Evidence of a narrow structure in $\Upsilon(1S) l^+ l^-$ mass spectrum and CMS Phase I and II silicon detector upgrade studies

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EVIDENCE OF A NARROW STRUCTURE IN $\Upsilon(1S)\ell^+\ell^-$ MASS SPECTRUM
AND
CMS PHASE I AND II SILICON DETECTOR UPGRADE STUDIES

by

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

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To my parents for their love and support.
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ABSTRACT

This thesis focuses on two parts, the evidence of a structure in a four lepton final state, and the CMS detector upgrade studies.

The first part of the thesis focuses on a search for structures in the $\Upsilon(1S)l^+l^-$ final state, where $\Upsilon(1S) \rightarrow \mu^+\mu^-$, $l$ can represent a muon or an electron and $m(l^+l^-)$ is required to be below the $\Upsilon(1S)$ mass. Using an integrated luminosity of 25.6 fb$^{-1}$ recorded in proton-proton collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV with the CMS detector at the CERN LHC, an excess in the mass distribution near 18.5 GeV of $\Upsilon(1S)l^+l^-$ is found. The mass of this enhancement is measured to be $18.4 \pm 0.1$ (stat.$) \pm 0.2$ (syst.$)$ GeV in the $\Upsilon(1S)\mu^+\mu^-$ channel, and $18.5 \pm 0.2$ (stat.$) \pm 0.2$ (syst.$)$ GeV in the $\Upsilon(1S)e^+e^-$ channel. For the two results combined, the enhancement is found to be $18.4 \pm 0.1$ (stat.$) \pm 0.2$ (syst.$)$ GeV with a local statistical significance of 4.9 standard deviations and a global significance, after taking into account the look-elsewhere-effect, of 3.6 standard deviations. The width of the observed enhancement is consistent with the mass resolution of the CMS detector.

The second part of the thesis focuses on detector upgrade studies for the silicon detector. The LHC has been increasing, and will increase, the instantaneous luminosity and collision energy. Due to radiation damage and increasing data loss, the CMS detector underwent a Phase I upgrade in 2016/2017, and will undergo a Phase II upgrade in 2018/2019. In the Phase I upgrade, silicon sensors and DC-DC converters were tested at Fermilab for the CMS Forward Pixel detector. In the Phase
II upgrade, a gantry robot system is built for module assembly at Fermilab for the CMS Outer Tracker detector.
Quarks can form matter with three quarks or a quark-antiquark pair in the standard quark model. Other possibilities, called exotic hadrons, like tetraquarks or pentaquarks are speculated but they were not established formally. An evidence of a structure is spotted in $\Upsilon(1S)l^+l^-$ final state, where $\Upsilon(1S) \rightarrow \mu^+\mu^-$, $l$ can represent a muon or an electron and $m(l^+l^-)$ is required to be below the $\Upsilon(1S)$ mass. Using an integrated luminosity of 25.6 fb$^{-1}$ recorded in proton-proton collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV with the CMS detector at the CERN LHC, an excess in the mass distribution near 18.5 GeV of $\Upsilon(1S)l^+l^-$ is found. The mass of this enhancement is found out to be $18.4 \pm 0.1$(stat.$) \pm 0.2$(syst.$)$GeV with the local statistical significance is 4.9 standard deviations and the global significance, after taking into account the look-elsewhere-effect, is 3.6 standard deviations. The width of the observed enhancement is consistent with the mass resolution of the CMS detector.

The silicon tracker detector is the closest of the CMS sub-detectors to the interaction point. It is crucial to get the precise position and path of the particles right after the collision, since most of the new particles are created and decay to other particles inside the tracker. However, its performance will degrade as a function of number of particles are passing through the detector over time. In Phase I upgrade cycle, new detector parts were installed on CMS detector. At Fermilab, silicon detector sensors and DC-DC converters (required for the new powering scheme for the detector) were tested. There is another Phase II upgrade cycle in 2018/2019, CMS
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CHAPTER 1
THEORETICAL INTRODUCTION

1.1 Historical Introduction

The desire to understand nature led Aristotle to develop the concept of earth, wood, fire, and air. Even though it was just a coincidence, Democritus proposed the idea of *atom* around 400 BC. He derived the name atom from the Greek word "atomos" which means uncuttable. He thought that the atom is the fundamental particle from which the rest of the matter is built. It turned out that his prediction was quite accurate.

1.1.1 The Atom

In 1803, John Dalton combined the idea of Democritus and some advancements in chemistry, and he proposed that all matter is made out of atoms, such that they cannot be created or destroyed. In 1896, J. J. Thomson discovered the electron which was different than what was expected based on Dalton’s model of atoms. He also calculated the charge-to-mass ratio of the electron. In 1914, Ernest Rutherford performed the famous *Rutherford Gold Foil Experiment* discovering that every atom contains a nucleus. Almost all the mass of the atom was concentrated at the positively charged center. He established the structure of an atom as a heavy nucleus at the center with electrons rotating around it [42]. However inconsistencies in the mass and charge of the atoms raised more questions. In 1930, an experiment was performed by Bothe and Becker who bombarded beryllium with alpha particles from
a radioactive source. Using the same experimental data, James Chadwick discovered the existence of the neutron \cite{16} in 1932. After combining the advancements with the Bohr Model \cite{12}, an understanding of atomic picture was completed.

1.1.2 The Photon

As we expect, there is no specific scientist that discovered the quantum of light, the photon. In history, some scientists claimed that light is a particle and some claimed that it is a wave. Scientific discoveries in recent history changed our understanding of light and put an end to the particle versus wave discussion.

In 1900, Max Planck was trying to explain the \textit{blackbody spectrum}, and found that electromagnetic radiation was quantized. He introduced the concept of quantization because he could formulate the blackbody spectrum in this way. The energy of the radiation could be calculated with $E = h\nu$, where $\nu$ is the frequency of the radiation and $h$ is a constant number which is called Planck’s constant today, where $h = 6.626 \times 10^{-34} m^2 kg/s$.

In 1905, Albert Einstein took the idea of quantization and explained the \textit{photoelectric effect}. When electromagnetic radiation strikes a surface, it can knock off electrons. The kinetic energy of the electron can be calculated as $K = h\nu - w$, where $w$ is called the work function. In other words, incoming radiation needs to transfer some of its energy to break off the electron from the atom. The interesting part of the discovery was that changing the intensity of the radiation did not change the kinetic energy of the outgoing electrons. Kinetic energy only changed by changing the color (frequency) of the radiation. Einstein proved that light was indeed quantized.
However, at the time Einstein was not as famous as Planck, so his paper created a lot of resistance and debate in the scientific committee.

In 1923, Arthur Holly Compton observed that the scattered photons from electrons had longer wavelengths than the incident photons. He formulated the results using Planck’s equation. The difference in the wavelengths: \( \Delta \lambda = (1 - \cos \theta) h/(m_e c) \). Compton showed that photons have particle-like behavior.

Today we know that charged particles interact with each other, and the mediator (force carrier) is a photon. It is called electromagnetic interaction.

1.1.3 Mesons

The atomic model indicates that positively charged protons and neutral charged neutrons stay in the nucleus together. The concept creates the next question: How do the protons remain near each other with same charge? There must be some force holding them together. Hideki Yukawa proposed a theory of nuclear forces which involves the exchange of particles between protons and neutrons [14]. Since the force has a short range, the exchanged particle must be heavy. This particle turned out to be a meson. Mesons and muons were discovered in 1947 by Cecil Powell and his colleagues when they were analyzing cosmic rays. Later in the 1970’s the Quark Model was developed. In the Quark Model, exchange of mesons between nucleons was a residual effect of the strong force.

1.1.4 Antiparticles

In 1927, P.A.M. Dirac was formulating the behavior of the electron at relativistic speeds. He found that his energy solutions were giving both positive and negative
energy results. In 1932, Carl D. Anderson found that cosmic ray interactions were creating positively charged particles in a cloud chamber. The calculated charge-to-mass ratio of these new particles was the same as that of electrons. In 1955, the antiproton and antineutron were also discovered. Today we know that for every particle, there is an antiparticle with the same properties but with the opposite charge.

1.1.5 Neutrinos

Another interesting part of this story is that of beta decay. Henri Becquerel discovered radioactivity in 1896, and Marie Curie observed it in 1898. Later, Rutherford separated alpha and beta decays. It turned out that beta decay particles were actually electrons. However, energy in a beta decay was not conserved. Wolfgang Pauli proposed that there must be another particle emitted along with the electron \([13]\). Today, we know that the fundamental beta decay is as the following.

\[
n \rightarrow p^+ + e^- + \bar{\nu}
\]  

(1.1)

The \(\nu\) is called a neutrino. Today we know that there are three types of neutrinos; details of which will be covered in the following sections.

1.1.6 The Eightfold Way

In subsequent years many more particles were discovered. Some of the mesons were: \(K^0, K^+, \eta, \phi, \rho, \omega\) and some of the baryons were: \(\Delta, \Sigma, \Xi\). Scientists started to call the situation a particle zoo. In 1961, Murray Gell-Mann introduced the Eightfold Way. He grouped mesons and baryons according to their charge and strangeness. Mesons and spin-1/2 baryons were classified into the Meson or Baryon Octet in
Fig. 1.1, and spin-3/2 baryons were classified into Baryon Decuplet in Fig. 1.2.

Figure 1.1. Left: This group is called the Baryon Octet. Charge is represented with q and strangeness is represented with s. Right: The Meson Octet group is shown.

Figure 1.2. This group is called as Baryon Decuplet.
1.1.7 Quark Model

The Eightfold Way organizes baryons and mesons; however, it does not answer why the hadrons fit into those models. In 1964, Murray Gell-Mann proposed the Quark Model. The Quark Model posited that all hadrons are composed of more elementary particles. Gell-Mann called them quarks. He introduced three types of quarks; up\((q = 2/3e)\), down\((q = -1/3e)\), and strange\((q = -1/3e)\). The Quark Model introduced two rules:

- Every baryon is composed of three quarks, and antibaryons are composed of antiquarks.

- Every mesons is composed of a quark and an antiquark.

For example, the proton is made up of \(uud\) (two up quarks and a down quark) quarks. Since the model introduced the quarks, scientists tried to discover individual quarks but they failed. The Pauli exclusion principle also prevents the existence of particles with the same spin. The solution was to introduce quark confinement. Quark confinement assigns three colors to quarks (red, green, blue). A baryon includes quarks with colors of red, green, and blue, leading to a colorless baryon. The same concept is true for the mesons. A red quark and an anti-red quark cancels their color and the resultant meson is colorless. Quark confinement dictates all naturally occurring particles are colorless!
1.1.8 Vector Bosons

In 1933, Enrico Fermi proposed the Fermi theory of beta decay [29]. In his theory beta decay could be explained by a four-fermion interaction (a neutron, proton, electron and a neutrino) involving a contact force with no range. The name Weak Force stems from the fact that the force has a very short range \(10^{-18} m\). In 1967 and 1968, Glashow, Weinberg and Salam predicted the mass of the mediator particles of the weak interaction [11]. The calculated masses were; \(M_{W}^\pm = 82 \pm 2 \text{ GeV}\), and \(M_{Z} = 92 \pm 2 \text{ GeV}\). They received the Nobel Prize in 1979 for their discovery. Five years later, \(W\) and \(Z\) bosons were discovered at CERN [47] with \(M_{W}^\pm = 80.403\pm0.029\) GeV, and \(M_{Z} = 91.188 \pm 0.002 \text{ GeV}\).

1.1.9 Higgs Boson

Over the years, particle physicists developed a model that explains the fundamental particles and forces in nature. One major ingredient was a hypothetical quantum field that is responsible for giving particles their masses. As a consequence of particle wave duality, all the quantum fields have a particle associated with them. Peter Higgs and Francois Englert predicted the field and the particle responsible for particle mass [26, 32]. It was the missing piece of the ultimate theory, called the Standard Model. Nearly 50 years later after the prediction, or just before I started my PhD, in July 2012, the Higgs boson was discovered at CERN where both the CMS and ATLAS experiments confirmed its existence [2, 18]. Peter Higgs and Francois Englert received the 2013 Nobel Prize in Physics for their prediction.
1.2 Standard Model

The Standard Model describes the elementary particles and their interactions with each other. It was first formulated in 1970s; after that time, confirmation of top quark, tau neutrino, and Higgs boson solidified the theory. However, it does not explain many things like neutrino oscillations or dark matter. Physicist are searching for new physics beyond the Standard Model which can open doors to new fields for us to explore.

According to the Standard Model, there are three types of families; *lepton* and *quark* families with spin-1/2, and the *gauge boson* family with spin-1. Also there is one spin-0 particle, called the Higgs boson. Figure 1.3 summarizes the distinct types of quarks, leptons and bosons. The particles on Fig. 1.3 are assumed to be elementary; e.g., they can’t be divided.

The electron, $e$, for example, can be bound by positively-charged protons in the nucleus of the atom. The binding force is called *electromagnetic interaction* which is mediated by photons($\gamma$). The electron neutrino ($\nu_e$), on the other hand, appears during $\beta$-decay. The *weak interaction* is responsible for the decay and $W$ boson is the mediator during the decay. In a general weak interaction, either $W^\pm$ or $Z$ bosons can be a mediator depending on the interaction type.

Figure 1.3 shows the quark family. Hadrons are made of quarks. Protons($p$), neutrons($n$), and pions($\pi^0, \pi^\pm$) are common examples. Quarks inside hadrons are bound together by the *strong interaction* which is mediated by *gluons*.

Unfortunately (maybe not), the matter around us is made out of only up,
down, and electrons. As it can be seen from the Fig. 1.3, second and third generation quarks and leptons are a lot heavier. Their combinations are not stable, and they decay very fast depending on the interaction type. Maybe in the future, humanity will find a way to use second and third generation quarks and leptons which can open endless possibilities. For example, if communication with neutrinos is possible in the future and we would be able to send signals to deep space without signal loss.

The Standard Model is a big theory, but there are many missing pieces from which to find answers. We can only observe matter, of which only 5% of the universe consists. Particle physics has a long way to be completed, high energy physics experiments around the world are trying to answer those questions.

Figure 1.3. The Standard Model of elementary particles.
1.3 Exotic Mesons

The Quark Model only explains baryons \((qqq)\) or mesons \((q\bar{q})\). Actually there are other possibilities for the quarks to make a bound state; such as exotic mesons \((qq\bar{q})\) or exotic hadrons \((qqq\bar{q})\), or more.

In more detail, strong interaction conserves the following quantities; \(B\): Baryon number, \(J\): total angular momentum, \(P\): Parity, \(C\): Charge conjugation, \(Q\): Charge, \(S\): Strangeness, \(I\): Isospin. The table 1.1 summarizes the quantum numbers of \(u,d,s\) quarks.

<table>
<thead>
<tr>
<th>Quark</th>
<th>B</th>
<th>J(spin)</th>
<th>S(strangeness)</th>
<th>Q</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>(1/3)</td>
<td>(1/2)</td>
<td>0</td>
<td>(2/3)</td>
<td>(1/2)</td>
</tr>
<tr>
<td>d</td>
<td>(1/3)</td>
<td>(1/2)</td>
<td>0</td>
<td>(-1/3)</td>
<td>(-1/2)</td>
</tr>
<tr>
<td>s</td>
<td>(1/3)</td>
<td>(1/2)</td>
<td>(-1)</td>
<td>(-1/3)</td>
<td>(0)</td>
</tr>
</tbody>
</table>

If we have a quark-antiquark pair, we can have orbital angular momentum \((L)\) between the two quarks. The formulas below summarizes the \(J,P,C\) numbers.

- \(J = L \oplus S\)
- \(P = (-1)^{L+1}\)
- \(C = (-1)^{L+S}\)

As one can see from the table 1.2, the possible quantum numbers for mesons are
Table 1.2. Possible quantum number configuration system of a quark-antiquark system.

<table>
<thead>
<tr>
<th>State</th>
<th>S</th>
<th>L</th>
<th>J</th>
<th>P</th>
<th>C</th>
<th>J^PC</th>
<th>Mesons</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1S_0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0^-</td>
<td>π, η, η', K</td>
<td>pseudoscalar</td>
</tr>
<tr>
<td>3S_1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>1</td>
<td>1^-</td>
<td>ρ, ω, φ, K^*</td>
<td>vector</td>
</tr>
<tr>
<td>1P_1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>+</td>
<td>-</td>
<td>1^+</td>
<td>b_1, h_1, h'_1, K_1</td>
<td>pseudo-vector</td>
</tr>
<tr>
<td>3P_0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0^+</td>
<td>a_0, f_0, f'_0, K_0^*</td>
<td>scalar</td>
</tr>
<tr>
<td>3P_1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>+</td>
<td>+</td>
<td>1^+</td>
<td>a_1, f_1, f'_1, K_1^*</td>
<td>axial-vector</td>
</tr>
<tr>
<td>3P_2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>+</td>
<td>+</td>
<td>2^+</td>
<td>a_2, f_2, f'_2, K_2^*</td>
<td>tensor</td>
</tr>
</tbody>
</table>

0^-, 0^+, 1^-, 1^+, 2^-, 2^+, .... It is also possible to see some of the missing numbers are not allowed; 0^-, 0^+, 1^-, 2^+, .... These numbers are known as explicitly exotic quantum numbers [39].

Table 1.2 shows some of the scalar mesons. Some scalar states have peculiar decay patterns. Some of these mesons might be the expected two-quark mesons and some of them might be exotic states, like a four quark state(two-quarks, two antiquarks), glueballs (only gluons), or hybrids(quark-antiquark and a gluon). States like a_0 and f_0 are not well understood either theoretically or experimentally [30].

One might ask how we determine that they are exotic mesons. The first tetra-quark state X(3872) was announced by Belle experiment in 2003 [8]. They observed a narrow charmonium state in exclusive B^± → K^±π^±π^- J/ψ decays. They investigated the invariant mass distribution of π^+π^- J/ψ, which is shown in Fig. 1.4 on left. Also in 2007, the Belle collaboration reported Z(4430)^+. They investigated the process, B → Kπ^±ψ' [21]. They found the invariant mass distribution of π^±ψ' shown in Fig. 1.4 on right. In which, B → KZ^+ (some intermediate state), then Z^+ → π^±ψ'.
Figure 1.4. Indication of an intermediate state from exclusive decays. On the left: A new charmonium state in exclusive $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ decays [8], on the right: A resonance-like structure in the $\pi^+ \psi'$ mass distribution in exclusive $B \rightarrow K\pi^+ K'$ decays [21].

Numerous discoveries such as the $X(3872)$ [8], $Z(4430)^+$ [21], $Y(4140)$ [5], $Z(4430)^-$ [3] provide strong evidence of tetra-quark states.

In the following chapters, a possible 4b-quark state will be investigated in more detail.
CHAPTER 2

APPARATUS

2.1 Introduction

In nature we almost only see matter made out of up and down quarks, and electrons. For example, we don’t see a structure made from a muon. Muons are only created in nature due to highly energetic cosmic rays in the outer atmosphere but they decay very fast. In order to create heavier and unstable particles, one needs accelerators.

In order to search subatomic particles, one needs to destroy the structure of the atom to see what is inside. If we assume that atoms are like walnuts, in order to break it, one needs a hammer which is stronger than the walnut. Unfortunately we don’t have such a hammer. The only way to break the walnuts is to accelerate them, and smash them head to head. The process creates heavy and short lived particles which gives us an opportunity to explore them, and also simulates the time just before the Big Bang.

The journey of particle accelerators started with a cyclotron, invented by Ernest O. Lawrence in 1934. As shown in Fig. 2.1 (left) charged particles are accelerated from the center along a spiral path. A magnetic filed is applied to keep the electrons in their path. The electric field in the gap accelerates electrons. The first cyclotron was 69 cm in diameter, and it could accelerate particles up to 4.8 MeV.

Throughout the years particle accelerators got bigger and stronger as can be seen in Fig. 2.1 (right) which led to many discoveries. For example, protons and
anti-protons were accelerated to 1 TeV at Fermilab’s Tevatron accelerator which led to the discovery of the Top quark in 1995 [7]. The Tevatron also found a hint of the Higgs Boson just before the discovery announced by the Large Hadron Collider (LHC) [6].

Figure 2.1. Top: The drawing of the cyclotron from Lawrence’s patent [41]. Bottom: The graph of collision energy of various accelerators versus year.

Our main focus will be the LHC and the CMS detector because our research is completed using the LHC collision data provided by the CMS detector.
2.2 Large Hadron Collider (LHC)

The European Organization of Nuclear Research (CERN) is the largest particle physics center in the world. It is located near Geneva, Switzerland and on the Switzerland-France border. It provides infrastructure to the LHC [15], the most powerful particle accelerator operational today, and the most complex experiment ever built. It is located 100 meters underground in a 27 kilometer in circumference circular tunnel. The ring consists of superconducting magnets and accelerating structures to boost the energy of the particles. It can collide protons with 13 TeV center-of-mass collision energy as of today. Each proton reaches an energy level of 6.5 TeV, which means protons have 6500 times more energy than their rest mass.

Figure 2.2 shows the complex structure of CERN. Initially protons are stripped off of hydrogen atoms under a large electric field. They are then accelerated to 50 MeV by LINAC 2. Protons are later accelerated to 1.4 GeV in the Booster, and to 25 GeV in the Proton Synchrotron (PS) splits. Before switching to the Super Proton Synchrotron (SPS), they are split into bunches with 25 ns spacing. Protons reach 450 GeV in SPS, then they are injected into the LHC ring. The LHC increases proton energies up to 6.5 TeV.

Although the main purpose of the LHC is to accelerate protons, heavy ions (Pb-Pb) are also accelerated for other physics searches. Heavy ions are initially accelerated through LINAC 3, then they are injected into the Low Energy Ion Ring (LEIR). These ions are later injected into the PS, SPS, and the LHC accordingly. Figure 2.2 shows the path of heavy ions before collision. The collision energy of
heavy ions is 2.76 TeV.

Figure 2.2. CERN accelerator complex [CERN].

In the LHC Run-I period (2010 to 2013), protons were accelerated to 3.5 TeV, and later to 4 TeV in the same period. The accelerator was upgraded for two years after the Run-I period. The LHC reached 6.5 TeV per beam in 2015. The designed center-of-mass collision energy is 14 TeV which will be expected to be reached after Long Shutdown II of LHC in 2021.
Protons are initially accelerated with 8 radio frequency (RF) cavities with an alternating current of 400 MHz [27]. As mentioned earlier, the Proton Synchrotron splits protons to bunches with 25 ns interval and each bunch has $1.15 \times 10^{11}$ protons. When the bunches are injected into the LHC ring, LHC ring carries up to 2808 bunches at a given time. A 25 ns collision interval means a 40 MHz collision rate. The design luminosity is $10^{34}$cm$^{-2}$s$^{-1}$. Protons inside the beam pipe are kept aligned with an 8 Tesla magnetic field. This strong magnetic field is achieved by superconducting electromagnets which require a operating temperature around 1.9K to stay in the superconducting state. A temperature of 1.9K is achieved by liquid helium which cools the magnets and other related services. Figure 2.3 shows the LHC ring, in which protons circulate with superconducting magnets keeping them aligned through the ring.

There are four collision points on the LHC ring, where there are four detectors to record the collision data. They are marked on Fig. 2.2;

- **ATLAS (A Toroidal LHC ApparatuS):** A general purpose detector, it studies signs of new physics, extra dimensions and measure the known properties of the SM with better precision. ATLAS was one of the detectors which discovered the Higgs boson [2].

- **CMS (Compact Muon Solenoid):** Another general purpose detector, it studies the same physics topics as in ATLAS. CMS was the other detector which discovered the Higgs boson [18]. The CMS detector will be covered in more detail in the following section.
- LHCb (LHC beauty): It is trying to answer why there is less antimatter in the universe compared to matter. In 2015 LHCb discovered a penta-quark state with a mass of 4.4 GeV [4].

- ALICE (A Large Ion Collider Experiment): It is studying the quark-gluon plasma which existed right after the Big Bang using heavy ion collision data.

![Image of the LHC accelerator ring](CERN)

Figure 2.3. The LHC accelerator ring[CERN].

### 2.3 Compact Muon Solenoid (CMS)

CMS is one of the two large general purpose detectors built on the LHC. It weighs about 14500 tons, is 21.6 meters long, and is 14.6 meters in diameter. The CMS detector has a solenoid magnet inside that generates a 3.8 T magnetic field. The detector is composed of an silicon tracker, electromagnetic calorimeter, hadronic
calorimeter, and the muon chamber. The magnet covers the silicon tracker, the electromagnetic calorimeter and the hadronic calorimeter. The innermost layer is the silicon tracker which is responsible for tracking all charged particles. The second layer is the electromagnetic calorimeter which can measure the energy deposited by electrons and photons. The third layer is the hadronic calorimeter which measures the energy of hadrons, particles made of quarks and gluons such as protons, pions, kaons, and neutrons. The last layer is the muon chamber which can detect muons.

Figure 2.4 shows a sectional view of the CMS detector. The layers of the detector will be briefly explained in the following sections.
CMS uses the right-handed coordinate system. The $x$-axis points radially outward, the $y$-axis points vertically outward, and the $z$-axis is along the beam line. The azimuthal angle $\phi$ is measured on the $x-y$ plane. The polar angle is measured from the $z$-axis. The pseudorapidity ($\eta$) is calculated as $\eta = -\ln \tan(\theta/2)$. Notice that when $\theta = 0$ or 180 (along the $z$-axis), $\eta$ becomes $\infty$ or $-\infty$ respectively. When $\theta = 90$ (perpendicular to the $z$-axis), $\eta$ becomes 0. Pseudorapidity is used to describe the detector boundaries, it is convenient to use due to the cylindrical shape of the CMS detector. Transverse momentum ($p_T$) and transverse energy ($E_T$) are computed from the projection of $p$ and $E$ on the $x-y$ plane.

2.3.1 Inner Tracker

Measuring the momentum of the particles is crucial to reconstruct the events. The silicon tracker is able to track charged particles and measure their momentum inside the magnetic field. The construction materials were also carefully chosen to resist high radiation damage. The tracker has two sections: silicon pixels and silicon strips. Figure 2.5 shows the schematic structure of the inner tracker.

2.3.1.1 Pixel Detector

The pixel detector is the closest subdetector to the beam pipe. It contains 65 million pixels, they track the particles emerging from the collision with extreme accuracy. It has three cylindrical layers at 4 cm, 7 cm and 11 cm with disks at either end, and it has two forward pixel disks on either side as shown in Fig. 2.6 (left). The layers extend to $\eta = 2.5$. Each layer is split into segments that includes silicon sensors which are 100$\mu$m by 150$\mu$m. When a charged particle passes through the sensor,
it knocks off electrons, creating electron-hole pairs. Applying reverse bias voltage, electron-hole pairs can be collected. The working principle of the silicon detectors is shown in Fig. 2.6 (right). An electronic chip bonded to the sensors collects those signals. By combining the signals from the sensors from each layer, a 3D path of a particle can be constructed.

2.3.1.2 Strip Detector

After the pixel detector, particles pass through the Silicon Strip Tracker (SST) that extends to 130 cm in the radial direction. It has a total of 10 million detector strips read by 80,000 microelectronic chips. It consists of four TIB layers, two TIDs, the TOB with 6 layers and, finally two TECs. Each has silicon modules designed differently for its position within the detector. The system operates below $-10^\circ C$.
Figure 2.6. Left: Layers of the pixel detector. Right: Working principle of silicon detectors.

The total strip area is about 200 m$^2$ and there are more than 75 million readout channels.

2.3.2 Electromagnetic Calorimeter (ECAL)

The main purpose of ECAL is to measure the energies of electrons and photons. The ECAL also needs specialized detector materials able to withstand high magnetic fields, resist radiation damage, and be read in the 25 ns interval between collisions. ECAL uses lead tungstate (PbWO$_4$) crystals to detect particles. It is an extremely dense but transparent material, which is ideal for stopping particles. Radiation length is the travel distance after a particle looses 63% of its energy. The radiation length in lead tungstate is about 0.89 cm, which can stop electromagnetic showers inside ECAL. When the electrons or photons pass through the crystal, the crystal scintillates. The produced light is proportional to the particle’s energy. The crystal scintillates fast, short and well-defined photon bursts that allow a precise, fast, and compact detector.
The crystals can emit 80% of the scintillation light within 25 ns, and are connected to photodetectors that can convert light to electrical signals.

The ECAL is made up of a barrel section and two endcaps, that forms a layer between the tracker and the HCAL. The barrel section includes 61,200 crystals and the endcaps are made up of 15,000 crystals. Each crystal has a mass of 1.5 kg, and the volume of a coffee cup.

Figure 2.7 shows the cross sectional view of ECAL detector. The Barrel ECAL (EB) covers up to $|\eta| \leq 1.479$ and the Endcap ECCAL (EE) covers $1.479 \leq |\eta| \leq 3.0$.

Figure 2.7. Crossectional view of the ECAL [17].

2.3.3 Hadronic Calorimeter (HCAL)

The HCAL measures the energy of hadrons. It also provides an indirect measurement of the uncharged non-interacting particles like neutrinos. Measuring all kinds of particle energies is important in discovering new particles. The HCAL has a
hermetic structure so that one can determine any noninteracting particles via measuring missing momentum and energy. The HCAL finds a particle’s position, energy and arrival time using alternating layers of absorber and fluorescent scintillator materials that produce light when the particles pass through. The passing particles create new particles as they lose energy in the absorber, and these new particles also interact with the scintillator; the result is a shower of particles depositing their energy. The light coming out of scintillators is collected and transferred via "wavelength-shifting" fibers which are connected to photosensors and readout boxes.

The HCAL has the following subsections; Hadronic Barrel (HB), Hadronic Outer (HO), Hadronic Endcap (HE), and Hadron Forward (HF) calorimeter. The coverage range of these subsections are shown in Fig. 2.8
HB and HE are sampling calorimeters, they consist of brass layers and plastic scintillators. The HO on the other hand is installed outside of the superconducting solenoid magnet. The HO absorbs about 5% of all hadronic showers above 100 GeV. The HF calorimeter is installed very close to the beam pipe between $3.0 \leq |\eta| \leq 5.2$. It is built with quartz fibers and steel absorbers which are radiation tolerant.

2.3.4 Muon Chamber

Detecting muons is one of the CMS’s most important tasks. Muons can travel several meters in iron without interacting. They easily pass the calorimeters with a minimal or no energy loss. Therefore, muon chambers are placed after the calorimeters and are quite large, the relative size can be seen on Fig. 2.4. To identify muons, CMS uses three types of detectors: Drift Tubes (DT), Cathode Strip Chambers (CSC), and Resistive Plate Chambers (RPC). Figure 2.9 shows the coverage range of DT, CSC, and RPC layers.

The DT, system measures muon positions in the barrel part. Each tube is 4 cm wide and it contains a stretched wire within a gas volume. In total there are 250 DTs at CMS. When a muon passes through the gas, it knocks electrons from the gas atoms, those electrons are then collected by the wire at the center. DTs provides two dimensional position of the muon. There are 12 DT chambers in the transverse direction, they provide the muon’s travel path.

The CSCs are used in the endcap disks where the magnetic field is uneven. There are 540 CSCs at CMS. CSCs consist of positively charged wires crossed with negatively charged copper strips within a gas volume. Passing muons knock off elec-
trons, and create electrons and positive ions. The charged wires collect them. There are 6 layers in each module. The wires are closely spaced so they have fast response time which provides space and time information about the muon.

The RPCs are fast gaseous detectors that are parallel to DTs and CSCs and they provide a muon trigger system for CMS. There are 610 RPCs in CMS. They have two parallel plates, one is positively charged and the other is negatively charged separated by a gas volume. The passing muons knock off electrons. The knocked electrons as well as its ions are collected in opposite directions. The pattern of the hit gives a quick measure of momentum, which is used by a trigger.
2.3.5 The CMS Software (CMSSW)

The CMSSW is a C++ framework and it consists hundreds of packages. Event reconstruction is performed using CMSSW packages. They combine electrical signals from various subdetectors, and reconstruct physics objects. It is built around a framework called Event Data Model (EDM). An event is a collection of RAW data or Monte Carlo (MC) data, after processing, using the data from all the subdetector parts, it is recorded as a reconstructed (RECO) event object. Analysis Object Data (AOD) is a subset of RECO data, and events in AOD contains most of the required physics information for the analyses.

2.3.6 CMS Trigger System

LHC collides particles with 40 MHz rate, and for each bunch collision, there are about 20 particle interactions. Most of these interactions are soft collisions, meaning no high $p_T$ particles are produced in a collision. These collisions mostly don’t create interesting particles. There is also too much data to record for the CMS detector so the uninteresting events need to be filtered before saving the data. In CMS trigger system, there are two stages; the Level-1 trigger (L1) and the High Level Trigger (HLT).

- **The L1** is a hardware based trigger system and it decides which events need to be saved to disks within 3.2 $\mu$s. It uses the information from the calorimeter and muon detectors to choose the interesting events in real time. It decreases the event rate from $10^9$ Hz to $10^5$ Hz level.
• *The HLT* is a software based trigger system and it uses the events that are already passed from L1. There are many different HLT trigger versions for specific purposes. Each HLT trigger uses optimized reconstruction algorithms for specific purposes. For example, some high level triggers only records information where there are 2 or more muons in an event. The HLT contains many trigger paths, each corresponding to a dedicated trigger. The HLT decreases event rates from $10^5$ Hz to $10^2$ Hz level.

2.3.7 Muon Reconstruction

Muons tracks are reconstructed independently both in the inner tracker and in the muon chamber. Reconstructed muon tracks are called *tracker track* in the inner tracker and *standalone-muon track* in the muon system. Both tracks are reconstructed using the electrical signals from pixel layers in the inner tracker and from layers of DT,CSC,RPC in the muon system. Both of them stored in `reco::Track` collection. There are two approaches to reconstruct the muons.

• *Global Muons*: Starting from stand-alone muons, best matching tracker tracks are found. Using Kalman filtering technique [34], the tracker track and the standalone muon track pair is fitted. The resulting objects are called global muons and they are stored in a collection of `reco::Track`.

• *Tracker Muons*: This approach is the reverse of global muon reconstruction. All tracker tracks are considered potential muon candidates, and for each track compatible signatures from the calorimeters and the muon chambers are searched.
If there is any matching signal tracker muons are reconstructed.

All the information about reconstructed muons are stored in the `reco::Muon` collection.

2.3.8 Electron Reconstruction

Electrons carry electric charge and leave tracks in the inner tracker. They deposit their entire energy in the ECAL. They can be reconstructed by combining information from both ECAL and the inner tracker. Since the ECAL is inside the magnet, electrons are severely affected by bremsstrahlung before they start to deposit their energy in the ECAL. The Hybrid algorithm is used in the barrel section and Multi 5x5 algorithm used in the endcaps. Both algorithms use the trajectory of the electrons and combine the energies of the radiated bremsstrahlung photons [36].

The first step of reconstruction is electron track reconstruction, which is called seeding, in which two or three first hits in the tracker are combined and the track is initiated. The ECAL seeding starts from the super cluster (SC, electrons and photons deposit their energy in several crystals in ECAL. The magnetic filed spreads up the energy deposit in $\phi$. The spread energy is clustered into small clusters, and the small clusters are combined by a super cluster.) energy and position. Using both information from the tracker and the ECAL, electron trajectory can be estimated.

Once all the hit points are determined, Gaussian Sum Filter (GSF) method is used to get the track parameters which also included bremsstrahlung energy loss. Reconstruction efficiency of the electron is greater than 90% where $E_T > 20$ GeV [36].
CHAPTER 3

EVIDENCE OF A NARROW STRUCTURE IN $\Upsilon(1S)l^+l^-$ MASS SPECTRUM

3.1 Motivation

In 2003, researchers in Japan observed an unexpected particle, $X(3872)$ [20], which is made of a charm quark, an anti-charm quark and at least two other quarks using the electron-positron collider at Belle Experiment. While the researchers were trying to understand the particle, they also found $X(4430)$ [21] composed of four quarks. These recent discoveries of charmonium-like structures provide strong evidence for the existence of four-quark states. A. V. Berezhnoy and his colleagues predicted the production cross section of $J/\psi J/\psi$ events in the LHC and they also discussed the possibility of a $cc\bar{c}\bar{c}$ structure [9]. In 2014, the production cross section of $J/\psi J/\psi$ events was calculated [35] by the CMS Collaboration. Later, by using a diquark-antidiquark model, Berezhnoy and his colleagues predicted the masses of $bb\bar{b}\bar{b}$, $b\bar{c}\bar{b}\bar{c}$, and $c\bar{c}\bar{c}\bar{c}$ [10]. Color-triplet configurations were considered in their model. The mass of a diquark-antidiquark system is calculated by solving the two-particle Schrodinger equation. The predicted masses are summarized in Table 3.1. Figure 3.1 shows the diquark-antidiquark model of a tetraquark state.

In 2017, CMS published the observation of $\Upsilon(1S)\Upsilon(1S)$ events [37]. The production cross section of $\Upsilon(1S)\Upsilon(1S)$ was measured to be $68.8 \pm 12.7$ (stat.) $\pm 7.4$ (syst.) pb. If the predicted $bb\bar{b}\bar{b}$ state exists [10], CMS is able to produce such states. The predicted masses of bound state of $bb\bar{b}\bar{b}$ are below the VV meson mass.
Table 3.1. Predicted masses of 4b quark states for different quantum numbers.

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>Calculated Mass</th>
<th>Mass Difference from $m(\Upsilon(1S)\Upsilon(1S))$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^{++}$</td>
<td>18.754 GeV</td>
<td>$M - M_{th} = -544$ MeV</td>
</tr>
<tr>
<td>1$^{+-}$</td>
<td>18.808 GeV</td>
<td>$M - M_{th} = -490$ MeV</td>
</tr>
<tr>
<td>2$^{++}$</td>
<td>18.916 GeV</td>
<td>$M - M_{th} = -382$ MeV</td>
</tr>
</tbody>
</table>

threshold, so the search channel would be $VV^*$. Here $V$ means dimuon vector meson resonances, and $V^*$ means the vector meson mass of the decay particles is less than the mass of the vector ($m(V^* \rightarrow \mu^+\mu^-) < m(V)$). The following sections describe a search for these states and an enhancement around 18.5 GeV in the four lepton final state, which is in the $\Upsilon(1S)\Upsilon(1S)^*$ state; where $\Upsilon(1S) \rightarrow \mu^+\mu^-$ and $\Upsilon(1S)^* \rightarrow \mu^+\mu^-$ or $\Upsilon(1S)^* \rightarrow e^+e^-$. Details of the checks on the robustness and properties of the excess are also described.

3.2 Trigger

The trigger for $\Upsilon(1S)\mu^+\mu^-$ uses information from the muon detectors to select events with at least three muon candidates. CMS does not provide a four-muon trigger; instead, we use three-muon triggers. There are two HLT trigger paths. The
first one is $\text{HLT}_{\text{Dimuon0}}\text{Upsilon}_{\text{Muon}}$, which requires two of the muon candidates with opposite charges and a common vertex to form a pair with an invariant mass in between 8.5 GeV to 11.5 GeV. There is no $p_T$ requirement on a single muon or on the dimuon pair. The second one which is $\text{HLT}_{\text{TripleMu5}}$, requires each muon $p_T$ to be greater than 5 GeV.

The trigger for $\Upsilon(1S)e^+e^-$ is $\text{HLT}_{\text{Dimuon5}}\text{Upsilon}$. It requires events to contain at least two muon candidates. The two muons with opposite charges form a pair with a common vertex. The pair mass is required to be between 8.5 GeV and 11.5 GeV. The $p_T$ requirement for each muon is 5 GeV.

### 3.3 Data and Monte Carlo Samples

The data is from proton-proton collisions at 7 and 8 TeV center of mass energies collected by CMS in 2011 and 2012 respectively. Events used in this analysis are certified for the muon analysis. Monte Carlo (MC) samples are produced either officially or privately. In $\Upsilon(1S)\mu^+\mu^-$ analysis, both 7 and 8 TeV data is used, and in $\Upsilon(1S)e^+e^-$ analysis, only 8 TeV data is used.

#### 3.3.1 Data and MC for $\Upsilon(1S)\mu^+\mu^-$ Channel

To maximize statistics, Data sets from 2011 and 2012 are analyzed together. The following table summarizes the data sets with the trigger applied.

- 2011 MuOnia dataset with $\text{HLT}_{\text{Dimuon0}}\text{Upsilon}_{\text{Muon}}$ trigger
- 2012 MuOnia dataset with $\text{HLT}_{\text{Dimuon0}}\text{Upsilon}_{\text{Muon}}$ trigger
- 2011 DoubleMuon dataset with $\text{HLT}_{\text{TripleMu5}}$ trigger
• 2012 DoubleMuon dataset with HLT_TripleMu5 trigger

CMS provides sub-datasets for specific purposes, otherwise one single dataset would be almost impossible to analyze. Different dataset versions provide different sets of triggers. In this analysis, two different datasets were used, which are prepared with similar three muon triggers from the same collision data. Some events might overlap, meaning the same events can be triggered and can exist in both datasets. In order to prevent double counting of overlapping events, we made sure that one event appearing in one data set does not appear in the other dataset. Table 3.2 and 3.3 show the datasets, run ranges, delivered and recorded luminosities for the $\Upsilon(1S)\mu^+\mu^-$ channel. The events used in this analysis are required to pass the official JSON files: Cert_160404-180252_7TeV_ReRecoNov08_Collisions11_JSON.txt (2011 data) or Cert_190456-208686_8TeV_22Jan2013ReReco_Collisions12_JSON_MuonPhys.txt (2012 data). A JSON file includes the good data taking periods where all the detector parts work as expected. We reconstruct events using CMSSW_4_4_5 for 2011 data and CMSSW_5_3_7_patch5 for 2012 data.

Any unexpected signal may or may not be an exotic particle. In order to have a model to assess the CMS mass resolution, we consider two signals. An official 500k events was generated based a Higgs model with 0 intrinsic width, in which $H_0 \rightarrow \Upsilon(1S)\mu^+\mu^-$. A generic model was chosen only to determine the detector resolution. It has been created with PYTHIA8 [45, 46], and analyzed with CMSSW version 5_3_23_patch1.
Table 3.2. Data sets, run ranges and corresponding luminosities for Upsilon_Muon trigger for $\Upsilon(1S)\mu^+\mu^-$ channel.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Run range</th>
<th>Delivered Lumi</th>
</tr>
</thead>
<tbody>
<tr>
<td>/MuOnia/Run2012A-22Jan2013-v1/AOD</td>
<td>190456, 193621</td>
<td>0.965 fb$^{-1}$</td>
</tr>
<tr>
<td>/MuOnia/Run2012B-22Jan2013-v1/AOD</td>
<td>193834, 196531</td>
<td>4.925 fb$^{-1}$</td>
</tr>
<tr>
<td>/MuOnia/Run2012C-22Jan2013-v1/AOD</td>
<td>198022, 203742</td>
<td>7.430 fb$^{-1}$</td>
</tr>
<tr>
<td>/MuOnia/Run2012D-22Jan2013-v1/AOD</td>
<td>203777, 208686</td>
<td>7.718 fb$^{-1}$</td>
</tr>
<tr>
<td>/MuOnia/Run2011A-08Nov2011-v1/AOD</td>
<td>160329, 175770</td>
<td>2.389 fb$^{-1}$</td>
</tr>
<tr>
<td>/MuOnia/Run2011B-19Nov2011-v1/AOD</td>
<td>175832, 180296</td>
<td>2.865 fb$^{-1}$</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td><strong>26.292 fb$^{-1}$</strong></td>
</tr>
</tbody>
</table>

Table 3.3. Data sets, run ranges and corresponding luminosities for the TripleMu5 trigger for $\Upsilon(1S)\mu^+\mu^-$ channel.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Run range</th>
<th>Delivered Lumi</th>
</tr>
</thead>
<tbody>
<tr>
<td>/DoubleMuParked/Run2012A-22Jan2013-v1/AOD</td>
<td>190456, 193621</td>
<td>0.965 fb$^{-1}$</td>
</tr>
<tr>
<td>/DoubleMuParked/Run2012B-22Jan2013-v1/AOD</td>
<td>193834, 196531</td>
<td>4.925 fb$^{-1}$</td>
</tr>
<tr>
<td>/DoubleMuParked/Run2012C-22Jan2013-v1/AOD</td>
<td>198022, 203742</td>
<td>7.430 fb$^{-1}$</td>
</tr>
<tr>
<td>/DoubleMuParked/Run2012D-22Jan2013-v1/AOD</td>
<td>203777, 208686</td>
<td>7.718 fb$^{-1}$</td>
</tr>
<tr>
<td>/DoubleMu/Run2011A-08Nov2011-v1/AOD</td>
<td>160329, 175770</td>
<td>2.389 fb$^{-1}$</td>
</tr>
<tr>
<td>/DoubleMu/Run2011B-19Nov2011-v1/AOD</td>
<td>175832, 180296</td>
<td>2.865 fb$^{-1}$</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td><strong>26.292 fb$^{-1}$</strong></td>
</tr>
</tbody>
</table>
Table 3.4. Data sets, run ranges and corresponding luminosities for the MuoniaParked and DoubleMuParked data for $\Upsilon(1S)e^+e^-$ channel.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Run range</th>
<th>Delivered Lumi</th>
</tr>
</thead>
<tbody>
<tr>
<td>/DoubleMuParked/ Run2012A-22Jan2013-v1/AOD</td>
<td>190456, 193621</td>
<td>0.413 fb$^{-1}$</td>
</tr>
<tr>
<td>/MuOniaParked/ Run2012B-22Jan2013-v1/AOD</td>
<td>193833, 196531</td>
<td>4.829 fb$^{-1}$</td>
</tr>
<tr>
<td>/MuOniaParked/ Run2012C-22Jan2013-v1/AOD</td>
<td>198022, 203746</td>
<td>7.308 fb$^{-1}$</td>
</tr>
<tr>
<td>/MuOniaParked/ Run2012D-22Jan2013-v1/AOD</td>
<td>203768, 208686</td>
<td>7.570 fb$^{-1}$</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td>20.13 fb$^{-1}$</td>
</tr>
</tbody>
</table>

3.3.2 Data and MC for $\Upsilon(1S)e^+e^-$ Channel

For the $\Upsilon(1S)e^+e^-$ channel, only 8 TeV data is used because CMS does not provide a similar trigger for 7 TeV data. Table 3.4 summarizes the datasets used in the analysis. The events are required to pass the official JSON file: Cert_190456-208686_8TeV_22Jan2013ReReco_Collisions12_JSON_MuonPhys.txt. The data are analyzed using CMSSW 5.3.11.

For the $\Upsilon(1S)e^+e^-$ channel, 250k private MC signal events are generated with zero signal width, $H_0 \rightarrow \Upsilon(1S)e^+e^-$, $\Upsilon(1S) \rightarrow \mu^+\mu^-$ at $m=18.5$ GeV for 8 TeV using the PYTHIA8 [45, 46] event generator.

3.4 $\Upsilon(1S)\mu^+\mu^-$ Channel

3.4.1 Pre-Selection

Each dataset is tens of terabytes in size. It is not convenient to run the full dataset for every iteration in the analysis which can take a week. Instead, we apply some quality cuts which can decrease the dataset size by about 90% while keeping all the interesting events. The following pre-selection cuts applied to clean the data.

- We require at least four muons (from the muon collection) in an event. We
keep events with both zero and non-zero total charge. Four-muon events with non-zero total charge are used for cross-check purposes.

- Offline muon particle identification has not been applied, but we have the following quality requirements:
  
  - Muon tracks should have at least one pixel detector hit.
  
  - Muon tracks should have at least three silicon strip hits.
  
  - Muon track normalized $\chi^2$ is required to be less than 15.
  
  - Muon track transverse impact parameter ($d_{xy}$) should be smaller than 10 cm ($d_{xy}$ is the transverse distance from the primary vertex).
  
  - We require the selected four muons to have no geometrical overlap.

- Four muons are fitted to a common vertex and all candidates are kept including those with an invalid fit. A four muon candidate in the final state is labelled as $\mu_1^+ \mu_2^- \mu_3^+ \mu_4^-$. Four muons with invalid vertex kept for cross-check purposes.

- There are 2 combinations of dimuon pairs with 0 charge. $(\mu_1^+ \mu_2^-)$ vs. $(\mu_3^+ \mu_4^-)$; $(\mu_1^+ \mu_3^-)$ vs. $(\mu_2^- \mu_4^+)$. Each zero-charged dimuon pair is fitted to a common vertex and information is recorded for each vertex. Later this information is used to confirm the dimuon vertex fit probability which was already applied at HLT level. In order to look for any possible dimuon resonance, no mass constraint is applied to any dimuon pair.
3.4.2 Inclusive Dimuon Mass

Before trying to observe something new, it is important to test the code with the known resonances. In the MuOnia data set, we investigate the $\mu^+\mu^-$ invariant mass by requiring dimuon candidates to satisfy the following conditions.

- Dimuon total charge is required to be 0.
- Each event is triggered by HLT\_DiMuon0\_Jpsi\_Muon or HLT\_DiMuon0\_Upsilon\_Muon. In the initial stages of the analysis, both triggers were used but later only the HLT\_DiMuon0\_Upsilon\_Muon trigger was used.
- Dimuon vertex probability must be greater than 0.005.
- Each muon should pass the soft-muon criteria as described in A.1.
- Each muon must have $|\eta| \leq 2.4$.
- Each muon must have $p_T \geq 2.0$ GeV.

Figure. 3.2 shows the $\mu^+\mu^-$ invariant mass in the low mass region (top left and right) and high mass region(bottom). There are clear signals of $J/\psi$, $\Upsilon(nS)$ and $Z$ bosons in the $\mu^+\mu^-$ mass spectrum. As a comparison, for the control samples $\mu^+\mu^+$ and $\mu^-\mu^-$ invariant mass distributions are shown in Figure. 3.3. As expected, there is no structure appearing in the spectrum.

3.4.3 Dimuon Event-by-Event Mass Error from Data

In the analysis, we have the $\Upsilon(1S)\mu^+\mu^-$ channel for which $\Upsilon(1S)$ needs to be chosen efficiently. We looked at several possibilities in order to chose the $\Upsilon(1S)$
Figure 3.2. Inclusive $\mu^+\mu^-$ invariant mass in low mass region (top left and right) and in high mass region (bottom).

Figure 3.3. Inclusive $\mu^+/\mu^- \mu^+/\mu^-$ invariant mass for total charge 2 (left) and for total charge -2 (right).
most efficiently. One can choose a static mass window around $\Upsilon(1S)$. One can also measure the $\Upsilon(1S)$ mass resolution in the CMS detector and apply a $3\sigma$ mass window. A $3\sigma$ window covers 99.7% of the area in a Gaussian signal. However, muons in the forward region have worse resolution compared to the central region. If there are two muons and both of them are in the forward region but in opposite directions, the resulting $\Upsilon(1S)$ might look like it is in the central region where one might apply small mass resolution to those events, then one might reject those events. One needs to understand the dimuon mass resolution which depends on each muon’s rapidity. Event-by-event mass error (EBE) takes individual muon’s momentum resolution and applied it to the $\Upsilon(1S)$’s mass resolution, which solves the problem. In fact, using EBE increased the selection efficiency by 10%.

To investigate any possible bias coming from the use of the EBE, we study the pull distribution which is defined to be $(m(\mu^+\mu^-) - 9.46)/\sigma_{EBE}$ (9.46 GeV is the PDG mass of $\Upsilon(1S)$). We then fit the pull distribution with a single Gaussian function to $\Upsilon(1S)$, a single Landau function to $\Upsilon(2S)$, and a single Landau function to $\Upsilon(3S)$. The fit returns a Gaussian width of $\Upsilon(1S)$ of $1.105 \pm 2.11275 \times 10^{-3}\sigma$. We then scale the EBE mass resolution by a factor of 1.105 and refit the pull distribution after scaling, which returns a Gaussian width of $1.00606 \pm 1.53308 \times 10^{-3}\sigma$ that now correctly describes the dimuon mass resolution. Figure 3.4 shows the $\Upsilon(nS)$ pull distributions before and after scaling.

Figure 3.5 shows the EBE distribution of the dimuon pair for those events with $|m(\mu^+\mu^-) - 9.46| \leq 0.25$. We scale the EBE dimuon mass resolution by a factor
of 1.105 when we select the Υ(1S) candidate in the analysis.

Figure 3.4. Υ(nS) pull distributions before scaling(left) and after scaling(right). After scaling, the Gaussian width becomes 1σ.

Figure 3.5. Event by event mass error for the (μ⁺μ⁻)₁ pair. |m(μ⁺μ⁻)₁ − 9.46| < 0.25 GeV is required to get the distribution.
3.4.4 Event Selection

$\Upsilon(1S)$ is a particle that is formed from a bottom and an anti-bottom quark $(b\bar{b})$ with zero total charge. It has a mass of 9.46 GeV and lifetime of $1.21 \times 10^{-20}$ s. It decays either leptonically or hadronically. CMS can reconstruct and identify a muon with a transverse momentum ($p_T$) larger than a few GeV with an efficiency above 95% in the pseudorapidity $|\eta| < 2.4$ range, while the probability to misidentify a hadron as a muon is well below 1%. The transverse momentum resolution varies from 1% to 6% depending on pseudorapidity [19]. Since our search channel is $\Upsilon(1S)\Upsilon(1S)^*$, the cleanest channel would be $\Upsilon(1S)\mu^+\mu^-$, where $\Upsilon(1S) \rightarrow \mu^+\mu^-$. Also, at the detector level one cannot know precisely which combination of muons are forming a real $\Upsilon$. There is an ambiguity that one has to keep in mind.

For this analysis muon candidates are required to satisfy CMS standard muon identification criteria [19]. We select events that have at least four muons. We fit the muons to the same vertex using the KinematicParticleVertexFitter algorithm which uses the Least Square minimization technique. With four muons in the final state, we have three different combinations with six dimuon pairs. Assuming that we have $\mu_1^+, \mu_2^-, \mu_3^+, \mu_4^-$ particles, Table 3.5 shows all the possible combinations. Due to the charge constraint on dimuon pairs, the dimuon pairs with non-zero charge are rejected. The pairs in each of the two combinations are ordered such that the mass of pair $(\mu^+\mu^-)_1 > (\mu^+\mu^-)_2$. We check both the first and the second combination, if the dimuon pair (we can call it as $(\mu^+\mu^-)_1$) in a combination satisfies $|m(\mu^+\mu^-)_1 - 9.46 \text{ GeV}| < 3\sigma_{EBE}$, where $m(\mu^+\mu^-)_1$ is the mass of the dimuon pair, and $\sigma_m$ is
determined with the event-by-event mass error in $m_{\mu^+\mu^-}$ computed from uncertainties in momentum measurements in the tracker, we retain the four-muon system as a signal candidate. If neither of the two $(\mu^+\mu^-)_1$ pairs lie in the $\Upsilon(1S)$ region but the pair with higher mass is in the sideband region, we retain that event as a sideband candidate.

We also require the other dimuon pair to satisfy $m(\mu^+\mu^-)_2 < (9.46 - 3\sigma_{EBE})$. We apply the following event selection criteria.

- At least four muons in the event with zero total charge.
- All four muons point to the same vertex with $\chi^2$ probability is greater than 5%.
- Dimuon $\chi^2$ probability is greater than 0.5%.
- Each muon must have $|\eta| < 2.4$ and $p_T > 2.0$ GeV.
- Each event is triggered by HLT_DiMuon0_UpsilonMuon for the MuOnia data set, and each event is triggered by only HLT_TripleMu5 for the DoubleMu data set.
- Each muon should pass the soft-muon criteria and there must be at least 2 tight muons in the event. Definitions of soft and tight muon ID can be found in A.1 and A.2.
- We require at least one combination of the two zero-charged dimuon pairs $(\mu_1^+\mu_2^-)$ vs. $(\mu_3^+\mu_4^-)$ or $(\mu_1^+\mu_4^-)$ vs. $(\mu_3^+\mu_2^-)$ to pass the dimuon mass requirements as described above.
Table 3.5. Possible combination of muon pairs.

<table>
<thead>
<tr>
<th>Combination Id</th>
<th>First Dimuon Pair</th>
<th>Second Dimuon Pair</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$\mu_1^+ \mu_3^+$</td>
<td>$\mu_2^- \mu_4^-$</td>
</tr>
<tr>
<td>1</td>
<td>$\mu_1^+ \mu_2^-$</td>
<td>$\mu_3^+ \mu_4^-$</td>
</tr>
<tr>
<td>2</td>
<td>$\mu_1^+ \mu_4^-$</td>
<td>$\mu_3^+ \mu_2^-$</td>
</tr>
</tbody>
</table>

- If there are light mesons ($\omega, \phi, J/\psi$) in the unselected combination within $2\sigma_{E_E}$ of their PDG values, they are rejected.

We applied this selection to the 2011 and 2012 data, and observed an excess of events in the four-muon mass spectrum around 18.5 GeV, as shown in Fig. 3.32. The following sections will provide details of cross-checks and investigations of this excess.

Note: During the initial stages of the analysis, both HLT_DiMuon0_Upsilon_Muon ($\Upsilon(1S)$ trigger) and HLT_DiMuon0_Jpsi_Muon ($J/\psi$ trigger) triggers were applied and light mesons in the unselected combination were not rejected. If there is any variation from the items listed above, they will be indicated explicitly.

3.4.5 $\Upsilon(1S)\mu^+\mu^-$ Mass Spectrum

Variations from the event selection for this section: 1.) $\Upsilon(1S)$ and $J/\psi$ triggers were applied together. 2.) Light mesons in the unselected combination were not rejected.

The main purpose of this section is to show the mass spectrum in the combined data and in both 7 and 8 TeV data separately. Figure 3.6 shows the four-muon mass
distributions after we require $|m(\mu^+\mu^-)_{i1} - 9.46| \leq 3\sigma(\Upsilon(1S)_{EBE})$ and $m(\mu^+\mu^-)_{i2} \leq 9.46 - 3\sigma(\Upsilon(1S)_{EBE})$ for either $i=1$, or $i=2$. Since we can have only 2 combinations as explained in Table 3.5, $i$ can be 1 or 2. The top two plots in Figure. 3.6 show the mass distributions in 2011 and 2012 data separately, and the bottom left plot shows the combination of 2011 and 2012 data. The excess is visible in both datasets separately. The bottom right plot shows a comparison for the four-muon mass distribution from $\Upsilon(1S)$ mass window and the four-muon mass distribution for those events from the $\Upsilon(1S)$ low-sideband (defined by $8.6 < m(\mu^+\mu^-) < 9.2$ GeV). As it can be seen from the plot, there is no excess when the $\Upsilon(1S)$ mass windows is shifted to the low-sideband region.

3.4.6 Investigation of the Mass Cut on the Second Dimuon Pair

**Variations from the event selection for this section:** 1.) $\Upsilon(1S)$ and $J/\psi$ triggers were applied together. 2.) Light mesons in the unselected combination were not rejected.

The purpose of this section is to show that there is no kinematic effect on the signal due to the mass cut on the second dimuon pair.

There has been a concern about the mass cut on the second dimuon pair–$m(\mu^+\mu^-)_2 < (9.46 - 3\sigma_{EPE})$. The possibility has been raised that the excess is due to the cut since the excess mass is very close to the sum of the first and the second dimuon pair masses. To address this issue, the four-muon mass is investigated by removing the mass cut on the second dimuon pair.

Figure 3.7 shows the four-muon mass with (top left), without (top right) the
Figure 3.6. The $\Upsilon(1S)\mu^+\mu^-$ mass distributions after all event selections and dimuon masses requirement, using 2011 and 2012, MuOnia and Double Muon data sets. Top left plot is from 2011 data sets, top right plot is from 2012 data sets. Bottom left is the addition of 2011 and 2012 data sets. Bottom right is the overlap of bottom left plot (blue) and four muon mass with two of the muons coming from lower side band of $\Upsilon(1S)$. 
requirement of $m(\mu^+\mu^-)_2 < (9.46 - 3\sigma_{E_{BE}})$ and a comparison between the above two plots (bottom). After removing the requirement, the excess is still clear.

Figure 3.7. The default four muon invariant mass spectrum is shown in the top left; the four muon mass spectrum without applying a mass cut in the second dimuon pair is shown in the top right; the overlap of the two mass spectrums is shown in the bottom.

The second dimuon mass distribution is shown in Fig. 3.8. There is an accumulation of blue points close to the $\Upsilon(1S)$ mass which is not present in the red histogram. The dimuon mass cut on the second pair is varied to investigate any possible unexpected behavior. Figure 3.9 shows that the excess is still visible with
varying mass cuts on the second dimuon pair. Figure 3.8 also shows that \( \Upsilon(1S)^* \) is created almost at rest. This makes sense because the \( \Upsilon(1S)\Upsilon(1S)^* \) mass is very close to the \( \Upsilon(1S)\Upsilon(1S) \) mass.

![Image](image_url)

Figure 3.8. Comparison of \( m(\mu^+\mu^-)_2 \) distribution for both in signal region and the sideband region.

3.4.7 Investigation of Four-muon Mass with \( \Upsilon(1S)\mu^+/\mu^- \)

Variations from the event selection for this section: 1.) \( \Upsilon(1S) \) and \( J/\psi \) triggers were applied together. 2.) Light mesons in the unselected combination were not rejected.

In this section, non-zero charged control channels were investigated. Since we are looking for a zero charged structure in the final state, an excess in a non-zero charged channel would indicate there is a problem either in our event selection strategy or a problem in the event taking process.

Figure 3.10 shows the \( \Upsilon(1S)\mu^+\mu^+ \) and \( \Upsilon(1S)\mu^-\mu^- \) plots as control channels.
Figure 3.9. Υ(1S)μ⁺μ⁻ mass distributions with varying second dimuon mass cut.
As it can be seen from the plots, there is no unexpected excess around 18.5 GeV region, however the statistics are limited.

Figure 3.10. \( \Upsilon(1S)\mu^+/\mu^-\) mass distribution from 2011 and 2012 combined data sets(left). \( \Upsilon(1S)\mu^+/\mu^-\) mass distribution from 2011 and 2012 combined data sets without a mass cut on the 2\(^{nd}\) dimuon pair(right).

3.4.8 Muon Acceptance and \( p_T \) vs. \( \eta \) Distributions

We studied muon acceptance from two privately generated MC models; \( H_0 \rightarrow \Upsilon(1S)\mu^+\mu^- \) with pileup and \( \chi_{b0} \rightarrow \Upsilon(1S)\mu^+\mu^- \) without pileup. Acceptance is defined as reconstructed muons over generated muons. Reconstructed muons are required to pass the official soft muon ID and they are required to match GEN muons (generated muons are the muons before simulation in the detector environment) with \( \Delta R < 0.1 \) \((DeltaR = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2)}\) and \( \Delta p_T < 0.1 \) criteria. Figure 3.11 shows the muon acceptance for both \( \chi_{b0} \) (left) and \( H^0 \) (right) models. To maximize the statistics for a structure search, we don’t have any acceptance requirements. Instead we investigate
the acceptance for each muon in the signal region after the event selection.

The muon $p_T$ vs. $\eta$ distribution in data from the signal region ($18 < m(\mu^+\mu^-\mu^+\mu^-) < 19\text{GeV}$) and sideband region ($m(\mu^+\mu^-\mu^+\mu^-)$ in $[16 - 17] + [20 - 21]\text{GeV}$) for the four muons, from highest $p_T$ to the lowest $p_T$, are shown in Fig 3.12. The acceptance from the Higgs model is checked for all events in the signal region. A custom function is applied to the dataset to cover events where efficiency is above 80% and $p_T > 2\text{GeV}$. There are only two events with one muon’s acceptance less than 20%; one is 5% and the other is 2%. The two events are kept in the analysis to maximize statistics.

3.4.9 Variations of Different Kinematics

**Variations from the event selection for this section:** 1.) $\Upsilon(1S)$ and $J/\psi$ triggers were applied together. 2.) Light mesons in the unselected combination were not rejected.

To investigate the possibility that the kinematic requirements may produce an artifact somewhere in the spectrum, we vary the kinematic cuts one by one systemat-
Figure 3.12. The 2-dimensional histograms show the transverse momentum versus pseudorapidity for each muon from the signal region (left column) and the sideband region (right column). The 1st muon with highest $p_T$ plots are in the 1st row, and the 2nd, 3rd, and 4th muon with lowest $p_T$ plots are in the following rows. Double Muon 2011 and 2012 data sets and MuOnia 2011 and 2012 data sets are combined.
ically to look at the four-muon mass spectrum which are described as the following:

- Figure 3.13 shows the $\Upsilon(1S)\mu^+\mu^-$ mass distributions where the number of “tight” muons is required to be at least 0, 1, 3, and 4, where the default requirement is 2. There are reasonable signals for the variations except 4 tight muons where the statistic are too low.

- In Figure 3.14 the $p_T$ threshold for the $\Upsilon(1S)$ and $\mu^+\mu^-$ states is varied from 1 to 6 GeV. In the default distribution there is no $p_T$ requirement for either state. There is some evidence of the signal in all of the distributions, although the event count again becomes marginal when the threshold is 6 GeV.

- A similar study is shown in Fig. 3.15 where here the $p_T$ requirement is on each of the four muons. Four thresholds were considered: 1.5, 2.5, 3.0, and 3.5 GeV. For the default $\Upsilon(1S)\mu^+\mu^-$ distributions the requirement is that each muon must have a transverse momentum greater than or equal to 2 GeV.

- In Figure 3.16 the $p_T$ threshold of the four-muon system is varied from 5 to 20 GeV. There is no requirement on four-muon state for the default $\Upsilon(1S)\mu^+\mu^-$ mass distributions. The signal is visible for the 5 and 10 GeV thresholds and the lack of events limits the probative value of the 15 and 20 GeV thresholds.

- Figure 3.18 gives the $\Upsilon(1S)\mu^+\mu^-$ mass distributions where the mass windows for the $\Upsilon(1S)$ is varied from 1 to $5\sigma$. (The default value is $3\sigma$.) As the mass window of the $\Upsilon$ is varied the upper threshold for the $\mu^+\mu^-$ state changes accordingly.
• Figure 3.19 displays the $\Upsilon(1S)\mu^+\mu^-$ mass distribution as the 4$\mu$ vertex probability requirement is varied from 0.01 to 10%. The default value is 5%, meaning the 4$\mu$ vertex probability must be at least 5%. In all cases there is some evidence of the signal.

Background and signals shapes are determined either from MC or from data which will be explained in the following sections. The rapid decrease of events by requiring 4 tight muons, dimuon $p_T$ requirements and each muon $p_T$ requirements can be understood from the muon $p_T$ distributions from two signal MC models as shown in Fig. 3.17. The lowest $p_T$ muon is too soft to pass the tight muon selection and the higher $p_T$ requirement.

All the cross-checks show reasonable behavior with no evidence of bias introduced by the event selection or analysis methods.
Figure 3.13. $\Upsilon(1S)\mu^+\mu^-$ mass distributions with tight muon requirements for 2011 and 2012, MuOnia and Double Muon data sets combined. The top left plot is for 0 tight, the top right plot is for 1 tight, the bottom left plot is for 3 tight, and the bottom right plot corresponds to a 4-tight muon requirement. The plots are fitted with the default signal and background shape.
Figure 3.14. $\Upsilon(1S)\Upsilon(1S)^*$ mass distributions with both dimuon transverse momentum requirements for 2011 and 2012, Muonia and Double Muon data sets combined. The requirements are like the following starting with the top left plot, 1 GeV, 2 GeV, 3 GeV, 4 GeV, 5 GeV, and 6 GeV. The plots are fitted with the default signal and background shape.
Figure 3.15. $\Upsilon(1S)\mu^+\mu^-$ mass distributions with minimum muon $p_T$ requirements for 2011 and 2012 data sets combined with the following values starting from top left plot and ending with the bottom right plot, 1.5 GeV, 2.5 GeV, 3.0 GeV and 3.5 GeV. The plots are fitted with the default signal and background shape. For the bottom right plot, we fit the background with a 5$^{th}$ order Chebychev polynomial.
Figure 3.16. $\Upsilon(1S)\mu^+\mu^-$ mass distributions with 4$\mu$ transverse momentum requirement for 2011 and 2012 data sets combined. Plots require the following transverse momentum cuts: 5 GeV, 10 GeV, 15 GeV and 20 GeV, from left to right and from top to bottom. The plots are fitted with the default signal and background shape.

Figure 3.17. Muon MC generator level $p_T$ distributions from $\chi_{b0}$(Left) and $H_0$(Right).
Figure 3.18. $\Upsilon(1S)\mu^+\mu^-$ mass distributions with $\Upsilon(1S)$ mass window requirement for the combined 2011 and 2012 data sets. Plots require the following mass windows: $1\sigma$, $2\sigma$, $4\sigma$, and $5\sigma$, from left to right and from top to bottom. The plots are fitted with the default signal and background shape.
Figure 3.19. $\Upsilon(1S)\mu^+\mu^-$ mass distributions with 4$\mu$ vertex probability requirement for the combined 2011 and 2012 data sets. Plots require the following vertex probability values: 0.01% (top left), 0.1% (top right), 1% (bottom left), and 10% (bottom right). The plots are fitted with the default signal and background shape.
Figure 3.20. Left plot shows the $\Upsilon(1S)\Upsilon(1S)$ mass distribution from DPS MC, right plot shows the $\Upsilon(1S)\Upsilon(1S)$ mass distribution from SPS MC.

3.4.10 Artifact Investigation due to Double Parton Scattering (DPS)

A resonance cannot be produced in a DPS process [37]. However, it may be conceivable that DPS could generate an artifact, perhaps in combination with some detector, reconstruction, or other effect. In order to investigate the issue, we created two private $\Upsilon(1S)\Upsilon(1S)$ MC samples using DPS and SPS (single parton scattering) model [37]. We ran through both MC samples with our default selections. The plots in Fig. 3.20 show the four-muon mass spectrum for DPS (left) and SPS (right) MC. In both cases there is no leakage from double upsilon to the 18.5 GeV region.

3.4.11 Artifact Investigation due to Pileup

There are multiple collisions per bunch crossing in the CMS detector, which leads to overlapping particles in the interaction of interest to us; this effect is called pileup. Even though it is a low probability, sometimes events might mix up during the reconstruction process. As a cross-check, we also investigated the $\Delta z$ detachment between two dimuon pairs to see if the signal is an artifact due to pileup. We plotted
the four-muon mass spectrum with $\Delta z > 0.5$ cm and $\Delta z > 1.0$ cm in Fig. 3.21. If there is any mixing of pileup in the events, the expectation would be that the pileup tracks would be located some distance along the beam direction. There is no indication of an artifact at 18.5 GeV from pileup events.

### 3.4.12 Studies of Light Mesons in the Unselected Combination

We have two possible opposite-sign dimuon combinations from a four-muon final state as described in Table 3.5. We require at least one combination to satisfy our mass requirements. The combination that passes the mass requirements on the dimuon pairs is called the *selected combination* and the other one is called the *unselected combination*. One interesting feature is that there is some contribution to this excess from light mesons in the unselected combination. To quantify the effect, we performed the analysis in the two sub-categories, where the light meson combinations were removed or kept within $2\sigma_{EBE}$ (one trial) or $3\sigma_{EBE}$ (another trial):

- Light mesons are removed in the unselected combination. Figure 3.22 shows the
four-muon mass distributions after removing the light mesons ($\omega, \phi, J/\psi, \psi(2S)$) in the unselected combination within the $2\sigma_{EBE}$ or $3\sigma_{EBE}$ of the PDG value for the corresponding light meson mass.

- Light mesons are included in the unselected combination. Figure 3.23 shows the four-muon mass distributions including the light mesons ($\omega, \phi, J/\psi, \psi(2S)$) in the unselected combination within the $2\sigma_{EBE}$ or $3\sigma_{EBE}$ of the PDG value for the corresponding light meson mass.

Light mesons in the unselected combinations within $2\sigma_{EBE}$ were removed in the following part of the analysis.

![Figure 3.22](image-url)

Figure 3.22. Four-muon mass spectrum if there are no light mesons in the unselected combination within $2\sigma_{EBE}$ (left), and $3\sigma_{EBE}$ (right).

3.4.13 Repeating the Analysis by Shifting the $\Upsilon(1S)$ Candidate

During the review process, it was suggested to shift $\Upsilon(1S)$ candidate to $\Upsilon(2S)$, $\Upsilon(3S)$ region and a fake $\Upsilon$ region which is in the [11.0-11.4] GeV mass window, to see
if there is any shift. If we see a shift in the signal, that would suggest that the excess
is due to kinematical effects. Fig. 3.24 shows the shifted $X\mu^+\mu^-$ mass distributions
and there is no indication of any excess in the spectrum.

3.4.14 Track Splitting Check

During the reconstruction step, CMS might misidentify the same sign tracks,
if their trajectories are very close to each other. In order to check the muons are not
coming from the same tracks, $|\Delta P_x| + |\Delta P_y| + |\Delta P_z|$ are plotted between $\mu^+\mu^+$
and $\mu^-\mu^-$. Figure 3.25 shows $\Delta P$ distributions of $\mu^+\mu^+$ and $\mu^-\mu^-$. There should be
a spike around $|\Delta P_x| + |\Delta P_y| + |\Delta P_z| = 0$, if there are tracks that are the same.

Minimum $\Delta R$ of the same sign and opposite sign muon pairings are also in-
vestigated. In order to get $(\Delta R)_{\text{min}}$ for the same sign muons, $\Delta R$ of $\mu^+\mu^+$ and $\mu^-\mu^-$
are compared and, the pair which has a smaller $\Delta R$ is chosen. For the opposite
sign muons, $\Delta R$ of $\mu^+\mu^-$ from $\Upsilon(1S)$ and the other $\mu^+\mu^-$ are compared, and the
Figure 3.24. Test of moving the Υ(1S) mass window to Υ(2S), Υ(3S), and 11.0 - 11.4 GeV range. Υ(2S)µ⁺µ⁻ (top left), Υ(3S)µ⁺µ⁻ (top right) and fake Υµ⁺µ⁻ (bottom) mass distributions are shown.

pair which has a smaller ∆R is chosen. Figure 3.26 shows the (ΔR)_{min} of same sign dimuon pairings(left) and opposite sign dimuon pairings(right).

In order to see if there is any strange behavior in XY and Z detachment between dimuon pairs, the ∆_{xy} and ∆_{z} separation between dimuon pairs is also plotted. Figure 3.27 shows the distributions.

3.4.15 Muon Isolation Quality Checks

Since muons interact less with the detector compared to other particle types, they tend to be isolated from other tracks around them. Muon isolation requirements
Figure 3.25. Track splitting check: $\Delta P$ distributions between $\mu^+\mu^+$ and $\mu^-\mu^-$.

Figure 3.26. Track splitting check: $(\Delta R)_{\text{min}}$ of the same sign dimuon pairings(left), and $(\Delta R)_{\text{min}}$ of the opposite sign dimuon pairings(right). Blue plots are a zoom of the 0.0 to 0.5 range.

Figure 3.27. $\Delta_{xy}$ and $\Delta_z$ distributions between dimuon pairs.
are used in many other particle physics analyses. We do not use muon isolation in this analysis; however, we examined isolation as a quality check. We apply different isolation cuts and check the signal region. Strict isolation cuts indicate high-quality muons. First, loop over all the muons and find the closest vertex for each muon. Then, loop over tracks coming from the closest primary vertex but only accept the tracks with the following criteria for the isolation calculation:

- The track should be a high purity track
- The track $p_T$ should be greater than 0.9 GeV
- The track and the selected muon track should not be the same.
- $\Delta R$ between the track and the muon should be smaller than 0.3.
- If the track is a muon (different than the selected muon), we excluded that track.

Then muon isolation is defined as the total $p_T$ of the tracks in the cone around the muon (excluding the muon $p_T$) divided by our selected muon $p_T$. Figure 3.28 shows each muon's isolation distribution. Typical loose cuts are $\text{Isolation} \leq 0.5$, whereas a tight cut is $\text{Isolation} \leq 0.1$. Most of the selected muons are within a loose isolation definition of 0.5. We also included the $\Upsilon(1S)\mu^+\mu^-$ mass distributions with various isolation cuts on the highest $p_T$ muon in Fig. 3.29 which shows that tightening the isolation cuts improves the quality of the muons and appears to reduce the background.
Figure 3.28. Muon isolation distributions of each muon.
Figure 3.29. $\Upsilon(1S)\mu^+\mu^-$ mass distributions with different isolation cuts on the highest $p_T$ muon. The top plot uses a tight isolation cut of 0.1 and bottom plot uses a loose isolation cut of 0.5.
3.4.16 Investigation of the Final State Radiation (FSR) Effect on Signal Shape

Figure 3.30 shows an example of the Feynman diagram of the $Z$ decay. FSR does not have to be electromagnetic radiation. If it is electromagnetic radiation, it is also called bremsstrahlung. Since some of the muons in the final state may radiate, we may partially reconstruct the signal with four-muons. In order to investigate the effect of FSR on the signal, we used two privately-generated MC samples. Both of them are generated for $H_0 \rightarrow \Upsilon(1S)\mu^+\mu^-$ but one includes the FSR corrections and the other does not. In Fig. 3.31, the top plots show the four-muon signal without and with FSR corrections, bottom plots show the overlap of the top plots in linear scale and in log scale. From the figures, it can be concluded that FSR does not have a significant effect on the four-muon signal.

3.4.17 Final Event Selection and Mass Spectrum

The final event selection criteria and mass distribution is finalized below.

- Each event is triggered by HLT_DiMuon0_Upsilon_Muon for the Muonia dataset, or triggered by HLT_TripleMu5 but not by HLT_DiMuon0_Upsilon_Muon in the
Figure 3.31. Four-muon mass signal without FSR (top left) and with FSR (top left). Overlap of first two plots in normal scale (bottom left) and in log scale (bottom right).
DoubleMu dataset.

- Each muon must have $|\eta|\leq 2.4$.

- Each muon must have $p_T \geq 2.0$ GeV.

- Each muon must pass the soft-muon criteria, and at least two muons must pass the tight muon criteria.

- Four-muon total charge is required to be 0.

- Fit the four muons to a common vertex and label the four muons in the final state as $\mu_1^+ \mu_2^- \mu_3^+ \mu_4^-$. The four-muon vertex probability is required to be greater than 0.05.

- There are 2 combinations of dimuon pairs with 0 charge. $(\mu_1^+ \mu_2^-)$ vs. $(\mu_3^+ \mu_4^-)$; $(\mu_1^+ \mu_4^-)$ vs. $(\mu_2^- \mu_3^+)$. Order the two combinations of zero charged dimuon pair as: $m(\mu^+ \mu^-)_{i1} > (\mu^+ \mu^-)_{i2}$ for $i = 1, 2$; $m(\mu^+ \mu^-)_{11} > m(\mu^+ \mu^-)_{21}$;

- Require $|m(\mu^+ \mu^-)_{i1} - 9.46| \leq 3\sigma(\Upsilon(1S)_{EBE})$ and $m(\mu^+ \mu^-)_{i2} \leq 9.46 - 3\sigma(\Upsilon(1S)_{EBE})$ for either $i=1$, or $i=2$.

- Each dimuon vertex probability for the selected dimuon pair must be greater than 0.005–confirm HLT trigger requirement.

- There are no $\omega/\phi/J/\psi$ mesons within $2\sigma(EBE)$ of their PDG values in the unselected combination.
Figure 3.32. The invariant mass distribution of $\mu^+\mu^-\mu^+\mu^-$ in the $\Upsilon(1S)$ signal region and in the side band region.

- Muons from the first dimuon pair are matched to the muons coming from the HLT_DiMuon0_Upsilon_Muon in the Muonia dataset.

Figure 3.32 shows the four muon invariant mass distribution after applying the final event selection criteria.
There is excess in the $\Upsilon(1S)\mu^+\mu^-$ channel, there is a possibility of confusion among the muons. One way to check this would be to examine similar channels, in which there is no possibility of confusion on pairings. Since CMS provides an $\Upsilon(1S) \to \mu^+\mu^-$ trigger, the easiest and closest channel as a cross check is $\Upsilon(1S)e^+e^-$. Compared to muons, electrons interact with matter a lot faster and lose their energy via bremsstrahlung due to their low mass. Electrons require more sophisticated energy correction algorithms during reconstruction. There was a small issue when reconstructing the $\Upsilon(1S)e^+e^-$ mass because electron energy corrections are designed for high $p_T$ analyses. In this analysis electron tracks’ momentum information is used from the vertex and it also shows and validates that this method correctly predicts the invariant mass of $\Upsilon(1S) \to e^+e^-$ and $J/\psi \to e^+e^-$. Figure 3.33 shows the difference between calibrated ECAL energy, GSF (Gaussian Sum Filter) track momentum, and track momentum at vertex at low-$p_T$.

### 3.5.1 Event Selection

We used the following event selections for $\Upsilon(1S) \to \mu^+\mu^-$:

- 2 oppositely charged soft muons [A.1].
- Each muon $p_T > 2$ GeV
- Each muon $|\eta| \leq 2.4$
- Dimuon vertex probability is bigger than 0.005

For electrons, we have the following requirements:
Figure 3.33. Comparison of different mass reconstruction algorithms for Υ(1S) and J/ψ.

- Two oppositely charged electrons.
- Each electron $p_T > 2$ GeV
- Each electron $|\eta| \leq 2.4$
- Each electron track is required to have a normalized $\chi^2 < 1.8$
- Each electron track is required to have a $\Delta z$ relative to primary vertex $< 30$ cm
- Each electron is required to have MVA (multivariate analysis) [33, 36] $\geq 0.5$ or to be a CMS standard loose electron[B.1].

The above cuts are called general cuts. We require the dimuon mass to be within $3\sigma$ of the $\Upsilon(1S)$ nominal mass and then require the dielectron mass to be less than 9.2 GeV. As in the case of the four muon final state, the width of the $\Upsilon(1S)$ mass is scaled by 1.105, and the dielectron mass is calculated from track momenta at the vertex.
3.5.2 Υ(1S)e+e− Mass Distribution

Figure 3.34 (left) shows the dimuon mass distribution after applying the cuts on the dimuon system, there are clearly J/ψ, ψ(2S) and Υ(1S) signals there, and the right plot shows the dielectron mass after applying the dimuon mass cut (|m(μ+μ−) − 9.46| < 3σ). Figure 3.35 shows the μ+μ−e+e− mass distributions after dimuon and dielectron mass requirements, which show an excess between 18 and 19 GeV in both plots.

3.5.3 Variation of Different Kinematics

As we did in the Υ(1S)μ+μ− case, we investigated the Υ(1S)e+e− mass spectrum with different kinematic requirements. Kinematic cuts are varied one by one systematically to look at the Υ(1S)e+e− mass spectrum which is described as the following:

Figure 3.34. (Left) μ+μ− mass after general cuts. (Right) e+e− mass after general cuts and |m(μ+μ−) − 9.46| < 3σ
Figure 3.35. (Left) The $\mu^+\mu^-e^+e^-$ mass distribution without a dielectron mass cut. (Right) The $\mu^+\mu^-e^+e^-$ mass after $|m(e^+e^-)| < 9.2$ requirement. The blue histogram represents $\Upsilon(1S)$ signal region with dimuon mass to be within $3\sigma$ of nominal $\Upsilon(1S)$ mass and the red histogram represents $\Upsilon(1S)$ sideband region with dimuon mass in [8.6, 9.2] GeV.

- Figure 3.36 shows the $\Upsilon(1S)e^+e^-$ mass distributions where the dielectron $p_T$ is greater than 2, 3, 4, 5, and 6 GeV, while there is no requirement in the default selection.

- In Figure 3.37 the $p_T$ threshold for each lepton is required to be greater than 2.5, and 3.0 GeV. The excess with lepton $p_T > 3$ GeV is very marginal.
Figure 3.36. $\Upsilon(1S)e^+e^-$ mass distributions with different dielectron $p_T$ requirements.
Figure 3.37. $\Upsilon(1S)e^+e^-$ mass distributions with different lepton $p_T$ requirements.
3.6 Signal & Background Shapes

3.6.1 Signal Shape for $\Upsilon(1S)\mu^+\mu^-$

This analysis performs a search in the $\Upsilon(1S)\mu^+\mu^-$ and $\Upsilon(1S)e^+e^-$ channels where the $m(\mu^+\mu^-)$ and $m(e^+e^-)$ masses are required to be less than the nominal $\Upsilon(1S)$ mass. An excess is found at 18.5 GeV, which is less than twice the $\Upsilon(1S)$ mass. We investigated the natural width of this excess and concluded that it is consistent with the CMS detector resolution. We fixed the excess shape to that obtained from Monte Carlo simulation in the fit to the data to extract the strength of the excess. The width investigations which were done can be summarized as follows:

1. The excess mass is less than twice the $\Upsilon(1S)$ mass. Naively, the width of a resonance with this mass is expected to be “narrow” because the decay to double $\Upsilon(1S)$ is not allowed.

2. Our test with event-by-event mass errors assuming a Gaussian shape also shows that the natural width of this excess is essentially consistent with the detector resolution. The details of this study are described in Section 3.7 and Fig. 3.50.

3. We fit data with the signal shape fixed from MC simulation. The pull of all the data points are around 0, which shows that our modeling of the excess with detector resolution is reasonable.

In order to extract the signal shape, we produced 5 MC samples to simulate 5 mass points for each channel. 15, 18.5, 25, 36, 50 GeV mass points were generated for the $4\mu$ channel and 13, 15, 18.5, 25, 36, 50 GeV mass points were generated for the $2\mu2e$ channel. We use two Crystal Ball (CB) functions to model the $\mu^+\mu^-\mu^+\mu^-$.
signal shape and we use a Breit-Wigner (BW) function plus a CB function to model the $\mu^+\mu^- e^+e^-$ signal shape.

Each signal p.d.f. parameter $k_i(m)$ is a function of the signal mass $m$. We try to parametrize these functions $k_i(m)$ by fitting them with polynomials $k_i(m) = p0 + p1 \times m + p2 \times m^2 + \ldots$. We first performed separate fits to each MC sample one by one. For each parameter $k_i(m)$, we found 5 values corresponding to different mass points after all the fits, we then parameterized the trend of these 5 points with a polynomial. We can now get a set of $\{p0, p1, p2, \ldots\}$ for each $k_i(m)$ after the parametrization. As a next step, in order to take into account the correlations of the 5 mass points and the correlations of $k_i$, a simultaneous fit to all the 5 MC samples was used to extract the polynomial parameters $\{p0, p1, p2, \ldots\}$ for all the $k_i(m)$ at the same time. The initial values of each set of $\{p0, p1, p2, \ldots\}$ in the simultaneous fitter were taken from the output of the separate fits. In the end, we compared the two fitting methods and concluded that the parametrized polynomials in the simultaneous fit are consistent with the ones we got from the separate fits.

For the $\mu^+\mu^- \mu^+\mu^-$ channel, the separate fits of each MC signal sample are shown in Fig. 3.38, while a simultaneous fit to all the 5 signal samples is shown in Fig. 3.39. The pull distributions for the simultaneous fit are shown in Fig. 3.40, which indicates that the quality of the fit is good. The signal p.d.f. extracted from the fits is shown in Fig. 3.41.

In Fig. 3.42, we try to find a trend of all of the signal p.d.f. parameters $k_i(m)$ versus the signal mass $m$. These trends are parametrized by polynomials $p0 +$
\( p_1 \star m + p_2 \star m^2 + ... \). The polynomial parameters \( \{p_0, p_1, p_2, \ldots\} \) returned from the simultaneous fit are shown in Table 3.6. They will be passed into the Higgs Combination Tool to do the final data fit and compute the significance.

A similar study is done for the \( \Upsilon(1S)e^+e^- \) channel and the result is shown in the following sections.

Figure 3.42 shows the variation of signal parameters for different mass points. We used two Crystal-Ball functions to model the signal shape for each MC sample (15, 18.5, 25, 36, 50 GeV). There are seven parameters \( k_i \) used in the signal p.d.f., which are shown in the seven plots, respectively. For each plot, the red points represent the parameter values from separate fits to each MC signal sample. Then we try to find the trend of the red points by performing a polynomial fit \( k_i(m) = p_0 + p_1 \star m + p_2 \star m^2 + ... \) (red curve). Alternatively, we can do a simultaneous fit to all the 5 mass points. The blue curve for each parameter shows the polynomial directly extracted from the simultaneous fit. The blue and the red curves are consistent with each other. The parametrization for all the \( k_i \) returned from the simultaneous fit is summarized in Table 3.6.
Figure 3.38. Separate fits of $H \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ MC signal for different $m_H$ assumptions.
Figure 3.39. A simultaneous fit to $H \rightarrow \mu^+\mu^-\mu^+\mu^-$ MC for different $m_H$ assumptions.
Figure 3.40. Pull of the simultaneous fit to \( H \to \mu^+\mu^-\mu^+\mu^- \) MC for different \( m_H \) assumptions.

Figure 3.41. Signal p.d.f. for the \( H \to \mu^+\mu^-\mu^+\mu^- \) signal. Left: separate fits for each mass point. Right: simultaneous fit to all the mass points.
Figure 3.42. Variation of signal parameters for different mass points for the $H \rightarrow \mu^+\mu^-\mu^+\mu^-$ channel.
Table 3.6. Parametrized polynomial returned from the simultaneous fit in the 4µ channel. For example, the signal p.d.f. parameter CB1 σ is parametrized as
\[ \sigma_{CB1}(m) = p0 + p1 \times m + p2 \times m^2. \]

<table>
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<th>fitted value</th>
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<tr>
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<tr>
<td>CB1 σ p2</td>
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<tr>
<td>CB1 n p2</td>
<td>0.0012 ± 0.0002</td>
</tr>
<tr>
<td>CB2 σ p0</td>
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</tr>
<tr>
<td>CB2 σ p1</td>
<td>0.0072 ± 0.0017</td>
</tr>
<tr>
<td>CB2 σ p2</td>
<td>0.00010 ± 0.00003</td>
</tr>
<tr>
<td>CB2 α p0</td>
<td>-2.14 ± 0.08</td>
</tr>
<tr>
<td>CB2 n p0</td>
<td>1.38 ± 0.18</td>
</tr>
<tr>
<td>fraction</td>
<td>0.46 ± 0.03</td>
</tr>
</tbody>
</table>

3.6.2 Background Shape for Both Channels

It is agreed by the review committee to take the event-mixing background shape for Υ(1S)e+e− channel and floating polynomial background shape for Υ(1S)µ+µ− channel as basis to evaluate the local significance for each channel using the CMS Higgs Combination Tool.

For the Υ(1S)e+e− channel, the dimuon pair (Υ(1S)) and dielectron pair are selected from different events to form the event-mixing shape. For the Υ(1S)µ+µ− channel, the first dimuon pair (Υ(1S)) and the second dimuon pair are selected from different events. However, as we explained before, there is a confusion in the dimuon pairing, and we abandon the event-mixing shape for the Υ(1S)µ+µ− channel.
For 4\(\mu\) channel, we use a floating polynomial to model our background shape. In order to determine the order of the polynomial, we exclude the events in the signal region, between 18 and 19 GeV in the four-muon mass spectrum, and perform an F-test: fit the rest of the events with different order polynomials (starting from the lowest order, and increase one order for each test) and compare the \(\Delta \chi^2\) (equivalent 2X of the log-likelihood ratio) between the two fits, the lower order is chosen once the ratio is less than 1. The 4th order Chebychev polynomial was determined to be the right order in this case, and the fit is shown in Fig. 3.43 (left). The returned values for all the parameters are shown in the plot, the boundary for each polynomial parameters are set between -2 and 2.

The event-mixing mass spectrum shape for the 2\(\mu\)2\(e\) channel is shown in Fig. 3.43 (right). We use a Chebychev function to model the event-mixing shape. We restrict the fit range from 13 to 26 GeV in order to make a reasonable fit. The order of the Chebychev polynomial is decided by the same F-test, which shows that a 5th order polynomial should be used for the 2\(\mu\)2\(e\) background.

The full background shape uncertainty can be calculated with the uncertainties of each parameter in the polynomial and a corresponding covariant matrix. A script named PdfDiagonalizer is used to decorrelate these parameters, so that we can easily pass the shape uncertainties into the Higgs Combination Tool, which is used to compute the significance.
Figure 3.43. Fit the event-mixing background shape for the $2\mu 2e$ channel and fit the background shape excluding signal region in the $4\mu$ channel. Left: A 4th order polynomial fit to the $4\mu$ channel; right: A 5th order polynomial fit to the $2\mu 2e$ channel method.

3.6.3 Signal Shape for $Y(1S)e^+e^-$

Just as in the previous section, the signal shape is extracted from MC simulation for the $\mu^+\mu^-e^+e^-$ channel. The separate fits for each MC signal sample are shown in Fig. 3.44, while a simultaneous fit to the 5 signal samples are shown in Fig. 3.45. The pull distributions for the simultaneous fit are shown in Fig. 3.46, which indicates that the quality of the fit is good. The signal pdfs extracted from the fits are shown in Fig. 3.47.

In Fig. 3.48, we try to find a trend in the signal p.d.f. parameters $k_i(m)$ versus the signal mass $m$. These trends are parametrized by polynomials as $k_i(m) = p0 + p1 \times m + p2 \times m^2 + \ldots$ The $\{p0, p1, p2, \ldots\}$ returned from the simultaneous fit are shown in Table 3.7. They are passed to the Higgs Combination Tool to do the final data fit to determine the significance.
Figure 3.44. Separate fits of $H \rightarrow \mu^+\mu^-e^+e^-$ MC signal for different $m_H$ assumptions.
Figure 3.45. A simultaneous fit to $H \to \mu^+\mu^-e^+e^-$ MC for different $m_H$ assumptions.

Parametrized polynomial returned from the simultaneous fit in the $2\mu2e$ channel. For example, the signal p.d.f. parameter BW width is parametrized as $Width_{BW}(m) = p0 + p1 \times m + p2 \times m^2$.

Table 3.7. Parametrized polynomial returned from the simultaneous fit in the $2\mu2e$ channel.

<table>
<thead>
<tr>
<th>Parametrized polynomial for each signal p.d.f. parameter</th>
<th>fitted value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BW width p0</td>
<td>0.45 ± 0.15</td>
</tr>
<tr>
<td>BW width p1</td>
<td>-0.013 ± 0.011</td>
</tr>
<tr>
<td>BW width p2</td>
<td>0.00080 ± 0.00020</td>
</tr>
<tr>
<td>CB $\sigma$ p0</td>
<td>-0.081 ± 0.016</td>
</tr>
<tr>
<td>CB $\sigma$ p1</td>
<td>0.016 ± 0.001</td>
</tr>
<tr>
<td>CB $\alpha$ p0</td>
<td>0.94 ± 0.04</td>
</tr>
<tr>
<td>CB $\alpha$ p1</td>
<td>-0.052 ± 0.003</td>
</tr>
<tr>
<td>CB $\alpha$ p2</td>
<td>0.00082 ± 0.00005</td>
</tr>
<tr>
<td>CB n p0</td>
<td>11.99 ± 0.86</td>
</tr>
<tr>
<td>CB n p1</td>
<td>-0.23 ± 0.02</td>
</tr>
<tr>
<td>fraction</td>
<td>0.74 ± 0.01</td>
</tr>
</tbody>
</table>
Figure 3.46. Pull of the simultaneous fit to $H \rightarrow \mu^+ \mu^- e^+ e^-$ MC for different $m_H$ assumptions.

Figure 3.47. Signal p.d.f. for the $H \rightarrow \mu^+ \mu^- e^+ e^-$ signal. Left: separate fits to each mass point. Right: simultaneous fit to all the mass points.
Figure 3.48. $H \rightarrow \mu^+ \mu^- e^+ e^-$ channel. We used two Crystal-Ball functions to model the signal shape for each MC sample (13, 18.5, 25, 36, 50 GeV). There are five parameters $k_i$ used in the signal p.d.f., which are shown in the five plots, respectively. For each plot, the red points represent the parameter values from separate fits of each MC signal sample. Then we try to find the trend of the red points by performing a polynomial fit $k_i(m) = p0 + p1 \times m + p2 \times m^2 + \ldots$ (red curve). Alternatively, we can do a simultaneous fit to all the 5 mass points. The blue curve for each parameter shows the polynomial directly extracted from the simultaneous fit. The blue and the red curves are consistent with each other. The parametrization for all the $k_i$ returned from the simultaneous fit is summarized in Table 3.7.
Figure 3.49. A fit to the signal shape from $H^0$ model using a single Gaussian function.

### 3.7 Investigating the Intrinsic Width of the Structure

In order to investigate the intrinsic width of the signal, we fit the signal shape with an S-wave Breit–Wigner function convoluted with a Gaussian resolution function. The width of the Gaussian function is determined from signal MC. The range of the signal is confined between 18.2 and 18.8 GeV and is fitted to a single Gaussian. The fit returned the Gaussian width to be 143 MeV. Fig. 3.49 shows the fit.

Using an S-wave Breit–Wigner function convoluted with a Gaussian resolution function with a fixed width (143 MeV), the mass spectrum is refit and the returned intrinsic width is $0 \pm 35$ MeV as shown in Fig. 3.50. The width is essentially consistent with 0 but we cannot determine it precisely. We state that the intrinsic width is consistent with the detector resolution.
Figure 3.50. Fit to get the intrinsic width of the structure. The width is consistent with 0.
3.8 Final Fit and Significance

During the review process, it was agreed upon to use the HiggsCombinationTool, which was developed for the Higgs discovery to combine different decay channels, and to calculate the global significance when combining several channels [1]. The package was used to calculate the significance of the Higgs boson discovery by combining different Higgs decay channels. In our analysis, we pass all the signal and background parameters with their uncertainties to the HiggsCombinationTool.

In both channels, the test statistic is evaluated as $\sqrt{-2\ln(L_0/L_s)}$. $L_0$ is the background hypothesis and $L_s$ is the signal hypothesis. By scanning the mass spectrum the best mass value is determined at the largest log-likelihood value.

Figure 3.51 shows the four-muon mass distributions after the above event selections and a fit using 4th order polynomial shape as background p.d.f., and the signal shape from MC. The number of excess events is found to be $44 \pm 13\, (\text{stat.})$ with a mass of $18.4 \pm 0.1\, \text{GeV}$. The local significance, including systematics, for this excess is $4.9\sigma$. The mass of the excess, including systematics, is measured to be: $18.4 \pm 0.1\ (\text{stat.}) \pm 0.2\ (\text{syst.})\ \text{GeV}$.

Figure 3.52 shows the $\mu^+\mu^-e^+e^-$ mass distributions after the above event selections. We fit the mass spectrum using the signal shape obtained from MC and a 5th order polynomial obtained from the event-mixing shape for the background p.d.f.. The number of excess events is found to be $35\pm13\, (\text{stat.})$ with a mass of $18.5 \pm 0.2\, \text{GeV}$. The local significance, including systematics, for this excess is $3.2\sigma$. The mass of the excess, including systematics, is measured to be: $18.5 \pm 0.2\ (\text{stat.}) \pm 0.2\ (\text{syst.})\ \text{GeV}$.
Figure 3.51. Fit data with the background p.d.f. fixed to the $4\mu$ background shape, and the signal p.d.f. parameters fixed to the parametrized polynomials.

Figure 3.52. Fit data with the background p.d.f. fixed to the $2\mu2e$ event-mixing shape, and the signal p.d.f. parameters fixed to the parametrized polynomials.

Finally, we do a simultaneous fit to both $4\mu$ and $2\mu2e$ channels using the HiggsCombinationTool in Fig. 3.53. The background pdfs are from the two event-mixing shapes respectively, and the signal shape parameters are fixed to the parametrized function obtained from MC. The returned $2\Delta nll$, likelihood ratio between signal- and null-hypothesis fit, is 26.48. Since all the shape parameters are fixed, but the total
signal yields and the relative signal ratio of the two channels are floating, thus the number of degrees of freedom is 2. The local significance is $4.9\sigma$ computed by the HiggsCombinationTool. The returned mass is: $18.4 \pm 0.1\text{ (stat.)} \pm 0.2\text{ (syst.) GeV}$.

Figure 3.53. Final simultaneous fits to data.

In order to calculate the global significance we need to consider the look-elsewhere-effect (LEE). A $5.0\sigma$ significance corresponds to a $p_{value}$ of $3 \times 10^{-7}$. A large amount of pseudo-data is needed, which is a CPU intensive task. In other words, what is the probability that the excess can appear in the spectrum from 13 to 26 GeV? In this case, we need to generate about $10^7$ toy MC samples, and try to find a distribution as significant as ours. In toy MC, we generate the distribution according to the original background shape and number of events by using poisson statistics. However, we simply cannot know the distribution of the entire spectrum. Instead of
Figure 3.54. Top) A simultaneous fit to background only $\Upsilon(1s)\mu^+\mu^-$ and $\Upsilon(1s)e^+e^-$ MC simulation. The solid line shows the best signal fit and the dotted line shows the background. Bottom) The likelihood ratio test statistic $q(m)$. The red solid lines shows the $c_0$ reference level which cross about 12 times with the test of statistics.

using a toy MC technique, it is agreed to use the G-V (Gross-Vitells) method [31], which significantly decreases the number of pseudo-data to be generated. With the G-V method, the global significance is calculated as: $p_{global} = p_{local} + < N(c_0) > \times (c/c_0)^{(s-1)/2} \times e^{-(c-c_0)/2}$. The constant $< N(c_0) >$, is the number of upcrossing points from reference level across the test statistic in a certain mass range. Figure 3.54 shows the number of upcrossings for G-V method in one pseudo-data sample. $s$ denotes the number of channels (it is two in our case) and $c_0 = s - 1 = 1$. $c$ is the likelihood ratio between signal and null-hypothesis fit ($2\Delta nll$) in our analysis and it is 26.48.
$< N(c_0) >$ can be calculated counting the number of upcrossings in a small set of background-only pseudo-data. A total of 20 pseudo-data samples based on the $4\mu$ and $2\mu2e$ background-only are generated to find the upcrossing points. The average $< N(c_0) >$ value is found to be: $11.6\pm0.3$ which gives us a global p-value of $1.7\times10^{-4}$, corresponding to a global significance of $3.57\,\sigma$.

### 3.9 Systematics

In order to calculate the systematic uncertainties on the mass of the excess, we changed the selection cuts, signal shape, or background shape one at a time. We refitted the spectrum and found the mass value. We summarize the largest variations as follows:

- **Systematic uncertainty due to muon momentum scale:** We fit $\Upsilon(1S)$ and found that $m_{\Upsilon(1S)} = 9.4369$ GeV, which deviates 23.4 MeV compared to PDG value. In our case, we have 2 $\Upsilon(1S)$, so we assign muon momentum scale uncertainty as 47 MeV.

- **Systematic uncertainty due to vertex constraint:** In the analysis we use the momentum information from the fit muons (muon momentum is adjusted according to the vertex.) Instead we tried raw muon momentum information. We determine the uncertainty due to the vertex constraint is 12 MeV.

- **Systematic uncertainty due to signal shape:** In $2\mu2e$ channel, if we use a single Gaussian shape to model the signal shape, we found out that the signal is shifted 130 MeV from its original value. Thus, we assign 130 MeV uncertainty due to
the signal shape choice.

- Systematic uncertainty due to background shape: In 2µ2e channel, we changed the order of the polynomial of the background shape and we assign the biggest uncertainty of 20 MeV as our uncertainty.

To summarize, the systematic uncertainties we investigated by combining both channels are listed in Table 3.8—we choose the larger one from the two channels for each item. The total systematic is calculated as \( \sqrt{47^2 + 12^2 + 130^2 + 20^2} \) MeV = 140 MeV \( \approx 0.2 \) GeV.

Table 3.8. Summary of the systematic uncertainties on the mass of the excess.

<table>
<thead>
<tr>
<th>Source</th>
<th>Mass Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum Scale</td>
<td>±47 MeV</td>
</tr>
<tr>
<td>Vertex Constraint</td>
<td>±12 MeV</td>
</tr>
<tr>
<td>Signal Shape</td>
<td>±130 MeV</td>
</tr>
<tr>
<td>Background Shape</td>
<td>±20 MeV</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>±0.2 GeV</td>
</tr>
</tbody>
</table>

3.10 Conclusion

We present evidence for an enhancement in the invariant mass distribution of \( \Upsilon(1S)l^+l^- \) final states, with \( l \) an electron or muon. The width of the enhancement is consistent with the CMS detector resolution, and the mass is determined to be 18.4 \( \pm 0.1 \) (stat.) \( \pm 0.2 \) (syst.) GeV. The global significance of the result is 3.6 standard deviations. A possible standard model interpretation of this enhancement is a
tetraquark state composed of two bottom quarks and two bottom antiquarks with a mass slightly below the $\Upsilon(1S)\Upsilon(1S)$ mass and a width smaller than 150 MeV. However, a new physics explanation, such as an elementary light scalar particle, remains a possibility.
CHAPTER 4

CMS SILICON DETECTOR UPGRADE STUDIES

4.1 Introduction to LHC-CMS Upgrade

The LHC is one of the world’s most complex instruments. It was built between 1998 and 2008. It is designed to handle instantaneous luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$. The CMS detector took data with $\sqrt{s} = 7\text{ TeV}$ and $\sqrt{s} = 8\text{ TeV}$ from 2010 to 2013. In 2013 and 2015, LHC had a Long Shutdown 1 (LS1), to upgrade the detectors. CMS started to take data again in 2015 with $\sqrt{s} = 13\text{ TeV}$, and it took data until the end of 2016. During the technical stop in the first half of 2017, the CMS pixel detector components were upgraded. The detector upgrades implemented during this technical phase are called Phase I Upgrade projects.

At the end of 2018, there will be another long shutdown (LS2), in which CMS will have the Phase II Upgrade. After the Phase II Upgrade, CMS will be ready for instantaneous luminosities of $2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$. The long shutdowns and technical stops provide CMS with an opportunity to improve its detector components in order to make the detector more efficient and repair the problems encountered during the run period.

Figure 4.1 shows the data taken by CMS throughout the years. The total integrated luminosity expected to be delivered by the LHC is 500 fb$^{-1}$.

In order to benefit from higher instantaneous luminosities, CMS needs to improve its granularity, trigger performance, and data taking process. For the CMS silicon tracker, there will be two major upgrades in two phases. Starting from late
Figure 4.1. The total data taken by the CMS detector during the years in terms of total integrated luminosity over time.

2016 to mid 2017, the CMS pixel detector will be replaced and the number of pixel detectors and readout channels will be almost doubled. As a second step, during LS2, a new tracking system will be installed in the CMS detector.
4.2 CMS Forward Pixel Phase I Upgrade

The performance of the pixel detector at high luminosity is limited by the readout chips (ROCs) and optical fibers for high instantaneous luminosity. Current ROCs have limited bandwidth and cannot handle the amount of data collected in high instantaneous luminosity conditions. A new detector is designed to solve these problems. The barrel section (BPIX) will contain four layers instead of three, and, the forward region (FPIX) will have three disks instead of two (in one side). In this design, particles will be interacting with four layers in $|\eta| < 2.5$ region. The number of pixels in BPIX will increase from 48 million to 79 million, and 18 million to 45 million in FPIX. The ROCs will be upgraded to a higher hit rate capability with a new power supply system using DC-DC converters to reduce the power loss. The new pixel detector is expected to survive under $2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ luminosity and collect 500 $\text{fb}^{-1}$ of data. The overall configuration of the new detector and comparison with the current one is shown in Fig 4.2.

4.2.1 FPIX Sensor Quality Assurance at FNAL

For the upgrade CMS will be using similar type of sensors with the same type of construction techniques and processing steps. Each pixel is essentially a silicon detector, in which a reverse bias voltage is applied on both sides. Energetic particles that are passing through the pixels create electron-hole pairs. These pairs are then collected on each side using ROCs. Fig. 4.3 shows the structure of an individual pixel sensor. The sensors are $100\mu$m $\times$ $150\mu$m. To reduce the cost, the wafer size has been increased from four to six inches. The wafers are produced by Sintef, a research
company located in Norway. The wafers we tested are shown in Fig 4.4 (left). Each wafer has eight sensors. After the testing, good sensors were cut from the wafer and bonded with modules. A probe station is used to measure the leakage current as shown in Fig. 4.4 on the right.

Figure 4.3. The structure of the pixels detectors.
Due to the radiation damage, the reverse bias voltage will be increased throughout the years to maintain expected performance. Also an increase of leakage current leads to a higher power dissipation and to a rise of the sensor temperature. We need to make sure that the break down voltage is high enough that sensors won’t die after installation and the leakage current does not increase too much. After production, Sintef made the initial measurements. To ensure that only good sensors are installed at CMS, we chose about 10% of those wafers and checked their leakage current values at SiDet (Silicon Detector Facility), Fermilab.

The quality assurance process includes the following steps: 1) visual inspection,
2) Current-Voltage (IV) measurement, 3) Capacitor-Voltage (CV) measurement, and 4) comparing with Sintef results. Later all the measurements are saved to a CMS database, for future reference. Two criteria are required to define a good sensor. I) The leakage current at 100 V must be smaller than 1 \( \mu \)A. II) The leakage current at 150 V must be smaller than 2\( \times \) the current at 100 V. Sintef also uses a similar criteria. Fig. 4.5 shows IV measurements from two different wafers. Left plot shows the consistent measurements between Fermilab and Sintef, while the right plot shows an inconsistent result. The CV measurement was performed on sensors at Fermilab but on diodes at Sintef. The differences in the CV measurements is expected but we still look for a plateaued graph in CV measurements.

Figure 4.5. Left: Sensor measurement comparisons with Sintef from a single wafer. Both measurements are consistent with each other. Right: There is a discrepancy between two measurements. Those sensors are removed from FPIX installation.

We also compared the breakdown voltages between two measurements. The breakdown voltage is defined as the voltage when the leakage current reaches 1\( \mu \)A. Fig. 4.7 shows the comparisons between the Fermilab and Sintef wafers.
Figure 4.6. Left: CV measurements on sensors at Fermilab and on diodes at Sintef.

Figure 4.7. Breakdown voltage comparisons between Fermilab and Sintef.

Sintef shipped 165 wafers in total from March 2015 to May 2016 in 4 different batches (B, C, D, E batches). Fig. 4.8 shows the delivery summary of the batches. About 10% of them were chosen and measured. We found that only 3% of the measurements were inconsistent with Sintef. The average leakage current was about $5\text{nA/cm}^2$ at 150 V. After the measurements, the sensors were shipped to RTI, a company in the U.S for bump bonding process.
4.2.1.1 Summary

We measured about 10% of all the wafers and there was only a 3% inconsistency of measurements between Fermilab and Sintef. The average current at 150V is found to be 5nA/cm$^2$, and the depletion voltage is found to be around 80V. The yield is about 95.2% according to Sintef measurements which were confirmed by our measurements. Installation of the sensors was finished before May 2017.
4.2.2 DC-DC Converter Upgrade

Doubling the number of pixels requires twice as many channels to transfer the data. This requires more power to operate. However, due to the limited space, the existing cable plant must be re-used and the current flowing the cable will be doubled. This increases the power loss by a factor of four. A new powering solution is required to reduce the power loss inside the pixel detector.

CMS has chosen the DC-DC powering scheme for the pixel upgrade [25]. A DC-DC converter can decrease the current passing through the cables while maintaining the power which can decrease the power loss through the cables. Since, there is no past experience with this kind of powering scheme in any HEP experiments, careful designs and tests are mandatory [28].

CMS has chosen the DC-DC converters to be “buck” type. Fig. 4.9 shows the circuits of a buck converter. A buck converter is also called step-down converter because the input is high voltage - low current and the output is low voltage - high current.

Converters are built based on FEAST2 chip designed by CERN and named as PIX_V13. The rest are manufactured and tested by Physikalisches Institut, RWTH Aachen University, Germany. The transistors are embedded in a radiation tolerant material. The chip is designed for operation in a strong magnetic field (4 T) and it has a protection for over-temperature and over-current. The converters include a 430nH inductor and the switch frequency is about 1.5 MHz.

Two variants of DC-DC converters are required by the ROCs. One type, which
Figure 4.9. Simplified schematics of a DC-DC converter in on and off state (left); output voltage and the current on the inductor graph of a continuous converter.

has an output voltage of 2.4 V, will power the analog circuitry of the ROC. Second type, which has an output voltage of 3.5 V, will power the digital circuitry of the ROC. The converters are equipped with an electromagnetic shield, shown in Fig 4.10.

Figure 4.10. Photographs of a PIX_V13 DC-DC converter without (left) and with shield (right).

Individual converters were delivered to Fermilab for installation in the new
CMS FPIX detector for the Phase I upgrade in November, 2015. All the testing and the assembly were finished in February, 2016. Figure 4.10 shows the individual DC-DC converters. For better cooling, cable management purposes and due to the design of the actual pixel detector, 4 analog and 4 digital DC-DC converters are installed on the same board with a cooling bridge. All the cooling bridges are aligned in order to improve electrical contact for grounding. There will be sub-cooled bi-phase (part liquid, part gas) $CO_2$ passing through the cooling bridge. Analog and digital converters do not provide analog or digital voltages but they provide 3.5V and 2.4V stable voltage values for analog and digital converters respectively. Analog and digital converters power the analog and digital sections of the ROCs. Fig. 4.11 shows the board installed with 8 DC-DC converters with power-in, monitor, outputs, and the cooling bridges on the left and the board itself shown on the right.

Due to the design of the FPIX detector, there will be 4 half-cylinders (HC) and each cylinder will hold 12 DC-DC converter boards with a total of 48 boards. Figure 4.12 shows the design of one of the HC with planned board installation. 24, 12, and 12 boards will be installed in the middle, on the right edge, and on the left edge respectively on the HC. Since they are grouped according to the installation area; 24, 12, and 12 boards will have no notches, notches on the “left” side, and notches on the “right” side of the cooling bridges respectively. Figure 4.13 shows the boards with notches on the “left” side, and notches on the “right” side of the cooling bridges. A total of 54 boards were assembled at SiDet, Fermilab; in which 26, 13, and 13 boards will have no notches, notches on the “left” side, and notches on the
4.2.2.1 Testing the Boards

Individual DC-DC converters were tested at RWTH Aachen University and their individual voltage outputs were sent to Fermilab. However they used a different experimental setup when testing the individual converters. They were able to change the load resistance. They measured the voltage output at 1 Amp. They also used a thicker cable which decreases the power loss.

In order to make sure that DC-DC converters are working properly after the assembly, we retested all the DC-DC converters again. During the testing, we applied
Figure 4.12. Design of one HC with DC-DC converter boards.

Figure 4.13. The cooling bridge design with notches on the left side (left) and on the right side (right).
∼ 10 V to the boards. We used an AA battery (∼ 1.5 V) to enable the output of the converters. Our setup includes copper but two different types of wires; one type is short (colored) that are connected to the load resistance, and the long cables (white) are connected between the board and the analog, digital and enable part of circuit and shown in the Fig. 4.14. The short cables are 19 cm long and 16 gauge (1.29032 mm in diameter), and the long cables are 40 cm long and 20 gauge (0.81280 mm in diameter). Figure 4.14 shows the experimental setup at Fermilab. For cooling purpose, we mount the DC-DC boards to a heatsink during the testing as shown in Fig. 4.14.

![Testing setup](image)

Figure 4.14. Testing setup.

### 4.2.2.2 Results

We measured $54 \times 4 = 216$ analog and $54 \times 4 = 216$ digital converters and compared them with the data taken from the Aachen University. The results are
shown in Fig 4.15 and 4.16. The Aachen measurements were, on average, 50mV higher than ours, but there is not much difference when the load is removed in our setup. The load is $2\,\Omega$ resistor in our setup.

![Figure 4.15. Comparison of analog converters between the measurements from Aachen (left) and Fermilab (right).](image1)

![Figure 4.16. Comparison of digital converters between the measurements from Aachen (left) and Fermilab (right).](image2)
4.2.2.3 Sorting the DC-DC Boards According to Voltage Output

Pixel modules that are close to the beam line will be exposed to the radiation more. After some time, they will need more power to operate. DC-DC converters with better voltage output can be connected to those modules. Since we have 4 digital and 4 analog converters on each board, we sorted the boards according to their total DC output, that is $D_1 + D_2 + D_3 + D_4$. Since a total of 54 boards were assembled at SiDet, we chose 48 of them. Each HC has 3 disks and the boards with higher voltage output are chosen for the inner disks for installation.

4.2.2.4 Thermal Cycling

The boards were also tested under thermal cycling. The temperature was changed between $-30^\circ C$ and $+50^\circ C$, 10 times. Once the temperature reaches the high or low points, it stays there for 30 minutes. During the cycling, humidity is kept below 40%. Without applying any power, the durability of soldered connections is tested since some connections can break due to temperature change. After testing, no breaks or unexpected results are observed.

4.3 CMS Outer Tracker Phase II Upgrade

The present Outer Tracker was designed to operate up to an integrated luminosity of 500 fb$^{-1}$, with an average pileup (PU) of less than 50 collisions per bunch crossing. Around 2022, LHC is foreseen to be replaced with HL-LHC (high luminosity LHC), which is expected to deliver 2500 fb$^{-1}$ with an instantaneous luminosity of $5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$. Before 2022, the outer tracker has to be replaced, and the replacement will happen during LS2 which will start around December, 2018.
Additionally current tracking detectors restrict the data acquisition to the Level-1 trigger acceptance rate of about 100 kHz. Operating at a high luminosity requires an upgrade to the trigger system which will increase the data accept rate. Radiation damage in the pixel sensors reduces the charge collection, leading to worse spatial resolution. Worse hit-resolution directly decreases the precision of primary vertex construction, and track impact parameter resolution.

The new outer tracker will be more radiation tolerant and will be able to operate at $-20^\circ\text{C}$ which makes the tracker functional up to $3000\text{ fb}^{-1}$ of data taking. Increased granularity and the new layout 4.17 will improve the pattern recognition and it will be able operate above 150 pile-up events. Readout bandwidth rate will increase to 750kHz and $12\mu\text{s}$ latency. Also optimization of the passive materials will reduce unexpected multiple scattering or nuclear reactions.

![Figure 4.17. New outer tracker layout.](image)
4.3.1 Modules

The new outer tracker modules can contribute to the trigger decision by the $p_T$ measurements of the particles passing through the modules. If the $p_T$ of the passing particles through the sensor is low, these events can be rejected at the trigger level. Fig. 4.20 shows the idea of using two sensors stacked together and the design of a module. The two closely spaced sensors are connected to ASICs which can correlate the hits from the two sensors. ASICs are programmable and the tracking volume can be adjusted for a given magnetic field and sensor spacing.

There are two types of modules. 2S Modules (Strip - Strip Modules) are composed of 2 strip sensors and each sensor has an area of $10 \times 10 \text{ cm}^2$. The strips on both sensors are parallel to each other. They will be used in the outer sides of the tracker. PS Modules (Pixel - Strip Modules) are composed of a pixelated and a strip sensor. The area of these sensors are $5 \times 10 \text{ cm}^2$. PS modules will be installed in the radial range between 20 cm to 60 cm of the inner region of the tracker. Figure 4.18 shows the 3D view of both modules.

4.3.2 Performance

A pile-up increase is a big concern for the Phase-II upgrade. Figure 4.19 compares the track reconstruction efficiency at 140 pile-up(Phase-II) and 50 pile-up (Phase-I) for muons and $t\bar{t}$ events [44]. The detailed performance is covered in more detail in [44, 23]. It looks like there is a performance drop at $|\eta| > 2.4$ which is related to the pixel detector during simulation. In the central region, in which most of the analyses are performed, the performance matches with the old pile-up.
Figure 4.18. 3D view of 2S (left) and PS (right) module.

Figure 4.19. Comparison of track reconstruction efficiency for muons (left) and $t\bar{t}$ events (right).
4.3.3 Module Assembly

Fermilab and Brown University are responsible for assembling the module parts together. Figure 4.20 (right) shows the detailed parts of the 2S module. Figure 4.26 shows the two parts of the 2S module before wirebonding and encapsulation (left), and during the encapsulation process (right). More than 10000 modules will be assembled, with 20 modules assembled per day in both institutions. This requires at least 500 days to finish. Wire bonding is performed with a robot. For encapsulation, one needs to cover the wire bonds properly otherwise the bonds can break apart very easily. Also, human errors will always be a problem for this process. The proposed solution was to use a Gantry robot, which can increase the encapsulation speed significantly and reduce unexpected errors.

Fermilab has an Aerotech gantry robot, which includes the Aerotech A3200 Software Based Machine Controller and Aerotech AGS10000 Gantry System. It is programmable in many different languages, but our choice is LabVieW, which makes it easier to interact with the machine. The system can move along the x, y, z, and u(rotation) axes. It is 50 cm × 50 cm on x-y axes with an accuracy of ±5µm. It can move up to 3 m/s, accelerate up to 3g, and apply up to 1200N force. Figure 4.21 shows the robot and the machine controller.

Of course, the machine itself cannot encapsulate the wire bonds without additional devices connected to it. It needs to be able to pick up a syringe filled with some epoxy, move to a desired position, and release the epoxy on wire bonds. The pick up process is achieved by a vacuum switcher device, and dispensing epoxy is
Figure 4.20. (Left) Drawing of two sensors with a high $p_T$ and a low $p_T$ object passing through it in a magnetic field [22]. (Right) Schematic view of a module with two sensors (yellow) [38].

Figure 4.21. (Left) Gantry robot and (Right) machine controller.
achieved by a pressure device.

Figure 4.22 shows the gantry head. There are U and Z axis switches to protect both the machine and the module. The head also has pressure and vacuum channels which can pick up the syringe and dispense the epoxy.

Figure 4.22 shows the gantry head security switch. In order to prevent possible damages, we want to make sure that robot does not apply too much force on the syringe when connecting. The computer reads a digital input signal from NI 9403 (a National Instruments module that enables sending signals from the robot to the computer), according to the resultant binary value, we design our code to stop automatically. The process is accomplished by going down in z-axis with 150µm incremental values. For each step, we check the switch status. If the switch is closed,
we turn on the vacuum and pick up the syringe.

Figure 4.23. The gantry head touch switch with the circuit setup.

For the pressure control we use an EFD Ultimus Dispenser. It is a programmable air pressure device. As the glue gets thicker, one needs to apply more pressure on the epoxy. Figure 4.24 shows the EFD Ultimus device and its connection to the power supply. It is connected to the computer via NI 9403 connector. The NI module has computer controlled switches/channels. If the switch is on, power is transferred to another channel, in which the EFD Ultimus is connected. A voltage change triggers the Ultimus to run its custom program. For example; to turn on pressure for 1 sec at 40 psi.

Vacuum control is achieved by using a Festo Valve Manifold (CPV10-VI). Figure 4.25 shows the device and its connection the power supply. Each vacuum channel is connected to NI 9476 (a National Instruments module that enables sending signals from the computer to the robot). If the power is on for a specific channel, the device enables the vacuum. Currently, only two vacuum channels are connected to
Figure 4.24. EFD Ultimus Dispenser setup.

the gantry head. Later, we want to apply a vacuum under the modules when they are on the assembly surface to prevent the modules from moving unexpectedly.

Figure 4.25. Festo Valve Manifold setup.
4.3.4 Outlook

The project is still in the research and development stage. As a first step, we were able to connect different devices to the robot and write some LabView code to process a simple encapsulation process. A bigger robot with larger surface area was ordered which will be delivered in 2018. With the new machine one can put multiple modules on the robot table and encapsulate them all at once. Figure 4.26 shows the encapsulation process of the 2S module before wire bonding (left) and after wire bonding and encapsulation (right).

Figure 4.26. 2S modules parts before wirebonding and encapsulation (left) and during encapsulation process (right).

Once the development process is completed, it will be ready for the assembly process.
CHAPTER 5

CONCLUSION

The first part of the thesis focuses on the evidence of a narrow structure in \( \Upsilon(1S)l^+l^- \) mass spectrum. The main motivation for this study was the developments in exotic meson searches in recent years and the prediction of a possible tetra-quark state [9]. We have shown that there is an excess around 18.5 GeV in the \( \Upsilon(1S)l^+l^- \) mass spectrum with 3.6 global significance. The excess is visible in both 7 and 8 TeV CMS data and in both \( \Upsilon(1S)\mu^+\mu^- \) and \( \Upsilon(1S)e^+e^- \) channels separately. The nature of the excess is not exactly known and further study is required.

The second part of the thesis focuses on the upgrade studies performed for both CMS Phase I & II Upgrades. Silicon sensors and DC-DC converters were tested at Fermilab and they were installed in the CMS detector for the Phase I Upgrade. Furthermore, an initial Gantry Robot system was assembled and the initial code was developed for the Phase II Upgrade.
APPENDIX A

MUON IDENTIFICATION

A.1 Soft Muon ID

The tracker track should match with at least one muon segment (in any station) in both X and Y coordinates (< 3σ) (TMOneStationTight) and it should be arbitrated. The number of track layers with hits is required to be greater than 5. There should be at least 1 pixel layer hit. The track should be a high-purity track. A muon track transverse impact parameter $d_{xy} < 3\text{cm}$ and longitudinal impact parameter $d_z < 20\text{cm}$ w.r.t primary vertex are required. Soft muon identification code is given below:

```cpp
if(muon::isGoodMuon(*rmu, muon::SelectionType(12))
    && rmu->track()->hitPattern().trackerLayersWithMeasurement()>5
    && rmu->innerTrack()->hitPattern().pixelLayersWithMeasurement()>0
    && rmu->innerTrack()->quality(reco::TrackBase::highPurity)
    && fabs(rmu->innerTrack()->dxy(RefVtx))<0.3
    && fabs(rmu->innerTrack()->dz(RefVtx)) <20.0
)
    goodSoftMuon=1;
```

A.2 Tight Muon ID

Tight muons should satisfy global muon and particle flow muon criteria. $\chi^2$/ndof of the global muon track fit should be smaller than 10. There should be at least one
muon chamber hit in the global muon track fit. Muon track fit should match at least 2 in the muon stations. The number of pixel hits is required to be greater than 0. The number of track layers with hits should be greater than 5. Muon track transverse impact parameter \( d_{xy} < 0.2 \text{cm} \) with respect to primary vertex and a longitudinal impact parameter \( d_z < 0.5 \text{cm} \) are required. Tight muon identification code is given below:

```cpp
if( rmu->isGlobalMuon()
    && rmu->isPFMuon()
    && rmu->globalTrack()->normalizedChi2() < 10.0
    && rmu->globalTrack()->hitPattern().numberOfValidMuonHits()>0
    && rmu->numberOfMatchedStations()>1
    && fabs(rmu->muonBestTrack()->dxy( RefVtx ))<0.2
    && fabs(rmu->muonBestTrack()->dz( RefVtx )) < 0.5
    && rmu->innerTrack()->hitPattern().numberOfValidPixelHits()>0
    && rmu->track()->hitPattern().trackerLayersWithMeasurement()>5
)

goodTightMuon=1;
```
APPENDIX B

ELECTRON IDENTIFICATION

B.1 Loose Electron ID

Table B.1 and B.2 shows the accepted loose electron id cuts as well as medium and tight electron id cuts.

Table B.1. Barrel Cuts ($|\eta_{\text{supercluster}}| \leq 1.479$)

<table>
<thead>
<tr>
<th></th>
<th>Veto</th>
<th>Loose</th>
<th>Medium</th>
<th>Tight</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Delta \eta</td>
<td>&lt;$</td>
<td>0.007</td>
<td>0.007</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \varphi</td>
<td>&lt;$</td>
<td>0.8</td>
<td>0.15</td>
</tr>
<tr>
<td>$\sigma_{\text{inv}} &lt;$</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$H/E &lt;$</td>
<td>0.15</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>$d_0(vtx) &lt;$</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>$d_z(vtx) &lt;$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$</td>
<td>1/E - 1/p</td>
<td>&lt;$</td>
<td>N/A</td>
<td>0.05</td>
</tr>
<tr>
<td>$PF_{\text{isolation}}/pT(\Delta R = 0.3) &lt;$</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.10</td>
</tr>
<tr>
<td>Conversion rejection: vertex fit probability</td>
<td>N/A</td>
<td>1E-6</td>
<td>1E-6</td>
<td>1E-6</td>
</tr>
<tr>
<td>Conversion rejection: missing hits $\leq$</td>
<td>N/A</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
Table B.2. Endcap Cuts ( 1.479 < |η_{supercluster}| < 2.5)

<table>
<thead>
<tr>
<th></th>
<th>Veto</th>
<th>Loose</th>
<th>Medium</th>
<th>Tight</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T &gt; 20$($p_T &lt; 20$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta\eta</td>
<td>&lt;$</td>
<td>0.01</td>
<td>0.009</td>
</tr>
<tr>
<td>$</td>
<td>\Delta\varphi</td>
<td>&lt;$</td>
<td>0.7</td>
<td>0.10</td>
</tr>
<tr>
<td>$\sigma_{\text{mean}} &lt;$</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>$H/E &lt;$</td>
<td>N/A</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>$d_0(vtx) &lt;$</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>$d_z(vtx) &lt;$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$</td>
<td>1/E - 1/p</td>
<td>&lt;$</td>
<td>N/A</td>
<td>0.05</td>
</tr>
<tr>
<td>$PF_{\text{isolation}}/pT(\Delta R = 0.3) &lt;$</td>
<td>0.15</td>
<td>0.15(0.10)</td>
<td>0.15(0.10)</td>
<td>0.10(0.07)</td>
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<tr>
<td>Conversion rejection: vertex fit probability</td>
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<td>1E-6</td>
<td>1E-6</td>
<td>1E-6</td>
</tr>
<tr>
<td>Conversion rejection: missing hits $\leq$</td>
<td>N/A</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
REFERENCES


[40] M. Monemzadeh, N. Tazimi, and P. Sadeghi. Tetraquarks as diquark antidiquark bound systems. 741, 02 2015.


