertex. This correction is applied to barrel superclusters...
only. Next, there is a correction which is designed to compensate for energy lost in the inner tracker material if the shower begins before the ECAL face. Since the energy is spread along the $\phi$ direction, this energy loss can be parameterized as a function of the $\phi$ size of the cluster. Finally, there is a residual correction for the variations in the amount of material along $\eta$ and the $E_T$ dependence of the pair production and bremsstrahlung processes. These corrected superclusters become the basis for the photon object [27].

4.3 Photon candidate reconstruction and selection

Photon objects are created from the list of corrected super clusters. The photon energy is determined on the basis of the variable known at $r9$, which is the ratio of the energy in a $3 \times 3$ crystal window around the seed of the supercluster to the total energy of the supercluster. Small values of $r9$ are typical of converted photons, since more of the energy is spread along $\phi$. If the $r9$ is more than 0.94 (0.95) for EB (EE) candidates, the photon is assumed to be unconverted and the energy of a fixed $5 \times 5$ around the seed crystal is used as the photon energy. For these unconverted photons, this technique is found to produce superior energy resolution to using the supercluster energy. For smaller values of $r9$ the dynamic superclustering gives the better result and so the corrected supercluster energy is used as the photon energy. The slightly higher threshold in EE is due to the slightly larger crystal size [27].

When the photon object is reconstructed, a number of isolation and identification variables are calculated to provide handles for selecting a higher purity photon sample. In order to allow the possibility of constraining the photon identification efficiency with electrons from e.g. $Z \rightarrow e^+e^-$ events, these variables are
designed to be as similar as possible to those used in electron identification. The selection variables include:

- $H/E$ is the ratio of HCAL energy behind the photon candidate in a radius of $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \leq 0.15 \ (H)$ to the photon candidate energy $(E)$. Typically, signal photons have a value $\lesssim 0.05$.

- ECAL isolation is the sum of the transverse energy collected by the crystals in a cone of $\Delta R = 0.4$ around the photon momentum direction. The contribution to the sum due to the photon itself is subtracted by removing a region with inner cone of radius $R = 0.06$. The contribution due to conversions, which spread in the $\phi$ direction, is also removed by excluding from the transverse energy sum as strip of dimensions $\Delta \eta \times \Delta \phi = 0.04 \times 0.4$. Since electrons also tend to radiate as they move through the tracker material, the removal of this $\eta$ strip also allows us to use the electrons from $Z$ boson decays as a control sample. In addition, we require that the energy in a crystal must satisfy $|E| > 80$ MeV to reduce the contribution due to electronics noise. The double sided cut avoids biasing the sum in favor of positive fluctuations of the noise.

- HCAL isolation is the sum of the transverse energy collected in the HCAL towers within a cone of $\Delta R = 0.4$ around the photon momentum direction. A region at the center of the cone, with radius $R = 0.15$, corresponding to the region used to measure the H/E ratio, is excluded from the sum.

- Tracker isolation is the scalar sum of transverse momentum of tracks originating from the primary interaction vertex and lying in a cone of $\Delta R = 0.4$ around the photon momentum direction. A strip of dimensions $\Delta \eta \times \Delta \phi = 0.04 \times 0.4$. 
0.015 × 0.4 is excluded from the sum so that tracks from photon conversions are not considered as part of the isolation sum.

- $\sigma_{in\eta}$ is the size of the super-cluster measured along the $\eta$ direction and expressed in terms of the variable $\sigma_{in\eta}$ defined by Eq. 4.1.

$$
\sigma_{in\eta}^2 = \frac{\sum (\eta_i - \bar{\eta})^2 w_i}{\sum w_i}, \bar{\eta} = \frac{\sum \eta_i w_i}{\sum w_i}
$$ (4.1)

where the sum runs over the 5x5 crystal matrix around the most energetic super-cluster and $w_i = \max(0, 4.7 + \log E_i / E_{5x5})$. The $\sigma_{in\eta}$ is typically larger for jets, where more than one EM particle are clustered into the photon candidate, than for genuine photons.

A robust selection based on the above variables is applied for this measurement. Cut values, which in the case of the isolation sums include a small $p_T$-dependent component, were chosen based on Monte Carlo simulation to have efficiency $\gtrsim 90\%$ on isolated direct photon signal events and to have minimal dependence on the $p_T$ and $\eta$ of the candidate. The cut values are given in Table 4.1.

4.4 Photon conversion reconstruction and identification

Isolated photons converting to electron-positron pairs should have conversion track momentum equal to the cluster energy in ECAL. Instead, if the photon candidate is a fake from meson decay, there will be at least two photons clustered together. Since we measure the momentum from a single pair of tracks, the energy-momentum matching fails in this case, since on average the energy released in the ECAL will be more than the photon momentum measured by the track pair. This
TABLE 4.1

ISOLATED PHOTON SELECTION

<table>
<thead>
<tr>
<th>Cut</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H/E</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Track iso</td>
<td>&lt; 2.0 + 0.001p_T</td>
</tr>
<tr>
<td>ECAL iso</td>
<td>&lt; 4.2 + 0.003p_T</td>
</tr>
<tr>
<td>HCAL iso</td>
<td>&lt; 2.2 + 0.001p_T</td>
</tr>
<tr>
<td>σ_{inv} (EB)</td>
<td>&lt; 0.010</td>
</tr>
<tr>
<td>σ_{inv} (EE)</td>
<td>&lt; 0.030</td>
</tr>
</tbody>
</table>

is the feature on which our identification method is based. Here we review the algorithm which is used to reconstruct the photon conversions.

4.4.1 Photon conversion kinematics

The primary form of interaction for high energy photons traversing a material is $e^+e^-$ pair production. The radiation length $X_0$, defined by the amount of material over which an electron loses $(1-1/e)$ of its energy via bremsstrahlung, is also $\frac{7}{9}$ of the mean free path for a photon before it converts. Pair production is only possible if the photon has more than $2m_e$ of energy, and the cross section for photon conversion rises rapidly up to initial photon energies of about 50 MeV. In this thesis, we are concerned with photon energies of tens or hundreds of GeV, and the conversion cross section as a function of energy is flat to a good approximation (Figure 4.1). The energy sharing between the $e^+e^-$ pair is also relatively constant below 1 TeV as shown in Figure 4.2. The photon conversion reconstruction and
identification strategy employed in this thesis is based on the distinctive kinematics of photon conversions. Since the photon rest mass is zero, and the momentum transferred to the nuclear electric field by the conversion interaction is small, conversion tracks are parallel at the conversion vertex. The invariant mass of the tracks and the angle between them along both $\phi$ and $\eta$ should all be zero for photon conversions, whereas they will be non-zero for displaced secondary vertices from decays in flight and hadron-nuclear interactions.

4.4.2 ECAL seeded conversion reconstruction

Because the rest mass of the photon is zero, conversion tracks are parallel at the conversion vertex (neglecting the small momentum transfer to the conversion medium). The CMS 3.8 T magnetic field causes the $e^+e^-$ tracks to bend along the $\phi$ direction. The bremsstrahlung photons emitted by the electrons as they traverse the inner tracker material are therefore also spread along $\phi$. Since the superclustering is designed to cluster together the energy along the $\phi$ coordinate, it is used as the starting point for conversion reconstruction [21], [22], [27]. Any basic cluster in the supercluster could be the result of a conversion electron impact, so each of them are considered as possible seeds for the conversion track finding. From each basic cluster, the algorithm looks inward to the outermost three layers of the tracker. Using the basic cluster energy as an initial guess for the track momentum, and the nominal interaction vertex as an intial guess for the track direction, the conversion finder looks for at least two compatible hits in the outer three layers. Figure 4.3 displays the three possible hit arrangements that can satisfy this requirement. Arrangement (a) is tried first, followed by (b) and then (c).
Figure 4.1. Cross sections for photon interactions with a light element (C, Z = 6, top) and a heavy element (lead, Z = 82, bottom). At lower energies the photoelectric effect $\sigma_{\text{p.e.}}$, Rayleigh scattering, and Compton scattering dominate the cross sections. At higher energy pair production from the nuclear ($\kappa_{\text{nuc}}$) and electron ($\kappa_e$) electric fields dominate [23].
Figure 4.2. Normalized pair production cross sections versus the fractional $e^-$ energy for various values of the initial photon energy. Energies less than 1 TeV are well approximated by the 1 TeV curve [23].

Figure 4.3. The three possible hit arrangements in the outermost tracker layers which can seed the inward conversion track reconstruction. Reproduced with modifications from [22].
Once at least two compatible hits are found in the outer layers, the track parameters are re-estimated without using any constraint on the conversion vertex. The Kalman Filtering method is used to reconstruct the tracks, using the electron mass hypothesis [9]. This method updates the track parameters as each hit is added to the track, and then refines the prediction for where the next hit should be found. A special difficulty in reconstructing the tracks of electrons in the CMS tracker is the large amount of energy lost by radiation as the electrons cross the tracker material. For this conversion track reconstruction, the energy loss between each tracker layer is parameterized as a Gaussian, with the mean and width taken from the Bethe-Heitler parameterization [8]. The mean is used to correct the track momentum and the track momentum variance is increased by the variance of the predicted energy loss at each step. Up to two of the inward tracks with the largest number of hits are then used to seed an outward track finding procedure. We assume that the innermost hit on the inward track is close to the true conversion vertex. The constraint that the tracks are parallel at the vertex is used to estimate the outward track parameters. Using the same track fitting procedure, the outward track is built and then matched to an ECAL basic cluster if possible. Oppositely charged pairs of tracks are combined to form conversion candidates. Finally, the tracks are refit using the position of the conversion vertex as an additional constraint. A schematic view of the inward-outward track finding procedure is shown in Figure 4.4.

4.4.3 Conversion pair ambiguity solving

There may be more than one pair of conversion track candidates reconstructed for a single photon candidate. Before trying to identify if a candidate is signal or
background, we wish to choose the track pair which is most likely to correspond to a true conversion. We solve the ambiguity between multiple conversion track pairs by means of a multivariate discriminant, trained on simulated single photon events. The variables we choose to characterize the conversion-track pairs are the following:

- $\Delta \cot(\theta)$ between the tracks’ momenta at the vertex (Figure 4.5): this quantity is sharply peaked near 0 for reconstructed track pairs which match simulated conversion tracks.
- $\Delta \phi$ between the tracks’ momenta at the vertex (Figure 4.6), which also peaks sharply at 0 for matched tracks.
- $E_{sc}/P_{tracks}$ is peaked near 1 for matched track pairs (Figure 4.7).
- Normalized $\chi^2$ of each track measures the track goodness of fit. Matched
The distributions were obtained from a simulated sample of 500,000 single $\gamma$ generated with a flat $P_T$ ranging from 10 to 150 GeV/c.

The above variables were combined into a likelihood discriminant using the ROOT TMVA package [1]. For training the likelihood, the track pairs matching Monte Carlo simulated conversion tracks are considered signal, and those that do not match are considered background. The output of the likelihood discriminant on another sample of simulated single $\gamma$ with the same $p_T$ distribution is shown in Figure 4.10. To resolve the ambiguity, we choose to keep only the candidate track pair with the highest likelihood value. In the simulated sample considered here, the track pair with the highest likelihood matches the MC conversion tracks 83.3% of the time, compared with 76.4% for selecting the track pair with $E/p$ nearest 1 and 50.8% with no selection.
Figure 4.6. $\Delta \phi$ for matched and unmatched track pairs.

Figure 4.7. $E_{sc}/P_{\text{tracks}}$ for matched and unmatched track pairs.
Figure 4.8. The $\chi^2$ of the highest-$p_T$ track for matched and unmatched track pairs.

Figure 4.9. The $\chi^2$ of the lowest-$p_T$ track for matched and unmatched track pairs.
Figure 4.10. The output of the likelihood discriminant for matched and unmatched track pairs in simulation [22].

4.4.4 Conversion identification selection

After we select isolated photons, we require that the photon has an associated conversion where the vertex fit converged successfully and the $\chi^2$ probability of the vertex fit is greater than $5 \times 10^{-4}$. The latter ensures that only true conversion vertices are retained and most random pairs are rejected by this requirement. Furthermore, since our method is based on the matching between energy-momentum of the conversions, we require $E_T/p_T < 3$. Candidates with $E_T/p_T > 3$ are overwhelmingly likely to be background.
This measurement uses the full dataset collected by CMS during the 2010 run, for a total integrated luminosity of 36 pb$^{-1}$. Simulated data samples were also used for the analysis. The event generation was performed with PYTHIA 6.4; the full detector response was simulated assuming start-up conditions for detector alignment and calibration. The version of the CMSSW reconstruction software used to reconstruct data was 3.9.7 and for simulation it was 3.8.6.

5.1 PYTHIA simulated events

The Monte Carlo data samples used in this measurement were generated with the PYTHIA event generator, version 6 [26]. At the most basic level, PYTHIA uses leading-order matrix element calculations to generate hard scattering events between partons in the initial state. On top of this level are a number of corrections and additions which are intended to reproduce as closely as possible the final state particles observed in experimental measurements.

Arranged in approximate time order, the processes simulated by PYTHIA are as follows. The initial beam particles are described in terms of the experimentally determined PDFs, which contain the distributions of parton flavor and momentum. From each incoming particle (protons in the reactions used for this thesis), a
“shower initiator” parton is chosen. The incoming partons may shower before the scattering, for example the emission of a gluon by an incoming quark, and the resulting initial shower particles are then also tracked by the simulation. Depending on the parameters given to the generator, one or more hard processes can happen between the incoming partons. Typically the hard scatter is described in terms of a $2 \rightarrow 2$ process. The outgoing particles from the hard process may be stable (e.g. $\gamma$) or they may decay immediately (e.g. $Z$). The outgoing particles may also branch, for example, the final-state radiation of a photon by an outgoing quark. There may also be additional interactions between the other partons in the beam particles, typically these are “semi-hard” processes that give the characteristics of the underlying event. The partons in the beam particles that do not interact with each other form the beam remnant, and these are also tracked by the simulation. Because of the confinement property of QCD, the outgoing partons must in turn fragment into colorless hadrons. The results of this process can mostly be treated separately for each outgoing parton, but correlation effects can complicate the picture at this stage. Finally, many of the outgoing hadrons are unstable and must also be decayed (the decay $\pi^0 \rightarrow \gamma\gamma$ is of particular relevance in this case).

Many of the above steps cannot be treated directly by the perturbative QCD calculation and must instead be handled by empirically determined functions. In particular, the simulated data used in this thesis use the “Z2” PYTHIA tune which sets several parameters of the simulation to values that attempt to mimic the behavior observed experimentally in LHC $pp$ collisions. Measurements of the underlying event typically proceed by looking at events in terms of forward, away, and transverse regions. The forward region is defined by a $120^\circ$ slice in $\phi$ centered on the leading jet in the event, the away region is the $120^\circ$ slice centered opposite
the leading jet, and the transverse region consists of the two 60° slices left on either side. Since we expect the majority of the products of the hard interaction to fall into either the forward or away regions due to $p_T$ balance considerations, the amount of activity in the transverse region can be used as a proxy for the level of underlying event activity. Both the density of charged tracks ($dN/d\eta$) and the momentum density of charged tracks ($d\sum p_T/d\eta d\phi$) are used. For the Z2 tune, the parameters of PYTHIA were varied to obtain a best fit to the minimum bias collision data collected by CMS at both 900 GeV (injection energy) and 7 TeV in the center of mass.

The event generator creates the outgoing products of the physics reaction in terms of individual particles. In order to simulate the interaction of these particles with the detector, we need a simulation which tracks particles as they pass through the layers of material which constitute the CMS detector, as well as the various showerings, scatterings, and radiations that they produce. GEANT4 is a software package which is used extensively in high-energy physics to provide a simulation of this process. It takes as input the list of produced particles, the geometry of the detector, the material composition of its elements, and the EM field inside its volume. It produces as output a set of simulated particle trajectories and information on the simulated detector “hits” which are used in the reconstruction.

The following physics processes were simulated with PYTHIA for this measurement. The $\gamma$+jet process was used for several purposes: it provided a source of signal photons for the measurement of efficiencies in Monte Carlo, it provided the response matrix for the unfolding of the photon $p_T$, and it provided the signal template for the extraction of the photon yield. The QCD jet samples primarily provided the background template for the yield extraction and a source of frag-
mentation/ISR/FSR photons which are also considered signal so long as they are isolated. Finally, electron samples from Drell-Yan and $Z \rightarrow ee$ processes were used mainly to estimate the conversion fake rate from electrons.

5.2 Event selection in data

The events used in this analysis were required to pass at least one single photon HLT path. Photon HLT paths are seeded by $e/\gamma$ Level-1 triggers which require the energy in a single ECAL trigger tower plus its highest-energy neighbor to exceed a programmable threshold (8 GeV for the triggers used here). Level-1 triggers can also be “isolated” meaning that the energy in adjacent ECAL and corresponding HCAL towers must be below a programmable threshold, but this option was not used for the triggers in this analysis. The photon HLT runs at Level-2 and requires only a reconstructed ECAL supercluster above a given $E_T$ threshold. Optionally, Level-3 filters can also be added in order to require that the cluster be isolated in the tracker and calorimeters, or that it satisfies shower shape requirements. However, the only selection applied for this dataset was that the photon candidate satisfies the condition $H/E < 0.15$.

Since the luminosity of the LHC machine changed by several orders of magnitude during the 2010 run, we apply a run-range dependent trigger selection in order to use the lowest unprescaled photon HLT path during each luminosity step. This simplifies the analysis and the loss of luminosity is only a few percent for each HLT path. For each bin of photon $p_T$ we use the OR of any unprescaled triggers below the photon $p_T$, selecting on the run range for which each trigger was not prescaled. For example, for photon transverse momenta of $35 < p_T < 55$, we use the 20 GeV threshold trigger up to run 143962, at which point a prescale
TABLE 5.1

HLT PATHS USED AND THE ACCOMPANYING RUN RANGES AND LUMINOSITIES

<table>
<thead>
<tr>
<th>$p_T^\gamma$</th>
<th>HLT path name</th>
<th>Run range</th>
<th>$\int \mathcal{L}$ (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25-35</td>
<td>HLT_Photon20_Cleaned_L1R</td>
<td>138564-143962</td>
<td>2.46</td>
</tr>
<tr>
<td>35-55</td>
<td>HLT_Photon30_Cleaned_L1R OR HLT_Photon20_Cleaned_L1R</td>
<td>138564-147116</td>
<td>8.23</td>
</tr>
<tr>
<td>55-80</td>
<td>HLT_Photon50_Cleaned_L1R_v1 OR HLT_Photon30_Cleaned_L1R OR HLT_Photon20_Cleaned_L1R</td>
<td>138564-148058</td>
<td>17.70</td>
</tr>
<tr>
<td>80+</td>
<td>HLT_Photon70_Cleaned_L1R_v1 OR HLT_Photon50_Cleaned_L1R_v1 OR HLT_Photon30_Cleaned_L1R OR HLT_Photon20_Cleaned_L1R</td>
<td>138564-149294</td>
<td>36.14</td>
</tr>
</tbody>
</table>

was applied. CMS collected 2.46 pb$^{-1}$ under these conditions. Then we use the 30 GeV trigger up to run 147116, when that path was also prescaled. 5.77 pb$^{-1}$ were collected for this case. Using the OR of the two triggers, in total we collected 8.23 pb$^{-1}$ of data for photons in this $p_T$ range. The full HLT selection is given in Table 5.1. By requiring that the HLT threshold be at least 5 GeV less than the photon candidate $p_T$, we are well above the effects of the HLT turn-on curves. The HLT efficiency has been measured in $Z \rightarrow ee$ events to have a plateau at $99.8 \pm 0.1\%$ in the barrel region and $99.0 \pm 0.7\%$ in the endcap region [31].

To ensure that our sample is not contaminated by cosmic or beam backgrounds, we also require the presence of a vertex with at least 5 degrees of freedom, $|z_{vtx}| <$
24 cm, and $|r_{\text{etz}}| < 2$ cm. The selection on the vertex location is intended to remove beam-gas interactions or other non-collision backgrounds from the sample, while the requirement that the vertex has at least 5 degrees of freedom is a vertex quality cut designed to ensure that the primary vertex of the event is cleanly reconstructed.

5.3 Binning in transverse momentum and pseudorapidity

We perform the analysis in four bins of pseudo-rapidity: $|\eta| < 0.9$, $0.9 < |\eta| < 1.44$, $1.57 < |\eta| < 2.1$, $2.1 < |\eta| < 2.5$. This choice is motivated by several factors. The narrow $\eta$ strip between 1.44 and 1.57 contains the gap between the EB and the EE. This gap region is excluded because the efficiency of photon reconstruction is substantially smaller here. The EB is further subdivided into the regions with $|\eta| < 0.9$ and $0.9 < |\eta| < 1.44$. This division is motivated by the fact that there is relatively little material in front of ECAL for $|\eta| < 0.9$, covered by the tracker barrel structures, compared to $0.9 < |\eta| < 1.44$, which contains the transition region between the tracker barrel and endcap structures, as well as the majority of tracker service cabling. The large amount of material in the transition region coupled with the larger gaps between tracker layers makes the reconstruction of conversion tracks more difficult, and makes the momentum resolution for the reconstructed tracks somewhat worse. The division into two barrel bins also provides additional information on the shape of the cross sections versus $\eta$. The EE is also divided into two bins, mainly to provide additional information of the $\eta$ shape of the cross section. It is worth noting that the measurement of the photon cross section up to $|\eta| < 2.5$ is a large improvement for this analysis compared to measurements at e.g. the Tevatron experiments CDF and DØ, where the cross
section was measured only out to about $|\eta| < 1$.

The analysis is also divided into thirteen bins of $p_T$: $25 < p_T < 30\text{GeV}/c$, $30 < p_T < 35\text{GeV}/c$, $35 < p_T < 40\text{GeV}/c$, $40 < p_T < 45\text{GeV}/c$, $45 < p_T < 50\text{GeV}/c$, $50 < p_T < 55\text{GeV}/c$, $55 < p_T < 60\text{GeV}/c$, $60 < p_T < 65\text{GeV}/c$, $65 < p_T < 70\text{GeV}/c$, $70 < p_T < 80\text{GeV}/c$, $80 < p_T < 100\text{GeV}/c$, $100 < p_T < 120\text{GeV}/c$, and $120 < p_T < 200\text{GeV}/c$. The $p_T$ binning is likewise motivated by a combination of effects. In general the large statistics at low $p_T$ allow finer binning and a more detailed picture of the shape of the cross section. However, the amount of data in each $p_T$ bin is not always the same due to the trigger selection. We found a reasonable compromise between the expected statistical error in each bin by making equally sized bins in 5 GeV steps up to 70 GeV, with the bin width increasing after that.
CHAPTER 6

SIGNAL EFFICIENCY AND BACKGROUND SUBTRACTION

The background-subtracted photon yield $N_{\gamma}^{\text{obs}}$ will be obtained by using the $E_T/p_T$ variable. In order to estimate the total number of signal photons $N_{\gamma}^{\text{tot}}$ for the cross section measurement, we must know the detection and identification efficiency $\epsilon$ for the selections used in the analysis: $N_{\gamma}^{\text{tot}} = N_{\gamma}^{\text{obs}}/\epsilon$. The total selection efficiency for this analysis can be factorized into the following terms:

$$\epsilon = \epsilon_{\text{iso}} \times (P_{\text{conv}} \times \epsilon_{\text{convReco}} \times \epsilon_{\text{convID}}) \quad (6.1)$$

In the above expression,

- $\epsilon_{\text{iso}}$ is the efficiency of the photon isolation selection,
- $P_{\text{conv}}$ is the probability for the photon to convert before reaching ECAL, determined by the amount of material in the inner tracking detector,
- $\epsilon_{\text{convReco}}$ is the efficiency with which conversions are reconstructed, mostly dependent on the location of the conversion vertex, and
- $\epsilon_{\text{convID}}$ is the efficiency of the selection on the conversion vertex quality.

In order to correct the observed number of photon events for the efficiency of the selection, we use several different techniques, combining a control sample of
$Z \rightarrow ee$ events in data, the photon data used in the measurement, and studies on the simulated distributions of the identification variables. Here we describe the techniques used and the estimated efficiencies. We then present the fit results for the background subtraction technique as well as the measured signal purity in each bin of the analysis.

6.1 Isolation efficiency $\epsilon_{iso}$

The first term is the efficiency due to the requirement of photon selection. The efficiency of the photon reconstruction is not explicitly mentioned because it is close to 100%. The $\epsilon_{iso}$ has been measured in data with the tag-and-probe technique applied to a sample of $Z \rightarrow e^+ e^-$ in [25]. The measurement exploits the fact that electrons should also pass the photon ID selection so long as no veto on the presence of a matching track is applied. A good-quality electron is used as the tag leg, and a second super-cluster in the event is considered the probe. By fitting the number of events under the $Z$ peak for both the passing probe and failing probe case, an estimate is of the efficiency $\epsilon_{iso}$ is obtained for the tag leg and compared with the results in the simulation.

The number of signal events is fitted using three different techniques in order to cross-check the results. The simplest method is the so-called “counting” method, which leverages the low background contamination of the sample after the selection on the tag leg. For this method the contribution of non-$Z$ events to the invariant mass distribution is estimated by the Monte Carlo simulation. The number of passing and failing events are estimated by counting the number of events where the di-electron invariant mass falls between 50 and 120 GeV. The number of background events in Monte Carlo which fall inside this mass range is
then subtracted from the count.

A second method used to estimate the efficiency is the “fit” method. In this method the $Z$ peak shape is parameterized as the convolution of a Breit-Wigner function with the Crystal Ball function for energy resolution [17]. The background shape is parameterized by a falling exponential. The total yield of $Z$ events in the passing and failing categories are estimated by simultaneously fitting each of the functions to the data.

The third and final method is to compare the results from opposite-sign and same-sign electron pairs. The opposite-sign sample should be dominated by the decay $Z \rightarrow ee$ while the same-sign sample should be dominated by background. The effect of electron charge misidentification is accounted for in the efficiency estimate but it is very small for electrons in this $p_T$ range.

The level of agreement between the various methods is good, and differences between the efficiencies in data and simulation are at the one percent level. The ratio between data and simulation is used here as a scale factor ($96.3 \pm 1.5\%$ EB, $99.0 \pm 1.9\%$ EE) on the simulated isolation efficiency. The $\epsilon_{iso}$ extracted from simulated events for each bin is multiplied by this scale factor to obtain the factor $\epsilon_{iso}$ in the equation above.

6.2 Efficiency of the conversion selection

The conversion fraction $f_{\text{conv}} = (P_{\text{conv}} \times \epsilon_{\text{convReco}} \times \epsilon_{\text{convID}})$ represents the overall fraction of photons passing the conversion selection in a sample of isolated photons. Without a clean sample of signal photons in data, it is difficult to evaluate each term independently. Our approach instead is to evaluate the product $f_{\text{conv}}$ from a data-driven method.
Because the overall conversion fraction $f_{\text{conv}}$ is the product of conversion probability, conversion reconstruction efficiency (itself the product of tracking and vertexing efficiencies), and conversion identification efficiency, it may not be correctly simulated in the Monte Carlo due to various effects:

- The (mis)alignment of the silicon pixel and tracking detectors is different in data than in simulation. This can influence the tracking, vertexing, and ID steps.

- Detector occupancy due to the underlying event and pile-up is different in data than in simulation. This can influence the tracking, vertexing, and ID steps.

- Studies with tracker-driven conversions have shown that the overall material distribution in simulation is similar to that in data [30]. The amount of tracker material in the MC simulation is estimated to be within about 10% of the true material distribution. There can still be some effect on the conversion probability as well as the tracking, vertexing, and ID steps from the differences between the simulation and the real detector.

For all the above reasons, we use the data to extract an estimate of $f_{\text{conv}}$ rather than relying on the simulation.

To measure the conversion fraction $f_{\text{conv}}$ in data we exploit a tag-and-probe method based on an independent signal extraction using the combined isolation fit method [28]. The general strategy is as follows:

- First, we select a sample (the “isolation only” sample) in data using the combined isolation selection, requiring only that the shower shape variable $\sigma_{\text{ijet}}$ be less than 0.010 in the barrel pseudo-rapidity bins and 0.030 in the
end-cap. We use the combined isolation variable as a template to extract the yield of signal photons in the isolation only sample, \( N_{tag} \). For the signal shape the convolution of a Gaussian with a lifetime function is used as in [28]. The background template comes from MC truth. The fit result is shown in Figure 6.3.

- Next, we select the sub-sample (the “isolation and conversion” sample) which passes the shower shape selection and in addition has conversions passing the conversion selection applied elsewhere in the analysis. We perform the signal extraction in the same way as above and count the number of passing probes \( N_{probe} \). The fit results is shown in Figure 6.4.

- The ratio \( N_{probe}/N_{tag} \) in data gives the conversion fraction in data. The efficiency in simulation depends weakly on the \( p_T \) of the photon but varies strongly with \( \eta \). Since we lack sufficient statistics in data to perform the tag-and-probe process for each \( p_T \) bin of the analysis, we extract a average value for each \( \eta \) bin from data and correct this average value for the \( p_T \) dependence observed in the simulation.

The above procedure was checked against the MC truth by performing the procedure outlined above on a simulated sample where the true conversion fraction was known. We found that the ratio between the truth \( f_{conv} \) and the extracted \( f_{conv} \) was always statistically compatible with 1. We also checked that the conversion fraction does not depend strongly on the isolation sum around the photon, and thus there should not be a bias introduced in the \( f_{conv} \) extraction if the isolation values are different in data than in the simulation.

The selection used for the \( f_{conv} \) extraction (\( combIso < 5 \) GeV) is different than that used for the signal extraction. This is chosen so as to provide an at least
partially independent sample for the $f_{\text{conv}}$ extraction as compared to the signal extraction. Since we aim only to measure the $f_{\text{conv}}$ of the conversion part of the selection, it is sufficient to show that the change of ID criteria does not bias the extracted $f_{\text{conv}}$. Section 7.2 contains additional checks against the bias introduced by changing the selection. In addition, we have studied the dependence of the conversion $f_{\text{conv}}$ on the combined isolation value and found that the dependence is negligible near the combined isolation cut at 5 GeV (there is a small dependence for isolation values less than 3 GeV).

Finally, to check if there is any statistical bias introduced by using overlapping samples for the $f_{\text{conv}}$ extraction and signal extraction, we separated the data randomly into two halves A and B, and then performed the analysis twice, first using the signal extracted from half A and the $f_{\text{conv}}$ extracted from half B, and then using the signal extracted from half B and the $f_{\text{conv}}$ extracted with from half A, and comparing the $f_{\text{conv}}$-corrected yields. We found that the ratio between the efficiency corrected yields was always statistically compatible with 1. The results for the total efficiency-corrected yield comparison between the two scenarios are shown in Figure 2.

6.3 Photon signal extraction

The signal extraction method relies on the difference in the shape of the $E_T/p_T$ distributions between a single isolated converted photon and the background. For an isolated photon, the $p_T$ measured from the conversion electron pairs should match the energy of the photon candidate in ECAL, and thus the $E_T/p_T$ distribution should peak sharply near one. For photons produced in a jet from the decay of e.g. neutral pions, the photon candidate will contain the energy of additional
Figure 6.1. The results of the A/B statistical independence test. For each eta bin of the analysis, the ratio between the total efficiency-corrected result is shown when using half A for the signal extraction and half B for the $f_{conv}$ measurement and vice versa. The errors include the statistical error from the split samples as well as the systematic error quoted on the efficiency measurement.
Figure 6.2. Efficiencies calculated in Monte Carlo simulation.
Figure 6.3. Fit results for the combined isolation signal extraction technique. These are the fit results before applying the conversion selection. Black points are data, the red line is the background template, the blue dotted line is the signal fit, and the solid blue line is the sum of the fitted components.
Figure 6.4. Fit results for the combined isolation signal extraction technique. These are the fit results after applying the conversion selection. Black points are data, the red line is the background template, the blue dotted line is the signal fit, and the solid blue line is the sum of the fitted components.
Figure 6.5. Efficiencies extracted from data for each $\eta$ bin. Error bars are those computed according to the procedure described in Section 7.2.
particles besides the converted photon (like the second photon from a $\pi^0$ decay) and thus we expect the $E_T/p_T$ distribution for such candidates to be shifted to larger values ($E_T > p_T$). Once we have obtained templates for the $E_T/p_T$ distribution of signal and background, we can evaluate the purity of the sample and extract the signal.

6.3.1 Signal template

Templates for the signal $E_T > p_T$ distribution are obtained from simulated photon-plus-jet events. The signal shape is extracted from simulation by requiring that a reconstructed photon matches an isolated photon at generator-level. The latter can either originate from the hard scattering process or from initial/final state radiation (i.e. PDG ID number of the mother particle to be less than or equal to 22). The isolation at generator level is defined by summing all other final state particles in a cone around the photon ($\Delta R < 0.4$). This sum is required to be less than 5 GeV. The size of the cone is chosen to match that used for measuring the isolation at reconstructed level. The generator-level isolation values for direct photons are typically much less than 5 GeV so this cut is not sensitive to uncertainties in the generator modeling of isolated photon processes. Photons which come from the fragmentation of an initial state quark or gluon are included as long as they pass the isolation at generator level; the shape of the $E/p$ distribution is not substantially different for these fragmentation photons than for direct photons. We require the matched reconstructed photon to pass the selections given in Table 4.1.
6.3.2 Background template

The background templates are extracted from both simulation and data to evaluate their dependence on the background modeling in simulation. The background template can be extracted from data by inverting some of the isolation criteria to produce a sample of photons candidates that is background-dominated. This sample is used to understand the degree of mis-modeling of the background shape between the MC simulation and data. To obtain this sample, we apply the selection summarized in Table 6.1.

We define a 2-dimensional control region in the variables $\sigma_{i\eta i\eta}$ and $I_{oTRK}$. This region is illustrated in Figure 6.6 separately for Barrel and End-cap. For the barrel (end-cap) the region is defined by $2 < I_{oTRK} < 5$ and $0.010 < \sigma_{i\eta i\eta} < 0.015$ ($0.030 < \sigma_{i\eta i\eta} < 0.045$). In the rest of the discussion, we will refer to the candidates which pass the selection in Table 4.1 as the “signal” region and the candidates which pass the selection in Table 6.1 as the “control” region. The signal region is used to extract the isolated photon signal and the control region is used to provide a background template from data.

We also extract the background template from simulation. The background is defined by considering all reconstructed photon candidates not matching an isolated photon (refer to previous paragraph for the definition of isolation in simulated events). The comparison between the $E_T/p_T$ background distribution obtained from data and simulation gives a measure of the discrepancy and will be used to quantify the systematic uncertainty related to the background shape.

Because the selection used in data gives a very high purity, the number of background conversion candidates in unfiltered QCD Monte Carlo is too small to form a useful background template. Instead we use EM enriched QCD samples
### TABLE 6.1

**CONTROL REGION SELECTION**

<table>
<thead>
<tr>
<th>Cut</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>H/E</td>
<td>$&lt; 0.05$</td>
</tr>
<tr>
<td>Track iso</td>
<td>$2.0 + 0.001 p_T &lt; x &lt; 5.0 + 0.001 p_T$</td>
</tr>
<tr>
<td>ECAL iso</td>
<td>$&lt; 4.2 + 0.003 p_T$</td>
</tr>
<tr>
<td>HCAL iso</td>
<td>$&lt; 2.2 + 0.001 p_T$</td>
</tr>
<tr>
<td>$\sigma_{i\eta i\eta}$ (EB)</td>
<td>$0.010 &lt; x &lt; 0.015$</td>
</tr>
<tr>
<td>$\sigma_{i\eta i\eta}$ (EE)</td>
<td>$0.030 &lt; x &lt; 0.045$</td>
</tr>
</tbody>
</table>

To form the background templates. To control for any possible bias introduced by the use of EM enriched samples, we checked the template fit result with the EM enriched samples against the unfiltered QCD samples and find no statistically significant difference between the result (although the statistical errors from the unfiltered sample are large). Since the data control sample used to set the systematic error for the background shape has no filtering applied, this error (derived from comparing the MC truth and data control region templates) also covers any bias introduced by the filtering.

The $E_T/p_T$ distributions are fit to the data, in each $p_T$ bin, with a binned maximum-likelihood function of the signal and background component distributions, $P_s$ and $P_b$ defined by Eq. 6.2

$$-\ln L = -(N_s + N_b) + \sum_{i=1}^{n} N_i \ln(N_s P_s^i + N_b P_b^i)$$  \hspace{1cm} (6.2)
where \( n \) is the number of bins, \( N_s \) and \( N_b \) are the number of signal and background events and \( N \) is their sum.

The results of the fit in each \( p_T \) bin and in the four regions of \( \eta \) are shown in Figs. 6.7 to 6.19. In Fig. 6.20 the corresponding purity, i.e. the fraction of signal to background, is shown as a function of the photon transverse momentum. Finally, the photon yield, before and after the correction for efficiency, are shown in Tables 6.2-6.5. The theory predictions shown use the JETPHOX package [6] which provides the NLO calculation of the photon cross section. These predictions were obtained using the CTEQ6.1M PDFs, setting the renormalization, factorization,
| $0 < |\eta| < 0.9$ | Purity | Raw yield |
|-----------------|--------|-----------|
| $25 < p_T < 30$ | $0.6 \pm 0.02$ | $1253.8 \pm 44.1$ |
| $30 < p_T < 35$ | $0.67 \pm 0.03$ | $647.7 \pm 30.8$ |
| $35 < p_T < 40$ | $0.71 \pm 0.02$ | $1126 \pm 40$ |
| $40 < p_T < 45$ | $0.81 \pm 0.05$ | $711.3 \pm 49.3$ |
| $45 < p_T < 50$ | $0.8 \pm 0.06$ | $435.8 \pm 34.8$ |
| $50 < p_T < 55$ | $0.86 \pm 0.08$ | $262.4 \pm 27$ |
| $55 < p_T < 60$ | $1 \pm 0.06$ | $444.4 \pm 27.3$ |
| $60 < p_T < 65$ | $0.83 \pm 0.07$ | $254.8 \pm 22.1$ |
| $65 < p_T < 70$ | $0.91 \pm 0.06$ | $180.6 \pm 13.1$ |
| $70 < p_T < 80$ | $0.91 \pm 0.06$ | $253.6 \pm 17.6$ |
| $80 < p_T < 100$ | $0.96 \pm 0.04$ | $437.3 \pm 18.8$ |
| $100 < p_T < 120$ | $0.98 \pm 0.03$ | $176.5 \pm 6.6$ |
| $120 < p_T < 200$ | $0.97 \pm 0.04$ | $134 \pm 6.4$ |

and fragmentation scales all to $p_T^\gamma$. 
<table>
<thead>
<tr>
<th>Bin</th>
<th>Purity</th>
<th>Raw yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$25 &lt; p_T &lt; 30$</td>
<td>0.58 ± 0.05</td>
<td>274.6 ± 26.2</td>
</tr>
<tr>
<td>$30 &lt; p_T &lt; 35$</td>
<td>0.66 ± 0.1</td>
<td>156.9 ± 25.5</td>
</tr>
<tr>
<td>$35 &lt; p_T &lt; 40$</td>
<td>0.76 ± 0.11</td>
<td>261.7 ± 40.3</td>
</tr>
<tr>
<td>$40 &lt; p_T &lt; 45$</td>
<td>0.89 ± 0.09</td>
<td>196.7 ± 21</td>
</tr>
<tr>
<td>$45 &lt; p_T &lt; 50$</td>
<td>0.87 ± 0.1</td>
<td>115.1 ± 13.4</td>
</tr>
<tr>
<td>$50 &lt; p_T &lt; 55$</td>
<td>0.84 ± 0.11</td>
<td>75.3 ± 10.1</td>
</tr>
<tr>
<td>$55 &lt; p_T &lt; 60$</td>
<td>0.93 ± 0.07</td>
<td>100.5 ± 7.5</td>
</tr>
<tr>
<td>$60 &lt; p_T &lt; 65$</td>
<td>0.92 ± 0.07</td>
<td>56.3 ± 4.7</td>
</tr>
<tr>
<td>$65 &lt; p_T &lt; 70$</td>
<td>1 ± 0.15</td>
<td>41 ± 6.3</td>
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<td>$70 &lt; p_T &lt; 80$</td>
<td>1 ± 0.11</td>
<td>73 ± 8.5</td>
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<td>$80 &lt; p_T &lt; 100$</td>
<td>0.91 ± 0.07</td>
<td>97.8 ± 8.4</td>
</tr>
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<td>$100 &lt; p_T &lt; 120$</td>
<td>0.96 ± 0.07</td>
<td>42.3 ± 3.2</td>
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<td>$120 &lt; p_T &lt; 200$</td>
<td>0.94 ± 0.1</td>
<td>21.7 ± 2.3</td>
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TABLE 6.4

RAW SIGNAL YIELDS AND PURITIES FOR THE FIRST EE $\eta$ BIN

<table>
<thead>
<tr>
<th>$p_T$ Bin</th>
<th>Purity</th>
<th>Raw yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$25 &lt; p_T &lt; 30$</td>
<td>0.51 ± 0.03</td>
<td>660.6 ± 43.1</td>
</tr>
<tr>
<td>$30 &lt; p_T &lt; 35$</td>
<td>0.46 ± 0.05</td>
<td>280.4 ± 30.8</td>
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<tr>
<td>$35 &lt; p_T &lt; 40$</td>
<td>0.57 ± 0.03</td>
<td>617.6 ± 39.3</td>
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<tr>
<td>$40 &lt; p_T &lt; 45$</td>
<td>0.62 ± 0.05</td>
<td>362.3 ± 31</td>
</tr>
<tr>
<td>$45 &lt; p_T &lt; 50$</td>
<td>0.71 ± 0.12</td>
<td>235.3 ± 40.1</td>
</tr>
<tr>
<td>$50 &lt; p_T &lt; 55$</td>
<td>0.81 ± 0.11</td>
<td>183.4 ± 25.5</td>
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<tr>
<td>$55 &lt; p_T &lt; 60$</td>
<td>0.75 ± 0.09</td>
<td>241.3 ± 31.4</td>
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<tr>
<td>$60 &lt; p_T &lt; 65$</td>
<td>0.88 ± 0.08</td>
<td>158.5 ± 15.4</td>
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<td>$65 &lt; p_T &lt; 70$</td>
<td>0.84 ± 0.1</td>
<td>103.6 ± 13.3</td>
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<td>$70 &lt; p_T &lt; 80$</td>
<td>0.81 ± 0.11</td>
<td>129.7 ± 18.1</td>
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<td>$80 &lt; p_T &lt; 100$</td>
<td>0.84 ± 0.09</td>
<td>230.6 ± 26.4</td>
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<td>$100 &lt; p_T &lt; 120$</td>
<td>1 ± 0.12</td>
<td>61 ± 7.7</td>
</tr>
<tr>
<td>$120 &lt; p_T &lt; 200$</td>
<td>0.99 ± 0.04</td>
<td>65.3 ± 2.8</td>
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</table>
TABLE 6.5

RAW SIGNAL YIELDS AND PURITIES FOR THE SECOND EE $\eta$ BIN

<table>
<thead>
<tr>
<th>$p_T$ Bin</th>
<th>Purity</th>
<th>Raw yield</th>
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<tbody>
<tr>
<td>$25 &lt; p_T &lt; 30$</td>
<td>$0.5 \pm 0.03$</td>
<td>$577.3 \pm 39.8$</td>
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<tr>
<td>$30 &lt; p_T &lt; 35$</td>
<td>$0.56 \pm 0.05$</td>
<td>$297.9 \pm 29.1$</td>
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<td>$35 &lt; p_T &lt; 40$</td>
<td>$0.51 \pm 0.04$</td>
<td>$446.3 \pm 36.3$</td>
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<td>$40 &lt; p_T &lt; 45$</td>
<td>$0.54 \pm 0.05$</td>
<td>$268.4 \pm 26.3$</td>
</tr>
<tr>
<td>$45 &lt; p_T &lt; 50$</td>
<td>$0.7 \pm 0.14$</td>
<td>$169.6 \pm 34.5$</td>
</tr>
<tr>
<td>$50 &lt; p_T &lt; 55$</td>
<td>$0.71 \pm 0.11$</td>
<td>$114.2 \pm 18.3$</td>
</tr>
</tbody>
</table>

$2.1 < |\eta| < 2.5$

<table>
<thead>
<tr>
<th>$p_T$ Bin</th>
<th>Purity</th>
<th>Raw yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$55 &lt; p_T &lt; 60$</td>
<td>$0.65 \pm 0.07$</td>
<td>$142.3 \pm 17$</td>
</tr>
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<td>$60 &lt; p_T &lt; 65$</td>
<td>$0.9 \pm 0.09$</td>
<td>$119 \pm 11.8$</td>
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<tr>
<td>$65 &lt; p_T &lt; 70$</td>
<td>$1 \pm 0.08$</td>
<td>$89 \pm 7.6$</td>
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<td>$70 &lt; p_T &lt; 80$</td>
<td>$0.81 \pm 0.12$</td>
<td>$93 \pm 14$</td>
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<td>$80 &lt; p_T &lt; 100$</td>
<td>$0.88 \pm 0.1$</td>
<td>$121.7 \pm 14.9$</td>
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<td>$100 &lt; p_T &lt; 120$</td>
<td>$0.9 \pm 0.1$</td>
<td>$40.5 \pm 4.7$</td>
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<tr>
<td>$120 &lt; p_T &lt; 200$</td>
<td>$0.75 \pm 0.16$</td>
<td>$21.8 \pm 4.8$</td>
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</table>
TABLE 6.6

EFFICIENCY FOR THE FIRST EB BIN

<table>
<thead>
<tr>
<th>$p_T$ Range</th>
<th>$\epsilon_{iso} \times f_{conv}$</th>
</tr>
</thead>
<tbody>
<tr>
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TABLE 6.8

EFFICIENCY FOR THE FIRST EE BIN

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<td>$80 &lt; p_T &lt; 100$</td>
<td>$7 \pm 0.8$</td>
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<tr>
<td>$100 &lt; p_T &lt; 120$</td>
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</tr>
<tr>
<td>$120 &lt; p_T &lt; 200$</td>
<td>$6.4 \pm 0.7$</td>
</tr>
</tbody>
</table>
## Table 6.9

**Efficiency for the Second EE Bin**

| $\epsilon_{iso} \times f_{conv}$ |  
|-------------------------------|-------------------------------|
| $25 < p_T < 30$    | $7 \pm 0.7$               |
| $30 < p_T < 35$    | $7.5 \pm 0.6$              |
| $35 < p_T < 40$    | $7.4 \pm 0.6$              |
| $40 < p_T < 45$    | $7 \pm 0.6$                |
| $45 < p_T < 50$    | $6.7 \pm 0.6$              |
| $50 < p_T < 55$    | $6.8 \pm 0.6$              |
| $2.1 < |\eta| < 2.5$ | $55 < p_T < 60$            |
|                  | $7.3 \pm 0.6$              |
|                  | $60 < p_T < 65$            |
|                  | $7.5 \pm 0.6$              |
|                  | $65 < p_T < 70$            |
|                  | $7 \pm 0.6$                |
|                  | $70 < p_T < 80$            |
|                  | $6.8 \pm 0.6$              |
|                  | $80 < p_T < 100$           |
|                  | $6.4 \pm 0.5$              |
|                  | $100 < p_T < 120$          |
|                  | $5.8 \pm 0.5$              |
|                  | $120 < p_T < 200$          |
|                  | $5.9 \pm 0.5$              |
Figure 6.7. Fit results for candidates with $p_T$ between 25 and 30.
Figure 6.8. Fit results for candidates with $p_T$ between 30 and 35.
Figure 6.9. Fit results for candidates with $p_T$ between 35 and 40.
Figure 6.10. Fit results for candidates with $p_T$ between 40 and 45.
Figure 6.11. Fit results for candidates with $p_T$ between 45 and 50.
Figure 6.12. Fit results for candidates with $p_T$ between 50 and 55.
Figure 6.13. Fit results for candidates with $p_T$ between 55 and 60.
| Figure 6.14. Fit results for candidates with $p_T$ between 60 and 65. |}

(a) $0 < |\eta| < 0.9$

(b) $0.9 < |\eta| < 1.44$

(c) $1.57 < |\eta| < 2.1$

(d) $2.1 < |\eta| < 2.5$
Figure 6.15. Fit results for candidates with $p_T$ between 65 and 70.
Figure 6.16. Fit results for candidates with $p_T$ between 70 and 80.
Figure 6.17. Fit results for candidates with $p_T$ between 80 and 100.
Figure 6.18. Fit results for candidates with $p_T$ between 100 and 120.
Figure 6.19. Fit results for candidates with $p_T$ between 120 and 200.
Figure 6.20. Purity measured in the conversion sample for each bin of pseudorapidity.
In this chapter, we present the sources of systematic uncertainty on the measured cross section, coming primarily from the following sources:

- isolation efficiency;
- photon conversion selection efficiency from tag-and-probe;
- conversion $E_T/p_T$ signal and background template shapes;
- bias in the fit results;
- contamination of the sample due to mis-identification of prompt electrons as converted photons;
- ECAL energy scale;
- unfolding.

7.1 Isolation efficiency

The total statistical and systematic uncertainty on the isolation efficiency scale factor $\epsilon_{iso}$ (Section 6.1) is propagated to the final cross section as a systematic uncertainty on the isolation efficiency.
7.2 Conversion selection efficiency

We considered two possible sources of systematic error on the conversion selection efficiency.

The first source we considered was from the error returned by the fitting procedure. The statistical error on the number of tags and probes is propagated to the systematic error on the efficiency. This error is only a few percent.

The second source of systematic error is a mismodeling of the signal and background shapes. Since the fit procedure we use is similar to that applied in [28], we use the numbers quoted there for signal and background shape systematic errors. These are 11% in the barrel and 8% in the endcap. Since the final efficiency comes from the ratio of two fits done with the same procedure, we expect that these effects should largely cancel between the numerator and the denominator of the efficiency calculation.

To check the size of variations between the MC template and the true distributions in data, we extract a data-driven background template from a sideband in the shower-shape variable $\sigma_n^\eta$. The sideband is defined as $0.011 < \sigma_n^\eta < 0.015$ in EB and $\sigma_n^\eta > 0.038$ in EE. The efficiency extraction procedure is performed once again; this time the signal is extracted by using the data-driven background template instead of the MC truth background. The efficiencies measured with both data-driven and simulated background are shown in Table 7.1 in bins of pseudo-rapidity.

The variation of the signal efficiency resulting from our tests is confirmed to be less than or equal to the size of the quoted systematic on the shape.

As an additional cross-check against the possibility that using the combined
### TABLE 7.1

DIFFERENCE BETWEEN THE EFFICIENCY MEASURED WITH DATA-DRIVEN AND MC TRUTH BACKGROUND TEMPLATES FOR THE ISOLATION VARIABLE

| $|\eta|$ | $\Delta \epsilon$ (%) |
|---|---|
| $< 0.9$ | 5.4 |
| $0.9 < |\eta| < 1.44$ | 5.3 |
| $1.57 < |\eta| < 2.1$ | 8.9 |
| $2.1 < |\eta| < 2.5$ | 4.8 |

### TABLE 7.2

RATIO BETWEEN THE CROSS SECTION VALUES OBTAINED WITH THE COMBINED ISOLATION SELECTION AND THE SELECTION FROM TABLE 4.1

<table>
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<tr>
<th>$\eta$</th>
<th>Ratio</th>
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<td>$0 &lt;</td>
<td>\eta</td>
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<tr>
<td>$0.9 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>$1.57 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>$2.1 &lt;</td>
<td>\eta</td>
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</table>
isolation selection for the efficiency extraction biases the results obtained using the selection in Table 4.1, we perform the cross section analysis again using the combined isolation selection for the signal extraction and compare the results for each point. The average ratio between the points in each $\eta$ bin is shown in Table 7.2. In each case the average ratio is statistically compatible with one.

The total systematic uncertainty on the conversion selection efficiency is calculated by adding the statistical and shape systematics in quadrature.

7.3 Signal shape

Since the $E_T/p_T$ signal distribution shape is extracted from the simulation, we evaluate the systematic effect due to possible differences between the data and simulation. Unfortunately we lack a sufficiently large control sample of clean photons to extract the signal shape directly from data. Instead, we fix the background shape and then vary the parameters of the signal shape, checking the $P(\chi^2/ndof)$ values of the resulting fits. We tried varying two parameters, the peak position and the width.

The peak position for each pseudo-rapidity bin is varied in steps between -5% and +5%. For each step, a new simulated signal template is created with all entries shifted by that amount and used to repeat the fit to data. As we shift the peak through successive steps, we record two values for each peak position: the signal yield extracted from data with the modified (shifted) template, and the $P(\chi^2/ndof)$ for the resulting fit.

The $P(\chi^2/ndof)$ of each fit is used to calculate a weighted variance of the signal yields for each modified template which is then assigned as systematic error.
due to the signal shape. The weighted variance is given by:

\[ \sigma^2 = \frac{\sum w_i (x_i - x^*)}{\sum w_i} \]  

(7.1)

This weighting procedure gives more weight to variations of the peak position which better describe the data, and less weight to variations which describe the data poorly. In this way, we allow the data to determine the scale of variations used to evaluate the systematic. The resulting systematic uncertainty varies between 0.5% and 3% depending on the pseudo-rapidity bin. Plots of the fit \( P(\chi^2/ndof) \) probability as a function of the shift value are shown in Fig. 7.1.

We apply the same procedure for templates with a Gaussian smearing of the simulated signal shape, to check if the shape in data is well described for the Monte Carlo. However, the weighted variance for smeared signal widths is negligible. Therefore, we assign the shift systematic as the signal shape systematic.

7.4 Background shape

The background shape is extracted from simulated “true” background candidates (i.e. not matching a true isolated photon) falling in the signal region and compared with the background shape from the control region in data, as shown in Fig. 7.2 separately for each \( \eta \) region.

The background shape from the control region underestimates the “true” simulated background contribution by about 5-15% depending on the \( \eta \) bin. Since the same effect is visible using the control region templates in simulation, we choose to consider as our central value the result obtained from the fit with the simulated truth. However, since we do not know the true background shape in the signal region in data, we assign a systematic uncertainty equal to the difference between
Figure 7.1. Plots of $P(\chi^2)$ for each energy shift considered for the signal shape systematic.
the results obtained in the two cases.

Statistical fluctuations in the number and distribution of background template events give some variation in the size of this systematic uncertainty between adjacent bins. These variations are unphysical because we expect the background shape to change smoothly as $p_T$ increases. In order to give a smooth estimate of the size of the systematic uncertainty, we assume that the measured values are spread evenly about the true size of the effect. We fit a line to the measured shape systematic versus $p_T$ in each eta bin, and report the fitted value for each $p_T$ bin. The values and fits used are displayed in Figure 7.3.

7.5 Fitting

To evaluate possible fitting biases, we use a toy Monte Carlo to repeatedly make ten thousand pseudo-experiments in each bin. For each experiment, we allow the number of signal and background events to float within the statistical error extracted from the fit. We fill the toy data with the varied number of signal and background template entries, choosing randomly from the Monte Carlo truth template. We then perform the fit again and compare the result with the known number of signal and background events used to generate the toy data. We calculate the mean and standard deviations of the pulls ($(fitted - true)/true$) for the signal yield. In bins with high purity we sometimes observe that the mean of the pull may not be zero, or the standard deviation may not be one. In these cases, we scale the statistical error from the fit by the standard deviation of the pulls, and assign the difference between the mean and zero as a systematic fitting bias. The size of the systematic typically varies between zero and five percent depending on the bin. Plots of the mean and standard deviations used to evaluate
Figure 7.2. Plots of background shapes summed over transverse momentum for each $\eta$ obtained from MC truth and data control region.
Figure 7.3. Linear fit of the background shape systematic vs. $p_T$ bin.
the error are in Figures 7.4 and 7.5.

7.6 Prompt electrons

From simulation we expect a small number of prompt electrons from W and Z decays to fake photon conversions in the sample. We can evaluate the contribution from these electrons in the following way.

First, we make the invariant mass peak for the two leading isolated candidates in the event. Then, we ask that either one or both legs additionally pass the conversion selection. The peak from $Z \rightarrow ee$ decays can be seen in the isolated selection, and the small contribution from converted legs beneath the peak can be used to evaluate the fake rate for the electrons to enter the conversion selection. To count these events, we use a 30 GeV mass window about the Z mass and subtract the non-Z contribution as estimated from 15 GeV sidebands on either side. The remaining isolated and converted entries beneath the peak are used to estimate the fake rate.

Having counted the contribution from Zs, we use the measured W/Z production ratio [29] and the MC distribution of electron fakes from Ws to estimate the additional contribution from Ws. The error on the W/Z ratio and the statistical error on the count of converted legs under the peak combine to be about 15%. We correct the central value from the fit for the expected electron contribution and take 15% of the correction size as a systematic.

7.7 Energy scale

The ECAL energy scale factor is taken from [24] and varied by the corresponding total error. The resulting uncertainty is about 4%.
Figure 7.4. Distributions of the mean pulls for the fitting systematic.
Figure 7.5. Distributions of the RMS pulls for the fitting systematic.
7.8 Unfolding

The $E_T$ of photon candidates can be distorted as the particle traverses the detector. These distortions can be caused by finite resolution or limited acceptance of the detector. An expression relating the distorted and the true distributions is written as:

$$x = \hat{A}^{-1}b,$$  

(7.2)

where $x$ represents the true $E_T$ distribution, $b$ is the measured (distorted) $E_T$ distribution from data, and $\hat{A}$ is known as the response matrix. The response matrix describes the distortions expected of measured observables and is usually built through the use of simulated events of particles traversing the detector. The inverted response matrix operates on the measured $E_T$ distribution, resulting in the true $E_T$ distribution of prompt photon candidates in data. The response matrix is built using simulation with the generator level photon $E_T$ and it’s matched reconstructed photon candidate. The $E_T$ of photon candidates located in barrel is smeared by 0.5% and 2% in endcap in order to account for the ECAL resolution. The related systematic uncertainty on the cross-section is estimated by taking the difference between the corrected and uncorrected results.
Figure 7.6. P values for the conversion vertex fit used in the ID step. The MC bkg. (red) and signal (blue) are summed according to the purity in data. Overflow entries are shown in the last bin.
Figure 7.7. $Z \rightarrow e^+e^-$ peaks for unconverted legs (blue) and converted legs (red). The contribution of converted legs beneath the $Z$ peak is used to estimate the fake rate for prompt electrons.
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<th>$\epsilon_{iso}$</th>
<th>$\epsilon_{conv}$</th>
<th>Sig shp</th>
<th>$\epsilon^{\pm}$</th>
<th>Bkg shp</th>
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<td>$\epsilon^\pm$</td>
<td>Bkg shp</td>
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<td>± 2.3</td>
<td>± 0.1</td>
<td>± 5.9</td>
<td>± 0.1</td>
<td>± 4</td>
<td>± 15.6</td>
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<td>± 2.3</td>
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<td>± 5.8</td>
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<td>± 1.8</td>
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<td>± 0.02</td>
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<td>± 2.2</td>
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<td>± 15.1</td>
</tr>
<tr>
<td>120 &lt; $p_T$ &lt; 200</td>
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<td>± 11.3</td>
<td>± 2.3</td>
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<td>± 4.1</td>
<td>± 0.2</td>
<td>± 4</td>
<td>± 14.9</td>
</tr>
</tbody>
</table>

$0.9 < |\eta| < 1.44$
### TABLE 7.5: SYSTEMATIC ERRORS IN PERCENT FOR THE FIRST EB BIN

| $|\eta| < 2.1$ | $E_{\text{scl}}$ | $\epsilon_{\text{HLT}}$ | $\epsilon_{\text{iso}}$ | $\epsilon_{\text{conv}}$ | Sig shp | $\epsilon^\pm$ | Bkg shp | Fit | $U$ | Tot |
|----------------|----------------|----------------|----------------|----------------|--------|--------------|--------|-----|-----|-----|
| $25 < p_T < 30$ | $\pm 4$ | $\pm 0.7$ | $\pm 5$ | $\pm 8.9$ | $\pm 3$ | $\pm 0.3$ | $\pm 13.6$ | $\pm 0.1$ | $\pm 4$ | $\pm 18.6$ |
| $30 < p_T < 35$ | $\pm 4$ | $\pm 0.7$ | $\pm 5$ | $\pm 8.9$ | $\pm 3$ | $\pm 1.1$ | $\pm 12.5$ | $\pm 0.2$ | $\pm 4$ | $\pm 17.9$ |
| $35 < p_T < 40$ | $\pm 4$ | $\pm 0.7$ | $\pm 5$ | $\pm 8.9$ | $\pm 3$ | $\pm 0.6$ | $\pm 11.4$ | $\pm 0.1$ | $\pm 4$ | $\pm 17.1$ |
| $40 < p_T < 45$ | $\pm 4$ | $\pm 0.7$ | $\pm 5$ | $\pm 8.9$ | $\pm 3$ | $\pm 0.6$ | $\pm 10.3$ | $\pm 0.1$ | $\pm 4$ | $\pm 16.4$ |
| $45 < p_T < 50$ | $\pm 4$ | $\pm 0.7$ | $\pm 5$ | $\pm 8.9$ | $\pm 3$ | $\pm 0.4$ | $\pm 9.1$ | $\pm 2.7$ | $\pm 4$ | $\pm 15.9$ |
| $50 < p_T < 55$ | $\pm 4$ | $\pm 0.7$ | $\pm 5$ | $\pm 8.9$ | $\pm 3$ | $\pm 0.3$ | $\pm 8$ | $\pm 1$ | $\pm 4$ | $\pm 15.1$ |
| $1.57 < |\eta| < 2.1$ | $55 < p_T < 60$ | $\pm 4$ | $\pm 0.7$ | $\pm 5$ | $\pm 8.9$ | $\pm 3$ | $\pm 0.1$ | $\pm 6.9$ | $\pm 2.2$ | $\pm 4$ | $\pm 14.7$ |
| $60 < p_T < 65$ | $\pm 4$ | $\pm 0.7$ | $\pm 5$ | $\pm 8.9$ | $\pm 3$ | $\pm 0.1$ | $\pm 5.8$ | $\pm 0.3$ | $\pm 4$ | $\pm 14$ |
| $65 < p_T < 70$ | $\pm 4$ | $\pm 0.7$ | $\pm 5$ | $\pm 8.9$ | $\pm 3$ | $\pm 0.1$ | $\pm 4.7$ | $\pm 4.2$ | $\pm 4$ | $\pm 14.2$ |
| $70 < p_T < 80$ | $\pm 4$ | $\pm 0.7$ | $\pm 5$ | $\pm 8.9$ | $\pm 3$ | $\pm 0.1$ | $\pm 3.6$ | $\pm 2.9$ | $\pm 4$ | $\pm 13.6$ |
| $80 < p_T < 100$ | $\pm 4$ | $\pm 0.7$ | $\pm 5$ | $\pm 8.9$ | $\pm 3$ | $\pm 0.05$ | $\pm 2.5$ | $\pm 3.4$ | $\pm 4$ | $\pm 13.4$ |
| $100 < p_T < 120$ | $\pm 4$ | $\pm 0.7$ | $\pm 5$ | $\pm 8.9$ | $\pm 3$ | $\pm 0.09$ | $\pm 1.4$ | $\pm 1$ | $\pm 4$ | $\pm 12.8$ |
| $120 < p_T < 200$ | $\pm 4$ | $\pm 0.7$ | $\pm 5$ | $\pm 8.9$ | $\pm 3$ | $\pm 0.04$ | $\pm 0.3$ | $\pm 0.5$ | $\pm 4$ | $\pm 12.7$ |
| $|E_{T}|$ | $< 30$ | $30 < |E_{T}| < 60$ | $> 60$ | $< 5$ | $> 5$ | $< 10$ | $> 10$ |
|-------|--------|-----------------|-------|-------|-------|-------|-------|
|       | $\pm 4$ | $\pm 4$         | $\pm 4$ | $\pm 4$ | $\pm 4$ | $\pm 4$ | $\pm 4$ |
| $\epsilon_{H}\epsilon_{L}$ | $\pm 0.7$ | $\pm 0.7$ | $\pm 0.7$ | $\pm 0.7$ | $\pm 0.7$ | $\pm 0.7$ | $\pm 0.7$ |
| $\epsilon_{\text{iso}}$ | $\pm 0.3$ | $\pm 0.3$ | $\pm 0.3$ | $\pm 0.3$ | $\pm 0.3$ | $\pm 0.3$ | $\pm 0.3$ |
| $\epsilon_{\text{conv}}$ | $\pm 0.8$ | $\pm 0.8$ | $\pm 0.8$ | $\pm 0.8$ | $\pm 0.8$ | $\pm 0.8$ | $\pm 0.8$ |
| $\epsilon_{\text{sig}}$ | $\pm 0.3$ | $\pm 0.3$ | $\pm 0.3$ | $\pm 0.3$ | $\pm 0.3$ | $\pm 0.3$ | $\pm 0.3$ |
| Sig shp | $\pm 0.5$ | $\pm 0.5$ | $\pm 0.5$ | $\pm 0.5$ | $\pm 0.5$ | $\pm 0.5$ | $\pm 0.5$ |
| Bkg shp | $\pm 0.6$ | $\pm 0.6$ | $\pm 0.6$ | $\pm 0.6$ | $\pm 0.6$ | $\pm 0.6$ | $\pm 0.6$ |
| Fit | $\pm 0.2$ | $\pm 0.2$ | $\pm 0.2$ | $\pm 0.2$ | $\pm 0.2$ | $\pm 0.2$ | $\pm 0.2$ |
| Tot | $\pm 0.7$ | $\pm 0.7$ | $\pm 0.7$ | $\pm 0.7$ | $\pm 0.7$ | $\pm 0.7$ | $\pm 0.7$ |
Figure 7.8. Relative systematic uncertainties on the photon cross section measured with the photon conversion method in the four $\eta$ regions. Systematic uncertainties due to the uncertainties on the fit bias, energy scale, selection efficiency, unfolding corrections, and signal and background shapes are shown, as well as their total quadrature sum (upper curve).
8.1 Final cross section results

Figures 8.1 and 8.2 show the final results of the cross section measurement, including the statistical and systematic uncertainties on the measurement as well as the prediction from JETPHOX and its associated errors. The CT10 PDF set and the BFG II fragmentation functions are used to compute the JETPHOX prediction. The isolation cut on the JETPHOX cross section is set at 5 GeV of energy in the cone $\Delta R \leq 0.4$ around the photon, matching the signal definition used elsewhere in the analysis.

The scales $\mu_F, \mu_R, \mu_f$ are varied independently between one half and twice the photon $p_T$, allowing them to differ by at most a factor of two. The largest variation under these scale choices is retained as the scale uncertainty. For the $\alpha_s$ uncertainty, $\alpha_s$ is varied between $0.118 \pm 0.001$ corresponding to the 68% CL on the value of $\alpha_s(M_Z)$. The fragmentation functions are also varied between the BFG I and BFG II sets but the difference observed is negligible.

The JETPHOX prediction is also corrected by a factor $C$ which models the additional energy in the isolation cone on average due to the underlying event, which JETPHOX does not model. $C$ is computed using PYTHIA, by observing the difference in the number of simulated photons passing the isolation cut with
Figure 8.1. Fully corrected cross section, binned in $p_T$ for the four $\eta$ bins used in the analysis. The JETPHOX prediction is also shown for comparison.

and without the underlying event and multiple parton interactions. $C$ is found to have a value of $0.975 \pm 0.006$ and there is no significant dependence on the $p_T$ or pseudorapidity bin.
8.2 Conclusions

This thesis has presented a complete measurement of the isolated prompt photon cross section at $\sqrt{s} = 7$ TeV. Isolated photons with $p_T$ between 25 and 200 GeV and $|\eta| < 2.5$ are used to perform the measurement on 36 inverse picobarns of data. The conversion $E_T/p_T$ variable is used to estimate how many of the selected photon candidates are isolated prompt photons. The extracted number of signal events is then corrected for the conversion rate, the reconstruction and identification efficiency, and the detector response. This measurement extends the transverse momentum and pseudorapidity range past previous measurements. We test the predictions of NLO QCD for this process over about four orders of magnitude and find that the results of the measurement agree with the theory within errors. In contrast to some previous measurements, we do not observe any excess of photons in data at low $p_T$ with respect to the theoretical prediction. Specifically, we see no evidence to support the intrinsic $k_T$ hypothesis in the kinematic range considered by this measurement.

In addition to testing NLO QCD, the results in this thesis illustrate the performance of a promising and powerful technique to identify signal photons using conversions. We have demonstrated that a purity of better than 50% can be achieved at transverse momenta as low as 25 GeV. We have also demonstrated that the systematic uncertainties, especially those on the template shapes and the conversion selection, can be controlled in a data-driven way at the 10% level. The conversion method gives us a useful and independent method to evaluate the purity of a photon sample, and it should be a useful technique for further measurements and searches with photons at CMS.

The work presented in this thesis is included in a publication scheduled to
Figure 8.2. Fully corrected cross section, binned in $p_T$ for the four $\eta$ bins used in the analysis. The ratio of data to the JETPHOX prediction is shown.
<p>| $E_T$  | $0 &lt; |\eta| &lt; 0.9$                                      | $0.9 &lt; |\eta| &lt; 1.44$                                      |
|-------|------------------------------------------------------|------------------------------------------------------|
| 25 − 30 | $(7.82 \pm 0.33 \pm 1.43) \times 10^{-1}$          | $(6.57 \pm 0.75 \pm 1.3) \times 10^{-1}$            |
| 30 − 35 | $(3.74 \pm 0.2 \pm 0.62) \times 10^{-1}$          | $(3.92 \pm 0.51 \pm 0.74) \times 10^{-1}$          |
| 35 − 40 | $(1.85 \pm 0.07 \pm 0.29) \times 10^{-1}$          | $(1.78 \pm 0.17 \pm 0.34) \times 10^{-1}$          |
| 40 − 45 | $(1.18 \pm 0.05 \pm 0.17) \times 10^{-1}$          | $(1.44 \pm 0.12 \pm 0.27) \times 10^{-1}$          |
| 45 − 50 | $(7.28 \pm 0.46 \pm 1.08) \times 10^{-2}$          | $(7.28 \pm 0.89 \pm 1.34) \times 10^{-2}$          |
| 50 − 55 | $(4.28 \pm 0.34 \pm 0.65) \times 10^{-2}$          | $(4.65 \pm 0.65 \pm 0.87) \times 10^{-2}$          |
| 55 − 60 | $(3.58 \pm 0.17 \pm 0.51) \times 10^{-2}$          | $(3.13 \pm 0.34 \pm 0.51) \times 10^{-2}$          |
| 60 − 65 | $(2.1 \pm 0.15 \pm 0.3) \times 10^{-2}$           | $(1.8 \pm 0.25 \pm 0.29) \times 10^{-2}$           |
| 65 − 70 | $(1.39 \pm 0.11 \pm 0.2) \times 10^{-2}$          | $(1.27 \pm 0.19 \pm 0.21) \times 10^{-2}$          |
| 70 − 80 | $(9.32 \pm 0.65 \pm 1.33) \times 10^{-3}$         | $(1.04 \pm 0.12 \pm 0.16) \times 10^{-2}$          |
| 80 − 100 | $(4.08 \pm 0.23 \pm 0.58) \times 10^{-3}$         | $(3.44 \pm 0.37 \pm 0.52) \times 10^{-3}$         |
| 100 − 120 | $(1.84 \pm 0.14 \pm 0.26) \times 10^{-3}$         | $(1.66 \pm 0.26 \pm 0.25) \times 10^{-3}$         |
| 120 − 200 | $(3.41 \pm 0.3 \pm 0.49) \times 10^{-4}$          | $(3.21 \pm 0.71 \pm 0.47) \times 10^{-4}$         |</p>
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<th>Cross section (nb)</th>
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<tr>
<td>120 – 200</td>
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appear in Physics Review D.


