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Testing lepton flavour universality
and activities of phase-II upgrade in
CMS

A thesis

*submitted in fulfilment of the requirements for the degree of
Doctorate of Philosophy in Physics*

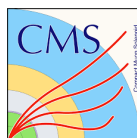
by

Shubhi Parolia

under the supervision of

Prof. Alberto Messineo

Prof. Fabrizio Palla



June 2022



Declaration of Authorship

I, Shubhi Parolia, declare that this thesis titled, "Testing Lepton flavour Universality and Activities of phase-II upgrade in CMS" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
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Abstract

I carried out my research activities for the PhD in Physics within the Compact Muon Solenoid (CMS) experiment team at the University and INFN of Pisa. CMS is one of the two multipurpose detectors at the Large Hadron Collider (LHC), credited for the discovery of Higgs Boson in 2012.

Within the CMS Pisa group, I am working in the Beyond Standard Model (BSM) physics searches, in particular, the study of Lepton Flavour Non-Universality (LFNU) in collaboration with other international groups. LFNU can be observed by investigating deviations from the Standard Model (SM) prediction of all the three charged leptons, that in the SM are supposed to have the same coupling constants for the electroweak interactions. For this investigation, I am looking at a specific decay channel $B_c^+ \rightarrow J/\Psi \tau^+ \nu_\tau$; To measure the ratio $R(J/\Psi)$, where: $R(J/\Psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\Psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\Psi \mu^+ \nu_\mu)}$. I am studying this particular decay, since measurements of semi-leptonic decay of b hadron provide a direct handle to study the origin of LFNU and non-universal coupling. The analysis is ongoing and seems to converge soon. CMS Run3 data shall have some positive impact on the results but better statistical results are expected from high luminosity upgrades.

The LHC is undergoing an upgrade to accomplish the transition to the high-luminosity phase (HL-LHC), foreseen from ~ 2027 . To withstand this high radiation flux, CMS is having major upgrades. I have actively worked on the upgrade of the inner pixel tracker of the CMS, which is located closest to the interaction point and susceptible to the highest amount of radiation. I have performed TCAD simulation studies, to study the effect of these high doses of radiation on the silicon pixels. Since the present tracker will be completely replaced with a new and high radiation resistant sub-detector, extensive R&D is ongoing. As part of this R & D, I am pursuing the studies of planar and 3D silicon pixels of varying dimensions for the innermost layer of the tracker. Modules are being irradiated at high fluences and beam test studies are being done before and after irradiation for evaluating the performances in realistic conditions.

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Last but not the least, I would like to thank my fiance Nimish Parmar (Husband, by the time I submit), for being a constant throughout. He was there for me through every ups and downs, through every frustration, through every mood swings. His trust in me made me overcome any doubts I ever had. He nourishes my passion for science and research more than me, and that's my current driving force. His family's support has also been a cherry on a wonderful cake.

This has been a long, yet a very small part of my overall scientific endeavour. I hope this experience helps me build a better world for everyone.

Thank You...

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Dedicated to my Mumma and Papa...

Chapter 1

Introduction

High energy physics has come a long way from the revelation of fundamental particles to the last missing piece of Standard Model physics. Discovery of Higgs Boson in 2012, not only completed the puzzle of the standard model, but also opened the gates for future opportunities. The quest of LHC to explore further energies and higher luminosity, motivates the young generation to look beyond the current scientific limits. Being involved in Beyond Standard Model (BSM) searches thus seems very exciting and fortunate. In the process we learn the state of art of the experiment, data collection and processing techniques and statistical analysis, etc. On the detector front, I feel getting involved in the upcoming tracker upgrade, gave me a unique opportunity to contribute to a cutting-edge project.

The open questions of today are just as profound as they were a century (or a century and a half) ago, but there are more of them. The question is from where are the answers or clues going to come? A broad range of experiments need to be carried out, and we note that it is a good time to be an experimental physicist.

For my doctoral research work, I have performed both experimental and analysis activities in CMS experiment. Analysis involves studies searching deviations from Standard Model (SM) of physics, which is by far the most successful theory of elementary particle physics and their interactions. At the time of writing, no evidence has been found for physics beyond the SM (BSM) in collider experiments. But we shall give the motivation for expecting BSM physics that includes observations from experiments other than those at hadron colliders.

The SM predicts the same coupling constant for all the three charged leptons in electroweak interactions. Recently, some deviations are indicated in this prediction through experiments like BaBar[1], Belle[2] and LHCb[3] and theoretical hints seen in electroweak loop-induced B-meson decays. This is called the non universality of lepton flavour, probably arising due to weak couplings to the third generation leptons and quarks such as interactions involving a charged Higgs boson, leptoquarks or new vector bosons [4]. Figure 1.1 shows Flavour-Changing Charged-Current (FCCC) transitions $b \rightarrow c \ell^- \bar{\nu}_\ell$ decays, where ℓ represents any of the three charged leptons and a single CKM matrix element is involved (V_{cb}). Details are discussed in Chapter 2.

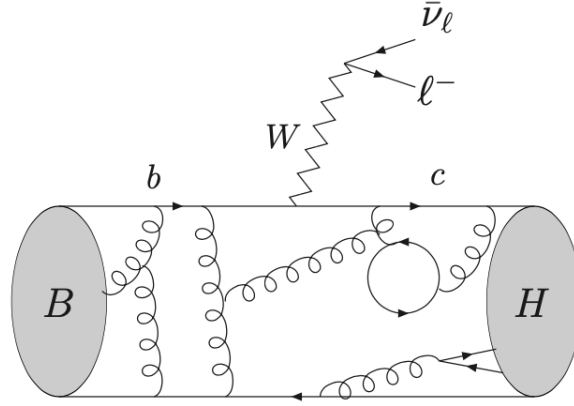


FIGURE 1.1: Illustration of a $b \rightarrow c \ell^- \bar{\nu}_\ell$ transition in the SM, as seen at the hadronic level, in the case of a B meson decaying into an unspecified H meson.

In this thesis work, the $b \rightarrow c \tau^- \bar{\nu}_\tau$ transition in $B_c^+ \rightarrow J/\Psi \tau^+ \nu_\tau$ leptonic decay is studied. The B_c meson cannot be produced at B-factories (Belle, BaBar, BelleII) because the $\sqrt{s}$ available is not enough. CMS, which is specifically designed for the detection of muons is thus particularly suitable to efficiently study final states which include 2μ or 3μ . Details of the analysis are discussed in Chapter 5.

Going forward the highest priority in the global strategy for particle physics is the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting 10 times more data than in the initial design, by around 2035. The work towards this goal is proceeding well. Figure 1.2 illustrates the long-term evolution of the LHC programme and the arrow indicates our present position in the LHC programme.



FIGURE 1.2: Timeline for the High Luminosity LHC

Foreseen are increases in instantaneous luminosity, from $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ to $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, and in integrated luminosity, from 300 fb^{-1} to 3000 fb^{-1} . This would lead to the production of about 50 million Higgs bosons, among other states. Considerable detector R&D is being carried out to build new inner trackers and forward calorimeters, as well as extensive upgrades of electronics to allow selection of approximately 1 million events at the first level of triggering. Introduction of information from the inner tracker also is envisaged at this first level of triggering.

My experimental activities mostly consist of the upgrade related R&D work including simulations, testing new pixel modules first in our lab, then in the beam tests. Pixel modules are tested for radiation hardness by irradiating them to the expected fluences of phase-II upgrade. The activities and results are described in detail in Chapter 4. This work has been presented in conferences and published as proceedings [5] and [6].

Short description of the current experiment and the upgrade is presented in Chapter 3.

Chapter 2

Theory and Motivation

2.1 The Standard Model

The Standard Model of particle physics is the current most successful theoretical model that describes all the known fundamental particles and the interactions among them. The Higgs boson with a mass of nearly 125 GeV was discovered in 2012, by the ATLAS and CMS collaborations. After the discovery of the Higgs boson, the main areas where LHC experiments have been focusing on are searches for new physics (beyond standard model searches) and the measurement of the Higgs boson properties.

The Standard Model (SM) is a renormalizable Quantum Field Theory which describes the interactions among fundamental matter components. It has successfully passed numerous stringent tests at both collider and non-collider experiments. Nature is regulated by the presence of four fundamental forces, three of which are successfully described in the standard model: the electromagnetic interaction, the weak interaction and the strong interaction. Electromagnetic and weak forces are grouped together in a unique force called 'Electroweak interactions'. The gravitational interaction is much weaker and is not expected to contribute to the physical processes currently investigated in high energy physics. The SM does not include gravity in the theory.

2.1.1 Fundamental particles and interactions of SM

The elementary particles of SM are represented in figure 2.1. They include two types of fundamental particles: *fermions* described by spin-half fields are the matter particles and *vector bosons*, described by integer spin or vector fields are the mediators of the interactions. Finally, the Higgs boson with spin 0 is described by a scalar field.

The matter particles are divided into *leptons* and *quarks*. There are six leptons and six quarks organised in generations according to their mass. Both families of fermions have doublets in each generation. Their antiparticles follow the same trend¹. The doublet of leptons consists of a charged massive lepton (tau, muon or electron) and a neutral particle, which is called neutrino. In SM theory, neutrinos are assumed to be massless²; the leptons interact only through electroweak forces and not through the strong interactions.

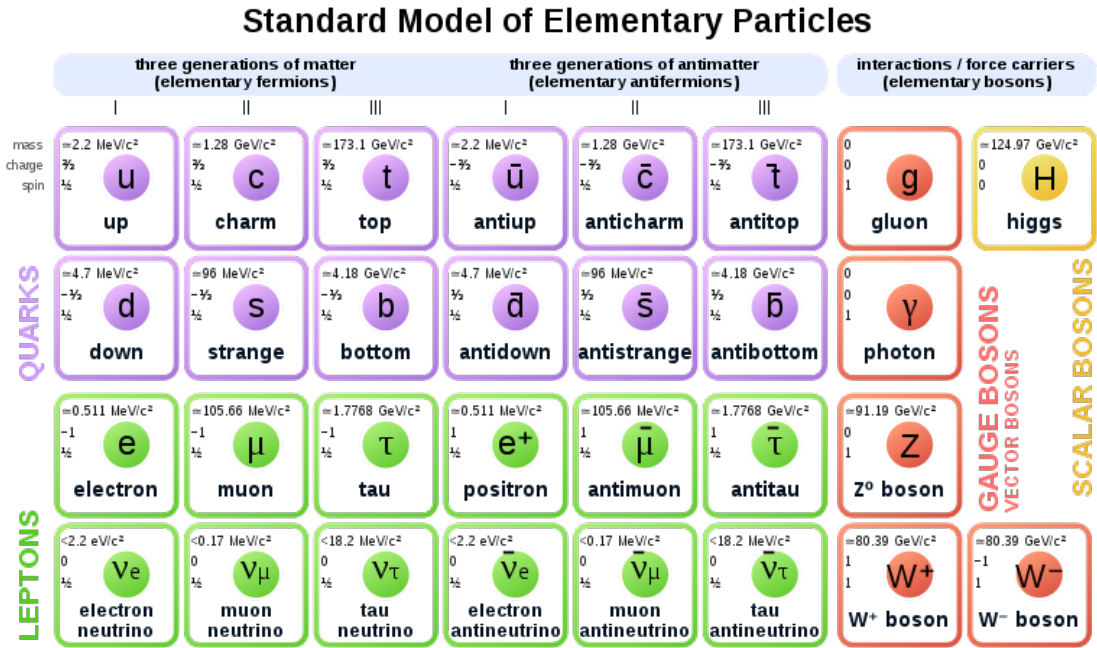


FIGURE 2.1: Pictorial description of SM elementary particles

The Quark doublets follow the same organisational characteristics. There are six types of flavours known for quarks: up, down, charm, strange, top, and bottom.

¹Antiparticles are particles with the same mass, spin and lifetime of its partner but opposite charge.

²By the observation of the neutrino flavour oscillation the different neutrino flavours have different masses, although these masses have been shown to be very tiny by the experiments [7]

Up and down quarks have the lowest masses of all quarks. Quarks also have intrinsic properties like mass, a fractional electric charge and they interact through all three fundamental forces; strong and electroweak interactions. Quarks have an additional charge called the color charge, which exists in three states: “red” (R), “green” (G) and “blue” (B). These colors are the charges that quantify the strong interactions. Owing to a phenomenon known as color confinement, quarks are never found as free particles but they combine in “white” color charge states, called hadrons. Hadrons are divided into baryons (made up of three quarks) and mesons (made up of quark and an antiquark pair). For this reason, much of what is known about quarks has been drawn from observations of hadrons.

The heavier quarks are unstable and rapidly decay into up and down quarks through a process of particle decay: the transformation from a higher mass state to a lower mass state. Similar transformation happens in higher mass leptons.

As mentioned earlier, these elementary particles interact via vector fields also known as interaction forces, mediated by bosons. The photon (γ), is the carrier of electromagnetic interactions. It is massless and electrically neutral. The eight gluons (g) mediate the strong interactions among quarks. They have no electric charge, are massless, carry colour quantum number and they can interact with quarks as well as amongst themselves. The three weak bosons: $W^\pm$, Z are the corresponding intermediate bosons of the weak interactions. They are massive and self-interacting. The $W^\pm$ carry electric charge ($Q = \pm 1$) while the Z boson is neutral. Properties of bosons are summarised in table 2.1.

Force	Particle	Charge	Mass
Electromagnetic	γ	0	$< 1 \times 10^{-18}$ eV
Weak	$W^\pm$	± 1	80.39 GeV
	Z	0	91.19 GeV
Strong	g	0	0 (theoretical)

TABLE 2.1: Properties of SM Bosons

The strength and range of fundamental forces vary. The strong force acts within the range of $\approx 10^{-15}$ m which is the typical dimension of the nucleus. The strength of the strong force depends on the strong coupling constant and varies from large values at low energies to the vanishing asymptotic limit at very high energies. The weak force acts in the range $\approx 10^{-18}$ m. The strength is given by the Fermi

constant and is 10^{-6} times weaker relative to the strong force. The electromagnetic force has infinite range and the strength is governed by the electromagnetic coupling constant.

2.1.2 Standard Model as Gauge Symmetry

Symmetry is an important factor in particle physics. A system is considered symmetric if it remains unchanged despite the changes of its properties, under a global transformation that does not depend on the space–time coordinates or under a local transformation which depends on space–time coordinates.

The local internal symmetries, or gauge symmetries, are the building blocks of the SM. In the SM, fermions and bosons are described by fields which depend on the four-dimensional space-time coordinates. The mathematical formulation of SM is based on the construction of a local gauge invariant Lagrangian [8] under the non-abelian group $SU(3)_C \times SU(2)_L \times U(1)_Y$.

The description of each fundamental force depends on its group symmetry and the number of associated gauge boson fields is equal to the number of generators of the symmetry group.

$SU(3)_C$ stands for the symmetry group of strong interactions between quarks and gluons. This is included in Quantum Chromodynamics (QCD), which is a non-abelian Yang and Mills [9] theory. The group has 8 generators, the Gell–mann matrices, which correspond to eight physical gauge fields, the gluons. The non-abelian property of the group allows it to have interactions among gluons, which are the color carriers and as a consequence of the gauge invariance, they are massless. The quarks are a triplet under $SU(3)_c$ and cannot be observed as free states. They exist in three copies with different color charges. Only colorless bound states, in the form of mesons and baryons can be observed. The leptons have no color charge and they are singlets under $SU(3)_c$.

$SU(2)_L \times U(1)_Y$ is the symmetry group for unified electromagnetic and weak interactions (EWK) as theorised by Glashow, Weinberg and Salam [10]–[12], where the Quantum Electrodynamics (QED), represented by $U(1)_{em}$ is a subgroup. $SU(2)_L$ has three generators ($W^\pm, Z$), so the Lagrangian consists of three gauge fields. Spin-half fields behave differently under $SU(2)_L$ depending on their

transformation properties under the Lorentz group: left-handed chirality fermions are all doublets under $SU(2)_L$, while right-handed chirality fermions are singlets [9]. Specifically, the quark sector is described by two singlets (u_R, d_R) and one doublet $(q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix})$ under $SU(2)_L$, while the lepton sector is described by one singlet (e_R) and one doublet $(l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix})$. As already mentioned, each has three copies, one per generation. The right-handed neutrinos (ν_R) are not included in the SM description.

The $U(1)_Y$ hypercharge symmetry corresponds to a local phase invariance: the group has just one generator and the hypercharge quantum number defines the interaction properties for each field. The associated particle is the photon which is massless and so far this property has been confirmed experimentally [13]. Brout–Englert-Higgs mechanism [14][15] (Higgs mechanism in short) in the SM theorised in the 60s, predicted the spontaneous breaking of electroweak symmetry, thus confirming these experimental results.

If the Lagrangian of a system is invariant under some symmetry transformation but the ground state of the system is not, the symmetry is said to be spontaneously broken. In quantum field theory, spontaneous symmetry breaking (SSB) occurs when there exists a symmetric Lagrangian but a non-symmetric vacuum. For local gauge theories, the Higgs mechanism is required to explain the SSB and generate mass for the gauge bosons.

In case of the SM of electroweak interactions, the Higgs mechanism should be able to generate masses for the three gauge bosons: $W^\pm, Z$. Since the SM Lagrangian is symmetric under $SU(2)_L \times U(1)_Y$ symmetry, any additions to the Lagrangian from the Higgs mechanism should preserve this symmetry. Also, the Higgs mechanism must respect the $U(1)_{em}$ symmetry since it is the symmetry of the vacuum. The Higgs mechanism in the SM is achieved by introducing a complex scalar field in the theory. Masses of the fermions and gauge bosons are achieved by interactions with this scalar field which is assumed to be present everywhere in vacuum.

Figure 2.2 depicts the results from discovery of Higgs Boson at LHC. Two experiments: ATLAS and CMS, announced the discovery simultaneously on 4th July, 2012.

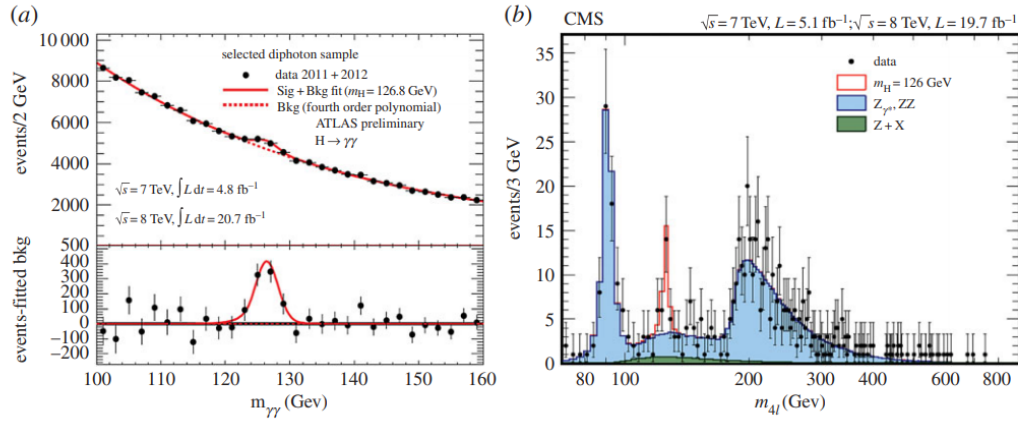


FIGURE 2.2: (a) Invariant mass distribution of di-photon candidates in ATLAS. The result of a fit to the background described by a polynomial and the sum of signal components is superimposed. The bottom inset displays the residuals of the data with respect to the fitted background component. (b) The four-lepton invariant mass distribution in the CMS experiment for selected candidates relative to the background expectation. The expected signal contribution is also shown.

2.1.3 Anomalies and open questions

Discovery of Higgs Boson in 2012, elucidated the mechanism of the generation of mass of fundamental particles in SM. Yet it is clear that the standard model is not the final theory. There are many open questions that still await clues or answers from the LHC and other experiments:

- Explanation for cosmic inflation?
- What is the composition of dark matter and of dark energy?
- Why is there matter, antimatter asymmetry in universe?
- Are there more space dimensions than the familiar three?
- What is the path to the unification of all the fundamental forces?
- Why do neutrinos have mass?

No significant deviations from the theoretical predictions of the SM have been found so far at precision collider experiments. On the other hand, it is generally agreed that there are a number of fundamental problems in particle physics and cosmology which require new physics beyond the SM.

In fact, there is compelling evidence that nearly 85% of the matter in the Universe is non-baryonic [16]. This evidence is supported by observations on many scales, ranging from the shapes of the rotation curves of spiral galaxies to the temperature fluctuations of the cosmic microwave background (CMB). Furthermore, the SM cannot explain the exponential expansion of the very early universe called inflation which is required to explain the isotropic, gaussian and nearly scale-invariant temperature fluctuations of the CMB.

Moreover, the CP violation within the SM is too feeble to explain the asymmetry between the fraction of the baryonic matter and antimatter in the Universe. Furthermore, the SM does not feature masses for the active neutrinos, while the observed flavour oscillations of the active neutrinos require tiny neutrino masses. Last, but not least, there is the strong CP problem: the SM has no explanation for the smallness of the θ -angle of quantum chromodynamics (QCD) which induces CP-violation in flavour-diagonal interactions. [16]

All collider experiments are investigating the frontier of physics and LHC probes the highest energy of this frontier. LHC was designed to discover the Higgs Boson, but the purpose was also to search for unknowns. In the early 1990s, there were several open issues and many are still open:

- There are too many parameters in SM that must be determined from experimental measurements, such as the mixing angles, the particle masses and more. The hope is that the unified theory in future, might make their values emerge naturally.
- Before the discovery of the Higgs boson, the nature of electroweak symmetry breaking in the SM was unknown. This was an unproven element impinging on the generation of mass. The main concern was the photon being massless, while W and Z bosons being approximately 100 times more massive than the proton. There was confidence that the answer would be found at the LHC. Having now found the Higgs boson, we know the mechanism through which the fundamental particles get masses. But there is still a lot to understand about the Higgs and its properties. Do we have more than one Higgs Boson?
- The mathematical consistency of the SM. At the LHC energies, the occurrence of some processes had a calculated probability of greater than one: e.g.

$W_L W_L$ scattering. One way to resolve this is to include the exchange of a Higgs boson to make it finite. This ‘closure’ test has still to be made and is likely to take over 10 years of data taking.

- Constituents particles that make up dark matter. It was known well before that even if the Higgs boson is found, everything could not be explained with the SM alone. The next question would be why the mass of the Higgs boson is in the range explored by the LHC. It was conjectured that a new symmetry, postulated for many other reasons, would protect the mass of the Higgs boson and that this symmetry should show up at the Tera electron-volt scale. This symmetry is labelled ‘supersymmetry (SUSY)’. The lightest particle of this species could be a candidate for dark matter [17].
- The SM is also logically incomplete without having included the fourth fundamental force of nature: gravity. The much-discussed superstring theory includes SUSY and the existence of extra dimensions.

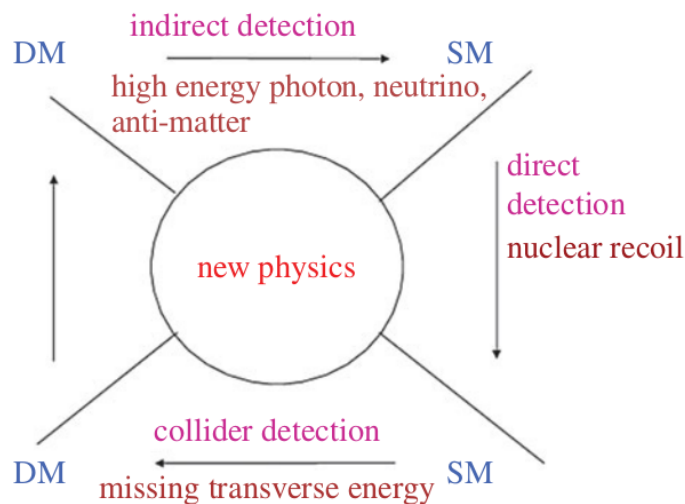


FIGURE 2.3: Direct and indirect searches from SM

All these open questions tell us that particle physics is yet to reach closure and it motivates theorists and experimentalists to work in close co-operation and strive to answer these questions.

2.2 Beyond Standard Model

This section discusses some details of the status and prospects for the search for new particles, symmetries and forces in order to address the open questions.

Through the mechanism of spontaneous symmetry breaking, the Higgs boson plays a crucial role in SM by giving masses to almost all the elementary particles of the SM. Although we have measured the mass of the Higgs boson to be around 125 GeV, we do not know the fundamental origin of the Higgs boson and where its mass and self-coupling comes from. Thus, a theory beyond the SM that dynamically explains the mass and the coupling of the Higgs boson is required to truly understand the masses of elementary particles around us. In fact, various beyond the SM theories, where we can calculate the Higgs mass from first principles, often predict a Higgs mass hierarchically larger than its observed value of 125 GeV, giving rise to the so-called Higgs Hierarchy Problem.

We know about so many open questions, but how do we proceed to find answers? Which direction we shall look into or how shall we begin? Some points to follow could be[\[17\]](#):

- Looking into the past discovery patterns.
- Looking into some radical breakthroughs, like antiparticles.
- Looking at the deviations of current theoretical predictions from the experimental measurements.
- Examining the mathematical consistency (finiteness) of predictions.

Questions might arise about the experimental evidence for the need for new physics. But there is already ample observational evidence of BSM physics. Among some examples are:

- Neutrinos have mass and oscillate from one type to another, marking a quantum mechanical phenomenon.
- The lightness of the Higgs boson.
- The existence of dark matter.

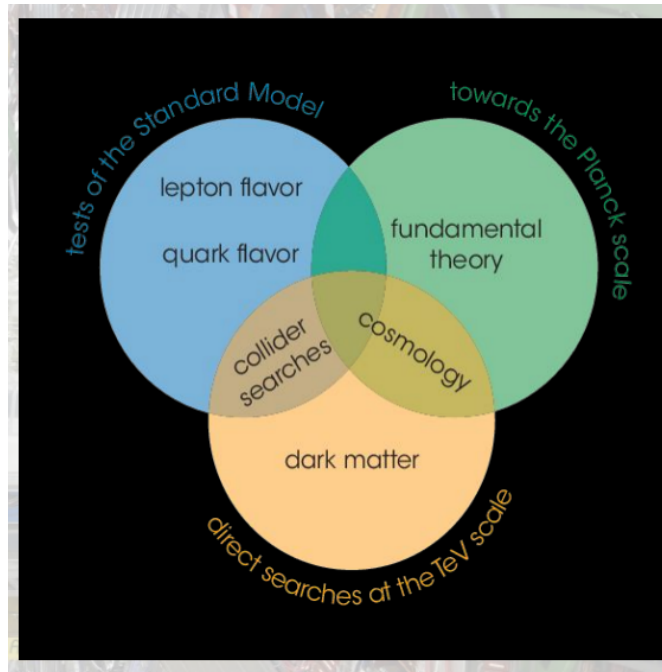


FIGURE 2.4: New physics beyond the SM

- Matter and antimatter asymmetry.

Different ways are incorporated to look at these BSM channels by many currently running experiments. Thousands of scientists are working in close collaborations to find the signs of new physics, possibilities of which are shown in figure 2.4.

To summarise searches for new physics at LHC:

- New resonances such as heavy bosons predicted by many BSM theories, e.g. the Z' , a heavier cousin of the Z-boson
- Non-resonant states, e.g. SUSY particles signed by the presence of weakly interacting particles yielding a large missing (transverse) energy
- Dark matter particles, e.g. by extending SUSY-like searches
- Deviations from the precise predictions of the SM, e.g. those that could signal compositeness.
- Neutrinos having mass

LHC also allows looking for deviations from the precise predictions of SM processes. It should be pointed that in addition to the LHC now being a Higgs

factory, it is also a top-quark factory, a W/Z factory, a b-quark factory, etc. producing enormous numbers of these particles. Thus opening possibilities to new physics in many directions.

In quantum chromodynamics (QCD), flavour symmetry is a globally conserved symmetry. On the other hand, this symmetry is broken in the electroweak (EW) theory and flavour changing processes exist; such as quark decay or neutrino oscillations. Such a violation of flavour quantum number is now under investigation also in the sector of the three charged leptons.

Standard Model envisages that all three charged leptons have the same coupling in EW interactions. This is directly followed by the assumption that the $SU(2) \times U(1) \times SU(3)$ group is the same for all the three generations of fermions and that flavour is a universal quantity. Whereas, the Higgs field distinguishes between fermions of different flavours and gives them different masses due to different couplings. In other words, the gauge forces such as the EW force, are flavour-universal in the SM, while the Higgs interaction is not flavour universal. Such a difference between the EW and Higgs interaction generates major doubts about the effectiveness of the assumption of Lepton Flavour Universality (LFU) and suggests the deep study of processes that can test Lepton Flavour Non-Universality (LFNU); a fact that could lead to a new physics beyond the SM.

2.3 Lepton flavour non-universality

As mentioned in the last section, the standard model theory of particle physics predicts that the three generations of leptons have the same coupling to gauge bosons. This symmetry is called the lepton flavour universality (LFU) and is an accidental symmetry which is broken only by Yukawa interactions with the Higgs boson. Many LFU experimental tests [19] do not agree with the theoretical predictions [18]. LEP and SLC [21] have studied interactions mediated by neutral current and the direct precision tests of LFU in Z couplings results are compatible with the SM prediction, with relative uncertainty values at the order of 10^{-3} . The situation is different for interactions mediated by charged currents. Where on one hand, direct tests of LFU in W couplings by LEP present a 2.6σ difference between the measurement of the branching fraction of $W \rightarrow \tau\nu$ decay with respect to fractions of $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays (all with uncertainties of the order of

10^{-2}) [21]. On the other hand, new results from the ATLAS collaboration suggest a much better agreement with the SM predictions [22].

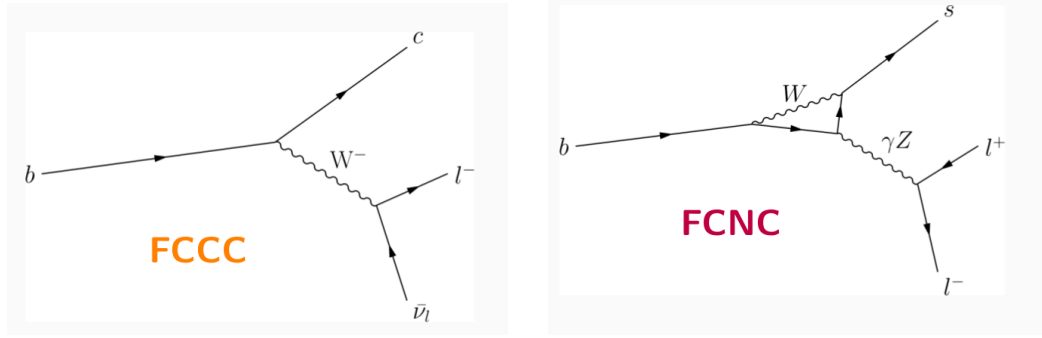


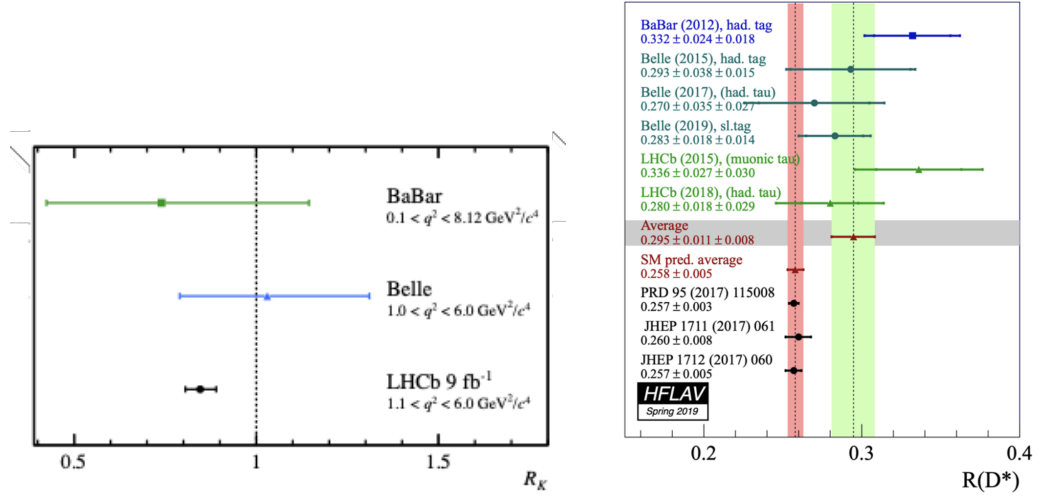
FIGURE 2.5: R measurements in B sector

LFU can be tested in the B sector in two different forms: tree level, where $b \rightarrow cl^- \bar{\nu}_l$ and loop level, where $b \rightarrow sl^- l^+$ (shown in figure 2.5). The former has large statistics but due to the presence of neutrino (which is not detectable), it cannot be fully measured; the latter can be fully reconstructed but has small statistics. Interesting investigations can be done by studying the ratio between the branching fraction of two different semi-leptonic decays of a meson. This will allow the test of LFU among the two leptons involved.

$$R(H_c) = \frac{\mathcal{B}(H_b^+ \rightarrow H_c \tau^+ \bar{\nu}_\tau)}{\mathcal{B}(H_b^+ \rightarrow H_c l^+ \bar{\nu}_l)} \quad (2.1)$$

The ratios that are being used to investigate physics beyond SM (BSM) are the ones including the massive leptons (Eq 2.1) because SM contributions are suppressed by the mass of the τ . Note that ratios between muonic and electronic decay channels can be used to extract information about the $|V_{cb}|$ CKM matrix element and hadrons form factors.

Recently, other experiments like Belle-II, BaBar and LHCb, also performed LFU tests through precise measurements of heavy mesons branching fractions [23]. It should be noted from figure 2.6 how the experimental uncertainty exceeds the SM prediction uncertainty by more than a factor 2 [24]. This underlines the focus needed within the experimental community to close this gap and enhance our understanding of LFU.

FIGURE 2.6: Current experimental results for $R(K)$ and $R(D)$ channels

The recent measurement of ratios of muon to electron decays by LHCb experiment [25] at CERN in the process:

$$R(K) = \frac{\mathcal{B}(B^+ \rightarrow K\mu^+\mu^-)}{\mathcal{B}(B^+ \rightarrow Ke^+e^-)} \quad (2.2)$$

based on the full LHC Run 1 and 2 dataset showed a 3.1σ difference from the SM prediction.

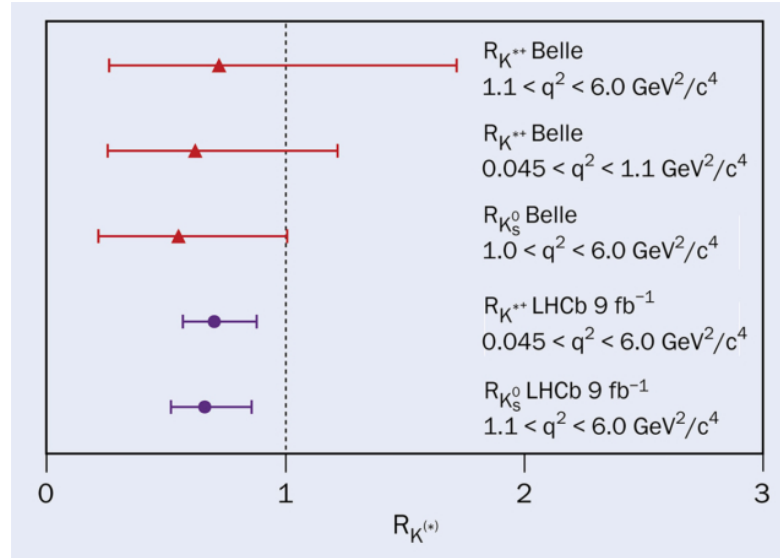


FIGURE 2.7: New recent results from LHCb with reduced errors, shown in comparison with older results from Belle

None of the results is individually significant enough to constitute evidence of new physics, which requires a deviation of 5σ (generally agreed) from theoretical

prediction. But all these results coherently point towards a signature of physics processes beyond the SM with flavour-dependent couplings.

Many models have been developed through years to explain the LFU tensions, but the possible reasons for this lepton flavour non-universality could be divided into three main categories: extensions of SM, involving enhanced weak couplings to the third generation leptons and quarks such as interactions involving a charged Higgs boson, models with a leptoquarks or a new vector bosons [4]. Figure 2.8 shows diagrams of such new physics (middle and right).

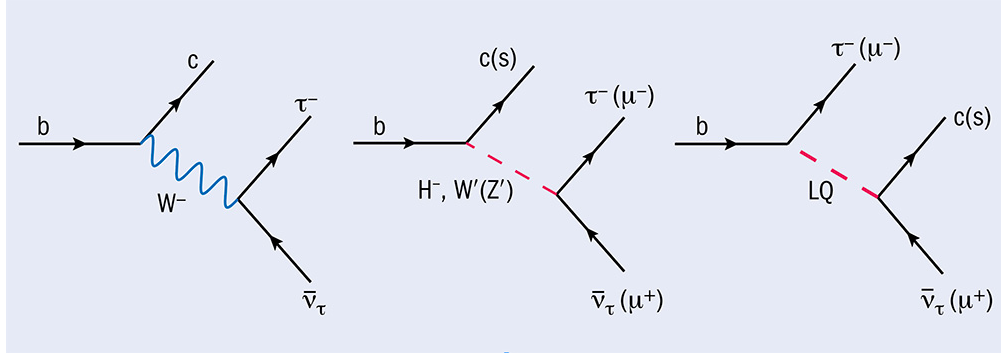


FIGURE 2.8: Semi-leptonic decay of b quark in the SM (left). Possible new contribution to the process with exchange of new color-singlets (middle). Possible new colored state (LeptoQuark) coupling simultaneously to both quarks and leptons (right)

2.4 R(J/Ψ) Analysis: Leptonic channel

One of the more effective processes to study LFU is the ratio $R(J/\Psi)$ [eq 2.3]. The LHCb experiment in its last published measurement of $R(J/\Psi)$ [19], reported results showing the projections of the nominal fit result onto the quantities m_{miss}^2 , decay time, and Z. Figure 2.9) shows the contributions of various components to the sample of $J/\Psi\mu^+$ candidates, represented by three-dimensional histogram templates binned in m_{miss}^2 , the decay time of the B_c^+ candidate, and a categorical quantity Z representing eight bins in (E_μ^*, q^2) . The values 0–3 of Z correspond to bins where $q^2 < 7.15 \text{ GeV}^2/c^4$ and E_μ^* is divided with thresholds at [0.68, 1.15, 1.64] GeV. The values 4–7 correspond to bins with the same E_μ^* ranges but where $q^2 \geq 7.15 \text{ GeV}^2/c^4$. These multidimensional histograms reflect nontrivial correlations among the three quantities. The fit yields 1400 ± 300 signal and 19140 ± 340 normalisation decays, where the errors are statistical and correlated.

Accounting for the $\tau^+ \rightarrow \mu^+ \nu_\mu \nu_\tau$ branching fraction and the ratio of efficiencies $((52.4 \pm 0.4)\%)$ gives an uncorrected value of 0.79 for $R(J/\Psi)$. Correcting for the mean expected bias at this value, we obtain $R(J/\Psi) = 0.71 \pm 0.17$ (stat). The significance of the signal, determined from a likelihood scan procedure and corrected for the systematic uncertainty, is found to be 3 standard deviations, for which the central values of the current SM predictions are in the range of 0.25–0.28, where the spread arises from the choice of modelling approach for form factors [20].

This thesis is related to the measurement of the ratio $R(J/\Psi)$ in CMS experiment with 2018 data and we plan the evaluation of the projections for this search at the HL-LHC. Analysis showcases the measurement of the ratio using $B_c \rightarrow J/\Psi l^+ \nu_l$ with the leptonic tau decay (i.e. $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$) and the evaluation of the ratio of branching fractions:

$$R(J/\Psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\Psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\Psi \mu^+ \nu_\mu)} \quad (2.3)$$

This tree level (FCCC in section 2.3) channel of investigation is especially interesting and chosen by us for studies, because:

- Measurements of semi leptonic decays of b hadrons provide a direct handle for investigating the origin of LFNU and non-universal coupling.
- The ratio in equation 2.3 cancels out the uncertainties from our knowledge of strong interactions contributing to both the production and decay processes.

Charge-conjugate processes are also considered throughout the studies. There are two channels to consider depending on the type of decay (shown in table 2.2). The analysis studies are made in collaboration among universities and research groups in CMS (Pisa, ETH, Zurich, University of Zurich and University of Wisconsin). The leptonic decay channel of the τ is studied by Pisa, along with ETH, Zurich. To complete the measurement, we also need to study the hadronic decay channel of τ , which is being studied by the University of Wisconsin and University of Zurich.

Now, we discuss the components of decay processes in $R(J/\Psi)$ ratio at fundamental level. The quark composition of B_c^+ meson is a beauty antiquark ($\bar{b}$) and a charmed quark (c). We are interested in the specific decay of beauty antiquark: $\bar{b} \rightarrow \bar{c} \tau^+ \nu_\tau$. The charmed quark originally present in the B_c^+ meson is called the ‘spectator

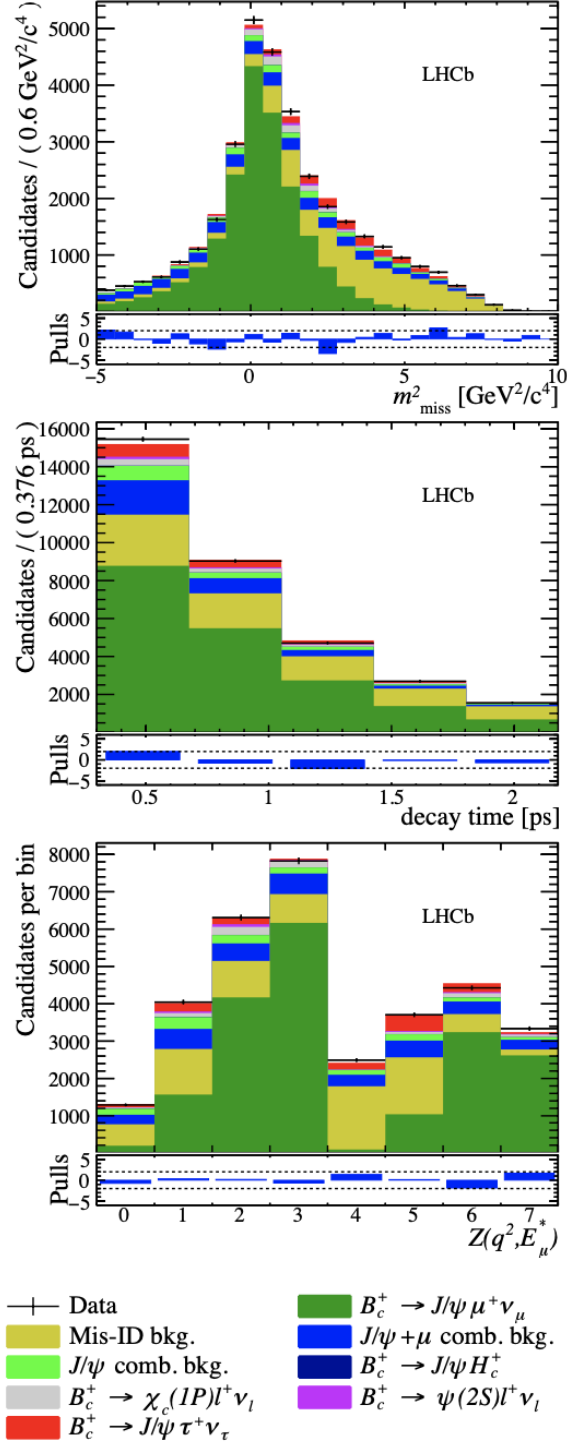


FIGURE 2.9: Distribution of (top) m^2_{miss} , (middle) decay time, and (bottom) Z of the signal data, overlaid with projections of the fit model with all normalisation and shape parameters at their best-fit values. Below each panel differences between the data and fit are shown, normalised by the Poisson uncertainty in the data; the dashed lines are at the values ± 2 . [19]

	τ decay processes	BR (%)
τ_h	$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$	10.8 ± 0.06
	$\tau^+ \rightarrow \pi^+ \pi_0 \bar{\nu}_\tau$	25.5 ± 0.09
	$\tau^+ \rightarrow \pi^+ \pi_0 \pi_0 \bar{\nu}_\tau$	9.3 ± 0.11
	$\tau^+ \rightarrow \pi^+ \pi^+ \pi^- \bar{\nu}_\tau$	9.3 ± 0.11
	$\tau^+ \rightarrow \pi^+ \pi^+ \pi^- \pi_0 \bar{\nu}_\tau$	4.6 ± 0.08
τ_l	$\tau^+ \rightarrow \mu^+ \bar{\nu}_\tau \nu_\mu$	17.4 ± 0.04
	$\tau^+ \rightarrow e^+ \bar{\nu}_\tau \nu_e$	17.8 ± 0.04

TABLE 2.2: Two τ decay modes investigated in CMS

quark' and combines with the $\bar{c}$ from the $\bar{b}$ decay, to form the J/Ψ . Thus the decay looks like: $B_c^+ \rightarrow J/\Psi \tau^+ \nu_\tau$.

The J/Ψ is not stable and we consider its decays into a pair of muons ($\mu^+ \mu^-$). τ^+ decays to $\mu^+ \nu_\mu \bar{\nu}_\tau$, whose branching ratio is $\mathcal{B}(\tau \rightarrow \mu \nu_\mu \bar{\nu}_\tau) = (17.41 \pm 0.04)\%$ [26]. This decay (with presence of τ) is called our signal channel. We define the normalisation mode, as the decay of the B_c^+ meson into a μ^+ lepton and a ν_μ instead of $\tau^+ \nu_\tau$. In both cases, the μ not originating from the J/Ψ decay is referred to as the unpaired muon and the ones originating from J/Ψ are referred as μ_1 and μ_2 . The two decay chains are represented in equation 2.4.

$$\begin{aligned}
 B_c^+ &\rightarrow J/\Psi \tau^+ \nu_\tau \rightarrow \mu^+ \mu^- \mu^+ \nu_\mu \nu_\tau \bar{\nu}_\tau \\
 B_c^+ &\rightarrow J/\Psi \mu^+ \nu_\mu \rightarrow \mu^+ \mu^- \mu^+ \nu_\mu
 \end{aligned}
 \tag{2.4}$$

CMS experiment has an excellent muon identification (section 3.3.2) as well as muon track reconstruction (section 3.3.1) thanks to the merging of information from the tracker system and muon detection detector. This performance allows also to reconstruct with extreme precision the J/Ψ resonance. This can be seen in the figure 2.10, where reconstruction peak of J/Ψ is shown in Montecarlo data before any reconstruction process.

The main complication left in measurement of processes in 2.4 is the presence of neutrinos in the final state, which cannot be directly detected. Due to the uncertainty related to the energy and momentum that they carry along with them, their presence in the final state also hinders the reconstruction of the B_c^+ candidate's four-momentum and mass peak. However, the different number of neutrinos in the two processes, 2.4, is helpful to discriminate between them (discussed in detail in Sec.5.3).

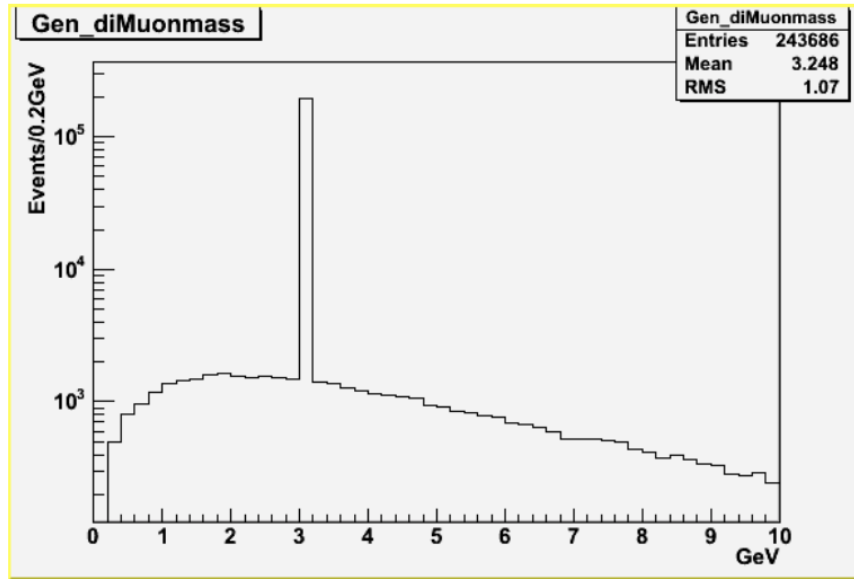


FIGURE 2.10: Di-muon invariant mass distribution (at generator level) [27].

In our analysis, the expected sources of background can be: mis identification or combinatorial sources. The largest background component is due to the inclusive decays of light b hadrons to J/Ψ mesons, in which the accompanying pion or kaon is misidentified as the unpaired muon, let's call it particle X along with the J/Ψ . The decay chain looks like:

$$J/\Psi X \rightarrow \mu^+ \mu^- X \quad (2.5)$$

Details of the analysis are further discussed in full length in chapter 5. To Summarise the points, why this study is of potential discovery in the data collected by CMS are as follows:

- The B_c meson cannot be produced at the current B-factories.
- At LHC, CMS has higher luminosity than LHCb and thus it can provide a result with smaller statistical uncertainty or error.
- $J/\Psi \rightarrow \mu\mu$ is efficiently triggered at CMS (now and in HL-LHC phase).
- We do not need to have particle ID detectors for both signal and normalisation channels, since there are only muons in the final state.

Chapter 3

The CMS Experiment

"Particle physics is the unbelievable in pursuit of the unimaginable. To pinpoint the smallest fragments of the universe you have to build the biggest machine in the world. To recreate the first millionths of a second of creation you have to focus energy on an awesome scale."

- The Guardian

3.1 Large Hadron Collider at CERN

The Large Hadron Collider (LHC) at CERN is currently the world's largest and most powerful particle accelerator, located at Swiss and French borders on the outskirts of Geneva. 10 September 2008 marked the first start of LHC and so far it remains the latest addition to CERN's accelerator complex (figure [3.1](#)).

The LHC consists of a 27-kilometre ring (most of which is underground), equipped with superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way. It is designed to collide two counter rotating beams of protons or heavy ions in two adjacent parallel beamlines at nearly the speed of light. Proton-proton collisions are foreseen at an energy of 7 TeV per beam. The LHC machine includes 1232 dipole magnets, R.F. cavities provides a "kick" that results in an increase in the proton energy of 0.5 MeV/turn. Current design of LHC has peak energy of 13 TeV, collision rate of approximately

40MHz and an instantaneous luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, which (or such features) have been chosen in order to study physics at the TeV energy scale.

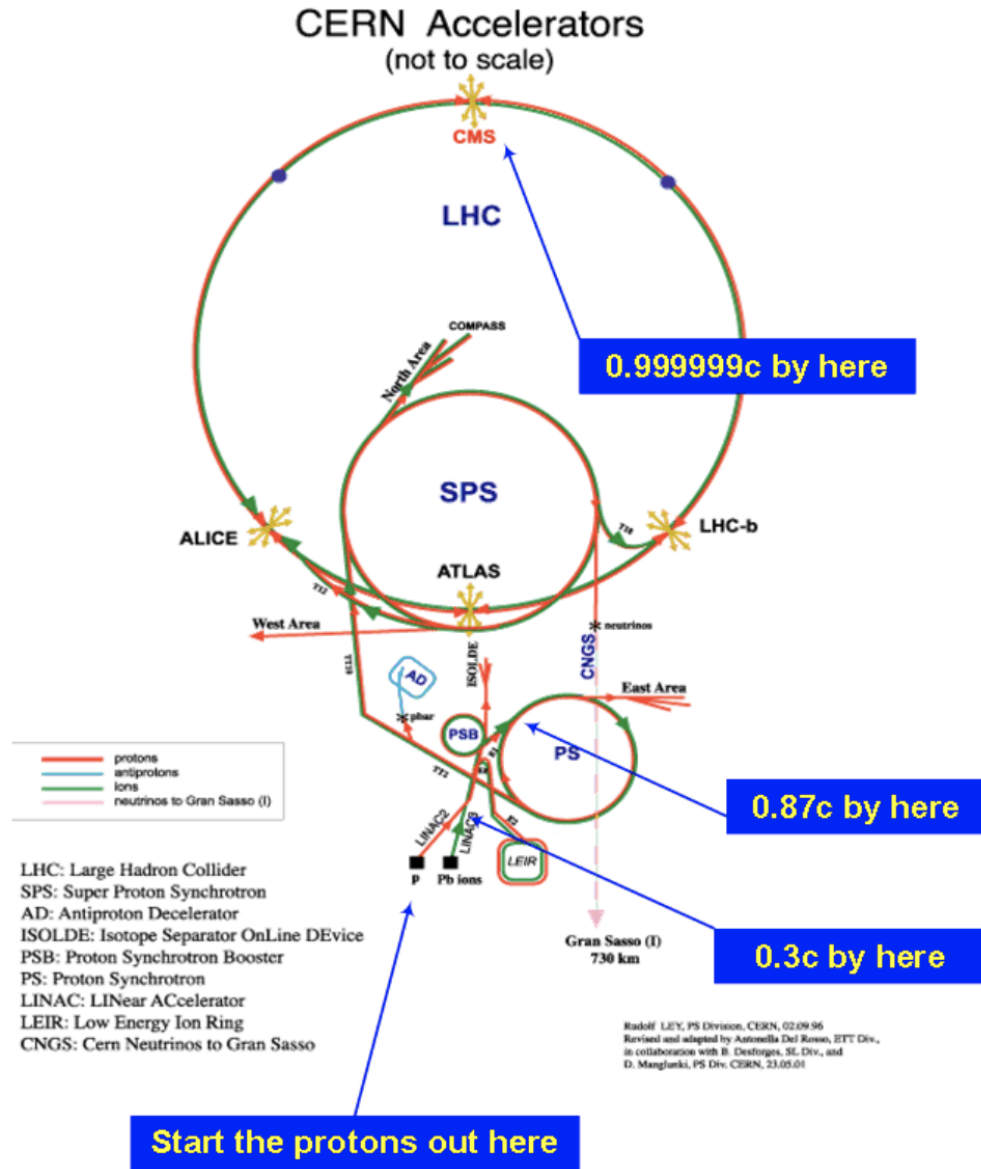


FIGURE 3.1: Large Hadron Collider at CERN (Image from: <https://www.science20.com>)

Protons are created from ionised hydrogen atoms and accelerated in the first stages by the Linac2 and PS Booster. Subsequently, the PS and SPS circular rings accelerate the protons, raising their energy to 450 GeV. At this energy, the particle bunches can be injected into the LHC where they reach their final energy and speed.

The four main detectors at LHC, are placed at four collision points: namely Compact Muon Solenoid (CMS), A Toroidal LHC ApparatuS (ATLAS), A Large Ion Collider Experiment (ALICE) and Large Hadron Collider beauty (LHCb) (shown in figure 3.2). CMS and ATLAS are two general purpose detectors (together responsible for discovery of Higgs Boson in 2012), ALICE is a heavy ion detector and LHCb specialises in b physics.

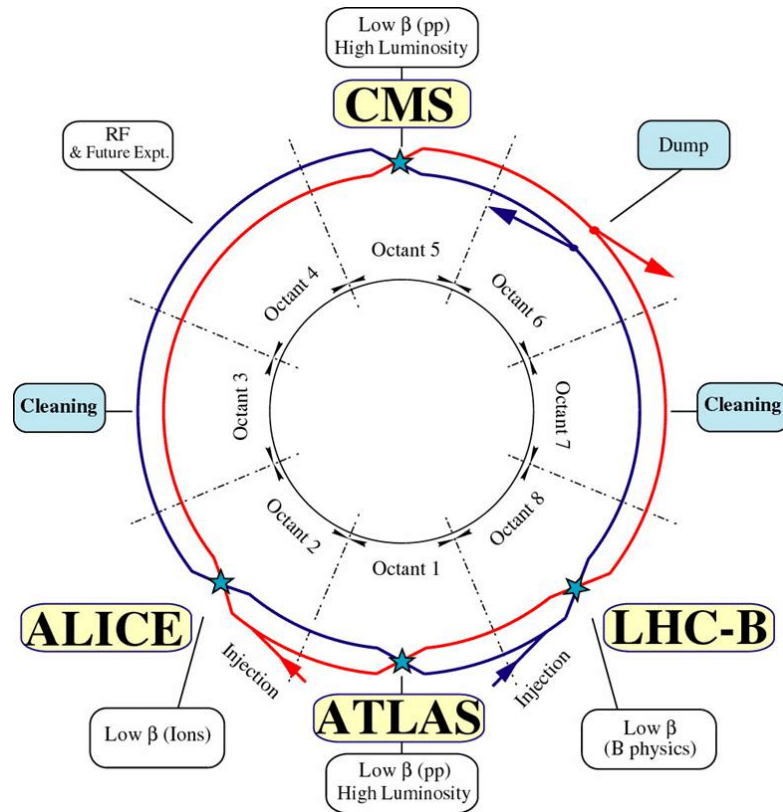


FIGURE 3.2: Four experiments at LHC

After the accident in 2008, repair through technical intervention took a long time and first collisions took place on 30th March 2010 with the rest of the year mainly devoted to commissioning. After the restart, the LHC has achieved many successes and set a new record year by year for the amount of data collected and for the energy in the center of mass, as shown in figure 3.3. These data ultimately paved the way for the groundbreaking announcement of the Higgs on 4th of July 2012.

The machine parameters relevant for the operation of LHC are listed in table 3.1. The rate of produced events for a process that has a given cross section, known as luminosity is given by:

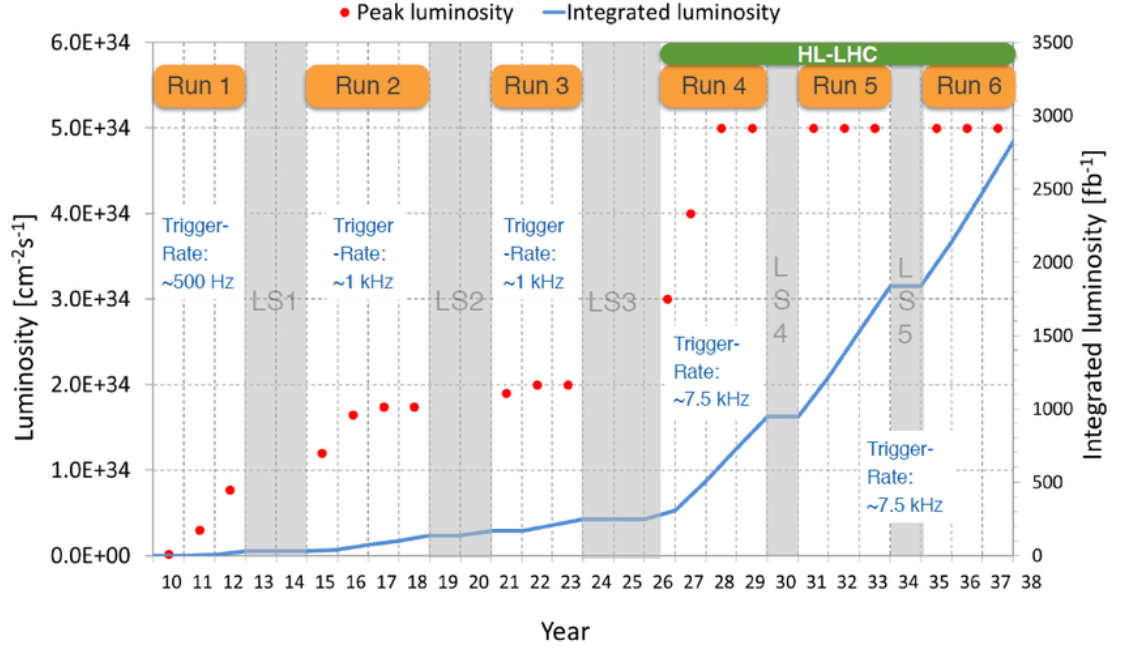


FIGURE 3.3: The integrated luminosity of LHC, over the years of operation.

$$L = \frac{\gamma f K_B N_p^2}{4\pi \epsilon_n \beta^*} F \quad (3.1)$$

where γ is the Lorentz factor, f is the revolution frequency, K_B is the number of bunches, N_p is the number of protons/bunch, ϵ_n is the normalised transverse emittance (with a design value of $3.75 \mu\text{m}$), β^* is the betatron function at the IP, and F is the reduction factor due to the crossing angle [28].

The LHC is now in its Run 3 era, three years of operation at a center-of-mass of 14 TeV and a peak luminosity twice the original machine design. Experiments are planned to record an integrated luminosity of around 300 fb^{-1} during Run 3. The third long shutdown (LS3), which will begin in 2024, will conclude Phase I of LHC operations started in 2016. The LHC will undergo significant upgrades during the next 30 months after Run3.

Since my work is mostly focused on the activities of CMS and analysis of data collected by it, we only discuss the CMS detector in detail out of all the LHC experiments.

	Symbol	pp
Energy per nucleon	E	7 TeV
Dipole field at 7 TeV	B	8.33 T
Design Luminosity	L	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Bunch separation		25 ns
No. of bunches	k_B	2808
No. particles per bunch	N_p	1.15×10^{11}
Collisions		
β -value at IP	β^*	0.55 m
RMS beam radius at IP	σ^*	$16.7 \mu\text{m}$
Luminosity lifetime	τ_L	15 hr
Number of collision-s/crossing	n_c	≈ 20

TABLE 3.1: The machine parameters relevant for the LHC detectors.

3.2 CMS Detector

CMS is a Multipurpose detector (sectional view in figure 3.4) with an overall length of 22 m, a diameter of 15 m, and weight of 12500 tonnes, located at point 5 of LHC. It is a multi-layered detector with each layer having specific detection capabilities. The CMS Detector is divided into a central barrel region and two endcap regions.

As in the name, the main feature of the detector is the central superconducting solenoid with magnetic field of 3.8T (parallel to beam direction), providing the measurement of charged particle's momentum. The main distinguishing features of CMS are a high-field solenoid, a full silicon-based inner tracking system, and a fully active scintillating crystals-based electromagnetic calorimeter.

Within the volume of the solenoid, lies three sub-detectors: The silicon tracker, crystal electromagnetic calorimeter (ECAL) and the sampling hadron calorimeter (HCAL). Outside the magnet, muon spectrometers lie within the steel return yoke of the solenoid as seen in figure 3.5. Details of sub-detectors are presented in further sections.

CMS uses a right-handed coordinate system, with the origin at the nominal interaction or collision point, the x-axis pointing to the centre of the LHC, the y-axis pointing up (perpendicular to the LHC plane), and the z-axis along the

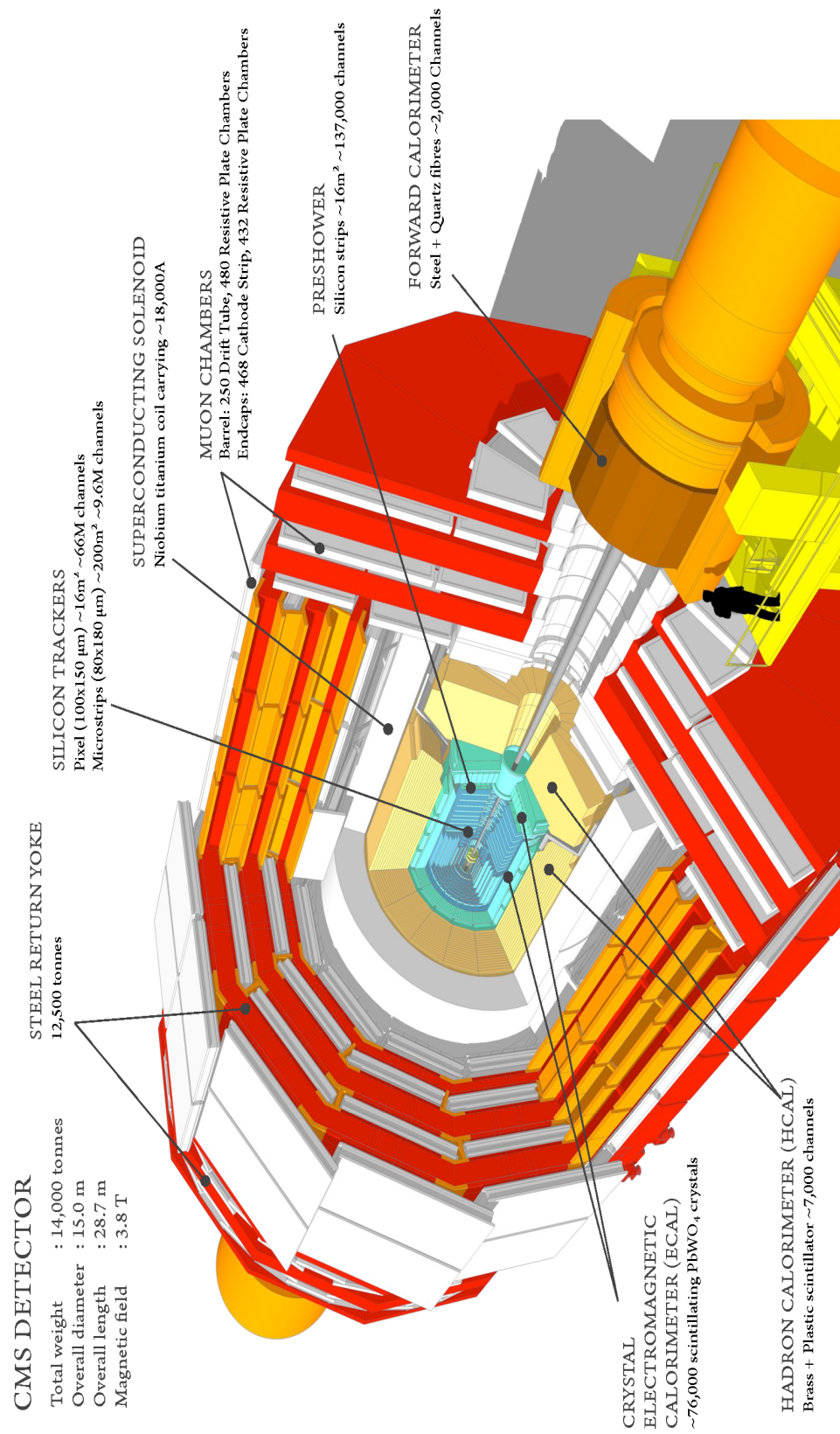


FIGURE 3.4: Compact Muon Solenoid

anticlockwise-beam direction toward the Jura mountains from LHC Point 5. The polar angle, θ is measured from the positive z -axis and the azimuthal angle, ϕ is measured in the x - y plane. The pseudorapidity is defined as ($\eta = -\ln(\tan \frac{\theta}{2})$). Thus, the momentum and energy measured transverse to the beam direction, denoted by p_T and E_T , respectively, are computed from the x and y components. The imbalance of energy measured in the transverse plane is denoted by E_T^{miss} .

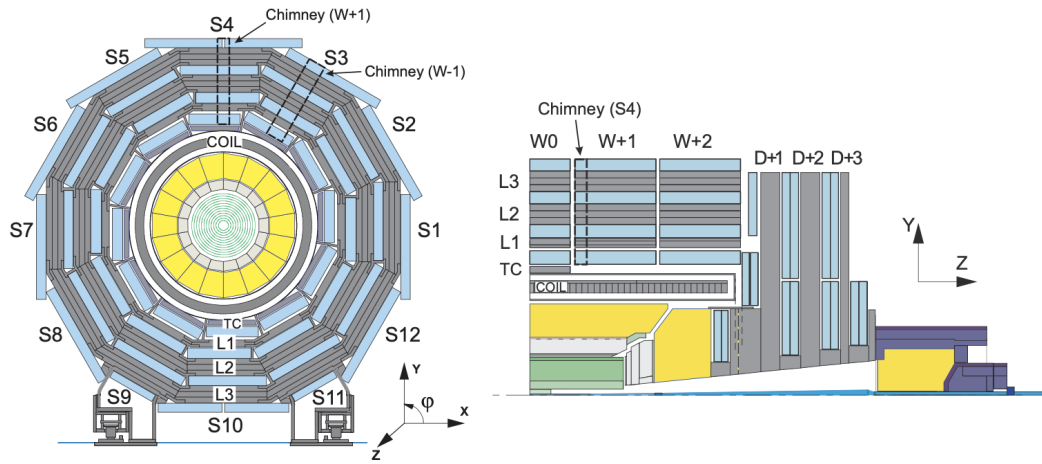


FIGURE 3.5: Schematic views of the CMS detector, with the numbering convention for azimuthal sectors (S), wheels (W), barrel yoke layers (L) and endcap disks (D). "TC" is the "tail catcher", an additional steel layer present in the central barrel wheel only. Left: transverse view at $z = 0$. Right: longitudinal view of one quarter of the detector. Wheels on the $z < 0$ side (not shown) are labelled W-1 and W-2.

A detailed description of the CMS detector can be found in [29]. The detector features for the CMS to meet the goals of the LHC physics programme can be summarised as follows:

- Good muon identification and momentum resolution over a wide range of momenta in the region $|\eta| < 2.5$, good dimuon mass resolution ($\approx 1\%$ at 100 GeV/ c^2), and the ability to determine unambiguously the charge of muons with $p < 1$ TeV/ c .
- Good charged particle momentum resolution and reconstruction efficiency in the inner tracker.
- Efficient triggering and offline tagging of τ 's and b-jets, requiring pixel detectors close to the interaction region.

- Good electromagnetic energy resolution, good diphoton and dielectron mass resolution ($\approx 1\%$ at $100 \text{ GeV}/c^2$), wide geometric coverage ($|\eta| < 2.5$), measurement of the direction of photons and/or correct localization of the primary interaction vertex, π^0 rejection and efficient photon and lepton isolation at high luminosities.
- Good E_T^{miss} and dijet mass resolution, requiring hadron calorimeters with a large hermetic geometric coverage ($|\eta| < 5$) and with fine lateral segmentation ($\Delta\eta \times \Delta\phi < 0.1 \times 0.1$).

Even after having so much technical superiority, CMS has some experimental challenges: the major one is the pile up. At the design luminosity, a mean of about 20 inelastic (hard-core scattering) collisions are superimposed on the event of interest (shown in figure 3.6) per each beam crossing. This implies that around 1000 charged particles emerge from the interaction region every 25 ns. The products of an interaction under study may be mixed with those from other interactions in the same bunch crossing. This problem clearly becomes more severe when the response time of a detector element and its electronic signal is longer than 25 ns. The effect of this pile-up is reduced by using high granularity detectors with good time resolution, resulting in low occupancy. The resulting millions of sub-detector electronic channels have very good synchronisation and are working well currently.

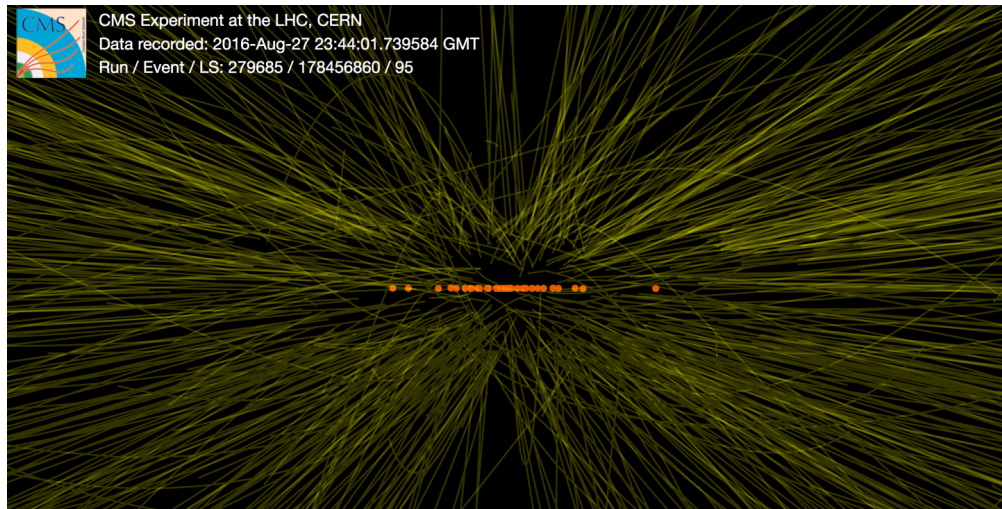


FIGURE 3.6: A high-pileup collision event in CMS with 30 reconstructed vertices, here given by the orange dots.

Initial installation and periodic commissioning of the detector

For ease of assembly, installation and maintenance, CMS has been designed along the following lines:

- All the sub-detectors should be maintainable by opening CMS in large sections.
- The movements of these sections should be possible without uncabling the attached sub-detectors and without breaking the chain of services (cooling, LV, etc.) allowing fast re-commissioning after closing
- Access must be possible to the Tracker flange for at least 1 day during a 10-day shut-down [28].

And the main design consequences are as follows:

- The barrel yoke is sectioned into 5 ring sections and each Endcap yoke into 3 disk sections (4 with YE4) to allow maintenance of the Muon stations.
- The Hadron Forward (HF) calorimeters can be pushed outside of the yoke to allow easy sliding of the Endcaps along the beam-pipe.
- This allows the beam-pipe to flare out, which reduces the background from secondary interactions, and improves pumping without having to put a vacuum pump too near the interaction point.

3.2.1 Inner Tracker

The tracker represents the innermost part of CMS and is designed to provide a precise and efficient measurement of the charged particle tracks and of the primary and secondary interaction vertices. It is immersed in a homogeneous magnetic field of 3.8 T provided by the CMS solenoid.

The tracker has to be light, both in the detecting and supporting structures, in order not to alter the trajectories of charged particles and to provide the best possible resolution. It also has to be fast enough to take data every 25 ns (40 MHz). High granularity is necessary due to the high particle multiplicity. However, a fast

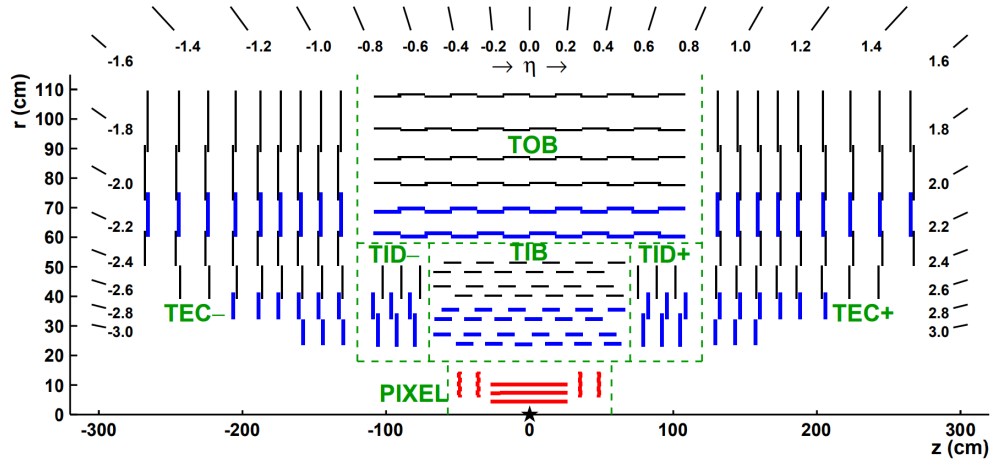


FIGURE 3.7: CMS phase-0 tracker layout

and granular detector needs adequate numbers of readout channels and an efficient cooling, which results in dead material.

CMS silicon tracker consists of two parts: *Inner pixel detector* and *outer strip detectors*. It precisely measures the charged particle trajectories and position of primary and secondary interaction vertices of the events. Being closest to the interaction point (covering pseudorapidity range of $|\eta| < 2.5$) tracker is subjected to high levels of radiation damage. Figure 3.7 shows the layout of the phase-0 CMS tracker. The total length of the tracker is 5.8m and its diameter 2.5m.

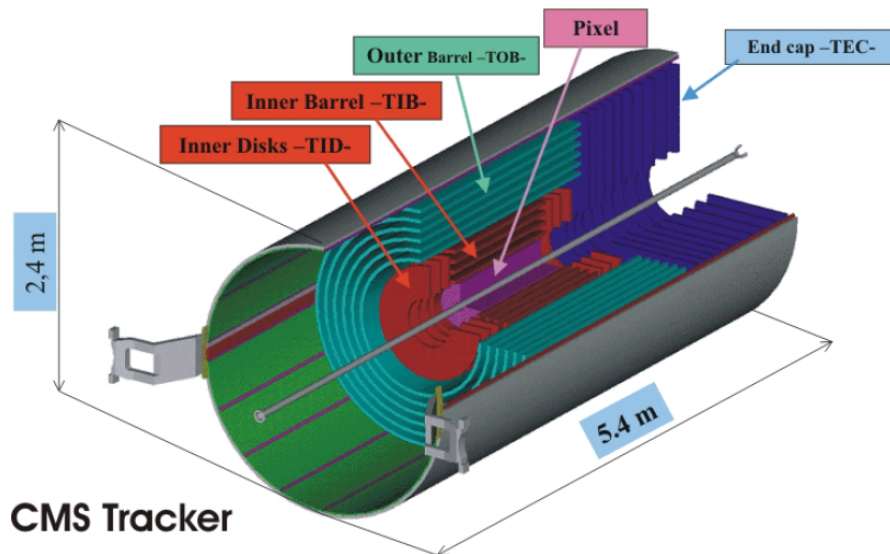


FIGURE 3.8: Layout of Tracker in the CMS [30]

The current pixel detector (Phase-I replacing phase-0 in 2016) has 4 barrel layers and 3 endcap disks (figure 3.8). It works well along with the phase-0 outer strip tracker through LHC Run3. There are total 66 million silicon square pixel detectors with the size of $100\mu\text{m} \times 150\mu\text{m}$ to obtain low cell occupancy (order 10^{-4} per pixel and collision) and a spatial resolution of about $10\mu\text{m}$ in the transverse direction (ϕ for the barrel, with r given by the sensor position) and $15\mu\text{m}$ in the longitudinal direction (z for the barrel). There are a total of 15840 read out chips (ROC) bump bonded to pixel sensors to read the data. The pixel detector provides 3D measurement of the charged track hit and is crucial for vertices determination. More details on current pixel performance and its future upgrade are discussed in chapter 4.

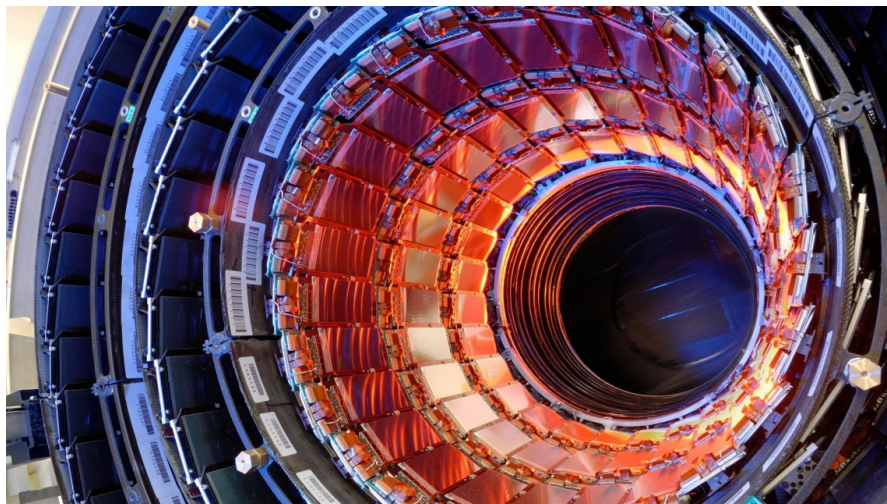


FIGURE 3.9: Silicon strip detectors in the barrel module

The silicon strip sub-detector has 4 barrel layers (tracker inner barrel or TIB), 3 endcap disks (tracker inner disks or TIDs) in the inner part and 6 barrel layers (tracker outer barrel or TOB), 9 endcap disks (tracker endcaps or TECs) in the outer part (figure 3.9). There are 9.6 million silicon strips covering all the four regions TIB, TID, TOB and TEC. The thickness of the sensors is $320\mu\text{m}$ for the inner layers or disks and $500\mu\text{m}$ for the outer layers or disks. The hit efficiency for both pixel and strip detectors is $\sim 99\%$.

Our group in Pisa designed all the strip sensors for phase 0, built the TIB and TID phase-0 and built a fraction of pixel phase-I. Currently, we are commissioned for Phase-II activities: pixel barrel mechanical support and cooling loop rings. In addition, I am working on Phase-II activities of inner pixel sensors (Chapter 4).

A rigorous alignment procedure is performed with Cosmic Ray tracks and tracks from the collision data to extract the position of each module in the tracker system with respect to a common CMS reference frame. The relative movement of modules in the system affects track reconstruction. After the reconstruction of hits in the tracker, an iterative tracking algorithm is used to reconstruct tracks. In this process, each iteration produces a set of tracks and the hits belonging to these reconstructed tracks are ignored for the next iteration of track finding.

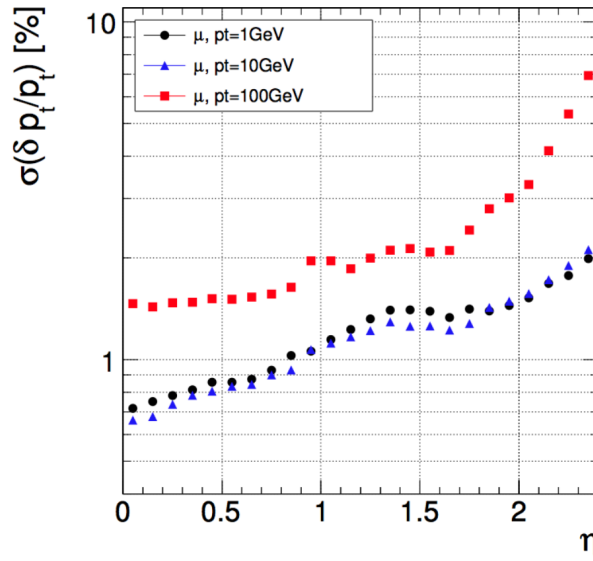


FIGURE 3.10: Stand-alone transverse momentum resolution of tracks measured by the CMS Tracker as a function η , for muons of $p_T = 1, 10$ and 100 GeV, without beam constraint.

The expected p_T resolution of the CMS tracker as a function of η for single muons is shown in figure 3.10. For high p_T (~ 100 GeV) tracks, the resolution is around 1-2%. The expected impact parameter resolution is shown in figure 3.11 which varies between 10-20 (20-40) μm for the transverse (longitudinal) plane.

The track reconstruction efficiency of the tracker is shown in figure 3.12, as a function of pseudorapidity for single muons and pions. The material inside the active volume of the tracker increases from $\approx 0.4X_0$ at $\eta = 0$ to around $1X_0$ at $|\eta| \approx 1.6$, before decreasing to $\approx 0.6 X_0$ at $|\eta| = 2.5$ [28]. Muons do not actively interact with material and thus have an efficiency of 99% or more at all η . At large η the efficiency decreases, given that the hits start to be lost. Instead Pions interact more with material and their efficiency is affected by the material budget and is smaller than muon.

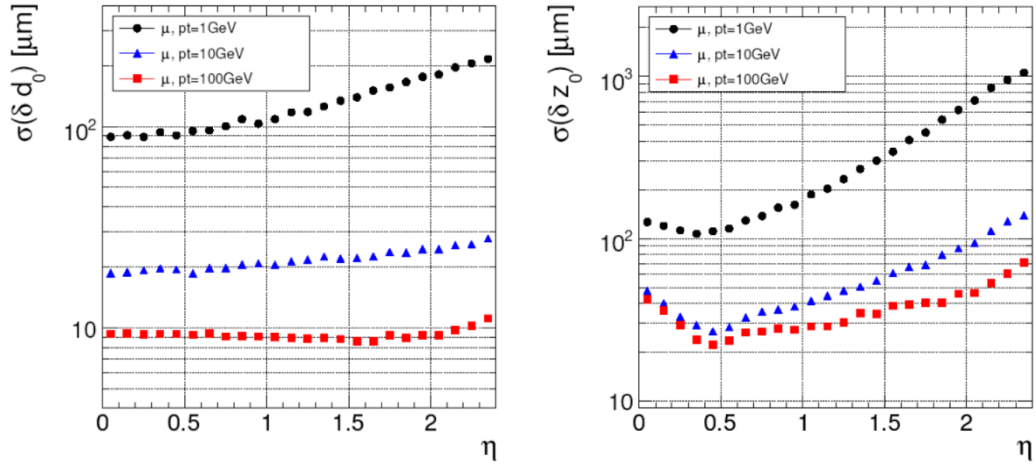


FIGURE 3.11: Transverse (left) and longitudinal (right) impact parameter resolution as a function of η , for muons of p_T 1, 10 and 100 GeV.

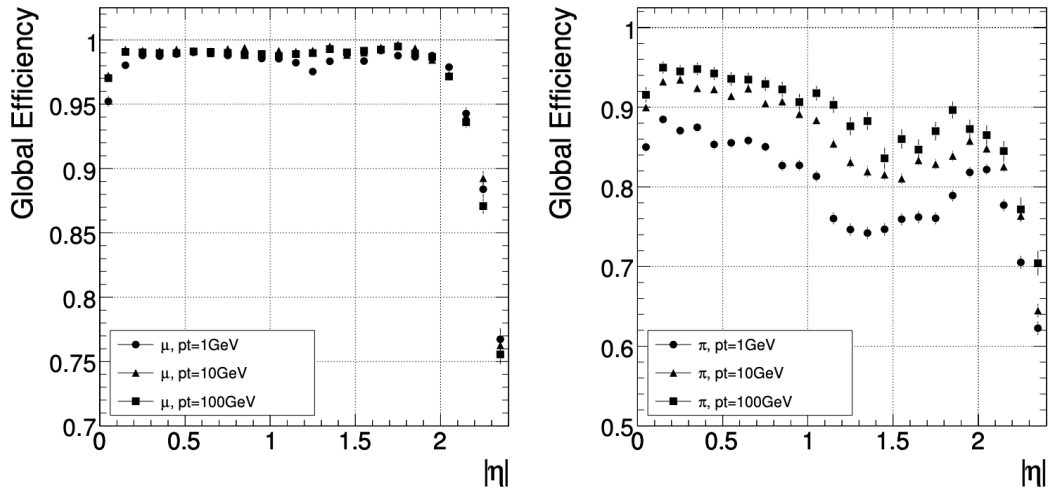


FIGURE 3.12: Global track reconstruction efficiency for muons (left) and pions (right) of transverse momenta of 1, 10 and 100 GeV/c

3.2.2 Electromagnetic Calorimeter

The Electromagnetic Calorimeter (ECAL) is a hermetic, homogeneous calorimeter comprising of 61200 lead tungstate (PbWO_4) crystals mounted in the central barrel part and closed by 7324 crystals in each of the 2 endcaps. CMS has chosen lead tungstate scintillating crystals for its ECAL because: these crystals have short radiation ($X_0 = 0.89$ cm) and Moliere (2.2 cm) lengths, are fast (80% of the light is emitted within 25 ns) and are radiation hard (up to 10 Mrad). The relatively low light yield ($30 \gamma/\text{MeV}$) requires use of photodetectors with intrinsic gain that can operate in a magnetic field.

Silicon avalanche photodiodes (APDs) are used as photodetectors in the barrel and vacuum phototriodes (VPTs) in the endcaps. In addition, the sensitivity of both the crystals and the APD response to temperature changes requires a temperature stability (the goal is 0.1°C). The use of PbWO_4 crystals has thus allowed the design of a compact calorimeter inside the solenoid that is fast, has fine granularity, and is radiation resistant.

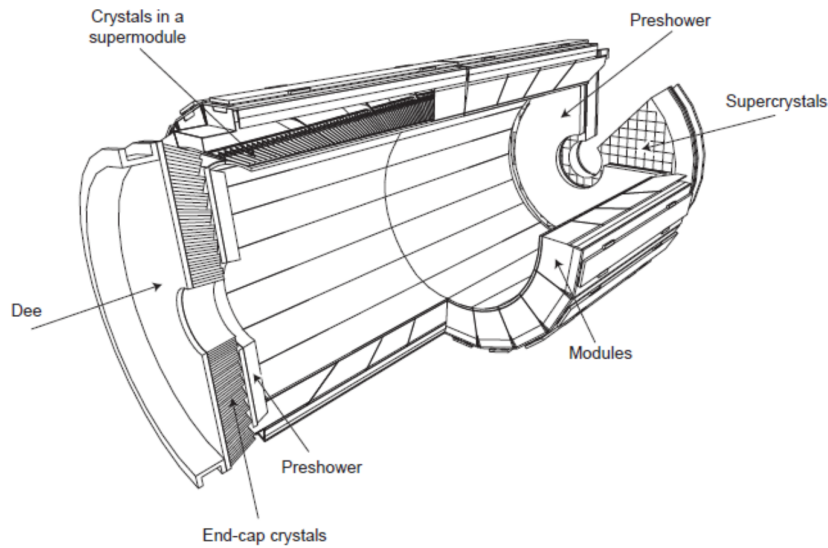


FIGURE 3.13: Layout of the CMS electromagnetic calorimeter (ECAL) showing the barrel, endcap sections.

The barrel section (EB) has an inner radius of 129 cm. It is structured as 36 identical "supermodules," each covering half the barrel length and corresponding to a pseudorapidity interval of $0 < |\eta| < 1.479$. The crystals are quasi-projective (the axes are tilted at 3° with respect to the line from the nominal vertex position)

and cover 0.0174 (i.e. 1°) in $\Delta\phi$ and $\Delta\eta$. The crystals have a front face cross-section of $\approx 22 \times 22 \text{ mm}^2$ and a length of 230 mm , corresponding to $25.8 X_0$.

The endcaps (EE), at a distance of 314 cm from the vertex and covering a pseudorapidity range of $1.479 < |\eta| < 3.0$, are each structured as 2 “Dees”, consisting of semi-circular aluminium plates from which are cantilevered structural units of 5×5 crystals, known as “supercrystals [28].”

A preshower device is placed in front of the crystal calorimeter over much of the endcap pseudorapidity range (figure 3.13). The active elements of this device are 2 planes of silicon strip detectors, with a pitch of 1.9 mm , which lie behind disks of lead absorber at depths of $2 X_0$ and $3 X_0$.

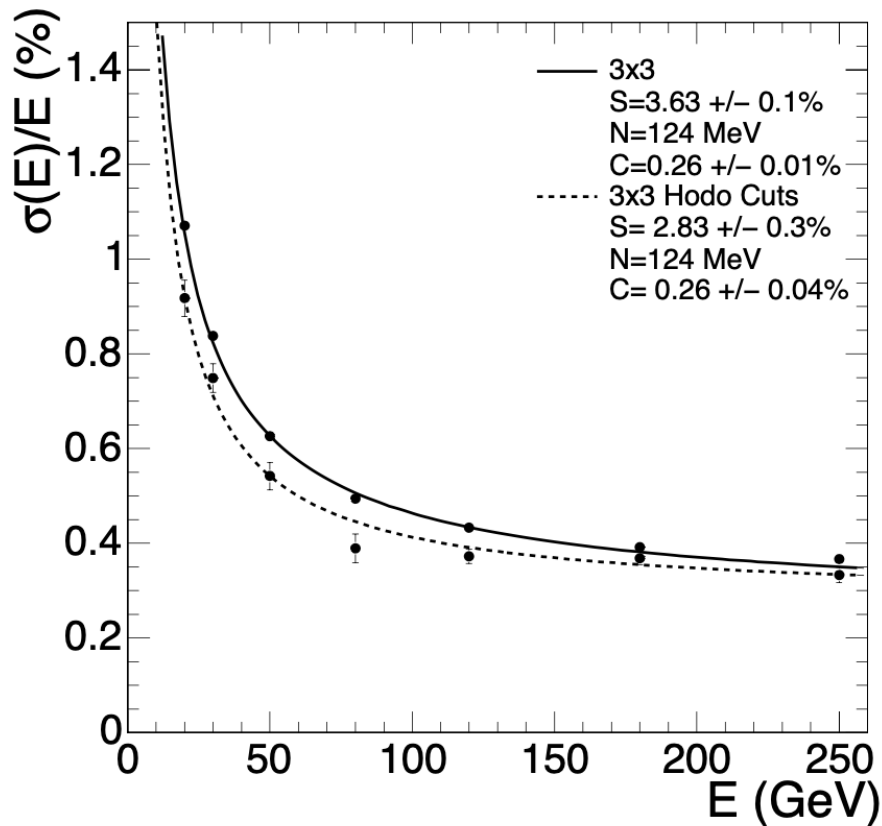


FIGURE 3.14: ECAL supermodule energy resolution, $\sigma(E)/E$, as a function of electron energy as measured from a beam test. The upper series of points correspond to events taken with a $20 \times 20 \text{ mm}^2$ trigger. The lower series of points correspond to events selected to fall within a $4 \times 4 \text{ mm}^2$ region. The energy was measured in an array of 3×3 crystals with electrons impacting the central crystal.

The performance of a super-module was measured in a test beam. Representative results on the energy resolution as a function of beam energy are shown in figure 3.14. The energy resolution, has been parameterized as a function of energy:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{\sqrt{E}}\right)^2 + C^2 \quad (3.2)$$

where S is the stochastic term, N the noise and C the constant term. The values of these parameters are listed in the figure 3.14.

3.2.3 Hadronic Calorimeter

The ECAL is surrounded by a brass/scintillator sampling Hadron Calorimeter (HCAL) with coverage up to $|\eta| < 3.0$. The design of the hadron calorimeter (HCAL) is strongly influenced by the choice of magnet parameters since most of the CMS calorimetry is located inside the magnet coil. The HCAL plays an essential role in the identification and measurement of quarks, gluons, and neutrinos by measuring the energy and direction of jets and of missing transverse energy flow in events. Accurate measurements of high-energy jets is important for searches for high mass Standard Model and Supersymmetric Higgs bosons and missing energy forms a crucial signature of new particles, like the super symmetric partners of quarks and gluons.

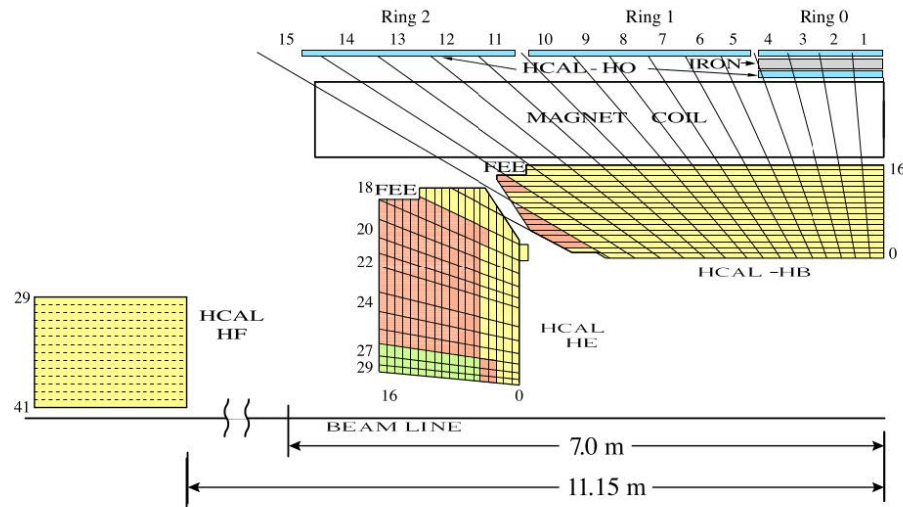


FIGURE 3.15: Schematic quarter view of the CMS hadronic calorimeter (HCAL) in the barrel (HB and HO), endcap (HE) and forward (HF) region

The scintillation light is converted by wavelength-shifting (WLS) fibers embedded in the scintillator tiles and channelled to photo-detectors via clear fibres. This light is detected by novel photo-detectors (hybrid photodiodes, or HPDs) that can provide gain and operate in high axial magnetic fields. While most of the HCAL is contained inside the CMS magnet, there are several additional layers of scintillators outside the magnet to detect particles from high energy showers, referred to as the hadron outer (HO) detector (shown in figure 3.15). The central calorimetry is complemented by a "tail-catcher" in the barrel region - ensuring that hadronic showers are sampled with nearly 11 hadronic interaction lengths. This "depth" of the HCAL is needed to contain high-energy jets and also to filter out hadrons from jets involving muons.

The hadron calorimeter has both a *barrel* and *endcap* component which are sampling calorimeters with 50 mm thick copper absorber plates interleaved with 4 mm thick scintillator sheets. There are also "forward" HCAL's installed at each end of the CMS detector which provide coverage up to a pseudorapidity of 5.0. Here steel absorber plates are used in the harsher radiation environment of the forward systems and hadronic showers are seen by radiation-resistant quartz-fibers. The Cerenkov light emitted in the quartz fibers is detected by conventional photomultiplier tubes. The forward calorimeters ensure full geometric coverage for the measurement of the transverse energy in the event [28]. Wide rapidity coverage and accurate energy measurements are the main requirements of the hadron calorimetry system as several Higgs modes, as well as other important modes, require good missing transverse energy measurements.

For gauging the performance of the HCAL, it is usual to look at the jet energy resolution and the missing transverse energy resolution. The granularity of the sampling in the 3 parts of the HCAL has been chosen such that the jet energy resolution, as a function of E_T , is similar in all 3 parts. This is illustrated in figure 3.16. The missing transverse energy (E_T^{miss}) resolution is given by $\sigma(E_T^{miss}) \approx 1.25\sqrt{\Sigma E_T}$, if energy clustering corrections are not made.

3.2.4 Solenoid

At the heart of CMS sits a 13-m-long, 5.9 m inner diameter, 12,000 ton, 4 T superconducting solenoid which in part gives CMS its name. The energy of 270 GJ is stored in the magnet, which if liberated, is large enough to melt 18 tons

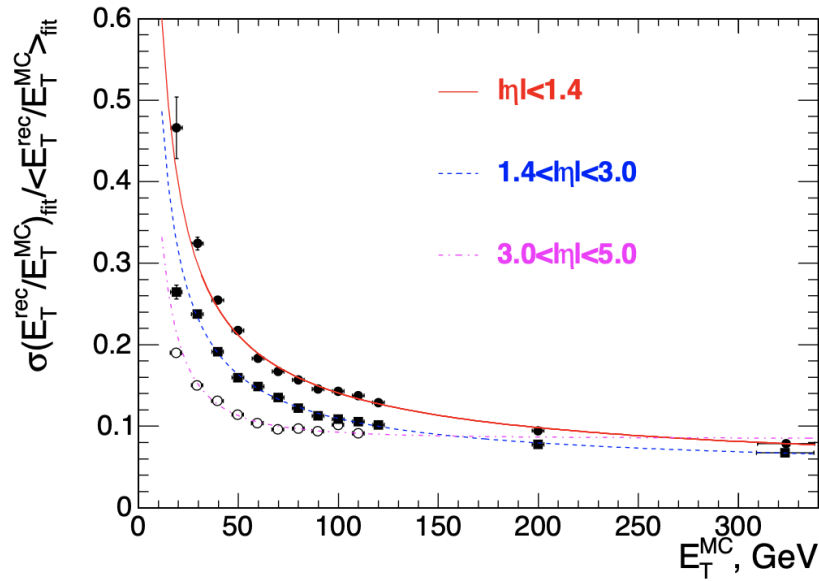


FIGURE 3.16: The jet transverse energy resolution as a function of the simulated jet transverse energy for barrel jets ($|\eta| < 1.4$), endcap jets ($1.4 < |\eta| < 3.0$) and very forward jets ($3.0 < |\eta| < 5.0$). The jets are reconstructed with the interactive cone $R = 0.5$ algorithm

of gold. The CMS magnet system consists of a superconducting coil, the magnet yoke (barrel and endcap), a vacuum tank and ancillaries such as cryogenics, power supplies and process controls. Inside the bore of the magnet sit the inner tracker and the calorimetry, while outside is the flux return system and muon detector. The CMS magnet has been assembled in the surface experiment hall (figure 3.17).

CMS chose a large superconducting solenoid, the parameters of which are given in table 3.2.

Field	4 T
Inner Bore	5.9 m
Length	12.9 m
Number of Turns	2168
Current	19.5 kA
Stored energy	2.7 GJ
Hoop stress	64 atm

TABLE 3.2: Parameters relevant for CMS superconducting Solenoid

The overall conductor cross section is $64 \times 22 \text{ mm}^2$. The conductor was manufactured in twenty continuous lengths, each with a length of 2.65 km. Four lengths were wound to make each of the 5 coil modules. These modules were assembled and connected together in SX5 at Point 5.

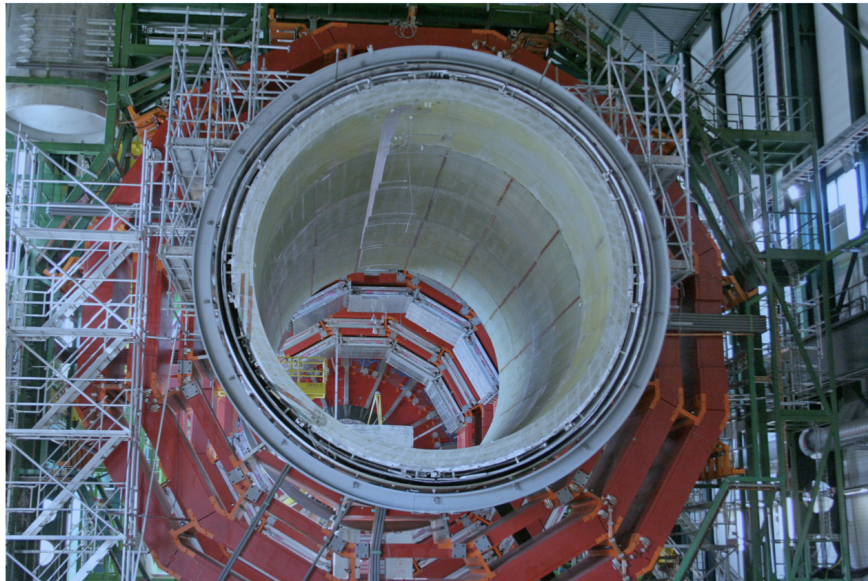


FIGURE 3.17: Assembly of the yoke of the CMS magnet. The outer vacuum tank and the coil can be seen

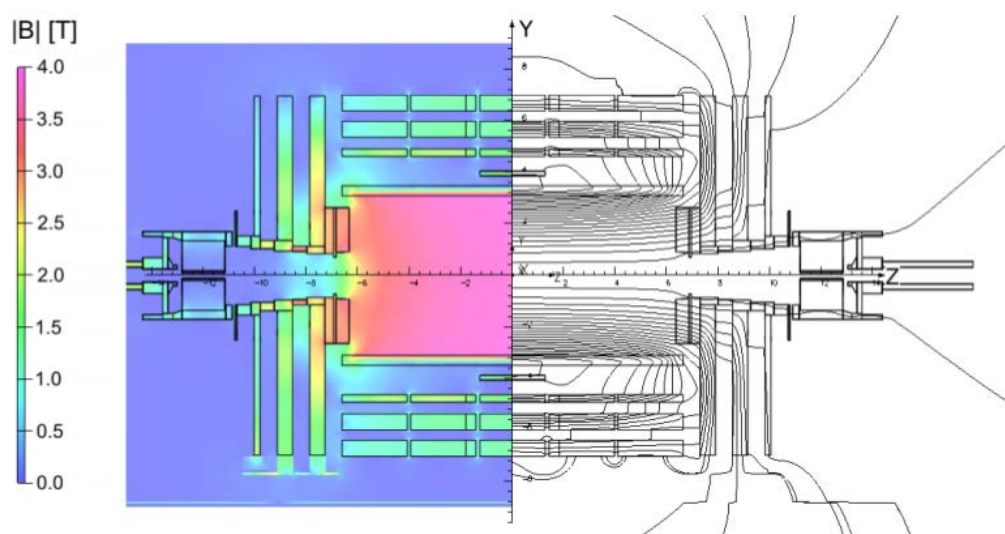


FIGURE 3.18: The magnetic field strength (left) and lines (right) of the CMS solenoid [31].

In order to achieve good momentum resolution with a compact spectrometer it is necessary to have a combination of a high magnetic field and high precision on the spatial resolution and alignment of the detectors. The momentum measurement of charged particles in the detector is based on the bending of their trajectories. The 3.8T magnetic field also brings benefits for calorimetry - it enables the detection of many isolated electrons produced by the decays of W's, Z's and b quarks. Using these electrons, the CMS crystal electromagnetic calorimeter can be calibrated to an accuracy of a fraction of a percent.

The magnetic field lines and strength of the magnet is shown in figure 3.18. The magnetic flux is returned via a 1.5 m thick saturated iron yoke instrumented with four stations of muon chambers.

3.2.5 Muon system

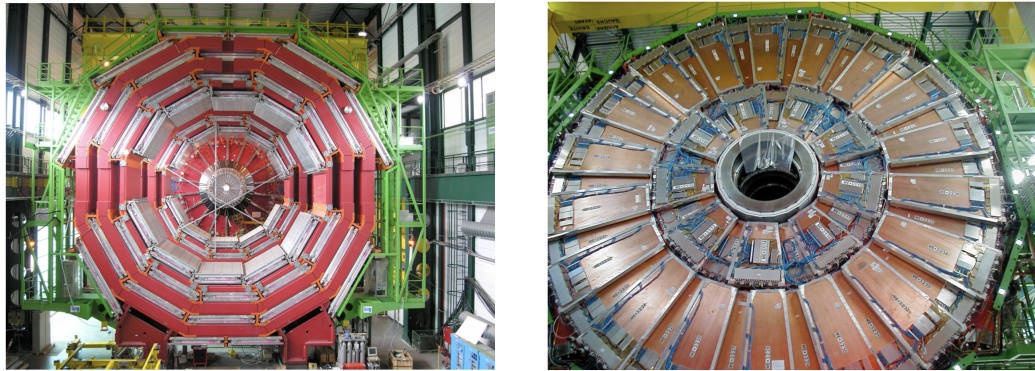


FIGURE 3.19: Installation of DT chambers into the YB+1 wheel (left) and Installation of CSC chambers onto the YE+2 disk (right)

Outside the Solenoid sits the huge Muon detection system to catch hold of the only particles that survived till this distance of the detector. Centrally produced muons are measured 3 times: in the inner tracker, after the coil, and in the return flux. Muons are expected to provide clean signatures for a wide range of physics processes. The return field of the solenoid is large enough to saturate 1.5 m of iron, allowing 4 muon "stations" to be interleaved with the iron return yoke plates of the magnet system (figure 3.19). This provides a muon system with reconstruction efficiency better than 98% over the full pseudorapidity range. A reconstruction trajectory of a muon is shown in figure 3.20

Three types of gaseous detectors are used to identify and measure muons. The choice of the detector technologies has been driven by the very large surface to be

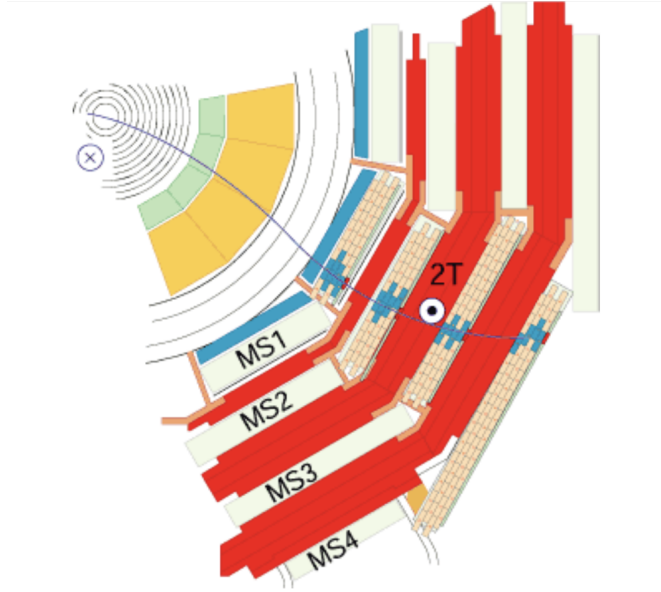


FIGURE 3.20: Muon detection trajectory in the detector [32]

covered and by the different radiation environments. In the barrel region ($|\eta| < 1.2$), where the neutron induced background is small, the muon rate is low and the residual magnetic field in the chambers is low, *Drift tube (DT)* chambers are used. In the 2 endcaps, where the muon rate as well as the neutron induced background rate is high, and the magnetic field is also high, *Cathode strip chambers (CSC)* are deployed and cover the region up to $|\eta| < 2.4$. In addition to this, *Resistive plate chambers (RPC)* are used in both the barrel and the endcap region.

The DTs or CSCs and the RPCs operate within the first level trigger system, providing 2 independent and complementary sources of information. The complete system results in a robust, precise and flexible trigger device. In the initial stages of the experiment, the RPC system covered the region $|\eta| < 1.6$. The coverage was extended to $|\eta| < 2.1$ later.

The layout of one quarter of the CMS muon system is shown in figure 3.21. In the Muon Barrel (MB) region, 4 stations of detectors are arranged in cylinders interleaved with the iron yoke. The segmentation along the beam direction follows the 5 wheels of the yoke (labelled YB-2 for the farthest wheel in -z, and YB+2 for the farthest is +z). In each of the endcaps, the CSCs and RPCs are arranged in 4 disks perpendicular to the beam, and in concentric rings, 3 rings in the innermost station, and 2 in the others. In total, the muon system contains of order 25000 m² of active detection planes, and nearly 1 million electronic channels [28].

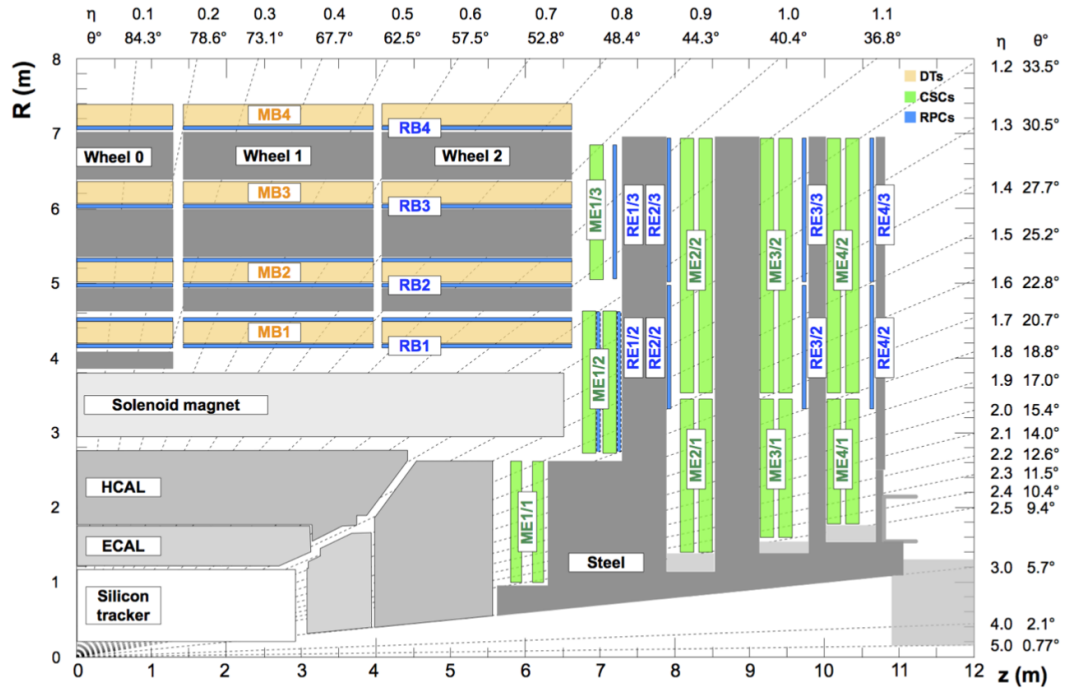


FIGURE 3.21: An R-z cross section of a quadrant of the CMS detector with the axis parallel to the beam (z) running horizontally and the radius (R) increasing upward. The interaction point is at the lower left corner. The locations of the various muon stations and the steel flux-return disks (dark areas) are shown. The drift tube stations (DTs) are labelled MB (“Muon Barrel”) and the cathode strip chambers (CSCs) are labelled ME (“Muon Endcap”). Resistive plate chambers (RPCs) are mounted in both the barrel and endcaps of CMS, where they are labelled RB and RE, respectively.

Muon measurements taken in the muon stations outside the solenoid are used for fast triggering and standalone muon reconstruction, but can also be combined with information from the inner tracking detectors for more precise reconstruction and momentum measurement.

The performance of the muon system was studied with Cosmic Rays and the momentum resolution was found to be between 1% and 10% for $10 \text{ GeV} < p_T < 10 \text{ TeV}$ as seen in figure 3.22. The best measurement of position comes from combining the tracker and muon system information.

3.2.6 Trigger system

The LHC bunch crossing rate of 40 MHz leads to $\approx 10^9$ interactions/sec at design luminosity. Out of this the data from only about 10^2 crossings/sec can be written

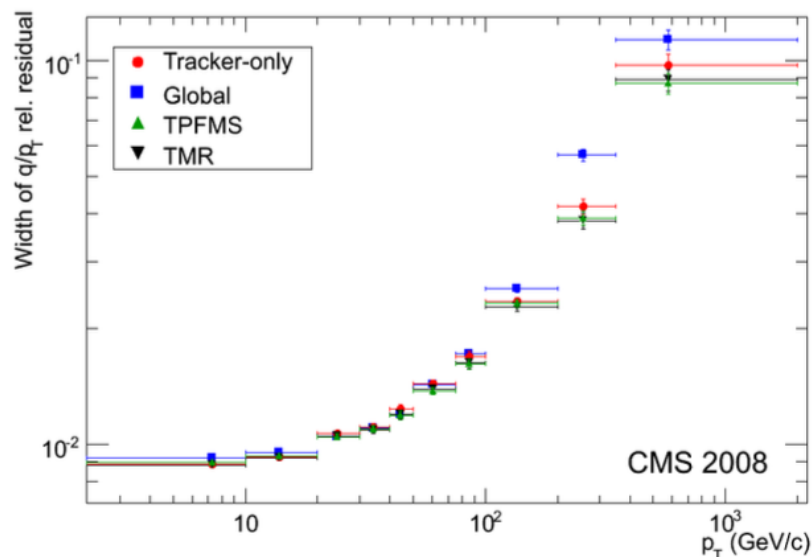


FIGURE 3.22: Resolution of the muon momentum measurement using cosmic ray data

to archival media; Hence, the trigger system is required to achieve a rejection factor of nearly 10^6 . The CMS trigger and data acquisition system [33] consists of 4 parts: the detector electronics, the Level-1 trigger processors (calorimeter, muon, and global), the readout network, and an online event filter system (processor farm) that executes the software for the High-Level Triggers (HLT).

- **Level-1 Trigger:**

The size of the LHC detectors and the underground caverns imposes a minimum transit time for signals from the front-end electronics to reach the services cavern housing the Level-1 trigger logic and return back to the detector front-end electronics. The total time allocated for the transit and for reaching a decision to keep or discard data from a particular beam crossing is $3.2 \mu\text{s}$. During this time, the detector data must be held in buffers while trigger data is collected from the front-end electronics and decisions reached that discard a large fraction of events while retaining the small fraction of interactions of interest (nearly 1 crossing in 1000). Of the total latency, the time allocated to Level-1 trigger calculations is less than $1 \mu\text{s}$.

Custom hardware processors form the Level-1 decision. The Level-1 triggers involve the calorimetry and muon systems, as well as some correlation of information between these systems. The Level-1 decision is based on the

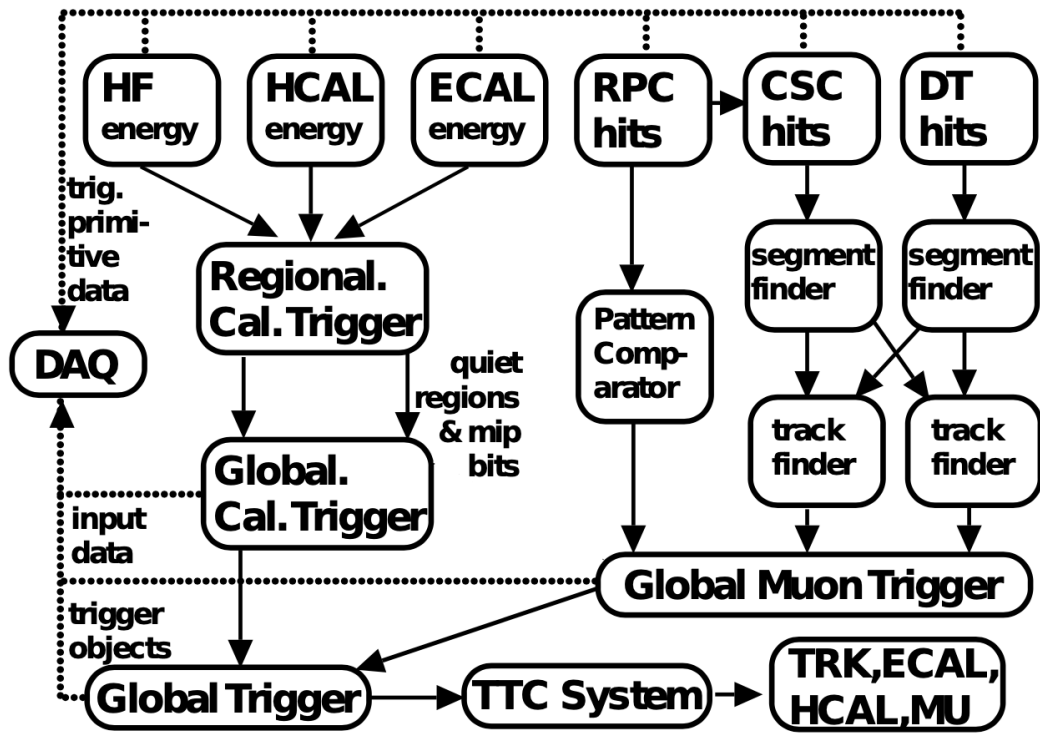


FIGURE 3.23: Overview of the CMS L1 trigger system. Data from the forward (HF) and barrel (HCAL) hadronic calorimeters, and from the electromagnetic calorimeter (ECAL), are processed first regionally (RCT) and then globally (GCT). Energy deposits (hits) from the resistive-plate chambers (RPC), cathode strip chambers (CSC), and drift tubes (DT) are processed either via a pattern comparator or via a system of segment- and track-finders and sent onwards to a global muon trigger (GMT). The information from the GCT and GMT is combined in a global trigger (GT), which makes the final trigger decision. This decision is sent to the tracker (TRK), ECAL, HCAL or muon systems (MU) via the trigger, timing and control (TTC) system. The data acquisition system (DAQ) reads data from various subsystems for offline storage. MIP stands for minimum-ionising particle.

presence of “trigger primitive” objects such as photons, electrons, muons, and jets above set E_T or p_T thresholds. It also employs global sums of E_T and E_T^{miss} . Reduced-granularity and reduced-resolution data are used to form trigger objects.

During the Level-1 of decision-making period, all the high-resolution data is held in pipe-lined memories. Commodity computer processors make subsequent decisions using more detailed information from all of the detectors in more and more sophisticated algorithms that approach the quality of final reconstruction.

- **High Level Trigger:**

On collection of a Level-1 trigger, after a fixed time interval of about $3.2\ \mu\text{s}$, the data from the pipelines are transferred to front-end readout buffers. After further signal processing, zero- suppression and/or data-compression, the data is placed in dual-port memories for access by the DAQ system. Each event, with a size of about 1.5 MB (pp interactions), is contained in several hundred front-end readout buffers. Through the event building "switch," data from a given event are transferred to a processor. Each processor runs the same high-level trigger (HLT) software code to reduce the Level-1 output rate of 100 kHz to 100 Hz for mass storage.

Various strategies are chosen to guide the development of the HLT code. Rather than reconstructing all the possible objects in an event, whenever possible only those objects and regions of the detector that are actually needed are reconstructed. Events are to be discarded as soon as possible. This leads to the idea of partial reconstruction and to the notion of many virtual trigger levels, e.g., calorimeter and muon information are used, followed by use of the tracker pixel data and finally the use of the full event information (including full tracking) [28].

3.3 Physics objects reconstruction

After the data is collected by each sub-detector of the CMS, it is analysed to extract the physics processes. This task is done in two parts: first the physical information is collected from each sub-detector and objects like vertices, tracks and calorimeter clusters etc are built using the local reconstruction. Then these reconstructed objects are combined together to identify the high level objects like electrons, muons and jets etc.

The local reconstruction occurring in each individual sub-detector module uses real data coming from the DAQ system or from simulated data. The data at this level is called the "digis". After applying the reconstruction algorithm, one goes from "digis" to reconstructed hits (RecHits). The reconstructed hits contain information about the positions and energy clusters of the particle signatures in each sub-detector.

We discuss below in detail the reconstruction procedure of objects required in the scope of this thesis.

3.3.1 Tracks

Tracks are the reconstructed trajectories of charged particles. They play an important role in the event reconstruction in CMS and are also the main components in particle flow algorithms. Track reconstruction is a complex algorithm to estimate the trajectory and the momentum of the charged particles passing through the inner tracking system. Inside the tracker region, due to the almost uniform magnetic field, the trajectory of a charged particle can be parameterized by a helix. The five parameters used by CMS to determine track trajectory are: d_0 , z_0 , ϕ , $\cot\theta$ and the transverse momentum (p_T) of the track. Here d_0 is the impact parameter of the track in the transverse plane and is defined through the coordinates of the impact point $d_0 = -y_0 \cos\phi + x_0 \sin\phi$. ϕ and θ are respectively the polar and azimuthal angles of the track momentum vector at the impact point. p_T is defined at the point of coordinates (x_0, y_0, z_0) , the closest to the nominal beam axis ($z = 0$) point of the track trajectory [34].

Charged particles deposit small charges as they pass through the inner tracking system in the pixel and in the strip detectors. The first step of the reconstruction is a *local reconstruction*, where the signals collected by the pixels and strips of the silicon detectors above specified thresholds are grouped together into clusters. The spatial positions of the charge deposits called *hits* are reconstructed from clusters using specific algorithms for each sub-detector, with a hit reconstruction efficiency of around 99%.

These hits are used in the pattern recognition algorithms, which reconstruct the original trajectories of the particle associating a group of hits to a track and measuring the five parameters of the helix that best match to the observed hits. CMS uses the Combinatorial Track Finder (CTF) [35], an extension of the Kalman Filter (KF) [36] algorithm, to perform the pattern recognition and the track fitting. Track fitting is an iterative procedure where the first iteration searches for tracks with high p_T coming from the primary vertex. Once found, these tracks are removed from the following iterations to reduce the combinatorics and simplify the subsequent iterations with a complex topology (like lower p_T or with displaced vertex).

The iteration process has following steps:

- **Track Seed Generation:** in this step track seeds candidates, consisting of two or three hits in the pixel detector, are used to give estimates of the track parameters. The seeds are constructed from the inner part of the tracker (pixel detector) and the tracks are built outwards, in order to keep high reconstruction efficiency and to facilitate the reconstruction of low-momentum tracks.
- **Track finding:** the track finding is based on the Kalman filter method. It starts from the trajectory seed and adds the hits of the outer layers updating the track parameters and their uncertainties in each layer, as well as the material crossed. This procedure is repeated until the final tracker layer is reached. Only a limited number of track candidates are accepted on the basis of number of hits and minimum χ^2 criteria. For these tracks a search in the inward direction is then performed to find new hits, and use them to update the trajectory parameters. To avoid duplicates of the real tracks, an algorithm, the trajectory cleaner, is applied: it keeps, among the tracks sharing more than 19% of hits, the track with the highest number of hits. If both tracks have the same number of hits, the track with the lowest χ^2 value is retained.
- **Final Track Fitting and Smoothing:** the collection of hits provided during the track-finding step is refitted to remove any bias and complete the information about the trajectory. The fit is performed using a Kalman filter (filtering) and a Runge-Kutta propagator [37] (smoothing) to obtain optimal track parameters by taking into account material effects and accommodating possible inhomogeneities in the magnetic field. Starting from the innermost hits of the track outwards and iteratively, the track trajectory is sequentially updated with new valid hits, as well as its position uncertainty. To extrapolate the trajectory from one hit to the next and to improve the precision, the Runge-Kutta [37] method is used. Then hits incorrectly associated to the track, outliers, are removed by applying requirements on the distance between track candidate and hit or the probability that a pixel hit is consistent with the track. This procedure is repeated many times until no more outliers are found, filtering and smoothing the track every time.

- **Track selection:** The first three steps create a significant amount of fake tracks, which are not associated with a charged particle. To remove fake tracks, tracks are selected by applying requirements based on the number of layers with hits associated to the track, the track quality (χ^2 of the final fit) and on the compatibility that the track is originating by one of the reconstructed vertices, primary plus pile-up.

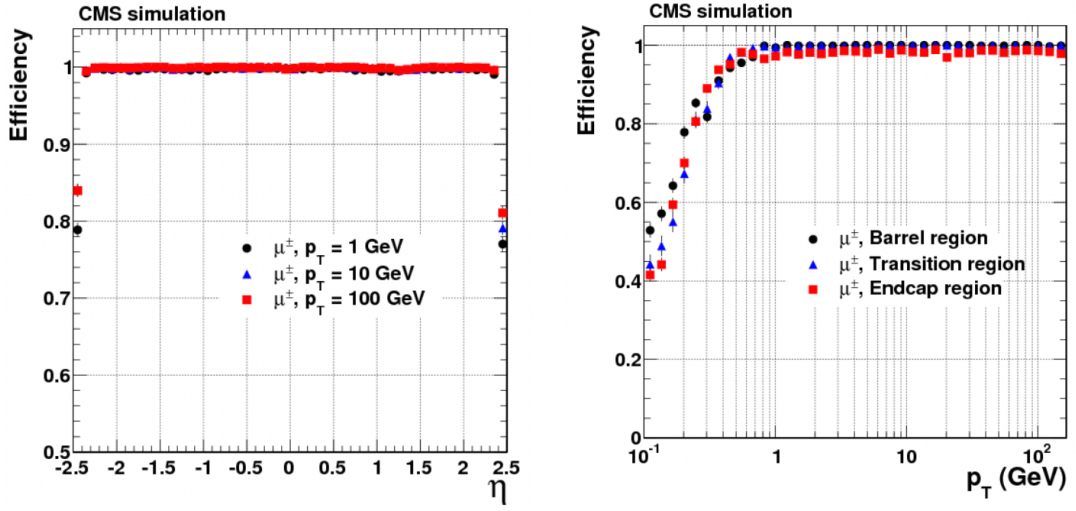


FIGURE 3.24: Track reconstruction efficiencies for single, isolated muons satisfying the high-purity quality requirements. Results are shown as a function of η (a) for $p_T = 1, 10$, and 100 GeV. They are also shown as a function of p_T (b), for η intervals of 0 – 0.9 (barrel), 0.9 – 1.4 (transition) and 1.4 – 2.5 (endcap), respectively.

The average track reconstruction efficiency for promptly charged particles with transverse momenta of $p_T > 0.96$ GeV is 94% for $|\eta| < 0.9$ and 85% for $0.9 < |\eta| < 2.5$ are shown in figure 3.24

Primary vertex reconstruction

Reconstructed tracks are also used to measure the position of the primary vertices, which are the proton collision points. Tracks with good quality criteria and no significant displacement from the beam spot are clustered and fit to obtain the vertex position. Tracks are clustered in z using the deterministic annealing algorithm [38]. Track clusters are then fitted using the Adaptive Vertex Fitter [36] algorithm. This algorithm is an iterative re-weighted Kalman filter that fits a candidate vertex starting from a collection of tracks. Tracks are re-weighted at each iteration so that the contribution of fake tracks gradually diminishes.

The primary vertex resolution depends on the number of associated tracks, as shown in figure 3.25 in x or y (A) and z (B). The resolution is about 10-50 μm [39].

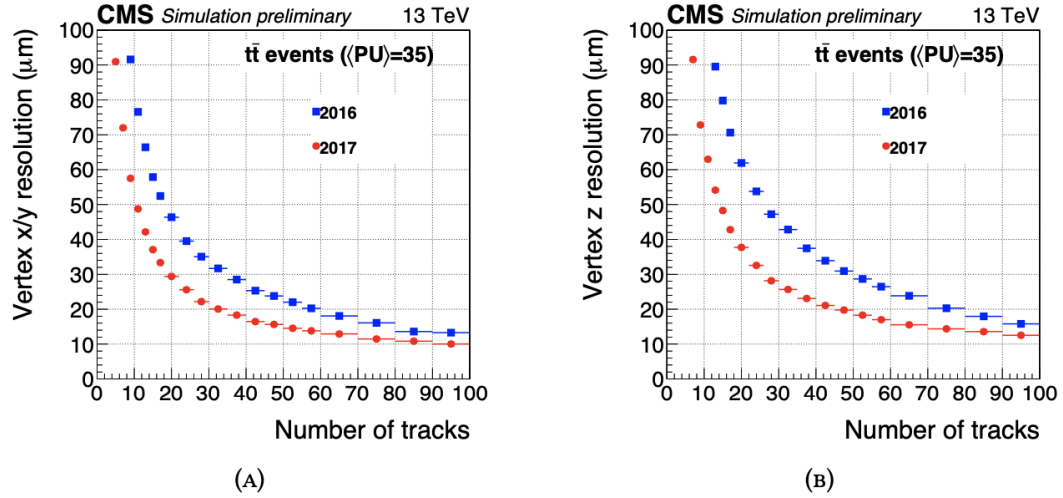


FIGURE 3.25: Vertex transverse resolution as a function of the number of tracks used in the vertex fit. The 2017 detector shows better performance than 2016 detector

There are multiple vertices in an event due to the pileup, and once they are reconstructed, one is chosen as the signal vertex and used for analysis. During Run 1, the signal vertex was chosen as the primary vertex with the largest $\Sigma_{tracks} p_T^2$. This algorithm has been improved during the Long Shutdown 1 in order to choose the vertex depending on the Σp_T^2 of all the collision products, as reconstructed using the Particle Flow algorithm.

3.3.2 Muons

The CMS experiment offers an excellent muon reconstruction and identification efficiencies due to its tracker and dedicated muon system. Muons with $p_T > 5$ GeV typically leave hits in the inner tracker, travelling through the CMS calorimeters with minimal energy deposit and finally leave hits in the muon chambers. Thus muons can be reconstructed like tracks in two independent places of the detector - the inner tracker and the muon chambers. This feature greatly improves the ability to isolate muons from hadronic activity.

Initially, muon tracks are reconstructed independently in the inner tracker, called the 'tracker muon' and in the muon system, called standalone muon [40]. Based on these objects, three reconstruction approaches are used:

- **Standalone muon** reconstruction uses only muon chambers taking the track segments from local reconstruction and from the three muon chambers. Starting from the segments of innermost chambers the muon trajectories are built using a Kalman-filter technique [36]. The Kalman filter is then applied backward from the outermost surfaces; the track parameters are defined in the innermost layers and the track is extrapolated to the nominal interaction point, setting a constraint to the vertex.
- **Tracker muon** reconstruction starts from the tracks reconstructed in the inner tracker, considering all the tracks with $p_T > 0.5$ GeV and $|\vec{p}| > 2.5$ GeV, and extrapolates them to the muon system. If an extrapolated track position matches within the uncertainties to at least one muon segment, the corresponding track is considered as a tracker muon track. The muon momentum resolution can be greatly improved by utilising hits in both the muon system and the tracker using the Global Muon reconstruction.
- **Global Muon** reconstruction starts with a standalone muon track and searches for a compatible tracker track. A global-muon track is fitted combining hits from the tracker track and standalone-muon track, using a Kalman filter technique to take into account the expected energy loss within the magnet and support structure; in the fit, the muon track is constrained to originate from the beamspot.

Due to high efficiency of tracker reconstruction and even higher efficiency of reconstructing segments in muon systems, 99% of the muons produced in pp collisions within the geometrical acceptance of the muon, are reconstructed as Global or Tracker Muon. The Global Muon reconstruction provides better momentum resolution for the tracks with $p_T > 200$ GeV, while the Tracker Muon reconstruction is more efficient for the low momentum tracks with $p_T < 5$ GeV. Muons reconstructed only as standalone muon tracks have worse momentum resolution and thus are not usually used in physics processes.

3.3.3 Missing transverse energy

Neutrinos or neutral weakly interacting particles not yet discovered don't leave any signature in the detector. The presence of these particles can be inferred by the momentum imbalance in the transverse detector plane. The transverse momentum of the colliding proton pair is negligible, and therefore, from the conservation of 4-momentum, the sum of the transverse momenta of all the particles produced in a p-p interaction must be null. As a consequence of the imbalance, the missing transverse energy ($\vec{E}_T^{miss}$), is measured by the sum of all the particle flow candidates in the event and is defined as:

$$\vec{E}_T^{miss} = - \sum_{visible} \vec{P}_T \quad (3.3)$$

The missing transverse energy plays an important role at LHC in several analyses, among these the ones aiming to the discovery of new physics or to the precision measurements in the SM processes in particular in the Higgs sector.

The source of real ($\vec{E}_T^{miss}$) in my analysis is from neutrinos created in electroweak interactions. There are also several false sources which are often difficult to control. These sources include the mis-measurement of jets energy, the detector inefficiencies, the reconstruction inefficiency and the pile-up.

The p_T^{miss} performance and resolution are usually measured in events with $Z/\gamma +$ jets, where no genuine p_T^{miss} is expected. In such events the p_T^{miss} resolution is dominated by hadronic activity, since the momentum resolution for leptons and photons is of order 1%, compared to 5–20% for the jet momentum resolution. The p_T^{miss} for $Z \rightarrow \mu\mu +$ jets events is shown in figure 3.26 (left), the peak value is at about 30 GeV. In the $Z \rightarrow \mu\mu +$ jets topology one can also measure the performance in p_T^{miss} by comparing the momenta of the vector boson to that of the hadronic recoil system. The hadronic recoil system is defined as the vector p_T sum of all PF candidates except for the muons from the Z. The hadronic recoil vector is projected along the Z axis to evaluate the response, and the orthogonal component, as well as the difference between the recoil along the axis and the Z transverse momentum provide a similar estimate of the p_T^{miss} resolution, as shown in figures 3.26 (middle and right). The intrinsic resolution, after removing the pileup contribution, is ~ 10 GeV for both the components of the recoil.

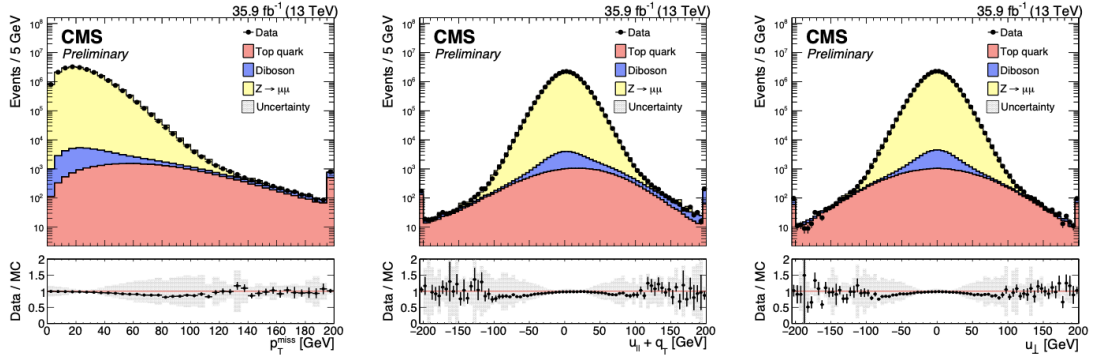


FIGURE 3.26: Distribution of p_T^{miss} (left) of the two orthogonal components of the hadronic recoil (middle) and (right) in the $Z \rightarrow \mu\mu + \text{jets}$ topology. The points in the lower panel of each plot show the data to simulation ratio. The systematic uncertainties due to the jets and the unclustered energy are shown in the shaded band [41]

3.3.4 Particle flow

Once the sub-detectors collect the data and is written in memory, selected events can be reconstructed for analysis purposes. This event reconstruction is based on the Particle Flow (PF) idea and an algorithm is used by CMS to correlate all single detector measurements, to identify the final state particles and measure their properties.

Charged particles leave signatures in the inner tracking system, and the vertices from decaying short-lived particles like b quarks and short-lived kaons can be identified. Photons, electrons, neutral pions and kaons are stopped in the crystals of the electromagnetic calorimeter (ECAL) and the scintillation light is used to determine the deposited energy. Hadrons punch through further and are generally stopped by the hadronic calorimeter (HCAL) where jets are confined and only the highest-energy hadrons and muons pass through the superconducting solenoid into the outer regions of the CMS barrel. Finally, muons are detected in the various muon detectors which interleave the return yoke of the magnet. Neutrinos escape from the CMS detector and are inferred from an imbalance of energy in the reconstructed event called missing transverse energy. This simplified view is graphically summarised in figure 3.27, which displays a sketch of a transverse slice of the CMS detector.

Figure 3.28 shows a jet with a p_T of 65 GeV simulated in the CMS detector made up of five constituents: two charged hadrons (π^+ and π^-), two photons from the π^0

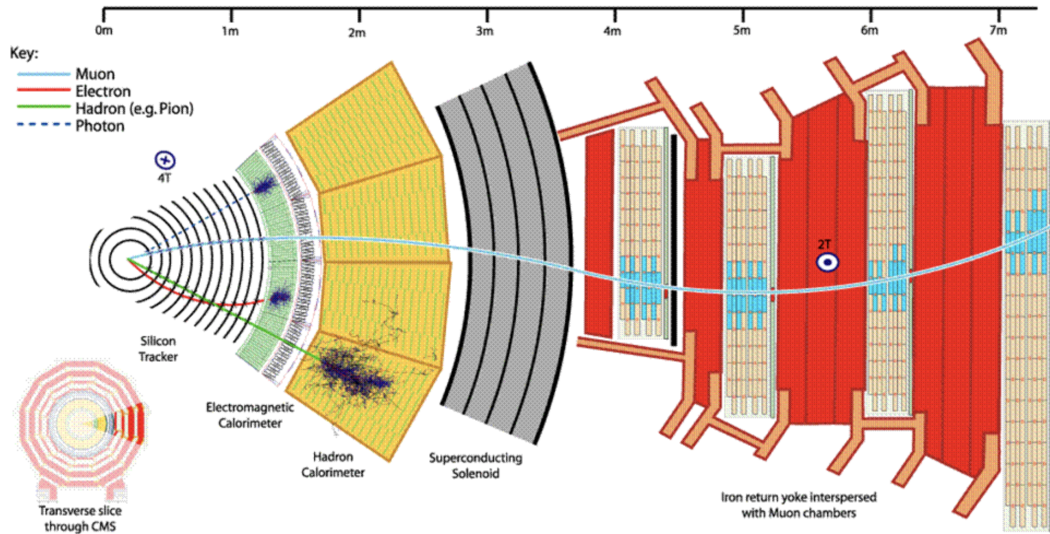


FIGURE 3.27: A sketch of the specific particle interactions in a transverse slice of the CMS detector, from the beam interaction region to the muon detector. The muon and the charged pion are positively charged, and the electron is negatively charged. Image is taken from twiki

decay and a neutral hadron (K_L^0). The K_L^0 , the π^- , and the two photons from the π^0 decay are detected as four well-separated ECAL clusters denoted by $E_{1,2,3,4}$. The π^+ does not create a cluster in the ECAL. The two charged pions are reconstructed as charged particle tracks $T_{1,2}$, appearing as vertical solid lines in the $(\eta - \phi)$ view and circular arcs in the (x,y) view. These tracks point towards two HCAL clusters $H_{1,2}$. In figure 3.28 B, the ECAL and HCAL cells are represented as squares, with an inner area proportional to the logarithm of the cell energy. Cells with an energy larger than those of the neighbouring cells are shown in dark grey. In all three views, the cluster positions are represented by dots, the simulated particles by dashed lines, and the positions of their impacts on the calorimeter surfaces by various open markers. The PF approach allows a global event description for CMS with all identified particles.

Due to the powerful magnetic field, the trajectories of charged particles are bent in a direction perpendicular to the magnetic field. The direction of bending depends on the charge of the particle, while the amount of bending is a function of particle momentum - this is a central feature of particle identification in modern particle physics detectors. After particles pass through the solenoid, their bending is in the opposite direction, as indicated by the picture in this section. This is due to the fact that the magnetic field is in the opposite direction.

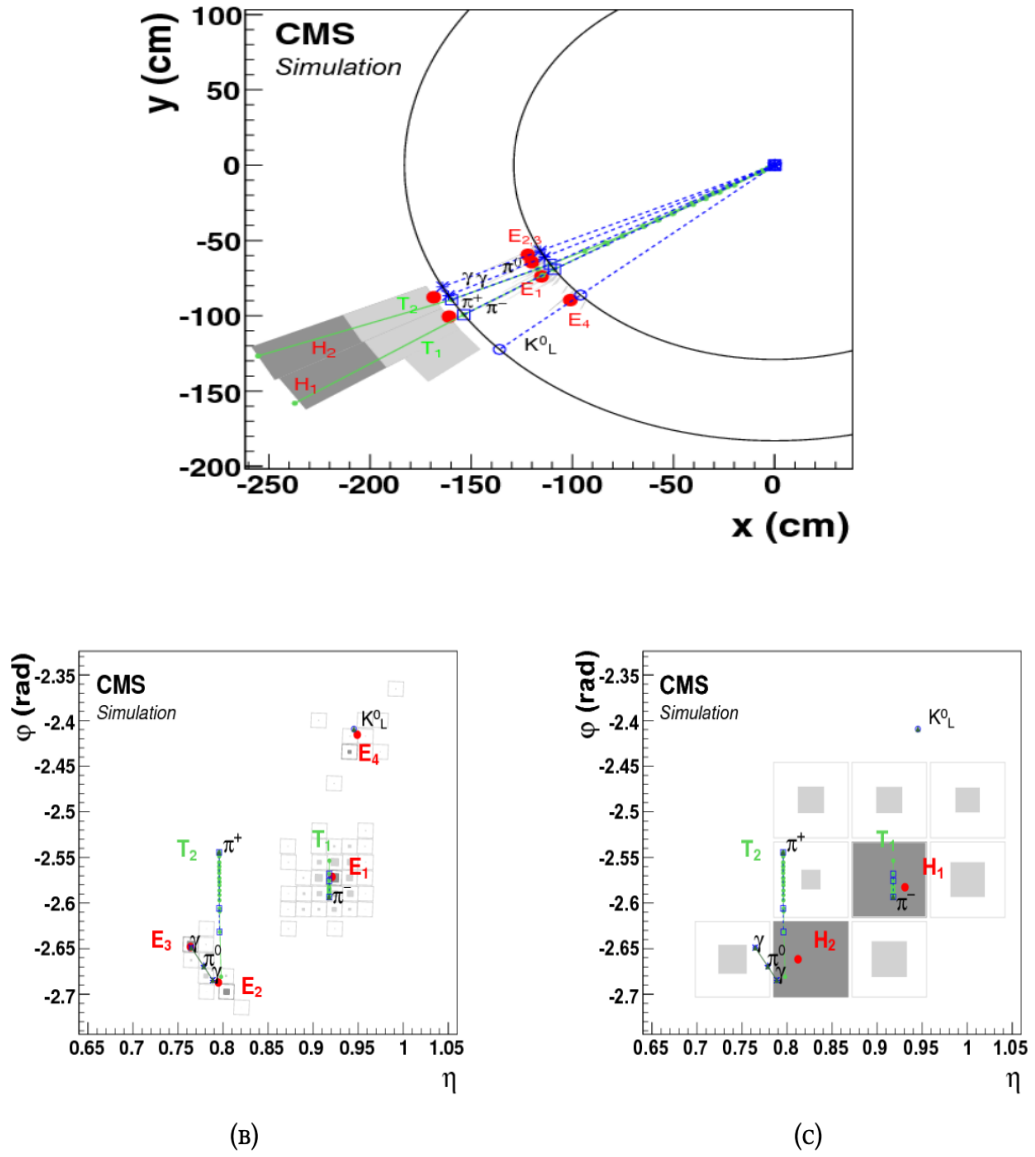


FIGURE 3.28: Display of five particles in a jet. The transverse plane view (A) shows the tracks in green; the circumferences indicate the ECAL and HCAL surfaces. The ECAL (B) and HCAL (C) clusters in the $\eta \times \phi$ plane are also shown.

This apparent simplicity has led to a tradition at hadron colliders of reconstructing physics objects based at least to a large extent on the signals collected by a given detector as follows:

- Jets consist of hadrons and photons, the energy of which can be inclusively measured by the calorimeters without any attempt to separate individual jet particles. Jet reconstruction can therefore be performed without any

contribution from the tracker and the muon detectors. The same argument applies to the missing transverse momentum1 (p_T^{miss}) reconstruction.

- The reconstruction of isolated photons and electrons primarily concerns the ECAL.
- The tagging of jets originating from hadronic τ decays and from b quark hadronization is based on the properties of the pertaining charged particle tracks, and thus mostly involves the tracker.
- The identification of muons is principally based on the information from the muon detectors.

A significantly improved event description can be achieved by correlating the basic elements from all detector layers (tracks and clusters) to identify each final-state particle, and by combining the corresponding measurements to reconstruct the particle properties on the basis of this identification. This holistic approach is called particle-flow (PF) reconstruction.

In figure 3.29 the muon reconstruction and identification efficiencies are reported for the PF muon showing a very good agreement between data and MC simulation.

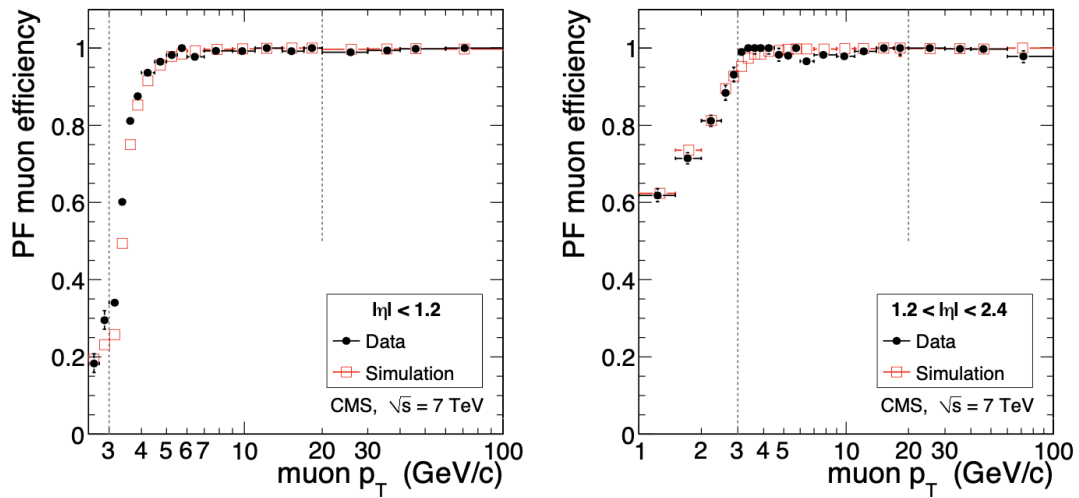


FIGURE 3.29: Muon reconstruction and identification efficiency measured by tag and probe method in $J/\Psi \rightarrow \mu^+\mu^-$ events for $p_T < 20$ GeV and in $Z \rightarrow \mu^+\mu^-$ events for $p_T > 20$ GeV. The plots show the efficiency as a function of p_T in the barrel and endcap regions for the PF muon selection.

3.3.5 Simulation

The simulation is a crucial aspect of high energy physics experiments. Looking at the scale of detector infrastructure and the amount of computing required, first the simulation parameters are studied for initial understanding and tuning purposes. In CMS it is used at analysis level and for testing the algorithms before deployment with data. The simulation targets the relatively rare processes, which originate from a hard interaction between two proton components. These are signal or background for specific analyses. Single particles or hadronic jets can also be simulated for specific purposes.

Several theoretical, phenomenological and experimental inputs go into building a simulation of the proton-proton collisions. Different techniques are used in particular to describe the QCD processes, whose phenomenology varies greatly at different energy scales [42].

Proton-proton collisions are very complex and difficult to model accurately. Protons are composed of 3 quarks, called valence quarks, by virtual gluons and virtual quark antiquark pairs coming from gluon splitting. All constituents of hadrons are generically called partons. Quarks and gluons can emit additional radiation via the strong interaction. All the quarks and gluons go through the hadronization process, forming colorless hadrons. Finally, unstable particles are going to decay. A representation of all these elements is shown in figure 3.30.

The elements involved in the calculations of a process can be summarised as:

- The Parton Distribution Functions (PDFs) that are phenomenological functions computed using experimental information
- the hard scattering, computed perturbatively order by order
- the parton showering, used to simulate additional emissions in perturbative QCD
- the hadronization, describing the transition from colored particles to hadrons, treated using phenomenological models
- the decay of unstable particles, modelled based on experimental data

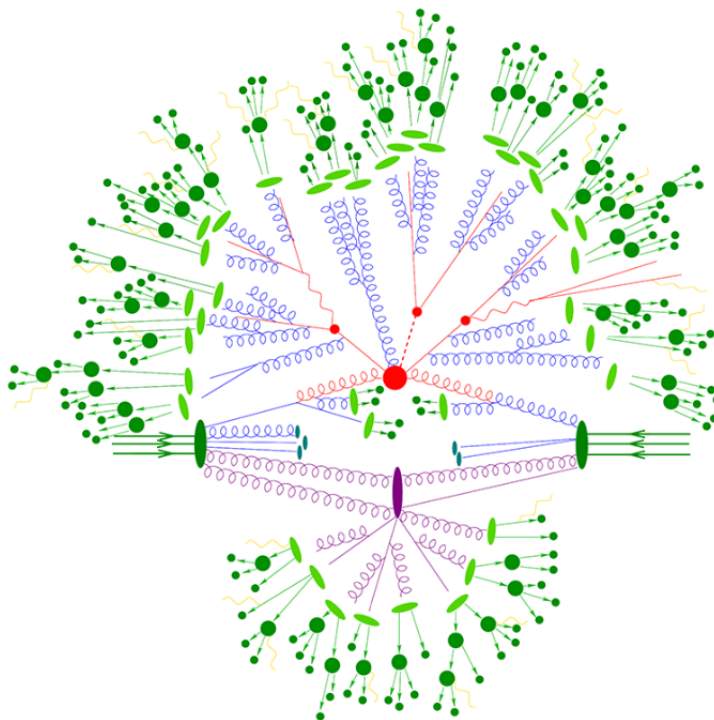


FIGURE 3.30: Representation of a proton-proton collision event. The red part includes the hard interaction and the decay of the products. Initial and final state radiation are in blue. A secondary interaction can take place, in purple, before the represented by the green blobs, and the hadron final-state partons hadronize. The hadronization is decay in dark green. Photon radiation is in yellow. [43]

Monte Carlo techniques are then used for the simulation of the interaction of the stable particles with the detector. The detector simulation is implemented using Geant4 [44]. Pileup interactions are also added at this stage. A library of simulated hits of minimum bias events is used to add a number of extra interactions onto the signal event according to a specified pileup scenario. Out-of-time pileup is modelled by modifying the timing of the detector hits when adding a minimum bias interaction.

Once the simulation of the detector is run, all the detector signals are converted to electronic signals in a format identical to the one used for data. From this point onward the simulated events go through the same reconstruction steps as the collision data.

3.4 HL-LHC and Phase-II upgrade

In the High Luminosity upgrades of the Large Hadron Collider (HL-LHC), luminosity is going to increase by a factor of 10 beyond the LHC's design value, reaching up to $10^{35} \text{ cm}^{-2}\text{s}^{-1}$. This upgrade planned during long shut down 3, will allow ATLAS and CMS to collect integrated luminosities of the order of 300 fb^{-1} per year and up to 3000 fb^{-1} during the HL-LHC projected lifetime of ten years (up to 4000 fb^{-1} if the ultimate instantaneous luminosity can be achieved). The HL-LHC is expected to run at a centre-of-mass energy of 14 TeV and with a bunch spacing of 25 ns.

The increase of the instantaneous luminosity will be achieved by a set of upgrade actions (or projects). Most importantly, the inner triplet quadrupole magnets in the insertion regions will be replaced with more radiation tolerant ones based on Nb_3Sn technology. The new quadrupole magnets will provide a higher magnetic field strength and feature a larger aperture, allowing for a luminosity increase through a lower beam beta function, β^* , in the collision region [45].

The number of simultaneous pp collisions (pileup) happening during a single bunch crossing is proportional to the instantaneous luminosity. To limit the number of pileup events, it is foreseen to level the luminosity during an LHC fill, i.e. to operate at a constant luminosity below the maximum achievable value .

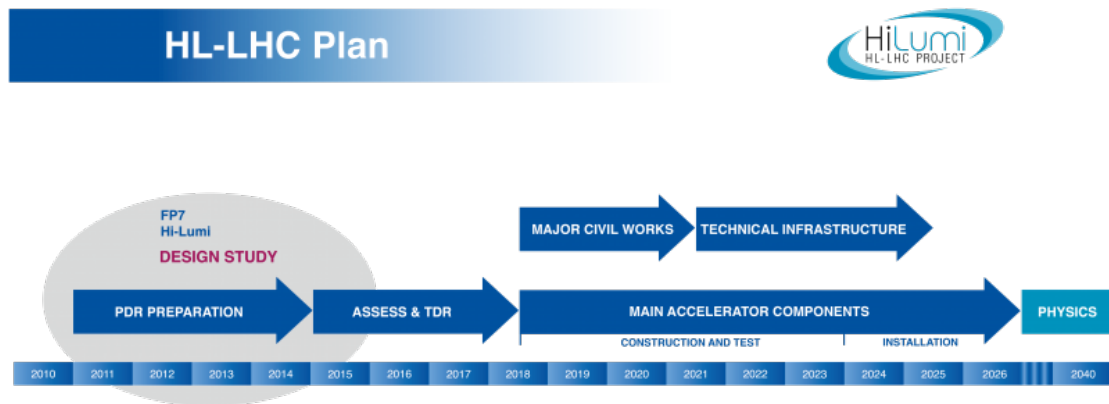


FIGURE 3.31: The HL-LHC plan. Image from CERN-courier

While the mean number of pileup events reached 53 at the highest instantaneous luminosity in 2016, in a special high pileup run, about 140 pileup events on average are expected for an instantaneous luminosity of $5.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, increasing to

200 pileup events in the ultimate luminosity scenario (expected $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$). The radiation level will be unprecedented: for the design integrated luminosity of 3000 fb^{-1} a 1 MeV neutron equivalent fluence of $2.3 \times 10^{16} \text{ n}_{eq} / \text{cm}^2$ and a total ionising dose (TID) of 12 MGy (1.2 Grad) is expected at the centre of CMS, where the innermost silicon pixel tracking layers will be installed.

The HL-LHC upgrade is accompanied by an upgrade programme of the CMS experiment, to maintain the excellent performance of the detector and to allow us to fully profit from the HL- LHC capabilities, in spite of the challenging radiation levels and operating conditions.

The HL-LHC upgrade will greatly expand the physics potential of the LHC, in particular for rare and statistically limited standard model (SM) and beyond standard model (BSM) processes. The discovery potential for many BSM studies, including searches for Supersymmetry (SUSY), extra dimensions, and extra gauge bosons, will reach higher masses. New channels with low production cross sections or small coupling strengths will open up.

The CMS detector needs to be substantially upgraded during LS3 in order to exploit the increase in luminosity provided by the HL-LHC. This upgrade is referred to as the CMS Phase-2 Upgrade. The increase in radiation levels requires improved radiation hardness, while the larger pileup and associated increase in particle density requires higher detector granularity to reduce occupancy, increased bandwidth to accommodate higher data rates, and improved trigger capability to keep the trigger rate at an acceptable level while not compromising physics potential.

The CMS trigger system consists of two stages, the first level hardware trigger (L1) and the high-level trigger (HLT). Trigger rates will be limited to 750 kHz at L1 and 7.5 kHz at the HLT. The L1 trigger latency will be improved to about 12.5 μs as compared to current 3.4 μs . It will provide sufficient time for the hardware track reconstruction and matching of tracks to muons and calorimeter information. This change will require upgrades of the readout electronics in some of the existing sub-detectors that will be kept for Phase-II.

Muon system: While the muon chambers are expected to cope with the increased particle rates, the front end electronics for the drift tube chambers (DTs) and cathode strip chambers (CSCs) will be replaced with improved versions to increase radiation tolerance, readout speed, and performance. In the forward region the muon system will be enhanced, both with improved resistive plate chambers

(RPCs) and new chambers based on the gas electron multiplier (GEM) technique. The new chambers add redundancy, improve the triggering and reconstruction performance, and increase the acceptance in the forward detector region. GEM detectors have already been mounted during this last shut down (2018 - 2021)

Calorimeters:

In the barrel, the electromagnetic calorimeter (ECAL) uses lead-tungstate crystals read out with avalanche photo diodes (APDs). The crystals will be cooled to lower temperatures than currently used and the front-end electronics will be improved in order to cope with the trigger latency and bandwidth requirements. New front-end boards will allow the exploitation of the information from single crystals in the L1 trigger, while the present system integrates the same information only in groups of 5×5 crystals. The hadronic calorimeter (HCAL) consists in the barrel region of brass absorber plates and plastic scintillator layers, read out by hybrid photodiodes (HPDs), which will be replaced with silicon photomultipliers (SiPMs) already before LS3. During LS3 the scintillator tiles close to the beam line will be replaced.

Endcaps: The electromagnetic and hadronic endcap calorimeters will be replaced with a new combined electromagnetic and hadronic sampling calorimeter (High Granularity CALorimeter: HGCal) based primarily on silicon pad sensors. Plastic scintillator tiles, read out by SiPMs, will be used at large distances from the beam line in the hadronic section. With silicon pad cell sizes of $0.5 - 1 \text{ cm}^2$ and 28 (12) sampling layers in the electromagnetic (hadronic) sections, this detector will provide high transverse and longitudinal granularity, leading to improved pileup rejection and identification of electrons, photons, tau leptons, and jets [46].

Figure 3.32 compare rates between the Phase 1 trigger running at an instantaneous luminosity resulting in a mean of 40 pileup interactions per bunch crossing, and the HGCal with a mean of 140 pileup interactions per crossing, the Level-1 single electromagnetic trigger rate is only 1.5 times higher for thresholds up to 20 GeV, and 2.5 times higher for thresholds up to 30 GeV, despite the increase in the instantaneous luminosity by a 3.5 factor. The algorithm results in only a 1–2% inefficiency for electrons.

MIP Timing Detector (MTD): As mentioned above, HL-LHC will see a rise in pile-up number. This Pileup confuses the trigger and also the offline reconstruction and interpretation of events. It increases the amount of data that has to be read

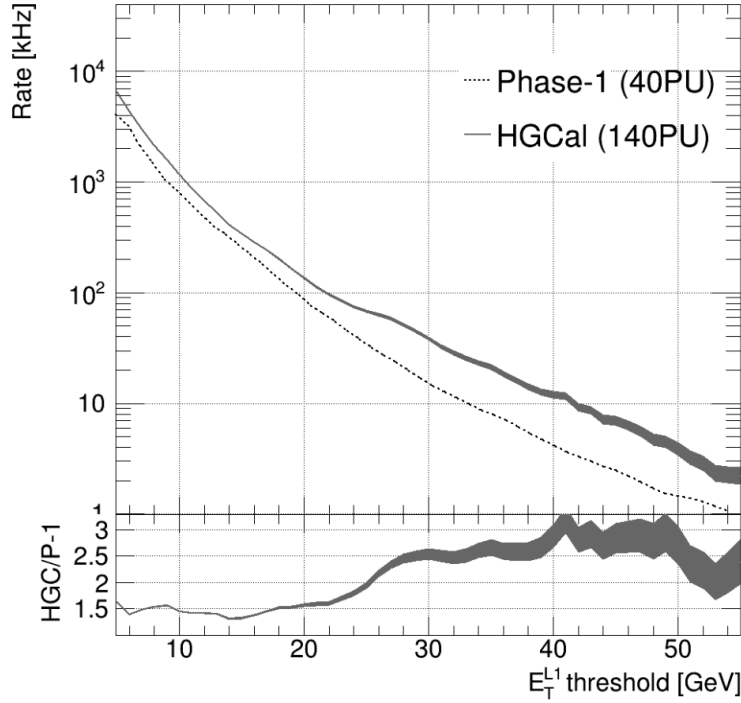


FIGURE 3.32: Comparison of rates between the Phase 1 electromagnetic object trigger running at an instantaneous luminosity resulting in a mean of 40 pileup interactions per bunch crossing, and the HGC with a mean of 140 pileup interactions per crossing. [45]

out in each BX that contains a hard scatter. In fact, at the HL-LHC, most of the data read out will be associated with the “pile-up” collisions rather than the collision containing hard scatters. It also increases the execution time for the reconstruction of events in the High Level Trigger and the offline analysis.

To take care of this challenge, the time dimension of the beam spot is exploited and a detector layer is planned to be placed between tracker and the calorimeter. MTDs are capable of marking each hit with a timestamp, MIP sensitivity with time resolution of ~ 30 ps and hermetic coverage of $|\eta| < 3$ makes them distinguish between different proton collisions within the same p-p bunch crossing. This is necessary in avoiding the mixing of tracks from different collisions. MTDs will be present in barrel and endcap both with the features mentioned in table 3.3, where LYSO = Lutetium-yttrium oxyorthosilicate, SiPM = Silicon Photomultiplier and LGAD = Low Gain Avalanche Detector technology. Significant object-level improvements like: Pileup-jet tagging, Lepton isolation, Flavour tagging, E_T^{miss} are expected with the MTDs.

	Barrel (LYSO+SiPM)	Endcap (LGAD)
Coverage	$|\eta| < 1.5$	$1.5 < |\eta| < 3$
Surface area	$\sim 40 \text{ m}^2$	$\sim 12 \text{ m}^2$
Power Budget	$\sim 0.5 \text{ kW/m}^2$	$\sim 1.8 \text{ kW/m}^2$
Radiation dose	$\leq 2e^{14} \text{ n}_e\text{q/cm}^2$	$\leq 2e^{15} \text{ n}_e\text{q/cm}^2$
Installation date	2022	2024

TABLE 3.3: List of the sources that contribute to the $J/\Psi + \pi^+$ invariant mass distribution

Tracker: The entire silicon tracking system, presently consisting of pixel and strip detectors, will be replaced. To maintain adequate track reconstruction performance at the much higher PU levels of the HL-LHC, the granularity of the outer tracker will be roughly increased by a factor of 4 and of the pixel systems by a factor of 6. The new tracker will feature increased forward acceptance, increased radiation hardness, higher granularity, and compatibility with higher data rates and a longer trigger latency.

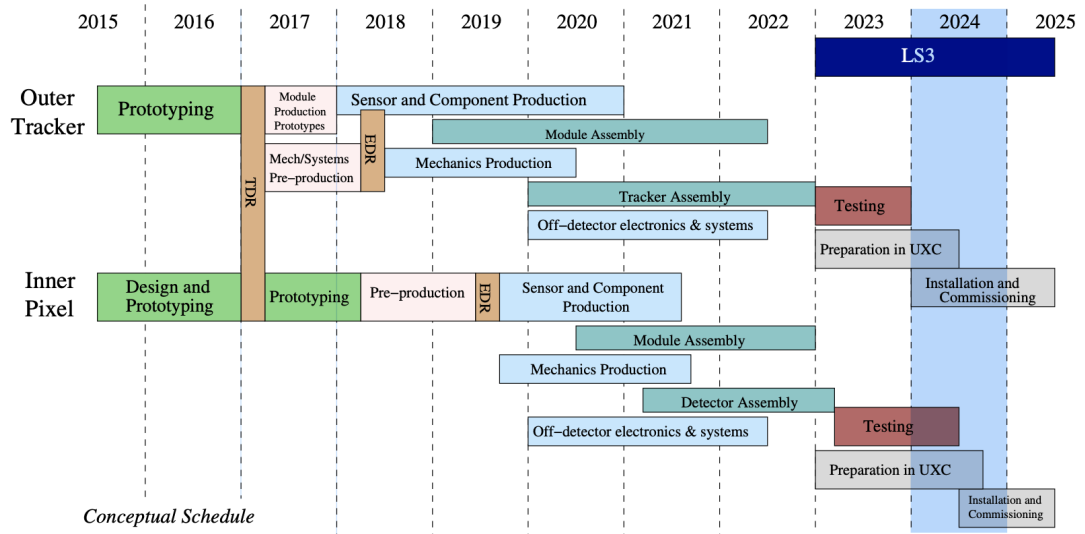


FIGURE 3.33: Sketch of one quarter of the Tracker layout. Outer Tracker: blue lines correspond to PS modules, red lines to 2S modules. The Inner Pixel detector, with forward extension, is shown in green

In the outer tracker, this will be achieved by shortening the lengths of silicon sensor strips relative to those in the current detector, without changing the pitch very significantly. A number of design improvements will lead to a much lighter Outer Tracker providing significantly improved p_T resolution and a lower rate of γ -conversions compared to the present detector. In addition, the module design

will be capable of providing track-stub information to the L1 trigger at 40 MHz for tracks with $p_T \geq 2$ GeV. This will ensure powerful background rejection at the earliest stage of the event selection.

The Outer Tracker provides data both for the L1 reconstruction (for each bunch crossing), and for the global event processing upon reception of a L1 trigger decision. The L1 functionality depends upon local data reduction in the front-end readout electronics, in order to reduce the required bandwidth of the L1 data stream. This is achieved with modules that are themselves capable of rejecting signals from particles below a certain p_T threshold, that are referred to as “ p_T modules”. A threshold of around 2 GeV corresponds to a data volume reduction of roughly one order of magnitude, which is sufficient for the purposes of L1 data transmission.

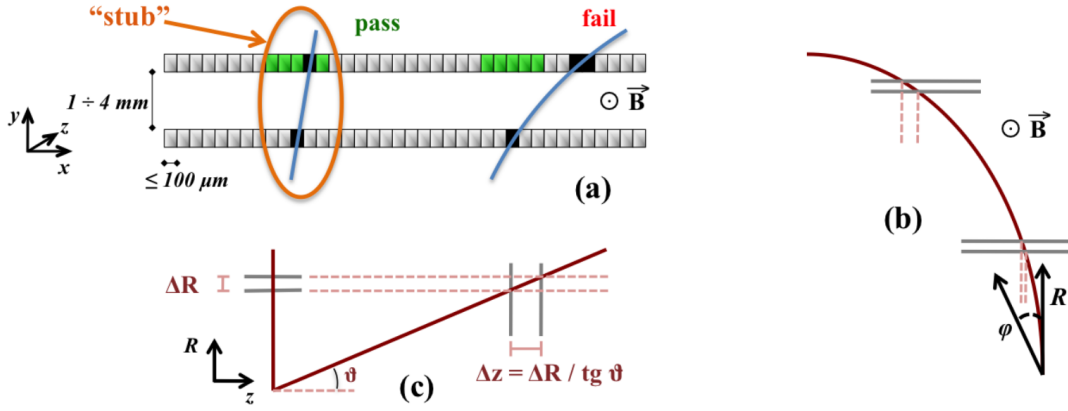


FIGURE 3.34: (a) Correlation of signals in closely-spaced sensors enables rejection of low- p_T particles; the channels shown in light green represent the “selection window” to define an accepted “stub”. (b) The same transverse momentum corresponds to a larger distance between the two signals at large radii for a given sensor spacing. (c) For the end-cap disks, a larger spacing between the sensors is needed to achieve the same discriminating power as in the barrel at the same radius. The acceptance window can therefore be tuned along with the sensor spacing to achieve the desired p_T filtering in different regions of the detector.[45]

The modules are composed of two closely spaced silicon sensors read out by a common front-end. The front-end ASICs correlate the signals collected in the two sensors, and select pairs that form “stubs” compatible with particles above the chosen p_T threshold. The strong magnetic field of CMS provides sufficient sensitivity to measure p_T over the small sensor separation, enabling the use of p_T modules in the entire radial range above $R \approx 20$ cm. Stub data are sent out at

every bunch crossing, while all other signals are stored in the front-end pipelines for reading out when a trigger is received. In order to implement the same p_T threshold for the stubs throughout the tracking volume, the acceptance window must be programmable in the front-end ASICs, and different sensor spacings must be implemented in different regions of the Tracker (see sketches in figure 3.34).

Two types of p_T modules are under development.

- “2S” modules are composed of two superimposed strip sensors of approximately $10 \times 10 \text{ cm}^2$, mounted with the strips parallel to one another. They populate the outer regions, above $R \approx 60 \text{ cm}$ (in red in the sketch of figure 3.33), which corresponds to a sensor surface area of approximately 150 m^2 .
- “PS” modules are composed of two sensors of approximately $5 \times 10 \text{ cm}^2$, one segmented in strips, and the other segmented in “macro-pixels” of size $100 \mu\text{m} \times 1.5 \text{ mm}$. These are deployed in the radial range between $R \approx 20 \text{ cm}$ and $R \approx 60 \text{ cm}$ (in red in the sketch of figure 3.33), resulting in a sensor surface area of about 60 m^2 (30 m^2 short-strip sensors and 30 m^2 macro-pixel sensors).

The pixel system will implement smaller pixels and thinner sensors for improved impact parameter resolution and better two-track separation. This will improve b-tagging as well as τ -hadronic decay and track reconstruction efficiencies within boosted jets. With up to 10 additional pixel disks in each of the forward regions the system coverage will be extended to close to $|\eta| = 4$, to better match the range of coverage of the calorimetry.

Pixel sizes of $25 \times 100 \mu\text{m}^2$ or $50 \times 50 \mu\text{m}^2$ are being considered, representing a factor of 6 reduction in surface area compared to the present pixel cells. An alternative option that is being actively pursued is the possibility to use 3D silicon sensors, offering intrinsically higher radiation resistance because of the shorter charge collection distance. Pixel phase-II upgrade is described in detail in the next chapter.

Chapter 4

The Experimental activities for Pixel phase-II upgrade

As described in the last chapter, LHC experiments and their planned high luminosity upgrades [47] will face challenging operational conditions in future. Silicon detectors are the most affected by the radiation damage among the CMS sub-detectors, which affect their performance and degrade the detection capabilities. In order to maintain or improve the physics performance of the CMS detector in the high pileup conditions of the HL-LHC, the entire tracking system must be replaced with new detectors featuring higher radiation tolerance and enhanced functionality [46].

Below we discuss the limitations of the present tracking system (phase 0 and phase I) and requirements for the upgraded tracking detectors, followed by an overview of the design concepts and ongoing developments of Pixel detector in section 4.1. The study of new modules before and after radiation damage in our laboratory and testbeam facilities is discussed in section 4.2 and 4.3 respectively. Lastly, the modelling of the detectors through Monte Carlo simulation is described in section 4.4.

Pixel sub-detector observed some dynamic inefficiencies during Run 1, of the order of about 5% at an event pile-up of 40 in the first barrel layer. This was due to the limited size of the readout bandwidth. A new pixel detector was then installed in March 2017, equipped with one additional barrel layer and one additional forward disk. In the new pixel detector, the innermost layer was closer to the interaction point and the outermost one was further away from it (shown in figure 4.1). It also

uses new Readout Chips (ROCs) with reduced data loss at higher collision rates with respect to Phase 0 and the bandwidth of the readout electronics was increased approximately by a factor of eight (320 Mbit/s). In addition, to allow the reuse of the existing fibres and cables, DC-DC power converters were installed. Hence, the upgraded pixel detector has a higher rate capability and number of channels, providing increased tracking efficiency, reduced fake rate, and improved impact parameter resolution [48].

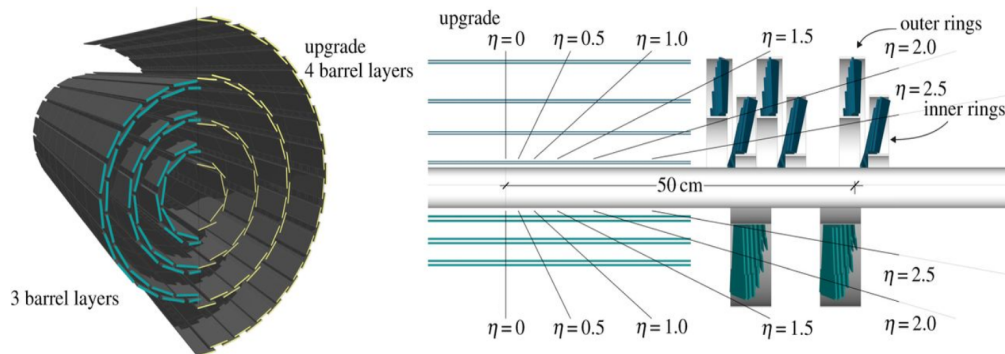


FIGURE 4.1: Schematic drawing showing the upgrade of the pixel detector. The number of barrel layers in the present and the upgraded detector (left). In the right figure: the lower half shows the old pixel detector, and the upper half represents the newly-installed detector.

Figure 4.2 shows the comparison of the hit efficiency observed during 2016 with the previous pixel detector and the hit efficiency observed in 2017 with the new one. Layer 1 shows a clear improvement even though being closer to the beam pipe, making the overall hit efficiency improve.

In late 2017, a failure of about 5% of the DC-DC power converters, resulted in a marginal impact on the 2017 data quality. All DC-DC modules were replaced in the end-of-year technical stop of 2017–2018. After this intervention, the issue of the DC-DC power converters did not repeat in 2018, with the pixel detector running with high efficiency and a high fraction of active channels.

In HL-LHC, the Outer Tracker and Phase-I Pixel (replaced ones) detector would be unable to cope with even the first few years of operation. In addition to their intrinsic limitations, the Phase-I tracking detectors restrict the CMS Data Acquisition (DAQ) to a maximum Level-1 (L1) accept rate of about 100 KHz, with an available latency of 4 μ s for the trigger decision. Operation at high luminosity requires a substantial upgrade of the trigger system, with significantly higher rate capability and longer latency.

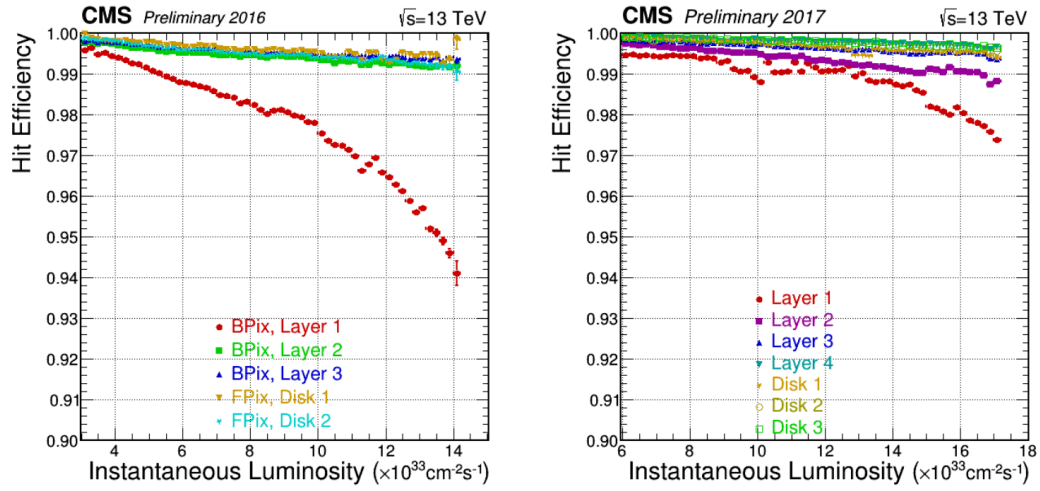


FIGURE 4.2: Hit efficiency of the pixel detector as a function of the instantaneous luminosity during Run 1 measured with 2016 data (left) and during Run 2 measured with 2017 data (right) [49]

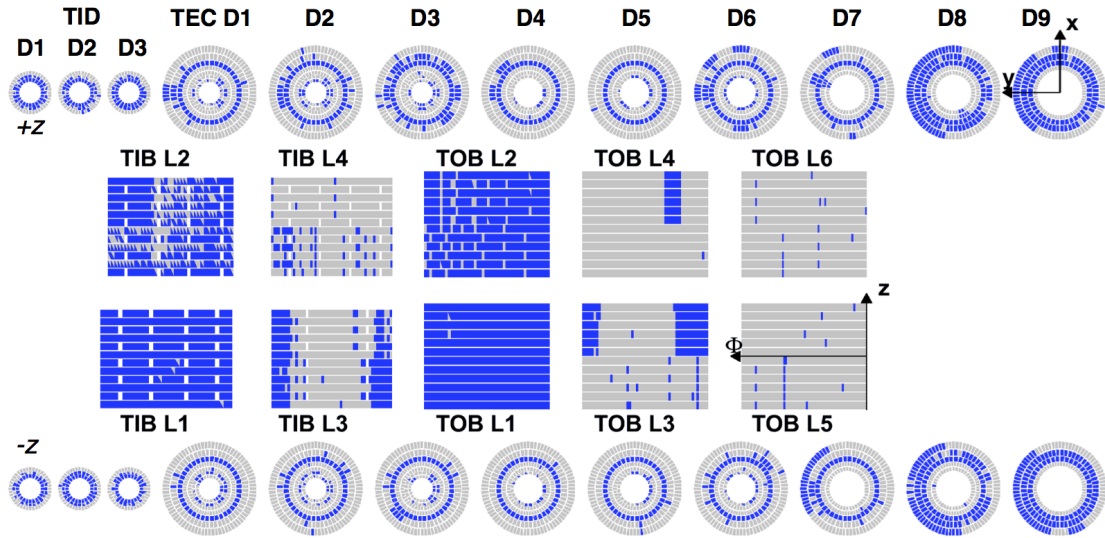


FIGURE 4.3: Map of non-functional modules (in blue) after an integrated luminosity of 1000 fb^{-1} , for the achievable minimum coolant temperature of -20°C .

A map of non-functional modules (current sensors) after 1000 fb^{-1} (foreseen by mid of Run 4-5 in HL-LHC era) for the achievable minimum coolant temperature of -20°C , is shown in figure 4.3. Almost all the stereo modules in the barrel (Inner Barrel layers 1 and 2 and Outer Barrel layers 1 and 2), as well as in the endcap (rings 1, 2 and 5), will be no longer operational.

The main reasons for tracker upgrade can be summarised as follows:

- radiation tolerance,

- increased granularity,
- improved two-track separation,
- reduced material in the tracking volume,
- robust pattern recognition,
- inclusion in the L1 trigger upgrade,
- extended tracking acceptance.

4.1 Pixel phase-II upgrade

The upgraded Tracker must be able to operate efficiently up to an integrated luminosity of 3000 fb^{-1} . The expected particle fluences that must be tolerated are shown on the left of figure 4.4. As can be seen from the figure, the requirement of radiation tolerance is particularly demanding for the Pixel detector [50].

Out of the reasons mentioned above for tracker upgrade, main challenges for inner most pixel to handle would be:

- higher pileup,
- small pixel size,
- better track separation and
- high radiation tolerance.

The target integrated luminosity of 3000 fb^{-1} corresponds to a hadron fluence¹ of $2 \times 10^{16} \text{ n}_{eq} \text{ cm}^{-2}$ at 3 cm from the interaction region. This is roughly where the first layer of the pixel detector is located in the case for the phase-I and phase-II detector. The fluence decreases rapidly with distance and is about $3 \times 10^{15} \text{ n}_{eq} \text{ cm}^{-2}$ at a radius of 11 cm.

Pixels are silicon based semiconductor detectors. The n-in-p technology has an advantage over the currently used n-in-n technology, which was developed for the

¹It is common practice to express the fluence as the number of 1 MeV neutrons per unit surface area that would produce an equivalent damage in silicon

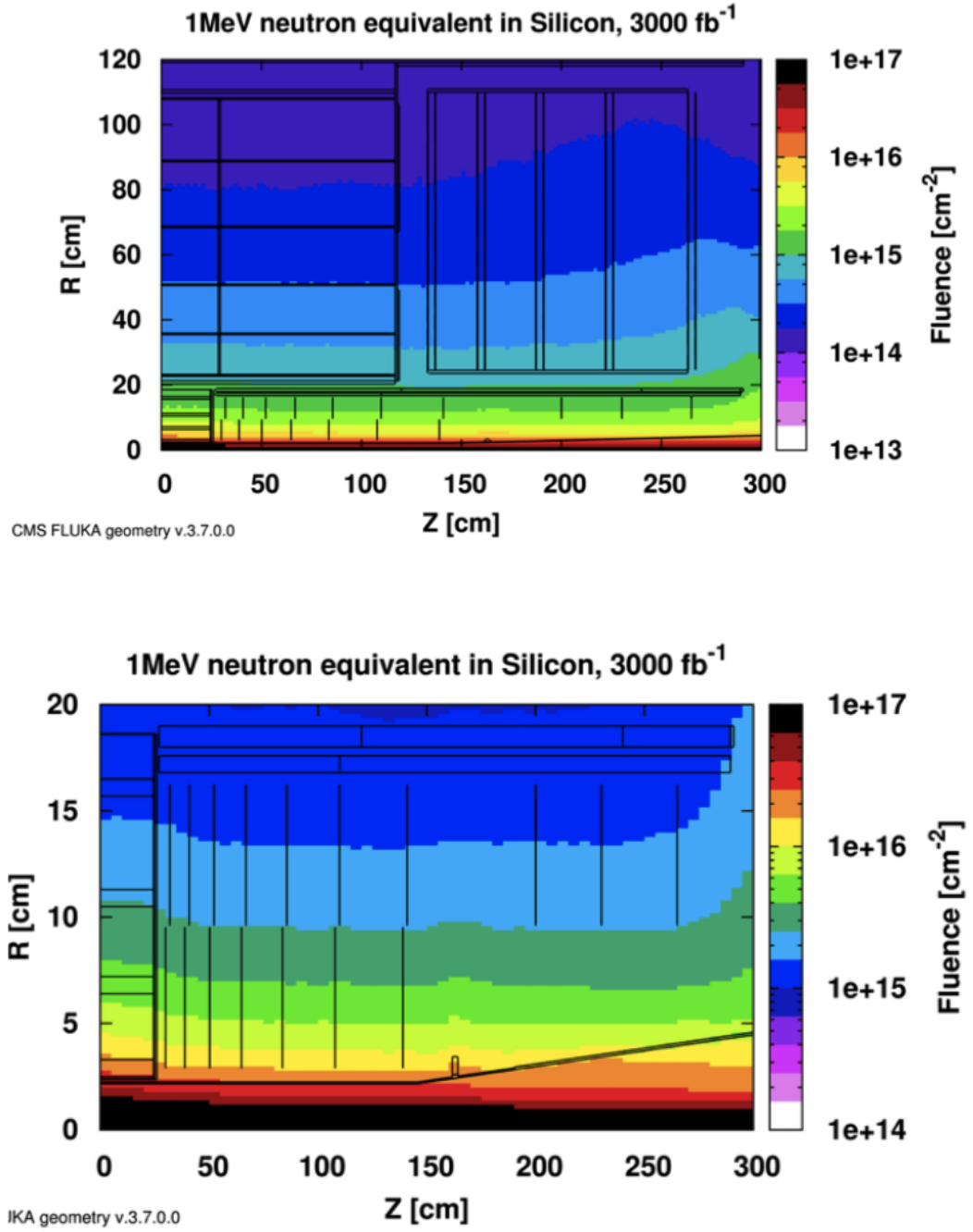


FIGURE 4.4: Top: map of the expected particle fluence in the Tracker volume corresponding to an integrated luminosity of 3000 fb⁻¹, expressed in terms of 1 MeV neutron equivalent fluence. Bottom: detail of the fluence in the pixel volume. The expected fluence has a strong dependence on radius, while it is almost independent of the Z coordinate [50].

first pixel detector and its Phase-I replacement. Adoption of n-in-p sensors reduces the cost, as they are produced with single-sided photo-lithography which is cheaper than the double-sided processing required for n-in-n sensors.

In n⁺-in-p technology, the bulk has a low p (boron) doping concentration of around $p_{bulk} \sim 10^{12} \text{cm}^{-3}$. Top implant which sits on the bulk, has a high peak concentration n⁺ with $n_{top} \sim 10^{19} \text{cm}^{-3}$ and between 1 and 2 μm deep. The most common element utilised for this implant is phosphorus. The backside is again heavily doped with boron. Each n⁺ pixel implant is covered by an aluminium layer, which is connected to the readout chip via bump bonding. The bumps are balls of size 20-30 μm diameter and have a density of 40000/cm². Chip has a slightly larger area, in order to exploit the protective effect of a metal overhang of few μm along all sides. The backside of the detector is totally covered with aluminium for the high voltage connection.

Through preliminary studies, good results are observed by using thin planar silicon sensors (150 μm for phase-II), segmented into very small pixels. For this configuration detector resolution is much more robust with respect to radiation damage compared to the current detector. This is because for thick detectors such as the 300 μ thick Phase-I pixels, the charge collection efficiency is strongly affected by the charge trapping, increase of leakage current and increased depletion voltage. The effects of the radiation damage are more pronounced for larger active thickness. Thin sensors (150 μm or less) offer advantages in terms of lower bias voltage and lower leakage current.

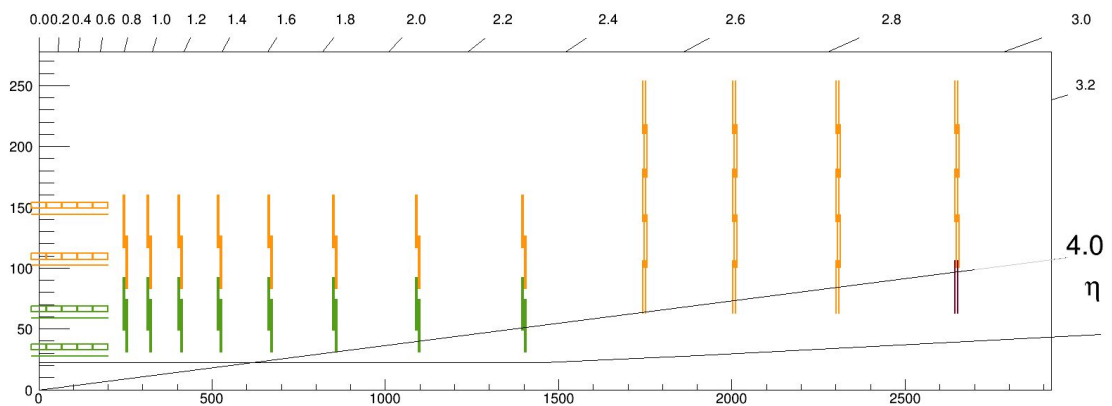


FIGURE 4.5: Sketch of one quarter of the Inner Tracker layout. Tracker barrel, forward and endcap pixels are shown

An alternative option that is being actively pursued and is part of my studies, is the possibility to use 3D silicon sensors in the first layer only [53]. These 3D

sensors offer intrinsically higher radiation resistance because of the shorter charge collection distance. Their lower bias voltage and shorter drift distance leads to lower trapping probability. However for small pixel cells, 3D sensors may suffer from significant charge loss in the implant region. As the production process of 3D sensors is slower and expensive, it might not be suitable for large volumes. The option to equip the first layers, suffering from the highest particle fluence with 3D sensors, is still under discussion.

The new design shall continue to preserve the ease-of-access of the current detector that enables the possibility to replace degraded parts over an Extended Technical Stop. The geometry of the Phase-I detector is taken for reference as a starting point with 4 barrel layers and the forward extension is simply realised by increasing the number of forward disks to 8 per side and endcap disks to 4 per side. Out of these 10 disks, the last 3 consist of the outer part only, in order to be compatible with the conical section of the beam pipe (shown in figure 4.5). The outer part shall have 2736 2×2 pixel modules and the inner part (green) shall have 1156, 2×2 pixel modules. Such an extended pixel detector will have an active surface of approximately 4.9 m^2 , compared to 2.7 m^2 for the Phase-I detector [50].

The pixel readout chip (ROC) is the core building block of the pixel electronics system. Compared to the Phase-I implementation, the Phase-II ROC will feature six times smaller pixels, will have to cope with about five times higher hit rates, five or ten times higher trigger rates, as well as longer trigger latency. To address the challenges associated with the anticipated hit density and corresponding needs for I/O and buffering capabilities, ATLAS and CMS have chosen 65 nm CMOS technology, developed by RD53 collaboration.

A common pixel chip architecture, that is fully digital after the basic threshold detection and charge digitization in the analogue pixel cell, has been defined as shown in figure 4.6. Digital hit processing, including the critical trigger latency buffer, is implemented within the pixel array in local pixel regions (e.g. 2×2 or 4×4 pixels) followed by data merging, data formatting and readout after the Level-1 trigger accept. Buffering requirements have been analysed with a statistical model and simulations and have been verified to be compatible with the proposed extended CMS trigger latency of $12.5 \mu\text{s}$. A buffer depth of 16 pixel clusters for a 4×4 pixel region is sufficient to guarantee a hit loss probability below 10^{-3} for the highest hit rate of 2 GHz/cm^2 .

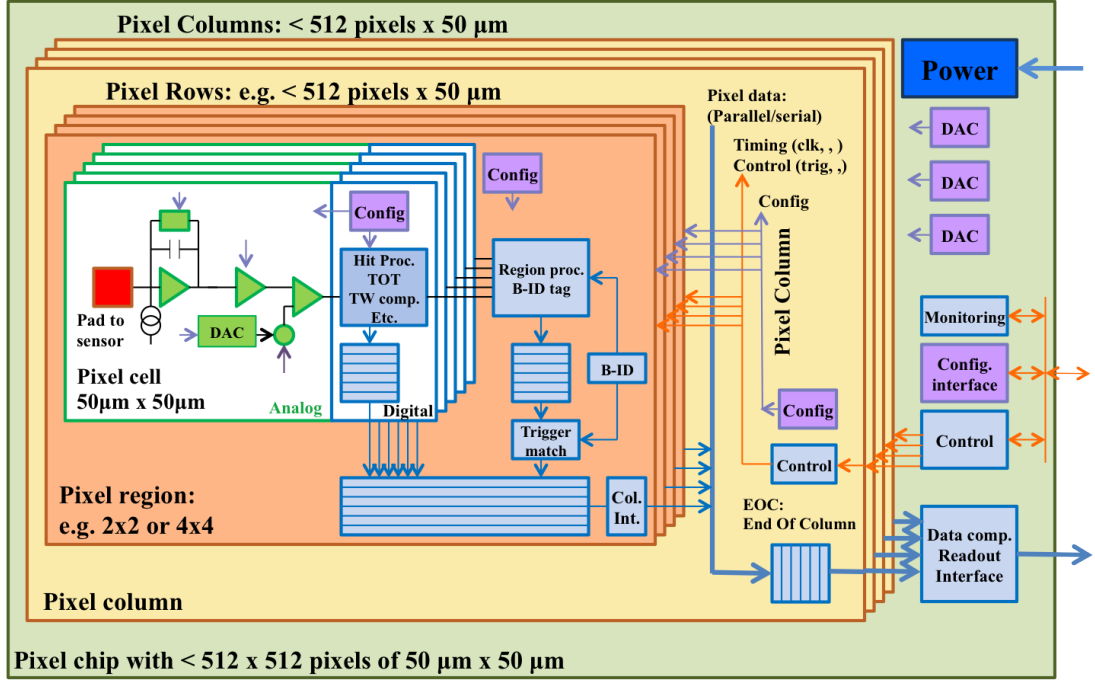


FIGURE 4.6: RD53 digital pixel chip architecture

A pixel surface of $2500\mu\text{m}^2$ has been chosen as a target, to be implemented by $25 \times 100\mu\text{m}^2$ pixel geometry. For the readout chip, achieving such a small pixel size can be made possible with the use of CMOS technology and an architecture where digital electronics for buffering, control, and data formatting are shared by a group of channels (pixel region). Also, with the possibility to tune the bias currents, the sensor choices of 3D or planar, different thickness and sizes can be accommodated. RD53 community is involved in the production of a large prototype chip with $50 \times 50\mu\text{m}^2$ pixels, which will serve as a common basis for the final designs of the ATLAS and CMS pixel ROCs (CROCs). In addition, RD53 is developing a pixel chip and system simulation and verification framework with the defined readout and control protocols.

4.2 Calibration and validation of Modules

Before exposing the modules to testbeam, they are calibrated and studied in our laboratories. The full DAQ chain is set up and voltage - current measurements are done as the first tests. The VDD and VDA are setup as per module specification and basic monitoring scans are done to be sure of the sensor being fully functional. μDTC system is used for this purpose.

The readout and control of the future CMS tracker front-end modules, will be performed by the DAQ, Trigger and Control (DTC) system. This μ DTC project was established to perform these tasks in the prototyping and production phases. This common framework used for both Outer and Inner Tracker, is based on the FC7 board and IPBus². My work in this thesis is focused on inner tracker.



FIGURE 4.7: μ DTC system for inner tracker

Figure 4.7 shows the full chain we use for data acquisition. The software suite is CMS Tracker Phase2 Acquisition & Control Framework (Ph2_ACF) [52]. Different crates can be used for assembly (nano or micro). We use a μ TCA crate, with an FC7 board, which is a back-end board with an FPGA. A Golden image firmware is loaded on a SD card, which is mounted on the hardware board FC7. This firmware establishes a communication between PC and the FC7 board.

Following is the full list of hardware components needed, which are described in detail further below:

- μ TCA crate
- FC7 Board
- FMC card (CERN or Kansas)
- DIO5 card
- Single chip card
- micro SSD
- Power board for FC7
- Power supply for FC7 (12V - 6A)

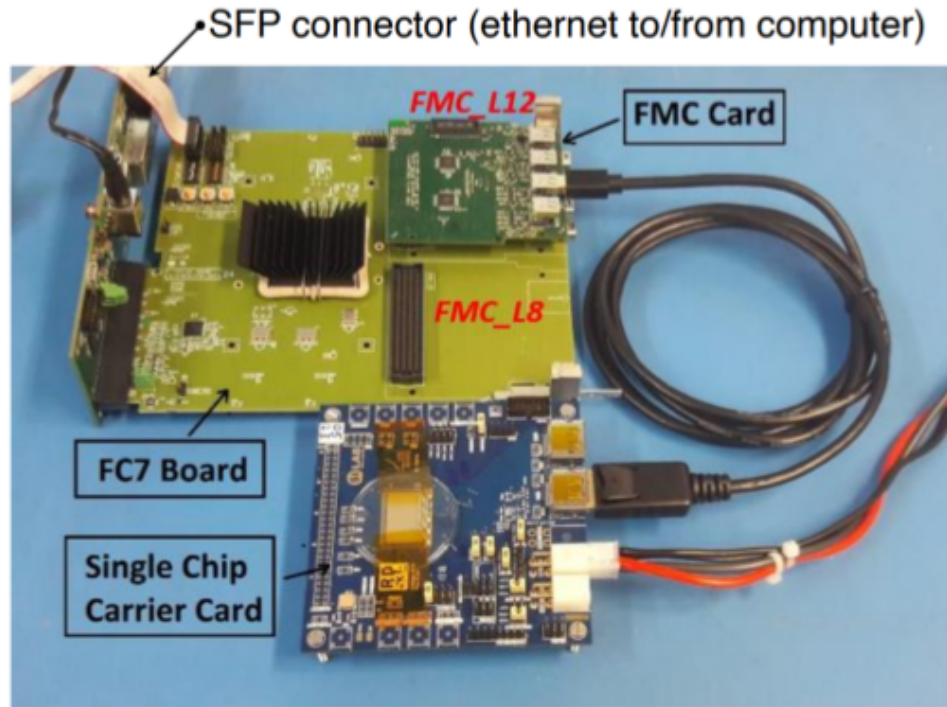


FIGURE 4.8: Full electrical readout for test bench

The figures show FC7 card mounted in a nano crate, but similar connections follow also for the microTCA crate. A FMC board with FPGA mezzanine card, is required to interface the multi-pins on FPGA to particular readout. Display port cable connects this readout to the card holding the front-end chip(s) (as shown in figure 4.8). Connection of this whole assembly with a computer is done via Ethernet cable through SFP (Small Form-factor Pluggable transceiver) connector. Finally, a firmware for our analysis (specific to the hardware configuration we use) is installed.

Two types of FMC cards are supported by the system: CERN-FMC and KSU-FMC (figure 4.9). We have used and tested both the cards for our purposes. Either of the card is installed at the FMC-L12 position and at FMC-L8 position, another FMC card is used. This can be the same as L12 position or a card for external trigger purposes. We use a DIO5 card at this location, as shown in figure 4.10.

Also, the single chip card which holds the module, comes in two flavours: Bonn card and Rice card (figure 4.11). Both the cards contain the RD53A readout chip. We have tested 3D module with 50×50 pixel size and a planar module

²Ethernet based communication protocol

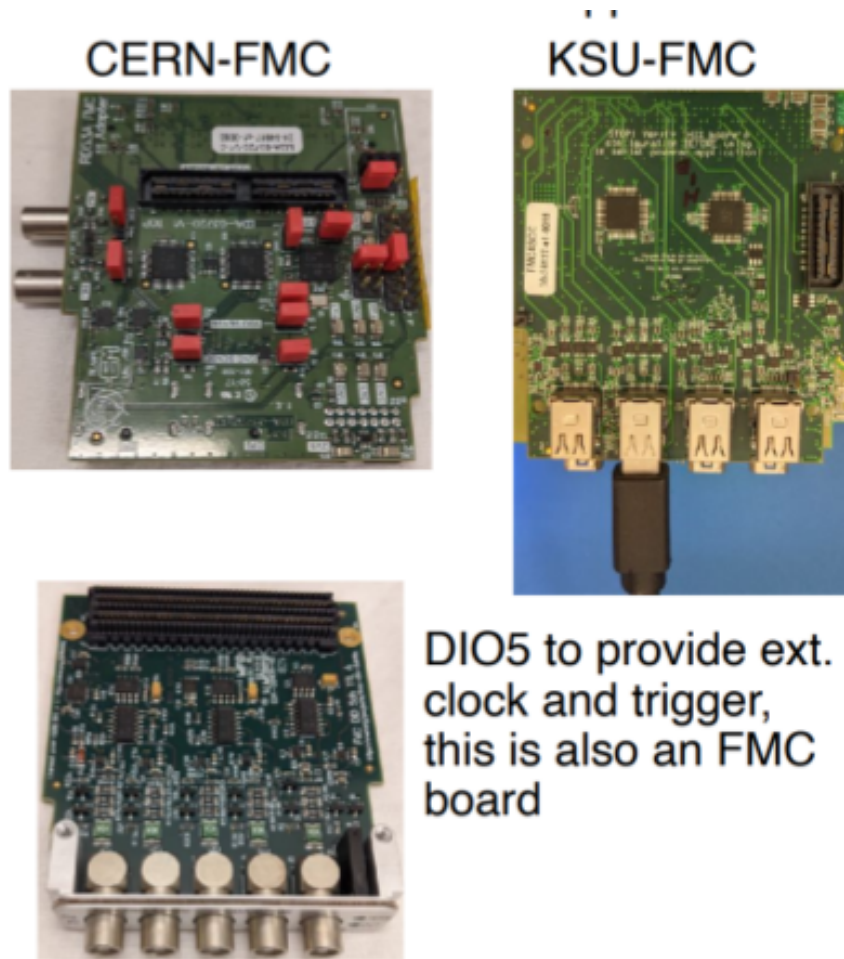


FIGURE 4.9: FMCs used in the setup

with 25×100 pixel size mounted on the Rice card. All the studies presented in this thesis were obtained with the Linear front-end of RD53A, which is located in the central region of the ROC and is 136 columns wide (6.8 mm), from column 128-263 and Row: 0-191.

After measurement and tuning of voltage and current values, scans are done sequentially to tune the module for our usage. First scans are taken with internal injection to calibrate basic parameters.

- Physics scan
- Noise scan
- Pixel alive scan
- Threshold equalisation scan

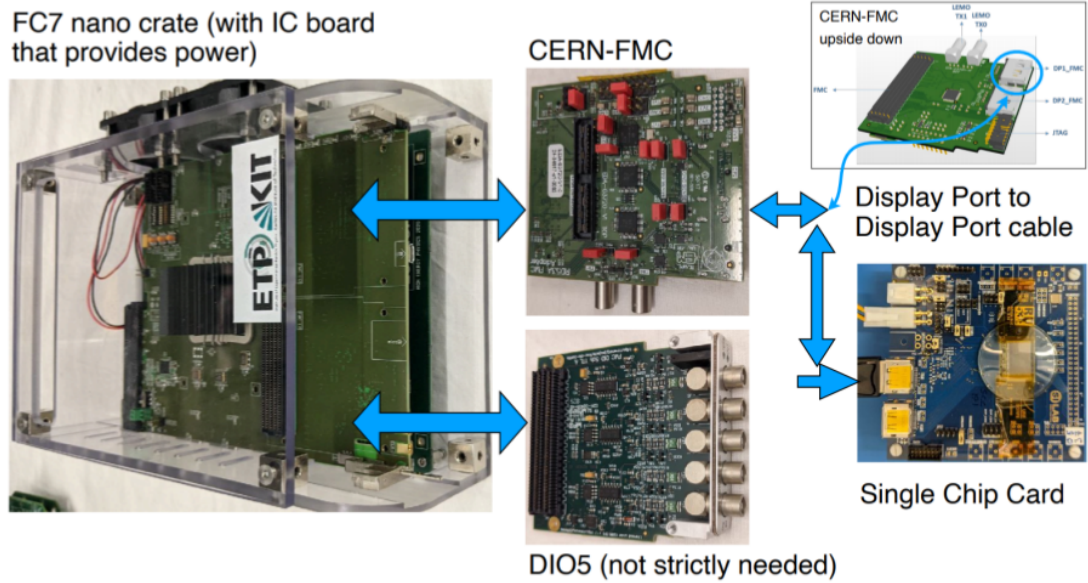


FIGURE 4.10: The full chain with DIO5 usage

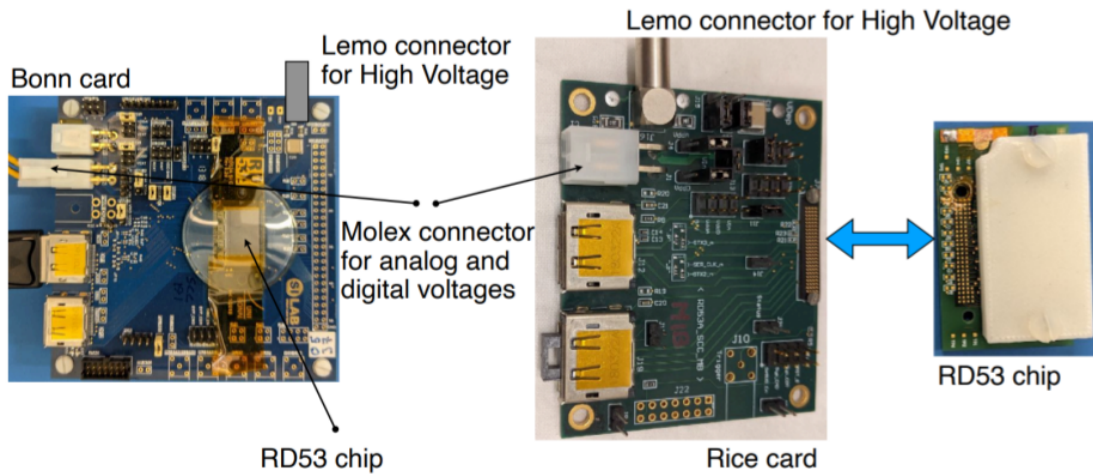


FIGURE 4.11: Single chips card flavours

- Threshold adjustment
- Gain scan
- SCurve scan

This tuning provides us with useful outputs, which are used in testbeam. Also, the values obtained from various scans are set in software suites for further studies.

Physics scan tells if the whole chain is working fine. Noise scans indicate the total number of pixels which misfire, i.e the pixels whose charge collection is above the

given target value. These pixels are called noisy and are masked (6 in this case). Pixel alive scans give us information about the working pixels and their map. The pixels whose charge collection is below the target threshold are considered dead. Figure 4.12 shows a pixel alive distribution.

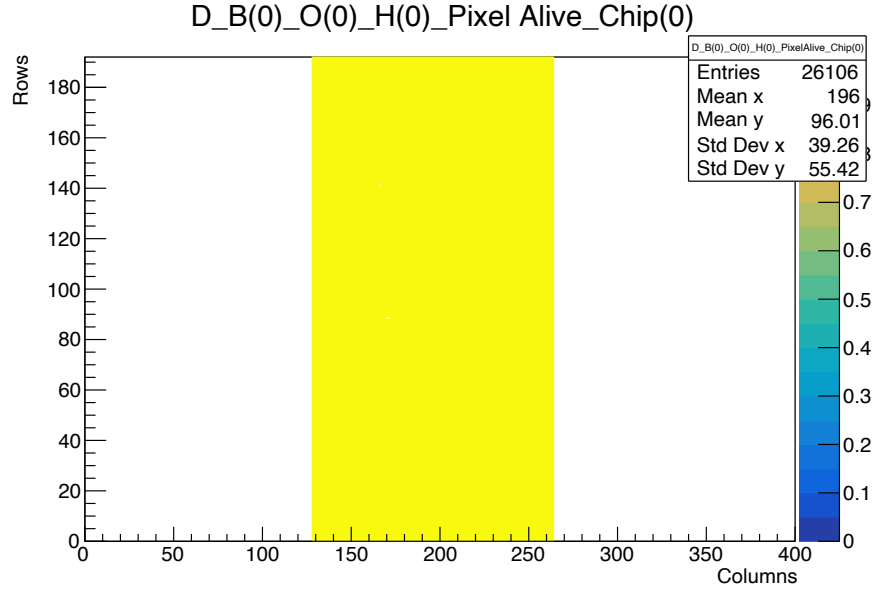


FIGURE 4.12: Pixel alive map

Threshold equalisation and threshold adjustment scans give us the global threshold for all pixels in terms of calibration voltage (V_{cal}). This value is unique for each sensor and set accordingly in further studies. These scans are shown for both 3D and planar sensors later.

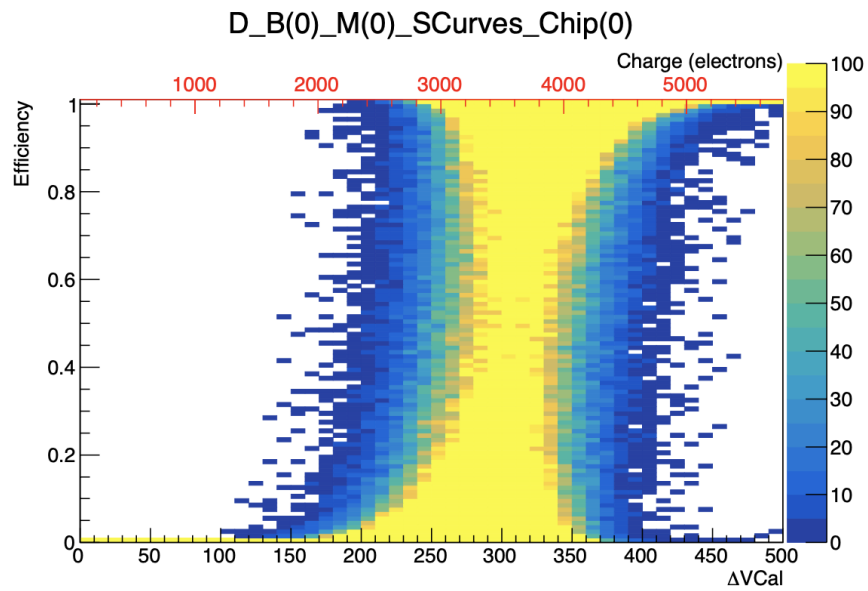


FIGURE 4.13: SCurve scan for 100 triggers per pixel

Gain scan gives us the conversion factor between ToT (Time over Threshold) values, V_{cal} and charge electrons. SCurve between the occupancy vs injected charge for every pixel, gives us the nice sigmoid distribution of the tuned pixels. Figure 4.13 shows one such SCurve distribution. Running noise scan again, guarantees that noisy pixels are understood correctly.

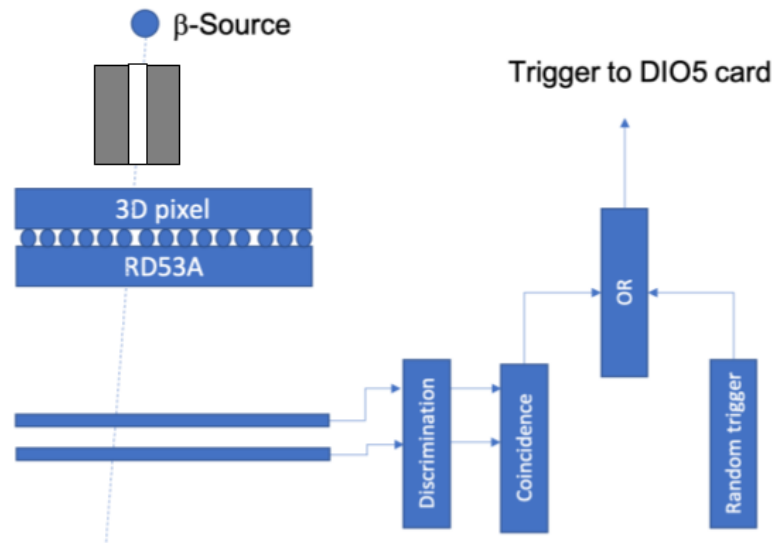


FIGURE 4.14: Schematic representation of the experimental setup in laboratory

To imitate the testbeam structure in our laboratory, we did an additional study with an experimental setup similar to testbeam. The setup is shown in figure 4.14. It consists of a beta source, whose radiation is directed to the silicon sensor via an aluminium collimator. Below this assembly, is the overlap of two scintillators that act as the coincidence trigger (figure 4.15). Both 3D and planar sensors are tested with this configuration.

After the scans with internal injection, we move to the external trigger as discussed above. We used a DIO5 card for an external trigger from the coincidence of two scintillators, as shown in figure 4.14. The software suite is modified accordingly. First thing after this is to know the Latency. In an ADC, latency depicts the time lag between an applied analog input and the arrival of a digital output word. Basically, the time between the trigger and the electronic signal reaching the sensor. It synchronises the location of the buffer cell, where our MIP charge is stored with the time of trigger. Obtaining the correct latency is very important to catch our signal. For RD53A, Trigger encoding/decoding latency is less than 200 ns on top of transit time from the DAQ chain. Scan is run over a range of 512 units. Figure

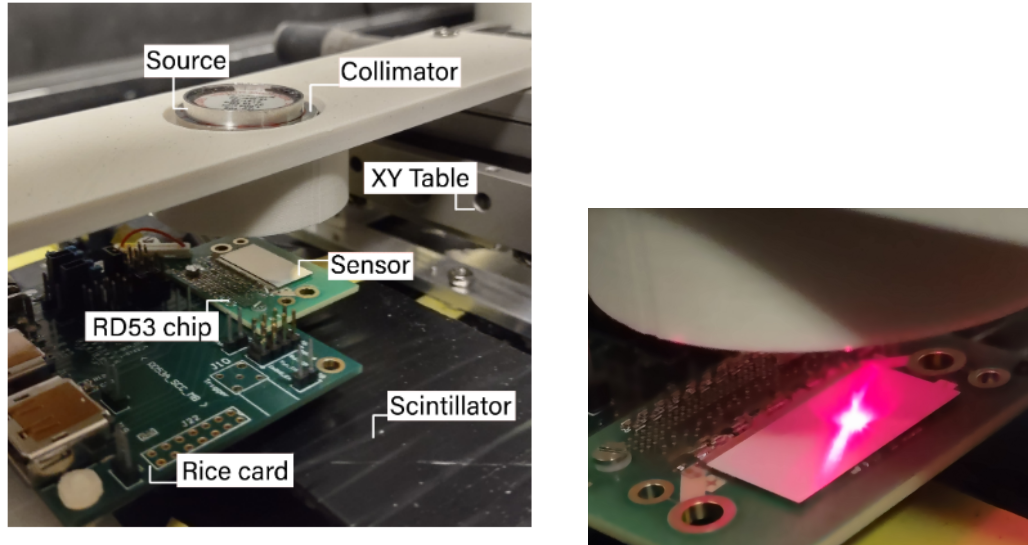


FIGURE 4.15: The experimental setup in the laboratory (left) and centering of module using the laser pointer (right)

4.16 (left) shows the latency scan giving us the optimised value as 34 units. This value is used in xml files for further studies. The latency is found to be the same irrespective of the sensor tested, since it depends on the delay provided by the electric circuit between the trigger and the signal.

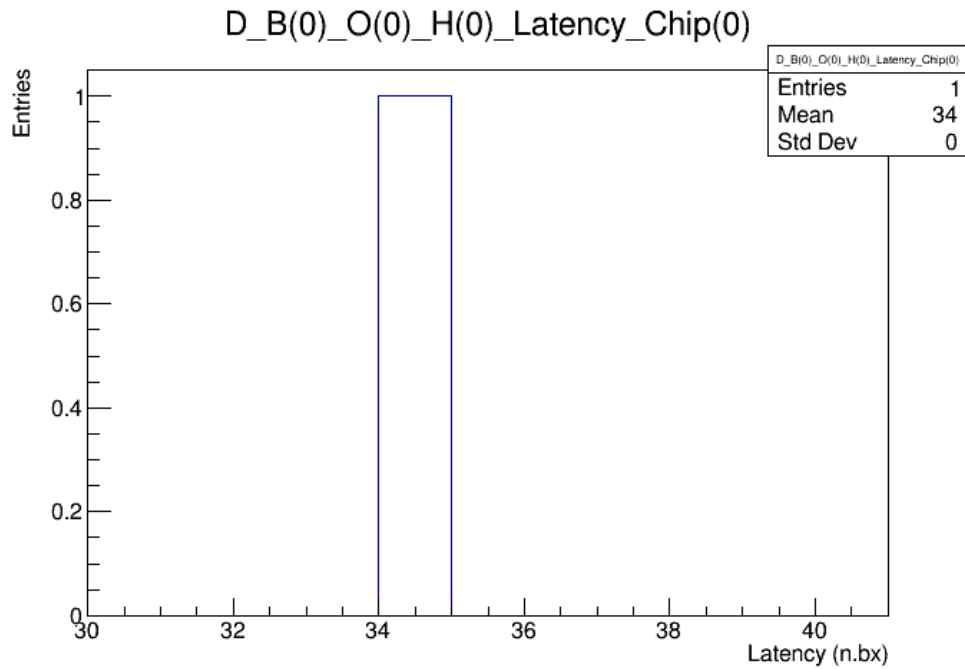


FIGURE 4.16: Latency value obtained after scan

Figure 4.17 and 4.18 shows the threshold scan, which provides the optimised value as 358 and 366 (in terms of ΔV_{cal}) for 3D and planar respectively. This value is

obtained for the target threshold of 2000 electrons and set in xml files for further studies.

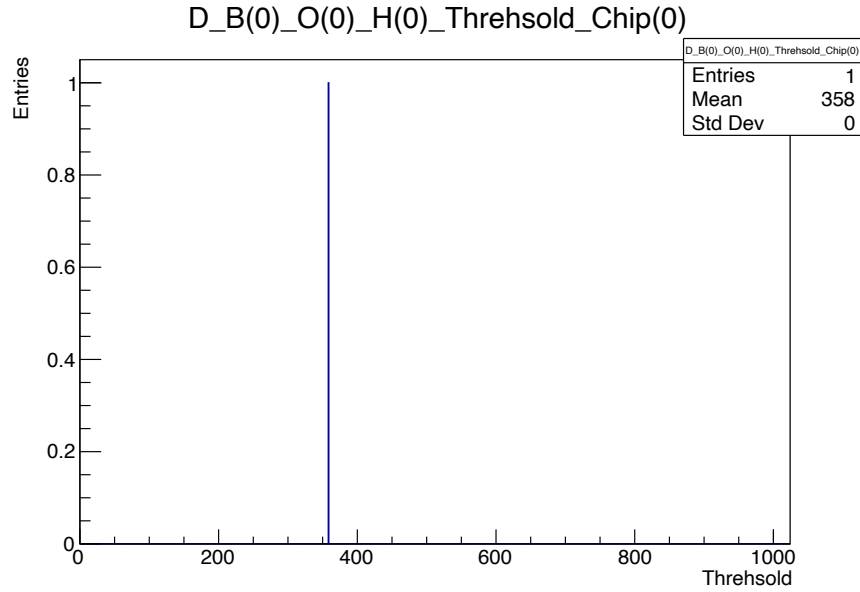


FIGURE 4.17: Threshold adjustment for 3D pixels giving the optimised value as $358 \Delta V_{cal}$

Finally, to study the minimum ionising signal of our beta source, we take long runs with circular collimators to focus the beam. The histograms includes:

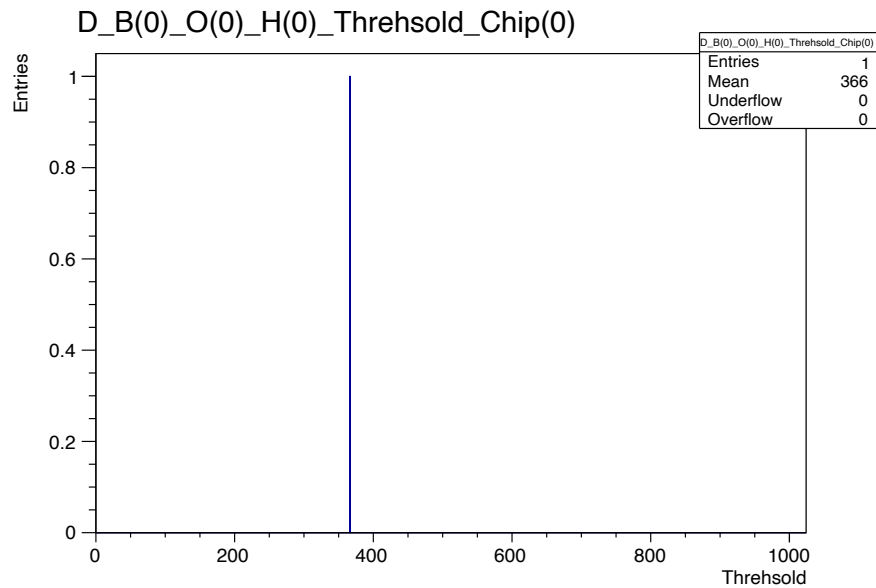


FIGURE 4.18: Threshold adjustment for Planar pixels giving the optimised value as $366 \Delta V_{cal}$

- Pixel alive distribution: showing the mapping of the source and number of hits. Typical distribution is shown in figure 4.19 collected for planar sensor.
- ToT distributions: Time over threshold is the measurement of the energy released by the MIP track incident on the silicon pixel sensor, which after calibration is proportional to the charge collected by the pixel. Two distributions in figure 4.20 are shown for the 3D and planar sensor.

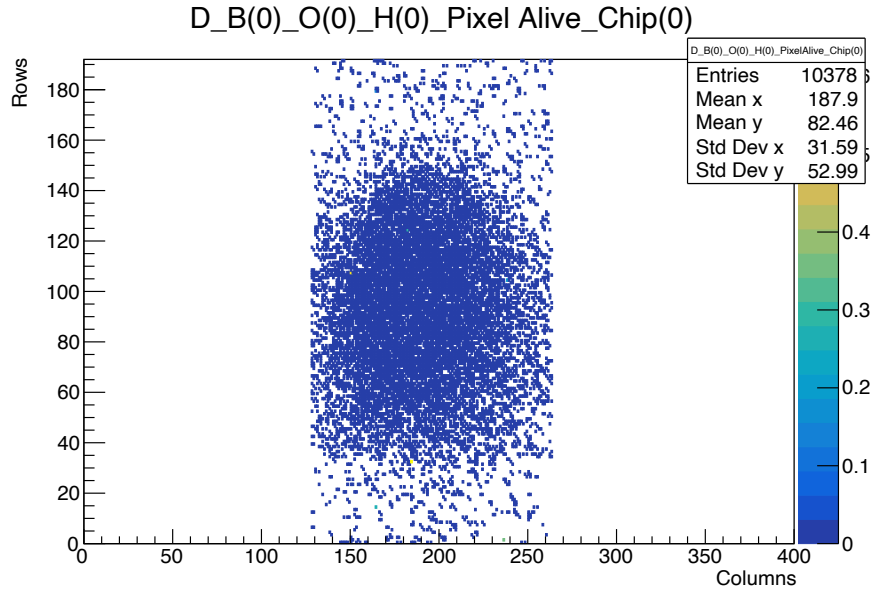


FIGURE 4.19: Pixel alive distribution showing the centred source (planar sensor)

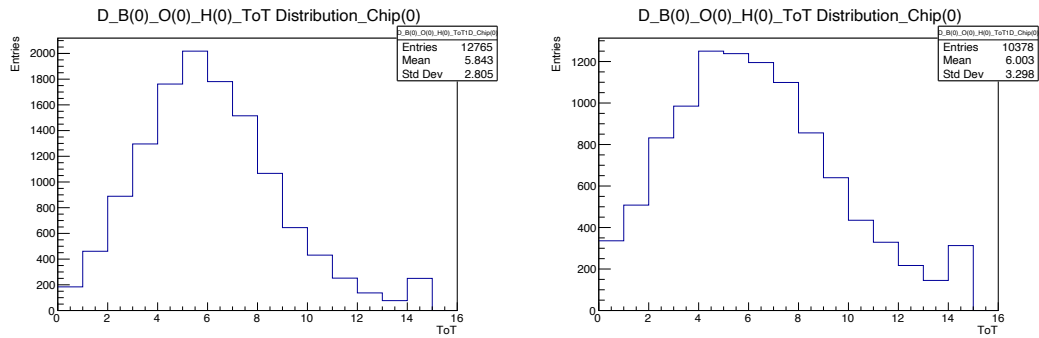


FIGURE 4.20: Tot distributions for 3D sensor (left) and planar (right) in ADC units

The ToT distribution is fitted with a Landau distribution convoluted with a Gaussian to obtain the Most probable value (MPV), as shown in figure 4.21. Figure 4.22 shows the voltage scan of ToT for 3D sensor in ToT units.

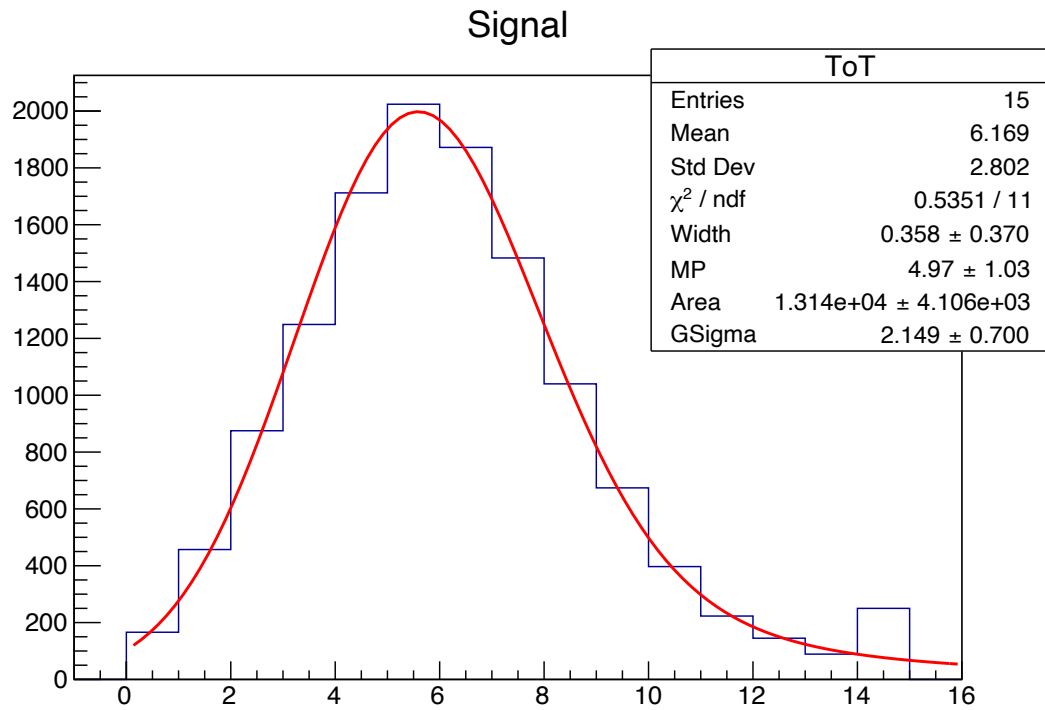


FIGURE 4.21: Fit for the Entries vs ToT distribution at 20V

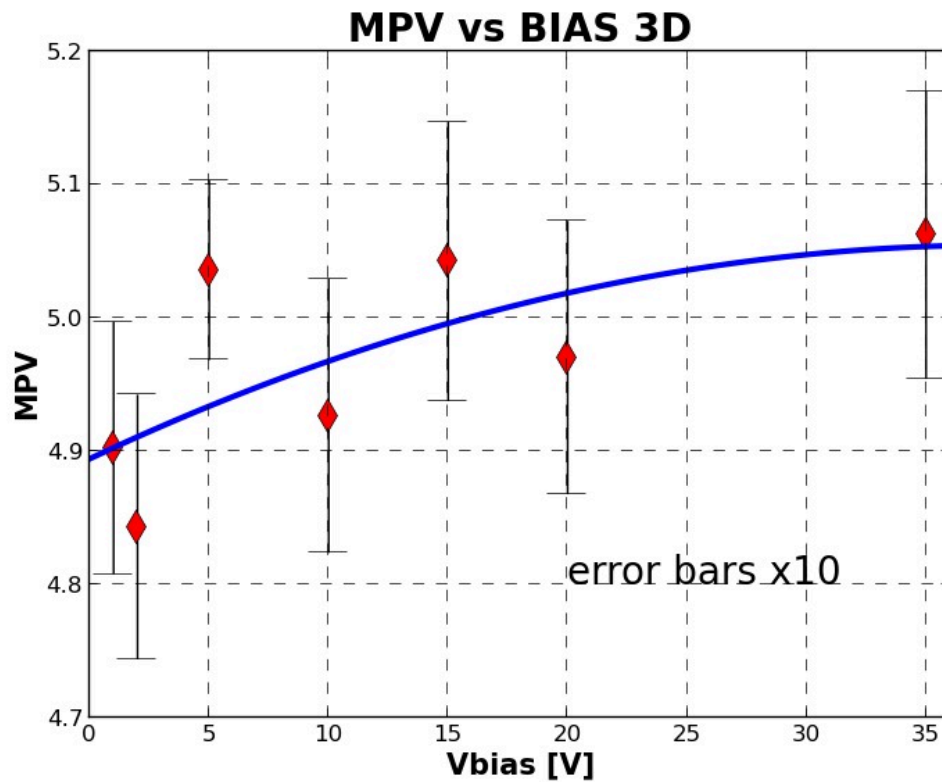


FIGURE 4.22: Distribution of the fit values (ADC) obtained at various bias voltages for 3D sensor

We also did a small study for validating the tuning procedure. The read out chip diagram, used for both 3D and planar sensors and its working principle is shown in figure 4.25.

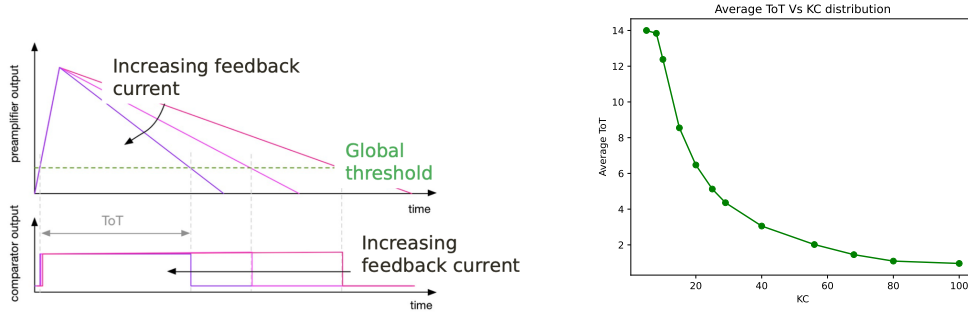


FIGURE 4.23: KC theoretical behaviour wrt time (left) and the observed behaviour (right)

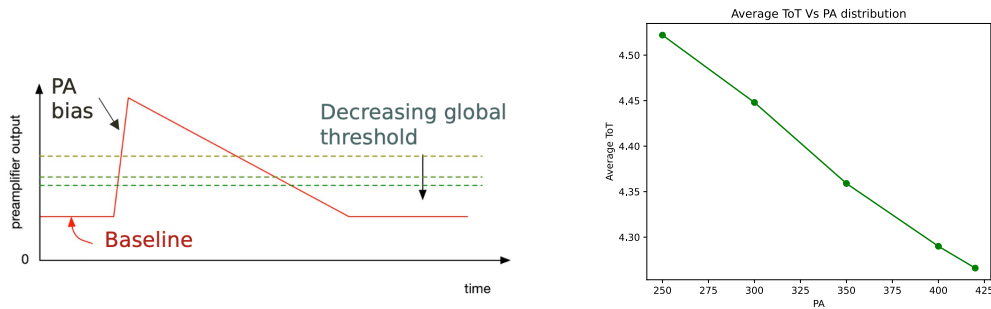


FIGURE 4.24: PA Bias voltage theoretical behaviour wrt time (left) and the observed behaviour (right)

The Krummenacher current measurement shown in figure 4.23 (right) and PA bias, shown in figure 4.24 (right) was done as a part of this tuning. Krummenacher current linearly discharges the preamplifier feedback capacitance. Increasing krummenacher current results in a faster preamplifier return to baseline and a reduced Time Over Threshold (ToT), as schematically shown in figure 4.23 left. PA bias sets the current in the preamplifier input branch. This current represents the main contribution to the Linear Analog Front End current consumption. This parameter can be slightly decreased to reduce power, at the cost of an increased noise, as schematically shown in figure 4.24 left. Analog front end parameters are defined as following:

- Global threshold: Sets the global threshold of the comparator
- Baseline voltage: Sets the preamplifier output DC baseline

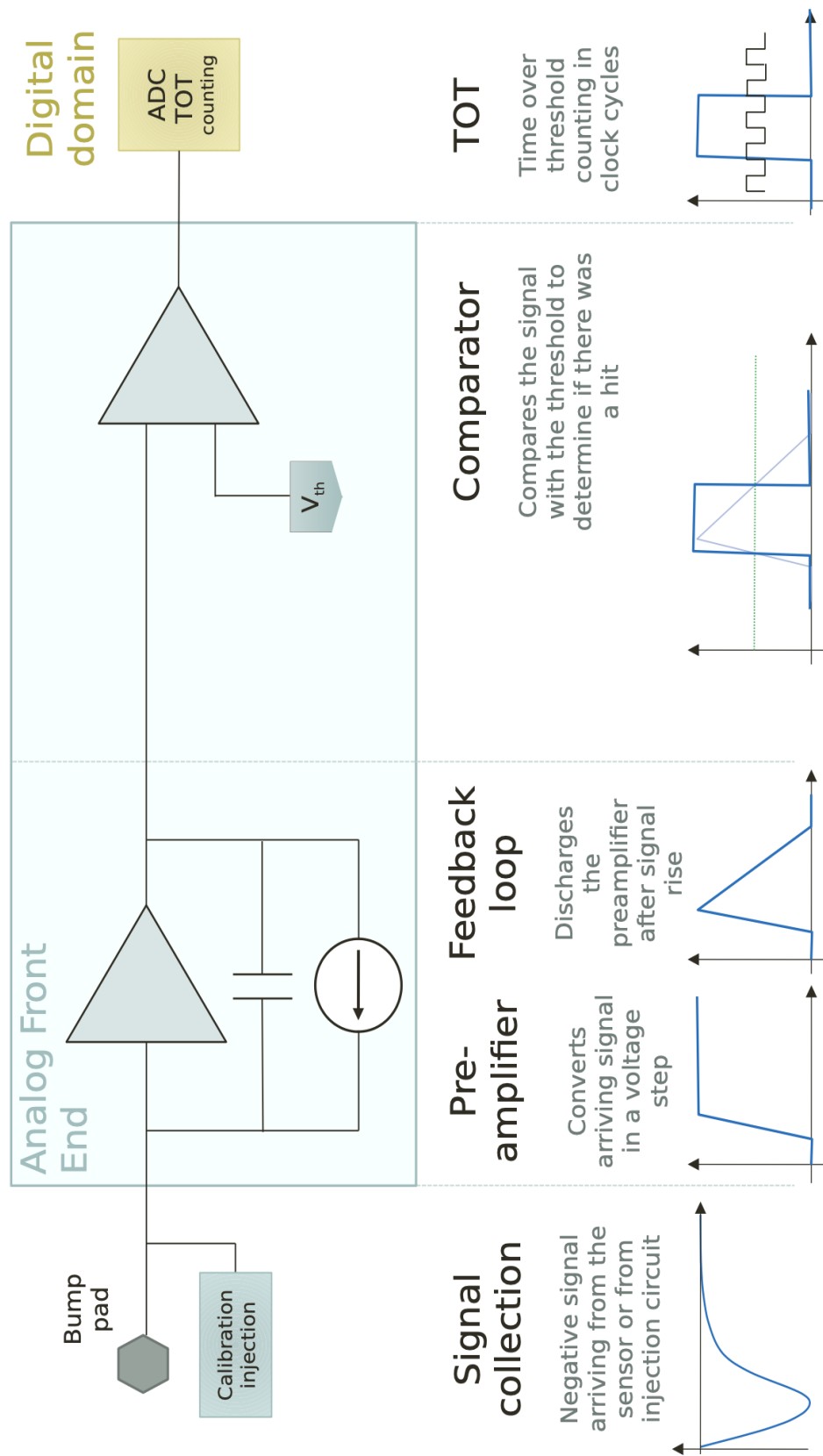


FIGURE 4.25: Sketch of the signal processing stages of the RD53A readout chip

- Preamplifier bias: Determines the speed of rise of the signal, main contribution to the power consumption, influence on the noise
- Feedback current: Determines the speed of the preamplifier return to baseline and therefore the time over threshold

4.3 Test beam experiment

The pixel detectors, with the first layer located at 30 mm from the beam line, have to be working with good charge collection efficiency up to a fluence which is estimated to reach $2.0 \times 10^{16} \text{ n}_{eq} \text{ cm}^{-2}$. To reach this goal a single pixel can have a size of either $50 \times 50 \mu\text{m}^2$ pixel size or $25 \times 100 \mu\text{m}^2$ pixel size (shown in figure 4.26) and the sensor has a small active thickness, presently fixed in CMS to $150 \mu\text{m}$. The option of 50×50 in CMS has been recently dropped for all layers in favor of the 25×100 given that it provides a better resolution along the 25μ pitch that will be used for the $r-\phi$ (orthogonal to beam line) co-ordinate. Currently, in the CMS tracker the options on final pixel type, should it be planar or 3D, are still open. Here we first discuss some details about both 3D and planar sensors, followed by the most recent results obtained with them.

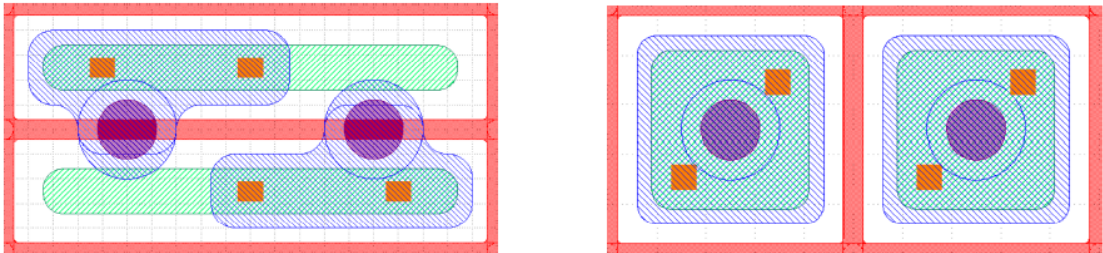


FIGURE 4.26: Two neighboring pixel cells for sensors drawn (view from above), with pixel size $25 \times 100 \mu\text{m}^2$ (left) and $50 \times 50 \mu\text{m}^2$ (right). Green represents the n^+ implants, blue represents the metal layers, red represents the p-stop sections, the contact in orange squares and the bump bond pads in purple.

4.3.1 FBK 3D and Planar sensors

The sensors in our R&D program are developed and fabricated in the framework of a collaboration activity between INFN and FBK ³ [53]. The sensors are designed and processed on special p-type 6-inch substrates Si-Si Direct Bond Wafers

³Fondazione Bruno Kessler, Trento

(DBW), which consists of a high resistivity (3-10 k Ω cm) Float Zone wafer (150 micron thick, used for the particle detection: active layer), glued by a specific melting process on a support wafer (handle wafer) made of 500 μ m thick ($\sim$ 1 Ohm cm resistivity), Czochralski (CZ) silicon, needed to simplify the processing of the thin FZ active layer.

Figure 4.27 on the left shows one image of the first stepper-processed ⁴ 3D wafer with many 3D sensors designed, and a planar wafer on the right. Both these wafers are produced by FBK and represent today the most advanced solutions for the phase 2 pixel sensors.

After a preliminary qualification, the wafers selected are submitted to a hybrid assembly process: the wafer carrier is partially removed by a grinding process and a bump bonding process is done after that, in order to assemble each sensor with a Read Out Chip (ROC) [54]. ⁵.

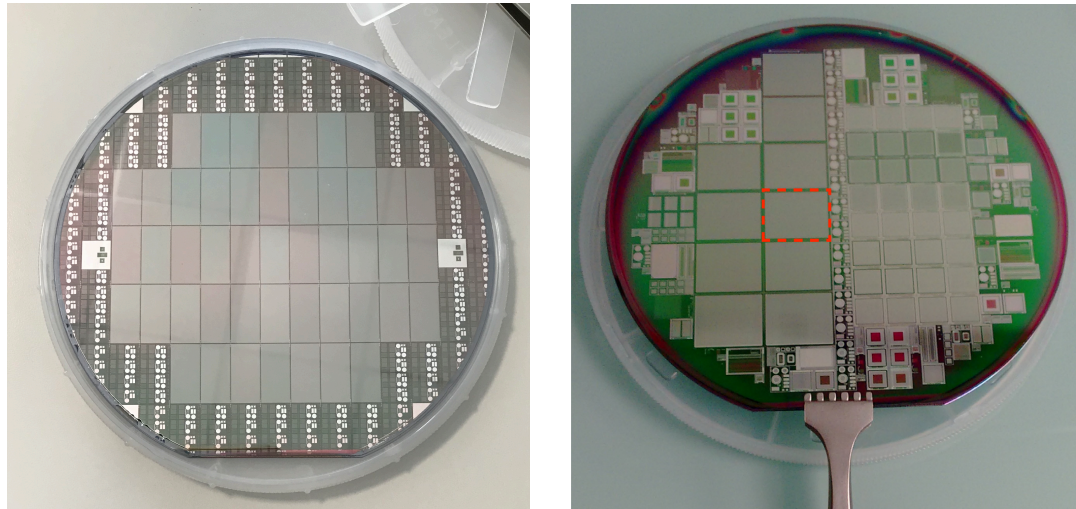


FIGURE 4.27: FBK stepper 3D wafer (left); Wafer from the n-on-p planar technology (right). Red rectangle encircles one pixel sensor.

For 3D (figure 4.28), the columnar electrodes are implanted on a Float Zone (FZ), high resistivity (>3000 Ohm cm), 130 μ m or 150 μ m thick wafer. The columns of both p^+ and n^+ types are etched by Deep Reactive Ion Etching (DRIE) in the FZ wafer using a top-side only process, before being doped. The Ohmic p^+ columns reach the low resistivity layer in the support wafer, where the reverse bias voltage is applied, while junction n^+ columns are optimised to have a length which is on

⁴Stepper is a specific processing technology that improves the precision of the standard lithographic (Mask aligner) steps in micro-electronics

⁵The bump bonding process is performed by Fraunhofer IZM, Berlin

average about $20\ \mu\text{m}$ shorter than the FZ wafer thickness. The column diameter is about $5\ \mu\text{m}$ for both types.

Metal bump pads for the ROC are connected to the junction columns via dedicated metal routing, which requires special attention in the case of rectangular pixel cell design because the RD53A readout chip (ROC) has a square $50 \times 50\ \mu\text{m}^2$ bump pad pitch. A temporary metal layer is used for current voltage (I-V) measurements (both in reverse and forward biasing) at FBK to identify defective sensors; the temporary metal is removed before shipping the wafer to the bump-bonding company. Figure 4.29 shows the doping profile for planar sensors.

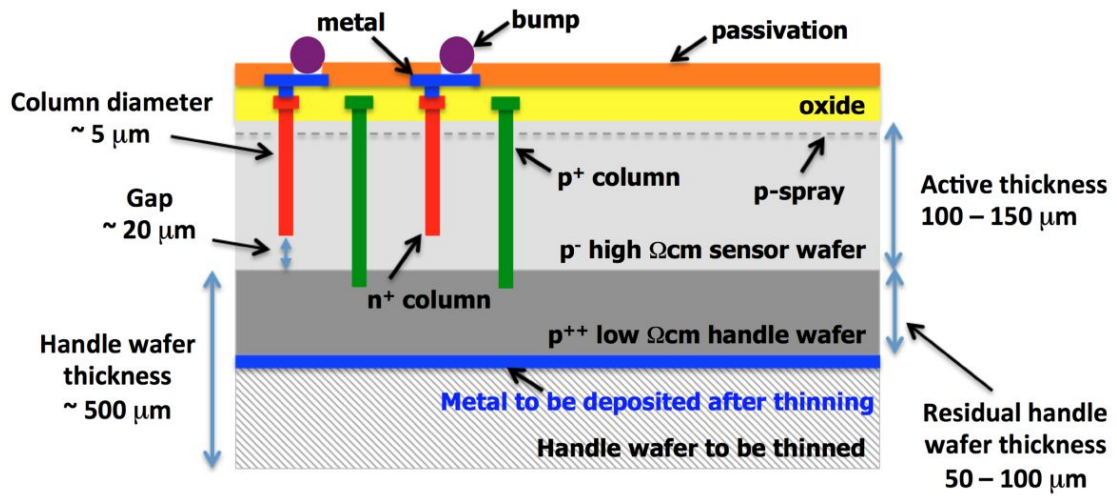


FIGURE 4.28: 3D sensor

In 3D columnar pixel sensors, the charge carriers released by an ionising particle traversing the sensitive volume, have to travel distances of at most $35\ \mu\text{m}$, for a $50 \times 50\ \mu\text{m}^2$ pixel cell (or $50\ \mu\text{m}$ for a $25 \times 100\ \mu\text{m}^2$) to reach the central collecting electrode, as compared to 100 - 150 μm in planar.

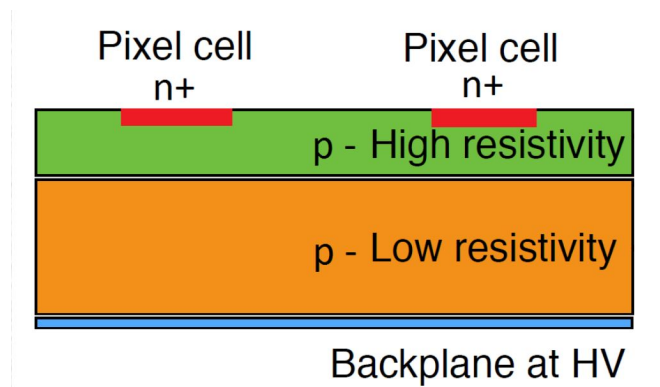


FIGURE 4.29: Planar pixel sensor

The inter-electrode distance also determines the bias voltage needed to fully deplete the active volume for a given silicon bulk resistivity. This distance is much shorter than the sensor thickness, which is the basic parameter determining the amount of released charge. In addition to that, after irradiation to the fluences foreseen for the HL-LHC, the radiation damage greatly reduces the effective drift distance of charge carriers because of charge trapping. In 3D pixels the above mentioned short inter-electrode distance and the lower operational bias voltage give an important advantage over the standard planar pixel sensors both before and after irradiation.

Advantages of 3D module over planar module can be summarised as:

- Smaller bias voltage needed to deplete the sensor
- Less trapping in irradiated sensors, due to shorter drift distance
- Same charge produced as planar
- Promising candidates for the high radiation environment of the inner layers and rings

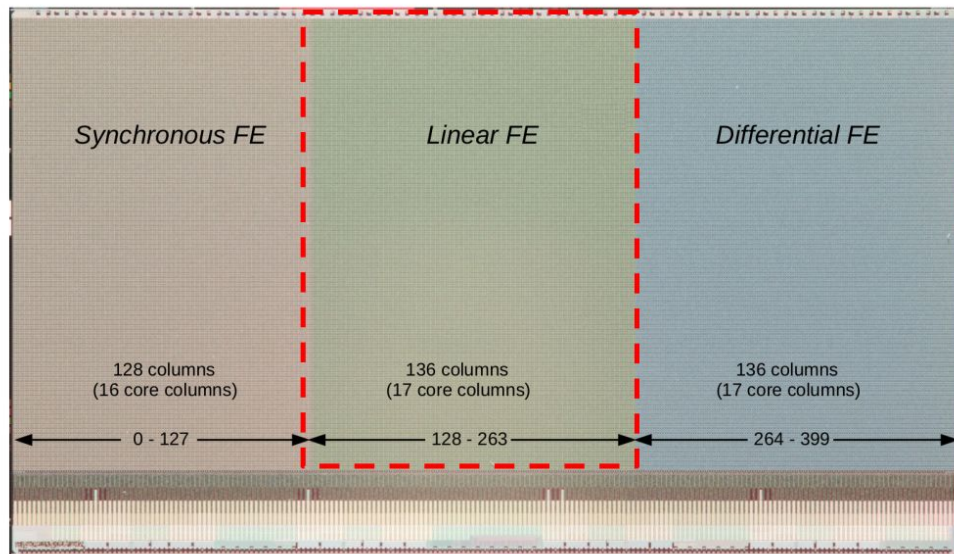


FIGURE 4.30: Analog front end regions of RD53A

Read out chip RD53 is radiation hard to about 5MGy and has low thresholds and noise. RD53A prototype is used for R&D purposes. It has three analog front-ends: Synchronous, Linear and Differential, which are compatible with both planar and

3D sensors. CMS chose the Linear front-end for the final experiment. All results presented in this study are obtained with the Linear front-end of RD53A, which is located in the central region of the ROC and is 136 columns wide (6.8 mm), from column 128 to 263 (as shown in figure 4.30).

4.3.2 Beam test at DESY

I participated in the testing of the pixel modules at the DESY (Deutsches Elektronen Synchrotron) test beam Facility at Hamburg. DESY has a cycling electron synchrotron of 300 m circumference with electron beam energy in the range 0.45-6.3 GeV. The synchrotron provides electron bunches of 1.6 nC ($10^{10}e$) charge every 80 ns. The electron beam hitting an internal carbon target produces gamma rays. These rays in turn produce e^+e^- pairs after passing through the external Cu conversion target. A dipole and collimators are used to direct the electron beam in the testbeam area with rate of $\sim 20\text{kHz}/\text{cm}^2$ at 4 GeV and $0.5\text{ kHz}/\text{cm}^2$ at 6 GeV. Figure 4.31 shows the full chain of events.

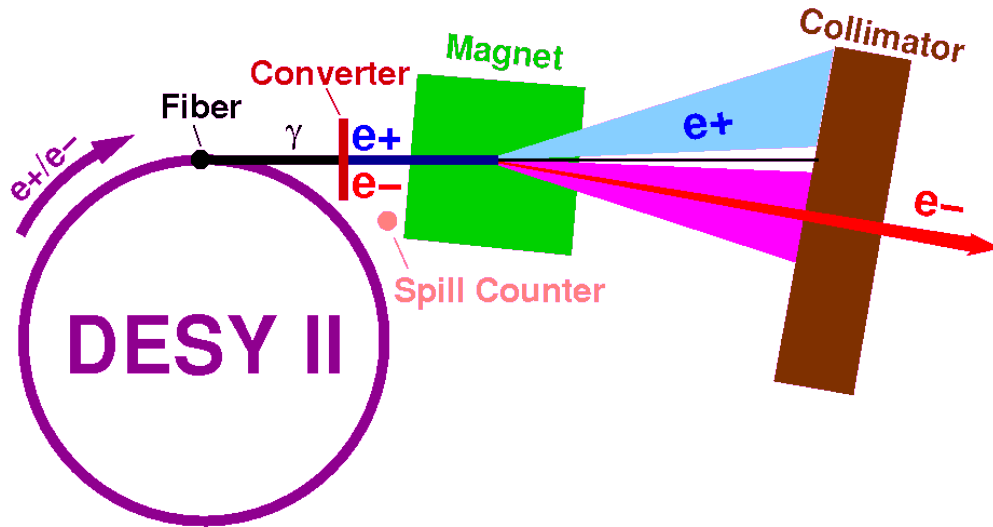


FIGURE 4.31: DESY testbeam facility

The TB21 area of DESY was assigned for testing the modules, by selecting an electron (and positron) beam of 5.2 GeV momentum. The test beam area is equipped with a EUDET beam telescope which allows tracking the beam particles. The telescope is composed of two arms, each of them made up of three planes of MIMOSA 26 monolithic active pixel silicon sensors. Each MIMOSA 26 sensor consists of pixels sized $18.4\mu\text{m} \times 18.4\mu\text{m}$, which are arranged in 1152 columns and 576 rows. This adds up to a total of about six hundred thousand readout channels

per sensor, covering an active area of about $10.6 \text{ mm} \times 21.1 \text{ mm}$. The MIMOSA 26 sensors are $50 \mu\text{m}$ thick [55].

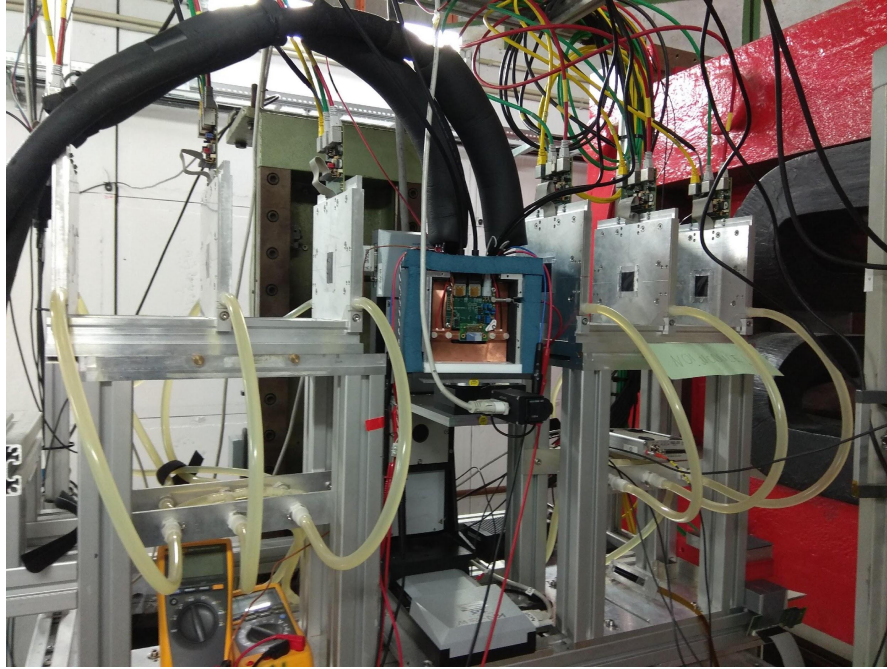


FIGURE 4.32: Eudet telescope in TB21 testbeam area

The Device Under Test (DUT) is placed between the two arms, called upstream and downstream with respect to the beam direction (shown in blue colour box in the figure 4.32). Two scintillators, whose coincidence signals are used to trigger the DAQ sequence, are placed in front of the first telescope plane, giving a geometrical window of approximately $10 \text{ mm} \times 10 \text{ mm}$ centred on the electron beam. In order to have a fast timing reference to correctly reconstruct tracks in the telescope and in the DUT, a pixel module of the type presently in use in the CMS Tracker is placed upstream in front of the first scintillator (figure 4.33). It has $100 \times 150 \mu\text{m}$ pixels with $285 \mu\text{m}$ thickness and mounted with a 27° tilt and 19° turn for best position resolution.

The irradiated module was installed inside a cooling box, keeping the sensor at a low and constant temperature in order to reduce the HV bias current. The cooling box is made of aluminium, thermally insulated, with a cut-out entry window for the incoming electron beam. Inside the box, the downstream face of the DUT was in contact, through a thermally conductive paste, with a thin copper bar, which was kept cold (temperature about -27°C) by two Peltier cells, cooled by an external chiller. The irradiated tested module, mounted in the cooling box, is shown in figure 4.34.

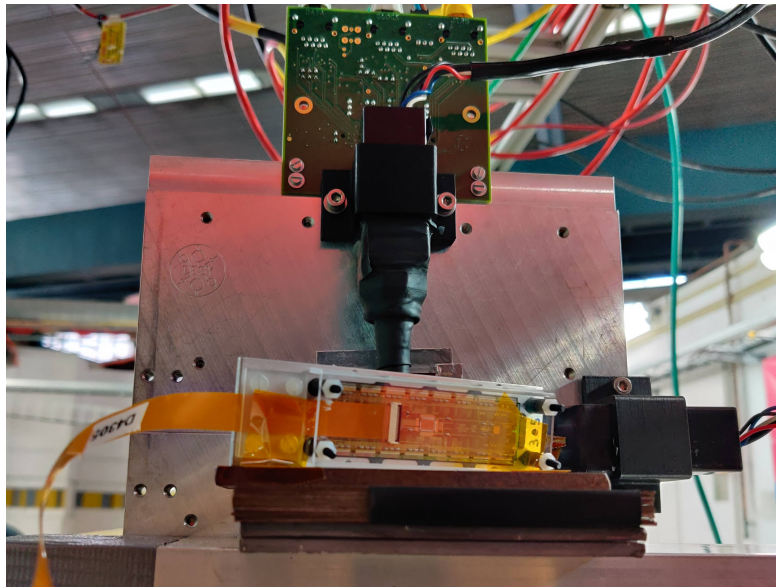


FIGURE 4.33: Phase-I pixel module used as reference and two scintillators for trigger purpose

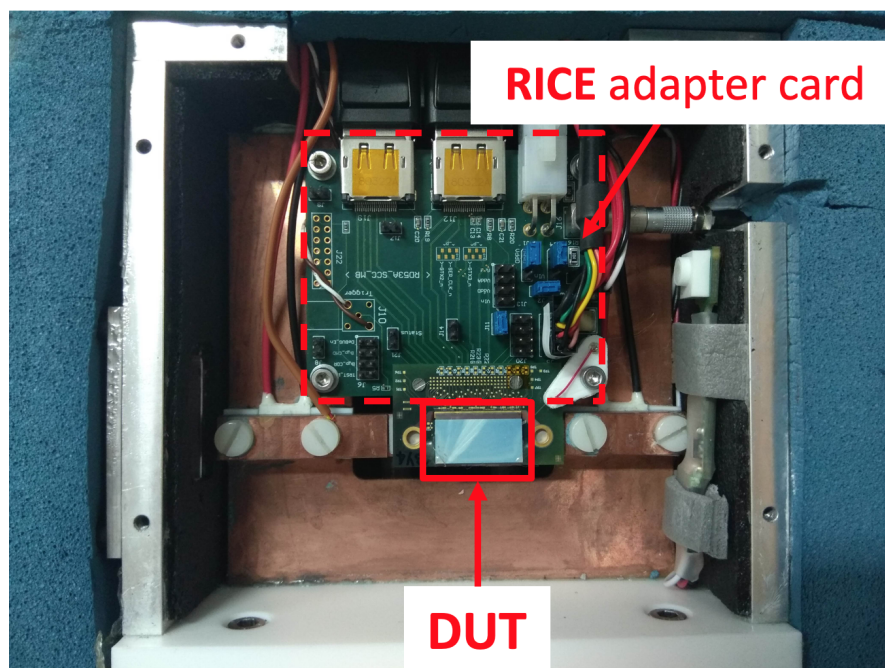


FIGURE 4.34: The irradiated $50 \times 50 \mu\text{m}^2$ module connected to the Rice adapter card and mounted inside the cooling box.

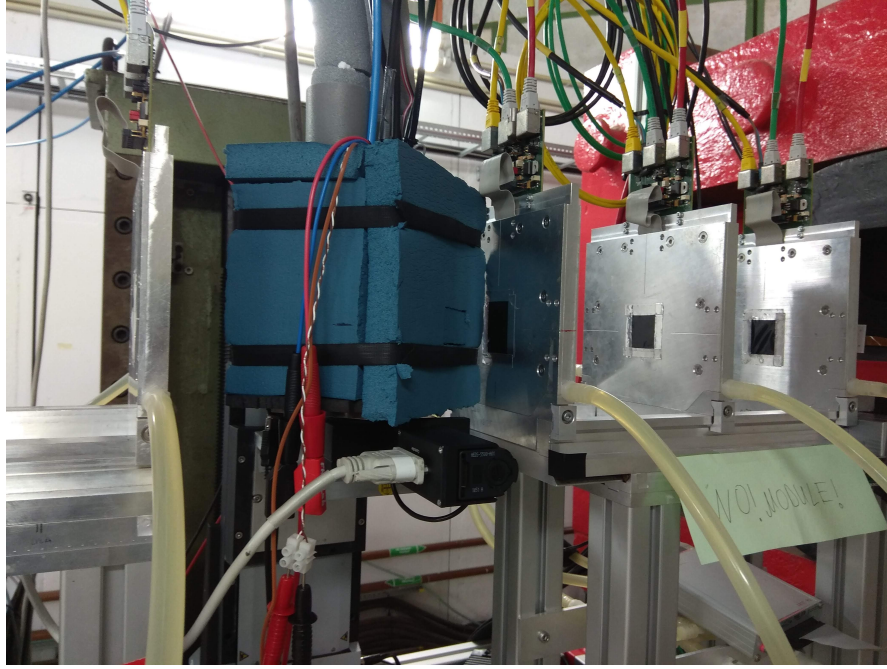


FIGURE 4.35: The cooling box on the beam line housing the irradiated module during an angular scan data taking.

The non-irradiated modules were tested in free air, as due to low leakage current no cooling was needed. The cold box can have some impact on the final achievable track resolution, because of the multiple scattering of the electron beam in the insulating material in front of the module and the metal structure downstream. Thus we chose to take data without the box whenever possible. All the DUTs were mounted on a movable precision stage which also allowed them to turn with respect to the beam axis and take data at different beam incidence angles. The two configurations for a DUT with and without the cooling box in the beam are shown in figures 4.35 and 4.36.

The sensor has to be studied before and after irradiation, to understand its performance in a high radiation environment. Thus beam tests are performed before and after irradiation and results are compared. I have attended two such beam tests at DESY, Hamburg. First one was to study the material interaction in August 2019 and the second in November 2019 with the detector detailed here. The last one was attended recently in September 2021 at the SPS centre at CERN. Studies of the last one are currently ongoing and results not included here.

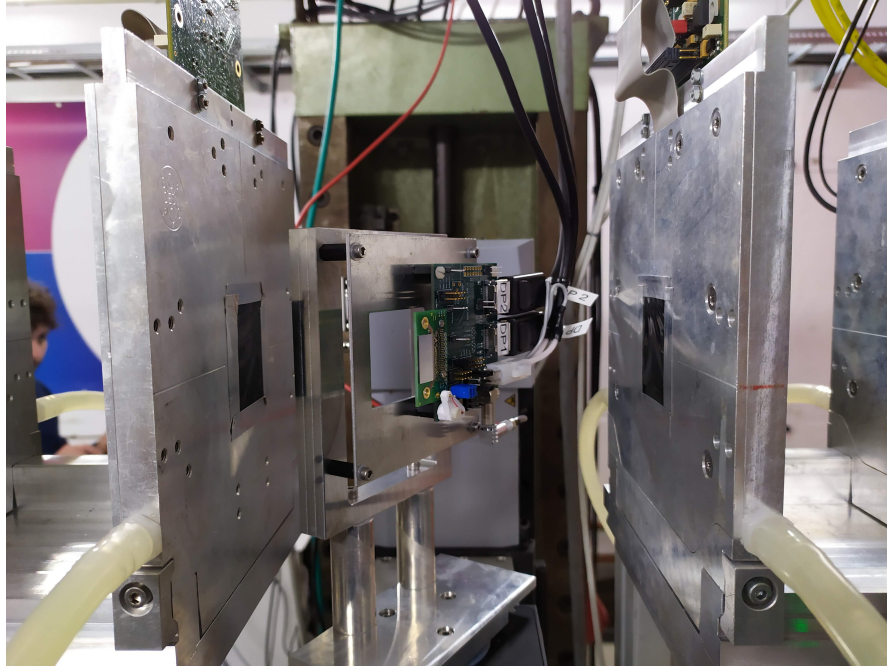


FIGURE 4.36: The $25 \times 100\mu\text{m}^2$ module mounted on the beam line for the angular scan along the 25mm pitch coordinate

4.3.3 3D pixel sensors

Prototypes of 3D sensors are interconnected with the RD53A readout chip, which is the first prototype of 65 nm CMOS pixel readout chip designed for the HL-LHC pixel trackers. The results reported here come from four single-chip assemblies, also called “modules” in the following. They originate from two different FBK production batches: first $25 \times 100\mu\text{m}^2$ and $50 \times 50\mu\text{m}^2$ sensors were made in 2017 with a Mask Aligner batch (MA), second $50 \times 50\mu\text{m}^2$ was made in 2019 with a Stepper batch (ST). Mask Aligner and Stepper (Step-and-repeat exposure) are two different photolithographic technologies used in silicon foundries; the Stepper has a higher, sub- μm , precision but it is less flexible with respect to Mask Aligner. In case it is needed to have different cell and sensor designs on the same wafer layout, they can be then patterned in one go, on the full wafer by the Mask Aligner.

The active thickness of the MA sensors is $130\mu\text{m}$, while for the ST sensor it is $150\mu\text{m}$. The depletion voltage is lower than 5V for all these 3D sensors. The MA sensors were bump-bonded (with Sn-Ag bumps) to the ROC at Fraunhofer-Institut IZM (Berlin, Germany); the ST sensor was bump-bonded (with Indium bumps) at Leonardo Company (Rome, Italy). The flip-chip assemblies were glued on a printed circuit board specifically designed for test beams and proton irradiations,

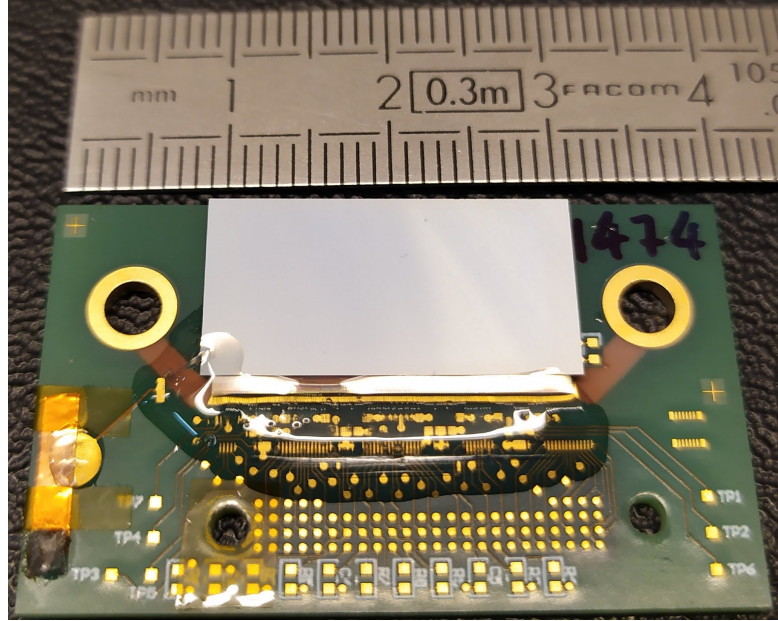


FIGURE 4.37: Sensor and RD53A assembly (flip-chip) glued and wire-bonded onto a Rice irradiation card. Wire bonds are encapsulated with silicone elastomer for protection. The light-gray upper surface is the metalised sensor back-side, where HV bias wire-bonds are connected in the lower left corner

called the Rice card (designed by the CMS group of Rice University, Houston, TX), and then wire-bonded in the INFN Firenze laboratory. The Rice card, shown in figure 4.37, is a very lightweight PCB; the region below the flip-chip is free from material to avoid multiple scattering on the test beam and to minimise the activation under irradiation. Wire bonds are encapsulated with silicon elastomer for protection. The light-grey upper surface is the metalised sensor back-side, where HV bias wire-bonds are connected in the lower left corner. The card is connected to an adapter card in order to allow readout by the DAQ system both in the lab or at the test beam. One of the 3D $50 \times 50 \mu\text{m}^2$ MA modules was irradiated at the CERN IRRAD facility in 2018 in a high intensity 24 GeV proton beam to an estimated fluence of $1 \times 10^{16} \text{n}_{eq} / \text{cm}^2$. This fluence in the IRRAD beam corresponds to a TID (Total Ionising Dose) of about 6 MGy: this is the dose that has to be taken into account for the radiation damage of RD53A readout chip. The IRRAD proton beam has a FWHM of 12 mm in X and Y directions. The module was mounted with a turn angle of 55° with respect to the beam direction to achieve a more uniform irradiation.

4.3.3.1 Non-irradiated Sensor

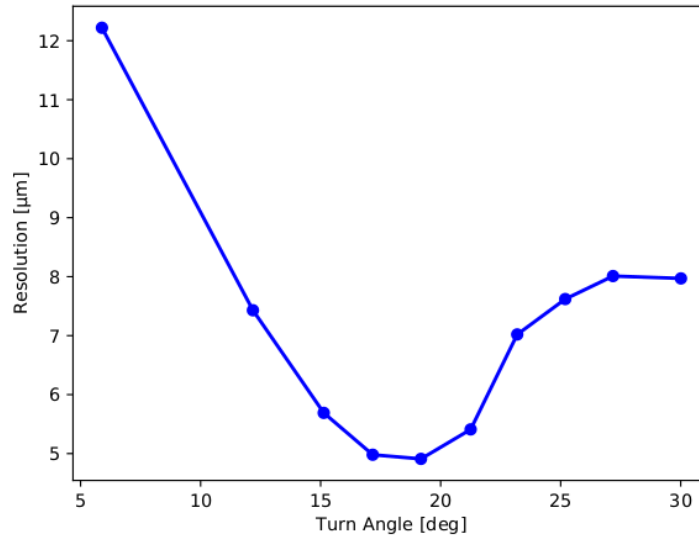
The non-irradiated modules were tuned to about 900 e^- threshold and then tested at two bias voltages: 6 V (which was the minimum stable voltage value provided by the power supply) and 30 V. All modules had hit efficiencies greater than 99% for orthogonally incident tracks, already at very low bias voltage. The measured bias currents are reported in figure 4.38.

3D Type and Cell Size	Voltage [V]	Current [nA]	Efficiency
MA 50x50	6	150	>99%
MA 50x50	30	250	>99%
MA 25x100	6	130	>99%
MA 25x100	30	190	>99%
ST 50x50	6	6500	>99%
ST 50x50	30	16500	>99%

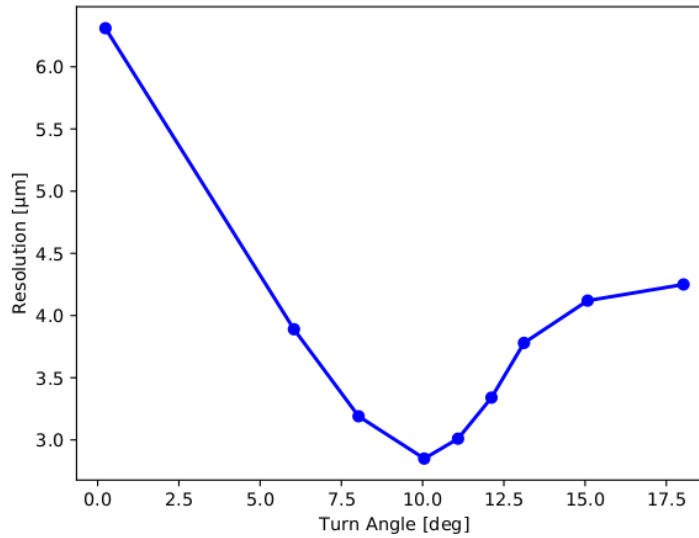
FIGURE 4.38: 3D modules bias voltages, currents and efficiencies. The sensor temperature was around 45°C .

The stepper module had a bias current much higher than the one measured on sensor wafer (before dicing and flip-chipping). However even with the higher bias current the module was working even in overnight runs of over 25 M collected triggers. The reason for taking data with high statistics and high bias voltage was that we also wanted to prove that 3D sensors can be safely operated with a large margin with respect to the depletion voltage. This could eventually be needed because the upgraded CMS pixel detector will be powered in a serial powering scheme with up to eight modules in the serial chain.

An effect of the serial powering, together with a common HV bias line, is that the HV bias voltage drop between the last and the first module in the chain will be 2 V (maximum) per module times the number of modules in the same HV chain. We showed that the 3D modules can be operated at 30 V bias with a 1.5 safety factor with respect to the maximum foreseen bias voltage difference of 16 V bias between modules in the same chain. In order to evaluate the spatial resolution of the 3D modules, we took data at different turn angles up to 30° with respect to the beam, using the rotating precision stage. Particularly interesting was measuring the $25 \times 100\mu\text{m}^2$ pitch module resolution along the $25\mu\text{m}$ pitch coordinate, a measurement not yet done, to our knowledge, on 3D pixel sensors.

FIGURE 4.39: Resolution vs. turn angle for the $50\mu\text{m} \times 50\mu\text{m}$ sensor

The spatial resolution Res_{DUT} is estimated by the σ obtained fitting the Student's t-distribution of the track residuals on the DUT after subtracting the telescope resolution Res_{tele} in quadrature. Res_{tele} goes from 3.8 to $6.2\mu\text{m}$ depending on the telescope configuration. The angular scans were made at 30 V bias for the two MA modules, and the results are plotted in figures 4.39 and 4.40. There was not enough beam time to make the angular scan on the ST $150\mu\text{m}$ thick sensor.

FIGURE 4.40: Resolution vs. turn angle for the $25 \times 100\mu\text{m}^2$ along the $25\mu\text{m}$ pitch coordinate

No selection on the hit cluster size of the DUT was applied to obtain these distributions. The minimum in the resolution plot is reached for the angle at which a track is crossing two adjacent pixels. This angle is given by $\tan^{-1}$ (pitch/active thickness), which for a thickness of $130\mu\text{m}$ results in 21° for $50\mu\text{m}$ pitch, and 11° for $25\mu\text{m}$ pitch; these angles are compatible with the ones where the resolution distributions have a minimum. The best resolutions obtained are $5\mu\text{m}$ for $50\mu\text{m}$ pitch and slightly better than $3\mu\text{m}$ for $25\mu\text{m}$ pitch.

Studies with non-irradiated sensors give us some knowledge, which is helpful for the irradiated sensors, like the basic design choices etc.

4.3.3.2 Irradiated Sensor

In order to take good quality data, the $3\text{D } 50 \times 50\mu\text{m}^2$ irradiated module was tuned in the cooling box, at low temperature, to a threshold of about 1150 e^- . We performed a bias voltage scan, and the hit efficiency was measured at each point. The maximum effective bias voltage, subtracting the drop on the HV limiting series resistors, was 146 V with a bias current of $120\mu\text{A}$ at -27°C .

Figure 4.41 (left) shows a 3D pixel cell with p^+ columns in red and n^+ columns in blue colour. The beam is incident orthogonally on the module and figure 4.41 (right) shows the efficiency map of 2×2 pixel grid (overlap of full module) with a drop of efficiency near p^+ columns at high voltage (146 V).

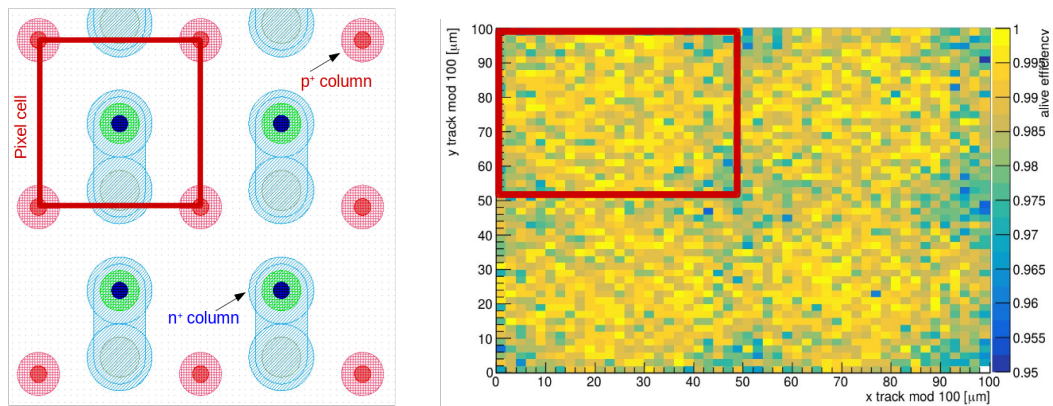


FIGURE 4.41: 3D Module Pixel cell(on the left) and Efficiency maps for 2×2 pixel grid at 146 V (on the right)

The hit efficiency curve is shown in figure 4.42. The hit efficiency reaches a "plateau" around 110 V , and has a maximum value of 98.8% at 146 V . The power

dissipation of the sensor is below 9 mW/cm^2 .

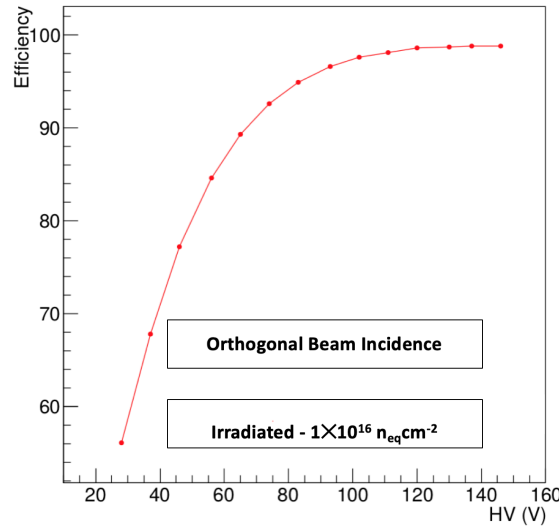


FIGURE 4.42: Hit efficiency vs. bias voltage for the irradiated 3D $50 \times 50 \mu\text{m}^2$ module

Since we were aware that the fluence received by the module in IRRAD was not very homogenous, we performed some cross checks to verify the impact of non-uniformity on the module efficiency. The non-uniformity of the irradiation on the module can be seen by measuring the hit efficiency at a bias voltage which is suitable for having almost full efficiency where the received fluence is lower, but which is not enough to get high efficiency in the most irradiated region. The high fluence region is highlighted with a dotted oval in the module efficiency map obtained for 28 V bias reported in figure 4.43.

In the data analysis the DUT was then subdivided in six smaller zones, and the hit efficiency recalculated in each region. The results are compatible with the full DUT hit efficiency of 98.8% for bias voltage above 120 V. As an example, the hit efficiencies in the two most irradiated regions are shown in figure 4.44. As in the case of non-irradiated modules, we made an angular scan to estimate the pixel resolution as a function of the turn angle. During the scan we verified that a track angle of 6° is already sufficient to get a hit efficiency greater than 99%.

To estimate the spatial resolution we applied a slightly different fitting procedure because the presence of the material introduced on the beam line by the cooling box made it almost impossible to use the extrapolated exit point on the DUT from the three downstream telescope planes. The telescope resolution was extrapolated

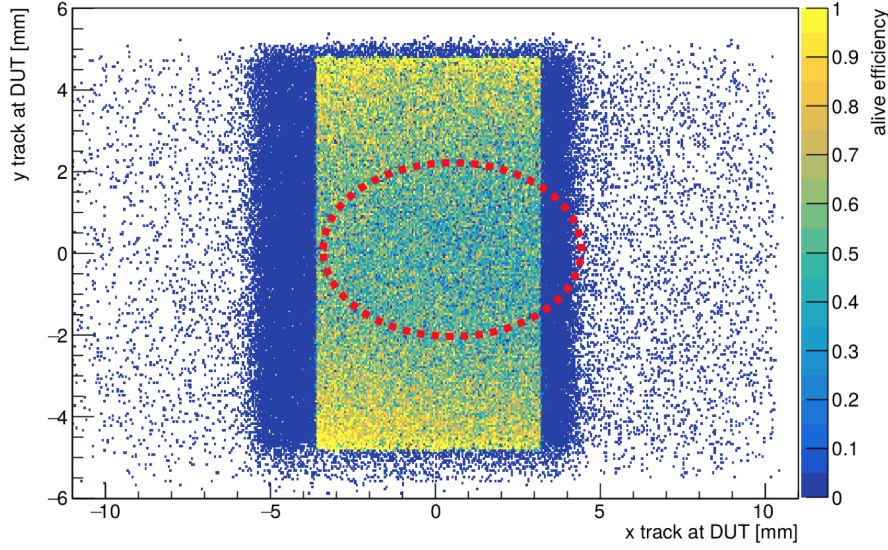


FIGURE 4.43: Hit efficiency map for the irradiated 3D $50 \times 50 \mu\text{m}^2$ module at 28 V bias. The higher fluence (lower efficiency) is indicated with the dotted oval

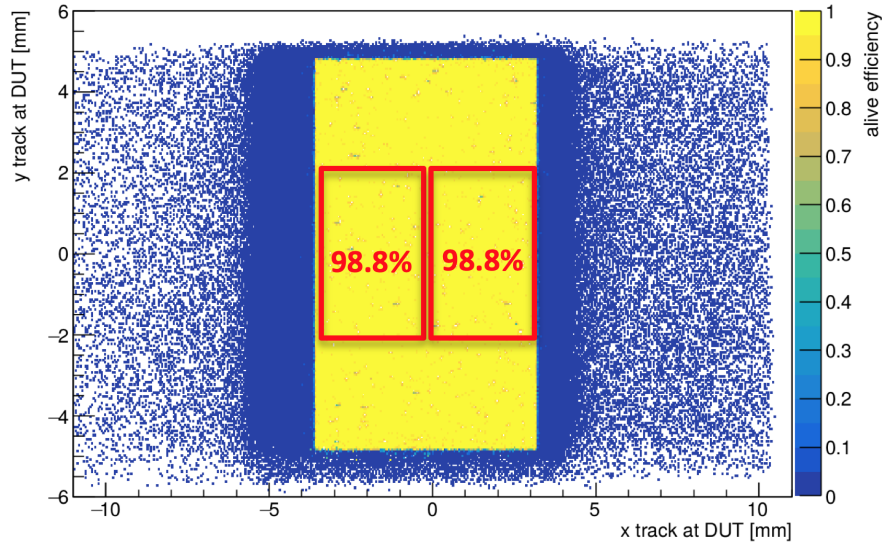


FIGURE 4.44: Hit efficiency map in the two most irradiated regions of the 3D module at 146 V bias

using the not-rotated DUT coordinate and then the final DUT resolution was obtained as in the case of non-irradiated modules. The spatial resolution as a function of the angle is reported in figure 4.45. The best resolution for the $50 \mu\text{m} \times 50 \mu\text{m}$ irradiated module is about $5.7 \mu\text{m}$, obtained at $\approx 20^\circ$.

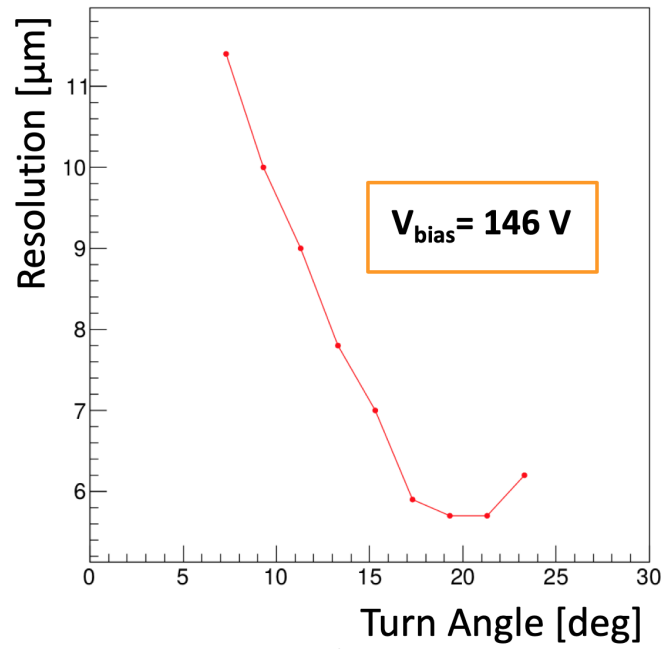


FIGURE 4.45: Resolution vs. turn angle for the irradiated 3D $50 \times 50 \mu\text{m}^2$ module

4.3.4 Planar Sensor (non-irradiated)

Two non irradiated planar sensors are tested: w₆₀₆₇-BFTP and w₆₀₆₇-BITE. Both sensors are extracted from the same wafer W6067. The layout process consists of a FZ high resistivity wafer, with the active thickness of $150 \mu\text{m}$, bonded (by a surface melting process) on top of a Cz carrier wafer (about $500 \mu\text{m}$ thick). The wafers are produced by the Icmos industry and the sensors are assembled by the bump bonding process at IZM to the RD53A chip.

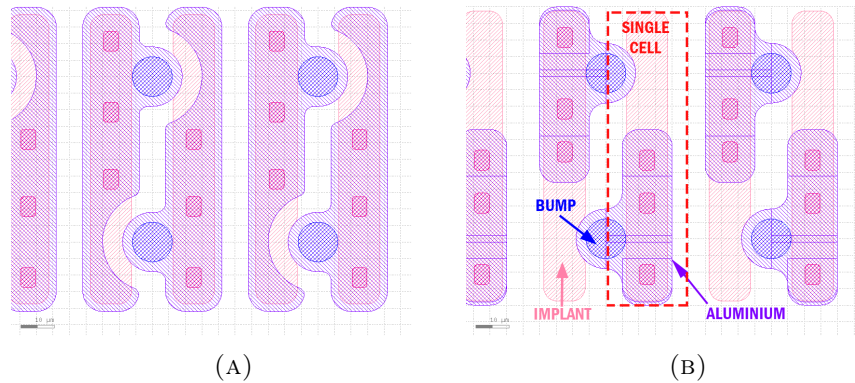


FIGURE 4.46: Pixel cell layout of $25 \times 100 \mu\text{m}^2$ for (A) w₆₀₆₇-BFTP and (B) w₆₀₆₇-BITE

Figure 4.46a and 4.46b shows the CAD layout of both devices having $25 \times 100 \mu\text{m}^2$ pixel cell dimension. The basic visible difference between both the devices is the metal layer covering the implant.

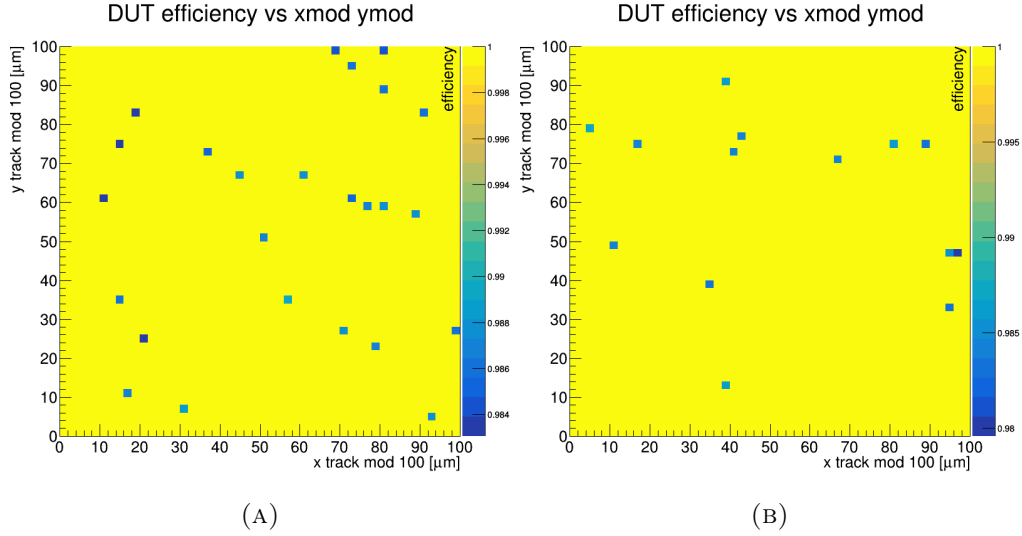


FIGURE 4.47: Hit efficiency for (A) BITE and (B) BFTP at 80V

In BFTP sensor, the metal covers almost completely the junction implant (n^+) and metal overhang in almost the full perimeter, improving high voltage performance. In the BITE sensor, the metal coverage as well as overhang are minimised, supposedly improving charge collection.

Both modules are analysed with orthogonal incidence at bias voltage 80 V and have a hit efficiency of $> 99.9\%$ as shown in figure 4.47a and 4.47b.

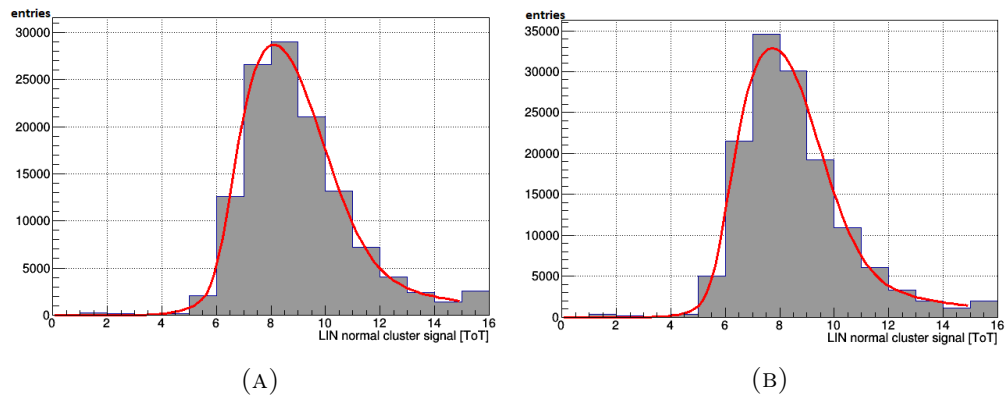


FIGURE 4.48: Distribution of the charge collected for the (A) BITE and (B) BFTP at $V_{bias}=10V$

Figure 4.48a and 4.48b shows the charge distributions of the two sensors obtained by considering an associated cluster of 1-pixel size on the DUT. The red line is

a Landau convoluted with a Gaussian fit function, which accounts for electronic noise as well as other dispersive effects such as calibration errors.

A voltage scan is performed from 10 to 100V, to observe the average hit efficiency at each value. The efficiency for both the devices are comparable with value being around 99.99% and no visible differences, as shown in figure 4.49a and 4.49b.

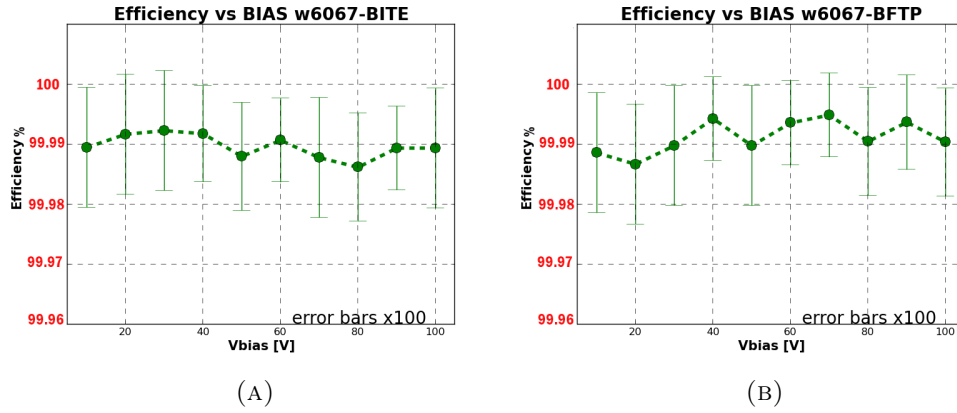


FIGURE 4.49: Average efficiency Vs Bias voltage for (A) BITE and (B) BFTP

Finally, angular scans are made for both the modules at bias voltage 70 V and results are plotted in figure 4.50 and 4.51. The curves have a minimum at an angle of incidence equal to 8 degrees.

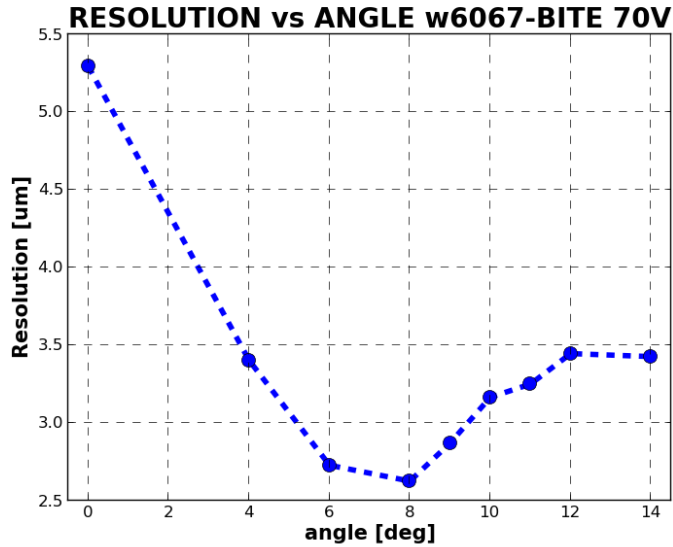


FIGURE 4.50: Resolution vs turn angle for $25 \times 100 \mu\text{m}^2$ BITE sensor with $25 \mu\text{m}$ pitch coordinate

The trace of charges released by the Minimum Ionising Particle (MIP) at this angle of incidence, generates a charge sharing between at least 2 pixels; which improves

the spatial resolution. For larger angles the charge is shared by more pixels but the resulting signals are below the threshold.

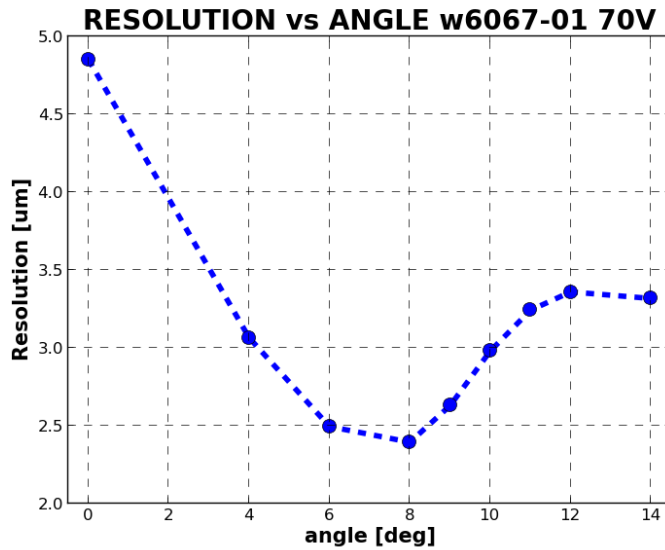


FIGURE 4.51: Resolution vs turn angle for $25 \times 100 \mu\text{m}^2$ BFTP sensor with $25 \mu\text{m}$ pitch coordinate

All the studies presented above and the results shown, point towards advantages of 3D over planar. But this is just a set of preliminary tests with the current RD53A chip in the latest beam tests and not the detailed description of all the possibilities with full R&D. Both layouts are under consideration. In future, results with final configuration CROC shall be crucial.

4.4 TCAD (Technology Computer-Aided Design) Simulations

The harsh radiation environment of the HL-LHC will severely affect the performance of silicon detectors. Device modelling is, therefore, necessary for:

- the optimization of sensors design,
- to address and set up design rules and process details,
- the detailed understanding of the silicon detector's performance,
- to evaluate, and feedback further optimization, the radiation tolerance.

All the previous steps can be performed in the simulation. This will optimise the production, limiting R&D costs by focusing on pre-validated sensor designs.

The behaviour of p-n junction before and after irradiation is studied. The effect of irradiation is included by implementing a trap model in the simulation package. A systematic study of the sensitivity of various macroscopic parameters of silicon detectors to the trap models adopted is performed. The simulation results for the leakage current (I_{leak}) and the full depletion voltage (V_{depl}), are discussed.

4.4.1 Simulation Framework

In order to study the effect of radiation damage exclusively on the silicon bulk, the simulation is implemented and processed on a high resistivity float zone silicon material. Two different geometries are simulated:

- Simple pad diode; we compare silicon device simulations performed using two TCAD simulation software: Silvaco Atlas [56] and Synopsys Sentaurus [57].
- Planar Pixel; current work includes only Synopsys Sentaurus TCAD. It is a commercial simulation package offered by Synopsys [57].

The purpose of these packages is to simulate the semiconductor detector technology for various applications, not necessarily for silicon sensors in high energy physics. There are plenty of options available for silicon devices designing and many models to simulate silicon sensors under operation conditions. This includes a basic analysis of the leakage current, an AC small signal analysis and a transient analysis for the time evolution of the signals. Changes in the parameters of certain models are made to describe silicon sensors.

The working principle of the simulated silicon sensor, which is just a semiconductor with p-n junction operated in reverse bias, is depicted through figure 4.52.

The sensor is free of charge in the depleted zone, because the depletion zone created by the applied voltage can be extended through out the whole sensor due to its high resistivity. When a charged particle traverses the sensor, electron-hole pairs

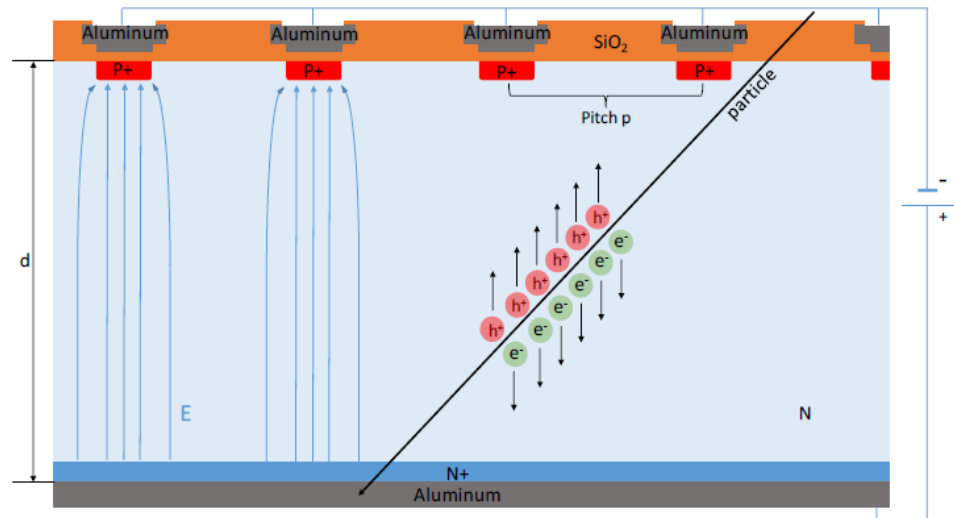


FIGURE 4.52: Working principle of a silicon detector: the pn-junction is reverse biased and the detector is depleted of free charge carriers. A traversing particle creates electron-hole-pairs, which are separated by the electric field and read out at the electrodes.

are created. These electron-hole-pairs cannot recombine and drift to the readout electrodes because of the applied electric field. Since, there are almost no other charge carriers in the depleted zone, the drifting charges can be detected as a signal.

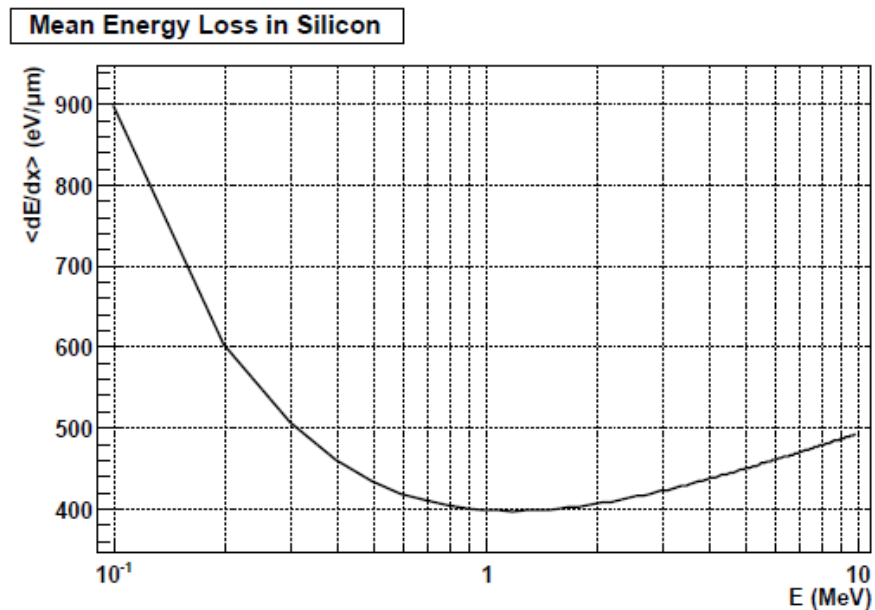


FIGURE 4.53: The mean energy loss of electrons in silicon. A particle at the minimum is called a minimum ionising particle, MIP.

The created charge in the silicon sensor is proportional to the absorbed energy. Free charges collected are the released energy divided by the energy required to create one electron hole pair, which is 3.6 eV for silicon. The mean energy loss of electrons in silicon is illustrated in figure 4.53.

4.4.2 Simulation results for simple pad diode

For the simulation of the simple pad diode, I have used both the Silvaco Atlas and Synopsys Sentaurus TCAD to predict the effects of radiation damage. Each package includes its own effective bandgap multiple traps modelling.

The geometry used in the device simulations assumes an active detector thickness of $150\mu\text{m}$ and a rectangular planar area of $1\mu\text{m} \times 80\mu\text{m}$. The selected thickness corresponds to the one foreseen for the next generation of pixel detectors, to be used in the innermost layers of the upgraded tracker systems of the LHC experiments. However, the transverse size ($1\mu\text{m} \times 80\mu\text{m}$) is kept small, in order to optimise the simulation parameters, (e.g. the number of simulation mesh points) achieving a good and robust simulation [5].

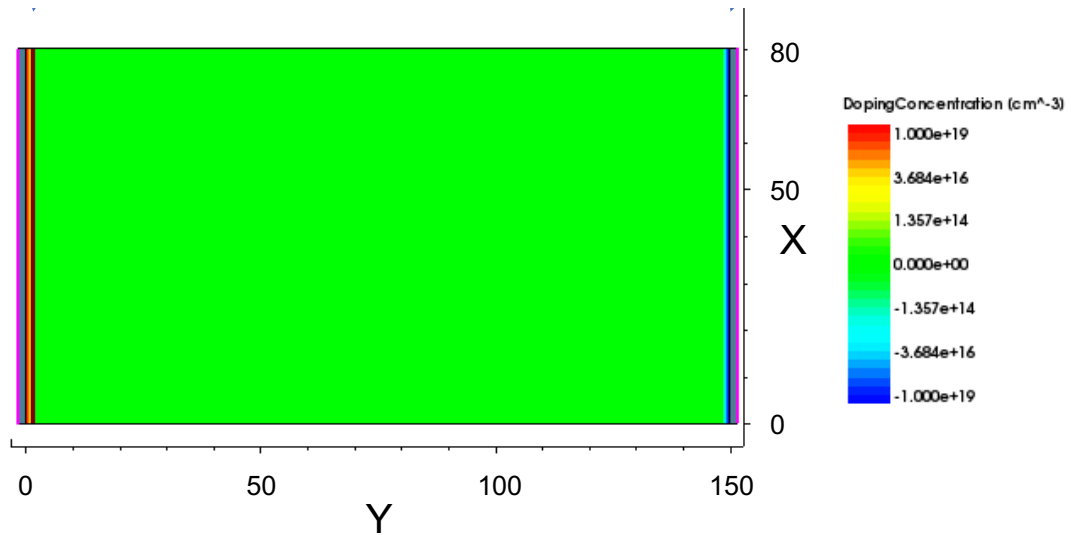


FIGURE 4.54: Diode structure: doping map.

The diode structure, shown in figure 4.54, is designed implementing a highly doped n-type junction layer (Phosphorus doped "front", uniform in space with a dopant concentration of $N_n \sim 10^{19}\text{cm}^{-3}$) on a high resistivity p-type bulk (Boron doped, "bulk", uniform in the volume with a concentration of $N_p \sim 2.94 \times 10^{11}$

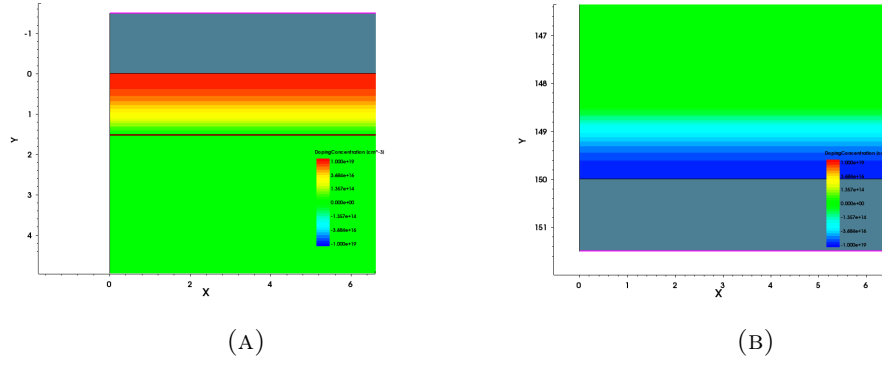


FIGURE 4.55: Diode layout: (A) Junction layer and (B) Ohmic layer; doping profile modelled by half Gaussian with maximum located at layer border (see text for details of values).

cm^{-3}), with an ohmic contact layer (Boron doped, "back", uniform in space with concentration $N_{\Omega p} \sim 10^{19} \text{ cm}^{-3}$). Ohmic and junction layers are covered on their external surfaces by aluminium contacts.

In the junction and ohmic layers, shown in figure 4.55a and 4.55b respectively, the shape of doping is implemented as a Gaussian distribution with RMS of $1.5 \mu\text{m}$; with maximum doping located at the bulk region borders. The simulation parameters are chosen for the non-irradiated devices, to match the known electrical characteristics. Simulations, before and after radiation damage, are performed at a device temperature of 253 K (one of the target temperatures foreseen for the innermost tracker), unless otherwise specified.

Among different simulated quantities, the absolute value of the electric field, the $|E|$, as a function of the device thickness and device capacitance versus the applied bias voltage are reported respectively in figure 4.56 and figure 4.57. The $|E|$ is calculated with the bias voltage applied. It shows the linear decrease given by stepwise implant doping. The transition point in capacitance measurement, shows the point of depletion voltage. Similar results are produced by both simulations, as seen from the plots.

4.4.2.1 Radiation damage models

To simulate the radiation damage effects, the specific models for Synopsis [58] and Silvaco [59] have been implemented. The modelling has been verified with experimental data, in a fluence range of $10^{14} - 10^{15} \text{ MeV n}_{eq} \text{ cm}^{-2}$. Given that

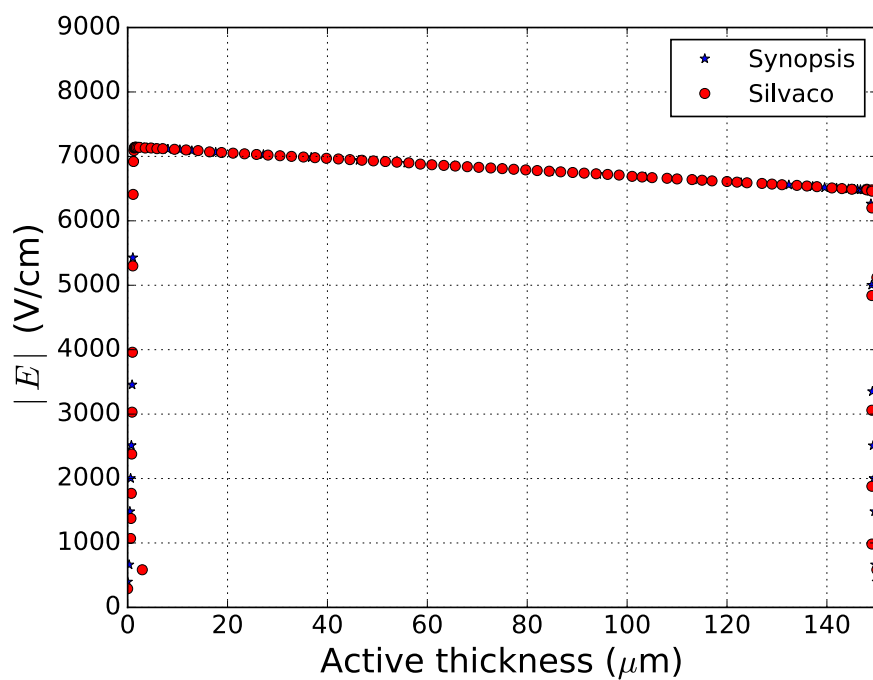


FIGURE 4.56: TCADs comparison for a non-irradiated diode: $|E|$ versus active thickness.

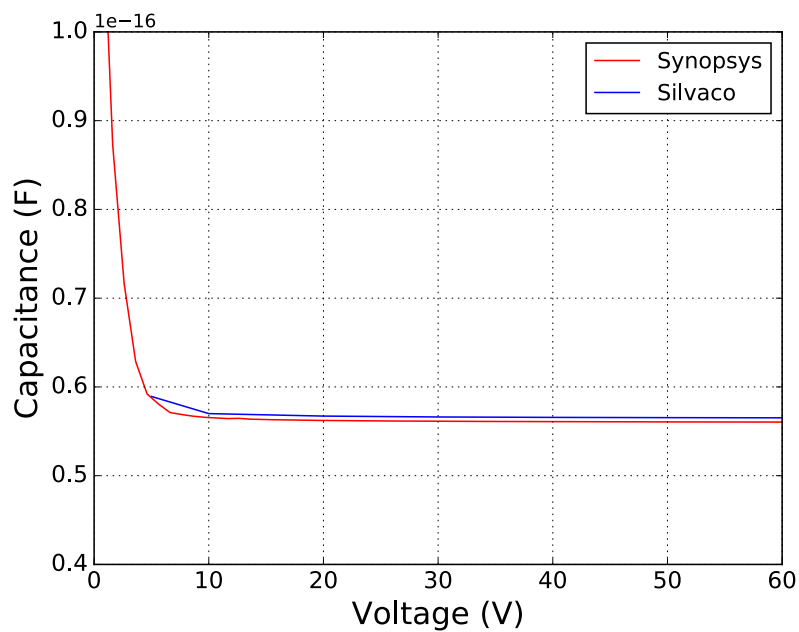


FIGURE 4.57: TCADs comparison for a non-irradiated diode: C versus Bias Voltage.

the most relevant contribution of radiation damage in the region where silicon pixel detectors are planned to be used is due to charged particles; the model implemented here is related to “proton” damage. Common features of the proton damage models are [58]:

- Two defects model (Acceptor and Donor trap levels), located in the silicon bandgap.
- Donor and Acceptor traps concentration growing linearly with the fluence.

The models differ in the traps bandgap energy location, the defects cross-sections and the increase of traps concentration related to the radiation level.

After the irradiation both TCAD models show the double junction effect [60]. This effect is shown in figure 4.58 for a high irradiation fluence of $1 \times 10^{15} \text{ MeV n}_{eq} \text{ cm}^{-2}$. The electric field profile at a bias voltage of 100 V is compared for both TCAD models, with comparable profiles along the device-bulk. However, Silvaco simulation shows a more pronounced double junction in the ohmic side that grows faster than Synopsys. We expect a larger negative depletion voltage for the latter TCAD at this fluence.

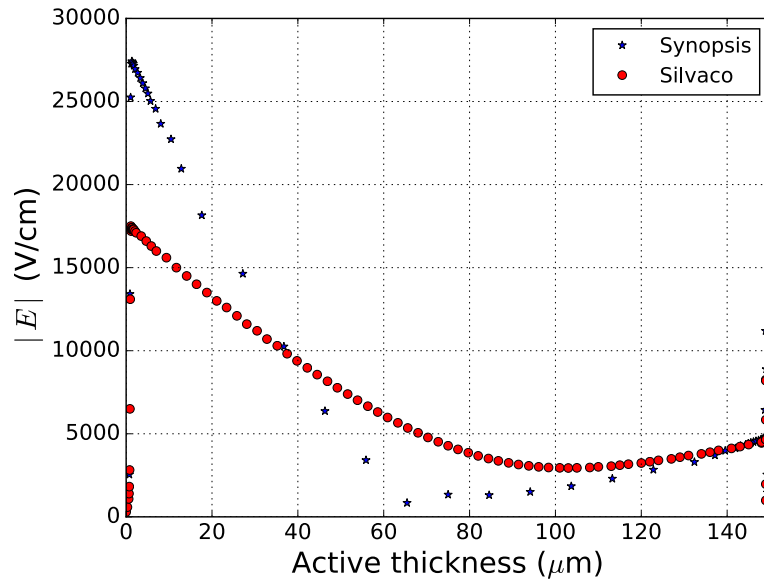


FIGURE 4.58: TCADs comparison for an irradiated diode at $1 \times 10^{15} \text{ MeV n}_{eq} \text{ cm}^{-2}$: $|E|$ versus active thickness.

4.4.2.2 Device capacitance

The full depletion voltage V_{depl} of a pad diode is measured by the device's effective doping concentration ($|N_{eff}|$) and active thickness (d).

$$V_{depl} = \frac{e}{2\epsilon\epsilon_o} |N_{eff}| d^2 \quad (4.1)$$

The $|N_{eff}|$ value in the bulk can be measured by the analysis of the CV characteristics of diode. The derivative of $1/C^2$ versus the depleted depth of the device is given by [61]:

$$\frac{d(1/C^2)}{dV} = \frac{2}{A^2 e \epsilon \epsilon_o |N_{eff}|} \quad (4.2)$$

Before irradiation the V_{depl} value is determined by the crossing point of two linear

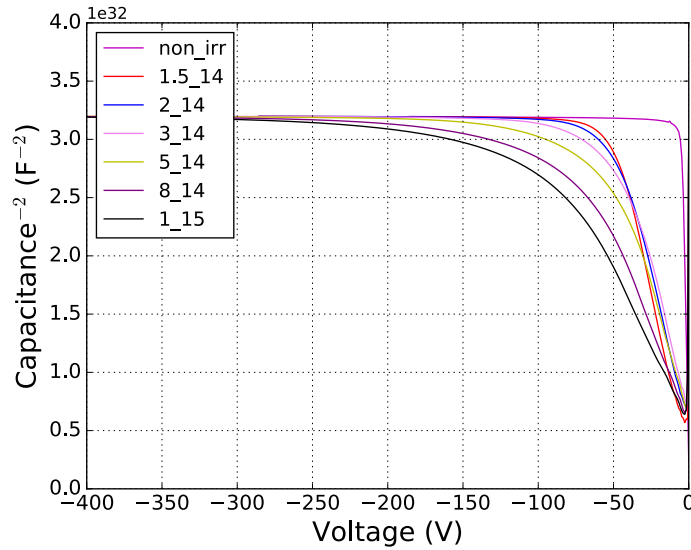


FIGURE 4.59: Synopsys: $1/C^2$ vs Bias voltage for different fluences, showing the double junction effect.

regions in the $1/C^2$ as a function of the bias voltage (V_{bias}). After irradiation this method is not robust enough, given that the shape of the $1/C^2$ plots shows a fluence dependence curvature between the linear increasing (low voltage region) and the flat (high voltage region) parts. The method, used in this work to approximate the depletion voltage, identifies V_{depl} as the bias voltage at which the measured capacitance reaches the 90% of the geometrical capacitance. The simulation performed for the high resistivity diode shows that the V_{depl} value increases with the induced radiation damage (figure 4.59), with similar slope for both TCAD models.

As expected, the device becomes more “p-type” due to introduction of the acceptor damage related traps.

The traps induced by radiation damage will increase the dark leakage current (I_{leak}). In this work we have selected simulated values well above the approximate V_{depl} evaluated for each fluence in order to correctly evaluate the total bulk current. Indeed the value of saturated leakage current is obtained by fitting the plateau region at bias voltages above twice the full depletion voltage at a particular fluence. The I_{leak} per unit volume is proportional to the fluence [62]. This proportionality is expressed by α , which is the current related damage rate, shown for both TCADs on the left in figure 4.60.

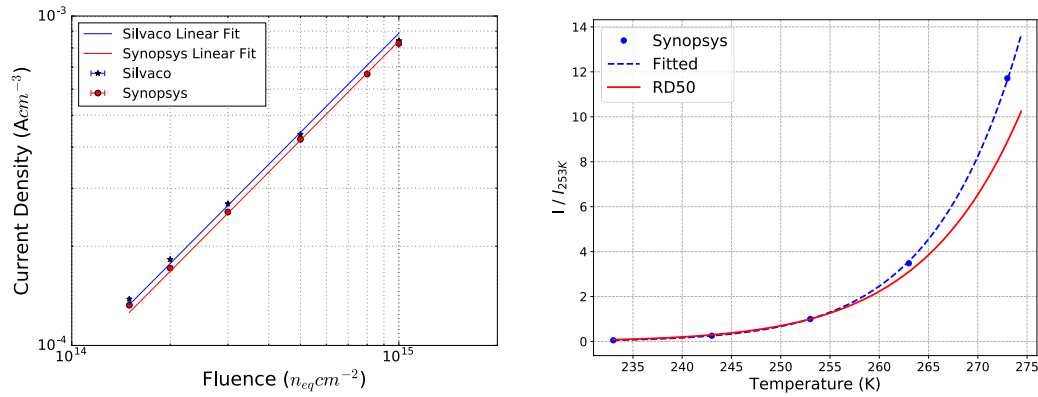


FIGURE 4.60: TCADs comparison for an irradiated diode (on the left) and Synopsys: temperature dependence of I_{leak} (on the right)

The predicted α values obtained (in A/cm³) are: $\alpha_{Synopsys} = (8.33 \pm 0.04) \times 10^{-19}$ and $\alpha_{Silvaco} = (8.54 \pm 0.11) \times 10^{-19}$, which are compatible with each other ⁶, and roughly correspond to what is expected when extrapolating at -20°C [63], the experimental values measured at a temperature of $+20^\circ\text{C}$ [61].

In order to check the contribution of traps to the I_{leak} increase, its dependence on the temperature has been simulated. At a fluence of 5×10^{14} MeV n_eq cm⁻², the I_{leak} has been simulated with the diode operated in the range of temperatures [233-273] K, as shown in figure 4.60 on the right. The current interpretation of data [61], assesses that the dark leakage current increases with temperature as exponential function with an activation energy, as below:

$$I(T) \propto T^2 \exp\left(-\frac{E_g}{2K_B T}\right) \quad (4.3)$$

⁶The quoted errors on alpha values include only statistical uncertainties on the fitting procedure.

The simulation performed here shows a value of activation energy compatible with results from RD50 collaboration's experimental value [63].

4.4.3 Simulation results for silicon pixel

After satisfactory results from simple pad diode simulations, we moved to pixel geometry. The basic parameters were defined in the last section. A set of 5-pixel implants has been implemented, with a pitch of $25\mu\text{m}$ with the active thickness of $150\mu\text{m}$ to match typical design for the vertex detector foreseen for experiments at HL-LHC (figure 4.61).

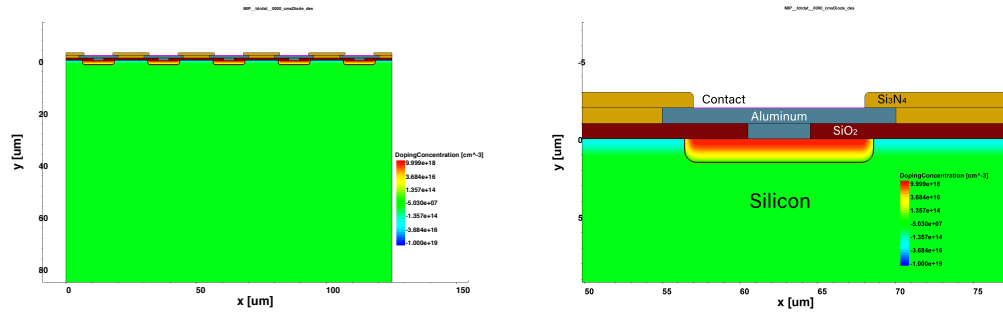


FIGURE 4.61: Full device design for 5 pixels (on the left) and detailed junction geometry/doping for one pixel (on the right)

Each pixel has been detailed with an implant geometry (taken from the design of pixel sensors prototypes used in the beam test) and implant doping profile (taken from the diode simulation, mentioned earlier), as well as including a detailed inter pixel region in terms of oxide layers. The detector performance has been measured using the signal of a minimum ionising particle (mip) included in the simulation and measuring the electrical characteristic as function of operating voltage. Figure 4.62 (left) shows a MIP with an impact angle of 10 degrees, as example, together with the electron cloud as collected by the nearby pixel implants.

Charge collected by one pixel from orthogonal MIP impinging in its center showed an efficiency compatible with the classical depletion voltage ($1/C^2$ vs V). Detail is shown in figure 4.63 and 4.64, where the charge deficit shown for under-depleted pixel is compared to over-depleted (or asymptotic) pixel operational condition ⁷.

The simulation for irradiated detector, up to HL-LHC foreseen fluences for the innermost detector layers, has been performed, implementing a radiation model

⁷This work has been done in collaboration with a master's student: Angelo Maria Raso

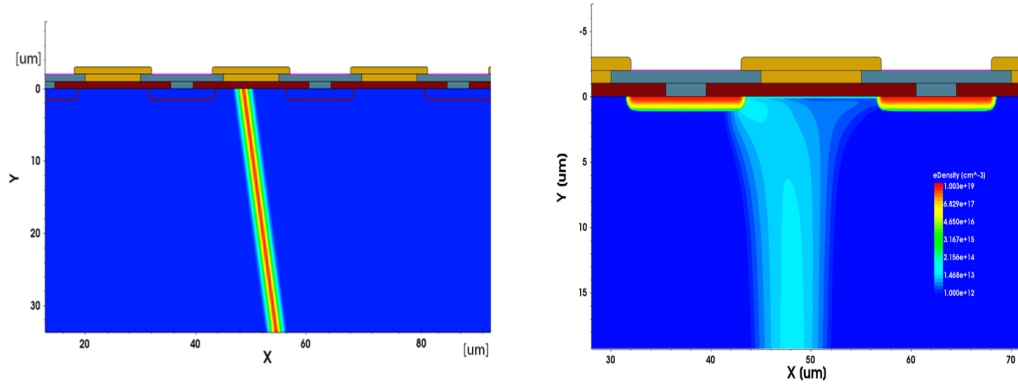


FIGURE 4.62: Track generated by a MIP traversing the entire device at an impact angle of 10 degrees (left). Electrons from a orthogonal MIP drifting to implants 2 and 3 (right)

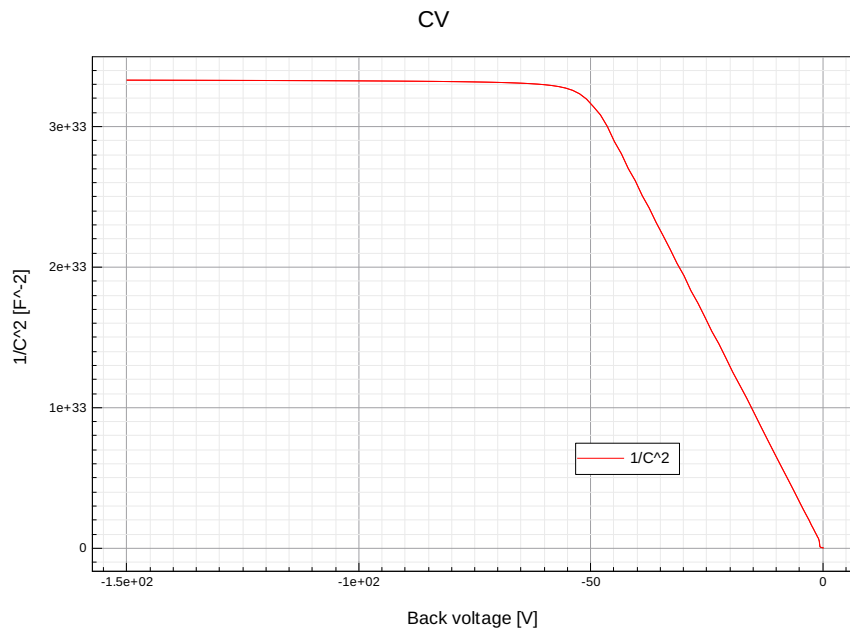


FIGURE 4.63: $1/C^2$ vs operating voltage, showing the depletion voltage

within the TCAD package. Ultimately the damage will affect the charge collected by a pixel and its performance inside the particle detector. The radiation damage model implemented correctly predicts the maximum charge deficit of 74% at high fluences, shown by the charge collection efficiency distribution in figure 4.65. The first point in the plot corresponds to the non irradiated sensor. The results are compatible with published test beam data ⁸ within errors, where 62 % reduction was shown at similar fluences.

⁸<https://doi.org/10.1016/j.nima.2019.02.033>

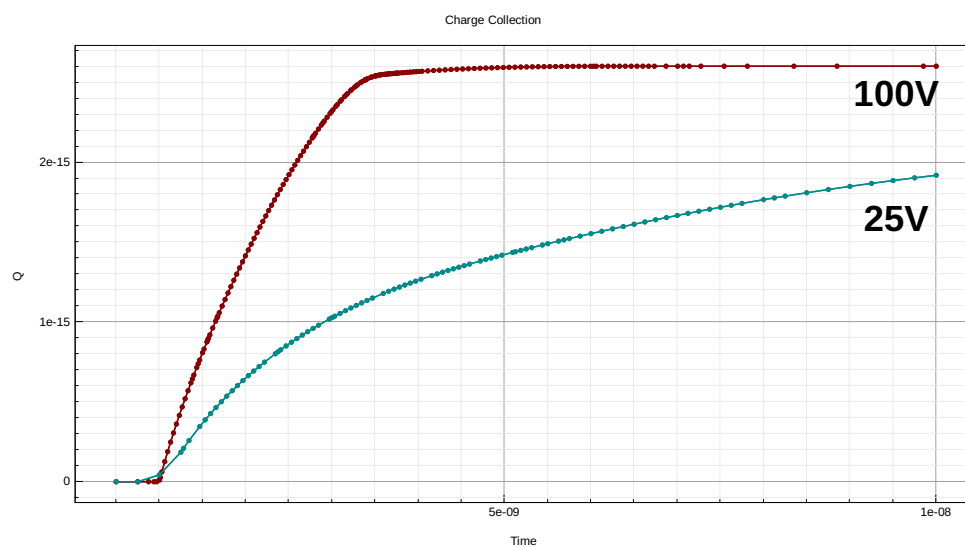


FIGURE 4.64: Asymptotic value of charge collected in under depletion (25V) and over depletion (100V)

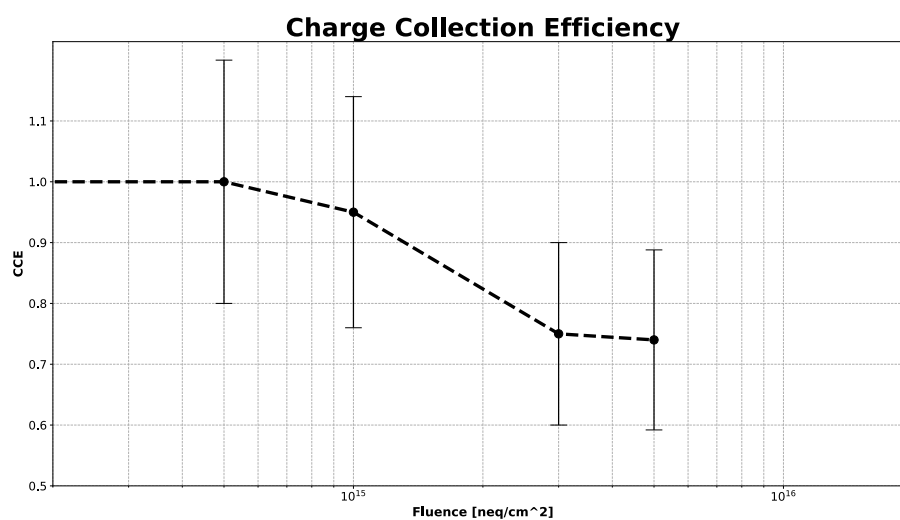


FIGURE 4.65: Charge collection efficiency as a function of the dose for irradiated module. Results are achieved at operational bias of $\sim 2 \times V$ depletion.

Chapter 5

Kinematic study and data analysis

In this chapter, we shall analyse the kinematics of the processes which are involved in our studies. We shall also find ways to discriminate between the signal, normalisation and the background processes.

The analysis framework introduced in the chapter 1 and in details in section 2.3, shows that the processes involved in our investigation are the following:

$$\begin{aligned} \text{Signal} &:: B_c^+ \rightarrow J/\Psi \tau^+ \nu_\tau \rightarrow \mu^+ \mu^- \mu^+ \nu_\mu \nu_\tau \bar{\nu}_\tau \\ \text{normalisation} &:: B_c^+ \rightarrow J/\Psi \mu^+ \nu_\mu \rightarrow \mu^+ \mu^- \mu^+ \nu_\mu \\ \text{Background} &:: J/\Psi X \rightarrow \mu^+ \mu^- X \end{aligned} \tag{5.1}$$

As we have mentioned before, the analysis of processes in section 5.1 benefits from the excellent performance of CMS in charged particle tracking, muon identification, J/Ψ resonance reconstruction and last but not the least the size of the branching ratio in the specific channel.

5.1 Signal and Background kinematics

In the analysis the mass of the B_c^+ meson and its decay lifetime have been set to the best experimental value available today: $m_{B_c^+} = (6.2756 \pm 0.0011)\text{GeV}$ and $\tau_{B_c^+} = (0.500 \pm 0.013) \times 10^{-12}\text{s}$ [26]. Due to its short lifetime, the B_c^+ cannot be detected by the CMS detector and therefore we estimate the B_c^+ candidate momentum starting from the kinematics of particles reconstructed in the final state. The

decay chain of all three processes from equation 5.1, foresee the production of the J/Ψ resonance (a charmonium state), whose experimentally known mass is $m_{J/\Psi} = (3096.916 \pm 0.011) \text{ MeV}$ [26]. The narrow resonance of ($\Gamma_{J/\Psi} = 92.9 \pm 2.8 \text{ keV}$ [26]), excellent muon-muon identification and tracking allows to identify the J/Ψ with high efficiency and with a very low background. Therefore, the identified muons μ_1 and μ_2 (see section 2.3) as daughters of the J/Ψ allows to fully reconstruct the J/Ψ resonance, kinematics and resonance mass value.

The detectable final states from B_c decay for both signal and normalisation channel are identical due to presence of three muons (two of the same charge and one opposite). Out of the these three muons, the two oppositely charged muons whose invariant mass is nearest to the J/Ψ mass, can be identified as the reconstructed J/Ψ and the remaining one is the unpaired muon. Only the neutrinos in the final state are different for the considered processes. Since neutrinos cannot be detected, we need to define quantities to discriminate the three channels. Missing mass (m_{miss}) and missing transverse momentum (p_T^{miss}) can be used for this purpose, where m_{miss} is the invariant mass of the neutrino system in the final state and p_T^{miss} is the momentum fraction of the neutrino system in the plane transverse to the beam axis (defined in detail in section 5.3). In our signal process, we have three neutrinos, so $m_{miss} \neq 0$ and $p_T^{miss} \neq 0$ in such an event. Whereas in normalisation process only one neutrino and therefore we have $p_T^{miss} \neq 0$ but, $m_{miss} = 0$ (because of neutrino being massless). Presence of neutrinos also hinders the direct reconstruction of the B_c^+ candidate, requiring some other technique to be employed (explained in detail in Sec. 5.2.1)

As mentioned in equation 2.5, the largest background source has a spurious particle X which fakes the unpaired muon. This unpaired muon has no relation to the other two muons coming from the J/Ψ (unlike in case of signal and normalisation channel) and therefore this kinematic property can be used to filter out the background from the signal and normalisation. All backgrounds are defined in detail in section 5.4.

5.2 Event reconstruction

As shown in figure 5.1, the final state particles for our studies are muons, since neutrinos cannot be reconstructed. In CMS, we have a dedicated muon system

as the outermost sub-detector for reconstruction of muons, covering the pseudo-rapidity range of $|\eta| < 2.5$ (detailed in section 3.2.5).

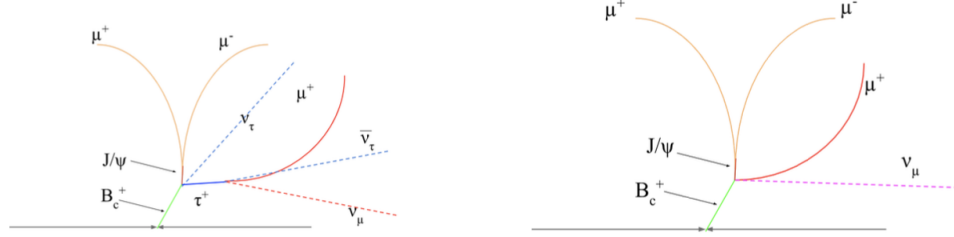


FIGURE 5.1: Event reconstruction for tau (left) and muons (right)

In standard CMS procedure for reconstruction, tracks are first independently reconstructed [40] in the inner tracker (tracker track) and in the muon system (stand alone track), as mentioned in section 3.3. Then they are used as inputs for muon track reconstruction. Iterative approach is used for building the Tracker tracks, running a sequence of tracking algorithms. While standalone muon tracks are built exploiting information from muon sub-detectors using a Kalman-filter technique. The tracks of the muons are then used to evaluate their p_T .

The basic pre-cuts applied during the reconstruction are shown in table 5.1

$|\eta|$ (muons)	< 2.4
$|dz(\mu_1) - dz(\mu_2)|$ (distance b/w closest approach of tracks of muons wrt PV)	≤ 0.4 cm
Dimuon (muons from J/Ψ) mass	$[2,4]$ GeV
$\Delta R_{\mu_1\mu_2}$	> 0.01
$p_T^{\mu_1}$ (highest muon p_T from J/Ψ)	> 2.5 GeV
Secondary vertex probability	$> 1e^{-5}$
Dimuon (muons from J/Ψ P_T)	> 3 GeV (after fit)
$B_c \cos 2D$ (Cosine of the angle between the line going from the beamspot to B_c^+ vertex and the direction of the 3μ in the final state)	≥ 0
B_c^{mass}	< 10 GeV
Muon ID	None
Tracks required	High purity

TABLE 5.1: Basic cuts applied during reconstruction

For muon identification (ID), a large set of variables is studied at CMS and selection criteria are defined to allow each analysis to achieve the desired balance between efficiency and purity. For our analysis, muon ID studies are discussed in

detail in section 5.5.1. The Monte-Carlo simulation gives the generator level value of the variables; we assume the measurement of η and ϕ to be of infinite precision by retaining the Monte Carlo generated level value as the detected one.

5.2.1 B_c^+ reconstruction

As mentioned in Sec. 5.1 the presence of neutrinos in the final state hinders the direct reconstruction of the B_c^+ candidate four-momentum, which we need for the complete kinematical study. Thus only detectable final state particles can be used. The B_c^+ candidate momentum in the laboratory frame is estimated using a method inspired by the one used by the LHCb collaboration in Ref. [64]. LHCb uses a method, where a unit vector from the associated primary vertex (PV) to the the B_c^+ decay vertex (secondary vertex, SV) determines the B_c^+ momentum direction. The component of the B_c^+ momentum along the beam axis is approximated using the relation $p_z^B = \frac{m_B}{m_{reco}}(p_{reco})_z$ where m_B is the known B_c^+ mass, and m_{reco} and p_{reco} are the mass and momentum of the system of reconstructed particles.

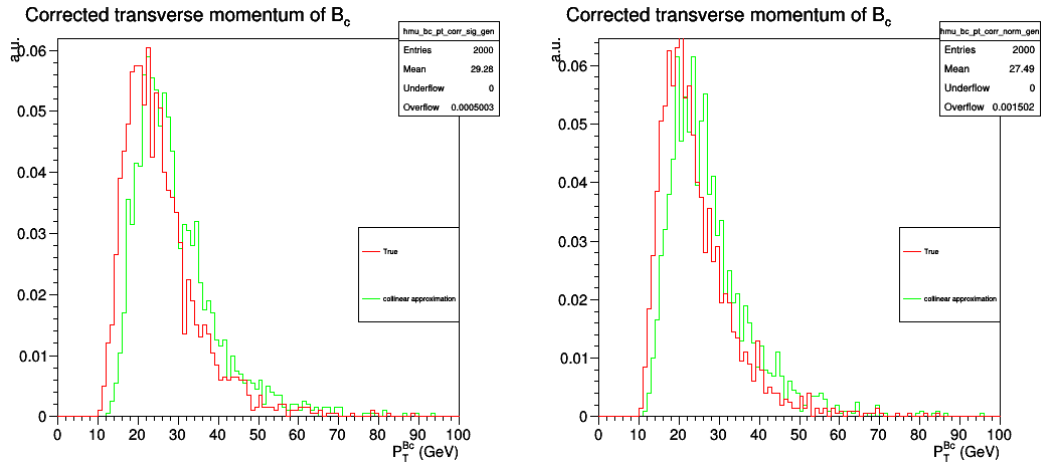


FIGURE 5.2: B_c^+ Momenta for Signal and normalisation channel. Monte Carlo (red) vs collinear approximation (green)

This reconstruction method is useful in forward physics, which is important for LHCb since its acceptance covers the region $2.5 < \eta < 5$ [65]. On the contrary, the acceptance of many CMS detector components covers the region $|\eta| < 2.5$. Therefore the previous method is modified as $p_T^B = \frac{m_B}{m_{reco}}(p_{reco})_T$ where the subscript T identifies the components in the transverse plane [66]. We call it the “Collinear Approximation”. The momentum direction is then taken to be the one of the final

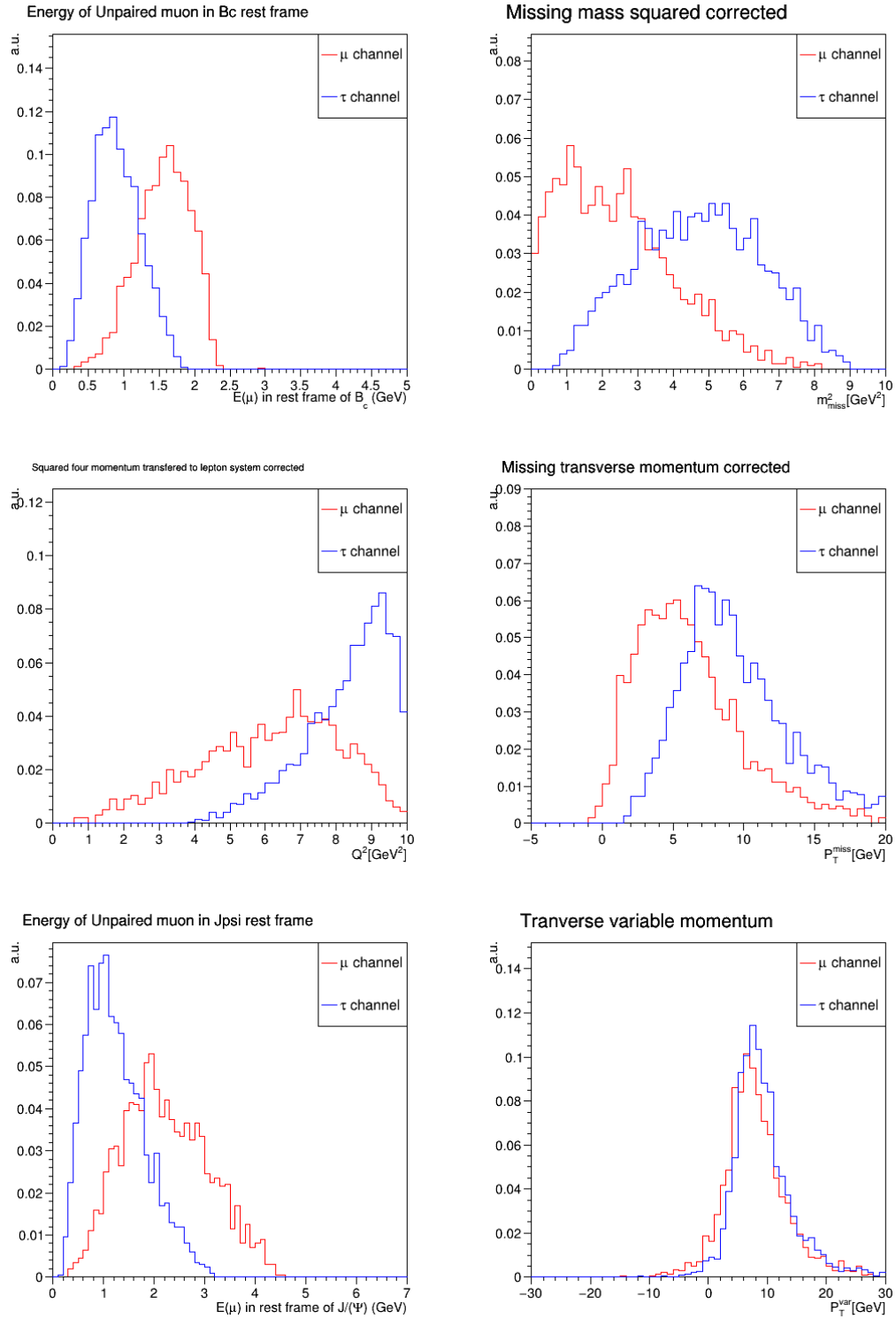
state muon system. Figure 5.2, shows the B_c^+ candidate four momenta, with and without collinear approximation to signal and normalisation channel.

5.3 τ and μ channel discrimination

The differences in the kinematic distributions of the various processes can be exploited to disentangle their respective contributions to the sample. In fact, the large $\mu\tau$ mass difference and the presence of extra neutrinos from the decay $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$ result in distinct distributions for the signal relative to the normalisation mode. The discriminating variables are:

- E_μ^* , the unpaired-muon energy in the B_c^+ candidate rest frame.
- $m_{miss}^2 = (p_B - p_{\mu_1} - p_{\mu_2} - p_\mu)^2$, the missing mass squared; where $p_B, p_{\mu_1}, p_{\mu_2}$ and p_μ are the four-momenta of the B_c^+ candidate, the two muons coming from the J/Ψ decay and the unpaired muon respectively.
- $Q^2 = (p_B - p_{\mu_1} - p_{\mu_2})^2$, the squared four-momentum transfer to the lepton system.
- $p_T^{miss} = (p_T^B - p_T^{\mu_1} - p_T^{\mu_2} - p_T^\mu)$, the scalar missing transverse momentum; where $p_T^B, p_T^{\mu_1}, p_T^{\mu_2}$ and p_T^μ are the magnitudes of the transverse momenta of the B_c^+ candidate, the two muons coming from the J/Ψ decay and the unpaired muon, respectively.
- $E_\mu^\#$, the unpaired-muon energy in the rest frame of the other two muons system.
- $p_T^{var} = (p_T^{\mu_1+\mu_2} - p_T^\mu)$, where $p_T^{\mu_1+\mu_2}$ and p_T^μ are scalar transverse momenta of the system of the two muons coming from the J/Ψ decay and of the unpaired muon, respectively.
- $\Delta R(\mu_1, \mu_2) = \sqrt{(\phi_{\mu_1} - \phi_{\mu_2})^2 + (\eta_{\mu_1} - \eta_{\mu_2})^2}$, where the μ_1 and μ_2 subscripts identify the variables associated to the two muons coming from the J/Ψ decay.

The normalised distributions of the discriminating variables along with the unpaired muon's η, ϕ and p_T are shown below:



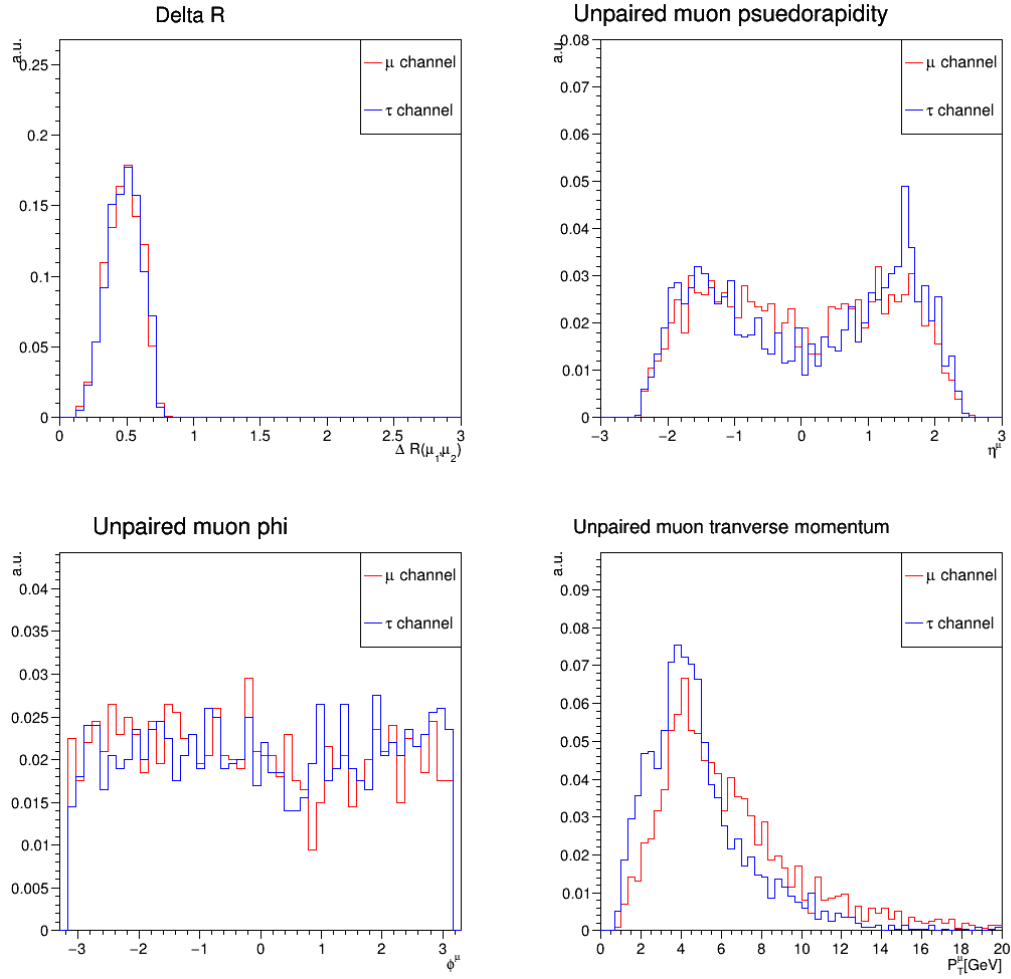


FIGURE 5.3: normalised distributions of the features used for the discrimination of signal (blue) and normalisation (red) processes

5.4 Dataset, trigger and Background

The analysis uses data recorded by the CMS detector in pp collisions in 2018 corresponding to an integrated luminosity of 59.6 fb^{-1} (Run 2 of the LHC). Following datasets are used:

- /Charmonium/Run2018A-12Nov2019 UL2018 rsb-v1/MINIAOD
- /Charmonium/Run2018B-12Nov2019 UL2018-v1/MINIAOD
- /Charmonium/Run2018C-12Nov2019 UL2018-v1/MINIAOD
- /Charmonium/Run2018D-12Nov2019 UL2018-v1/MINIAOD

The collision events selected by high level trigger (HLT) algorithms which require the presence of leptons passing relaxed identification cuts [67] are used in the analysis. Presence of three muons is by trigger, two of which should have an invariant mass close to the J/Ψ mass. The HLT path for the charmonium data used is:

- **HLT_Dimuon0_Jpsi3p5_Muon2_v** : The HLT requires three muons in the CMS geometrical acceptance: two of these muons need to be oppositely charged and form a J/Ψ candidate with $p_T > 3.5$ GeV and the invariant mass in the range $[2.95, 3.25]$ GeV. The third muon is required to have $p_T > 2.0$ GeV. Since this trigger has a low P_T cut, it provides the ideal muons for our requirements. Further we refer to this trigger as “Dimuon0”.

Sources of background are:

- **Fakes**: inclusive decays of b hadrons to J/Ψ in which the accompanying pion or a kaon is misidentified as a muon. Data driven method is used to study fakes 5.6.
- **Combinatorial ($J/\Psi + \mu$)**: Consists of J/Ψ mesons from b hadrons and a accompanying μ^+

$J/\Psi X$ decays paired with muon candidates from the rest of the event (dominant at high 3 muon reconstructed mass)

J/Ψ mesons paired with muon from the same b hadron (low 3 muon reconstructed mass).

- **Combinatorial J/ψ** . The J/ψ candidate coming from the B_c^+ decay may be reconstructed using unrelated muons. The studies on this background are still ongoing and thus are not presented in this thesis, but some cuts on the isolation variable are used in the reconstruction code to reject these events.

- **B_c Background:**

Feed downs: Higher cc states decaying to J/Ψ ; $B_c^+ \rightarrow \Psi(2S), \chi_{c0,1,2}, h_c \mu \nu$.

Other J/Ψ^+ charmed hadron, mostly $B_c \rightarrow D_s^{(*)} J/\Psi$

These background events though being part of MC, are generated using

branching fractions with not negligible uncertainties. These uncertainties in the branching fractions will be a part of the systematic uncertainty of $R(J/\psi)$ measurement.

A total of three kinds of MC samples are produced to find the distributions of the various background components. Misidentification, combinatorial and those coming from the B_c^+ decay modes are denoted as: B_c *hybrid*, $H_b \rightarrow J/\psi + X$ and $H_b \rightarrow J/\psi + \mu$ respectively.

The software used to generate the Monte Carlo events are:

- *PYTHIA*, a general purpose Monte Carlo generator programmed to generate high-energy physics collision events. It includes the theoretical models that describe the interactions of the particles (hard and soft interactions, parton distributions, initial- and final-state parton showers, multi parton interactions, fragmentation and decay [68])
- *EvtGen*, a Monte Carlo event generator programmed to simulate the decays of the heavy flavour particles (just like the B_c^+ meson). It contains a range of decay models for intermediate and final states containing scalar, vector and tensor mesons or resonances, as well as leptons, photons and baryons [69]

PYTHIA has been used to generate the collision events for the H_b samples and *EvtGen* to simulate the decay of the hadron in the initial state (both B_c^+ and H_b). The branching ratio described in literature for each decay mode, is preserved by all these samples. Note that some events in the H_b sample overlap with those in the hybrid sample, so they must be taken care of properly. The integrated luminosity of the data and the MC samples are different: $\mathcal{L}_{int}^{data} \neq \mathcal{L}_{int}^{MC}$. To accommodate this difference in the number of expected events, the MC samples are *normalised* to reproduce the data.

5.5 Selection studies and optimisation of cuts

5.5.1 Muon identification studies

As described in section 3.3, muon reconstruction and identification is an important part of analysis in CMS. Dedicated muon sub-detectors are responsible for efficient muon identification.

In our analysis, we aim at finding muon selection criteria that maximise the signal and the normalisation yields while keeping the background from misidentified hadrons at the lowest level as possible. We have investigated six algorithms present in the miniAOD: Soft, Tight, Loose, Global, PF and Tracker. Here, for this particular study, we are considering only pion sample ($B_c^+ \rightarrow J/\Psi \pi^+$) as the background. This pion can be reconstructed as an unpaired muon.

Basic kinematic selection on the sample (as described in section 5.1) is performed, with candidate muons required to belong to the muon collection. Selection of unpaired muons is carried out within the detector acceptance: ($|\eta| < 1.2$ and $p_T > 3.0$) or ($1.2 < |\eta| < 2.4$ and $p_T > 0.8$). Also, we use trigger selection and divide according to 3 exclusive categories: J/Ψ +Mu only, J/Ψ +Tk only and J/Ψ +Mu & J/Ψ +Tk only, where Mu refers to muon and Tk refers to the track. The reconstructed candidate muon is matched to the one in the trigger (except for J/Ψ +Tk of course) and also matched to the original MC truth particle (either muon or pion, depending on the sample) to determine whether is fake or not. These studies are summarised in table 5.2.

Table 5.2, shows the current optimisation study for muon identification. The upper part of the table shows the statistics for the event rate, efficiency or fake rate. Pion and muon describe the particle X along with the two muons (from J/Ψ) in the process: $B_c \rightarrow \mu_1 \mu_2 X$. In Pion sample (column1), Pion misidentified as a muon, contributes to the fake rate, whereas in Muon sample (column2), muon reconstructed as a Muon, contributes to the efficiency. First row defines the total number of events with an unpaired muon candidate. Second row gives the number of events out of the total events which pass the detector acceptance cuts (mentioned above). Third row is the number of events in which we have at least one reconstructed muon. Ratio of the third and second row gives us the fake rate/efficiency in the fourth row.

	No trigger		Either trigger		JpsiMu only		JpsiTk only		JpsiMuJpsiTk	
	Pion	Muon	Pion	Muon	Pion	Muon	Pion	Muon	Pion	Muon
Events with an un-paired candidate μ	12388	19400	1614	1596	173	891	1376	348	65	357
Events after acceptance cuts	11487	18897	1517	1588	170	890	1283	341	64	357
Reconstructed at least one μ	2424	10040	473	1251	58	756	384	197	31	298
Fake rate/ efficiency	0.21	0.53	0.31	0.79	0.34	0.85	0.3	0.58	0.48	0.83
Fraction of events with a muon candidate reconstructed with one of the algorithms below										
Soft	0.44	0.99	0.4	0.99	0.55	0.99	0.36	0.96	0.61	1
Tight	0.06	0.72	0.12	0.86	0.48	0.95	0.03	0.45	0.48	0.93
Loose	0.38	0.97	0.33	0.98	0.59	0.99	0.27	0.94	0.61	0.99
Global	0.38	0.97	0.33	0.98	0.59	0.99	0.27	0.94	0.61	0.99
Particle Flow (PF)	0.21	0.81	0.24	0.93	0.59	0.99	0.17	0.61	0.52	0.99
Tracker	0.71	0.99	0.58	0.99	0.62	0.99	0.57	0.96	0.65	1

TABLE 5.2: Muon identification studies

Table has several columns with different triggers applied as indicated by the labels. Lower part of the table gives us the fake rate/efficiency when the reconstructed muon candidate passes that algorithm (eg. soft, tight etc). We can use these rates to select the criteria which maximises the muon efficiency while minimising the fake reconstruction rate of pion simultaneously. Even the combinations of different triggers and algorithms can be used as shown in table 5.3. The fraction of events X means the fraction of events with at least one unpaired muon candidate within the acceptance that pass any trigger.

Combination	Fraction of events X	
	Muon sample	Pion sample (Fakes)
Soft (JpsiMu + jp-siMu&JpsiTk) only	0.84	0.11
+Tight for JpsiTk trigger only	0.91	0.13
+PF for JpsiTk trigger only	0.93	0.25
+Loose for Jpsi trigger only	0.99	0.40

TABLE 5.3: Combination of trigger cuts for optimisation

From the table we can infer that, when the event is triggered by the J/Ψ +Muon the number of fake muons is lower than when it is triggered with J/Ψ +Track only. In this case there are no differences among the different muon identification algorithms, except for the tight muon one, which considerably reduces the efficiency for muons while marginally decreasing the muon misidentification. In order to reduce considerably the fake rate in case of J/Ψ +Tk only trigger, the Loose, Global, Soft muons are giving the best performance, while the Tracker muon is the worse one. To keep the fakes at the same level of the other two trigger categories a Tight muon id is recommended for J/Ψ +Tk trigger only category. More such cases can be studied with higher statistics. This work has to be further optimised.

5.5.2 Primary vertex selection

The Primary Vertex reconstruction in CMS is defined in detail in section 3.3. Our decay channel is reconstructed by extrapolating the J/Ψ vertex position along the z and finding the closest Primary Vertex in z. A study is performed to confirm whether this criteria gives the best vertex out of all the reconstructed vertices or not. This is achieved by calculating the number of times our reconstructed vertex is closest to the true vertex in Monte Carlo. The criteria was found to be

$\approx 95.5\%$ effective in selecting the closest primary vertex to the true PV. Figure 5.4 shows the difference between the z-coordinate of the reconstructed PV and the true value. We continue to use this reconstructed vertex as PV in our analysis.

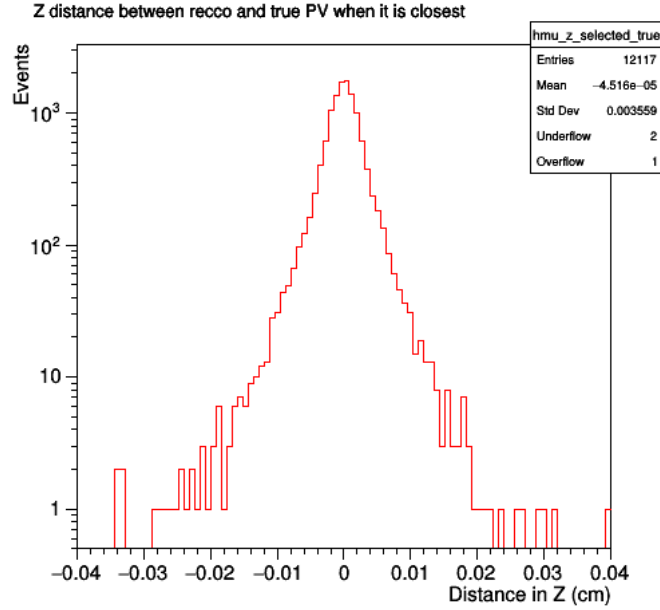


FIGURE 5.4: Difference between the z-coordinate of the reconstructed PV and the Monte Carlo value.

5.5.3 Monte Carlo samples normalisation

The MC normalisation is done differently for the three samples ¹:

- **B_c hybrid sample normalisation.**

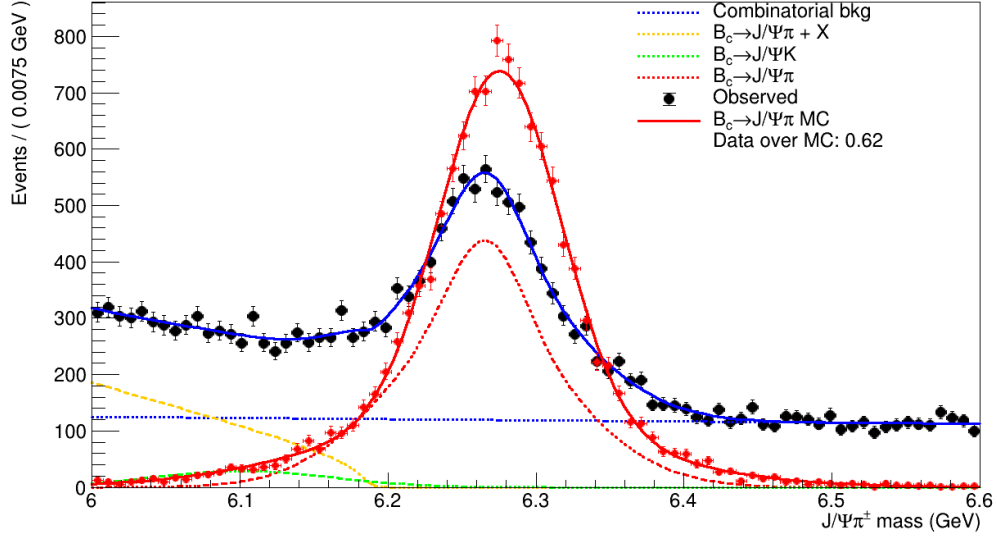
The B_c hybrid sample includes the $B_c^+ \rightarrow J/\psi + \pi^+$ control channel. This decay mode is a standard candle to compute the normalisation between the data and the MC hybrid sample. The $J/\psi + \pi^+$ invariant mass is fitted for both data and MC samples, to extract the number of signal (i.e. $J/\psi + \pi^+$) events and the normalisation is computed as $N_{Data}^{sig}/N_{MC}^{sig}$.

The signal events in the dataset are mixed with different background events as described in [70]. The fit model takes into account all these contributions and the components are listed in table 5.4.

The fit function is defined as the sum of all the probability density functions listed below and its normalisation is constrained to be 1. Thus, the signal

¹This work has major contribution from a master's student: Pasquale Andreola

Event type	Contribution	Model
Signal	$B_c^+ \rightarrow J/\psi \pi^+$	Two Gaussian functions with different means and widths
Background	Combinatorial: J/ψ associated with uncorrelated particle	First-order Chebyshev polynomial
	Partially reconstructed B_c^+	Generalised ARGUS distribution
	$B_c^+ \rightarrow J/\psi + K^+$	Two Gaussian functions with different means and widths

TABLE 5.4: List of the sources that contribute to the $J/\Psi + \pi^+$ invariant mass distributionFIGURE 5.5: Invariant mass distribution for the $J/\psi + \pi^+$ system.

yield for the dataset is computed as: $N_{Data}^{sig} = N_{Data}^{tot} - N_{Data}^{bkg}$. The signal yield for the MC sample is computed as the sum of the integrals of the two Gaussian functions modelling the $J/\psi + \pi^+$ contribution (background is rejected because the final state is unambiguous in the MC sample). The result of the fit procedure is shown in figure 5.5.

The B_c^+ hybrid sample normalisation is computed as $\frac{N_{Data}^{sig}}{N_{MC}^{sig}} = 0.62 \pm 0.04$.

- **$H_b \rightarrow J/\psi + X$ sample normalisation.**

The $J/\psi + X$ sample includes the $B^+ \rightarrow J/\psi + K^+$ control channel. This decay mode can be used as a standard candle to compute the normalisation

between the data and the $J/\psi + X$ MC sample (the background sources are similar to those of $J/\psi + \pi^+$). The procedure to extract the normalisation of this sample is similar to that of the hybrid sample, but the fit function does not include the contribution from $J/\psi + \pi^+$. The fit model components are listed in table 5.5 and the result of the fit is shown in 5.6.

The $J/\psi + X$ sample normalisation is computed as $\frac{N_{Data}^{sig}}{N_{MC}^{sig}} = 5.58 \pm 0.04$.

Event type	Contribution	Model
Signal	$B^+ \rightarrow J/\psi + K^+$	Two Gaussian functions with different means and widths
Background	Combinatorial: J/ψ associated with uncorrelated particle	First-order Chebyshev polynomial
	Partially reconstructed B^+	Generalised ARGUS distribution

TABLE 5.5: List of the sources that contribute to the $J/\psi + K^+$ invariant mass distribution

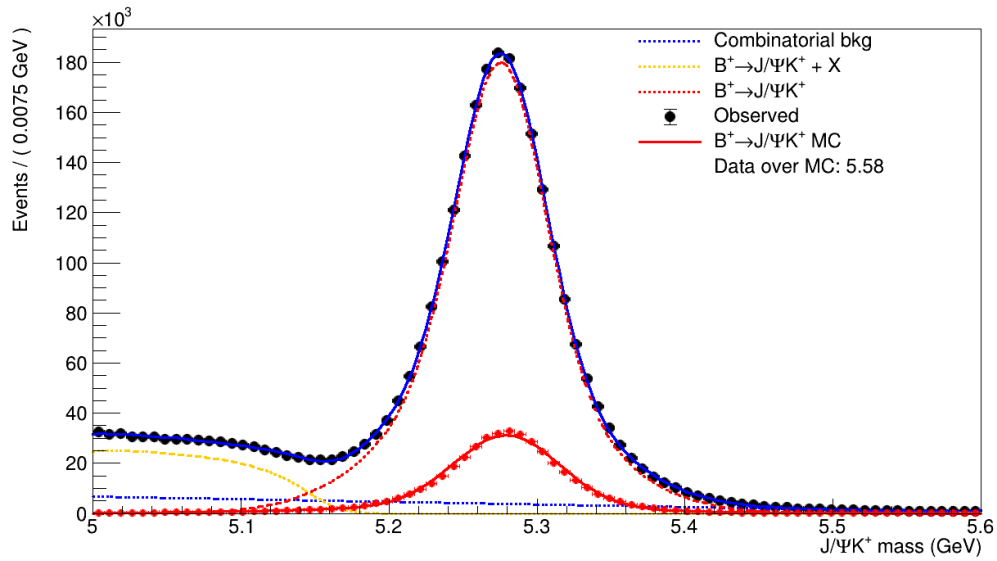


FIGURE 5.6: Invariant mass distribution for the $J/\psi + K^+$ system.

This sample includes the *fake* events, but the normalisation computed above can not be used for them: fake shapes and yields depend on the cuts chosen to reject them, thus the normalisation cannot be considered constant. Section 5.6 contains the details.

- **$H_b \rightarrow J/\psi + \mu$ sample normalisation.** The $H_b \rightarrow J/\psi + \mu$ sample has been produced with PYTHIA8 and the H_b decays have been simulated by EvtGen, using the branching fractions predicted by the theoretical models. EvtGen is set up to produce decays of the type: $H_b \rightarrow J/\psi(\mu\mu) + \mu$, so this sample can be used to model the combinatorial $J/\psi(\mu\mu) + \mu$ background but not the fake events because the unpaired muon is selected to be a real muon. The $J/\psi + \mu$ sample does not include any standard candle. However, in the high mass region ($m_{3\mu} > m_{B_c^+}$), which is called *side-band*: the events from the other background sources are negligible. Therefore, the normalisation of the $H_b \rightarrow J/\psi + \mu$ sample can be found computing the ratio: $N_{Data}(m_{3\mu} > m_{threshold})/N_{MC}(m_{3\mu} > m_{threshold})$, where the *threshold* is the $m_{3\mu}$ over which the background can be considered negligible (Figure 5.7). The threshold was fixed at 6.5 GeV because it is higher than B_c^+ mass $((6274.47 \pm 0.32) \text{ MeV})$: the contributions from background sources different from the combinatorial one can be neglected. The normalisation obtained is:

$$\frac{N_{Data}(m_{3\mu} > 6.5 \text{ GeV})}{N_{MC}(m_{3\mu} > 6.5 \text{ GeV})} = 8.53 \pm 0.63$$

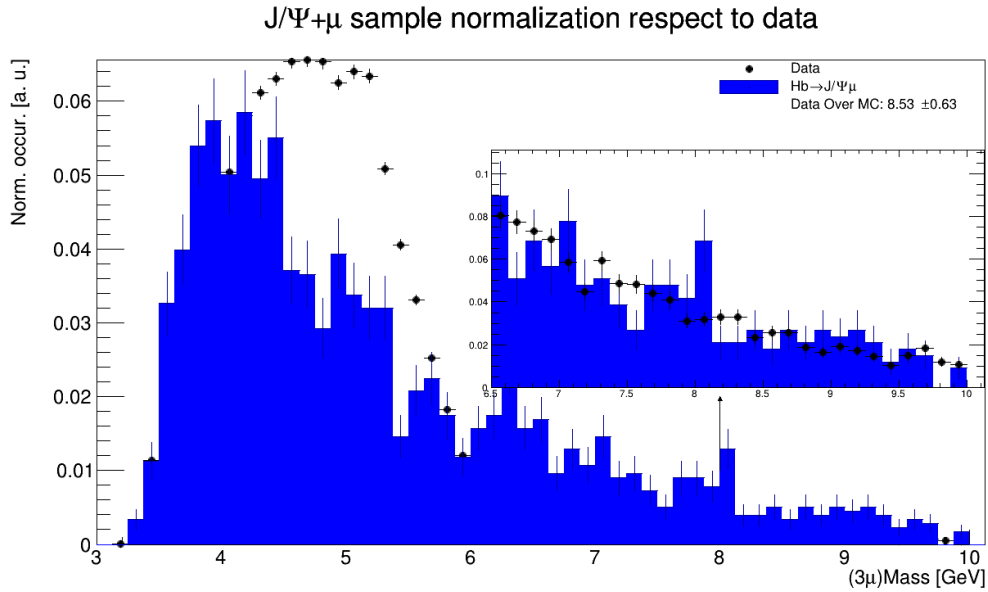


FIGURE 5.7: Mass of the three muons system in the final state

5.5.4 Genetic Algorithm for optimisation of parameters

Genetic algorithm (GA) is one of the simplest random-based Evolutionary Algorithms (EAs). Evolutionary algorithms are dynamic in nature, as they evolve with time [71]. Their main characteristics are as follows:

- Population-Based: Evolutionary algorithms optimise a process in which current solutions are poor to generate new better solutions. The set of current solutions from which new solutions are to be generated is called the population.
- Fitness-Oriented: If there are several solutions, one has to find out the best one. There is a fitness value associated with each individual solution calculated from a fitness function. Such fitness value reflects how good the solution is.
- Variation-Driven: If there is no acceptable solution in the current population according to the fitness function calculated from each individual, we should still try to generate new better solutions. As a result, individual solutions will undergo a number of variations to generate new solutions.

The genetic algorithm is a random based classical evolutionary algorithm. The word random here means that in order to find a solution using GA, random changes are applied to the present solutions to generate the new possible ones. Since GA is simple in its application compared to other EAs, it is often called Simple GA (SGA). GA as the name suggests, is based on Darwin's theory of evolution. Both are slow and gradual processes that work by making changes slowly over a time period. Below is a typical flowchart of the Genetic algorithm routine:

- Initialization
- Population
- Fitness Calculation
- Mating Pool
- Parent Selection

- Mating : Crossover; Mutation
- Offspring

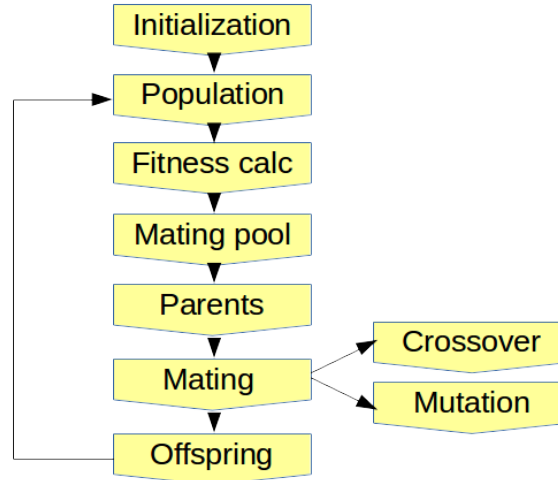


FIGURE 5.8: Flowchart of Genetic Algorithm

In living organisms, there are several genes on a chromosome, which makes an individual unique and decides the superiority of that individual over other individuals in a population. Similarly in GA, one possible set of values forms a solution or an individual. Group of such possible solutions makes a population. Below is a more elaborate description.

Initialisation: The variables which are optimised using the GA are first initialised with a starting value within a pre described range. This starting value is chosen randomly within a range which is different for different variables. For example transverse mass of unpaired muon is initialised to have a random value between 2 and 4 GeV. Each variable is like a gene, which makes the chromosome. Each variable is thus assigned some initial random value. One such set is called an individual or a chromosome. Many such individuals are defined in the given ranges.

Population: All possible sets of solutions after initialisation form a group, called the population. The individuals in the population are also called parents, because they give rise to offspring in the future.

Fitness Value: Like genes decide the fitness of an individual in living beings, similarly in GA they decide which individual is fit to generate the offspring. It is

the survival of the fittest rule. A figure of merit is chosen to be a fitness value and is calculated for each individual. The higher the fitness value, the higher is the quality of the solution. Based on these fitness values, individuals are selected for what is called a mating pool.

Individuals in a mating pool are called parents. The number of parents to be present in the mating pool is predefined by the user. Every two parents will give rise to two offspring (children), naturally passing on good qualities to them. By repeating this process of selecting high quality individuals, we have higher chances of keeping only good qualities and to reach an optimal solution.

The offspring generated by crossover of selected parents will only have the characteristics of the parents, without any variations or improvements. The bad qualities of parents might also pass onto the new offspring. To overcome this fault, each offspring is modified to create a new individual. This modification is called a mutation. A random change of a gene can lead to an individual called a mutant. Mutated individuals and new sets of individuals form a new population which replaces the old one. Each new population created is called a Generation and the entire process is repeated again.

The user provides:

- The number of individuals comprising the population.
- The number of generations required
- The number of parents in each generation
- The number of mutations desired
- Fitness function

For our analysis, we optimise the transverse momenta of muons coming from J/Ψ , the unpaired muon and the B_c , the vertex probabilities of J/Ψ and B_c , angular parameters, B_c mass, the delta R between the J/Ψ and unpaired muon, impact parameter significance. For fitness function we use the combination of two figures of merits. First one (F_1) is the ratio of signal (tau channel) over square root of signal plus background. Where signal and background means the number of signal and background events which cross the cuts value for each variable after optimisation respectively. The second one (F_2) is the deviation of ratio of efficiencies of tau and

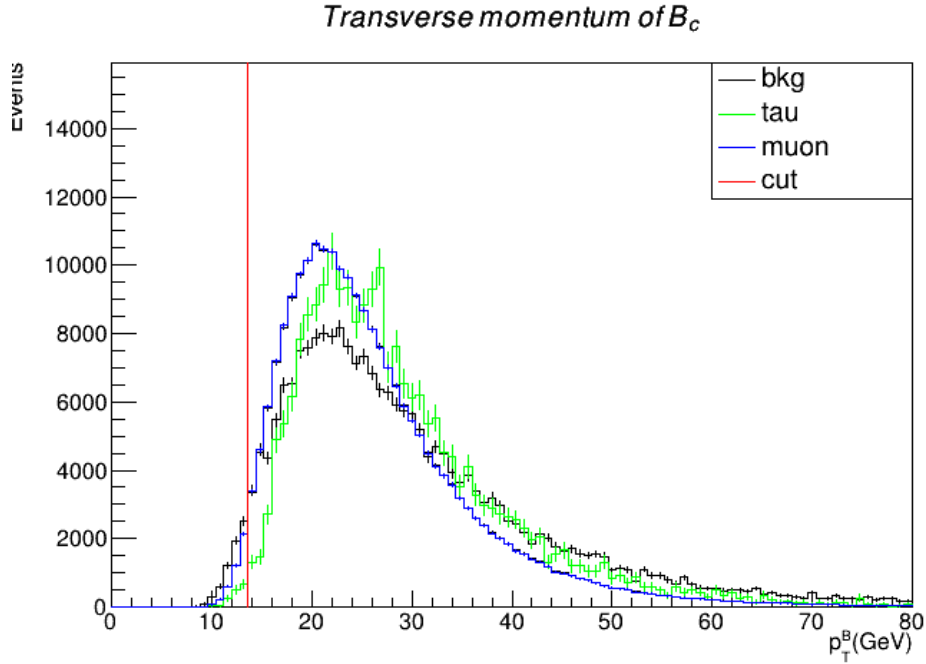
muons (ϵ_T and ϵ_M respectively) from 1. The formulae for both the figures of merits and the combination of these two to form the fitness functions (F) is described below:

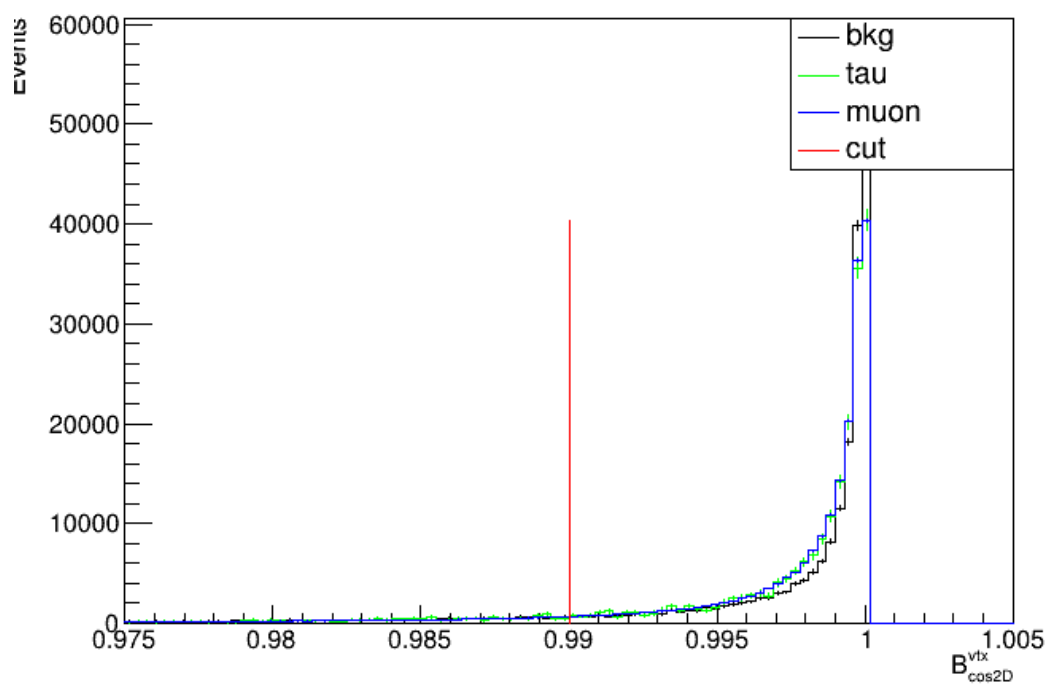
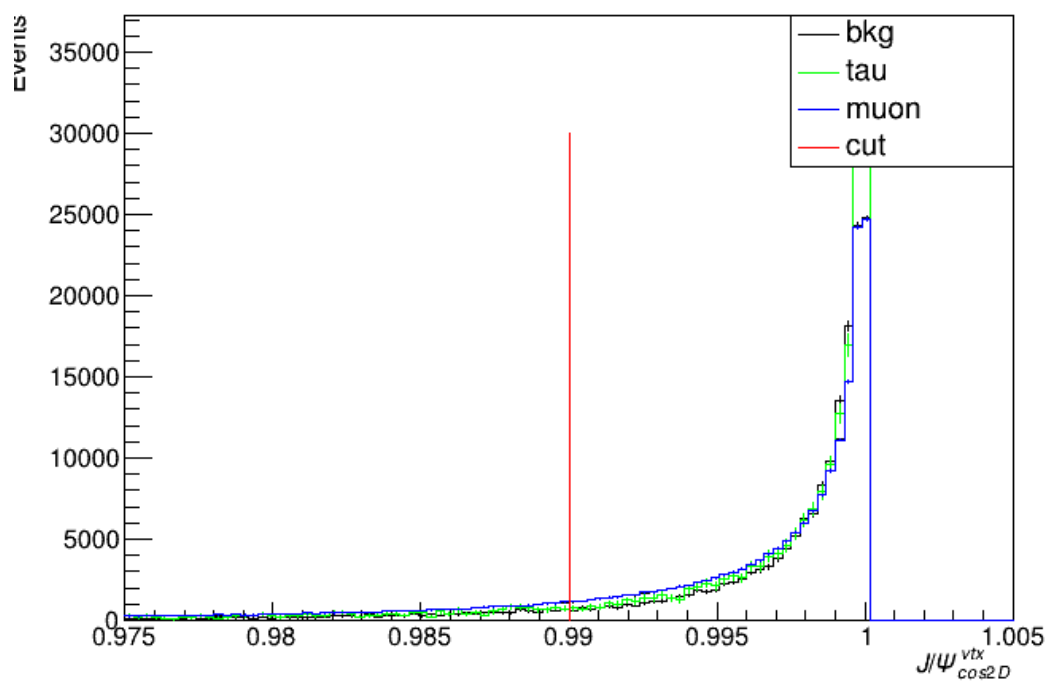
$$\begin{aligned} F_1 &= \frac{N_{\tau}}{\sqrt{N_{bkg}}} \\ F_2 &= \left| 1 - \frac{\epsilon_T}{\epsilon_M} \right| \\ F &= F_1\lambda + \frac{(1-\lambda)}{F_2} \end{aligned} \quad (5.2)$$

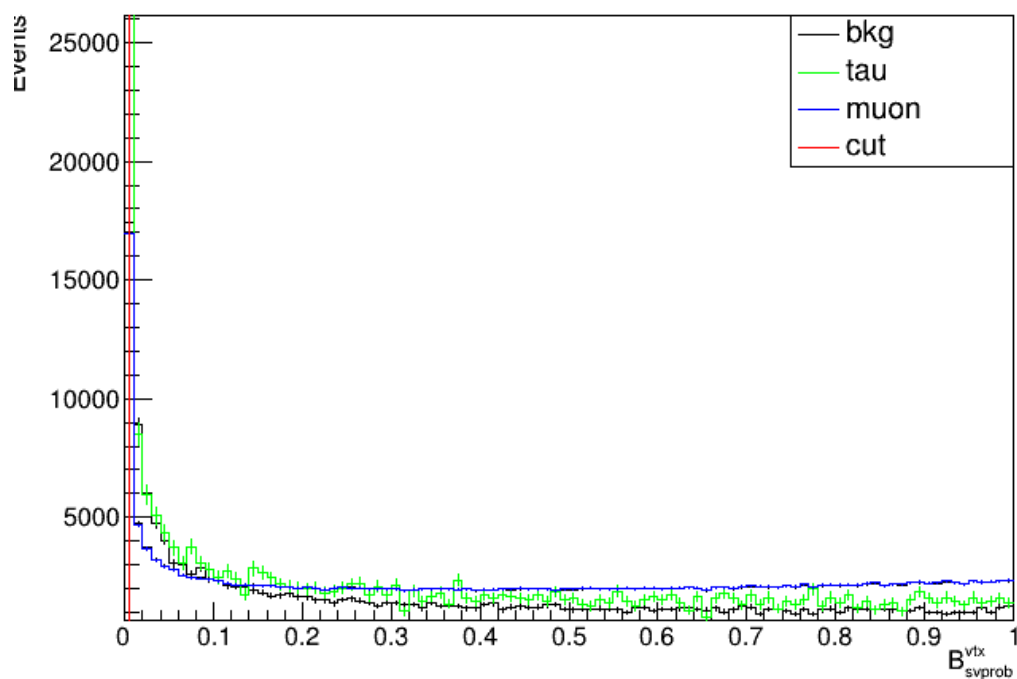
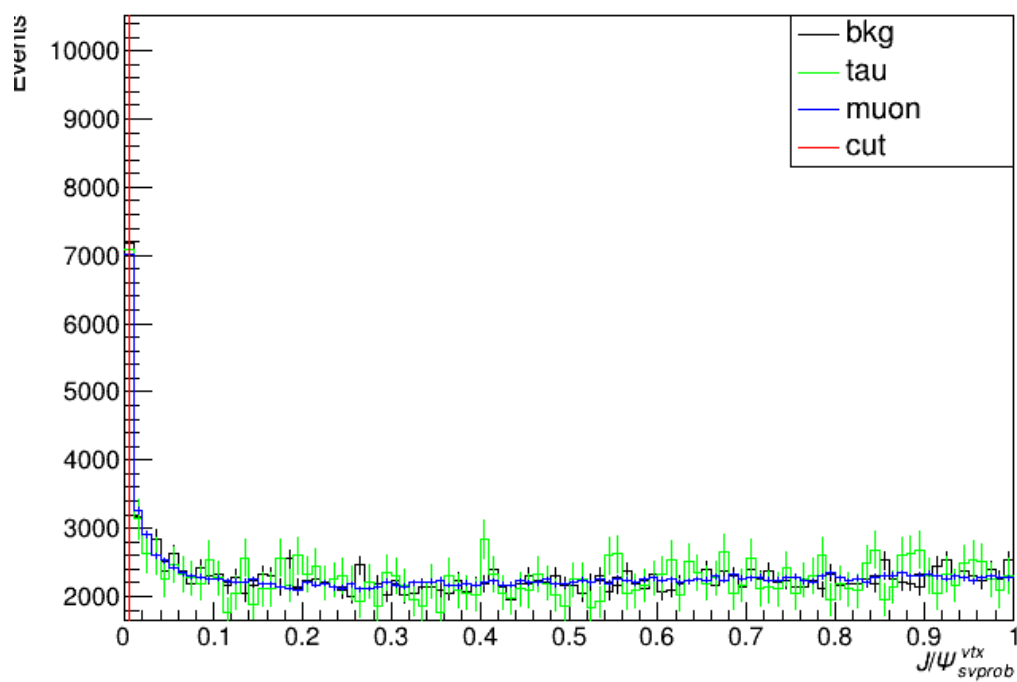
where, λ is a scaling factor between the combination of two figures of merits. The value of lambda decides the weight given to individual figure of merit. The goal of this algorithm is two fold:

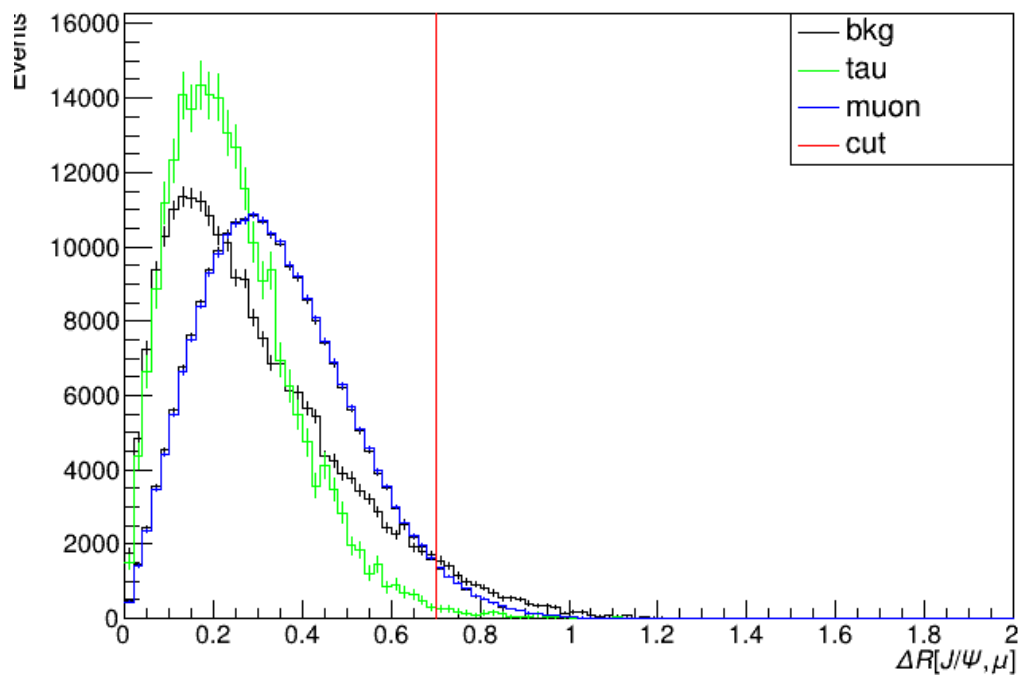
- To maximise F_1 , which in turn results in distinguishing signal over background efficiently.
- To minimise F_2 , which ensures similar tau and muon events efficiencies.

λ value of 0.75 ensures more weight to the tau and background discrimination factor. This value to lambda gave us the best background rejection efficiencies. The variable distributions after are shown below.

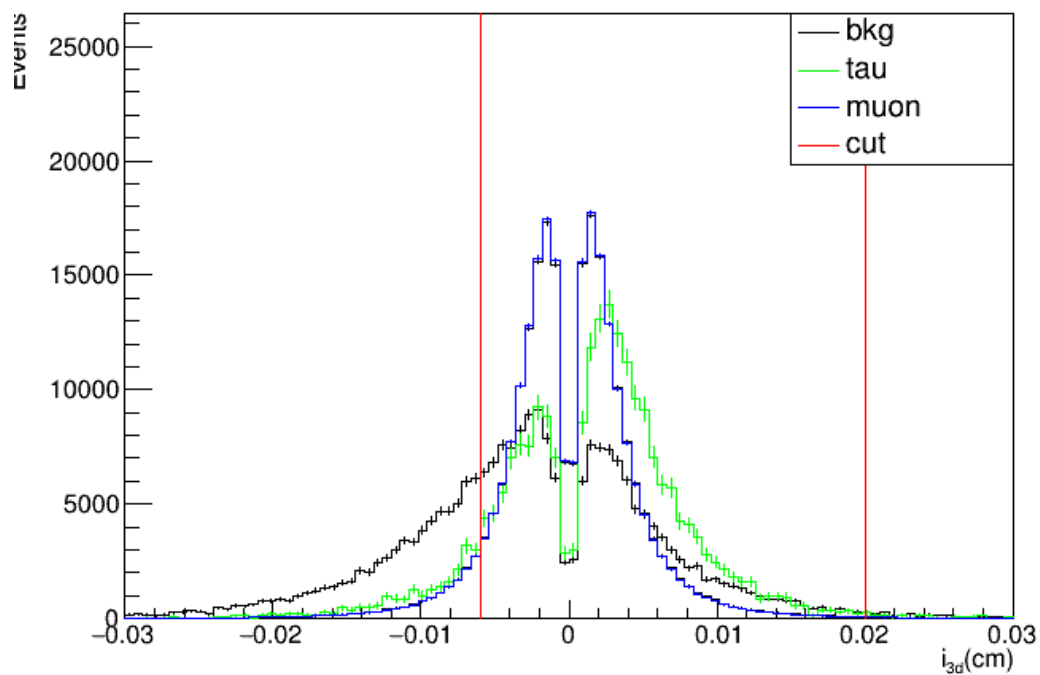


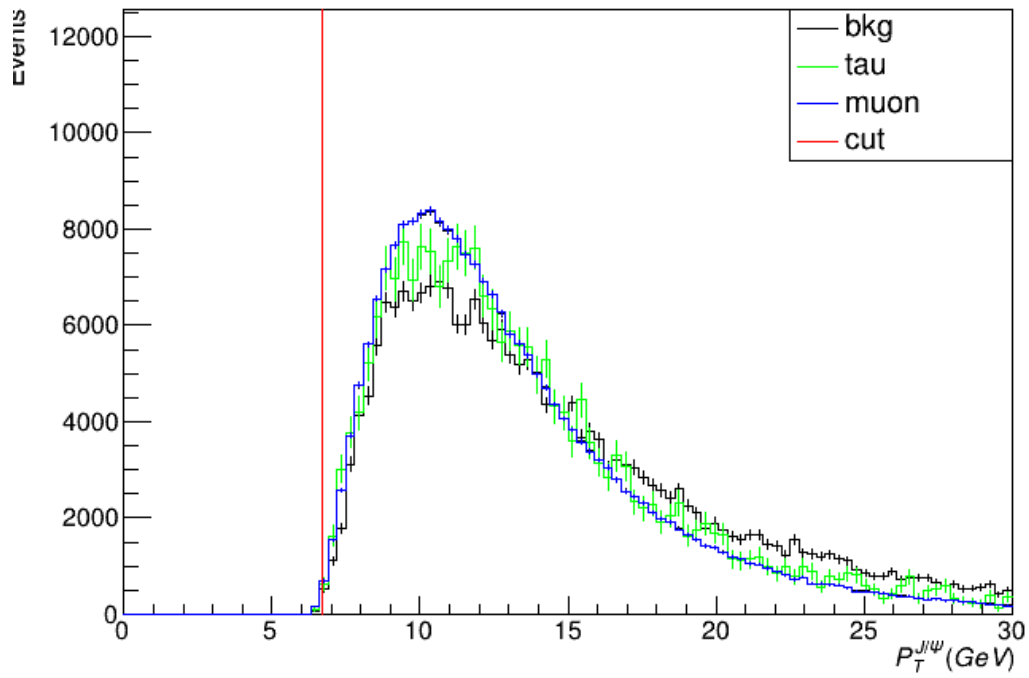
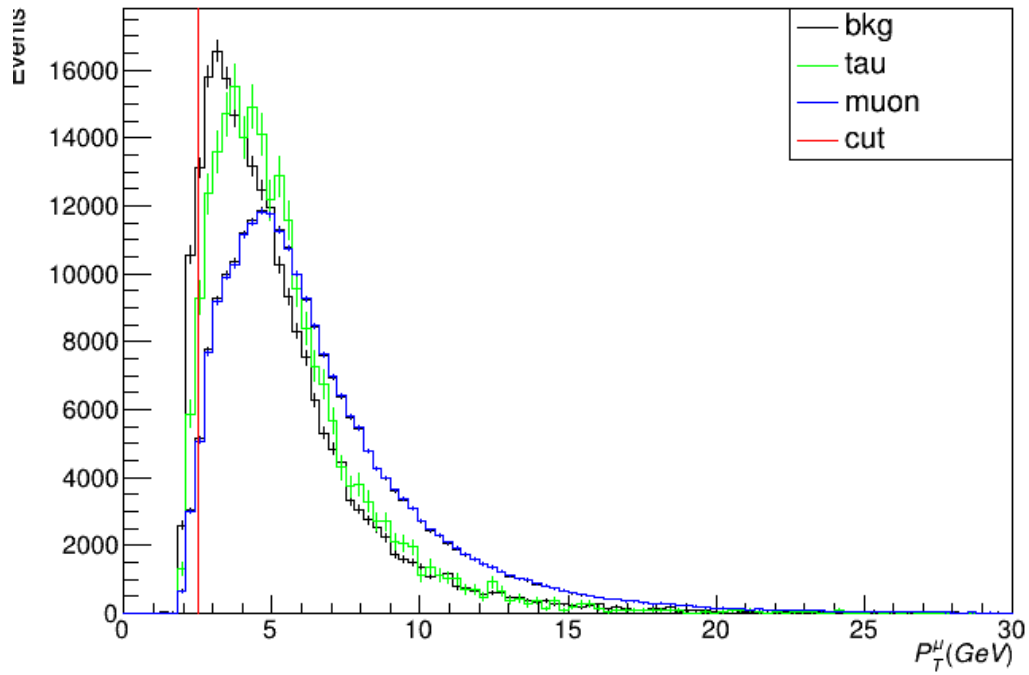
B_c vertex angular parameter J/ψ vertex angular parameter

Vertex probability of B_c *Vertex probability of J/ψ* 

ΔR between J/ψ and unpaired muon

3D impact parameter



Transverse momentum of J/ψ *Transverse momentum of unpaired muon*

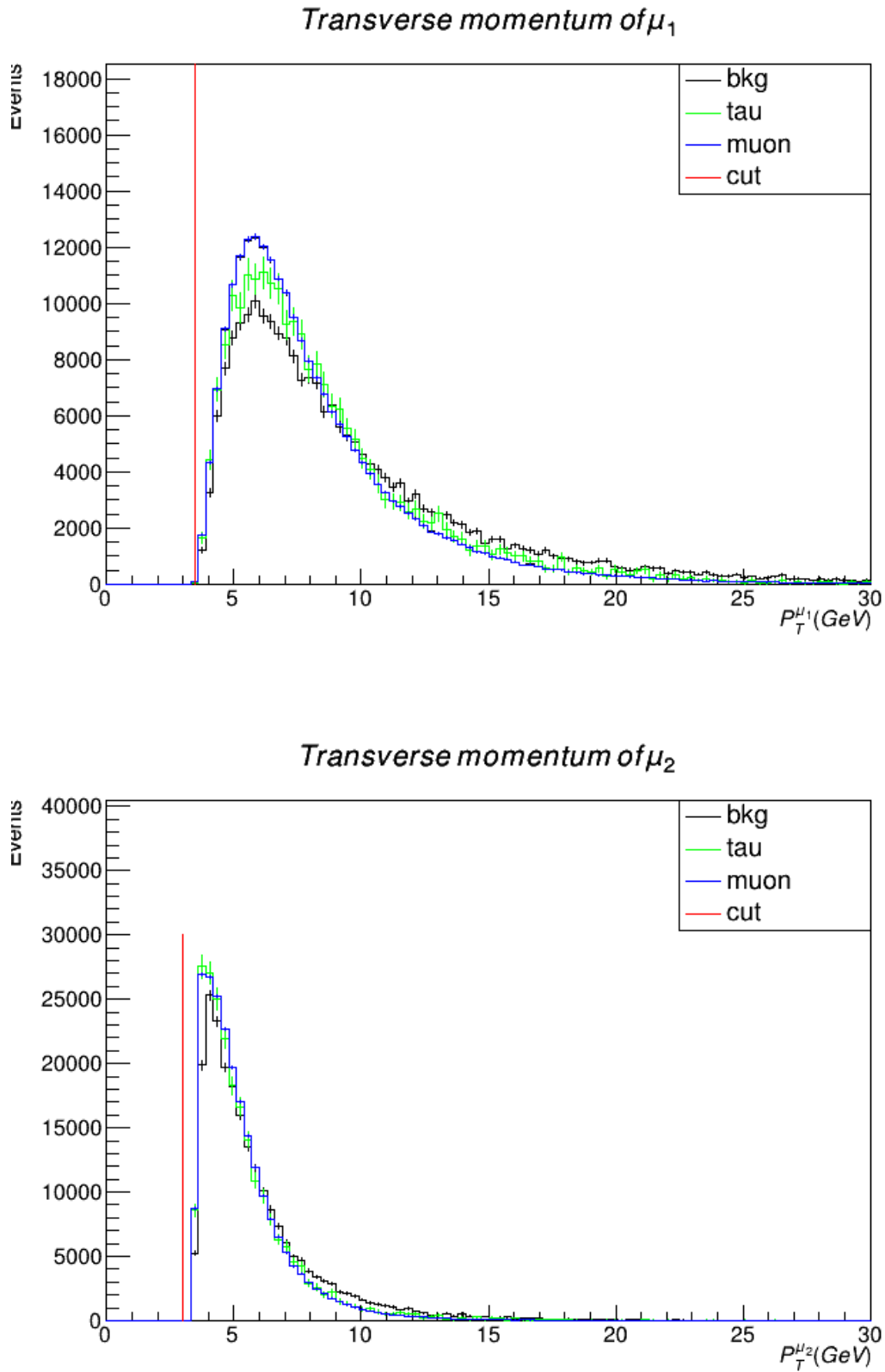


FIGURE 5.9: Distribution of the various kinematic variables. Black depicts the background, green is τ channel and blue is μ channel. The optimised cuts are shown with red lines.

The optimised variables:

- Transverse momentum of $\mu_1 > 3.5$ GeV
- Transverse momentum of $\mu_2 > 3.0$ GeV
- Transverse momentum of unpaired muon > 2.5 GeV
- Transverse momentum of $J/\Psi > 6.7$ GeV
- Vertex probability of $J/\Psi > 0.005$
- J/Ψ vertex angular parameter > 0.99
- Vertex probability of $B_c > 0.005$
- B_c vertex angular parameter > 0.99
- Transverse momentum of $B_c > 13.5$ GeV
- ΔR between J/Ψ and unpaired muon < 0.7
- 3D impact parameter is in between -0.006 and 0.02

along with the signal and background efficiencies as:

- Tau efficiency = $57.2 \pm 0.1\%$
- Muon efficiency = $59.5 \pm 0.1\%$
- Background efficiency = $51.1 \pm 0.2\%$

These efficiency values are in addition to the basic cuts, which are mentioned in table 5.6.

Final efficiency values, after putting all the cuts (reconstruction level, basic and the ones optimised) are:

- Signal channel = $41.8\% \pm 0.8\%$
- Normalisation channel = $47.7\% \pm 0.7\%$
- Background channels = $7.0\% \pm 0.5\%$

Trigger	Dimuon0
Muon Id for all 3 μ	Medium
Mass of B_c	< 6.0 GeV
$|\text{Mass of } J/\Psi - 3.0969|$ for both μ in barrel	< 0.08 GeV
$|\text{Mass of } J/\Psi - 3.0969|$ for both μ in endcap	< 0.01 GeV
$|\text{Mass of } J/\Psi - 3.0969|$ for one μ in barrel and other in endcap	< 0.01 GeV

TABLE 5.6: Basic cuts applied after the reconstruction procedure and before selection optimisation

5.5.5 Montecarlo validation

To check if the selected cuts are properly optimised or not, a validation procedure is adopted. If the same cuts used on data and Monte Carlo simultaneously, give rise to similar distribution of variables, the cuts are said to be optimised. This procedure of mimicking Monte Carlo as close as possible to experimental data is called *Montecarlo validation*.

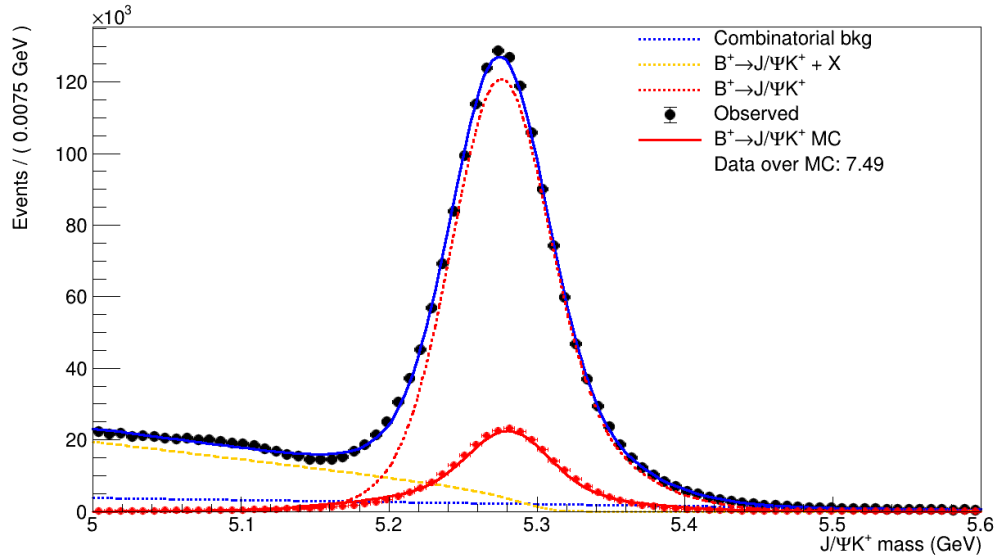


FIGURE 5.10: $J/\Psi + K$ mass peak

Monte Carlo validation is done using the $J/\Psi + \text{Kaon}$ channel. Figure 5.10 shows the $J/\Psi + \text{kaon}$ invariant mass distribution fitted with the signal and various background contributions. We see that there is only one major contribution beyond

mass 5.35 and that is combinatorial background. This can be efficiently used in calculating the $J/\Psi + K$ signal contributions.

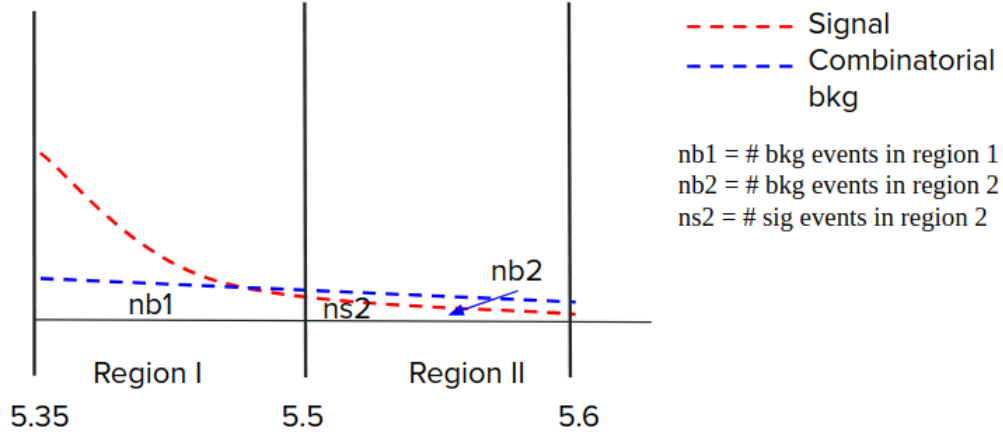


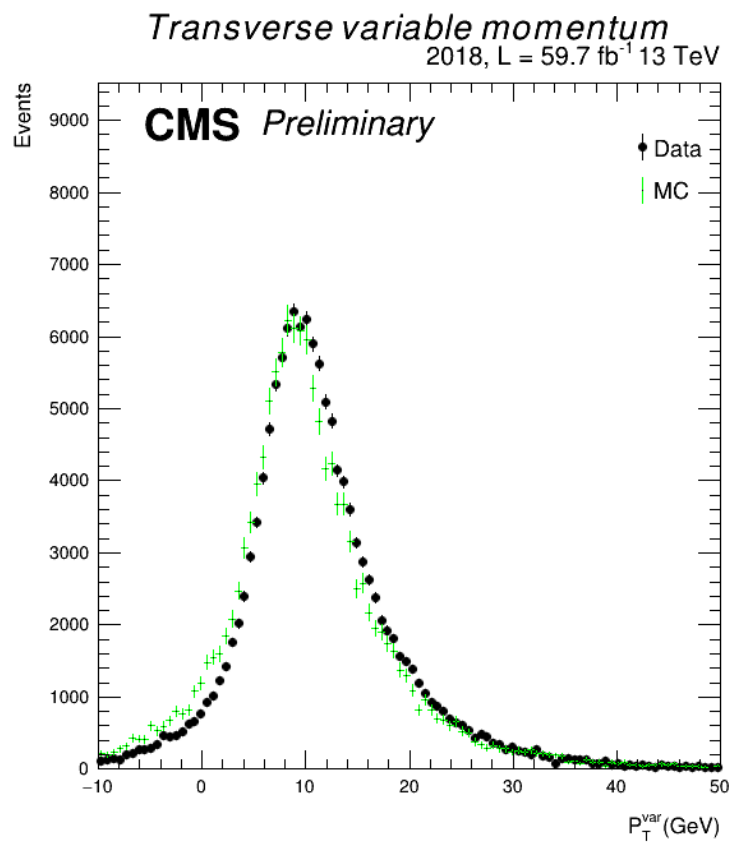
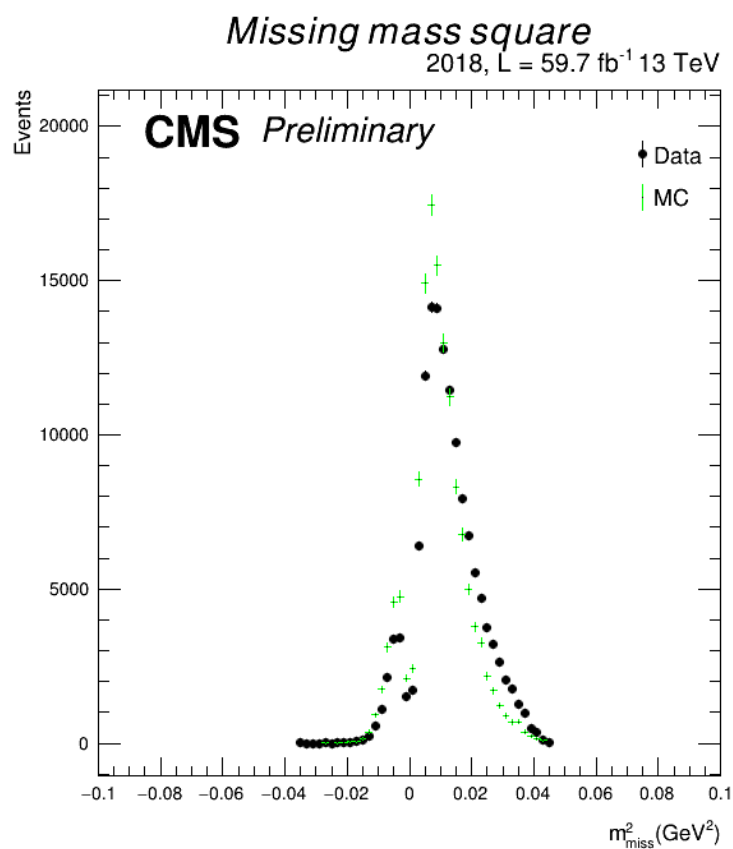
FIGURE 5.11: Method used for validation

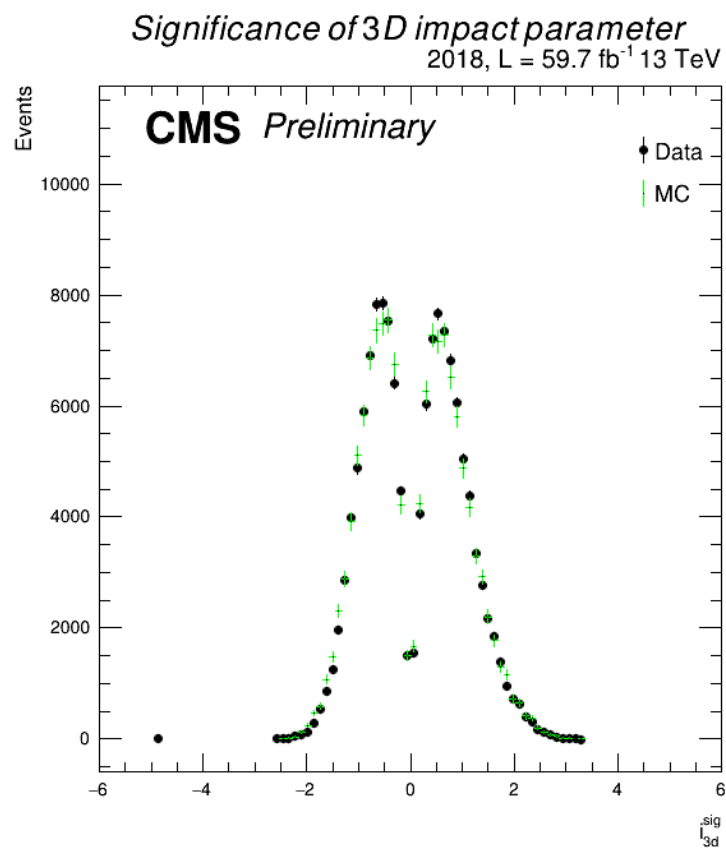
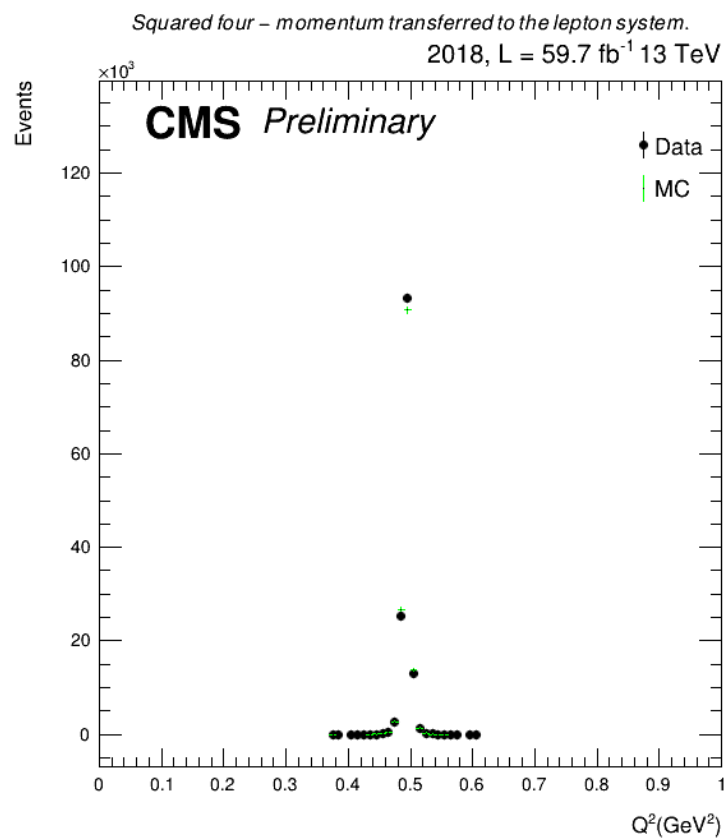
Method used is shown in figure 5.11. Region beyond 5.35 is divided in two parts. Region I from 5.35 - 5.5 and Region II from 5.5 - 5.6 mass value. $nb1$ and $nb2$ are the number of background events in Region I and Region II respectively. $ns2$ is the number of signal events in region II. Combinatorial background contribution which is almost constant in both the regions is used to calculate the weighing factor W and distributions of discriminating variables in Region II are plotted using equation 5.3.

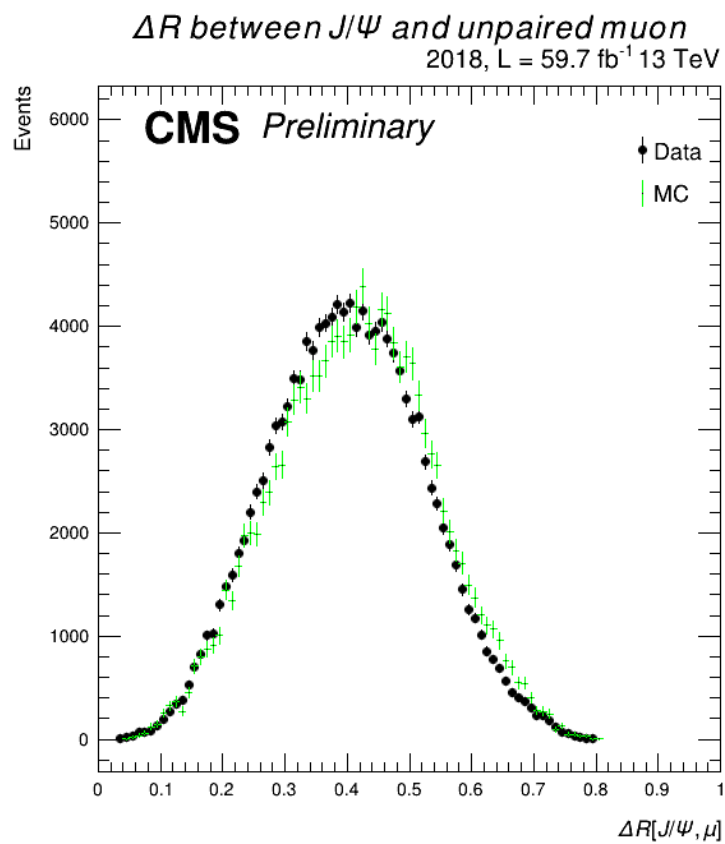
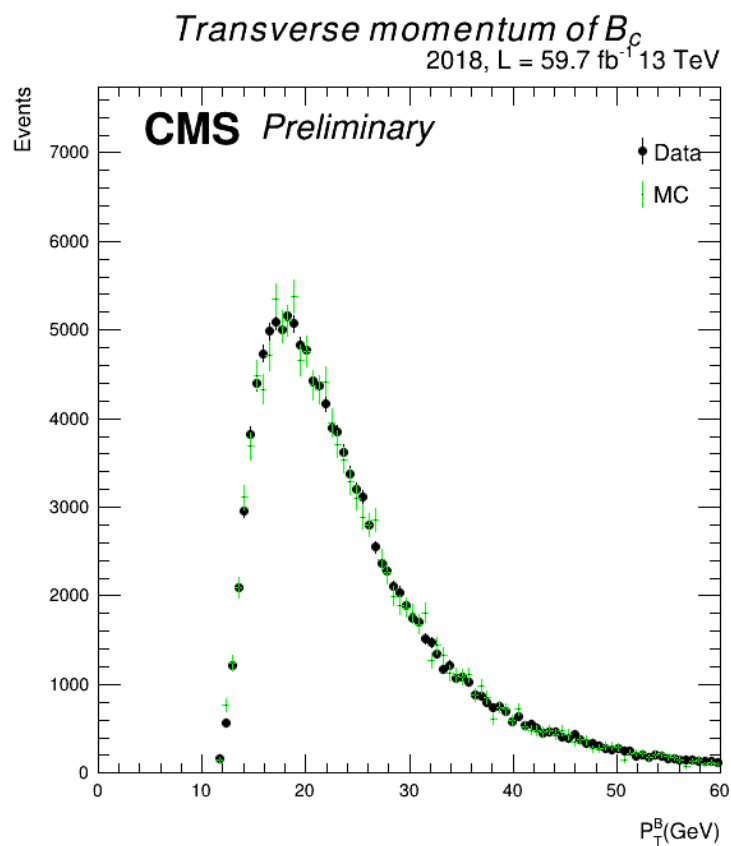
$$W = \frac{nb1}{ns2 + nb2} \quad (5.3)$$

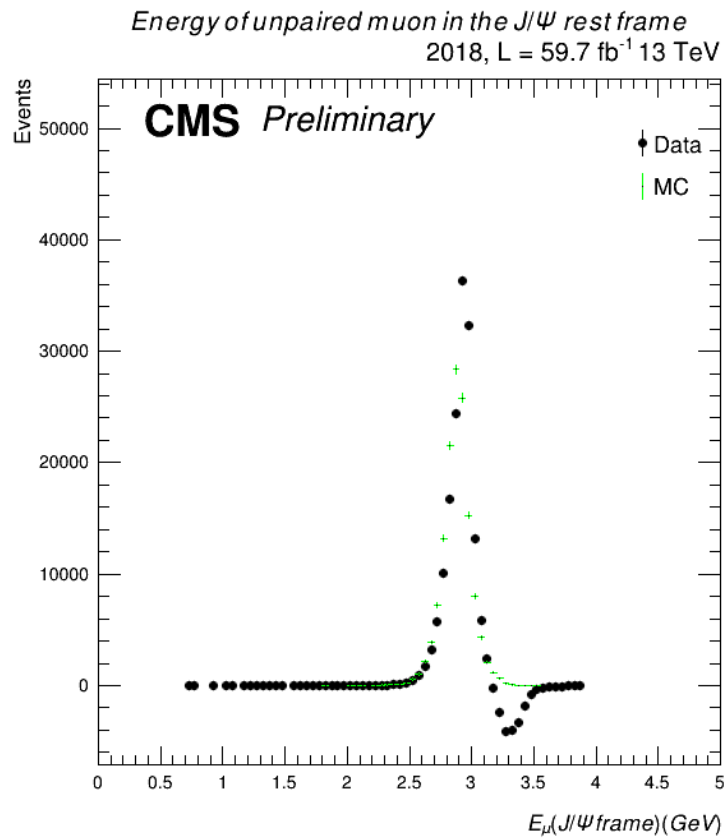
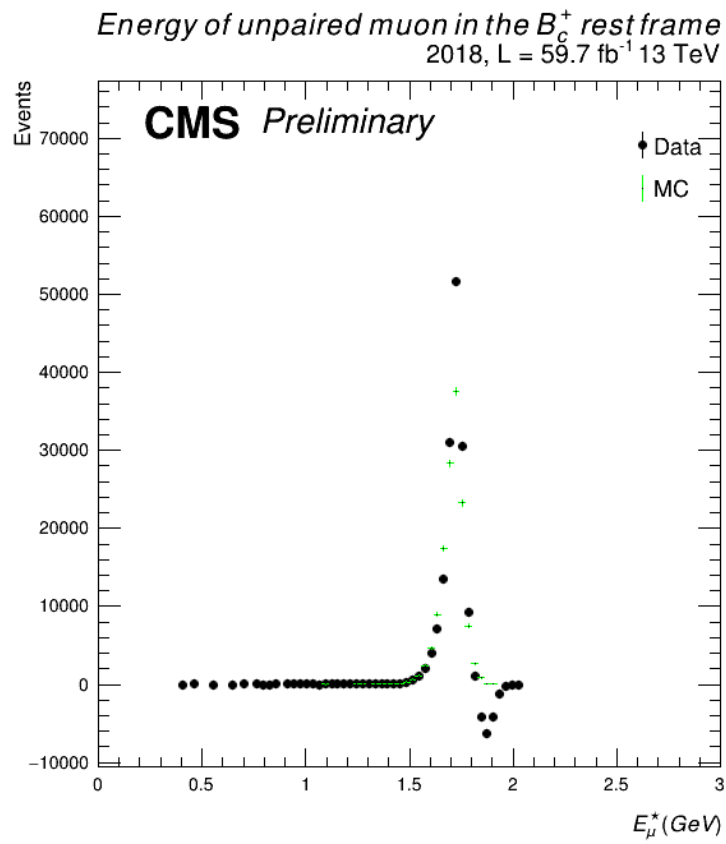
$$PDF(sig) = PDF(regI) - W \times PDF(regII)$$

Plots of discriminating variables for $J/\Psi + K$ channel, are shown below:









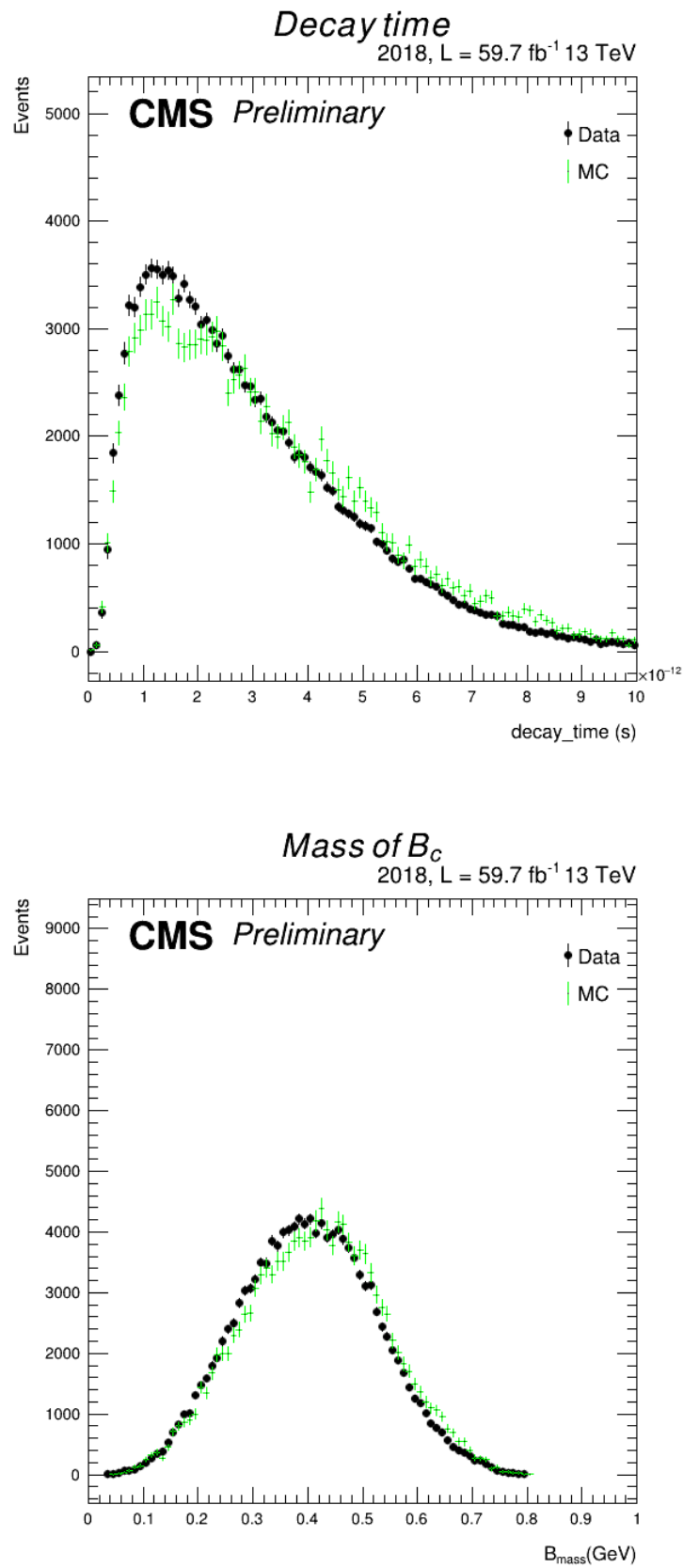


FIGURE 5.12: Validation plots for $J/\Psi+K$ channel, with data in black points and Monte Carlo in green points.

5.6 Fit with Montecarlo

Binned maximum likelihood fits for the discriminating variables are done using the templates for fakes from Monte Carlo samples. A closure test of the fit procedure is performed by splitting the Monte Carlo sample into half: where one half is used to extract the shapes and the other half is used to perform the fit. Finally, this fit procedure is applied to data and systematic uncertainties are evaluated ².

Type	Component	# events
Signal	$B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau$	2281 ± 107
normalisation	$B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu$	2717 ± 160
Background	$B_c^+ \rightarrow \chi_{c0} \mu^+ \nu_\mu$	814 ± 121
	$B_c^+ \rightarrow \chi_{c0} \mu^+ \nu_\mu$	
	$B_c^+ \rightarrow \chi_{c1} \mu^+ \nu_\mu$	
	$B_c^+ \rightarrow \chi_{c2} \mu^+ \nu_\mu$	
	$B_c^+ \rightarrow \psi(2S) \tau^+ \nu_\tau$	
	$B_c^+ \rightarrow \psi(2S) \mu^+ \nu_\mu$	
	$B_c^+ \rightarrow h_c \mu^+ \nu_\mu$	
	$B_c^+ \rightarrow J/\psi H_c^+$	
Fakes	Unpaired muon misidentified	395 ± 55

TABLE 5.7: List of the templates used for the fit of the Q^2

In order to extract the $R(J/\psi)$ measurement, a binned maximum likelihood fit of the Q^2 is performed using the shapes of the various components from the MC. The fit is performed using the **RooFit** suite and ROOT. The probability density function (PDF) of each component is built from the relative binned distribution with **RooHistPdf**, returning a PDF sampled from a histogram with an interpolation order, set to 0 for this work. The fit model is described by equation 5.4 and the components are listed in table 5.7.

$$f(Q^2) = \alpha \cdot PDF_{signal} + \beta \cdot PDF_{normalisation} + \gamma \cdot PDF_{bkg} + \delta \cdot PDF_{fakes} \quad (5.4)$$

where $\delta = 1 - \alpha - \beta - \gamma$

The four templates are fitted to the Q^2 distribution. The PDFs of these templates, including the fakes are taken from the Montecarlo. The results of the procedure are shown in 5.13. The evaluated χ^2 is: 7.5.

²This work has major contribution from a master's student: Pasquale Andreola

The result of the closure test, performed splitting in half the MC sample, is shown in 5.14. The ratio between the number of signal events and normalisation events estimated by the fit on the first half of the MC sample is: $\mathcal{R}_{J/\psi}^{\text{MC, half1}} = 0.09 \pm 0.04$. This result is compatible with the value obtained counting the signal and normalisation events in the other half of the MC sample: $\mathcal{R}_{J/\psi}^{\text{MC, half2}} = 0.0995 \pm 0.0001$. The evaluated χ^2 for the fit performed as a closure test is: $\chi_{\text{Closure}}^2 = 1.2$.

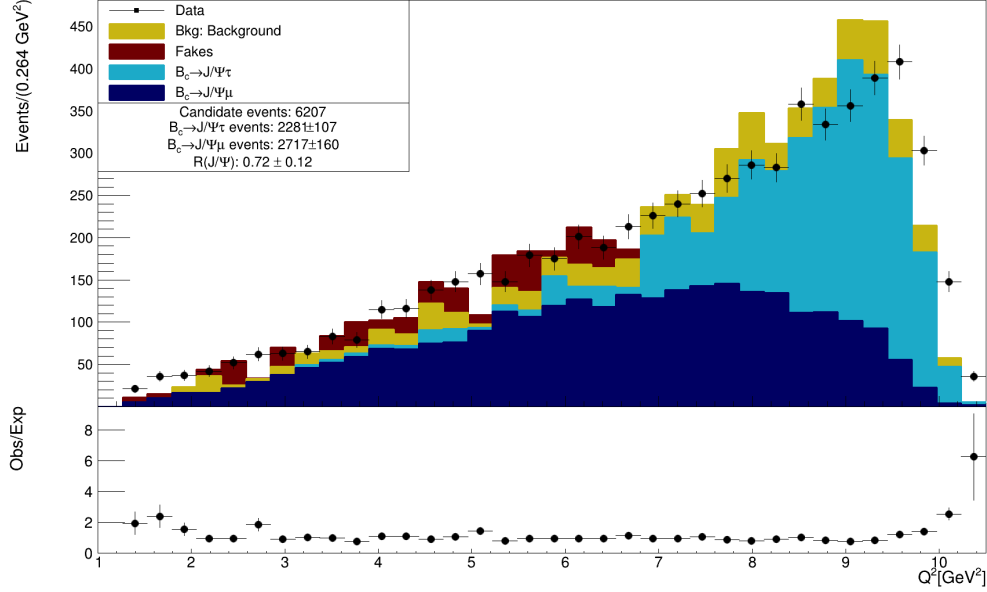


FIGURE 5.13: Fit of the Q^2 distribution. The model of the fit is described in 5.4. Light blue represents the signal events, blue represents the normalisation events, yellow represents the background events and red represents the fakes events

The number of signal ($B_c^+ \rightarrow J/\psi\tau$) events obtained from the fit is 2281 ± 107 whereas the number of normalisation ($B_c^+ \rightarrow J/\psi\mu$) events is 2717 ± 160 . In order to extract the correct $\mathcal{R}_{J/\psi}$ measurement, the numbers of events extracted from the fit have to be weighted by the relative reconstruction efficiencies:

$$\mathcal{R}_{J/\psi} = \frac{\#_{\text{Signal}}}{\epsilon_{\text{Signal}}} \cdot \frac{\epsilon_{\text{normalisation}}}{\#_{\text{normalisation}}} \quad (5.5)$$

The reconstruction efficiencies are defined as the ratio between the number of signal (normalisation) events in the MC sample after and before the cuts (these efficiencies differ from the one evaluated in 5.5.4 because those are evaluated in comparison to the preselection cuts). The resulting efficiencies are listed in 5.6. The uncertainties that affect the efficiencies (the relative uncertainties are $\sim 1\%$ for the signal efficiency and $\sim 4\%$ for the normalisation efficiency) are caused by

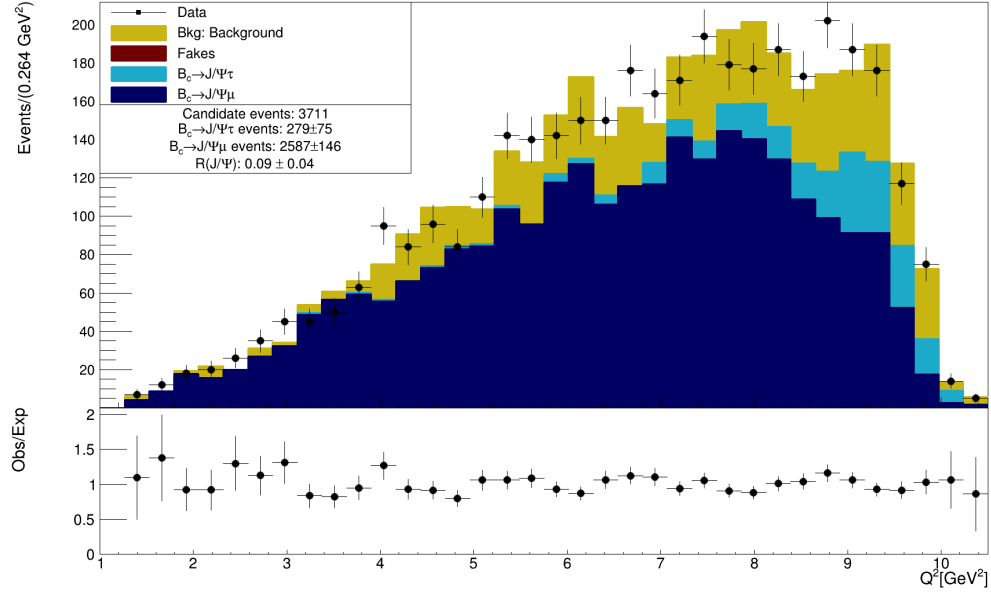


FIGURE 5.14: Fit of the Q^2 distribution of half of the MC sample. The model of the fit is described in 5.4. Light blue represents the signal events, blue represents the normalisation events, yellow represents the background events and red represents the fakes events

the limited size of the MC sample.

$$\begin{aligned}\epsilon_{\text{Signal}} &= (1.64 \pm 0.02)\% \\ \epsilon_{\text{normalisation}} &= (1.42 \pm 0.06)\%\end{aligned}\tag{5.6}$$

Finally, the value of $\mathcal{R}_{J/\psi}$ is extracted:

$$\mathcal{R}_{J/\psi} = 0.72 \pm 0.12^3\tag{5.7}$$

where the uncertainty is statistical only and it is obtained from the uncertainties of the signal and normalisation yields and the uncertainties of the efficiencies. This result lies within 3.8 standard deviations from the Standard Model estimate (0.2582 ± 0.0038 , from [72]). However this result is compatible with the result from LHCb ($0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$ [19]).

The systematic uncertainties are still under study. Possible sources are:

- Finite simulation size
- $B_c^+ \rightarrow J/\Psi$ form factors

³The result quoted is preliminary.

- $B_c^+ \rightarrow \Psi(2S)$ form factors
- Fit bias correction (Injection of events with signal or missidentified background to see the effect.)
- Z binning strategy. (varying the threshold in the definition)
- Miss-ID background strategy
- Combinatorial background cocktail
- Combinatorial J/Ψ background scaling
- $B_c^+ \rightarrow D^* H_c X$ contribution
- $\Psi(2S)$ and χ_c feed-down.
- Weighting of simulation samples.
- Efficiency ratio.
- B ($\tau^+ \rightarrow \mu^+ \nu \mu \nu^- \tau$)

Chapter 6

Conclusions

Current understanding of the Standard Model, doesn't answer several existing questions. We have to look beyond it to explore the unknowns. The search for lepton flavour universality is one such exploration. The recent results from other experiments, motivates us and guides us on the right path. Our channel of study specifically has a lot of scope to dig in. We are happy with the current ongoing studies and have positive hopes in the future. The analysis is not yet finalised, but definitely in its mature form. We expect to have some positive presentable results soon.

On the other side, the experimental work going on regarding the upgrade of the inner tracker shall be helpful for the analysis side too. The phase-II upgraded pixel sensor shall aid in achievement of better efficiency in our analysis channel.

The lepton flavour non universality in the Standard Model is caused by the different masses of the various leptons. Even if these mass differences are taken into account in the theory, physics beyond the Standard Model can be explored through the study of some flavour changing charged processes. The $B_c^+ \rightarrow J/\Psi \tau^+ \nu_\tau$ and $B_c^+ \rightarrow J/\Psi \mu^+ \nu_\mu$ process transitions have been presented throughout this work. CMS at LHC is currently a suitable detector to study these processes because it can detect and identify efficiently the muons produced in these interactions. It has been seen that, even if the Collinear Approximation is not the most precise one with respect to the Monte Carlo, it has the most discriminating power.

This thesis, presents the test of the lepton flavour universality (LFU) using the data sample collected by CMS in 2018, corresponding to an integrated luminosity of 59.6 fb^{-1} . The LFU test has been done measuring $R(J/\Psi) = \frac{B(B_c^+ \rightarrow J/\Psi \tau^+ \nu_\tau)}{B(B_c^+ \rightarrow J/\Psi \mu^+ \nu_\mu)}$.

Signal events ($B_c^+ \rightarrow J/\Psi \tau^+ \nu_\tau \rightarrow \mu^+ \mu^- \mu^+ \nu_\mu \nu_\tau \bar{\nu}_\tau$) are discriminated from normalization events ($B_c^+ \rightarrow J/\Psi \mu^+ \nu_\mu \rightarrow \mu^+ \mu^- \mu^+ \nu_\mu$) using cuts on the kinematic variables. In fact, the different numbers of neutrinos in the final state can be exploited to distinguish the two kinds of events. The cuts are optimized to discriminate signal, normalization and background events using a Genetic Algorithm.

A final fit of the Q^2 is performed using four different templates representing signal, normalization, background and fake events. The $R(J/\Psi)$ measurement presented in this work is: $R(J/\Psi) = \frac{B_c^+ \rightarrow J/\Psi \tau^+ \nu_\tau}{B_c^+ \rightarrow J/\Psi \mu^+ \nu_\mu} = 0.72 \pm 0.12$. This result doesn't include the systematic uncertainties at this moment but is compatible with the value measured from LHCb [19] and shall improve after all considerations.

To keep the experiment running smoothly, the detector needs continuous monitoring and development. It is a great opportunity to learn closely about the detector's working and be a part of the experimental upgrades planned for the future. I actively studied test beam analysis for phase-II upgrade of tracker (as described in experimental chapter) and also did some validation tasks in Data Quality Monitoring (DQM) for the phase-II tracker upgrade. Simulations are extremely important for finalising designs, extracting physics potential etc. DQM is an important tool in CMS to check detector or physics performances. The work consists of developing software to allow monitoring (validation of histograms for hit properties) of reconstructed hits in Silicon tracker, especially implementing new diagnostic histograms depending on phase-II conditions. New pixel designs are about to be finalised after the final round of beam tests and soon the large scale production shall begin. All these studies are presented in detail in this thesis and point towards positive results in future.

It has been a great learning experience on both fronts: to monitor the detector closely and also analyse the data coming from it. I feel with all these activities, just the tip of the big iceberg has been touched. A lot is remaining to learn and discover the potentials of new physics from the CMS experiment. I hope for many fruitful results to present in future.

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Abbreviations

CERN		European Organization for Nuclear Research
INFN		Istituto Nazionale di Fisica Nucleare
LHC	.....	Large Hadron Collider
HL-LHC	.....	High Luminosity Large Hadron Collider
CMS	.....	Compact Muon Solenoid
ATLAS	.....	A Toroidal LHC ApparatuS
LHCb	.....	Large Hadron Collider beauty
ALICE	.....	A Large Ion Collider Experiment
IT	.....	Inner Tracker
OT	.....	Outer Tracker
HCAL	.....	Hadron Calorimeter
ECAL	.....	Electromagnetic Calorimeter
TIB	.....	Tracker Inner Barrel
TID	.....	Tracker Inner Disks
TOB	.....	Tracker Outer Barrel
TEC	.....	Tracker End Caps
SM	.....	Standard Model
BSM	.....	Beyond Standard Model
LFNU	.....	Lepton FLavour Non-Universality
TCAD	.....	Technology Computer-Aided Design
TeV	.....	Tera Electron Volts
ROC	.....	Read Out Chip
PV	.....	Primary Vertex

SV	.....	Secondary Vertex
NN	.....	Neural Network
DNN	.....	Deep Neural Network
BDT	.....	Boosted Decision Tree
MC	.....	Monte Carlo
PF	.....	Particle Flow
AOD	.....	Analysis Object Data entry
FBK	.....	Fondazione Bruno Kessler
RD53	.....	Radiation Damage chip
CMOS	.....	Complementary Metal–Oxide–Semiconductor
HV	.....	High Voltage
DESY	.....	Deutsches Elektronen-SYnchrotron
DQM	.....	Data Quality Monitoring
DAQ	.....	Data Acquisition
CROC		CMS Read Out Chip
DIO5		Digital input output 5(sockets)
ToT		Time over Threshold

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