Study of the production of prompt photons in association with hadronic jets with the ATLAS detector at the LHC

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Chapter 1

Introduction

The study of the production of prompt photons in association with hadronic jets, provides a test of perturbative Quantum Chromodynamics (pQCD) and gives informations on the proton’s parton distribution functions (PDFs). The colorless prompt photon represents a clean probe of the hard partonic interaction since the photon is produced in the hard scattering. The measurement of the angular correlations between the photon and the hadronic jets is a test of pQCD at large hard-scattering scales and over a large range of parton momentum fraction. Since the dominant production mechanism in $p-p$ collisions is through the $qg \rightarrow q\gamma$ process, which dominates at Leading Order (LO), the process $pp \rightarrow \gamma + Jet + X$ is used to constrain the gluon density in the proton. In addition, the study of prompt photon production is important because this process constitutes the main reducible background in the identification of the Higgs boson decaying into a photon pairs. The QCD predictions can be tested in $\gamma + Jet$ production at LHC. The $pp \rightarrow \gamma + Jet + X$ process, could proceeds through two different mechanisms:

- direct photon (mostly quark-gluon Compton scattering, $qg \rightarrow \gamma g$, or quark-antiquark annihilation, $q\bar{q} \rightarrow \gamma g$), originated during the hard process;
- fragmentation photon, produced in the fragmentation of a parton with high $P_T$.

The measurements of prompt photon production require the application of an isolation condition on the photons, based on the amount of transverse energy inside a cone of radius $R$, centered around the photon direction in the pseudorapidity and azimuthal angle plane. As a consequence of this isolation cut, the relative contribution to the total cross section from fragmentation photons decreases. These requirements are thought to avoid the contribution
coming from neutral hadrons decays into photons, such as $\pi^0$ and $\eta$ mesons inside jets.

The production of isolated prompt photons has already been studied by the ATLAS collaboration[1][2]. This thesis presents studies on the production of inclusive isolated photons plus jets, in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector using an integrated luminosity of 20.3 fb$^{-1}$. The goal of this analysis is to study the kinematics and dynamics of the photon plus jets events, through the measurement of the differential cross sections as function of the main photon’s and jets’ variables. The differential cross sections have been compared to the predictions of the SHERPA Monte Carlo event generator.

This thesis is structured as follows:

chapter 2 contains a description of the ATLAS detector. Chapter 3 provides the theoretical framework for the prompt photon production and a short description of the jet algorithm applied. In Chapter 4, the main features of the SHERPA event generator are discussed. Chapter 5 is devoted to the photon and jets reconstruction procedure used by ATLAS. In Chapter 6 the applied event selection is discussed and control plots are shown. Chapter 7 reports the data-driven method approach used to estimate the signal fraction of the selected sample of photon candidates which satisfy the tight identification and the isolation criteria. In Chapter 8 the measured differential cross sections are shown together with a study of the systematic uncertainties.
Chapter 2

The LHC and the ATLAS detector

The Large Hadron Collider (LHC) [3] is a superconducting hadron collider built in a 27 km underground tunnel, constructed beneath the French-Swiss border close to Geneva (see Fig. 2.1). The main goal of the LHC is to reveal physics beyond the Standard Model. The number of events per second generated in collisions is given by the expression:

$$N_{\text{events}} = \mathcal{L} \cdot \sigma,$$

(2.1)
where $\mathcal{L}$ is the machine instantaneous luminosity and $\sigma$ is the cross section of the process that we are studying. There are four main experiments which study the results of proton-proton collisions provided at the LHC: ATLAS [4], CMS [5], LHCb [6] and ALICE [7]. ATLAS and CMS are two high luminosity multi-purpose experiments, LHCb is a low luminosity experiment designed to study b-quark physics while ALICE is a heavy ion experiment. Luminosity at the LHC is not constant during physics runs, but decays because of the degradation of intensities and emittance of the circulating beams, due to collisions.

ATLAS searches for new phenomena as well as test of the Standard Model. The main components of the ATLAS detector (see Fig. 2.3) are the inner detector, calorimeters and muon spectrometer. Because of the large amount of events, the detector requires fast electronics and sensor elements. They also require high granularity to reduce the influence of overlapping events. It also needed a large acceptance in pseudorapidity, with full coverage in azimuthal angle. The electromagnetic calorimeter is essential to identify electrons, positrons and photons, and their kinematic variables. Meanwhile the hadronic calorimeter is used to measure jet transverse and missing energies. Good muon identification is also required, with high momentum resolution.

To reject background events, high-efficient triggers are required to get an adequate trigger rate for the processes, which are object of study. The ATLAS dimensions are 25 m height and 44 m in length. Its weight is about 7000 tons. It is symmetric around the interaction point, covering the whole solid angle. There is a superconducting solenoid surrounding the inner-detector cavity, and there are three superconducting toroids (a barrel and two endcaps) set with an eight-fold azimuthal symmetry around the calorimeters.

<table>
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<tr>
<th>Detector component</th>
<th>Required resolution</th>
<th>$\eta$ coverage</th>
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<tr>
<td>Tracking</td>
<td>$\sigma_{p_T}/p_T=0.05% \oplus 1%$</td>
<td>$\pm 2.5$</td>
</tr>
<tr>
<td>EM calorimetry</td>
<td>$\sigma_{E}/E=10%/\sqrt{E} \oplus 0.7%$</td>
<td>$\pm 3.2$</td>
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<tr>
<td>Hadronic calorimeters (jets)</td>
<td>$\sigma_{E}/E=50%/\sqrt{E} \oplus 3%$</td>
<td>$\pm 3.2$</td>
</tr>
<tr>
<td>forward</td>
<td>$\sigma_{E}/E=100%/\sqrt{E} \oplus 10%$</td>
<td>$3.1&lt;</td>
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<tr>
<td>barrel and end-cap</td>
<td></td>
<td></td>
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<tr>
<td>Muon spectrometer</td>
<td>$\sigma_{p_T}/p_T=10%$ at $p_T = 1$ TeV</td>
<td>$\pm 2.7$</td>
</tr>
</tbody>
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Figure 2.2: Resolutions and $\eta$ coverage of the main ATLAS detector components
2.1 Inner Detector

The Inner Detector (ID) (as shown in Fig. 2.4), is permeated by a solenoidal field of 2 T generated by a central solenoid. The ID has length of 5.3 m and diameter of 2.5 m and it consists of 3 complementary sub-detectors. It is possible to get pattern recognition, momentum, vertex measurements and particle identification. This is the result of a combination of high resolution semiconductor pixel and strip detectors in the inner part of the tracking volume, and straw-tube tracking detector, which has the capability of detect transition radiations in its outer part. The highest granularity is achieved around the vertex region using semiconductor pixel detectors followed by a silicon microstrip detector. At larger radii typically 36 tracking points are provided by the straw tube tracker. In the barrel region the high-precision detectors are arranged in concentric cylinders around the beam axis, while the end-cap detectors are mounted on disks perpendicular to the beam axis. The barrel TRT straws are parallel to the beam direction. All end-cap tracking elements are located in planes perpendicular to the beam direction.

2.1.1 Tracking

The ID provides tracking measurements in a range matched by the precision measurements of the electromagnetic calorimeter [8]. The electron identification abilities are provided by the detection of transition radiation photons.
The semiconductor trackers also allow impact parameter measurements and vertexing for heavy-flavour and $\tau$-lepton tagging. The TRT (Transition Radiation Tracker) is made of various layers of gaseous tube elements interleaved with same radiation materials. It gives a continuous tracking, 36 hits per track, with a good pattern recognition, given by the 4 mm diameter gas mixture tubes. TRT provides only $R - \Phi$ information, with an accuracy of 130 $\mu$m per straw. In the barrel, straws are 144 cm long and they are parallel to the beam axis, while in the endcap region, they are 37 cm long and are arranged radially in wheels. The TRT readout channels are 351000.

### 2.1.2 Pixel Detectors

The Pixel Detector is the innermost part of the detector and contains three concentric layers and three disks on each end-cap, usually crossed by each track, with a total of 1,744 modules. Using silicon pixel detectors, the highest granularity is found around the vertex region. The pixel sensors are all the same, with a minimum pixel size in $(R - \Phi) \times z$ of $50 \times 400 \ \mu m^2$. The detecting material is silicon 250 $\mu$m thick. Each module contains 16 readout chips and other electronic components. The smallest unit that can be read out is a pixel (50 by 400 $\mu$m); there are roughly 47,000 pixels per module. The minute pixel size is designed for extremely precise tracking very close to the interaction point. In total, the Pixel Detector has over 80 million readout channels, which is about 50 of the total readout channels of the
whole experiment. Having such a large count created a considerable design and engineering challenge. Another challenge was the radiation to which the Pixel Detector is exposed because of its proximity to the interaction point, requiring that all components be radiation hardened in order to continue operating after significant exposures.

2.1.3 SCT

The Semi-Conductor Tracker (SCT) is the middle component of the inner detector. It is similar in concept and function to the Pixel Detector but with long, narrow strips rather than small pixels, making coverage of a larger area practical. For the SCT, eight strip layers are crossed by each track. It uses small angle strips to measure both coordinates $(R - \Phi)$ and $Z$. Each strip measures $80 \mu m$ by 12 cm. The SCT is the most critical part of the inner detector for basic tracking in the plane perpendicular to the beam, since it measures particles over a much larger area than the Pixel Detector, with more sampled points and roughly equal (albeit one-dimensional) accuracy. It
is composed of four double layers of silicon strips, and has 6.3 million readout channels and a total area of 61 square meters. The main parameters of the inner detector are shown in Fig. 2.6.

2.2 Calorimeters

ATLAS calorimeters [9] (see Fig. 2.7 and 2.8) consist of many sampling detectors with a fully $\Phi$ symmetry and coverage around the beam axis. They cover the range of $|\eta| < 4.9$, ideally suited for particle precision measurements, and the granularity is set to satisfy the requirements for jet reconstruction and measurements for missing $E_T$. The main features of the ATLAS calorimeter system, are shown in Fig. 2.7.

2.2.1 Electromagnetic Calorimeter

The Liquid Argon electromagnetic calorimeter (LAr), which covers a range of $|\eta| < 3.2$, provides great performances in terms of energy and position resolution, thanks to its high granularity. It is divided into a barrel and two end-caps, with respectively $|\eta| < 1.475$ and $1.375 < |\eta| < 3.2$ coverage. The LAr barrel section consists of two semi-barrels, separated by a 4 mm gap at
Figure 2.7: View of calorimeters

$z = 0$. On the other hand, the end-caps sections are divided in two coaxial wheels, which cover a different value of $|\eta|$.

### 2.2.2 Hadronic Calorimeters

The Hadronic Calorimeters in ATLAS are the tile calorimeter, the liquid argon end-cap calorimeter and the liquid argon forward calorimeter.

**Tile Calorimeter**

The tile calorimeter, with a range of $|\eta| < 1.7$, has scintillator-tile detectors, divided into a big barrel and two small barrel cylinders, it is placed just outside the LAr calorimeter. It uses steel as the absorber and scintillating tiles as active materials. The barrel covers a region of $|\eta| < 1$, while the two extended barrels cover a range of $0.8 < |\eta| < 1.7$, both are segmented into three layers with different $\lambda$. To read the scintillating tiles, wavelength shifting fibers into two different photon multiplier tubes are used. In pseudorapidity, the cells, built by grouping fibers into the photons multipliers are pseudo-projective towards the region of interaction.
2.2.3 LAr hadronic end cap calorimeter

The HEC (hadronic end cap calorimeter) is composed of two independent wheels per end cap, located just behind the electromagnetic calorimeter end caps. Each wheel was built with 32 identical modules and is divided into two segments (4 segments per end cap). The inner wheel is made of 25 copper plates, with a radius of 0.475 m, while the outer wheel is built from 50 mm copper plates with a radius of 2.03 m. These copper plates are interleaved with LAr gaps, providing the active medium.

2.2.4 LAr forward calorimeter

The FCal (Forward Calorimeter) is approximately 10 λ deep and was built with three modules per end cap. The modules are made of copper (the first) and tungsten to measure respectively electromagnetic particles and the energy of hadronic interactions. Every single module consists of a matrix with longitudinal channels containing an electrode structure with concentric rods and tubes (parallel to the beam axis). In the gap between the rods and the tube, LAr is the active medium. The FCal provides a reduced background radiation in the muon spectrometer.

2.3 Magnet system

The ATLAS detector uses two large superconducting magnet systems to bend charged particles so that their momenta can be measured. This bending is due to the Lorentz force, which is proportional to velocity. Since all particles produced in the LHC’s pp collisions are traveling at very close to the speed of light, the force on particles of different momenta is equal. (In the theory of relativity, momentum is not linear proportional to velocity at such speeds.) Thus high-momentum particles curve very little, while low-momentum particles curve significantly; the amount of curvature can be quantified and the particle momentum can be determined from this value.

2.3.1 Solenoid magnet

The central ATLAS solenoid has a length of 5.3 m with a core of 2.4 m. The conductor is a composite that consists of a flat superconducting cable located in the center of an aluminum stabilizer with rectangular cross-section. It is designed to provide a field of 2 T with a peak magnetic field of 2.6 T. The total assembly weight will be 5.7 tons.
2.3.2 Toroidal magnets

The outer toroidal magnetic field is produced by eight very large air-core superconducting barrel loops and two end-caps air toroidal magnets (see Fig. 2.9), all situated outside the calorimeters and within the muon system. The End-Cap coils systems are rotated by 22.5 degrees with respect to the Barrel Toroids in order to provide radial overlap and to optimise the bending power in the interface regions of both coil systems. This magnetic field extends in an area 26 m long and 20 m in diameter, and it stores 1.6 GJ of energy. Its magnetic field is not uniform, because a solenoid magnet of sufficient size would be prohibitively expensive to build. It varies between 2 and 8 T m.
2.4 Muon Spectrometer

The muon spectrometer [10], is the outer part of the ATLAS detector, it surrounds the hadronic calorimeter with a long barrel and two end-caps magnets, providing an excellent muon momentum resolution and minimum multiple scattering effects, in the range of $|\eta| < 2.7$ with three layers of high precision tracking chambers. A cross sectional and a longitudinal view of the muon spectrometer are presented, respectively, in Fig.2.10 and 2.11.

Muons are particles just like electrons, but 200 times heavier. They are the only detectable particles that can traverse all the calorimeter absorbers without being stopped. The barrel toroid provides a range of bending power between 1.5 and 5.5 Tm in the pseudorapidity range $0 < |\eta| < 1.4$. For $1.6 < |\eta| < 2.7$, tracks are bent by two end caps magnets put into the ends of the barrel toroid, providing a range of bending power between 1 and 7.5 Tm. The field provided by these magnets is orthogonal to the muon trajectories. The momentum measurement is given by the Monitored Drift Tube chambers, covering a pseudorapidity range of $|\eta| < 2.7$. The chambers consist of three to eight layers of drift tubes, operating at a pressure of 3 bar and provide a resolution of 80 $\mu$m per tube and 35 $\mu$m per chamber. Cathode-Strips Chambers (CSC) are used in the region of $2 < |\eta| < 2.7$ into the tracking layer, for their high rate capability and great time resolu-
tion, allowing the measurement of both coordinates by the induced charge distribution.

2.5 Forward detectors

Three smaller detector systems cover the ATLAS forward region. The main function of the first two systems is to determine the luminosity delivered to ATLAS. At 17 m from the interaction point lies LUCID (LUminosity measurement using Cerenkov Integrating Detector). It detects inelastic $pp$ scattering in the forward direction, and is the main online relative-luminosity monitor for ATLAS. The second detector is ALFA (Absolute Luminosity For ATLAS). Located at 240 m, it consists of scintillating fibre trackers located inside Roman pots which are designed to approach as close as 1 mm to the beam. The third system is the Zero-Degree Calorimeter (ZDC), which plays a key role in determining the centrality of heavy-ion collisions. It is located at 140 m from the interaction point, just beyond the point where the common straight-section vacuum-pipe divides back into two independent beam-pipes. The ZDC modules consist of layers of alternating quartz rods and tungsten plates which will measure neutral particles at pseudorapidities $\eta \geq 8.2$. 
2.6 Trigger System

The trigger system has three different levels: L1, L2 and Event Filter (EF). Each level has the goal to refine the decision took from the previous level and, when necessary, applies another selection criteria [11]. L2 plus EF form the High Level Trigger (HLT) and they consist of commercially available hardware technology. The L1 is implemented instead using custom made electronics.

2.6.1 L1 trigger

L1 trigger uses reduced granularity informations coming from the detectors, it searches signature from muons, electrons, photons, jets and events with large missing $E_T$. Its accept rate is 75 kHz, 2.5 $\mu$s after the bunch crossing. In the calorimeters (L1Calo) it is a digital system, working with 7000 reduced granularity trigger towers.

2.6.2 L2 and EF triggers

For events selected by the L1 trigger, the information from the detector must be retained for further analysis. The data for such events are transferred to readout buffers where they remain until the L2 decision is available. The data can be accessed selectively by the L2 trigger which uses regions of interest (ROI) defined by the L1 trigger on coordinates and energies. The L2 trigger refines the selection of candidate objects compared to L1, using full-granularity information from all detectors, including the inner tracker which
is not used at L1. L2 reduces the event ratio under 3.5 kHz, with an event processing time of 40 ms. EF is an offline level to select events for an offline analysis. The event rate is now \( \approx 200 \) Hz with an event processing time of 4 s. The ATLAS trigger architecture is shown in Fig. 2.12

### 2.7 Data acquisition system

#### 2.7.1 Event filter and data acquisition

The Readout Drivers (ROD’s) are detector-specific functional elements of the front-end systems, which achieve a higher level of data concentration and multiplexing by gathering information from several front-end data streams. Although each sub-detector uses specific front-end electronics and ROD’s, these components are built from standardised blocks and are subject to common requirements. The front-end electronics sub-system includes different functional components:
• the front-end analogue or analog-to-digital processing;

• the L1 buffer in which the (analog or digital) information is retained for a time long enough to accommodate the L1 trigger latency;

• the derandomising buffer in which the data corresponding to a L1 trigger accept are stored before being sent to the following level. This element is necessary to accommodate the maximum instantaneous L1 rate without introducing significant deadtime (maximum 1 %);

• the dedicated links or buses which are used to transmit the front-end data stream to the next stage.

After an event is accepted by the L1 trigger, the data from the pipe-lines are transferred off the detector to the ROD’s. Digitised signals are formatted as raw data prior to being transferred to the DAQ system. The ROD’s follow some general ATLAS rules, including the definition of the data format of the event, the error detection/recovery mechanisms to be implemented, and the physical 1565 interface for the data transmission to the DAQ system. The first stage of the DAQ, the readout system, receives and temporarily stores the data in local buffers. For L2-selected events, event building is performed. Each readout buffer contains fragments of many events for a small part of one subdetector. The event builder collects all the fragments from one event into a single memory of an Event Filter processor. The event building is performed using a data switch. Event Filter processing is performed using farms of processors acting on the full-event data. The complicated selection criteria of the off-line analysis will be used in a real-time environment. The processing time per event could be about 1 second on a 1000 MIPS (Million Instructions Per Second) processor (today’s processors are typically 100-200 MIPS). The DCS (Detector Control System) permits the coherent and safe operation of the ATLAS detector hardware, and serves as a homogeneous interface to all sub-detectors and to the technical infrastructure of the experiment. It controls, continuously monitors and archives the operational parameters, signals any abnormal behaviour to the operator, and allows automatic or manual corrective actions to be taken. Typical examples are high and low-voltage systems for detector and electronics, gas and cooling systems, magnetic field, temperatures, and humidity. The DCS enables bi-directional communication with the data acquisition system in order to synchronise the state of the detector with 1580 data-taking. It also handles the communication between the sub-detectors and other systems which are controlled independently, such as the LHC accelerator, the CERN technical services, the ATLAS magnets, and the detector safety system.
Chapter 3

Theoretical Framework

3.1 Introduction

Quantum Chromodynamics (QCD) [12] is the theory of the strong interactions, based on the group SU(3) with a non-abelian gauge invariance. Quarks and antiquarks are particles with spin \( \frac{1}{2} \) and they strongly interact via the exchange of gauge bosons called gluons. The gluons can interact between themselves, unlike the photons in Quantum Electro Dynamics, because they carry a color charge. For this reason, gluon dynamics is mainly responsible of the asymptotic freedom property of QCD. The idea of quarks came from the need to have the manifestation of the SU(3) group of flavour, observed in the spectra of low mass mesons and baryons. In the quark model, baryons are made of three valence quarks (or antiquarks) and mesons by valence quark-antiquark pairs. In a naive picture, the proton is made of three quarks, two up quarks and one down quark, of respective electric charge \( \frac{2}{3} \) and \( -\frac{1}{3} \)

![Quark characteristics](image)

Figure 3.1: Quark characteristics
as shown in Fig. 3.1. The proton is a colorless object of charge +1. It is seen as a bound system of partons each carrying a fraction $x$ of the proton’s momentum. In addition to the three valence quarks, the vacuum polarization generates gluons and sea-quarks (quark-antiquark pairs). The proton structure is described by the parton distribution functions which takes account of gluons, valence and sea-quarks.

### 3.2 The factorization theorem

The interaction between two protons can be calculated in pQCD only in the presence of an hard scale, which characterizes the partonic cross section. This condition is due to the behaviour of the strong coupling constant $\alpha_s$. As a result of the renormalization of the theory, $\alpha_s$ depends on the renormalization scale, which is typically set equal to an high energy scale, or a transferred momentum, $Q$, which characterizes the given process. Fig. 3.2 shows that the strong coupling decreases as the transferred momentum increases, and in the high energy limit, the coupling vanishes showing the asymptotic freedom of QCD. Instead, at low values of the transfer momentum, $\alpha_s$ has a steep increase, so that it is not possible to use a perturbative approach to describe soft processes in QCD.

When pQCD can be applied, the factorization theorem states that the cross section of any QCD process can be written as the convolution of the proton’s PDF with the partonic cross section, as shown in Eq. 3.1.

$$\sigma(P_1, P_2) = \sum_{q_1,q_2} \int dx_1 f_{q_1/p}(x_1, \mu_F^2) \int dx_2 f_{q_2/p}(x_2, \mu_F^2) \hat{\sigma}(x_1, x_2, \alpha_s(\mu_F^2), \mu_R^2, \mu_R^2),$$

(3.1)

where $P_1$ and $P_2$ are the momenta of the incoming hadrons, $q_1$ and $q_2$ are the partons inside the two colliding protons involved in the hard subprocess of cross section $\hat{\sigma}$, and $\hat{s}$ is the invariant mass of the initial partons system. $f_{q/p}(x, \mu_F^2)$ is the PDF of the parton $q$, carrying a fraction $x$ of the proton’s momentum.

#### 3.2.1 Partonic cross sections

The partonic cross section can be calculated using pQCD and Feynmann diagrams techniques [13]. The partonic cross section $\hat{\sigma}$ can be expressed as:

$$\hat{\sigma} = \hat{\sigma}^{(0)} + \alpha_s \hat{\sigma}^{(1)} + O(2)$$

(3.2)
where $\sigma^{(0)}$ is the contribution at leading order (LO), $\sigma^{(1)}$ is the contribution at next to the leading order (NLO).

Calculating high orders terms of the perturbative expansion, two kinds of divergences appear, the ultraviolet and infrared and collinear divergences:

- Ultraviolet divergences (UV), come from the integration over large values of loop momenta, but they are removed after the renormalization of the theory. There isn’t an universal scheme for the renormalization method, but several are available:
  - Minimal subtraction scheme,
  - $\overline{MS}$ scheme,
  - on shell scheme.

Figure 3.2: Evolution of $\alpha_s$ as function of $Q$. 
The renormalization of the theory implies the introduction of a scale parameter $\mu_R$, called renormalization scale. The $\mu_R$ dependence of the strong coupling constant, $\alpha_s(\mu_R)$, is described by the Callan - Symanzik equation [15].

- Infrared and collinear divergences appear in the calculation of the Feynman diagrams of the real and virtual corrections in the limit of vanishing energy of an emitted parton or when two partons become collinear. In analogy to the renormalization procedure, a factorization scale, $\mu_F$, has to be introduced for the removal of the infrared and collinear divergences. After this removal, both the PDFs and the partonic cross sections acquire a dependence on the factorization scale.

### 3.2.2 PDFs

The PDFs parametrize the proton constituents in the non-perturbative regime and, once determined in a given process, they can be used to compute cross sections for other perturbative hadronic processes. They are functions of the momentum fraction $x$ of the hadron momentum carried by the parton at a given factorization scale. They cannot be determined by perturbative QCD calculations but when their $x$ dependence at a fixed scale $Q^2_0$ is known, they can be determined at any higher scale $Q^2$, see Fig 3.3. The evolution of the PDF with respect to the factorization scale is determined in pQCD, by the DGLAP (Dokshitzer, Gribov, Lipatov, Altarelli, Parisi) equations

$$\frac{d}{d\ln \mu_F} f_{a/p}(x, \mu_F^2) = \sum_b \int_0^1 \frac{dz}{z} P_{ab}(z, \alpha_s(\mu_F^2)) f_{b/p}(x z, \mu_F^2),$$

where $P_{ab}$ is the splitting function, related to the probability of emission of a parton $a$ from a parton $b$. $f_{a/p}$ and $f_{b/p}$ are respectively the PDFs of partons $a$ and $b$ inside a proton. The splitting function in analogy with the partonic cross section can be computed as a power expansion in the strong coupling constant:

$$P_{ab}(x, \alpha_s(\mu_F^2)) = P_{ab}^{(1)}(x)(\frac{\alpha_s(\mu_F^2)}{\pi}) + P_{ab}^{(2)}(x)(\frac{\alpha_s(\mu_F^2)}{\pi})^2 + O(2)$$

where $P_{ab}^{(1)}$ and $P_{ab}^{(2)}$ are the splitting functions at LO and NLO.

### 3.3 Theory of prompt photon production

High transverse energy direct photon production and high transverse momentum jet production are related. The production and associated measurement
Figure 3.3: $x f_{q/p}(x)$ as a function of $x$ for the proton.

of prompt photons provide a direct test of pQCD predictions. Moreover, one of the main motivations for these measurements is their potential to constrain the gluon distribution of the proton since the dominant contribution to the cross section comes from gluon-quark interactions [18]. The study of prompt photon production has some advantages respect to the study of jets: the energy resolution of the electromagnetic calorimeter is generally better than the energy resolution of the hadronic calorimeters, and the systematics uncertainties in the photon energy scale are smaller. Since photons do not fragment, their direction and energies are straightforwardly measured in the calorimeter, without a jet algorithms needed for the reconstruction. To investigate this process, the variable $\theta^*$ is used,

$$\cos \theta^* = \frac{\Delta y}{2},$$

where $\Delta y$ is the difference in rapidity of the two final state particles. $\theta^*$ coincides with the scattering angle in the centre-of-mass system and whose distribution is sensitive to the spin of the exchanged particle. In proton-proton collisions, a prompt photon with high $P_T$, can be produced in two possible ways:
• direct photon, where the photon originates from an hard subprocess and is well separated from any hadronic activity;

• fragmentation photon, where the photon is the result of the collinear fragmentation of a parton and it is accompanied by hadrons.

\[
\sum |M|^2 / \left( g^2 \epsilon_\gamma^2 q \right)
\]

Table 3.1: Lowest order processes for virtual photon production. The colour and spin indices are averaged over initial states, while are summed over final states. For real photons \((s + t + u) = 0\) and for SU(3) \(N = 3\).

The amplitudes of the lowest order processes are shown in Tab. 3.1. The contribution at leading order to the direct photon production, is given by the processes \(q\bar{q} \rightarrow \gamma q\) (also called QCD Compton process) and \(q\bar{q} \rightarrow g\gamma\) (annihilation process).

The contribution at leading order for the fragmentation production, is given by processes like \(qq \rightarrow qq, qg \rightarrow gq, gg \rightarrow qq\). The contribution to the fragmentation photon appears when a collinear singularity occurs in the calculation of the subprocess \(gq \rightarrow g\gamma q\). At LO, in pQCD, the direct photon contribution is expected the following angular distribution

\[
(1 - |\cos\theta^*|)^{-1},
\]

while the fragmentation contribution is expected to have a \((1 - |\cos\theta^*|)^{-2}\) dependence, when \(|\cos\theta^*| \rightarrow 1\). Depending on the nature of the colliding hadrons and on the values of \(\sqrt{s}\) and \(P_T\), either of these processes can dominate. For centrally produced photons, with \(\eta \approx 0\) in the colliding hadrons centre of mass frame, the initial state partons are probed at \(x \approx 2P_T/\sqrt{s}\).

At medium and large \(x\), there is a hierarchy of parton distributions in the proton: \(q \gg g \gg \bar{q}\), while at small \(x\), \(g \gg q, \bar{q}\). Thus in proton-proton or proton-nucleus collisions, the Compton process dominates over all the \(P_T\) ranges, while in proton-antiproton collisions, the Compton process dominates at low \(P_T\) and the annihilation process dominates for high \(P_T\). According to the factorization theorem, this kind of singularities are factorized to all orders in \(\alpha_S\) and absorbed into quark and gluon fragmentation functions of the photon, \(D^q_{\gamma}(z, \mu_f)\) and \(D^g_{\gamma}(z, \mu_f)\), where \(z\) is the relative fraction of the fragmenting parton momentum taken by the photon. These fragmentation
functions are defined in a factorization scheme at a chosen \( \mu_F \), to be in the same order of the hard scale of the process. When \( \mu_F \) is larger than \( O(1) \) GeV, these fragmentation functions behave as \( \alpha/\alpha_s(\mu_f) \) and the photon fragmentation contribution is of the same order \( O(\alpha \alpha_s) \) as the Born level terms in the direct mechanism.

At leading order, the final state for direct and fragmentation photon production, is formed by a \( \gamma \) and a high \( P_T \) parton. From an experimental point of view, the topology of the event is described by \( \gamma + \text{jet} \) in the final state. When the direct process occurs, the photon in generally well separated from the hadronic activity, while when a fragmentation photon comes out, the \( \gamma \) will be probably accompanied by hadrons, except when it carries with itself most of the momentum of the fragmenting parton. But most of these fragmentation processes are suppressed by an isolation criterium. The LO hadron differential cross section, denoted by \( d\sigma^{\text{LO}} / dP_T^\gamma \) for the process \( pp \rightarrow \gamma + \text{jet} + X \), is given by the sum of the fragmentation and direct contributions, and can be written as:

\[
d\sigma^{\text{LO}} \frac{d\hat{\sigma}^{\text{LO,}\gamma}}{dP_T^\gamma} = \frac{d\hat{\sigma}^{\text{LO,}\gamma}}{dP_T^\gamma}(p_T^\gamma, \mu_F) + \sum_a \int_0^1 \frac{dz}{z} \frac{d\hat{\sigma}^{\text{LO,}\alpha}}{dP_T^\gamma}(\frac{p_T^\gamma}{z}, \mu_F; \mu_f) D_a^{\text{LO}}(z, \mu_f) \tag{3.7}
\]

where \( \frac{d\hat{\sigma}^{\text{LO,}\alpha}}{dP_T^\gamma} \) and \( \frac{d\hat{\sigma}^{\text{LO,}\gamma}}{dP_T^\gamma} \) are the partonic cross sections convoluted with the partonic distribution functions. \( \frac{d\hat{\sigma}^{\text{LO,}\alpha}}{dP_T^\gamma} \) is the production differential cross section of a parton in the hard collision; \( D_a^{\text{LO}}(z, \mu_f) \) is the fragmentation function of the parton into a photon and \( \mu_F \) is the factorization scale for partons in the initial state. In Eq. (3.7) the dynamics is contained in the...
partonic cross section, while the no-perturbative contributions are factorized into the parton density of the proton and the fragmentation functions of the photon. In figure 3.5(a) there is a collinear singularity when the momenta of the final state quark and gluon are parallel, as the case of the $e^+ e^- \rightarrow q\bar{q}$ process, but the divergence cancels when real and virtual gluon contributions are summed. The contribution coming from Fig. 3.5 (b) is more interesting. The singularity (when the photon quark are parallel), does not cancel, but it has to be absorbed into the photon fragmentation function $D_{\gamma q}(z, \mu^2)$ representing the probability of finding a photon carrying longitudinal momentum fraction $z$ in a quark jet at scale $\mu$. $D_{\gamma q}(z, \mu^2)$ is not calculable in perturbation theory, but follows a DGLAP evolution equation similar to that one for the hadron fragmentation function.

### 3.3.1 NLO calculation

The distinction between the direct and the fragmentation photon production has no physical meaning beyond LO. From a theoretical point of view, the distinction is defined by an arbitrary choice, which follows from the necessity of factorizing the final state collinear singularities and absorbing them into the fragmentation functions. This factorization requires the introduction of an arbitrary fragmentation scale $\mu_F$, which relies on the arbitrary choice of the factorization scheme and defines the finite part of the high-order corrections, absorbed in the fragmentation functions together with the singularities. The Feynman diagrams for prompt photon production at NLO are shown in Fig. 3.6. The remaining finite part is then included in the high order contribution to the partonic cross sections. In general, taking into account high-order
Figure 3.6: NLO Feynman diagrams for the prompt photon production

The cross sections $d\hat{\sigma}^\gamma / dP_T^\gamma$ and $d\hat{\sigma}^a / dP_T^\gamma$ are known up to NLO in $\alpha_s$:

$$
\frac{d\hat{\sigma}^\gamma}{dP_T^\gamma} = \frac{\alpha_s(\mu_R)}{\pi} \frac{d\hat{\sigma}_{\text{Born}}^\gamma}{dP_T^\gamma}(P_T^\gamma, \mu_F) + \frac{\alpha_s(\mu_R)}{\pi} \frac{d\hat{\sigma}_{\text{HO}}^\gamma}{dP_T^\gamma}(P_T^\gamma, \mu_F, \mu_R, \mu_f)
$$

(3.9)

$$
\frac{d\hat{\sigma}^a}{dP_T^\gamma} = \frac{\alpha_s(\mu_R)}{\pi} \frac{d\hat{\sigma}_{\text{Born}}^a}{dP_T^\gamma}(P_T^\gamma, \mu_F) + \frac{\alpha_s(\mu_R)}{\pi} \frac{d\hat{\sigma}_{\text{HO}}^a}{dP_T^\gamma}(P_T^\gamma, \mu_F, \mu_R, \mu_f)
$$

(3.10)

The expressions of $\frac{d\hat{\sigma}_{\mu\mu}}{dP_T^\gamma}$ and $\frac{d\hat{\sigma}_{\mu\nu}}{dP_T^\gamma}$ for the direct and fragmentation contributions can be found in [19].

### 3.4 Jet algorithms

The reconstruction of the topology of the final state partons is possible through the use of jet algorithms. They have to make sure that there is a correspondence between jets and final state partons. There isn’t a general jet algorithm to reconstruct this final state particles, it depends on the case which is object of study. From an experimental point of view, jet algorithms must not depend on the presence of soft particles or decays products of
CHAPTER 3. THEORETICAL FRAMEWORK

hadrons. While, from a theoretical point of view, there are some guidelines of jet algorithms to follow:

- **Infrared safety**: If there are some additional soft particles between two particles belonging to the same jet, this should not interfere with the recombination of these two particles into a jet and its reconstruction; So if a soft particle is present, it should not affect the number of jets produced.

- **Collinear safety**: The jet should be reconstructed independently of the fact that an amount of transverse momentum is carried by only one particle or two splitted collinear particles;

- **Input-object independence**: the topology of jets should be reconstructed independently at detector, parton or particle level.

There are two methods to reconstruct jets starting from the particles in the final state:

- cluster algorithms
- cone type algorithms

Algorithms like $k_t$ or anti-$k_t$ [20], belong to the family of cluster algorithms and they are based on a sequential recombination of particles. Although cone type algorithms, like SISCone, are based on the maximization of energy density inside a cone of fixed size, with a special condition to disentangle overlapping stable cones. Jets are generally defined from the transverse energy flow in the rapidity-azimuthal angle plane. The transverse energy flow respect to the colliding axis makes sure the Lorentz invariance under longitudinal boosts. Inside the recombination algorithms, the distance between a pair of object ($d_{ij}$) is defined as:

$$d_{ij} = \min(E_{T,i}^2, E_{T,j}^2) \frac{\Delta_{ij}^2}{R^2}$$

(3.11)

where $E_{T,i}^2$ and $E_{T,j}^2$ are the distances between the objects and the beam. R is the radius parameter, $\Delta_{ij}^2 = (y_i - y_j)^2 + (\Phi_i - \Phi_j)^2$ while $E_{T,i}$, $y_i$ and $\Phi_i$ are the transverse momentum, the rapidity and the azimuth angle of i. Following (3.11), the clustering proceeds identifying the shortest distance and looking if it is a $d_{ij}$, recombining i and j, or if it is $d_{iB}$, where i is a jet, and removing it from the list of entities. This procedure is repeated until there are no entities


left. There is an extended definition for the distances expressed in the $k_T$ and in the Cambridge/Aachen algorithms:

$$d_{ij} = \min\left(E_{T,i}^{2p}, E_{T,j}^{2p}\right) \frac{\Delta_{ij}^2}{R^2}$$  \hspace{1cm} (3.12)

where

$$d_{ij} = E_{T,i}^{2p}$$  \hspace{1cm} (3.13)

If $p = 1$, the inclusive $k_t$ algorithm is defined, while if $p = 0$ it corresponds to the Cambridge/Aachen algorithm. Negative values of $p$, lead to a different behaviour of the jet algorithms, they became flexible to soft radiation. The case of $p = -1$ corresponds to the anti-$k_t$ jet-clustering algorithm, which is the one used in this analysis (with $R = 0.6$) to reconstruct jets.

### 3.4.1 anti-$k_t$ algorithm

Consider an event with well separated hard particles with transverse energies $E_{T,i}$ and lot of soft particles. The distance

$$d_{ij} = \min\left(\frac{1}{E_{T,i}^{2p}}, \frac{1}{E_{T,j}^{2p}}\right) \frac{\Delta_{ij}^2}{R^2}$$  \hspace{1cm} (3.14)

between an hard particle $i$ and a soft particle $j$ is determined only by the transverse energy of $i$ and the separation $\Delta_{ij}$ between the two particles, because soft particles tend to accumulate close to hard particles instead of clustering between themselves. $d_{ij}$ for similary separated soft particles will be much larger. If an hard particle doesn’t have an hard neighbour within a distance of $2R$, it will accumulate all the soft particles within a circle with a radius $R$, resulting as a perfect conical jet. If another hard particle is present and $R < \Delta_{12} < 2R$, there will be two jets, but is not possible that they both are perfectly conical.

### 3.4.2 Recombination schemes

The jet that has a higher $E_T$ is going to have a perfect cone shape, while the jet with lower $P_T$ is going to have a partly conical shape, due to the overlapping part with the first jet. If they have both the same transverse energy, neighter jet is going to be conical and the overlapping part will be divided by a line between the two. If $\Delta_{12} < R$, these particles cluster into a single jet, and if $E_{T1} > E_{T2}$, the new jet will be conical and centered on
$E_{T_1}$ For $E_{T_1} \approx E_{T_2}$, the shape will be a union of both cones (radius < R) around both hard particles, plus a cone of radius R centered on the final jet. Combining particles into jets, there are some schemes that can be followed to combine momenta.

- $E$-scheme
- $p_T$ scheme;
- $p_T^2$ scheme;
- $E_T$ scheme;
- $E_T^2$ scheme.
Chapter 4

Monte Carlo simulations

A Monte Carlo generator, simulates events according to a statistical distribution coming from the process cross section. The goal is to generate events as similar as possible to the data observed in a real detector. The output of an event generator should consist of events, with the same fluctuations and behaviours of the data. Monte Carlo techniques are used to select all relevant variables according to the desired probability distributions and, thereby, ensure almost randomness in the final events. It is possible to lose some informations, because some quantum mechanics interference phenomena could appear and cannot be translated in a probabilistic language, but this is really a rare case. An event generator has multipurpose use, in fact it could be used to give the physicist an estimate of the expected events and their rate, as a tool for devising the possible strategies for the data analysis (to optimize the signal-background ratio) or to understand the detector acceptance corrections. It also can be used to plan and optimize the construction and the efficiency of a new detector, to study new physics processes. To describe an high energy event, an event generator should contain simulation of several physics aspects:

- two beams coming in towards each other. Each particle of the beams has a set of PDFs, which defines the partonic substructure;
- an initial-state parton which starts to branch and building a initial state shower;
- an incoming parton from the two showers undergoes an hard scattering process and a number of outgoing partons or elementary particles are produced. This determines the main features of the event;
- the outgoing partons could branch and build the final state showers;
• the beam components left behind may have an internal structure and a colour charge relate to the rest of the final state;

• when the momentum scale starts to decrease and it is low enough, the hadronization takes place, so colour-neutral hadrons are observed;

• lots of the produced hadrons are unstable and decay into stable particles. This is called the MC hadron level.

The differences between the MC generators are in the modelling of the initial and final states radiation, hadronization and underlying events. In this analysis the event generator SHERPA, with ME + PS and CT10 PDFs was used [22]

4.1 SHERPA’s event generator framework

SHERPA [21] is an acronym for “Simulation of High Energy Reactions of PArticles”. The program is a complete event generator that has been constructed from scratch and entirely written in the modern, object oriented programming language C++. SHERPA’s physics modules are:

• AMEGIC++
  This is SHERPA’s default matrix-element generator based on Feynman diagrams, which are translated to helicity amplitudes. AMEGIC++ has been thoroughly tested for multiparticle production in the Standard Model and employs the Monte Carlo phase-space integration library PHASIC;

• APACIC++
  It generates initial and final state parton showering. The shower evolution is governed by the DGLAP equations and is ordered in parton virtualities. Coherence effects are accounted for by explicit ordering of the opening angles in subsequent branchings.

• AMISIC++
  This module simulates multiple parton interactions. In SHERPA the treatment of multiple interactions has been extended by allowing the simultaneous evolution of an independent parton shower in each of the subsequent collisions. This shower evolution is handled by APACIC++.

• AHADIC
  It is SHERPA’s hadronisation package for translating the partons (quarks and gluons) into primordial hadrons.
• HADRONs
  Is the module for simulating hadron and \(\tau\)-lepton decays. The resulting decay products respect full spin correlations (if desired). Several matrix elements and form-factor models have been implemented, such as the Kuhn-Santamaria model or form-factor parametrisations from Resonance Chiral Theory for the \(\tau\)-leptons and form factors from heavy quark effective theory or light-cone sum rules for hadron decays.

• PHOTONS
  This module holds routines to add QED radiation to hadron and \(\tau\)-lepton decays based on the YFS algorithm. The structure of PHOTONS is designed such that the formalism can be extended to scattering processes and to a systematic improvement to higher orders in perturbation theory.

4.2 Initial and final state radiation

QCD parton evolution and the occurrence of jets can be understood theoretically when the structure of perturbative amplitudes is examined in the kinematical regime of intrajet evolution, i.e. when two or more partons get close to each other in phase space. Whenever this happens, any QCD matrix element squared factorises into a matrix element squared containing the combined “mother” parton and a universal function describing the splitting into the “daughters”. In this limit, the theory becomes semi-classical and can be understood in a Markovian approach, where a single initiating parton develops a cascade of independent branchings. This is the basic concept of any shower Monte Carlo. Potential differences then arise in the factorisation scheme only.

4.3 Parton to hadron fragmentation

After the parton shower has terminated, a configuration of coloured partons at some low scale of the order of a few GeV in transverse momentum emerges. These partons, in order to match experiments, have to be translated into hadrons. Since there is no first-principles approach yielding quantitative results, hadronisation is achieved by phenomenological models only. Usually, they are based on some qualitative ideas on how the parton-to-hadron transition proceeds, like, e.g., local parton-hadron duality or infrared safety, defining the model’s coarse properties. However, many of the important finer
details, often related to how flavour is created and distributed in the procedure, are entirely undefined and subject to phenomenological parameters only. These are essentially free and must be fixed by extensive comparisons with data.

### 4.3.1 Cluster hadronisation model

For a long time, for the hadronisation of partons, SHERPA has relied on the implementation of the Lund string model in PYTHIA, accessible through a corresponding interface. Since version 1.1, SHERPA employs its own module AHADIC, which implements a cluster-hadronisation model. The basic assumption underlying this class of models is local parton-hadron duality, i.e. the idea that quantum numbers on the hadron level follow very closely the flow of quantum numbers on the parton level. In this framework, the mass spectrum of the emerging colour-neutral clusters is dominated by typical hadron masses or masses slightly above. It is therefore natural to think of them as some kind of “hadron matter”, carrying the flavour and momentum quantum numbers of hadrons. This motivates to translate the light clusters directly into hadrons or, if they are too heavy, to treat them like hitherto unknown heavy hadron resonances, which decay further into lighter ones. The idea underlying AHADIC is to take this interpretation literally, to compose clusters out of all possible flavours, including diquarks, and to have a flavour-dependent transition scale between clusters and hadrons. This results in solely translating the very light clusters directly into hadrons, whereas slightly heavier clusters experience a competition between being either translated into heavy hadrons or being decayed into lighter clusters, see below. In addition, for all decays, a QCD-inspired, dipole-like kinematics is chosen.

### 4.3.2 The ME + PS algorithm implementation

HEP event generation can be typically split into four steps: Matrix Element calculation, Parton Shower, Underlying Event and Hadronisation. Usually the interesting physics events, as well as the cross-section information is done with the computation of the Matrix Element, that involves PDF evaluation, phase space, amplitudes and spin correlations. The remaining steps are used to evolve the parton-level event to its final state. All these secondary steps are related heavily on models and are generally independent from the Matrix Element calculation. Therefore only few, typically multi-purpose event generators, implement those additional steps. Examples are Pythia 6 and 8, Herwig and Sherpa, which is used in this analysis. Most of these multi-purpose event generators give a limited set of Matrix Element (ME) processes, and of-
ten only in the leading order. Alternative Matrix-Element-only Monte Carlo event generators exist, like MadGraph, ALPGEN, HELAC, which provide more flexibility in Matrix Element calculations. For example they are able to generate additional hard emissions on Matrix Element level, that would otherwise have to be approximated by the Parton Shower in a less precise way (usually the Parton Shower underestimates additional hard emissions and should preferably be used only the soft and collinear case, whereas the (LO) Matrix Element calculations can describe those better taking into account all possible Feynman diagrams in the hard process). If such higher-order Matrix Element calculations are to be combined with Parton Showers of any multi-purpose event generator, a matching procedure has to be performed in order to avoid double-counting of emissions between the ME and the PS. Generators like MadGraph/MadEvent or ALPGEN come with their own preferred matching prescription, which should be used preferably. Also more recent Parton Showers come with an alternative matching procedure called CKKW reweighting which exploits knowledge of the Sudakov form factors during the Parton Shower evolution to reweight the events. Another big use case for alternative Matrix Element generators is to obtain calculations processes that are not covered by the multi-purpose generators, like new physics (anomalous couplings, exotics, ...), where the primary decay of the new particles is done inside the ME generator into known standard model particles, so that the Parton Shower can take over (or into invisible particles).

4.4 Montecarlo simulations of prompt-photon processes

The SHERPA treatment of prompt photons differs from other MC generators, as PYTHIA or HERWEG, by modeling the fragmentation functions as a part of the parton shower, thus making predictions with NLO accuracy while still providing parton-shower merging that can be used to study the detector response. MC events were generated to study signal and background events of prompt photons processes. These samples were also used to find out the response of the detector to jets of hadrons and the correction factors, which are needed to obtain the hadron level cross sections. For this analysis, five SHERPA samples were used, which have different RunNumber and number of entries.

The Sherpa direct photon samples have a simple generator level filter on the minimum photon $P_T$. To combine the samples one would weight events based on the cross section of the sample and the total number of events
CHAPTER 4. MONTE CARLO SIMULATIONS

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Number of events</th>
<th>$\sigma_{MC}[nb]$</th>
<th>Filter Eff.</th>
<th>$E_T$ range [GeV]</th>
</tr>
</thead>
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<td>1499991</td>
<td>$1.379 \cdot 10^{-1}$</td>
<td>1</td>
<td>$200 \leq E_T &lt; 350$</td>
</tr>
<tr>
<td>113717</td>
<td>999985</td>
<td>$5.963 \cdot 10^{-3}$</td>
<td>1</td>
<td>$350 \leq E_T &lt; 600$</td>
</tr>
<tr>
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<td>999976</td>
<td>$2.765 \cdot 10^{-4}$</td>
<td>1</td>
<td>$600 \leq E_T &lt; 950$</td>
</tr>
<tr>
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<td>99996</td>
<td>$1.335 \cdot 10^{-5}$</td>
<td>1</td>
<td>$950 \leq E_T &lt; 1150$</td>
</tr>
<tr>
<td>113717</td>
<td>99995</td>
<td>$2.382 \cdot 10^{-6}$</td>
<td>1</td>
<td>$1150 \leq E_T$</td>
</tr>
</tbody>
</table>

Table 4.1: Specific values of the used Monte Carlo sample generated.
The weights for each MC sample are:

- $1.3785 \cdot 10^{-1}/1499991$;
- $5.9627 \cdot 10^{-3}/999985$;
- $2.7645 \cdot 10^{-4}/999976$;
- $1.3346 \cdot 10^{-5}/99996$;
- $2.3821 \cdot 10^{-6}/99995$;

A cut on the truth $P_T$ of the event is necessary to create mutually exclusive datasets and a smooth distribution in $P_T$. The reconstructed $E_T$ of the simulated photons is corrected with the smearing method.

4.4.1 Hadron level results for prompt photon+jets production

The MC sample of prompt photon plus jet events at hadron level, was chosen applying these criteria:

- The selection of candidate photons is based on the particle data group identification, where for a MC generated photon the value of the pdgID is equal to 22. The selection criteria on photons are:

  - select the leading photon with $E_{T,HL}^\gamma > 300$ GeV and $|\eta_{HL}^\gamma| < 2.37$ (excluding the crack region $1.37 < |\eta_{HL}^\gamma| < 1.56$);
  - the isolation transverse energy $E_{T,HL,iso}^\gamma$, was required to be:

$$E_{T,HL,iso}^\gamma < 6.5 \cdot 10^{-03} \times E_{T,HL,Lead}^\gamma + 4.7$$  \hspace{1cm} (4.1)

Where $E_{T,HL}^\gamma$ and $|\eta_{HL}^\gamma|$ are the transverse energy and the rapidity of the photon at hadron level.
• jets were reconstructed from the final state particles, including the preselected photon, with the anti-kt algorithm with radius $R = 0.6$. The jet 4-momenta were computed from the jet constituents based on the E-scheme recombination scheme. The selection criteria are:

- events with at least one jet with $P_{T,HL} > 50$ GeV, $|Y_{HL}| < 4.4$ and

\[ \Delta R^{\gamma-jet} = \sqrt{(\eta_{HL}^\gamma - \eta_{HL}^{jet})^2 + (\phi_{HL}^\gamma - \phi_{HL}^{jet})^2} > 1. \]

The four leading jets were selected in this analysis.

### 4.4.2 Correction factors

The multiplicative correction factor, $C_{had}$, was defined as the ratio of the number of entries of the reconstructed events over the hadron level events and was estimated by using the MC programs described before. These correction factors are used in the calculation of the hadron level cross sections, which are the goal of this analysis.

This procedure is described in detail in Chapter 8.
Chapter 5

Photon and jet reconstruction and identification

5.1 Photon reconstruction and identification

Through the electromagnetic calorimeter in the ATLAS detector, photons are identified and reconstructed as electromagnetic clusters, which are not matched with tracks, due to their neutral behaviour [23] [24]. But photons can convert in an electron-positron pair, because of the interaction with the detector material, so not only the electromagnetic cluster is required for the reconstruction, but also a secondary vertex with at least two tracks, matching the cluster, is required. For $E_T$ above 20 GeV, neutral hadrons decay, like $\pi^0 \rightarrow \gamma\gamma$, and represent the main source of the background in this analysis. The LAr calorimeter has a fine segmentation in the lateral and longitudinal directions of the electromagnetic showers. For high energies, most of the electromagnetic clusters are collected in the second layer of the LAr calorimeter. Its first layer consists of grained strips in the $\eta$-direction, and they are good discriminator for the $\gamma/\pi^0$ ambiguity. The region between the barrel and the endcap, which has a range of $1.37 < |\eta| < 1.52$, has a low performance, due to the large amount of material in front of the first calorimeter layer, so it is excluded from the fiducial region. Before they deposit their energy in the electromagnetic calorimeter, photons have to pass through the tracker in the inner detector. In presence of material in the ID, the production of an $e^+e^-$ pair is dominant. This is known as photon conversion. The converted photon reconstruction is made with a great precision with the implementation of the pixel vertexing layer, in the innermost part of the ID. It provides a great rejection of the contribute coming from the photon conversion.
5.1.1 Trigger the photon candidates

At L1 of the trigger system, the selection of the photon candidates is focused on the calorimeter informations, based on the reconstruction of the electromagnetic clusters with the trigger towers, see Fig. 5.1. If the clusters have a transverse energy above a certain threshold, which is specified in the trigger menu, they are considered for the analysis. If the events pass the L1, they are considered for L2, which uses the position of the electromagnetic cluster, given by the L1, and looking for the most energetic cell. The EF uses the offline reconstruction algorithm, but without the reconstruction of the converted photons.

L1 selection
At L1, the information from the trigger towers is used, coming from the LAr and hadronic calorimeter system. They consist of towers with a dimension of $\Delta \eta \times \Delta \phi \approx 0.1 \times 0.1$. In this region, the cells are summed over the depth of the electromagnetic or the hadronic calorimeter. The selection algorithm is focused on a $4 \times 4$ window in trigger towers, which look for the local maximum. The found object is supposed to contain a photon candidate if these requirements are satisfied:

- the central $2 \times 2$ window of the cluster, consisting of electromagnetic and hadronic towers, is a local maximum in $E_T$. With this system, double counting of clusters by overlapping windows are avoid;

- the most energetic of the four combinations of two neighboring em towers passes the electromagnetic cluster threshold.

At this level, if required, is possible to fix the isolation requirement, to control the rate:

- $E_{EM}^{EM,isol}$: the total $E_T$ in the 12 EM towers surrounding the $2\times2$ core cluster is less than the electromagnetic isolation threshold;

- $E_{HAD,core}^{HAD}$: the total $E_T$ in the 4 towers of the hadronic calorimeter behind the $2\times2$ core cluster of the electromagnetic calorimeter is less than the hadronic core threshold.

- $E_{HAD,isol}^{HAD}$: the total $E_T$ in the 12 towers surrounding the $2\times2$ core cluster in the hadronic calorimeter is less than the hadronic isolation threshold.

L2 selection
L2 calorimeter reconstruction uses the $\eta$ and $\phi$ positions provided by level 1.
Now calorimeter cells in a window of size $\Delta \eta \times \Delta \phi = 0.4 \times 0.4$ are considered. At L2, the cluster-building algorithm scans the cells in the second layer of the EM calorimeter and searches for the cell with highest $E_T$. As a consequence, a cluster of $0.075 \times 0.175$ in $\eta \times \phi$ is built around this seed cell. The larger cluster size in $\phi$ reduces the low-energy tails due to photon conversion and electron bremsstrahlung. Photons deposit nearly all of their energy in the EM calorimeter and typically less than 1\% of their energy into the hadronic calorimeter. In addition, showers from photons are typically smaller in the plane transverse to its direction than showers from jets. These quantities are used to select a low-background sample of photons. The L2-photon algorithm selects events based on the following quantities:

- transverse energy of the EM cluster ($E_{EM}$): due to the energy dependence of the jet cross section, a cut on $E_{EM}$ provides the best rejection against jet background for a given high $P_T$ signal process;

- transverse energy in the first layer of the hadronic calorimeter ($E_{Had}$): this is required to be below a given threshold. This cut is relaxed for high $E_T$ triggers (90 GeV and above) as the leakage into the hadronic...
calorimeter increases with energy;

• shower shape in \( \eta \) direction in the second EM sampling: the ratio of the energy deposit in \( 3 \times 7 \) cells (corresponding to \( 0.075 \times 0.175 \) in \( \Delta \eta \times \Delta \phi \)) over that in \( 7 \times 7 \) cells is calculated, \( R_{\text{core}} = \frac{E_{3\times7}}{E_{7\times7}} \). Photons deposit most of their energy in \( 3 \times 7 \) cells and thus the corresponding ratio is typically larger than 80%;

• search for a second maximum in the first EM sampling: after applying the cuts in the hadronic calorimeter and the second sampling of the EM calorimeter, only jets with very little hadronic activity and narrow showers in the calorimeter remain. The fine granularity in rapidity of the first sampling of the EM calorimeter allows checks to be made for substructures within a shower for further rejection of background, such as single or multiple \( \pi^0 \)'s and \( \eta \)'s decaying to photons. The energy deposit in a window of size \( \Delta \eta \times \Delta \phi = 0.125 \times 0.2 \) is examined. The shower is scanned for local maxima in the \( \eta \) direction. The ratio of the difference between the energy deposited in the bin with highest energy, \( E_{1\,\text{st}} \), and the energy deposited in the bin with second highest energy, \( E_{2\,\text{nd}} \), divided by the sum of these two energies is calculated, \( R_{\text{strips}} = \frac{E_{1\,\text{st}} - E_{2\,\text{nd}}}{E_{1\,\text{st}} + E_{2\,\text{nd}}} \). This ratio tends to one for an isolated photon and to zero for photons coming from \( \pi^0 \) decay.

Event Filter selection
At this level, offline algorithms and tools are used. Only calorimeter informations and electromagnetic clusters are considered and reconstructed in RoI with size of \( \Delta \eta \times \Delta \phi = 0.4 \times 0.4 \). After that, the algorithms look for a local maximum inside the trigger towers. The electromagnetic clusters should have an \( E_T \) above a given threshold. The cluster parameters, like position and energy, are computed and refined by some corrections given by some cluster correction tools (position and energy calibration).

5.1.2 Photon reconstruction
The reconstruction of photons is made by a particular reconstruction algorithm. Photons can be classified in two categories, converted and unconverted. For the converted reconstructed photons, is necessary the presence of at least two track, matching a cluster in the electromagnetic calorimeter, originating from a vertex inside the tracker, while unconverted photons don’t have a matching track [26]. The reconstruction algorithm in the calorimeter assemble the deposits of energy in clusters, while a sliding window algorithms,
with the size of $3 \times 5$ in middle layer cell units, look for a cluster of longitudinal towers with $E_T$ above 2.5 GeV. The match between the cluster and a track, is given by following the last measured vertex to the middle layer of the electromagnetic calorimeter. The distance between the cluster and the track, has to be less than 0.05 along $\eta$ and less than 0.1 along $\phi$, to take in account bremsstrahlung losses. If multiples tracks match the same cluster, the tracks with hits in the silicon detectors are considered, and the closest in $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$ are chosen. To recover photons which have converted into a $e^+e^-$ pair, the cluster has to match pairs of tracks originating from a reconstructed vertex. For unconverted photons, the size of the cluster in the barrel is $\Delta \eta \times \Delta \phi = 3 \times 5$, while it is $3 \times 7$ for converted photons. In the endcap region, a cluster size of $5 \times 5$ is used for all the photon candidates.

To get the energy of photons, a weighted sum of four different contributions in the calorimeter system is performed:

- the energy deposit in the cluster;
- the energy deposit outside the cluster ("lateral leakage");
- the energy deposit in the material in front of the electromagnetic calorimeter;
- the energy deposit beyond the EM calorimeter ("longitudinal leakage").

An energy calibration is used, separately for converted and unconverted candidates, to consider the energy losses and the leakages, later and longitudinal. The position of the photon in the $\eta - \phi$ plane, is calculated independendly for each layer as the weighted energy baricenter of the cluster cells in that layer. After that, individual layer measurements are corrected with known systematic biases and measurements for the position, from the first two layers, are performed to produce the overall cluster position.

**Converted photons**

Photons could convert inside the inner detector, in the presence of material, so the reconstruction depends on the tracking algorithm used. The conversion is dominated by the production of an $e^+e^-$ pair, because all the other interactions between the material and the photon, have a small cross section so their contribution can be ignored [27]. The cross section for this process is theoretically well known and was measured with an high precision. For photon conversion energies above 1 GeV, the cross section formula is given
\[
\frac{d\sigma}{dx} = \frac{A}{X_0 N_A} \left(1 - \frac{4}{3} x(1 - x)\right)
\]

(5.1)

where \(x = \frac{E_\gamma}{E}\), \(X_0\) is the radiation length, \(7/9\) of the mean free path for photon conversion, \(A\) is the atomic number and \(N_A\) is the Avogadro number. The momentum of the photon is not shared equally between the electron and the positron, but in some fraction of the photon conversions [28], one of the two particles could be produced with low energy. If this energy goes below the threshold required to produce a reconstructed track in the inner detector, then the converted photon appears with only one track associated. Photon candidates are reconstructed by pairing tracks with opposite charge. There are three possible combination of track pairs considered:

- two tracks with at least four silicon hits each (Silicon-Silicon track pairs);
- two stand-alone TRT tracks (TRT-TRT track pairs);
- pairs with one track with at least four silicon hits and one stand-alone TRT track.

There are some selection criteria to reduce the background coming from secondary vertex. Because the photon is massless, the tracks emerging from the conversion, are almost parallel at the vertex, so they must have a small opening angle. Another condition is on the sum of the radii of the helices of the pair produced in the conversion. It must be comparable to the distance between the centre of the two helices.

If the conversion is generated asymmetrically, there is a number of conversions where only one track is reconstructed and, depending on the photon momentum scale, this track conversion saturate those that happen in the TRT.

### 5.1.3 Photon identification

After the reconstruction, not all of the reconstructed candidates are a real photon, but some fake photons can come from jets. To separate the real from the fake, discriminating variables are defined, using informations from the calorimeters and the inner detector. Some cuts on these variables are used to maintain high photon identification efficiency [29] even in presence of overlapping minimum bias events.
Discriminating variables

Inside the electromagnetic calorimeter, real photons are shrink and confined, while fake photons usually have a jagged shape and can reach the hadronic calorimeter, depositing a fraction of their energy. For these reasons, longitudinal and transverse shower shape, reported in Fig. 5.2 variables are created to reject fake photons [30]:

- **hadronic leakage** \( R_{\text{had1}} \): defined as the ratio between the transverse energy in the first layer of the hadronic calorimeter, inside a window \( \Delta \eta \times \Delta \phi = 0.24 \times 0.24 \), and the transverse energy of the cluster. In the region of \( 0.8 < |\eta^{\text{cluster}}| < 1.37 \), is used \( R_{\text{had1}} \), which is defined in the same way has \( R_{\text{had1}} \), but instead of using the only \( E_T \) of the first layer of the hadronic calorimeter, the whole amount of energy in the calorimeter is used.

- **variables using the second compartment of the ECAL**: The electromagnetic showers deposit a big part of their energies in the sec-
CHAPTER 5. RECONSTRUCTION AND IDENTIFICATION

ond layer of the electromagnetic calorimeter. For this reason there are several variables that measure the shower shape:

- Real photons deposit most of their energy in a window with size $\Delta \eta \times \Delta \phi = 3 \times 7$. The lateral shower shape variables $R_{\eta}$ and $R_{\phi}$, are respectively given by the ratio of the energy reconstructed in a $3 \times 7$ middle cells to the energy in $7 \times 7$ cells, and the ratio between the energy reconstructed in $3 \times 3$ cells to the energy in $3 \times 7$ cells. Usually $R_{\phi}$ is less discriminating than $R_{\eta}$, because the effect of the magnetic field increases the width of the converted photon contributions in the $\phi$ direction;

- the lateral width in $\eta$ is calculated in a window of $3 \times 5$ cells using the energy weighted sum over all cells, $\omega_2$, given in units of $\eta$.

• variables using the first compartment of the ECAL: The main source of fake photons is from jets, which contains neutral hadrons such as $\pi^0$ or $\eta$. Using the high granularity of the first layer, is possible to identify substructures in the showers and distinguish isolated prompt photons and photons coming from a $\pi^0$ decays:

- Due to the $\pi^0 \to \gamma\gamma$, the associated energy deposit is usually found with two maxima, showers are studied in a window $\Delta \eta \times \Delta \phi = 0,125 \times 0,2$ around the cell with the highest $E_T$ to look for another maximum. If more than two maxima are found, only the second maximum is considered. The following two variables are constructed using the informations coming from the second high maximum:

  - $\Delta E_s = E_{\text{max}2} - E_{\text{min}}$, is the difference between the energy associated to the second highest maximum and the energy reconstructed in the strip with the maximum value, found between the maxima.

  - $E_{\text{ratio}}$, is the difference between the largest maximum and the second, over the sum of the two energies $E_{\text{ratio}} = \frac{E_{\text{max}1} - E_{\text{max}2}}{E_{\text{max}1} + E_{\text{max}2}}$.

- $F_{\text{side}}$, is the fraction of the energy outside the shower core of three central strips.

- $\omega_{s3}$, is the width of the shower over three strips around the one with the maximum deposit. It is expressed in units of strip cells and corrected for impact point dependence.

- $\omega_{stot}$, the width of the shower over the strips which covers 2.5 cells of the layer.
Loose selection
Loose is the basic selection, which includes shower shape variables coming from the EMC Middle layer ($R_\eta$, $\omega_2$), together with hadronic leakage, the fraction of the cluster energy deposited in the hadronic calorimeter layers beyond the EM calorimeter ($R_{\text{had}}$ or $R_{\text{had1}}$). These variables show small differences for converted and unconverted photons.

Tight selection
It provides a great rejection of the background [25]. Its requirements include tighter cuts on the variables used for the loose selection ($R_\eta$, $\omega_2$, $E_{\text{had1}}$, $R_{\text{had}}$, and $R_{\text{had1}}$), and additional cuts on $R_\phi$, a variable of the middle layer, and cuts on quantities coming from the deposits in the strip layer ($\omega_3$, $\omega_{\text{stat}}$, $F_{\text{side}}$, $\Delta E_s$, $E_{\text{ratio}}$). As consequence of these cuts, photons candidates should lie in the pseudorapidity region covered by the first layer of the electromagnetic calorimeter, so candidate photons in the regions $1.37 < |\eta| < 1.52$ and $|\eta| > 2.37$ are rejected for the tight criteria. These cuts are optimized for converted and unconverted photons separately, due to the different deposit in the two cases.

5.1.4 Photon isolation
A requirement on isolation should be introduced to obtain a meaningful studies about the production of prompt photons. They are supposed to
be more isolated than the background photons, coming from the $\pi^0$ and $\eta$ decays. A variable $E_T^{Iso}$ was introduced for this purpose. It depends on the energies in the cells around the photon candidate [29], in a cone of size 
\[ \sqrt{(\eta_{\text{cell}} - \eta_\gamma)^2 + (\phi_{\text{cell}} - \phi_\gamma)^2} < R_0, \]
where $(\eta_{\text{cell}}, \phi_{\text{cell}})$ are the cells coordinates. The core of the cone, where the photon is located, is excluded. For this analysis, the value of $R_0$ was set at 0.4.

5.1.5 Photon calibration

The Egamma calibration procedure consists in applying corrections to photon and electron energy response in data, and to smear their response on simulation to mimic the effect observed in the real detector [31]. The final step of the calibration procedure consists, as in the past, in applying in-situ energy scales $\alpha$ obtained from the comparison of the detector response to $Z \rightarrow ee$ events in data and MC. All the steps described above are implemented in a single calibration tool, which will return to the user the fully corrected energy for data, and MVA-calibrated and smeared energy for MC.

5.2 Jet reconstruction and identification

The principal detector for jet reconstruction in ATLAS is the calorimeter system. It provides almost hermetic coverage in the range $|\eta| < 4.9$. There are lot of jet finding algorithms, provided by the ATLAS software framework, such as cone and sequential combination or algorithms based on event shape analysis, in fact there is not an universal jet finder for the hadronic final state. In ATLAS all the algorithms have a common feature, which is full four momentum recombination. Another important aspect is that in ATLAS, the jet algorithm code could be run on different objects, like the calorimeter signal towers, topological cell clusters, in the calorimeter, reconstructed tracks and generated hadrons and partons. There are some features in the reconstruction that are reflected in the design of the detector. These are divided into three classes:

- Detector technology indipendence: the kinematic variables of the reconstructed jet, do not have to depend on the signal source. All the signal characteristics and inefficiencies have to be calibrated and corrected. The main effects are:
  - detector resolution;
  - detector environment: minimize the electronics noise and signal losses by the inactive materials and cracks;
CHAPTER 5. RECONSTRUCTION AND IDENTIFICATION

– stable signals;

• environment independence: the reconstruction could be affected by additional events, like multiple interactions and pile up, so:
  – stability: the reconstruction must go on, even if there is a changing of underlying event activity and instantaneous luminosity;
  – efficiency: all the jets coming from energetic partons must be identified with high efficiency;

• implementations: the reconstruction must use every computing resources in an efficient way, it must be fast and avoids excessive memory consumption.

5.2.1 Calorimeter jet reconstruction

In the ATLAS calorimeter system there are 200,000 individual cells, with different sizes and electrode geometries [32]. To find a jet, is necessary to combine these cell signals into bigger signal objects with physically reasonable four momenta. There are two signal objects available for this goal:

• Signal towers: to construct signal towers, cells are projected into a grid in the $\eta$-$\phi$ plane. The tower bin size is $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ in the acceptance region of the calorimeters. Projective and non-projective cells, which are larger than the tower bin size, contribute a fraction of their signal to several towers, depending on the overlap fraction of the area of the cell and the tower. The signal contribution is calculated as the ratio of the tower bin area over the projective cell area in $\eta$ and $\phi$, and it is expressed as a geometrical weight. Jet reconstruction from the towers starts with a summation step which addresses possible unphysical four momenta due to a negative $E_{\text{tower}} < 0$, that could be generated by signal fluctuations from noise in the cells entering into the corresponding towers. It is possible to delete some of the noise fluctuations and biases with the combination of negative tower signals and nearby positive signals. If they don’t have nearby positive signals, are dropped. The output of the finder are jets with energies at the electromagnetic energy scale and their constituents are the original calorimeter towers.

• Topological cell clusters: the goal of these clusters is to reconstruct three-dimensional energy blobs which represent the showers that a particle develops after entering in the calorimeter system. The clustering procedure uses seed cells with a ratio of the signal over the noise,
or signal significance $\Gamma = E_{\text{cell}}/\sigma_{\text{noise,cell}}$, above a certain threshold ($|\Gamma| > S = 4$). All the cells of the neighbourhood, in all three dimensions, are collected into the cluster. Next neighbours are included for those cells which have $\Gamma$ above a certain secondary threshold $N$ ($|\Gamma| > N = 2$). Some “guard” cells, with the shape of a ring and with a signal significance above a basic threshold, $|\Gamma| > P = 0$, are included in the cluster. After the initial clusters are formed, local signal maxima are searched for using a splitting algorithm and they are splitted between those maxima. The final object, called topocluster, has the same energy as energy sum of all the cells included, zero mass and a reconstructed direction given by a vector originating from the center of the ATLAS coordinate system pointing to the energy-weighted topocluster barycenter.

As in the case of the tower signals, clusters are initially formed using the basic EM energy-scale cell signals. The topoclusters could already be used for jet reconstruction. In addition, clusters can be calibrated to a local hadronic energy scale. The calibration begins with a classification step characterising clusters as electromagnetic, hadronic or noise, based on their location and shape. After that, cell signals inside hadronic clusters are weighted with some functions depending on the position of the cluster, on its energy and on the cell signal density. Then, a correction for the lost energy in inactive material close to or inside the cluster is applied. Finally, a correction for signal losses due to the clustering itself is applied. All calibrations and corrections for topological clusters are derived from Monte Carlo simulations.

The reconstruction flow is very similar to the tower signal jet reconstruction, where the main difference lies in the treatment of the negative signals. Because of the symmetric noise cut applied in the selection of the cells in the clustering step, some clusters could have negative signal as well. These can be ignored for jet reconstruction without significantly biasing the jet signal with positive noise contributions. The noise suppression applied by the cell clustering, severely reduces any noise contribution. The cluster jets are initially at the electromagnetic energy scale. After the jet reconstruction, they are calibrated to correct effects such as residual nonlinearities in the jet response, which are an effect of the applied algorithm, missing energy from the jet or adding energy, not belonging to the jet in the jet clustering procedure, suppression of signal contributions from the underlying event and pile-up.
5.2.2 Jet calibration

As mentioned before, jets are reconstructed at the electromagnetic scale, which is the basic signal scale for the ATLAS calorimeters. The electromagnetic calorimeters energy scale has been corrected using the invariant mass of $Z \rightarrow ee$ events from collision events [33]. The goal of this jet energy scale calibration is to correct the energy and momentum of the jets measured with the calorimeter to those of the hadron level (truth) Monte Carlo jets. Monte Carlo truth jets are reconstructed from the stable particles with a lifetime higher than 10 ps in the MC event record. The hadronic jet energy scale is on average restored using derived data corrections and calibration constants which come from the comparison of the reconstructed jet kinematics to the one of the corresponding truth-level jet in Monte Carlo studies. The jet energy-scale calibration is then validated with some in-situ techniques. The jet calibration corrects for detector effects that affect the jet energy measurement:

- partial measurement of energy deposited by hadrons;
- energy losses in inactive regions;
- energy deposits from particles not contained in the calorimeter;
- energy deposits of particles inside the truth jet, but that are not reconstructed;
- signal losses in calorimeter clustering and jet reconstruction.

The ATLAS collaboration has developed several calibration schemes with different levels of complexity and different sensitivity to systematic effects, which are complementary in how they contribute to the understanding of the jet energy measurement. These schemes are:

- simple $p_T$- and $\eta$-dependent calibration scheme (EM+JES calibration): this kind of calibration scheme corrects for the non linear correlation between the energy reconstructed in the calorimeter and the energy of the particles forming jets. Jets are found from clusters or towers at the electromagnetic scale and the calibration constants are applied as functions of the uncalibrated jet $p_T$ and $\eta$;
- global sequential calibration scheme (GS calibration): this calibration scheme uses longitudinal and transverse properties of the jet structure to reduce fluctuations in the jet energy measurement. In this scheme, the jet energy response is first calibrated with the EM+JES calibration.
Then the different jet properties are used to improve the jet energy resolution without changing the mean value of the response;

- global cell energy-density weighting calibration scheme (GCW calibration): this calibration scheme attempts to compensate for the different calorimeter response to hadronic and electromagnetic energy depositions. The hadronic signal is characterised by low cell-energy densities and, thus, weighted up. The weights, which depend on the cell energy density and the calorimeter layer only, are determined by minimising the energy fluctuations between the reconstructed and particle jets in Monte Carlo simulation. The weights also compensate for energy losses in dead material. Jets are found from uncalibrated clusters or towers, then cells are weighted and a final $P_T$ and $\eta$ dependent correction is added to ensure that the jet energy is properly reconstructed;

- local cluster weighting calibration scheme (LCW calibration): this calibration scheme uses properties of clusters to calibrate them individually. These weights are determined from Monte Carlo simulations of charged and neutral pions. Jets are found from calibrated clusters and a final correction of the jet energy is applied to account for jet-level effects.

Jets calibrated with the EM+JES scheme were used in this analysis. Therefore, the EM+JES calibration scheme is explained in detail in the following section.

### 5.2.3 EM+JES calibration scheme

The EM+JES calibration scheme consists of three subsequent steps:

- The average additional energy due to pile-up is subtracted from the energy measured in the calorimeters using correction constants extracted from an in-situ measurement (pile-up correction);

- the position of the jet is corrected such that the jet direction points to the primary vertex of the interaction instead of the geometrical center of ATLAS detector (jet-origin correction);

- the jet energy and position as reconstructed in the calorimeters are corrected using constants derived from the comparison of the kinematics of reconstructed jets and corresponding truth jets in Monte Carlo (final jet-energy correction).
Chapter 6

Event selection

6.1 Event selection

The data used in this analysis were collected by the ATLAS detector in 2012, and correspond to a total integrated luminosity of 20.3 fb$^{-1}$, when the LHC was operating at a centre of mass energy of $\sqrt{s} = 8$ TeV. This data set was chosen to study the dynamic of prompt photon plus jets production with photon transverse energy above 300 GeV. The data sample used in the analysis contains only those runs (belonging to periods A-M) where the LHC and the ATLAS detector were fully efficient ("good run list"). Events had to pass the trigger requirement EF-g120-loose, which has an energy range of $E_\gamma^T \leq 125$ GeV and an efficiency of 99.6 %. The average number of interaction per bunch crossing is shown in Fig. 7.1. Events with problems associated to noise burst and data integrity errors in the calorimeters and incomplete events are rejected. After that, the following selection criteria were applied:

- events were required to have at least one off-line reconstructed primary vertex, with at least two associated tracks;
- photons were reconstructed from electromagnetic clusters and tracking informations provided by the inner detector. Converted and unconverted photons were considered. Energy calibration was applied, through a scale factor, which depends on the $\theta$ of the cluster, its energy and the particle type (if it is converted or unconverted);
- events with at least one photon candidate with $E_\gamma^T > 300$ GeV and $|\eta^\gamma| < 2.37$ were selected, with the crack region excluded;
- the candidate photons were required to pass the loose identification criteria, based on the five discriminating variables $R_{\text{had}}$, $R_\eta$, $\omega_2$, $R_\phi$ and $\omega_{\text{stat}}$;
the leading photon was required to pass the tight identification criteria based on the nine discriminating variables, described before;

- the isolation transverse energy, $E_{T}^{iso}$ into a cone of radius 0.4, was required to be lower than $6.5 \cdot 10^{-3} \cdot E_{T,lead}^{\gamma} + 4.7$, to get an uniform efficiency, as shown in Fig. 6.2;

- the photon candidates must be matched with the trigger.

- jets were reconstructed from topoclusters at the EM scale, with the anti-$k_t$ algorithm with radius 0.6. The jet four-momenta were recalibrated. The jet selection criteria are:
  
  - select up to four jets with highest $P_T^{jet}$ above 50 GeV and $|Y^{jet}| < 4.4$;
Figure 6.2: The ratio of the tight and isolated over the tight as function of $E_T^\gamma$.

- jets with $\Delta \phi^{\gamma-jets} < 1$ are removed, to ensure the photon isolation.

Events in the signal region with at least one jet are 67782.

### 6.2 Comparison between data and Monte Carlo

In the following section, the control plots between data and Monte Carlo are shown. The SHERPA simulation of the signal was renormalized to the total number of events in the data distribution. This simulation provides a good description of the data. The measurements, as function of the jet transverse momentum, show a decreasing behaviour as $P_T^{jet}$ increases. The highest $P_T^{jet}$ spectrum, has a peak at 300 GeV as expected. In fact the leading photon and highest $P_T$ jet must be back to back and the $P_T^{jet}$ has to compensate the
300 GeV cut on $E_T^\gamma$. For the distributions of the photon rapidity ($|\eta^\gamma|$), the jet rapidity ($|\eta^{1,2,3,4}_{jet}|$) and the difference in rapidity between the photon and the jets ($\Delta\eta^\gamma-jet_{1,2,3,4}$), a good agreement with the SHERPA simulations was found. The data distribution as function of $\Delta\phi^\gamma-jet_{1,2,3,4}$, the difference in azimuthal angle between the photon and the selected jets, has increases as $\Delta\phi^\gamma-jet$ increases. The distributions for $\phi^\gamma_{lead}$ and $\phi^{1,2,3,4}_{jet}$ are essentially flat and they are in good agreement with the SHERPA simulations.

Figure 6.3: The number of selected events as function of $E_T^\gamma$ compared to the SHERPA MC predictions.
CHAPTER 6. EVENT SELECTION

Figure 6.4: The number of selected events as function of $|\eta^\gamma|$ and $\phi^\gamma$ compared to the SHERPA MC predictions.

Figure 6.5: The number of selected events as function of the leading jet $P_T$ and $|Y^{jet}|$ compared to the SHERPA MC predictions.
Figure 6.6: The number of selected events as function of $\phi^{jet1}$ and $\Delta \eta^{\gamma-jet1}$ compared to the SHERPA MC predictions.
Figure 6.7: The number of selected events as function of $\Delta \phi^{\gamma-jet}$ compared to the SHERPA MC predictions.
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Figure 6.8: The number of selected events as function of $P_T^{jet2}$ and $|Y^{jet2}|$ compared to the SHERPA MC predictions.

Figure 6.9: The number of selected events as function of $\Delta\eta^{\gamma-jet2}$ and $\Delta\phi^{\gamma-jet2}$ compared to the SHERPA MC predictions.
CHAPTER 6. EVENT SELECTION

Figure 6.10: The number of selected events as function of $P_{T}^{\ell\ell3}$ and $|Y^{\ell\ell3}|$ compared to the SHERPA MC predictions.

Figure 6.11: The number of selected events as function of $\Delta\eta^{\gamma-jet3}$ and $\Delta\phi^{\gamma-jet3}$ compared to the SHERPA MC predictions.
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Figure 6.12: The number of selected events as function of $P_{T}^{jet4}$ and $|Y^{jet4}|$ compared to the SHERPA MC predictions.

Figure 6.13: The number of selected events as function of $\Delta\eta^{\gamma-jet4}$ and $\Delta\phi^{\gamma-jet4}$ compared to the SHERPA MC predictions.
Chapter 7

MC reweighting and background subtraction

7.1 Reweighting

In Fig 7.1 the $<\mu>$ distribution in data is shown. The comparison with SHERPA simulations shows a poor agreement between data and Monte Carlo. To evaluate the effects of this discrepancy, the MC distribution of $<\mu>$ was reweighted to data, as shown in Fig. 7.1. The value of the reweighting factor, calculated as the ratio bin by bin of $<\mu_{Data}>$ over $<\mu_{MC}>$, is used to reweight the other Monte Carlo distributions.

Figure 7.1: The average number of events per bunch crossing, before and after the reweighting.
A result of the MC reweighting is shown in Fig. 7.2.

Figure 7.2: The $P_T^{\text{jet1}}$ before and after the reweighting procedure.

7.1.1 $E_T^{\text{iso}}$ corrections

After the reweighting procedure, the data and MC $E_T^{\text{iso}}$ distributions were compared. Making a fit of the distributions a shift between MC and data was found.

Figure 7.3: The data distribution of $E_T^{\text{iso}}$ compared to the SHERPA MC distribution, after the shifting procedure.
Figure 7.4: The data distribution of $E_{T}^{\text{iso}}$ compared to the SHERPA MC distribution, after the shifting procedure.

To take this shift into account of that discrepancy, the MC $E_{T}^{\text{iso}}$ distributions were shifted according to the following equation:

$$E_{T}^{\text{iso,MC}} \rightarrow E_{T}^{\text{iso,MC}} + \Delta,$$

(7.1)

where $\Delta$ is defined as $\Delta = \mu_{\text{data}} - \mu_{\text{MC}}$, which are the two mean values of the fits. The results of this procedure are shown in Fig. 7.4 and 7.3. It is not important that data and MC distributions are in a perfect agreement, but it must be good for $E_{T}^{\text{iso}} \approx 5$ GeV, which is almost the cut on this variable.
7.2 Background subtraction technique

A non negligible contribution of background still affect the selected data sample, even after the application of tight identification and isolation requirements.

This amount of background, comes mainly from the misidentification of a jet as a photon. The jet contains a neutral meson, mainly a $\pi^0$ which decays into two collimated photons, that carry most of the energy of the jet. It is more evident looking at the Fig. 7.5 (a), which shows the measured $E_T^{iso}$ distribution, before any requirements on this variable, for the events who satisfy the tight identification criteria and the ones who fail it (non-tight photon candidates). The non-tight events (loose) have the same shape of the background which passes the tight identification criteria. The Fig 7.5 (b) shows the data distribution in $E_T^{iso}$ after performing a subtraction of the non-tight data distribution. In this analysis the background contamination was subtracted from the signal sample through the two-dimensional sideband method. The main advantage of this method is that no precise knowledge of the signal is required, and the background properties are deducted from
data. This method is based on the definition of a tight-isolated signal region and three background control regions. The four regions are defined as:

- **A** is the signal region, which contains tight and isolated photon candidates;
- **B** is a background control region, which contains tight and non-isolated photon candidates;
- **C** is a background control region, which contains isolated and non-tight photon candidates;
- **D** is a background control region, which contains non-isolated and non-tight photon candidates.

This method relies on two assumptions:

- The signal contamination in the three control regions is negligible;
• The variables used to define the axes are assumed to be uncorrelated [34], so that:

\[
\frac{N_{bkg}^A}{N_{bkg}^C} = \frac{N_{bkg}^B}{N_{bkg}^D}
\] (7.2)

The 7.2 becomes:

\[
\frac{N_{obs}^A - N_{sig}^A}{N_{obs}^C - \epsilon_C N_{sig}^C} = \frac{N_{obs}^B - \epsilon_B N_{sig}^B}{N_{obs}^D - \epsilon_D N_{iso}^D};
\] (7.3)

where \( N_{obs} \) and \( N_{sig} \) are respectively the number of observed events and the number of signal events, in the region \( i = A, B, C, D \). The coefficients \( \epsilon_k \), where \( k = B, C, D \), are called leakage factors, which are calculated with the Monte Carlo sample and are defined as the ratio of the number of signal events in the control region over the number of signal events.

\[
\epsilon_k = \frac{N_{kMC,sig}}{N_{MC,sig}^A};
\] (7.4)

The behaviour of the leakage factors for the leading photon and the highest \( P_T \) jet kinematic variables is shown in Fig. 7.7 to 7.9.
Figure 7.8: Signal leakage fractions from SHERPA for the three control regions for $P_T^{\text{jet}1}$ and $|Y^{\text{jet}1}|$.

Figure 7.9: Signal leakage fractions from SHERPA for the three control regions for $\Delta\eta^{\gamma\text{jet}1}$ and $\Delta\phi^{\gamma\text{jet}1}$. 
CHAPTER 7. MC REWEIGHTING AND BKG SUBTRACTION

7.2.1 Purities

After getting $N_A^{\text{sig}}$ from the Eq. 7.3, it is possible to evaluate the purity of the signal, through the ratio of the number of signal events after the background subtraction over the total number of signal events selected.

$$Purity = \frac{N_A^{\text{sig}}}{N_A^{\text{obs}}} \quad (7.5)$$

After the two dimensional sidebands method application, the purity of the signal is around 98%.

---

Figure 7.10: The purity fractions of the signal as function of $E_T^\gamma$ and $|\eta^\gamma|$.
Figure 7.11: The purity fractions of the signal as function of $P_T^{jet1}$ and $|Y^{jet1}|$.

Figure 7.12: The purity fractions of the signal as function of $\Delta \eta^{\gamma-jet1}$ and $\Delta \phi^{\gamma-jet1}$.
Chapter 8

Results

Differential cross sections for prompt photons in association with jets were measured in pp collisions, \( pp \rightarrow \gamma + \text{jet} + X \) at \( \sqrt{s} = 8 \) TeV, in the phase space given by \( E_{T,\text{lead}} > 300 \) GeV and \( |\eta\gamma| < 2.37 \) (crack region excluded, between \( 1.37 < |\eta\gamma| < 1.56 \)) and isolation \( E_{T}^{\text{iso}} < 6.5 \cdot 10^{-3} E_{T,\text{Lead}} + 4.7 \), for the photons, \( P_{T}^{\text{jet}} > 50 \) GeV and \( |Y^{\text{jet}}| < 4.4 \) for the four jets with highest transverse momenta. The distance between the leading selected photon and the selected jets must be;

\[
\Delta R = \sqrt{(\eta^{\gamma} - \eta^{\text{jet}})^2 + (\phi^{\gamma} - \phi^{\text{jet}})^2} > 1
\]  

(8.1)

The jets were reconstructed using the anti-\( k_{T} \) algorithm with \( R = 0.6 \) in the \( \eta - \phi \) plane. The cross sections were measured as function of \( E_{T,\text{lead}}, |\eta\gamma|, P_{T}^{\text{jet}}, |Y^{\text{jet}}|, \Delta \eta^{\gamma-jet} \) and \( \Delta \phi^{\gamma-jet} \).

8.1 Unfolding

After background subtraction, it is possible to evaluate the differential cross section, in the i-bin, through the formula:

\[
\left( \frac{d\sigma}{dX} \right)_i = \frac{(N^{\text{obs}}_A - N^{\text{bkg}}_A) \cdot C^{\text{Had}}_i}{\Delta X_i \cdot \mathcal{L}};
\]  

(8.2)

where \( N^{\text{obs}}_A - N^{\text{bkg}}_A \) is the number of events after the background subtraction, \( \Delta X_i \) is the bin width and \( \mathcal{L} \) is the integrated luminosity.

\( C^{\text{Had}}_i \) is a correction factor defined as the ratio of the Monte Carlo hadron level events over the Monte Carlo reconstructed and reweighted events:

\[
C^{\text{Had}}_i = \frac{N^{\text{Truth}}_i}{N^{\text{recon,rew}}_i}
\]  

(8.3)
The correction factors, $C^{had}$, used in the measurements of differential cross sections are shown in Fig. 8.1 to 8.5. While the $C^{had}$ values, related to the kinematic variables of third and the fourth jets, and their difference in rapidity and azimuthal angle with the photon, are shown in Appendix A.

### 8.2 Cross sections

The measured differential cross sections for inclusive isolated prompt photon + jets production at $\sqrt{s} = 8$ TeV are shown in Fig. 8.2 to A.12, along with a comparison to the corresponding Monte Carlo predictions. The ratio of the measured cross section to the predicted cross section is also shown. The uncertainties on the measured values include the systematic and the statistical uncertainties [35]. The values of the differential cross sections as functions of $E_T^\gamma$, $|\eta^\gamma|$, $P_T^{jet1,2,3,4}$, $|Y_{jet1,2,3,4}|$, $\Delta \eta^{\gamma-jet1,2,3,4}$ and $\Delta \phi^{\gamma-jet1,2,3,4}$ are shown in Tables 8.2 and 8.18. The quoted systematic uncertainties take only into account the sources affecting the measurement of the $E_T^\gamma$. In particular the uncertainty associated to the energy scale of the electromagnetic calorimeter and the uncertainty associated to the smearing procedure.

The differential cross section for $E_T^{\gamma,lead}$ shows a falling spectrum as $E_T^\gamma$ increases. For high values of $E_T^\gamma$, a very low data statistics was found and it is not possible to make a precise measurement. The measurements for the jets transverse momentum differential cross sections, show a decreasing behaviour as $P_T^{jet}$ increases. For the distributions of $d\sigma/d|\eta^\gamma|$, $d\sigma/d|Y_{jet}^{1,2,3,4}|$
Figure 8.2: $P_T^{\text{jet1}}$ and $|Y^{\text{jet1}}|$ correction factors.

Figure 8.3: $\Delta\eta^{\gamma-\text{jet1}}$ and $\Delta\phi^{\gamma-\text{jet1}}$ correction factors.
CHAPTER 8. RESULTS

Figure 8.4: $P_{T}^{jet2}$ and $|Y^{jet2}|$ correction factors.

Figure 8.5: $\Delta\eta^{\gamma-jet2}$ and $\Delta\phi^{\gamma-jet2}$ correction factors.
CHAPTER 8. RESULTS

and $d\sigma/d\Delta\eta^{\gamma-jet1,2,3,4}$ a good agreement with the SHERPA simulations was found. The differential cross section distribution as function of $\Delta\phi^{\gamma-jet1,2,3,4}$ has an increase as $\Delta\phi^{\gamma-jet}$ increases. The agreement between data and MC in the $0 < \Delta\phi^{\gamma-jet} < 1.8$ range is low. While the data distributions for $\phi_{lead}^{\gamma}$ and $\phi_{jet}^{1,2,3,4}$ are essentially flat and they are in good agreement with the SHERPA simulations. The measured $d\sigma/d[Y^{jet1,2,3,4}]$ and $d\sigma/d\Delta\phi^{\gamma-jet1,2,3,4}$ display a maximum at $|Y^{jet}| \approx 0$ and $\Delta\phi^{\gamma-jet} \approx \pi$, respectively. The differential cross sections and the tables related to the kinematic variables of third and the fourth jets, and their difference in rapidity and azimuthal angle with the photon, are shown in Appendix A.

Figure 8.6: The measured differential cross-section for isolated-photon plus jet production as a function of $E_T^\gamma$ compared with the SHERPA predictions.
### Table 8.1: The measured differential cross section $d\sigma/dE_T^\gamma$, statistical ($\sigma_{\text{stat}}$) and systematic ($\sigma_{\text{sys}}$) uncertainties.

<table>
<thead>
<tr>
<th>$E_T^\gamma$ bin [GeV]</th>
<th>$d\sigma/dE_T^\gamma$ [pb/GeV]</th>
<th>$\pm\sigma_{\text{stat}}$</th>
<th>$\pm\sigma_{\text{sys}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 - 350</td>
<td>$4.04 \cdot 10^{-2}$</td>
<td>$2 \cdot 10^{-4}$</td>
<td>$8.2 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>350 - 400</td>
<td>$1.77 \cdot 10^{-2}$</td>
<td>$1.4 \cdot 10^{-4}$</td>
<td>$5.5 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>400 - 500</td>
<td>$6 \cdot 10^{-3}$</td>
<td>$5.84 \cdot 10^{-5}$</td>
<td>$1.9 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>500 - 600</td>
<td>$1.6 \cdot 10^{-3}$</td>
<td>$3.05 \cdot 10^{-5}$</td>
<td>$5.1 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>600 - 700</td>
<td>$5 \cdot 10^{-4}$</td>
<td>$1.71 \cdot 10^{-5}$</td>
<td>$1.6 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>700 - 800</td>
<td>$2 \cdot 10^{-4}$</td>
<td>$9.68 \cdot 10^{-6}$</td>
<td>$5.83 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>800 - 1000</td>
<td>$4.04 \cdot 10^{-5}$</td>
<td>$3.47 \cdot 10^{-6}$</td>
<td>$1.56 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>1000 - 1500</td>
<td>$2.95 \cdot 10^{-6}$</td>
<td>$6.01 \cdot 10^{-7}$</td>
<td>$1.38 \cdot 10^{-6}$</td>
</tr>
</tbody>
</table>

### Table 8.2: The measured differential cross section $d\sigma/d|\eta^\gamma|$, statistical ($\sigma_{\text{stat}}$) and systematic ($\sigma_{\text{sys}}$) uncertainties.

| $|\eta^\gamma|$ bin | $d\sigma/d|\eta^\gamma|$ [pb] | $\pm\sigma_{\text{stat}}$ | $\pm\sigma_{\text{sys}}$ |
|---------------------|-----------------|----------------|----------------|
| 0 - 0.2             | 2.44            | 0.05           | 0.06           |
| 0.2 - 0.4           | 2.43            | 0.02           | 0.061          |
| 0.4 - 0.6           | 2.36            | 0.018          | 0.058          |
| 0.6 - 0.8           | 2.27            | 0.0179         | 0.061          |
| 0.8 - 1             | 2.25            | 0.017          | 0.056          |
| 1 - 1.2             | 2.07            | 0.018          | 0.055          |
| 1.2 - 1.37          | 1.85            | 0.017          | 0.054          |
| 1.37 - 1.56         | -               | -              | -              |
| 1.56 - 1.8          | 1.45            | 0.0175         | 0.027          |
| 1.8 - 2             | 0.89            | 0.013          | 0.021          |
| 2 - 2.2             | 0.57            | 0.012          | 0.014          |
| 2.2 - 2.37          | 0.26            | $9.08 \cdot 10^{-3}$ | $9.7 \cdot 10^{-3}$ |
CHAPTER 8. RESULTS

Figure 8.7: The measured differential cross-section for isolated-photon plus jet production as a function of $|\eta^{\gamma}|$ compared with the SHERPA predictions.

Table 8.3: The measured differential cross section $d\sigma/dP_T^{\text{jet}}$, statistical ($\sigma^{\text{stat}}$) and systematic ($\sigma^{\text{sys}}$) uncertainties.
Figure 8.8: The measured differential cross-section for isolated-photon plus jet production as a function of $P_T^{jet1}$ compared with the SHERPA predictions.

Figure 8.9: The measured differential cross-section for isolated-photon plus jet production as a function of $|Y^{jet1}|$ compared with the SHERPA predictions.

| Bin number | $d\sigma/d|Y^{jet1}|$ [pb] | $\pm \sigma^{stat}$ | $\pm \sigma^{sys}$ |
|------------|---------------------------|---------------------|---------------------|
| 1          | 2.71                      | 0.04                | 0.16                |
| 2          | 2.79                      | 0.041               | 0.1                 |
| 3          | 2.59                      | 0.038               | 0.041               |
| 4          | 2.26                      | 0.036               | 0.058               |
| 5          | 2.06                      | 0.034               | 0.084               |
| 6          | 1.74                      | 0.031               | 0.083               |
| 7          | 1.49                      | 0.029               | 0.11                |
| 8          | 1.16                      | 0.026               | 0.051               |
| 9          | 0.81                      | 0.021               | 0.015               |
| 10         | 0.53                      | 0.017               | 0.041               |
| 11         | 0.31                      | 0.013               | 0.081               |

Table 8.4: The measured differential cross section $d\sigma/d|Y^{jet1}|$, statistical($\sigma^{stat}$) and systematic ($\sigma^{sys}$) uncertainties.
Figure 8.10: The measured differential cross-section for isolated-photon plus jet production as a function of $\Delta \eta^{\gamma-jet_1}$ compared with the SHERPA predictions.

Figure 8.11: The measured differential cross-section for isolated-photon plus jet production as a function of $\Delta \phi^{\gamma-jet_1}$ compared with the SHERPA predictions.
<table>
<thead>
<tr>
<th>Bin number</th>
<th>$d\sigma/d\Delta\eta^{\gamma-jet_1}$ [pb]</th>
<th>$\pm\sigma^{stat}$</th>
<th>$\pm\sigma^{sys}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.36</td>
<td>0.02</td>
<td>0.042</td>
</tr>
<tr>
<td>2</td>
<td>1.28</td>
<td>0.019</td>
<td>0.042</td>
</tr>
<tr>
<td>3</td>
<td>1.18</td>
<td>0.018</td>
<td>0.025</td>
</tr>
<tr>
<td>4</td>
<td>1.08</td>
<td>0.017</td>
<td>0.046</td>
</tr>
<tr>
<td>5</td>
<td>0.92</td>
<td>0.016</td>
<td>0.057</td>
</tr>
<tr>
<td>6</td>
<td>0.78</td>
<td>0.014</td>
<td>0.037</td>
</tr>
<tr>
<td>7</td>
<td>0.63</td>
<td>0.013</td>
<td>0.024</td>
</tr>
<tr>
<td>8</td>
<td>0.49</td>
<td>0.011</td>
<td>0.013</td>
</tr>
<tr>
<td>9</td>
<td>0.39</td>
<td>0.01</td>
<td>0.016</td>
</tr>
<tr>
<td>10</td>
<td>0.32</td>
<td>$9.43 \cdot 10^{-3}$</td>
<td>0.018</td>
</tr>
<tr>
<td>11</td>
<td>0.23</td>
<td>$8.01 \cdot 10^{-3}$</td>
<td>0.029</td>
</tr>
<tr>
<td>12</td>
<td>0.18</td>
<td>$7.24 \cdot 10^{-3}$</td>
<td>0.011</td>
</tr>
<tr>
<td>13</td>
<td>0.11</td>
<td>$5.42 \cdot 10^{-3}$</td>
<td>0.017</td>
</tr>
<tr>
<td>14</td>
<td>0.09</td>
<td>$5.02 \cdot 10^{-3}$</td>
<td>$8.88 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>15</td>
<td>0.073</td>
<td>$4.57 \cdot 10^{-3}$</td>
<td>0.014</td>
</tr>
<tr>
<td>16</td>
<td>0.045</td>
<td>$3.53 \cdot 10^{-3}$</td>
<td>$5.83 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>17</td>
<td>0.029</td>
<td>$2.96 \cdot 10^{-3}$</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Table 8.5: The measured differential cross section $d\sigma/d\Delta\eta^{\gamma-jet_1}$, statistical($\sigma^{stat}$) and systematic ($\sigma^{sys}$) uncertainties.

<table>
<thead>
<tr>
<th>Bin number</th>
<th>$d\sigma/d\Delta\phi^{\gamma-jet_1}$ [pb/rad]</th>
<th>$\pm\sigma^{stat}$</th>
<th>$\pm\sigma^{sys}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$5.7 \cdot 10^{-3}$</td>
<td>$1.2 \cdot 10^{-3}$</td>
<td>$1.4 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>2</td>
<td>$7.5 \cdot 10^{-3}$</td>
<td>$1.1 \cdot 10^{-3}$</td>
<td>$2.5 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>3</td>
<td>0.021</td>
<td>$1.9 \cdot 10^{-3}$</td>
<td>$2.6 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>4</td>
<td>0.098</td>
<td>$4 \cdot 10^{-3}$</td>
<td>0.01</td>
</tr>
<tr>
<td>5</td>
<td>0.41</td>
<td>$8.6 \cdot 10^{-3}$</td>
<td>0.04</td>
</tr>
<tr>
<td>6</td>
<td>1.6</td>
<td>0.017</td>
<td>0.09</td>
</tr>
<tr>
<td>7</td>
<td>9.78</td>
<td>0.042</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Table 8.6: The measured differential cross section $d\sigma/d\Delta\phi^{\gamma-jet_1}$, statistical($\sigma^{stat}$) and systematic ($\sigma^{sys}$) uncertainties.
Figure 8.12: The measured differential cross-section for isolated-photon plus jet production as a function of $P_T^{jet}$ compared with the SHERPA predictions.

Figure 8.13: The measured differential cross-section for isolated-photon plus jet production as a function of $|Y^{jet}|$ compared with the SHERPA predictions.

<table>
<thead>
<tr>
<th>$P_T^{jet}[GeV]$ bin</th>
<th>$d\sigma/dP_T^{jet}$ [pb/GeV]</th>
<th>$\pm \sigma^{stat}$</th>
<th>$\pm \sigma^{sys}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 - 70</td>
<td>$2.04 \cdot 10^{-2}$</td>
<td>$2.27 \cdot 10^{-4}$</td>
<td>$7.81 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>70 - 90</td>
<td>$1.69 \cdot 10^{-2}$</td>
<td>$2.18 \cdot 10^{-4}$</td>
<td>$3.42 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>90 - 110</td>
<td>$1.45 \cdot 10^{-2}$</td>
<td>$2.04 \cdot 10^{-4}$</td>
<td>$7.36 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>110 - 130</td>
<td>$1.201 \cdot 10^{-2}$</td>
<td>$1.84 \cdot 10^{-4}$</td>
<td>$6.05 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>130 - 150</td>
<td>$1.05 \cdot 10^{-2}$</td>
<td>$1.78 \cdot 10^{-4}$</td>
<td>$7.86 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>150 - 200</td>
<td>$5.96 \cdot 10^{-3}$</td>
<td>$8.26 \cdot 10^{-5}$</td>
<td>$1.05 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>200 - 400</td>
<td>$1 \cdot 10^{-3}$</td>
<td>$1.69 \cdot 10^{-5}$</td>
<td>$2.91 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>400 - 500</td>
<td>$1 \cdot 10^{-4}$</td>
<td>$7.61 \cdot 10^{-6}$</td>
<td>$4.24 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>500 - 600</td>
<td>$2.76 \cdot 10^{-5}$</td>
<td>$3.81 \cdot 10^{-6}$</td>
<td>$1.36 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>600 - 800</td>
<td>$1.1 \cdot 10^{-5}$</td>
<td>$1.75 \cdot 10^{-6}$</td>
<td>$4.97 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>800 - 1000</td>
<td>$8.52 \cdot 10^{-7}$</td>
<td>$4.92 \cdot 10^{-7}$</td>
<td>$9.28 \cdot 10^{-7}$</td>
</tr>
</tbody>
</table>

Table 8.7: The measured differential cross section $d\sigma/dP_T^{jet}$, statistical ($\sigma^{stat}$) and systematic ($\sigma^{sys}$) uncertainties.
Table 8.8: The measured differential cross section $d\sigma/d|Y^{jet2}|$, statistical ($\sigma^{stat}$) and systematic ($\sigma^{sys}$) uncertainties.

| Bin number | $d\sigma/d|Y^{jet2}|$ [pb] | $\pm\sigma^{stat}$ | $\pm\sigma^{sys}$ |
|------------|---------------------------|--------------------|-------------------|
| 1          | 1.15                      | 0.03               | 0.019             |
| 2          | 1.06                      | 0.026              | 5.85 $\cdot 10^{-3}$ |
| 3          | 1.05                      | 0.025              | 0.025             |
| 4          | 0.98                      | 0.023              | 0.013             |
| 5          | 0.94                      | 0.023              | 0.032             |
| 6          | 0.85                      | 0.022              | 7.29 $\cdot 10^{-3}$ |
| 7          | 0.74                      | 0.019              | 0.016             |
| 8          | 0.72                      | 0.02               | 9.06 $\cdot 10^{-3}$ |
| 9          | 0.58                      | 0.018              | 6.4 $\cdot 10^{-3}$ |
| 10         | 0.48                      | 0.016              | 0.023             |
| 11         | 0.39                      | 0.015              | 0.014             |

Figure 8.14: The measured differential cross-section for isolated-photon plus jet production as a function of $\Delta\eta^{\gamma-jet2}$ compared with the SHERPA predictions.

Figure 8.15: The measured differential cross-section for isolated-photon plus jet production as a function of $\Delta\phi^{\gamma-jet2}$ compared with the SHERPA predictions.
### Table 8.9: The measured differential cross section $d\sigma/d\Delta\eta^{\gamma-jet}$, statistical ($\sigma^{\text{stat}}$) and systematic ($\sigma^{\text{sys}}$) uncertainties.

<table>
<thead>
<tr>
<th>Bin number</th>
<th>$d\sigma/d\Delta\eta^{\gamma-jet}$ [pb]</th>
<th>$\pm\sigma^{\text{stat}}$</th>
<th>$\pm\sigma^{\text{sys}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.96</td>
<td>0.012</td>
<td>3.01 \cdot 10^{-3}</td>
</tr>
<tr>
<td>2</td>
<td>0.95</td>
<td>0.011</td>
<td>3.11 \cdot 10^{-3}</td>
</tr>
<tr>
<td>3</td>
<td>0.97</td>
<td>0.011</td>
<td>6.75 \cdot 10^{-3}</td>
</tr>
<tr>
<td>4</td>
<td>0.86</td>
<td>0.011</td>
<td>0.028</td>
</tr>
<tr>
<td>5</td>
<td>0.81</td>
<td>0.011</td>
<td>5.22 \cdot 10^{-3}</td>
</tr>
<tr>
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<td>0.82</td>
<td>0.011</td>
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<td>5.59 \cdot 10^{-3}</td>
</tr>
<tr>
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<td>4.1 \cdot 10^{-3}</td>
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<td>0.59</td>
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<td>5.35 \cdot 10^{-3}</td>
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<td>10</td>
<td>0.46</td>
<td>7.95 \cdot 10^{-3}</td>
<td>0.027</td>
</tr>
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<td>3.43 \cdot 10^{-3}</td>
</tr>
<tr>
<td>12</td>
<td>0.35</td>
<td>6.97 \cdot 10^{-3}</td>
<td>0.029</td>
</tr>
<tr>
<td>13</td>
<td>0.29</td>
<td>6.33 \cdot 10^{-3}</td>
<td>0.025</td>
</tr>
<tr>
<td>14</td>
<td>0.25</td>
<td>6.11 \cdot 10^{-3}</td>
<td>0.012</td>
</tr>
<tr>
<td>15</td>
<td>0.18</td>
<td>4.81 \cdot 10^{-3}</td>
<td>0.022</td>
</tr>
<tr>
<td>16</td>
<td>0.19</td>
<td>5.11 \cdot 10^{-3}</td>
<td>0.012</td>
</tr>
<tr>
<td>17</td>
<td>0.17</td>
<td>5.04 \cdot 10^{-3}</td>
<td>0.016</td>
</tr>
</tbody>
</table>

### Table 8.10: The measured differential cross section $d\sigma/d\Delta\phi^{\gamma-jet}$, statistical ($\sigma^{\text{stat}}$) and systematic ($\sigma^{\text{sys}}$) uncertainties.

<table>
<thead>
<tr>
<th>Bin number</th>
<th>$d\sigma/d\Delta\phi^{\gamma-jet}$ [pb/rad]</th>
<th>$\pm\sigma^{\text{stat}}$</th>
<th>$\pm\sigma^{\text{sys}}$</th>
</tr>
</thead>
<tbody>
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Chapter 9

Conclusions

In this thesis, the production of isolated prompt photons in association with jets has been studied. The measurements are based on a data sample collected in 2012 with the ATLAS detector in the pp collisions of the LHC at a centre of mass energy of 8 TeV. To achieve the best precision in the measurements, these selection cuts were applied: $E_{T}^{\gamma} > 300$ GeV; $|\eta^{\gamma}| < 2.37$; $P_{T}^{jets} > 50$ GeV; $|Y^{jets}| < 4.4$ and $\Delta R = \sqrt{(\eta^{\gamma} - \eta^{jet})^2 + (\Phi^{\gamma} - \Phi^{jet})^2} > 1$.

The selected sample of events, despite the isolation and tight requirements, still contained some contamination from the decays of mesons such as $\pi^0$ and $\eta$. The removal of this background events necessitated a data driven method, which was explained in chapter 7. As a result, the purity of the sample has been determined as a function of every observable under consideration and found to be above $\approx 96 \%$. The differential cross sections were measured as function of $E_{T}^{\gamma}$, $|\eta^{\gamma}|$, $P_{T}^{jet}$, $|Y^{jet}|$, $\Delta\eta^{\gamma-jet}$ and $\Delta\phi^{\gamma-jet}$. The prediction of the Sherpa Monte Carlo were compared to the measurements, showing a reasonable agreement in all the measured differential cross sections. For the near future, we plan to complete the study of the systematic uncertainties and compare the measured differential cross sections with NLO predictions.
Appendix A

In this appendix, the correction factors (Fig. A.1 to A.4), the differential cross sections (Fig. A.5 to A.12) and the tables, (Tab. A.1 to A.8), related to the kinematic variables of third and fourth highest $P_T^{jet}$ and their differences in rapidity and azimuthal angle with the photon are shown.

Figure A.1: $P_T^{jet}$ and $|Y^{jet}|$ correction factors
Figure A.2: $\Delta \eta^{\gamma-jet3}$ and $\Delta \phi^{\gamma-jet3}$ correction factors

Figure A.3: $P_T^{jet4}$ and $|Y^{jet4}|$ correction factors
Figure A.4: $\Delta \eta^{\gamma-jet4}$ and $\Delta \phi^{\gamma-jet4}$ correction factors

Figure A.5: The measured differential cross-section for isolated-photon plus jet production as a function of $P_T^{jet3}$ compared with the SHERPA predictions.

Figure A.6: The measured differential cross-section for isolated-photon plus jet production as a function of $|\mathbf{Y}^{jet3}|$ compared with the SHERPA predictions.
Figure A.7: The measured differential cross-section for isolated-photon plus jet production as a function of $\Delta \eta^{\gamma - \text{jet}^3}$ compared with the SHERPA predictions.

Figure A.8: The measured differential cross-section for isolated-photon plus jet production as a function of $\Delta \phi^{\gamma - \text{jet}^3}$ compared with the SHERPA predictions.
Figure A.9: The measured differential cross-section for isolated-photon plus jet production as a function of $P_T^{jet}$ compared with the SHERPA predictions.

Figure A.10: The measured differential cross-section for isolated-photon plus jet production as a function of $|Y^{jet1}|$ compared with the SHERPA predictions.
APPENDIX A.

Figure A.11: The measured differential cross-section for isolated-photon plus jet production as a function of $\Delta \eta^{\gamma-jet}$ compared with the SHERPA predictions.

Figure A.12: The measured differential cross-section for isolated-photon plus jet production as a function of $\Delta \phi^{\gamma-jet}$ compared with the SHERPA predictions.
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<th>$P_T^{jet}[GeV]$</th>
<th>bin</th>
<th>$d\sigma/dP_T^{jet}$ [pb/GeV]</th>
<th>±σ_{stat}</th>
<th>±σ_{sys}</th>
</tr>
</thead>
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<td>1.45 $\cdot$ 10^{-6}</td>
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Table A.1: The measured differential cross section $d\sigma/dP_T^{jet}$, statistical (σ_{stat}) and systematic (σ_{sys}) uncertainties.

| Bin number | $d\sigma/d|Y^{jet}|$ [pb] | ±σ_{stat} | ±σ_{sys} |
|------------|----------------------------|-----------|----------|
| 1          | 0.31                       | 0.013     | 0.02     |
| 2          | 0.32                       | 0.014     | 6.49 $\cdot$ 10^{-3} |
| 3          | 0.33                       | 0.014     | 0.036    |
| 4          | 0.32                       | 0.013     | 0.02     |
| 5          | 0.31                       | 0.013     | 0.035    |
| 6          | 0.28                       | 0.012     | 7.4 $\cdot$ 10^{-3} |
| 7          | 0.24                       | 0.011     | 0.014    |
| 8          | 0.21                       | 0.0111    | 9.05 $\cdot$ 10^{-3} |
| 9          | 0.19                       | 0.01      | 6.4 $\cdot$ 10^{-3} |
| 10         | 0.17                       | 9.93 $\cdot$ 10^{-3} | 0.023    |
| 11         | 0.14                       | 8.89 $\cdot$ 10^{-3} | 0.014    |

Table A.2: The measured differential cross section $d\sigma/d|Y^{jet}|$, statistical (σ_{stat}) and systematic (σ_{sys}) uncertainties.
### Table A.3: The measured differential cross section $d\sigma/d\Delta\eta^{\gamma-jet3}$, statistical ($\sigma^{stat}$) and systematic ($\sigma^{sys}$) uncertainties.

<table>
<thead>
<tr>
<th>Bin number</th>
<th>$d\sigma/d\Delta\eta^{\gamma-jet3}$ [pb]</th>
<th>$\pm\sigma^{stat}$</th>
<th>$\pm\sigma^{sys}$</th>
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<td>$0.05$</td>
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<td>$0.013$</td>
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### Table A.4: The measured differential cross section $d\sigma/d\Delta\phi^{\gamma-jet3}$, statistical ($\sigma^{stat}$) and systematic ($\sigma^{sys}$) uncertainties.

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Table A.5: The measured differential cross section $d\sigma/dP_T^{\text{jet}}$, statistical ($\sigma^{\text{stat}}$) and systematic ($\sigma^{\text{sys}}$) uncertainties.

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<th>$P_T^{\text{jet}}$ [GeV]</th>
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<td>$1.39 \cdot 10^{-5}$</td>
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</table>

Table A.6: The measured differential cross section $d\sigma/d|Y^{\text{jet}}|$, statistical ($\sigma^{\text{stat}}$) and systematic ($\sigma^{\text{sys}}$) uncertainties.

| Bin number | $d\sigma/d|Y^{\text{jet}}|$ [pb] | $\pm\sigma^{\text{stat}}$ | $\pm\sigma^{\text{sys}}$ |
|------------|---------------------------------|-----------------|-----------------|
| 1          | 0.18                            | 0.0016          | 0.011           |
| 2          | 0.2                             | 0.0018          | $9.98 \cdot 10^{-3}$ |
| 3          | 0.18                            | 0.0017          | $9.59 \cdot 10^{-3}$ |
| 4          | 0.16                            | 0.0015          | 0.011           |
| 5          | 0.15                            | 0.0014          | 0.011           |
| 6          | 0.13                            | 0.0013          | $9.59 \cdot 10^{-3}$ |
| 7          | 0.2                             | 0.0019          | $6.53 \cdot 10^{-3}$ |
| 8          | 0.13                            | 0.0014          | $6.42 \cdot 10^{-3}$ |
| 9          | 0.11                            | 0.0012          | $7.07 \cdot 10^{-3}$ |
| 10         | 0.076                           | $9.57 \cdot 10^{-3}$ | $6.66 \cdot 10^{-3}$ |
| 11         | 0.094                           | 0.001           | $5.84 \cdot 10^{-3}$ |

Table A.7: The measured differential cross section $d\sigma/d\Delta\phi^{\gamma-\text{jet}}$, statistical ($\sigma^{\text{stat}}$) and systematic ($\sigma^{\text{sys}}$) uncertainties.

<table>
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<tr>
<th>Bin number</th>
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<th>$\pm\sigma^{\text{stat}}$</th>
<th>$\pm\sigma^{\text{sys}}$</th>
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Table A.8: The measured differential cross section $d\sigma/d\Delta\eta^{\gamma-jet}$, statistical ($\sigma_{stat}$) and systematic ($\sigma_{sys}$) uncertainties.
Bibliography


[33] ATLAS Collaboration , Properties of jets and input to jet reconstruction and calibration with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 7$ TeV. ATLAS-CONF-2010-053.

[34] Michael Hance, Measurement of inclusive isolated prompt photon production in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector.