A compact fine-grained calorimeter for luminosity measurement at a linear collider

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- on behalf of the FCAL Collaboration -

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Performance and Molière radius measurements using a compact prototype of LumiCal in an electron test beam

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Abstract A new design of a detector plane of sub-millimetre thickness for an electromagnetic sampling

1 Introduction

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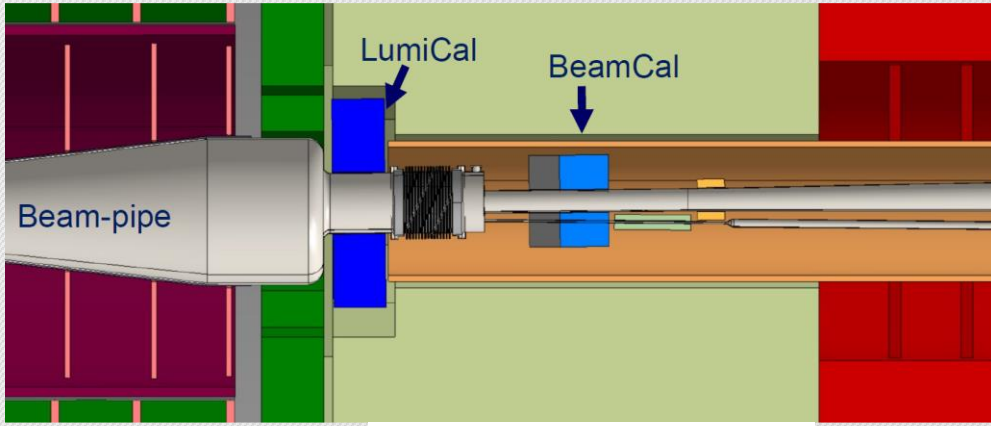
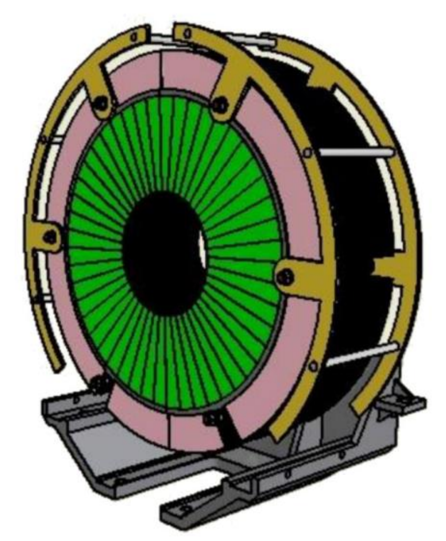
Motivation for forward calorimeters

- Luminosity measurement
  - Instantaneous - BeamCal
  - Beam-tuning (as a part of the fast-feedback system)- BeamCal
  - Integrated – LumiCal ($\delta\mathcal{L}$~10^{-3})
- High-energy electron identification at low angles - all
  - Detector hermeticity (coverage < 5 mrad)
  - Physics studies (BSM, background suppression, etc.)
- Shielding the central tracker from the backscattered particles



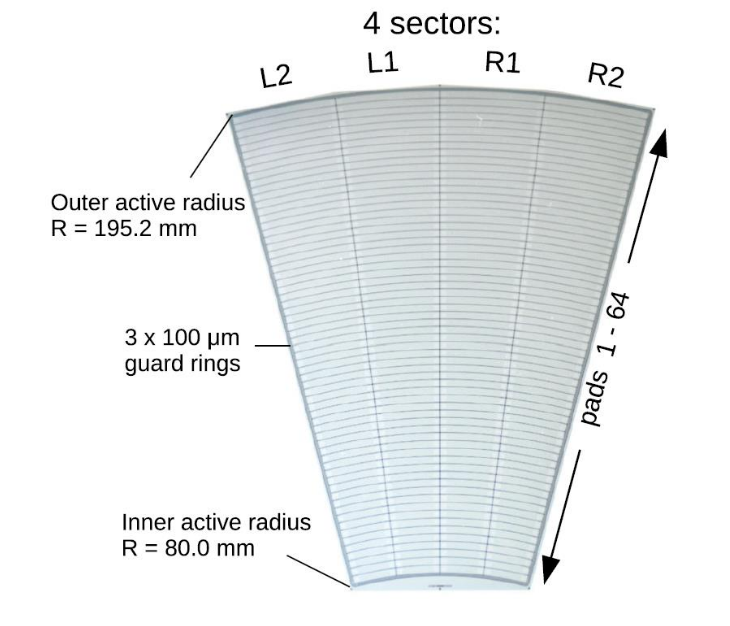
A common sandwich design for LumiCal and BeamCal
FCAL development for ILC and CLIC



Design

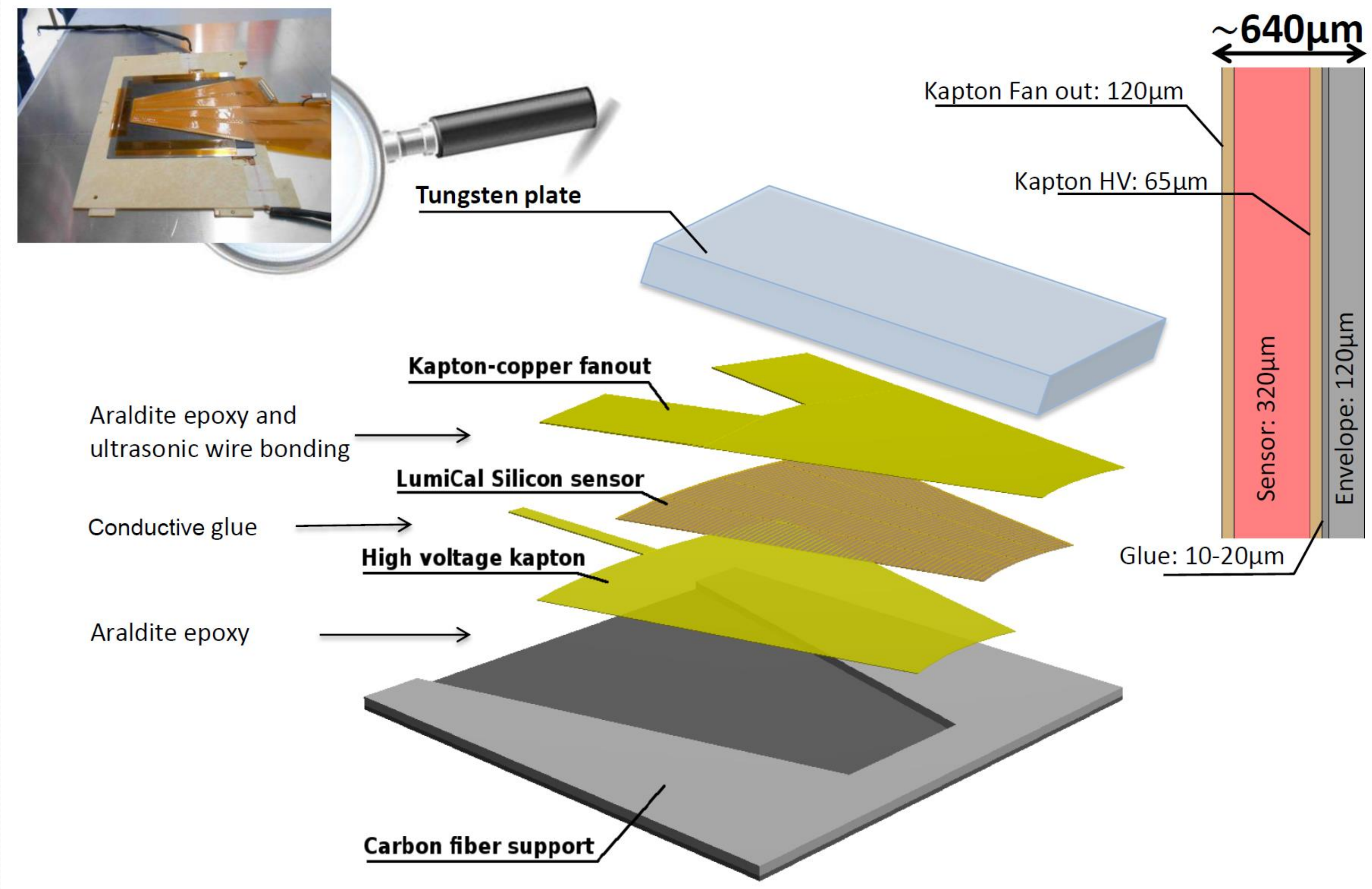
- Design
  - Cylindrical Silicon-Tungsten sandwich
  - 30-40 sensor/1 X_0 (3.5mm) absorber planes
  - 320 μm sensor thickness/1 mm gap
  - Radial segmentation: 64 pads with 1.8 mm pitch
  - Azimuthal segmentation: 48 sectors covering 7.5 deg each
  - FE electronics outside the calorimeter

- Requirements
  - High mechanical precision (polar angle measurement, luminosity systematics)
  - Small Moliere radius (shower position and energy measurement in the presence of widely spread background)
  - Electron-photon discrimination
  - Radiation hardness, high occupancy (BeamCal, GaAs instead of Si in the baseline design)

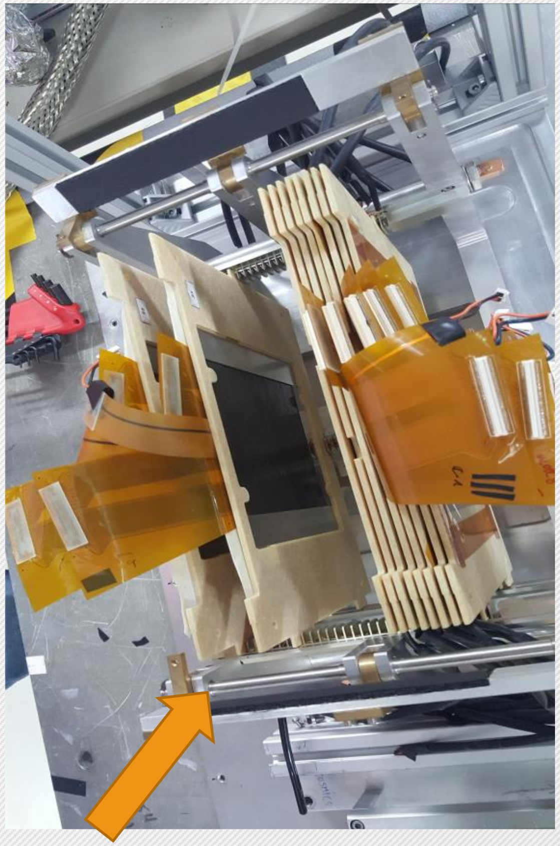


Test-beam with ultra-thin detector planes

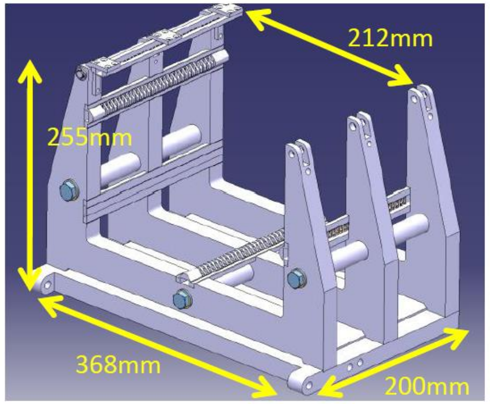
- Several test-beam campaigns
  - In 2014 with 4-plane calorimeter prototype
- The 2016 one with the ultra-thin detector planes <1mm
  - 8 detector planes
  - Ultrasonic wire-bonding (50-100 μm loop height)
- Aimed to test:
  - Performance of the compact calorimeter
  - Concept of the tracker+calorimeter for e/γ separation (ongoing)



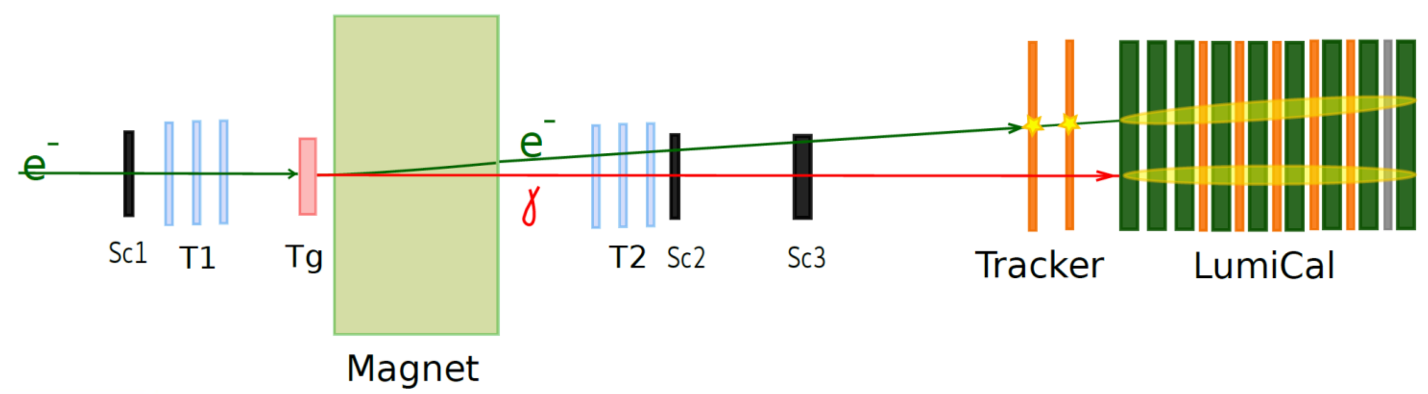
Test-beam setup



tracker planes

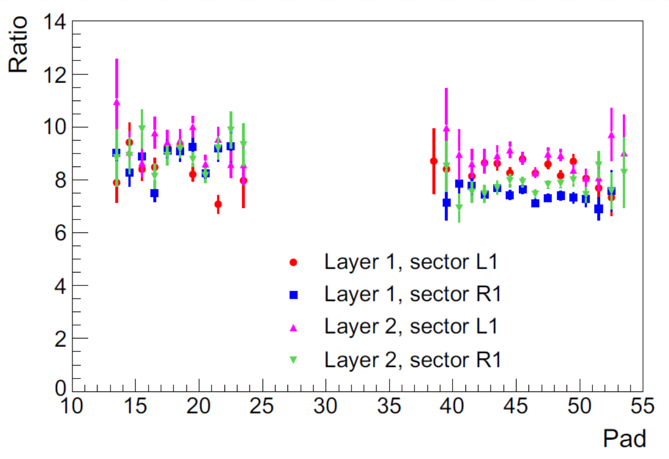


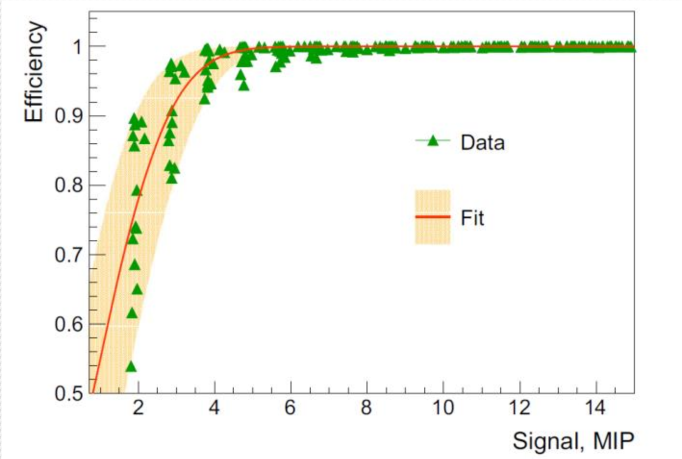
Mechanical structure developed by CERN

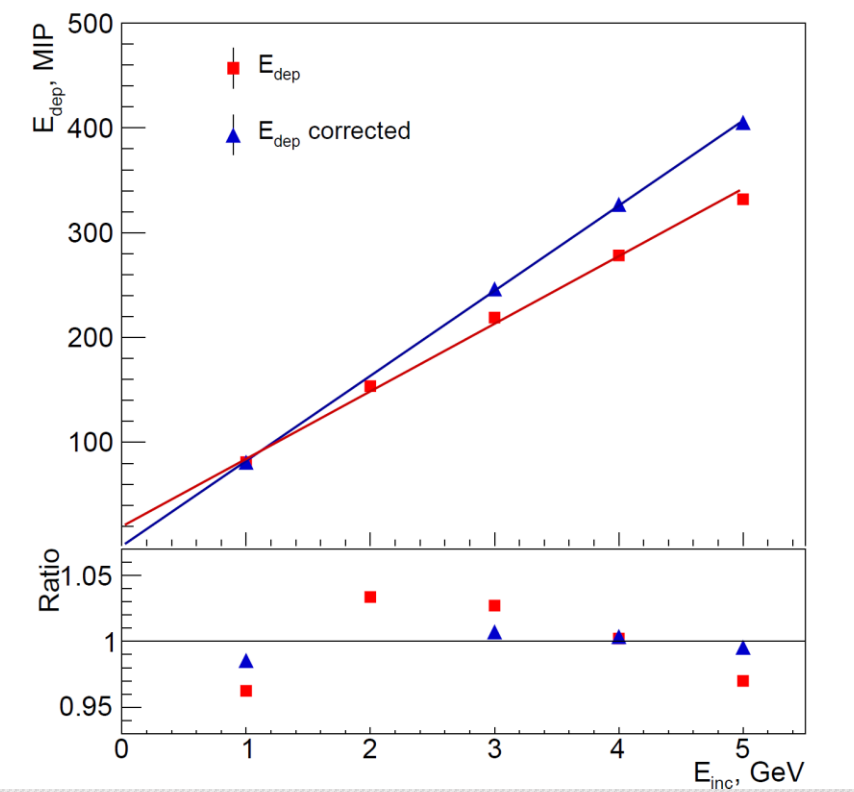


- DESY-II Synchrotron electron beam 1-5 GeV (beam size 5x5 mm^2)
- T1, T2 Eudet telescopes each with 3 MIMOSA Si-pixel planes
- Sc1,2,3 scintillator trigger
- Tg copper target
- Dipole magnet –13 kGs for e/γ separation
- 8 detector planes (6 -LumiCal, 2-tracker)
- 128 read-out channels per plane
- 8 W absorber plates
- External electronics

Overall performance







- FE electronics performance (modified APV25 board):
  - Efficiency vs. signal size is used to correct (simulation) for signals with amplitude smaller than 10 MIPS (1MIP=88.5 keV)
  - Signal to noise ratio is (7-10) for most channels
- Detector response:
  - Excellent linearity (after leakage correction from simulation)

Measurement of the shower position

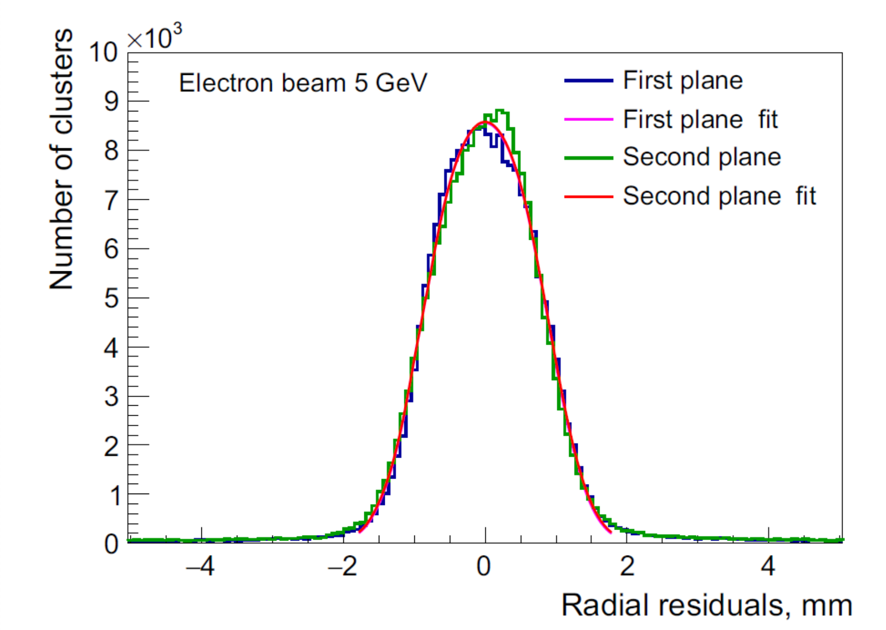
- Reconstruction of the shower radial position:

$$Y_c = \frac{\sum_m Y_m w_m}{\sum_m w_m},$$

  - Y_m- postion of the pad, *m* runs over all hit pads
  - W_m – logarithmic weight, $W_0=3.4=const.$ (obtained from simulation)

$$w_m = max\left\{0;\, W_0 + \ln\frac{E_m}{\sum_j E_j}\right\}$$

- Reconstruction is evaluated w.r.t. to the hit positions in tracker planes
- Resolution of (440±20) μm is found



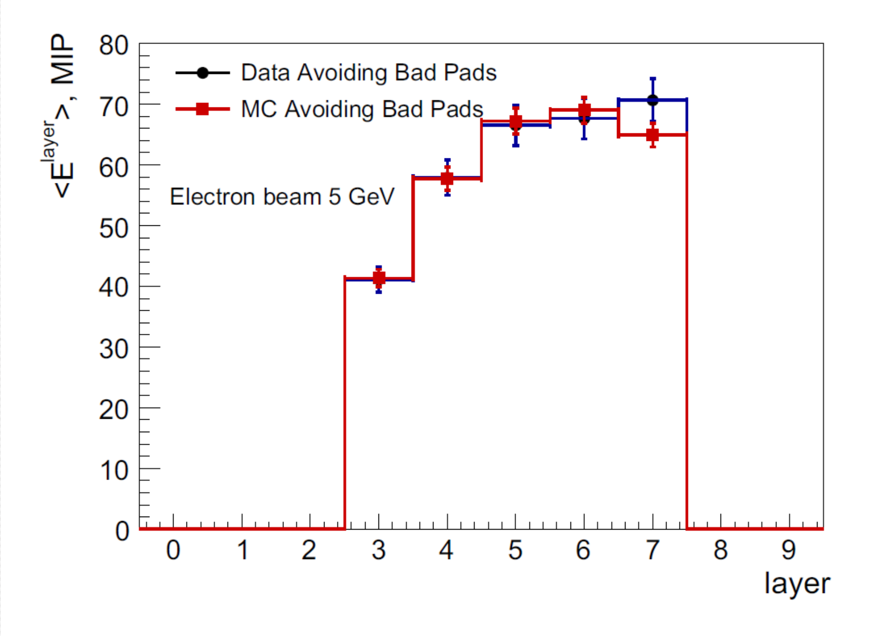
Longitudinal shower development

- Energy deposition per layer (averaged):

$$\langle E_l^{layer} \rangle = \sum_n \langle E_{nl}^{det} \rangle$$

  - Runs over radial pads *n* of the two instrumented central sectors

- Shower maximum at layer 7
- Good agreement between data and MC (within statistical uncertainties)



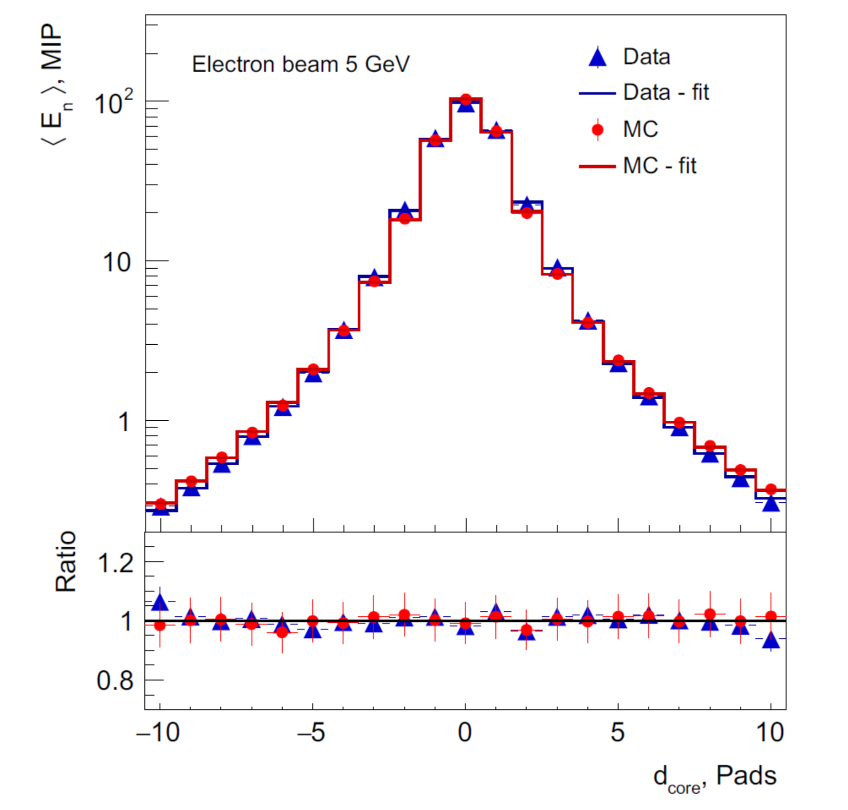
Transverse shower development

- Function used to describe (fit) the transverse profile:

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

  - Gaussian terms to describe shower core, Grindhammer-Peters term to describe the tail

- Very good agreement between data and Geant4 based MC

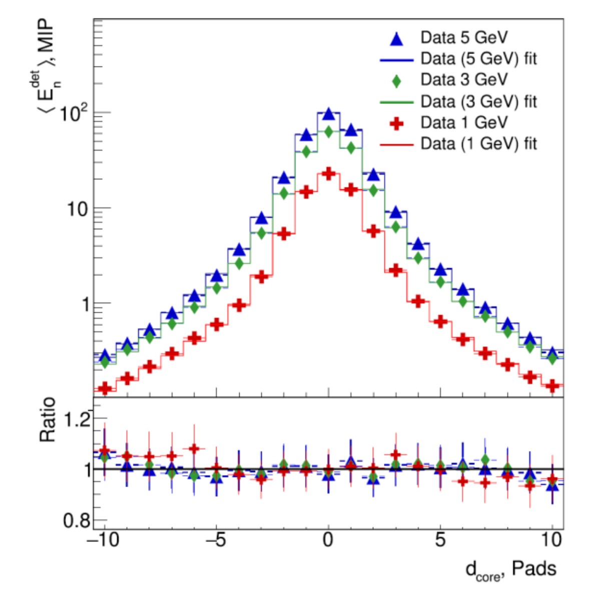


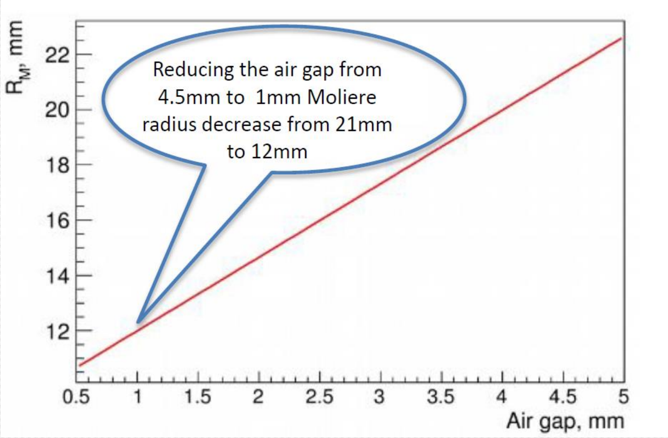
Effective Moliere radius

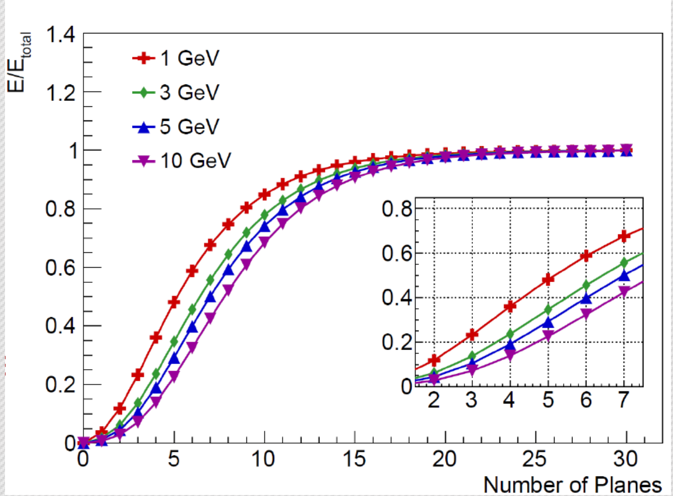
- For a prototype as a whole an *effective* Moliere radius R_M can be defined:

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

  - corresponding to the radial size within which 90% of a shower energy is contained
- Effective R_M depends a bit on electron energy due to the limited longitudinal coverage with existing number of sensor planes
- R_M also depends on the detector structure (i.e. air-gaps)
- With R_M=(8.1±0.1(stat.)±0.3(syst.))mm, feasibility of constructing a compact calorimeter is demonstrated
- Consistent with the ILC conceptual design

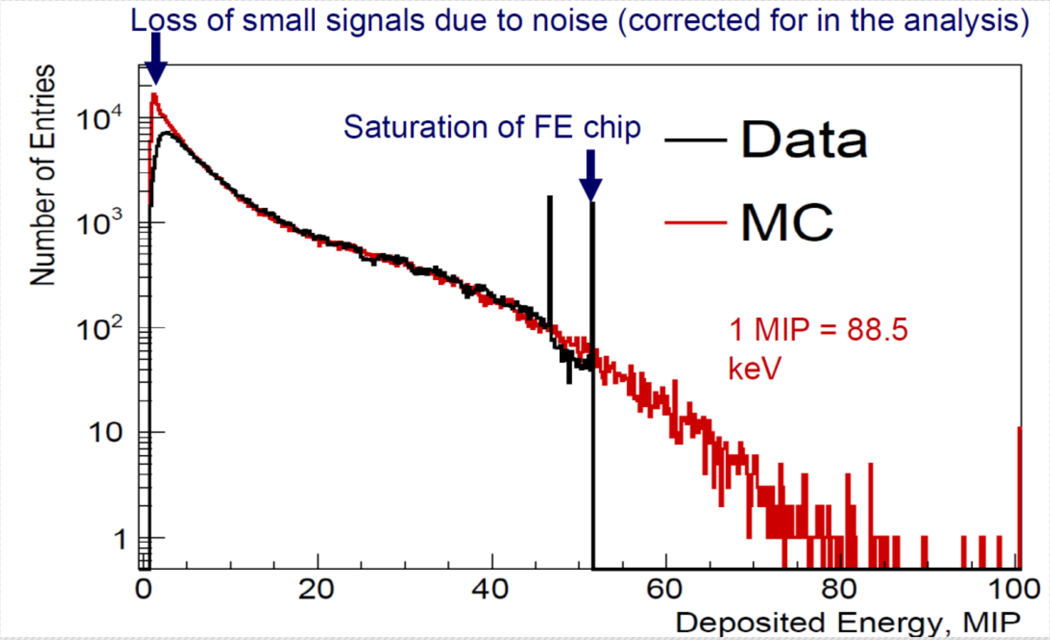






Towards the compact calorimeter prototype

- Ongoing analyses and efforts:
  - Impact of the Si-tracker planes in front of the LumiCal
  - Development of FE electronics with large input range/smaller signal
  - Maximization of the instrumented sensor area
- FLAME (FCAL ASIC for multiplane readout) development
  - 8 FLAME ASICs per plane (256 channels) ready for the test-beam
- Test-beam 2019 & 2020 goals with 20 instrumented detector planes:
  - Shower angular and energy resolution
  - Moliere radius
  - e/γ separation



FCAL is taking unique data allowing development of expertise in compact calorimetry

Summary

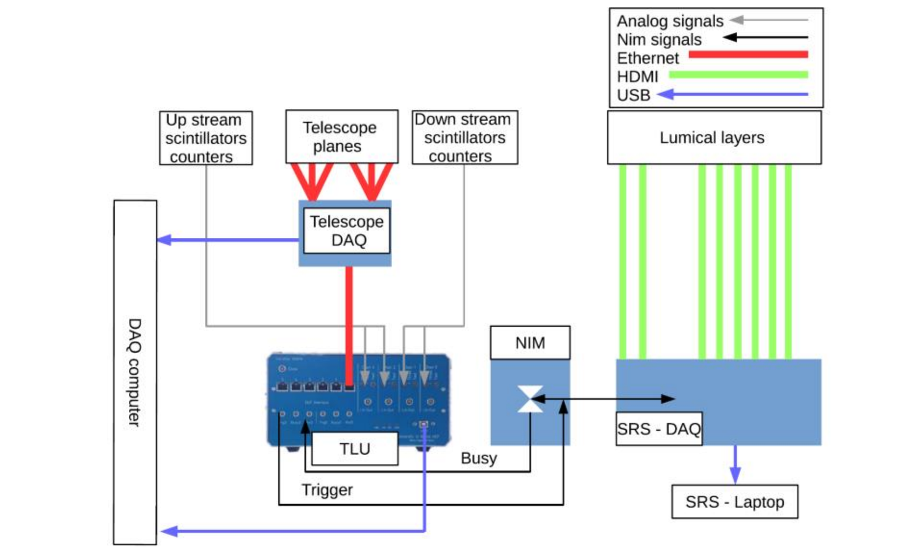
- Compact calorimeters to instrument the very forward region of an e+e- collider are designed, simulated and prototyped by the FCAL Collaboration.
- Moliere radius of R_M=8.1±0.1(stat.)±0.3(syst.) mm, measured in the test-beam, demonstrates feasibility of such a compact calorimeter. For the first time in this effort, sub-millimeter detector planes are produced.
- Detector prototype exhibited linearity of response to 1-5 GeV electron test-beam.
- Measured shower reconstruction precision and longitudinal shower development are in agreement with MC expectation.
- Further steps lead into direction of development/production of FE electronics with large input range and maximization of the instrumented sensor area (FLAME).

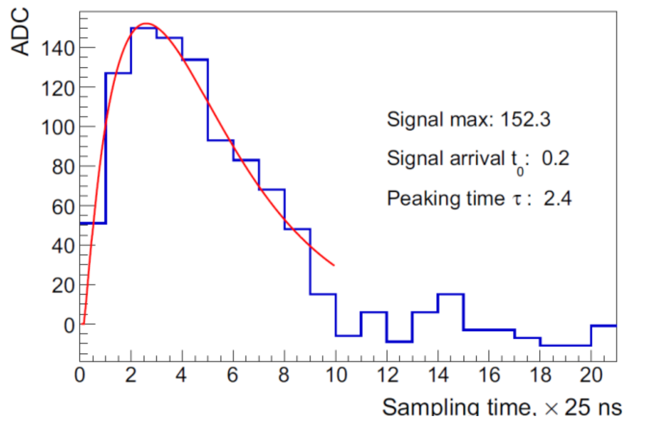
Such a calorimeter is consistent with the conceptual design optimized for a high precision luminosity measurement at ILC and CLIC

Backup

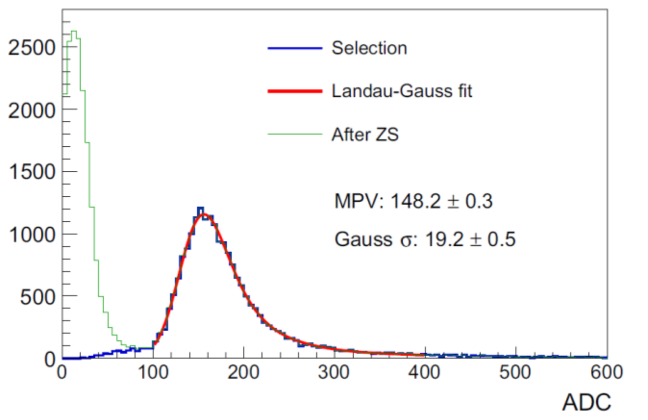
DAQ for the test-beam

- Scalable Readout System (SRS), based on APV25 front-end chip used for read-out:
  - 128 channels per detector plane
  - APV25 FE board applicable for signal >8 MIP
  - To correct for that, Capacitive Charge Divider connected to the APV input





Signal wave-form sampled in 25 ns intervals



Signal shape per single pad of a detector plane

Uncertainties of R_M

- Uncertainty of the measured efficiency of the signal identification $\pm$0.16 mm
- Uncertainty of the particle impact position $\pm$0.13mm
- Misalignment of detector planes $\pm$0.08 mm
- Uncertainty due to bad channels $\pm$0.14mm
- Noise uncertainty - negligible
- Calibration uncertainty of 5% for the APV read-out $\pm$0.14mm