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The first observation of $\bar{t}(1S)$ pair production and Hadron calorimetry upgrade at CMS

Maksat Haytmyradov
University of Iowa

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THE FIRST OBSERVATION OF $\Upsilon(1S)$ PAIR PRODUCTION AND HADRON
CALORIMETRY UPGRADE AT CMS

by

Maksat Haytmyradov

A thesis submitted in partial fulfillment of the
requirements for the Doctor of Philosophy
degree in Physics
in the Graduate College of
The University of Iowa

May 2017

Thesis Supervisor: Associate Professor Jane Nachtman

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Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph.D. thesis of

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has been approved by the Examining Committee for the
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To my parents Guljan and Dovlet. For their endless love and support to make this thesis complete.

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ABSTRACT

This dissertation dicusses two topics; the cross section measurement of $\Upsilon(1S)$ meson pair production [1] and simulation studies of High Granularity Calorimetry (HGCAL).

The first part of the dissertation is dedicated for the analysis of $\Upsilon(1S)$ meson pair production and measurement of its cross section. The data for this analysis were collected by the CMS experiment at Large Hadron Collider (LHC) at a center-of-mass energy of 8 TeV and correspond to an integrated luminosity of 20.7 fb^{-1} . Simultaneous production of two $\Upsilon(1S)$ mesons is observed for the first time with 38 events, corresponding to a local significance exceeding five standard deviations from the expected combinatorial background b-quark decays. Both $\Upsilon(1S)$ candidates are fully reconstructed via their decays to $\mu^+\mu^-$. The fiducial acceptance of the detector is measured from the simulation and is defined by an absolute $\Upsilon(1S)$ rapidity smaller than 2.0. To minimize the model-dependence, the acceptance and efficiency corrections are calculated on an event-by-event basis using measured Υ meson and muon momenta. The fiducial cross section of $\Upsilon(1S)$ meson production, assuming both $\Upsilon(1S)$ mesons decay isotropically, is measured to be $68.8 \pm 12.7 \text{ (stat)} \pm 7.4 \text{ (syst)} \pm 2.8 \text{ (}\mathcal{B}\text{)} \text{ pb}$, where the third uncertainty comes from the uncertainty in the branching fraction of $\Upsilon(1S)$ decays to $\mu^+\mu^-$. Different assumptions about Υ productions imply modifications to the cross section ranging from -38% to $+36\%$. Cross section measurement of Υ pair production will provide better understanding of the parton

structure of proton and enhance precision of existing particle production models.

LHC is planning to increase luminosity and energy of colliding protons. Due to accumulated radiation damage and to improve detector performance CMS experiment is expected to undergo upgrade plans. Hadron calorimeter is among them, and it is planned to be replaced with better performance high granularity calorimetry (HGCAL). HGCAL needs to be integrated with existing components of CMS and its smooth functioning is essential. The second part of the dissertation describes simulation studies performed to validate readiness of HGCAL for the Phase II upgrade.

PUBLIC ABSTRACT

Simultaneous production of two $\Upsilon(1S)$ mesons is observed for the first time in proton-proton collisions at $\sqrt{s} = 8$ TeV by the CMS experiment. The data analyzed corresponds to an integrated luminosity of 20.7 fb^{-1} . To reconstruct each $\Upsilon(1S)$ candidate two oppositely charged muons are utilized. The fiducial acceptance of the detector is constrained by the coverage of muon stations, and it is defined as an absolute Υ rapidity smaller than 2.0. The fiducial cross section of $\Upsilon(1S)$ pair production is measured to be $68.8 \pm 12.7 \text{ (stat)} \pm 7.4 \text{ (syst)} \pm 2.8 \text{ (}\mathcal{B}\text{)} \text{ pb}$, where uncertainties are statistical, systematic and branching fraction of $\Upsilon(1S)$ decays to $\mu^+\mu^-$, respectively. Different assumptions about $\Upsilon(1S)$ polarization imply modifications to the cross section ranging from -38% to $+36\%$. Cross section measurement of Υ pair production will provide better understanding of the parton structure of proton and enhance precision of existing particle production models.

The second half of thesis is devoted for the future plans of the LHC and upgrade preparations for high-luminosity HL-LHC, specifically High Granularity Calorimeter (HGCAL) studies. Rigorous studies are performed to validate simulation of HGCAL geometry. Within this work automated validation package is created which allows the production of validation plots for inspection and detection any anomaly introduced in the simulation.

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CHAPTER 1 INTRODUCTION

This thesis reports the results of the Large Hadron Collider (LHC) at CERN, Switzerland on the first observation of $\Upsilon(1S)$ pair production and measurement of its total cross section using the Compact Muon Solenoid (CMS) detector. This measurement is important because it contains rich physics information and will provide input to better understand quarkonium production mechanisms at the LHC.

The Standard Model (SM) is one of the most successful theories in particle physics. It unifies three fundamental forces (strong, weak and electromagnetic) in nature to explain interactions between twelve elementary particles called quarks and leptons (Fig. 1.1). In the SM, particles interact with each other via interaction mediating bosons that are of three types: γ , which mediates electromagnetic force, gluon, which causes strong force and $Z^0, W^\pm$ which are involved in weak interactions. Electromagnetic interactions are described by a theory called Quantum Electrodynamics (QED), while strong interactions are described by Quantum Chromodynamics (QCD). Weak interactions, based on QED, can combine with electromagnetic interactions as described by electroweak theory. According to the SM, leptons exist as free particles while quarks can only exist inside the hadrons. In particle physics this phenomenon is known as confinement, and its not yet fully understood. One way of understanding the way quarks are confined and how they are produced is to examine proton-proton (pp) collisions at the LHC.

The proton-proton collisions at the LHC are described by parton models [4]

that explain the internal structure of protons. In this framework each colliding proton is described as a collection of free quarks, gluons or virtual quark-antiquark pairs (collectively referred as partons). Because of the composite nature of protons, in a single collision two partons usually undergo a single interaction called single parton scattering (SPS), but it is also possible that multiple interactions (MPI) occur. The simplest kind of multi-parton scattering, when only two partons interact, is called double parton scattering (DPS). The formation of quark-antiquark bound states is governed by one of the two mechanisms. The SPS mechanism for heavy quarkonium productions can be described by NRQCD [5], a nonrelativistic effective theory of QCD. However, contributions from the DPS mechanism are not simply addressed within the framework of perturbative QCD [6], and it is widely invoked to account

for the observations that SPS mechanism can not explain. Production of heavy quarkonium pairs such as J/ψ (charm-quark content) and Υ (bottom-quark content) are especially valuable as they provide an input to better understand the SPS /DPS production mechanism by probing the QCD calculations in perturbative and non-perturbative regimes [7].

The main part of this thesis is devoted to the analysis of $\Upsilon(1S)$ pair productions in data collected by CMS experiment at the 8 TeV center of mass energy ($\sqrt{s}$). It also describes future plans of the LHC and upgrade preparations for high-luminosity LHC (HL-LHC), specifically High Granularity Calorimeter (HGCAL) studies.

The dissertation is organized as follows. Chapter 2 presents the theoretical overview and importance of Υ pair production and its production mechanisms. Chapter 3 describes the LHC and CMS with a detailed description of the subsystems. Chapter 4 describes an analysis, data used, Monte Carlo (MC) samples and cross section measurements. Chapter 5 describes the rationale for the HL-LHC and the initial studies performed for the HGCAL detector. Chapter 6 concludes by summarizing findings of this work and its importance to high energy physics community.

CHAPTER 2 THEORY OVERVIEW

2.1 The Evolution of Standard Model

By the end of 1960's the conventional understanding of matter, where all atoms are composed of protons, neutrons and electrons, was insufficient to explain the countless number of new discovered particles. Great minds like Gell-Mann and George Zweig solved this puzzle and laid the groundwork for the currently-known Standard Model of Elementary Particle Physics. Over the next forty years the SM was expanded gradually and validated with new discoveries and new experiments. The SM has a long history before it was fully accepted and several important achievements are summarized below.

In 1964 Murray Gell-Mann [8] and George Zweig [9] proposed the Quark Model. They suggested quarks can combine into a quark-antiquark (meson) or three quarks (baryons) to form composite objects. Initially three types of quarks called up, down and strange (u, d, s) were proposed with a spin $1/2$ and electric charges of $+2/3$, $-1/3$, $-1/3$, respectively. Due to non-existence of experimental evidence, an introduction of fractional charges was treated as a mathematical explanation rather than as a postulate of actual physics particles. During the same year Sheldon Glashow and James Bjorken [10] suggested the existence of a fourth quark which was named as a charm (the c-quark).

In 1965 O.W. Greenberg, M.Y. Han, and Yoichiro Nambu introduced the quark

property of color charge [11, 12]. Their study postulated that all observed hadrons are color neutral. During these years the Quark Model progressed slowly due to the lack of experimental evidence for the observation of free quarks.

In 1967-68 Steven Weinberg [13] and Abdus Salam [14] separately proposed a theory that unifies electromagnetic and weak interactions into an electroweak interaction. Their theory requires the existence of a neutral, weakly interacting particle (now known as Z^0) that had not been observed at that time.

With increased statistics compared to previous neutrino experiments, in 1971, Lagarrigue, Rousset and Musset proposed a neutrino-detector to measure neutral current interactions using a bubble chamber, later named the Gargamelle bubble chamber, at CERN. Shortly after the operation of the chamber, in 1973, the Gargamelle collaboration observed neutral currents (those due to a Z^0 exchange) [15] that had been predicted by the Weinberg-Salam theory.

In 1973 a quantum field theory of strong interactions was formulated. This theory of quarks and gluons, similar to QED in structure because it deals with the color charge of strong interactions, is called Quantum Chromodynamics. According to theory, quarks carrying a color charge are determined to be real particles, and gluons being massless quanta are responsible for strong interactions. Later that year David Gross, Frank Wilczek [16] and David Politzer [17] discovered the special property of strong interaction, now referred as asymptotic freedom, for which they were awarded the Nobel Prize in 2004.

In 1974, in a summary talk for a conference, John Iliopoulos presented, for

the first time in a single report, the view of physics now called the Standard Model. Later same year Burton Richter and Samuel Ting independently announced the discovery of the new particle. Ting and his collaborators at Brookhaven called it the J particle [18], while Richter and his collaborators at SLAC called this particle the ψ (psi) particle [19]. This particle is now known as J/ψ meson and is composed of charm-anticharm quark. This event is now known as the November Revolution and it was followed by many unexpected or predicted experimental discoveries.

In 1975 an unexpected particle, now known as the tau (τ) lepton, was discovered by Martin Perl and collaborators at SLAC collaboration [20].

In 1977 Leon Lederman and his collaborators at Fermilab discovered yet another quark (and its antiquark) [21]. This quark was called the bottom quark and the bound state of two bottom quarks is called a Υ (Upsilon) meson. The Upsilon meson, like J/ψ meson, is a special meson which is composed of the same flavor quark and antiquark combination making it a flavorless meson (also called a quarkonium).

In 1979, at PETRA, a colliding beam facility at the DESY laboratory in Hamburg, reported strong evidence for radiated gluon which supported the existence of gluons as real quanta [22].

Carlo Rubbia and Simon Van der Meer proposed the construction of a particle accelerator powerful enough to observe the direct production of $W^\pm$ and Z^0 bosons. The first such machine to become available was the Super Proton Synchrotron at CERN. At the beginning of 1983, both UA1 [23] and UA2 [24], at the Super Proton Synchrotron facility, reported the observation of $W^\pm$ bosons.

In 1989 experiments in both SLAC and CERN strongly suggested the existence of three generations of fundamental particles. This was inferred by showing that the Z^0 boson lifetime is consistent only with the existence of exactly three very light (or massless) neutrinos. After eighteen years of searching for the last quark in Standard Model, it was finally discovered in 1995 by the CDF and D0 experiments at Fermilab with a mass of 175 GeV [25].

In 2000 the first detection of tau-neutrino (ν_τ) interactions was announced by the DONUT collaboration at Fermilab, making it the latest particle of the Standard Model to have been directly observed [26].

In 2012, after four years of operating the LHC, the Higgs boson was discovered by the CMS and ATLAS experiments and completed the elements in Standard Model [27].

The SM unifies three (electromagnetic, weak and strong) of the four fundamental forces in the universe. Gravity, which is responsible for the force between massive objects, is not a part of the Standard Model. However, research is ongoing to develop a unified theory that combines all forces together. One of these theories predicts a hypothetical particle called a graviton, and if discovered, this would be able to unite quantum field theory with gravity [28]. Particle colliding facilities such as the LHC play an important role in the search for such particles and probe the SM at a scale which has never been investigated before.

2.2 Quantum Chromodynamics

Quantum Chromodynamics (QCD) is a non-Abelian gauge theory based on SU(3) color symmetry. It describes the interaction mechanism of spin 1/2 quarks (fermions) and spin 1 gluons (bosons). In both QCD and QED interactions between fermions are governed by the properties of bosons. The strength of the force exerted in the interaction is determined by the coupling constants α and α_s for QED and QCD, respectively. The major difference between QED and QCD is that gluons carry a strong interaction charge called color, enabling them to self-interact. In QED photons are charge neutral which means photons do not couple to each other. This difference produces a dramatic effect on the energy scale dependence, Q^2 , of α 's. In QED α is described as follows [29]:

$$\alpha(Q^2) = \frac{\alpha_0}{1 - \frac{\alpha}{3\pi} \cdot \ln \frac{Q^2}{m_e^2}} \quad (2.1)$$

where m_e^2 is the mass of the electron, and α_0 is the coupling constant when the energy scale is equal to the electron mass. The energy scale Q^2 measures momentum transfer between two charged particles, and in QED, it determines monotonically enhancing behaviour of a coupling constant. In QCD the coupling constant (α_s) is expected to behave differently, explaining the absence of free quarks (also known as confinement of hadrons) and the quasi-free behavior of quarks at high energy scales (phenomenon known as asymptotic freedom). In QCD the interaction rate of physics processes (the cross section) are calculated as expansions, in terms of powers of α_s , at the interaction vertex. Higher order expansions only converge when α_s is small. The expansion terms after the first or the second order terms determines the precision of calculation. In

the leading order (LO) calculations expansion is completed after linear term of α_s while in the next-to-leading order (NLO) approximation expansion is continued until the quadratic term of α_s . The coupling constant of QCD is usually expressed as:

$$\alpha_s(Q^2) = \frac{4\pi}{(11 - \frac{2}{3}n_f) \cdot \ln \frac{Q^2}{\Lambda_{\text{QCD}}^2}} \quad (2.2)$$

where Q^2 is the scale of momentum exchange, $\Lambda_{\text{QCD}}^2 \approx 0.2 \text{ GeV}$ is a fundamental QCD parameter, and n_f is the number of quark flavours with masses less than Q^2 . For high momentum transfers ($Q^2 \gg \Lambda_{\text{QCD}}^2$) the QCD coupling constant approaches zero and the interaction of quarks and gluons behave as free particles (asymptotic freedom). When energy scale is in the order of Λ_{QCD}^2 the interacting quarks and gluons are bound together to form color neutral hadrons (confinement). The energy scale Q^2 introduces two different physics regimes; interactions which involve large momentum transfer (called hard-process) and interactions where no large Q^2 is available (referred as soft-process). Contributions from hard processes can be calculated using a perturbative QCD (pQCD) approach, while for the soft process, more complex non-perturbative models are required.

2.3 Quarkonium Production Mechanism

The production of heavy quarkonia ($c\bar{c}$ or $b\bar{b}$) provides a unique opportunity to study the relationship between the theory of perturbative hard process and hadronization models of non-perturbative theory. The meson properties in QCD are calculated using a fully non-perturbative regime. One such successful calculations is based on lattice QCD (LQCD) techniques which are formulated on a grid of points in space

and time. However, for heavier quarkonium states other perturbative methods exist.

For light mesons the constituent quark masses are much lighter than the bound state mass which makes their motion inside the hadrons relativistic. However, due to their heavy mass, the motion of the charm or bottom quark in the quarkonium is much slower allowing them to be treated as non-relativistic objects. The heavy quark velocity, in the speed of light units (v/c), in the center-of-mass frame is approximately 0.3 and 0.1 in charmonium and bottomonium states, respectively. This allows the computation to be approximated by expansion in the powers of v/c and v^2/c^2 . One of the methods which utilizes this technique, and successfully explains Υ states, is called non-relativistic QCD (NRQCD) [30, 5]. In NRQCD the cross section of quarkonium productions can be expanded in the following form [5, 31]:

$$d\sigma(\mathcal{I} \rightarrow \mathcal{H}) = \sum_n d\sigma(\mathcal{I} \rightarrow Q\bar{Q}[n]) \langle \mathcal{O}^{\mathcal{H}}[n] \rangle \quad (2.3)$$

where the sum is over the possible intermediate states of heavy quarkonia ($Q\bar{Q}$) pairs $[n] = {}^{2S+1}L_J^{(1,8)}$, with orbital momentum L , total angular momentum J and color-singlet (CS)⁽¹⁾ or color-octet (CO)⁽⁸⁾ quantum numbers. Factor $d\sigma$ is the partonic production cross section of $Q\bar{Q}[n]$ from the partonic initial state, $\mathcal{I}$, and it can be solved perturbatively in series of α_s . The $\langle \mathcal{O}^{\mathcal{H}}[n] \rangle$ are non-perturbative matrix elements (NME) that describe the hadronization of the partonic intermediate state $Q\bar{Q}[n]$ to the heavy quarkonium $\mathcal{H}$ (J/ψ or Υ). Fig. 2.1 shows a Feynman diagram for leading order contributions to heavy quarkonium hadronization.

According to the power-counting rule [32] only terms with the same spin-orbital quantum numbers contribute to the production of quarkonia. Leading or-

Figure 2.1: Examples of leading order Feynman diagram for heavy quarkonia production. Top, production through gluon fusion process (left) and quark annihilation process (right) in color-singlet model. Bottom, production through gluon fusion process (left) and quark annihilation process (right) in color-octet model.

der contributions arise from the following CS non-perturbative matrix elements:

$\langle \mathcal{O}^{\mathcal{H}}[{}^3S_1^{(1)}] \rangle$ and $\langle \mathcal{O}^{\mathcal{H}}[{}^3P_J^{(1)}] \rangle$. While CO non-perturbative matrix elements $\langle \mathcal{O}^{\mathcal{H}}[{}^1S_0^{(8)}] \rangle$,

$\langle \mathcal{O}^{\mathcal{H}}[{}^3S_1^{(8)}] \rangle$ and $\langle \mathcal{O}^{\mathcal{H}}[{}^3P_J^{(8)}] \rangle$ give the next leading order contributions. CS NMEs

can be expressed through the quarkonia wave functions, and calculated in the quark

model. CO NMEs describe the transition of intermediate $Q\bar{Q}$ into quarkonia through

the radiation of soft gluons, and hence can not be computed either in perturbative

QCD, or in the potential quark model. One option to calculate CO NMEs contribu-

tions is by fitting it to the experimental data [33, 34].

The CS model is a natural approach to explain quarkonia production, and

it was the first attempt to describe experimental data in e^+e^- colliders. The CO

model was introduced later and was successful in explaining the large discrepancy

between the data and the CS model for prompt S-wave charmonium productions at Tevatron [35].

2.4 Quarkonium Pair Production

As the center-of-mass energy of colliding particles increases more partons can participate in hard interactions and thus increase the sensitivity of higher order calculations. Moreover, it is possible that multiple quarkonium states are produced in single parton-parton interactions, as shown in the Fig. 2.2. The first such heavy quarkonium pair production was observed in 1982, when the NA3 experiment reported the direct production of two J/ψ -mesons [36]. At NA3, the main contribution was from quark-antiquark annihilation and early calculations successfully described experimental results assuming only SPS color singlet states [37, 38, 39]. However, gluon-gluon and quark-gluon contributions are expected to dominate at LHC [40] by enhancing the possibility that multiple parton interactions (MPI) occur [41].

A MPI occurs when more than one parton is exchanged between incoming hadrons. The simplest case of MPI, known as double parton scatterings (DPS), is when only two partons are exchanged as depicted in Fig. 2.3. Contributions from the DPS are not addressed within the framework of QCD [6], and DPS or MPI is widely invoked to account for observations that can not be explained otherwise, such as the rates of multiple heavy-flavor production [42]. The quarkonium pair production via DPS mechanism is assumed to result from the two independent SPS occurrences [40, 41]. With this assumption several DPS production processes, including final states

Figure 2.2: Examples of leading order processes in the order of α_s^4 for quarkonia productions. Top quarkonium pair production through color-singlet model and bottom through color-octet model.

with associated jets, are commonly described by an effective cross section (σ_{eff}). It is estimated as the product of single quarkonium production cross sections divided by the corresponding quarkonium pair cross section via DPS [40]. In case of factorization, this quantity is expected to be independent of the process and the center-of-mass energy. Recent measurements of σ_{eff} in final states with jets find it to be factorized in the range 12–20 mb [43, 44, 45], while measurements of J/ψ pair [46] and $J/\psi + \Upsilon(1S)$ [47] production in pp or $p\bar{p}$ collisions yield lower values.

The J/ψ pair production measurements at LHCb [48], CMS [49], and D0 [46] motivated a new round of calculations including higher order SPS singlet states, octet states and DPS. At LHC DPS is expected to play a significant role in double quarkonium productions [41], and results from this report will confirm or deny the

trend seen in σ_{eff} .

Figure 2.3: Typical Feynman diagram for double parton scattering process for $pp \rightarrow c\bar{c}c\bar{c}$ [3].

CHAPTER 3

LARGE HADRON COLLIDER AND COMPACT MUON SOLENOID EXPERIMENT

The LHC, located at the border of Switzerland and France, is currently the largest particle accelerator in the world. It was constructed underground in a twenty seven kilometers long tunnel. Protons are propelled by two beams, guided by superconducting magnets, around the LHC at a speeds close to the speed of light. These two beams are then made to cross paths and some of protons collide to produce conditions similar to the Big Bang.

Figure 3.1: The map of LHC main loop, Super Proton Synchrotron and four major detectors located around the loop. The trajectory of the LHC tunnel and location of detectors are shown with a yellow line.

There are four main detectors installed at the LHC as depicted in Fig. 3.1.

Each detector is designed for a specific research program. Two important experiments, CMS and ATLAS, are general purpose detectors designed to search for heavy particles as well as to increase the precision of previous measurements. ALICE and LHC-b experiments are specialized for heavy-ion and b-meson physics studies, respectively. The LHC started operation in 2008 colliding protons at center-of-mass energy 7 TeV in 2011 and 8 TeV in 2012. The total integrated luminosity is 5.55 fb^{-1} and 21.79 fb^{-1} at 7 TeV and 8 TeV, respectively. The center-of-mass energy at LHC increased to 13 TeV in 2015.

3.1 CMS Detector

The CMS detector is a general purpose detector located in north side of the LHC ring. The CMS detector is cylindrical in shape and 21.6 m long, 15 m in diameter, and is built around a solenoid coil which takes a form of a cylindrical coil of superconducting cable that generates a magnetic field of 3.8 Tesla. The CMS detector is composed of an inner tracker, electromagnetic calorimeter, hadron calorimeter and muon chamber layers as shown in Fig. 3.2. Each subdetector is designed and optimized for measuring an energy and momentum of specific particles. The innermost part of the detector is a tracker which is designed for tracking all charged particles. The second layer is an electromagnetic calorimeter which is designed to measure energy deposited by photons and electrons. The third layer is a hadron calorimeter which is intended to measure energy deposited by hadrons such as π , K and proton. Finally the outermost layer is a muon chamber which has a main purpose of detecting muon

particles and measuring their momenta. Combining all of the components, the CMS detector provides powerful identification, tracking and efficient energy measurement of outgoing particles.

Figure 3.2: Technical drawing of CMS detector. The major components, from the closest to interaction point outwards, are an inner tracker, electromagnetic calorimeter, hadron calorimeter and muon chambers.

3.2 Silicon Tracker

At the CMS the tracker detector is split into two segments: silicon pixels and silicon strips. The silicon pixels are composed of 65 million pixels which have cylindrical layers at 4 cm, 7 cm and 11 cm and disks at either end. The purpose of the pixel detector is to disentangle and reconstruct tracks of all charged particles that pass through, and withstand high radiation during operation period. Each layer is

split into silicon sensors which are $100\text{ }\mu\text{m}$ by $150\text{ }\mu\text{m}$ thick. When a charged particle passes through the pixels it releases enough energy to knock electrons from silicon atoms, which are then collected on sensors connected to the surface of the silicon. The signal is then amplified by a microscopic chip that is located on the disc.

The silicon strip detector is composed of 10 million detector strips. Silicon strips surround the outer pixel strips and consist of four segments: four layers of inner barrel (TIB) assembled in shells, two inner endcaps (TID), an outer barrel (TOB) consisting of six layers and two endcaps (TEC). Each layer has separate silicon modules consisting of three elements: a set of sensors, the mechanical support and readout electronics. The charge in each microstrip is read and amplified by an Analogue Pipeline Voltage (APV25) chip. The APV25 stores signals in memory for few milliseconds before sending it to the laser which converts the signal to infrared pulses. Next, the pulse is transmitted through a 100 m fiber optic cable for analysis in a radiation-free environment.

3.3 Electromagnetic Calorimeter

The main purpose of the electromagnetic calorimeter (ECAL) is to precisely measure energy of photons and electrons. The energy of photons and electrons is measured using scintillating material, a material that produces light when charged particle passes through. The light from the scintillating crystal is then directed to a photo multiplier tube (PMT), which converts it to an electronic signal.

Compact and high granular scintillating crystal detectors must have a short

scintillation decay time, short radiation length, small Moliere radius and high density. The fast decay time must be comparable to the bunch crossing interval at the LHC; the signal output from scintillation crystals must be collected before the next collision event happens which was 50 ns at the LHC during the 2012 data taking period. Radiation length (X_0) describes how much depth is required for an electron to lose all but $1/e$ of its energy via the bremsstrahlung process (a dominant process for electrons with energies greater than 10 MeV). Materials with a small X_0 allow construction of more compact crystal detectors. The CMS ECAL uses lead tungstate (PbWO_4) as scintillating crystals. These crystals have a fast scintillation response, high density (8.3 g cm^{-3}), short radiation length ($X_0 = 0.89 \text{ cm}$) and a small Moliere radius ($R_M = 2.0 \text{ cm}$), features that allowed a highly granular, compact detector to be built [50].

Figure 3.3: Internal view of barrel electromagnetic calorimeter during the construction.

3.4 Hadron Calorimeter

The outer part of ECAL calorimeter is surrounded by the Hadronic Calorimeter (HCAL). The purpose of the HCAL is to measure energies deposited by hadrons, particles made up quarks and gluons, e.g., pions, protons, neutrons and kaons.

The HCAL at the CMS consists of two parts; the barrel (HB) and endcap (HE). Both barrel and endcap calorimeters experience magnetic field of 3.8 Tesla. Therefore, it is composed of a non-magnetic material (stainless steel and copper alloy). The HB calorimeter is a sampling calorimeter: it contains a sensitive material inserted between copper absorber plates. The absorbers are 5 cm thick in the barrel and 8 cm thick in the endcap. In the HB there are 13 copper and 2 stainless steel plates and a sampling depth of 79 cm, with a nuclear interaction length of 5.15λ at $|\eta|=0$ which increases up to 9.1λ at $|\eta|=1.3$. The HE part contains 19 layers of absorbers (90% Cu+10% Zn) with an average of 10.5λ (interaction length). An electromagnetic calorimeter (EE) with $27 X_0$ (radiation length) is also placed in front of the HE. The sensitive area of the whole hadron calorimeter is made of 4 mm thick scintillators [citeCMS:1997tfa](#). Photons that are produced in the scintillators are collected with wavelength-shifting (WLS) plastic fibers and converted into an electronic signal via hybrid photodiode (HPD). Fig. 3.4 shows a sketch of the HCAL at the CMS.

3.5 Muon Chamber

The purpose of the muon system at the CMS is to identify and reconstruct muons with high resolution. The muon system contains three different technologies:

Figure 3.4: The side view of hadron calorimeters. Color codes in the endcap region shows longitudinal segmentation of calorimeter. Numbers from 1 to 29 corresponds to single channel readout of the detectors in the transverse plane.

drift tubes (DT) in the barrel, a cathode strip chamber (CSC) in the endcap, and resistive plate chambers (RPC) in both the endcap and barrel. Chambers cover 2π in ϕ plane and upto 2.4 in η plane. DTs extend upto $[0, 1.3]$ in η plane while the endcap CSCs cover $[0.9, 2.4]$. The RPCs cover the region between $\eta = 0$ and $\eta = 2.1$ [51].

Due to the low intensity of magnetic field in this area, DTs were chosen for the barrel region. The barrel region contains four muon stations inserted in the iron yoke of the magnet. Two stations are attached in the inner and outer yoke; the other two are inserted into iron slots. In total, 60 chambers compose inner three stations, while 70 chambers are present in the outer station. Each chamber contains 12 planes of drift tubes that are organized to measure the coordinates in the bending plane ϕ along the beam direction [51].

The endcap of the CMS detector has four muon stations (ME1, ME2, ME3,

ME4) with CSCs. CSCs are chosen to fit the endcap since they can provide precise space and time information in the presence of a high magnetic field and high particle rate. CSC modules contain six layers to provide robust pattern recognition for rejection of non-muon backgrounds and to match external muon tracks to internal track segments. Each station is composed of six layers of wires sandwiched between cathode panels that provide six measurement in the ϕ -coordinate and six measurements in the r -coordinate system.

Both the endcap and barrel portion of CMS detector have RPCs. An RPC is a gaseous parallel-plate chamber which can provide spatial resolution and fast time response, comparable to that of scintillators. Consequently they can be used to assign bunch crossing. RPCs don't require an expensive photomultiplier readout hence they can be segmented to measure not only transverse momentum but also used to trigger time of an event. Thus RPCs are designed to provide fast triggers which can be used to identify muon candidate tracks. A total of six layers of RPCs are mounted in the barrel chambers, two layers with MB1 and MB2, and one in each outer station. In the endcap region, each of the CSC layers has a layer of RPCs in conjunction with it [51].

3.6 CMS Trigger System

At normal operating speed the LHC generates collision events at a rate of 40 MHz. This is too high to be recorded by the CMS detector. Therefore, to select events that are most likely contain interesting processes, the data needs to be filtered

before saving to a disc. To filter unimportant events, the CMS utilizes a two stage trigger system; a hardware based Level-1 trigger (L1) and a software based high-level trigger (HLT). The L1 trigger is fully automated and designed to look for signs of interesting events by selecting particles with large energy. The L1 trigger reduces the collision rate by a factor of 10^3 within $3.2 \mu\text{s}$ of each collision. In the next step, the HLT system uses information from all parts of the detector to recreate the entire collision and a decision is made based on predefined conditions to select events with special characteristics. At the HLT an event rate is further reduced by a factor of 10^2 to 100 Hz before they are stored in the cluster of computers.

The CMS L1 trigger is entirely hardware based and it uses information from muon system and calorimeters. Due to its complexity and large data, tracker information is not used at this stage. L1 seeding starts from the individual sub-detectors when particle deposits its energy in the calorimeter or a particle is detected in the muon chamber. The highest-quality primitives (defined as muon track segments or electron/photon energy towers) are sent to regional triggers called Regional Calorimeter Trigger (RCT) and the DT or CSC muon system. The RCT is designed to combine information from HCAL and ECAL to detect electron/photon candidates. The second regional trigger uses DT and CSCs to convert raw detector information from the muon system into r and ϕ coordinates. Muon candidates are reconstructed in each muon station by generating a momentum hypothesis. If the hypothesis matches the actual hits in the detector the information is sent to a track finding algorithm that combines information from several stations to measure the muon transverse mo-

mentum. All information from calorimeters and muon stations are then sent to the CMS Global Trigger (GT) which decides to accept an event based on the predefined selection criteria. If the GT finds an event interesting it sends a L1 accept message to each subdetector and Data Acquisition (DAQ) begins.

The HLT at the CMS is designed to reconstruct collision events during the data collection. It uses information from all subdetectors and decides whether to save an event on disk or not. At the HLT, information from the inner tracker is also utilized to reconstruct trajectory of particles and achieve better track resolution. The HLT is configured to select events based on the list of algorithms which can be composed of one or many physics objects. Single HLT module can contain objects that are reconstructed in the same subdetector (one or more photons/electrons, one or more muons, one or more jets, etc) or in many different subdetectors (lepton plus jets, photon plus jets, etc). For the studies of charmonium and bottomonium states, such as J/ψ and Υ , a dedicated set of unbiased triggers with muon selections are used. The triggers that contain two muons are collectively called DoubleMu_X, and they occupy bandwidth of approximately 40 Hz from the total 1000 Hz. In this analysis triple muon trigger called HLT_Dimuon0_Upsilon_Muon HLT path is utilized. This trigger requires three muons from L1 seed without any kinematic restriction. At the HLT level, at least one combination of selected muons must meet following criteria: (i) oppositely charged muon pair has an invariant mass, $M_{\mu\mu}$, between 8.5 and 11 GeV (ii) oppositely charged muon pair point to a same vertex with χ^2 probability greater than 0.5%, as determined by a Kalman filter algorithm [52].

3.7 CMSSW Software

CMSSW is special software package developed for the CMS experiment to provide a development and analysis framework. It manages application control during the event process, provides an interface with common tools like generator, magnetic field, and Monte Carlo (MC) truth handling, and infrastructure for hits, event mixing and digitization.

The CMSSW event-processing module is executed with a command called `cmsRun` which is guided by synchronised event setup data that provides information about the geometry, calibration and alignment of the detector. For MC samples, the communication between different modules is done through the event bus which starts with event generation, and then adds to it simulation hits, digitization hits and reconstructed physics objects. Detector simulation of generated events are interfaced with a specific CMSSW version, as each version contains different detector calibration parameters and reconstruction algorithms. In this analysis, CMSSW version 5.3.7 patch 5 is used to process data and reconstruct muon objects.

CHAPTER 4

OBSERVATION OF $\Upsilon(1S)$ PAIR PRODUCTION AT CMS

An analysis overview and the importance of quarkonium pair production is discussed in Chapter 2. As pointed out earlier, heavy quarkonia pair production in hadronic collisions provides important tests of understanding various aspects of QCD. The cross section calculation of quarkonium production can be split in two sub-processes; the process where incoming partons combine to form $Q\bar{Q}$ (referred as partonic hard scattering process) and the subsequent process where $Q\bar{Q}$ hadronize to form quarkonia states such as J/ψ or Υ . The partonic hard scattering process can be calculated in the framework of perturbative QCD, while the hadronization process requires a non-perturbative treatment as it involves soft momentum scales. The cross section measurements of heavy quarkonia pair production provides an important testing ground for these calculations, and this section is dedicated to presenting results from such experimental measurement.

Quarkonia pair production with J/ψ final states was reported by CMS [49], LHCb [48] and D0 [46] experiments previously. An advantage of a J/ψ final state in quarkonium production is that it provides a clean sample with large statistics. However, a significant fraction of J/ψ mesons originate from the B meson decays. These events are usually referred to as a non-prompt contribution since they do not originate at the interaction vertex of the initial proton-proton collision, and special techniques are used to separate them from the promptly produced J/ψ 's. Early experimental results from J/ψ pair production motivated the inclusion of SPS higher

order, color octet and DPS contributions in the calculations. Unlike the SPS mechanism, DPS is difficult to address within the framework of QCD calculations and it is usually attributed to measurements that can not be explained otherwise. The DPS mechanism is also studied in jet and multi-boson final states and many experimental measurements were recently reported [43, 44, 45]. In jet related studies the DPS mechanism is the most dominant process. However, jets are complex objects and their identification/reconstruction requires sophisticated algorithms which can be challenging as pileup increases. Compared to J/ψ and jet final states, reconstruction of Υ final states is simpler as it involves only muon objects. Moreover, contributions of non-prompt production can be neglected as there is no known SM particle that decays to a Υ meson.

4.1 Analysis Strategy

The data for this analysis was recorded by the CMS detector at $\sqrt{s} = 8$ TeV during the 2012 data collection period. Analyzed data was collected by an unscaled triple muon trigger with total integrated luminosity corresponding to 20.7 fb^{-1} . In this analysis simultaneous production of two Υ mesons are searched via their decays into pair of oppositely charged muons. The signature of Υ pair production is then events containing at least four muons with combined electric charge of zero.

Initial preselection starts by selecting events that have at least four muons and that also fired HLT_Dimuon0.Upsilon_Muon trigger path. Further selections, explained in detail at Sec. 4.2, are applied to reject cosmic muons and in-flight decay

muons. The major components of the background are mainly combinatorics which comes from Drell-Yan [53] processes or muons that derive from the weak decays of b, c quarks passing the trigger and offline selection cuts. The contributions from the combinatorial components are extracted from the data and separated from the signal using an unbinned maximum likelihood fit method.

The total cross section of $\Upsilon(1S)\Upsilon(1S)$ events is measured in a predefined Υ acceptance $|y^\Upsilon| < 2.0$ which is constrained by the single muon acceptance, $|\eta^\mu| < 2.4$ and $p_T^\mu > 3.5$ GeV. Υ candidates failing muon acceptance, identification and triggering requirements are recovered on event-by-event basis using a data-embedding method. A cross section formula derived from the measured signal yield, $N_{\Upsilon\Upsilon}$, is then calculated as,

$$\sigma(\text{pp} \rightarrow \Upsilon(1S)\Upsilon(1S)) = \frac{N_{\Upsilon\Upsilon} \cdot \bar{\omega}}{[\mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-)]^2 \cdot \mathcal{L}} \quad (4.1)$$

where, $N_{\Upsilon\Upsilon}$ is the number of $\Upsilon(1S)\Upsilon(1S)$ events extracted with two-dimensional (2D) unbinned maximum likelihood fit, $\bar{\omega}$ is the average correction factor that accounts for muon inefficiencies stemming from reconstruction, identification and triggering requirements as well the fraction of events lost due to acceptance requirements, $\mathcal{L}$ is the integrated luminosity for the 2012 data set and $\mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-)$ is the branching fraction of $\Upsilon(1S)$ decays to a pair of muons from the Ref. [54].

4.1.1 Data and MC samples

During the 2012 data collection period CMS has collected nearly 22 fb^{-1} of data. Due to evolving upgrades data collection conditions might change throughout

the months-long run. Therefore collisions with similar conditions are grouped together by range of run numbers. During the Run I analysis there have been four major run periods labeled as Run2012A, Run2012B, Run2012C and Run2012D. The data set names, luminosities and corresponding trigger versions for each run are summarized in Table: 4.1.

Table 4.1: Summary of data set names with corresponding run number ranges, collected trigger names, and recored/delivered luminosities.

Data sets	Run range	Trigger	Effective lumi	Delivered
Run2012A	[190456,193621]	HLT_Dimuon0_Upsilon_Muon_v15	0.924 fb ⁻¹	0.965 fb ⁻¹
Run2012B	[193833,196531]	HLT_Dimuon0_Upsilon_Muon_v15	1.376 fb ⁻¹	4.925 fb ⁻¹
		HLT_Dimuon0_Upsilon_Muon_v16	3.453 fb ⁻¹	
Run2012C	[198022,203746]	HLT_Dimuon0_Upsilon_Muon_v17	1.826 fb ⁻¹	7.430 fb ⁻¹
		HLT_Dimuon0_Upsilon_Muon_v18	5.484 fb ⁻¹	
Run2012D	[203768,208686]	HLT_Dimuon0_Upsilon_Muon_v18	7.576 fb ⁻¹	7.718 fb ⁻¹
Total			20.639 fb ⁻¹	21.038 fb ⁻¹

Monte Carlo (MC) simulation is the backbone of experimental physics as it provides an interface for testing, validating and optimizing experimental setups and thoretical models. At the CMS MC samples are produced via CMSSW software, usually with same version that is used to reconstruct collision events. MC simulation consist of three steps; (i) an underlying physics process is generated and hadronization is performed, (ii) particles are fed into GEANT4 [55] package to simulate detector response and reconstruct hits, (iii) same reconstruction chain as performed on data is processed.

For this analysis two types of models are utilized to simulate $\Upsilon(1S)$ meson

pair production. Strongly correlated $\Upsilon(1S)$ meson pairs produced via SPS are generated with the CASCADE-2.3.13 simulation program [56], while less correlated $\Upsilon(1S)$ meson pairs produced via DPS are generated with the PYTHIA8.1.58 package [57]. These samples are used to validate efficiency, acceptance correction factors and parameterize kinematic distributions of Υ mesons in the data. All samples are produced with appropriate conditions for the data analyzed, including the effects of alignment, efficiency, and an average number of pileup. A list of MC samples with descriptions is summarized below.

- Double parton scattering Υ pair simulation:

A Υ pairs is produced via the DPS mechanism using PYTHIA8 event generator software by enabling two hard scattering of bottomonium states. A generator level filter is applied to select events containing at least one Υ that decays to pairs of muon. Muons are also required to be within the coverage of detector with $|\eta^\mu| < 2.6$ and $p_T^\mu > 2.5$ GeV. These filters avoid simulation of soft muons that don't reach detector acceptance and those speed up reconstruction process.

- Single parton scattering Υ pair simulation:

The SPS is simulated using CASCADE event generator. CASCADE event simulation uses an off-shell matrix-element description of the $g^*g^* \rightarrow \Upsilon(1S)\Upsilon(1S)$ production and includes the k_T -dependent parton distribution function JH-2013-set2 [58]. The parton evolution follows the CCFM prescription [59, 60], which forms a bridge between the DGLAP and BFKL parton resummation models. Similar generator level filter is applied to speed up reconstruction process

and save disk space.

- Data embedding MC sample:

This MC sample is used to study muon identification, reconstruction and triggering efficiency of the detector. Unlike two previous MC samples, this sample doesn't require underlying hard process as it simulates detector response using final products of the reconstructed muons in the data. Data embedding procedure is achieved by repeatedly substituting measured muon momenta with the generated muon momenta and passing it through CMS detector simulation, reconstruction and trigger chain. During the data collection period pileup conditions vary depending on the number of hard proton-proton collisions. To avoid underestimation of this effect, substituted events are also simulated with the same pileup condition as in the data event where it is estimated as the number of reconstructed primary vertices. One thousand of such substitutions are repeated for each selected event to calculate identification, reconstruction and selection efficiency.

4.2 Event Selection Procedure

The search for $\Upsilon\Upsilon$ events involves careful investigation and analysis of a large data sets which requires an efficient filtering algorithm. In this analysis the selection process is achieved in two steps; an online process where algorithm performs reconstruction of muon objects using detector hits and selects events that contain at least four muon candidates with combined zero electric charge, and an offline process

where selected sample is further analyzed to reject events from background contribution and misidentified muons. The online processing scans the entire data set and a single computer is not powerful enough to perform this task. Therefore, the scanning is divided into smaller pieces and shared among the cluster of computers for processing. In the second step, due to reduced size, files are analyzed locally in a single computer. Online reconstruction of $\Upsilon\Upsilon$ candidate starts with muon candidates identified by reconstruction algorithm called Physics Analysis Toolkit (PAT) objects. The PAT Muon is a high-level analysis layer dedicated for the muon analysis which reconstructs muon candidates utilizing detector hits from the inner tracker and the muon chamber. It converts electric signals in the detector into a measurable quantity such as momenta, charge and position.

Additional selections are imposed as follows to reject cosmic ray muons and in-flight decays; each muon candidate has associated track in the inner tracker, tracker muon has at least one hit in the pixel detector, total number of hits in the inner tracker is greater than three, normalized χ^2 of muon track is less than 15 and reconstructed vertex of track in transverse plane with respect to the beam is less than 10 cm. Oppositely charged muons that satisfy above criteria are paired to form Υ candidate. Selected four muon allows formation of four dimuon pairs and two paired dimuon combinations as depicted in the Table 4.2

An offline selection further checks for misidentified muons and muon candidates that originate from different proton-proton interaction vertices. To avoid contributions from displaced muons and pileup events, selected four muon combination

Table 4.2: Possible combinations of dimuon pairs for each selected four muon system.

Paired Pair Combination	$M_{\mu\mu}^{(1)}$	$M_{\mu\mu}^{(2)}$
Paired dimuon 1	$\mu_1\mu_2$	$\mu_3\mu_4$
Paired dimuon 2	$\mu_1\mu_3$	$\mu_2\mu_4$
Paired dimuon 3	$\mu_1\mu_4$	$\mu_2\mu_3$

is required to originate from a common vertex with a χ^2 fit probability larger than 5%. Additionally, to remove fake muons, each muon is required to satisfy following criteria; each muon is identified as a reconstructed track, identified track has at least five hits in silicon tracker, identified track has at least one hit in pixel tracker, track of muon matches at least one muon segment in muon detector, transverse distance of track vertex is less than 0.3 cm with respect to beam and longitudinal distance of track vertex is less than 20 cm with respect to beamspot. Sometimes reconstructed muon can be different than the muon which triggered an event. To avoid this mismatch, reconstructed muons are matched to the muon object that triggered an event, specifically HLT_Dimuon0_Upsilon_Muon trigger. Matching is performed with two conditions; an offline muons that constitute Υ candidate are matched to the L3 *hltVertexmumuFilterUpsilonMuon* object and 3rd muon is matched to L3 *hltTripleMuL3PreFiltered0* object. The default matching criteria is $\Delta R < 0.5$ and $\Delta p_T/p_T < 0.5$ between the reconstructed muon and the trigger object. After these selections total of 341 events make to final sample, and the lego plot of $\Upsilon\Upsilon$ candidates are shown in the Fig. 4.1. There are 14 events that contain multiple $\Upsilon\Upsilon$ candidates which are subsequently discarded from the analysis.

Higher-mass states of $\Upsilon(1S)$ meson such as $\Upsilon(2S)$ and $\Upsilon(3S)$ are indistinguishable at the trigger level. This allows all states to appear in the same mass spectrum. To resolve ambiguity as to which dimuon pair contains the higher-mass Υ meson states, the dimuons are further sorted with respect to their reconstructed invariant mass, by inserting heavier dimuon mass into the $M_{\mu\mu}^{(1)}$ column, while lighter ones into the $M_{\mu\mu}^{(2)}$ column, as depicted in the Table 4.2. An independent study shows no bias is introduced with this choice.

Figure 4.1: Lego plot of selected events with $M_{\mu\mu}^{(1)}$ on the x-axis and $M_{\mu\mu}^{(2)}$ on y-axis. Vertical axis corresponds to the number of entries per area (x-axis times y-axis) in horizontal plane.

4.3 Efficiency and Acceptance Corrections

The acceptance of muons is defined by the geometry of the CMS detector and minimum momentum required to reach the muon stations. The muon acceptance region is established based on the studies of simulated prompt double $\Upsilon(1S)$ events. Upsilon acceptance is in turn constrained by the acceptance of muons.

Efficiency of four muon system stems from the single muon reconstruction, identification and triggering, and it is defined as how much of signal events survive final selection requirements given they are within detector acceptance. In this analysis special care is taken to account for any correlation between any combination of muons which can dramatically depend on selected model.

Significant fraction of $\Upsilon\Upsilon$ events that are produced at the interaction vertex do not make it into final sample due to reconstruction inefficiencies and acceptance requirements. The cross section measurement needs to account for this effect, so weighting factors calculated from the MC studies are assigned to each selected candidate. The fraction of events failing selection requirements are calculated by dividing the number of samples passing selection criteria and the number of generated events. One major limitation of this method is that correlations among the Υ mesons or muon candidates are not considered. This may result in the underestimation of weighting factors, especially, for the highly correlated Υ pairs production. To account for this complication novel approach is utilized where efficiency and acceptance weighting factors are calculated using measured momenta of muons. This method is further validated using two different models of Υ pair production described in Section 4.1.1.

4.3.1 Acceptance Corrections

The cross section measurement is performed in the region of the detector where acceptance probability of single muon is relatively smooth. To define the acceptance region of detector, kinematic distributions of muons for two different production mechanisms are investigated as depicted in Fig. 4.2. The acceptance of detector, as the name implies, is independent of the underlying production mechanism.

Figure 4.2: Left, accepted muons as a function of p_T vs η for SPS model. Right, accepted muons as a function of p_T vs η for DPS model.

No muon is detected beyond physical boundary of detector ($|\eta^\mu| > 2.4$), and for the barrel region ($|\eta^\mu| < 1.0$) muons must possess enough momentum to reach detector before they are deflected by the magnetic field. Based on this study we define muon acceptance of the detector to be $|\eta^\mu| < 2.4$ and $p_T^\mu > 3.5$ GeV.

The Υ acceptance in turn is defined as the rate at which muons from Υ decays fall into the muon acceptance and it is dictated by the muon acceptance. The Υ

acceptance is probed with SPS and DPS signal MC samples. Fig. 4.3 shows the acceptance contours for Υ mesons for two different production mechanisms.

Figure 4.3: Accepted Υ p_T versus y for DPS (left) and SPS (right) signal MC samples.

Unlike muons decaying from J/ψ mesons, Υ decay products have a higher p_T spectrum which allows a significant fraction of them to be reconstructed, as long as there is no momentum threshold in the trigger, even when the Υ meson is produced at rest. Based on this study we define Υ acceptance to be $|y^\Upsilon| < 2.0$. Our definition of acceptances are consistent with previous CMS measurements [61, 49].

4.3.2 Event-by-Event Acceptance Corrections

Events failing muon acceptance requirements are recovered on event-by-event basis by repeatedly simulating the isotropic decay of measured Υ four-momenta. The acceptance correction, a_i for an event i , is defined as the number of times decay muons

pass muon acceptance criteria, $N_{\text{pass}}(\Upsilon\Upsilon)$, divided by the total number of simulated decays, $N_{\text{tot}}(\Upsilon\Upsilon)$, given that $|y^\Upsilon| < 2.0$ in both case. Acceptance correction for each selected event is calculated separately by simulating ten thousand of such decays. The fraction of $\Upsilon(1S)$ candidates lost due to the muon acceptance criteria, as a function of $\Upsilon(1S)$ transverse momentum versus rapidity, for two different production MC samples and data is shown in the Fig. 4.4. Dip around 6 GeV is chiefly due to the muons flying opposite direction of $\Upsilon(1S)$ meson fail to reach muon stations, which is then recovered as transverse momentum of $\Upsilon(1S)$ meson increases.

Figure 4.4: Fraction of $\Upsilon(1S)$ mesons lost due to the muon acceptance as a function of $|y^\Upsilon|$ (left) and p_T^Υ (right) for SPS, DPS and data.

Acceptance correction method is validated using signal SPS and DPS signal MC samples. For each generated Υ pair events, N_{gen} , the muon acceptance criteria is applied to obtain a sample of N_{pass} survivors. For each surviving event, event-based acceptance correction, a_i , is calculated as described above. Acceptance corrected

events, $N_{\text{recovered}}$, is then calculated as $N_{\text{recovered}} = \sum_{i=1}^{N_{\text{pass}}} 1/a_i$. The matching between N_{gen} and $N_{\text{recovered}}$ represents closure of the acceptance correction method. Statistical uncertainties for each correction factor is estimated using binomial error formula, $\sigma_i = \sqrt{a_i \cdot (1 - a_i) / N_{\text{gen}}}$. Results of the closure test for SPS and DPS signal MC sample is summarized in Table: 4.3. Consistency test between N_{gen} and $N_{\text{recovered}}$ [62]

Table 4.3: Relative difference between true generated events, N_{gen} , and acceptance corrected events $N_{\text{recovered}}$.

Model	N_{pass}	N_{gen}	$N_{\text{recovered}}$	Relative Difference
SPS	3922	22524	23155 ± 556	2.80 %
DPS	4819	29858	30605 ± 753	2.50 %

shows they are not within the statistical uncertainty of each other, and thus a systematic uncertainty of 2.8% is assigned for this method. Acceptance correction method assumes $\Upsilon(1S)$ mesons decay isotropically, and thus uncertainty associated with possible polarization is estimated separately.

4.3.3 Data Embedding Efficiency Correction

An efficiency correction factors for the four muon system is determined on event-by-event bases by repeatedly substituting the measured four muon momenta into the generated event, which is then subjected to the complete CMS detector simulation and reconstruction chain. To mimic conditions of reconstructed data event, substituted muons are simulated at the same four muon decay vertex measured from

the reconstructed data event. Reconstruction, identification and triggering efficiencies may be different for different pileup conditions. Therefore, each substitution event is simulated with the same number of pileup conditions as in the data which is approximated by the number of reconstructed good primary vertices.

An efficiency correction factor ϵ_i for i^{th} event is defined as the number of substitution events passing reconstruction and trigger requirements divided by the total number of substitutions. For each i^{th} reconstructed candidate in the data one thousand such different substitutions are performed. Fig. 4.5 shows the distribution of data embedding efficiencies with respect to various kinematic variables.

The data embedding efficiency correction method is validated using signal SPS and DPS MC samples. For each sample of generated events within muon acceptance, N_{true} , final selection requirements are applied to find surviving N_μ candidates. For each N_μ events the event-based efficiency correction, ϵ_i , is calculated as described above. The corrected number of signal events within muon acceptance, N_{corr} , is then calculated as $N_{\text{corr}} = \sum_{i=1}^{N_\mu} 1/\epsilon_i$. Mismatch between N_{corr} and N_{true} , listed in Table: 4.4 provides a quantitative estimate of the systematic uncertainty associated with this method.

Table 4.4: Relative difference between true generated events, N_{true} , and efficiency corrected events N_{corr} .

Model	N_μ	N_{true}	N_{corr}	Relative Difference
SPS	1642	3922	3855 ± 170	1.71%
DPS	1654	4819	4642 ± 232	3.67%

Figure 4.5: Average ϵ in bins of double Υ transverse momentum, number of primary vertices, lowest muon η , lowest muon p_T .

4.3.4 Scaling Factor

Data embedding efficiency corrections are based on the measured muon momenta. Due to the detector resolution a net migration effect can depopulate events near the kinematic threshold region. Therefore, the substitution method may overestimate efficiency corrections. To account for this effect, a separate study is performed following a strategy developed by a similar analysis at CMS [49]. Initially, an average efficiency correction factor is determined as the ratio between the number of events that survive triggering and reconstruction requirements divided by the number of

events recovered with efficiency correction method. Alternatively, it is also defined as the ratio between the number of events that survive selection cuts and the number of generated events. This procedure is repeated for two different production models, SPS and DPS.

An average efficiency is determined by correcting back to the generated population using the data embedding efficiency correction values, ϵ_i , is designated the *backward* efficiency,

$$\epsilon_b = \frac{N_{\text{pass}}}{N_{\text{corrected}}} \quad (4.2)$$

where, $N_{\text{corrected}}$ is the number of efficiency corrected events, and N_{pass} is the number of events generated within Υ and muon acceptance that also pass final selection cuts.

Alternatively, an average efficiency determined by generating events and stepping forward through the normal detector simulation is designated as the *forward* efficiency,

$$\epsilon_f = \frac{N_{\text{reco}}}{N_{\text{gen}}} \quad (4.3)$$

where, N_{gen} is the number of events generated in the Υ and muon acceptance region, and N_{reco} is the number of events generated within Υ and muon acceptance that also pass final selection requirements. Unlike *backward* efficiency the *forward* efficiency method is based on the generated muon momenta and thus detector resolution is automatically accounted for.

The scaling factor S is calculated as the ratio of the *forward* and *backward* efficiencies, $S = \frac{\epsilon_f}{\epsilon_b}$, for the SPS and DPS MC samples separately as shown in Table: 4.5. The error in ϵ_f is due to the number of generated events, and in the case

of ϵ_b , due to the statistical uncertainty of the number of events found from the substitution method. Scaling factors for both SPS and DPS models are close to 100% implying efficiency correction method is performing well and depopulation effect is small. Furthermore, scaling factors for two models are relatively close and they can be averaged to account for the detector resolution effect. The final efficiency corrections that determine total cross section are then calculated using the average scaling factor from SPS and DPS models, $\epsilon'_i = \bar{S} \cdot \epsilon_i$, where

- $\bar{S}$ is $\frac{1}{2} \cdot (S^{SPS} + S^{DPS})$,
- ϵ_i is event-based efficiency correction calculated in Section: 4.3.3

Table 4.5: Average efficiency(%) ϵ_f and ϵ_b for signal MC sample.

	Forward efficiency $\epsilon_f(\%)$	Backward efficiency $\epsilon_b(\%)$	$S(\%)$
SPS	42 ± 2	43 ± 4	98 ± 10
DPS	34 ± 1	36 ± 5	96 ± 14

4.4 Efficiency Correction with Tag and Probe Method

Data embedding efficiency corrections partially rely on the detector simulation which may contain imperfections due to alignment or dynamic upgrades. To quantify this effect additional study is performed in this section which compares data driven muon efficiencies with default data embedding method.

A data driven muon efficiency is determined using a Tag and Probe method for tracking, quality, identification and triggering separately. The Tag and Probe

method utilizes well known dimuon decays, such as $J/\psi \rightarrow \mu^+ \mu^-$, to provide a sample of objects. A well-identified muon, called a Tag, is combined with second object in the event called Probe and invariant mass is computed. The Tag-Probe pairs are divided into two samples based on whether probe satisfies criteria for the efficiency being measured. The two Tag-Probe mass distributions of each pair contains J/ψ peak, the area of which corresponds to the number of probes from the decay that satisfy and fail the criteria imposed. The efficiency parameter is extracted from the simultaneous unbinned maximum-likelihood fit to both mass distributions.

Overall single muon efficiency is calculated in five different factors, shown in the Fig. 4.6, where each factor is defined exclusively, i.e. relative to previous efficiency. The order with which efficiency has been defined by CMS muon experts is as follows;

$$\epsilon_{\text{tot}} = \epsilon_{\text{Track}} \cdot \epsilon_{\text{MuonID}} \cdot \epsilon_{\text{MuonQual}} \cdot \epsilon_{\text{L1-L2}} \cdot \epsilon_{\text{L3}} \quad (4.4)$$

where,

- ϵ_{Track} is taken from Ref: [63] and measured to be 99% or higher in the entire tracker acceptance,
- ϵ_{MuonID} is an identification efficiency; the efficiency that the reconstructed tracker track of the muon is also identified in the muon system,
- $\epsilon_{\text{MuonQual}}$ is an efficiency of the muon to satisfy *HighPurityTrack* flag, at least has 5 hits in the tracker, at least has one pixel hit, longitudinal impact parameter is less than 20 cm, and transverse impact parameter is less than 0.3 cm,
- $\epsilon_{\text{L1-L2}}$ is an efficiency of passing probe muon to match *hltDimuonL2PreFiltered0*

filter,

- ϵ_{L3} is an efficiency of the passing probe muon to match L3 muon.

Figure 4.6: Tag and probe muon reconstruction and identification efficiency.

Assuming single muon efficiencies are factorizable, four muon efficiency is derived as the product of the single muon efficiencies measured with tag and probe method. Triple muon trigger efficiency is not computed with tag and probe method, and hence it is accounted separately as follows;

$$\epsilon_{4\mu}(\text{TnP}) = \rho(p_T^{4\mu}, y^{4\mu}) \cdot \epsilon_{\mu 1} \cdot \epsilon_{\mu 2} \cdot \epsilon_{\mu 3} \cdot \epsilon_{\mu 4} \quad (4.5)$$

where $\rho(p_T^{4\mu}, y^{4\mu})$ is total correlation factor measured as a function of four muon kinematics, and $\epsilon_{\mu i}$ can take two values,

- $\epsilon_{\mu i} = \epsilon_{\text{Track}} \cdot \epsilon_{\text{MuonID}} \cdot \epsilon_{\text{MuonQual}} \cdot \epsilon_{L1 \cdot L2} \cdot \epsilon_{L3}$ if one of the three muons matched to

the trigger object,

- $\epsilon_{\mu i} = \epsilon_{\text{Track}} \cdot \epsilon_{\text{MuonID}} \cdot \epsilon_{\text{MuonQual}}$ fourth muon in the event.

The Tag and probe method omits correlations among muon candidates and Υ mesons which may result in the overestimation of weighting factors. Therefore correlation factor, ρ , is calculated using signal MC samples as a function of four-muon kinematics,

$$\rho(p_{\text{T}}^{4\mu}, y^{4\mu}) = \frac{\epsilon(p_{\text{T}}^{4\mu}, y^{4\mu})}{\epsilon_{\text{HLT}}(p_{\text{T}}^{4\mu}, y^{4\mu}) \cdot \prod_{i=1}^4 \epsilon_{\mu i}(p_{\text{T}}, \eta)} \quad (4.6)$$

where, $\epsilon(p_{\text{T}}^{4\mu}, y^{4\mu})$ is an efficiency of four-muon system to be reconstructed, identified and triggered, calculated with signal MC, $\epsilon_{\text{HLT}}(p_{\text{T}}^{4\mu}, y^{4\mu})$ is an efficiency of four-muon system to be triggered given they are reconstructed and identified, $\epsilon_{\mu i}(p_{\text{T}}, \eta)$ is an efficiency of single muon to be reconstructed and identified. Total correlation factor is studied in the four-muon phase space for both SPS and DPS MC samples separately and distributions are plotted in Fig. 4.7.

To estimate the uncertainty due to detector simulation, four-muon system efficiencies calculated with the data embedding method are compared with the four-muon efficiency using the tag and probe method. The corrected number of signal events, N_1 , using tag and probe method is calculated as,

$$N_1 = N_{\text{TT}} \cdot \frac{\sum_{i=1}^N 1/\epsilon_{4\mu}^i(\text{TnP})}{N} \quad (4.7)$$

where, $\epsilon_{4\mu}(\text{TnP})$ is four-muon efficiencies calculated using tag and probe from the Formula 4.5. The correlation factor is model dependant, and thus mean of DPS

Figure 4.7: Left, ρ factor obtained from DPS signal MC. Right, ρ factor obtained from SPS signal MC

and SPS is used. An efficiency corrected yield using data-embedding method, N_2 , procedure described in the section 4.3.3 is used. From this study N_1 and N_2 are found to be 138 and 145, respectively. Difference between two methods is small and relative uncertainty of 4.9% is assigned to account for the imperfect detector simulations.

4.5 Extraction of Υ Pair Production Yield

Selected data events may contain contamination from the combinatorial background. An extended maximum likelihood fit to the data is performed to extract signal weights. Genuine Υ kinematic distributions are modeled with parameters extracted from MC samples which are used to define probability distribution function (pdf). The fitting procedure is validated by repeatedly applying the fitting procedure to simulated samples generated with the pdf that describes the data. The statistical significance of $\Upsilon(1S)$ pair production is calculated using likelihood ratio test and it

is found to be well above five standard deviations.

4.5.1 Fitting Procedure

To extract genuine $\Upsilon(1S)\Upsilon(1S)$ and $\Upsilon(1S)\Upsilon(2S)$ events, a two-dimensional (2D) unbinned maximum likelihood fit to the invariant masses of reconstructed $\mu^+\mu^-$ pair is used. Two kinematic variables are employed to discriminate the $\Upsilon\Upsilon$ events from the background: the invariant mass of the higher-mass Υ candidate ($M_{\mu\mu}^{(1)}$) and the invariant mass of the lower-mass Υ candidate ($M_{\mu\mu}^{(2)}$). This choice of variables helps to resolve the ambiguity of having dimuon pair in which $\Upsilon(2S)$ candidates appears. There is no visible signal for $\Upsilon(3S)$, which is not further considered in this study.

Five categories of events are considered to represent the sample of events:

1. events containing a genuine $\Upsilon(1S)\Upsilon(1S)$ (labeled sig1),
2. events containing a genuine $\Upsilon(1S)\Upsilon(2S)$ (labeled sig2),
3. events containing a genuine $\Upsilon(1S)$ candidate and two unassociated muons that contribute to the $M_{\mu\mu}^{(2)}$ (labeled $\Upsilon(1S)$ -combinatorial),
4. events containing a genuine $\Upsilon(2S)$ candidate and two unassociated muons that contribute to the $M_{\mu\mu}^{(2)}$ ($\Upsilon(2S)$ -combinatorial), and
5. events containing four unassociated muons (labeled combinatorial).

The contributions from other categories (combinatorial $\Upsilon(1S)$ and combinatorial $\Upsilon(2S)$), where two unassociated muons form the higher-mass Υ candidate, are found to be negligible. There is no indication of $\Upsilon(2S)\Upsilon(2S)$ events which is not discussed.

Each opposite-sign dimuon invariant mass distribution contains contributions

from Υ candidate and a nonresonant background. The fit is performed over the entire rapidity range $|y(\Upsilon)| < 2.0$. The dimuon invariant mass resolution varies in this range, and it is found that a single Gaussian function is insufficient to describe the signal distribution. To capture this variation, an Υ candidate is modeled as a sum of two Crystal Ball functions [64], labeled DCB. The DCB parameters are extracted from the SPS signal MC sample and fixed in the fit to the data. The combinatorial background component is modeled with first-order Chebyshev polynomials (Poly). Fig. 4.8 and Fig. 4.9 shows $M_{\mu\mu}^{(1)}$ and $M_{\mu\mu}^{(2)}$ distributions with their fit to SPS and DPS signal MC samples. The yields of the five event categories and the two slope parameters for

Figure 4.8: Left, reconstructed $M_{\mu\mu}^{(1)}$ distribution fitted to double crystal ball ansatz, and right, $M_{\mu\mu}^{(2)}$ distribution fitted to double crystal ball ansatz for SPS MC sample.

the combinatorial background are the free parameters in the fit to the data. The likelihood function ℓ_k for an event k (ignoring the normalisation term for simplicity)

Figure 4.9: Left, reconstructed $M_{\mu\mu}^{(1)}$ distribution fitted to double crystal ball ansatz, and right, $M_{\mu\mu}^{(2)}$ distribution fitted to double crystal ball ansatz for DPS MC sample.

is given as:

$$\begin{aligned}
 \ell_k = & N_{\text{sig1}} \cdot [\text{DCB}_{\Upsilon(1\text{S})}(M_{\mu\mu}^{(1)}) \cdot \text{DCB}_{\Upsilon(1\text{S})}(M_{\mu\mu}^{(2)})] \\
 & + N_{\text{sig2}} \cdot [\text{DCB}_{\Upsilon(2\text{S})}(M_{\mu\mu}^{(1)}) \cdot \text{DCB}_{\Upsilon(1\text{S})}(M_{\mu\mu}^{(2)})] \\
 & + N_{\Upsilon(1\text{S})-\text{combinatorial}} \cdot [\text{DCB}_{\Upsilon(1\text{S})}(M_{\mu\mu}^{(1)}) \cdot \text{Poly}(M_{\mu\mu}^{(2)})] \\
 & + N_{\Upsilon(2\text{S})-\text{combinatorial}} \cdot [\text{DCB}_{\Upsilon(2\text{S})}(M_{\mu\mu}^{(1)}) \cdot \text{Poly}(M_{\mu\mu}^{(2)})] \\
 & + N_{\text{combinatorial}} \cdot [\text{Poly}(M_{\mu\mu}^{(1)}) \cdot \text{Poly}(M_{\mu\mu}^{(2)})]
 \end{aligned} \tag{4.8}$$

The yields N_i are determined by minimizing the quantity $-\ln\mathcal{L}$ [65], where $\mathcal{L} = \prod_k \ell_k$. The extracted yields with this procedure are $N_{\text{sig1}} = 38 \pm 7$, $N_{\text{sig2}} = 13_{-5}^{+6}$, $N_{\Upsilon(1\text{S})-\text{combinatorial}} = 9_{-6}^{+7}$, $N_{\Upsilon(2\text{S})-\text{combinatorial}} = 8 \pm 8$ and $N_{\text{combinatorial}} = 245 \pm 18$.

The projection of the fit are shown in the Fig. 4.10.

The contribution due to the non-prompt Υ production or pileup events is investigated using kinematic distributions of the longitudinal distance between Υ

Figure 4.10: Projections of the 2D fit of Fig. 4.1. Left, invariant mass of higher mass muon pairs, $M_{\mu\mu}^{(1)}$. Right, invariant mass of lower mass muon pairs, $M_{\mu\mu}^{(2)}$. The lower pads show the difference between the total fit curve and data, with red lines corresponding to a difference of ± 2 standard deviations.

candidates, Δz , and pseudo-proper decay length, l . The pseudo-proper decay length is calculated as $l = \frac{m(\Upsilon) \cdot L_{xy}(\Upsilon)}{p_T(\Upsilon)}$, where decay length in the lab frame $L_{xy}(\Upsilon) = \frac{\vec{r}_T \cdot \vec{p}_T(\Upsilon)}{|\vec{p}_T(\Upsilon)|}$ and $\vec{r}_T$ is the vector pointing from beamspot to the Υ vertex. Distribution of these variables are plotted in the Fig. 4.11. Low values of Δz (l) signify that the non-prompt (pileup) contribution is negligible.

4.5.2 Validation of Fitting Procedure

The fitting procedure is validated by repeatedly applying fitting procedure to the samples that are generated using the probability density function (pdf) that describe the data. The known value of $\Upsilon(1S)\Upsilon(1S)$ events are injected to generate sample that represent distribution in the data and separate fit is performed to extract yields. 10,000 of such toy experiments are performed each time to reproduce likelihood

Figure 4.11: The pseudo-proper decay length of higher mass dimuon pair (left), and the longitudinal distance between higher mass Υ vertex and lower mass Υ vertex (right).

value. The deviation between extracted yield and injected true value divided by the error of the fit, also called pull distribution, is inspected. The result of the toy experiment for 38 injected signal events is plotted in Fig. 4.12. The mean of the pull distribution is consistent with zero, and the standard deviation is consistent with unity. The potential bias due to the residual correlation between the variables in signal events is tested by embedding signal MC events into the data sample; any correlation would be magnified by this process. In the first step 128 SPS MC events are embedded to data sample and unbinned maximum likelihood fit is performed. In the second step, 176 DPS MC events are added to data events and refitted. The extracted signal yields with the fitting procedure are 177 ± 15 and 228 ± 17 , while expected results are 166 and 214, for SPS and DPS MC samples respectively. The fitted signal yields are consistent within statistical error with the expected values.

Figure 4.12: Top left, pull distribution for 38 injected events. Top right, distribution of extracted signal yield. Bottom left, distribution of statistical errors in signal yield extraction. Bottom right, log-likelihood distribution of 10,000 repeated toy experiments with horizontal red line corresponding to the log-likelihood obtained from the data.

4.5.3 The Significance of $\Upsilon(1S)$ Pair Production

The likelihood ratio test is performed to evaluate significance of the $\Upsilon(1S)$ pair production. The test is performed by comparing the goodness of the fit of two models, the null hypothesis (only the background model) and alternative model (background model combined with signal hypothesis). The test is based on the likelihood ratio which expresses frequency of data to fall under certain hypothetical model. Then, the logarithm of the likelihood ratio can be used to calculate the p-value and compute the statistical significance of the alternative hypothesis [66]. To evaluate statistical

significance of $\Upsilon(1S)\Upsilon(1S)$ events two separate models consisting of the following event categories are considered.

- The background only model (null hypothesis) is the sum of
 - (a) events containing a genuine $\Upsilon(1S)\Upsilon(2S)$ candidate,
 - (b) events containing a genuine $\Upsilon(1S)$ candidate and two unassociated muons that contribute to the $M_{\mu\mu}^{(2)}$,
 - (c) events containing a genuine $\Upsilon(2S)$ candidate and two unassociated muons that contribute to the $M_{\mu\mu}^{(2)}$, and
 - (d) events containing four unassociated muons.
- Signal model (alternative hypothesis) is the sum of
 - (a) events containing a genuine $\Upsilon(1S)\Upsilon(1S)$, and
 - (b) the components that contain in background model.

The null hypothesis and an alternative hypothesis are separately fitted to the data to compute log-likelihoods; labeled as $\mathcal{L}_0$ for null hypothesis and $\mathcal{L}_1$ for alternative hypothesis. The test statistics, usually called D, is twice the difference in the log-likelihoods. The probability distribution of test statistics is approximately a χ^2 distribution with degrees of freedom equal to difference in the number of free parameters of two models [67], in this degrees of freedom is one. Then, the statistical significance of alternative hypothesis is estimated, under certain assumptions [68], to be $\sqrt{2 \cdot (\ln(\mathcal{L}_0) - \ln(\mathcal{L}_1))} = 9.2$. This corresponds statistical deviation of alternative hypothesis to be more than five standard deviations from the null hypothesis.

4.6 Systematic Uncertainties

Several sources of systematic uncertainty in the cross section measurement are considered and discussed below.

To estimate the uncertainty caused by the imperfect modeling of the data, several variations are checked: (i) the parameters for the Υ resonance shape that are fixed for the maximum likelihood fit are varied by their uncertainty, as determined from the MC simulation samples; (ii) the $\Upsilon(1S)$ resonance shape alternatively is parameterized with a relativistic Breit-Wigner convolved with a Gaussian function; (iii) the $\Upsilon(1S)$ mesons are alternatively parameterized using signal parameters obtained from the DPS simulations sample. The largest difference in the signal yield among these fits of 7.9% is taken as the corresponding systematic uncertainty.

Evaluation of the trigger and reconstruction efficiencies for Υ pair production rely on the detector simulation. To estimate the systematic uncertainty owing to the detector simulation, the four-muon efficiency is also calculated from the single-muon efficiencies measured in data with a tag and probe method [69] that utilizes data samples containing a single J/ψ meson decaying into a muon pair. To calculate the four-muon efficiency using the tag and probe method, the correlations among the muons is separately derived from the simulation. A total correlation factor, determined from simulation as a function of the $p_T^{4\mu}$ and $|y^{4\mu}|$ of the four-muon system, is multiplied by the product of the four single-muon efficiencies, also measured versus $|\eta^\mu|$ and p_T^μ . The difference of the corrected signal yield with the tag and probe method and the data-embedding method of 4.9% is taken as the systematic uncertainty from

the simulation.

The efficiency correction method is evaluated using the full detector simulation and reconstruction event samples generated according to the two production mechanisms: SPS and DPS. The systematic uncertainty from using the efficiency-correction method, a data-embedding efficiency correction method is applied to obtain the per-event efficiency, ϵ_i . The efficiency-corrected yield is compared to the number of generated events, and the fractional difference between the two is used to estimate the uncertainty in the correction method. This procedure is repeated for both simulated samples separately. The systematic uncertainty is then taken to be the larger of the differences in the two samples and is found to be 3.7%.

Signal SPS and DPS simulated samples are used to estimate the uncertainty in the event-by-event acceptance correction method. A sample of N_{gen} simulated events are subjected to the acceptance criteria. The event-based acceptance correction is then applied to the events passing full selection to arrive at a corrected yield, N'_{gen} . The uncertainty is taken as the relative deviation of N_{gen} from N'_{gen} . The larger deviation of 2.8% between the SPS and DPS samples is taken as a systematic uncertainty.

The luminosity delivered to CMS is measured based on cluster counting from the pixel detector. The overall systematic uncertainty in the integrated luminosity is estimated to be 2.6% [70].

Table 4.6 provides a summary of the individual systematic uncertainties. The total systematic uncertainty in the $\Upsilon(1S)\Upsilon(1S)$ cross section measurement of 10.7%

is calculated as the sum in quadrature of the individual components. In this analysis,

Table 4.6: Relative systematic uncertainties in the $\Upsilon(1S)$ pair production cross section.

Component	Uncertainty (%)
Resonance shape	7.9%
Simulation	4.9%
Efficiency	3.7%
Acceptance	2.8%
Integrated Luminosity	2.6%
Total	10.7%

$\Upsilon(1S)$ mesons are assumed to decay isotropically. To check the sensitivity of the fiducial cross section measurement on the $\Upsilon(1S)$ meson decay angular distribution, studies are performed for several extreme polarization scenarios. With θ^* defined as the angle between the μ^+ direction in the $\Upsilon(1S)$ meson rest frame and the direction of the $\Upsilon(1S)$ in the lab frame, the angular distribution is parameterized as $1 + \lambda_\theta \cos^2(\theta^*)$, where λ_θ is the polar anisotropic parameter [71]. The extreme cases $\lambda_\theta = 0$ or $\lambda_\theta = +1(-1)$ corresponds to an isotropic $\Upsilon(1S)$ meson decay or 100% longitudinal (transverse) polarization. The polar anisotropic parameter for each $\Upsilon(1S)$ candidate, labeled as $\lambda_{\theta 1}$ and $\lambda_{\theta 2}$, are varied simultaneously, and Table 4.7 shows a summary of this study. Compared to an isotropic $\Upsilon(1S)$ meson decay, the corrected yield is 38% lower for $\lambda_{\theta 1} = \lambda_{\theta 2} = -1$ and 36% higher for $\lambda_{\theta 1} = \lambda_{\theta 2} = +1$. This variation is not included in the total systematic uncertainty, but is quoted separately. Compared to an isotropic Υ meson decay, the corrected yield is 38% lower for both $\lambda = -1$ and

36% higher for both $\lambda = +1$.

Table 4.7: Relative change of acceptance corrected yield for different polarization assumptions.

$\lambda_{\theta 1}$	+1	+1	+0.5	-0.5	+0.5	-1	+1	-0.5	-0.5	-1
$\lambda_{\theta 2}$	+1	+0.5	+0.5	+0.5	-0.5	+1	-1	-0.5	-1	-1
Change(%)	+36	+26	+18	-2	-3	-9	-9	-19	-29	-38

4.7 Cross Section and Discussion

The fiducial cross section of $\Upsilon(1S)$ pair production, σ_{fid} , is measured for events in which both $\Upsilon(1S)$ mesons have $|y^\Upsilon| < 2.0$. It is derived from the measured $\Upsilon(1S)$ pair yield, N_{signal} , using the expression:

$$\sigma_{\text{fid}} = \frac{N_{\text{signal}} \cdot \bar{\omega}}{[\mathcal{B}(\Upsilon(1S) \rightarrow \mu^+ \mu^-)]^2 \cdot \mathcal{L}} , \quad (4.9)$$

where $\bar{\omega}$ is the average correction factor that accounts for the inefficiencies stemming from reconstruction, identification, and trigger requirements, as well as the fraction of events lost because of the muon acceptance criteria, $\mathcal{L}$ is the integrated luminosity, and $\mathcal{B}(\Upsilon(1S) \rightarrow \mu^+ \mu^-) = (2.48 \pm 0.05)\%$ is the world-average branching fraction of the $\Upsilon(1S)$ to $\mu^+ \mu^-$ [54].

The factor $\bar{\omega}$ is the inverse product of per-event efficiencies, ϵ_i , and acceptances, a_i , averaged over the events with efficiencies greater than 1%. For the calculation of the total cross section, values of $\mathcal{L} = 20.7 \text{fb}^{-1}$, $N_{\text{signal}} = 38 \pm 7$, and $\bar{\omega} = 23.06$ are used. Under the assumption that both $\Upsilon(1S)$ mesons decay isotropically, the total

cross section for $\Upsilon(1S)$ pair production is measured to be $\sigma_{\text{fid}} = 68.8 \pm 12.7$ (stat) ± 7.4 (syst) ± 2.8 ($\mathcal{B}$) pb, where the uncertainties are statistical, systematic, and related to the $\Upsilon(1S) \rightarrow \mu^+ \mu^-$ branching fraction, respectively.

In quarkonium pair production, the measurement of the effective cross section σ_{eff} depends on the fraction of DPS, which is usually estimated either as a residual to the SPS prediction or as the result of a fit to the rapidity or azimuthal angle difference between quarkonia pairs. To estimate σ_{eff} using the fiducial $\Upsilon(1S)$ pair production cross section σ_{fid} , the following formula is used [40]:

$$\sigma_{\text{eff}} = \frac{[\sigma(\Upsilon)]^2}{2 \cdot f_{\text{DPS}} \cdot \sigma_{\text{fid}} \cdot [\mathcal{B}(\Upsilon(1S) \rightarrow \mu^+ \mu^-)]^2}, \quad (4.10)$$

where $\sigma(\Upsilon)$ is the cross section for single- $\Upsilon(1S)$ production [61] extrapolated to the fiducial region ($|y^\Upsilon| < 2.0$) and f_{DPS} is the fraction of the DPS contribution. To estimate the effective cross section, we use $\sigma(\Upsilon) = 7.5 \pm 0.6$ nb and a conservatively low value of $f_{\text{DPS}} \approx 10\%$ [72], which gives $\sigma_{\text{eff}} \approx 6.6$ mb. The cross section for $\Upsilon(1S)$ pair production, assuming SPS with feed-down from higher Υ states, is 48 pb [72]. This result, combined with our measurement, gives $f_{\text{DPS}} \simeq 30\%$, and with this estimation, σ_{eff} is calculated to be ≈ 2.2 mb. These two estimates of σ_{eff} are consistent with the range of values from the heavy-quarkonium measurements (2–8 mb) [46, 47], but are smaller than that from multijet studies (12–20 mb) [43, 44, 45, 73].

The quarkonium final states are dominantly produced from gluon-gluon interactions, while the jet-related channels that correspond to higher values of σ_{eff} are produced by quark-antiquark and quark-gluon parton interactions. The trend in the measured effective cross section might indicate that the average transverse distance

between gluons in the proton is smaller than between quarks, or between quarks and gluons. This result is in an agreement with the pion cloud model [74], predicting a smaller average transverse size of the gluon distribution in a proton as compared to quarks.

4.8 Future Directions

At the end of 2015, LHC started second round of data taking period with increased energy and beam intensity. The center-of-mass energy of colliding protons increased from 8 TeV to 13 TeV, and the total integrated luminosity reached 36 fb^{-1} in the first two years of operation. The cross-section of $\Upsilon(\text{nS})$ production is expected to increase twice with higher center-of-mass energy [75]. Assuming everything else stays same, with 36 fb^{-1} data, we expect ≈ 130 $\Upsilon(1\text{S})$ -pair events. This is enough statistics to measure differential cross section, which was not possible at 8 TeV data. The differential cross section of $\Upsilon(1\text{S})$ -pair production combined with single- $\Upsilon(1\text{S})$ differential cross section will allow separation of SPS and DPS components, which is inferred using theoretical calculation in this report. Moreover, increased statistics will allow measurement of $\Upsilon(2\text{S})$ - $\Upsilon(1\text{S})$ production cross-section which has not been reported in this paper due to low signal strength.

CHAPTER 5

HIGH GRANULARITY CALORIMETER FOR CMS PHASE II UPGRADE

During the High Luminosity LHC (HL-LHC) operation, the instantaneous luminosity is expected to increase by a factor of five. At increased luminosity, the machine will operate another 10 years. By the end of the operation period it is expected that total integrated luminosity will be roughly 2500 fb^{-1} . In order to meet the experimental challenges of high luminosity p-p collisions, the CMS collaboration needs to address aging due to radiation damage in their detectors.

The CMS calorimeters are designed to measure the energy of particles and are critical for identification of photons and electrons and measurement of jets and missing transverse momentum. In terms of Higgs physics, high resolution and efficient identification is required for observation of the $H \rightarrow \gamma\gamma$ decay process. Efficient separation of electrons from hadrons is necessary to study many physics models that are not predicted by the Standard Model. Jets and missing transverse momentum are usually measured using particle flow algorithm which utilizes information from all subdetectors. Under the high-luminosity conditions, particle flow algorithm requires good segmentation to associate tracks and calorimeter energies efficiently.

The existing CMS calorimeters were constructed to operate up to $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ instantaneous luminosity. The HL-LHC performance, however, require re-examination of the ability of the detector active material. Based on simulation studies, upgrades are proposed to replace the endcap calorimetry system. The following sections will

discuss these planned changes and present initial studies of the upgraded calorimeter.

5.1 Hadron Calorimeter of CMS Detector

The CMS HCAL has consist of four major subdetectors: Barrel HCAL (HB), Endcap HCAL (HE), Outer HCAL (HO), and Forward HCAL (HF). The HB and HE calorimeters are sampling calorimeters which are designed from brass absorber sandwiched in between active plastic scintillators. As energetic particles pass through active material they produce bursts of photons in the scintillator material which are then collected with wavelength-shifting (WLS) fibers. Fibers from the calorimeter tiles are grouped to form towers which are read out originally by hybrid photodetectors and then by SiPM devices after the Phase-I upgrade. The HO is designed to capture hadronic shower events and it is located outside the CMS solenoid magnet. The HF is based on a Cherenkov radiation principle and it consists of a steel absorbers and quartz fibers which run longitudinally (parallel to the beam). All together, these subdetectors cover the $0 < |\eta| < 5.0$ region and are mainly designed to measure the energy of jets and missing transverse momentum. The HL-LHC conditions are a significant challenge to detector performance and it is more prominent particularly in the endcap region, where the radiation levels are high, as shown in the Fig. 5.1. During the 2012 run, reduction in 30% of original light output from the HE tiles was observed. This decrease is measured by injecting 337 nm laser light into the center of each tile [76]. The reduction could be due to decreased light yield of scintillator material or by a decreased transparency of tiles. The WLS fibers could also be

Figure 5.1: Expected radiation dose in the central calorimeter (EB, HB, EE, and HE) after and integrated luminosity of 3000 fb^{-1} . Highest dose is represented with dark red color.

damaged and lose transparency.

The radiation damage parameters are therefore based on the fit of the data from the detector. The observed light attenuation, r , was found to be well described as a function of accumulated luminosity by the $r \sim e^{-L/D}$, where L is the integrated luminosity, and D is the parameter which depends on the tile position. In general, D mainly depends on the tile size, the dose rate and conditions of the irradiation, such as the gas content of the nearby atmosphere and temperature. Fig. 5.2 shows the observed decrease of light signal in the first layer of the HE as a function of the accumulated luminosity fitted to an exponential function.

The radiation damage to HB subdetector can be estimated using a parametrization derived from the HE laser data. The HB predictions suffer from large uncertain-

Figure 5.2: Fraction decrease of signal from the first layer of HE as a function of accumulated luminosity for different tile positions (η). Solid curves represent a fit line to an exponential function.

ties due higher nitrogen/oxygen ratio in the HB environment compared to HE [2].

The HO is located outside the magnet solenoid, and therefore, radiation damage is negligible compared to other subdetectors.

The HF is composed of quartz fibers and will be in the highest radiation zone. It is expected that 10^7 Gy of dose is accumulated over 3000 fb^{-1} of integrated luminosity. The optical transmission of fibers are monitored with the measurement of the attenuation from the front edge of fibers and it is expected that light output will decrease by a factor of 2.5 at $|\eta| < 4.5$ [77].

These effects will make reconstruction more challenging and degrade the resolution of physics objects, especially jets and missing transverse momentum. Fig. 5.3 shows the performance of calorimeter jet reconstruction after 1000 fb^{-1} integrated luminosity; the effect is more prominent in the far forward region. At the same time,

Figure 5.3: Performance of calorimeter jet reconstruction using the undamaged detector with 0 fb^{-1} (black solid line) and aged HCAL endcap detector after 1000 fb^{-1} (solid blue line). The comparison is made with 40 GeV quark jets generated with $2.3 < |\eta| < 2.7$ (left) and $2.7 < |\eta| < 3.0$ (right) [2].

due to the increased instantaneous luminosity, the pileup effects will be more unbearable, making the identification of electromagnetic objects more challenging and affecting isolation of VBF jets from increasing QCD multijet background. To address these challenges, CMS proposed to replace the endcap calorimeters with a new high-granularity sampling calorimeter. The timeline for the projects anticipate about 2 years for *R&D* to finalize designs before technical reports, and further 1-2 years for prototyping. The construction is then planned for 4-5 years with installation during long-shutdown phase-3 during 2023-2025.

5.2 High Granularity Calorimeter

The proposed high-granularity calorimeter design consists of a silicon/tungsten electromagnetic section (HEE) followed by two hadronic endcap calorimeters. Both endcap hadronic calorimeters use brass as the primary absorber material, and the front hadronic section (FH) uses silicon as an active material while the backing hadronic section (BH) uses plastic scintillator. The design is targeted to achieve very high performance for physics objects reconstructed in the presence of high pileup conditions. Compared to the current CMS hadron calorimeter, the proposed detector will have both transverse and longitudinal granularity which will allow tracking and separation of signal and pileup particles inside the calorimeter.

Recent advances in silicon detectors in terms of cost and radiation tolerance suggest their potential use in high-luminosity hadron collider experiments. A dense high-granularity calorimeter with silicon detectors offers promising performance in the presence of high pileup. It is possible to apply the methods of particle flow within the calorimeter to enhance the jet energy resolution. Similar technology was proposed for future International Linear Collider (ILC) detectors, for which they have been shown to provide very high resolving power for single particle with energies up to several hundred GeV [78]. For high-luminosity running in the LHC, the proposed calorimeter offers the prospect of resolving single particle and jets in the dense pileup environment of the endcap regions.

5.2.1 Design Overview

The technical drawing of the high-granularity calorimeter, HGCal, is shown in Fig. 5.4. The innermost volume of HGCal, beginning near the location of the front face of the current electromagnetic endcap calorimeter, is a tungsten/copper-silicon sampling electromagnetic calorimeter, the HEE. It is a 26 electromagnetic interaction length (X_0), and 1.5 radiation length (λ) detector. The HEE is followed by a brass-silicon hadron calorimeter, 3.5λ deep, the FH, which is followed by a 5λ brass-scintillator backing calorimeter, the BH. The total depth of calorimeter is about 10λ as measured in the longitudinal direction. The depth along the trajectories from the interaction point is between 0.5% and 10% greater, depending on the pseudo-rapidity. The active material in the HEE and FH will be silicon, while the BH, located in the low radiation zone, can be constructed with radiation sensitive plastic scintillator. In this configuration there will be only a small gap between the electromagnetic and hadron calorimeters, which is expected to improve the jet energy measurements. Additionally, bringing the hadron calorimeter closer to the inner tracker will allow a space behind BH to situate HGCal services in the low radiation zone. The HEE is proposed with longitudinal sampling determined by the absorber thickness:

- 10 layers: $0.65 X_0$ thickness absorber followed by a plane of silicon,
- 10 layers: $0.88 X_0$ thickness absorber followed by a plane of silicon,
- 8 layers: $1.26 X_0$ thickness absorber followed by a plane of silicon.

The absorber layers are composed of tungsten in an alveolar mechanical structure, and tungsten/copper in the units which slide into the alveolar structure. The design

is such that the absorber layers alternate: tungsten, tungsten/copper, tungsten etc. A similar configuration, but with tungsten only as the absorbing material, has been studied in test beams by the CALICE collaboration and, when instrumented with 525 μm -thick silicon sensors, gave an energy resolution of around $16.5\%/\sqrt{E}$ with a linear energy response [79]. The FH has a total thickness of about 60 cm with 12

Figure 5.4: Technical diagram of HGCal detector. The interaction point is on the right side with HEE being closest to interaction point followed by the FH and followed by BH [2].

layers. Each sampling layer in the FH, as in the HEE, is read out independently. The lateral granularity in HEE and FH is achieved by segmenting each cell in hexagon shape. The cell size is varied with the thickness of the active layer of the silicon so as to limit the capacitance of each cell to 60 pF. Most of the calorimeter uses cells of 1.05 cm^2 . Table 5.1 shows the main parameters of the HEE and FH. The BH has a depth

of 5λ , to give a total depth of 10λ for the whole calorimeter. The goal is to reduce radiation dose to minimum before the BH, allowing the use of plastic scintillator. The proposal is for the BH to have 24 staggered layers in the same geometry as the current HE, resulting in 12 longitudinal samplings which are grouped into two longitudinal readout segments.

Table 5.1: Parameters of electron calorimetry (HEE) and front hadron calorimetry (FH) for proposed hadron calorimeters. Numbers of channels and detector modules are provided in the unit of million and thousand, respectively.

	EE	FH	Total
Area of silicon (m ²)	380	209	589
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7
Number of Si planes	28	12	40

5.2.2 Mechanical Design

The overall mechanical design of the HEE is inspired by those prototyped for future ILC detectors and described in the technical design report for endcap calorimetry [78]. Tungsten absorber plates are integrated with carbon-fiber structure which alternate with empty slots into which “cassettes” of 30° sectors are inserted. The sectors are organized so that boundaries in the radial sectors can occur in three different orientations, each rotated by 10° with respect to others. This configuration allows the sector boundaries (possible gaps between sectors) to occur in different

locations for different layers. Each cassette is constructed with two active planes and their associated front-end electronics on either side of absorbers. In this setup absorber materials provide mechanical support and cooling for electronics.

Each cassette, consisting of hexagonal silicon sensor wafers mounted on a printed circuit board, built on either side of a 6 mm-thick copper plate with cooling channels as shown in Fig. 5.4. The other faces of the sensors are attached to a tungsten-copper composite (75% W, 25% Cu) baseplate of appropriate thickness to make up the required total absorber thickness in terms of radiation lengths. A thin Kapton layer is inserted between the baseplate and the silicon wafer to insulate the high voltage of the back-plane sensor.

The full thickness of the cassette which will be inserted in the slot is defined by two stainless steel side bars, and a thin shielding cover plate, and leaves an air-gap of 2 mm in which the power and signals are routed. The structure is illustrated in Fig. 5.5. The sensor pads are connected to the PCB with wire bonds. The silicon sensors for the HGCal will be single-sided and its readout will be DC-coupled. Cells are expected to have active thickness of 300, 200 or 100 μm depending where they are located. As mentioned previously, the cell sizes are adjusted so as to limit the cell capacitance to about 60 pF. Table 5.2 shows the regions of the HEE and FH where the different active thicknesses are used, together with the expected neutron fluence after 3000 fb^{-1} . The regions are specified by the radius, R , measured from the beam axis. In the calculation of signal over noise ratio, S/N , the charge collection efficiencies used to estimate the signal after 3000 fb^{-1} are taken from the Ref. [2]

Figure 5.5: HGCAL module (left) consisting of silicon sensors and printed circuit board. Cross sectional diagram of module (right) with absorber material inserted [2].

section 3.5.12.

5.2.3 Validation of HGCAL at CMS

The CMS experiment has been using simulation software from the initial inception of detector and it has helped to make the conceptual design. Initial CMS detector simulation efforts started with a Fortran software package CMSIM [80] using GEANT3 [81] toolkit which provides electromagnetic and hadronic physics processes as well as tools for detector geometry and response. The software has been updated in four generations through OSCAR [82], and the current version is embedded into CMSSW [83] which utilizes GEANT4 [55] toolkit. This section is dedicated to discuss initial efforts towards the simulation and integration of HGCAL at CMS.

The reconstruction of physics objects from the detector hits rely on sophisticated algorithms. The full power of a high-granularity calorimeter can be exploited

Table 5.2: Arrangement of silicon cells with respect to their thickness, followed by silicon wafer area and cell size. S/N for minimum ionizing particle (MIP), represents signal over noise ratio for each cell after and before the integrated luminosity of 3000 fb^{-1} . Radial distance from the center of the detector is represented by R [2].

Thickness	$300\mu\text{m}$	$200\mu\text{m}$	$100\mu\text{m}$
Maximum n fluence (cm^{-2})	$6 \cdot 10^{14}$	$2.5 \cdot 10^{15}$	$1 \cdot 10^{16}$
EE Region	$R > 120 \text{ cm}$	$120 > R > 75 \text{ cm}$	$R < 75 \text{ cm}$
FH Region	$R > 100 \text{ cm}$	$100 > R > 60 \text{ cm}$	$R < 60 \text{ cm}$
Si wafer area (m^2)	290	203	96
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance (pF)	40	40	60
Initial S/N for MIP	13.7	7.0	3.5
S/N after 3000 fb^{-1}	6.5	2.7	1.7

using fully developed particle-flow algorithm. The particle-flow (PF) algorithm uses information from both tracker and calorimeters to produce much improved energy resolution and efficiency. A dedicated PF reconstruction package with an excellent performance, designed and tuned around the existing CMS detector, is used in current data taking and analysis by CMS.

The core interface between GEANT4 and CMS is managed by Event Data Producer framework and customized RunManager. The geometry of the detector is created by a common detector description (DD) machinery in the extensive markup language (XML) format which is made available for both simulation and reconstruction steps. The Event Data Producer converts materials defined in DD framework to GEANT4 sensitive detector parts associated with geometrical volumes.

The magnetic field is described by a dedicated geometry of magnetic volumes. This is provided by an independent sub-system via the Event Setup. A flexible frame-

work allows selection of the magnetic field and tuning parameters for propagating particles at the run time. GEANT4 provides a large number of physics processes for simulating the passage of particles through matter, and CMSSW software provides a flexible interface to choose one. Several notifications classes are defined for the specific run, event, tracks or particle steps, etc. Users can access information for the GEANT4 objects at any stage of the simulation with the help of these classes called “watchers”. These are extremely useful tools for monitoring, diagnosing, tuning and bookkeeping.

The GEANT4 uses a detailed description of the detector (both sensitive and dead material components) to simulate interaction of the particle with all the materials. It gives control to the user to record the time, energy deposit and coordinates. This set of information is referred to as “SimHits” (simulated hits) in the CMS software jargon. The simulated hits from a hard scattering process are mixed with those from many minimum-bias interactions to mimic the chosen pileup scenario and the combined hits are processed further to simulate the detector readout system including the digitization of the signal, also referred as “Digis” in the CMS jargon. The next step in the software is to carry out a local reconstruction which takes care of the Digis; i.e. convert them into points in space associated with energy deposits. These are termed as reconstructed hits (RecHits).

The CMSSW software stores cumulative hit information for calorimeter. If more than one particle deposits energy in the same cell of the calorimeter within 1 ns, the information is recorded as one SimHit, but the energy is summed up. The

simulated hit evolved with time and recorded as a new hit after each nanosecond until the shower died out.

It is important to validate each new version of HGCal geometry to immediately find the problems. For this reason a validation software based on CMSSW is developed focused on SimHit, Digi and RecHit validation. For validation purposes only SimHit, Digi and RecHit coordinate variables are studied separately for each subdetector. Some of the validation plots are shown in the following three sub-sections to illustrate the properties of the high granularity calorimeter.

5.2.4 SimHit Validation

The output of the simulation of the particles passage through the matter is information regarding energy deposit, time etc labeled by unique detector identification (DetIds). The set of information is referred to as SimHits. The SimHit collection consists of individual hits with unique DetId, and it is recorded in a number of time slices (of 1 ns intervals). All time slices with time less than 100 ns are taken into consideration for SimHit validation. To validate SimHits the true position of particle trajectory, extracted from the GEANT4 simulation, is compared with the simulated position of the detector hits. The comparison is performed for three sub-detectors separately in three spatial dimensions. Fig. 5.6, Fig. 5.7 and Fig. 5.8 shows the comparison of the true hit position with simulated hit position of the three components of HGCal (HEE, FH and BH). As demonstrated in the plots there are no off-diagonal entries, as desired. The comparison of spatial coordinates provides better visualiza-

Figure 5.6: The validation of HEE geometry. The horizontal axis corresponds to the true hit position at GEANT4 level and the vertical axis is simulated position extracted from detector topology. The procedure is repeated for all coordinates separately.

Figure 5.7: The validation of FH geometry. The horizontal axis corresponds to the true hit position at GEANT4 level and the vertical axis is simulated position extracted from detector topology. The procedure is repeated for all coordinates separately.

tion of possible mismatch in the simulatio. Fig. 5.8 shows distribution of hits for generated muon sample in the BH section. No deviation is observed in X and Y coordinates of the simulation. In the Z coordinate there are some non-diagonal entries.

The reason for this discrepancy is due to the grouping of cells in the η/ϕ plane.

Figure 5.8: The validation of BH geometry. The horizontal axis corresponds to the true hit position at GEANT4 level and the vertical axis is simulated position using detector Id. The procedure repeated for all coordinates separately.

5.2.5 RecHit Validation

The Digi collection is a data from uniquely identified detector cells labeled by DetIds. The SimHit collection is converted into Digis in the “Digitization process”. They are labeled by DetIds and used to reconstruct the energy and time of the hit. Information from all time fragments and incident particles for a given DetId is combined in the digitization step. RecHits are reconstructed Digis containing energy and time information (including noise in the detector) and are used as the primary input for the high-level object reconstructions, such as clusters for photons and electrons. In the second step of the validation procedure the RecHit information is compared with the simulated hit positions. Unlike in the previous comparison, in this step the relative difference between hits are studied. This allows to detect any irregularities in the definition of the geometry or in the software. Fig. 5.9 shows the agreement between the SimHit position and the RecHit position in X coordinates. The compar-

Figure 5.9: The validation of HEE sector. Horizontal axis corresponds to the simulated hit position and vertical axis is the difference between SimHit and RecHit positions.

ison of Z coordinate demonstrates the granularity of HEE section where three silicon pads are grouped together $200 \mu\text{m}$ apart. The distance between these groups increase as distance from the center of the detector increases. Fig. 5.10 demonstrates the

Figure 5.10: The validation of FH sector. The horizontal axis corresponds to the simulated hit position and the vertical axis is the difference between SimHit and RecHit positions.

agreement between the SimHit position and the RecHit position for the FH sector. The comparison of Z coordinate indicates layers of sensitive material as expected. In the BH part shown in the Fig. 5.11, the comparison is done with respect to η and

Figure 5.11: The validation of BH sector. The horizontal axis corresponds to the simulated hit position and the vertical axis is the difference between SimHit and RecHit positions.

ϕ coordinates. The reason for this approach is at digitization step cells are grouped in η - ϕ plane. Plots agree with the expectations as the maximum separation is five radians. The Z coordinate in BH sector is asymmetric and shows bias towards the positive side which is due to the fact that in each digitization step the front face of the sensitive material is considered as where the particle interacted.

5.2.6 Conclusion and Future Work

The validation procedure described above is crucial for developing HGCal prototype, and it is planned to repeat for each new release of CMSSW software. This

will allow to locate any bug introduced in the simulation of detector. To make this process automatic and efficient, special package has been created withing CMSSW software. This package is designed to be flexible for additional objects as well as user friendly, where users can add/remove custom plots. The next step in this project is to add high-level reconstructed objects in the pipe-line such as jets, electrons and photons.

CHAPTER 6 CONCLUSION

The first observation of $\Upsilon(1S)$ pair production is performed with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV from a sample corresponding to an integrated luminosity of 20.7 fb^{-1} . A signal yield of $38 \pm 7 \text{ } \Upsilon(1S)\Upsilon(1S)$ events is measured with a significance exceeding five standard deviations. Using the measured muon kinematic properties in the data, an event-based acceptance and efficiency-correction method is applied, minimizing the model dependence of the cross section measurement. The fiducial cross section of $\Upsilon(1S)$ pair production measured within the single- Υ acceptance $|\eta^{\Upsilon}| < 2.0$ is found to be $\sigma_{\text{fid}} = 68.8 \pm 12.7 \text{ (stat)} \pm 7.4 \text{ (syst)} \pm 2.8$, where the $\Upsilon(1S)$ decay into muons is assumed to be isotropic. Assuming instead that the $\Upsilon(1S)$ mesons are produced with different polarizations leads to variations in the measured cross section in the range from -38% to $+36\%$. An effective cross section is also estimated using our result that is in agreement with the values from heavy-quarkonium measurements, but is smaller than that from multijet studies.

The quarkonium final states are dominantly produced from gluon-gluon interactions, while the jet-related channels that correspond to higher values of σ_{eff} are produced by quark-antiquark and quark-gluon parton interactions. The trend in the measured effective cross section might indicate that the average transverse distance between gluons in the proton is smaller than between quarks, or between quarks and gluons. This result is in an agreement with the pion cloud model [74], predicting a smaller average transverse size of the gluon distribution in a proton as compared to

quarks.

The second half of this thesis is devoted to describe future plans of the LHC and upgrade preparations for high-luminosity HL-LHC, specifically High Granularity Calorimeter (HGCAL) studies. Rigorous studies are performed to validate simulation of HGCAL geometry. Within this work automated validation package was created for future work which allows users to produce generic plots for inspection. In the future, it is planned to add high-level objects in the validation pipe-line to analyze reconstruction and identification performance of the HGCAL calorimeter.

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