ZDC MC Status (Taiwan Group)
EIC-Asia @ 20260501

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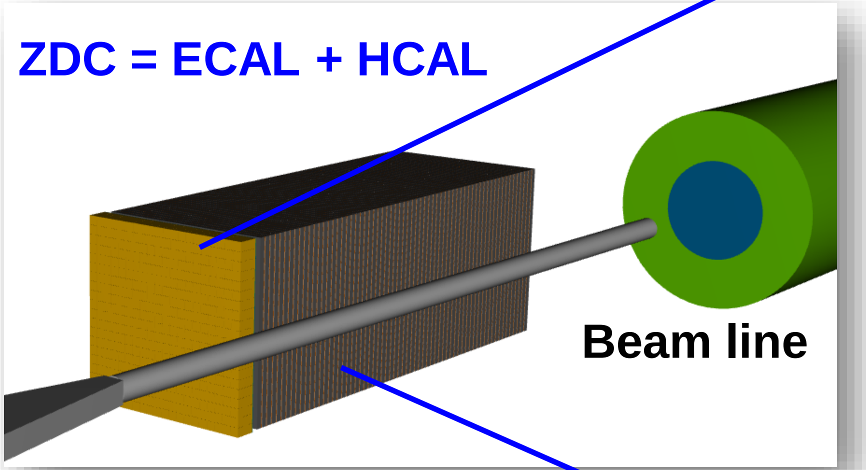
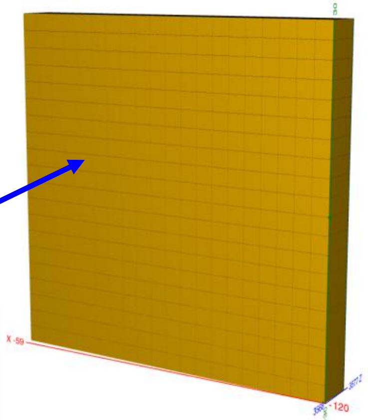
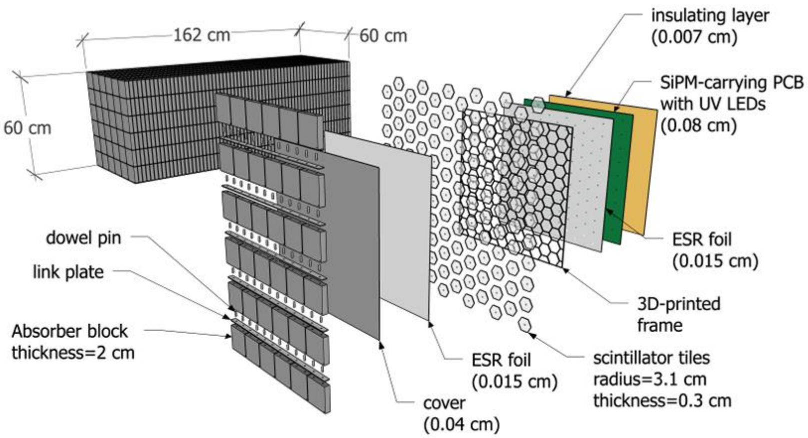
Official ZDC Design : Crystal ECAL + HCAL





ECAL

1. **LYSO Crystal**
2. 20*20 cells
3. 3cm*3cm*7cm / cell
4. 60cm*60cm
5. **7cm ~ 6.5X0 in Z**



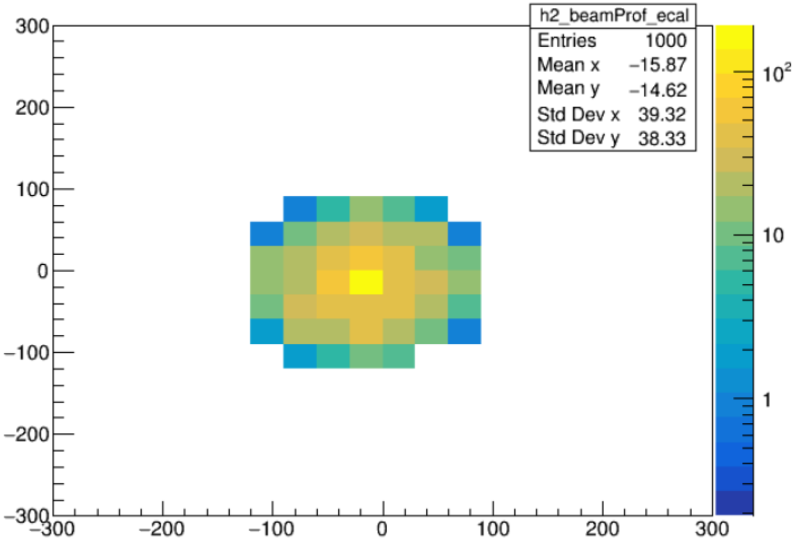
HCAL : sampling calorimeter

1. **1 layer = steel + scintillator tile + SiPM**
2. 64 layers, 8 slice/layer
3. 65cm in X, 60cm in Y, 163cm in Z

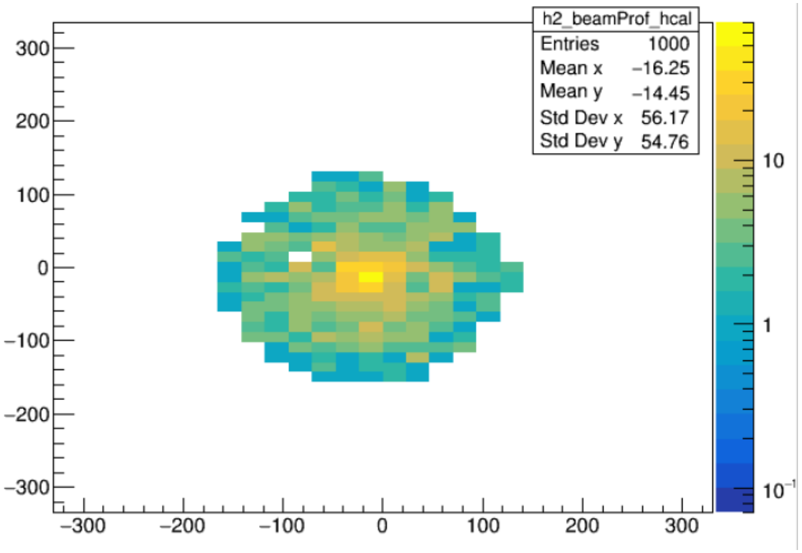
- **Official MC is used :**
ECAL crystal + HCAL SiPM-on-tile

Relocate Detector and Beam Position

Beam profile on ECAL surface
(300 GeV neutron)



Beam profile on HCAL surface
(300 GeV neutron)



- **Only ZDC in MC**
- ZDC is aligned straight along z-dir.
- Gun moves in front of ZDC.
- **Spread beam**
- **25 degree opening** angle
- 1 GeV – 40 GeV gamma
- 20 GeV – 300 GeV neutron

Energy Reconstruction

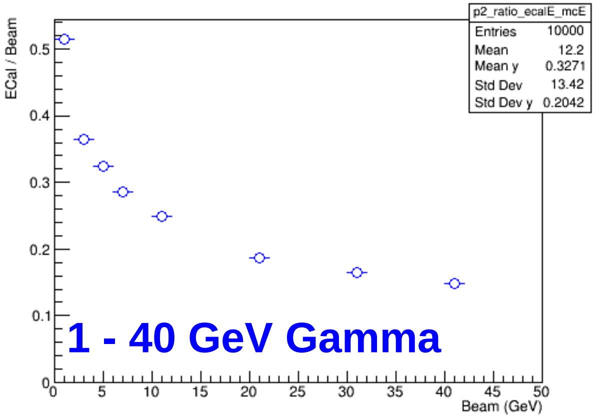
Energy Resolution
And
Energy Bias

Energy Dump

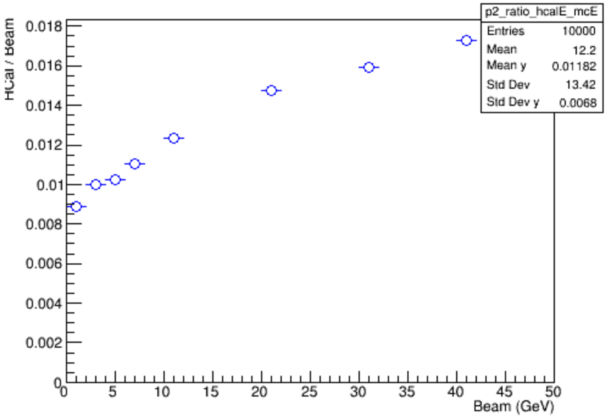
Beam VS ECAL/Beam

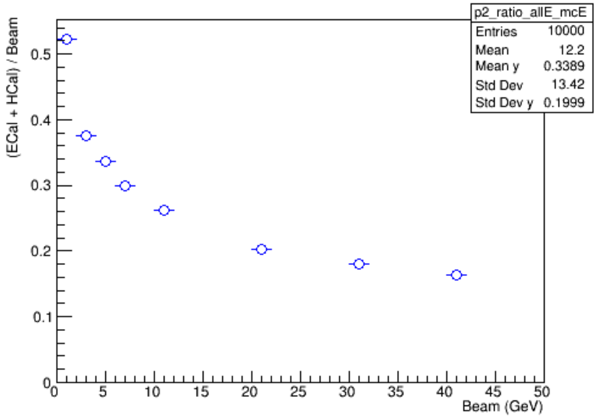
Beam VS HCAL/Beam

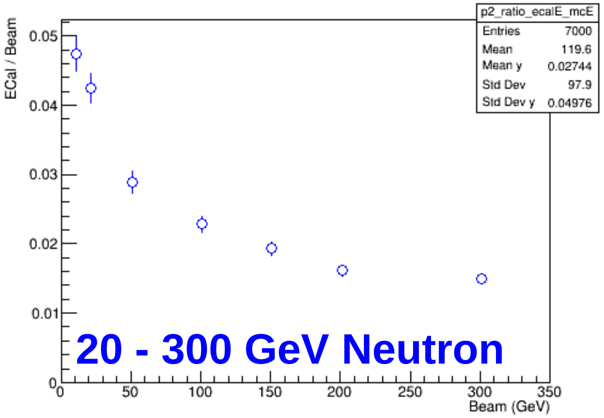
Beam VS (ECAL + HCAL)/Beam



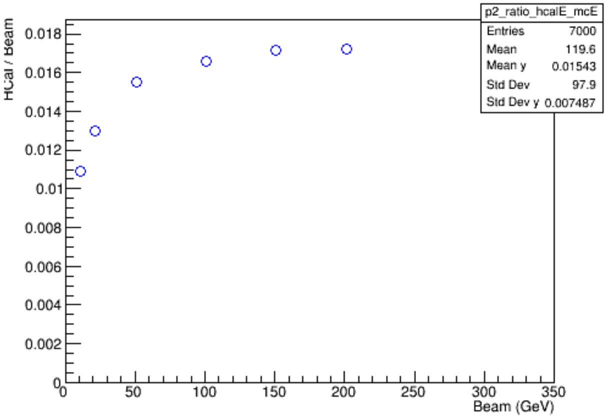
1 - 40 GeV Gamma

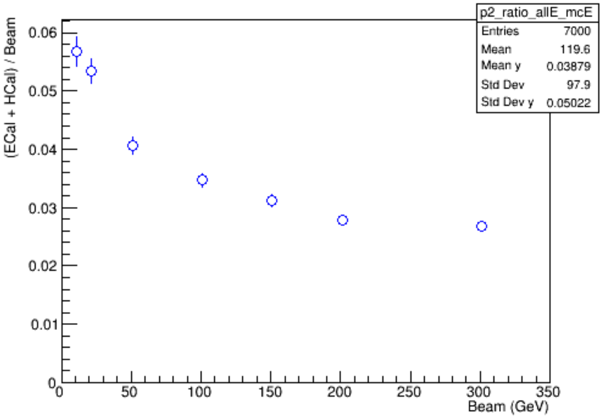






20 - 300 GeV Neutron



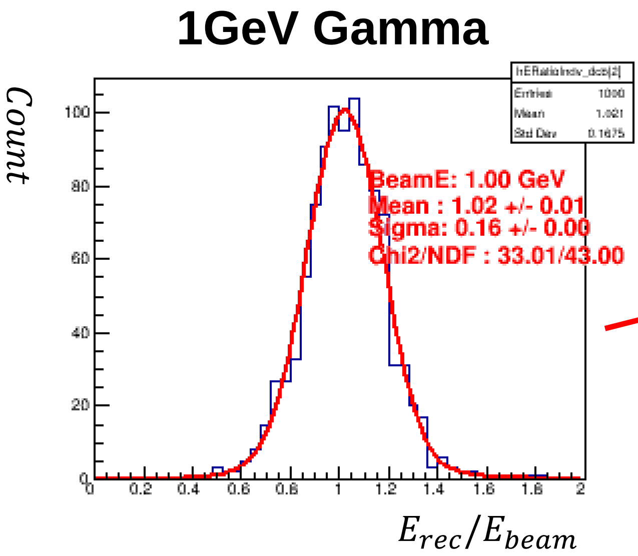


- 1 - 40 GeV gamma beam : Most of energy dumped in ECAL ~ 20% to 60%.
- 20 – 300 GeV neutron beam : Not much energy dumped in scintillator tile, only 3% to 6%.

Different Kinds of Energy Regression

- **Fitting Functions**
  - Linear function : $E_{rec} = p0 + p1 * E_{ECAL} + p2 * E_{HCAL}$
  - Linear function w/ ratio : $E_{rec} = p0 + p1 * E_{ECAL} + p2 * E_{HCAL} + p3 * E_{HCAL}/(E_{ECAL} + E_{HCAL})$
  - Quadratic function : $E_{rec} = p0 + p1 * E_{ECAL}^2 + p2 * E_{HCAL}^2$

- **Weighting (Events enter fitting with a certain weight)**
  - Equal weighting : $weighting = 1$ **(all the events are equal)**
  - Square-root of beam energy : $weighting = \sqrt{E_{beam}}$ **(higher energy beam has more weight)**



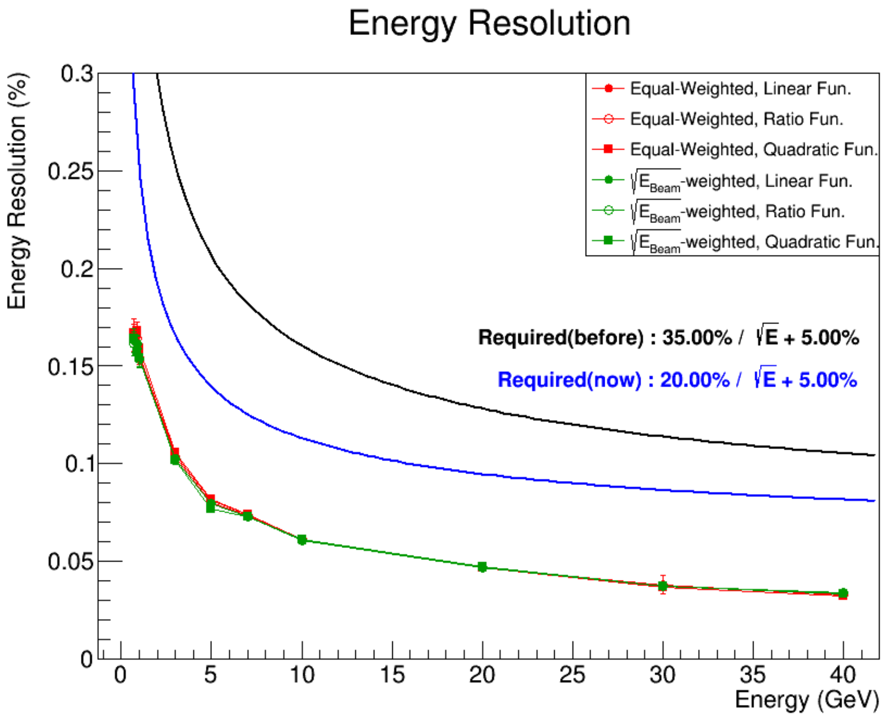
Linear energy regression

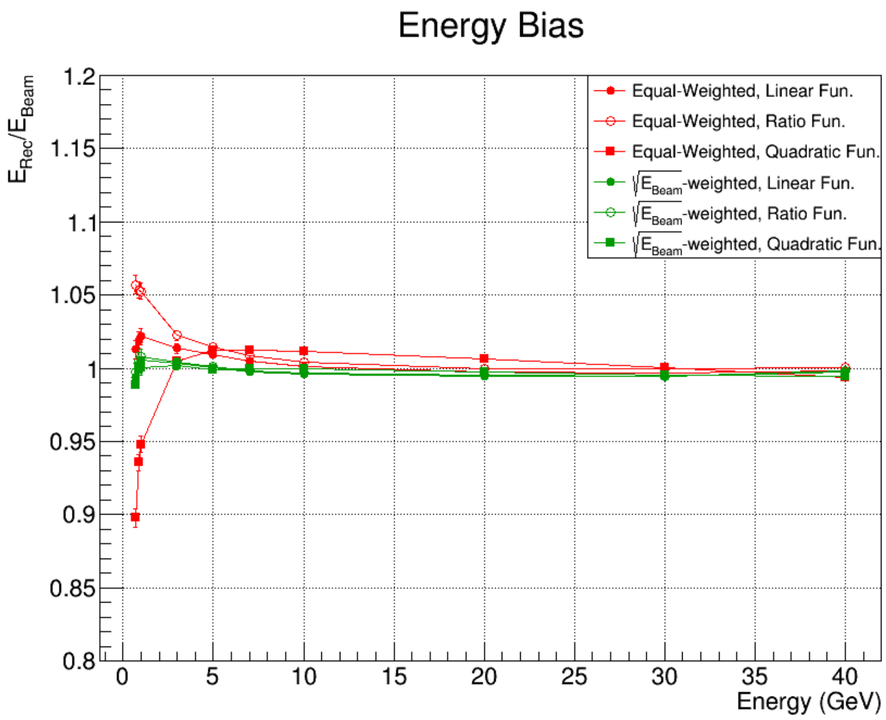
$$E_{rec} = p0 + p1 * E_{ECAL} + p2 * E_{HCAL}$$

Fit E_{rec} with doubld - side crystal ball function

- *Energy resolution* $= \frac{\sigma}{E_{beam}}(\%)$
- *Energy bias* $= \frac{\mu}{E_{beam}}$

Gamma Beam Energy Regression

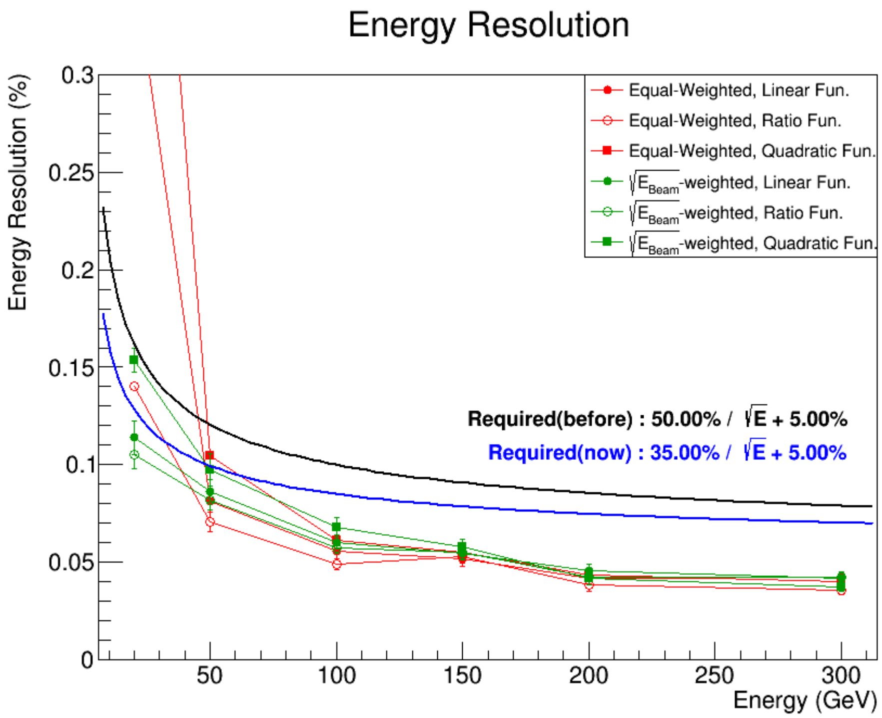


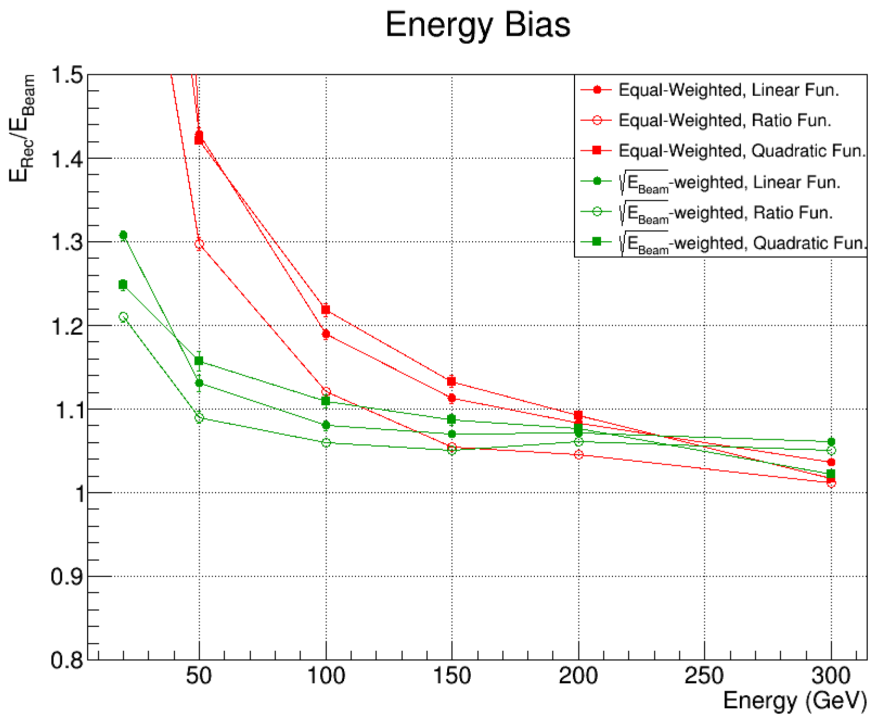


1–40 GeV Gamma Beam

- **Method : Sqrt(Ebeam) weighting** performs best. insensitive to fitting function.
- **Resolution:** Performance requirements fully satisfied.
- **Bias:** Negligible energy bias observed.
- **Nice energy reconstruction for gamma.**

Neutron Beam Energy Regression





- **Optimal Method: Sqrt(Ebeam) weighting** combined with the **Ratio Method** yielded the best results.
- **Energy Resolution: neutrons < 50 GeV does not meet the requirements.**
- **Energy Bias: A bias of approximately 2%** is observed for neutron > 50GeV. Large bias for low energy region (neutron < 50GeV).
- **The small fraction of neutron energy deposited in the scintillator tile (3%–6%) limits regression precision for beam energies under 50 GeV?**

Track Reconstruction

Position Resolution

And

Position Bias

Track Reconstruction Algorithm (1/2)

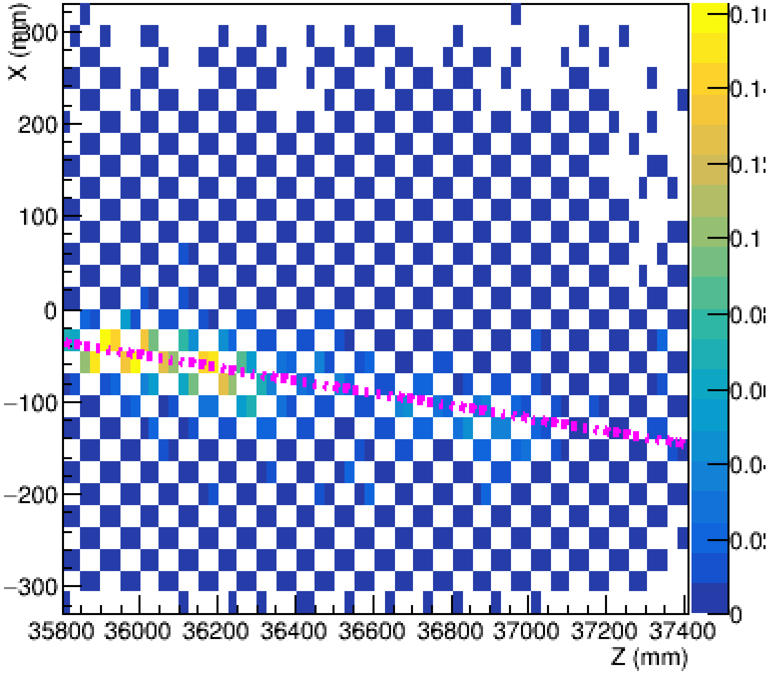
- **Only HCAL is used in track reconstruction.**
- **Method**

\- Three dimensional space => **XZ and YZ planes.**

\- Fit **averaged hit position in layers with polynomial1** to find track.

\- **Residual** can be estimated by compare beam extrapolation and reconstructed track.

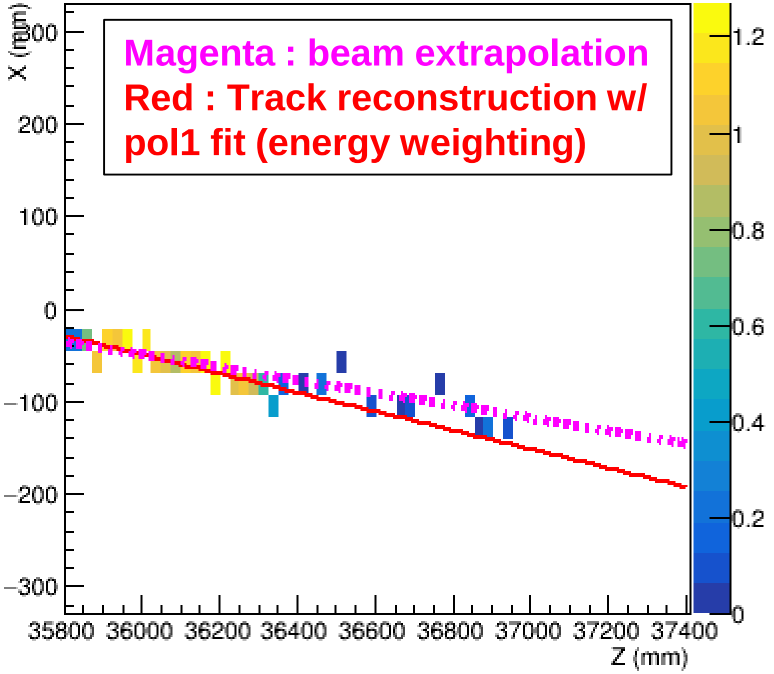
300 GeV neutron beam in HCAL
Hit position in XZ plane



Fit average hit position layer by layer

$$\bar{x} = \frac{\sum E_{hit} x_{hit}}{\sum E_{hit}}$$

300 GeV neutron beam in HCAL
Average Hit position in XZ plane



Track Reconstruction Algorithm (2/2)

- **Fitting Function : polynomial 1**

- **Weighting of each layer in fitting**

① **Linear energy :** $\mathbf{E_{layer}}$

② **Log energy :** $\mathbf{\log(E_{layer})}$

③ **Hit count :** $\mathbf{\frac{N_{layer}}{N_{sum}}}$

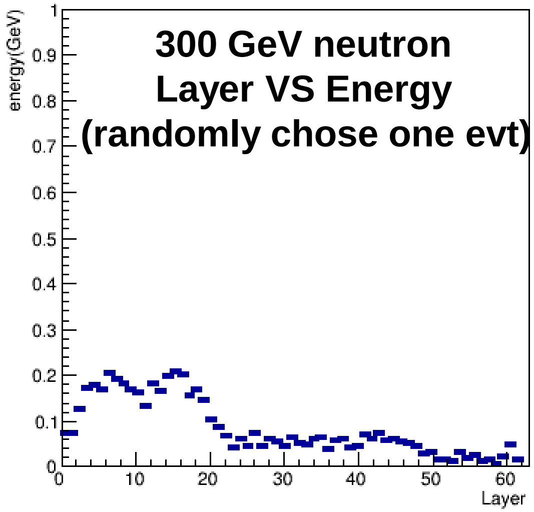
④ **Energy-and-hit :** $\mathbf{\frac{E_{layer}}{E_{sum}} + \frac{N_{layer}}{N_{sum}}}$

E_{layer} and E_{sum} are energy of layer and energy of all layers, respectively.

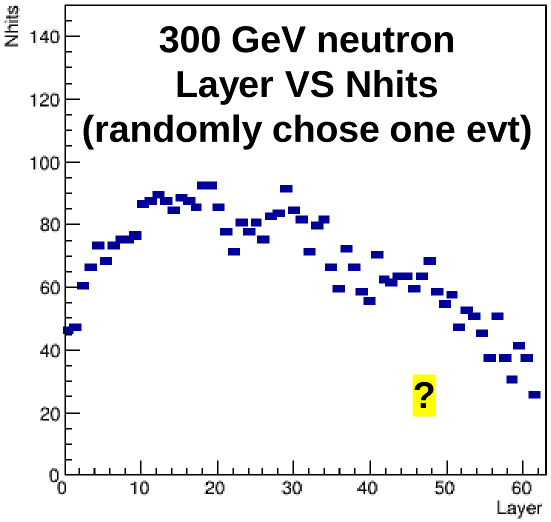
N_{layer} and N_{sum} are num. hits of layer and num. hits of all layers, respectively.

- **Cut low energy layers**

Most energetic layer +/- N layers



300 GeV neutron
Layer VS Energy
(randomly chose one evt)

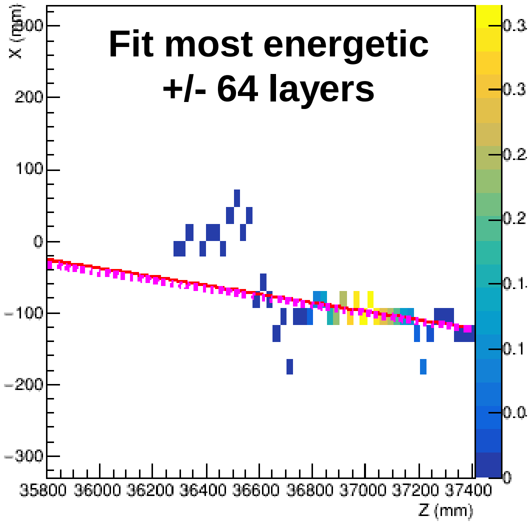


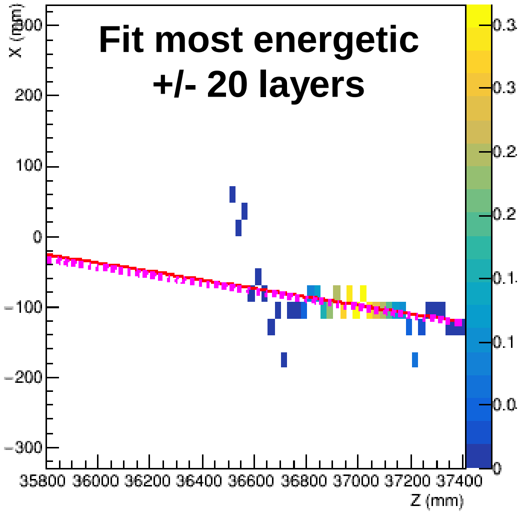
300 GeV neutron
Layer VS Nhits
(randomly chose one evt)

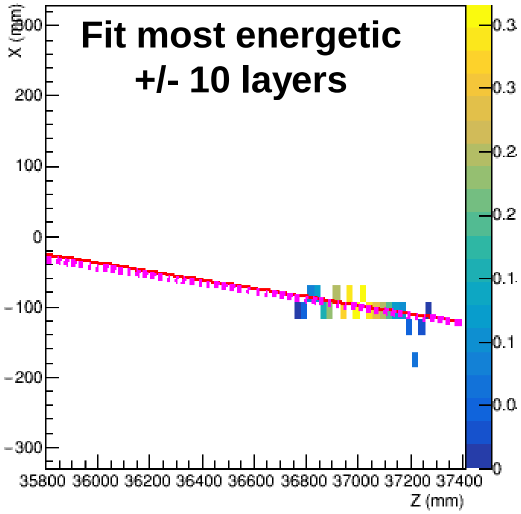
?

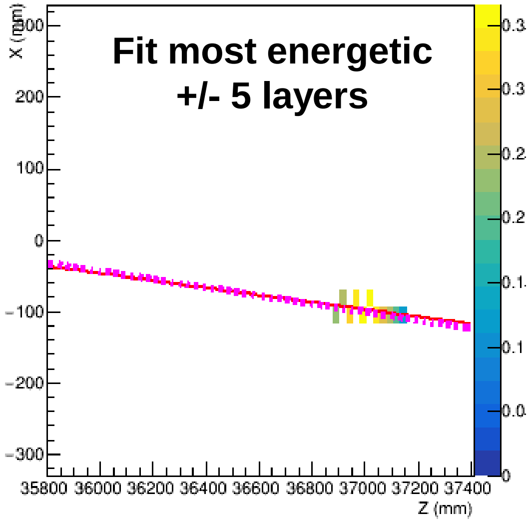
Test Different Num. of Fitting Layer (1)

One event from 300 GeV Neutron / Linear Energy Weighting





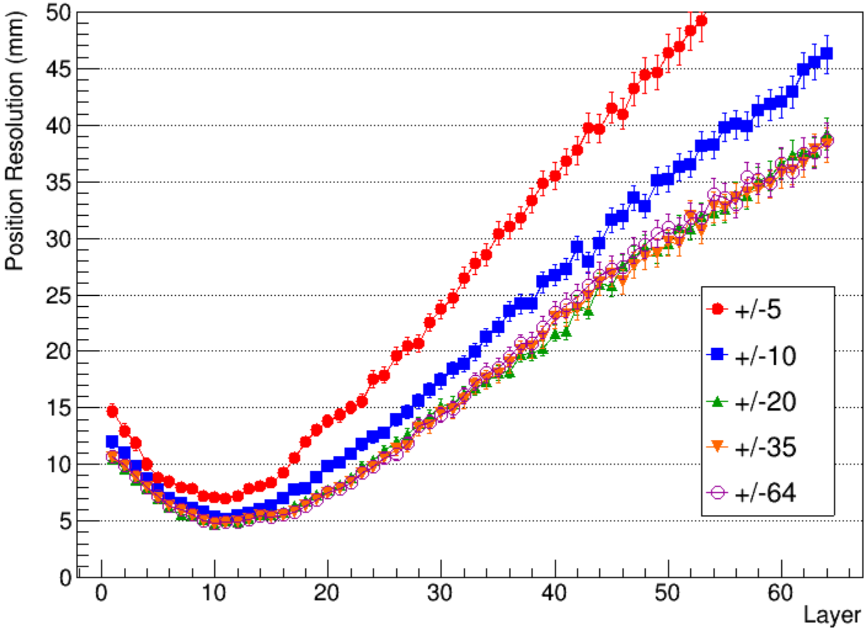




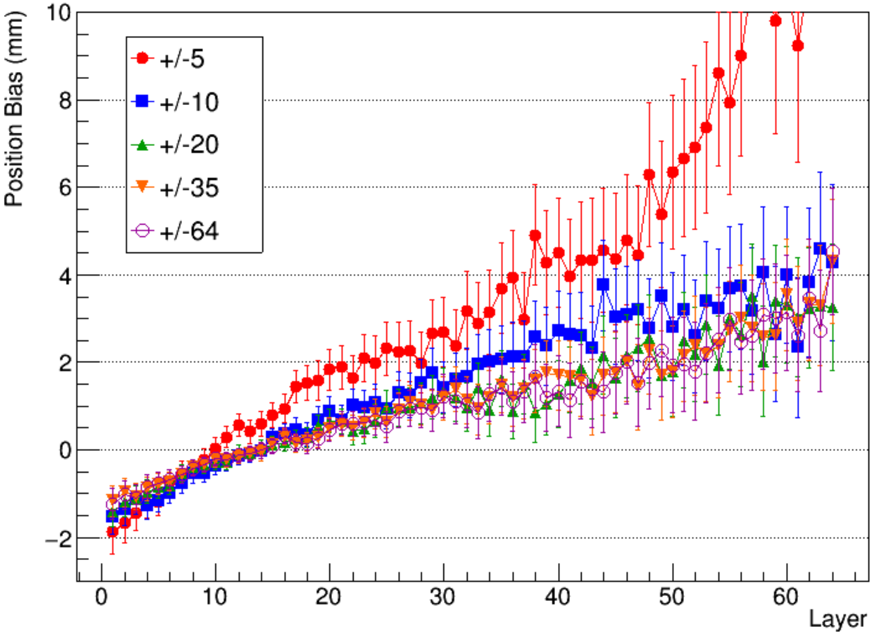
Test Different Num. of Fitting Layer (2)

300 GeV Neutron / Linear Energy Weighting / XZ plane

Position Resolution



Position Bias

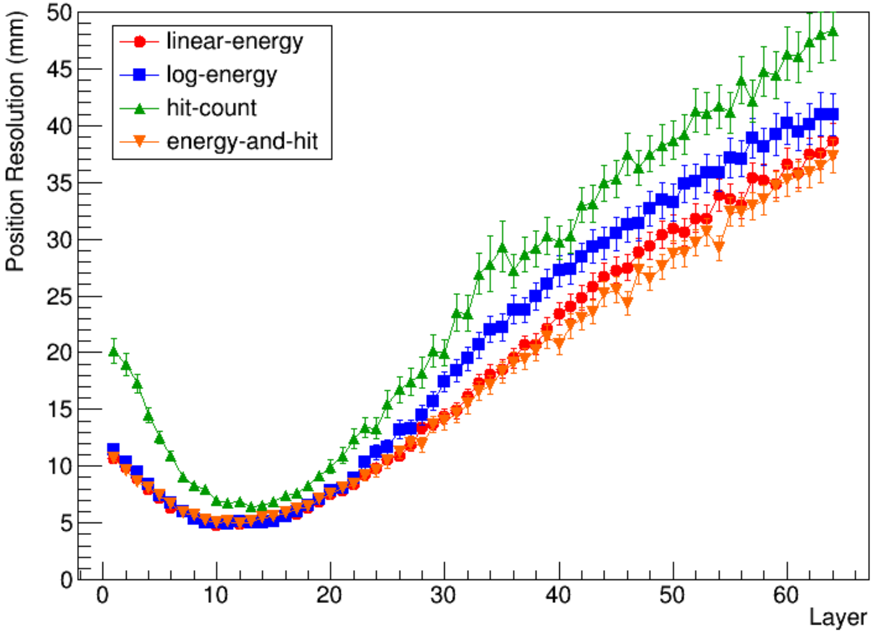


- All results utilize **linear weighting** with a **first-order polynomial (pol1)** fit.
- **Reducing the number of layers in the fit does not improve position residual or bias**. The **weighting** already assigns lower importance lower energy layers, effectively performing the same function as a layer cut.
- **Position resolution and bias degrade as the distance from the shower maximum (the most energetic layer) increases.**

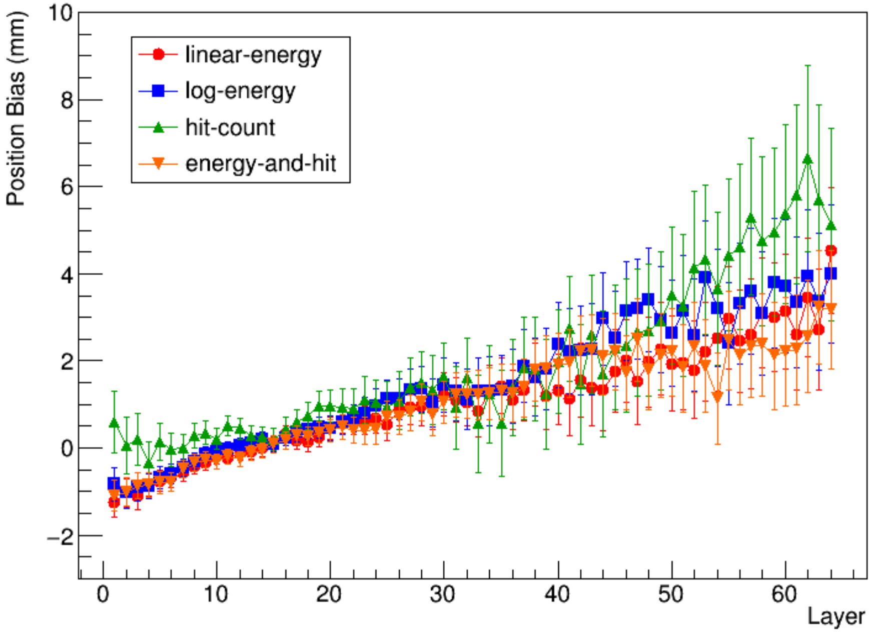
Test Different Weighting Factor

300 GeV Neutron / Fit 64 layers / XZ plane

Position Resolution



Position Bias

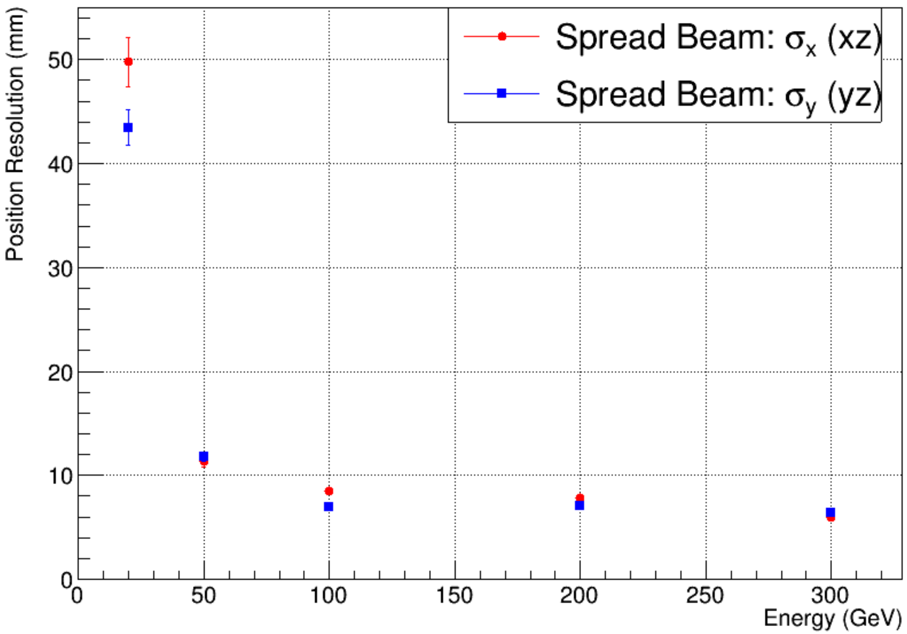


- Except for the hit-count weighting approach, all other weighting methods have consistent results.
- Based on its overall performance and stability, the **hit-and-energy weighting method** was chosen for the final track reconstruction.

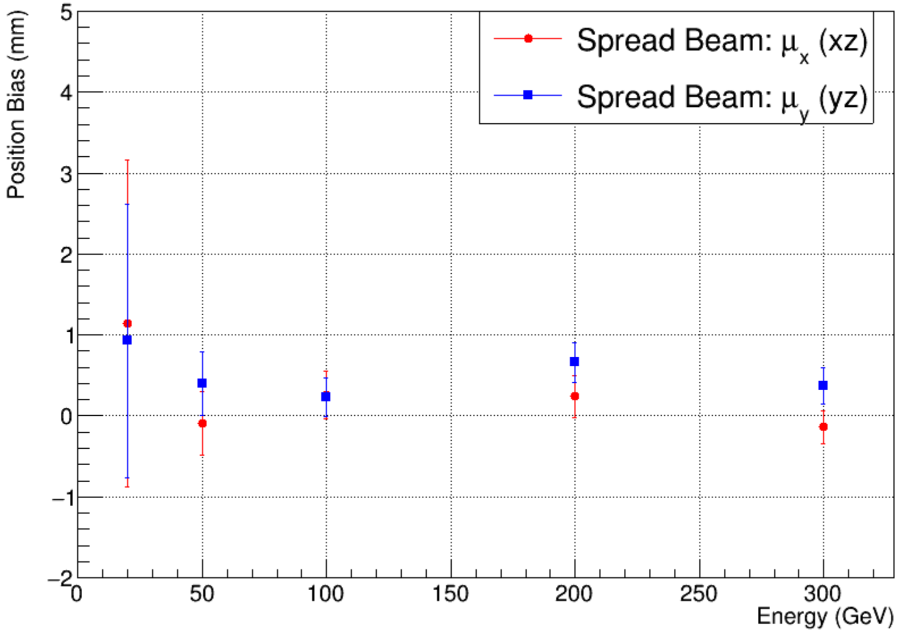
Neutron Beam Track Reconstruction

Fit 64 layers / hit-and-energy weighting

Position Resolution @ Weighted Z position



Position Bias @ Weighted-Z position

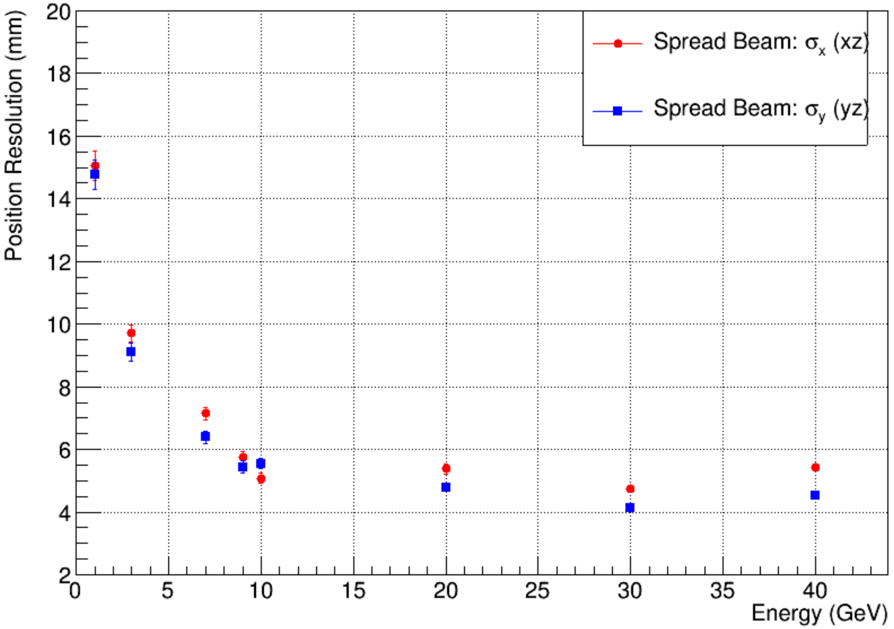


- The results here are shown at **weighted-z position is close to the most energetic layer**.
- **Position Resolution:** Achieved a peak resolution of **6 mm** for high-energy neutrons.
- **Reconstruction Bias:** Minimal bias observed, approximately **0.4 mm**.

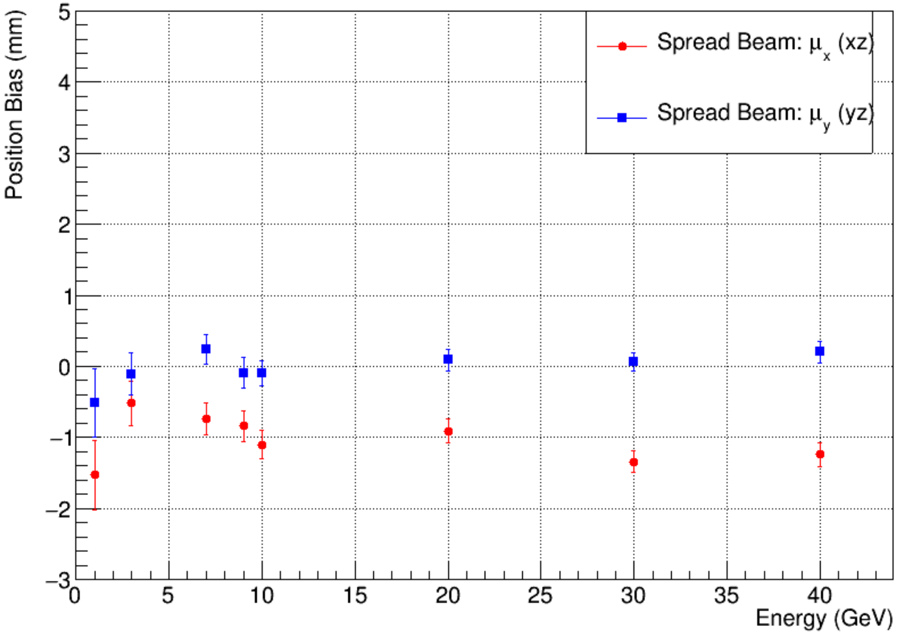
Gamma Beam Track Reconstruction

Fit 64 layers / hit-and-energy weighting

Position Resolution @ Weighted Z position



Position Bias @ Weighted-Z position



- The results here are shown at weighted z position of all hits which is close to the most energetic layer.
- **Position Resolution:** Achieved a peak resolution of **5 mm** for high-energy gamma.
- **Reconstruction Bias:** Large bias observed for xz plane, approximately **1 mm (reason still unknown)**.

Kaon/Pion Structure Study

DIS process

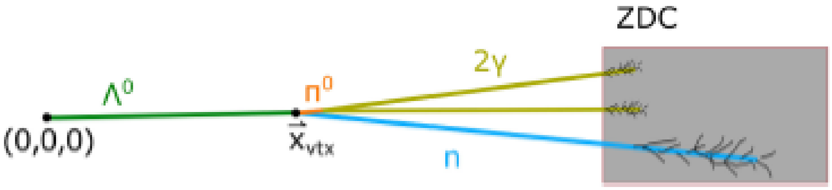
$$|p\rangle = \underbrace{\boxed{Z^{1/2}|uud\rangle}}_{\text{probe proton}} + \underbrace{\boxed{a\,|n\pi^{+}\rangle + b\,|p\pi^{0}\rangle + c\,|\Delta^{++}\pi^{-}\rangle}}_{\text{probe pion}} + \underbrace{\boxed{d\,|\Lambda K^{+}\rangle + e\,|\Sigma^{0}K^{+}\rangle + f\,|\Sigma^{+}K^{0}\rangle + \cdots}}_{\text{probe kaon}}$$

Pion-exchange Sullivan process for pion structure

$$\boldsymbol{e} + \boldsymbol{p} \;\to\; e' + X + \boldsymbol{n}$$

Kaon-exchange Sullivan process for kaon structure

$$e + p \;\to\; e' + X + \Lambda \qquad \boldsymbol{\Lambda} \;\to\; \boldsymbol{n} + \boldsymbol{\pi}^{0} \to \boldsymbol{n} + \boldsymbol{2\gamma}$$



- **It is important to check the position resolution at vertex point, also scan the lambda decay across different Z-positions.**
- **ZDC sits 35m away from the collision point. From the current results, to reconstruct gamma or neutron track with only HCAL will not be enough for the pion/kaon structure study. WSi ECAL is proposed to help.**

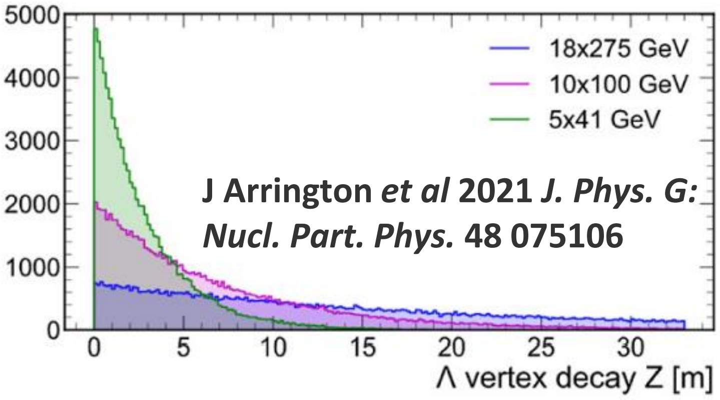


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Figure 13. The Λ-decay spectrum along the beamline for different beam energies.

Summary and To Do

- **MC simulation condition :**

The simulation utilizes a **ZDC (Crystal ECAL + SiPM-on-tile HCAL)** aligned with the z-axis. The setup uses **spread beams** (25 degree opening angle) to evaluate performance for **gammas (1–40 GeV) and neutrons (20–300 GeV).**

- **Energy reconstruction**

Nice energy reconstruction for gamma (requirement satisfied). However, for neutron the small fraction of energy deposited in the ZDC (3%–6%) limits regression precision for beam energies under 50 GeV. **Only neutron > 50GeV satisfied the requirement.**

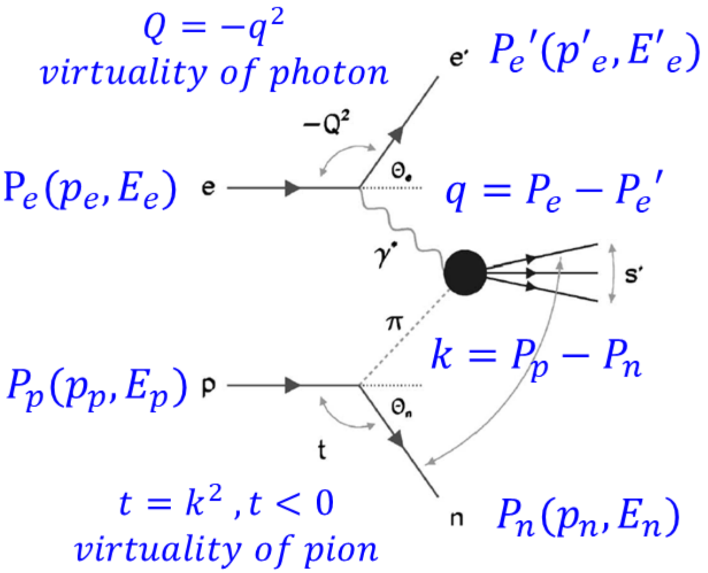
- **Track reconstruction**

Position resolution and bias degrade as the distance from the shower maximum (the most energetic layer). Lambda decay point could be up to 35m away from ZDC. It is important to check the position/vertex resolution across different Z-positions. From the current results, to reconstruct gamma or neutron track with only HCAL will not be enough for the pion/kaon structure study. WSi ECAL is proposed to help.

- **To do :**
  - **Update HCAL geometry (hexagonal -> rectangular scintillator tile)**
  - Evaluate performance with **crystal ECAL + HCAL SiPM-on-tile with neutron/gamma/lambda gun across varying Z-positions.**
  - Evaluate performance with **WSi ECAL + HCAL SiPM-on-tile with neutron/gamma/lambda gun across varying Z-positions.**
  - Explore **GNN** to and check energy/track reconstruction.

Back up

Sullivan Process for Pion Structure Study



J.D. Sullivan, ***"One-pion exchange and deep-inelastic electron–nucleon scattering"*, Phys. Rev. D 5, 1732 (1972).**

- **Pion kinematics**

① $t = k^2 = (1 - x_L)m_p^2 - p_T^2/x_L - [(1 - x_L)/x_L]m_n^2$ **, pion virtuality, $t<0$**

② $x_\pi = \frac{Q^2}{(2k\cdot q)} \approx \frac{x}{(1-x_L)}$, **momentum fraction of parton in pion**

- **Neutron observables**

① $x_L \approx E_n / E_p$ **: Neutron longitudinal momentum**

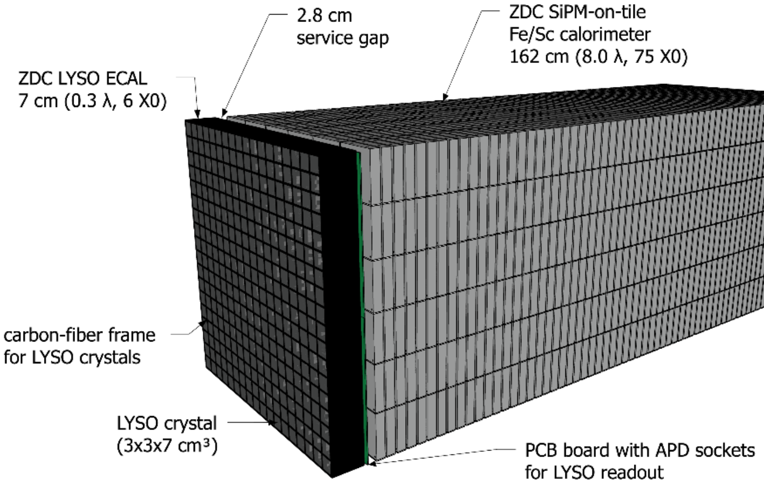
② $p_T \approx x_L E_p \theta_n$ **: Neutron transverse momentum**

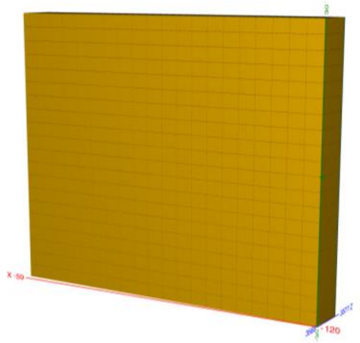
The essential measured quantities are x_L and p_T of very forward angle neutron ➔ zero-degree calorimeter.

The nucleon is not a rigid 3-quark system; **it is dressed by a cloud of mesons.** Therefore, the proton's wavefunction is expanded not just as a bare $|\, uud\rangle$ state, but as **a superposition that includes pion–baryon and kaon-hyperon components.** The **pion and kaon structures can be explored through the Sullivan process** from DIS data.

$$|p\rangle = \underbrace{\boxed{Z^{1/2}|uud\rangle}}_{\text{probe proton}} + \underbrace{\boxed{a\,|n\pi^+\rangle + b\,|p\pi^0\rangle + c\,|\Delta^{++}\pi^-\rangle}}_{\text{probe pion}} + \underbrace{\boxed{d\,|\Lambda K^+\rangle + e\,|\Sigma^0 K^+\rangle + f\,|\Sigma^+ K^0\rangle + \cdots}}_{\text{probe kaon}}$$

Zero Degree Calorimeter (ZDC) Current Design





ECAL
LYSO + SiPM
detect gamma
60cm*60cm
20*20 cells
3cm*3cm*7cm / cell
7cm ~ **6X0** in Z

- Pion-exchange Sullivan process for pion structure

$$e + p \rightarrow e' + X + n$$

- Kaon-exchange Sullivan process for kaon structure

$$e + p \rightarrow e' + X + \Lambda \qquad \boldsymbol{\Lambda} \rightarrow \boldsymbol{n} + \boldsymbol{\pi}^{0} \rightarrow \boldsymbol{n + 2\gamma}$$

- Spectator-neutron tagging for nuclear physics

$$e + d \rightarrow e' + X + n$$

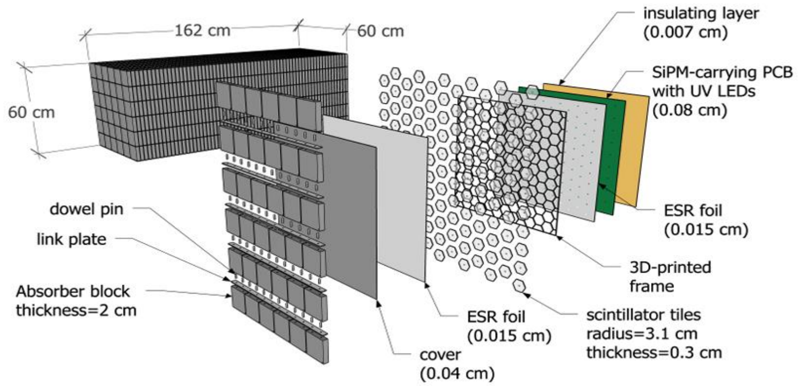
$$e + A \rightarrow e' + X + (A - 1) + n$$

- Background, secondary photons showers

$$\pi^0 \rightarrow \gamma\gamma$$

ZDC aims to measure gamma up to 40 GeV and neutron up to 300 GeV. Therefore, it is composed by ECAL and HCAL.

HCAL
sampling calorimeter
detect neutron



64 layers, 8 slice/layer
1 layer = steel + scintillator tile + SiPM
65cm in X, 60cm in Y, 163cm in Z

ZDC Acceptance

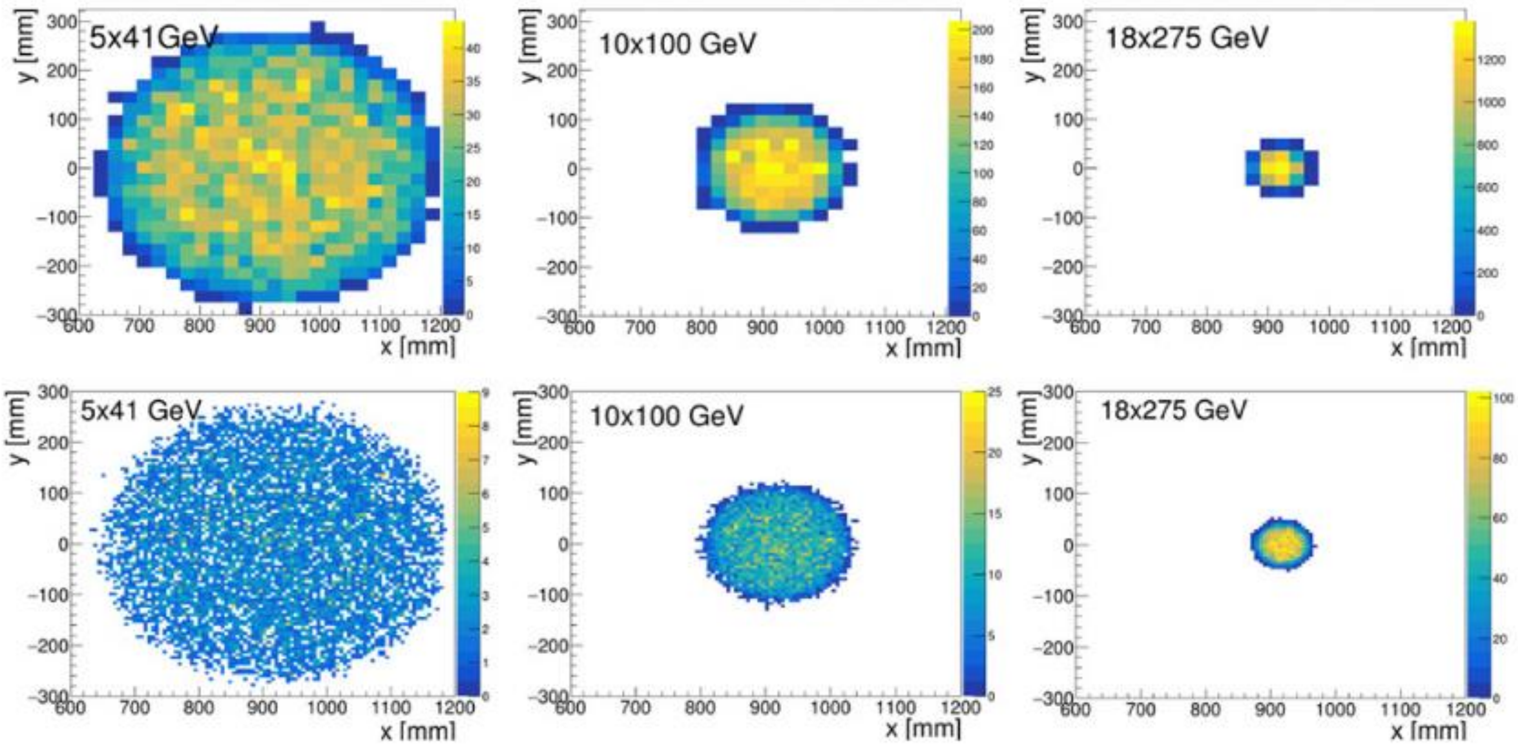


Figure 12. Acceptance plot for neutrons in the 60 × 60 cm^2 ZDC, with a low spatial resolution of 3 cm (upper panels) and with a high spatial resolution of 0.6 cm (lower panels), for different energy settings, from left to right, of 5 × 41, 10 × 100, and 18 × 275. The acceptance plot for 5 × 100 would be similar to that shown for 10 × 100. The lower proton (ion) energies set the requirement for the size of the ZDC, whereas the higher proton (ion) energies drive the spatial resolution requirement.

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Energy Resolution VS Energy

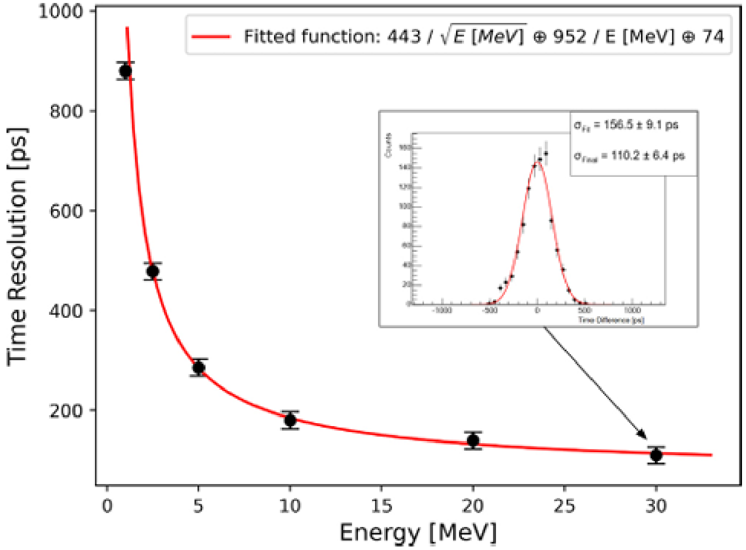
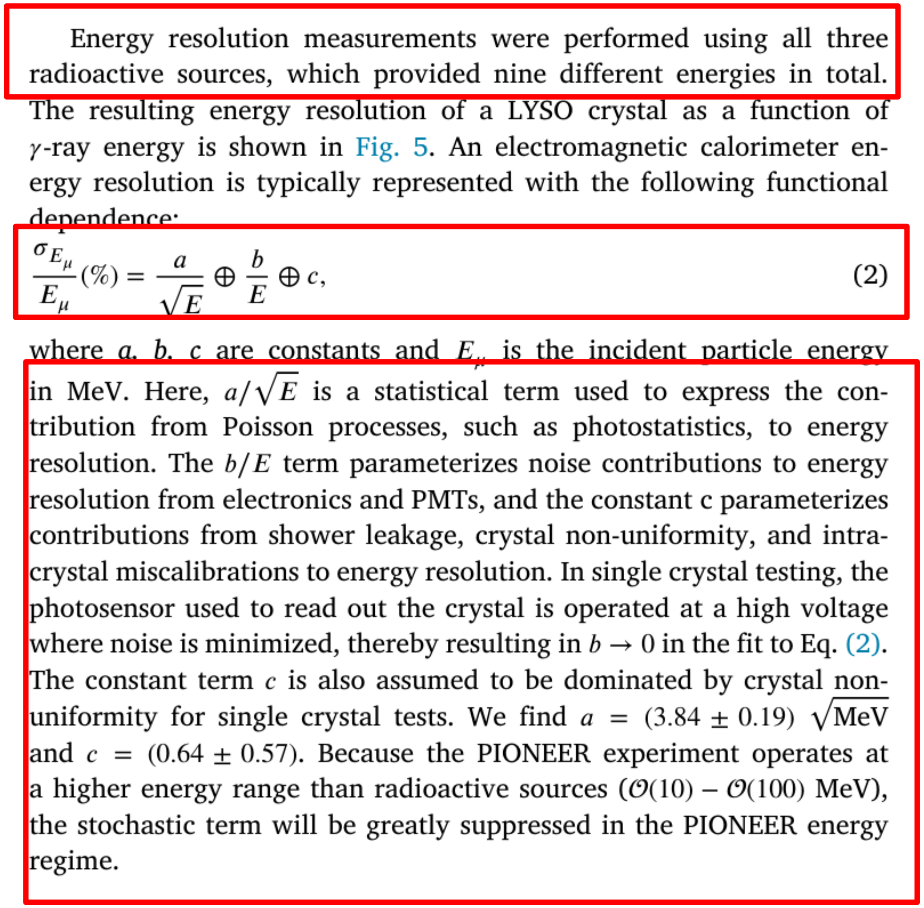


Fig. 13. Dependence of time resolution of a LYSO crystal in the array on the energy deposition in the LYSO crystal for energy deposition between 1–30 MeV. A 110 ps time resolution is measured for 30 MeV energy deposits after the resolution of the reference time is removed via quadrature from σ_{Fit}.



Energy resolution measurements were performed using all three radioactive sources, which provided nine different energies in total. The resulting energy resolution of a LYSO crystal as a function of γ-ray energy is shown in Fig. 5. An electromagnetic calorimeter energy resolution is typically represented with the following functional dependence:

$$\frac{\sigma_{E_\mu}}{E_\mu}(\%) = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \qquad (2)$$

where a, b, c are constants and E_μ is the incident particle energy in MeV. Here, $a/\sqrt{E}$ is a statistical term used to express the contribution from Poisson processes, such as photostatistics, to energy resolution. The b/E term parameterizes noise contributions to energy resolution from electronics and PMTs, and the constant c parameterizes contributions from shower leakage, crystal non-uniformity, and intra-crystal miscalibrations to energy resolution. In single crystal testing, the photosensor used to read out the crystal is operated at a high voltage where noise is minimized, thereby resulting in $b \to 0$ in the fit to Eq. (2). The constant term c is also assumed to be dominated by crystal non-uniformity for single crystal tests. We find $a = (3.84 \pm 0.19)\ \sqrt{\text{MeV}}$ and $c = (0.64 \pm 0.57)$. Because the PIONEER experiment operates at a higher energy range than radioactive sources ($\mathcal{O}(10) - \mathcal{O}(100)$ MeV), the stochastic term will be greatly suppressed in the PIONEER energy regime.