

Impact of inter-gain calibration on positron energy measurement with the CMS High Granularity Calorimeter

A Thesis

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by

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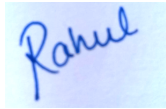
May 2022

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Certificate

This is to certify that this dissertation entitled **Impact of inter-gain calibration on positron energy measurement with the CMS High Granularity Calorimeter** towards the partial fulfilment of the BS-MS dual degree programme at the Indian Institute of Science Education and Research, Pune represents study/work carried out by Rahul Kumar at Indian Institute of Science Education and Research under the supervision of Dr. Seema Sharma, Associate Professor, Department of Physics , during the academic year 2021-2022.



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This thesis is dedicated to my parents.

Declaration

I hereby declare that the matter embodied in the report entitled **Impact of inter-gain calibration on positron energy measurement with the CMS High Granularity Calorimeter**, are the results of the work carried out by me at the Department of Physics, Indian Institute of Science Education and Research, Pune, under the supervision of Dr. Seema Sharma and the same has not been submitted elsewhere for any other degree.



Dr Seema Sharma



Rahul Kumar

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Abstract

For the upcoming High Luminosity operations of the LHC (HL-LHC), one of the major upgrades for the CMS experiment is the replacement of existing endcap calorimeter with new High Granularity Calorimeter (HGCAL). The calorimeter is being upgraded in order to withstand the large amount of radiation exposure expected at the HL-LHC and at the the same time have a fine transverse and longitudinal granularity, and precise timing capabilities in order to separate the pile up contribution within individual events. The HGCAL will be based on silicon sensors and scintillator tiles directly readout with the silicon photomultipliers, and will have more than 6M independently readout channels. As a part of this upgrade program, a prototype system was exposed to beams of positrons with energies ranging from 20GeV to 300 GeV in beam test experiments carried out at CERN in October 2018. The prototype used consists of 14 double layered structures, each equipped with hexagonal silicon module along with 4 Skiroc2-CMS readout chips, in the electromagnetic section. This corresponds to ~ 3600 number of independent channels. The charged generated by particles traversing the sensors undergoes amplification, shaping and digitization before these are saved for offline analysis. To be able to cover a large dynamic range of charge from few fC to a few pC, two gain stages of the pulse shaper and a time-over-threshold measurements are used. This thesis summarizes calibrations of each of the intergain calibrations of these channels using charge injection method.

Chapter 1

Introduction

After a long shut down of almost four years, the Large Hadron Collider (LHC), CERN is about to resume proton-proton collision operations with an instantaneous luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ for a period of three-to-four years called Run 3. Data corresponding to a total of $\sim 300 \text{ fb}^{-1}$ integrated luminosity is expected to be collected by the end of Run 3. In the next phase of the LHC expected to start at the end of this decade, pp collisions will take place at approximately five-seven times more instantaneous luminosity. This phase is called High Luminosity LHC (HL-LHC), and the end of this phase of ten years, data corresponding to a total of 3000 fb^{-1} integrated luminosity is expected to be collected [6]. This large dataset will facilitate new physics searches as well as the Standard Model (SM) precision measurements. However, this also brings new challenges for the detector and its components. Average pile up per bunch crossing is expected to be 140-200 (as compared to 30 - 40 in Run 2). It will be a challenge to maintain performance of physics objects like jets, leptons and missing transverse momentum against the degradation of detector performance by continuous radiation exposure. Refer to Chapter 3 of this thesis for a detailed discussion of these effects. Hence, different detector components, especially those closer in the direction of beam, need to be replaced or updated [7].

The CMS collaboration [12] is working towards upgrading many parts of the detector, including the replacement of the current endcap calorimeters [7], which were designed to perform for an integrated luminosity of $\sim 300 \text{ fb}^{-1}$. After this, the physics performance of the system will get affected badly. A high granularity calorimeter (HGCal) [7] has been decided to replace the current endcap calorimeters, providing a fine transverse and longitudinal segmentation, and precise timing measurements, for better pileup rejection and better particle identification.

Fig. 1.1 shows a schematic view of the proposed CMS HGCal which is a sampling calorimeter having 50 active layers. These active layers are built using silicon sensor modules and scintillating tiles. The electromagnetic section will use silicon as active material paired with lead, copper, and copper-tungsten absorbers. The electromagnetic section is followed by a hadronic section (CE-H) which uses two different types of sensors depending upon the intensity of radiation. The first section of CE-H is exposed to high radiation for which the active material is silicon, and steel is used as the main absorber. This is followed by a low radiation region having plastic scintillator tiles and on-tile silicon photomultipliers (SiPM) for readout. The three sections are marked in Fig. 1.1. For HGCal the total depth for CE-E corresponds to $\sim 25X_0$ or $\sim 1.3\lambda_{int}$ for the reconstruction of energies deposited by electrons, positrons, and photons. CE-H adds another $\sim 8.4\lambda_{int}$ to

the total depth of the HGCAL for the measurement of energies deposited by charged and neutral hadrons.

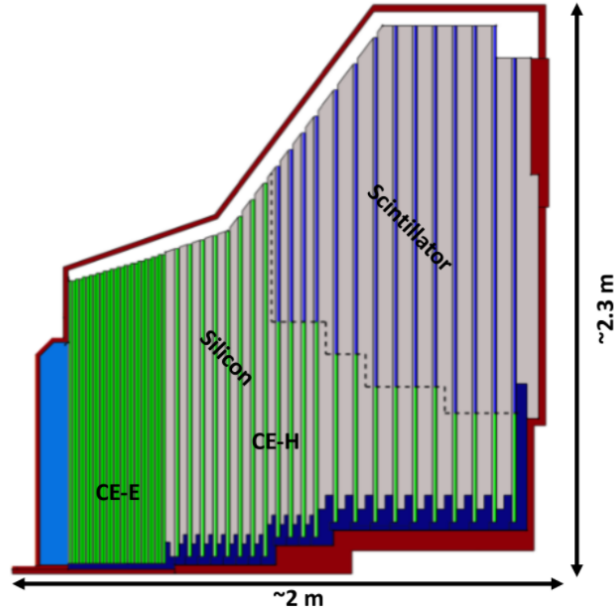


Figure 1.1: The schematic view of the design of the CMS High Granularity Calorimeter Endcap.

The CMS HGCAL group has been testing various prototype designs of the various detector and electronics components of the HGCAL calorimeter detectors in beam test experiments using single particle high energy beams at CERN, DESY & at Fermilab [1]. One such beam test experiment at the H2 CERN beamline was set up to test the performance of a HGCAL prototype equipped with a 28 layered CE-E and 12 layered Si-CE-H combined with CALICE Analog Hadronic Calorimeter (AHCAL) [20], which was based on rectangular scintillator tiles directly readout by SiPMs. The prototype was exposed to beams of positrons & pions with beam energies ranging between 20–300 GeV/c and 200 GeV/c muon beams. Fig. 1.2 shows the beam test setup from 2018 with the HGCAL prototype installed in the beamline.

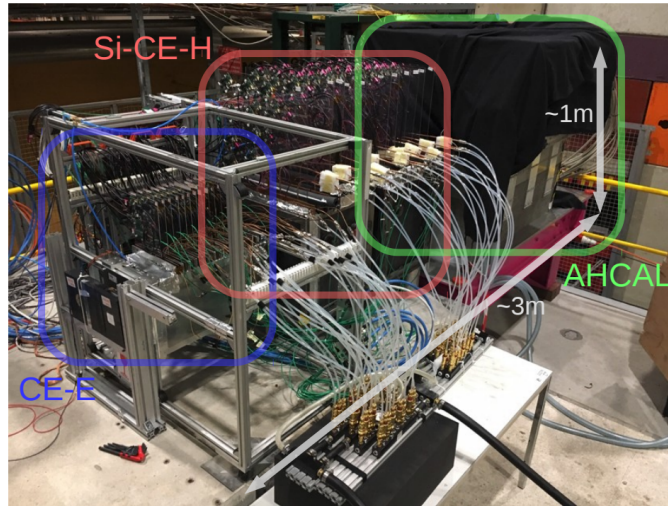


Figure 1.2: The beam test experiment setup equipped with 2018 HGCal prototype.

The building block for the electromagnetic section (CE-E) and some initial layers of the Hadronic section (CE-H) were 6" silicon modules [1], each equipped with 4 SKIROC2-CMS [10] readout chips. In this thesis, the performance of the CE-E prototype using positron data is studied in terms of energy resolution, energy linearity, and final reconstructed energies [8]. In this thesis, different gain linearization calibration methods are discussed, which were used to scale different gain stages provided by the SKIROC2-CMS chip in order to get a linear response over a large dynamic range [1].

In Chapter 2 of this thesis, an introduction to particle interaction with matter and the formation of an electromagnetic shower, along with a discussion on semiconductor detectors and calorimeters is presented, which is essential to understand in order to study the performance of HGCal prototype in high energy positron beams. Chapter 3 gives a brief introduction to CMS detector upgrades for HL-LHC, and HGCal is discussed along with the construction of the 2018 HGCal prototype. Chapter 4 discusses different calibrations performed on the Silicon channels in order to receive a linear response over a large dynamic range from the readout chips. This thesis majorly focuses on the Intergain calibration using the charge injection method. Chapter 5 presents detailed discussions of all the models created to perform Intergain calibration using charge injection data, along with their performance for reconstructing energies for positron beams.

Chapter 2

Particle interactions with matter

The general aim of any particle detector is to convert the energy deposited by the particles traversing through it by interacting with its material to a recordable electronic signal which could be digitized and stored for further analysis (refer to chapter 5 of [15] to read about detector response in detail). This thesis work aims to study the performance of a prototype sampling electromagnetic calorimeter based on silicon sensors and lead and copper based absorber material. In this chapter, I have summarized the key concepts required to understand the interaction of charged particles with matter via ionization processes and how high-energy positrons (as well as electrons and photons) deposit their energies as electromagnetic showers [sec 2.1]. This is followed by a discussion of the signal generation by semiconductor detectors, focusing on their use in sampling calorimeters to measure high-energy particles. More comprehensive accounts of different interaction mechanisms and detection techniques are available in [15] & [13], and are not included in discussion here.

2.1 Interaction of charged particles with matter

An incident charged particle can lose its energy by Coulomb interactions with atomic electrons either by processes in which an electron is ejected, called ionization process, or by exciting electrons to high energy levels, called excitation process. Relativistic electrons and positrons, however, primarily lose their energies through radiative processes, i.e., by emitting photons, called the bremsstrahlung process. Key features of ionization and radiative processes are briefly described in section 2.1.1 and section 2.1.2 respectively.

2.1.1 Energy loss due to Ionization

Traversing charged particles interact with the electromagnetic field of the atoms in the material. These interactions result in ionization or excitation of the atoms and energy loss of the incident particles. The "Bethe-Bloch" [2] formula :

$$-\frac{dE}{dx} = \rho N_A \frac{Z}{A} \frac{4\pi\alpha^2 \hbar^2}{m_e} \frac{q^2}{\beta^2} \left[\ln \left(\frac{2m_e c^2 \beta^2 \gamma^2}{I} \right) - \beta^2 - \frac{\delta}{2} \right] \quad (2.1)$$

where x is the distance traversed by the particle in the medium, ρ is the density of the medium, N_A is the Avogadro's number, Z is the atomic number, and A is the atomic weight

of the atoms of the material, m_e is the electron mass, c is the speed of light in vacuum, q is the electric charge of the incident particle, β is v/c , γ is the Lorentz boost factor, I is the ionization potential of the medium and d is the correction for dielectric screening effect at highly relativistic speed of the particle. The variation of energy deposited by ionization as a function of particle energy is shown in Fig. 2.1 (for muons).

The Bethe-Block equation [Eqn 2.1] shows that the energy loss increases as the particle speed decreases ($\sim \beta^{-2} \sim v^{-2}$), which implies that slow particles will deposit more energy per unit length as compared to fast particles. As the particle speed increases, the energy loss reaches a minimum of about $1.5 - 2.0 \text{ MeV cm}^2/\text{g}$. Hence, the concept of minimum ionizing particles (MIP) has an important role in detector calibration as it is a well-defined quantity for a given detector material. Relativistic charged particles with $\beta \cdot \gamma > 4$ are MIPs, i.e., the energy loss via the ionization process is minimum (other processes, of course, maybe more probably depending on the particle's energy).

This has an interesting implication for muons and their use as a standard reference for the calibration of detectors [1]. Ionization energy loss of muons passing through a copper medium is shown in Fig. 2.1. Since the muons are a hundred times heavier than the electrons, the radiative losses are not significant until very high energies. In the energy range of particles in which no other competitive processes, e.g., radiative losses or nuclear interactions, by which particle can lose energies, the ionization loss remains the primary interaction mechanism. Hence, the ionization loss for muons remains close to the minimum in an extensive momenta range of one to a few hundreds of GeV.

The ionization energy loss is a stochastic process. The Bethe-Block equation [Eqn 2.1] describes only the average energy loss by particles. So, for example, if one shoots many muons of the same incident energy on a thin detector medium like a silicon sensor, one expects to see that the signal collected (from ionization charge produced) follows a Landau distribution with a non-zero width around the maximum probable value. For thicker detectors, one expects to get closer to the Gaussian distribution.

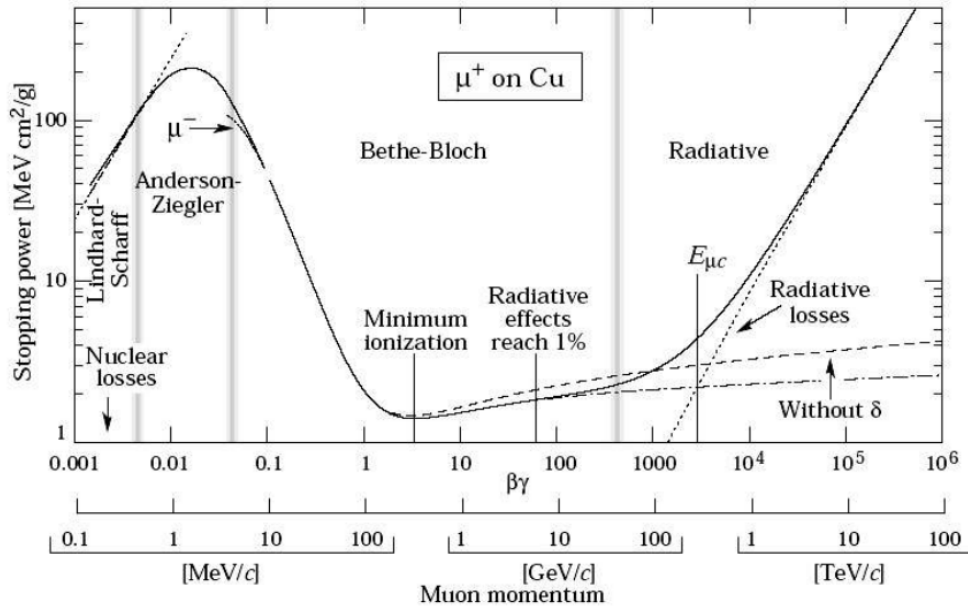


Figure 2.1: Energy loss of muons in copper. The y-axis is given in units of $\text{MeV cm}^2/\text{g}$ so that one can multiply by the density of any material and compute the energy loss in MeV/cm (energy lost per unit distance traversed)

2.1.2 Radiative energy losses

A charged particle traveling in the vicinity of the electric field of a nucleus of an atom can accelerate or decelerate by the action of an electric field. This change in momentum of incident particles is realized by the emission of radiation in the form of photons. This radiation is called bremsstrahlung([15], [13]), and the dependence of its probability on particle mass and material property is given as:

$$\sigma \propto \frac{Z^2 \alpha^3}{m^2 c^4} \quad (2.2)$$

The probability of the bremsstrahlung process [Eqn 2.2] is directly proportional to Z^2 , where Z is the atomic number of the material atoms. So, energy loss by ionization is the dominant one among the two interactions discussed.

Also, the σ is inversely proportional to the mass of the incident charged particle (m). This implies that the energy loss of muons due to bremsstrahlung radiation is very very small compared to electrons. This is the reason that muons are minimum ionizing particles for a wide range of momenta, while radiative losses start dominating in the case of electrons at low energies resulting in a shower of particles, as explained in the next section.

2.1.3 Development of particle shower in matter

When high energy particles interact with matter, they do not lose their entire energy all at once instead the higher energy particles repeatedly generates low energy secondary particles with lesser energies. This splitting continues further producing a large number of low energy particles which finally got absorbed and deposits their energy in matter by interacting via different processes. There exist two major types of these shower development [22]:

- Electromagnetic showers : formed by particles interacting with matter via electromagnetic forces, e.g. electrons, positrons, photons.
- Hadronic showers : Formed by particles interacting using strong nuclear forces, e.g. high energy pions.

Since, in this thesis the HGCal prototype is tested using positron beams which interact primarily using electromagnetic interactions, hence understanding electromagnetic showers is really important in order to study the performance of HGCal in positron beams. Section below briefly describes the electromagnetic shower development.

Electromagnetic Shower development

An electromagnetic shower starts when a high energy $e^\pm$ or γ particle enters a material, for particle energy as high as few GeVs, photon's primary mode of interaction is via pair production [15], i.e. , a photon converts into an electron-positron pair. These high-energy electrons and positrons interact with matter to emit photons, according to a process called bremsstrahlung. Continuous converting of photons into electron-positron pairs and production of new photons results in the formation of a cascade of particles in which each new particle formed is of lower energy. This process continues until the secondary particles formed have energies lower than a threshold value below which processes like Ionization,

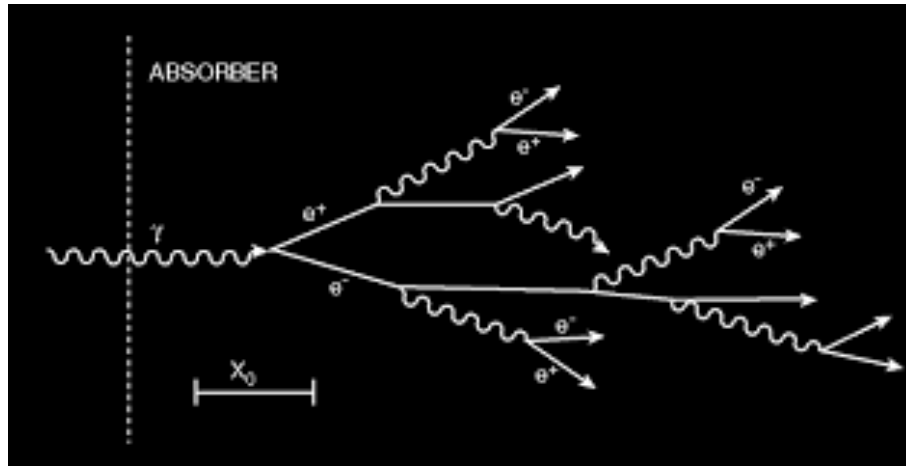


Figure 2.2: Schematic diagram of electromagnetic shower cascade development in the block of absorber material [3]

photoelectric effect, and Compton scattering are dominant, leading to complete absorption of the particle in the medium. Fig. 2.2 shows a schematic diagram of electromagnetic shower development in an absorber material.

2.2 Semiconductor detectors

In these types of detectors, the incident particles are made to traverse through semiconductor crystals, and the output signal is constructed from the collected electron-hole pairs created as a result of energy lost by the incident particle. These detectors can also be looked at as a solid-state version of the gaseous ionization detectors as they share a common working principle of creating charge pairs and collecting them as an electronic pulse. However, the energy required to generate an electron-hole pair in Si is roughly $1/10^{th}$ of the energy needed to create electron-ion pair in gaseous detectors (3.6 eV for Si compared to 25.5 eV for argon). So, more charge pairs are created for the same amount of energy deposited in a semiconductor detector than in a gas detector, resulting in a better signal resolution.

Before we discuss how semiconductors are used as active material in detectors, let us quickly recap the important properties of semiconductors relevant to us.

2.2.1 Some properties of semiconductors

Particles passing through the semiconductor crystal interact with the semiconductor atoms as per the Beth-Bloch equation [Eqn 2.1]. The deposited energy results in the excitation of electrons from the valance band to the conduction band, forming electron-hole pairs (charge carriers in semiconductors) [15]. The most commonly used semiconductors for particle detection are Silicon (Si) and Germanium (Ge). An intrinsic semiconductor is a pure semiconductor crystal with all the semiconductor atoms arranged in a well-defined periodic lattice. These pure semiconductor crystals are not suitable for particle detection. Instead, these crystals are arranged in a special configuration (p-n junction) to achieve excellent resolution and low statistical fluctuations.

Doping of semiconductor

To increase the conductivity of the semiconductors, specific impurities are introduced in the pure semiconductor crystals, referred to as acceptors or donors, and the semiconductor is said to be doped. Let us have a look at one example of both types of impurities and types of doped semiconductors formed and how they help in boosting the conductivity.

p-type semiconductors (acceptor impurity)

Acceptor impurity is a type of atom which has one less valence electron than that of a semiconductor. On introducing such particles to pure semiconductors, these atoms borrow one electron from a neighboring semiconductor, creating an acceptor level in the bandgap near the valence band. The energy gap between these newly formed acceptor sites and valence band is very low, and even by small thermal energies, electrons from valence bands jump to these acceptor sites and participate in a covalent bond having an energy level close to the valence band and hence increasing conductivity, as shown in Fig. 2.3 & the semiconductor is said to be a p-type semiconductor. An example of a p-type semiconductor is Silicon doped with group 3 elements of periodic table, e.g., Boron (trivalent).

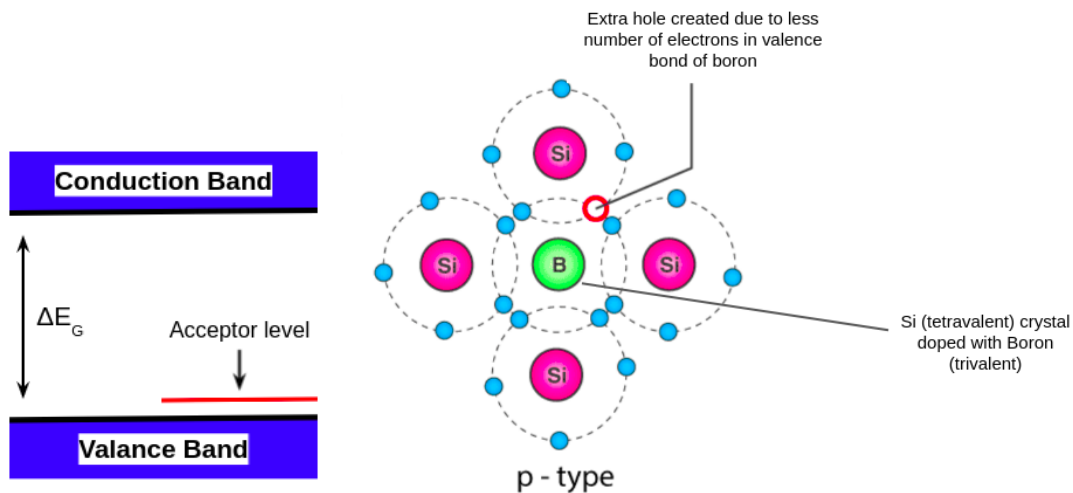


Figure 2.3: P type extrinsic semiconductor

n-type semiconductors (donor impurity)

In this type of doped semiconductor, pure crystal is doped with impurities having one extra valence electron. The impurity element has one electron left after all the covalent bonds are formed. This extra donor electron occupies energy levels very close to the conduction band, and very little energy is required to excite them into the conduction band. Even thermal fluctuations can surpass this small energy barrier between donor level and conduction band, and the donor will excite electrons into the conduction band even at low temperatures. Hence, every lattice point that has been replaced with a donor atom will result in an extra electron that will participate in conduction and boost the material's conductivity. The semiconductor is an n-type semiconductor with an excess of electrons as carriers. An example of an n-type semiconductor is Silicon (tetravalent) doped with the periodic table's group V elements, e.g., arsenic (pentavalent).

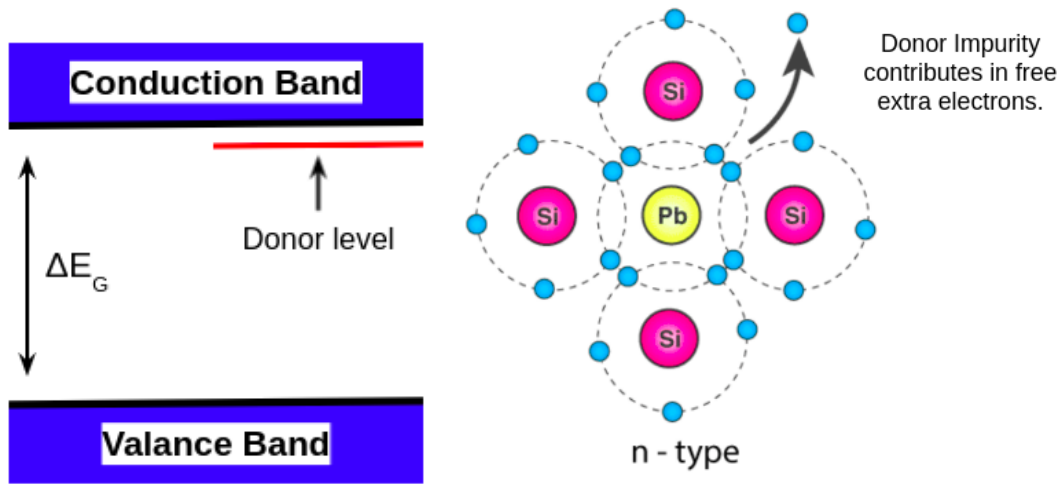
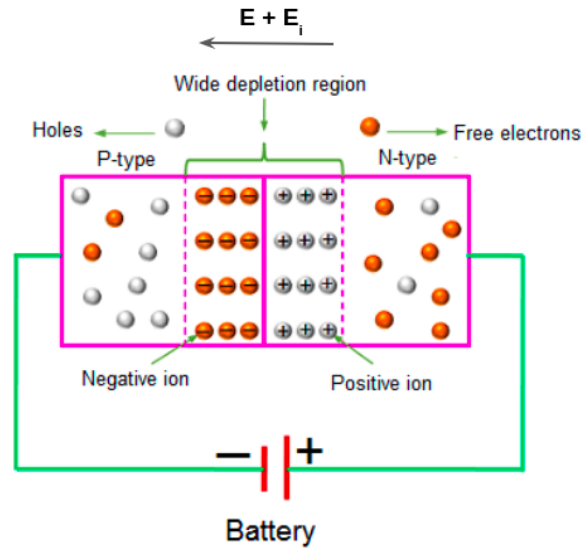


Figure 2.4: N type extrinsic semiconductor

2.2.2 P-N junction diode

These p-type and n-type semiconductors are infused together to form a p-n junction interface. When the two surfaces are joined together a movement of charge carriers begins at the interface due to the difference in concentration of the charge carriers at the interface. Since the electrons from n-type region are attracted to p-type region and vice versa for the holes. These movement of charge carriers near the interface region creates a depletion region called the *depletion zone* where all the charge carriers have been swept to the opposite sides due to imbalance in concentration of charge carriers. In the beginning both p type and n type semiconductor were neutral, this movement of charges from n side to p side results in distribution of charge densities in the depletion zone. This results in creation of an electric field (E_i) [Refer Fig. 2.5] across the depletion zone in the direction opposite to that of the movement charge carriers. Finally, the charge carriers stop diffusing further [15].

So the depletion region is free of any charge carriers. As an incident particle passes through this region and loses its energy, electron-hole pairs proportional to the amount of energy deposited will be created. These electrons and holes can be swept on the opposite sides under the influence of an external electric field and can be read out as an output electronic pulse which can be digitized and saved for further analysis.



PN junction diode in reverse bias configuration

Figure 2.5: P-N junction in reverse bias setup

In order to get fast signals and to avoid recombination of electron holes pairs created by the traversing particles, the depletion zone is widened further by using an external electric field (E) [Refer Fig. 2.5] by connecting the p side to the negative terminal and n-type to the positive terminal, i.e., reverse bias. This field will be able to stop any recombination of electron-hole pairs as the electrons and holes are separated to the opposite end instantaneously after they are formed. This configuration of the p-n junction diode is called reverse biasing. Fig. 2.5 shows a p-n junction in reverse bias configuration where E is the electric field due to reverse biasing and E_i is the electric field induced due to charge separation in the depletion zone.

Since semiconductor gives compactness to the detector compared to other detector materials and high sensitivity to small energy detection, a semiconductor is a good choice for the detector's active medium. Fig. 2.6 shows a transverse view of an ionizing particle traversing through a silicon sensor.

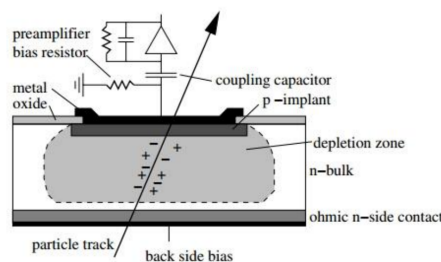


Figure 2.6: Charged particle traversing through a silicon sensor

2.2.3 Dealing with radiation damage

Incoming radiation may knock out atoms in the lattice, leaving defect points in the lattice of the silicon wafer resulting in the formation of additional energy levels in the forbidden gap, which allows the free charge carriers to occupy these states, thus reducing the

efficiency in collecting the induced signal. To minimize this effect, the charge collection time is reduced so that the induced charges would not get enough time to occupy these additional defect energy gaps. To do so, a reverse bias voltage is increased so that the induced charges got collected instantaneously. The only drawback of increasing the bias voltage is that it also increases the effects of leakage current in the system resulting in a worsening of resolution. To somewhat minimize the impact of these leakage currents, the HGCAL calorimeter will be operated in -35°C [1].

The CMS [7] detector combines different types of these detection techniques in order to measure different physical quantities with highest precision. The detectors that are used to measure energy of the incident particles by complete absorption of them are called calorimeters. Next section discuss more about calorimeters and their response to electromagnetic showers.

2.3 Calorimeter

Calorimeter is a device used to measure energy and position of the incident high energy particles. Signal formation in a calorimeter is a destructive method i.e, a high energy particle entering the calorimeter will undergo shower development (Electromagnetic or Hadronic depending upon the type of incident particle) and gets converted into a large number of low energy secondary particles which finally got absorbed completely in the active material of the calorimeter, giving an output signal.

Calorimeter detector systems are designed to fully contain the showers produced by $e^{\pm}$, γ and hadrons. Calorimeter has two main media, the first one is the absorber medium in which the cascade develops and other one is the active medium in which the energy got deposited and finally converted to a measurable output signal.

The HGCAL is designed with lead and steel as their main absorber mediums and silicon and plastic scintillators as active medium.

2.3.1 Response of calorimeter to Electromagnetic shower

Calorimeters are designed to contain the showers produced by $e^{\pm}$, γ and hadrons and need to be checked for the performance in it's operational energy ranges.

There are two main criterion as per which the calorimeter's performance is measured which are discussed in section below:

Response linearity

The amount of energy deposited by the shower particles in the sensors is called visible energy (E_{vis}). A calorimeter designed to contain full electromagnetic shower (CE-E) will generate a response proportional to the energy of incoming $e^{\pm}$ or γ . i.e,

$$E_{vis} \propto E \quad (2.3)$$

where E is the energy of the incoming particle beam. This is because shower will generate in CE-E and will end up depositing all the energy of the sub particles created in the active materials of calorimeter.

The first performance check is to ensure a linear response of the calorimeter for the energy ranges it is designed for. Otherwise, systematic biases may be propagated to the en-

ergy measurement of decaying particles, hereby impairing the calorimetric performance. Section 4.2.2 discusses the procedure followed in order to check the linearity of the response from CE-E for positron beams.

Energy resolution

Another important performance criteria to check for is the resolution. Since, the particle interaction with the active material of the calorimeter is a stochastic processes, results into widening of the visible energy spectrum with a spread σ_E . This spread directly affects the resolution of the calorimeter as per Eqn 2.4

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + C^2 + \left(\frac{N}{E}\right)^2 \quad (2.4)$$

Where, S contributes for the stochastic fluctuations called stochastic term, N is the noise term corresponds to the contribution via noise and C is the constant term to take miscalibrations, saturation effects, non linearities etc. into account. Section 4.2.2 demonstrated the calculation of resolution for HGCal prototype using positron beams.

In the next chapter a brief introduction to CMS and upgrade of it for HL-LHC is described.

Chapter 3

CMS upgrades for HL-LHC and the High Granularity Calorimeter

The LHC is currently at the end of second long shutdown (called LS-2), after which the LHC will be able to reach an instantaneous luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The LHC is scheduled to begin in May 2022 for a working period of 3 years which will be the completion of Phase-I of the LHC operation [6]. Refer to Fig. 3.1. Phase-2 [19] will start with a three-year shutdown called LS-3. After LS-3, the LHC will have an instantaneous luminosity as high as $7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ which will be the starting of the HL-LHC [9] phase, at the end of which the LHC's total integrated luminosity will boost up to 3000 fb^{-1} . Fig. 3.1 shows the LHC upgrade schedule.

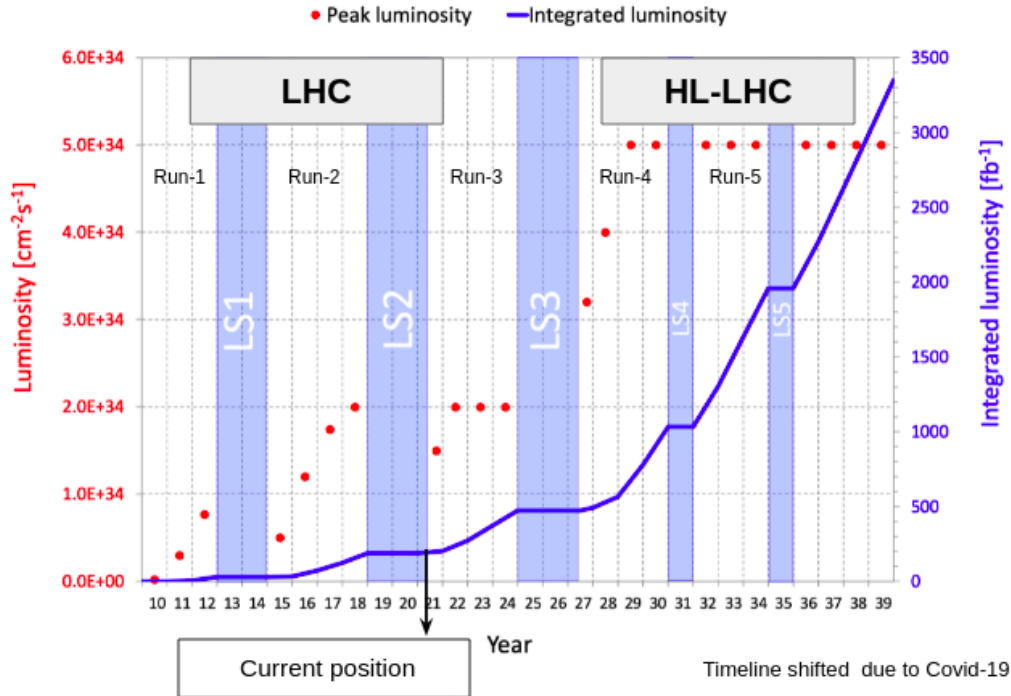


Figure 3.1: LHC upgrade schedule [16]

While the high luminosity upgrade helps to collect a large amount of data for direct searches for new physics and precision measurements of SM predictions, it also brings some challenges for the detectors, such as :

- Fig. 3.2 (left) shows expected fluence in the endcap calorimeter at the end of the HL-LHC upgrade indicating that the radiation dose will accumulate over the time and more in sections closer to beam pipe. This directly affects the performance of active detector components including the electronics components. One main challenge for these detectors is to maintain adequate physics performance and minimize impact of radiation damage in HL-LHC harsh high radiation environment.
- Inelastic proton-proton collisions, besides the collisions of interest are referred to as pile-ups. In general, pile-up causes substantial activity in the detector, and the signals need to be detected and rejected from particles that do not originate from the primary interactions. A very high pile-up is expected at the collision points with increased luminosity. The average pile-up will increase from 30-40 in Run-2 to 140-200. Fig. 3.2 (right) shows events of display of a collision with 140 pile-up collisions.

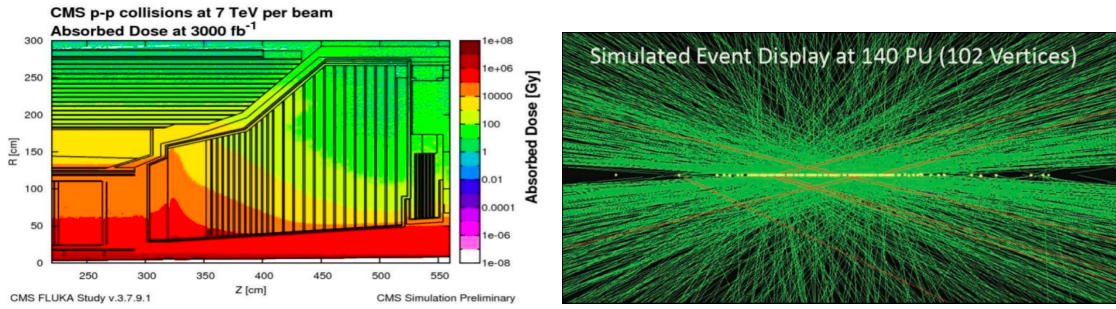


Figure 3.2: HL-LHC requirements

The CMS Collaboration has initiated a program to upgrade the current detector to fulfill the HL-LHC requirements to cope with these conditions. One of the major steps of the upgrade program is to replace the existing endcap calorimeter with a new High Granularity Calorimeter [21].

3.1 Compact Muon Solenoid (CMS)

The Large Hadron Collider (LHC) is the largest and most powerful particle accelerator ever built. It can accelerate protons to a speed close to the speed of light and then makes them collide at four collision points around its ring.



Figure 3.3: An aerial view of the LHC ring with four collision points and corresponding experiment

Fig. 3.3 shows an areal view of the LHC ring with the four collision points marked. The CMS detector is installed at one of the four collision points where proton beams are made to cross each other. The CMS detector is designed to detect various stable particles which are outcome of pp collisions and measure their physical quantities like momentum, energy, position and charge. Fig. 3.4 shows a schematic picture of the CMS detector design and highlights different parts of it. The CMS detector consists of a Tracking system [5] used for the identification of particle trajectories. Energy measurement tasks are performed by the calorimeters which is briefly discussed in section 2.3. Calorimeters are followed by superconducting solenoids used to bend the tracks of the charged particles by creating a strong magnetic field followed by muon systems which are gaseous detectors interleaved by the iron return yoke for the detection of muons [4].

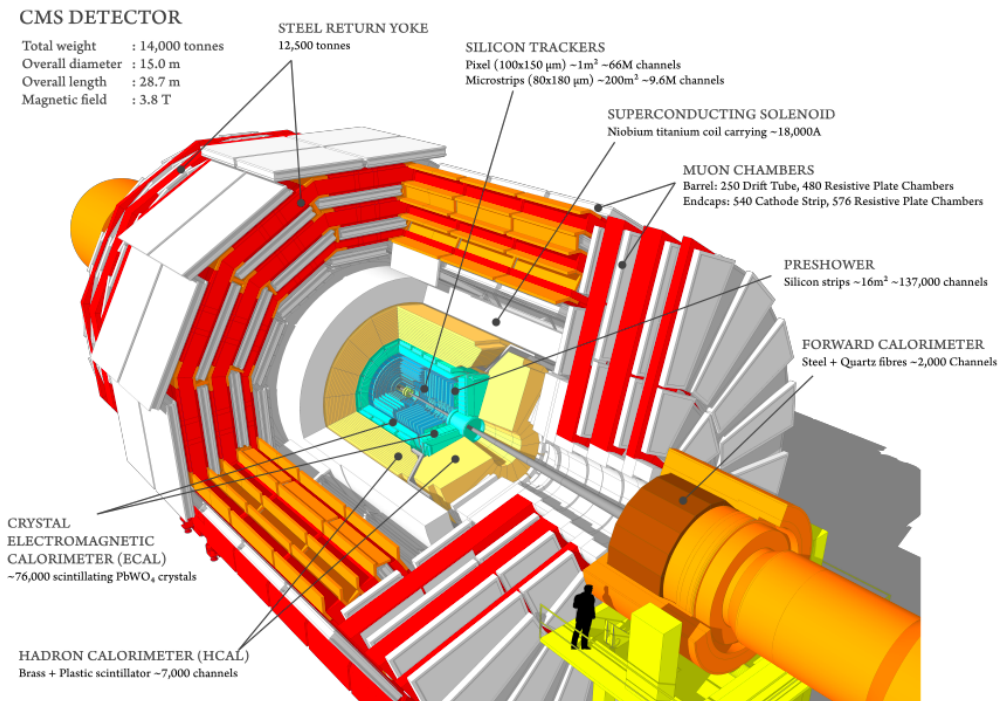


Figure 3.4: Schematic diagram of the CMS [12]

3.2 CMS upgrade for HL-LHC

The CMS collaboration has planned various improvements and upgrades for Phase-1 and Phase-2 operation of LHC to optimize the detector performance and make it more sustainable in the harsh environment of HL-LHC. Among different initiatives taken to upgrade the detector, one major step was to upgrade the existing calorimeter with a new upgraded High Granularity Calorimeter (HGCAL). The current endcap calorimeters will get damaged heavily from high radiations by the end of Run-3 [17] and will lose their physics performance. Therefore, the current endcap calorimeters will be replaced by a more radiation tolerant detector and will also account for high pile-ups expected in run-3 of LHC.

3.2.1 HGCAL endcap detectors

Considering the conditions of high radiation exposure and large pile-up, the sensitive material of the upgraded calorimeter must be radiation tolerant and should also be highly granular so that the energy measurements can be possible to a finer level in order to deal with pile-ups in the offline analysis.

In the final HGCAL design, Silicon will be used as the active material for the majority of the detector sensors. By using Silicon as active material, there will be two significant improvements over the present calorimeter system [21]:

- Silicon is more tolerant to high radiations, hence more suitable for the harsh environment at the HL-LHC.
- Silicon will also provide fast signals allowing for high precision time measurements of energy depositions which will in turn help in effectively dealing with high number of pile-up interactions.

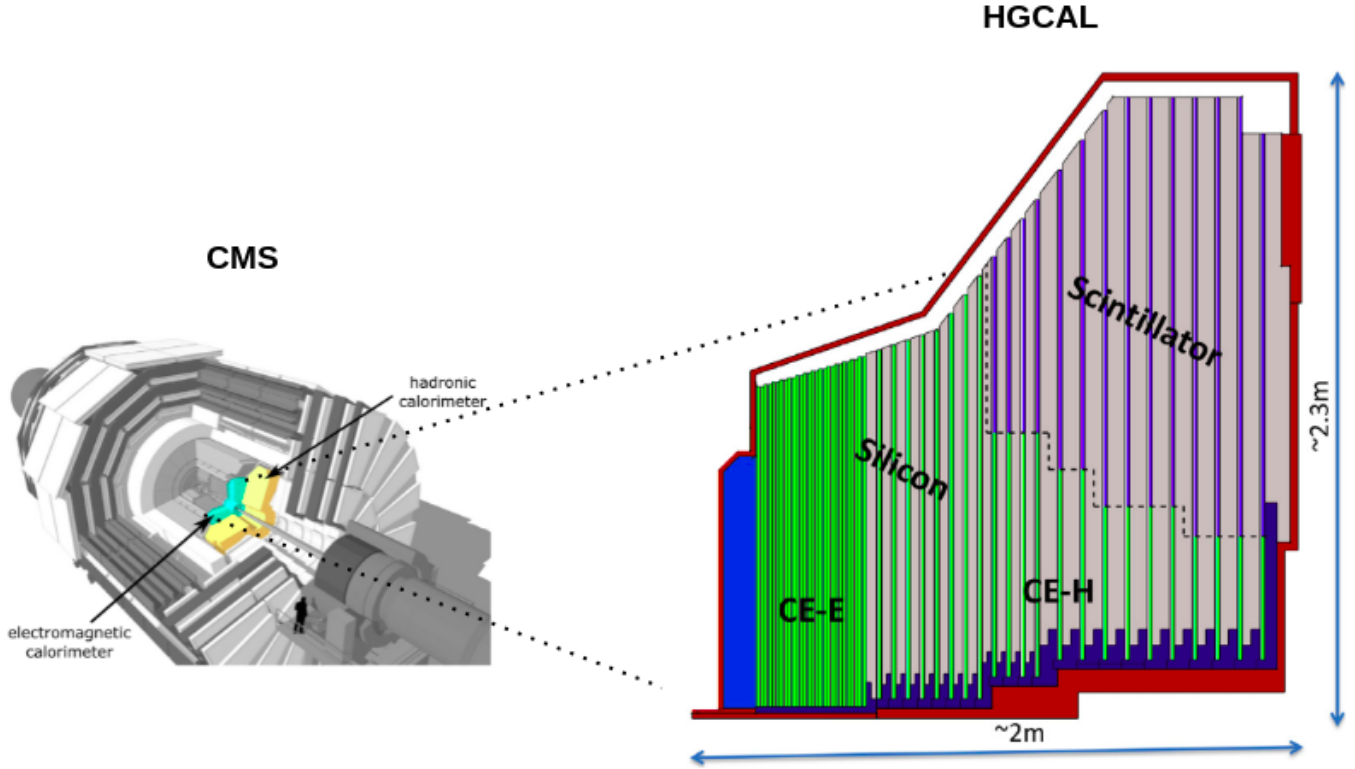


Figure 3.5: Schematic overview of the HGCAL detector.

The HGCAL comprises an electromagnetic compartment (CE-E) with 28 sampling layers with silicon as the active material. The CE-E will have a total depth of 25 radiation length ($\sim 25X_0$) or 1.3 nuclear interaction lengths ($1.3\lambda_{int}$). The Hadronic section of HGCAL will have a total of 22 sampling layers, with the front region sensors having silicon as active material due to exposure to high radiation, while the back section comprises scintillator tiles since the backend region is exposed to low radiation compared to CE-E and the front part of CE-H. The CE-H has a total depth corresponding to $8.5\lambda_{int}$ refer to [1] for a more detailed discussion on the HGCAL design. Fig. 3.5 shows the schematic view of the HGCAL and its positioning in the CMS.

For the construction of the final HGCAL, 8" silicon modules will be used, but for the HGCAL prototype used in 2018 test beam experiment (prototype used for our study), the building block was a 6" hexagonal silicon module equipped with 4 SKIROC2-CMS readout chips. Section below discusses the 2018 HGCAL prototype construction along with the construction of 6" silicon modules.

3.2.2 Test Beam 2018 experimental setup

The CMS group has been testing various prototype designs of the HGCAL calorimeter in beam test experiments using single-particle high energy beams at CERN, DESY & Fermilab. One such beam test experiment at the H2 CERN beamline was set up to test the performance of an HGCAL prototype. This prototype was assembled using 94 6" silicon modules with an electromagnetic and a hadronic section. It was placed in the H2 beamline of SPS CERN to irradiate the prototype to high-energy positron, pion, and muon beams of varying momenta. Fig. 3.6 shows the 2018 H2 beamline setup equipped with the HGCAL

prototype. Three different setup configurations for CE-E and CE-H were tried and tested in this 3-week test beam run in October 2018. In this thesis, we will be focussing on the performance of the HGCal prototype in configuration 1.

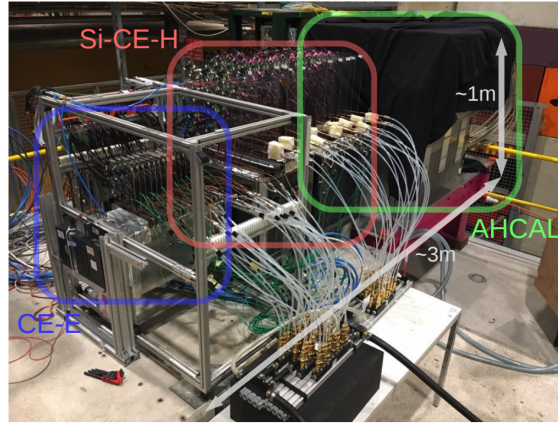


Figure 3.6: The detector setup for 2018 beam test experiment. Different compartments have been indicated with the different colour boxes and the beam enters the detector setup from the left.

3.2.3 HGCal prototype construction

In this section we will have a look at the construction of different section of the HGCal prototype [1] along with their properties.

Electromagnetic section prototype design (CE-E)

For CE-E prototype the modules were mounted in cassettes with two sensors per cassette, one on each side separated by a 6mm thick copper cooling plate and at the end of each cassette follows a 4.9mm thick Pb absorbers covered with steel plates shown in fig 3.7 (right).

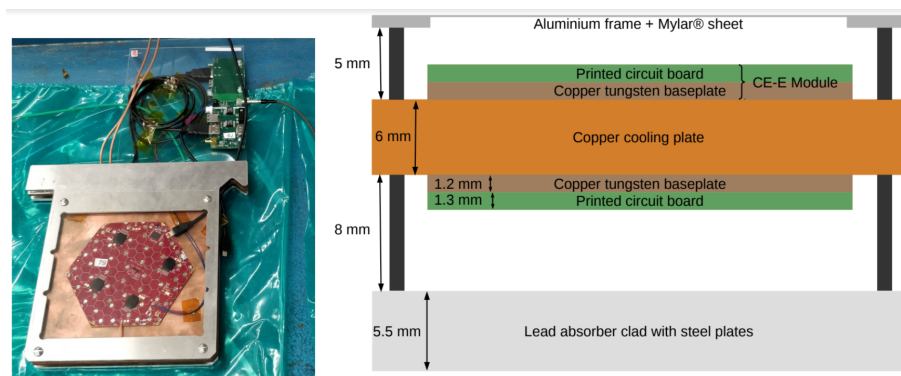


Figure 3.7: Figure on the left shows one mini-cassette built with single silicon sensor module each side of the cassette (only one is visible in this image). Right image shows schematic diagram of cross-sectional view for a mini-cassette with physical lengths shown in the image [1].

The CE-E prototype will have a total of 14 such cassettes each having 2 silicon modules placed face to face in total having 28 Silicon sensors each defining a sampling layer

in CE-E. Fig 3.7 shows a mini cassettes with two silicon sensors attached on either sides. The total depth of CE-E prototype corresponds to $\sim 27X_0$ or $\sim 1.4\lambda_{int}$. The CE-E prototype covers a cross-sectional area of $12 \times 14\text{cm}^2$ restricted by the dimensions of the silicon sensor.

In configuration 1 the first 24 layers has a $300\mu\text{m}$ thick silicon sensor with only the last two layers built with $200\mu\text{m}$ thick silicon.

Hadronic Section prototype design (CE-H)

CE-H was further subdivided into two section, the first section (Si-CE-H) corresponds to the high radiation region of CE-H having silicon as active material and the later section (AHCAL) corresponds to comparatively lower radiation region made up of scintallators.

Si-CE-H

Instead of single-single modules per layer, in Si-CE-H the first 9 layers out of 12 were made up of 7 silicon sensors arranged in a daisy like structure (shown in Fig. 3.8) this was done in order to increase the transverse coverage to capture the hadronic showers. The last 3 layers of CE-H has single modules placed just like in CE-E. All the modules are placed on 6mm thick Cu cooling plates with each module formed using $300\mu\text{m}$ thick silicon wafers except two modules which have $200\mu\text{m}$ thick silicon sensors placed in layer 5 and layer layer 6 of CE-H. The total depth of CE-H corresponds to $\sim 3.4\lambda_{int}$.

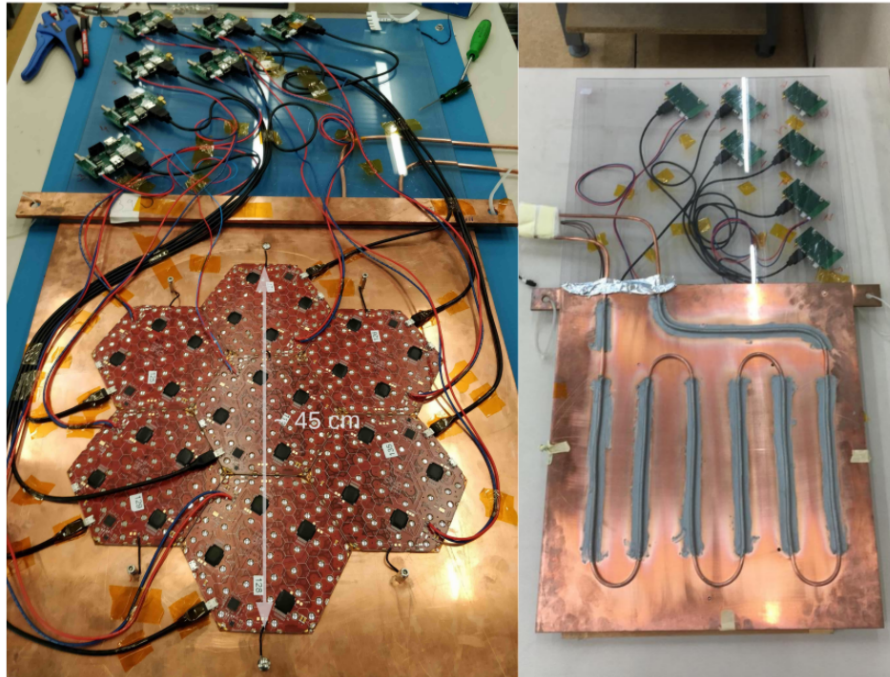


Figure 3.8: An image of CE-H layer with seven modules arranged in daisy like structure as shown in the left image. Right image shows the back-side of the layer with cooling pipes visible.

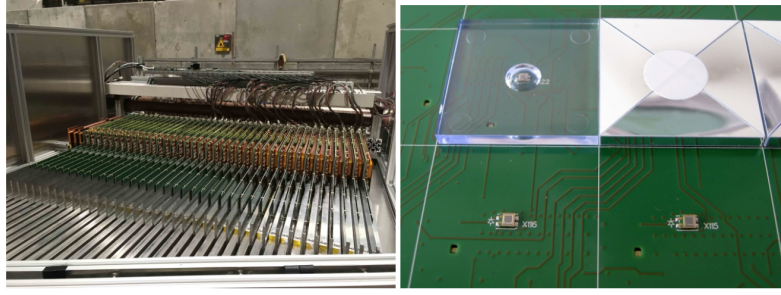


Figure 3.9: A close-up view of CALICE AHCAL engineering prototype is shown in the left image. On the right, the tiles mounted on SiPM is shown with tiles wrapped and unwrapped along with SiPM in the middle.

AHCAL

At the end of Si-CE-H an AHCAL prototype is placed with a total of 39 sampling layers alternately placed between 17.7 mm thick steel absorbers. Each of these layers of AHCAL has 144 rectangular shaped scintillator having dimensions of $3\text{cm} \times 3\text{cm} \times 3\text{mm}$. Each of these tiles are equipped with on-tile silicon photomultipliers (SiPM) for readouts. The AHCAL prototype used has a total of ~ 2200 scintillator channels giving a total depth of $\sim 4.5\lambda_{int}$ combined with CE-H giving a total depth of $\sim 9.6\lambda_{int}$.

Fig. 3.6 shows the complete setup used in 2018 Beam Test with all the section (CE-E, CE-H and AHCAL marked) and Fig. 3.10 pictorially shows the config 1 setup of the HGCal prototype.

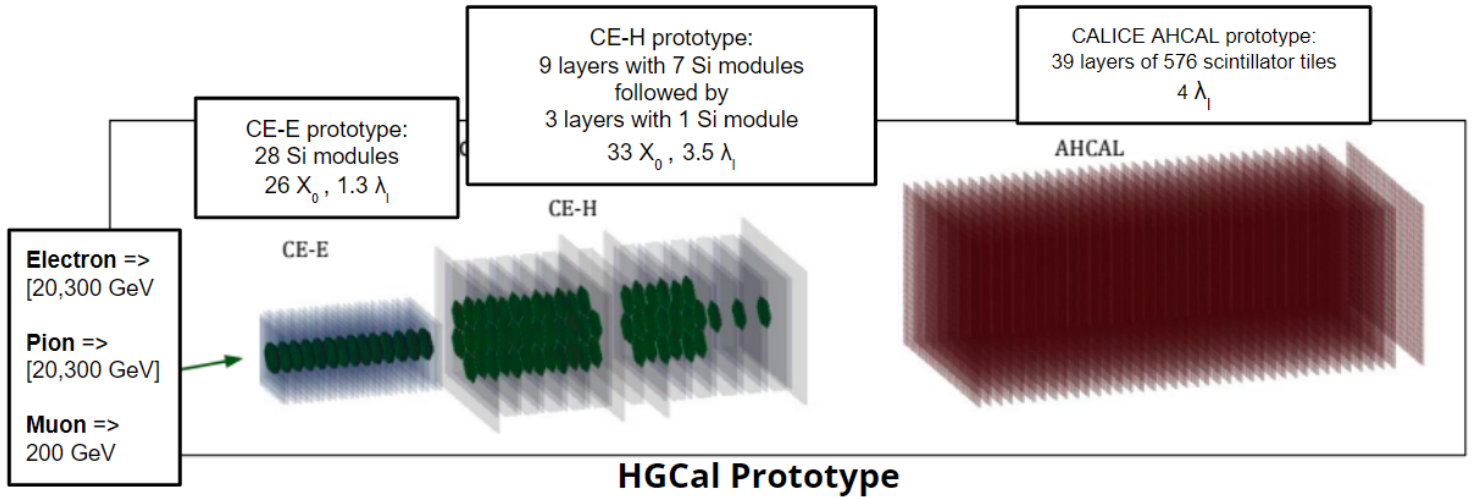


Figure 3.10: Pictorial representation of HGCal prototype

The building block of CE-E and Si-CE-H are the 6" silicon modules. In the section below the construction of these modules is discussed in detail.

6" Silicon prototype modules

The calorimeter shown in Fig. 3.5 is a 50 layered High granularity calorimeter with more than 6×10^6 channels. The calorimeter will be made up of silicon modules with a silicon

sensor, readout electronics, and an absorber plate (Pb & Cu as main absorbers in CE-E and steel as the main absorber) as its main components. The silicon sensors are subdivided into hexagonal cells with an area of $\sim 1.1\text{cm}^2$. CE-E and the front region of CE-H will be fully assembled using these silicon modules. And for later region plastic scintillator tiles were used along with on-tile silicon photomultipliers (SiPM) for readouts. The full calorimeter will be inside a cold volume kept at -30°C to reduce the dark currents in the silicon sensors and the SiPMs

Several quality tests were carried out with different prototypes of silicon modules arranged in various configurations in order to validate the performance of a silicon-based calorimeter. Our whole study is based on one such HGCAL prototype, which is discussed in more detail in the next section.

Our studies and analysis were based on a two-week beam test that was carried in october 2018 at the H2 beam line of the cern Super Proton Synchrotron (SPS). The H2 beamline was equipped with a HGCAL prototype having 94 6" silicon prototype modules, each equipped with 4 SKIROC2-CMS ASICs done in order to reduce the distance travelled by the signal from sensor to ASICs and hence to reduce the overall noise in the signal [11]. In the section below construction of these 6" silicon module is discussed and how they are assembled in the HGCAL prototype [1]. In chapter 4, calibrations performed for the assurance of the quality output response from the ASICs is discussed.

Prototype 6" silicon module construction

The silicon modules of the HGCAL prototype tested in 2018 follow a multi-layered structure, with each layer epoxied together using araldite epoxy layers in between. There were 4 main layers used for the assembly of the prototype modules, these were:

- **A baseplate:** which sits at the lowest end of the module and gives mechanical support and also helps with the heat transfer from the module to the cooling layers. The thickness of the baseplate is optimized to $100\mu\text{m}$. The CE-H baseplate is made of Cu, while the CE-E baseplate is made of copper-tungsten, which has higher density and hence makes the calorimeter more compact.

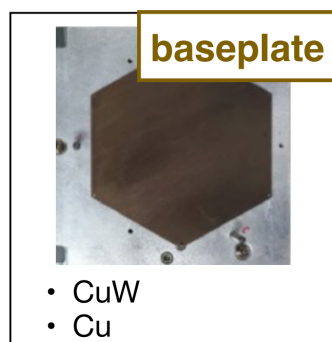


Figure 3.11: Baseplate used for construction of Silicon sensor module

- **Kapton sheet plated with gold:** provides insulation to the silicon sensor from the baseplate, and also provides a bias connection to the silicon sensor via the gold plating.



Figure 3.12: Kapton used for construction of Silicon sensor module

- **Silicon wafer:** A 6" p-n silicon wafer operating in reverse bias was used as the base for the silicon module. p-on-n type silicon wafer was selected on the basis of studies done to check radiation hardness of different types of silicon sensors. All the silicon modules were segmented into a total of 135 cells. Out of total 94 silicon sensors produced, 90 were made with $300\mu\text{m}$ depletion zone thickness and 4 were made with $200\mu\text{m}$ thick depletion zone with a total silicon sensor thickness of $300\mu\text{m}$. On a given cell out of 135 cells 107 cells were complete hexagonal shaped with area $\sim 1.1\text{cm}^2$ and rest were partial hexagons. 128 channels were formed from these 107 full hexagonal cells and rest from merging of the partial hexagons and are used for energy measurement in silicon sensors. Each of these channels are connected to the front end electronics where the signal is digitized by 4 SKIROC2-CMS readout chips.

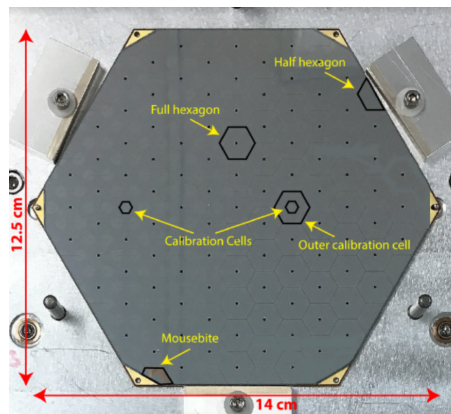


Figure 3.13: p-n type silicon wafer used for construction of Silicon sensor module

- **Printed circuit board:** The thickness of the PCB is 1.3mm. It holds four SKIROC2-CMS ASICs and contains stepped holes where wire bonds are attached. The wire bonds connect the silicon sensor cells with the PCB and the ground pads (Gnd) with the guard rings on the silicon sensor. They also connect the sensor bias voltage on the PCB with the gold layer of the Kapton sheet.

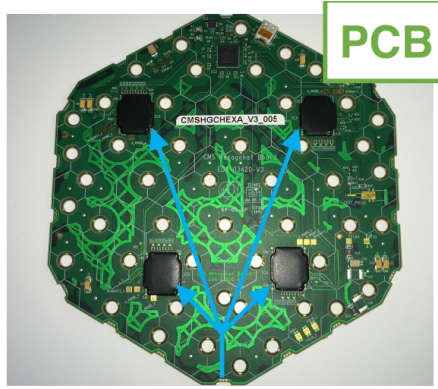


Figure 3.14: PCB with 4 SKIROC2-CMS readout chips along with other front-end electronics

Arrangement of these layers to form a silicon modules is shown in Fig. 3.15.

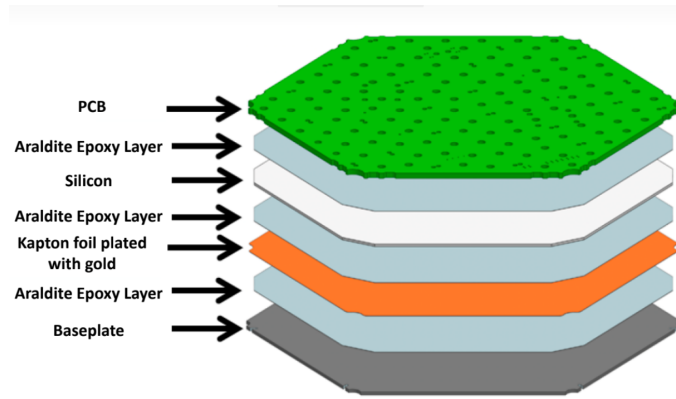


Figure 3.15: Different layers arrangement in a Silicon module

SKIROC2-CMS readout chip

The SKIROC2-CMS [10] chip was an upgrade to the SKIROC2 readout chip that were used in the silicon modules tested in 2016. For each channel SKIROC2-CMS readout chip offers a low-noise charge sensitive preamplifier followed by two pulse shapers of different gains, called High-Gain (HG) and Low-Gain (LG). The task of the preamplifier is to simply increase the order of magnitude of the signal while retaining its shape without distortion. To do so, a low noise preamplifier design is important. Pulse shaper transforms the amplified narrow signal from sensor to a broader output with a rounded maximum, whose maximum height is directly related to the peak height of the input signal. This is to ensure that the output pulse is wide enough to match the measurement time. Pulse shapers can also add in additional stages of amplification while shaping the input signal (HG & LG in HGCAL) .

The HG was built to measure small energy deposition in the silicon, corresponding to $\sim 2fC$ to $150fC$, whereas LG can measure energy deposition in the silicon, corresponding to $\sim 100fC$ to $900fC$. And for higher charge deposits greater than $900fC$ ToT is used which gives a response directly proportional to energy deposits [1].

The shaped pulse from HG and LG stage is sampled in 13 deep switched capacitor-array (SCA). The charge stored in these 13 SCAs from two gain stages is passed to 12-bit

Wilkinson analog to digital converter for digitization of the signal as the trigger system is activated and this digitized signal in terms of different ADC counts (HG, LG & ToT ADC counts) got stored. Fig. 3.16 shows the different stages in the readout of signal in SKIROC2-CMS chip & Fig. 3.17 shows the circuit diagram of the SKIROC2-CMS chip.

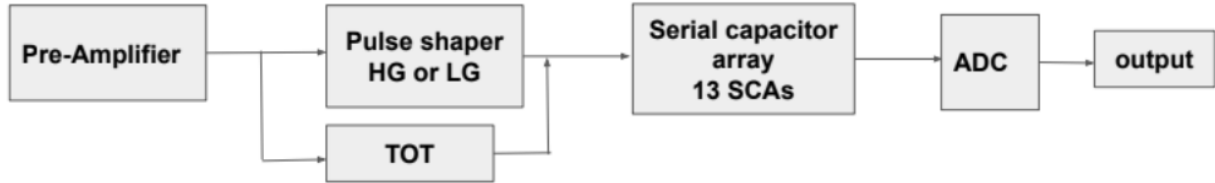


Figure 3.16: Signal flow of the SKIROC2-CMS readout chip

The main upgrade to the old SKIROC2 readout chip was the addition of new ToT circuit to measure high charge deposits ($\sim 900fC$ to $10pC$ range). One of the biggest advantage of using SKIROC2-CMS over SKIROC2 readout chip is the coverage of large dynamic range by the SKIROC2-CMS by combining the HG, LG and ToT.

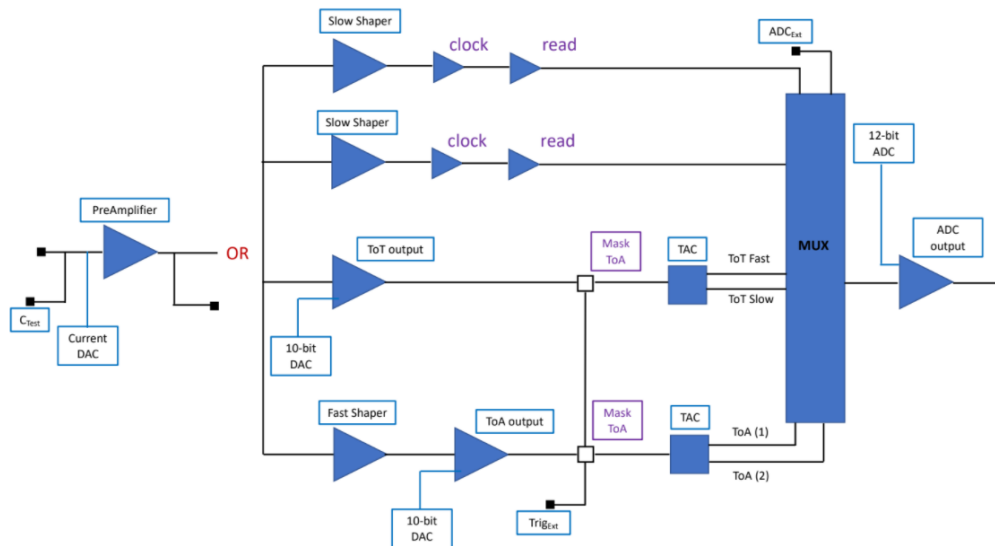


Figure 3.17: Circuit diagram of the SKIROC2-CMS readout chip

Chapter 4

Channel-to-channel response equalization and gain linearization

The final HGCALE detector will have approximately 6M channels, signal from each of which will be independently readout, digitized and reconstructed. In an ideal scenario, all these channels are expected to be identical and give a similar response for a given input signal. However, due to variations in manufacturing processes, non-uniformity in silicon wafers, non-uniformity in depletion regions, variations in shaping and integrating components of electronic circuitry, etc., the response of channels is not identical. As seen in chapter 2, the energies deposited by high energy particles like $e^\pm$, photons, and hadrons are shared, via showering, among neighboring channels of the same layers and across the depth of the detector. This means, to get the best measurement of energies deposited by an incident particle in the detector, each of these channels has to be individually calibrated to given input energy. Or in other words, how many ADC counts correspond to a given charge in the sensor channel, which is to be converted to the units of energy.

There are two steps for calibrating the response of silicon sensors. In the first step, inter-channel response is equalized by using high energy muon beams (180 GeV), and is described in section 4.1. In the second step, inter-gain calibration to convert LG and ToT counts to HG counts (and finally to MIP units using inter-channel response equalization constant) is done using charge injection technique facilitated by the functionalities available with the SKIROC-CMS chips. The inter-gain calibration is detailed in section 4.2.

4.1 Channel-to-channel response equalization

Channel-to-channel response equalization [1] is done to achieve uniformity in the response by accounting for variation in the depleted thickness of the silicon sensors and any variations in the response of electronic gains. As discussed in the previous chapter, the muons are minimum ionizing particles over a wide range of energies. So, these could be used for getting the calibration factors for converting ADC counts to energy in units of number of MIPs. A minimum ionizing particle passing through silicon sensors undergoes ionization interactions with the silicon atoms and creates electron-hole pairs, which define our signal from the sensors. The energy deposited by muons is measured with high precision using the High Gain stage and corresponds to HG ADC counts or HG counts.

The distribution of the energy deposited by an ionizing charged particle passing through

a silicon cell approximately follows a Landau function, Fig. 4.1 shows energy spectrum in terms of HG ADC counts for a 300 μm thick sensor. The most probable value of the Landau distribution formed is expected to be around 57 keV and 86 keV for 200 μm and 300 μm thick sensors respectively, for normal incidence [1].

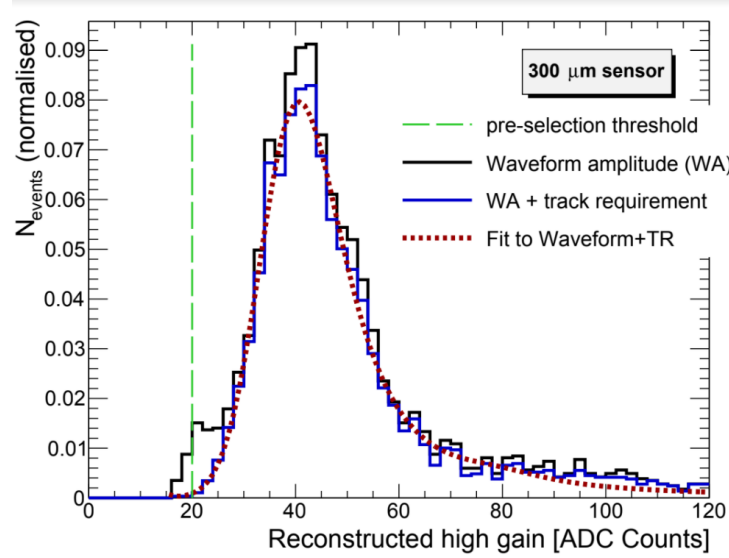


Figure 4.1: The energy spectrum of reconstructed ADC counts in high gain for an read-out channel due to incident 200 GeV/c muons. MIP-selected spectra were normalized to unity integral. The shown raw spectra were scaled accordingly [1].

For this purpose, a MIP-like particle beam like muon beam is used for this step of calibration which obtains the MIP calibration parameter C_{MIP} , i.e., the number of HG counts per MIP for each channel of all silicon sensors used. This step is also referred to as the MIP calibration. The C_{MIP} is extracted as the most probable value of muon energy spectrum by fitting it with a convolution of Gaussian and Landau function. In this way, the variation from channel to channel is taken away through MIP calibration constants as it is independently obtained for each channel. Fig. 4.2 displays a 200GeV/c muon event from 2018 beam test passing through the HGCal prototype.

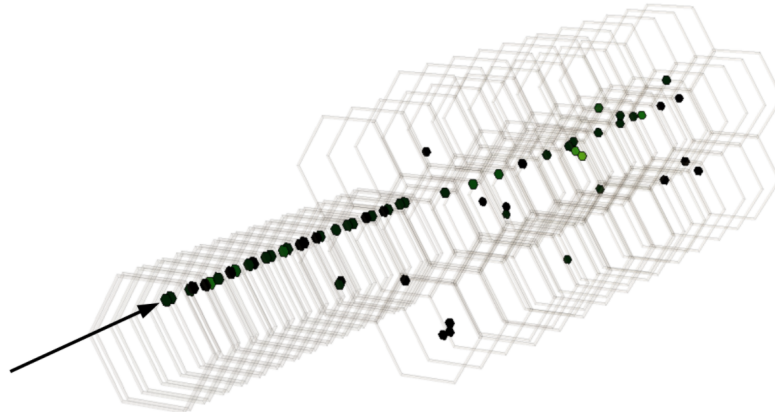


Figure 4.2: 200GeV/C muon event display from 2018 beam test passing through the HGCal prototype [1].

4.2 Intergain Calibration

The SKiROC2-CMS ASIC chip used in the construction of the CE prototype provides three different gain stages for the output, High Gain (HG), Low Gain (LG) & Time over Threshold (ToT). These gain stages perform optimally in specific energy ranges 200 fC for HG, 600 fC for LG, and above 600 fC for ToT. Now, energy signals from these three gain stages are combined to cover an extensive dynamic range. Here the LG and ToT counts are expressed in HG counts, and finally, all three outputs are converted into the units of number of MIPs as per Eqn 4.1. This calibration step is called inter-gain calibration, also called gain linearization calibration. With the digitized signal measured by HG, LG, and ToT stages expressed as the number of MIPs and inter-channel response equalized, the signal measured from different channels corresponding to a particle shower could be added to reconstruct the original energy of the particle.

For the 2018 prototype modules, two different methods are used for inter-gain calibration of silicon cells, namely, using 280 GeV positron beam data and charge injection data. In the following, I will summarize the calibration using these two methods.

4.2.1 Intergain calibration using positron data (TB_Calib)

The data collected with 280 GeV positron beams are used for intergain calibration. Since the intergain calibration is required to make the ADC output of all the three gain stages to the same scale, a high-energy incident beam was used to ensure sufficient data for ToT calibration [1]. The ToT is designed to be operated in the region of high charge production in a silicon sensor. The electromagnetic showers generated by 280 GeV positrons allow us to study all three stages and intercalibrate these. The key feature of this procedure is that this version of the SKIROC chip provided a good overlap region between the HG-LG and LG-ToT gain stages, allowing the translation from one to another possible, also providing an alternate check with beam data to validate the calibration procedure using the charge injection method.

Fig. 4.3 (left) and Fig. 4.3 (right) show the distribution of HG vs LG and LG vs ToT obtained using the 280 GeV positron data. Spline fitting is performed on both HG vs LG and LG vs ToT curves to find a correlation between the respective two measurements for each event. Using the information of first and second derivatives of the spline fits, linear ranges for correlations between HG and LG amplitudes, and LG and ToT amplitude. A linear fit is then performed on these ranges giving the inter-conversion factors from LG to HG and ToT to LG (which in turn uses LG to HG conversion constant to convert ToT to HG).

Fig. 4.3 also shows the common linear range between HG and LG, and LG and ToT for a channel of a CE-E prototype module from 280 GeV electromagnetic shower data. The HG saturates when the injected charge is larger than a threshold, and LG measurements need to be used beyond it. A deviation of 3% from linearity is set as a threshold for defining HG saturation level.

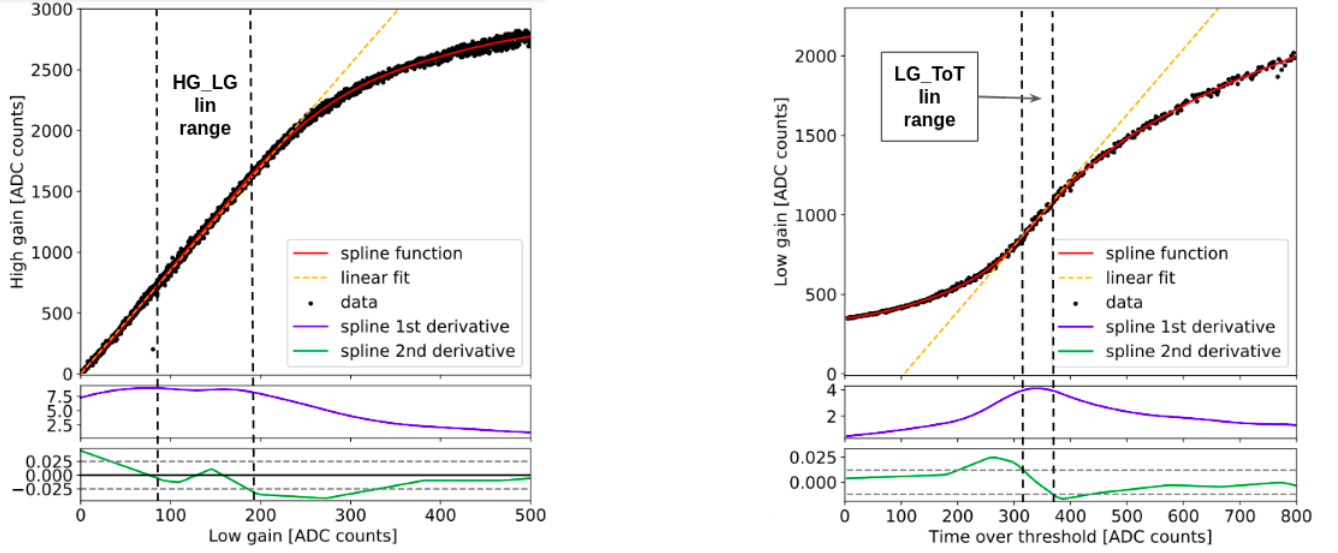


Figure 4.3: The high-gain amplitude as a function of the low-gain amplitude (left) in a CE-E prototype channel from 280 GeV electromagnetic shower data and the low-gain amplitude as a function the ToT (right) from the same channel. On the latter, the intercept between the dashed orange line and the x-axis defines the ToT offset.

A similar procedure is also used to find the LG saturation threshold beyond which ToT measurement should be used. Slopes were extracted from the straight-line fits as conversion factors between these gain stages to find HG equivalents of LG and ToT. For ToT, an additional term ToT_{offset} is also calculated to take into account the insensitivity of ToT at very low charges. Finally, HG ADC counts are converted into MIP equivalents using the channel-to-channel response equalization constants. Finally, when using this inter-calibration method, the deposited energy in a silicon cell is given by:

$$E = \begin{cases} E_{HG} = C_{MIP} \cdot A_{0,HG} & ,if \ A_{0,HG} < HG_{sat} \\ E_{LG} = C_{MIP} \cdot C_{HL} \cdot A_{0,LG} & ,if \ A_{0,HG} > HG_{sat} \text{ and } A_{0,LG} < LG_{sat} \\ E_{ToT} = C_{MIP} \cdot C_{HL} \cdot C_{LT} \cdot (ToT - ToT_{offset}) & ,otherwise \end{cases} \quad (4.1)$$

where $A_{0,HG}$, $A_{0,LG}$ & ToT are the respective HG ADC counts, LG ADC counts and ToT, C_{MIP} , C_{HL} , C_{LT} , ToT_{offset} are high-gain to MIP, low-gain to high-gain, ToT to low-gain conversion factor, and ToT offset, respectively & the HG_{sat} and LG_{sat} are the high gain saturation and low gain saturation points respectively.

4.2.2 Performance check

In 2018 Test Beam experiment, the CE-E prototype is irradiated with positron beams of 10 energy points ranging from 20GeV – 300GeV . Final energies of positrons in CE-E are reconstructed in MIP units for these beam energies using the response equalization and gain linearization constants obtained using beam test data or charge injection data. The performance of energy measured is passed in terms of response linearity (or linearity) and resolution, as described below.

Linearity & Resolution

Distributions of energies measured in terms of MIP units for a few representative beam energy points are shown in Fig. 4.4. Because of stochastic fluctuations inherent to the showering processes, imperfections in calibration processes, and noise, measured energies are distributed around an average value even for a mono-energetic beam of positrons. The distribution is close to a Gaussian with low energy tails mainly attributed to particles which have undergone some interactions before entering the detector. The response of positrons is expected to be linear i.e. total energy measured is directly proportional to the incident beam energy since almost all energy is covered to visible shower particles ($e^\pm$ and γ) in electromagnetic showers.

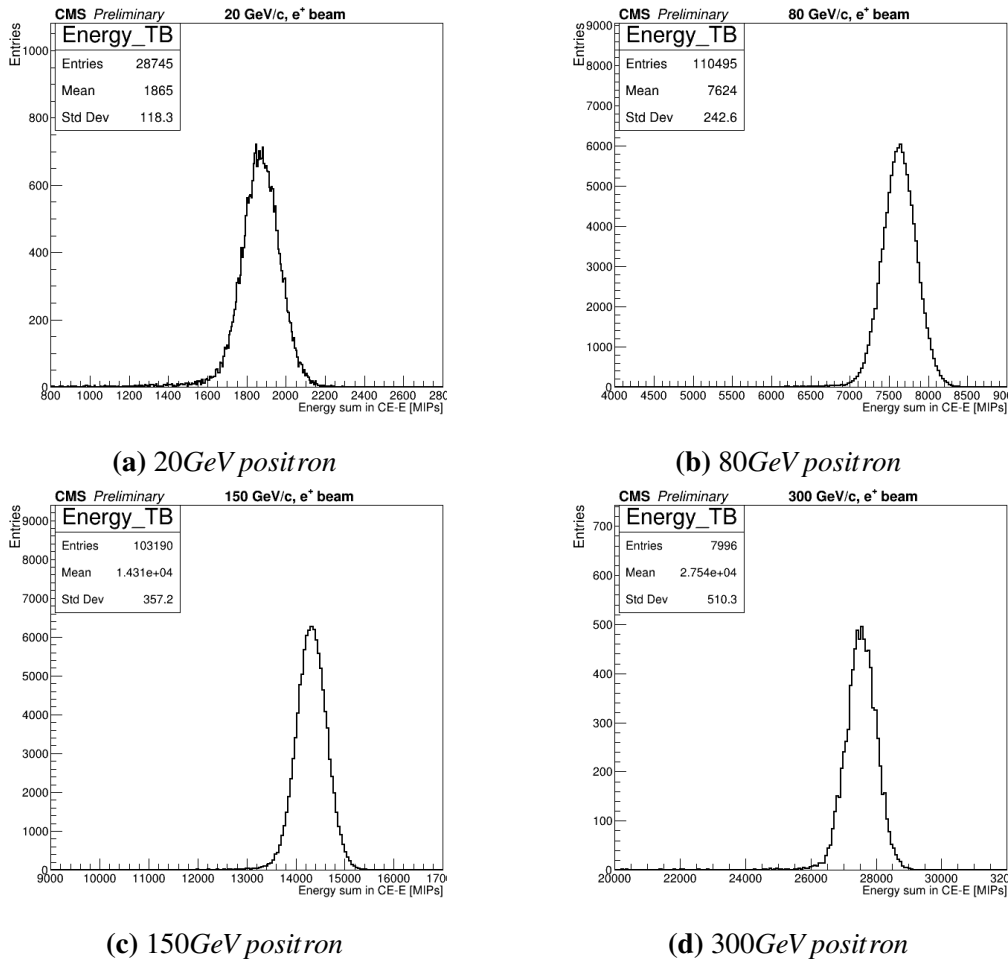


Figure 4.4: Distribution of measured energies in units of MIPs for four different energy beams for TB_calib with the Fitted Gaussian function

Now, these energy distributions are fitted with a gaussian function within a range of ± 1.5 standard deviation around the mean, and the range is updated after the first fit. The fitted distributions along with parameters are shown in Fig. 4.5. The fitted gaussian mean μ and variance σ_E are used to define response linearity and resolution.

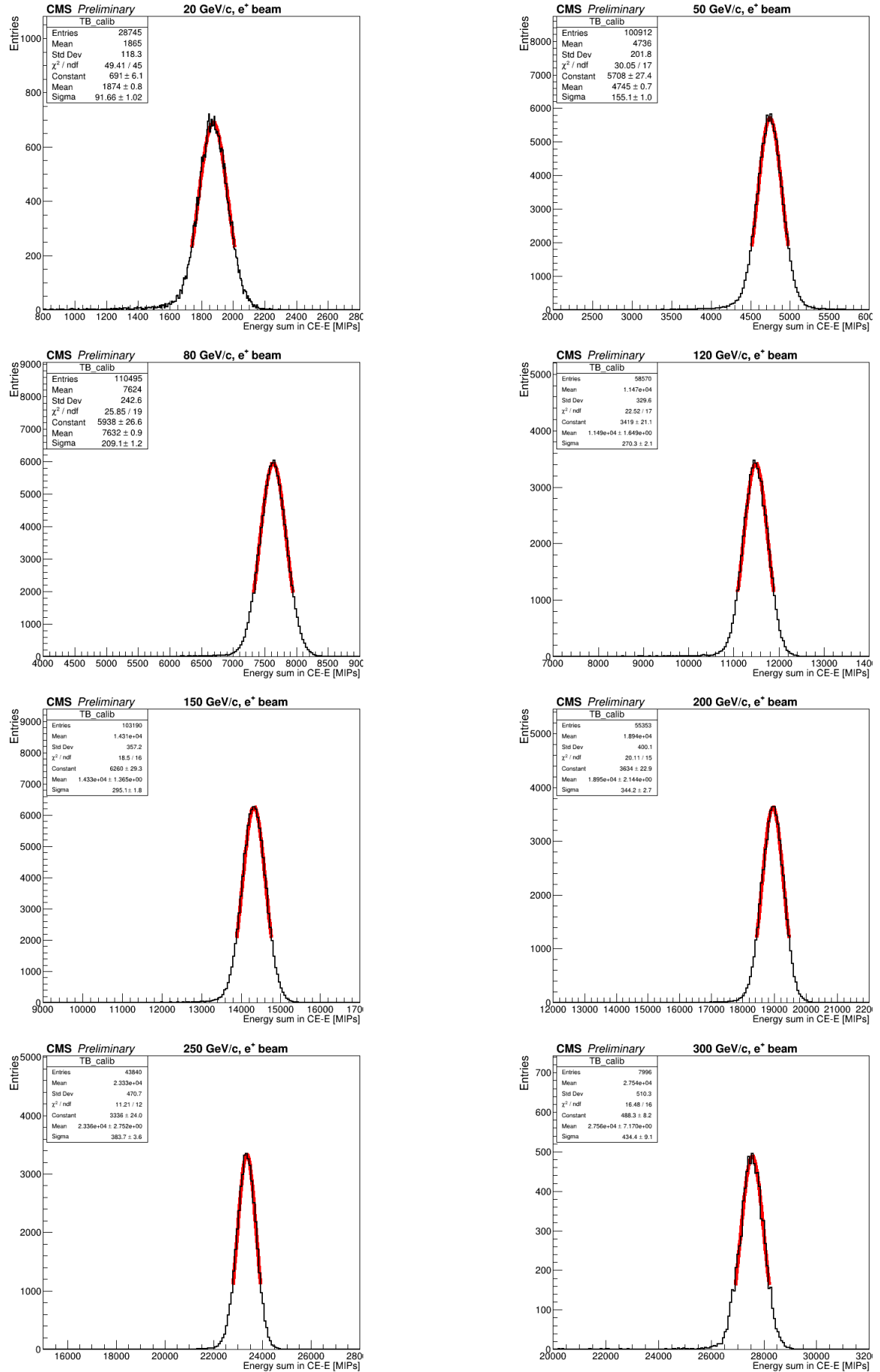


Figure 4.5: Distributions of measured energies (in units of MIPs) for 8 different positron beams for TB_calib along with fitted gaussian distributions.

The mean measured energy in units of number of MIPs as a function of beam energy is shown in Fig. 4.6 (top left). This is linearly increasing and is fitted with a straight line to obtain slope m . For checking the energy response linearity, we calculate the relative difference of the reconstructed positron energy with respect to the positron beam energy, where measured energies have been scaled by the factor m . So, response linearity is then presented in Fig. 4.6 (top right) and is defined as:

$$\frac{\langle \frac{E}{m} \rangle - E_{beam}}{E_{beam}} \quad (4.2)$$

where, E is the reconstructed energy in MIPs & E_{beam} is the positron beam energy in MIPs after subtracting the energy losses induced due to Synchrotron Radiation (SR) losses in case of positrons. The final fitted energy response for all the positron beam energies and the response linearity is shown in Fig. 4.6.

Energy resolution determines the capability of the detector to distinguish particles with different energies and is expressed as a percent of the incoming beam energy. It is defined as:

$$\frac{\sigma_E}{E} \quad (4.3)$$

where σ_E is obtained using Gaussian fit as described above. The relative resolution of positrons as a function of beam energy is shown in Fig. 4.6 (bottom).

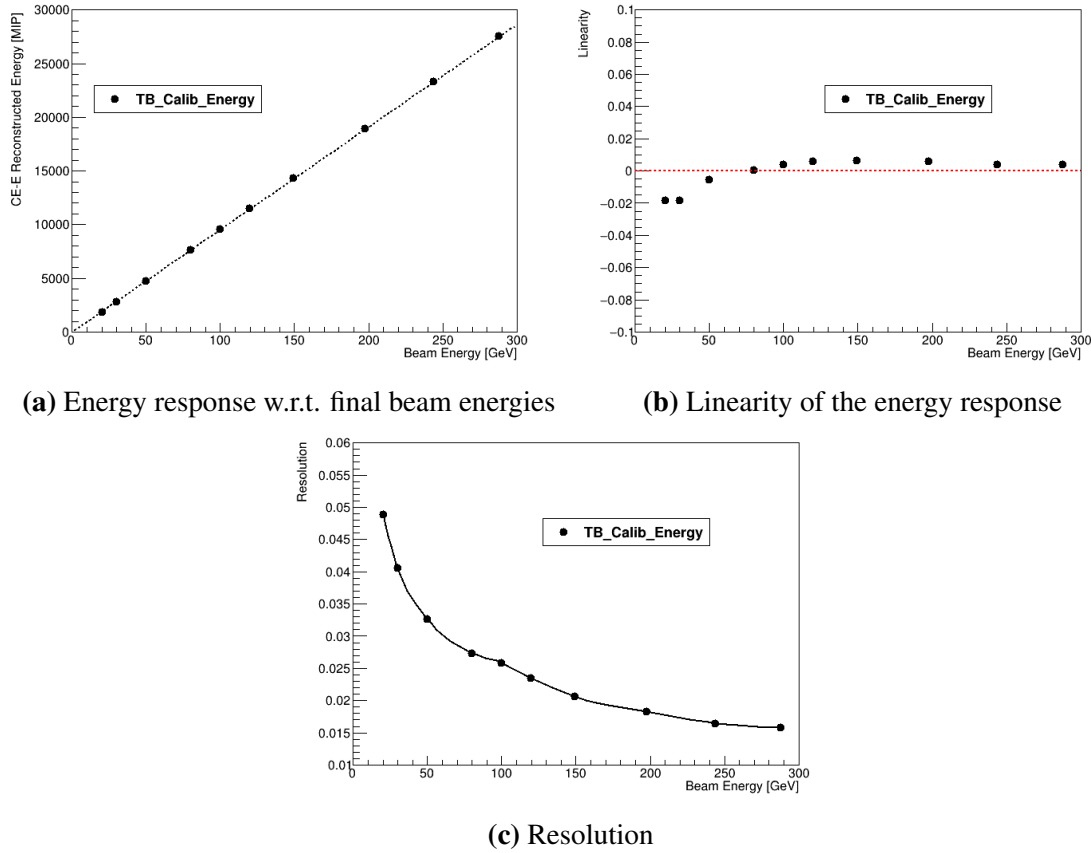


Figure 4.6: Performance summary of TB Calib

With this method, a total of 17% of HGCal prototype silicon cells are fully calibrated, i.e., for all three gain stages, while the HG-LG inter-calibration could be per-

formed for a much larger fraction of channels. This is because the channels situated away from the shower axis or in the layer away from shower maxima do not receive enough energy to fire the ToT sufficiently to be calibrated.

This is illustrated in Fig. 4.7, which shows ToT pedestal values obtained via this method. From the plots, we can see that majority of the channels connected to the same ASIC have the exact same values. This is because for these channels, a full calibration was unable to be performed using TB_Calib, and a chip average is used for these channels. From Fig. 4.7, it is also clear that for starting layers (e.g. layer 02 : module 90) and for later layers (e.g. layer 16 : module 87), the number of averaged entries is higher for near shower maxima layers (e.g. layer 7 : module 84 & layer 9 : module 69).

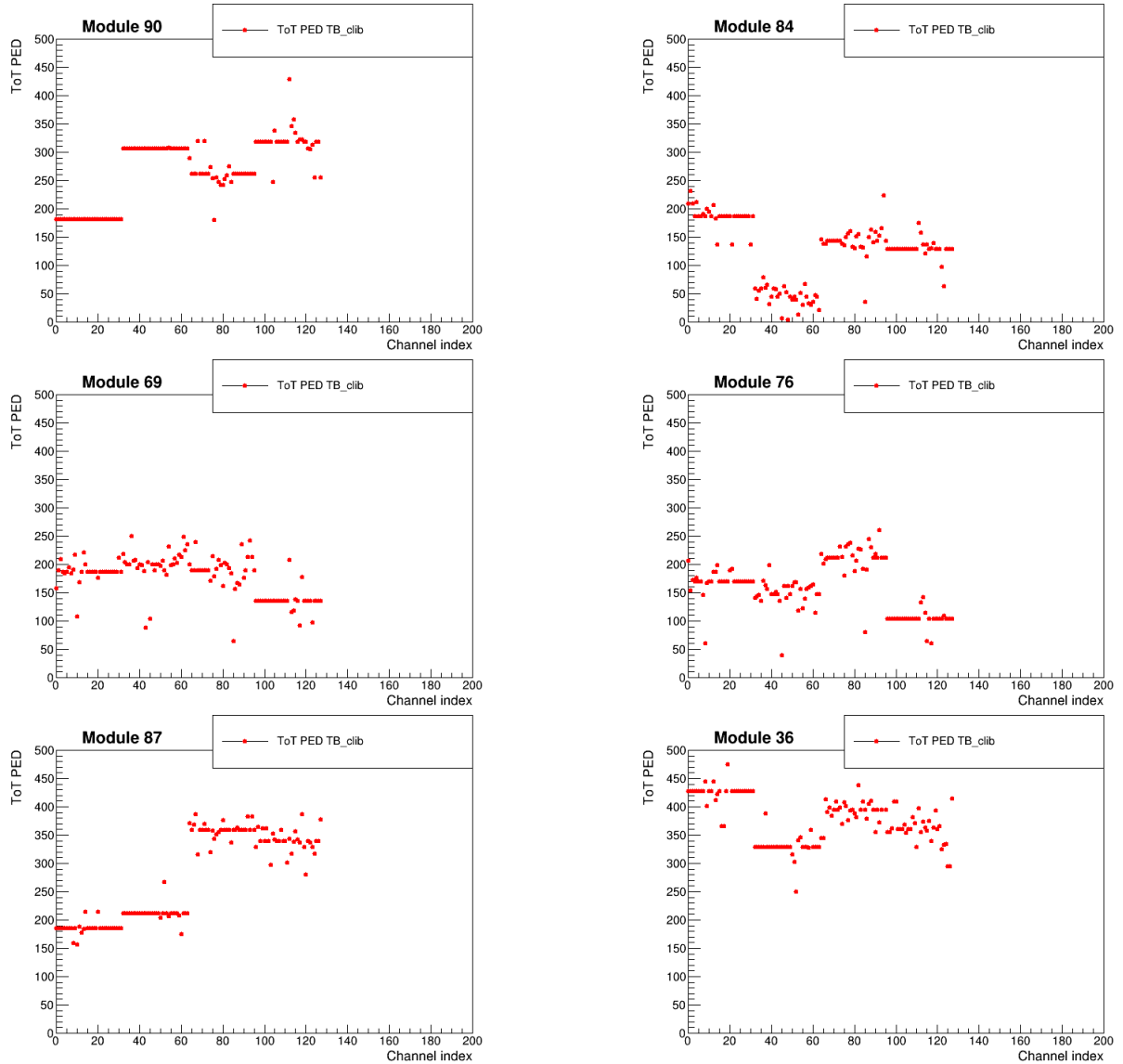


Figure 4.7: ToT pedestal values for all channels of a given module as obtained using TB data method, described above as TB_calib.

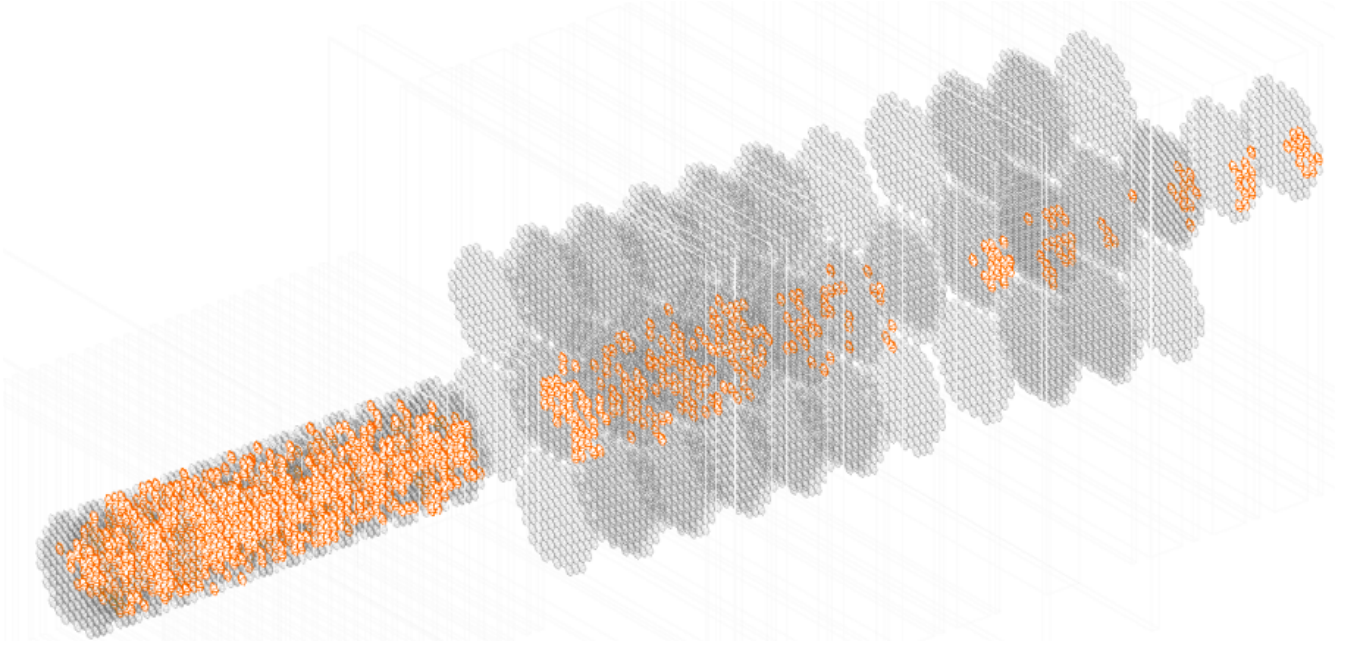


Figure 4.8: The yellow-coloured cells show the location of silicon cells that were fully calibrated using data-driven method. The cells lie almost near the center of the layer in both CE-E and CE-H prototype where the core of the shower deposits its energy.

Fig. 4.8 highlights the channels that have been fully calibrated using the data-driven method in CE-E and CE-H. With the final CE design having roughly 6 million channels, data-driven calibration will not be possible for a majority of the channels. Also, in the final chip to be used in the final HGCAL design, there may not be much overlap in different gain stages. The charge injection method provides an alternative approach to linearize the output of different gain stages which is discussed in next section [18].

4.2.3 Intergain Calibration using Charge Injection data (CI Prelim)

The inter-gain calibration parameters can not be achieved for all the channels using the test beam data driven method or later with the collision data in the early phase of operations. Also, the new ASIC chips to be used in the final HGAL setup will not have an overlap in different gain stages. Therefore, an alternative method is also tested for intergain calibration for all the channels independently. This method is based on injecting controlled known charge directly into all the channels of SKIROC2-CMS-ASICs.

The data is taken in the form of runs. In each run, 1000 events of increasing charge values are injected (in DAC inputs), and the corresponding digitized HG, LG, and ToT values are measured and stored for further analysis. Typical HG, LG, and ToT outputs of a single run of 1000 events for a cell are shown in Fig. 4.9.

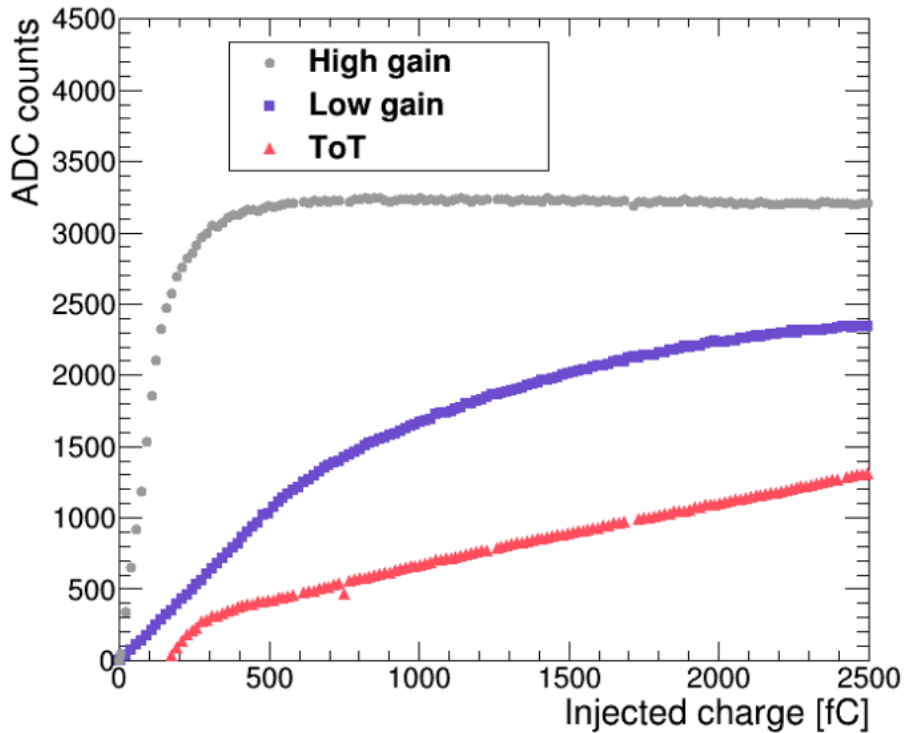


Figure 4.9: Output of a charge injection run for a single readout channel (cell). Here x-axis has been converted in fC.

Preliminary procedure for charge injection calibration method

Intergain calibration using Charge Injection method is carried out in two steps [1].

- **Step 1:-** Fitting the output (HG, LG and ToT) to find the intergain conversion factors.
- **Step 2:-** Finding the saturation points for HG and LG to accurately determine the gain switch points whenever a gain stage hits saturation.

So, the first step of calibration corresponds to fitting the outputs to find the linear regions (marked by dashed lines as shown in Fig. 4.10). Slopes of the fitted functions give us the desired intergain conversion factors. For HG and LG outputs equation of the form

$$Y(x) = m \cdot x \quad (4.4)$$

was used to fit an approximate linear range for both HG & LG where, x is the input charge signal, m is the free variable for fit which will finally give us the conversion factors & $Y(x)$ is the corresponding HG/LG output.

For ToT a more complex function is used for fitting in order to fit ToT over the full energy range. For ToT function of the form Eqn 4.5 is used.

$$ToT = \begin{cases} 0 & , \text{if } x < ToT_{thres} \\ p_0 + x \cdot p_1 - \frac{c}{x^\alpha - ToT_{thres}} & , \text{otherwise} \end{cases} \quad (4.5)$$

Three different functions have been clubbed together in order to fit the full ToT. The first part p_0 is the pedestal value, $p_1 \cdot x$ corresponds to the linear fit of the ToT, and the last term represents the non linearity in ToT.

An important step is to accurately find the saturation levels for HG and LG. This is done by iteratively searching for injected charge value for which the gain output under consideration shows significant negative onesided deviation (3%) between actual data and fitted function, in the Fig. 4.10 , HG_{sat} and LG_{sat} levels are marked by black and blue vertical lines respectively.

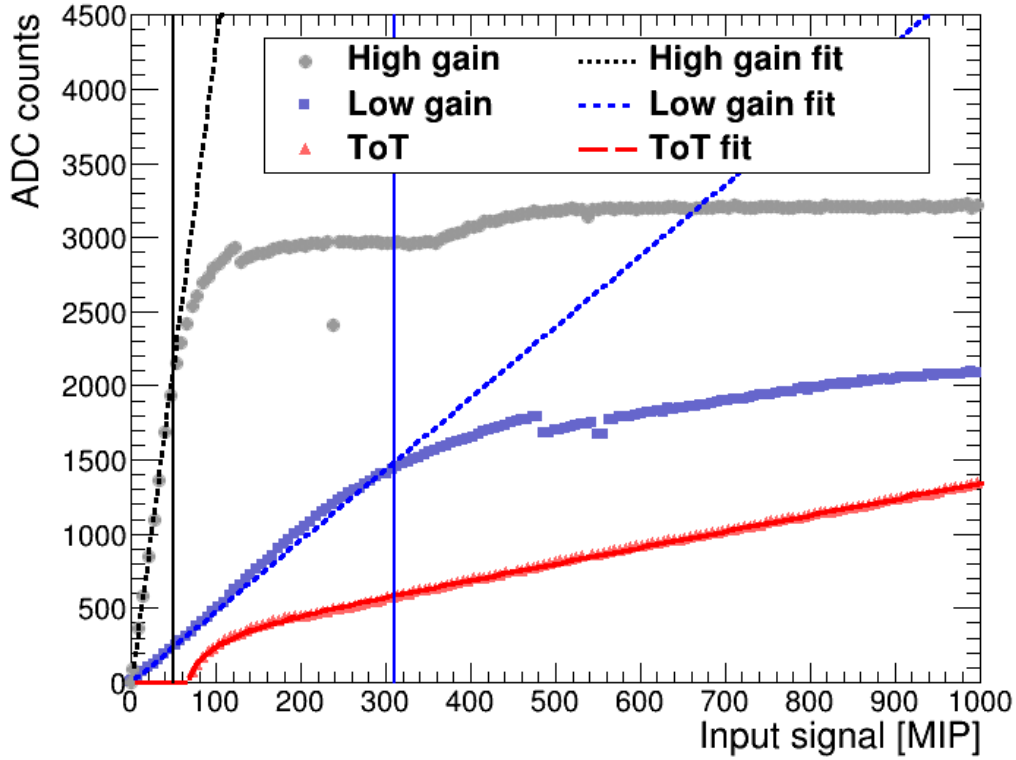


Figure 4.10: Charge injection calibration plot for channel 14 of chip 0 of layer 9 in CE-E. Here x-axis has been converted in number of MIPs.

Once the calibration is performed for all the channels of CE prototype the HG energy contribution and LG contribution is reconstructed for different positron beams as per Eqn 4.1 and for ToT energy contribution the full ToT function eq 4.5 is inverted using a binary search algorithm [14] to find the MIP equivalent of the ToT. The performance is discussed in sec 4.2.3. The calibration parameters obtained for some of the channels are shown in Fig. 4.11 & Fig. 4.12.

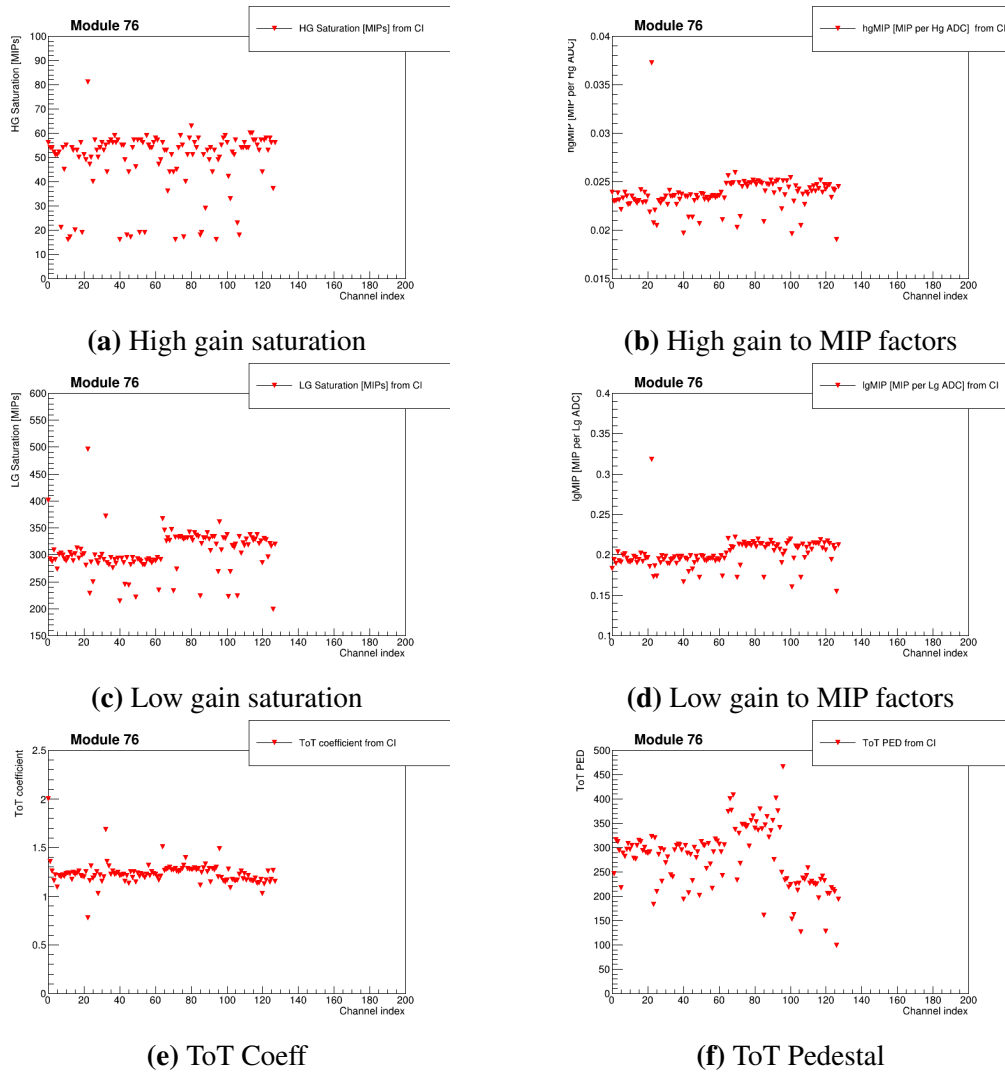


Figure 4.11: The Calibration parameters for CI Prelim for layer 11 : module 76.

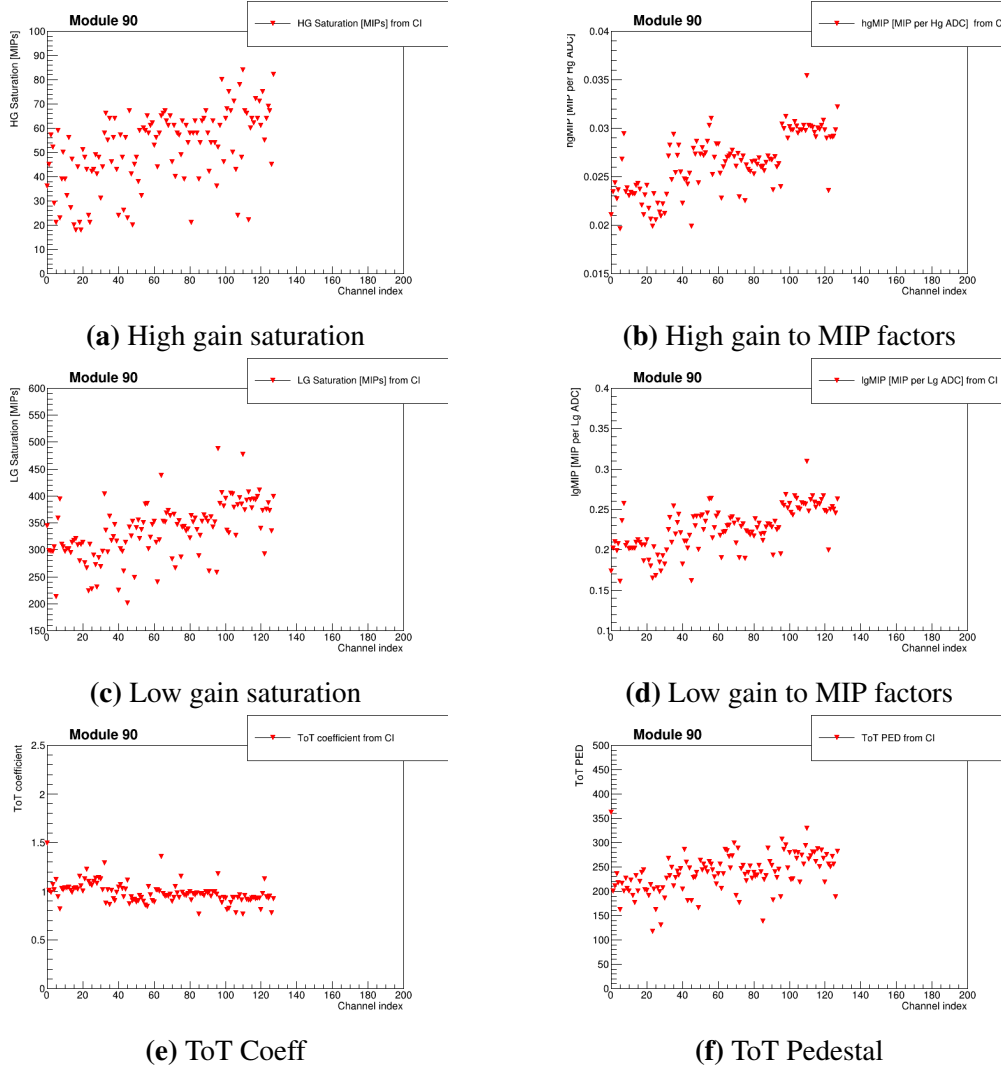


Figure 4.12: The Calibration parameters for CI_Prelim for layer 02 : module 90.

Performance

Using the intergain calibrations so obtained with the charge injection procedure, the positron energy is reconstructed for all beam energies, and response and resolution are defined in a similar way as described in section 4.2.2. Distributions of energies reconstructed in the units of a number of MIPs, fitted with Gaussian function, are shown in Fig. 4.13.

The response linearity and resolution as a function of beam energies are summarized in Fig. 4.14. The results are also compared with the calibration obtained using 280 GeV positron beam data described in the previous section. We observe that using **CI_Prelim** results in an overall higher value of resolution with respect to that obtained using **TB_Calib**, and it gets worse at higher energies as shown in Fig. 4.14 (right) showing ratios of resolutions of CI_Prelim to TB_Calib are plotted with respect to the beam energies.

The linearity is roughly within 2% variation range same as that for TB_Calib but a decreasing trend in linearity from energy range $[50\text{GeV}, 300\text{GeV}]$ as a function of beam energy observed when response is calculated using CI_Prelim calibrations.

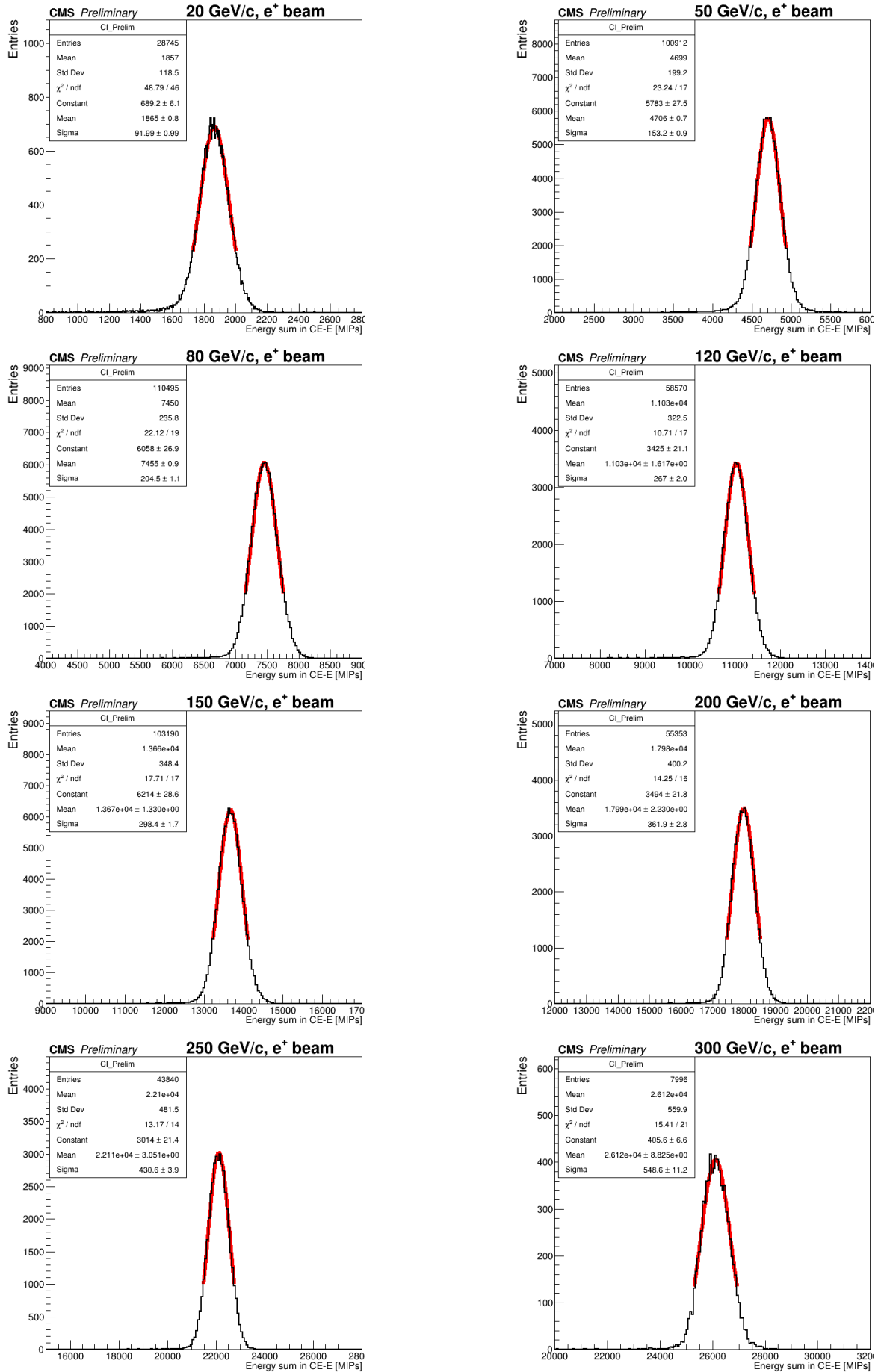


Figure 4.13: Energy response distribution for 8 positron energy beams for CI.Prelim with fitted Gaussian distributions.

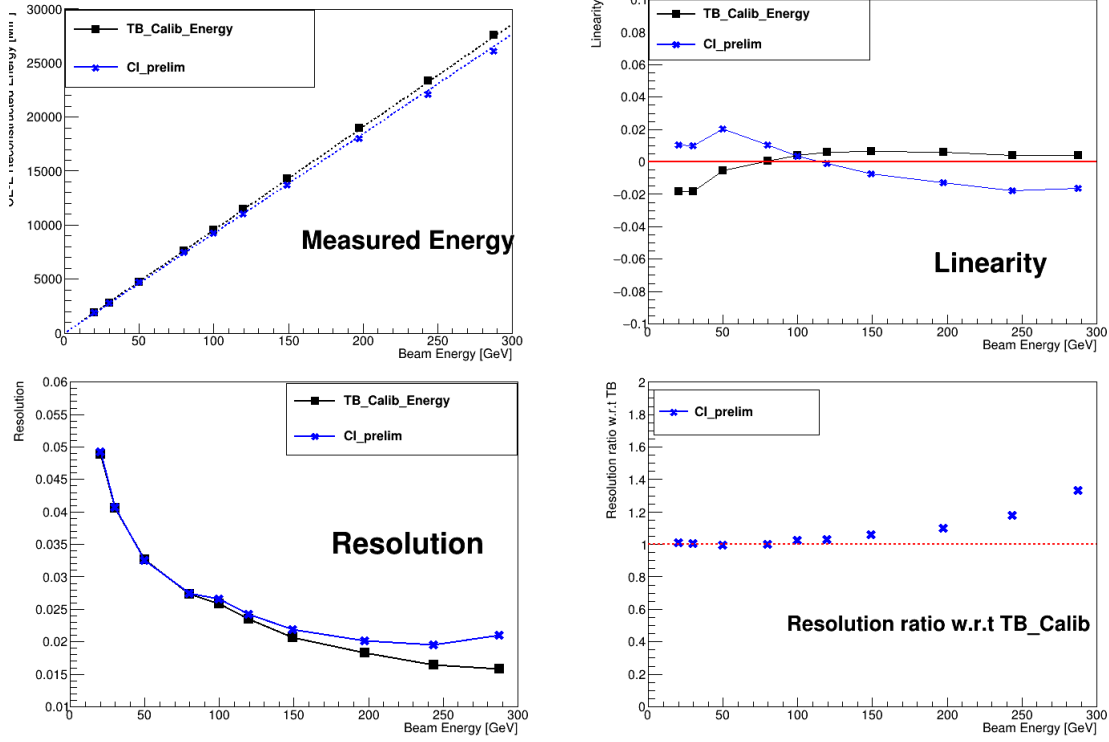


Figure 4.14: Performance summary of CI.Prelim.

The results above shows that the low level calibration of different gain stages is very important for getting the best performance of the CE-E for measuring electromagnetic showers created by positrons. With results using the beam dataset as benchmark, there is a lot of room for improving the charge injection calibration procedure.

In order to investigate further, we looked at distributions of energies reconstructed for individual cells of a given module for different positron energies as shown in Fig. 4.15 & Fig. 4.16. These are inclusive over all cells of a given module but not summed up (i.e. histograms are filled multiple times for each event). The distributions corresponding to reconstruction with the two intergain calibrations are presented for the purpose of comparisons : **TB.Calib** & **CI.Prelim**.

Observations from reconstructed hit spectrums of CI.Prelim.

- In most of the modules, the CI.Prelim calibrations result in smaller energy reconstruction on higher end of the spectrum. This under reconstruction of energy could also explain the lower energy response as observed in Fig. 4.14 (upper right figure) with respect to TB.Calib.
- This difference in entries in tail sides is also reflected near the LG to ToT transition regions resulting in change of dip (which was there in TB.Calib) to a hump (now in CI.Prelim), for e.g refer to layer 09 & layer 11 in Fig. 4.15 & Fig. 4.16.
- In some layers, dip already present in TB.Calib spectrum got enhanced in CI.Prelim spectrum, for e.g refer to layer 07 in Fig. 4.15 & Fig. 4.16.
- In some layers new dips were introduced in CI.Prelim rehit spectrums which were absent for TB.Calib. for e.g refer to layer 16 in Fig. 4.16.

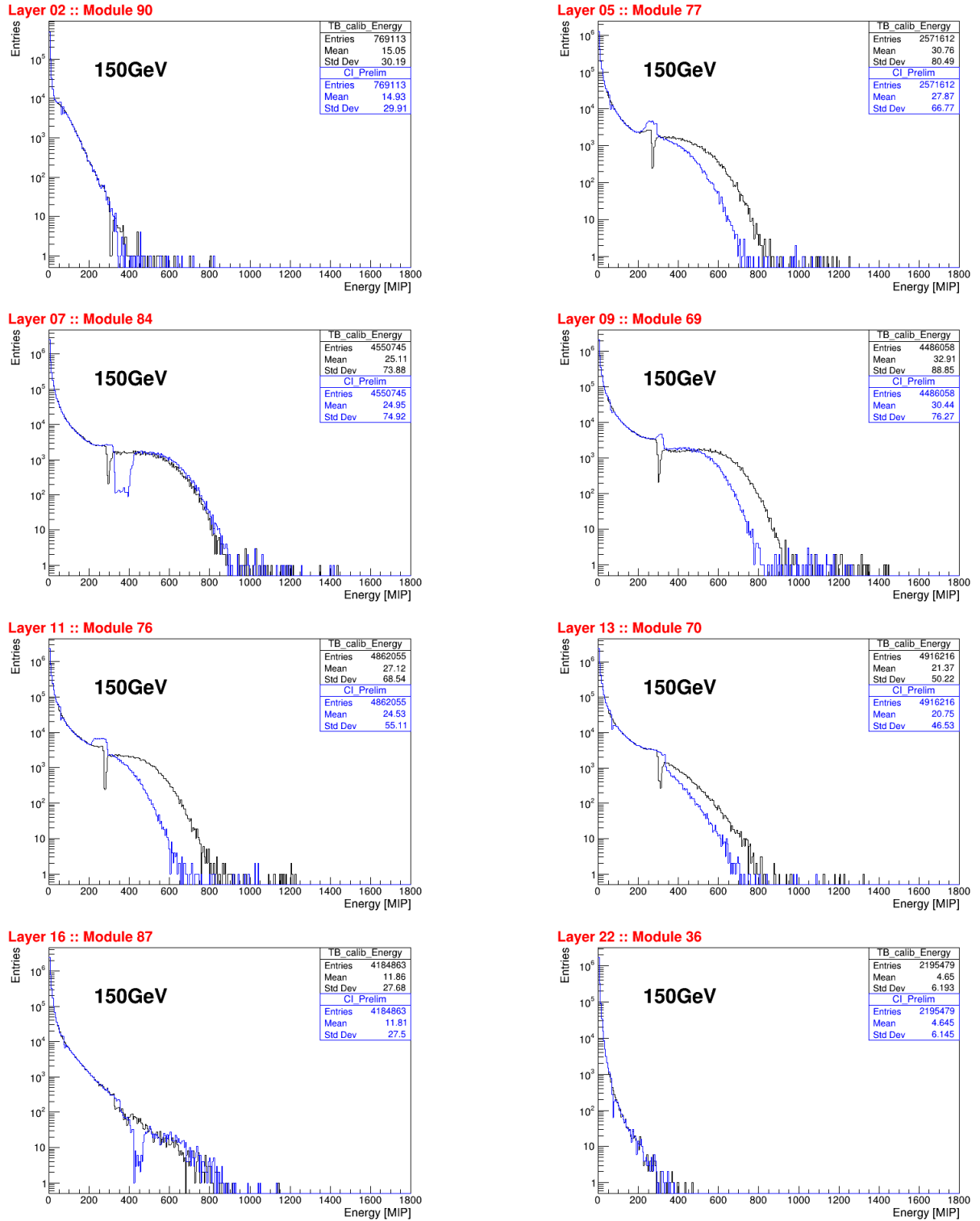


Figure 4.15: Rechit energy spectrum comparison of CI_Prelim wit TB_Calib for some layers of CE-E for 150GeV.

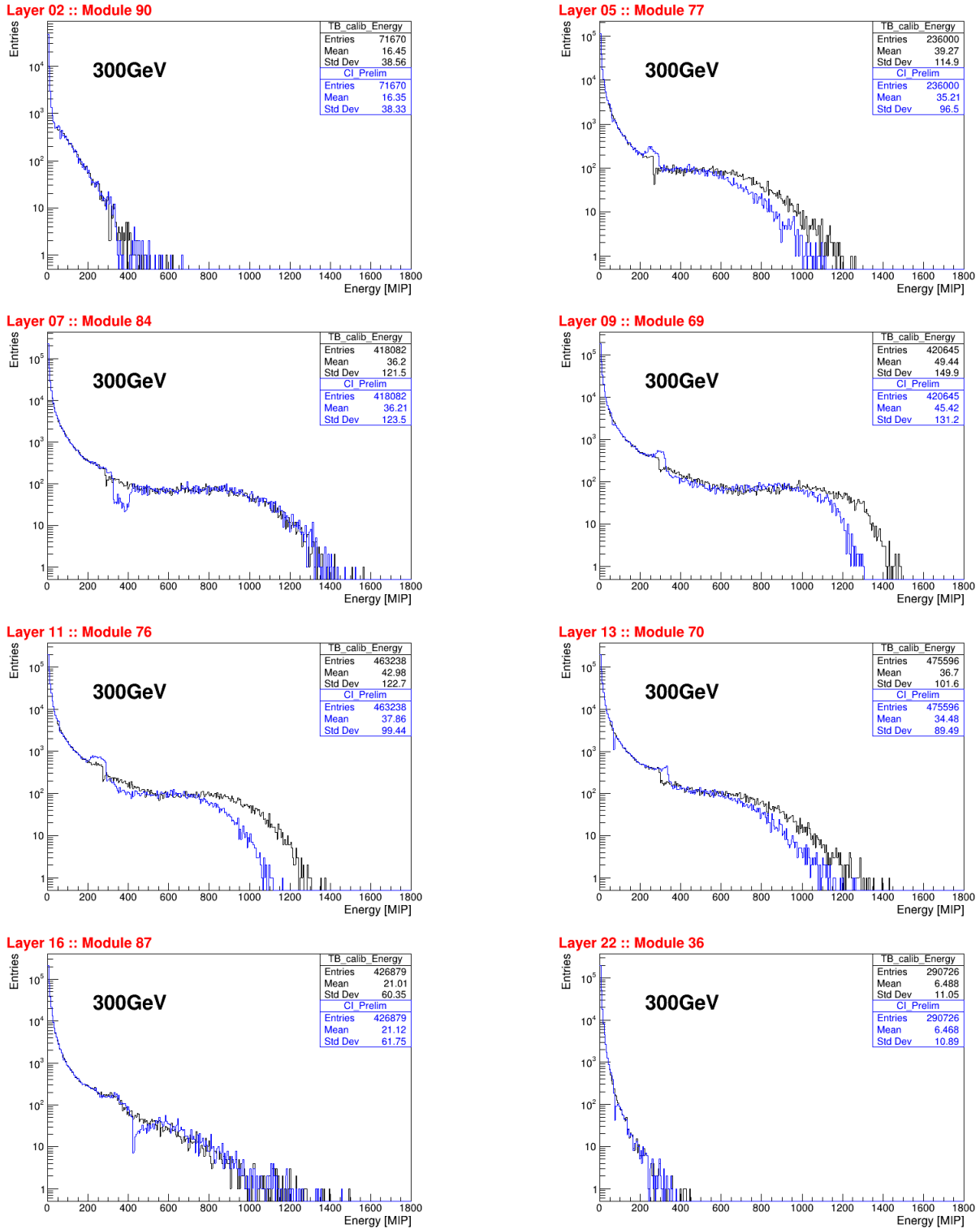


Figure 4.16: Rechit energy spectrum comparison of CI.Prelim wit TB.Calib for some layers of CE-E for 300GeV.

So, apart from worst performance in resolution and linearity (Fig. 4.14) we also observe unphysical features in rechit spectra which are expected to be smoothly falling (Fig. 4.15 & Fig. 4.16). The only advantage of CI.Prelim over TB.Calib is that using CI.Prelim a total of 98% channels were fully calibrated as compared to 17% in using TB.Calib. Due to these reasons CI.Prelim machinery needs refinement so that if not all, some of these problems can be sorted.

Based on these observations, we tried to improve a few aspects of charge injection calibration.

- As discussed in section 4.2.3, CI.Prelim uses onesided negative deviation for finding HG_{Sat} & LG_{Sat} . Now, onesided deviation allows a small non linear region in LG to contribute to total linear region and finally contribute in energy reconstruction as shown in Fig. 4.17. So, this non-linear LG part should be taken care of.
- The ToT energy contribution is calculated using a full ToT function and then inverting it using a binary algorithm where as in TB.Calib this is done by fitting a straight line in LG/ToT linear region. A detailed study of this new method used in CI.Prelim might also give some room for improvements.

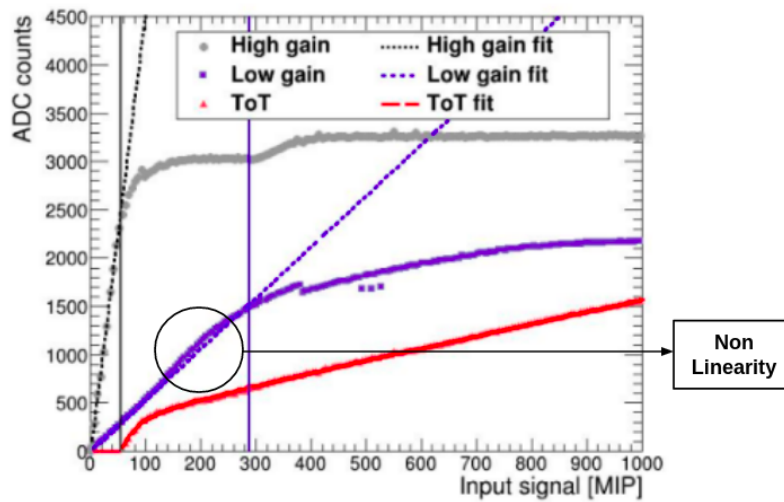


Figure 4.17: Calibration plot for one of the channel from CE-E showing non linear contribution in linear region of LG.

The various methods and alternatives I tried to improve intergain calibrations using charge injection data and performance with respect to preliminary results discussed here as well as with TestBeam calibration results are presented in the next chapter.

Chapter 5

Intergain calibration using charge injection method

In this section, I will be discussing the various methods tried for obtaining the intergain calibrations for TB 2018 modules using charge injection procedure. For each version of calibration coefficient and saturation threshold parameters obtained, the positron beam data is reconstructed for all energies. Energy response and resolution are used to compare the performance with the reconstruction using calibrations obtained with 280 GeV positron data and preliminary calibration as described in the previous chapter. Since the calibration derived from the TB data is applied to the same data itself, hence it is expected to perform well, it serves as a good benchmark for performance, and the preliminary calibration using charge injection is a good reference to improve upon.

A summary of five variations tried in the intergain calibration using the charge injection is documented in this chapter, and listed below for a quick overview of the content of this chapter. The methods 01-04 focuses more on finding improvements in thresholds for switching to using higher gain stages (LG and ToT) while keeping the calibration coefficient determined from respective measurements. The method 05 is motivated by the procedure used in TB_Calib version.

- CI Method 01 (Sec 5.1): In this version, we start with checking the effect of using absolute deviation on the response linearity as opposed to only one-sided deviation used in CI Prelim version.
- CI Method 02 (Sec 5.2): In this version, the three components of ToT are analyzed separately in order to set a threshold for allowed non-linearity in ToT using the respective component of ToT function.
- CI Method 03 (Sec 5.3): For this version, an additional step was performed over CI Method 02 in which the ToT linear part is refitted over a restricted range. That is ToT→LG calibration coefficients are updated with respect to CI Method 02.
- CI Method 04 (Sec 5.4): This method is almost same as CI Method 03 with the only changes in the non-linearity allowance for calculating ToT energy contribution using the non-linear component of the ToT fit.
- CI Method 05 (Sec 5.5): This method is closest to TB_Calib machinery in which ToT is fitted over the overlapping linear region with LG linear region.

5.1 Charge Injection Method 01 (CI Method 01)

As discussed in section 4.2.3, the CI-Prelim defines the HG and LG saturation threshold (HG_{Sat} & LG_{Sat} , respectively) when the ADC counts are small than what is expected from a linear fit by 3%. This is as expected from the definition of gain saturation in any measurement. However, we noticed that in many cases the deviation from straight line was on the higher side resulting in a higher threshold where the switch should have been made. This is illustrated in Fig. 5.1. So, to avoid that non-linearity, the criteria for finding the saturation levels were updated from an one-sided deviation criteria to an absolute both sided deviation criteria.

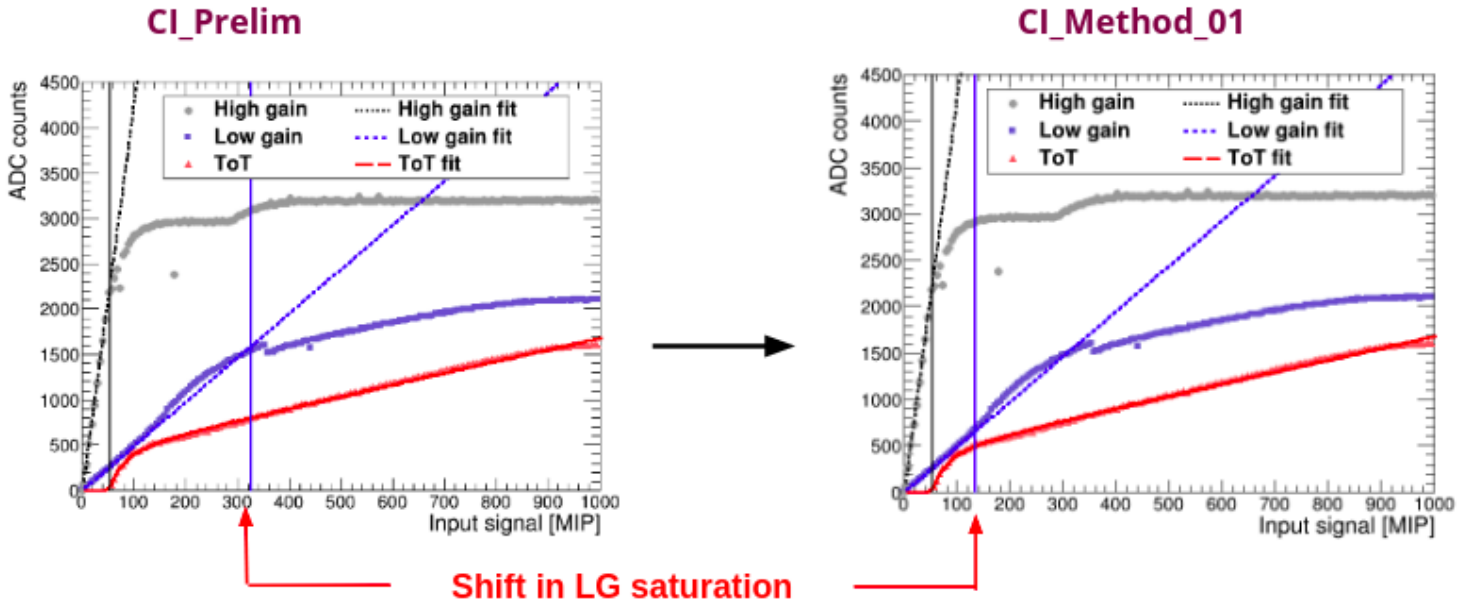
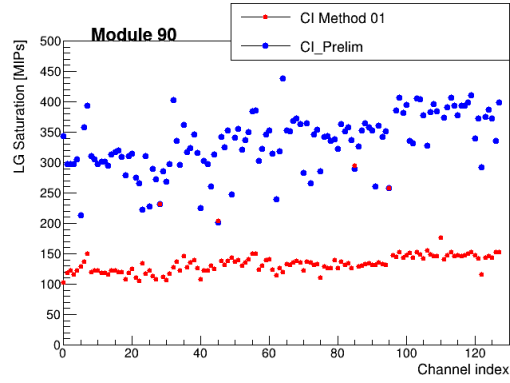


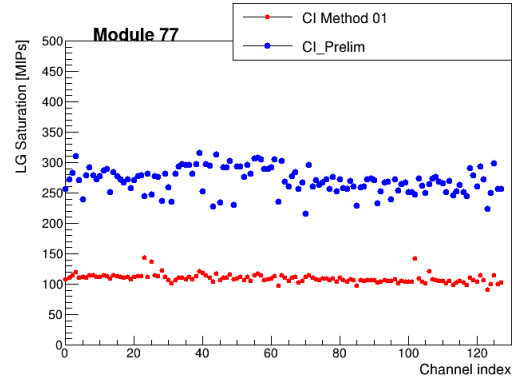
Figure 5.1: LG saturation shift between CI_Prelim and CI Method 01 for a channel in CE-E.

Fig 5.2 shows the updated LG saturation values as compared to the CI_Prelim version for a few modules for which the changes observed were significant.

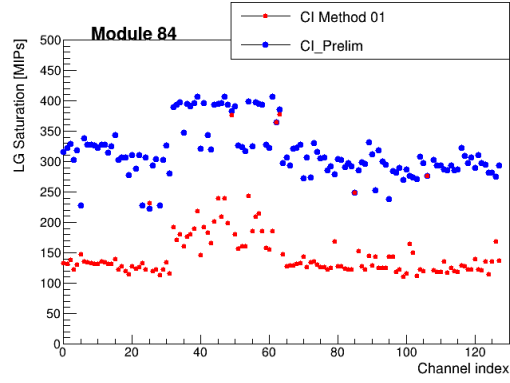
We reconstruct the energies using calibration coefficients and saturation thresholds obtained using this charge injection version for all the positron beam energies. Distributions of reconstructed energies along with Gaussian fits to the bulk are shown in Fig 5.3. Using the Gaussian fitted parameters μ and σ_e , the response linearity and the energy resolution as a function of beam energy are shown in Fig 5.4.



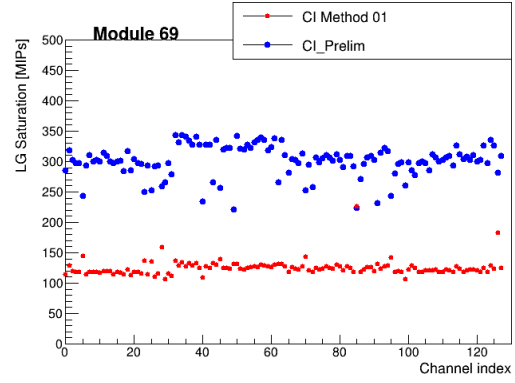
(a) LG saturation for layer 02



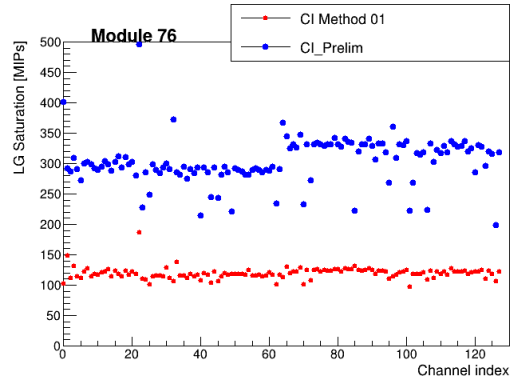
(b) LG saturation for layer 05



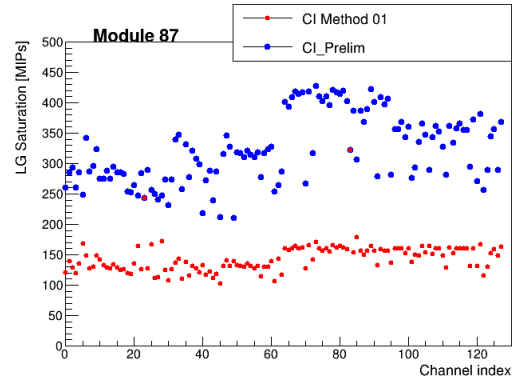
(c) LG saturation for layer 07



(d) LG saturation for layer 09



(e) LG saturation for layer 11



(f) LG saturation for layer 16

Figure 5.2: LG saturations calculated using CI method01 for some of the layers of CE-E

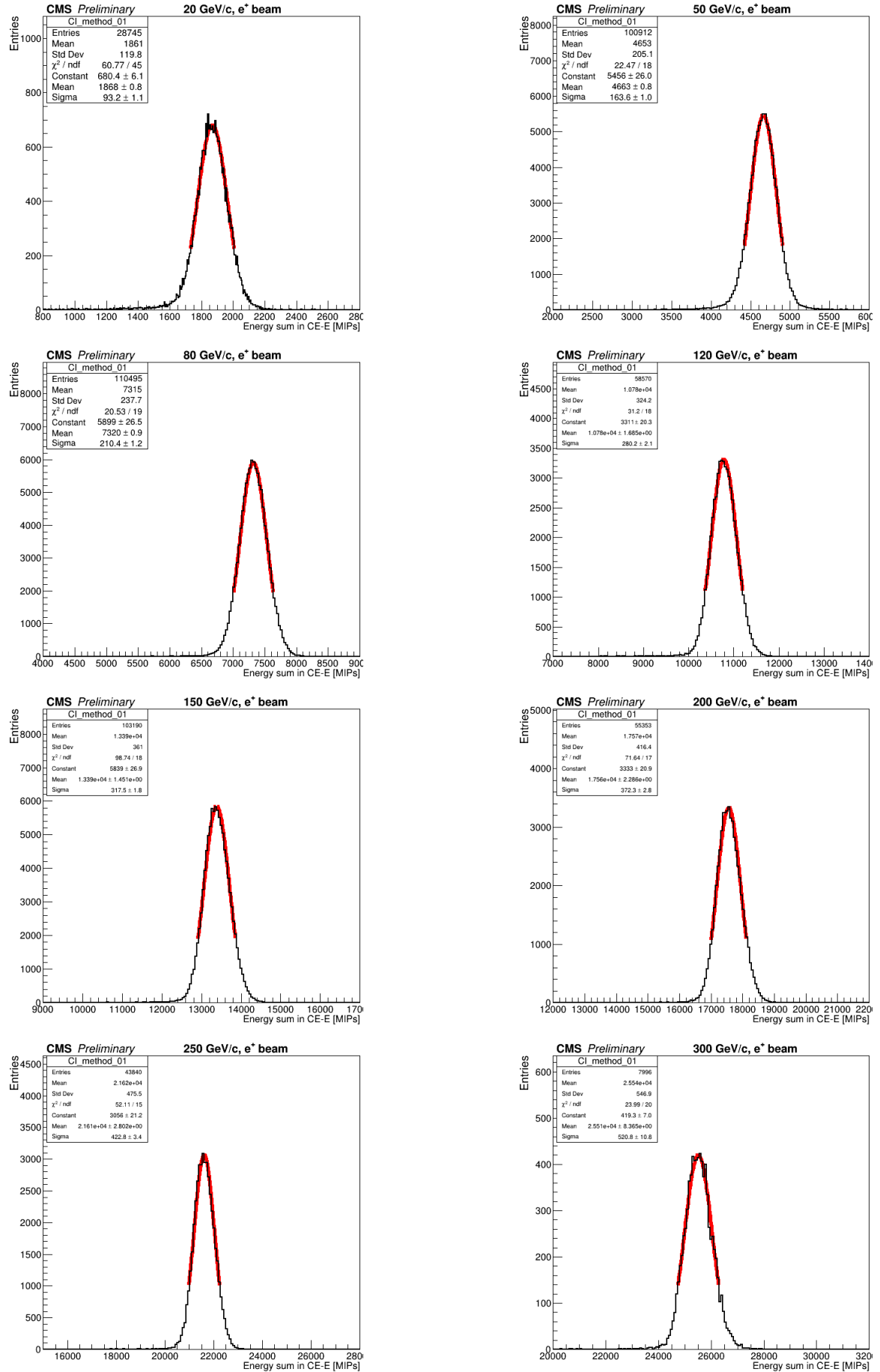


Figure 5.3: Distributions of positron energies reconstructed with CI Method 01 along with fitted Gaussian function for eight beam energies.

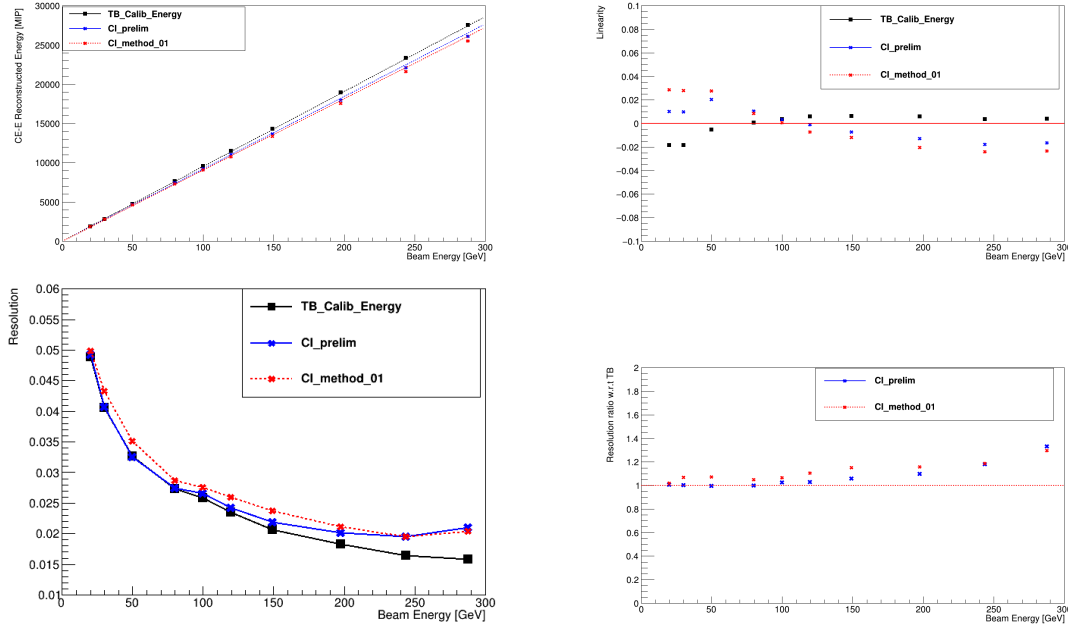


Figure 5.4: Performance results for CI method 01

5.1.1 Discussion

We observe, in Fig. 5.4, that **CI Method 01** has overall a higher value of resolution with respect to both **TB_Calib** and **CI_Prelim** for almost all the positron beams. The resolution is similar to CI_Prelim method at highest beam energies which is expected because our method has not changed the calibration parameters pertinent to ToT much. This is also visible from the rehit spectra shown in Fig. 5.5 and Fig. 5.6 for 150 GeV and 300 GeV positrons. The CI_Prelim and CI Method 01 completely overlaps on higher energy part of the spectrum. A few observations are:

- In most of the layers, the dip around 300-400 MIPs in CI_Prelim got shifted to a lower level or the dip got flattens out for many layers with respect to CI_Prelim, as observed in layers 7, 9 & 13 in Fig. 5.5 and Fig. 5.5.
- In few layers the use of absolute deviation criteria for saturation has resulted into worsening of the CI_Prelim dip or appearance of new dip e.g. of such layers are layer 2 in Fig. 5.5 and Fig. 5.6.
- The HG→LG dip in CI_Prelim was not present in any of the channel for CI Method 01.

The biggest drawback of this method could be lowering of LG→ToT switching threshold. One has to be careful with this because the ToT is not designed to perform best at lower energies. This may explain worsening of the resolution for intermediate positron beam energies. However, this method does help in resolving or completely removing the dip observed in reconstructed energies per cell around the regions of HG→LG switching. But this improvement alone cannot justify the bad performance of the model in terms of linearity and resolution, and hence, continue to investigate further.

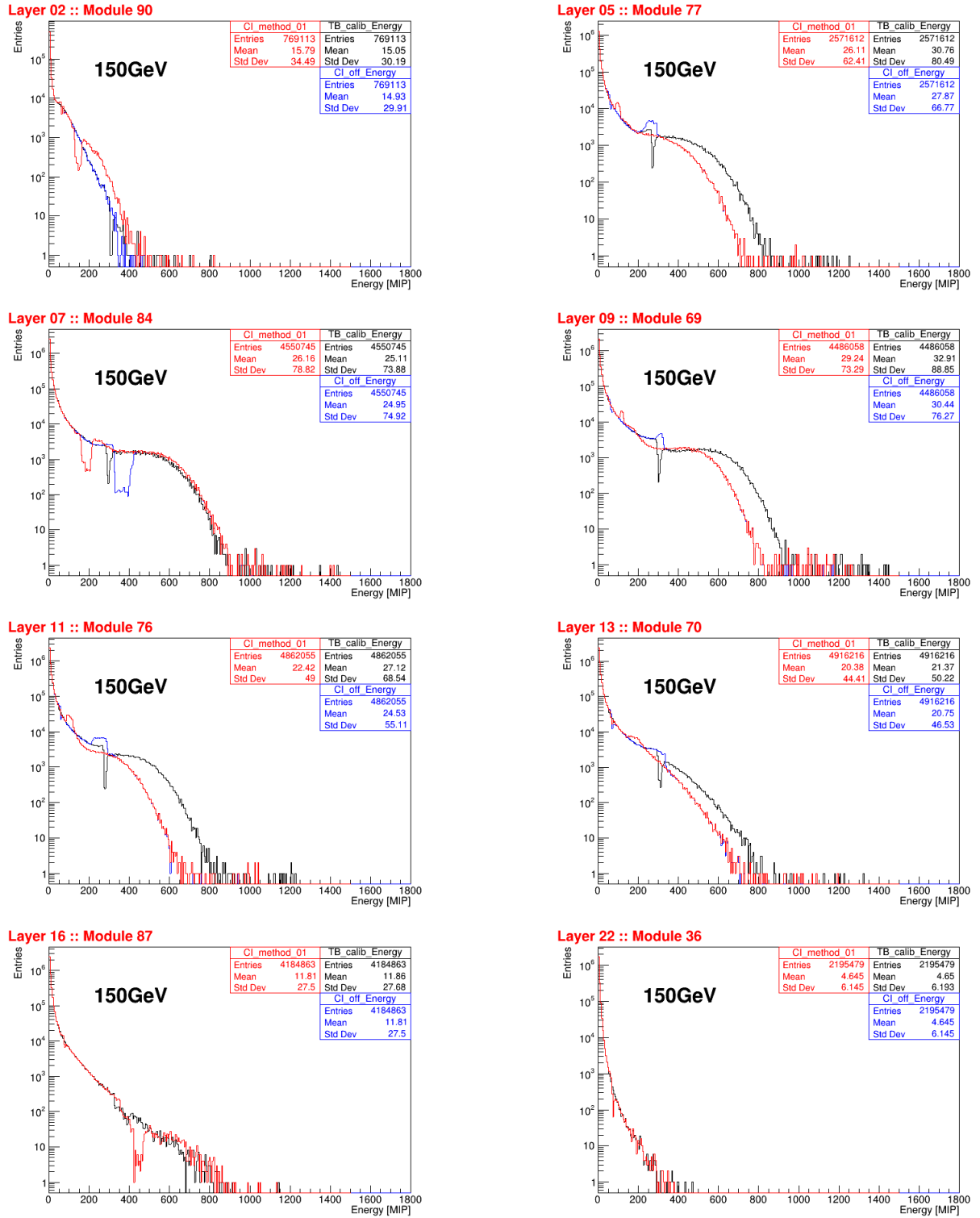


Figure 5.5: Rechet energy spectrum comparison of CI Method 01 with CI_Prelim and TB_Calib for some layers of CE-E for 150 GeV

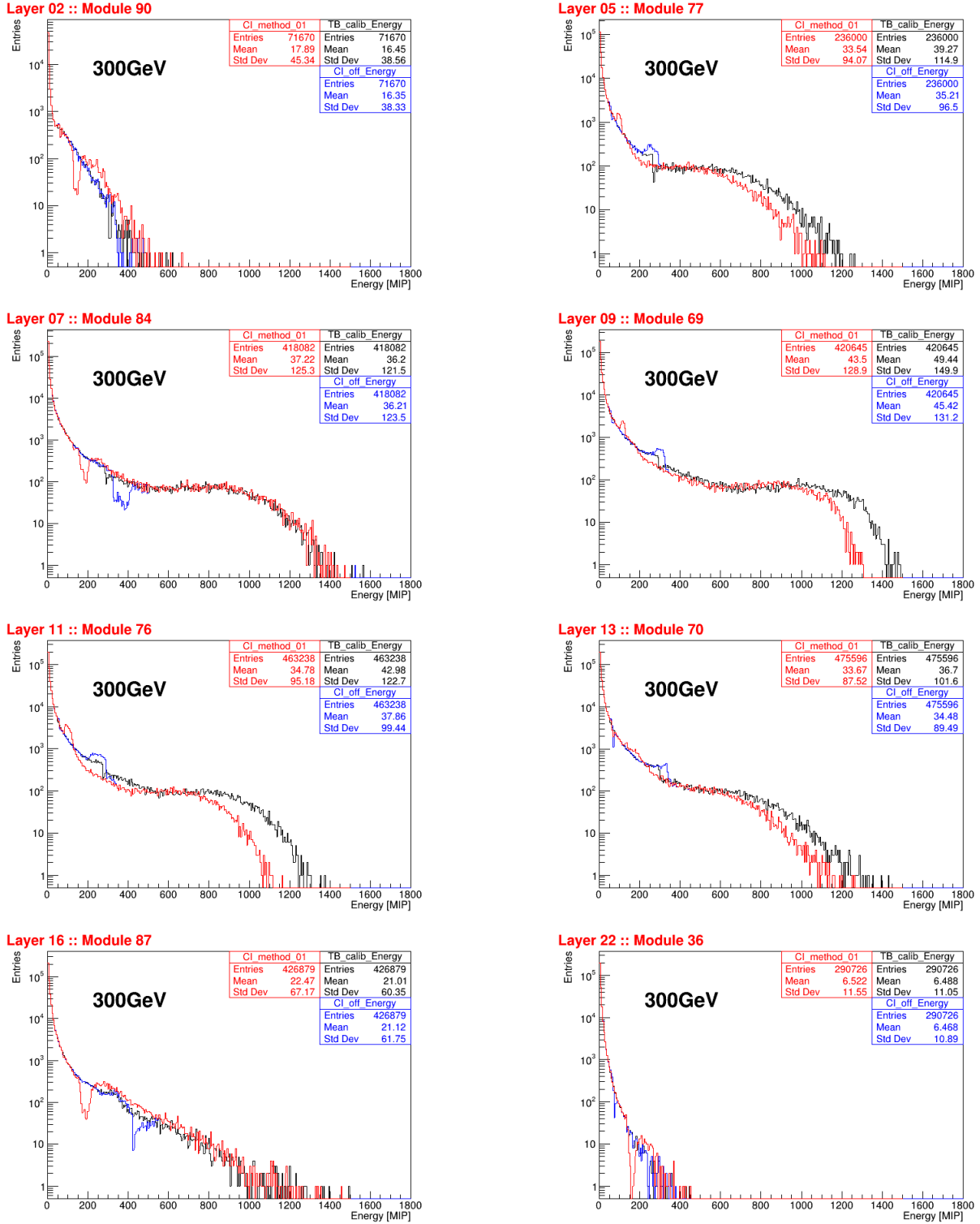


Figure 5.6: Rehit energy spectrum comparison of CI method 01 with CI_Prelim and TB_Calib for some layers of CE-E for 300GeV.

5.2 Charge Injection Method 02 (CI Method 02)

Using the CI Method 01, for almost all the channels the LG saturation levels shifted to a much lower level, mostly starts overlapping with the non-linear contribution starts adding into ToT region, which can account for some biasing in our final energy reconstruction. One such channel is illustrated in Fig. 5.7. We do not want to introduce this feature because ToT is not fully functional in this region. Instead, we decided to understand features in the ToT measurements and fits in details.

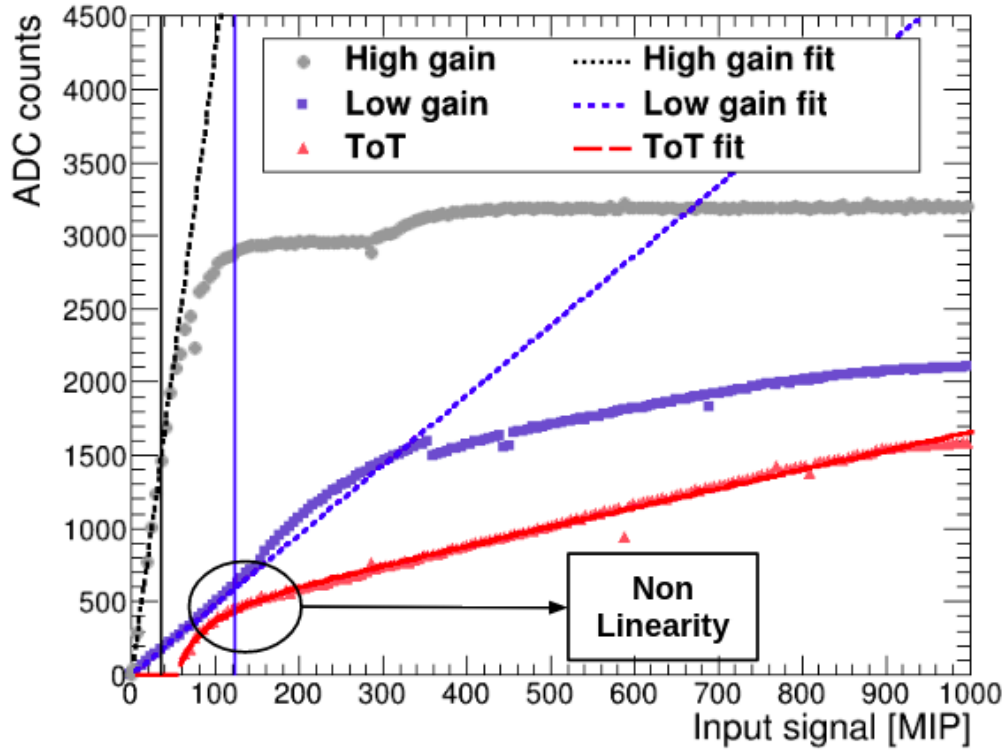


Figure 5.7: Calibration plot for a channel of CE-E showing non linear inclusion in ToT linear part.

Different components of ToT measurements

As explained in Section 4.2.3, the full function used for fitting a ToT measurement is of the form:

$$ToT = \begin{cases} 0 & ,if \ x < ToT_{thres} \\ p_0 + x \cdot p_1 - \frac{c}{x^\alpha - ToT_{thres}} & ,otherwise \end{cases} \quad (5.1)$$

From equation 5.1, we can see that full ToT function has two major components ToT_{Lin} and ToT_{NLin} such that:

$$ToT_{Lin} = x \cdot p_1 \quad (5.2)$$

and,

$$ToT_{NLin} = p_0 - \frac{c}{x^\alpha - ToT_{thres}} \quad (5.3)$$

where ToT_{Lin} and ToT_{NLin} corresponds to the linear and non-linear regions respectively. Fig. 5.8 shows calibration plots for two of the channels of layer 11 in which the linear, constant, and non-linear components are separately drawn using the parameters obtained by fitting the ToT spectrum with the full function. Fig. 5.9 shows a zoomed in calibration plot for one of the channel along with the two components drawn separately. From the zoomed in plot we can see that the ToT_{NLin} contribution just after low gain saturates ($\sim 100Mips$ in Fig. 5.9 is very high).

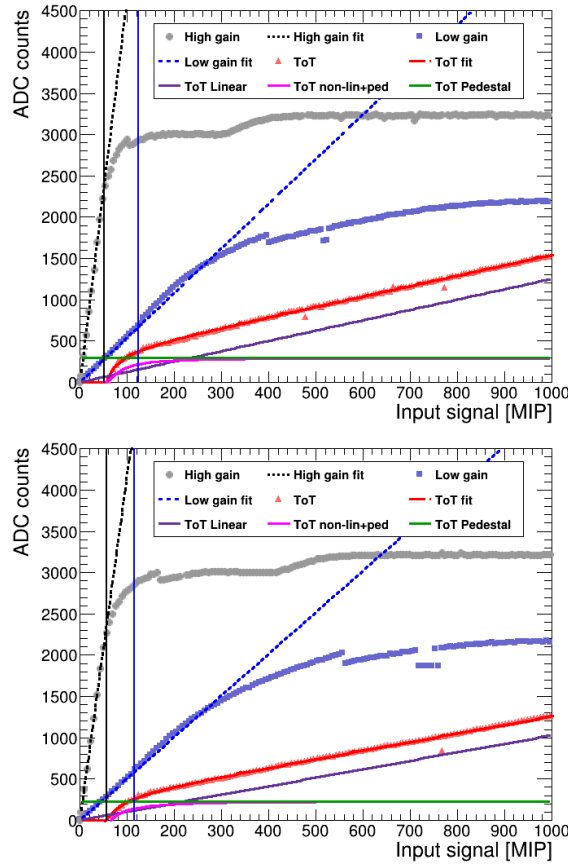


Figure 5.8: ToT different components for channel 28 of chip 00 (top) and channel 56 of chip 00 (bottom) Layer 11.

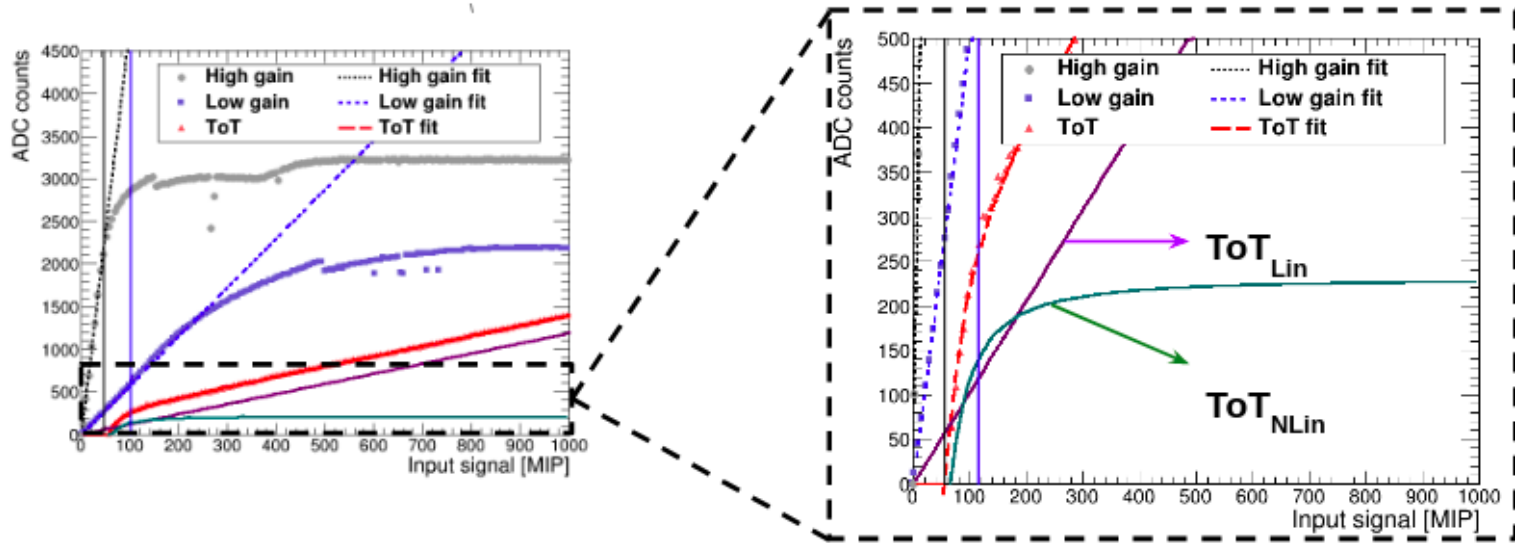


Figure 5.9: ToT different components

So, to take non-linearity of ToT into account, we set a threshold for LG saturation such that contribution of non-linearity term of ToT is less than 4% of total. With this criteria used as a threshold for LG→ToT switching, we update all the relevant calibration parameters accordingly.

Fig. 5.10 shows the reconstructed energy distributions for some of the positron beams reconstructed using CI Method 02.

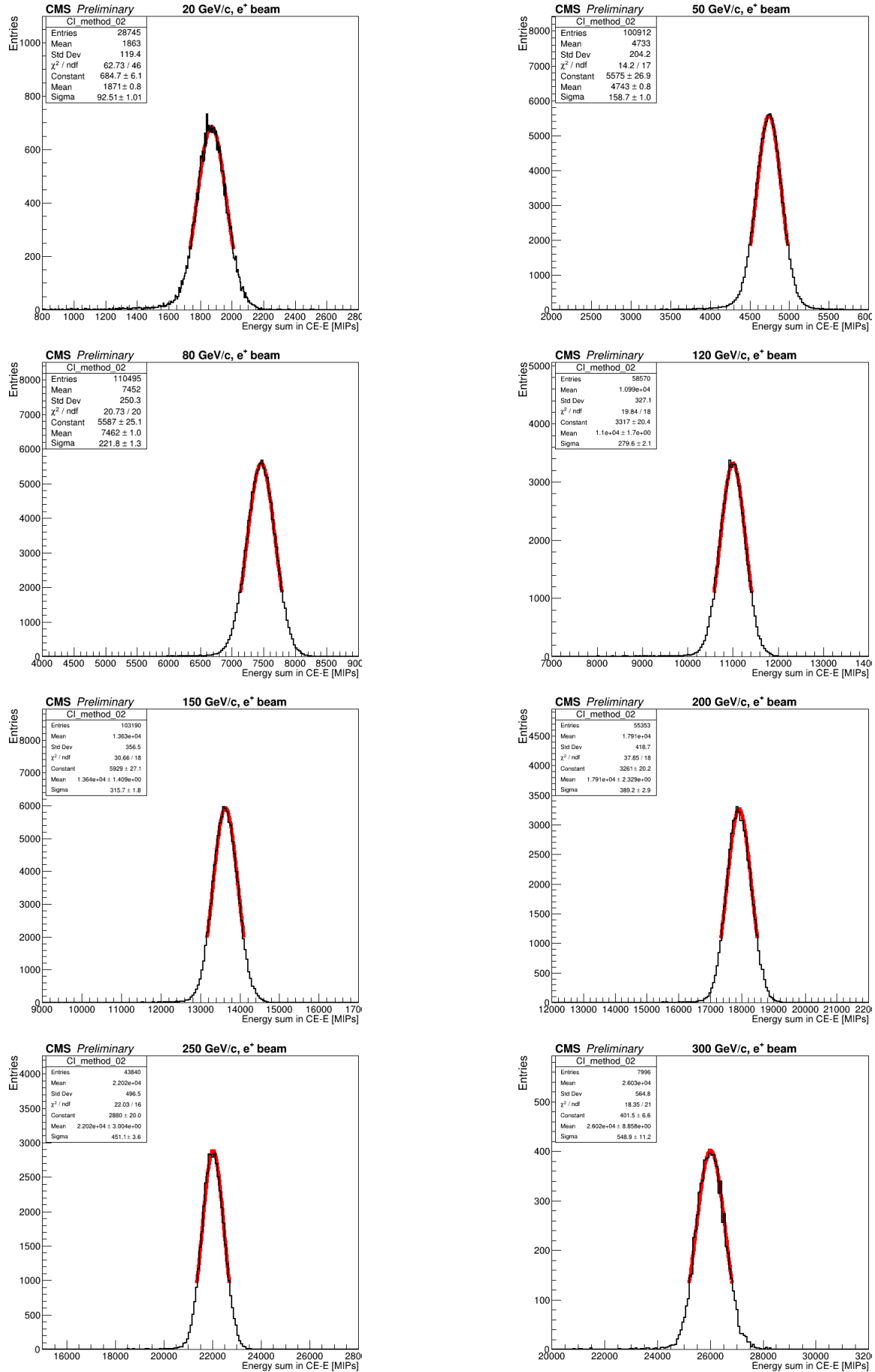


Figure 5.10: Distributions of positron energies reconstructed with CI Method 02 along with fitted Gaussian function for eight beam energies.

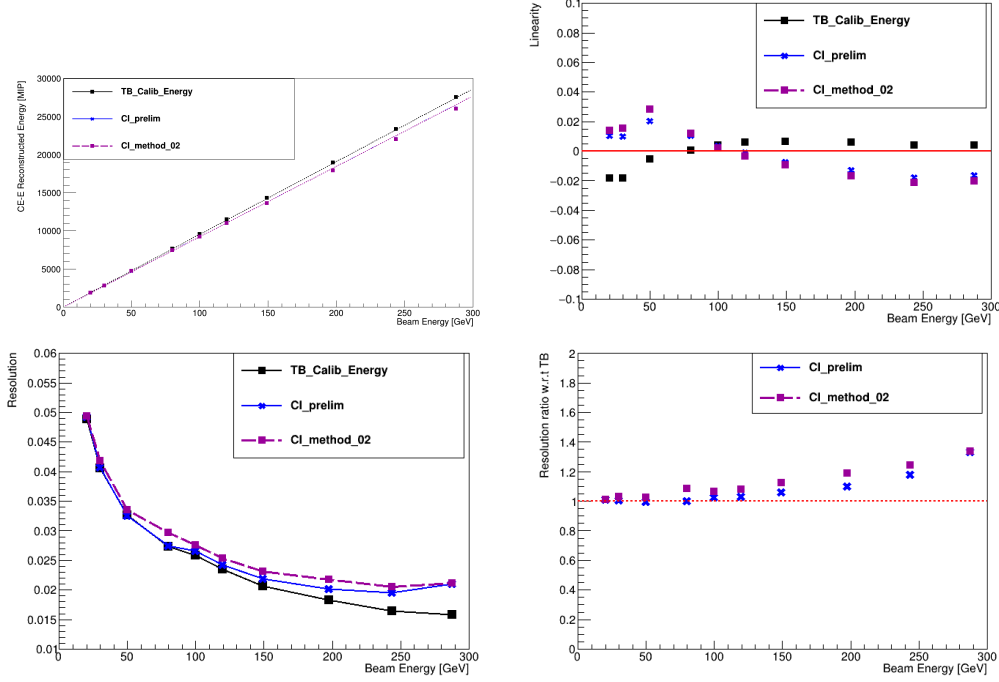


Figure 5.11: Performance results for CI Method 02

5.2.1 Discussion

Distributions of reconstructed energies for different positron beams are shown in Fig. 5.10 using inter-gain calibration parameter obtained with CI Method 02. Summary of response linearity and resolution as a function of beam energy are shown in Fig. 5.11 along with comparisons with respect to TB_Calib and CI_Prelim versions. Except in the intermediate energies, the linear is worse as compared to CI_Prelim, and resolution is also slightly worse as compared to CI_Prelim (and, hence also the TB_Calib version).

Fig. 5.12 and 5.13 compare rehit energy spectra corresponding CI Method 02, CI_Prelim & TB_Calib. The rehit energy distributions look similar for CI Method 02 and CI_Prelim except that the HG→LG dip that was observed in CI_Prelim is now completely resolved in CI Method 02, please refer to layers 11, 13 and 22 in Fig. 5.12 and 5.13. Also, in some channels LG→ToT dip shows some improvements e.g layer 16 in Fig. 5.12 and 5.13. So, we continue with this approach and try to improve the calibrations further in the next versions.

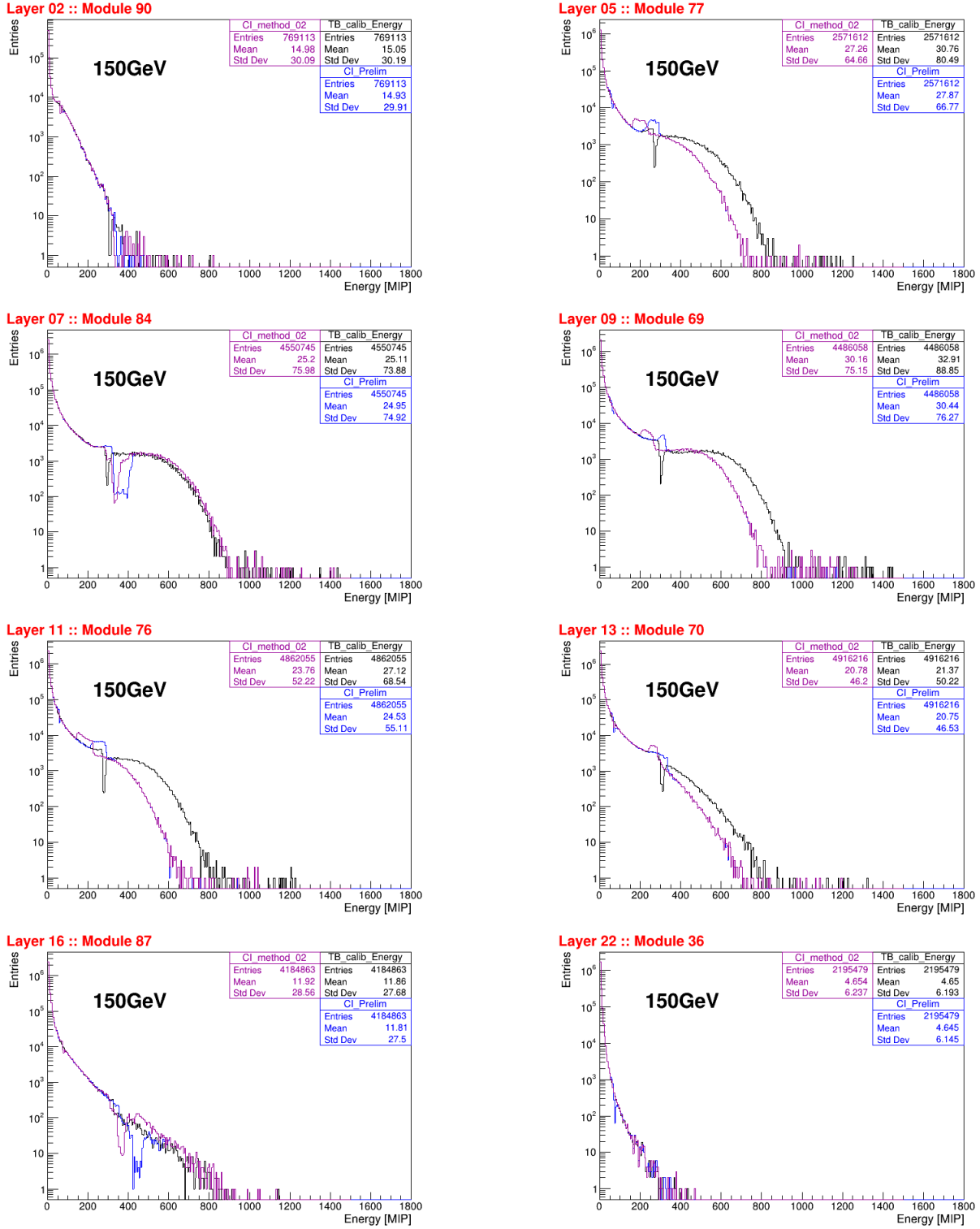


Figure 5.12: Reicht energy spectrum comparison of CI Method 02 with CI_Prelim and TB_Calib for some layers of CE-E for 150GeV.

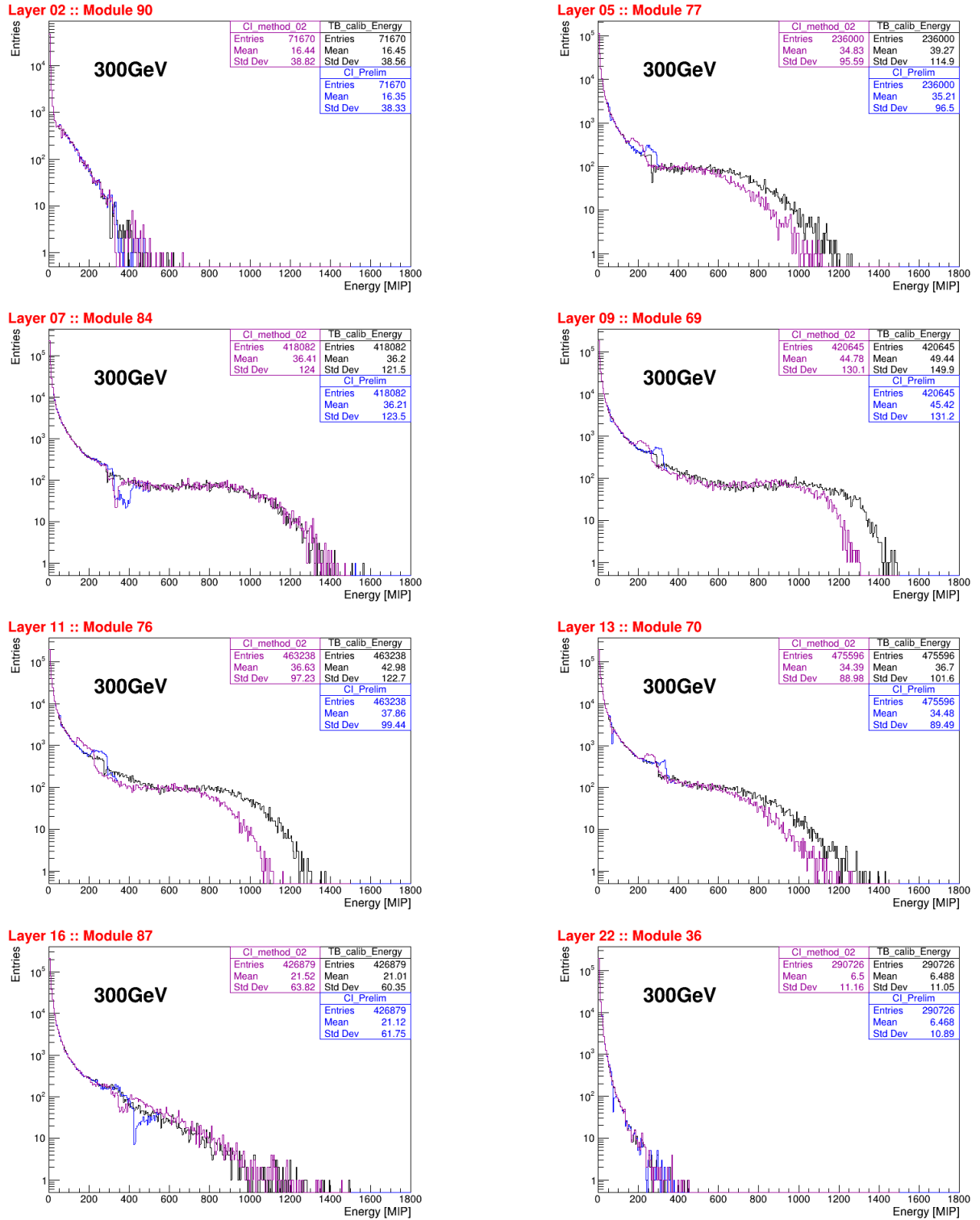


Figure 5.13: Rehit energy spectrum comparison of CI Method 02 with CI_Prelim and TB_Calib for some layers of CE-E for 300GeV.

5.3 Charge Injection Method 03 (CI Method 03)

In this version of charge injection framework is an extension to CI Method 02 where we applied a 4% ToT non-linearity contribution criteria to define LG saturation, and in addition, we also recalculated the ToT→HG calibration coefficient. To update these coefficients, we refitted linear part of ToT function in the range $[LG_{sat}, LG_{sat} + 50]$ where LG_{sat} is in MIP units.

Recall that in the previous methods, the full ToT function was inverted. Fig. 5.14 and Fig. 5.15 shows the ToTCoeff and ToTPed from the refitted ToT_{Lin} part for few of the layers of CE-E along with ToTCoeff and ToTPed from CI.Prelim.

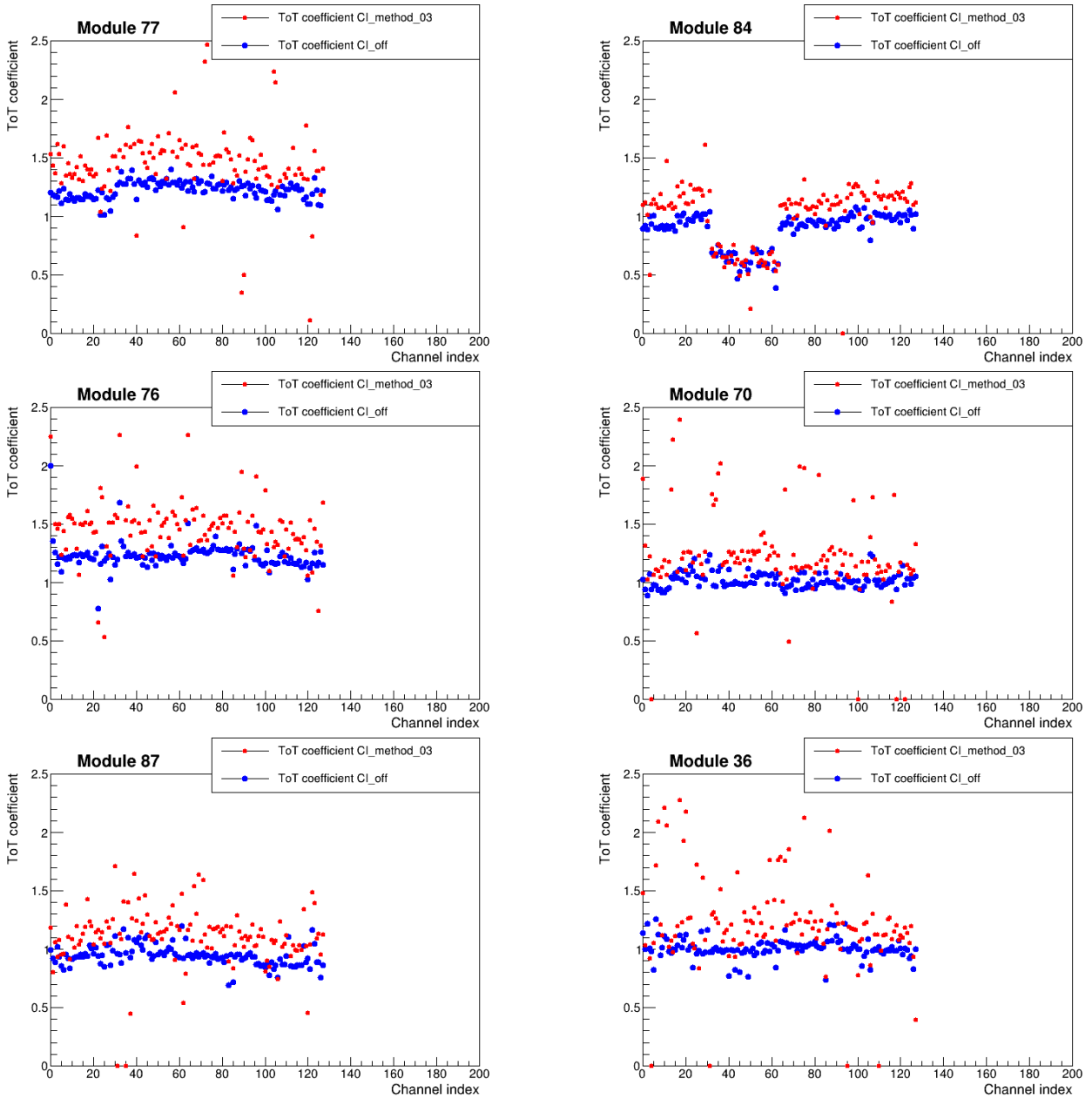


Figure 5.14: ToTCoeff summary for CI method 03 & comparison with CI_off

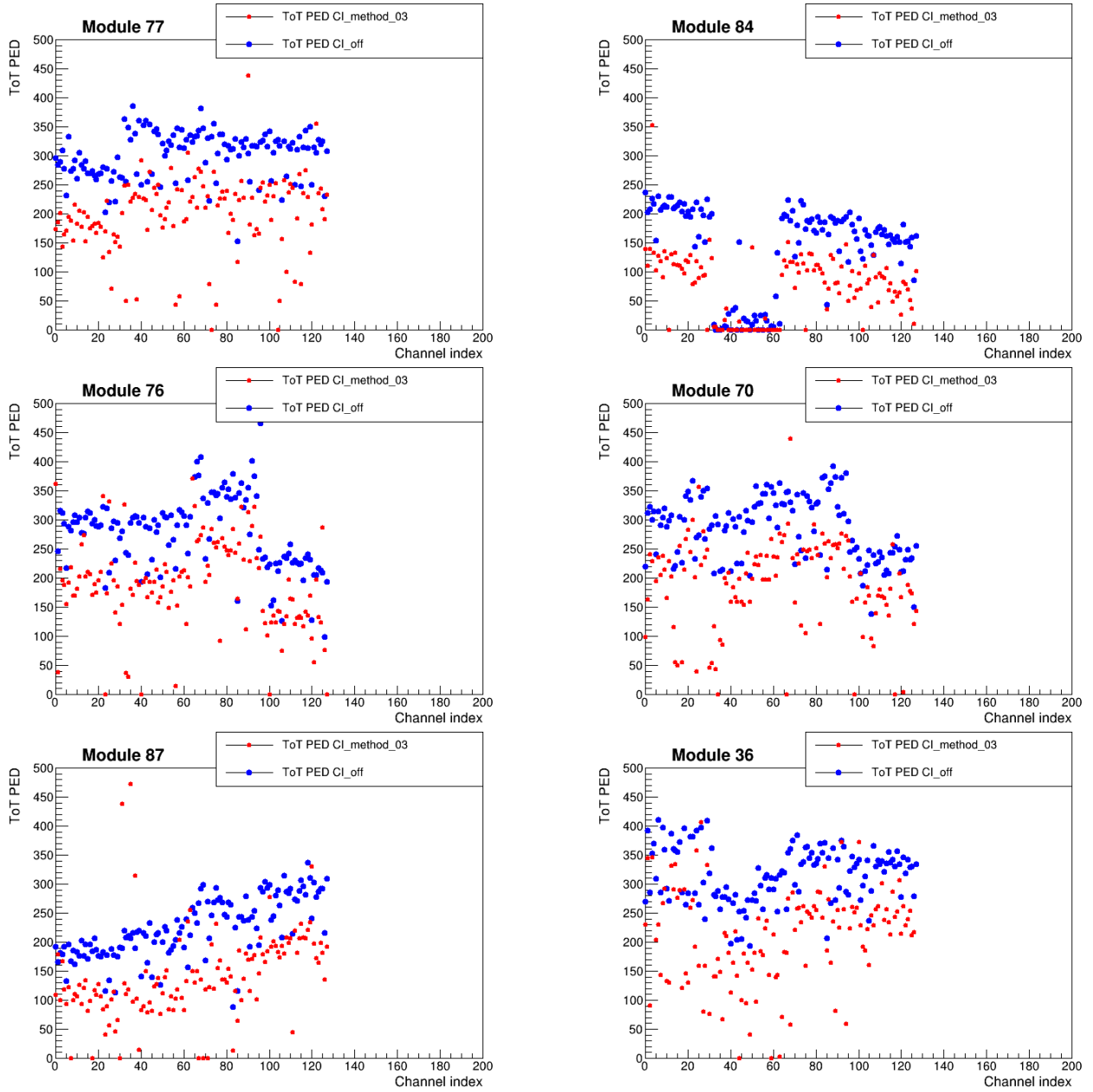


Figure 5.15: ToTPed summary for CI method 03 & comparison with CI_Off

Using the calibration values obtained using CI Method 03, energies were reconstructed for different positron beams. Fig. 5.16 shows distributions of reconstructed energies for different positron beams. The performance in terms of response linearity and energy resolution for this version is shown in Fig. 5.17 along with the CI.Prelim results for comparisons.

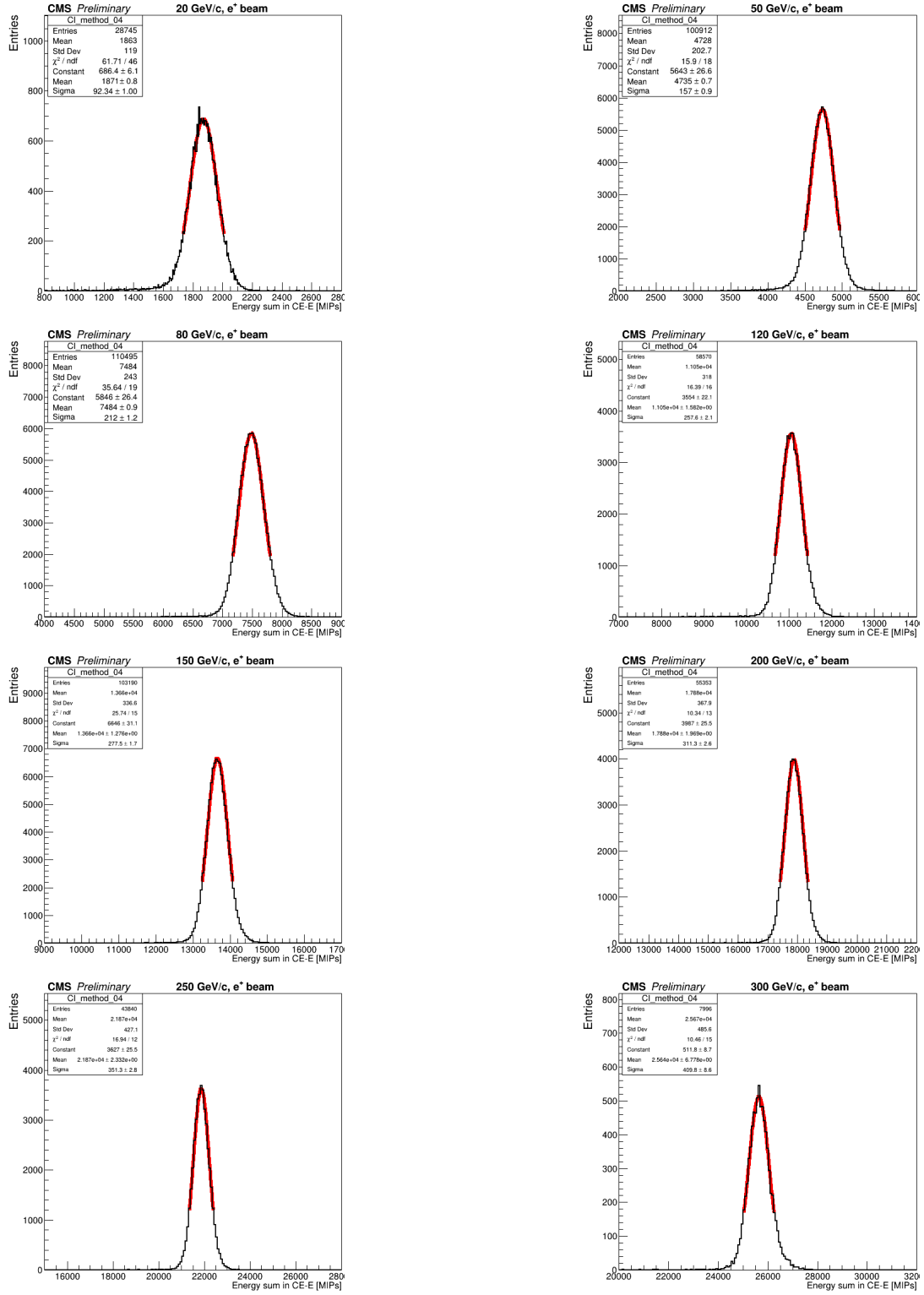


Figure 5.16: Distributions of positron energies reconstructed with CI Method 03 along with fitted Gaussian function for eight beam energies.

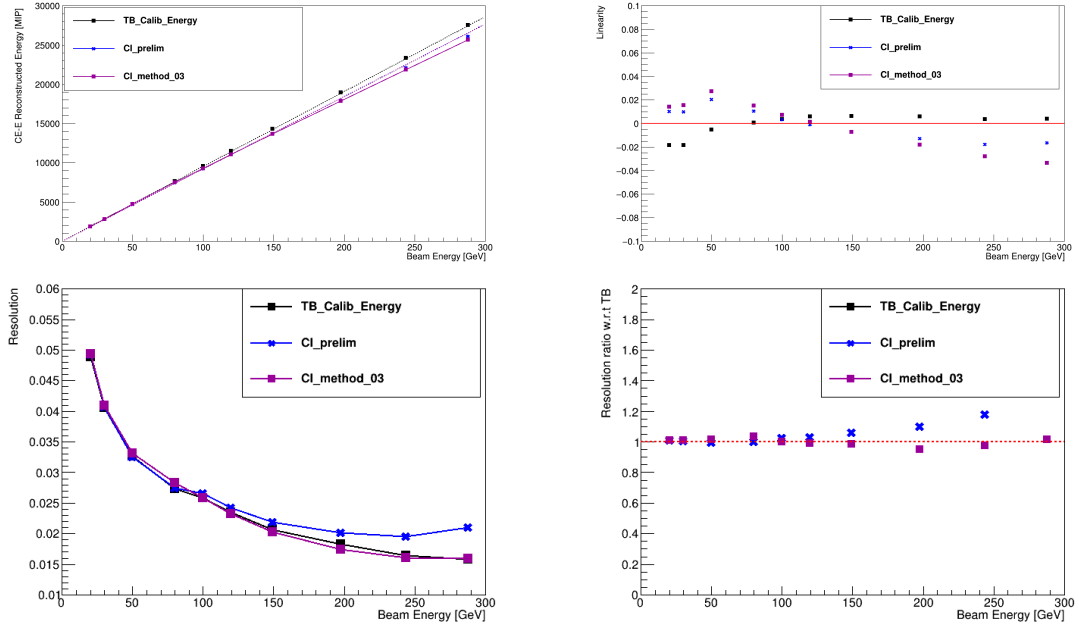


Figure 5.17: Performance summary of CI Method 03

5.3.1 Discussion

Performance of CI Method 03, in terms of energy resolution, is observed to be the best among all the intergain calibration methods considered so far. However, the CI Method 03 provides worst response linearity showing a trend of increasing deviation for higher energies. Since the response for CI Method 03 is lacking in performance for restoring the linearity by a large margin, this can lead to high biasing in final reconstructed energies. As the next step, we tried to play with the percentage contribution of non-linear component of ToT assuming some flexibility may allow better performance.

5.4 Charge Injection Method 04 (CI Method 04)

In this version of charge injection framework, we tried a different ToT non-linear allowance in LG linear region by setting the threshold to 7% non linearity in ToT to define LG saturation switch. This was earlier discussed and set to 4% in sec. 5.2. Apart from this we refitted the ToT_{Lin} function (Eqn. 5.1) over range $[LG_{sat}, LG_{sat} + 50]$, where LG_{sat} is in the MIP units.

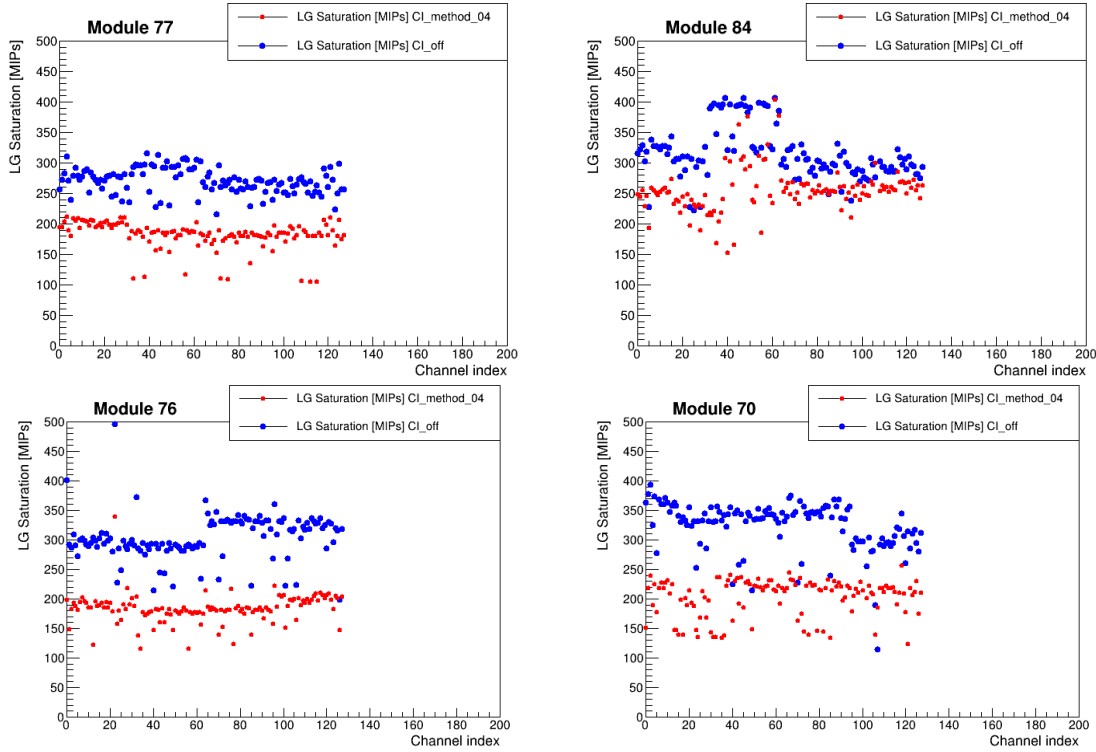


Figure 5.18: LG saturation summary for CI method 04 & comparison with CI.Off

Summary plot for LG_{sat} , ToT_{Coeff} , and ToT_{Ped} is shown in Fig. 5.18, Fig. 5.19 & 5.20 for layer 5, 7, 11 & 13 respectively.

As a part of the nominal checks, we reconstruct energies for positron beams using CI Method 04 and compare the performance of this version with other versions. Fig. 5.21 shows reconstructed energy distributions for different beam energies for CI Method 04. The energy response and resolution as a function of beam energies are shown in Fig. 5.22.

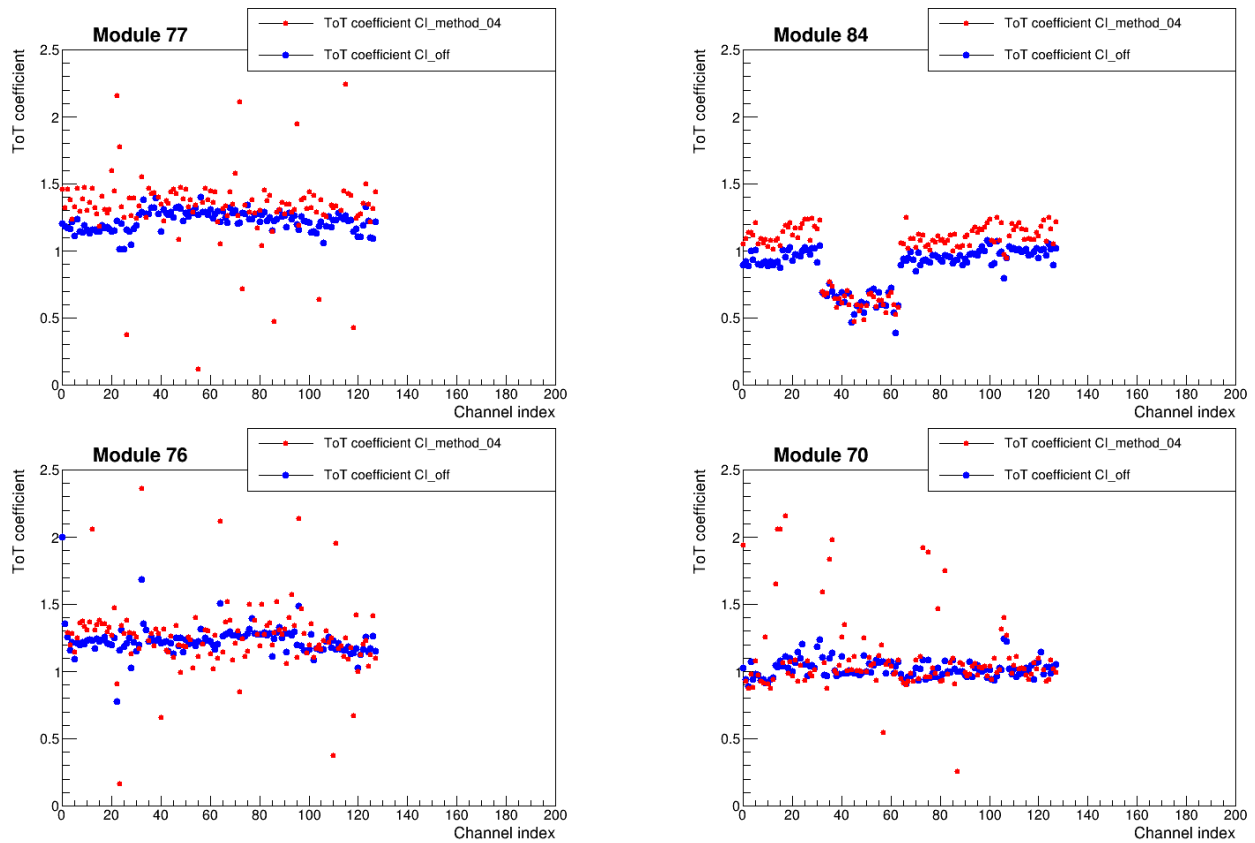


Figure 5.19: ToTCoeff summary for CI method 04 & comparison with CI_Off

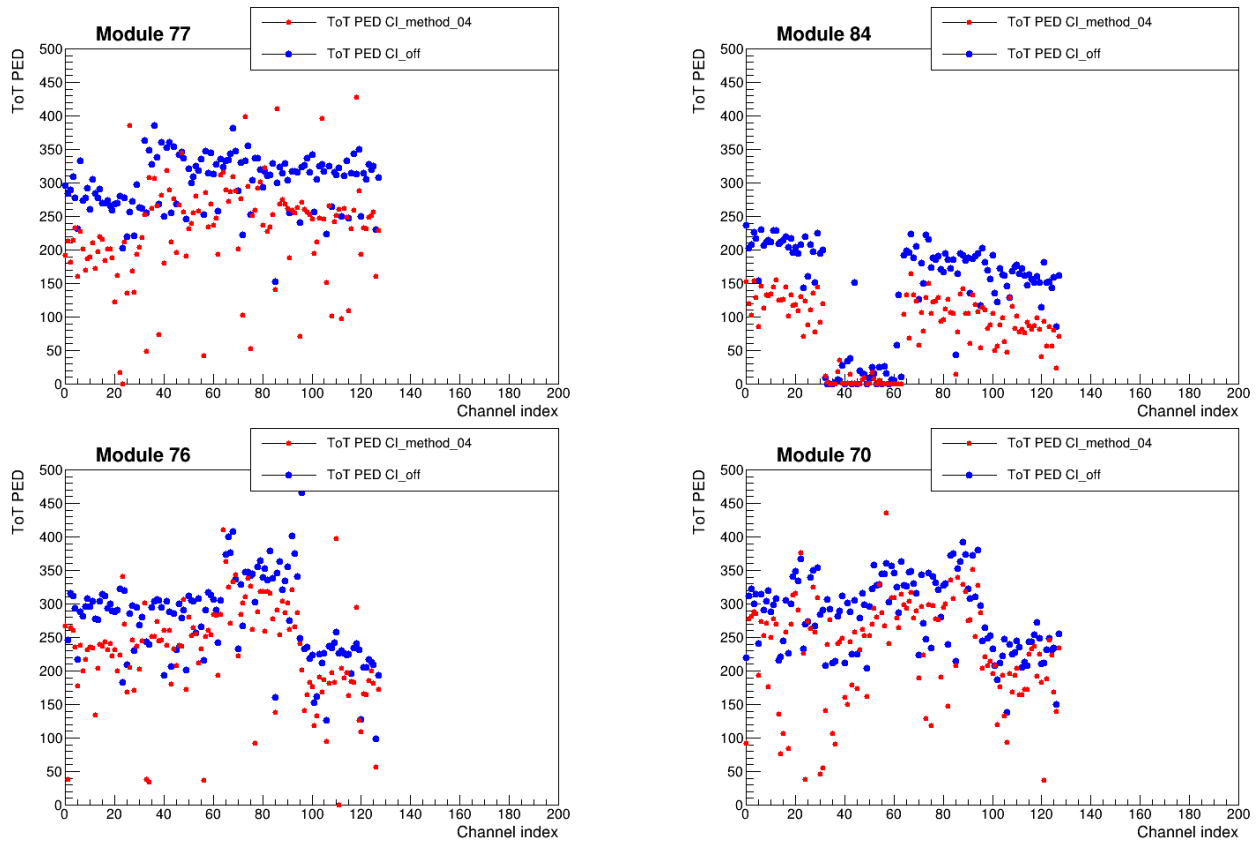


Figure 5.20: ToTPed summary for CI method 04 & comparison with CI_Off

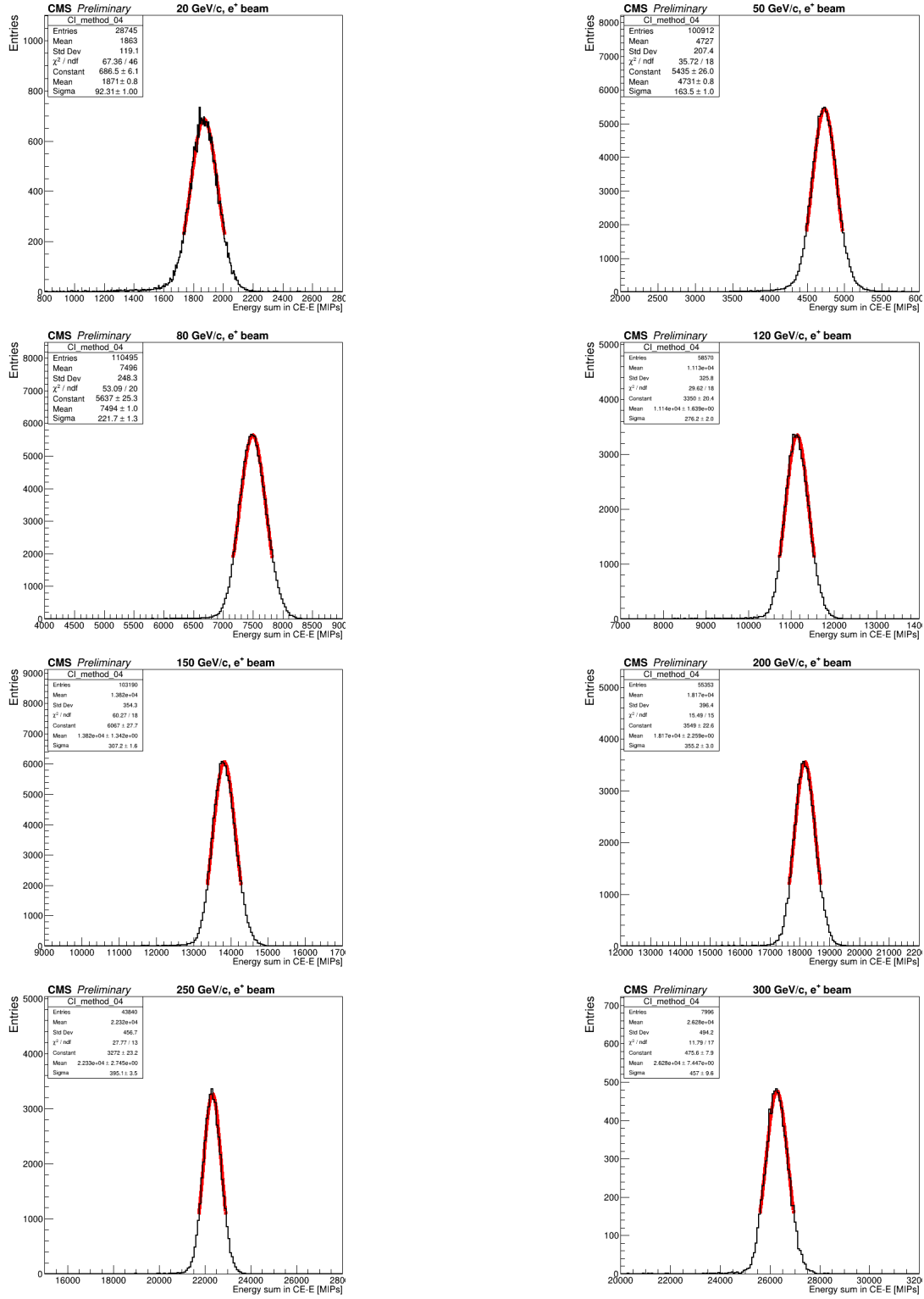


Figure 5.21: Distributions of positron energies reconstructed with CI Method 04 along with fitted Gaussian function for eight beam energies.

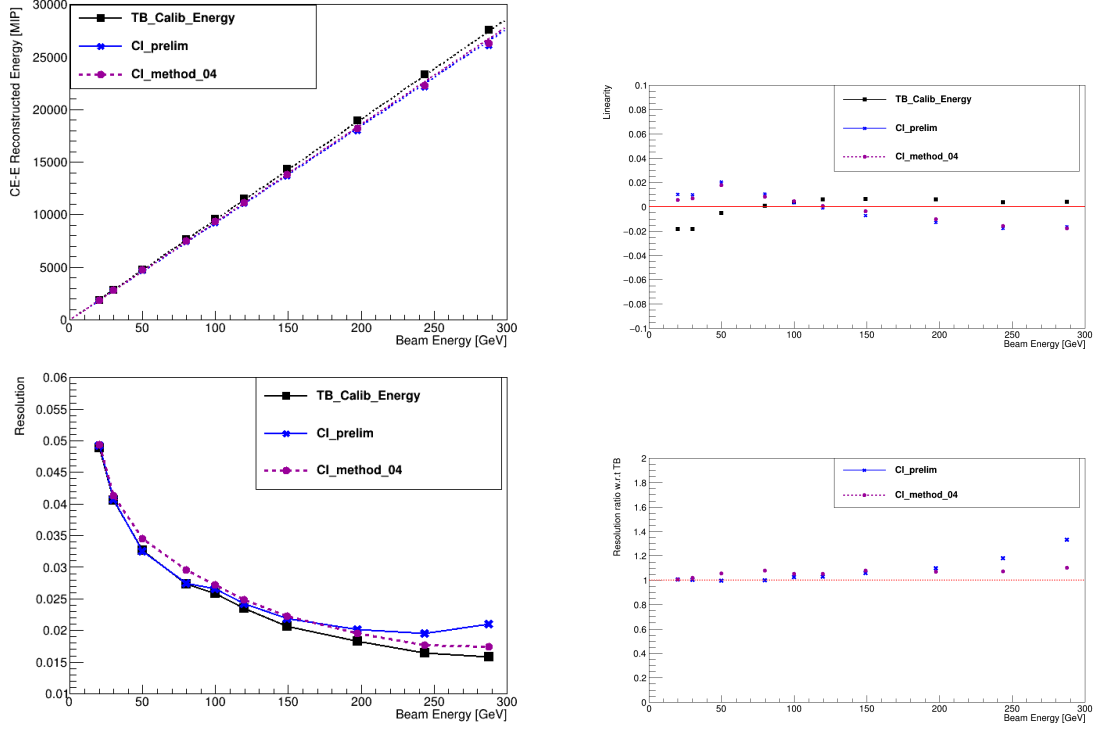


Figure 5.22: Performance summary of CI Method 04

5.4.1 Discussion

As seen from Fig. 5.22, performance of this method in terms of resolution is better overall with respect to CI_Prelim, and the improvement in resolution is distinctly visible at higher positron beam energies. The response is similar to that obtained using CI_Prelim although marginal improvements are observed across all energies.

Observations in terms of rechit energy spectra

- For several layers, reconstructed energies on higher end of rechit spectra moved closer to the TB_Calib as compared to CI_Prelim, e.g layer 11 in Fig. 5.23 & in Fig. 5.24. However, the energies are still under measured which can explain the lower response as observed in linearity plots shown in Fig. 5.22.
- The LG→ToT dip remains almost unchanged, just a small shift in position is noticed because of the shift of LG saturations w.r.t. CI_Prelim, e.g., layer 16 in Fig. 5.23 & in Fig. 5.24.
- The HG→LG dip is resolved completely for almost all the layers, e.g., layer 13 & layer 22 in Fig. 5.23 & in Fig. 5.24. .

In summary, this model showed improved results in terms of resolution and also showed some improvements in terms of rechit spectrums but response linearity is not fully resolved although within a few percent of CI_Prelim and TB_Calib. In the next step, we try to investigate a different approach using overlapping regions between different gain stages.

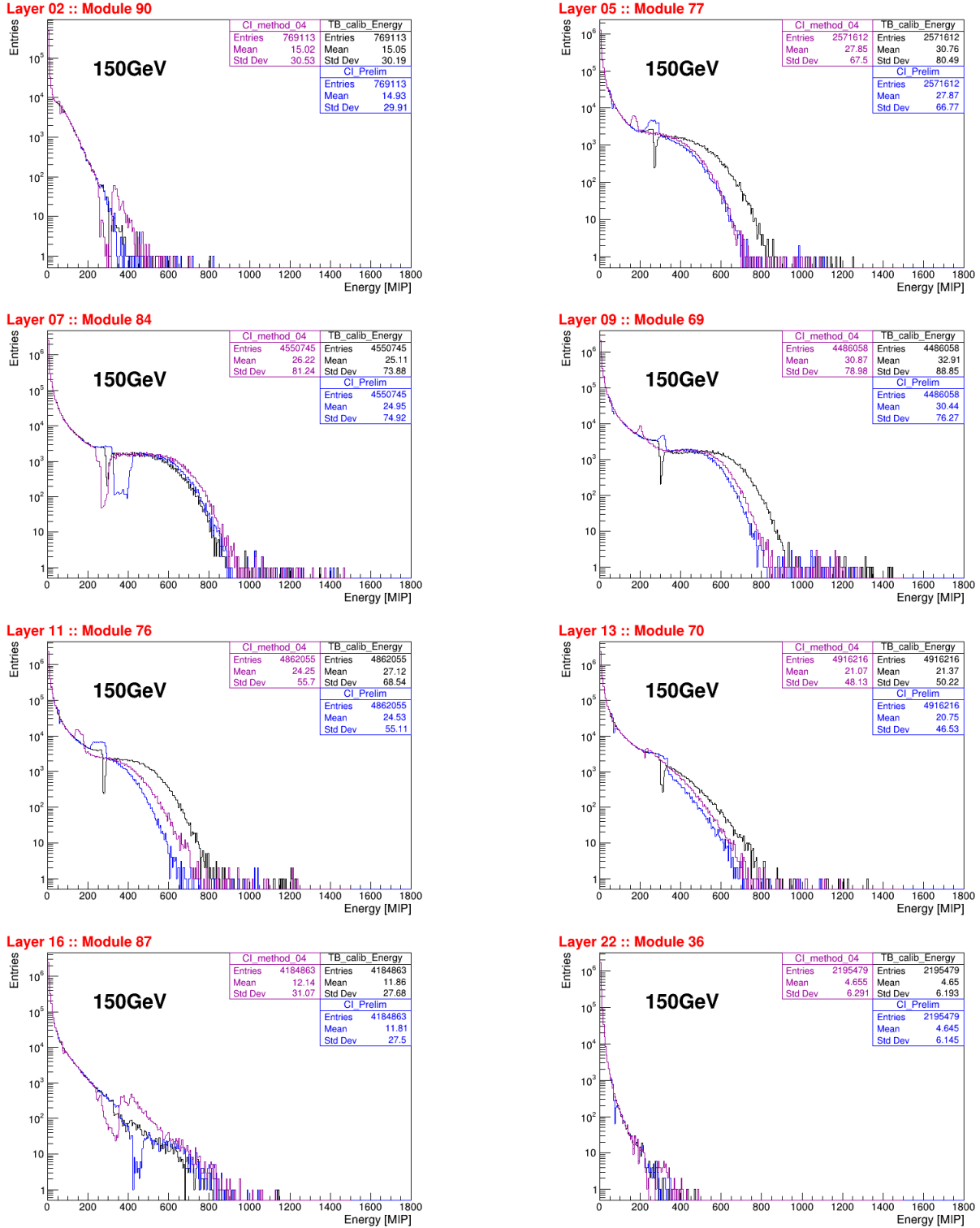


Figure 5.23: Rechit energy spectrum comparison of CI Method 04 with CI_Prelim and TB.Calib for some layers of CE-E for 150GeV.

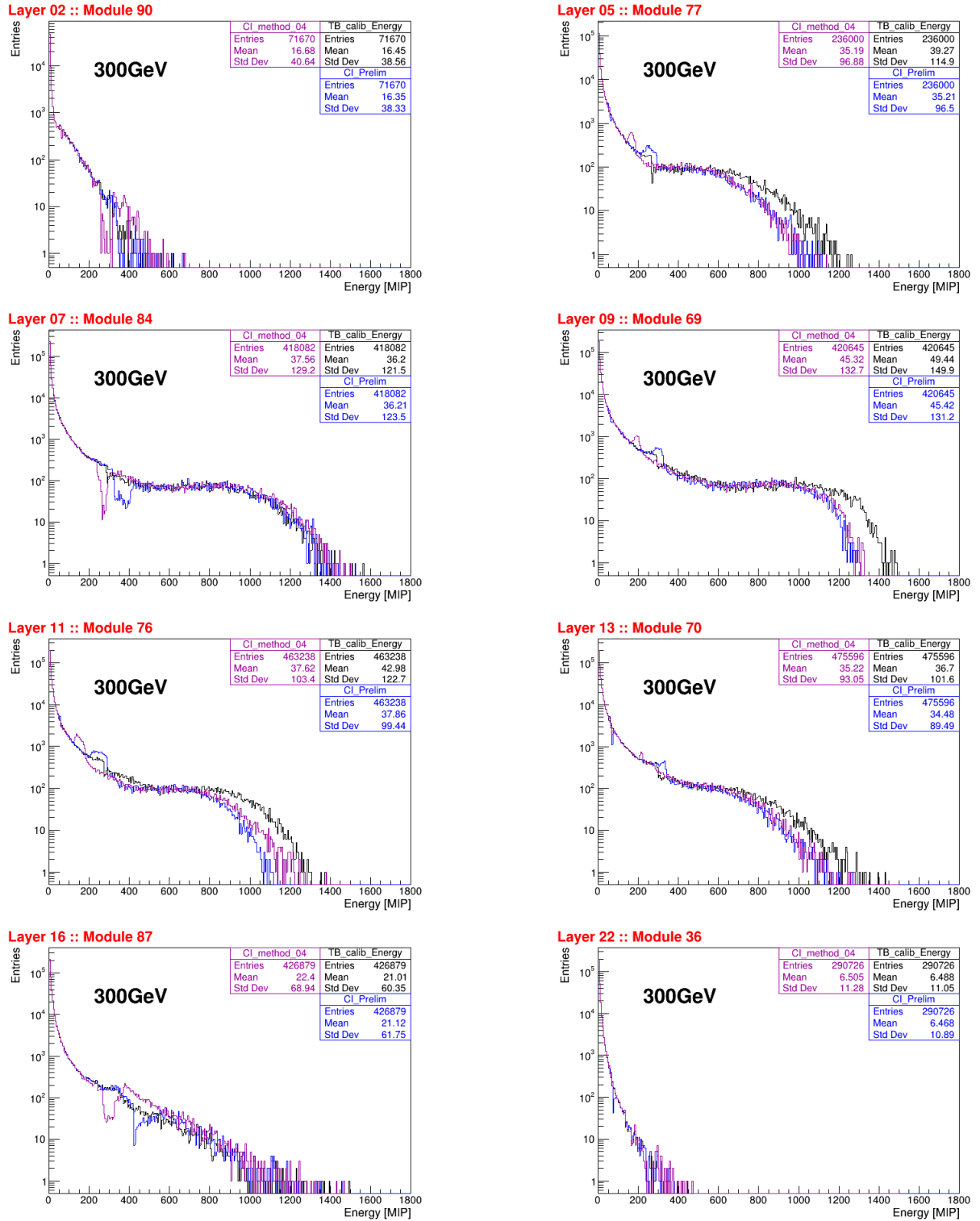


Figure 5.24: Rechit energy spectrum comparison of CI Method 04 with CI_Prelim and TB_Calib for some layers of CE-E for 300GeV.

5.5 Charge Injection Method 05 (CI Method 05)

This method is an upgrade to CI Method 02. A 4% non-linear ToT contribution allowance was used to update the LG saturations as in sec. 5.2. To obtain the coefficient to express ToT in terms of LG units, a straight line is fitted in the range where both the ToT and the LG are expected to be linear. Now, using this fitted function ToT energy is calculated by inverting this function, this process of calculating ToT is very much similar to that used in TB_Calib Ref sec. 4.2.1.

Fig. 5.25 and Fig. 5.26 shows the ToTCoeff and ToTPed comparison between CI Method 05 and CI_Prelim for some layers of CE-E.

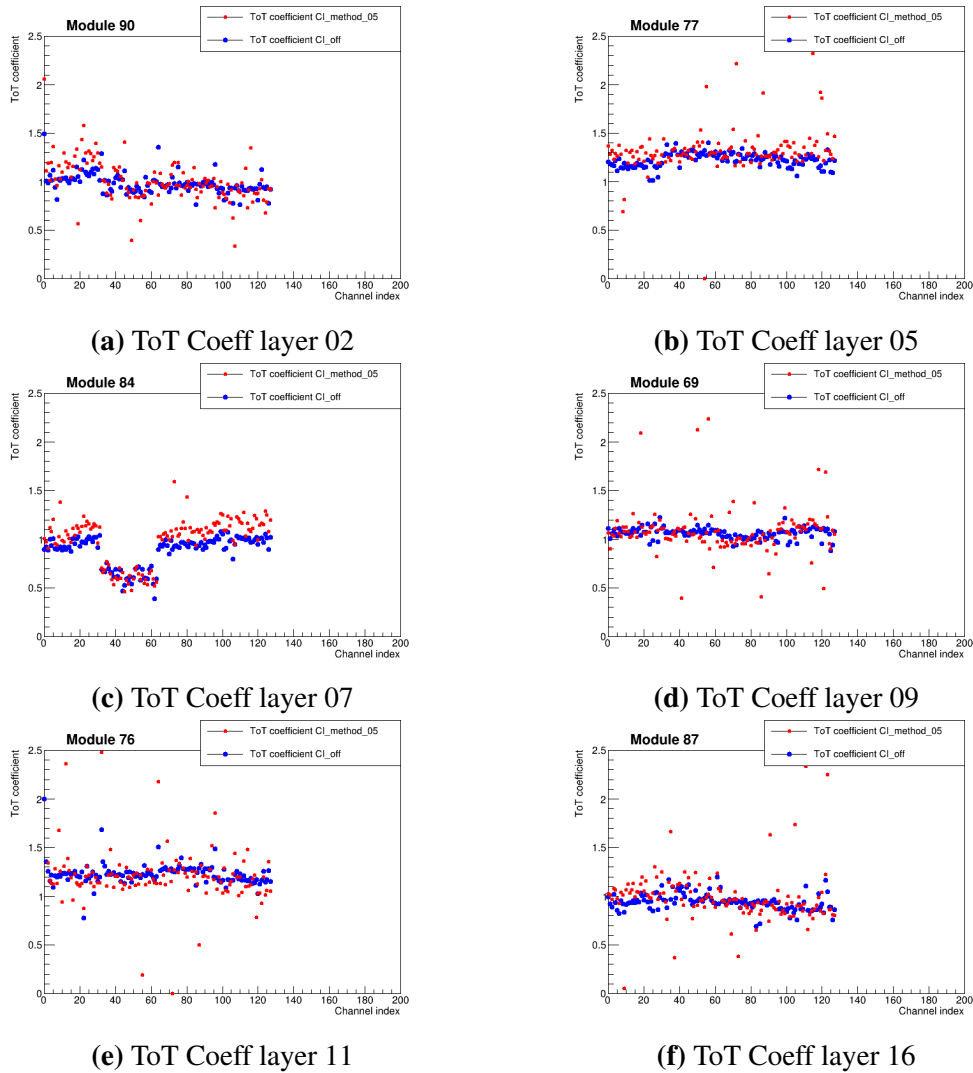
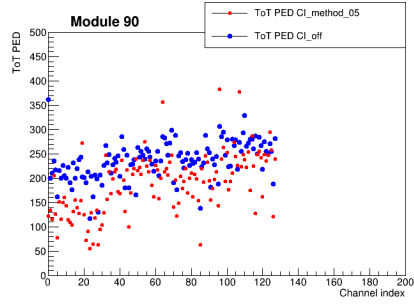
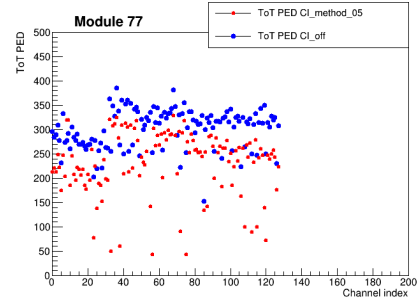


Figure 5.25: ToT Coeff comparison between CI Method 05 and CI_Prelim for some layers of CE-E.

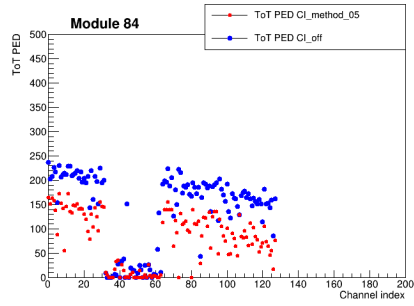
Fig. 5.27 shows the reconstructed energy distributions for CI Method 05 for 8 positron beams along with the Gaussian functions fitted over the range $[\mu - 1.5\sigma, \mu + 1.5\sigma]$.



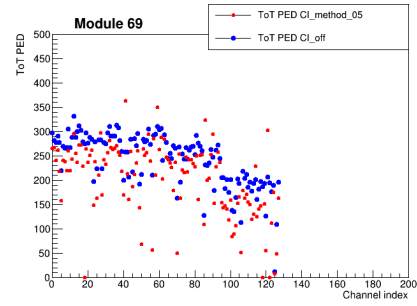
(a) ToT Ped layer 02



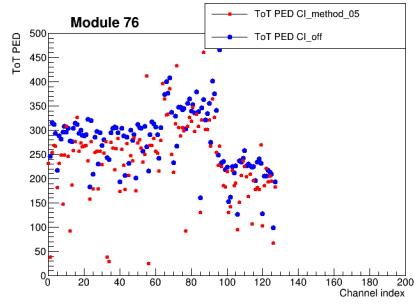
(b) ToT Ped layer 05



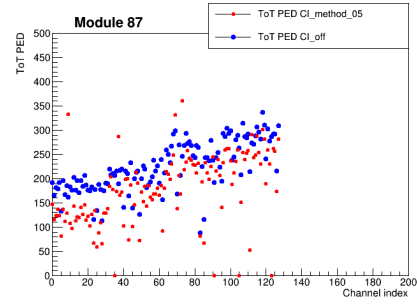
(c) ToT Ped layer 07



(d) ToT Ped layer 09



(e) ToT Ped layer 11



(f) ToT Ped layer 16

Figure 5.26: ToT ped comparison between CI method 05 and CI_Prelim for some layers of CE-E

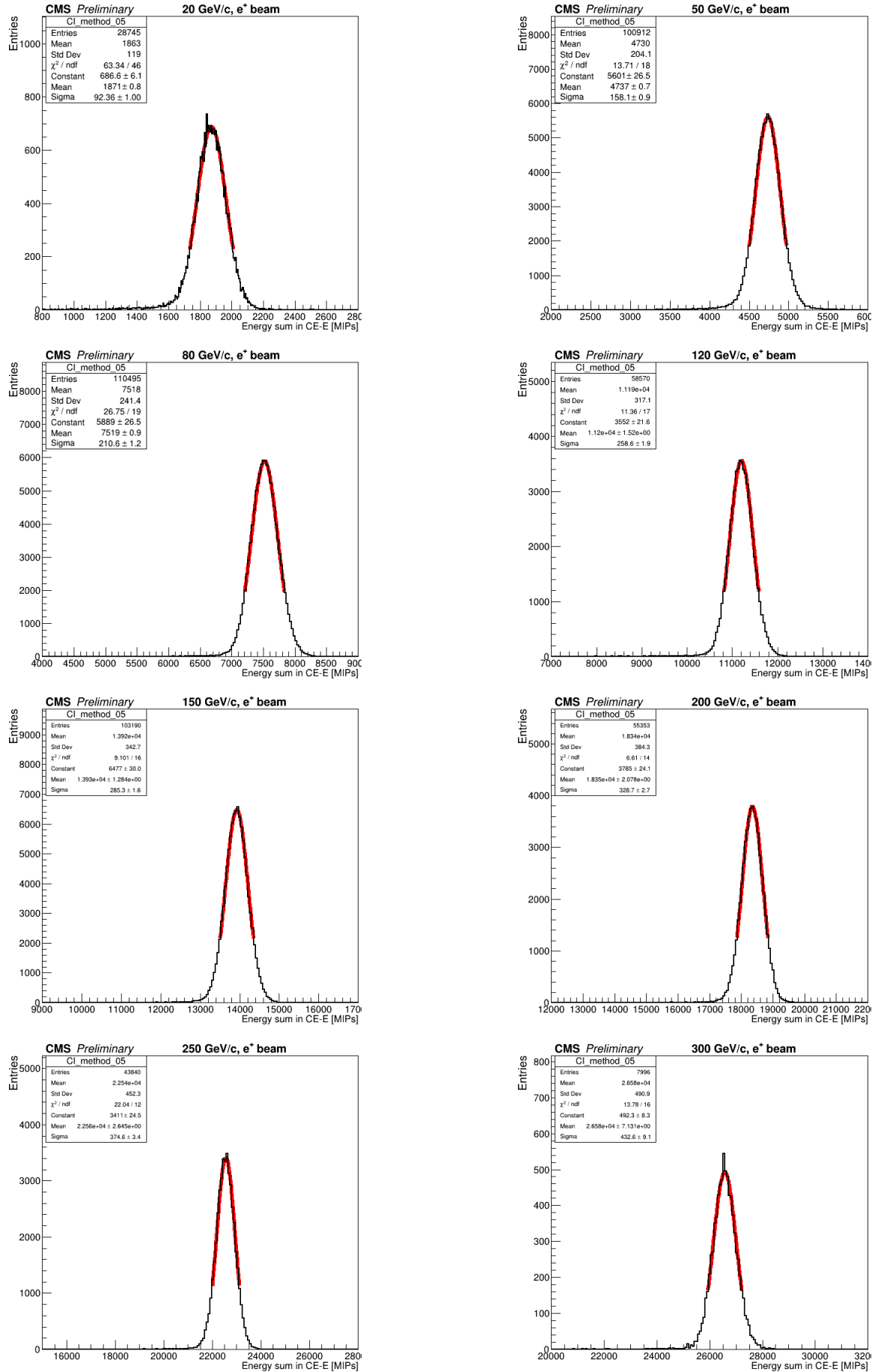


Figure 5.27: Distributions of positron energies reconstructed with CI Method 05 along with fitted Gaussian function for eight beam energies.

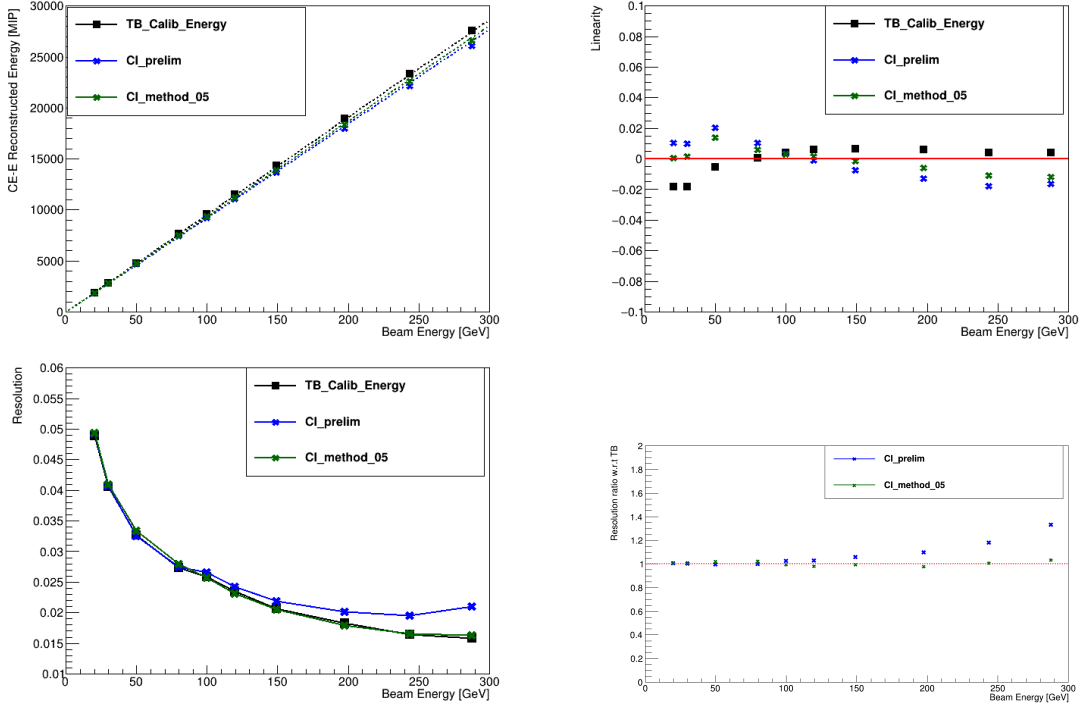


Figure 5.28: Performance results of CI Method 05

5.5.1 Discussion

Fig. 5.28 shows the response linearity and energy resolution results as a function of beam energy. The CI Method 05 has an overall improved linearity with respect to CI_Prelim, for lower energies the linearity is mostly restored. For higher energies too, the deviation does not strongly depend on positron energies (i.e. the trend is mitigated to a large extent). In terms of resolution, the resolution corresponding to the CI Method 05 reconstruction is close to TB_Calib reconstruction which has been our benchmark to compare with. The resolution difference between CI Method 05 & TB_Calib is observed to be less than 2-3% and the resolution values are overall better than that of CI_Prelim ref Fig. 5.27 across all energies. Hence, using CI Method 05 performance close to TB_Calib was achieved, to finalize the model few other checks are made.

Using CI Method 05 performance close to TB_Calib was achieved, to finalize the model few other checks were made.

Fig. 5.29 & Fig. 5.30 shows the rechit energy comparisons for reconstruction using CI Method 05 with respect to TB_Calib and CI_Prelim calibrations. Following observations are noted from these rechit spectrum comparisons.

- In most of the layers, the higher energy part of the rechit spectra have shifted closer to TB_Calib tails than CI_Prelim, e.g layer 9 & 13 in Fig. 5.29 & 5.30.
- The HG→LG dip is not present for CI_Method 05, for e.g layer 13 & 22 in Fig. 5.29 & 5.30.
- The LG→ToT dip got shifted to a lower level as compared to CI_Prelim as the LG saturations has been shifted to a lower level because of change in way of finding the saturations, e.g layer 9 & 13 in Fig. 5.29 & 5.30.

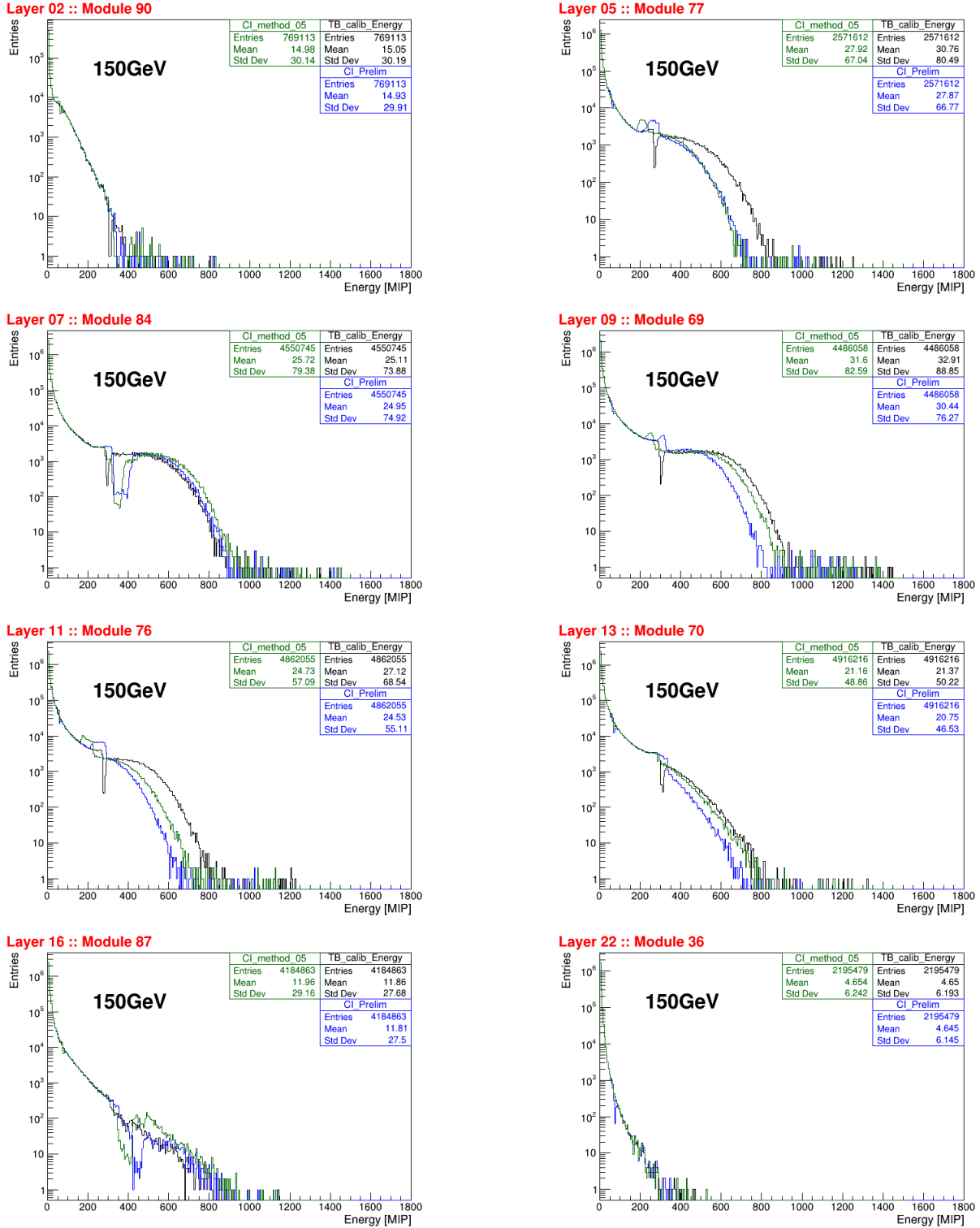


Figure 5.29: Rechet energy spectrum comparison of CI method 05 with CI_Prelim and TB.calib for some layers of CE-E for 150GeV

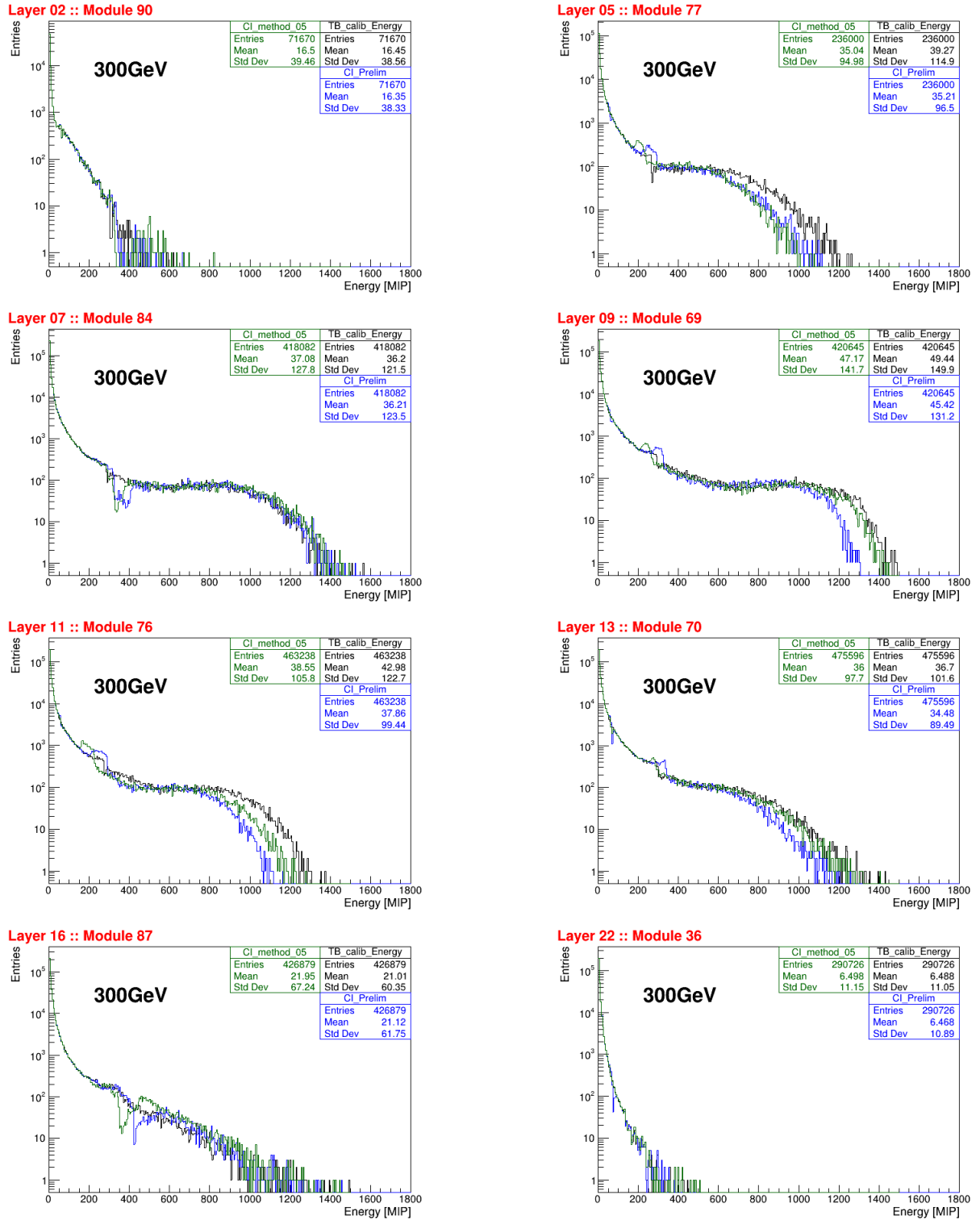


Figure 5.30: Rechit energy spectrum comparison of CI method 05 with CI_Prelim and TB_calib for some layers of CE-E for 300GeV

Hit by Hit energy comparison between CI Mthod 05 & TB_Calib

We made a few more checks with this method to understand potential improvements further. To compare CI Method 05 and TB_Calib on a more elementary level, we compared the rechit energies event by event and channel by channel for energy reconstruction

using these two intergain calibration methods. Fig. 5.31 & Fig. 5.32 shows rehit energy comparison between CI Method 05 (y axis) & TB_Calib (x axis) for some layers of CE-E for 150 GeV and 300 GeV respectively.

- For almost all the layers and for most of the Hits the reconstructed energies were close to that of TB_Calib, shown by events close to $y = x$ line in Fig. 5.31 & 5.32.
- In most of the layers there were very few high energy hits which were showing large deviations from the TB_Calib, for refer to layer 09 in Fig 5.31 & 5.32. These hits need to be carefully analysed.

Analysing outliers in the rehit energy comparisons

In order to is get a deeper insight for this model and to see from where are these deviations coming, the high energy outliers were extracted and analysed. Results of this exercise are discussed in sec. 5.6.

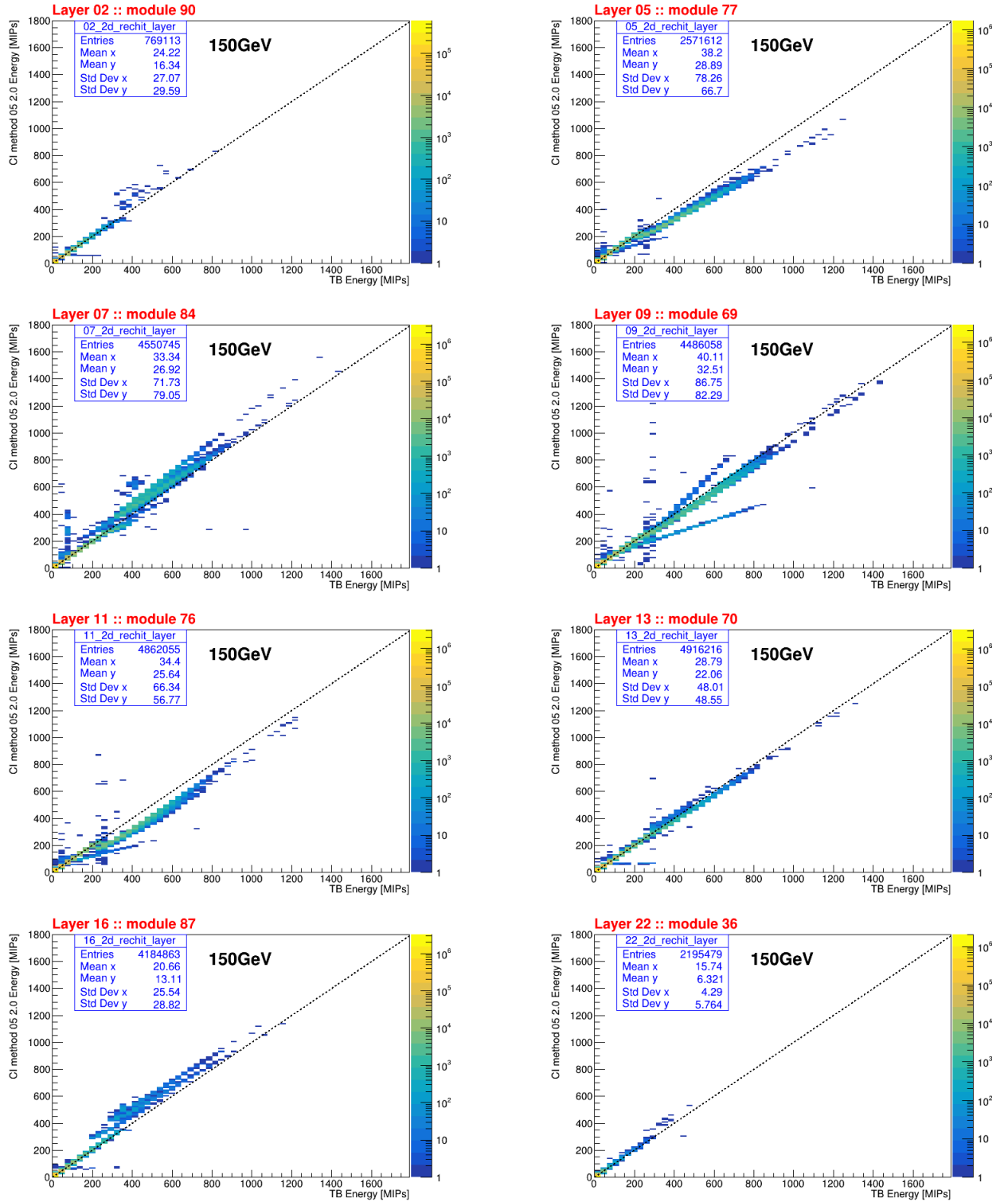


Figure 5.31: Hit energy comparison of CI method 05 V2.0 with TB_Calib for some layers of CE-E for 150GeV

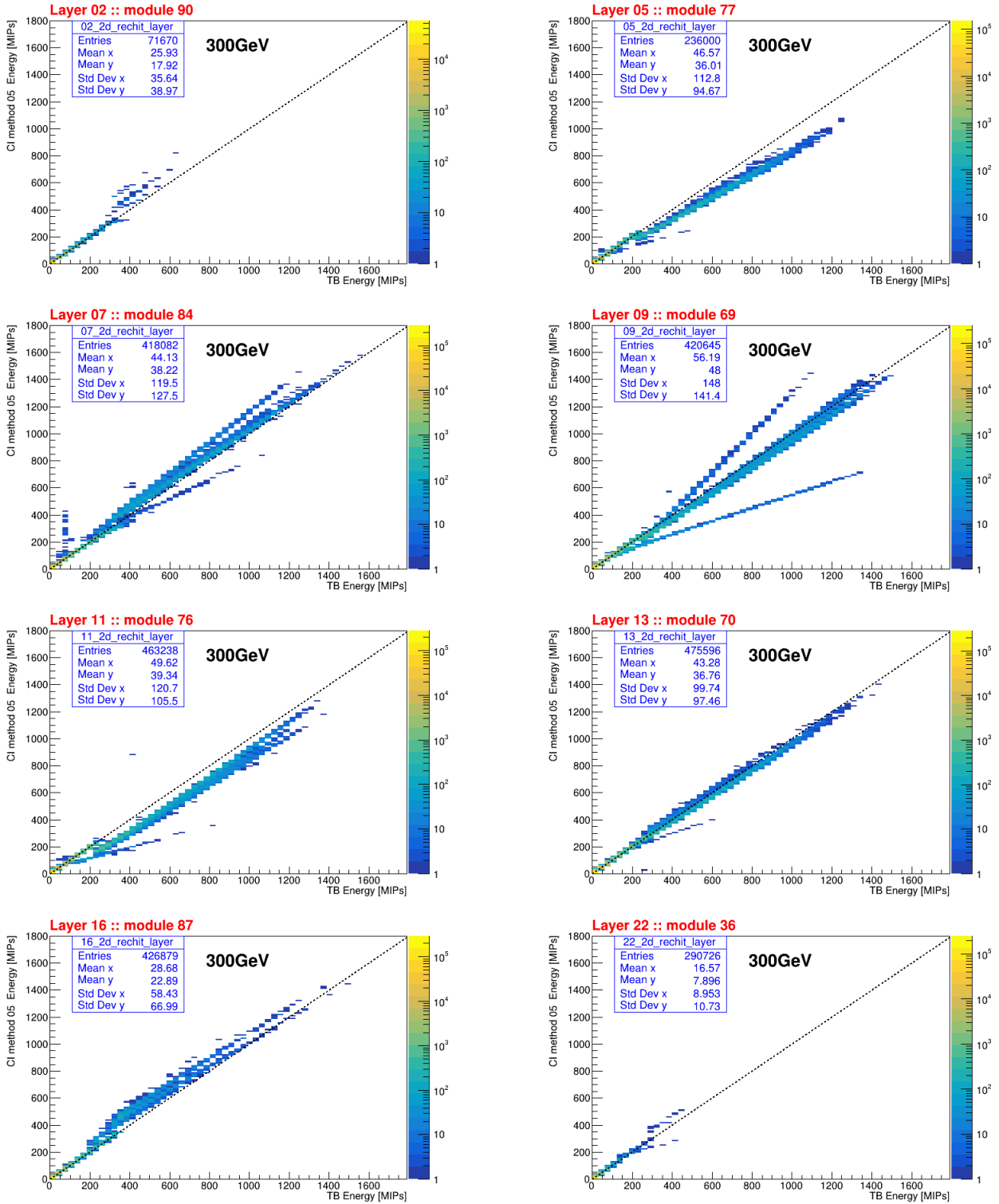


Figure 5.32: Hit energy comparison of CI method 05 V2.0 with TB_Calib for some layers of CE-E for 300GeV

5.6 Charge Injection Method 05 V2.0 (CI Method 05V2.0)

This method is a continuation of CI Method 05 (sec. 5.5) in which we have applied a outlier search using inter quartile range of the calibration parameters and the extracted outliers are updated using the respective average chip values.

Observations as per outlier search:

- These outlier hits were very low in number $\sim 1\% - 2\%$ of the total hits of that layer.
- These outliers were distributed among some specific channels in a given layer refer to sec. 5.6.1.
- These channels were the channels in which there were issues either in charge injection data itself Fig. 5.34, ToT fit is not good due to which ToT non linear contributions were getting off and hence the saturation points were getting affected Fig. 5.33 . All the types of outliers extracted are discussed in sec. 5.6.1.
- The channels belonging to chip 01 of layer 07 has not been updated by the chip averages because the entire chip is showing off calibration.

5.6.1 Type of outliers in Hit energy comparison with TB_Calib

There were some common behaviour seen among the outliers extracted out in rechit energy comparison.

- The major contribution in outlier hits in Fig. 5.31 & 5.32 were from the channels in which the ToT_{Nlin} Eqn. 5.3 was not fitted properly one calibration plot for one such channel is shown in Fig. 5.33. In this plot we can see ToT_{Nlin} fails to fit the ToT.

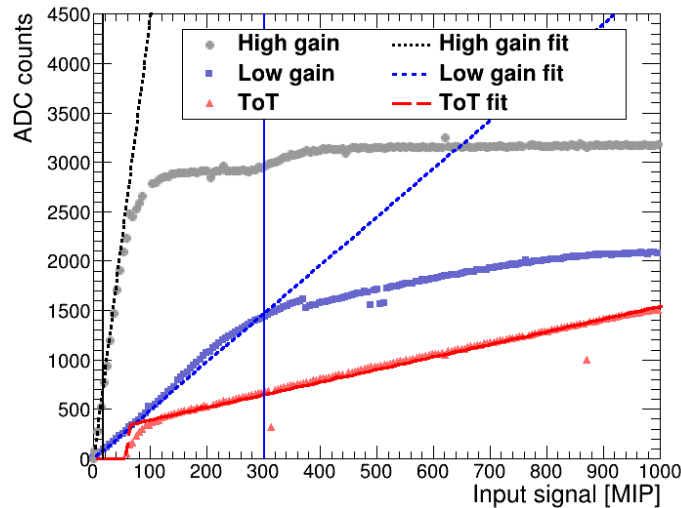


Figure 5.33: Calibration plot for channel 08 of chip 01 from layer 10 of CE-E

- Another type of channels were the channels showing compressed ToT outputs from CI run, one calibration plot for one such channel is shown in Fig. 5.34.

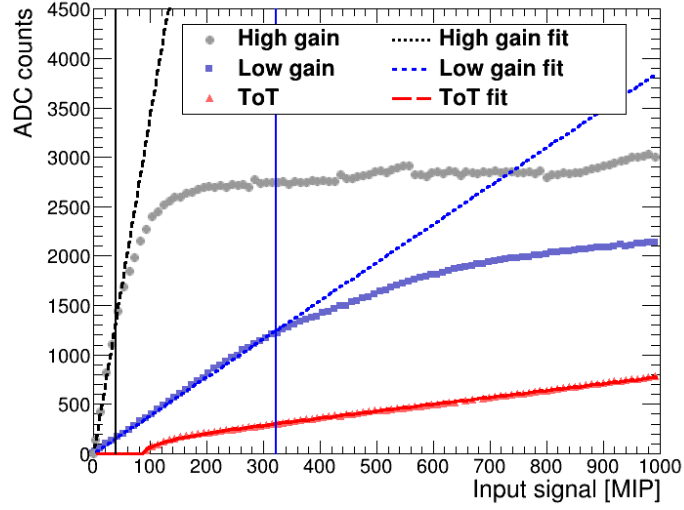


Figure 5.34: Calibration plot for channel 38 of chip 02 from layer 16 of CE-E

Fig. 5.35 shows the change in ToT_{coeff} & ToT_{ped} of layer 11 after updating the outlier calibration values with respective chip averages.

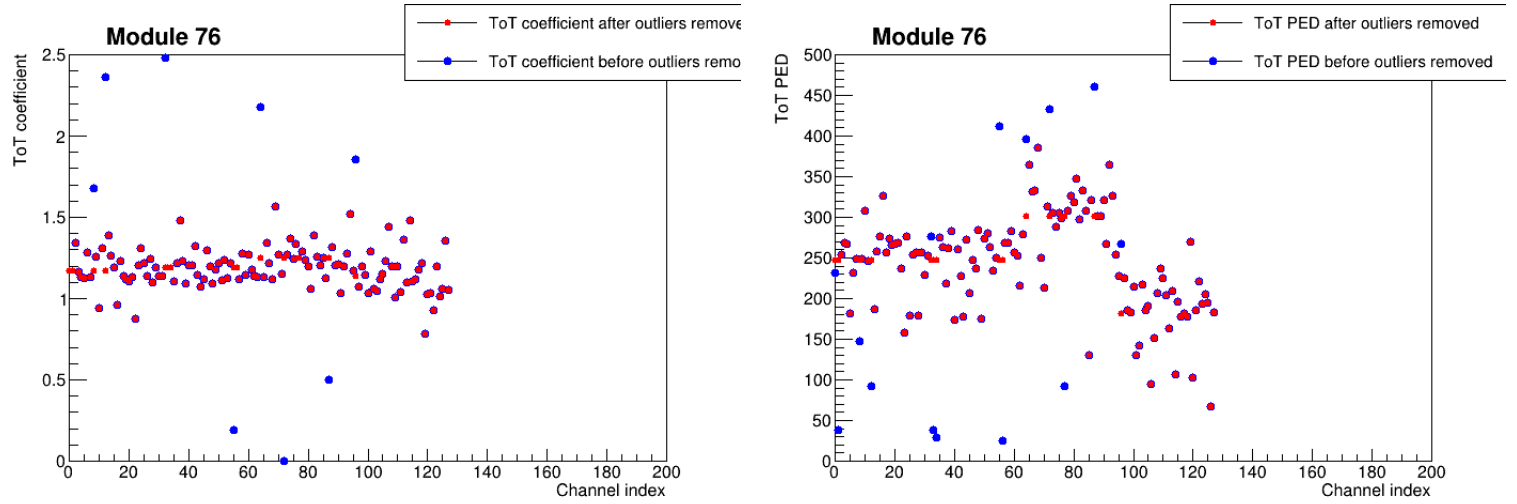


Figure 5.35: ToT Lin calib values after outlier update

5.6.2 Discussion

In terms of linearity & resolution updating outliers improves the linearity for CI Method_05 even further but changing the calibration values to chip averages results in widening of the energy distribution & hence little increase in resolution values was observed but still CI Method 05-V2.0 performs better with respect to CI.Prelim in terms of resolution. Refer to Fig. 5.36 for resolution and linearity results.

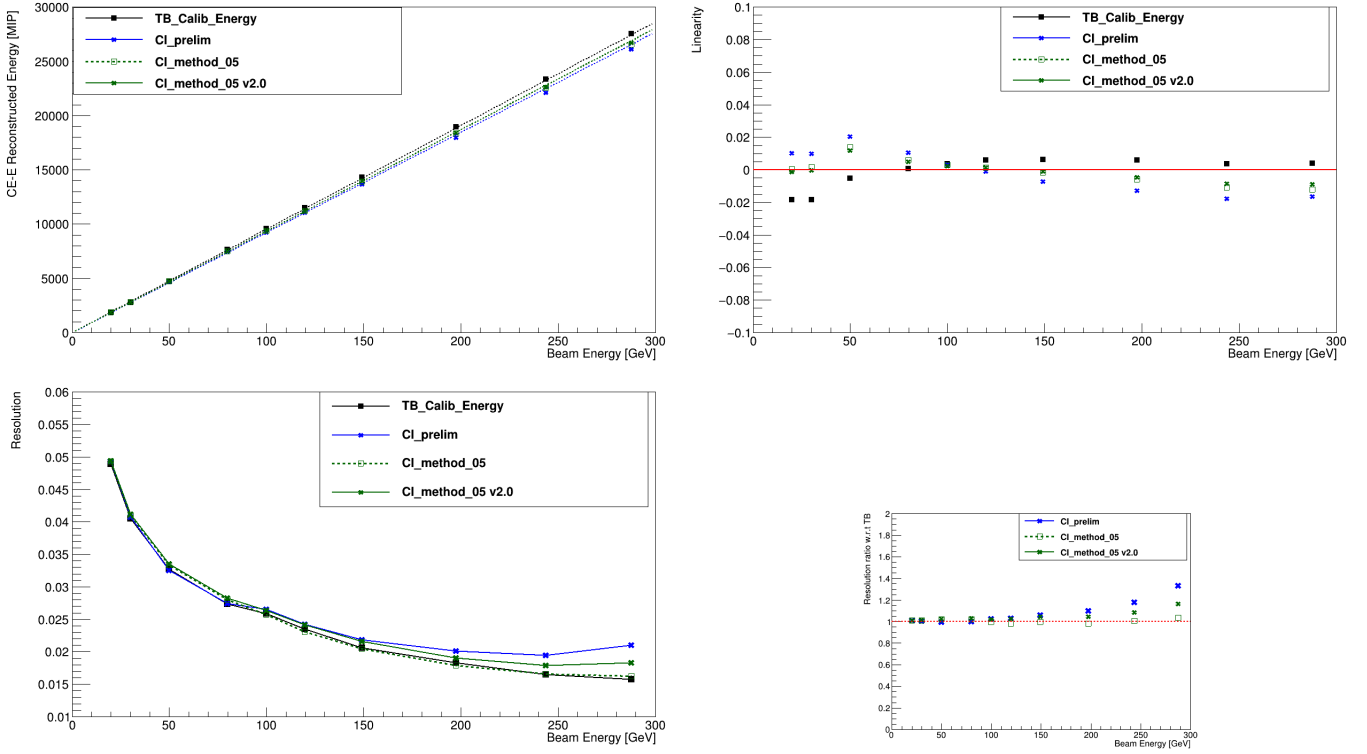


Figure 5.36: Performance results for CI Method 05 2.0

One of the concern with the CI Method05 was the high deviations in Hit energy comparisons with TB.Calib for High energy hits (e.g layer 9 in Fig. 5.31 & Fig. 5.32.

Fig. 5.37 & Fig. 5.38 shows the effect of updating the outliers with the average values. So, we can see that most of the deviations at Higher energy sides has shifted near to TB.Calib values for almost all the layers.

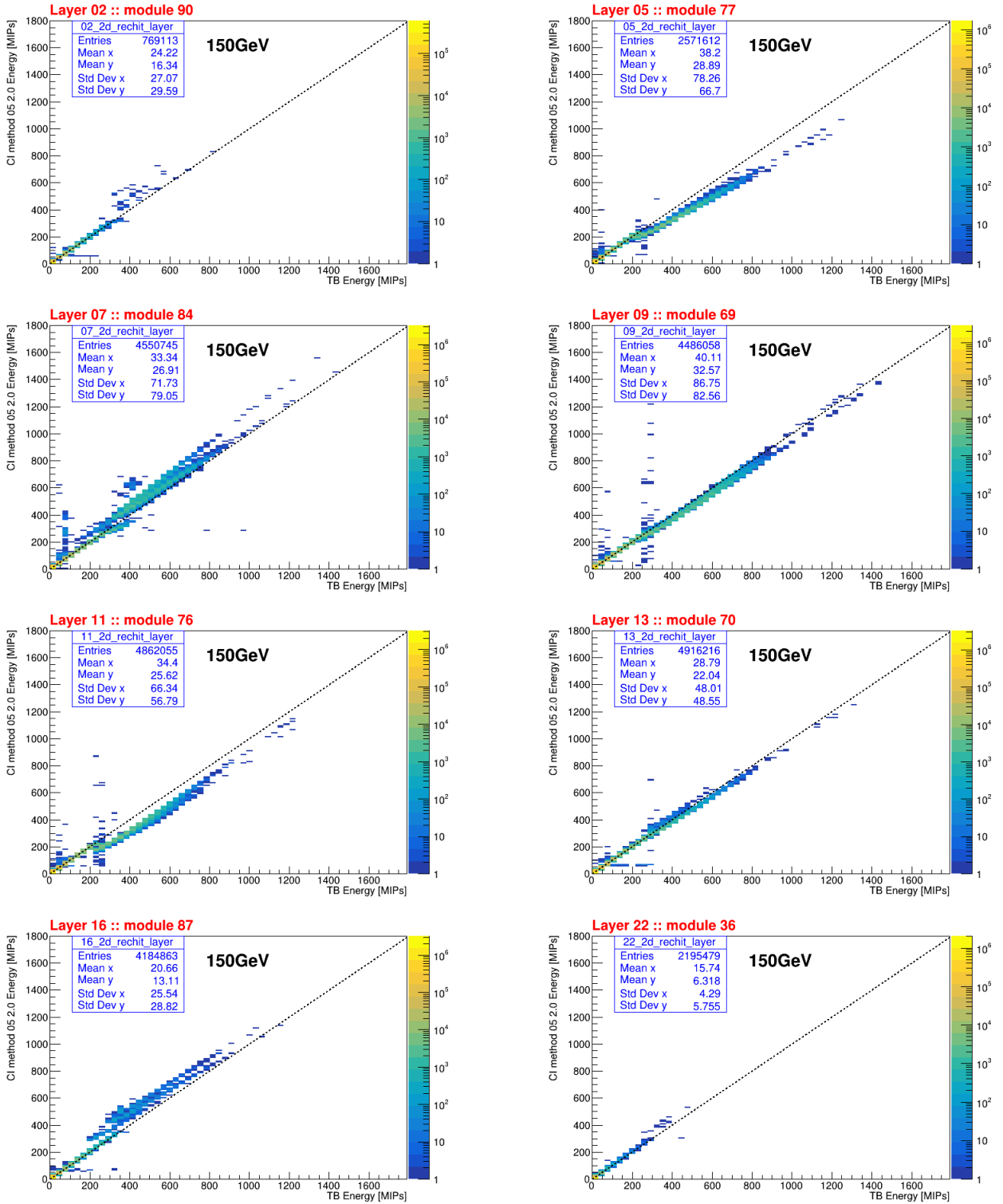


Figure 5.37: Hit energy comparison of CI Method 05 2.0 with TB_Calib for some layers of CE-E for 150 GeV.

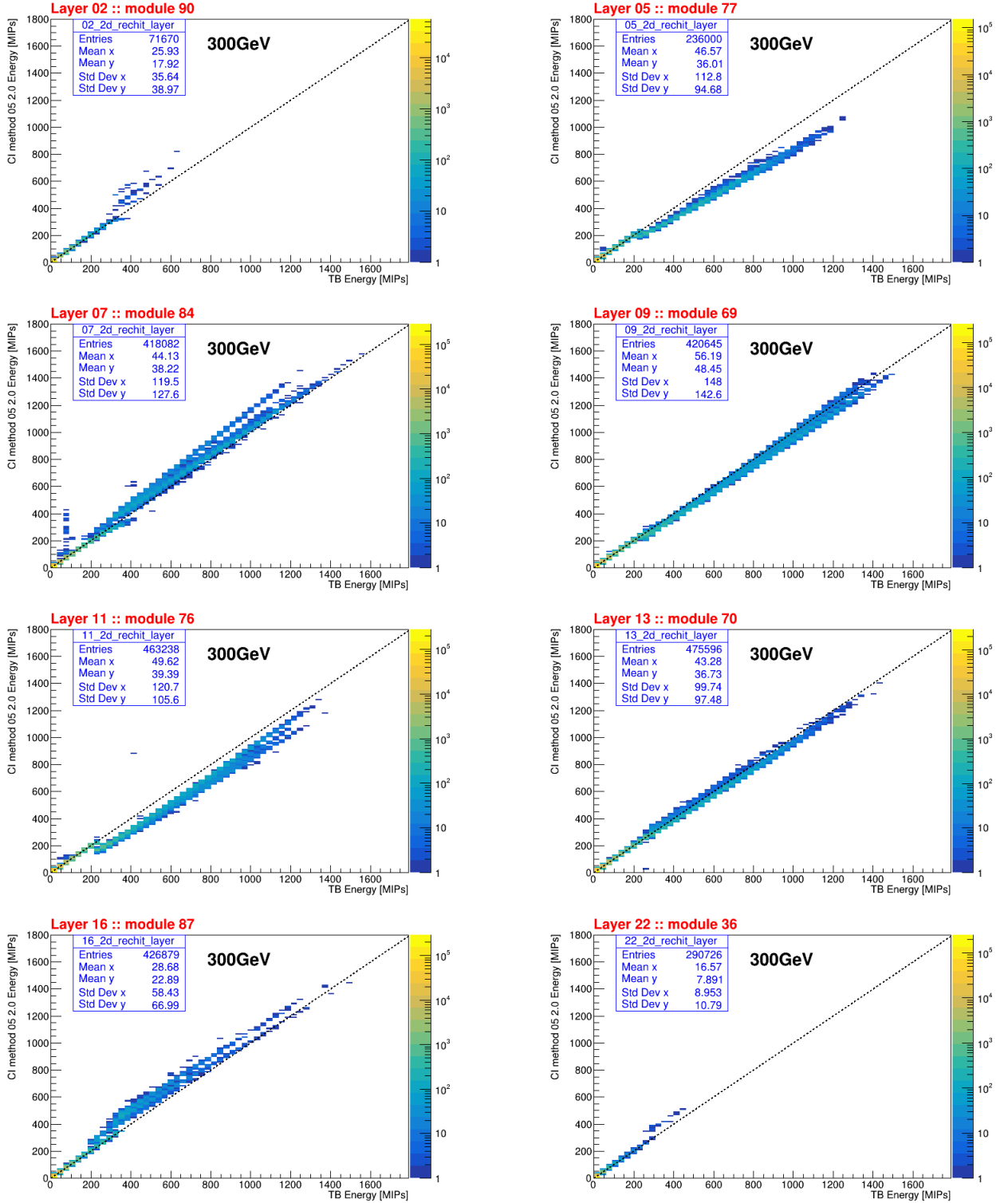


Figure 5.38: Hit energy comparison of CI Method 05 2.0 with TB_Calib for some layers of CE-E for 300 GeV

So, in this section we have seen 5 different versions of charge injection analysis framework, and also how they perform in terms of reconstructing energies for different positron beams. In the next chapter a summary of all the models discussed so far are listed.

Chapter 6

Summary & outlook

In this chapter all the models discussed in chapter 5 are summarized as per their performance in terms of linearity and resolution in comparison with TB_Calib and CI.Prelim.

6.1 Performance summary

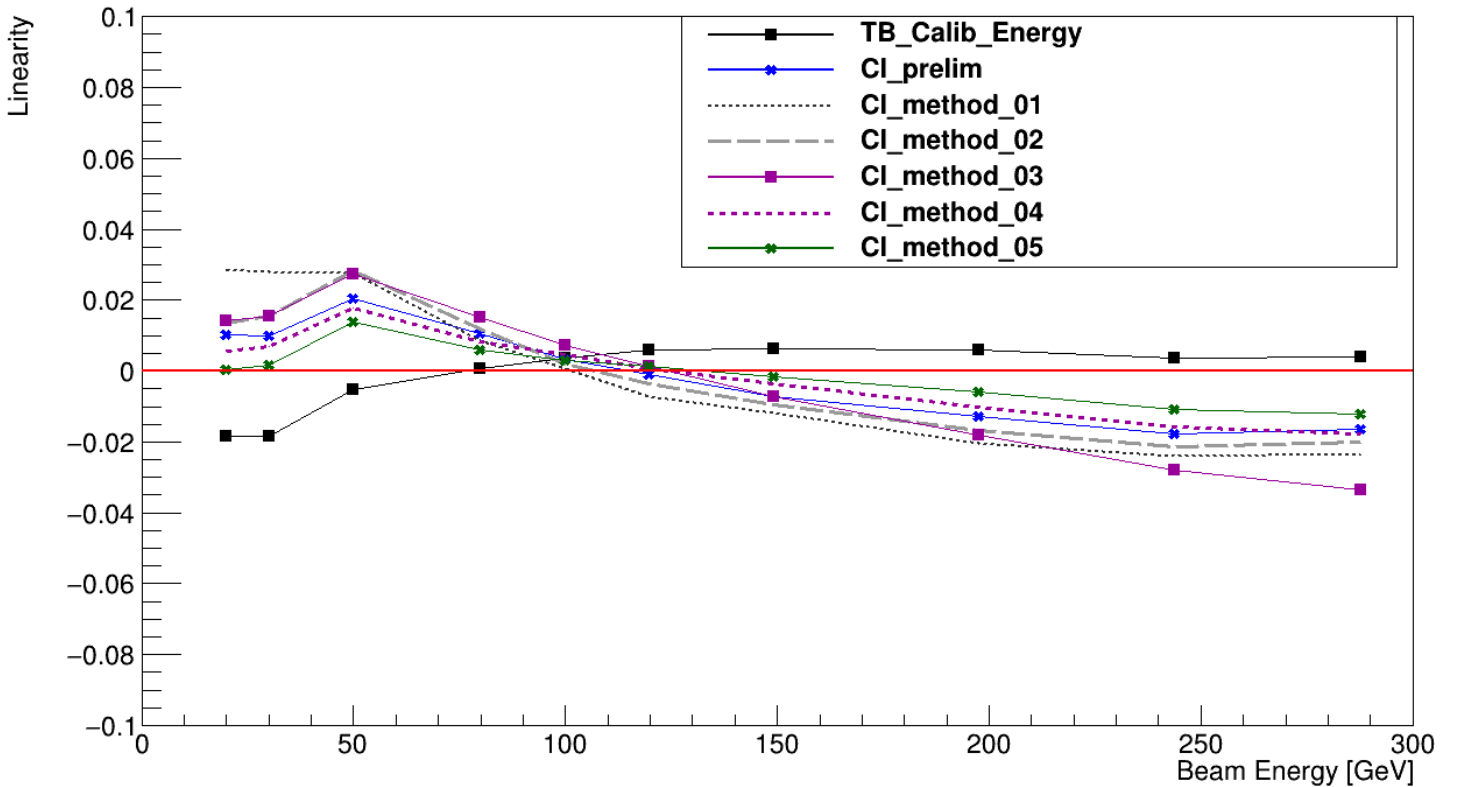


Figure 6.1: Linearity comparison for all the intergain calibration trials.

CI Method 05 V2.0 which is an extension of CI Method 05 is the best performing in terms of linearity Refer to Fig. 6.1. The linearity is almost restored for the CI Method 05 V2.0 with significant improvements with respect to CI.Prelim.

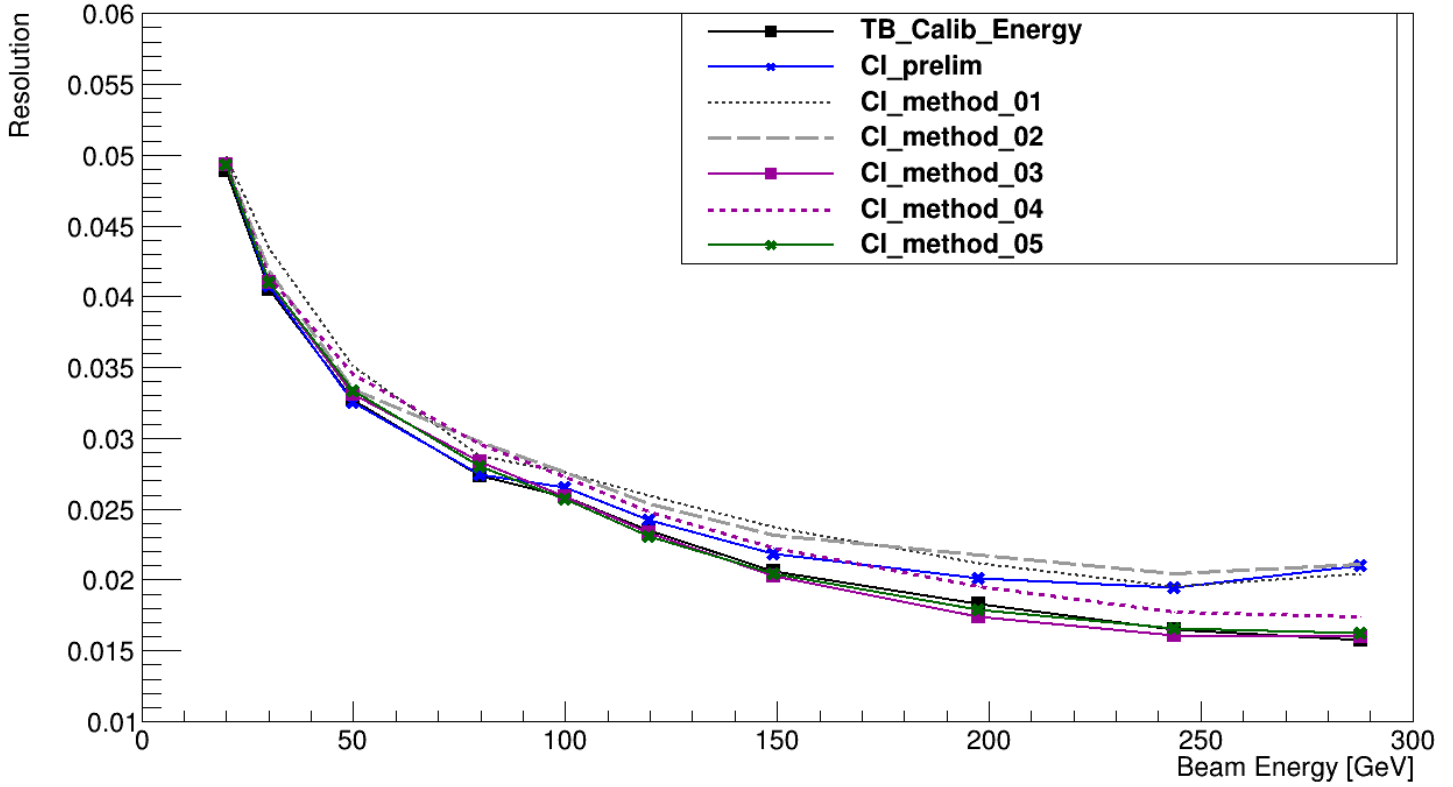


Figure 6.2: Resolution comparison for all the intergain calibration trials.

Resolution wise CI Method 03 delivers the best resolution even better than TB_Calib for some intermediate positron beams [Refer to Fig. 6.2], but the response of CI Method 03 is highly non linear with respect to positron beams [Refer to Fig. 6.1] where as CI Method 05 V2.0 still provides improved resolution with respect to CI_Prelim along with maintaining a linear response. Along with highly linear response and good resolution performance CI_Method 05 v2.0 also shows improvements in terms of unphysical dips observed in rechit spectrums of CI_Prelim [sec. 4.2.3].

Fig. 6.1, Fig. 6.2 shows the final comparisons of linearity, resolution & resolution ratio with respect to TB_Calib for all the models discussed in chapter 4 & chapter 5 respectively.

6.2 Conclusion

This thesis presents a brief description of different detection techniques, interaction of particles with matter, semiconductor detectors and sampling calorimeters (chapter 2). Along with a detailed description of the HGCAL calorimeter and the construction, I discussed calibration & testing of the HGCAL prototype and 6" silicon sensors using 2018 positron test beam data (chapters 3 & 4). My work was majorly aimed to study and improve the intergain calibration method using charge injection data (chapter 4 & 5). Based on these studies, it is clear that the inetrgain calibration of pulse shapers using in HCGAL readout is an important factor in defining the final performance of energy response and resolution of positrons. We tried to investigate the various handles available to improve the calibrations. The ToT non-linearity contributions play a major role, and it can be

explained by the fact that ToT measures larger energies deposited and hence larger gain factors. So, any mis-calibration may translate to larger mis-measurements in energies of the particles. From the studies performed in this thesis, we think that having an overlapping region among different gain stages provides an independent check and alternative handle to establish and debug the intergain calibrations using charge injection method, at the beginning as well as during the course of data taking with the HGCal detectors.

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