Compact LumiCal prototype tests for future e^+e^- collider

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[on behalf of the FCAL Collaboration]

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Overview

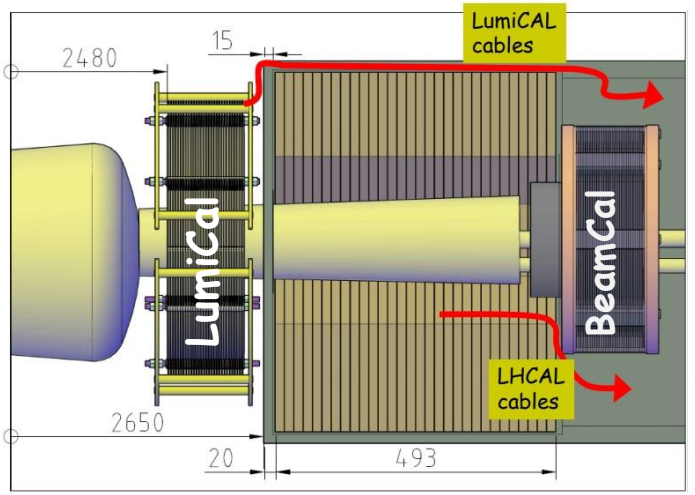
- Forward region in LC Experiments
- Thin LumiCal module design
- LumiCal prototype performance in beam-test
  - Beam-test setup
  - Results
- Conclusions and Future Steps

Forward region in LC Experiments

Two specialized calorimeters are foreseen:

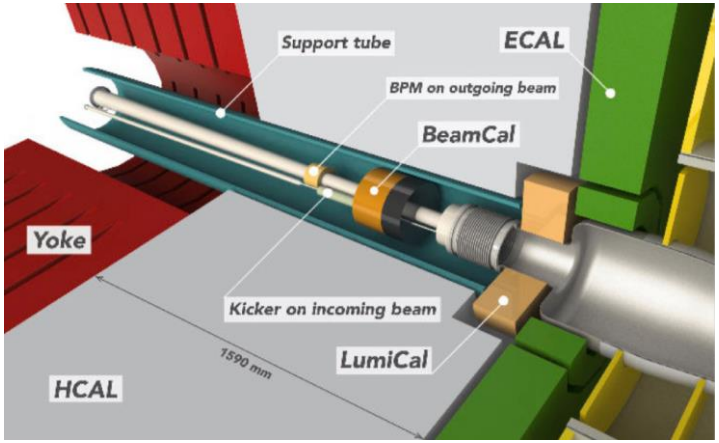
- **LumiCal** - precise integrated luminosity;
- **BeamCal** - fast luminosity estimate and beam parameters control;

Both forward calorimeters improve the hermeticity of the main detector at very small polar angles.



The very forward region of the ILD detector.

	Parameters		ILC (ILD)	CLICdet
LumiCal	geometrical acceptance	[mrad]	31 - 77	38 - 110
	fiducial acceptance	[mrad]	41 - 67	44 - 80
	z (start from IP)	[mm]	2480	2539
	number of layers (W + Si)		30	40
BeamCal	geometrical acceptance	[mrad]	5 - 40	10 - 40
	z (start from IP)	[mm]	3200	3181
	number of layers (W + sensor)		30	40



The layout of the CLICdet forward region.

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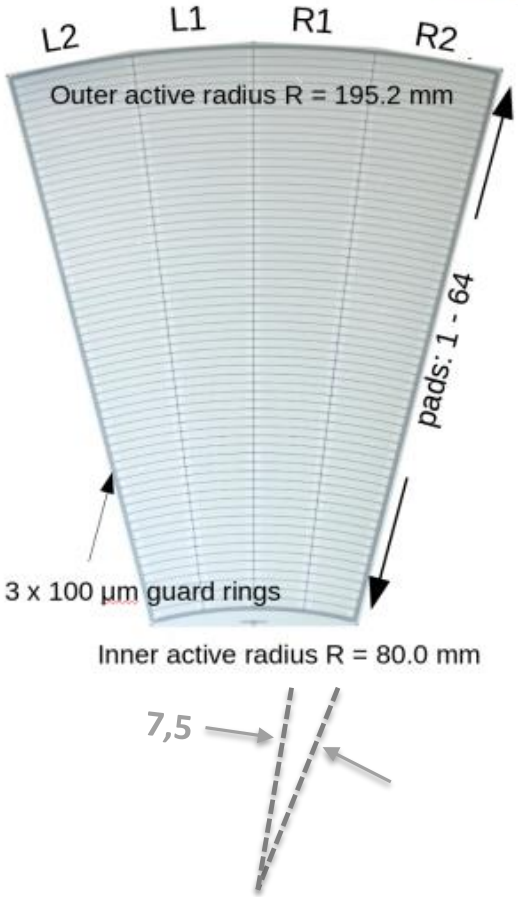
Forward region in LC Experiments

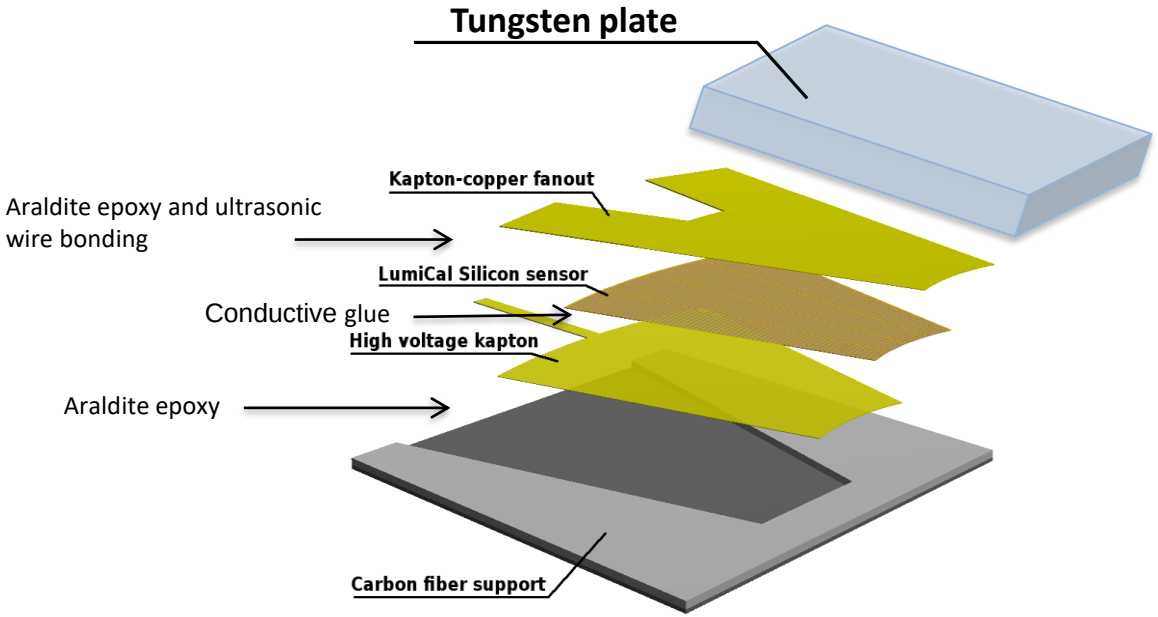
- The **LumiCal** is a Si-W electromagnetic sandwich calorimeter;
- 30 W absorber layers at ILC (40 at CLIC) interspersed with very thin detector planes;
- It is designed to measure the integrated luminosity with a precision better then 10^{-3} for ILC and 10^{-2} for CLIC;

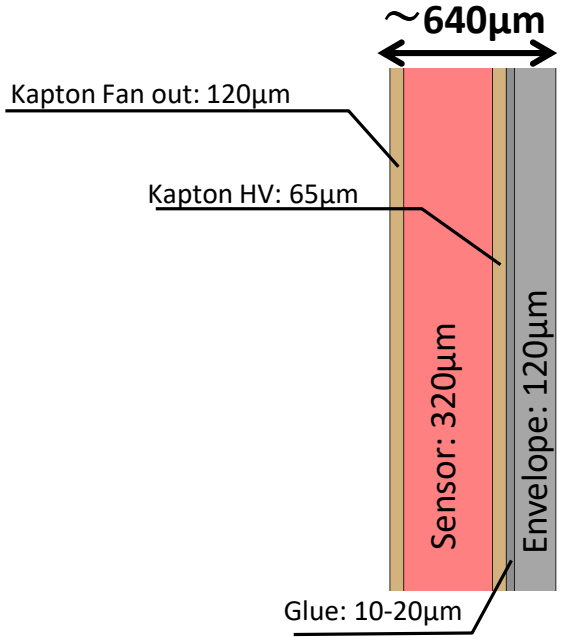
Main features of silicon sensor prototype produced by Hamamatsu:

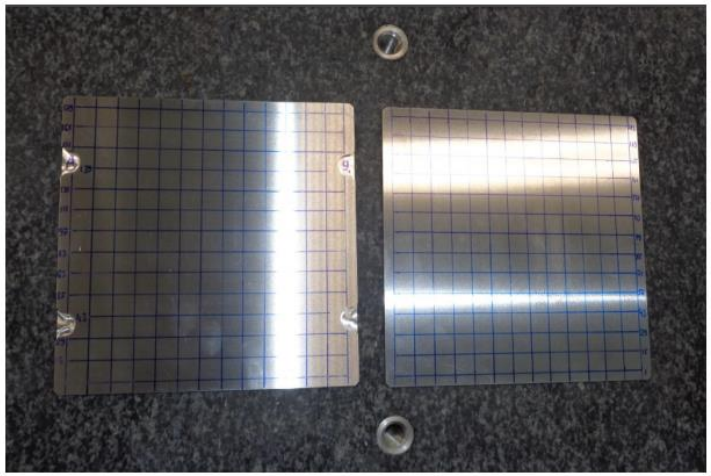
- 6-inch wafer;
- 320 μm thickness;
- 4 azimuthal sectors in one tile, each 7.5 degrees;
- Radially segmented – 64 pads with 1.8 mm pitch;
- 12 tiles make full azimuthal coverage.

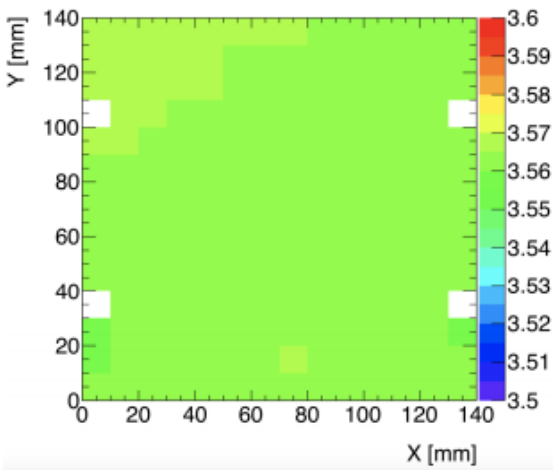


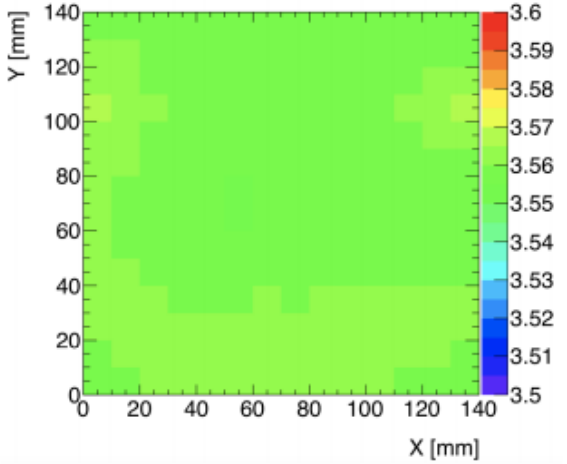
Thin LumiCal Module







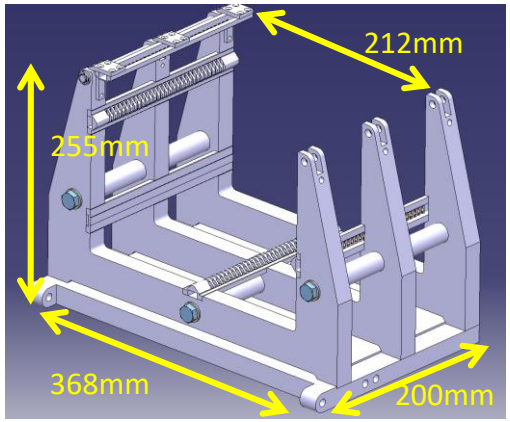




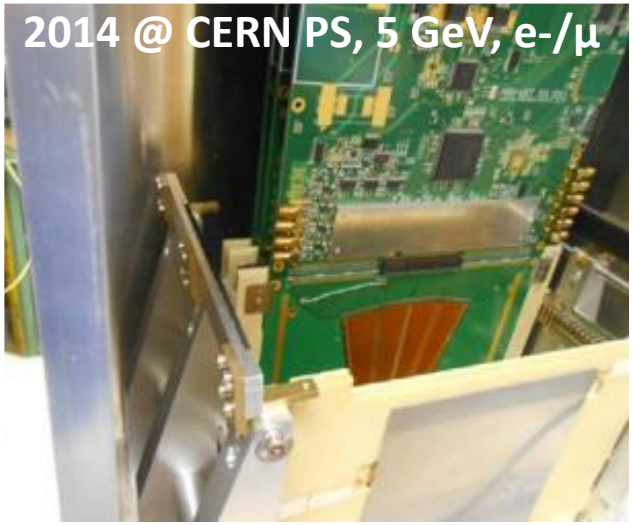
Dimensions 140 x 140 x 3.5 mm

Good flatness ~30 µm observed

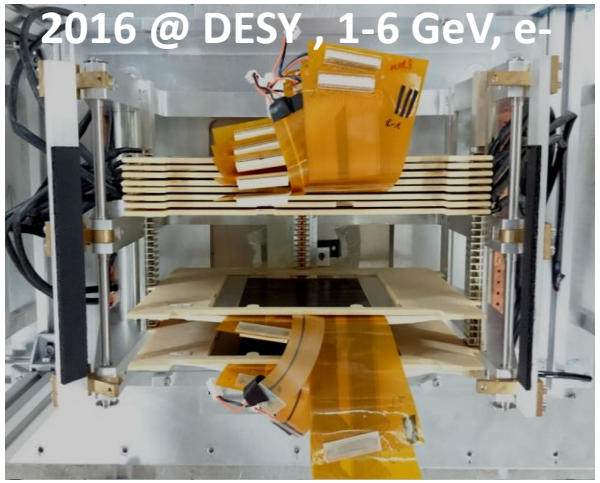
Beam-test campaigns



Mechanical frame for LumiCal detector planes



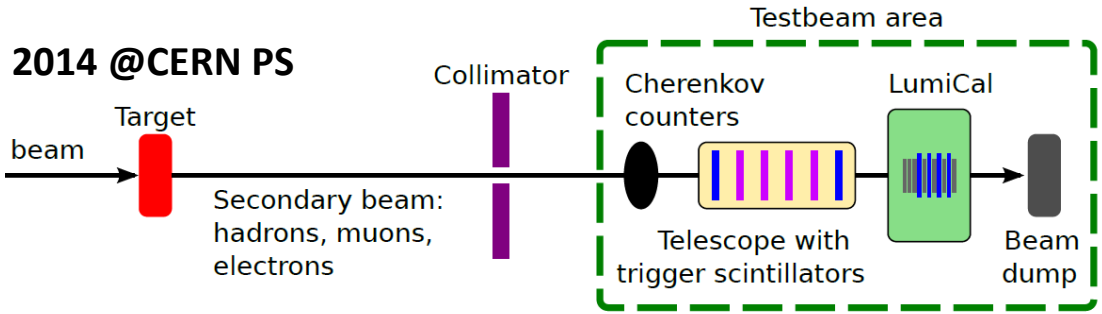
- 4 LumiCal detector planes;
- 4.5 mm between W plates;
- 8-ch. FE&ADC ASICs readout;
- 3 different configurations.

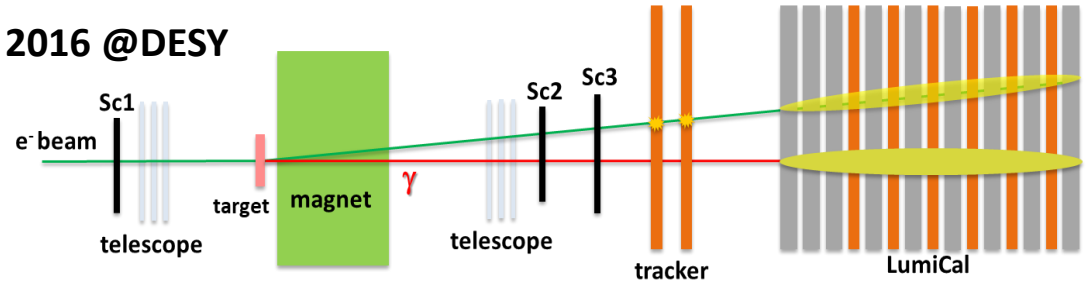


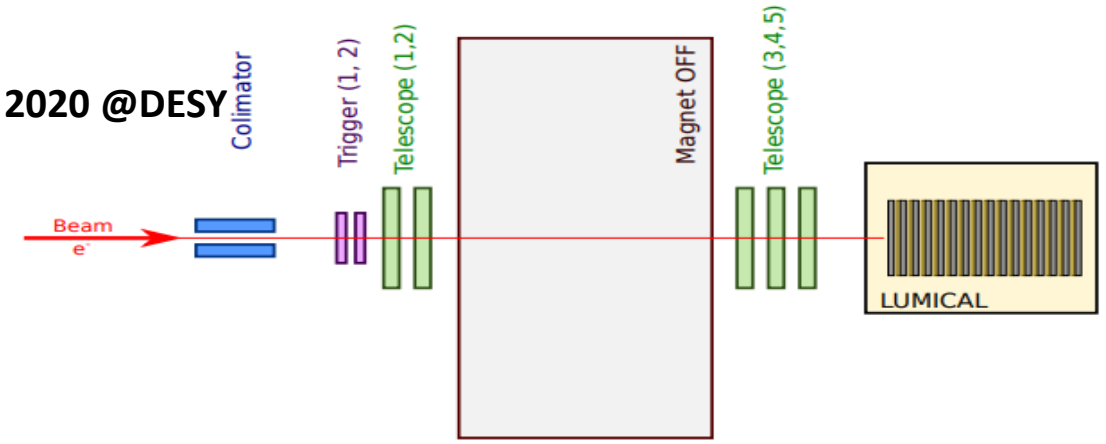
- 1st LumiCal multi-layer prototype;
- 8 LumiCal detector planes;
- APV25 readout;
- 1 mm between W plates;

- 15 LumiCal detector planes;
- FLAME readout;
- APV25 readout;
- 1 mm between W plates;

Beam-test campaigns







Goals:

- Tests and demonstration of multi-plane operation of the forward detector prototype;
- Study of the electromagnetic shower in a precise and well known structure and comparison with MC simulations;
- Measurement of Molière radius;
- Study of e-/γ identification using bremsstrahlung;
- Energy and spatial resolution studies;
- Polar angle bias study;

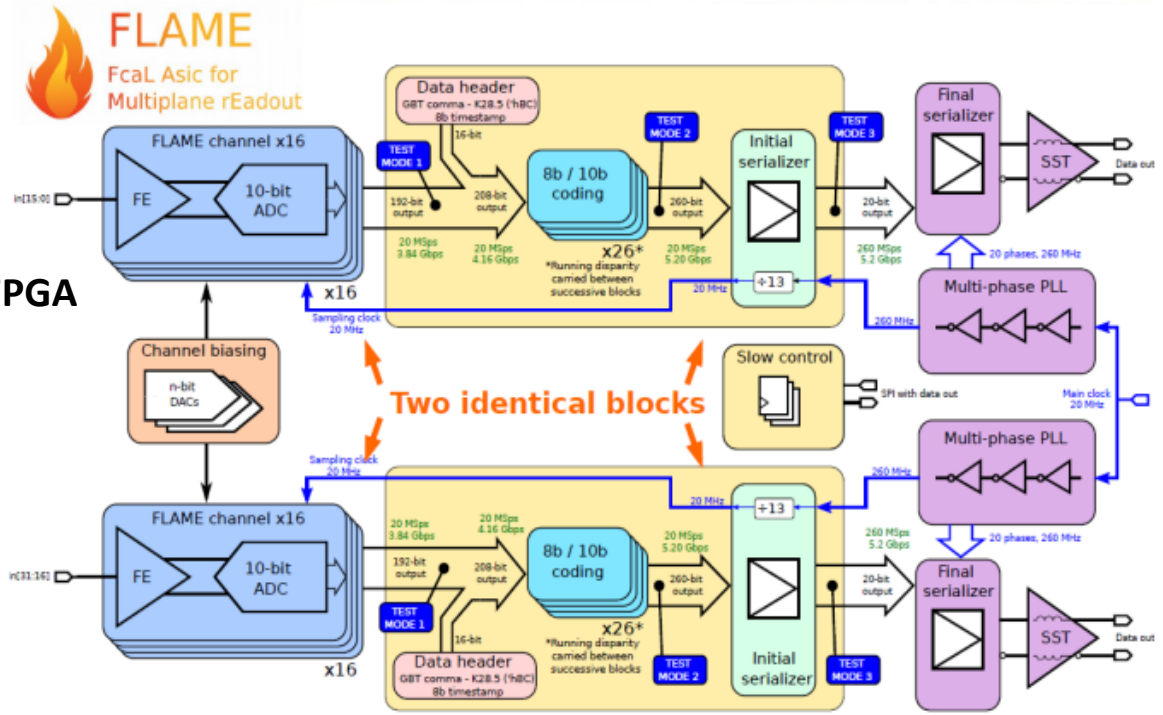
FLAME - LumiCal new readout

Architecture of **Fca**L **A**sic for **M**ultiplane r**E**adout:

- ✓ Designed in CMOS 130nm;
- ✓ 32 mix-mode channels per ASIC;
- ✓ Each channel contains FE+10 bit ADC;
- ✓ Followed by high speed data link.

Data send directly to **Zynq UltraScale FPGA** for online processing:

- ✓ pedestal, CM subtraction;
- ✓ Pulse detection;
- ✓ Deconvolution;
- ✓ ToA and amplitude reconstruction.



Analog front-end:

- ✓ Charge sensitive preamplifier with variable gain from 4fC (1 MIP) up to 6pC;
- ✓ Different CR-RC shaper – for simple amplitude and time deconvolution;
- ✓ Power consumption ~1mW.

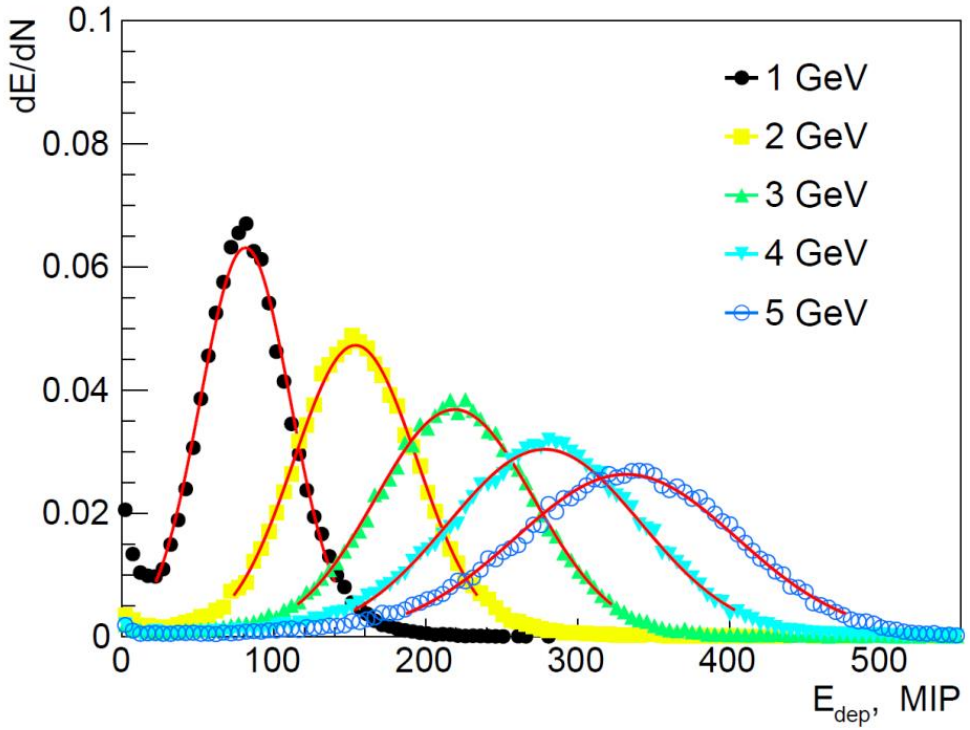
10-bit SAR ADC:

- ✓ Sampling rate 20MS/s (Max 50MS/s);
- ✓ ENOB > 9.5;
- ✓ DNL, INL < 0.5 LSB;
- ✓ Ultra low power consumption (0.5mW/ch @ 20MS/s).

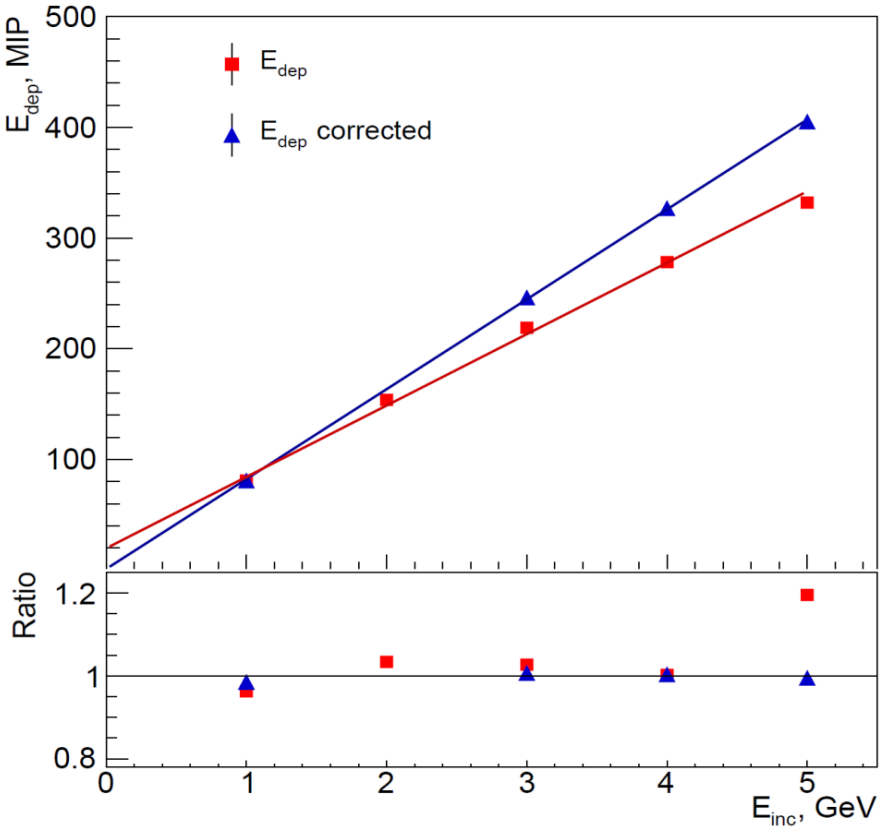
Serializer & driver:

- ✓ PLL generates 260MHz clocks from 20 MHz reference (x13);
- ✓ 5.2 Gb/s output data rate.

Results – LumiCal energy response



Energy deposited distribution in LumiCal prototype for different beam energy - fitted with Gaussian distribution function.



Average total energy deposited in LumiCal prototype as a function of beam energy before (red) and after (blue) APV25 front-end chip calibration. The lower part shows the ratio of the E_{dep} to the straight line.

Results – transverse shower

- The function used to describe the average transverse energy profile of the shower is:

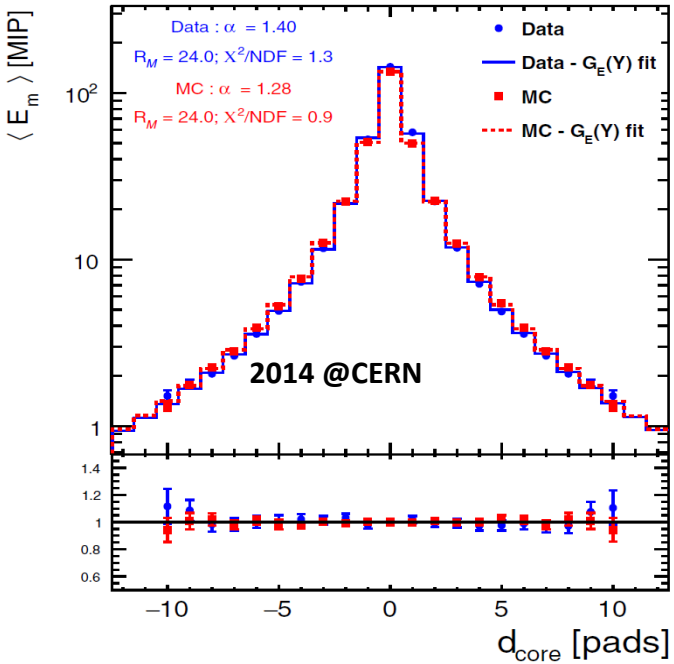
$$F_E(r) = A_C e^{-\left(\frac{r}{R_C}\right)^2} + A_T \frac{2r^{\propto} R_T^2}{\left(r^2 + R_T^2\right)^2} \qquad (1)$$

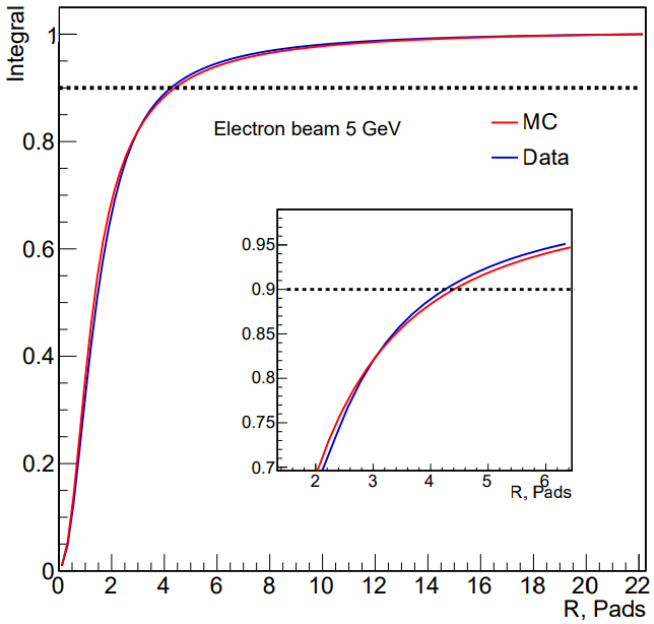
where: r is the distance from the shower center; A_C; A_T; R_C; R_T ; α are the fit parameters.

- The fitting range corresponds to the area connected to readout.
- The parameters of $F_E(r)$ are fixed by both test-beam data and MC simulation.
- The Molière radius, R_M, is a characteristic constant of a stack of materials. By definition, it is the radius of a cylinder with axis coinciding with the shower axis, containing on average 90% of the energy deposition of the shower.
- The Molière radius, R_M, can be found from the equation:

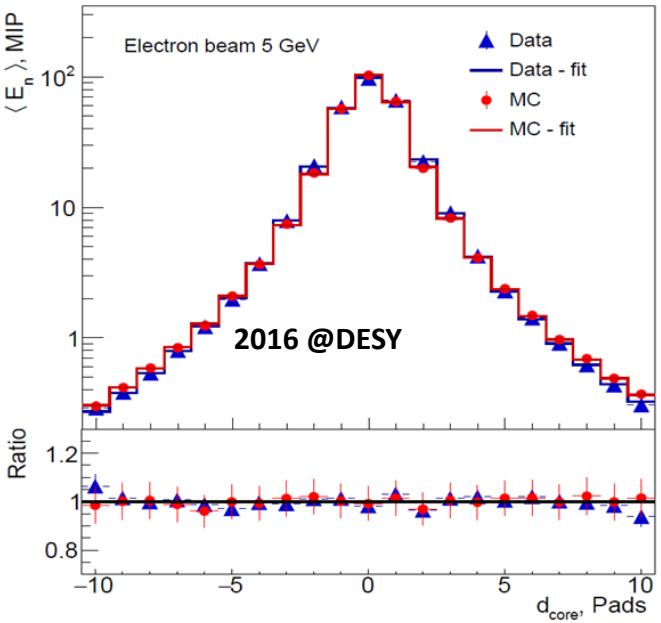
$$0.9 = \int_0^{2\pi} d\varphi \int_0^{R_M} F_E(r)\, r dr \qquad (2)$$

Results – transverse shower





The integral on $F_E(r)$, that was extracted from the fit, as a function of the radius, R, in units of pads (1,8mm). The insert shows an expanded view of the region 2 < R < 6 pads



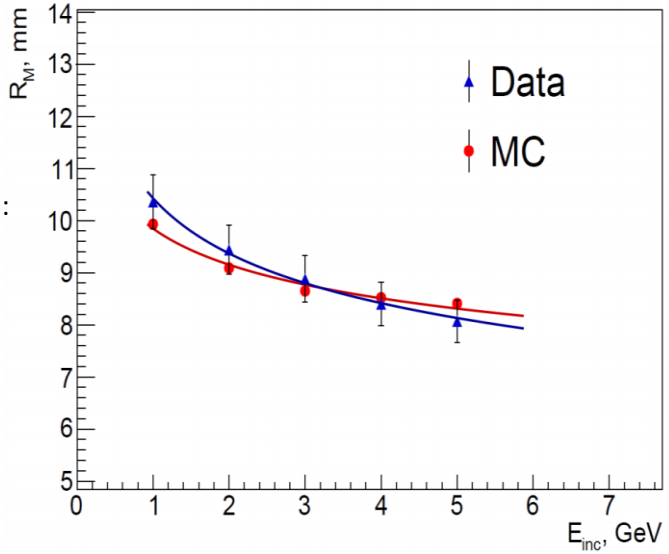
The effective R_M has been determined:

2014@CERN [*Eur. Phys. J. C (2018) 78:135*]:

- **R_M= 24.0 ± 0.6 (stat.) ± 1.5 (syst.) mm,**

2016@DESY [*Eur. Phys. J. C79 (2019) 579*]:

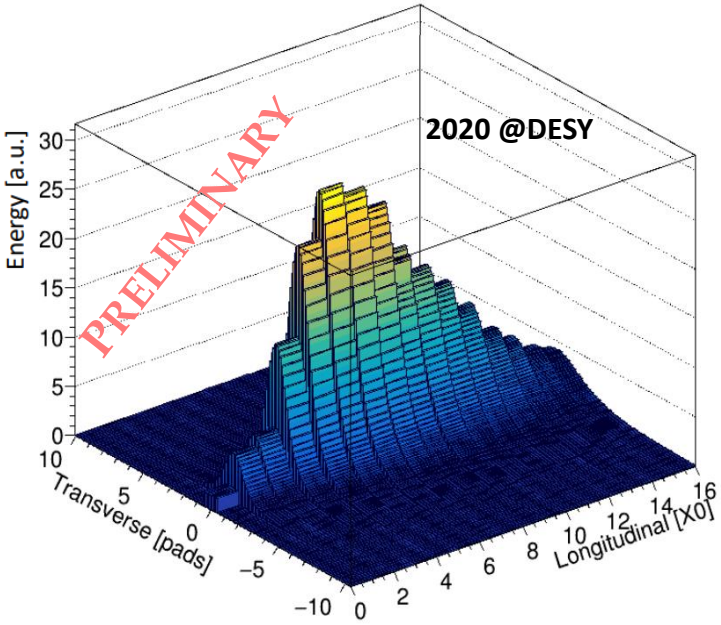
- **R_M = 8.1 ± 0.1 (stat) ± 0.3 (syst)) mm**



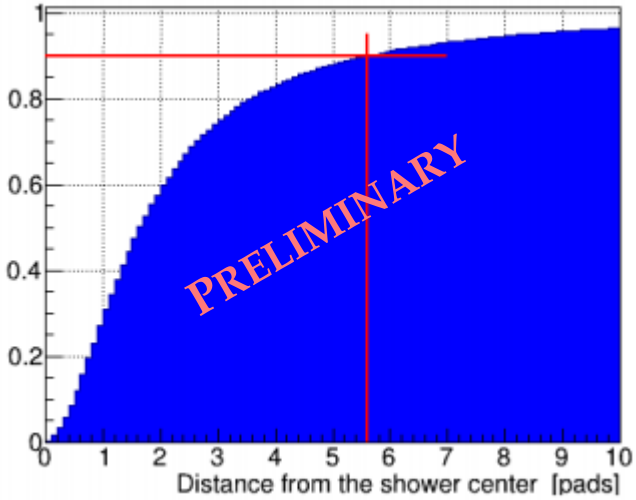
The effective Moli`ere radius as a function of the e⁻ energy for data (blue) and simulation (red).

Results – transverse shower

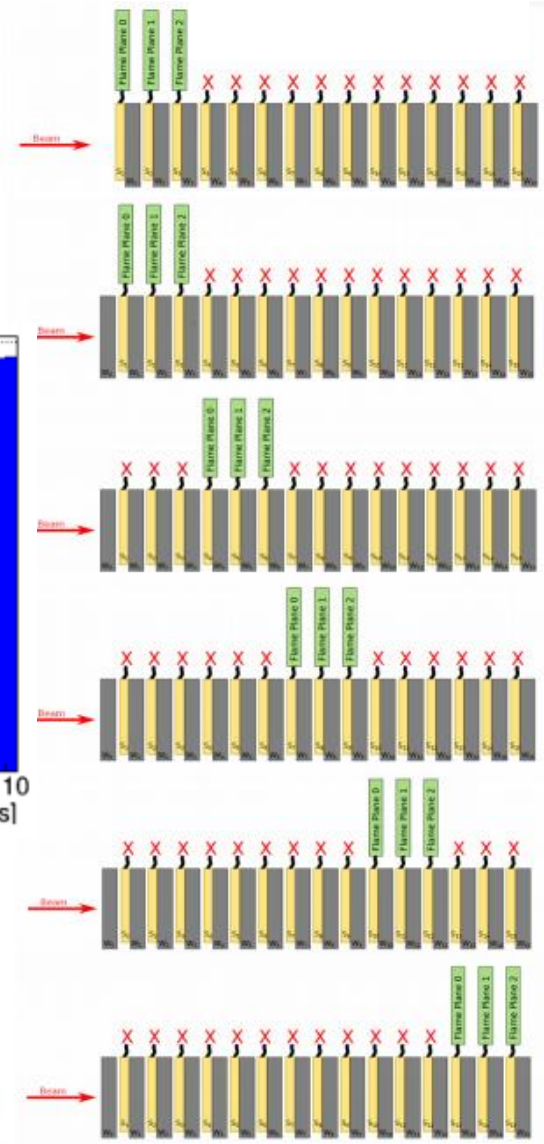
6 configurations has been done to study the shower development in the entire calorimeter using only 3 FLAME boards, the boards were successively connected to the different sensor layers.



A lego plot of the transvers profile for each layer from the beam-test data



The integral on $F_E(r)$, that was extracted from the fit, as a function of the distance in units of pads (1,8mm) for 5 GeV e- beam.



LumiCal stack configurations

The effective Moli`ere radius has been estimated to be **10.1 mm (5.6 pads)**

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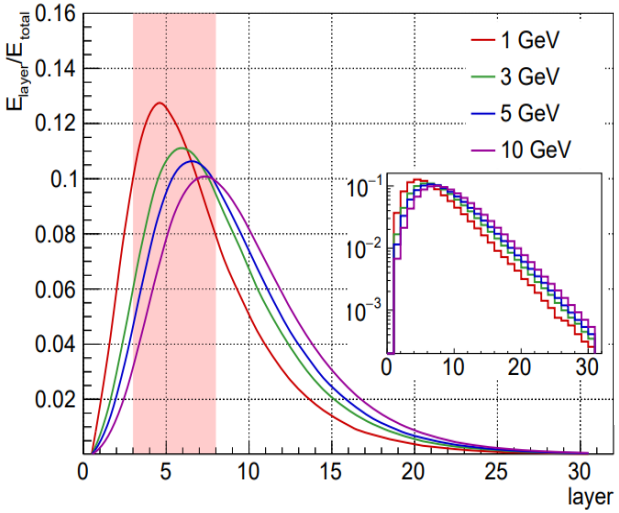
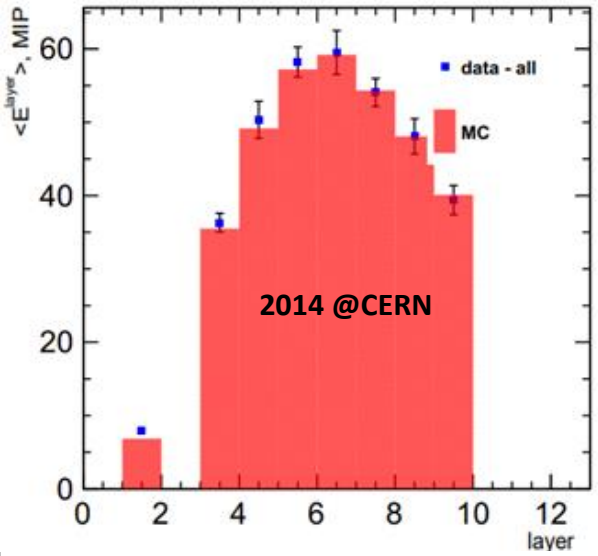
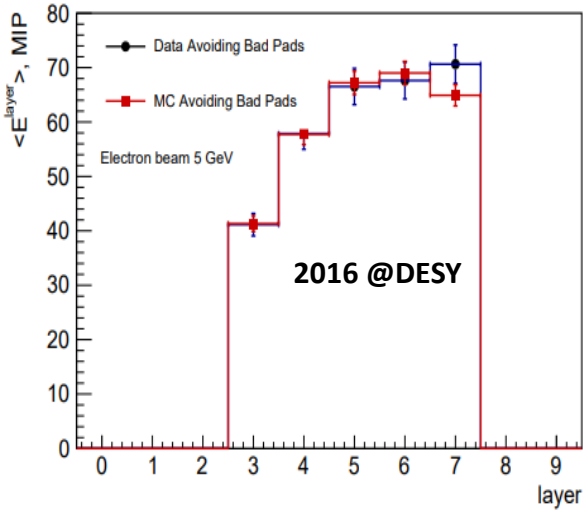
Results – longitudinal shower

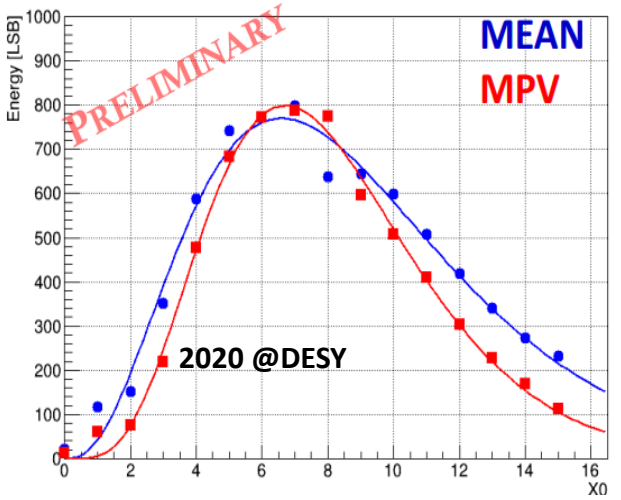


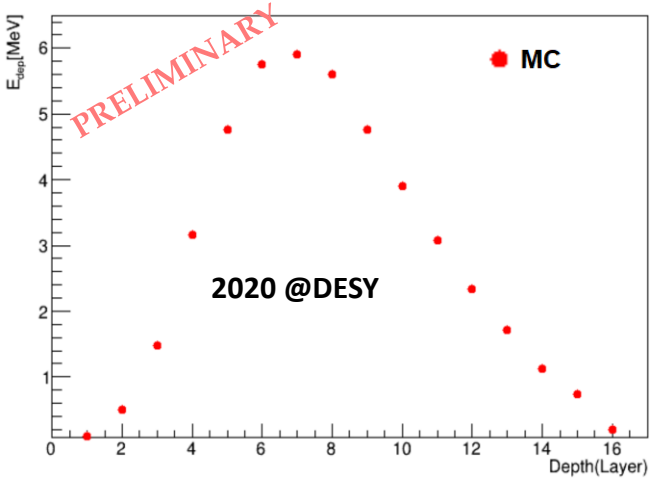
Normalised longitudinal shower profile for different electron energies obtained in simulation. The inset shows the same profiles in a logarithmic scale.





Longitudinal shower profile, comparison between data and simulation.





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Conclusions and Future Steps

- Major components developed by FCAL Collaboration can be operated as a system in the future LC experiments.
- The FCAL collaboration continues the detector R&D and forward region design optimisation.
- Thin LumiCal module with submillimeter thickness was developed and produced. Its geometry meets requirements of LumiCal conceptual design.
- Dedicated FLAME readout ASIC together with FPGA back-end were developed and for the first time tested on beam.
- Results from the test of the compact calorimeter demonstrator are promising.
- Analysis of data and MC from the full compact calorimeter prototype test beam is ongoing.
- Technologies developed in FCAL are applied in other experiments, e.g. CMS, XFEL and considered for LUXE at DESY.

THANK YOU FOR YOUR ATTENTION

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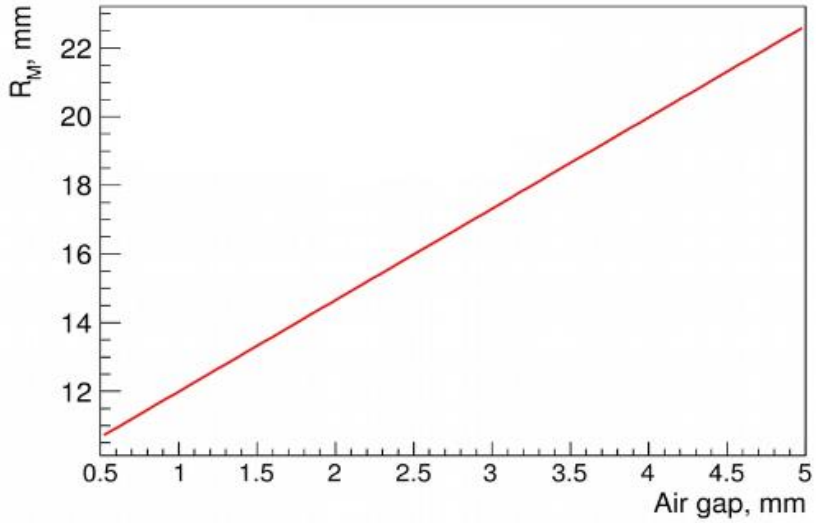
Back up slides

- The transverse size of the shower is characterized by the Molière radius and it can be estimated using the following formula:

$$\frac{1}{R_M} = \frac{1}{E_S}\sum \frac{w_j E_{cj}}{X_{0j}} = \sum \frac{w_j}{R_{Mj}}$$



R_M of a stack of $1X_0$ tungsten absorber plates as a function of the air gap between them