# FCAL Test Beam Data and Geant4 Simulations

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On behalf of the FCAL collaboration

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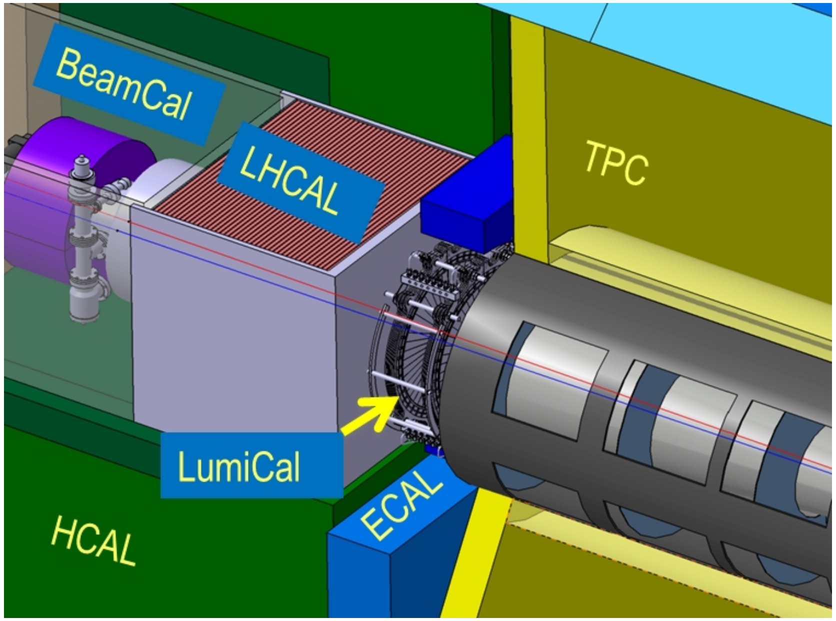
# Outline

- Introduction
- Beam test design in simulations
- Electromagnetic shower study in transverse plane
- Test beam design in simulations
- Calibration of the compact LumiCal prototype
- Clustering algorithms and position reconstruction
- Summary

# LumiCal in LC Experiments

**Goals:**

- Precise integrated luminosity measurements;
- Extend a calorimetric coverage to small polar angles. Important for physics analysis.



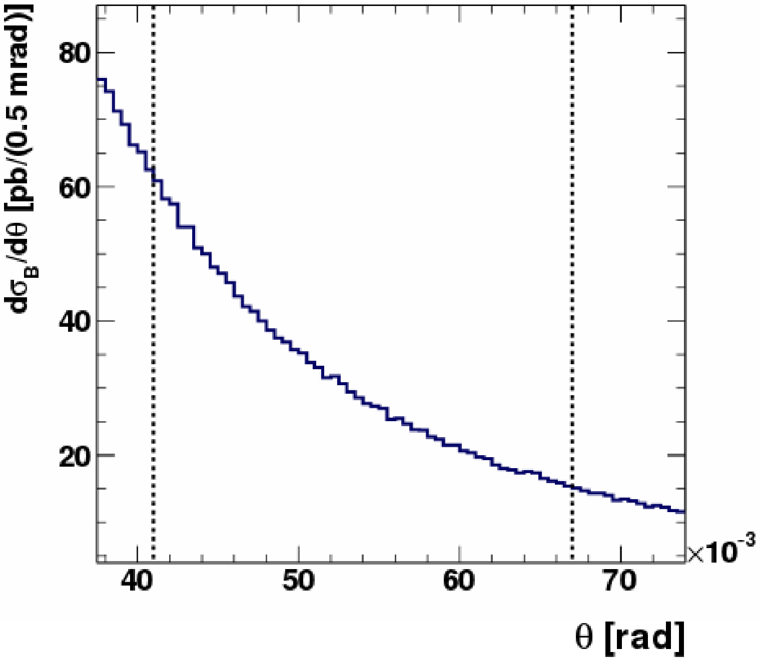

**LumiCal Design:**

- Electromagnetic sampling calorimeter;
- 30 layers of 3.5 mm thick tungsten plates with 1 mm gap for silicon sensors;
- symmetrically on both sides at ~2.5m from the interaction point.

**Luminosity measurement:** $L = \frac{N_B}{\sigma_B}$

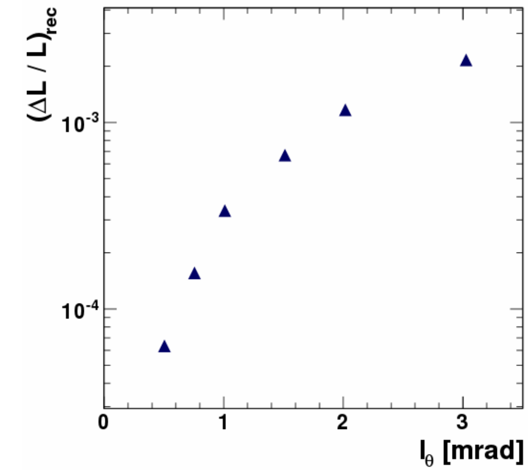
$N_B$ – Bhabha events in a certain polar angle (θ);

$\sigma_B$ – integral of the differential cross section over the same θ range.



# LumiCal Geometry

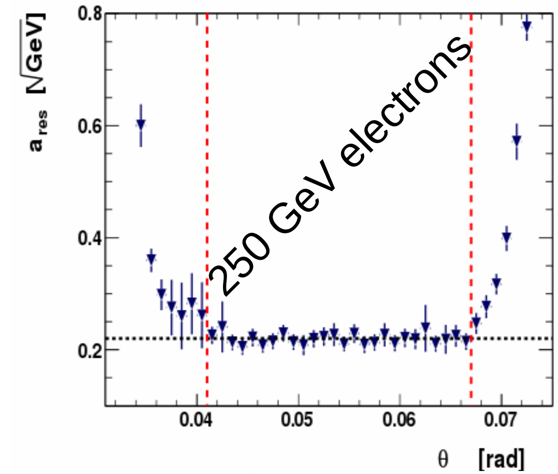
Uncertainty in luminosity measurement depends on the polar angle bias $\Delta\theta$ and minimum polar angle $\theta_{min}$ as:




$$\left(\frac{\Delta L}{L}\right)_{rec} \approx 2\frac{\Delta\theta}{\theta_{min}}$$

$\Delta\theta$ depends on polar angular pad size $l_\theta$.

For $l_\theta$=0.8 mrad, $\Delta L/L = 1.6\cdot10^{-4}$.

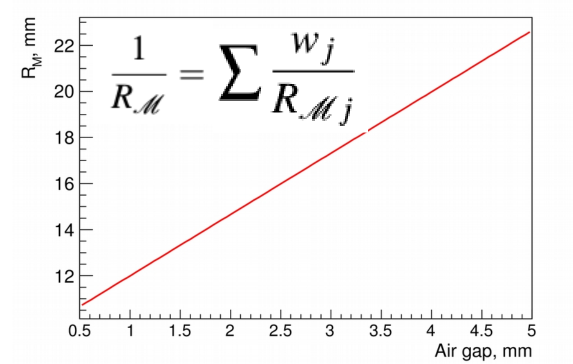



Energy resolution: $$\frac{\sigma_E}{E} = \frac{a_{res}}{\sqrt{E_{beam}\ (GeV)}},$$

$a_{res} = (0.21\pm0.02)\ \sqrt{GeV}$.

LumiCal fiducial volume: $41 < \theta < 67$ mrad

$R_M$ as function of the air gap between 3.5 mm thick tungsten plates



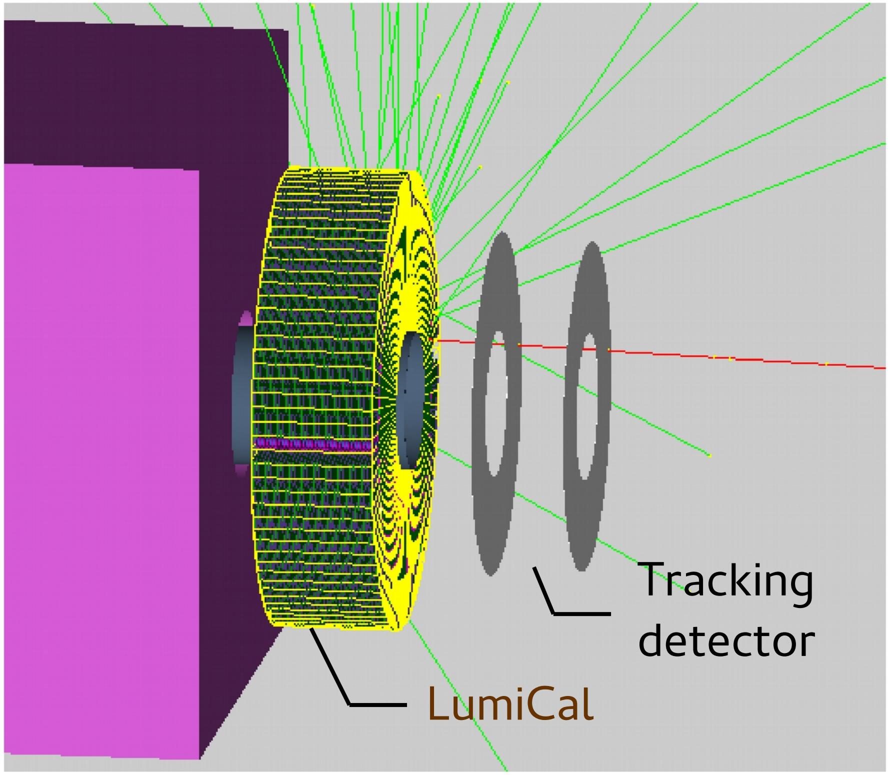

Reducing air gap from 4.5 mm to 1 mm gives $R_M$: 21 mm -> 12 mm.

# Tracking Detector in Front of LumiCal

- Improve polar angle measurement accuracy;
- LumiCal alignment;
- Provide more information to enable e/γ identification, important for various physics studies, e. g. photon structure function study,  important for BSM searches.

## Studied in Simulations

- Modified versions of LuCaS (Geant4 app. For LumiCal simulation);
- Two layers of Si sensors with different thickness and distance to LumiCal;
- No negative affects on reconstruction in LumiCal;
- High efficiency of e/γ identification for tracker with submillimeter position resolution for single e or γ event.




Study e/γ identification in beam test

# Shower Study in Transverse Plane

Electromagnetic shower development was studied in LumiCal prototype in 2014 beam test at CERN (PS, 5 GeV e- beam)

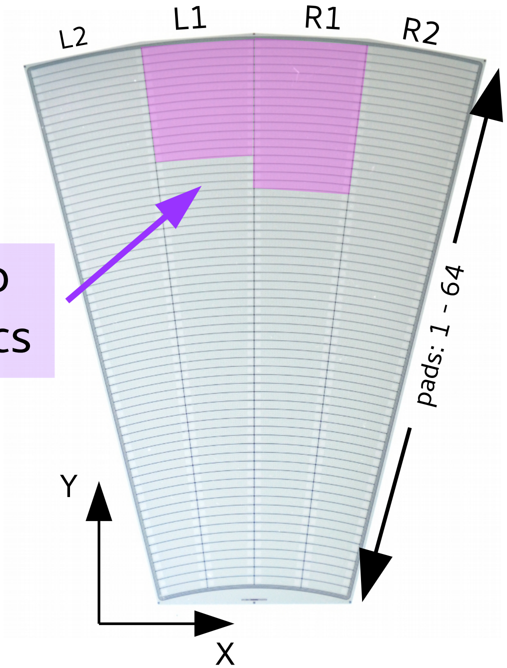
**LumiCal prototype:**

- 4 detector planes with 2 x 3.5 mm tungsten absorber plates between each two;
- Extra 1 (2, 3) absorbers installed in front.

**LumiCal sensor:**

- Si, thickness 300 µm;
- 4 sectors, 64 radial pads, pitch 1.8 mm;
- Inner(outer) radii: 80 mm (195.2 mm).

Area connected to readout electronics



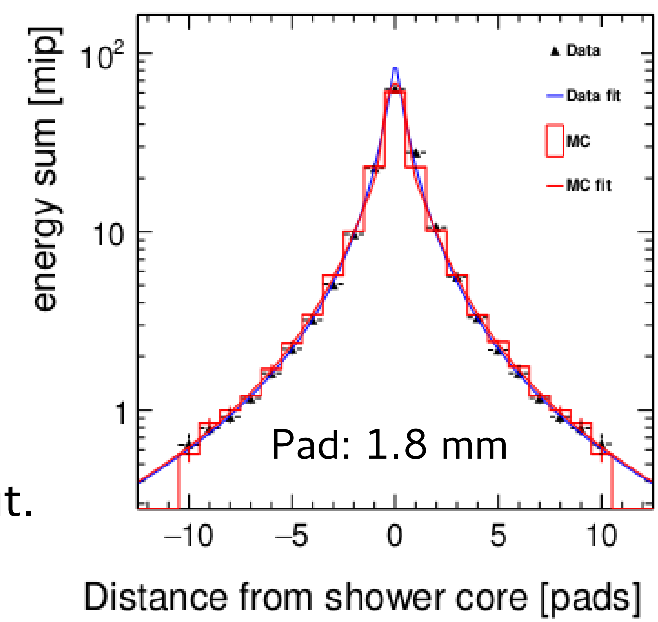

Consider $F_E(r, \{p_i\})$ - average distribution of deposited energy in transverse plane; $r=\sqrt{x^2+y^2}$

$\{p_i\}$ – fitting parameters.

$$G_E(y) = \int_{X_{min}}^{X_{max}} F_E(\sqrt{x^2+y^2})dx$$

$\{Xmin\ , Xmax\ \}$ correspond to the area connected to readout.

$p_i$ are found by fitting $G_E(y)$ to MC and data.



# Shower Development in Transverse Plane

Assuming $F_E(r, \{p_i\})$ normalized to unity,
Moliere radius $R_M$ can be found from the equation:

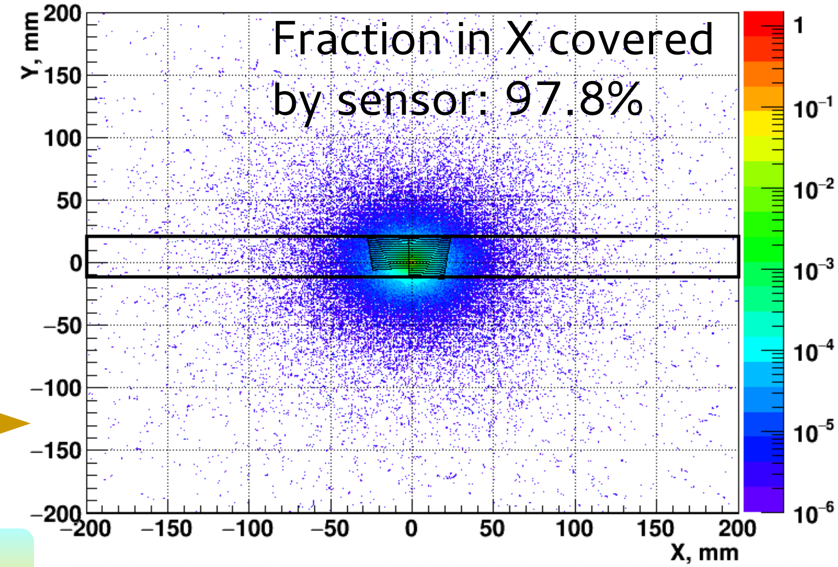
$$0.9 = \int_0^{2\pi} d\varphi \int_0^{R_{\mathscr{M}}} F_E(r) r dr$$

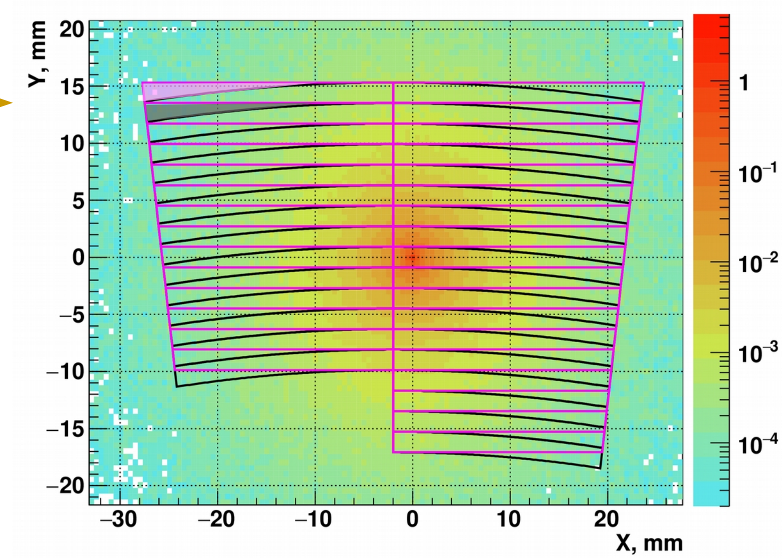
Systematic uncertainty of Moliere radius measurement were evaluated using simulations:

- Calorimeter with transverse size 40 x 40 cm$^2$;
- The same longitudinal structure;
- Sensor granularity 0.5 x 0.5 mm$^2$;

Detailed $F_E(r)$

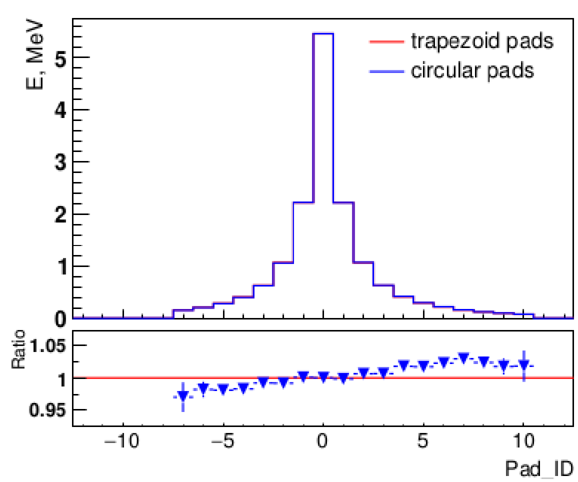
Transverse average deposited energy




Integrating $F_E(r)$ over studied areas (LumiCal sensor pads, strips, etc.) following systematic effects were studied:

- Range: Xmin, Xmax;
- Normalization range;
- Pads shape.




Resulting in ±1.5 mm

Effect of neglecting circular shape: below 2%

arXiv:1705.03885

# Thin Module Beam Test Goals

**DESY test beam facilities:**

- Electron beam 1 – 6 GeV;
- Dipole magnet 1 – 13 kGs;
- EUTelescope with 6 planes of Mimosa26 detectors;

**Performance of the compact LumiCal prototype:**

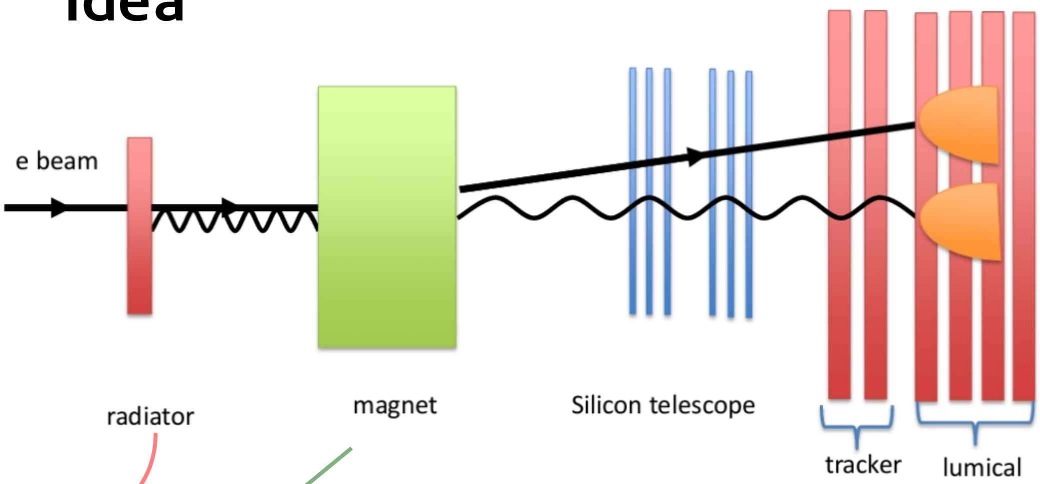
- Detector modules performance: noise, saturation, S/N, etc;
- Energy response to $e^-$ beam of 1 – 6 GeV;
- Electromagnetic shower development study, Moliere Radius measurement.

**e/γ identification with tracking detector in front of LumiCal:**

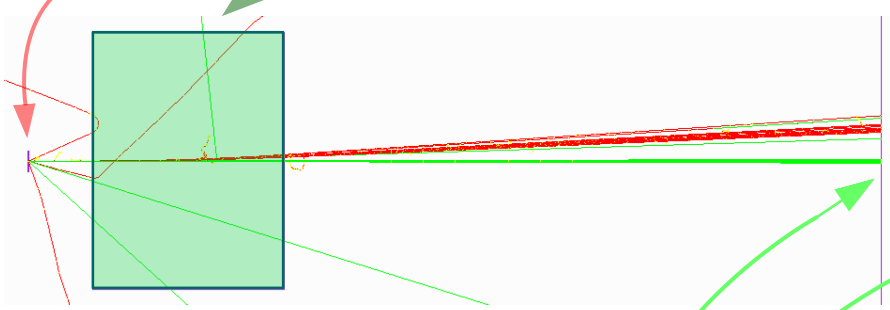
- Back scattering as a function of distance from LumiCal;
- Identification efficiency.

# Test-beam Design

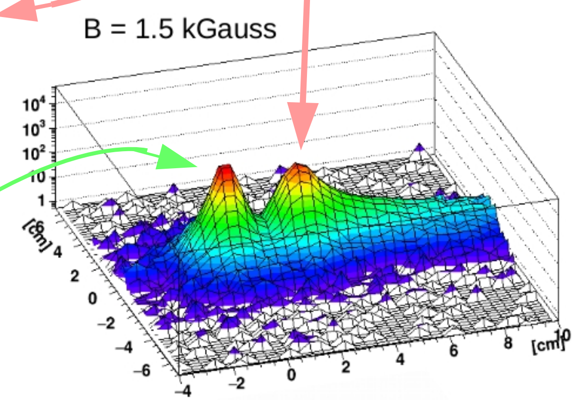
## Idea



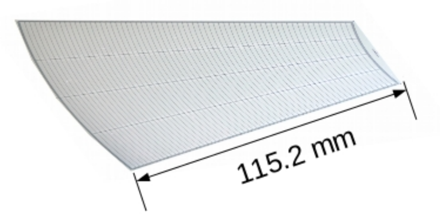

Electrons



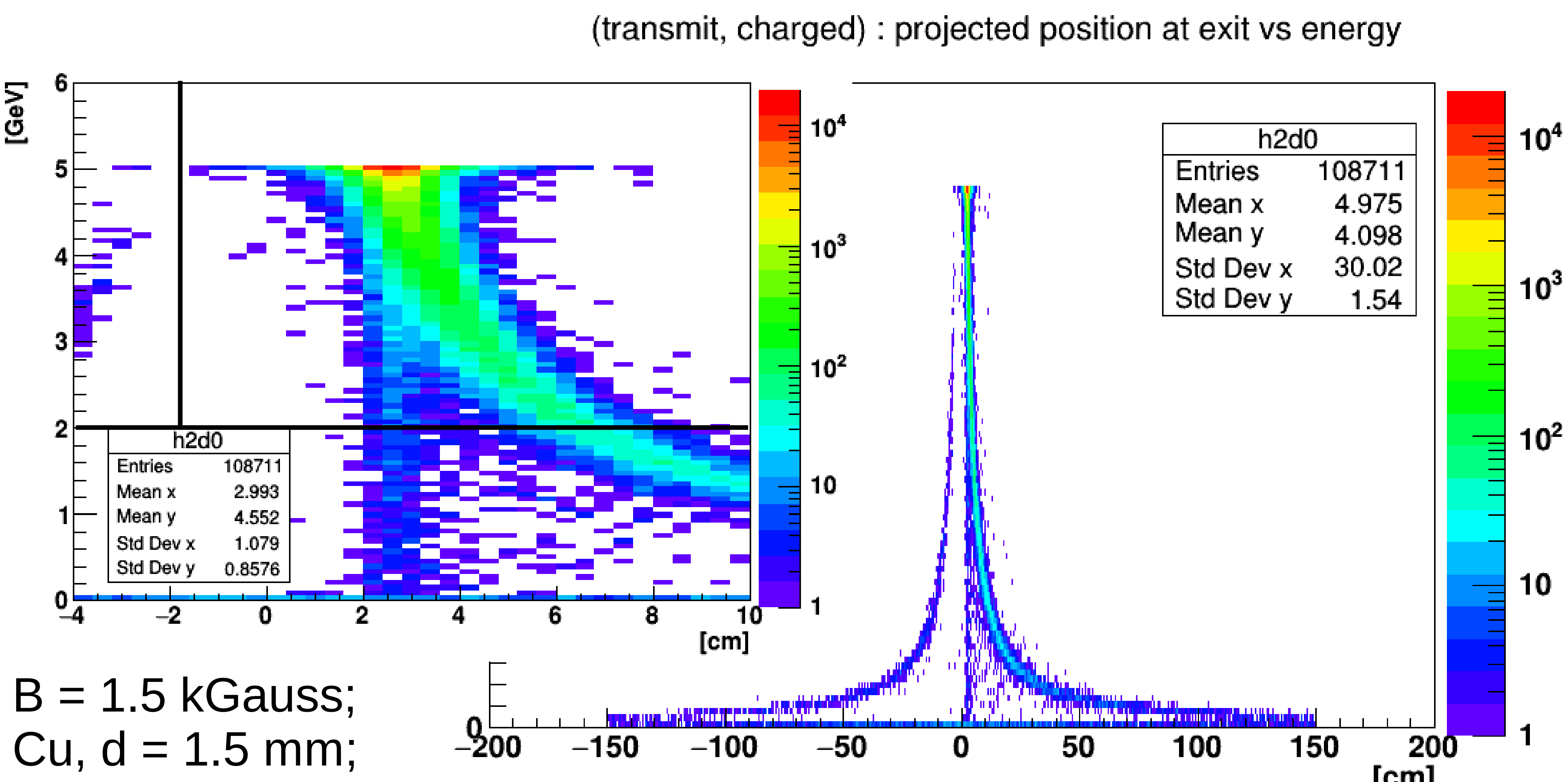
**Geant4 simulation**




Photons



# Electron Position vs Energy

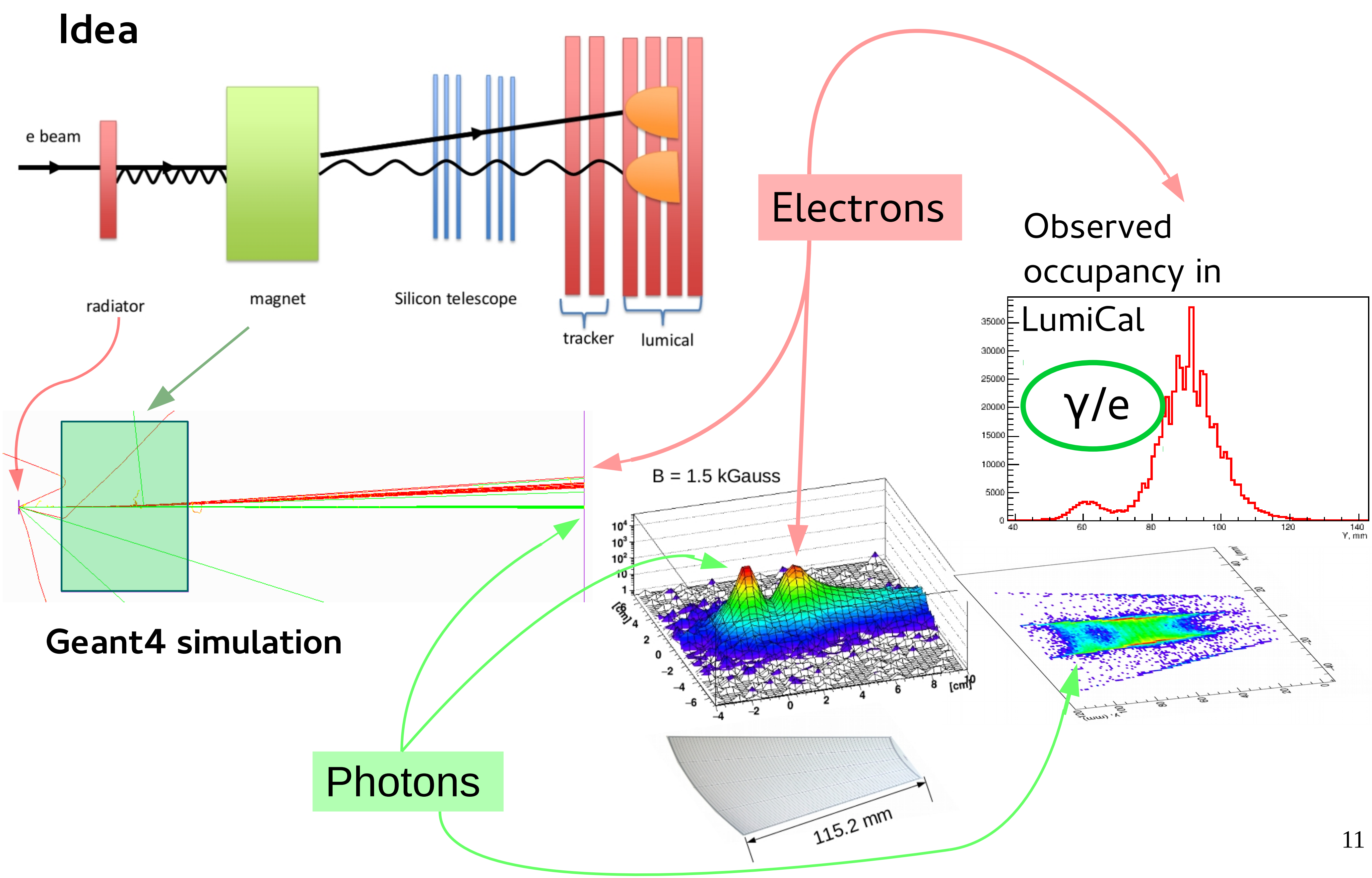



B = 1.5 kGauss;
Cu, d = 1.5 mm;
Distance from the magnet to LumiCal ~3 m.

| | | | |
|---|---|---|---|
| Electron energy in the range | 2 GeV – 5 GeV | : | 86% of events |
| | 3 GeV – 5 GeV | : | 82% of events |

| | | |
|---|---|---|
| 2 GeV – 4 GeV | : | 10% |
| 3 GeV – 4 GeV | : | 6.6% |

# Test-beam Design



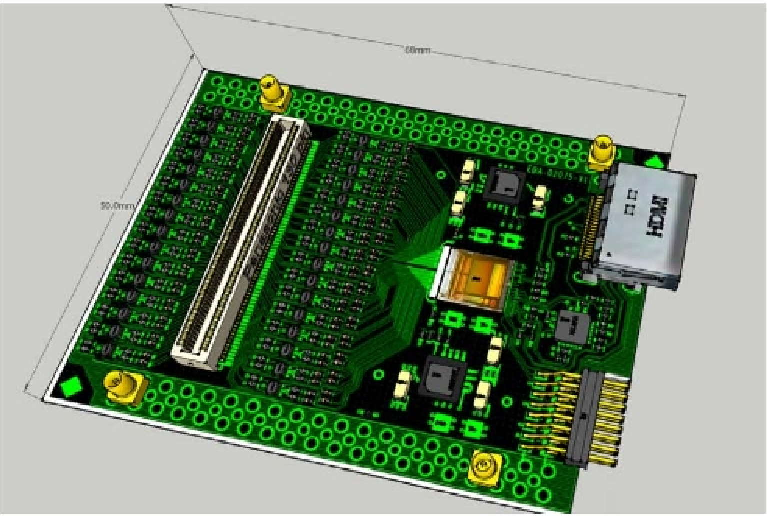
# Saturation in Readout with SRS and APV-25

Next generation of LumiCal electronics is under development and will be available in 2017.

Temporary alternative solution:

Front-end chip APV25:

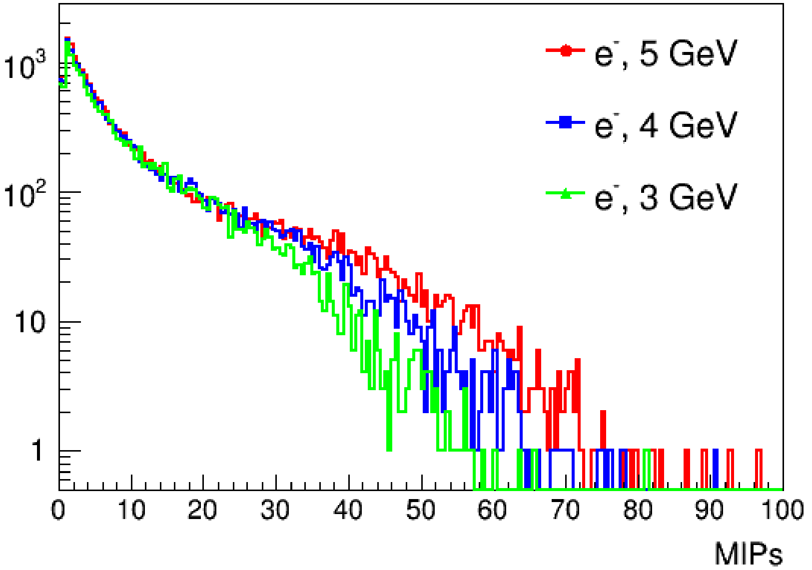
- Designed for CMS silicon microstrip detectors (used for Belle II SVT);



Front-end board (hybrid) with APV25 chip

The APV-25 range in case of LumiCals sensor: ~ 8 MIPs

Simulated energy deposition in single sensor pad in 5-th layer (after $5X_0$).




Additional circuit: "charge divider" - were designed and produced:

Parameters were optimized in simulations:

- Small division - big loss in few pads in shower core;
- Large division - loss in big number of pads in periphery of the shower because of noise;

# Identification of Particle Signal with Neural Network

Signal with time response function of CR-RC filter:

$$V(t) = A\frac{t - t_0}{\tau}e^{\frac{-(t-t_0)}{\tau}}$$

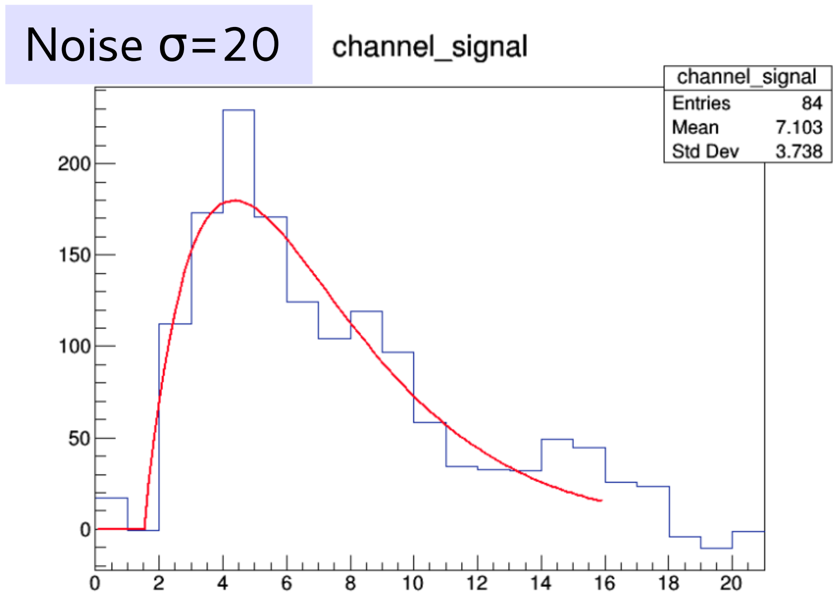
$\tau$, and $t_0$ are known parameter of the readout

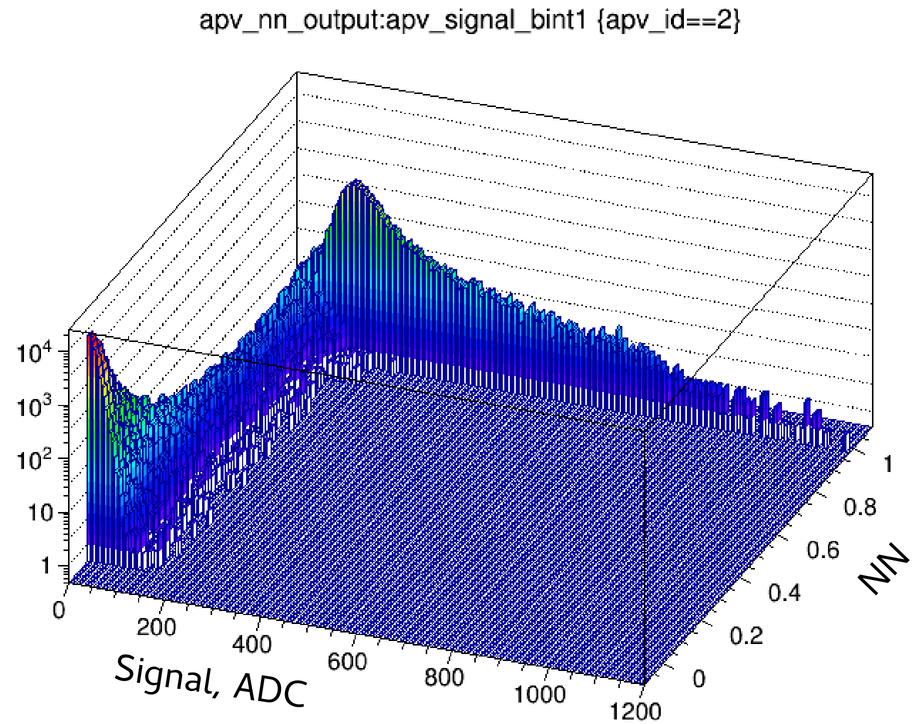
**<u>Neural network is tested to identify the signal in raw data:</u>**

- Input layer 21+1 nodes, one hidden layer with 10+1 node;
- Regularization;
- Training set is generated using the formula with random amplitude and noise generated from Landau and Gaussian distributions respectively.

Some specific noise patterns were revealed to be included in training set

NN demonstrates excellent signal identification in noisy environment

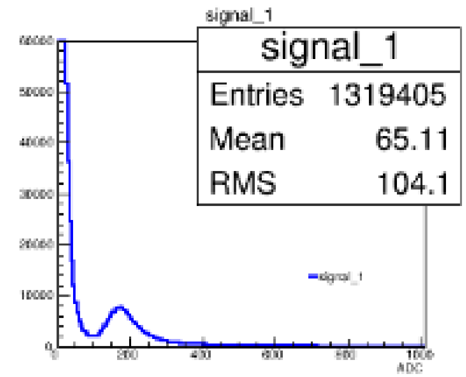


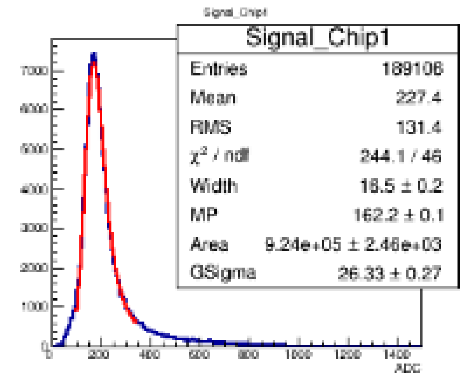
# LumiCal Energy Response

Cosmic muon events are collected for calibration.

No cuts

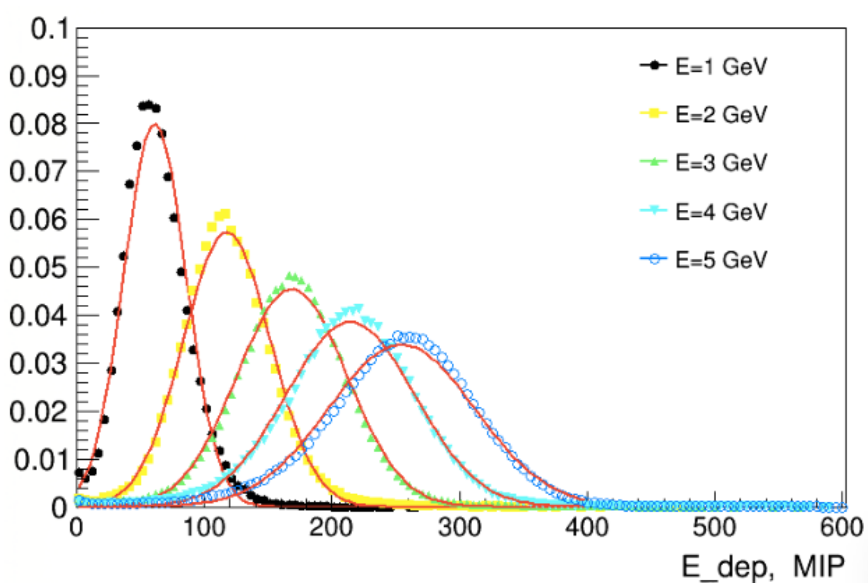


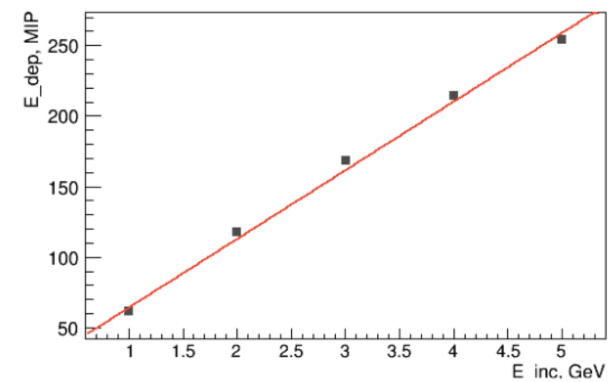

NN cut

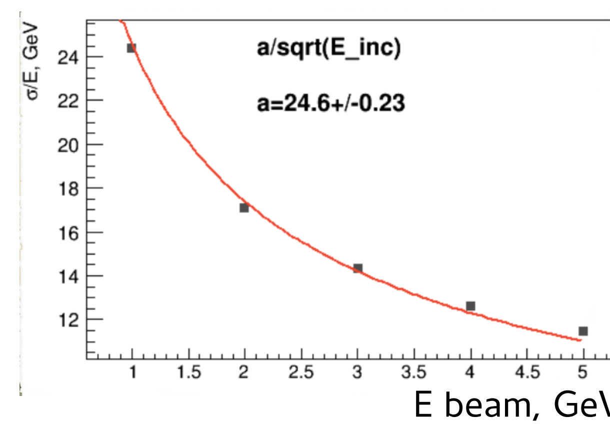



Energy deposited in LumiCal sensor by cosmic muon (ADC)

LumiCal response
when running with charge divider

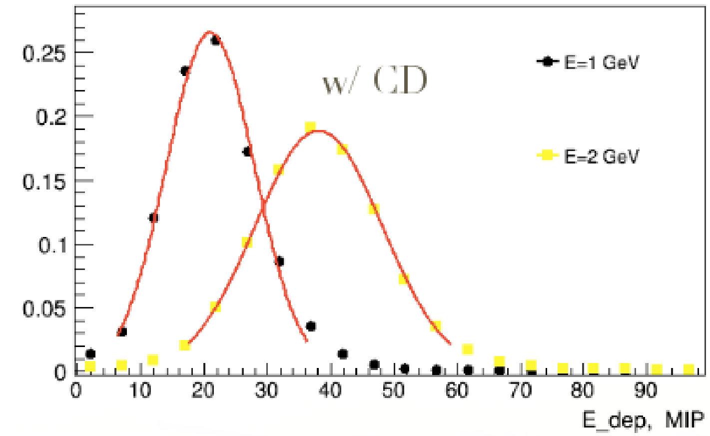


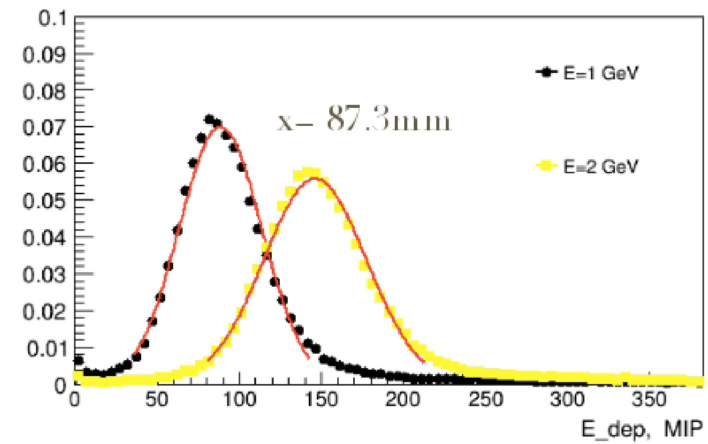
# Charge Divider Calibration

Calibration factor can be estimated by comparison of the deposited energy in LumiCal with and without charge divider for 1 GeV and 2 GeV beams, where the affect of saturation is relatively small.



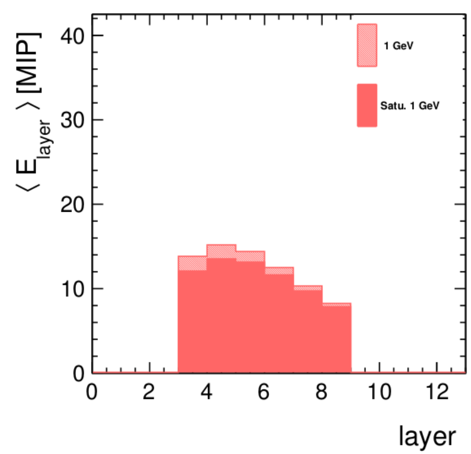

Estimation for

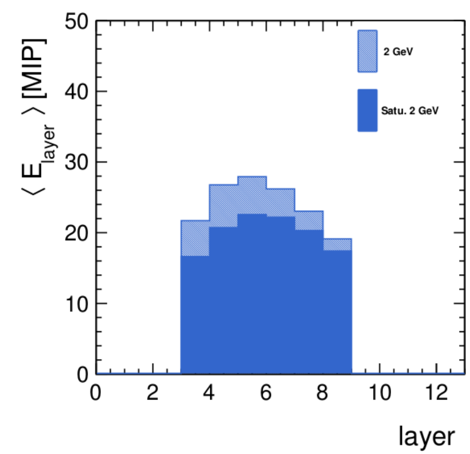
- 1 GeV beam is 4.22 and
- 2 GeV beam – 3.84




The simulations with Geant4 showed that correction for the saturation is:

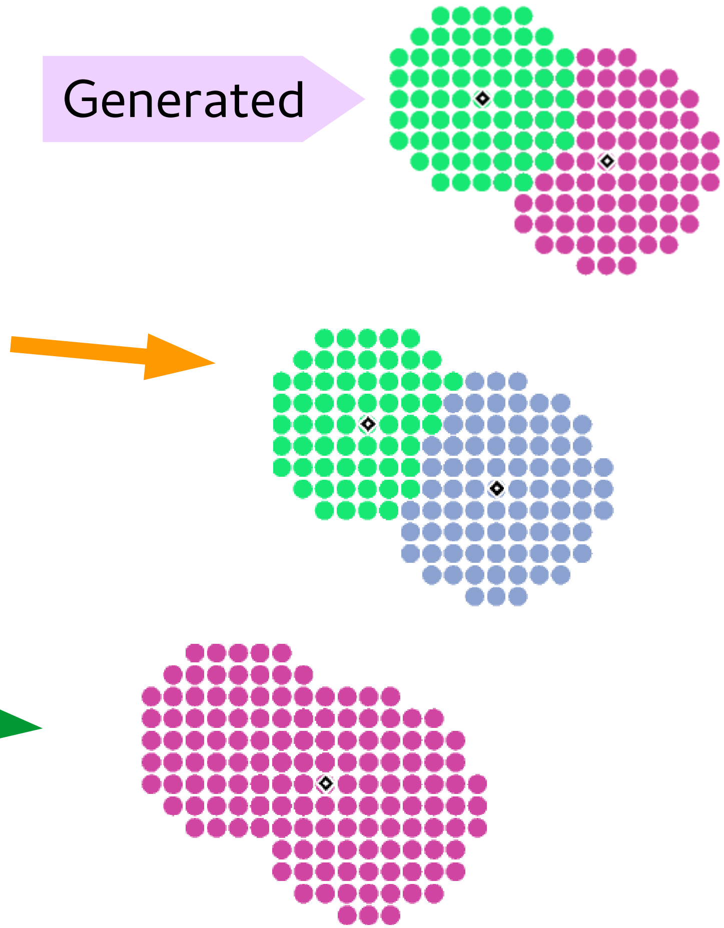
- 10 % for 1 GeV beam and
- 20 % for 2 GeV beam




- Taking into account this correction the calibration factor in both measurements is around 4.7.
- As expected there is dependence on the input capacitance observed in different beam positions.

# Clustering Algorithms




**E-clustering:**
First looks for hits with local maximum of deposited energy and consider them as seeds of the clusters.
Then all neighboring pads with descending energy are assigned to the seeds. Used in Zeus:

- Capable of resolving spatially joined clusters;
- Sensitive to the fluctuation in shower development.

**Linking neighboring pads:**
Looks for the closest neighbors (with distance no more then 1 pad in any direction) and then collects them to the cluster

- Very simple.

**k-means:**
Widely used in machine learning. Essentially, assigns points to cluster centers and locate them to minimize sum of the distances:

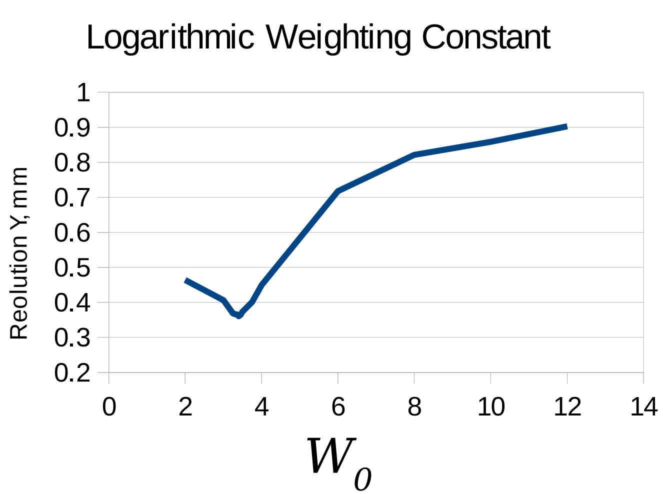
- Different implementations are available, easy to try;
- It assumes a certain given number of clusters and does not use all physics information;

# Cluster Position Reconstruction in Simulations

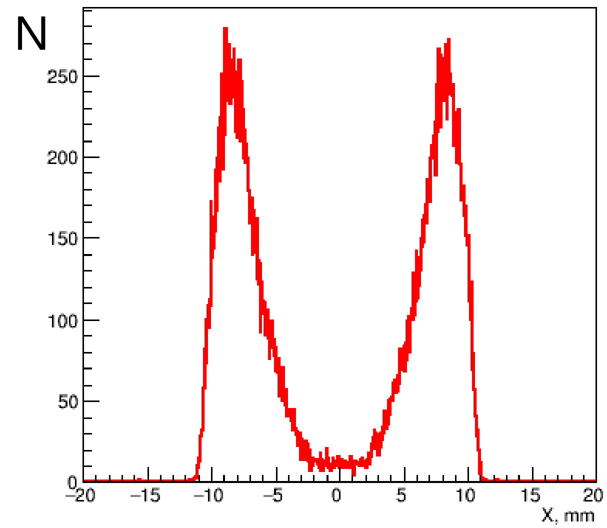
- Logarithmic weighting:

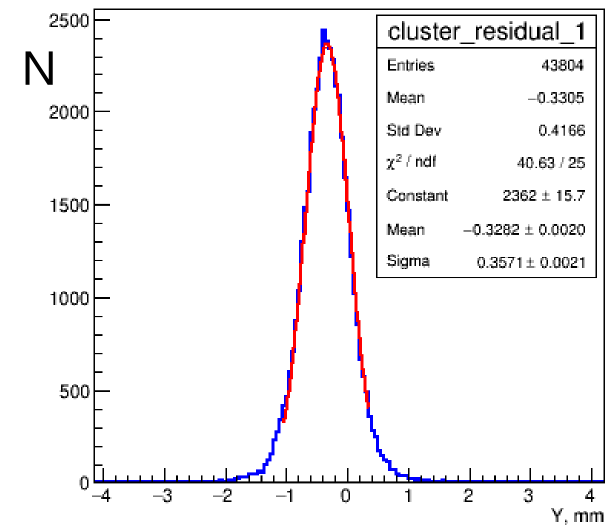
$$Y_s = \frac{\sum_n n w_n}{\sum_n w_n},$$

$$w_n = max\left\{0; W_0 + \ln\frac{E_n}{\sum_n E_n}\right\},$$




At $W_0$ = 3.4
Y resolution is 0.36 mm

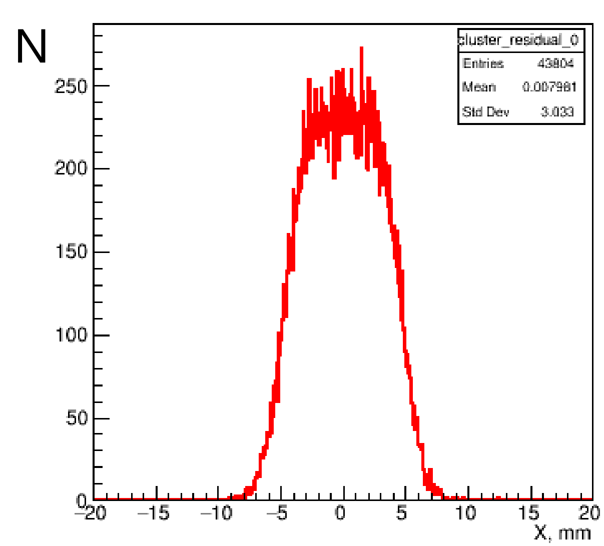


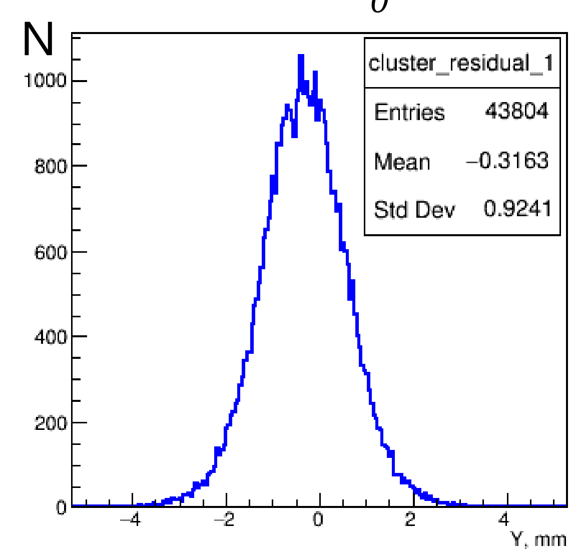




$W_0 = 3.4$

Distributions of X and Y residuals for

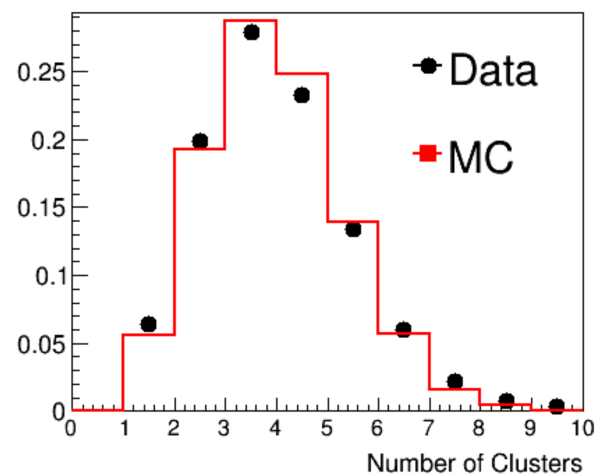
$W_0 = 12.0$



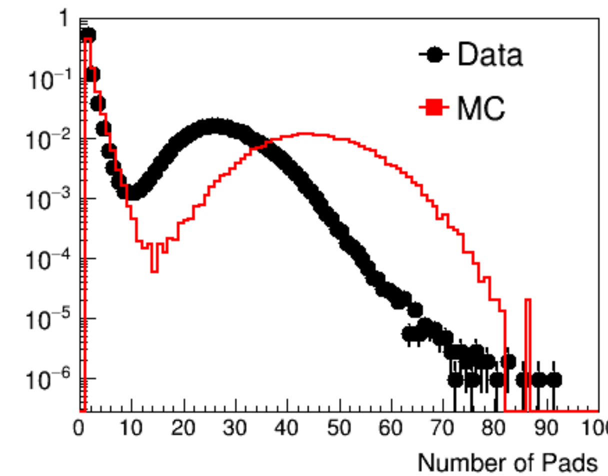



# Clusters: MC vs Data

5 GeV electron beam

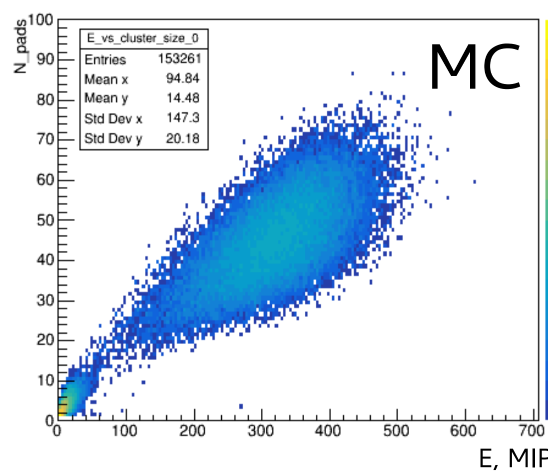


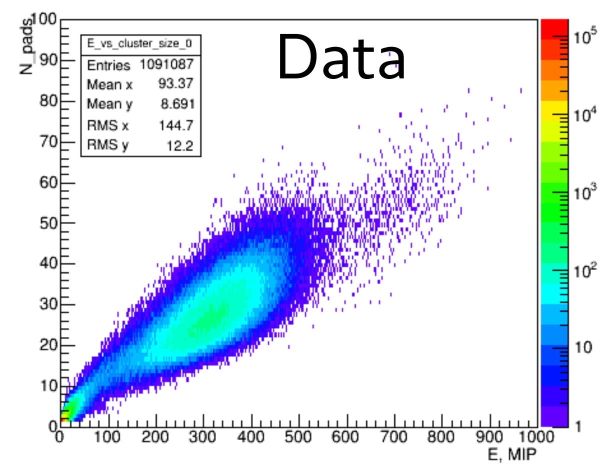

Number of clusters




Custer size

Simulation does not take into account electronic noise, which might explain the difference in cluster size

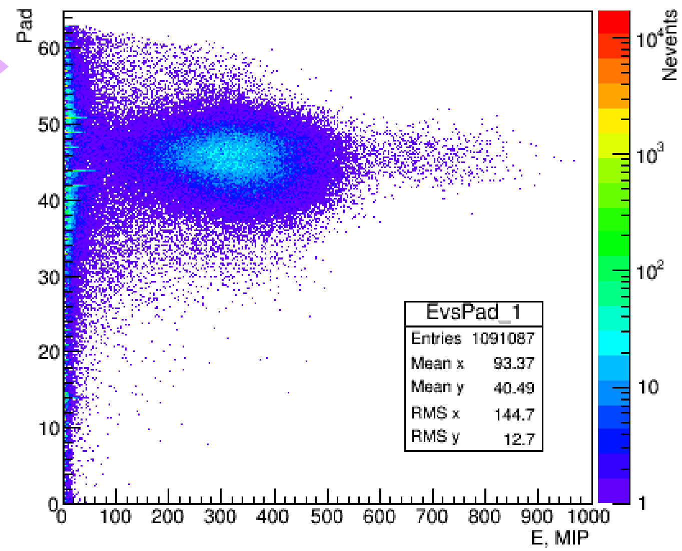



Custer energy vs size

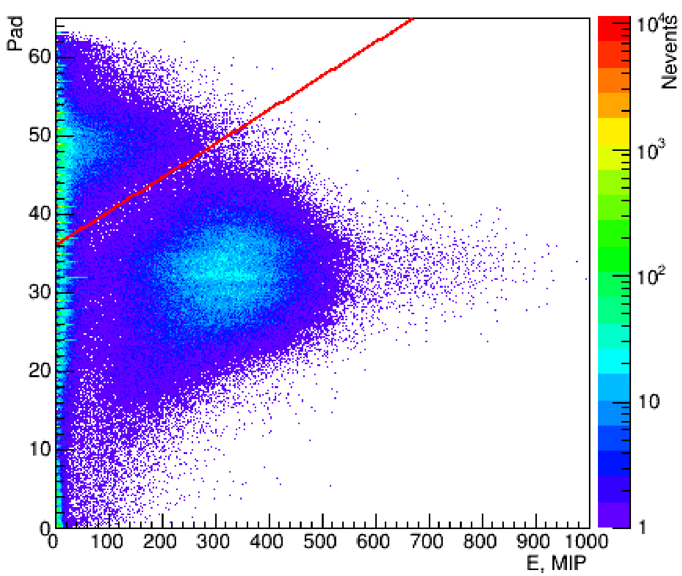
# Electron and Photon Energy

Clusters position vs. energy for the
Runs without target and without **B** field

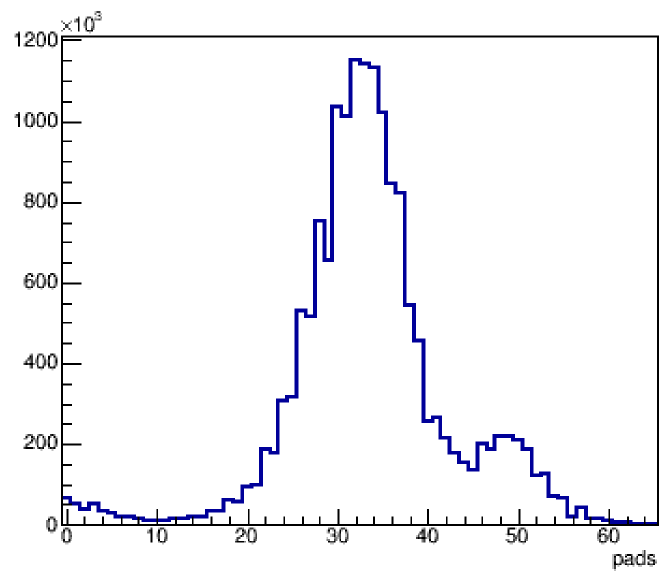



**Runs with 1.5 mm Cu target and B field:**

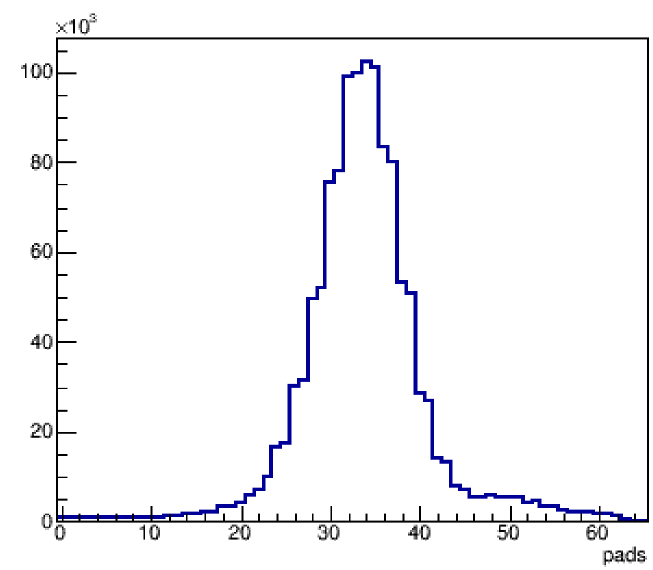
- Visible separation between photons and electrons in LumiCal;
- Expected dependence of electron position on its energy observed in 2D plot;
- Expected missing activity in tracker in photon beam location.




Clusters position vs. energy




Occupancy in LumiCal




Occupancy in tracker

# Summary

- Systematic uncertainty of Moliere radius measurements with Lumical prototype were evaluated taking into account the geometry of the LumiCal Sensor and beam test conditions.
- The design of the beam test setup and detector components were studied and optimized in simulations. It has been successfully realized at DESY and allowed to collect data for e/γ identification study in LumiCal combined with tracking detector.
- Neural network was successfully applied to identify the particle signal in raw detector data.
- Different cluster reconstruction algorithms were implemented and tested in simulation and data. Their performance is in good agreement for MC and data.
- Cluster position reconstruction with logarithmic weighting algorithm was optimized in simulation ($W_0$=3.4). It will be compared to the data using the position of the particle reconstructed in telescope.
- Ongoing study on back scattering and e/γ identification.