Test Beam Results and Recent R&D for a Compact Forward Calorimeter

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On behalf of the FCAL collaboration

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Outline

- Introduction
- Design and assembly of the thin LumiCal module
- Test-beam setup
- Calibration
- Electromagnetic shower development study
- Particle position reconstruction in LumiCal
- Summary

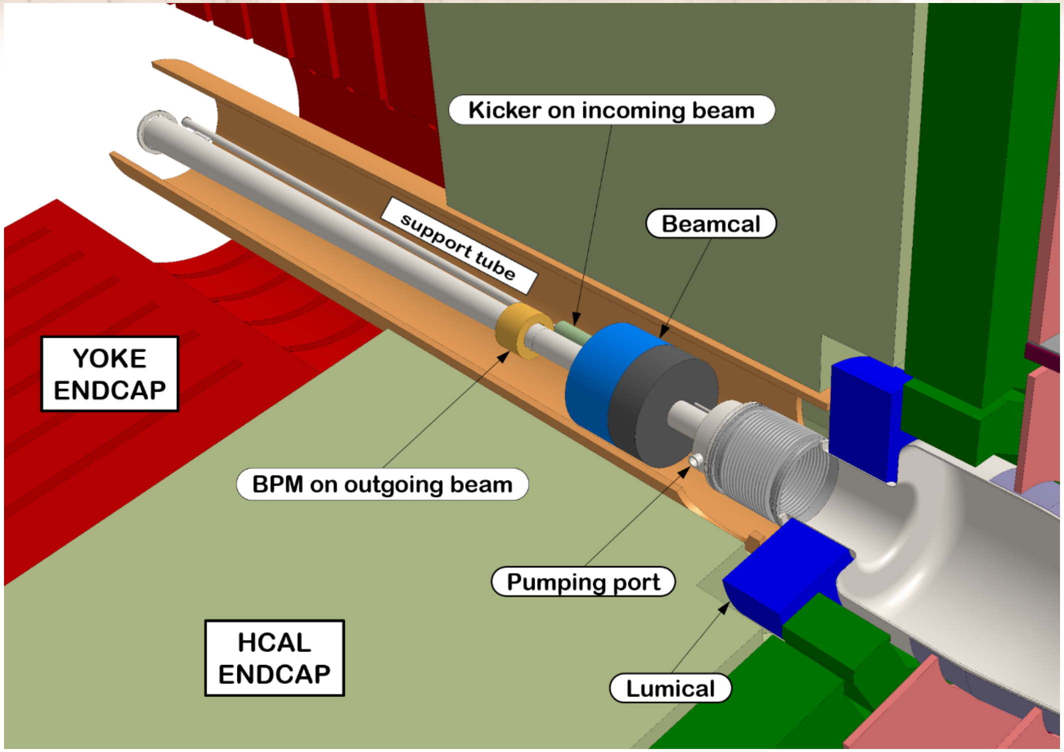
LumiCal and BeamCal in CLIC Detector

LumiCal:

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

BeamCal:

- Instantaneous luminosity measurements;
- High energy particle detection on the high background caused by beam-beam interaction.



Both are electromagnetic sampling calorimeters with tungsten absorbers.

	N_{Layers}	d_{Layer} [mm]	Absorber	d_{Abs} [mm]	Active	d_{Act} [mm]
LumiCal	40	4.27	Tungsten	3.5	Silicon	0.32
BeamCal	40	4.00	Tungsten	3.5	Diamond	0.30

BeamCal requires a radiation hard sensors (GaAs, CVD, sapphire)

LumiCal active layer: 0.8 mm

LumiCal thickness: $40X_0$ -> 17.1 cm.

- Compact design – small Moliere radius;
- Bigger fiducial volume;
- Electron showers detection on top of background.

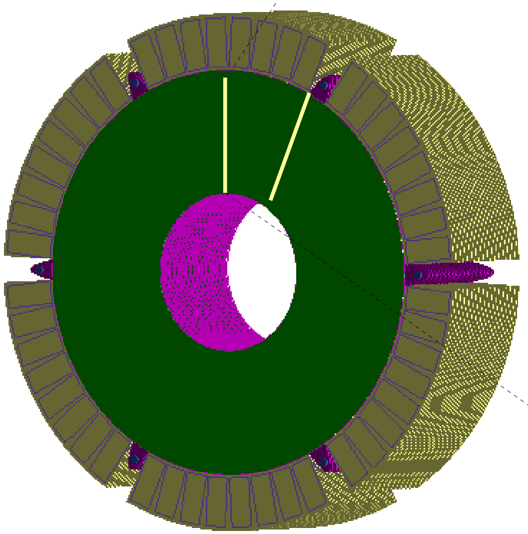
Luminosity Measurement and LumiCal Sensor

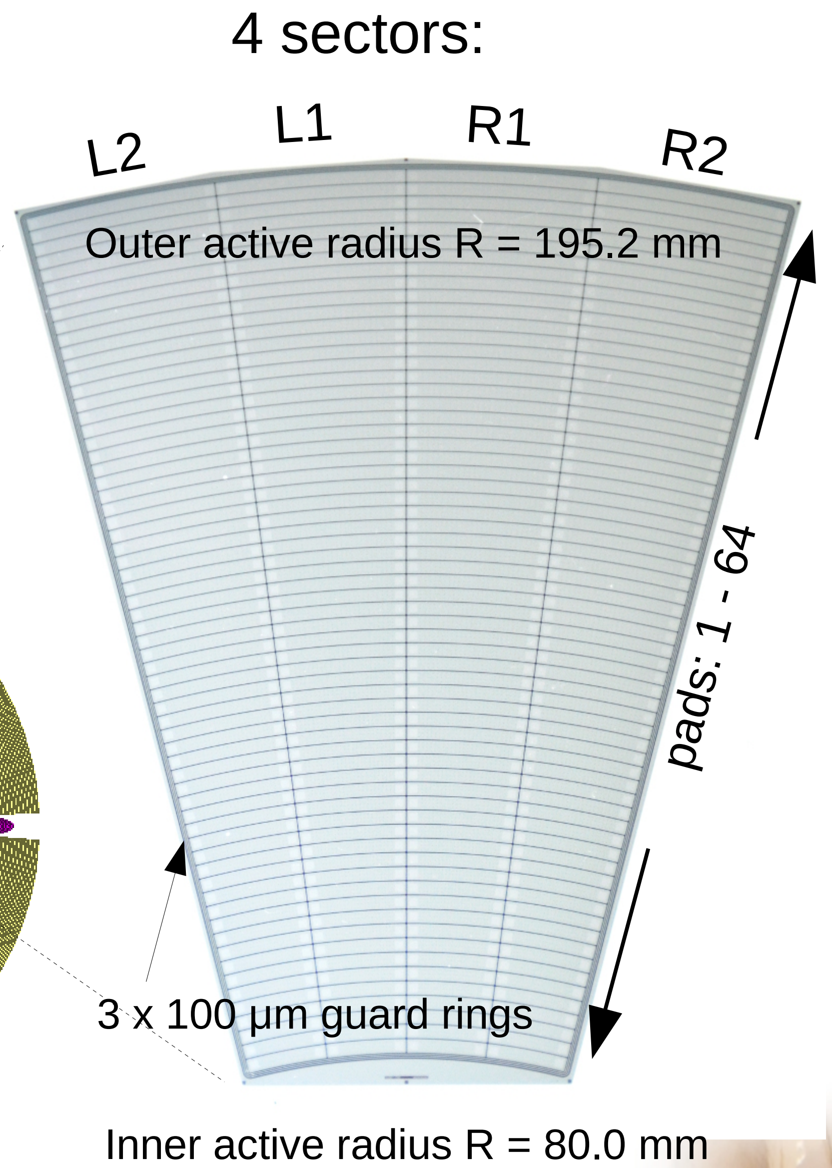
Luminosity measurement: $L = \frac{N_B}{\sigma_B}$

N_B – Bhabha events in a certain polar angle (θ);
σ_B – integral of the differential cross section over the same θ range.

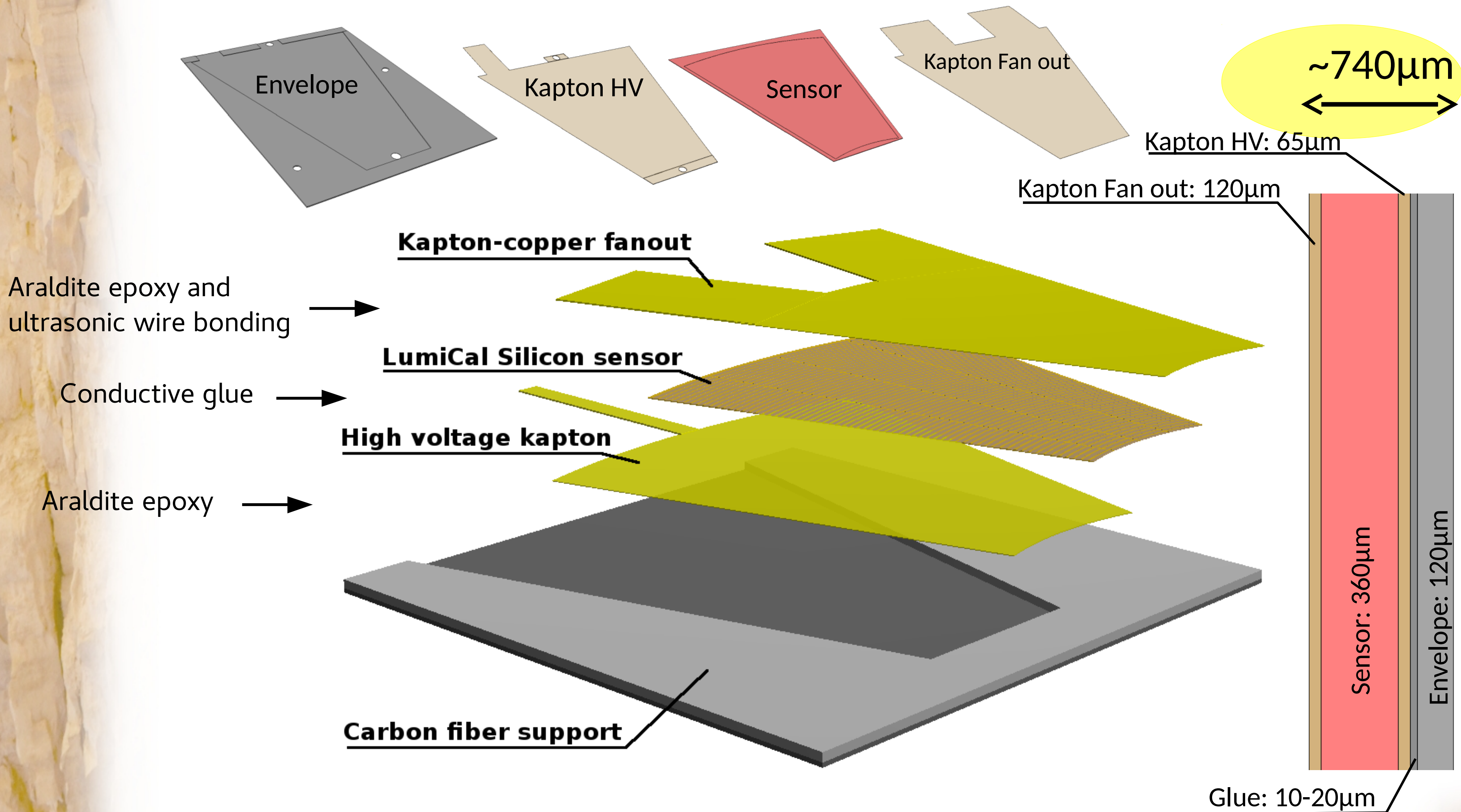
Silicon sensor prototype is designed for ILD

- thickness 320 μm
- DC coupled with readout electronics
- p+ implants in n-type bulk
- 64 radial pads, pitch 1.8 mm
- 4 azimuthal sectors in one tile, each 7.5°
- 12 tiles make full azimuthal coverage

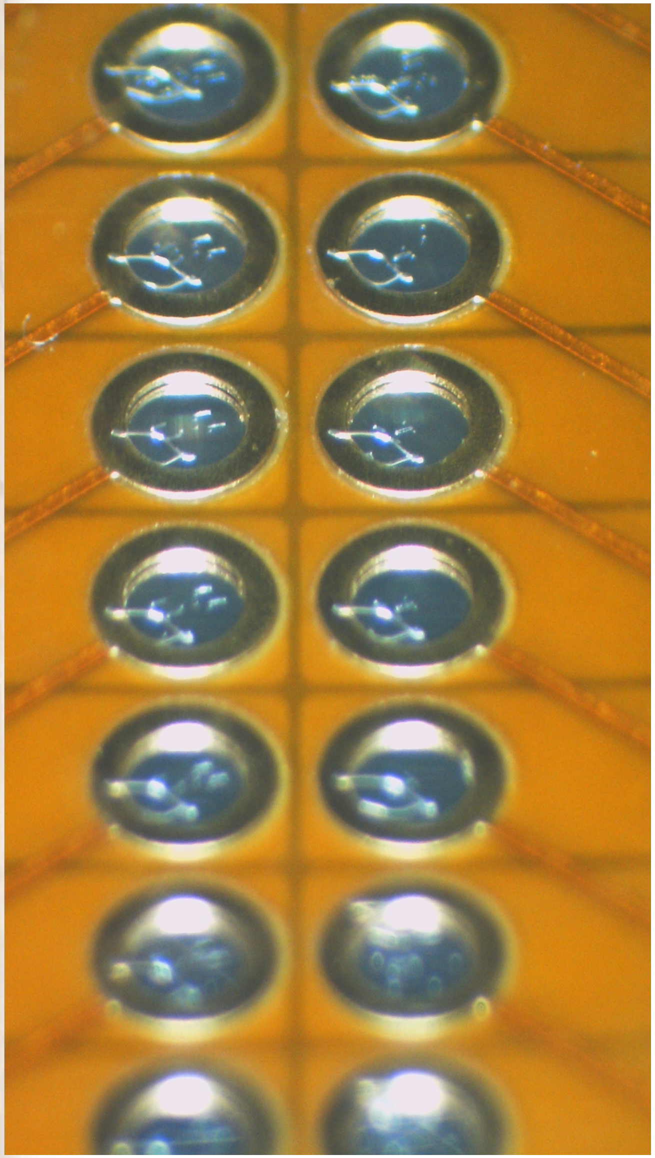




Design of the Thin LumiCal Module

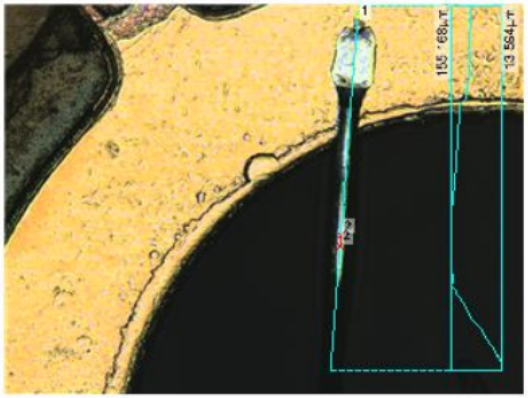


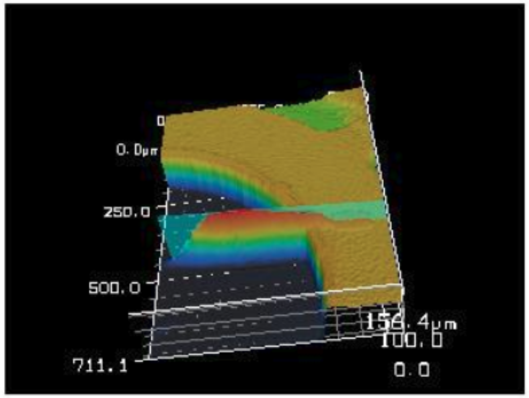
Wedge Wire Bonding for Front-end Contact

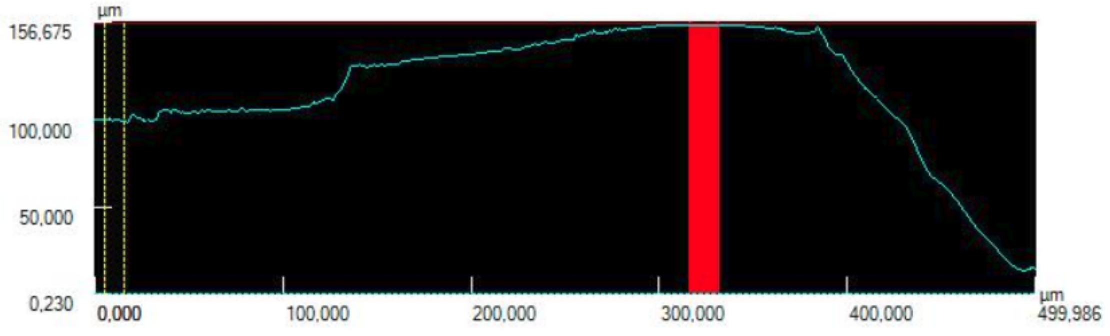


Achievable size of the bonding loops is in the range 50 µm - 100µm.

Bonding loop measured with 3D laser scanning confocal microscope at DESY Zeuthen.

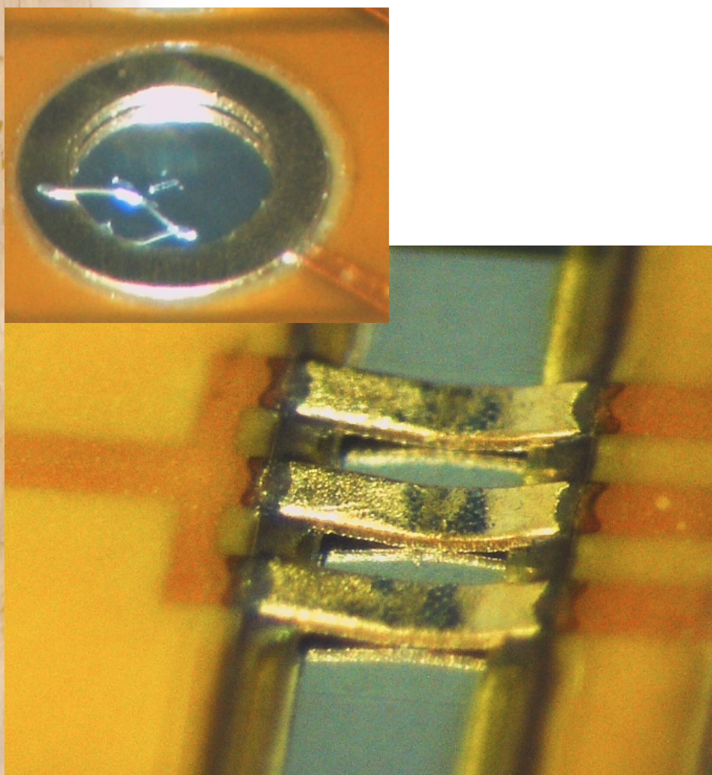


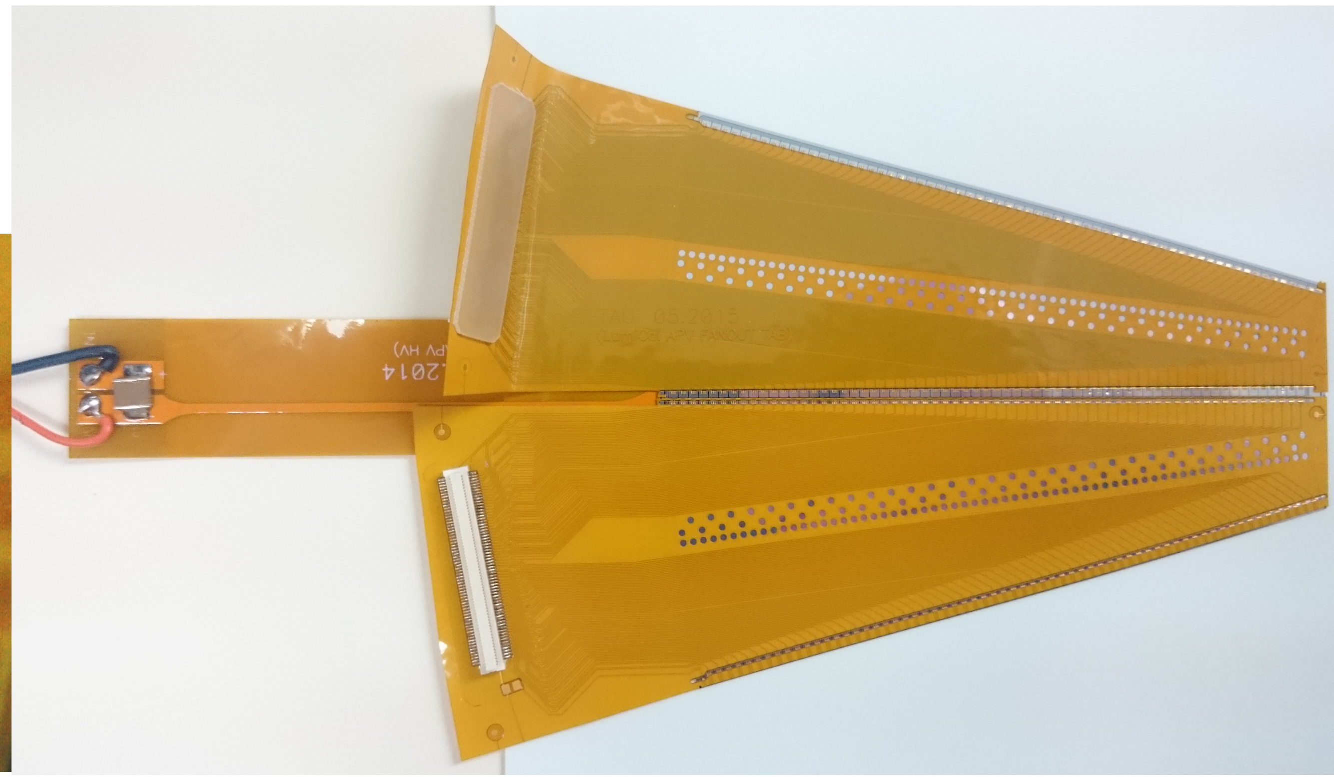




TAB Technology for Front-end Contact

Search for long-term stable contact between sensor and readout electronics which meets LumiCal geometrical (compactness) requirement





Single point Tape Automated Bonding (TAB):

- No wire loop, the bond can be covered by the glue for better protection;
- One LumiCal module is assembled and tested using TAB technology.

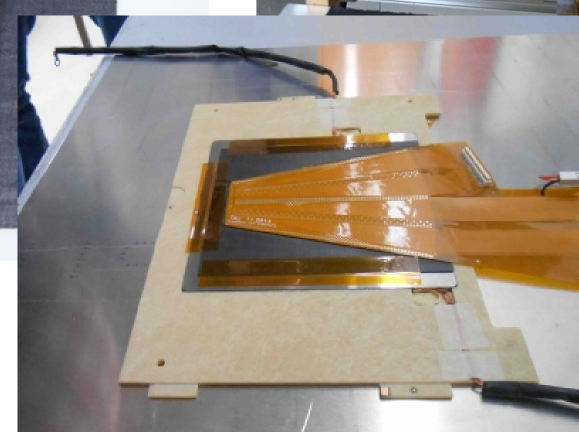
Thin LumiCal Module in Mechanical Frame

Kapton fanout

HV contact

130 pin Panasonic connectors provides interface to APV-25 hybrid and SRS DAQ system.

Carbon fiber supporting structure (“envelope”) provides mechanical stability and easy stack assembly.



- 8 thin modules with full readout (> 2k channels);
- 2 used as a tracker / tagger for e/γ separation;
- 6 used in calorimeter (3 - 8 X0) in 1 mm gap between tungsten;

Readout with SRS and APV-25

Next generation of LumiCal electronics is under development and will be available in 2018.

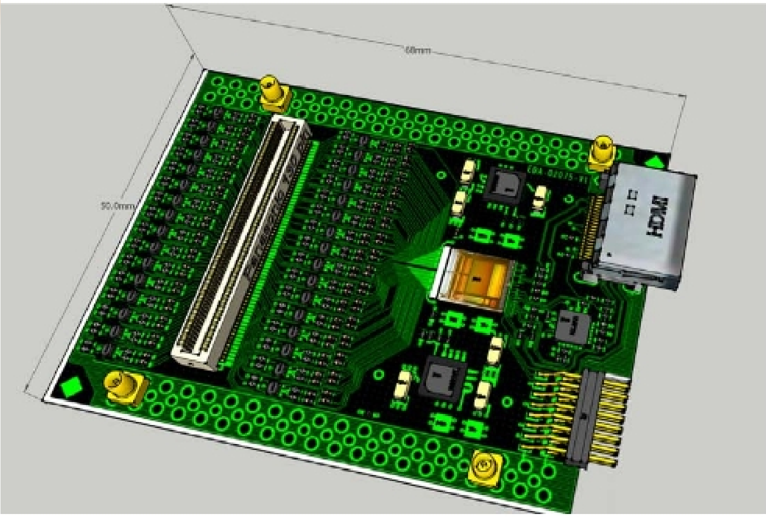
Temporary alternative solution:

Front-end chip APV25:

- Designed for CMS silicon microstrip detectors (used for Belle II SVT);
- 128 channels;
- Shaping time (min): 50 ns;
- Supports both signal polarity;
- Sampling rate 40 MHz;
- Supported by SRS;
- Available at CERN stock.

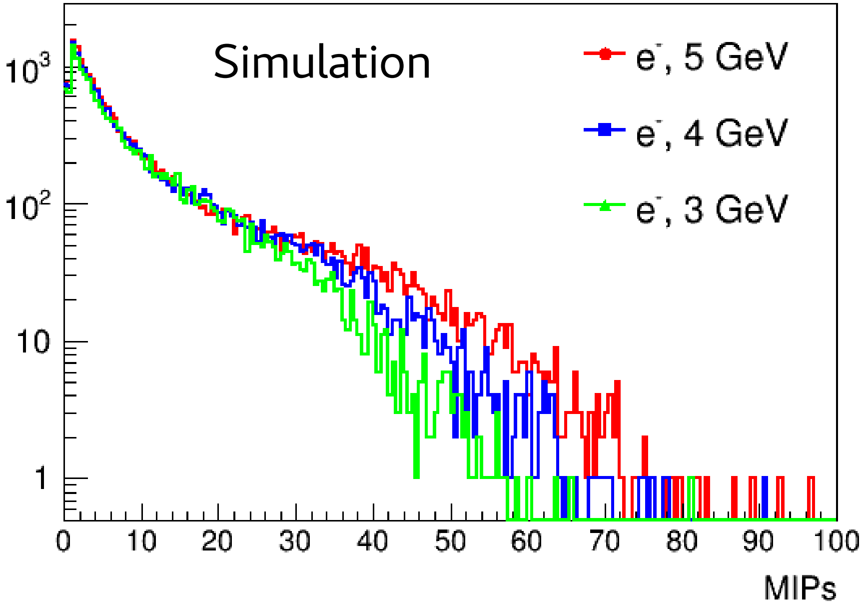
The APV-25 range in case of LumiCals sensor: ~ 8 MIPs

Additional board of “capacitive charge divider” was designed and produced to reduce saturation effect.



Front-end board (hybrid) with APV25 chip

Energy deposition in sensor pad in 5-th layer,



Thin Module Beam Test Goals, Setup

DESY test beam facilities:

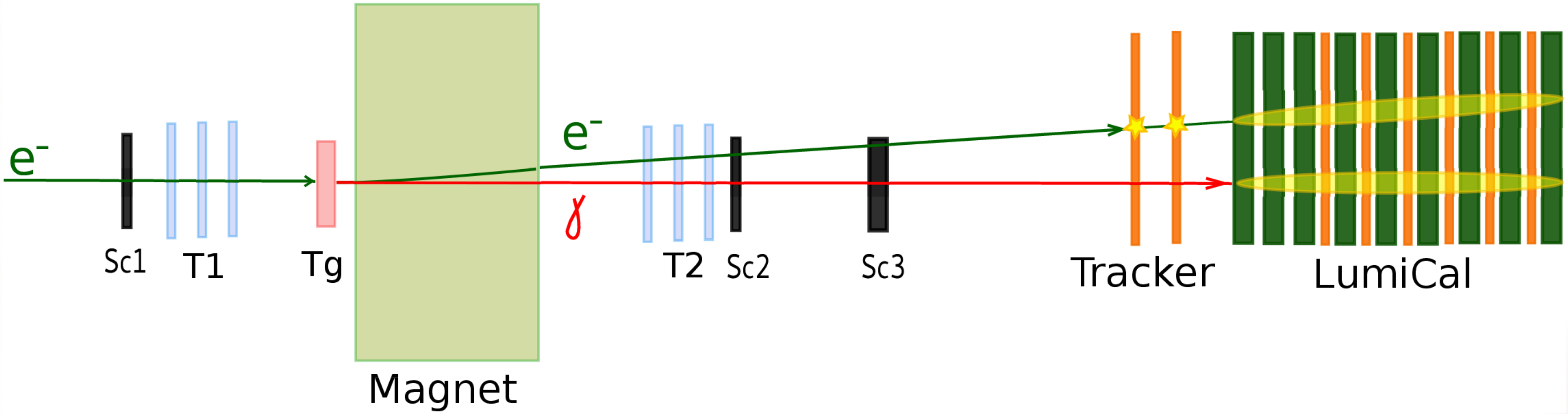
- Electron beam 1 – 6 GeV;
- Dipole magnet 1 – 13 kGs;
- EUTelescope with 6 planes of Mimosa26 detectors;

Performance of the compact LumiCal prototype:

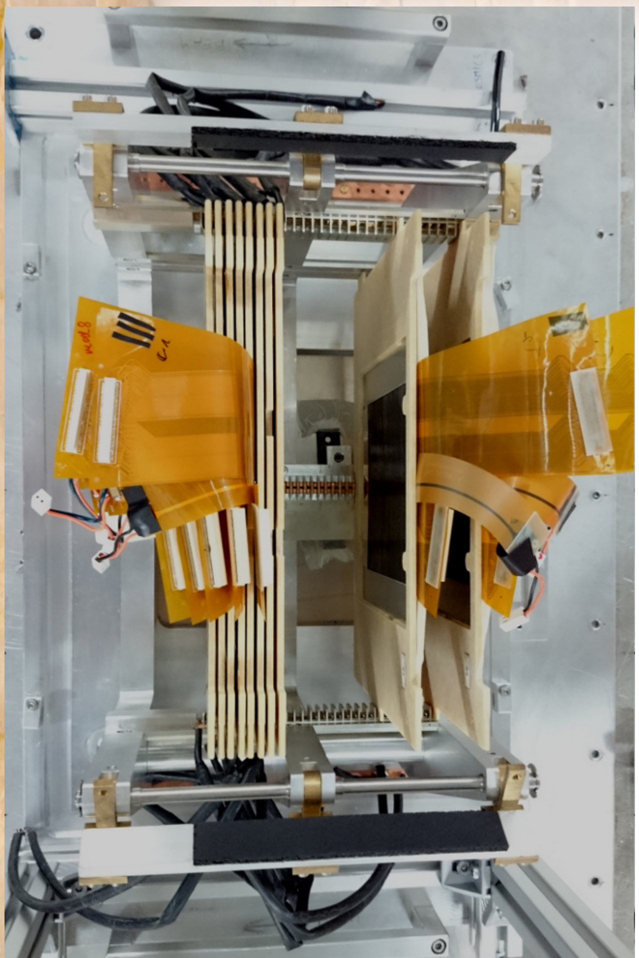
- Detector modules performance: noise, saturation, S/N, etc;
- Energy response to e^- beam of 1 – 6 GeV;
- Electromagnetic shower development study, Moliere Radius measurement.

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

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



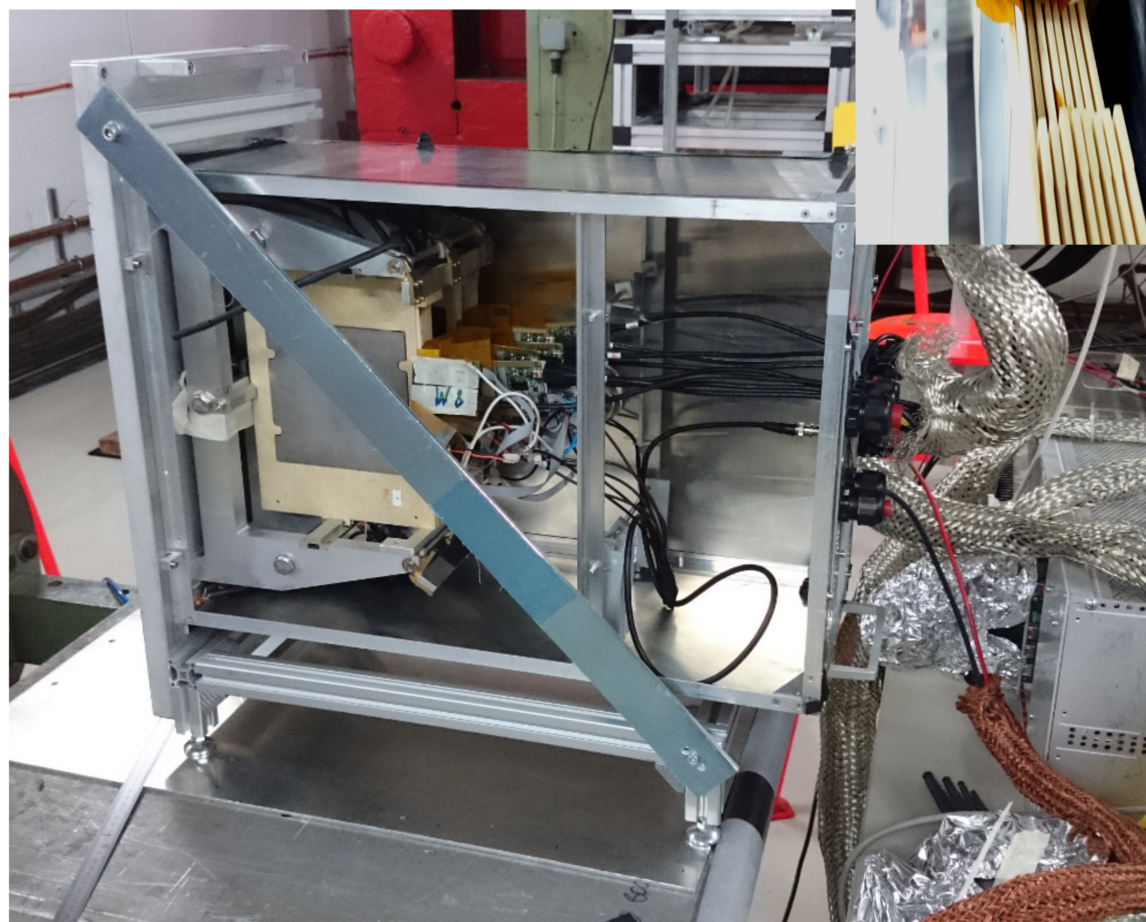
LumiCal Beam Test Installation

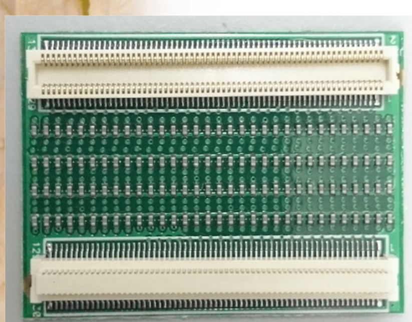


Top view of the thin modules in a stack

APV-25 front-end boards connected to the short side of the fan-out

Mainframe rotated by 90°



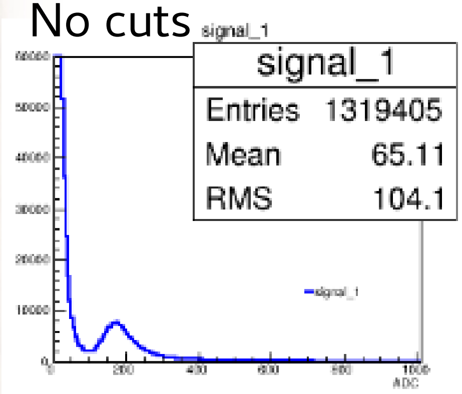


Charge divider board, 37x28 mm^2.

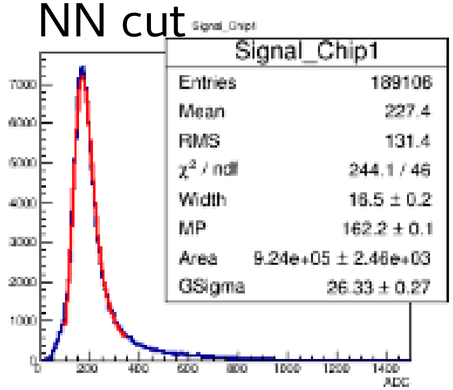
LumiCal Energy Response

Cosmic muon reconstruction in LumiCal module readout by APV25

No cuts

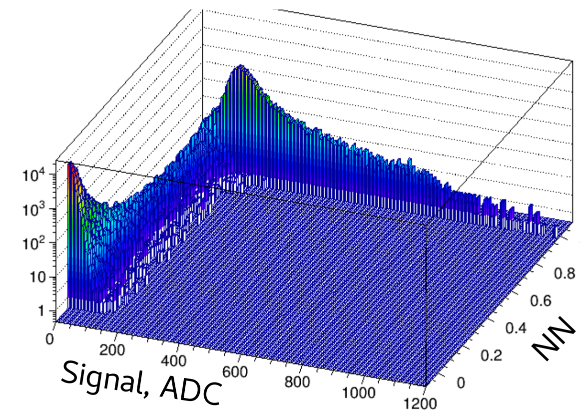


NN cut



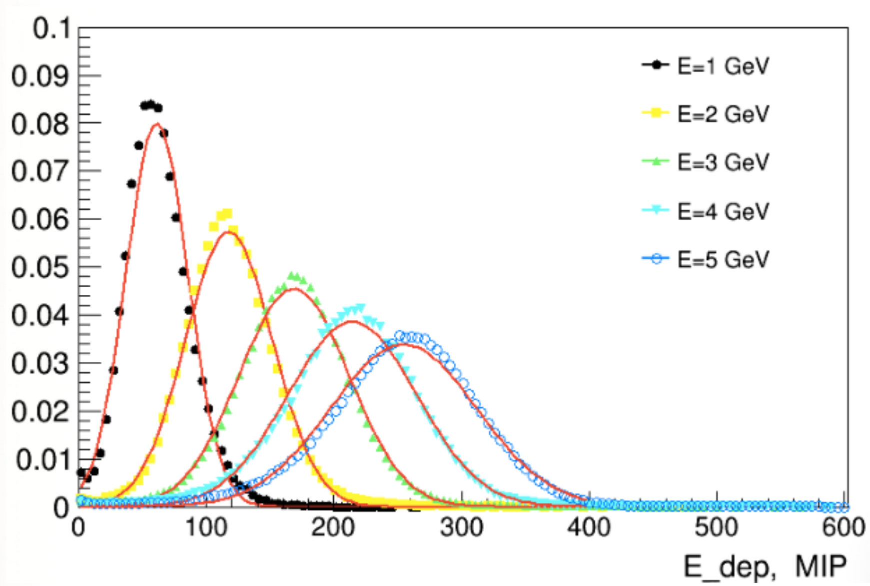
Energy deposited in LumiCal sensor by cosmic muon (ADC)

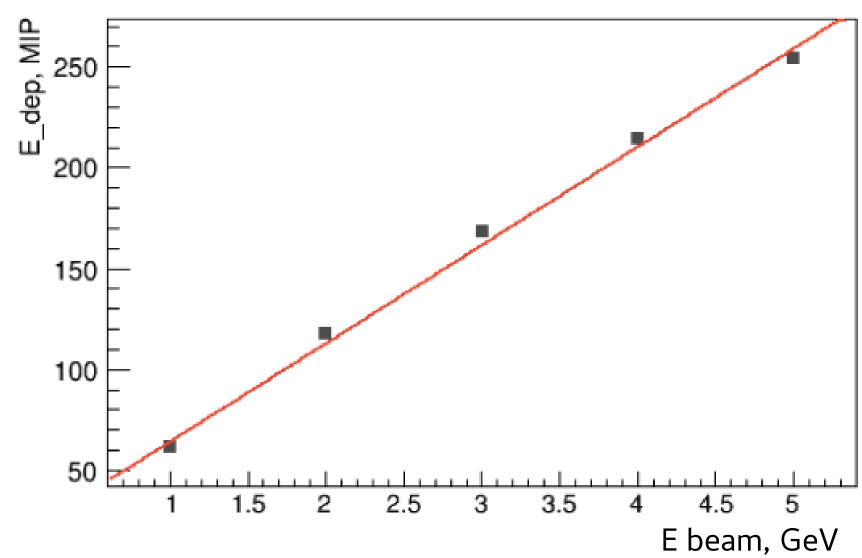
Signal selection with neural network (NN)



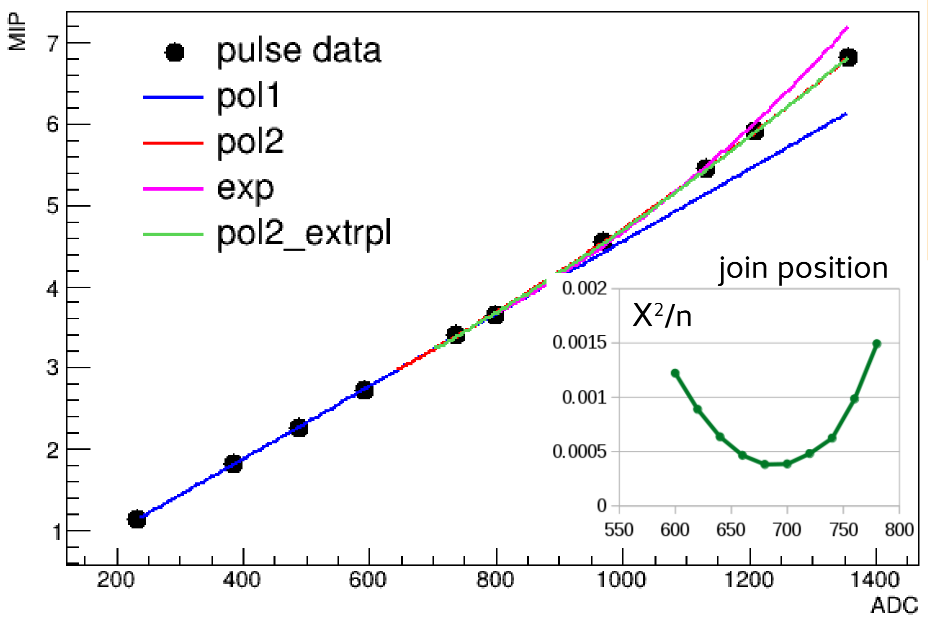
LumiCal response

when running with charge divider



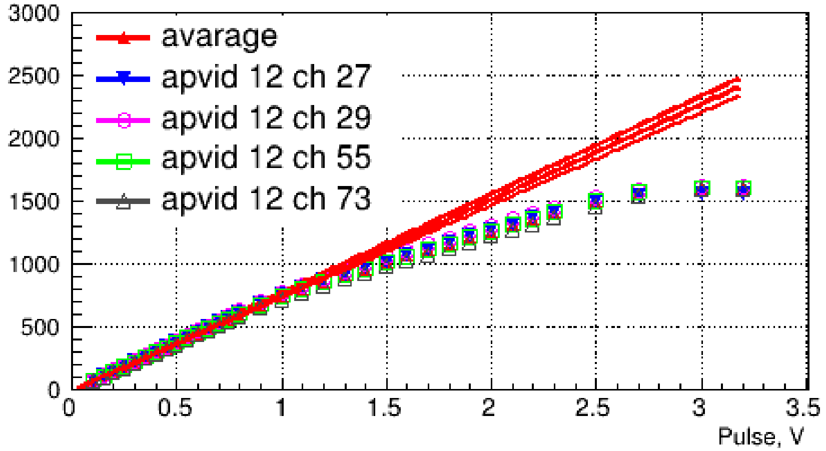


Non Linear Response of APV25

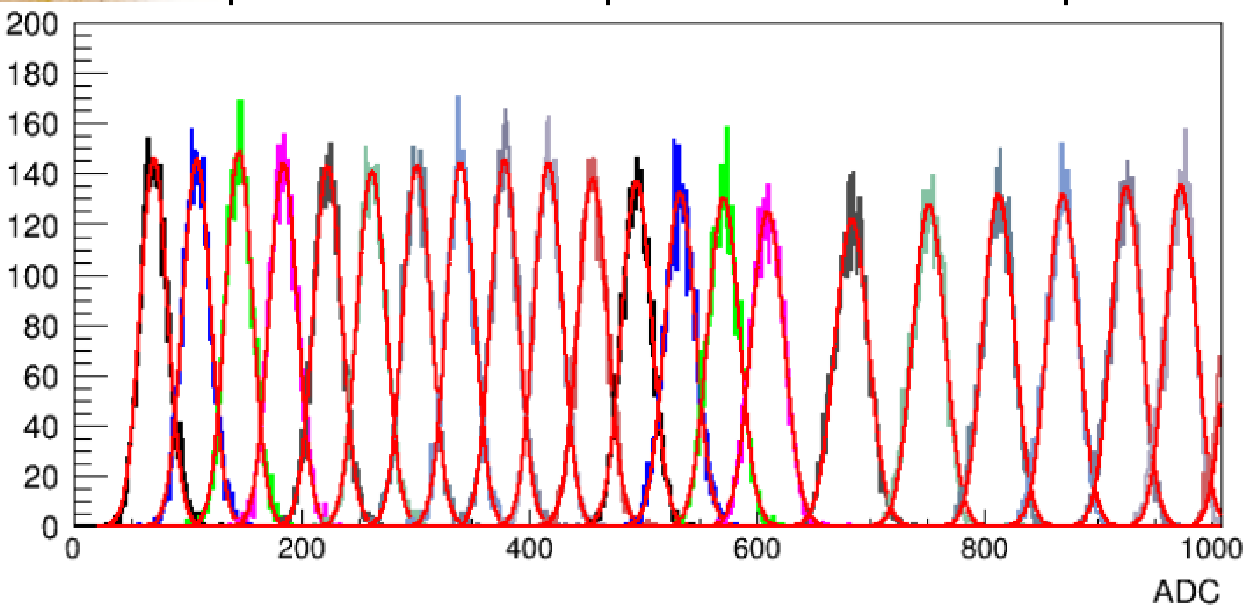


- APV25 is known to be linear up to about 4 MIPs.
- Different functions can be used to approximate non linear response;
- Direct measurements with external pulse.

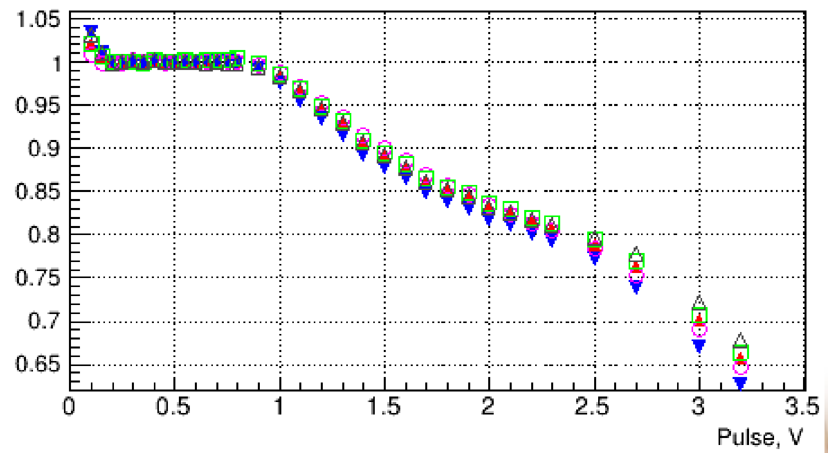
Average response and linear fit



APV25 response to external pulses of different amplitude



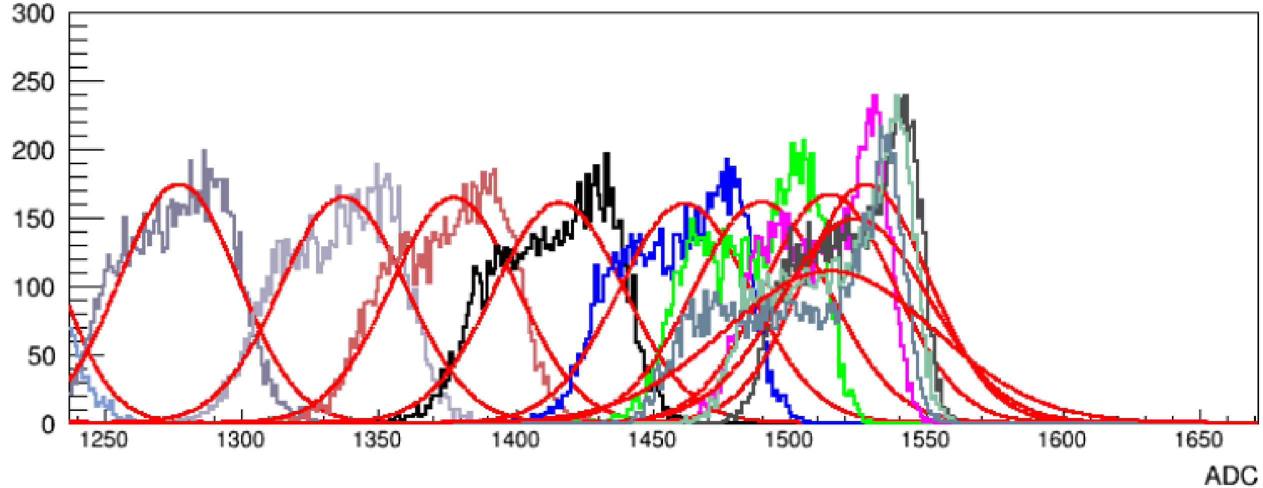
Ratio: data / pol1_fit

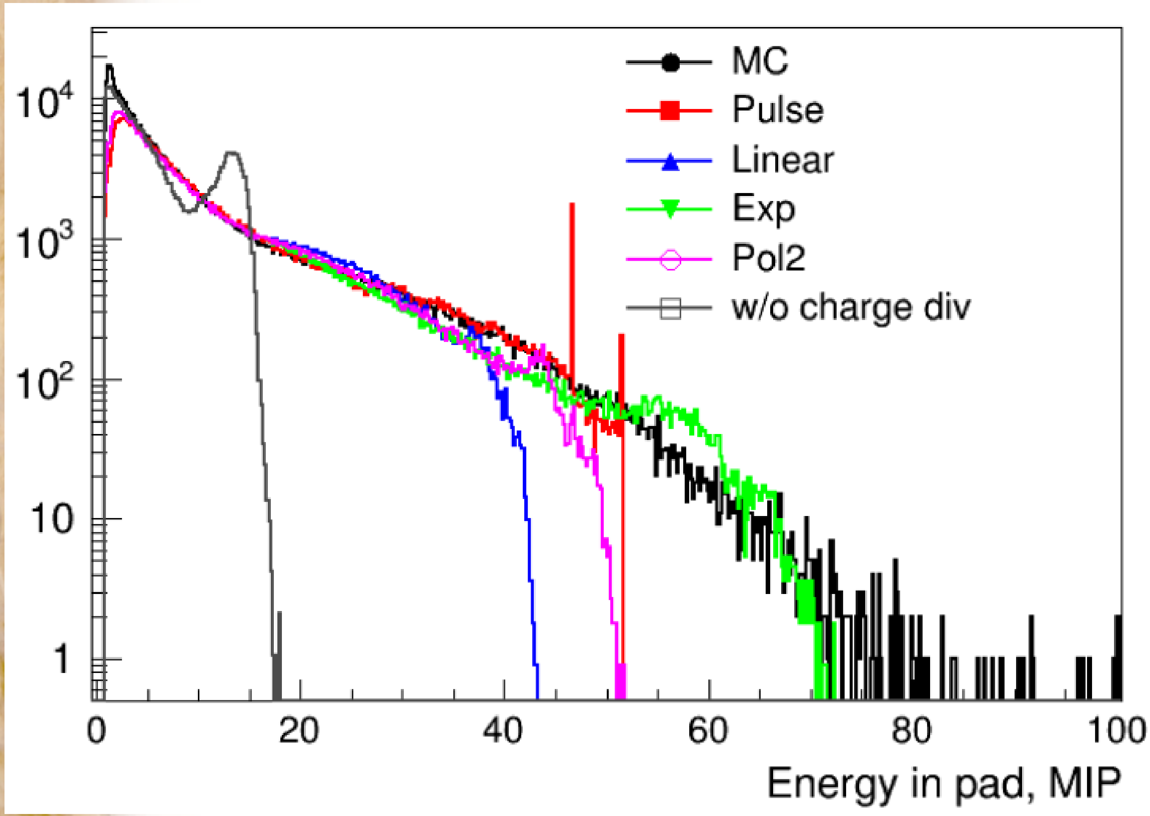


Energy Deposition in Single Pad

- In case of saturation effect the APV25 response is not Gaussian;
- Energy deposition can not be reliably measured;

APV25 response to external pulses. Saturation effect





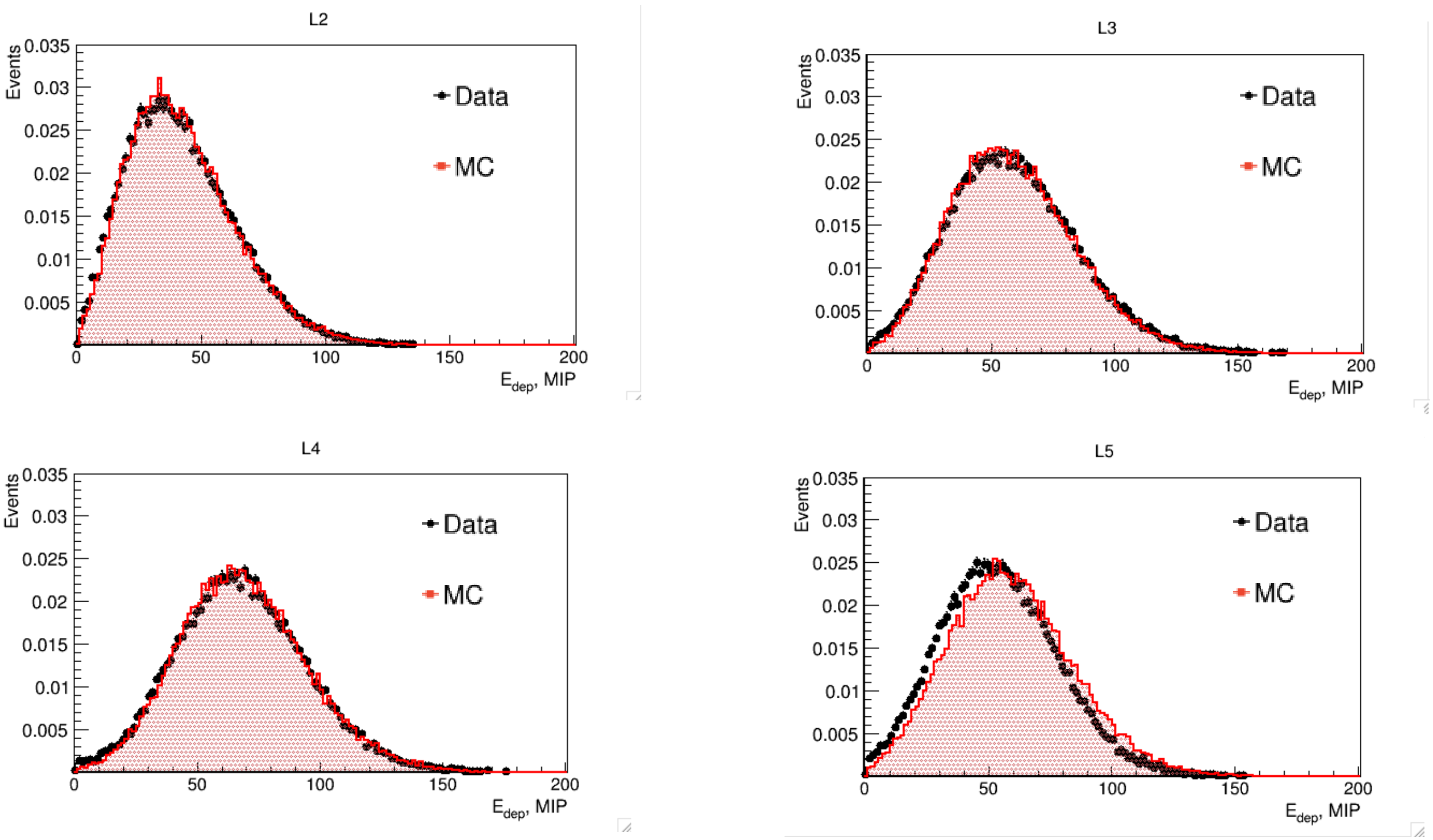
Distribution of the energy deposited in pad of active layer 5 (after ~5X0)

- The simulated distribution is well reproduced by the data calibrated based on pulse measurements;
- Small signals are well reproduced by readout w/o charge divider;
- Few per cent are above the saturation level.

Longitudinal Shower

Work in progress…

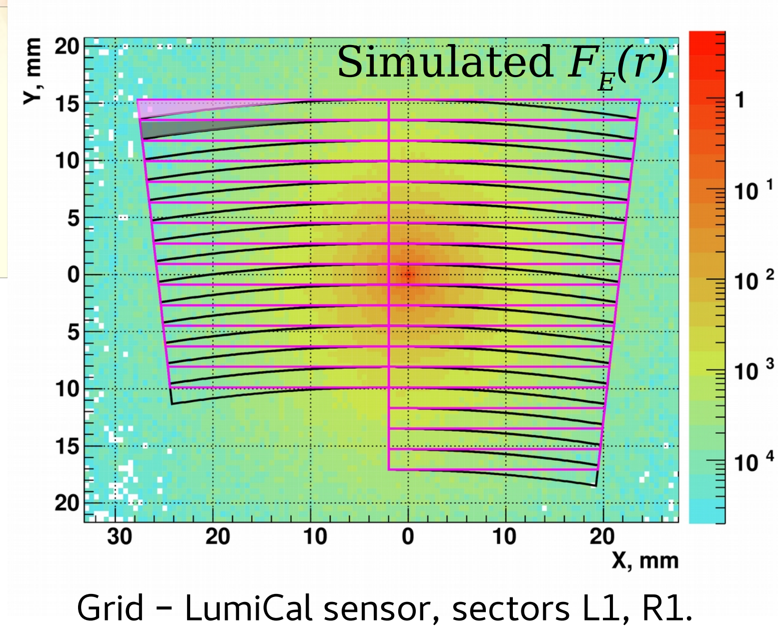
Sensitive layers are installed after 3, 4, 5, 6 tungsten plates, it roughly corresponds to 3, 4, 5, 6 X0.



- The difference between data and MC for layer 5 to be understood.
- Possible reasons: noisy channels cause loss of information about small depositions which becomes significant as shower develops.

Shower Study in Transverse Plane with LumiCal Sensor

Procedure was developed for 2014 beam test of LumiCal prototype at CERN (PS, 5 GeV e- beam).
Result is $\mathbf{R_M=24.0 \pm 0.6(stat.) \pm 1.5(syst.)}$ **mm**.
(arXiv:1705.03885)



Grid – LumiCal sensor, sectors L1, R1.

Average distribution of deposited energy in transverse plane:

$$F_E(r) = A_C e^{-\left(\frac{r}{R_C}\right)^2} + A_T \frac{2r^\alpha R_T^2}{(r^2+R_T^2)^2}$$

$r=\sqrt{x^2+y^2}$ – the distance from the shower center;
A_C, A_T, R_C, R_T, α – fit parameters.

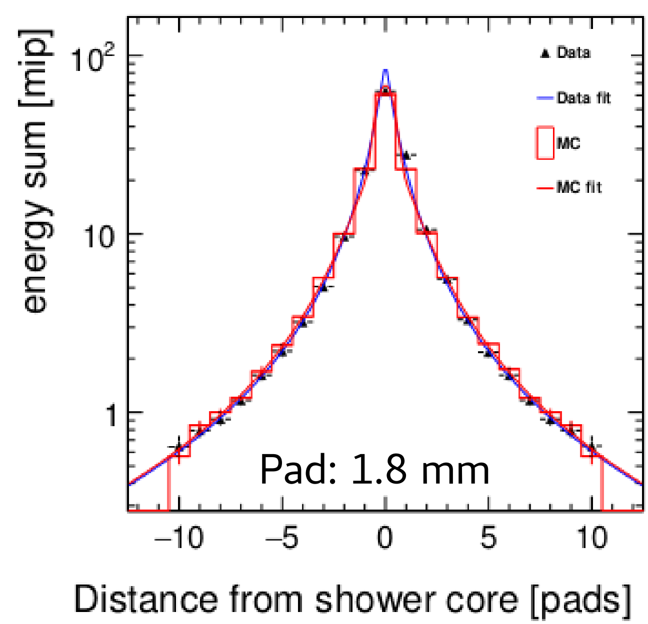
$$G_E(y) = \int_{X_{min}}^{X_{max}} F_E(\sqrt{x^2+y^2})dx$$

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

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

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

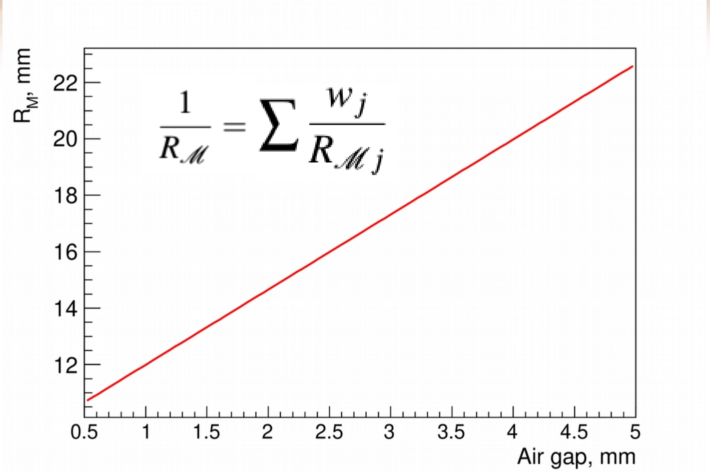
$$0.9 = \int_0^{2\pi} d\varphi \int_0^{R_{\mathcal{M}}} F_E(r) r dr$$



Shower Study in Transverse Plane

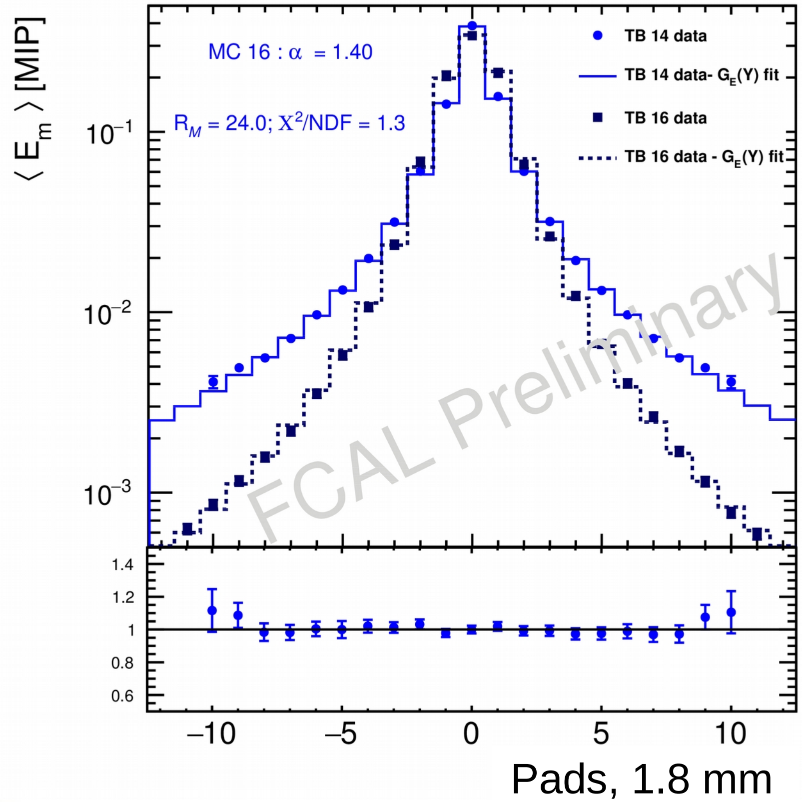
The dependence of R_M on the gap between absorbers can be estimated using the formula recommended by PDG for composite materials.

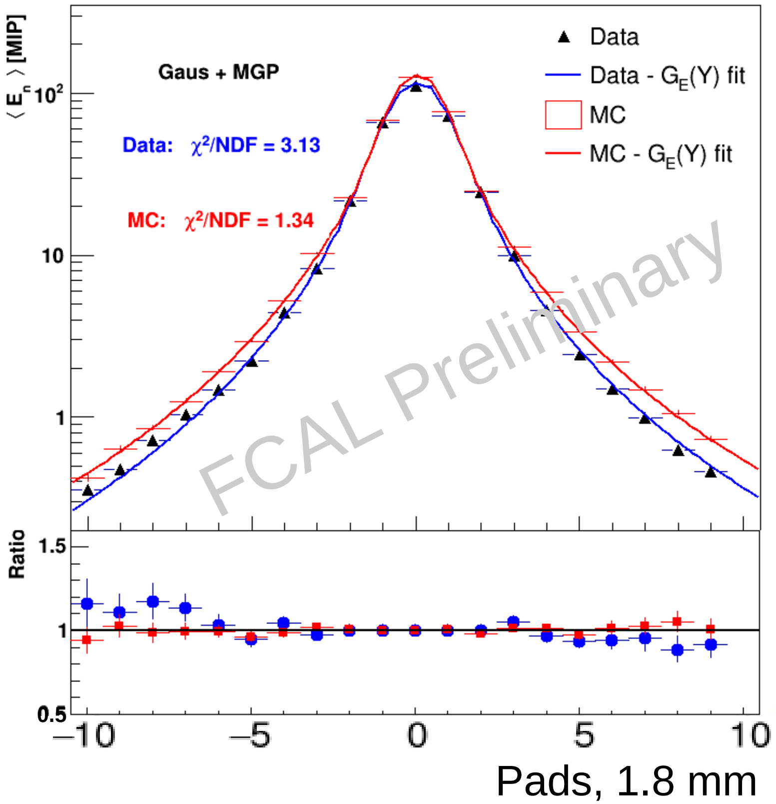
R_M as function of the air gap between 3.5 mm thick tungsten plates



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

Comparison of transverse shower in TB2016 (compact design) with TB2014





Position Reconstruction and e/γ Identification

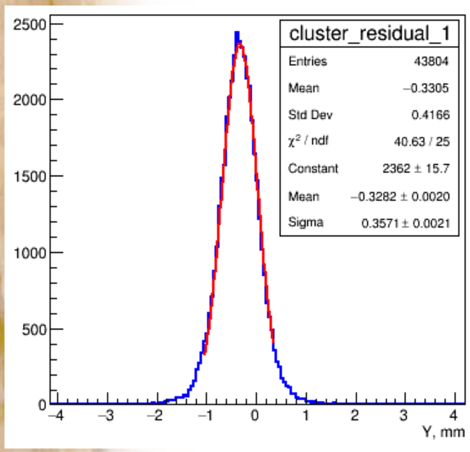
5 GeV electron beam

Reasonable agreement between parameters of reconstructed clusters in simulation and in data.

Position reconstruction with logarithmic weighting:

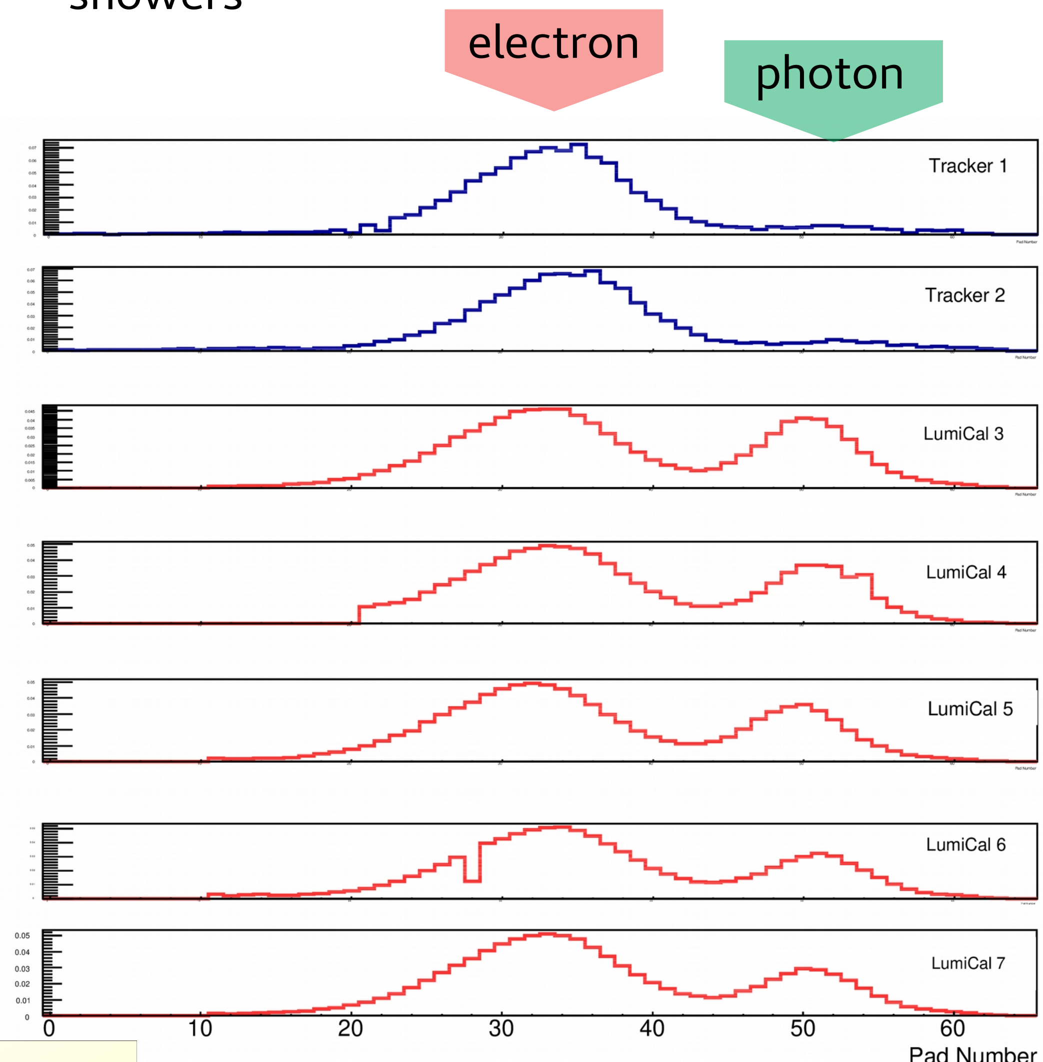
$$Y_s = \frac{\sum_n n w_n}{\sum_n w_n},$$

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



At W_0 = 3.4
Y resolution is 0.36 mm

Occupancy plot shows electron and photon showers



Identification efficiency:

- electron ~95%
- photon ~87%

FCAL R&D

FLAME (FCAL Asic for Multiplane Readout) is under development in Cracow.

Two main components were designed and produced:

Prototype ASIC comprising 8 functional FLAME channels:

- Front-end with variable gain, differential CR-RC shaper, Tpeak = 50ns, ENC~900el@20pF
- 10-bit multichannel SAR ADC, fs<40MSps
- Power (FE+ADC) <2mW/channel

Prototype serializer ASIC comprising:

- Fast ultra-low power multi-phase PLL
- Fast serializer 22b → 1b
- Fast SST driver

- Radiation tests of 10-bit SAR ADC, one of the key FLAME blocks.
- It was verified that the ADC is fully operational for TID doses up to several hundred Mrads.

Finalizing the design of 16-channel FLAME readout ASIC.

BeamCal Readout ASIC development at Pontificia Universidad Católica de Chile.

- Different sensor materials: GaAs, Si, Diamond, Sapphire;
- Different sensor segmentation – input capacitance;
- Different MIP response and maximum signal: 0.8 pC – 30 pC.

Summary

- Thin LumiCal module with submillimeter thickness was developed and produced. Its geometry meets requirements of LumiCal conceptual design.
- The LumiCal prototype with eight thin modules and existing mechanical structure was assembled and tested with electron beam. Data analysis is in progress and preliminary results are following:
  - LumiCal prototype demonstrates good linear response to the beam of 1 GeV – 5 GeV.
  - Compact assembly of LumiCal with thin detector module results in significantly narrower transverse shower compared to previous beam tests and much smaller Moliere radius.
  - The resolution of particle position reconstruction in LumiCal with logarithmic weighting algorithm for 5 GeV electrons is 0.36 mm.
- One LumiCal module prototype with TAB technology has been produced and installed for the beam test. Reasonable data were collected, further analysis will give more information.
- LumiCal front-end 8-channels ASIC and serializer prototypes have been produced. Ongoing work on their tests and design of fully functional FLAME chip with 16 channels.
- BeamCal front-end chip is under design with support of wide range of possible sensors solutions.
- Radiation hardness of BeamCal sensor materials (GaAs, Si, sapphire, SiC, CVD) are studied in JINR (Dubna) and UCSC (Ca, USA).