Chapter 1

The Theoretical Perspective

1.1 Introduction

“Physics is essentially a cultural activity . . . there is a need to know—there is a heritage handed down—a vision that the human brain can ‘solve’ or put into rational order the physical problems of our own existence, starting with the creation of the universe in a big bang and predicting its evolution to the infinite future.” - Dr. Leon M. Lederman.

An intriguing question has always bothered mankind since ancient times - “What is this world made of”. While Aristotle, a Greek philosopher, (ca. 585 BCE) believed everything to be made of earth, air, fire and water along with a fifth essence, “quintessence”, that supposedly resided in the celestial world, other philosophers, Leucippus (ca. 450 BCE) and (especially) his student Democritus, argued matter could be divided into smaller and smaller units until some indivisible stage was reached, which they called as the atom. It was not until the early twentieth century, it was recognized that atoms are made up of smaller constituents called the electrons, protons and neutrons. The concept that even the protons and neutrons are further made up of minuscule entities called the quarks and gluons came into existence in the later part of that century. All
this became possible with the technological advances in building up apparatus to study these innmerous particles. Thus, the efforts of the physicists of the last century helped in molding precise and exceptional theories for matter and its interactions.

The field of Particle Physics can infact be defined as a quest for the most fundamental forms of matter and the laws of nature governing them. It requires mankind to reveal matter’s most elementary nature and understand the forces which cause the elementary particles to interact and eventually form composite objects based on the properties they possess. The knowledge accumulated over the last few decades has led to the establishment of the Standard Model of Particle Physics. This chapter will give a brief overview of the Standard Model (SM) and the missing pieces associated with it. Further, I will also cover some aspects of quantum chromodynamics (QCD), direct photon physics and the motivation behind performing direct photon measurements at the LHC energies.

In principle, to probe matter at smallest of distances it becomes necessary to produce remarkably high energies. Thus, the study of particles at smallest of dimensions is also known as “High Energy Physics”.

1.2 Standard Model

1.2.1 Evolution of the Model

*From Atomic to Particle Physics* - The time period after the late 1500’s saw the formulation of many theories, most of them we read as a part of classical mechanics now, and which helped define the behaviour of our physical world. These include Galileo’s work on mechanics and celestial bodies, Kepler’s laws of elliptical planetary motion, Newton’s laws of mechanics and Newton’s law of universal gravitation. In 1802 an English Chemist, John Dalton, experimentally stated matter to be made up of elementary lumpy particles, the atoms. Further, Maxwell’s theory of electromagnetism also came up during that period. However, it was the work of many others which marked the birth and rise of quantum mechanics, which completely altered the fundamental precepts of physics. Planck’s theory of
quantization, Bohr’s atomic model, Pauli’s exclusion principle, Schrodinger’s equations on wave mechanics, and Heisenberg’s uncertainty principle were some of the chief architect’s in the building up of the quantum theory of matter [1].

The building up of what we call Standard Model of Particle Physics now, started way back in late 1800’s with the discovery of the electron by J. J. Thompson [2] in 1897. The atomic structure was then thought to be based on a “plum pudding model” with electrons embedded in a positive paste. When Rutherford performed the Gold foil scattering experiment in 1911, evidence claimed atom to be a positive charged heavy nuclei surrounded by light electron’s with negative charge [3]. Immediately after this in 1914, Neil Bohr succeeds in constructing a theory of atomic structure based on quantum ideas. Based on that, he also predicted the Hydrogen atom model explaining the Hydrogen spectrum. However, the understanding of the composition of the atom became complete after the discovery of the neutron by Chadwick in 1932 [4]. It had almost the same mass as the proton but no charge, explaining the mass and charge distribution inside the whole nuclei. Thus, proton and neutron became manifestations of the same state - the nucleon.

First Carrier of Force: In 1900, Max Planck proposed that the electromagnetic (em) radiation comes in packets as quanta of energy ($E = h\nu$ where $h$ is the Planck’s constant). However, he gave no reason for quantization. While in 1905, Einstein gave an explanation about quantization using the phenomenon of photo-electric effect [5]. The quantum of em radiation was later termed “photon” by Gilbert N. Lewis in 1926. However, the discovery of Compton effect by A. H. Compton in 1923 confirmed the particle nature of photons. This was the first example of interactions being mediated by exchange particles.

Anti-matter: In 1927, Dirac combined concepts from Quantum Mechanics and Special Relativity to form a relativistic theory of electrons in the form of Dirac equations [6]. Their solution predicted a new particle with positive charge and negative energy. The prediction was confirmed in 1932, when Carl Anderson observed a particle with mass of an electron and a positive charge. This turned out to be the first anti-particle observation. More anti-particles were observed later at the Bevatron accelerator at Berkeley, such as
the anti-proton in 1955 and anti-neutron in 1956.

*The Elusive Neutrino & Weak Interactions:* Neutrinos came into existence, with Pauli postulating in 1930 an invisible particle carrying away the missing energy and momentum in beta-decay process. Later in 1933-34, Enrico Fermi put forth a theory of beta decay [7] that introduced the theory of weak interaction. This is the first theory to explicitly use neutrinos and particle flavor changes. Neutrinos, however were first observed by Cowan & Reines at the Savannah river nuclear reactor (1956) with the observation of the reaction $\bar{\nu}_p^+ \rightarrow n e^+$. While anti-neutrinos were confirmed through the absence of this process $\bar{\nu}_n \rightarrow p^+ e^-$ by Davis & Harmes in 1959.

*Idea of Mesons:* Yukawa proposed that there should be a particle which mediates the short ranged strong force between nucleons with a mass between electron and proton [8]. At around the same time, a particle with similar intermediate mass was observed in cosmic ray experiments, and it was termed the meson. However, it was later discovered that the particle was not the one required by Yukawa’s theory but in fact was muon. The term “lepton” was coined to describe such particles which do not interact strongly and are light weight. More than 10 years later, in similar cosmic ray experiments using photo emulsion techniques, it was realized that two particles existed with similar mass but different properties. It was then that the pion ($\pi$) was discovered (by Powell et al. in Bristol, 1947), which met with the conditions which Yukawa proposed.

The period after 1940’s, saw the beginning of a “particle explosion” – a true proliferation of particles.

*Strangeness and Quark Model:* In 1947, the first strange particle, the Kaon, was discovered by Rochester & Butler. Kaon however possessed strangely a very long lifetime. Another strange particle $\Lambda$ was seen by Anderson in 1950. Strange particles were copiously produced but decayed really slowly (strong interaction in production but weak interaction in decay). These were classified in terms of a new quantum number, Strangeness, proposed by Gell-Mann and Nishijima. Gell-Mann [9] proposed a geometrical pattern of re-arranging the bunch of particles with identical spin and with strangeness along horizon-
tal lines and, charge along diagonals. It was the eightfold way of arranging particles. The triumph of the eightfold way was when the $\Omega^-$ particle was observed in 1964 as predicted as the missing piece in the geometric pattern of the eightfold earlier in 1961. Further developments by Gell-Mann and Zweig led to the formation of the quark model with the postulation of particles (quarks) with fractional charges and of the new quantum number - color.

In the meantime, from the works of Feynman, Schwinger and Tomonaga, emerged the theory of Quantum Electrodynamics (QED) [10]–[13]. It was a very successful theory in explaining the electromagnetic phenomenon. The mediator for QED interactions was the photon.

More Generations: Development over the years lead to discovery of further generations of leptons and quarks. In 1974, two separate groups observed narrow resonance of the $c\bar{c}$ bound state ($J/\Psi$ particle), one was led by S. C. C. Ting et al. at Brookhaven AGS proton synchrotron and other was led by B. Richter et al. at SLAC/SPEAR $e^+e^-$ collider with Mark-I detector, marking the discovery of the charm quark [14][15]. Uptil this, there were two generations each of leptons and quarks already discovered. Adding one more generation to the lepton family, Tau lepton events were observed by M. Perl at SLAC/SPEAR at 4 GeV in 1975 [16]. This led to an imbalance between the number of leptons and quarks. The observation of $b\bar{b}$ bound state ($\Upsilon$ particle) by L. Lederman at Fermilab in 1977 (Dimuon Resonance at 9.5 GeV in 400 GeV Proton-Nucleus Collisions) added bottom/beauty quark [17] to the family of quarks. The last of the quarks to be discovered after a wait of 18 years, was the top quark, as observed by the CDF and DØ experiments at Fermilab in 1995 [18][19].

Other Carriers of Force: A theory describing the strong interactions among quarks also came up during this period. The theory was termed as Quantum Chromodynamics. While the gluon (mediator for the strong interactions) was discovered at TASSO experiment [20] at PETRA collider at DESY in 1979 in 3 jet events. During the 1960’s, S. Glashow, S. Weinberg & A. Salam came up with a theory for weak interactions which demanded the
presence of weak gauge bosons, $W^\pm$ and $Z$ \cite{21}\cite{22}. The weak bosons were later discovered by UA1 & UA2 experiments at CERN in 1983 in proton-antiproton collisions at 540 GeV \cite{23}\cite{24}. The discoveries of these 3 bosons by the two independent experiments were major breakthroughs for particle physics. This was one of the great milestones in man’s quest to understand the Universe around him.

Every particle discovered over all these years is said to fill one by one the missing pieces of the puzzle which nature gave mankind to solve. Figures 1.1 and 1.2 show the evolution of particle physics over the years.

![Particle Discovery Timeline Part I.](image)

Let us now move from the historical development of the model to what all exists in the present day world to construct the model, what all forces exist in physics, the existence and importance of these forces and some important theoretical constructs, the existence of which is critical for the model.

### 1.2.2 Components of the Model

Standard Model \cite{25}–\cite{27}, in its present status, comprises of “matter particles”: fundamental units of which matter is composed of, and “force carriers”: mediators of the four forces recognized in physics. The elementary particles can be classified into 2 categories, according to the attributes they possess: the fermions, obeying Fermi-Dirac statistics and
the bosons, obeying Bose-Einstein statistics. The matter particles basically quarks and leptons exhibit properties of fermions while mediator particles exhibit bosonic nature.

Table 1.1 gives specific details about the fermionic constituents of matter in the SM. Every fermionic particle obeys “Pauli exclusion principle” which forbids two fermions from being in the same quantum mechanical state. Every particle briefed here also has its corresponding anti-particle with opposite charge and same mass. Every row corresponds to a particular generation. Particles in the first generation are lighter as compared to the second and third generations. They occur in ordinary matter more frequently due to their extended stability. Particles in the subsequent generation rows are similar to the ones in the first row except for differences in mass and stability as depicted in the table. Another additional property shared by all particles in the table, is Spin. All particles are said to possess a spin of $1/2$ and their corresponding anti-particles possess a spin of $-1/2$.

**Leptons**, light mass as the name suggests, are actually fundamental in nature. We have 3 generations of leptons discovered up to now as mentioned in the table. The first row of every generation, electron($e$) or muon($\mu$) or tau($\tau$), is a charge -1 lepton. While the second row of every generation is the corresponding neutrino of first row, $\nu_e$ or $\nu_\mu$ or $\nu_\tau$. The neutrino’s are charge neutral. The neutrinos were considered to be massless until recent experimental measurements proved neutrinos to possess mass on account of

![Particle Discovery Timeline Part II](image_url)
neutrino oscillations [28]–[31]. There are in total 12 leptons in the SM, summing up the 6 leptons and 6 anti-leptons.

**Quarks**, another set of fundamental particles also have 3 generations as shown in the right half of Table 1.1. There are 6 quarks - up(u), down(d), charm(c), strange(s), bottom/beauty(b) and top/truth(t) and corresponding 6 anti-quarks also. Quarks carry fractional charges, with u, c and t having a charge of +2/3 and d, s and b with a charge of −1/3. In order to obey Pauli’s exclusion principle, another property called the “color charge” was assigned to every quark. Three color charges were designated to the quarks, red, blue and green. Anti-quarks possess anti-color’s, anti-red (cyan), anti-blue (yellow), and anti-green (magenta) respectively. Colored quarks are not found freely in nature, due to their property of quark confinement (explained later in the next section). Various quarks bind together to form color neutral composite objects called mesons and baryons. Mesons are composite structures of one quark and one anti-quark (examples - π±, π0, η, ρ, J/ψ, Υ ...). Baryons are composite forms of 3 quarks and similarly anti-baryons of 3 anti-quarks (examples - proton, neutron, Λ, Sigma, Ξ, Ω ...). Mesons and Baryons together are also called Hadrons - particles composed of quarks. In the end summing up the number of quarks and anti-quarks of all flavours and colors, there are in all 18 types of quarks and 18 anti-quarks.

Figure 1.3 shows the particle family diagram showing all the fundamental constituents of matter, the leptons and quarks, along with the force mediators which mediate one of the forces known to exist between matter.
Another important property of the elementary particles states that each particle is susceptible to at least one out of all the forces known to physics. The electromagnetic force is felt by all in the table except the neutrinos, the weak force also is felt by all particles in the table. The only difference is with respect to the strong force, which is only experienced by quarks and hence by mesons and baryons formed from quarks. The next few sections will describe these forces in some more detail.

**Forces of Interaction:** Every fundamental particle experiences some force of interaction with other particles. These forces of interaction known to exist between matter are mediated in the form of exchange particles. The forces recognized in physics upto now can be classified as - electromagnetic (em), weak, strong and gravitational. For former three of these forces, well formulated successful theories have been predicted and verified at experiments with utmost precision. While no such well understood theory exists for gravity and nor do we have any experimental evidence of bosons which would mediate gravitational interactions. Table 1.2 gives details about each force and the corresponding gauge boson(s). The table lists all characteristics of bosons along with mentioning about the forces strength and its range of action.
<table>
<thead>
<tr>
<th>Force</th>
<th>Boson</th>
<th>Charge</th>
<th>Spin</th>
<th>Mass ($MeV/c^2$)</th>
<th>Range (m)</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>Photon ($\gamma$)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>$\infty$</td>
<td>$1/137$</td>
</tr>
<tr>
<td>Weak</td>
<td>$W^\pm$</td>
<td>$\pm 1$</td>
<td>1</td>
<td>80.42</td>
<td>$10^{-18}$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>0</td>
<td>1</td>
<td>91.19</td>
<td>$10^{-18}$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Strong</td>
<td>Gluon (g)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>$10^{-15}$</td>
<td>1</td>
</tr>
<tr>
<td>Gravity (Yet to be discovered)</td>
<td>Graviton</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>$\infty$</td>
<td>$10^{-38}$</td>
</tr>
</tbody>
</table>

**Table 1.2:** The bosonic particles in the SM.

Till this date, SM incorporates the electromagnetic, weak and strong forces of interaction into one common symmetry group. The fundamental particles and their interactions in the SM can be described in terms of group mathematics. In simple words - a group is a mathematical system comprising of a set of elements with specific properties. In particular, a transformation applied to an element in the group results in another element in the group. A “symmetry”, however, is a collection of transformations of the set of objects, which form the mathematical group. Some examples of this are - “Charge Conjugation symmetry”, an operation which takes a particle to its anti-particle, “Isospin symmetry”, which transforms a proton into a neutron and vice-versa or “Parity”, a spatial inversion symmetry. The following text will describe SM forces of interaction in more detail.

**Electromagnetic Interaction:** The earliest of forces coming into picture was with the theory of electromagnetism from the unification of electricity and magnetism by Maxwell in 1864. These forces only exist between electrically charged particles. The gauge invariance of Maxwell equations and the corresponding gauge symmetry group given by the Abelian unitary group $U(1)$ [32][33] define the theory of electromagnetism. The quantum version of electromagnetism is referred to as Quantum Electrodynamics (QED) [10]–[13][34]. “Photons” serve as the gauge bosons forming the exchange particles in em interactions. The force has infinite range and has a relative strength deduced from the fine structure constant, $\alpha_{em} = 1/137$. The effective coupling constant ($\alpha_{em}$) is given as per the following equation,

$$\alpha_{em} = \frac{\alpha(\mu)}{(1 - \frac{a(\mu)}{3\pi})ln(\frac{Q^2}{\mu^2})} \quad (1.1)$$
where,

\( Q \): Energy of the probe.

\( \mu \): lower cut-off energy.

**Weak Interaction:** The only force which acts on all of the particles, even the neutrinos, is the weak force. It is responsible for changing flavours among leptons and quarks themselves, converting one flavour into another. It is responsible for the phenomenon of radioactive decays such as beta decay. Weak force is defined by the \( SU(2) \) symmetry group (\( SU \) - special unitary). \( SU(2) \) represents rotations in three dimensions and therefore has three parameters corresponding to the single angle of \( U(1) \). Thus, we get three carriers of the weak force, the two oppositely charged \( W^\pm \) and the \( Z \). The weak force is very short range \( 10^{-18} \) m and is relatively very weak as compared to strong and em forces.

**Strong Interaction:** The force is responsible for binding the quarks together inside a nucleon and also for binding the nucleons (proton and neutron) inside a nuclei. Strong force acts on quarks but does not act on other SM particles, like the leptons, by virtue of the property of color charge which only the quarks possess. The gauge theory governing the strong interactions of the color charged particles is called Quantum Chromodynamics [35]. \( SU(3)_C \) is the gauge group describing the theory of strong interactions. Strong force is mediated by the exchange of gluons arising from the fields representing the force. Gluons themselves carry color charge and are also massless. Thus gluons can interact among themselves and this makes QCD theory much more complicated in contrast to QED where chargeless photons do not interact with each other. In QCD, we have 8 gluons, formed from one color and anti-color each. The strong force acts within the nucleus, having a range of about a fermi \( (10^{-15} \) m).

### 1.2.3 Electroweak Sector with Origin of Higgs Mechanism

The electromagnetic and weak force interactions are unified into forming the electroweak theory. The combined group called the Electroweak was formulated by S. Glashow, S. Weinberg, and A. Salam [21][22]. The unification of the forces is possible using the
The theory proposes three carriers of the weak force, the $W^\pm$ and the $Z$ boson. These are massive bosons whereas photon, the carrier for electromagnetic force, on the other hand is massless. The gauge symmetry requires the bosons to be massless in order to preserve the invariance. Standard model has been offered an unique way of dealing with massive particles. For this, electroweak symmetry should be broken in such a way that all the predictions of the symmetry are preserved, the $W^\pm$ and the $Z$ procure their masses while the photon still remains massless. This is achieved by the Higgs mechanism [36], which assumes the existence of a Higgs field with an associated particle called the Higgs boson. The massless gauge bosons of the weak interactions acquire their mass, through interaction with the Higgs field and due to the non-zero value of the field strength. The electroweak symmetry is spontaneously broken down into $U(1)_{em}$ group corresponding to the electromagnetic interactions. The process is called electroweak symmetry breaking (EWSB) [37]. In addition, the Higgs mechanism is also responsible for generating the masses of fermions due to their couplings with the Higgs field. Thus, in order for this mechanism to hold true, the Higgs boson should be discovered. Higgs particle are detectable via their decay modes to other particles, whose signatures are directly measured in the detector. Over the last few decades, there have been innumerable studies on the theoretical fronts as well as various searches on the experimental side of particle physics. LEPII experiments have already set strong lower bounds on the Higgs particle mass [38]. More recently, the LHC experiments (ATLAS and CMS) have seen slight hints of a Higgs-like boson with utmost significance in some decays channels [39][40].

Of all the known theories, Standard Model successfully merges the electroweak (EW) theory (electromagnetic & weak forces combined) and QCD (theory of strong interactions) to form one unified theory and which can be termed as the gauge theory described by the group $SU(3)_C \times SU(2)_L \times U(1)_Y$ (c - color, L - weak isospin & Y - hypercharge) [27]. Although, a unified theory incorporating the Gravitational force is still missing from the picture because of its low energy coupling and weak behaviour, which makes it hard to be
observed in experimental conditions currently. Besides this, SM has been deeply tested and proven at various high energy physics experiments with high precision.

Upto now, the Standard Model of Particle Physics has been introduced. Since the subject of the thesis concerns direct photons in the QCD sector, the following sections will concentrate basically on QCD and the explanations based on QCD formalism for direct photon processes.

## 1.3 Quantum Chromodynamics

### 1.3.1 Introduction

Quantum Chromodynamics [35][41][42], the theory of strong interactions, explains the interactions of quarks (q) and gluons (g) with each other. In group notation, QCD can be listed as a non-Abelian theory forming the $SU(3)_C$ group. The “Chromo” in the name comes from the fact that quarks and gluons possess color charge. Owing to this color charge possessed by gluons, they exhibit the property of self-interaction. Quarks can not be observed in isolated states but only occur as color singlet states in nature. Quarks combine to form hadrons such as mesons (bound state of $q\bar{q}$) or baryons (bound state of $qqq$). Gluons act as the force carrier bosons responsible for carrying the strong force within the nucleus.

Asymptotic freedom and confinement, the characteristics that describe this non-Abelian gauge theory, provide explanations for the short range and long range behaviour of partons inside the nucleons. Strength of a QCD interaction can be measured in terms of its coupling strength [43]. The expression for the coupling is given as:

$$\alpha_s(Q^2) = \frac{12\pi}{(11c - 2n_f)ln(Q^2/\Lambda^2)} \tag{1.2}$$

where,

$Q$: momentum transfer during the interaction.
$c$: number of quark colors ($c = 3$).

$n_f$: number of quark flavours ($n_f = 6$).

$\Lambda$: scale parameter for QCD.

Using the above expression, it can be visualized that, as $Q^2 \to \infty$, $\alpha_s(Q^2) \to 0$. In other words, as we move towards higher and higher energies with very high momentum transfers during the interaction, $(Q^2 \gg \Lambda^2)$, the strength of the coupling between the partons tends to decrease. The quarks and gluons in such a case behave as free entities inside the nucleon. This condition is referred to as “asymptotic freedom” [35] in QCD. QCD can thus be treated perturbatively and as an asymptotically free theory at very high energies. On the other hand, at very low values of $Q^2$, quarks and gluons start to imprison themselves into bounds, as $Q^2 \to 0$, $\alpha_s(Q^2) \to \Lambda^2$. No longer, can isolated singlet quarks and gluons be observed. They occur as hadronic bound states of quarks (called baryons or mesons as explained earlier) which are held together by gluons. This special attribute of the strong force is termed as “quark confinement”. Perturbation theory is inapplicable in this energy regime of QCD.

### 1.3.2 Proton-Proton Collisions

**Factorization theorem** - Parton model [44][45] states that at very high-momentum-transfer $Q^2$ values, the proton will disintegrate into constituent partons. In proton-proton (pp) collisions, most likely a pair of partons out of the bunch will participate in the hard interaction and leaving the other constituent quarks as mere spectators of the interaction. Due to the small couplings among partons inside a proton at such high energies, the partons do not interact among each other and behave as free. However this behaviour does not hold at small energies. A factorization scale, $\mu_F$ is introduced to split the interaction between long range and short range calculations. This acts like a bridge between the perturbative and non-perturbative regimes. Factorization theorem [46] enables the cross section of the interaction to be formulated in terms of non-perturbative parton density functions and the perturbatively calculated scattering cross sections. Cross section of any
QCD process $AB \rightarrow CX$ can be written as:

$$\sigma_{AB\rightarrow CX} = \int dx_a f_{A/a_i} (x_{a_i}, \mu_F^2) dx_b f_{B/b_j} (x_{b_j}, \mu_F^2) dz_c D_{c_k/C} (z_k, \mu_f^2) \sigma_{ijk}(\mu_R^2, \mu_F^2, \mu_f^2) \quad (1.3)$$

where,

- $a_i$ and $b_j$ represent the constituents of hadrons A and B respectively. They are the pair of partons which participate in the hard scattering yielding the final state $C + X$. While $c_k$ denotes the parton from the final state which will be forming the constituent of final state hadron C. Also, X in the final state can be anything.

- $f_{A/a_i} (x_{a_i}, \mu_F^2)$ and $f_{A/b_j} (x_{b_j}, \mu_F^2)$ represent the parton distribution functions (PDF). They are used to parametrize the distributions of partons inside the target hadrons. PDF, $f_{h/i}(x, \mu_F^2)$, depicts the effective density of partons of type/flavour i, as a function of the momentum fraction x, when a hadron of type h is probed at the factorization scale $\mu_F$. They are not calculable theoretically but are obtained from fits to the experimental data at fixed values of $Q^2$. PDF’s [47] are universal functions and their evolution from one scale to another is governed by a set of differential evolution equations [48]. Thus, we need to determine the form of PDF’s at one arbitrary scale ($\mu_0$) and we can get its form at other scales using the evolution equations. The main groups parametrizing PDF’s are “The Coordinated Theoretical and Experimental Project on QCD (CTEQ)” [49][50] and “The Martin-Stirling-Thorne-Watt (MSTW)” [51][52]. An example of fitted PDFs for two different values of $Q^2$ is shown in Figure 1.4 [53].

- $D_{c_k/C} (z_k, \mu_f^2)$ represents the fragmentation function. It signifies the probability that a final state parton $c_k$ will give a final state hadron with momentum fraction $z_k$ during the fragmentation process and at some fragmentation scale $\mu_f$. $\mu_f$ is introduced in the same respect as the factorization scale $\mu_F$. It is also not calculable theoretically. Fragmentation functions appear in this calculation when a final state particle is produced in the hard interaction as a result of fragmentation of the partons. One
such example is of the photon fragmentation function \((D_{g/\gamma} \text{ or } D_{q/\gamma})\) which denotes the fragmentation of quark and gluon into photons [54][55].

- Finally, \(\sigma_{a,b\rightarrow CX(\mu_R^2,\mu_F^2,\mu_f^2)}\) corresponds to the partonic cross section computed at some fixed order in QCD. The cross section is calculated at some fixed values of renormalization (\(\mu_R\)), factorization (\(\mu_F\)) and fragmentation (\(\mu_f\)) scales. Normally these scales are chosen to be of similar order with respect to each other.

- The momentum fraction \(x_a^b\) is given by the expression

\[
x_a^b = \frac{P_T^a}{\sqrt{s}}(e^{\pm y_a} + e^{\pm y_b})
\]

Any uncertainties due to choice of PDF’s and \(\mu_R\) and \(\mu_F\) scales are reported as systematic uncertainties to the final result later.

![Figure 1.4: Distributions of x times the parton distributions f(x) and their associated uncertainties using the MSTW2008 parametrization.](image)

**Some non-perturbative effects:** To completely define the picture of pp collisions, scenarios like underlying event [56] and hadronization also need to be described here. These play an important role in the definition of final-state observables at hadron colliders.
**Underlying events (UE):** When two bunches of proton collide, the final result consists of particles that originate from the hard interaction and other particles which show up due to the breakup of the protons. The hard scattering component of the event comprises of particles that arise from the hadronization of the two outgoing partons plus other particles that might arise from initial- and final-state radiation (for example in multijet processes). The beam-beam remnants (BBR) are what is left over after a parton is knocked out from each of the two initial hadron beams. Also, there can be some additional multi-parton-interactions (MPI) accompanying the main hard interaction. Sometimes there are some second “semi-hard” 2-to-2 parton-parton scatterings that can contribute particles to the UE. The underlying event consists of particles coming out of these other phenomenon such as beam-beam remnants and the multiple-parton interactions that accompany the hard scattering. In simple words, the UE [57] is everything except the two outgoing hard scattered final state particles. All these effects lead to deposition of extra energy in the detector surrounding the hard interaction. Theoretically, these processes are long range interactions and can not be calculated perturbatively. There are models describing underlying events inside different Monte Carlo generators.

**Hadronization:** The final state parton from the hard interaction undergoes a process called “Fragmentation” or “Hadronization” [58] as soon as it leaves the color field. The partons radiates gluons, which convert into a $q\bar{q}$ pair, which further radiates gluons and so on until a shower of low-energy particles is created. Clustering of these shower particles into colorless objects called hadrons leads to hadronization. Thus, partons (quarks or gluons) from the final state of the hard interaction emerge in the detector as a collimated stream of particles. This collection of particles is called a “Jet”. This phenomenon is described in the non-perturbative regime. Dynamics of the evolution of partons are absorbed in the fragmentation functions (described in the previous section).

Its these particles after hadronization along with the underlying event depositions and not the parton level objects which are observed as the end-products of a pp collision. Thus any theoretical calculation has to deal with the corrections for hadronization or under-
lying events to completely account for the cross section predictions and be meaningfully compared to the experimental measurements. Sophisticated present day Monte Carlo programs deal with the various steps of, as described in the text above, the QCD calculations through appropriate phenomenological models. The MC programs are explained in detail in the chapter “Event Simulation and Data Collection”.

1.4 Direct Photon Theory

1.4.1 Prompt Photons

Motivation: Prompt photon production at hadronic colliders has been a topic of interest for both experimentalists and theorists since last few decades. Direct photons [59]–[61], as the name suggests, are photons which emerge directly after the hard scattering interaction and not from any secondary decays of particles emerging from the interaction. It is an interesting probe for short-distance dynamics.

The study of high $P_T$ photons coming from the parton interactions serves as a rigorous testing ground for perturbative QCD (pQCD) [62]. Experimentally, the study of photons as a hard interaction probe has various advantages over using the purely hadronic final states. Firstly the energy resolution for photons (reconstructed in electromagnetic calorimeters) is in general better than for jets (reconstructed in hadronic calorimeters). Also since photons do not fragment, their position and energy measurement in the detectors is much more precise. The photon energy scale uncertainties are smaller compared to for jets. Additionally, the process gives access to lower transverse momenta region as compared to jets. A low production rate and non-negligible background from closed spaced photons coming from hadronic decays in jet production processes add up to some disadvantages of using direct photons as probes for studying parton interactions.

As the dominant contribution to direct photon production comes from quark-gluon scattering at LHC energies (described in the next section), the production rate for direct photon processes is sensitive to gluon distribution inside protons [63]–[67]. Thus, the study
will also provide valuable input to fits and help in constraining the parton distribution functions [68][69].

Understanding of final states with photons is also important in view of searches of intermediate mass Higgs boson [70]. Around this mass range (≤ 140 GeV), Higgs decaying into 2 photons is one of the clean and promising channel for observing it. The final states with two prompt photons form a major irreducible background to Higgs along with one prompt photon (γ + jets state) processes which serve as another large but reducible background to the same. Processes with energetic prompt photons also represents major chunk of the background for many new physics searches (beyond standard model) such as large extra dimensions [71][72], quark compositeness [73][74] and SUSY [75][76].

**Production:** At the leading-order, prompt photons are produced mainly by Compton like quark-gluon scattering (qg → qγ) and quark-antiquark annihilation (q̄q → gγ) processes. Out of these, due to high density of gluons at LHC energies, the Compton-like process rate is much higher than annihilation and dominates the cross section for the full transverse momenta (Pt) range. Figure 1.5 shows the Feynman diagrams contributing to Compton and annihilation processes respectively.

![Feynman diagrams](image)

**Figure 1.5:** Leading order contributions to direct photon processes from Compton and annihilation diagrams respectively.

Leading order calculations are incomplete and suffer from large theoretical uncertainties due to sensitivity of the renormalization and factorization scales. Thus the next-to-leading order (NLO) contributions [77][78] need to be incorporated in the full calculation. At NLO, there are contributions from real or virtual corrections to the Compton and annihilation processes. These consist of gluon radiation being emitted from either initial or final state partons. Gluon loop corrections to the leading order processes contribute...
to the virtual corrections. The supplementary gluons give rise to the non back-to-back behaviour in the $\gamma + jet$ topology. Further, there are fragmentation diagrams which can be visualized as a final state quark radiating off into a hard photon. There are contributions from the fragmentation diagrams where the final state parton fragments into a single photon including the cases where the photon is emitted collinear to the parton. The higher order terms of the fragmentation contribution are factorized and absorbed into photon fragmentation functions (as described earlier) $D_a^\gamma(z; \mu_f)$ (where “$z$” is the fraction of parton a’s momentum carried away by the photon). Figure 1.6 shows the various contributions to direct photon production coming from NLO, bremsstrahlung and fragmentation.

![Diagram](image)

**Figure 1.6:** Contributions to direct photon processes from NLO, bremsstrahlung and fragmentation diagrams.

The total inclusive cross section for photon processes is given as the sum of direct and fragmentation contributions. It can be written as:

$$
\sigma(p_\gamma) = \sum_a \int_1^0 \frac{dz}{z} \sigma^a \left( \frac{p_{R}}{z}; \mu_R, \mu_F, \mu_f \right) D_a^\gamma(z; \mu_f) + \hat{\sigma}^\gamma(p_\gamma; \mu_R, \mu_F, \mu_f)
$$

(1.5)
where,

\[ P_T^\gamma \text{ and } \eta^\gamma \] are the transverse momenta and pseudorapidity of the photon. \( \sigma(p_\gamma) \) denotes the differential cross section given as \( \frac{d\sigma}{dP_T^\gamma d\eta^\gamma} \). The fragmentation contribution is derived from \( \hat{\sigma}_a(\frac{P_T^\gamma}{z}; \mu_R, \mu_F, \mu_f) \) : the production of a parton “a” in hard collision along with \( D_a^\gamma(z; \mu_f) \) which is the fragmentation function of parton “a” into a photon. \( \hat{\sigma}_\gamma \) denotes the direct contribution. In fact only the sum coming from both the contributions (direct + fragmentation) has a physical meaning when being compared to experimental cross section results.

**Backgrounds:** The major source of background to direct photon production comes from hadronic jets. The production rate of hadronic jets compared to direct photons is of the order of \( \sim 10^3 - 10^4 \). This attributes to the factor \( \alpha/\alpha_s \) between the subprocesses for photon production and those for hadronic jets. Experimentally, this demands large acceptance photon detectors and high instantaneous luminosities. By definition jets consists of a bunch of hadronic particles, but a small fraction of jets fragment in such a way that a single particle bears most of the momentum of the parent parton. Most commonly produced single particles are neutral mesons such as \( \pi^0, \eta, K^0_s \) or \( \omega \) etc. Considering \( \pi^0 \), which is also the most commonly produced neutral meson, decays to 2 photons with a branching ratio of 98.823\%, the two photons from a very high \( P_T \pi^0 \) are so closely spaced in the detector that they form a single photon shower. Thus they are successful in faking a real direct photon signal. The fraction of jets resulting in single high \( P_T \) particles appears to be around \( 10^{-3} - 10^{-4} \) while the rate of production of jets dominates single photon production by a factor of \( 10^3 - 10^4 \). Thus, the contribution from this background is of the similar order with respect to the direct photon signal.

The contribution from final state radiation (FSR) can also act as a background to direct \( \gamma + \text{jet} \) processes, since the photon in this case does not emerge directly from the interaction vertex but rather can be treated as a secondary photon. These backgrounds are removed by applying certain isolation criteria on the photon as described in the text below.
**Isolated Prompt Photons:** Prompt photons at hadron colliders constantly suffer from large QCD backgrounds which are composed of light mesons giving multiple photons as their end product and also from secondary photon emitted off partons. These photons are generally accompanied by some additional hadronic jet activity. In order to differentiate prompt photons from these backgrounds, the photon candidates are required to be isolated from any hadronic activity. One way to give a measure of this activity is to evaluate the total sum of transverse energy in a cone of radius $\Delta R (\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2})$ around the photon candidate ($E_T^{iso}$). The isolation criteria then requires a cut on $E_T^{iso}$ by either defining a relative cut with respect to $P_T$ of the photon or defining an absolute cut not dependent on $P_T$ of the photon. For the case of fragmentation photons, slight hadronic activity can be observed in the vicinity of the photon. Application of isolation criteria on such photons might reject fair amount of contribution from fragmentation leaving behind a few large angle radiations. Calculations in case of isolated photons are shown to be realistic in reference [79].

### 1.4.2 Prompt Photon Pairs

Two prompt photons in the final state [80] in hadronic collisions is also an interesting process to probe. Photons pairs can also be used as a probe for short-distance dynamics and similarly provide a valuable testing ground for pQCD. Understanding these states gives a valuable input to the study of backgrounds for certain searches at hadron colliders. These searches include the light Higgs boson [70], extra-dimension gravitons [71][72] and some supersymmetric searches [76] also. Processes contributing to photon pair production [81][82] include quark-antiquark annihilation ($q\bar{q} \rightarrow \gamma\gamma$), gluon fusion ($gg \rightarrow \gamma\gamma$) and fragmentation photons radiated from final state partons.

Direct photon measurements have been studied for several decades both at the fixed target and hadron collider experiments. The next section gives an overview of some of these measurements. In addition, the recent CMS results, to which I have contributed [83][84], will be described in more detail.
1.5 Previous Direct Photon Measurements

Direct photon are a kind of precision measurements which have been consistently studied over the last three decades. The efforts have led to constant evolution on understanding of direct photon physics in both theoretical and experimental sectors. Experimentally it has been probed at both fixed target and collider experiments. Table 1.3 summarizes all direct photon results from the ISR to the most recent ones from Tevatron and LHC. In early days, direct photon measurements were done at SPS [89][90] and Tevatron [95][97][101][106] fixed target experiments. They provided data in the $x_T$ range from 0.1 to 0.6. Data from the WA70 and UA6 experiments were used for constraining some parton distribution fits previously. However, due to inconsistencies found between direct photon formalism and more recent fixed target data from E706 at Tevatron and combined with effect from large theoretical uncertainties present in the results, the earlier data was considered no longer fit to be included in the fits. Thus it was the results of the E706 experiment [101][106], which initialized the discussion on $k_T$ enhanced calculations. Later the Tevatron jet data from RunI was employed to constrain large-x gluon contents. Inclusion of direct-photon data in the global fits also provides additional input constraints, unbiased from the jet data from the Tevatron, on the gluon distribution.

Fixed target experiments at SPS (NA24), studied the direct photon production in pp and in $\pi^\pm$ collisions [89]. The increase in cross section ratio, $\sigma(\pi^- p \rightarrow \gamma X)/\sigma(\pi^+ p \rightarrow \gamma X)$, as a function of $P_T$, signalled the occurrence of quark-antiquark annihilation processes for photon production. While the measurements of the difference in cross section $\sigma(\bar{p}p \rightarrow \gamma X) - \sigma(pp \rightarrow \gamma X)$ led to the measurement of strong coupling constant $\alpha_S$, the difference being sensitive to only quark-antiquark annihilation contributions.

One of the first direct photon measurement at hadron colliders was done with pp collisions at Intersecting Storage Rings (ISR) at CERN [85]-[88][93]. Further studies at $Sp\bar{p}S$ strengthened the understanding of direct photons as a useful probe for parton interactions [91][92][94]. The gluon range probed by experiments at the ISR and $Sp\bar{p}S$ covered the region, $0.05 < x_T < 0.3$. It was common practice in literature to report the ratio of
direct photon to all neutral mesons by the earlier measurements at ISR, which was also systematically favoured at that time. With the advancement of technology in accelerators and detectors, more precise measurements became possible. The UA1 and UA2 gave qualitatively good agreements with the NLO calculations. Tevatron measurements with a higher center-of-mass energy ($\sqrt{s}$), could probe deeper into the proton at a much lower $x$ and experimentally spanned an extended rapidity coverage in the detector (covering the higher pseudorapidity region). The Tevatron was operated in two different run periods, with an upgrade to higher $\sqrt{s} = 1.96$ TeV during RunII. Earlier photon measurements [98][99][102]–[105] failed to describe the low $P_T$ behaviour. The disagreement with data was due to lack of a complete description of the initial-state parton shower in the NLO QCD calculation and also of the parton distributions. Later, calculations enhanced for soft gluon contributions provided a reasonable description of the data [108]. However, NLO pQCD predictions did not fully succeed in describing the $P_T$ dependence of cross section over the entire range [111], demanding an improved and consistent theoretical description for $\gamma + jet$ processes. Reference [110] shows results from DØ in different regions of rapidity for the photon and the jet.

The most recent measurements come from the ATLAS [112]–[114] and CMS [83] collaborations at LHC at CERN at higher $\sqrt{s} = 7$ TeV. The measured cross section at ATLAS quoted were a factor of 30 more than the Tevatron results and a factor of $10^4$ larger as compared to photo-production at HERA in similar kinematic range. The measured patterns are described better by theory than earlier experiments at lower $\sqrt{s}$ and higher $x_T$ values. For lower $P_T$ region, the NLO pQCD predictions are higher than the data [112][83][113][114], unlike the previous experiments where theory used to underestimate the predicted cross section values. Further, disagreement occur in various regions, not only in the lower $P_T$ regions, so an explanation dealing with non-perturbative effects could not be applied here. Another set of measurements are presented by the PHENIX collaboration at RHIC [107][109] at $\sqrt{s} = 200$ GeV, covering a range of $4 < P_T < 16$ GeV. The results are well described by the predictions from NLO pQCD.
The inclusive and isolated data from a range of fixed target and collider experiments till date is compared to theoretical predictions from a next-to-leading order pQCD calculation from JETPHOX in the reference [116]. Here I present a summary of the results from that paper. Firstly, the comparison is done in terms of ratios between data and theory computed at a scale of $\mu = P_T/2$. It reveals notable agreement between data and theory in the whole $x_T$ range except in the region covered by the E706 data. The ratio results are shown in left plot of Figure 1.7. The right plot in Figure 1.7 shows all available direct photon cross sections measured in $pp$ and $p\bar{p}$ collisions plotted together in one plot and compared to theoretical predictions from JETPHOX. The predictions are evaluated at the scale $\mu = P_T/2$ using BFG II (CTEQ6M) for fragmentation (structure) functions. The data shown here extends over two orders of magnitude in energy and the agreement between measured data and theory drags out to about nine orders of magnitude in the cross section.

![Figure 1.7](image)

**Figure 1.7:** Left plot shows the ratio data/theory for fixed target and collider data with a scale of $\mu = P_T/2$. While right plot depicts “World inclusive and isolated direct photon collider data (proton-proton and proton-antiproton)” compared to theoretical predictions from NLO JETPHOX calculations evaluated using BFG II (CTEQ6M) for fragmentation (structure) functions and at a common scale $\mu = P_T/2$. The E706 data is scaled by a factor of $10^4$ here.

Another precision measurement using prompt photons, consists of a pair of direct photons. Hadron colliders at Tevatron and LHC have been studying this interesting final state. The results were compared to the next-to-leading order calculations and found in
considerable agreement except in some regions of phase space where theory still needs improvement. Some of the diphoton measurement at Tevatron and LHC can be found in these references: [117]–[120][84].

Overview of Prompt Photon Results from CMS

Inclusive Photons with $2.9 \text{ pb}^{-1}$: The first measurement on photons in CMS [83] was performed with $2.9 \pm 0.3 \text{ pb}^{-1}$ data recorded in 2010 at $\sqrt{s} = 7 \text{ TeV}$. The study was done for isolated prompt photons within a pseudorapidity coverage of $|\eta| < 1.45$ and with a transverse momenta, $P_T > 21 \text{ GeV}$. Photons covered the kinematic region, $0.006 < x_T < 0.086$. The data was selected by an online selection criteria, which requires the presence of one reconstructed electromagnetic cluster with a minimum transverse energy of 20 or 25 GeV. The restricted dataset is required to pass further offline cuts. Events are shortlisted further by requiring at least one primary vertex consistent with the collision, a compatible electromagnetic calorimeter (ECAL) timing signal and no anomalous signals in the ECAL. The reconstructed photon candidates are then selected by the following offline criteria:

- **Fraction of hadronic energy in the shower (deposited in hadronic calorimeter (HCAL))** $\frac{E_{\text{HCAL}}}{E_{\gamma}}$ should be less than 5% of the total photon energy.

- **Pixel Veto**: Null hits in first two layers of the inner tracker matched to the location and energy of the photon candidate. This rejects any electron clusters overlapping with the photon ones.

- **IsoTRK**: Sum of the $P_T$ of tracks in an annulus of $0.04 < \Delta R < 0.40$ and excluding the rectangular strip $\Delta \eta \times \Delta \phi = 0.015 \times 0.400$ to remove any contribution coming from converted photons, is required to be less than $2 \text{ GeV}/c$.

- **IsoECAL**: Transverse energy deposited in the ECAL in an annulus of $0.06 < \Delta R < 0.40$ and excluding the rectangular strip $\Delta \eta \times \Delta \phi = 0.04 \times 0.40$ is required to be less than $4.2 \text{ GeV}$. 

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• Iso$_{HCAL}$: Transverse energy deposited in the HCAL in an annulus of $0.15 < \Delta R < 0.40$ is required to be less than 2.2 GeV.

The prompt photon yield is determined by the modified second moment of the electromagnetic energy cluster about its mean $\eta$ position, $\sigma_{\eta\eta}$ (defined in the chapter “Reconstruction of Physics Objects”). The $\sigma_{\eta\eta}$ distribution differs for isolated prompt photons and photons from any hadron decays. The differential cross section is then evaluated as a function of $P_T^\gamma$ and compared to next-to-leading-order predictions from JETPHOX 1.1 [79]. The ratio between data and theory is shown in Figure 1.8. The measured cross section is found to be in good agreement with predictions from JETPHOX within uncertainties.

![Figure 1.8: Inclusive photon cross section result with 2.9 pb$^{-1}$ CMS data.](image)

**Diphotons with 36 pb$^{-1}$**: This was the first study on diphotons in CMS [84]. The analyzed data sample corresponds to an integrated luminosity of 36 pb$^{-1}$ collected in 2010 at $\sqrt{s} = 7$ TeV. A pair of photons in an event is referred to as a diphoton candidate. The pair is selected in data with first isolated photon $P_T > 23$ GeV, second isolated photon $P_T > 20$ GeV and with a minimum $\Delta R$ separation of 0.45 between the two photons.
The measurement is performed in two regions of pseudorapidity, one up to $|\eta| < 1.44$, and the other covering the whole $\eta$ range up to $|\eta| < 2.5$ but excluding the transition region ($1.4442 < |\eta| < 1.566$) between barrel and endcap calorimeters. The data is selected by an online selection criteria, which requires two photon like candidates with a minimum transverse energy threshold of 15 or 17 GeV. The offline identification criteria satisfied by both the photon candidates in an event consists of the following:

- The spread along $\eta$ of the energy clustered in the ECAL, denoted by $\sigma_{\eta\eta}$ (described in the chapter “Reconstruction of Physics Objects”) is required to be less than 0.01 (barrel) or 0.03 (endcaps).
- $\frac{E_{\text{HCal}}}{E_{\gamma}} < 0.05$.
- $Iso_{\text{TRK}} \text{ barrel(endcaps)} < 2(4) \text{ GeV/c}$.
- $Iso_{\text{ECAL}} < 0.20P_{T}^{\gamma}$
- $Iso_{\text{HCal}} \text{ barrel(endcaps)} < 2(4) \text{ GeV}$.
- Pixel Veto set to true.
- Impinging track veto: No charge particle with transverse momenta $> 3 \text{ GeV}$, with the longitudinal and transverse impact parameters with respect to the primary vertex less than 1 mm and 2 mm respectively, and with one associated hit in the innermost layer of the pixel detector, should impinge on ECAL inside a cone of $\Delta R = 0.40$.

$\gamma + \text{jet}$, multijet events with one or two background photons from neutral hadron decays and Drell-Yan events with two mis-identified electrons act as backgrounds to diphoton events in the detector. The signal is estimated using a modified ECAL isolation variable, defined as the sum of transverse energy of the ECAL deposits with $E_T > 300 \text{ MeV}$ (minimum-ionizing-particle veto). The sum is evaluated in a hollow cone centered on the photon impact point of inner radius equal to 3.5 crystals and outer radius as $\Delta R$.
= 0.40. In addition, any deposits in the 5 crystal wide strip extending along \( \phi \) and the ones belonging to the photon itself are removed from this isolation sum. ECAL isolation probability density functions are formed based on this isolation variable to discriminate between signal and background photons. The diphoton differential cross section is measured with respect to four observables - the diphoton invariant mass \((m_{\gamma\gamma})\), the azimuthal angle between the two photons \((\Delta \phi_{\gamma\gamma})\), the photon pair transverse momentum \((P_{T,\gamma\gamma})\) and \(\cos \theta^*\), \(\theta^*\) being the center-of-mass scattering angle for the lowest order processes \((q\bar{q} \rightarrow \gamma\gamma\) and \(gg \rightarrow \gamma\gamma\)). The results are then compared to predictions from DIPHOX 1.3.2 \([81]\) and GAMMA2MC 1.1.1 \([82]\) programs. The results obtained for all the measured observables are shown in Figure 1.9. There is an overall agreement between the theory and the measured results. However, the theory underestimates the cross section corresponding to regions in phase space when the azimuthal angle difference between the two photons, \(\Delta \phi \leq 2.8\).

CMS updated its inclusive photon results, complementing the last one \([83]\) from 2.9 \(pb^{-1}\), by using the 36 \(pb^{-1}\) of recorded data. This thesis will cover the updated inclusive photon result with 36 \(pb^{-1}\) of data in a detailed manner. The measurement covers the kinematic region \(0.007 < x_T < 0.114\) and also extends the results for wider ranges of photon \(P_T\) and pseudorapidity. Additionally, the thesis will also present the first CMS results on \(\gamma + jet\) measurements using \(\sim 2.2 \ fb^{-1}\) of recorded and certified data. These results probe constituent proton momentum fractions in the range \(0.001 < x < 0.14\).

Direct photon measurements establishes a benchmark for photon identification and background estimation, and determines the rate of one of the background processes affecting searches for new physics involving photons. The next chapter briefs about the experimental setup employed at CERN to perform such measurements.
Figure 1.9: Diphoton cross section result with 36 pb$^{-1}$ CMS data.
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**Table 1.3:** History of direct photon measurements.