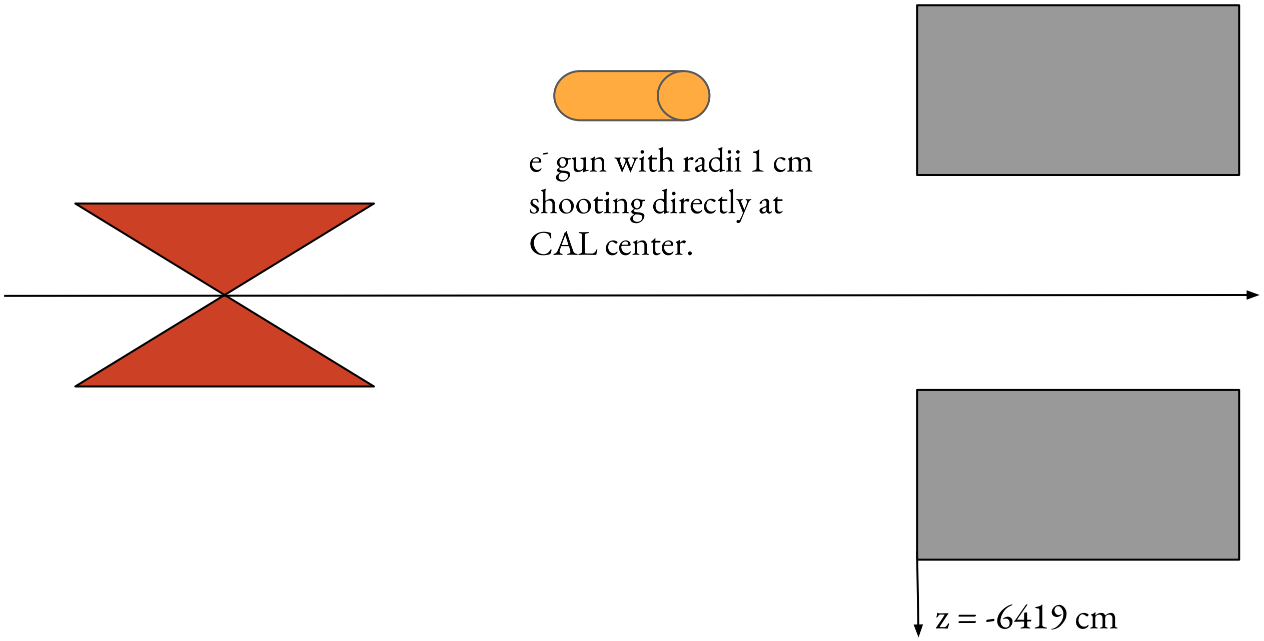
PS Luminosity Detector Simulation Study

Aranya Giri, University of Houston

Year 2025 updates

1. 02/27/25 - PSCAL in ZEUS (Beam Pipe Calorimeter) & Latest ePIC PSCAL design
2. 03/12/25 - Position resolution of latest ePIC PSCAL design

Design details for simulations study



*The dimensions change based on the specific calorimeter design.

Centroid Position Resolution

Method 1
(no W_0)

$$X = \frac{\sum_{i=1}^{N} w_i X_i}{\sum_{i=1}^{N} w_i} \qquad w_i = E_i \tag{8.4}$$

Method 2
(W_0)

$$X = \frac{\sum_{i=1}^{N} w_i X_i}{\sum_{i=1}^{N} w_i} \tag{8.7}$$

$$w_i = \begin{cases} W_0 + \ln\left(\frac{E_i}{E}\right) & \left(\frac{E_i}{E}\right) > e^{-W_0} \\ 0 & \left(\frac{E_i}{E}\right) \leq e^{-W_0} \end{cases} \tag{8.8}$$

$$E = \sum_{i=1}^{N} E_i \tag{8.9}$$

Centroid Position Resolution

	sigma_y (cm)					
Energy (GeV)/ w0	**3**	**3.5**	**4**	**4.5**	**5**	**No w0**
2	0.124	0.1338	0.1832	0.2225	0.2489	0.2193
4	0.1109	0.08525	0.09279	0.1194	0.1518	0.1574
6	0.1078	0.07729	0.06933	0.08165	0.1112	0.1305
8	0.11	0.07687	0.06106	0.06718	0.08486	0.1111
10	0.1108	0.07985	0.05759	0.05632	0.06901	0.09797
12	0.1158	0.08119	0.05378	0.04997	0.06109	0.09041
14	0.1123	0.08103	0.05212	0.04797	0.05575	0.08411
16	0.1147	0.08212	0.05101	0.04436	0.05029	0.07916
18	0.113	0.08296	0.05034	0.04112	0.04587	0.07347

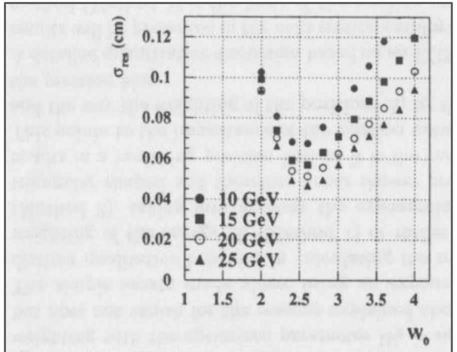
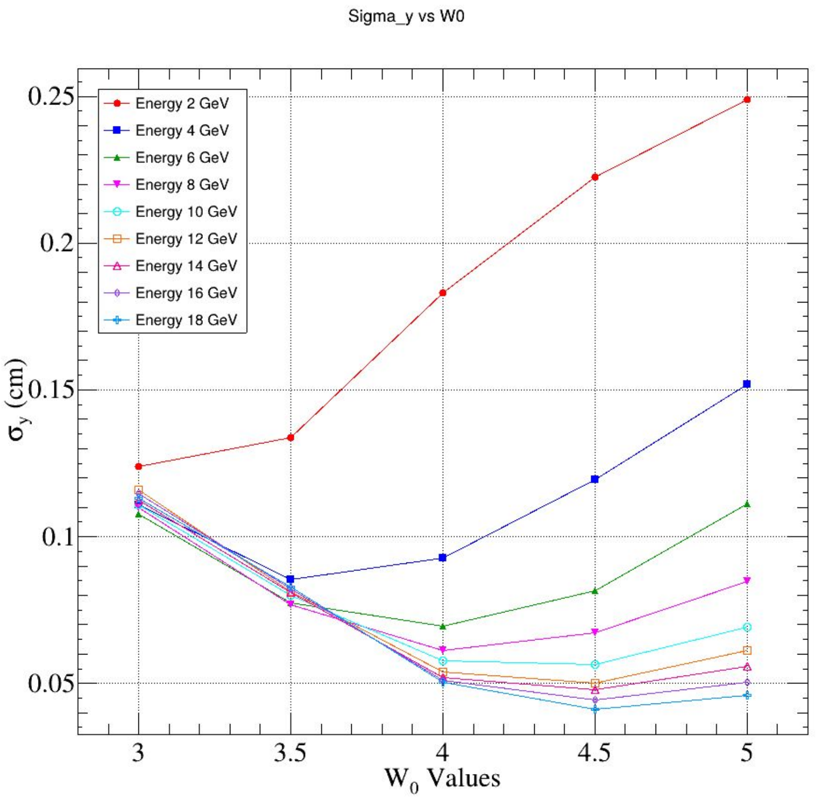
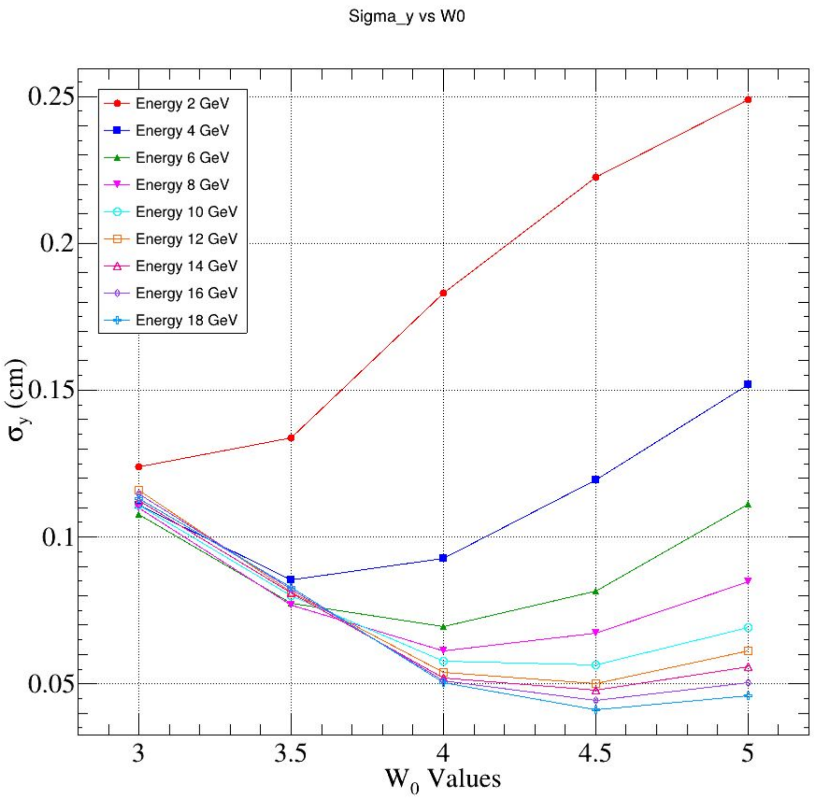


Figure 8.7: *Position resolution σ_{res} (left) and function of W_0 using an EGS4 MC-simulation.*



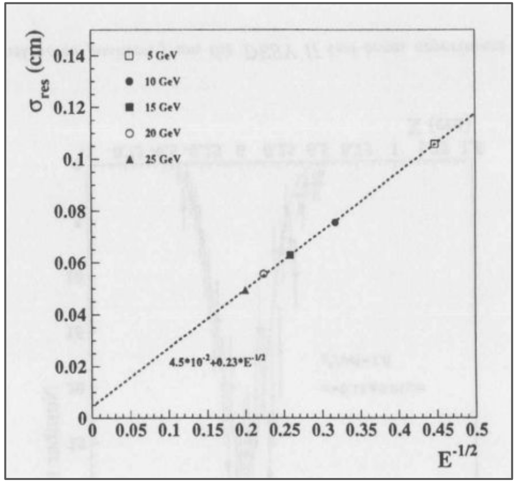
Centroid Position Resolution

	sigma_y (cm)					
Energy (GeV)/ w0	**3**	**3.5**	**4**	**4.5**	**5**	**No w0**
2	0.124	0.1338	0.1832	0.2225	0.2489	0.2193
4	0.1109	0.08525	0.09279	0.1194	0.1518	0.1574
6	0.1078	0.07729	0.06933	0.08165	0.1112	0.1305
8	0.11	0.07687	0.06106	0.06718	0.08486	0.1111
10	0.1108	0.07985	0.05759	0.05632	0.06901	0.09797
12	0.1158	0.08119	0.05378	0.04997	0.06109	0.09041
14	0.1123	0.08103	0.05212	0.04797	0.05575	0.08411
16	0.1147	0.08212	0.05101	0.04436	0.05029	0.07916
18	0.113	0.08296	0.05034	0.04112	0.04587	0.07347



- 2 GeV resolution > 1 mm & doesn't have a dip in its value for any value of W_0 .
- resolution < 1 mm for E >= 4 GeV , and
- Presence of dip in resolution for W_0 = 3.5 - 4.5, shift with increasing energy, looks like $W_0(E)$ or,
- Does this method work in lower energies ?

Centroid Position Resolution

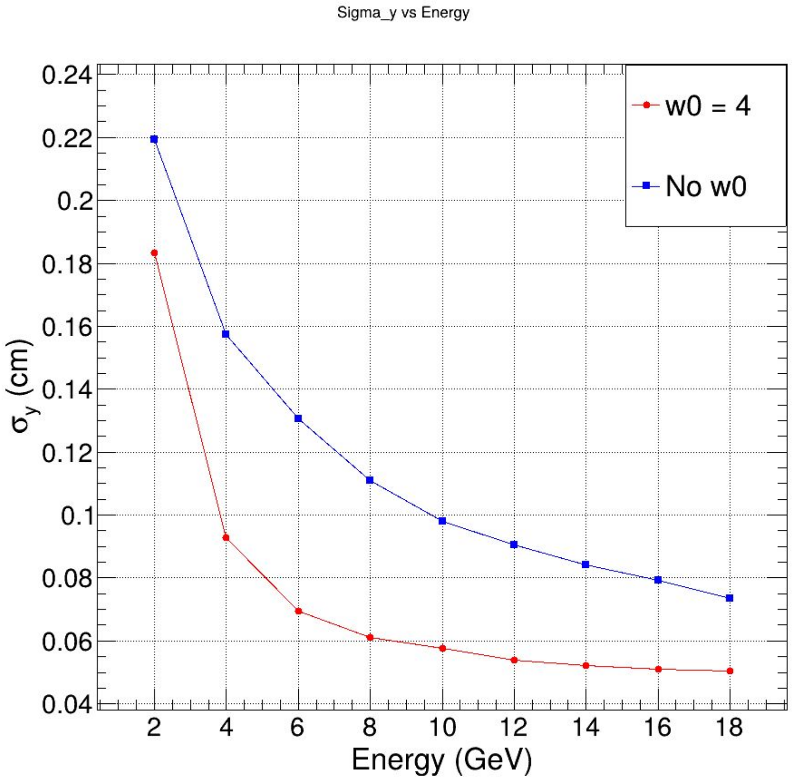


ZEUS resolution extracted for lower energies

$\sigma = 0.0045 + 0.23 \times E(\text{GeV})^{-1/2}$

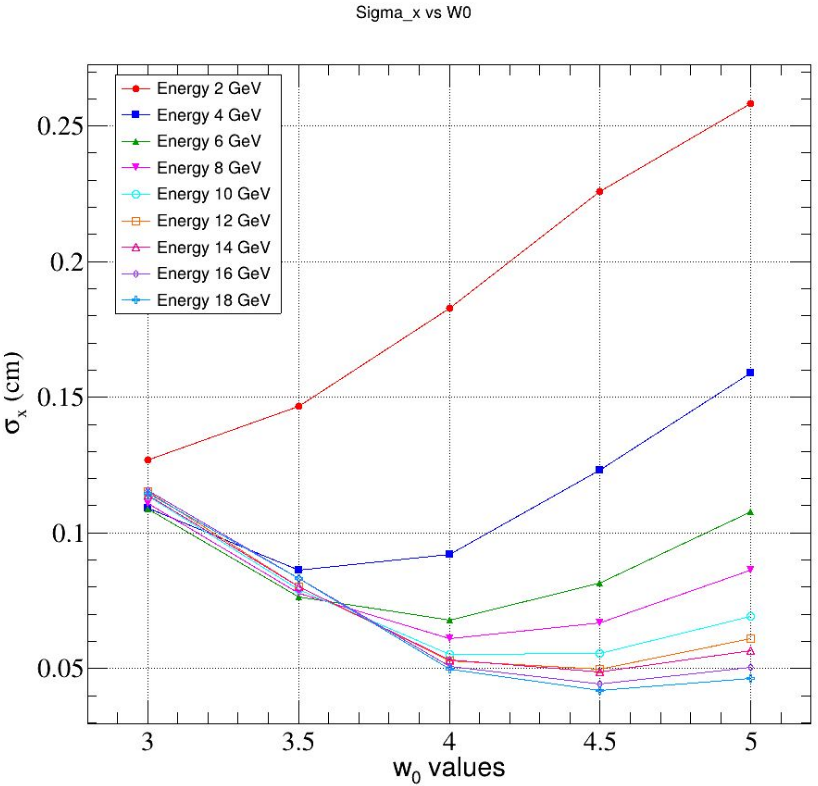
1. 2 GeV = 0.1671 cm
2. 4 GeV = 0.1191 cm

- ePIC has better resolution than ZEUS only in higher energies.
- Method 2 provides better resolution for all energies.



Centroid Position Resolution

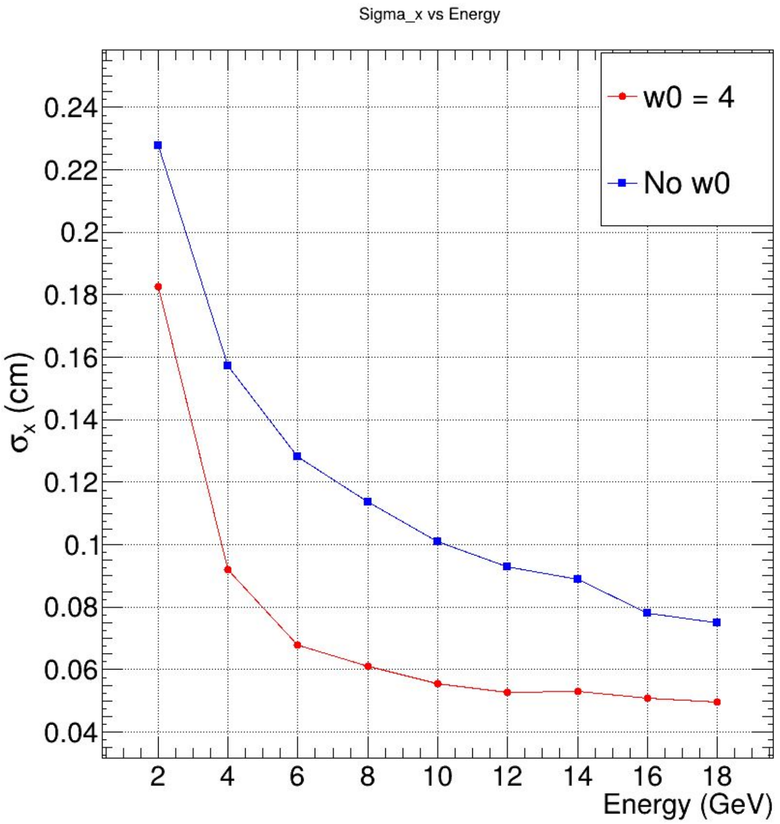
	sigma_x (cm)					
Energy (GeV)/ w0	**3**	**3.5**	**4**	**4.5**	**5**	**No w0**
2	0.1269	0.1468	0.1827	0.2258	0.2581	0.2278
4	0.1093	0.08632	0.09206	0.1231	0.1591	0.1572
6	0.1087	0.07637	0.06795	0.08133	0.1079	0.1281
8	0.111	0.07768	0.06097	0.0669	0.08619	0.1138
10	0.1135	0.07919	0.05538	0.05559	0.06914	0.101
12	0.1154	0.08029	0.05288	0.04985	0.06103	0.09303
14	0.114	0.08002	0.05311	0.04857	0.05649	0.08897
16	0.1155	0.08335	0.05086	0.04447	0.05029	0.07797
18	0.1145	0.08335	0.04962	0.04186	0.04636	0.07495



Same conclusion from x measurement.

Centroid Position Resolution

	sigma_x (cm)					
Energy (GeV)/ w0	**3**	**3.5**	**4**	**4.5**	**5**	**No w0**
2	0.1269	0.1468	0.1827	0.2258	0.2581	0.2278
4	0.1093	0.08632	0.09206	0.1231	0.1591	0.1572
6	0.1087	0.07637	0.06795	0.08133	0.1079	0.1281
8	0.111	0.07768	0.06097	0.0669	0.08619	0.1138
10	0.1135	0.07919	0.05538	0.05559	0.06914	0.101
12	0.1154	0.08029	0.05288	0.04985	0.06103	0.09303
14	0.114	0.08002	0.05311	0.04857	0.05649	0.08897
16	0.1155	0.08335	0.05086	0.04447	0.05029	0.07797
18	0.1145	0.08335	0.04962	0.04186	0.04636	0.07495



Same conclusion from x measurement.

Summary

1. Using w_0 (value close to 4) will reduce the position resolution significantly.
2. ePIC resolution using method 2 shows promising result in high energies but more study is needed for lower energies.

Last Presentation

BPC was used for PSCAL

http://www-library.desy.de/cgi-bin/showprep.pl?desy-thesis98-004

Measurement of the Proton Structure Function F_2 at Low Q^2 and Very Low x with the ZEUS Beam Pipe Calorimeter at HERA

by

B. Surrow

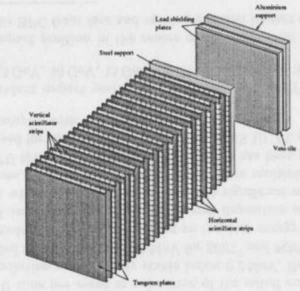
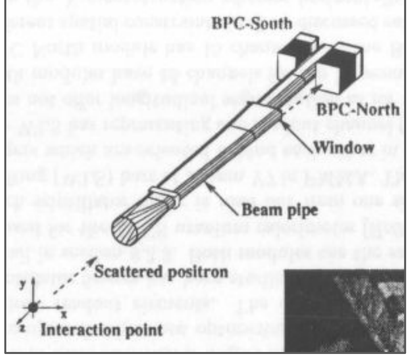


Figure 6.2: *Implementation of the BPC design within GEANT.*

The active layers of the BPC are laterally segmented into 7.9 mm-wide scintillator strips. The lateral segmentation allows to measure the energy deposition of the shower over distance intervals of 7.9 mm transverse to the shower axis. Taking all BPC readout channels together, one can then determine the centroid of the deposited energy and thus obtain an estimate of the impact position of the positron in the BPC.



Impact angle of e^- = 88^o - 90^o

BPC Specification

BPC specification	BPC performance	reference
Depth	$\simeq 24\,X_0$	5.2 and 5.4.2
Molière radius	$\simeq 13$ mm	5.2
Energy resolution	$17\%/\sqrt{E}$ (stochastic term)	8.5.4
Energy scale calibration	$\pm 0.5\%$	8.5.3
Energy uniformity	$\pm 0.5\%$	8.5.3
Linearity	$\leq 1\%$	8.5.4
Position resolution	< 1 mm	8.3.3
Intrinsic position bias	< 1 mm	8.3.3
Alignment accuracy	± 0.5 mm	5.8 and 8.3.4
Time resolution	< 1 ns	8.6

Table 5.2: *BPC performance specifications.*

Shower profile estimation along transverse side

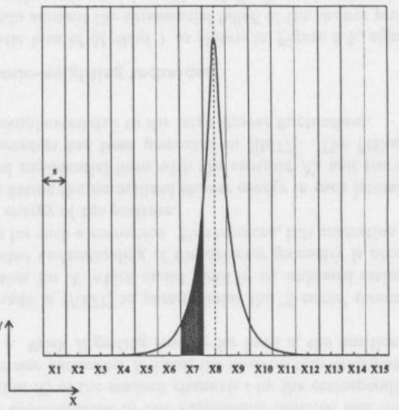


Figure 8.4: *Schematic drawing of the X-scintillator readout with an overlayed exponential lateral shower profile.*

Figure 8.4 shows schematically the X-scintillator strip readout channels ($X1$ - $X15$, $N = 15$) of the BPC North module with an exponential lateral shower profile given by equation 8.2. The width of the strips is denoted by s. X and Y are the two coordinates of the ZEUS-coordinate system describing the orientation of the X-scintillator strip readout channels.

in the scintillator strip readout channels. For that purpose, the assumption is made that the lateral shower profile dE/dX can be described approximately by one exponential function (Section 8.4). This ansatz is primarily chosen to present in a simple way the qualitative behavior of the two methods with respect to the position bias:

$$\frac{dE}{dX} = E_D(0)e^{-|X-X_0|/R} \tag{8.2}$$

where $E_D(0)$ is the energy per unit length at the impact position X_0 and R denotes the distance from the impact position X_0 for which the lateral shower profile dE/dX dropped down by a factor $1/e$. R therefore serves as a parameter to characterize the lateral shower size. It has been shown that using two exponential functions will not alter the conclusions of the following qualitative discussion.

The position resolution is of statistical nature whereas the position bias is of systematic nature. Both were studied by an EGS4 MC-simulation. In addition, an analytical approach was used to understand the position bias.

Position Measurement - Method 1

Method 1 - linear-weighting technique

One of the most straightforward techniques is to estimate the shower central position X by simply calculating the center of gravity of the shower using a linear weighting of the lateral center position X_i of the readout channels i by the corresponding measured energy E_i:

$$X = \frac{\sum_{i=1}^{N} w_i X_i}{\sum_{i=1}^{N} w_i} \qquad w_i = E_i \tag{8.4}$$

Using equation 8.3 and 8.4 together with the lateral shower profile given in equation 8.2, one then finds a simple expression for the measured position X as a function of the true position X_0 of the positron in the BPC:

$$X = \left(\frac{s}{2}\right) \frac{\sinh(\frac{X_0}{R})}{\sinh(\frac{s}{2R})} \tag{8.5}$$

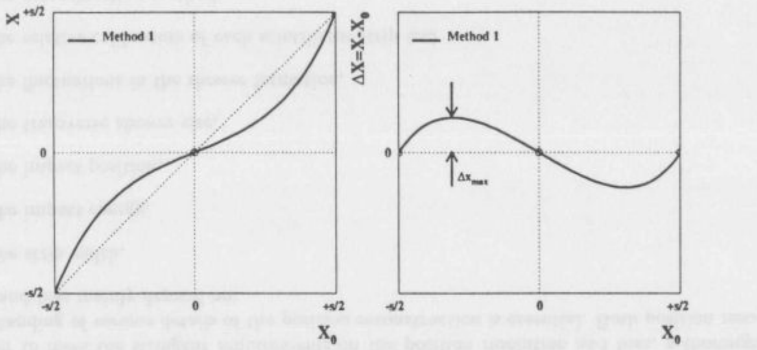


Figure 8.5: *Bias between the measured position X as a function of the true position X_0 for Method 1 (linear-weighting method).*

Position Measurement - Method 2 - Solution to the Bias problem from Method 1

within a calorimeter which is similar to those methods presented in [Ak77]. The position measured using the lateral segmented BPC readout employing this method is then given as follows (Method 2):

$$X = \frac{\sum_{i=1}^{N} w_i X_i}{\sum_{i=1}^{N} w_i} \tag{8.7}$$

where

$$w_i = \begin{cases} W_0 + \ln(\frac{E_i}{E}) & (\frac{E_i}{E}) > e^{-W_0} \\ 0 & (\frac{E_i}{E}) \leq e^{-W_0} \end{cases} \tag{8.8}$$

and

$$E = \sum_{i=1}^{N} E_i \tag{8.9}$$

8.8 contain W_0 as a free parameter. It has to be determined by optimizing both the position resolution as well as the position bias as discussed in the previous section. The existence of a simultaneous optimum value of W_0 on the position resolution as well as the position bias can be understood from the definition of w_i. The possible range of W_0 is as follows: $W_0 \in \,]0, \infty[$. For $W_0 \to \infty$, all laterally segmented readout channels are included in the determination of the measured position since $e^{-W_0} \to 0$. The position bias is expected to vanish and the position resolution to worsen.

In case of $W_0 \to 0$, only the most energetic readout channels are included in the position reconstruction since $e^{-W_0} \to 1$. Therefore, only a few readout channels dominate the position reconstruction. The position bias will increase. This can be understood by looking at two extreme cases of the impact position, namely first in the center of a scintillator strip and second between two adjacent strips. For $W_0 \to 0$, the actual number of strips being included in the position reconstruction changes in a discrete way from two for an impact position between two strips to one for an impact position in the center of one strip. This leads to a significant position bias when moving the impact position from one to the other of the two extreme points.

Position Measurement - Method 2- Choice of W_0

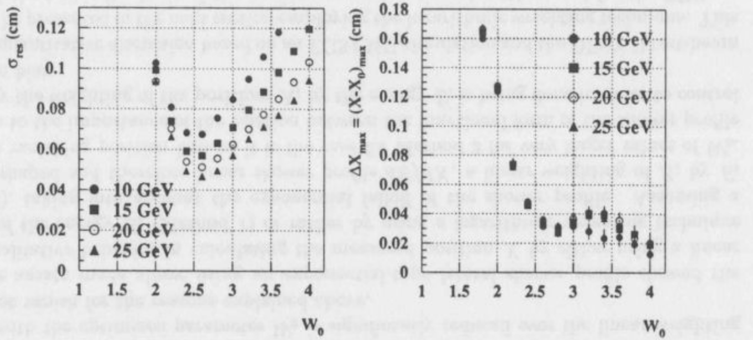


Figure 8.7: *Position resolution σ_{res} (left) and maximum position bias ΔX_{max} (right) as a function of W_0 using an EGS4 MC-simulation.*

of $W_0 = 2.8$. For the linear weighting method, the position resolution is about 30% larger compared to the logarithmic weighting method using $W_0 = 2.8$.

Position Resolution from MC and TestBeams of ZEUS PS CAL

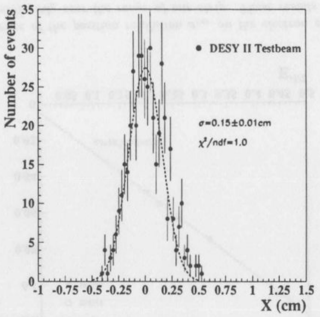


Figure 8.11: *Reconstructed position from the DESY II test-beam experiment with 5 GeV electrons.*

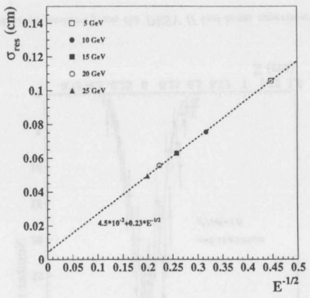


Figure 8.13: *Dependence of the position resolution σ_{res} on the electron energy. The impact position was chosen uniformly over the range of one strip. These results have been obtained from an EGS4 MC-simulation.*

Position resolution results from the DESY II test-beam

Using the LUMI scintillator-finger counter in the DESY II test-beam experiment, the transverse size of the electron test-beam was restricted to 0.75 mm. Figure 8.11 shows the reconstructed position obtained from 5 GeV-test-beam electrons. The mean reconstructed value has been subtracted from each reconstructed position. The value for σ of the Gaussian fit, together with the beam width of $\sigma_{\mathrm{beam}} = 0.75$ mm, allows an estimate of the intrinsic position resolution of the BPC, σ_{BPC}, for 5 GeV test-beam electrons. The relation between them is given as follows:

$$\sigma = \sqrt{\sigma_{\mathrm{BPC}}^2 + \sigma_{\mathrm{beam}}^2} \qquad (8.10)$$

One obtains a value for σ_{BPC} of 0.13 cm. The mean of the impact position lies in the center of one strip. An EGS4 MC-simulation was used to compare the position resolution between the DESY II test-beam and the simulation. The impact position, and therefore the mean of the reconstructed position, has been chosen for the EGS4 MC-simulation as well to be in the center of one strip. The position resolution of the EGS4 MC-simulation is equal to 0.13 cm and therefore the same as the one obtained from the DESY II test-beam result.

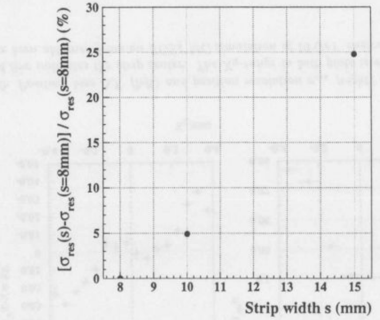
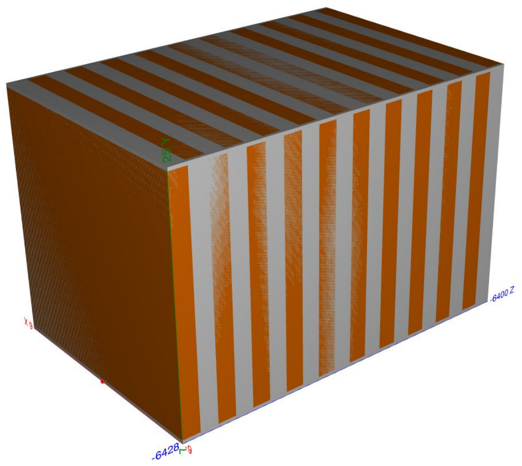
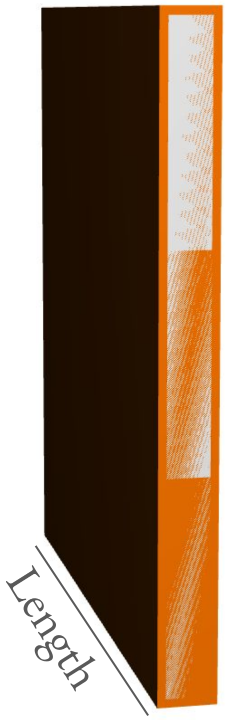


Figure 8.14: *Percent deviation of the position resolution with respect to the position resolution of 8 mm scintillator strips, as a function of the respective strip width. These results have been obtained from a simulation of 10 GeV electrons using an EGS4 MC-simulation.*

Current Design of PSCAL (DD4hep implementation ref : https://github.com/eic/epic/tree/aranya)



2 CALs (up & dw) with 20 layers
Alternating layers with Fiber parallel to X or Y.

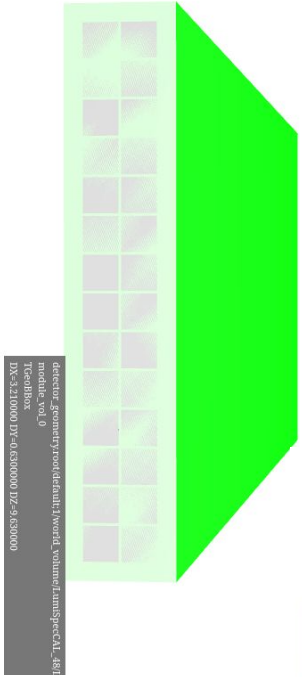


Layer

- 3 modules,
- Layer Coating with plastic = 0.25 cm (For SiPM holders)
- Width = 1.4 cm
- Height = 3*(6.06) + 0.25*2 = 18.68 cm
- Length = 3*(6.06) = 18.18 cm

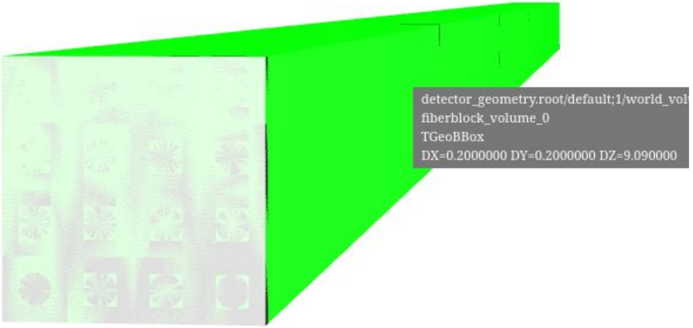
Design : Nick, Alex, Stephen, Aranya

Current Design of PSCAL



Module

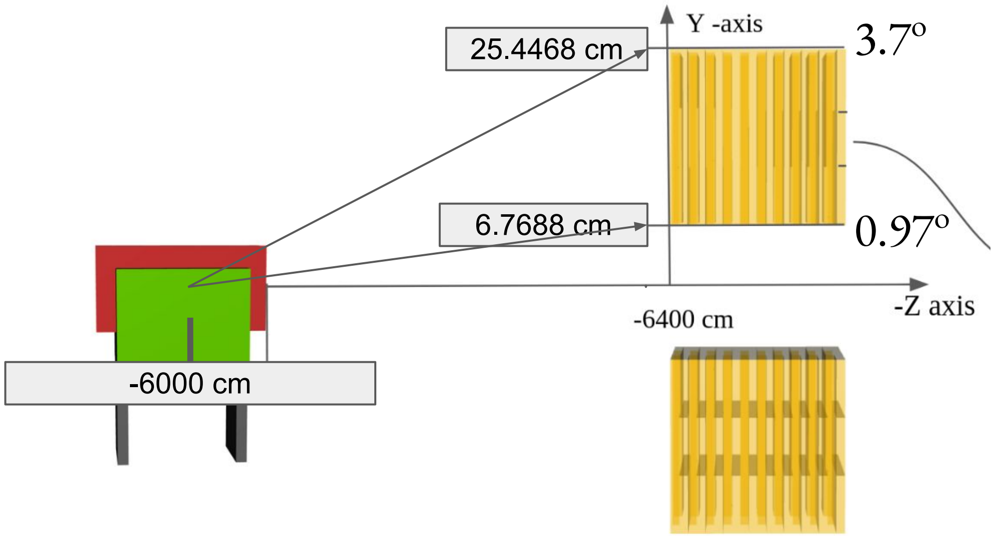
- 14x2 SiPM blocks (0.4 cm)
- Each SiPM center to center is separated by 0.03 cm
- Module coating with tungsten = 0.02cm (construction)
- Width = 2*(0.4 + 0.03) + 0.02*2 = 0.9 cm
- Height = 3*(0.4 + 0.03) + 0.02*2 = 6.06 cm
- Length = length of layer



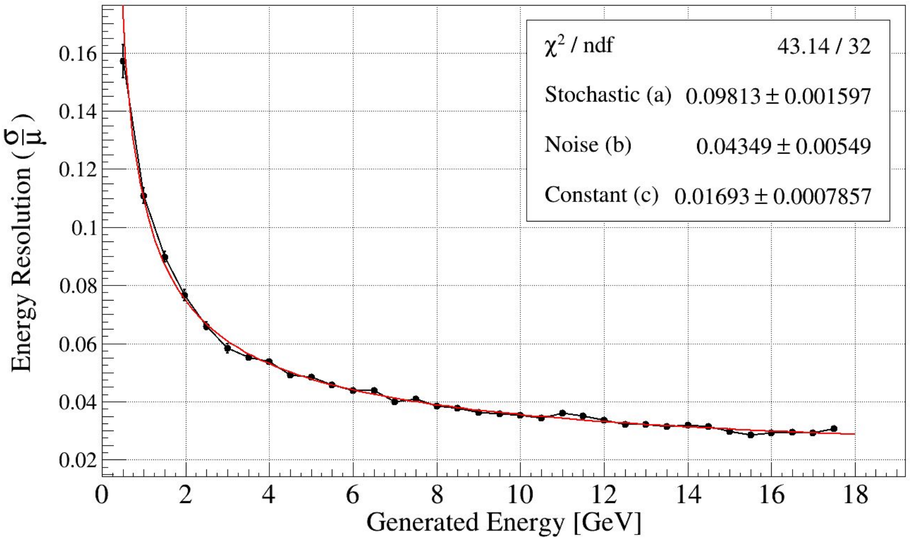
SiPM Block

- 4x4 ScFi
- ScFi Radii = 0.025cm
- ScFi CtoCenter Sepearation = 0.05 cm
- Length of fiber = length of layer

Impact Angle for PS luminosity detector



Energy Resolution with Current Design of PSCAL



9.8% / √E compared to 17/ √E ZEUS PSCAL

ZEUS PSCAL photon position reconstruction

The total energy of the electron was

$$E_e = E_x + E_y. \qquad (2)$$

The position coordinates were calculated using linear energy-weighted means over the deposited energy. For the upper calorimeter, the internal x-coordinate for the shower, x_e^{up}, was obtained from[3]

$$x_e^{up} = \frac{\sum_{x\text{-strips}} X_i \varepsilon_i^x S_i}{\sum_{x\text{-strips}} \varepsilon_i^x S_i} \qquad (3)$$

where X_i is the known central location of the ith channel strip within the calorimeter. Only channels above a threshold energy of 60 MeV were used for these sums. The x-position in the spectrometer coordinate system for the electron in the up detector is given by

$$x_{up} = x_e^{up} + \Delta x^{up} \qquad (4)$$

where Δx^{up} is the known alignment offset relative to the coordinate system of Fig. 1 for this calorimeter. The shower y-coordinate, y_{up}, was obtained similarly.

The energy of the photon is

$$E_\gamma = E_{up} + E_{dn}. \qquad (5)$$

The transverse x-position of the photon is

$$x_\gamma = \tfrac{1}{2}[x_{up} + x_{dn}] \qquad (6)$$

and the transverse y-position (bend plane of magnet) is

$$y_\gamma = \frac{E_{up} y_{up} + E_{dn} y_{dn}}{E_{up} + E_{dn}}. \qquad (7)$$

The energy weighting in the last equation arises because the magnet imparts equal transverse momentum to each electron.

1. ePIC PSCAL is more segmented in transverse area (nearly twice).
2. ePIC PSCAL has more energy resolving power (nearly twice).

ZEUS PSCAL photon position reconstruction

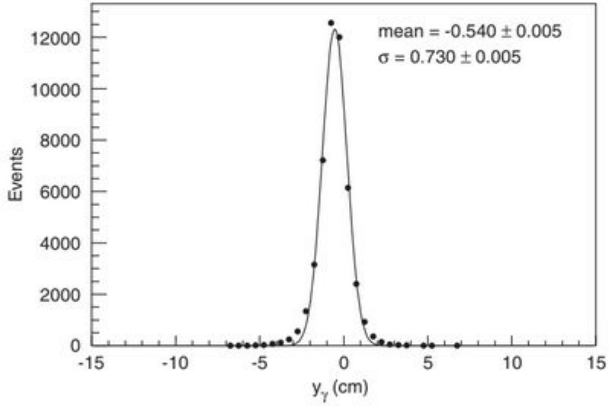


Fig. 17. The spectrum of reconstructed y_γ-positions with the slit collimator inserted into the beamline. Note that the mean of the spectrum is consistent with the offset of the slit collimator centroid.

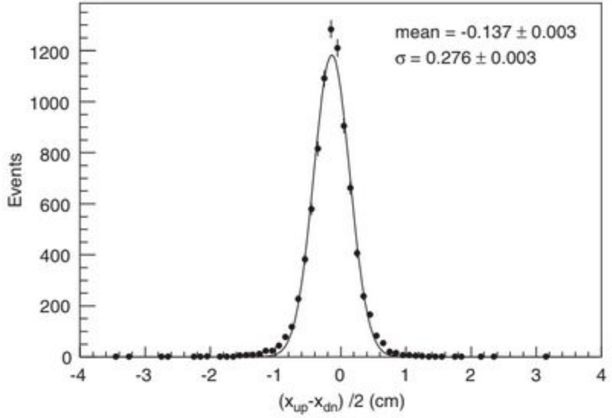


Fig. 16. Half the difference between x-coordinates measured in up and down calorimeters. This is a direct measure of the resolutions on x_γ.

1. ePIC PSCAL is more segmented in transverse area (nearly twice).
2. ePIC PSCAL has more energy resolving power (nearly twice).

Next Week Update -

Currently Some technical faults in y-pos measurement in new design.

1. Position resolution of latest design (by Linear Fit method and energy weighted method)

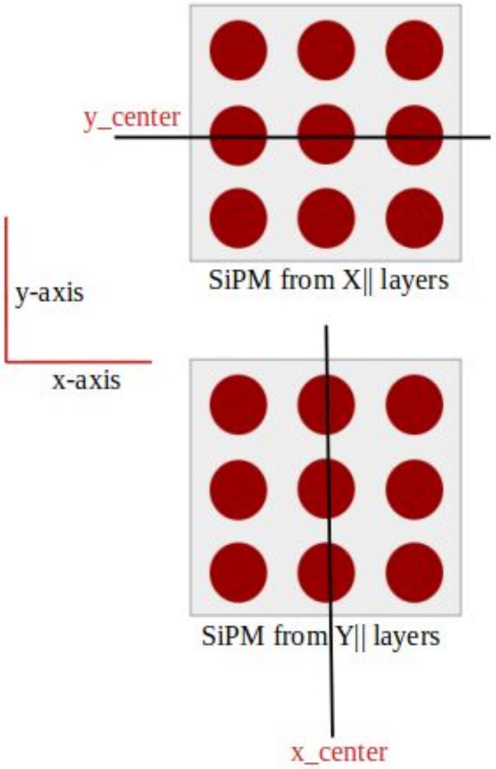
Old Design Results (3x3 SiPM) - Linear Fit Method

- Energy deposition (Edep_i) in 9 fibers of each SiPM is associated with a position, pos_i where i = {SiPMs}

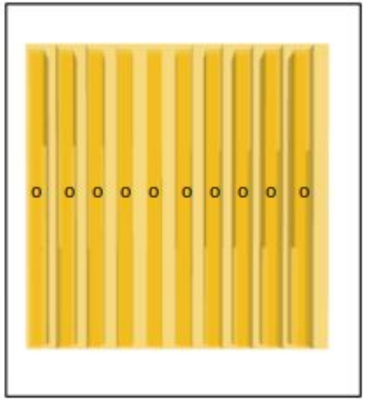
- The center of SiPM is the associated position , Pos_i = { x_center or y_center } depending on layer.

- For a slice say j, in Suppose X|| layers, the mean y_j is
- Find the mean position in each slice

$$y_j = \frac{\sum_i^{i \in j} y_i E_{dep}^i}{\sum_i^{i \in j} E_{dep}^i}$$

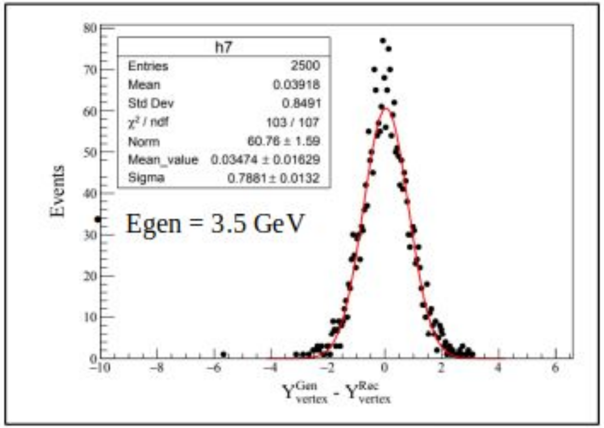


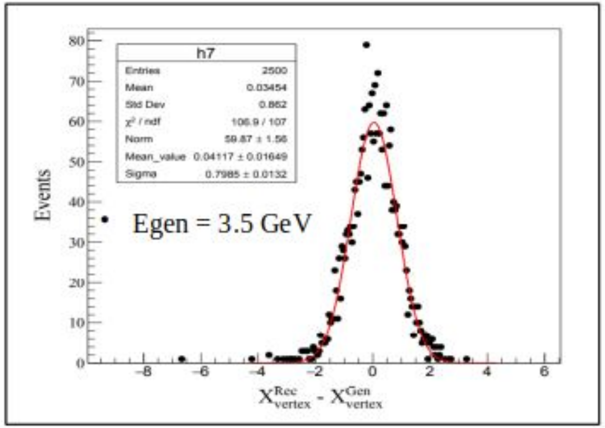
$$\bar{t} = \frac{\sum_j^{j \in slices} t_j E_{dep}^j}{\sum_j^{j \in slices} E_{dep}^j} \qquad t \in y, z$$

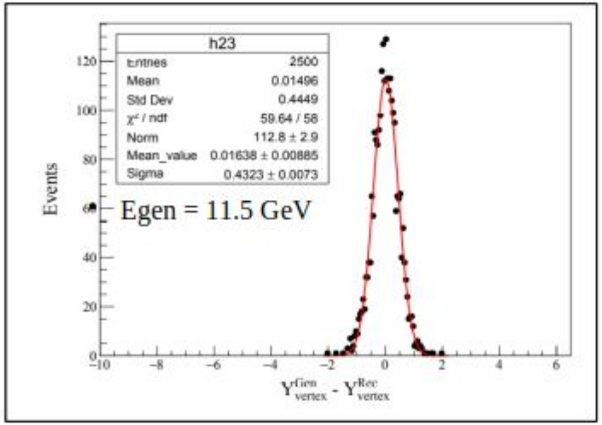


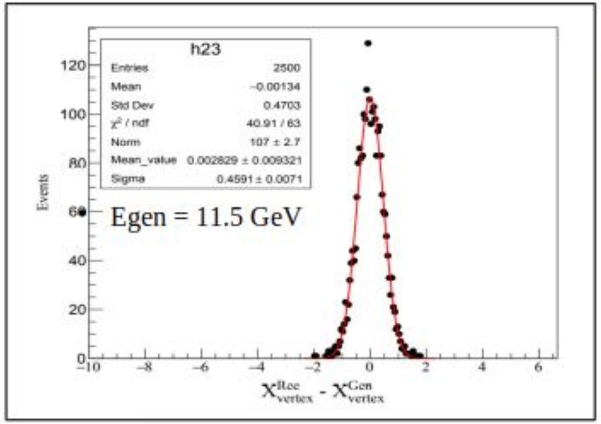
$$m = \frac{\overline{yz} - \bar{y}\bar{z}}{\overline{z^2} - \bar{z}^2}$$

Old Design Results





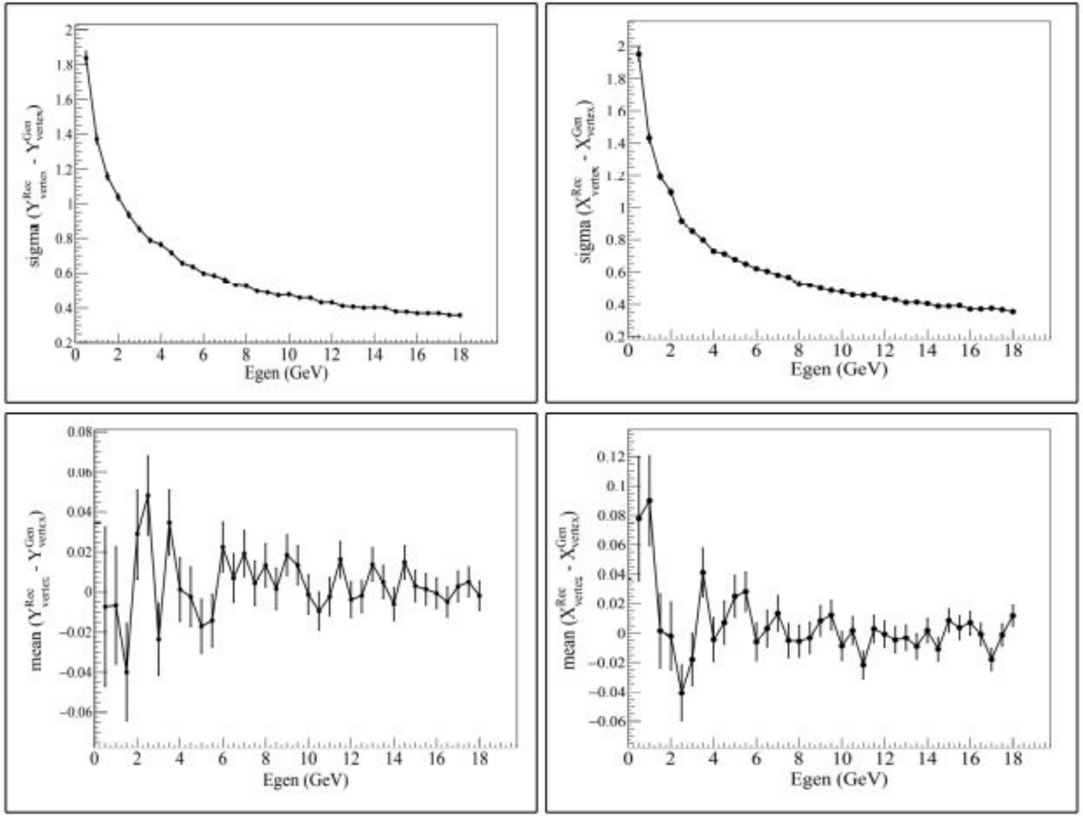




1) For each generated energy (1.0, 18.0) GeV, the (reconstructed – generated) vertex distribution is fitted with Gaussian distribution.

2) The fit parameters,
   i. sigma is used to calculate position resolution.
   ii. Mean ideally should be equal to zero but deviations was observed.

Old Design Results



- Both x or y resolution is inversely proportional to energy of incident particle.
- Position resolution increases as the energy increases.

- The mean should ideally be 0 but for both x & y shows max deviation of about 0.06 cm.