EFFECTS OF A DEGRADED TRACKER INNER BARREL IN THE CMS TRACKING RECONSTRUCTION

By

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This thesis reports the impact of the first two Tracker Inner Barrel’s layers degradation on the CMS detector tracking efficiency and how the new tracking detector and geometry proposed for the Phase 1 upgrade will improve this efficiency.

To make this study, we measured the tracking efficiency and the track fake rate, considering the Tracker Inner Barrel degradation, using $t\bar{t}$ Monte Carlo samples for the current and for the Phase 1 geometries in scenarios such as zero pileup and a scenario with average pileup of fifty interactions per crossing. In this second scenario, which corresponds to the upgrade Phase 1 LHC luminosity ($2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$), we have included the pixel detector inefficiency simulation due to data loss.

From these results, we have concluded that with the new geometry proposed in the Phase 1 it will be possible to recover the tracking efficiency loss and reduced the track fake rate produced by the impact of the super LHC (SLHC) luminosity.
EFECTOS DEL DETERIORO DEL “TRACKER INNER BARREL” EN LA RECONSTRUCCIÓN DE TRAZAS DEL DETECTOR CMS

Por

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Agosto 2011

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Esta tesis describe el impacto del deterioro de las dos primeras capas del “Tracker Inner Barrel” del detector CMS en la eficiencia de reconstrucción de trazas y como este nuevo detector y su geometría propuesta en la Fase 1 de actualización incrementará esta eficiencia de reconstrucción.

Este estudio consistió en medir la eficiencia de reconstrucción y la razón de “trazas falsas”, considerando el deterioro del “Tracker Inner Barrel”, al usar muestras de Monte Carlo de eventos $t\bar{t}$ para las geometrías actual y de la fase 1 en los escenarios de “pileup” cero y “pileup” promedio de cincuenta interacciones por colisión. En este segundo escenario, el cual corresponde a la fase 1 de la actualización de la luminosidad del LHC ($2 \times 10^{34}$ cm$^{-2}$s$^{-1}$), se incluyó la simulación de la ineficiencia en el Detector de “Pixeles” producida por pérdida de información.

A partir de estos resultados se concluyó que con la geometría propuesta en la fase 1 de la actualización de CMS se podrá recuperar la pérdida de eficiencia producida por el impacto del incremento de la luminosidad del super LHC (SLHC).
This thesis is dedicated to my parents Luis Enrique and Esperanza, and to my brother Luis Ernesto.
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1.1 Standard Model

The Standard Model (SM) is a theory that describes elementary particles and the interactions between them. Elementary particles in the SM are classified as fermions, bosons and the still undiscovered Higgs boson (See figure 1–1).

The elementary fermions are the fundamental building blocks of matter. They have spin $\frac{1}{2}$ and are classified into three generations or (families) of quarks and leptons. The flavours of quarks are the up ($u$), down ($d$), charm ($c$), strange ($s$), top ($t$) and bottom ($b$) quarks. They interact via the strong and electroweak forces and are the only carriers of fractional electric charge, it means $+\frac{2}{3}e$ or $-\frac{1}{3}e$ where $e$ is the magnitude of the electron electric charge ($1.602 \times 10^{-19}$ C).

Quarks do not exist as free particles, they combine to form composite particles known as hadrons. There are two families of hadrons: baryons (constituted by three quarks) and mesons (constituted by a quark and an antiquark). A great number of hadrons are known, most of them differentiated by their quarks content and the properties these constituent quarks confer. The existence of exotic hadrons such as tetraquarks and pentaquarks has been conjectured but not proven yet. A tetraquark is an exotic meson which have two quark-antiquark pairs, and a pentaquark is an exotic baryon which consists of four quarks and an antiquark [10].

Leptons interact via the electroweak force and consist of the electron ($e$) and electron-neutrino ($\nu_e$), muon ($\mu$) and muon-neutrino ($\nu_\mu$) and tau ($\tau$) and tau-neutrino ($\nu_\tau$) [11]. The charged leptons ($e, \mu, \tau$) have electric charge $-e$ and their associated neutrinos ($\nu_e, \nu_\mu, \nu_\tau$) have zero electric charge [11].
Each of the elementary fermions are composed of two leptons and two quarks (See figure 1–1). The first generation includes \( u, d, e, \nu_e \); the second \( c, s, \mu, \nu_\mu \); and the third \( t, b, \tau, \nu_\tau \). Each member of a higher generation has greater mass than the corresponding particle of the previous generation. This mass hierarchy causes particles of higher generations to decay to the first generation which is stable. This explains why everyday matter (atoms) is made of particles from the first generation [12].

The SM describes the interactions in terms of the exchange of characteristic bosons (particles of integer spin) between interacting fermions [11]. These boson mediators are listed in the figure 1–1. There are three types of fundamental interactions described in the SM [11]:

Figure 1–1: The Standard Model of elementary particles, with the gauge bosons in the rightmost column [2].
1. **Strong** interactions are responsible for binding the quarks in hadrons such as the neutron and proton, and neutrons and protons within nuclei. The inter quark force is mediated by a massless particle of spin 1 called *gluon*. Quarks and gluons have a property called *color charge*. There are three color charges (red, green, and blue), and three corresponding anti-color charges (anti-red, anti-green, anti-blue). Quarks constantly change their color charge as they exchange gluons with other quarks. Each quark has one of the three color charges; and each antiquark has one of the three complementary color charges. Gluons carry color/anti-color pair, they do not necessary have to be the same color; combinations such as red/anti-blue are legal. While there are 9 possible combinations of color/anti-color pairs, due to symmetry considerations one of these combinations is eliminated. A gluon can effectively carry one of eight possible color/anti-color combinations.

2. **Electromagnetic** interactions are responsible for all the phenomena in extra-nuclear physics, in particular for the bound states of electrons with nuclei, i.e. atoms and molecules, and for the intermolecular forces in liquids and solids. These interactions are mediated by the exchange of massless particles called *photons* which have spin 1.

3. **Weak** interactions are typified by the slow process of nuclear $\beta$-decay, involving the emission by a radioactive nucleus of an electron and neutrino. The mediators of the weak interactions are the $W^\pm$ and $Z^0$ bosons, which have spin 1 and masses of order 100 times the proton mass.

4. Although **gravity** is not included in the SM, it is the fourth interaction in nature in addition to the strong, weak and electromagnetic interactions. Gravity is postulated to be mediated by exchange of a massless boson of spin 2 called *graviton* which has not been found yet.
The Higgs boson is a neutral spin 0 particle whose existence is predicted by the SM, but which has not yet been observed because theoretically it required a large amount of energy and beam luminosity to be observed in high energy colliders [10].

The Higgs boson plays a unique role in the SM, by explaining why the other elementary particles (excepted the photon and gluon) are massive. In particular, the Higgs boson would explain why the photon has no mass, while the W and Z bosons are very heavy. Elementary particle masses, and the differences between electromagnetism (mediated by the photon) and the weak force (mediated by the W and Z bosons), are critical to many aspects of the structure of microscopic (and hence macroscopic) matter. In electroweak theory, the Higgs boson generates the masses of the leptons and quarks [11].

Although the SM provides an extremely compact and successful description, it has limitations which the Large Hadron Collider (LHC) will help to overcome as described below:

1. The SM does not explain the origin of mass, nor why some particles are very heavy while others have no mass at all. The answer may be the so-called Higgs mechanism [13]. According to the theory of the Higgs mechanism, the whole space is filled with a ‘Higgs field’, and by interacting with this field, particles acquire their masses. Particles that interact intensely with the Higgs field are heavy, while those that have feeble interactions are light. The Higgs field has at least one new particle associated with it, the Higgs boson. If such a particle exists, experiments at the LHC will be able to detect it.

2. The SM does not offer a unified description of all the fundamental forces, as it remains difficult to construct a theory of gravity similar to those for the other forces [13]. Supersymmetry, a theory that hypothesizes the existence of more massive partners of the standard particles we know, could facilitate the unification of the fundamental
forces. If supersymmetry is right, then the lightest supersymmetric particles should be found at the LHC.

3. Cosmological and astrophysical observations have shown that all of the visible matter accounts for only 4% of the Universe [13]. The search is open for particles or phenomena responsible for dark matter (23%) and dark energy (73%) [13]. A very popular idea is that dark matter is made of neutral, but still undiscovered, supersymmetric particles.

4. The LHC will also help to investigate antimatter. Matter and antimatter must have been produced in the same amounts at the time of the Big Bang, but from what has been observed so far, the Universe is made only of matter [13].

5. In addition to the studies of proton-proton collisions, heavy-ion collisions at the LHC will provide a window onto the state of matter that would have existed in the early Universe, called ‘quark-gluon plasma’. When heavy ions collide at high energies they form for an instant a “fireball” of hot, dense matter that can be studied by the experiments [11].

1.2 Top Quark and Higgs Decay Modes

The top quark has a mass of $172.0 \pm 2.2$ GeV/$c^2$, a mean lifetime of $5 \times 10^{-25}$ s, and its antiparticle is the top antiquark. The top quark decays through the weak interaction producing a $W$ boson and a down-type quark: bottom (99.8%), strange (0.17%), or down (0.007%) [14].

Top quarks are produced in pairs via the strong interaction processes quark-antiquark annihilation ($q\bar{q} \rightarrow t\bar{t}$) and gluon gluon fusion ($gg \rightarrow t\bar{t}$). The proton-proton $t\bar{t}$ cross section at the LHC is shown in figure 1–2 [15]. A top-antitop pair ($t\bar{t}$) decays into a total of four particles: two $W$ bosons, a bottom quark ($b$) and an antibotton quark ($\bar{b}$). The top quarks events are classified into three categories according to how the $W$s decays: The most common decay mode is the “all-hadronic” mode in which each $W$
decays into a pair of quarks. A rare decay mode is the “dilepton mode” in which each $W$ particle decays into a lepton (such as an electron or muon) plus a neutrino. And the “lepton-plus-jets” mode, one $W$ decays into a lepton (such as an electron or a muon) plus a neutrino while the other $W$ decays into two quarks, which subsequently produce a “jet”, or spray of particles [16].

The experimentally accessible Higgs decay modes as a function of the mass, $m_H$, are summarized in Table 1–1 [1]. The branching fractions of the Standard Model Higgs boson as a function of $m_H$ are shown in figure 1–3 [1]. In the cases shown the Table 1–1 signals are difficult to identify because of the presence of large backgrounds, and reliable predictions are necessary firstly to do design efficient search strategies, and secondly to perform the corresponding analyzes. In the case of $90 \text{ GeV} \leq m_H \leq 120 \text{ GeV}$ the dominant $H$ decay mode is into $b\bar{b}$ pair, which have QCD background. A possible
Table 1–1: Experimentally accessible Higgs decay channels as a function of mass [1].

<table>
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<tr>
<th>Mass range</th>
<th>Decay channel</th>
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<tr>
<td>$100 \text{ GeV} \leq m_H \leq 150 \text{ GeV}$</td>
<td>$H \rightarrow \gamma\gamma$</td>
</tr>
<tr>
<td>$90 \text{ GeV} \leq m_H \leq 120 \text{ GeV}$</td>
<td>$H \rightarrow b\bar{b}$ in $t\bar{t}H$</td>
</tr>
<tr>
<td>$130 \text{ GeV} \leq m_H \leq 200 \text{ GeV}$</td>
<td>$H \rightarrow ZZ^* \rightarrow 4l(e \text{ or } \mu)$</td>
</tr>
<tr>
<td>$140 \text{ GeV} \leq m_H \leq 180 \text{ GeV}$</td>
<td>$H \rightarrow WW \rightarrow l\nu l\nu$</td>
</tr>
<tr>
<td>$200 \text{ GeV} \leq m_H \leq 750 \text{ GeV}$</td>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
</tr>
<tr>
<td>$500 \text{ GeV} \leq m_H \leq 1 \text{ TeV}$</td>
<td>$H \rightarrow ZZ \rightarrow 2l2\nu$</td>
</tr>
<tr>
<td>$m_H \approx 1 \text{ TeV}$</td>
<td>$H \rightarrow WW \rightarrow l\nu + 2 \text{ jets}$</td>
</tr>
<tr>
<td>$m_H \approx 1 \text{ TeV}$</td>
<td>$H \rightarrow ZZ \rightarrow 2l + 2b \text{ jets}$</td>
</tr>
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Figure 1–3: Branching fractions of the Standard Model higgs boson as a function of $m_H$ [1]

solution is that of considering the Higgs in association with other easier-to-tag particles. The importance of the $t\bar{t}$ pair in this decay mode is that it can be exploited to extract the signal from its QCD multi-jet backgrounds [17]. This work uses Monte Carlo samples of $t\bar{t}$ events for the performances studies of the CMS tracker system due to its importance in background rejection that is mentioned before.
1.3 The Large Hadron Collider

The Large Hadron Collider (LHC) is a two ring superconducting accelerator and collider built at the European Organization for Nuclear Research (CERN) to explore particle physics beyond energy ranges of previous accelerators [4]. It is designed to collide two proton beams, circulating in opposite directions, every 25 ns at an energy of 7 TeV each (centre-of-mass energy $\sqrt{s} = 14$ TeV). The accelerator has been designed to run at a peak luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ and integrated luminosity of 100 fb$^{-1}$/year. This combination of the high energy scale and the high event rate (about 20 interactions per crossing) provides the potential to explore SM physics and possible new Physics beyond it. The LHC will also provide high-energy heavy-ions beams at energies over 30 times higher than at the previous accelerators, allowing us to further extend the study of QCD matter under extreme conditions of temperature [4].

The design total proton-proton cross-section is expected to be roughly 100 mb at the center-of-mass energy $\sqrt{s} = 14$ TeV [4]. Therefore, at design luminosity, the general purpose detectors will observe an event rate of approximately $10^9$ inelastic events/s. This lead to a number of formidable experimental challenges such as pileup and high radiation levels. Pileup are the additional interactions that will be superimposed to the observed interactions, originating that occurs multiple interactions in the same time gate as the interaction of interest [18]. This problem clearly becomes more severe when the response time of a detector element and its electronic signal is longer the 25 ns. Pileup can be reduced by using high granularity detectors with good time resolution, resulting in low occupancy [5]. This requires a large number of detector channels, and the high radiation levels are produced by the large flux of particles coming from the interaction region, requiring radiation hard detectors and front-end electronics.

The LHC has two high luminosity experiments, A Toroidal LHC ApparatuS (ATLAS) and the Compact Muon Solenoid (CMS), both are general purpose detector which
aiming at a peak luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ for proton operation [1]. The main focus of ATLAS and the CMS experiments is the search for the Higgs boson. In addition to their primary goals, studies of CP violating and rare B-decays will also be performed. There are also two low luminosity experiments: the Large Hadron Collider beauty experiment (LHCb) for B-physics, aiming at a peak luminosity of $10^{32}$ cm$^{-2}$s$^{-1}$, and TOTal cross section, Elastic scattering and diffracation dissociation Measurements (TOTEM) for the detection of protons from elastic scattering at small angles, aiming at a peak luminosity of $2 \times 10^{29}$ cm$^{-2}$s$^{-1}$ with 156 bunches [4]. In addition to the proton beams, the LHC will also be operated with ion beams. The LHC has one dedicated ion experiment, A Large Ion Collider Experiment (ALICE), aiming at a peak luminosity of $10^{27}$ cm$^{-2}$s$^{-1}$ for nominal lead-lead ion operation [1].

The basic layout of the LHC is shown in the figure 1–4. The LHC is not a perfect circle. It is made of eight arcs and eight straight sections. The arcs contain the dipole ‘bending’ magnets, with 154 in each arc. An straight section can serve as an experimental or utility insertion. The exact layout of the straight section depends on the specific use of the insertion: physics (beam collisions within an experiment), injection, beam dumping, and beam cleaning [4].

The two high luminosity experimental insertions are located at diametrically opposite straight sections: the ATLAS experiment is located at Point 1 and the CMS experiment at Point 5. Two more experimental insertions are located at Point 2 and Point 8, which also include the injection systems for Beam 1 and Beam 2, respectively. The remaining four straight sections do not have beam crossings. Insertions at Point 3 and 7 each contain two collimation systems. The insertion at Point 4 contains two RF systems: one independent system for each LHC beam. The straight section at Point 6 contains the beam dump insertion, where the two beams are vertically extracted.
Figure 1–4: Schematic layout of the LHC (Beam 1 - clockwise, Beam 2 - anticlockwise) [4].

from the machine using a combination of horizontally deflecting fast-pulsed magnets and vertically-deflecting double steel septum magnets.

A proposal to extend the physics potential of the LHC with a major luminosity upgrade, called *Super LHC* (SLHC), has been endorsed by the CERN council strategy group. The goal is a factor ten increase in luminosity \(10^{35}\) cm\(^{-2}\)s\(^{-1}\) [8].

### 1.4 The Super Large Hadron Collider

The increased physics potential of a luminosity upgrade proposed for the Super Large Hadron Collider can be divided into three areas [19]:

1. Extending the mass reach, due to the increased statistics of high-\(x\) parton interactions. Heavy multi-TeV particles appear in many extensions of the SM, for example;
extra gauge-bosons, resonances in extra-dimension models, heavy SUSY particles. For the case of the heavy gauge-boson $Z'$ an increased mass reach of $\sim 1$ TeV is gained.

2. Improved precision of measurements, especially in looking for deviations from the SM. For example, measurement of anomalous triple gauge-boson couplings (TGCs) provides a powerful test of the no-Abelian structure of the SM. A tenfold increase in statistics will provide typically a factor of $\sim 2$ improvement in precision. In addition, should physics beyond the SM be discovered at the LHC, then there will be strong motivation to measure as precisely as possible the parameters of the new physics.

3. Increased sensitivity to rare processes. For example, the decay of top quarks induced by flavour changing neutral currents (FCNCs) is suppressed in the SM. However a large class of theories beyond the SM predict much higher branching fractions for these decays, but which would be still at the limit of LHC sensitivity.

Upgrading the LHC to increase the luminosity by a factor of ten will be challenging and the implications are still being investigated. A two phase scenario is being explored. The first phase (Phase 1) would aim to push to the ultimate luminosity of $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. This would be facilitated with the replacement of the inner triplet focusing magnets. The second phase (Phase 2) would aim to reach $10^{35} \text{ cm}^{-2}\text{s}^{-1}$. In this phase two scenarios are being considered [19]:

1. Improved beam focusing, based on early separation of the proton beams. This would require positioning dipole magnets closer to the interaction point, deep inside the experiments. In this scenario a bunch spacing of either 25 ns or 50 ns is possible. However, it is not clear if the integration of machine elements within the experiments is feasible and studies are currently underway to know the implications.

2. Increasing the beam currents, which has the advantage of not requiring beam magnets inside the experiments. The disadvantage is that this would be more demanding
on the machine, with consequences for beam dynamics, machine-protection, radiation protection and beam injection. In this scenario only 50 ns bunch spacing is possible.

Improvements and upgrades to some CMS sub-detectors will be necessary to fully exploit the LHC upgraded luminosity. During the Phase 1 period the pixel detector will be replaced and the trigger upgraded, but CMS will use the current silicon strip tracker. In the Phase 2 period, the CMS tracker system will be completely replaced and there will be many other changes to sub-detectors, trigger and data acquisition systems.
CHAPTER 2
THE COMPACT MUON SOLENOID
EXPERIMENT

The Compact Muon Solenoid detector (CMS) is a general purpose detector designed to operate at the LHC at CERN. The physics goal of the CMS detector can be summarized as follows [5]:

1. Good charged particle momentum resolution and reconstruction efficiency in the inner tracker. Efficient triggering and offline tagging of τ’s and b-jets, requiring to have pixel detectors close to the interaction region.

2. Good muon identification and momentum resolution over a wide range of momenta and angles, good dimuon mass resolution ($\approx 1\%$ at 100 GeV), and the ability to determine unambiguously the charge of muons with $P < 1$ TeV.

3. Good electromagnetic energy resolution, good diphoton and dielectron mass resolution ($\approx 1\%$ at 100 GeV), wide geometric coverage, $\pi^0$ rejection, and efficient photon and lepton isolation at high luminosities.

4. Good missing transverse energy and dijet mass resolution, requiring to have hadron calorimeters with a large hermetic geometric coverage and with fine lateral segmentation.

2.1 General Description

The CMS detector measures 21.6 m in length, 15 m in diameter, and 12500 tonnes [5]. The main distinguishing features of CMS are the high field superconducting solenoid, the full silicon based inner tracking system, and the homogeneous scintillating crystals based electromagnetic calorimeter [5].
The global coordinate system adopted by CMS has the origin centered at the nominal collision point inside the experiment, the $y$-axis pointing vertically upward, the $x$-axis pointing radially inward toward the center of the LHC, and the $z$-axis points along the beam direction. The azimuthal angle $\phi$ is measured from $x$-axis in the $x$-$y$ plane and the radial coordinate in this plane is denoted by $r$. The polar angle $\theta$ is measured from the $z$-axis and the pseudorapidity is defined as $\eta = -\ln \tan(\theta/2)$ [5].

In a $pp$ collision, with $z$-axis pointing along the beam direction, rapidity is a variable used to describe the behaviour of particles in inclusively measured reactions and is defined as:

$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right)$$

(2.1)

where $p_z$ is the longitudinal momentum along the direction of the incident particle, $E$ is the energy, both defined for a given particle. The accessible range of rapidities for a given interaction is determined by the available center of mass energy and all participating rest masses of the particles [18]. To characterize the rapidity of a particle, it is necessary to measure two quantities of the particle, such as its energy and its longitudinal momentum. In many experiments, it is only possible to measure the angle of the detected particle relative to the beam axis. In that case, it is convenient to utilize this information by using the pseudorapidity ($\eta$) to characterize the detected particle [20]. The pseudorapidity of a particle is defined as:

$$\eta = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right]$$

(2.2)
where $\theta$ is the angle between the particle momentum and the beam axis. Pseudorapidity is an approximation of the rapidity in the case that the transverse momentum of the particle is much greater than its rest mass, and that the particle is relativistic [21].

The schematic representation of CMS is shown in the figure 2–1. The CMS superconducting solenoid is the central device around which the experiment is build, with a 4 T magnet field, 13 m in length, and 6 m in diameter. Its function is to bend the paths of particles emerging from high-energy collisions in the LHC. The more momentum a particle has the less its path is curved by the magnetic field, therefore tracing its paths gives a measure of momentum. CMS began with the aim of having the strongest superconducting solenoid because a higher strength field bend paths more and combined with the high precision position measurement of the tracker and muon detector, this allows accurate measurement of the momentum of even high energy particles [5].

Figure 2–1: Schematic representation of the CMS detector [5].
The tracker and calorimeter detectors (electromagnetic and hadron calorimeter) fit closely inside the magnet coil while the muon detectors are interleaved with a 12 side iron structure that surrounds the magnet coil and contains and guide the field. Made up to three layers, this return yoke reaches 14 m in diameter and also acts as a filter, thus, allowing through only muons and those weakly interacting particles such as neutrinos. The enormous magnet also provides most of the experiment’s structural support and must be very strong itself to withstand the forces of its own magnetic field [5].

The electromagnetic calorimeter (ECAL) uses lead tungstate crystals with coverage in pseudorapidity up to $|\eta| < 3.0$ [5]. The scintillation light is detected by silicon avalanche photodiodes (APDs) in the barrel region and vacuum phototriodes (VPTs) in the endcap region. A preshower system is installed in front of the endcap ECAL for $\pi^0$ rejection [5].

The ECAL is surrounded by a brass/scintillator sampling hadron calorimeter (HCAL) with coverage up to $|\eta| < 3.0$ [5]. The scintillation light is converted by wavelength-shifting (WLS) fibers embedded in the scintillator tiles and channeled to photodetectors via clear fibers. This light is detected by photodetectors (hybrid photodiodes, or HPDs) that can provide gain and operate in high axial magnetic fields. This central calorimetry is complemented by a tail-catcher in the barrel region (HO) ensuring that hadronic showers are sampled with nearly 11 hadronic interaction lengths. Coverage up to a pseudorapidity of 5.0 is provided by an iron/quartz-fiber calorimeter [5]. The Cerenkov light emitted in the quartz fibers is detected by photomultipliers. The forward calorimeters ensure full geometric coverage for the measurement of the transverse energy in the event. An even higher forward coverage is obtained with additional dedicated calorimeters (CASTOR, ZDC, not shown in figure 2-1) and with TOTEM tracking detectors [5].

The CMS muon detection system uses three technologies. Drift tubes (DT) used in the CMS barrel, Cathode Strip Chambers (CSC) used in the endcaps, and Resistive
Plate Chambers (RPC) used in parallel with the other detectors in both the barrel and endcap. The muon system is well shielded by the CMS iron yoke, and it is expected that the detectors should continue to operate in the SLHC regime, with only a potential need for changes in the shielding in the forward regions ($2 < |\eta| < 4$) and possible upgrades for the on-detector electronics required [5].

The CMS tracker volume is given by a cylinder that surrounds the interaction point and has a length of 5.8 m, a diameter of 2.6 m and is made entirely of silicon. CMS tracker employs 3 layers of pixels detectors closed to the interaction region to improve the measurement of the impact parameter of charged particles tracks, as well as the position of secondary vertices. Moreover, in order to deal with high track multiplicities 10 layers of silicon microstrip detectors, which provide the required granularity and precision, are placed surrounding the pixel detector [5].

### 2.2 CMS Tracker System

The CMS Tracker System is designed to provide a precise and efficient measurement of the trajectories of charged particles emerging from the LHC collisions, as well as a precise measurement of secondary vertices and impact parameters necessary for the efficient identification of heavy flavors which are produced in many of the interesting physics channels. The requirements of the CMS tracker are that it should operate at high radiation environment with a reasonable lifetime of several years, the amount of material needs to be kept to a minimum in order to limit effects such as multiple scattering, bremsstrahlung, photon conversions and nuclear interactions, and the occupancy should be keep below a certain level that can be handled by the detectors and readout electronics [5].

Taking into account the decrease of hit rate density of traversing particles from 1 MHz/mm$^2$ at a radius of 4 cm to 60 kHz/mm$^2$ at 22 cm and to 3 kHz/mm$^2$ at 115 cm,
Figure 2–2: Schematic cross section through the CMS tracker. Each line represents a detector module. Double lines indicate back-to-back modules which deliver stereo hits [5].

detectors with different cell sizes are used at different radial positions, thus the CMS tracker is composed of the Pixel Detector and the Silicon Strip Tracker. A schematic drawing of the CMS tracker is shown in figure 2–2 [5].

2.2.1 Pixel Detector

The pixel detector is the part of the CMS Tracker that is more close to the interaction point and consists of three barrel layers (BPIX) at radii of 4.4, 7.3 and 10.2 cm and is complemented by two end disks (FPIX) on each side at \( z = \pm 35.5 \) and \( \pm 46.5 \) cm [5]. In the figure 2–3 is shown the layout of the CMS pixel detector with the global and local coordinate systems.

A pixel cell size of \( 100 \times 150 \) \( \mu \text{m}^2 \) is expected to achieve similar track resolution in both \( r - \phi \) and \( z \) directions. The pixel detector covers a pseudorapidity range of \(-2.5 < \eta < 2.5\) and provides precise tracking points in \( r - \phi \) and \( z \). Therefore, the pixel
detector is responsible for a small impact parameter resolution which is important for good secondary vertex reconstruction. The pixel detector is also essential for forming seed tracks for the outer track reconstruction and high level triggering [5]. The arrangement of the 3 barrel layers and the forward pixels disks on each side gives 3 tracking points over almost the full $\eta$-range.

### 2.2.2 Silicon Strip Tracker

The Silicon Strip Tracker has a length of 5.4 m and a diameter of 2.4 m and consists of three main sub-assemblies: Tracker Inner Barrel (TIB)/Tracker Inner Disks (TID), Tracker Outer Barrel (TOB), and Tracker End Caps (TEC). In the figure 2–4 is shown the Silicon Strip Tracker layout and its sub-assemblies in the CMS Tracker system [22].
Figure 2–4: Overview of the CMS Tracker System. Pixel Detector is the innermost part and the Silicon Strip Detector the outer part [7].

(a) The Tracker Inner Barrel and Disks

The Tracker Inner Barrel (TIB) consists of four concentric cylinders placed at 255.0 mm, 339.0 mm, 418.5 mm, and 498.0 mm radius respectively from the beam axis that extend from $-700$ mm to $+700$ mm along the $z$ axis [22]. The two innermost layers (Layer 1 and Layer 2) host double sided modules with a strip pitch of 80 $\mu$m, while the outer two layers host single sided modules with a strip pitch of 120 $\mu$m. Each concentric cylinder is subdivided into four sub-assemblies: $\pm z$ and up/down. Each of these sub-assemblies (shells) contains independent electrical connections and cooling which has the advantage that one sub-assembly can be fully tested before integration in the final system [22].

The TID$\pm$ are assemblies of three identical disks placed in the $z$ range $800$ mm $< |z| < 900$ mm. The disks span the radius from 200 mm to 500 mm. Together the full TIB/TID guarantee hermetical coverage up to pseudorapidity $\eta = 2.5$ [7].
The cooling circuits must be able to efficiently cool the detectors with a cooling liquid temperature down to about $-25^\circ$C, while keeping the amount of material (material budget) as low as possible. The TIB/TID uses aluminium piping with a diameter of 6 mm cross section and a wall thickness of 0.3 mm. These pipes are bent into loops which are interconnected in parallel. For the TIB each loop hosts three modules placed in straight row (string), while in the TID arrangements are more varied even though the number of modules per cooling loop is similar [5].

The cooling loops are grouped in cooling circuits. The dimensions of this cooling circuits vary from layer to layer and depend on the amount of power dissipated by the modules used for that specific layer. The cooling circuits vary from a minimum of four loops (12 modules equivalent) for the double sided layers to a maximum of 15 loops for the outer single sided ones where individual module heat dissipation is much lower. The TIB/TID uses a total of 70 independent cooling circuits so that in case of an accidental break in one of the circuits only a small part of the tracker is affected [5].
(b) Tracker Outer Barrel

The Tracker Outer Barrel is comprised of 6 layers around the beam axis at distances of 608 mm, 692 mm, 692 mm, 780 mm, 868 mm, 960 mm, and 1080 mm (See figure 2–4). Each layer is made of rods (a similar concept to the TIB strings) with 6 modules arranged inside each rod. The full TOB length is covered by two consecutive rods. Rods are inserted in a single mechanical TOB structured called TOB wheel (See figure 2–5). The TOB wheel is 218 cm long and have coverage in $r$ between 555 mm and 1160 mm.

(c) Tracker End Caps

The Tracker End Caps (TEC) close the CMS Tracker on both sides and are located in the region $124 \text{ cm} < |z| < 280 \text{ cm}$. TEC contains 9 disks that extend radially from 220 mm to 1135 mm. The disks are made of substructures called petals. A total of 16 petals are mounted on each of the 9 disks of one end cap, eight on the front face of the disk (front petals) and eight on the back face (back petals). A schematic view of one end cap is shown in the figure 2–6.
2.3 CMS Pixel Detector Upgrade

The luminosity upgrade of the LHC will affect dramatically the CMS detector performance, in particular the pixel detector will be degraded due to severe data losses in the read out chip (ROC) and silicon sensor radiation damage. For this reason a replacement of the whole pixel detector is scheduled in conjunction with LHC shutdown for its Phase 1 upgrade.

The goal of the Phase 1 CMS upgrade is to replace the present pixel detector with one that can maintain a high tracking efficiency at luminosities up to \(2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\). The present system will not sustain the extreme operating conditions expected in Phase 1 after 2016. The main features of the upgrade detector are [8]:

1. Replacement of the current 3-layer barrel (BPIX), 2-disk end cap (FPIX) system with a 4-layer, 3-disk end cap system for four hit coverage.

2. Ultra lightweight support with CO\(_2\) cooling and displacement of the electronic boards and connections out of tracking volume for material reduction.

3. Development of a new readout chip with reduced data loss at higher collision rates expected in Phase 1.

4. Development of high bandwidth readout electronics and links as well as DC-DC power converters, which allow reuse the existing fibers and cables.

The addition of the fourth barrel layer at a radius of 16 cm and the third set of forward disks will maintain the present level of tracking performance even in the high occupancy environment of the upgraded LHC. In addition, it provides a safety margin in case the first silicon strip layer of the TIB degrades more rapidly than expected. The upgraded pixel system will have a reduced mass, a reduced innermost radius and increased lever arm, altogether resulting in a significant improvement over the present system in terms of tracking, vertexing and \(b\) jet identification [8].
2.3.1 Pixel detector limitations due to higher luminosity

The innermost pixel barrel layer operating at full LHC design luminosity is already at the efficiency limit: it is expected that the data loss will be 4 % due to the pixel readout chip occupancy and that the position resolution will degrade due to silicon sensor radiation damage. In addition, the present tracker amount of material reduces up to 10 % the tracking reconstruction efficiency of high momentum particles due to nuclear interactions [23].

Increasing the luminosity, even if only by a factor of 2, will increase the event rate and consequently both the occupancy of the readout electronics and the radiation damage. In this section the current detector limitations are listed below:

(a) Silicon sensor limitations

The particle position reconstruction in pixel detector relies not only on the charge measured by a single pixel but also on the charge shared between pixels. The analog interpolation of the charge between neighboring channels is in fact performed to improve spatial resolution. The charge sharing enhanced in a magnetic field by the Lorentz deflection for the charge deposited by ionizing tracks.

Due to radiation damage the depletion voltage increases, and higher depletion voltage means smaller Lorentz angle and then smaller charge sharing in the CMS pixel sensor design. Moreover, irradiation introduces traps in the silicon lattice with a consequent reduction of the total charge. Therefore it will not get the expected resolution.

These are the main reasons for substituting the pixel sensors after 2-3 years of running of LHC at the highest luminosity when the critical fluence should be reached in the innermost layer.
(b) **Readout chip limitations**

As the ROC is fabricated in a radiation hard technology, the performance of the readout electronics are basically limited by the readout losses at high rate.

The main sources of the data loss are due to:

1. *Pixel busy.* The hit pixel is insensitive to further hits until the charge is transferred to the periphery.

2. *Double column busy.* During the draining mechanism of one double column the readout is still sensitive to further hits, but only two pending column drains are possible while the first drain is ongoing.

3. *Buffer overflow.* The size of both data and time stamp buffer is limited.

4. *Reset loss.* This is the dominant source of data loss caused by the reset of the double column after each triggered readout.

As the particle rate is increased, the *Reset loss* increases as well even if not so drastically as it mainly depends on the trigger latency and rate which are assumed to stay constant; on the contrary the *Buffer overflow* becomes critical. For example to keep the *Buffer overflow* loss below 1% at the full Phase I luminosity, $2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$, the buffers have to be increased by a factor of 2.

In order to improve the rate capability of the pixel modules and allow the operation at higher luminosity some modifications to the ROC are considered. The short time scale cannot allow dramatic modification to the readout architecture. A redesign of the ROC to double the buffer sizes is possible in the current 0.25 $\mu$m technology, and will be pursued for Phase I.

(c) **Amount of material contribution**

The electrical connections, cooling system and support structure of the silicon tracker introduce a non-negligible amount of material into the tracking volume that reduces
the track reconstruction efficiency mostly because of nuclear interactions. The tracker material, and consequently this loss, depends on the rapidity ($\eta$) region considered. In the central region, $\eta < 1.2$, the main contribution to the material budget comes from silicon sensors, ROCs, carbon fiber mechanical structure, cooling pipes and kapton cables. While for $\eta > 1.2$ the main contribution is due to the cooling manifolds, the complex and heavy PCB end-flange print with more than 800 plugs, the kapton cables and the optical mother boards. In addition the cooling manifolds and the PCB end-flange are directly in front of the first forward pixel disk. This material unit of radiation length was evaluated as function of pseudorapidity considering tracks coming from the interaction point with a smeared primary vertex in $z$ of one sigma (7.5 cm). The fractional radiation length is around 0.05 at $\eta = 0$, increases up to 0.1 at $\eta = 1.1$, and has a maximum of 0.19 at $\eta = 1.7$ and then decreases with $\eta$.

2.3.2 Geometrical Description of the Pixel Detector Upgrade

For the Phase 1 upgrade of the CMS detector, it is proposed a pixel detector with 4 barrel layers and 3 disks in each end cap. The 4 barrel layers are of equal length and are placed at radii of 3.9, 6.8, 10.9, and 16.0 cm. The three end cap disks are placed on each side of the central barrel detector, with a radial coverage ranging from 4.5 to 16.1 cm. The location of the first disk along the beam lines is at 29.1 cm from the interaction point, the second and the third disks are located at 39.6 and 51.6 cm from the interaction point [8].

In the new design, there will be only one type of module with 16 readout chips in a $2 \times 8$ arrangement. They will be mounted on ultra lightweight support structures integrated with the cooling distribution system. Two-phase CO$_2$ cooling will replace the current single phase C$_6$F$_{14}$ resulting in significant material reduction. It is planned to use thin-walled stainless steel pipes with a diameter of about 1.6 mm and wall thickness
of 0.1 mm which will provide enough cooling power for each pixel sub-assembly based on a continuous loop. Further material reduction will be achieved by using longer twisted pair or light-weight flex-cables to carry the signal to the optical hybrid board; these boards, as well as the port cards and cooling manifolds, will be moved out of tracking region [8].

The outer and inner parts of the detector will be designed such that they would allow the inner layers and rings to be easily replaced after radiation damage. For FPIX, this requires each half-disk be divided into an inner and outer ring. Figure 2–7 shows a cross-sectional view of the new pixel system and its sections.
CHAPTER 3
OBJECTIVES

The current CMS pixel detector is designed for a maximum luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ and it will not be able to operate properly at the conditions of the Phase 1 LHC upgrade where the luminosity is expected to double ($2 \times 10^{34}$ cm$^{-2}$s$^{-1}$). The plan for the Phase 1 CMS upgrade is to keep the Silicon Strip detector and replace the entire Pixel detector. The upgraded pixel detector will be an ultra-light detector with improved ROCs, having four barrel layers and three end-cap disks. The addition of the fourth barrel layer and the third forward disks will improve the present level of tracking performance even in the high occupancy environment of the upgraded LHC. In addition, it provides a safety margin in case the first silicon strip layer of the Tracker Inner Barrel (TIB) degrades more rapidly than expected.

The implementation of the Phase 1 pixel detector would largely improve all aspects of CMS tracking due to the addition of the extra layers which will dramatically increase the efficiency of pixel-only tracks. The decrease in the amount of material and the increase in the number of measurement point improve the resolution of all track parameters. The efficiency and resolution improvements lead to much better primary and secondary vertexing.

The number of overlapping events during Phase 1 operation will be two to four time larger than during this period of LHC operation. The interesting physics to be pursued during Phase 1 is likely to involve among other the reconstruction of tracks in high-$p_T$ jets. These realities will emphasize the importance of reliable tracking in environments with high local hit densities. The fourth layer provides reasonable track seeding after high integrated luminosity. With four layers, even if the inner layer performance starts to degrade, the fourth layer will still provide three layer seeds.
The inner layers of the barrel of the silicon strip detector (TIB) are also important for pattern recognition and track reconstruction. There is a group of cooling loops in this part of the TIB which are not operating as their design. So far, this has not resulted in any significant reduction in efficiency. However, if there were in fact some unforeseen premature degradation in the performance of the TIB, it would negatively impact the performance of track pattern recognition and reconstruction. The new four-layer pixel detector, with fourth layer quite close to the first layer of the TIB, could significantly reduce such degradations.

The main objectives of this study are to analyze at high luminosity conditions (pileup fifty and ROC data loss) the performance of the standard and Phase 1 geometries of the tracker system pixel detector, in addition to determine the advantages of the new geometry when the TIB is degraded. Other objectives to be achieved are the implementation of the code used in this study into the official CMS Software to simulate the failure of cooling loops in the TIB and use this code to determine which configuration of the cooling loops that fail the efficiency loss of tracking reconstruction is high.
CHAPTER 4
ANALYSIS AND CONCLUSIONS

This work is a study of the effect of the Tracker Inner Barrel (TIB) degradation on the track reconstruction for the experiment’s current running conditions (standard geometry) and for the upgraded CMS tracking system (Phase 1 geometry) at the SLHC. This study was performed by comparing the tracking efficiency and the track fake rate for these two scenarios. The tracking efficiency and track fake rate were measured from the track reconstruction of Monte Carlo samples of $t\bar{t}$ events with zero and fifty pileup. In this study the normal CMS iterative tracking was modified by dropping the iterations that include large displaced tracks (steps 3-5) and with low transverse momentum track (step 2).

The study it was assumed that the degradation of the tracker inner barrel is caused by efficiency loss in its first two layers. This efficiency loss was simulated by setting a flat 20% inefficiency in these two layers and/or turning off the modules contained in some cooling loops of these layers. The cases in which the cooling loops overlap and non-overlap between them were also analyzed.

These results are used to study the performance of the standard and Phase 1 geometries of the tracker system in addition to determine the advantages of the new pixel detector geometry of the Tracker System [8].

4.1 Track Reconstruction

Track reconstruction is the task of determining the basic kinematic parameters of charged particles at their point of interaction. Five parameters are measured to describe the trajectory of a particle (track) passing through the tracking system: the coordinate of the impact point in the transverse ($d_0$) and longitudinal ($d_z$) plane, the azimuthal angle
(\phi) of the momentum vector of the track, the slope of the track (\cot \theta) and the transverse momentum (p_T) of the particle. All these parameters are defined at the impact point which is the closest approach of the track to the beam axis [24].

The method for track reconstruction uses the reconstructed local positions (hits) of the passage of charged particles in the silicon detectors to determine the helix trajectories of the charged tracks and, therefore, to measure their directions and momenta. The standard algorithm designed for the reconstruction of proton-proton collisions at CMS is called the Combinatorial Track Finder (CTF). The CTF proceeds in three stages: seeding, finding and fitting [25].

4.1.1 Pixel Vertexing

The pixel detector provides high resolution, three-dimensional points. This allows to reconstruct tracks approximately and find primary vertices (PV) using only data from the pixel detector. Such “pixel” reconstruction is useful for track seeding, primary vertex finding and in a variety of High Level Trigger (HLT) algorithms [9].

Primary-vertex finding based on the pixel hits (pixel vertexing) provides a simple and efficient method for measuring the position of the primary-vertex (PV). This measurement is subsequently used for track seeding and in many High Level Trigger (HLT) analyzes. It must, therefore, be sufficiently accurate and fast. For this reason, PV finding is reduced to a one-dimensional search along the z axis for the online mode.

The methods for PV finding make use of the pixel tracks reconstructed from hit triplets (triplets will be described in the next section). Usually triplets found in the full pixel detector acceptance are used. However the triplet finding can also be restricted to a selected region in order to make the vertex finding faster. The search for the primary vertex along the z axis is based on the longitudinal impact point (d_z) evaluated from pixel
tracks. Only pixel tracks reconstructed with $p_T$ greater than 1 GeV/c and a transverse impact point smaller than 1 mm are used for primary vertex finding.

Among the primary-vertex candidates, the closest primary vertex is defined as the closest in $z$ to the simulated signal primary vertex, and the tagged primary vertex as the one with the largest $p_T$ sum. The efficiency to find the primary vertex is defined with respect to vertices reconstructed inside a window of 500 μm around the position of the generated signal primary vertex.

4.1.2 Seeding

A trajectory seed is the starting point for the pattern recognition (finding stage) in the tracker [9]. The seed should constrain all five track parameters, thus the estimate of these parameters should be sufficiently close to their true value to allow the use of linear fitting algorithms and uncertainties of the parameters should be sufficiently small to allow a reasonable compact search region for hits.

A seed consists of pairs or triplets of hits, that are compatible with the interaction region above a $p_T$ threshold, are considered as possible candidates for charged tracks [25]. Pixel hits provide the best track seeding, given their three-dimensional position information and lower occupancy (fraction of detector channels with a hit in a local area). The seeding efficiency with pixel hits drops in the forward region ($2.0 < |\eta| < 2.5$), where a mixed seeding of hits from pixel and inner strips is needed to achieve a fully efficient track finding in the whole tracker acceptance (Fig. 4–1).

- Seeds from hits Pairs: A hit pair consists of an outer hit (with large radius) and an inner hit (smaller radius) coming from two different detector layers [9]. The various combinations of layers and disks used to find hit pairs are shown in the Fig. 4–2. Where the bold lines represent the layers used for finding hits pair. The combinations were
Tracks that lose a hit in any one of the layers may still be reconstructed in the other layers. To find pairs of hits, first an outer hit is searched for. The outer hit and the pixel vertex constraint are then used to search for a second (inner) hit in a layer between the vertex and the outer hit.

The minimal information from the pixel detector needed to construct a trajectory seed is a hit pair. Since hit pairs do not constrain the momentum, the additional assumption that the track passes through either a known vertex or the center of the interacting area must be used. The parameters of the seed are first estimated at the center of the interacting area, using the equations of an ideal helix passing through the two hits and the beam axis. The initial track parameters are then propagated to the surface of the closest hit and updated with the hit measurement information. The updated track state is again propagated to the surface of the outer hit, and updated with its measurement information.
Figure 4–2: Combination of layers (bold lines) used for finding pair of hits [9].

- **Seed from hits Triplets:** Finding pixel triplets requires hits from three different layers or disks [9]. Triplet finding is based on adding a third hit to pairs of hits. Each combination of pixels layers used in pair finding defines the layer in which the search for a third hit is performed. The layers and disks chosen are shown in Fig. 4–3. Where the dot lines represent the layer used for finding the third hit. The same sequence of operations, than in the seed pair, can be applied to transform a hit triplet into a trajectory seed; the only difference being an additional propagation and update on the surface of the third hit.

Figure 4–3: Combination of layers (bold lines) used for finding hits triplets [9].
4.1.3 Finding

The track finding stage is based on the standard Kalman Filter pattern recognition approach [25]. The Kalman Filter is a succession of alternating prediction and filtering steps. Starting with the seeded parameters \((d_0, d_z, \phi, \cot \theta, \text{ and } p_T)\), the track trajectory is extrapolated to the neighboring tracker layers and compatible hits are assigned to the track. At each stage the Kalman Filter updates the track parameters with new hits, allowing for a missing (lost) hit in a layer, in case of detector inefficiencies. The updated tracks are assigned a quality and only the best ones are kept for further propagation. Possible ambiguities with tracks sharing several hits are resolved in favour of the best quality trajectories. During the extrapolation, the uncertainties of each track trajectory in the \(r\phi\) transverse plane converge to a low level for tracks traversing many \((\geq 5)\) layers, so that the hit assignment becomes fast and efficient.

4.1.4 Fitting

The final estimate of the five parameters of each track helix is completed in the third stage applying again the Kalman Filter for the trajectory fitting. Each trajectory is refitted using a least-squares fit in two stages. A first forward fit, inside-out from the interaction region, removes the approximations and biases of the seeding and finding stages. A second outside-in smoother fit, yield the final best estimates of the track parameters at the origin vertex [25].

4.2 Iterative Tracking

In order to have high tracking efficiency and a minimum of fake rate, CMS used a tracking iterative procedure. The iterative tracking approach consists in repeating several times the CTF reconstruction with smaller subsets of reconstructed hits for each
iteration; it means the hits used by the previous iterations are removed from consideration and the CFT tracking algorithm is run again with progressively looser settings [26].

Four steps are applied for each iteration in the iterative tracking. First, a subset of reconstructed hits is selected by removing all of the hits used in the previous iteration. In the first iteration, the complete set of reconstructed hits is used. In the following iterations, all the hits attached to a track reconstructed in the earlier iterations are removed. Second, the track reconstruction is run on the selected seeds. After selecting the subset of hits, the CTF tracking algorithm is applied. Third, the track collection is cleaned. The cleaning is done according to the compatibility of the track with the reconstructed vertices. In the transverse plane, we applied a cut on the transverse impact parameter ($d_0$), while in the longitudinal direction, the compatibility between the $z$ coordinate of the position of closest approach to the beam line ($d_z$) and the $z$ coordinate of the vertices built using the pixel detector ("pixel vertex") is requested. If no pixel vertices are found, then, the $z$ coordinate of the vertex of the leading track is taken as a reference. A further filter on the track $\chi^2$ is applied. Finally, the tracks which pass the cleaning procedure are saved [26].

The default iterative tracking in CMS contains 6 iterations, labeled as 0 through 5. The main distinction between the iterations is the track seeding algorithm which is shown in the Table 4–1. In this table, $d_0$ and $d_z$ refer to the transverse and longitudinal impact parameters of the seeds with respect to the nominal interaction point respectively. Using triplet seeding is much faster and has a lower fake rate than pairs. Therefore, pixel triplet seeding is run first (iteration 0), followed by pixel pairs (iteration 1) for additional efficiency. In the iteration 1 hits are searched in the pixel detector and in the TEC (mixed-pair seeding) in order to reach large values of pseudorapidity $\eta$. Iteration 2 uses pixel triplets like iteration 0, but searches for very low momentum tracks. Iteration 3 uses pixels and strip triplets in order to find tracks, which miss a pixel layer and also
Table 4–1: Parameter for each of the iterative tracking steps in the normal track reconstruction.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Seeds</th>
<th>$p_T$ cut (GeV)</th>
<th>$d_0$ cut (cm)</th>
<th>$d_z$ cut (cm)</th>
<th>Min. hits</th>
<th>Max. lost hits</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>pixel triplets</td>
<td>0.8</td>
<td>0.2</td>
<td>15.9</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>pixel+TEC pairs with vtx</td>
<td>0.6</td>
<td>0.05</td>
<td>0.2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>pixel triplets</td>
<td>0.075</td>
<td>0.2</td>
<td>17.5</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>3A</td>
<td>pixel+(TID/TEC) triplets</td>
<td>0.25</td>
<td>2.0</td>
<td>10.0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>3B</td>
<td>BPIX+TIB triplets</td>
<td>0.35</td>
<td>2.0</td>
<td>10.0</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>TIB,TID,TEC pairs</td>
<td>0.5</td>
<td>2.0</td>
<td>10.0</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>TOB,TEC pairs</td>
<td>0.8</td>
<td>5.0</td>
<td>10.0</td>
<td>7</td>
<td>0</td>
</tr>
</tbody>
</table>

tracks which may decay within a couple of centimeters of the production vertex. In the iteration 3A, it is searched for two hits in the pixel and one in the TID or TEC. In the iteration 3B, it is searched for two hits in the pixel barrel and one in the TIB. Iterations 4 and 5 do not use pixels to seed and are designed to find tracks which are significantly displaced from the beam line or tracks which do no leave sufficient pixel hits to be found in the earlier iterations. Other differences between iterations during track building include the minimum number of hits (3 for iterations 0-3, 7 for iteration 4-5), the number of lost hits (1 for iterations 0-2 and 0 for iterations 3-5). The final cleaning stage is also different. The early steps have stricter requirements on tracks originating from the production vertex, while the later steps have stricter requirements on the track quality [27].

For the results presented in this study, the default iterative tracking steps have been modified to those as shown in Table 4–2. The tracking steps 3-5 were removed due to the less concerned in large displaced tracks. The step 2 was also removed due to less interest
Table 4–2: Parameters for each of the iterative tracking steps used for the simulations of the standard and Phase 1 upgrade pixel detector in this study.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Seeds</th>
<th>$p_T$ cut (GeV)</th>
<th>$d_0$ cut (cm)</th>
<th>$d_z$ cut (cm)</th>
<th>Min. hits</th>
<th>Max. lost hits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current pixel detector</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>pixel triplets</td>
<td>0.8</td>
<td>0.2</td>
<td>15.9</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>pixel+TEC triplets</td>
<td>0.6</td>
<td>0.05</td>
<td>0.2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Phase 1 upgrade pixel detector</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>pixel quadruplets</td>
<td>0.8</td>
<td>0.2</td>
<td>15.9</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>pixel+TEC triplets</td>
<td>0.6</td>
<td>0.05</td>
<td>0.2</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

in the lower $p_T$ tracks below about 1 GeV/c. The tracking step 1 was only modified by replacing the pair seeds into triplets seeds in order to make the number of seeds more manageable, and also, to reduce the fake rate for this step. Finally, the tracking step 0 is unchanged for the standard geometry. However, for the upgrade Phase 1 geometry, the pixel triplet seeds were replaced by pixel quadruplet seeds since there is an extra pixel layer in the upgrade geometry [27].

4.3 TIB degradation produced by uniform inefficiency

In this section we compared the tracking efficiency and the track fake rate of the standard and Phase 1 geometries. This comparison was made in the pileup zero and fifty scenarios. In the second scenario, we considered the efficiency loss in the pixel detector layers due to data loss in the readout chip (ROC). This data loss is produced by the increase in luminosity. In the table 4–3 are shown the data loss values used in the simulation for the standard and Phase 1 geometries [28]. In addition to the data loss,
Table 4–3: Values of data loss in the simulations of the standard and Phase 1 upgrade pixel detector geometries at $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$.

<table>
<thead>
<tr>
<th>CMS Tracker Geometry</th>
<th>Layer</th>
<th>Radius (cm)</th>
<th>% Data loss at $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ at 25 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>BPIX1</td>
<td>4.4</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>BPIX2</td>
<td>7.3</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>BPIX3</td>
<td>10.2</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>FPIX1 and 2</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Phase 1</td>
<td>BPIX1</td>
<td>3.9</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>BPIX2</td>
<td>6.8</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>BPIX3</td>
<td>10.2</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>BPIX4</td>
<td>16.0</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>FPIX1 and 3</td>
<td></td>
<td>0.6</td>
</tr>
</tbody>
</table>

There is some concern about a possible premature degradation of the first two layers of the Tracker Inner Barrel (TIB) produced by the increase in luminosity. In this section, this degradation is simulated as a 20% uniform inefficiency in the TIB layers 1 and 2.

The track reconstruction was made in Monte Carlo $t\bar{t}$ samples for standard and Phase 1 geometries, considering the modification mentioned in Table 4–2. In figure 4–4 is shown the tracking efficiency as a function of pseudorapidity ($\eta$) for the high purity track collection at pileup zero (left) and fifty (right) scenarios. Results are shown for the standard geometry (black circles, green triangles), and the Phase 1 geometry (red squares, blue inverted triangles); with TIB layers 1 and 2 at 100% efficiency (black circles, red squares), and with TIB layers 1 and 2 at 80% efficiency (green triangles, blue inverted triangles). The tracking efficiency was measured using the following expression [27]:

$$\text{Tracking efficiency} = \frac{\text{number of tracked tracks}}{\text{number of generated tracks}}$$
Figure 4–4: Tracking Efficiency as a function of $\eta$ for the standard and Phase 1 geometry at pileup zero (a) and fifty (b) scenarios. Standard geometry with TIB layers 1 and 2 at 100% efficiency (black circles), standard geometry with TIB layers 1 and 2 at 80% efficiency (green triangles), Phase 1 geometry with TIB layers 1 and 2 at 100% efficiency (red squares), Phase 1 geometry with TIB layers 1 and 2 at 80% efficiency (blue inverted triangles).

Tracking Efficiency = \frac{\text{N}\text{o of truth tracks matched to reconstructed tracks}}{\text{N}\text{o of truth tracks}} \quad (4.1)

where the truth tracks are the simulated tracks.

It can be seen that a uniform 20% inefficiency in the first two TIB layers reduces the tracking efficiency in both the standard and the Phase 1 upgrade pixel detector. In the central region of pseudorapidity when the TIB layers are 100% efficient the tracking efficiency at pileup zero scenario is approximately 84% for standard geometry and 94%
for Phase 1 geometry, while at pileup fifty scenario is approximately 56% for standard
groupy and 92% for Phase 1 geometry. For the case of degraded TIB layers the tracking
efficiency in the central region of pseudorapidity at pileup zero scenario is approximately
81% for standard geometry and 92% for Phase 1 geometry, while at pileup fifty scenario
is approximately 48% for the standard geometry and 87% for the Phase 1 geometry.
Therefore the efficiency loss in tracking efficiency is worse at high pileup. However,
the loss in tracking efficiency due to degradation in the TIB is reduced in the Phase 1
geometry compared to the standard. This behavior is shown in figure 4–5 where it
shows the ratio of tracking efficiencies with TIB layers 1 and 2 at a 80% efficiency to the
tracking efficiency with TIB layers 1 and 2 at 100% efficiency. The ratio is plotted as a
function of η with pileup zero (left) and fifty (right). Results are shown for the standard
groupy (blue circles), and Phase 1 geometry (red squares). At pileup zero, the tracking
efficiency loss is almost the same for the standard and Phase 1 geometry, approximately
3% for standard and 2% for Phase 1 in the central pseudorapidity region. At pileup fifty,
the efficiency loss with the standard pixel geometry is dramatically worse, approximately
14% for the standard geometry and 5% for the Phase 1 geometry in the central region
of pseudorapidity. The upgrade pixel detector can, thus, significantly mitigate the loss
in tracking efficiency due to a degradation in the TIB.

In addition to the tracking efficiency, we measured the track fake rates to evaluate
the performance of the standard and Phase 1 geometries. The track fake rate is mea-
sured using the following expression [27]:

\[
\text{Track Fake Rate} = \frac{N^\circ \text{ of reconstructed tracks not matched to truth tracks}}{N^\circ \text{ of reconstructed tracks}}
\] (4.2)

where all the reconstructed tracks are considered. Figure 4–6 shows the track fake rate
as a function of η for high purity tracks in a \( t\bar{t} \) sample with pileup zero (left) and fifty
Figure 4–5: Ratio of tracking efficiencies with TIB layer 1 and 2 at 80% efficiency to the tracking efficiency with TIB layers at 100% efficiency as a function of $\eta$ at pileup zero (a) and fifty (b) scenarios. Standard geometry (blue circles), Phase 1 geometry (red squares).

(right). Results are shown for the standard geometry (black circles, green triangles), and the Phase 1 geometry (red squares, blue inverted triangles); with TIB layers 1 and 2 at 100% efficiency (black circles, red squares), and with TIB layers 1 and 2 at 80% efficiency (green triangles, blue inverted triangles). This figure shows that in the central region of pseudorapidity at pileup fifty for the case of 100% efficient TIB layers the track fake rate is approximately 0.019 for standard geometry and 0.01 for Phase 1 geometry; while for the case of degraded TIB layers the track fake rate is approximately 0.03 for standard geometry and 0.015 for Phase 1 geometry. Therefore the Phase 1 geometry has the lowest track fake rate in both scenarios in spite of the degradation of the TIB layers. Figure 4–7 shows the gain in fake rate with the degradation in the TIB. For the standard
Figure 4–6: Track fake rate as a function of $\eta$ for the standard and Phase 1 geometry at the pileup zero (a) and fifty (b) scenarios. Standard geometry with TIB layers 1 and 2 at 100% efficiency (black circles), standard geometry with TIB layers 1 and 2 at 80% efficiency (green triangles), Phase 1 geometry with TIB layers 1 and 2 at 100% efficiency (red squares), Phase 1 geometry with TIB layers 1 and 2 at 80% efficiency (blue inverted triangles).

pixel detector the track fake rate increases in the central region by as much as 30% with pileup zero, while it increases by a factor of two to 60% with pileup fifty. In contrast, for the Phase 1 upgrade pixel detector the degradation in the TIB performance causes almost no increase in fake rate for pileup zero, and up to a 30% increase in the fake rate in the central region at pileup fifty. These results shown that the upgrade pixel detector can mitigate the increase in track fake rates for a degradation in the TIB efficiency.
Figure 4–7: Ratio of the track fake rates with TIB layers 1 and 2 at 80% efficiency to the track fake rates with TIB layers 1 and 2 at 100% efficiency as a function of $\eta$ at pileup zero (a) and fifty (b) scenarios. Standard geometry (blue circles), Phase 1 geometry (red squares).

4.4 TIB degradation produced by cooling loops failure

Degradation of the TIB might also occur if any of its cooling loops in its layers failed and, therefore, the corresponding modules have to be turned off to avoid the detector break down.

Figure 4–8 shows the TIB sub-assemblies: forward ($+z$), backward ($-z$), up ($+x$) and down ($-x$). The forward assembly covers positive values of $\eta$ and the backward assembly negative values of $\eta$. The numbers (inside squares) represent the numbering of the cooling loops. Each cooling loop is composed by an inner and outer layer of strings. These strings are the support structure of the modules.
In this section it is considered that the degradation of the first TIB layers is caused by the failure of the cooling loops. A failure of the cooling loops in the TIB layers 1 and 2 was simulated by turning off our Monte Carlo reconstructed sample of all the selected cooling loops. Based on which coolings were selected, the following cases were studied: failure of non-overlapped cooling loops and failure of overlapped cooling loops. Cooling loops are overlapped if a cooling loop in TIB layer 1 is located below the cooling loop in TIB layer 2.

In addition to the modifications described in the Table 4–2, a modification to the tracking reconstruction was made with the purpose of allowing two missing hits for the turned off cooling loops case. With this modification tracks will be reconstructed anyway in this region in order to see how much efficiency it can be lost.
4.4.1 Failure of non-Overlapped Cooling Loops

Figure 4–9 shows the case of failure non-overlapped cooling loops. Selected cooling loops are marked in red. Cooling loops 2, 5 and 8 were selected in layer 1; and cooling loops 1, 4, 5 and 8 in the layer 2.

As in the previous section it was measured the tracking efficiency and the track fake rates to compare the performance of the standard and Phase 1 geometries at pileup zero and fifty scenarios. Figure 4–10 shows the tracking efficiency as a function of $\eta$ for high purity tracks in the $t\bar{t}$ sample at pileup zero (left) and fifty (right) scenarios. Results are shown for the standard (black circles, green triangles) and Phase 1 geometry (red squares, blue inverted triangles), with the TIB layers at 100% efficiency (black circles, red squares) and TIB layers 1 and 2 with failure non-overlapped cooling loops (green triangles, blue
Figure 4–10: Tracking efficiency as a function $\eta$ for the standard and Phase 1 geometry at pileup zero (a) and fifty (b) scenarios. Standard geometry with TIB layers 1 and 2 at 100% efficiency (black circles), standard geometry with failure in TIB layers 1 and 2 overlapped cooling loops (green triangles), Phase 1 geometry with TIB layers 1 and 2 at 100% efficiency (red squares), Phase 1 geometry with failure in TIB layers 1 and 2 overlapped cooling loops (blue inverted triangles).

inverted triangles). It can be seen that the Phase 1 geometry has a higher efficiency than the standard at pileup zero and fifty scenarios in all the pseudorapidities regions. For the pseudorapidity region $0 < \eta < 0.5$, this region is chosen because is contained in the region covered by the failure cooling loops, when the TIB layers are 100% efficient the tracking efficiency at pileup zero is approximately 84% for standard geometry and 94% for Phase 1 geometry, while at pileup fifty is approximately 56% for standard geometry and 92% for Phase 1 geometry. In the case of a degraded TIB layers for the same region of pseudorapidity at pileup zero the efficiency is approximately 82% for standard geometry and 94% for Phase 1 geometry, while at pileup fifty is approximately 50%
Figure 4–11: Ratio of the tracking efficiencies with turned off non overlapped cooling loops to the tracking efficiency with TIB layers 1 and 2 at 100% efficiency as a function of $\eta$ at pileup zero (a) and fifty (b) scenarios. Standard geometry (blue circles), Phase 1 geometry (red squares).

for standard geometry and 92% for Phase 1 geometry. The tracking efficiency loss for standard geometry is higher than that obtained with Phase 1. For the pseudorapidity region $0 < \eta < 0.5$ at pileup zero scenario the efficiency loss is 1.5% for standard geometry and 0.5% for Phase 1 geometry; while at pileup fifty scenario the efficiency loss is 10% for standard geometry and 0.5% for Phase 1 geometry. This behaviour is seen in figure 4–11. It shows the ratio of tracking efficiencies with TIB layers 1 and 2 with failure non-overlapped cooling loops to the tracking efficiency with TIB layers at 100% efficiency as a function of $\eta$ for the $t\bar{t}$ samples with pileup zero (left) and fifty (right). The plots are shown for the standard (blue circles) and the Phase 1 (red squares) geometries. Figure 4–12 shows the track fake rates at pileup zero (left) and pileup fifty (right) for
Figure 4–12: Track fake rate as a function of $\eta$ for the standard and Phase 1 geometry at the pileup zero (a) and fifty (b) scenarios. Standard geometry with TIB layers 1 and 2 at 100% efficiency (black circles), standard geometry with turned off non overlapped cooling loops in TIB layers 1 and 2 (green triangles), Phase 1 geometry with TIB layers 1 and 2 at 100% efficiency (red squares), Phase 1 geometry with turned off non overlapped cooling loops in TIB layers 1 and 2 (blue inverted triangles).

standard (black circles, green squares) and Phase 1 geometry (red squares, blue inverse triangles), with TIB layers at 100% efficiency (black circles, red squares), and with TIB layers 1 and 2 with failure non-overlapped cooling loops. It can be seen that the Phase 1 geometry at both scenarios has lower track fake rates than the standard geometry in spite of the degradation of the TIB first layers. For the pseudorapidity region $0 < \eta < 0.5$ considering the degradation of the TIB first layers, at pileup fifty scenario the track fake rate is 0.035 for standard geometry while 0.018 for Phase 1 geometry.
4.4.2 Failure of overlapped Cooling Loops

The case with failure overlapped cooling loops is shown in figure 4–13. In the TIB layer 1 was selected the cooling loops 2, 5 and 8; and in the TIB layer 2 the cooling loops 2, 3, 6 and 7.

In figure 4–14 it is shown the tracking efficiency as a function of $\eta$ for high purity tracks in the $t\bar{t}$ sample at pileup zero (left) and fifty (right). Results are shown for the standard (black circles, green triangles) and Phase 1 geometry (red squares and blue inverted triangles.); with TIB layers at 100% efficiency (black circles, red squares), and TIB layers 1 and 2 with failure overlapped cooling loops. It can be seen that Phase 1 geometry has higher efficiency than the standard geometry. In the pseudorapidity region $0 < \eta < 0.5$ when the TIB layers are 100% efficient, at pileup zero scenario the tracking
Figure 4–14: Tracking efficiency as a function $\eta$ for the standard and Phase 1 geometry at pileup zero (a) and fifty (b) scenarios. Standard geometry with TIB layers 1 and 2 at 100% efficiency (black circles), standard geometry with turned off overlapped cooling loops in TIB layers 1 and 2 (green triangles), Phase 1 geometry with TIB layers 1 and 2 at 100% efficiency (red squares), Phase 1 geometry with turned off overlapped cooling loops in TIB layers 1 and 2 (blue inverted triangles).

Efficiency is approximately 84% for standard geometry and 94% for Phase 1, while at pileup fifty scenario the tracking efficiency is approximately 56% for standard geometry and 92% for Phase 1. For the same pseudorapidity region when the TIB layers are degraded at pileup zero scenario the tracking efficiency is approximately 81% for standard geometry and 93% for Phase 1 geometry, while at pileup fifty scenario the tracking efficiency is approximately 48% for standard geometry and 91% for Phase 1 geometry. Therefore the efficiency when the overlapped cooling loops failed is lower than in the case of failure non-overlapped cooling loops for both the standard and Phase 1 geometry.
Figure 4–15: Ratio of the tracking efficiencies with turned off overlapped cooling loops to the tracking efficiency with TIB layers 1 and 2 at 100% efficiency as a function of $\eta$ at pileup zero (a) and fifty (b) scenarios. Standard geometry (blue circles), Phase 1 geometry (red squares).

at pileup zero and fifty scenarios. The efficiency loss can be analyzed from figure 4–15. In this figure is shown the ratio of the tracking efficiency with TIB layers 1 and 2 with failure overlapped cooling loops to the tracking efficiency with failure TIB layers at 100% efficiency as a function of $\eta$ for the $t\bar{t}$ samples with pileup zero (right) and fifty (right). Results are shown for the standard (blue circles) and the Phase 1 (red squares) geometries. It can be seen that the efficiency loss is higher for the standard geometry than in the Phase 1 at pileup zero and fifty scenarios. In the pseudorapidity region $0 < \eta < 0.5$, at pileup zero scenario the efficiency loss is approximately 1.5% for standard geometry and 3.5% for Phase 1 geometry; while at pileup fifty scenario the efficiency loss is approximately 2% for standard geometry and 13.5% for Phase 1 geometry.
Figure 4–16: Track fake rate as a function of $\eta$ for the standard and Phase 1 geometry at the pileup zero (a) and fifty (b) scenarios. Standard geometry with TIB layers 1 and 2 at 100% efficiency (black circles), standard geometry with turned off overlapped cooling loops in TIB layers 1 and 2 (green triangles), Phase 1 geometry with TIB layers 1 and 2 at 100% efficiency (red squares), Phase 1 geometry with turned off overlapped cooling loops in TIB layers 1 and 2 (blue inverted triangles).

geometry. Comparing with the previous section results, the efficiency loss in the case of failure overlapped cooling loops is higher than in the case of failure non-overlapped cooling loops for both geometries and scenarios.

The track fake rate for this case is shown in figure 4–16. This figure shows the track fake rate as a function of $\eta$ for high purity tracks in the $t\bar{t}$ sample with pileup zero (left) and fifty (right). Results are shown for the standard (black circles, green triangles), and the Phase 1 (red squares, blue inverted triangles) geometries; with TIB layers at 100% efficiency (black circles, red squares), and with TIB layer 1 and 2 with failure overlapped cooling loops (green triangles, blue inverted triangles). The Phase 1 geometry presented
less track fake rates than the standard geometry for the pileup zero and fifty scenarios. In the pseudorapidity region $0 < \eta < 0.5$ at pileup fifty scenario when the TIB layers are degraded the fake rate is approximately 0.045 for the standard geometry and 0.019 for the Phase 1 geometry. Comparing this result with that of the previous section it can be seen that there is more track fake rates in the case of failure overlapped cooling loops.

4.5 Conclusions

This work presented the study of the performance of the tracker system for the standard and Phase 1 geometries of the pixel detector in the pileup zero and fifty scenarios. The study compared the reconstruction tracking efficiency and the track fake rate for both geometries in the case of a degraded and non-degraded tracker inner barrel.

It was found that for Tracker System without inefficiencies, the loss of reconstruction efficiency due to higher luminosity (pileup fifty and ROC data loss) is worse in the standard geometry (approximately 28% loss) than in the Phase 1 (approximately 2% loss). The track fake rate is also worse for the standard geometry as it is expected.

The degradation of the Tracker Inner Barrel, due to uniform inefficiency or cooling loops failure, decreases the tracking efficiency and increases the track fake rate. However, the tracking efficiency loss for Phase 1 geometry is much lower (between 0.5%-5%) than the tracking efficiency loss (between 10%-14%) for the standard geometry at higher luminosity condition. It is also shown in this study that the Phase 1 geometry has better performance at higher luminosity, implying that the presence of an additional layer in the upgraded pixel detector (placed close to TIB) can significantly reduce the impact of the degradation of the first layers of the TIB and help to recover the efficiency loss due the increase in luminosity.
In addition, the configuration of failed cooling loops in the first Tracker Inner Barrel layers for which the Tracker System performance is most affected is when these cooling loops overlapped each other.

Finally, in this work we concluded that the CMS pixel detector Phase 1 geometry has better performance than the pixel detector standard geometry at high luminosity conditions as it is expected for the SLHC.

4.6 Future Work

The uniform efficiency loss of 20%, in the first two layers of Tracker Inner Barrel, was selected just as a case study. The purpose of this was to evaluate how the pixel detector geometry proposed in the Upgrade Phase 1 improves the tracking efficiency in the pileup zero and fifty scenarios.

As future work is suggested that different values efficiency loss in the first layers of Tracker Inner Barrel, such as 10%, 30%, 50%. In order to see if the tracking efficiency decreases smoothly with those value or if there is a sudden reduction.
REFERENCES


