Overview of FCAL

The CEPC MDI Workshop

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KINR & DESY
On behalf of the FCAL collaboration

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Outline

- Introduction
- design of the very forward region of e+e- collider experiments
- radiation hard solid state sensors
- performance tests of prototype detectors in the beam
- dedicated front-end and ADC ASICs
- FCAL Spin offs
- Summary & Outlook

- FCAL Collaboration
- FCAL detectors
- Luminosity measurements
- LumiCal Silicon Sensors
- LumiCal beam tests 2014-2020
- BeamCal
- New readout ASIC for LumiCal -FLAME
- BeamCal ASIC

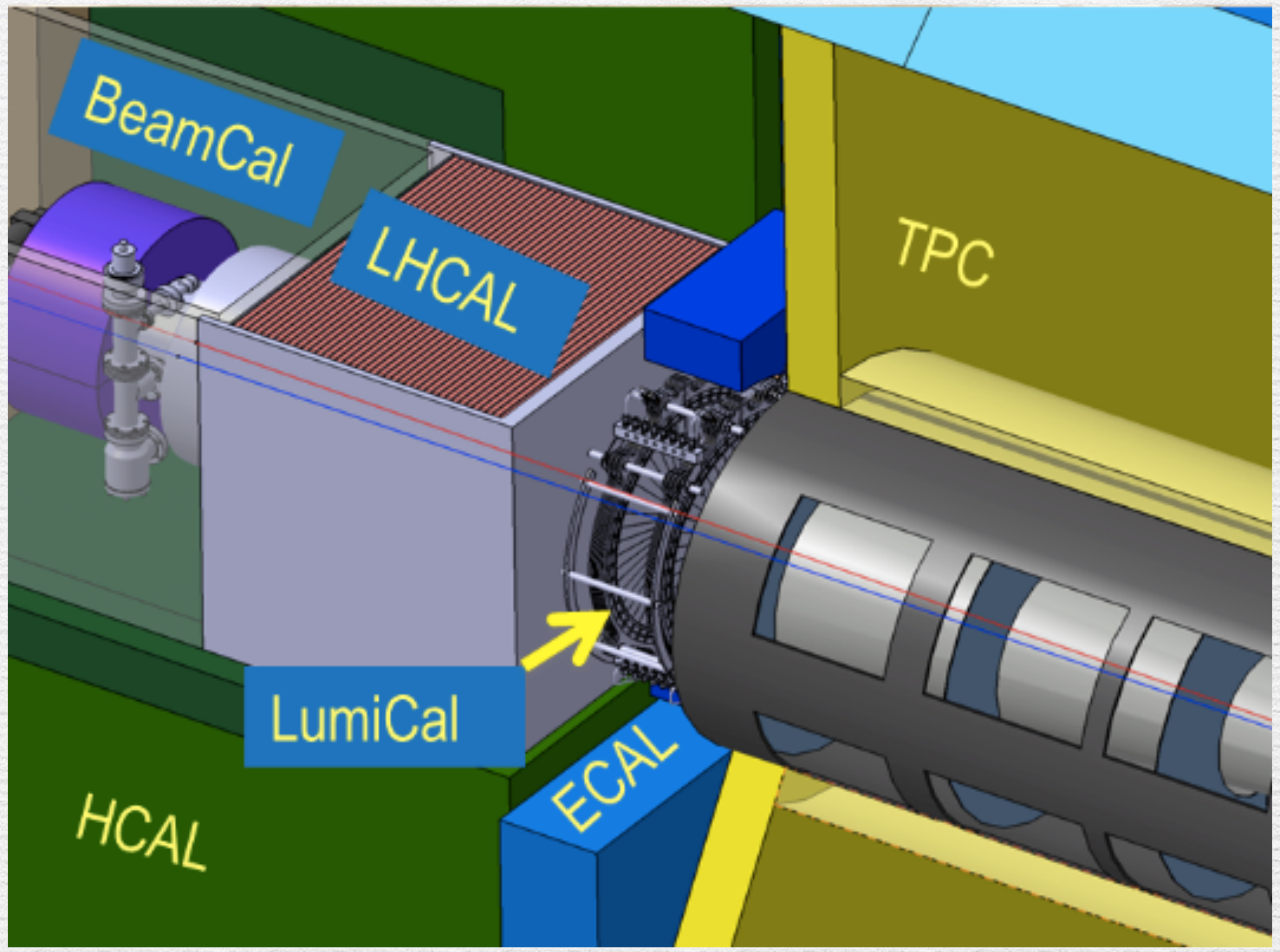
FCAL Collaboration

FCAL is a worldwide detector Research & Development collaboration.

~ 70 physicists join their effort to develop the technologies of special calorimeters in the very forward region of future experiments at e+e- colliders

FCAL collaborates with the Detector Concepts ILD and SiD of the ILC and works together with CLICdp, and now may consider luminometers for the CEPC detector.

FCAL detectors in LC Experiments



LumiCal

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

Design

- electromagnetic sampling calorimeter;
- 30 (40 for CLIC) 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 for ILD.

BeamCal

- Complete the coverage of e.m. calorimetry down to very small angles to reject SM backgrounds w/ far-forward activity;
- Bunch-by-bunch luminosity measurements;
- Beam diagnostics and tuning;
- similar construction, with tungsten absorber but radiation hard sensors (GaAs, CVD diamond)

LHCal

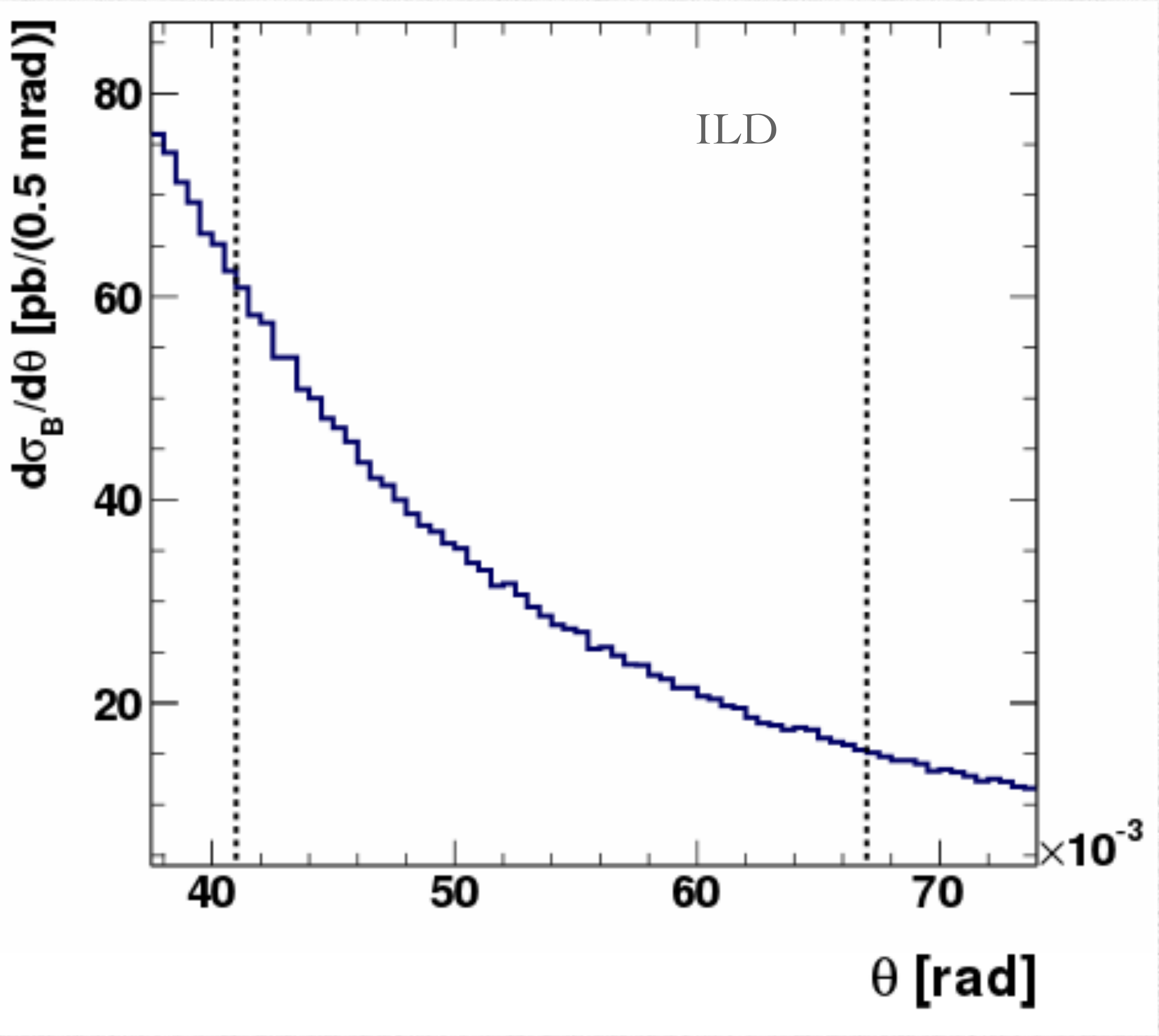
- extends the coverage of HCAL;
- Sampling calorimeter (silicon)
- 29 layers of 16mm thickness. Absorber : tungsten or iron

Luminosity measurement

- The luminosity at an e+e- collider can be measured by counting number N_B of Bhabha events in a certain polar angle (θ) range of the elastically scattered electron.

$$L = \frac{N_B}{\sigma_B}$$

σ_B – integral of the differential cross section over the same θ range.



LumiCal (ILD) fiducial volume: 41 < θ < 67 mrad

The cross section of the Bhabha process can be precisely calculated.
In leading order:

$$\frac{d\sigma_B}{d\theta} = \frac{2\pi\alpha_{em}^2}{s} \frac{\sin\theta}{\sin^4(\theta/2)} \approx \frac{32\pi\alpha_{em}^2}{s} \frac{1}{\theta^3},$$

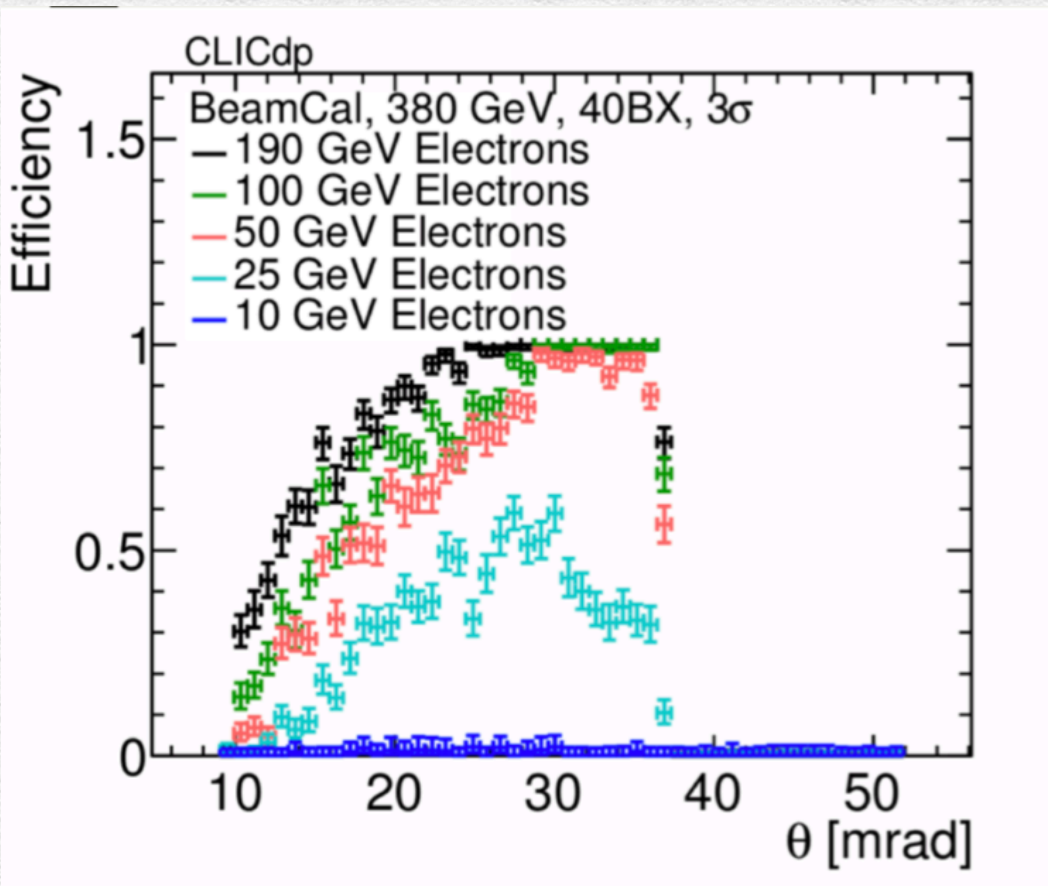
the approximation holds at small θ.

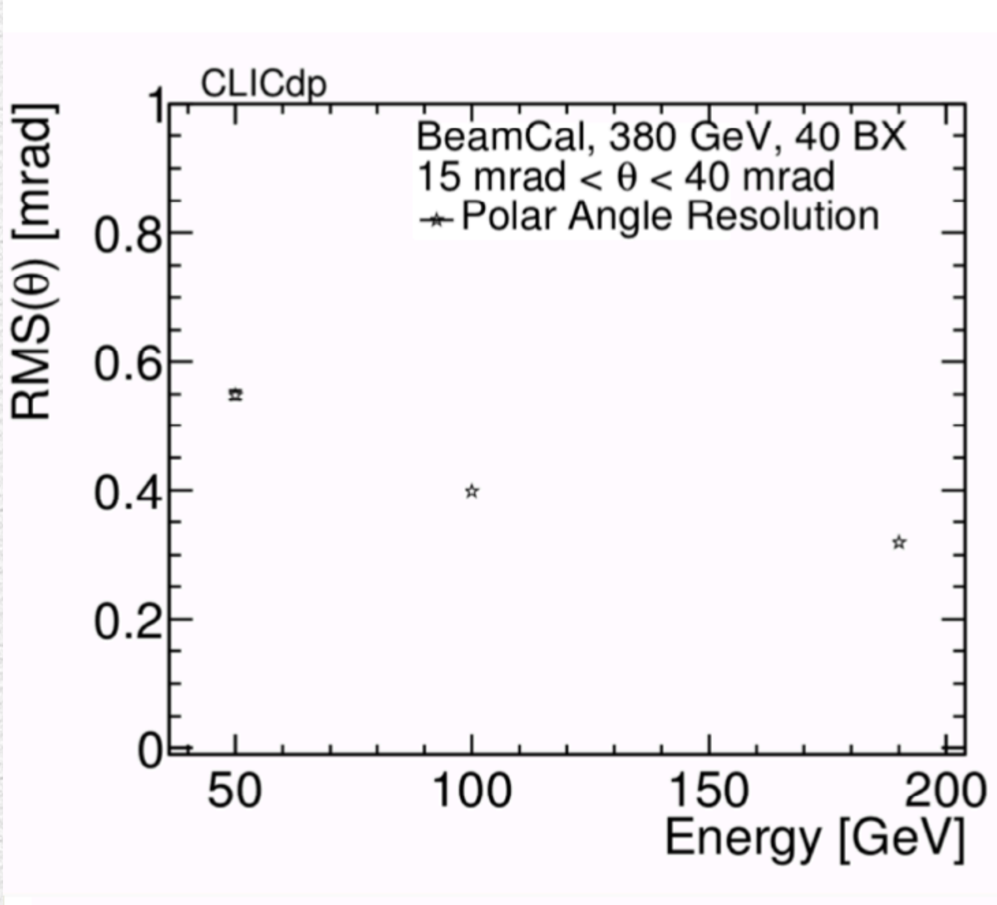
The scattered electrons are distributed in the forward direction with a $1/\theta^3$ dependence.

α is the fine-structure constant, s - center-of-mass energy squared.

Optimisation of the design of the very forward region using Monte Carlo simulations

CLICdp-Note-2018-005





- BeamCal

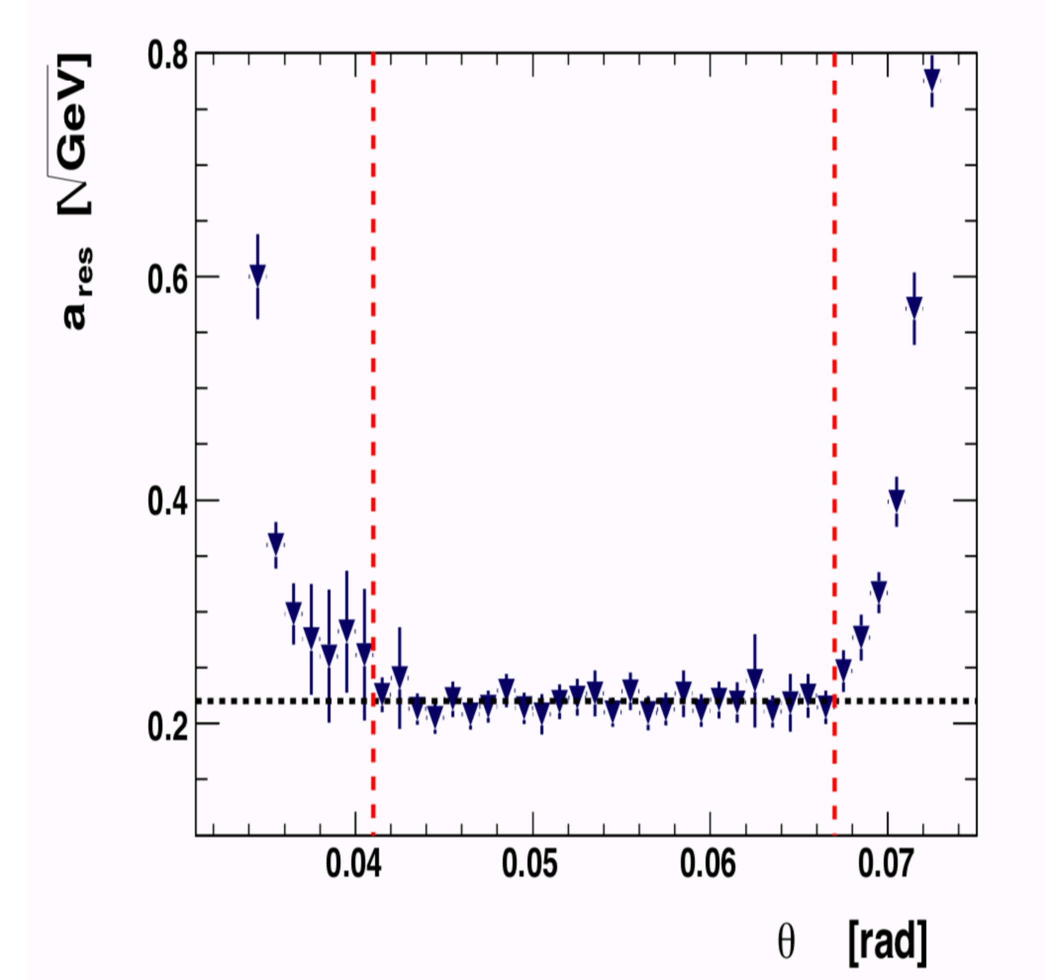
- Cover the polar angles from 10 mrad (CLIC)/6 mrad (ILC) to 43 mrad
- background simulated for different beam parameters and magnetic fields and different reconstruction algorithms compared

- LumiCal

- Cover the angles between 41 mrad to 67 mrad (ILC)
- Sensor segmentation is optimised to obtain the given precision of luminosity measurement

- LHCal

- Located between the LumiCal and BeamCal
  Total thickness : 463 mm
- Simulation of W-Si and Fe-Si with different incident particles



H Abramowicz *et al* 2010 *JINST* 5 P12002

Simulation outcome

- Bigger fiducial volume => higher statistics on Bhabha events
- The smaller Molière Radius => the bigger fiducial volume
- Compact Calorimeter => Smaller Molière Radius
- High energy resolution to correctly identify Bhabha events
- Smaller Molière Radius => higher efficiency of electron detection over low energy background (relevant for BeamCal)
- Radiation hardness of sensors (more relevant for BeamCal)

LumiCal silicon sensor

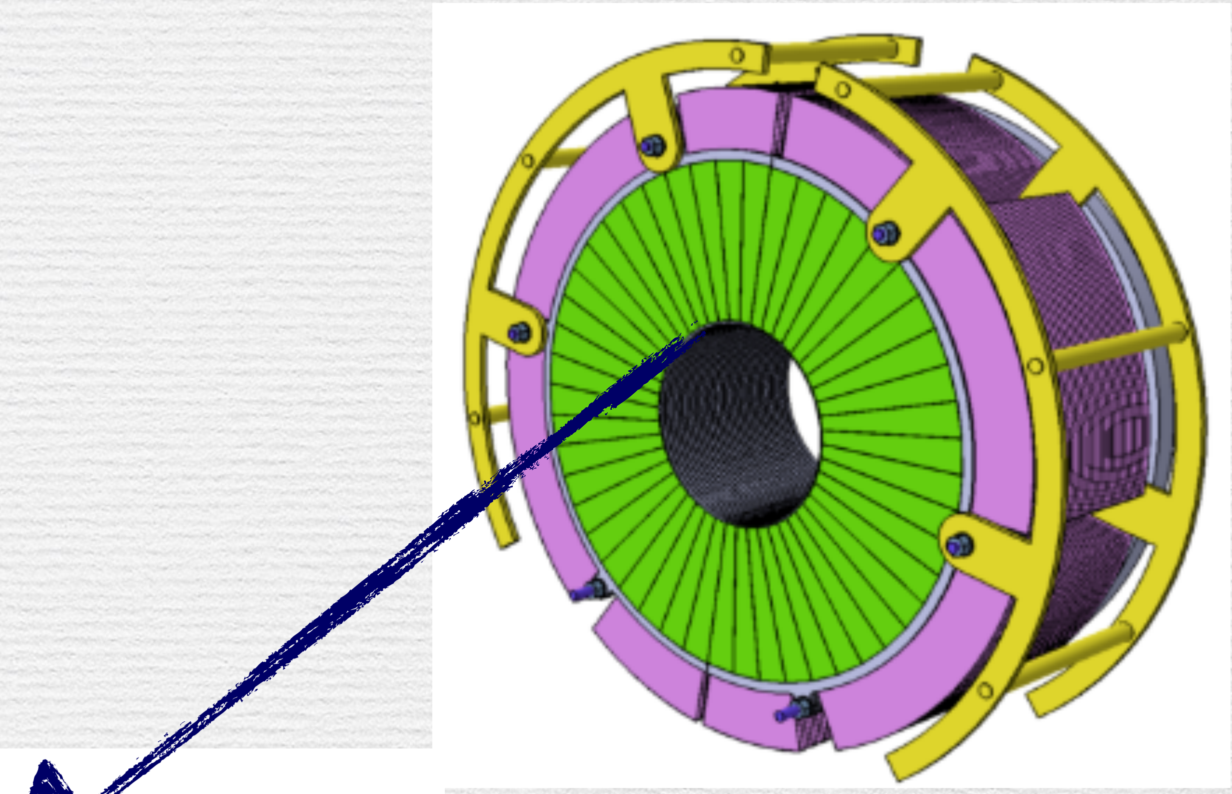
LumiCal is a Si-W electromagnetic sampling calorimeter

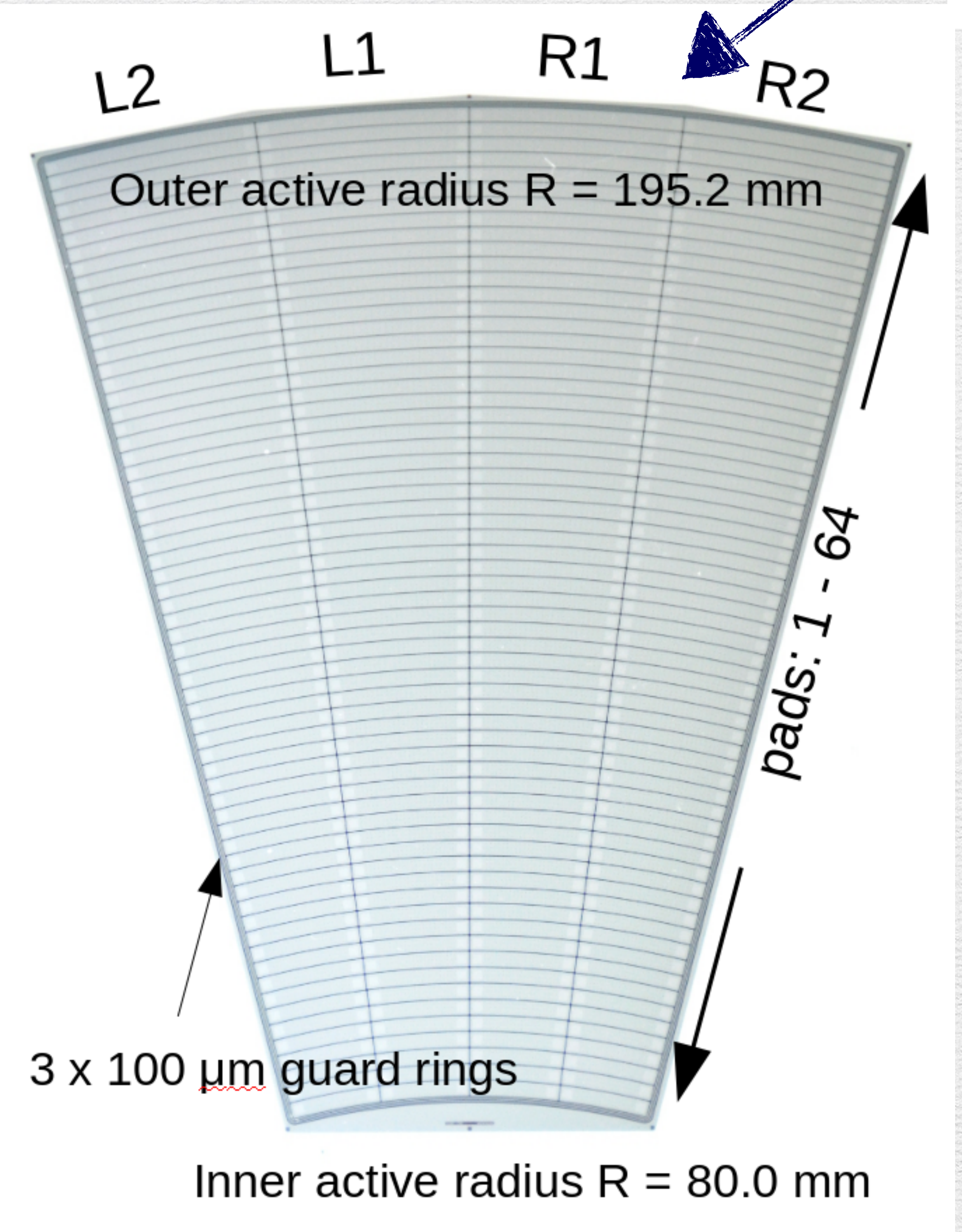
- Compact design provides
- small Molière radius;
- bigger fiducial volume;
- better HE particle detection on top of background.

- Challenging requirements on geometrical compactness

Silicon pad sensor prototype is designed for ILD; produced by Hamamatsu

- 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



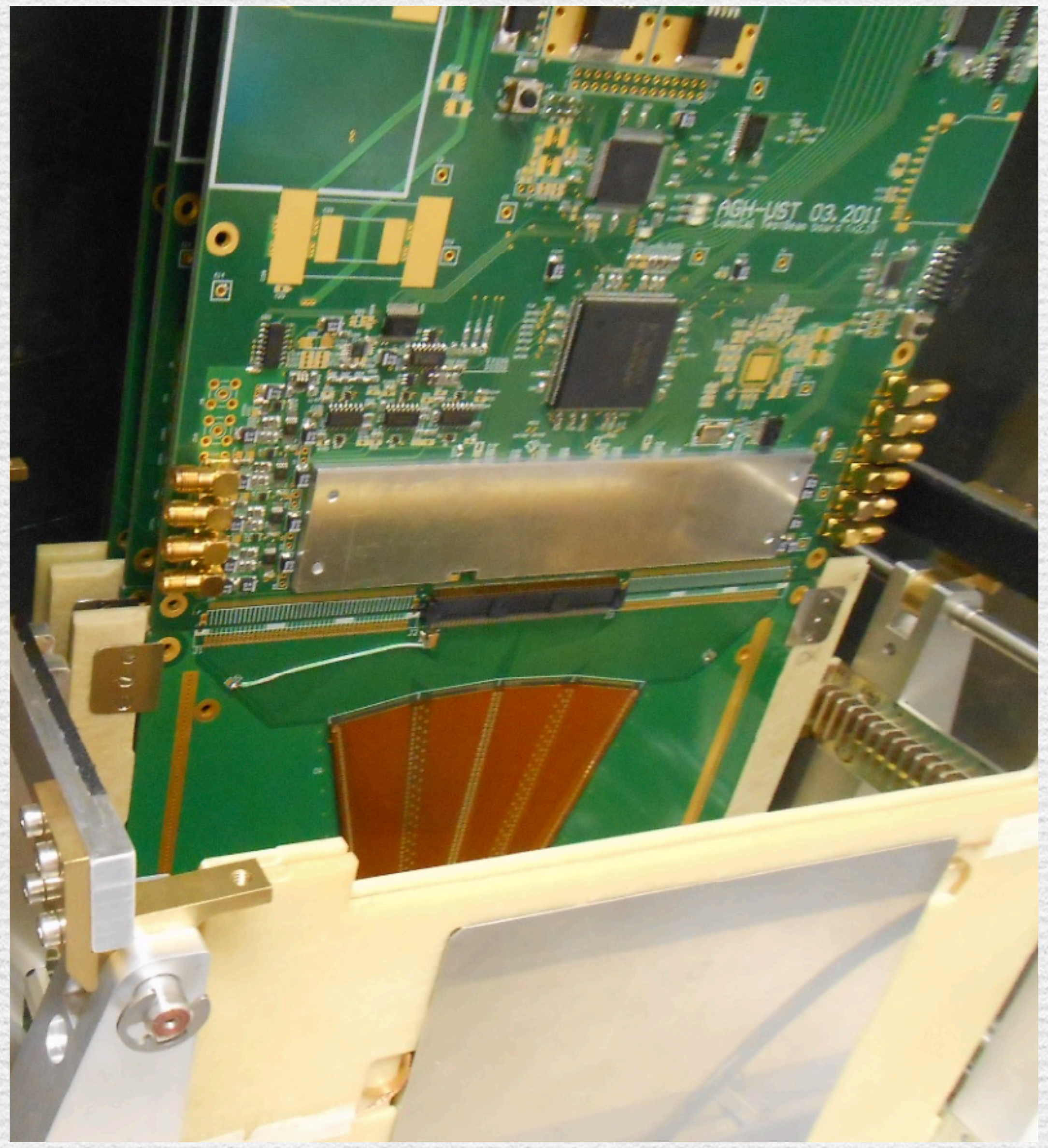


Designed in IFJ PAN Cracow

performance tests of prototype detectors in the beam

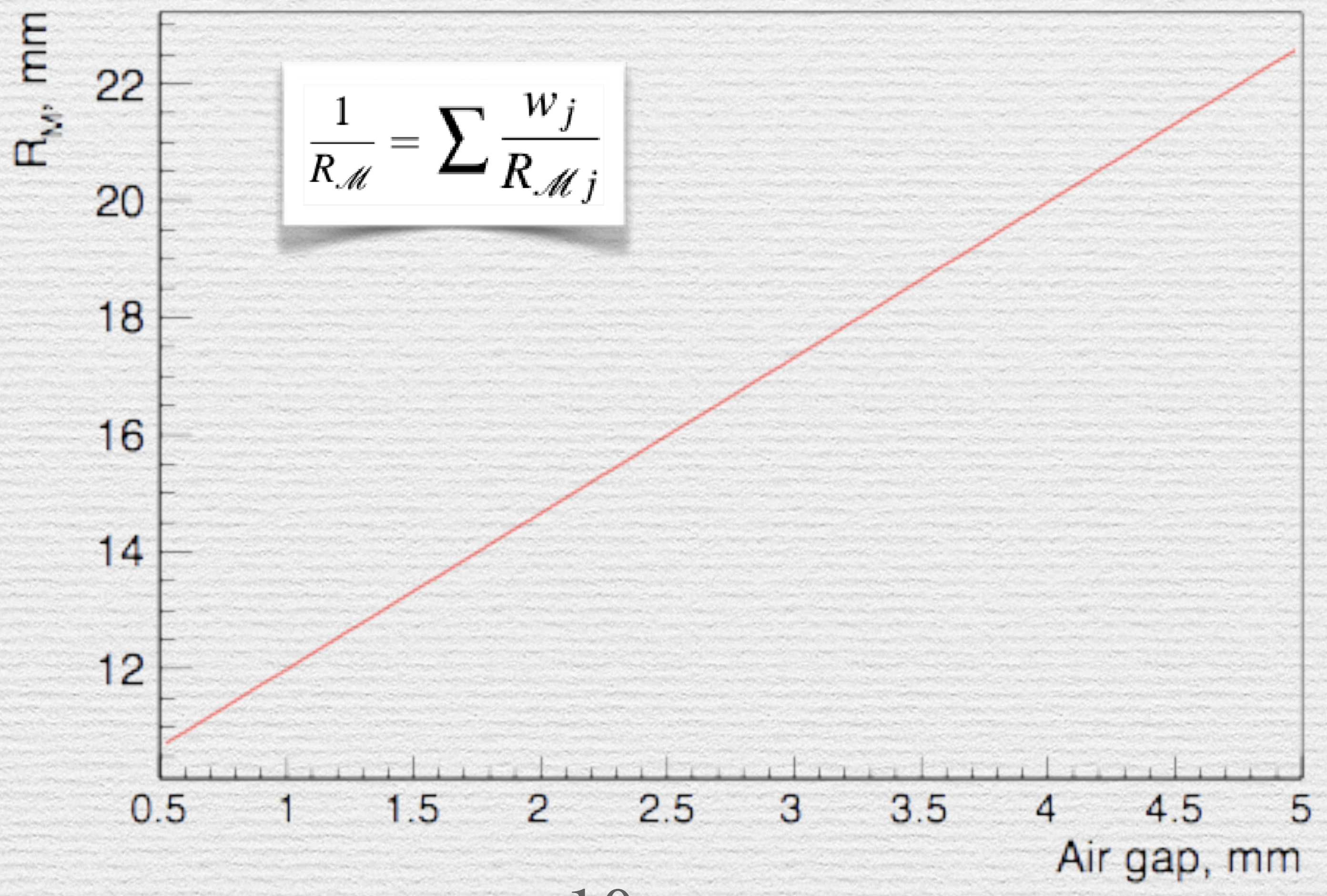
2014 Test Beam at CERN

- Test of multi-detector plane operation
- Transversal and longitudinal shower measurement, data MC comparison
- Molière radius



- 4 LumiCal detector planes equipped with dedicated electronics (32 channels)
- 4.5 mm between tungsten plates
- Tested in test beam at PS with 5 GeV e-/μ

The importance of the gap size between absorber layers in the calorimeter design on the Molière radius



$R_{\mathcal{M}}$ as function of the air gap between 3.5 mm thick tungsten plates

Reducing air gap from 4.5 mm to 1 mm gives $R_{\mathcal{M}}$: 21 mm -> 12 mm

Shower Study in Transverse Plane for 2014

The sensor geometry doesn't allow direct measurement of transverse shower development

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

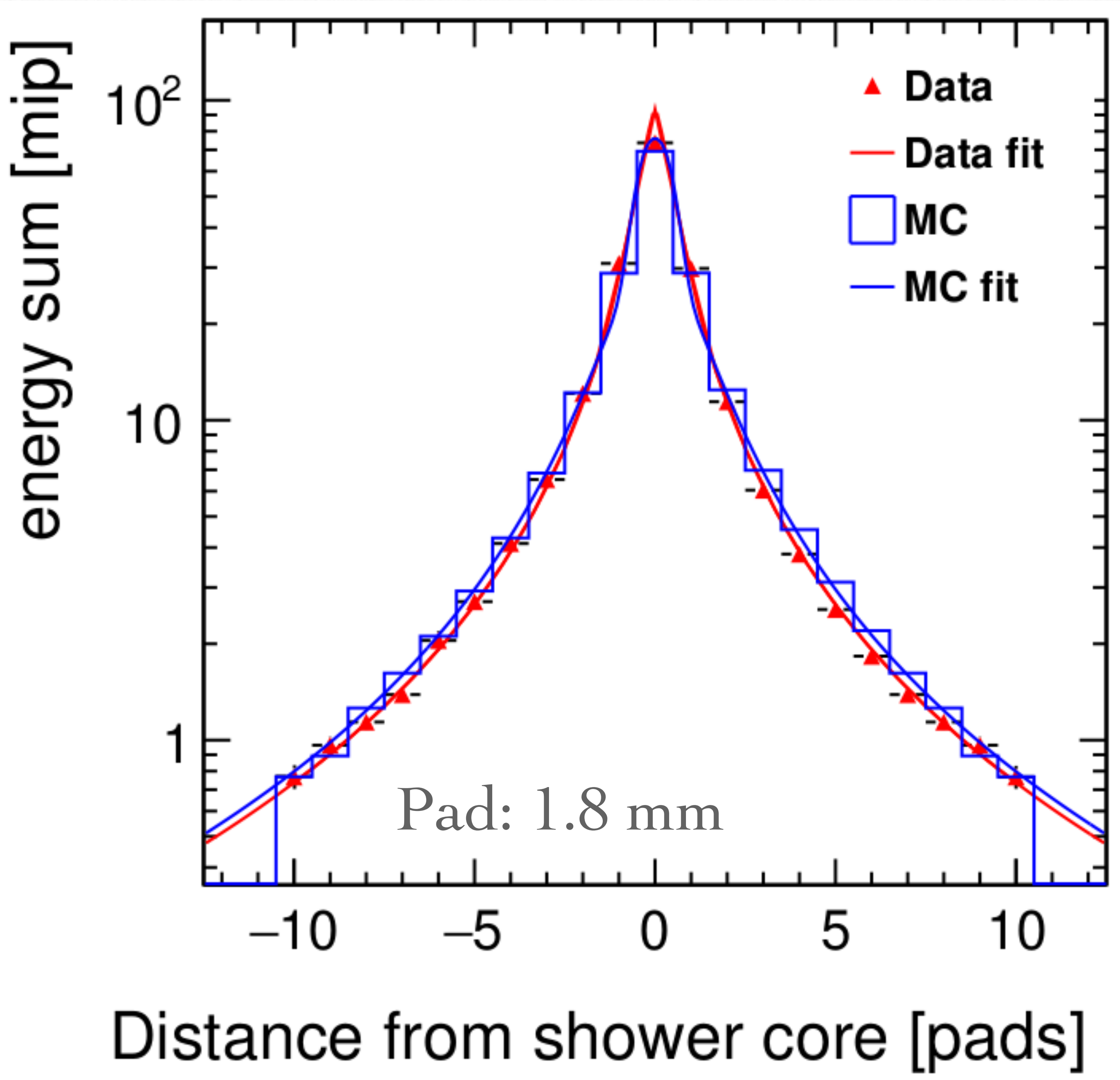
r – the distance from the shower center;
A_C, A_T, R_C, R_T, α – fit parameters.

The fitting range corresponds to the area connected to readout.
Fit parameters are found by fitting to MC and data.

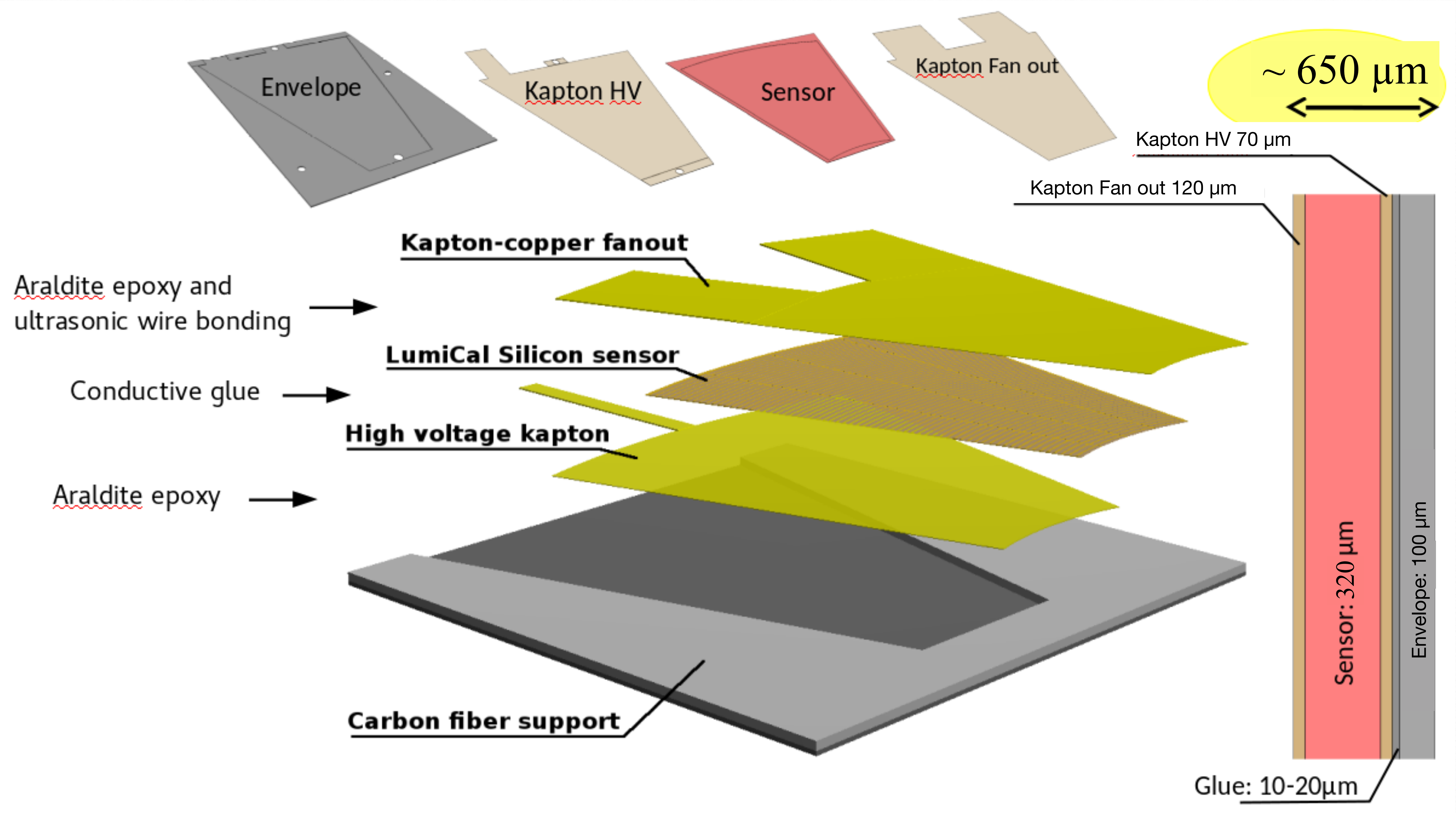
Molière radius $R_{\mathcal{M}}$ can be found from the equation:

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

Procedure was developed for 2014 beam test of LumiCal prototype at CERN (PS, 5 GeV e- beam).
Result is
$R_{\mathcal{M}} = 24.0 \pm 0.6(\text{stat.}) \pm 1.5(\text{syst.})$ mm
(Eur. Phys. J. C 78 (2018) 135.)



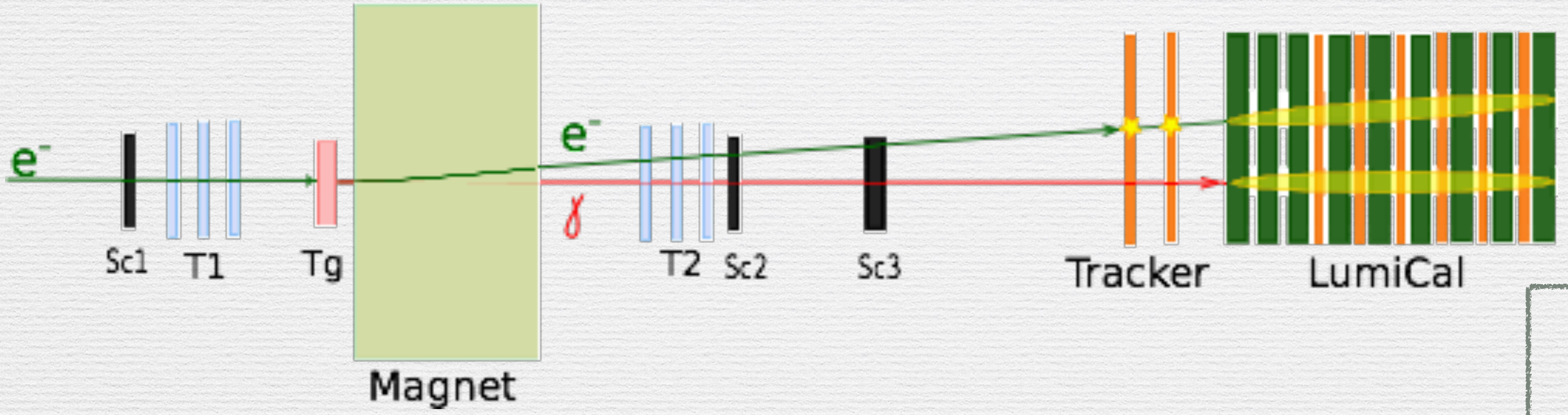
LumiCal thin module prototype assembly



- Compactness is an essential requirement to provide small Molière radius/accurate shower position reconstruction.
- In current LumiCal conceptual design the space between absorbers is 1 mm!
- Carbon fiber support facilitate handling and mounting on tungsten planes

Designed at TAU

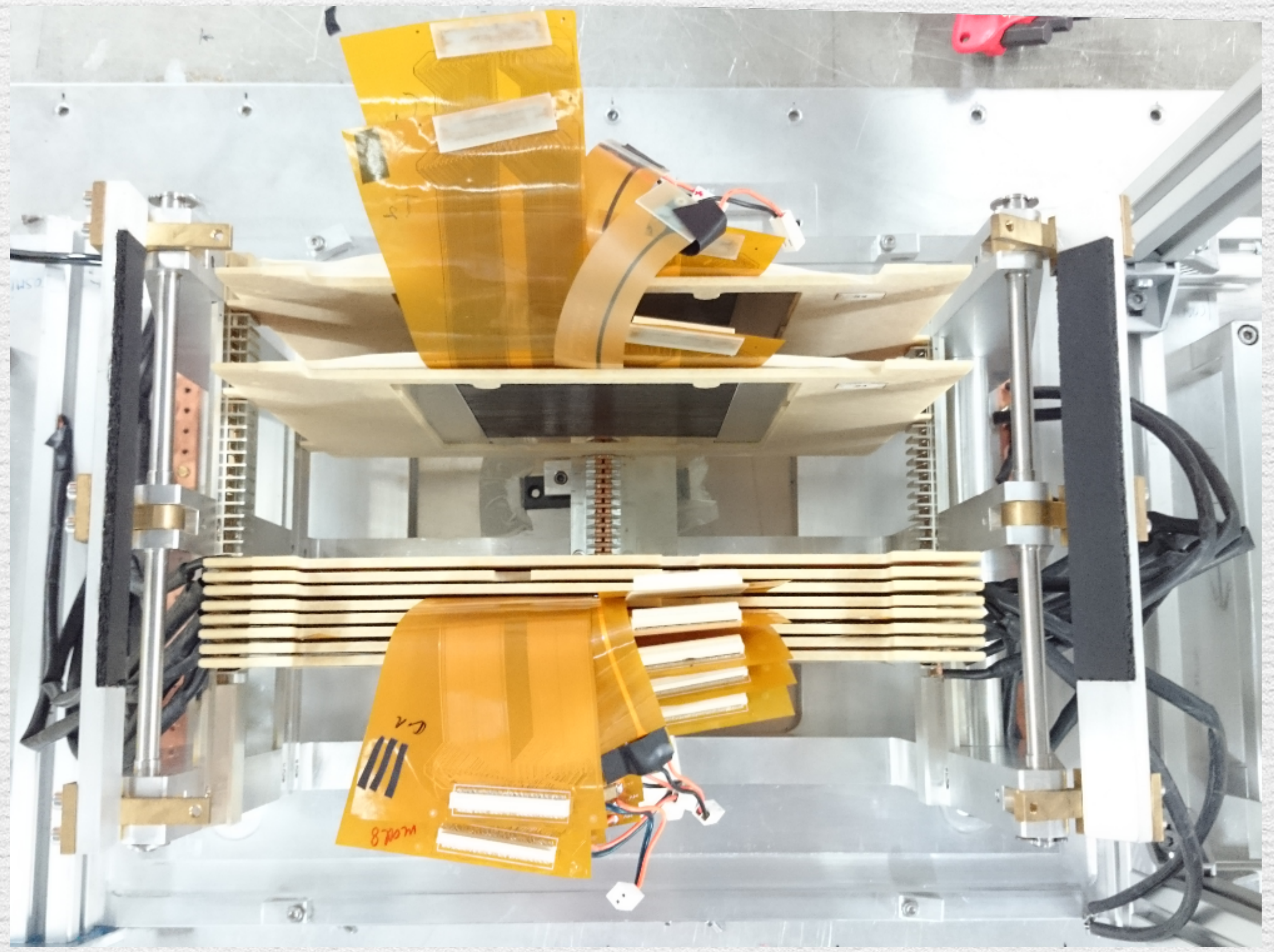
2016 Test Beam at DESY



Sc1, Sc2 and Sc3 are scintillator counters; T1, T2 – three pixel detector planes; Tg – the copper target for bremsstrahlung photon production.

DESY test beam facilities:
- Electron beam 1 – 5 GeV;
- Dipole magnet 1 – 13 kGs;

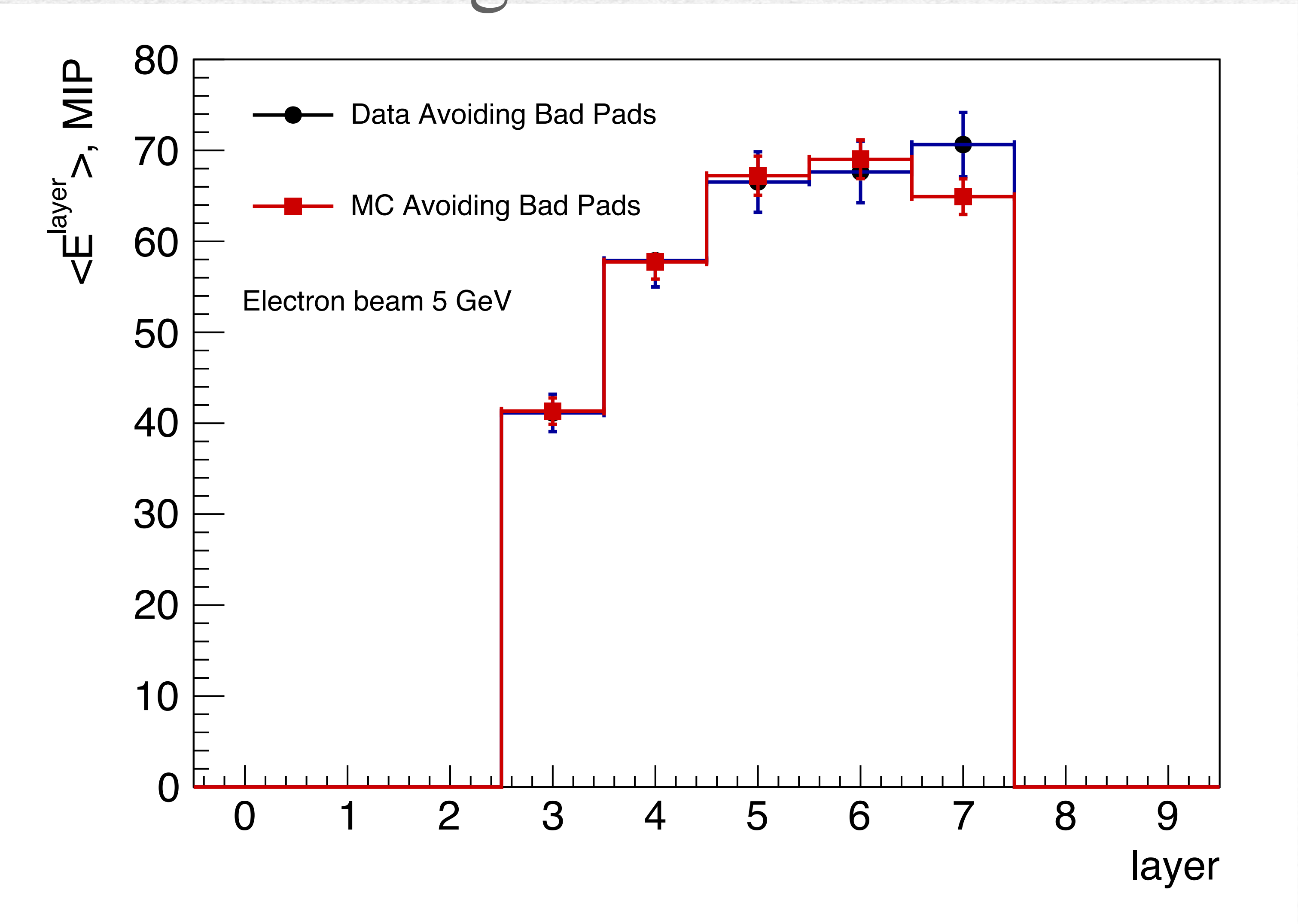
- 8 (256 channels) thin LumiCal modules (> 2k channels);
- 2 - used as a tracker / tagger for e/γ separation;
- 6 - in calorimeter (3 - 8 X0) installed in 1 mm gaps between absorbers;
- DAQ : SRS system, designed by RD51 collaboration;
- EUDET / AIDA beam Telescope : 6 planes with MIMOSA chip;



mechanical frame designed at CERN

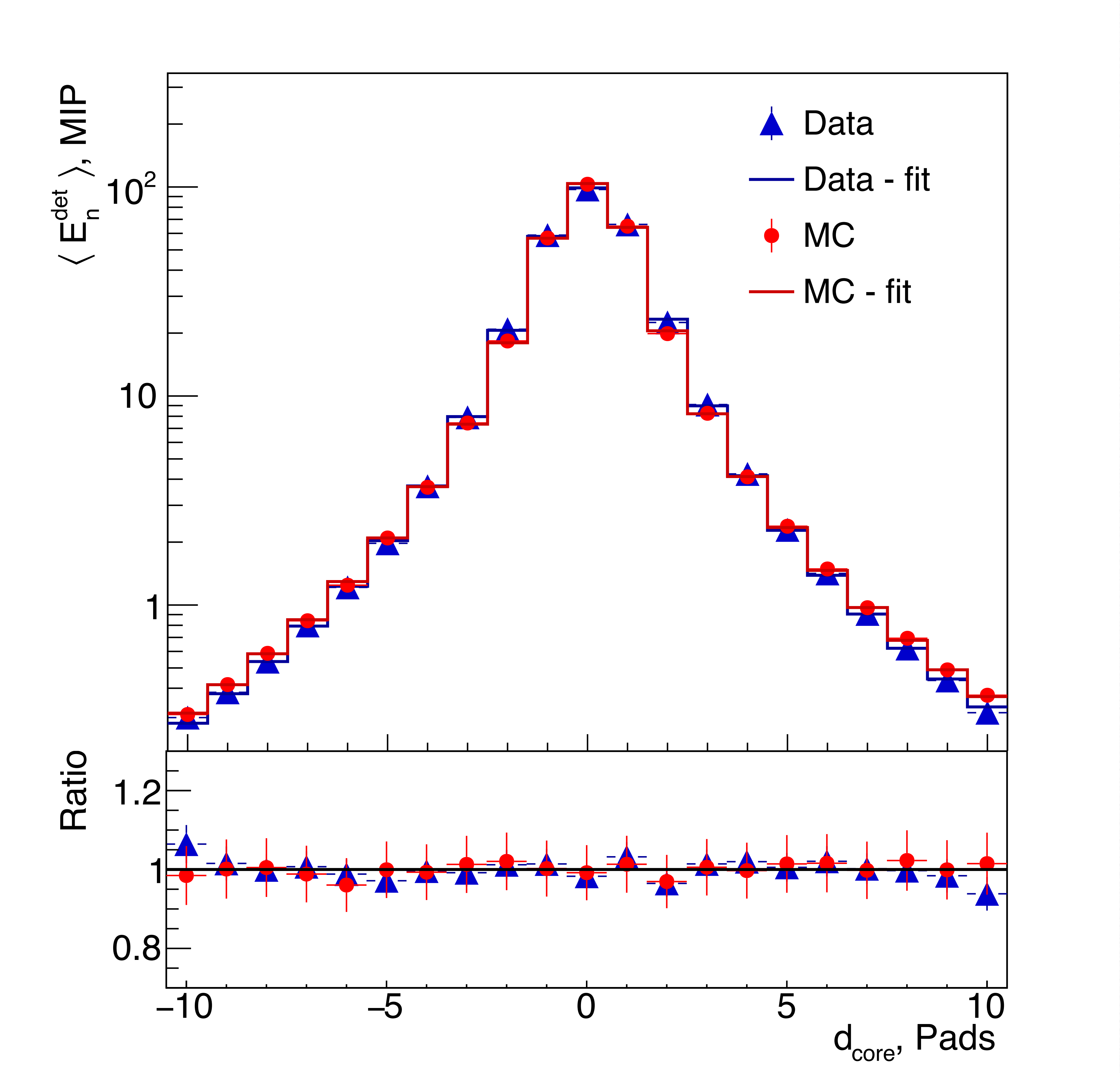
Shower Study for 5 GeV electrons 2016 test beam

longitudinal shower



The measurement of the longitudinal and transverse shower size is in good agreement with simulations

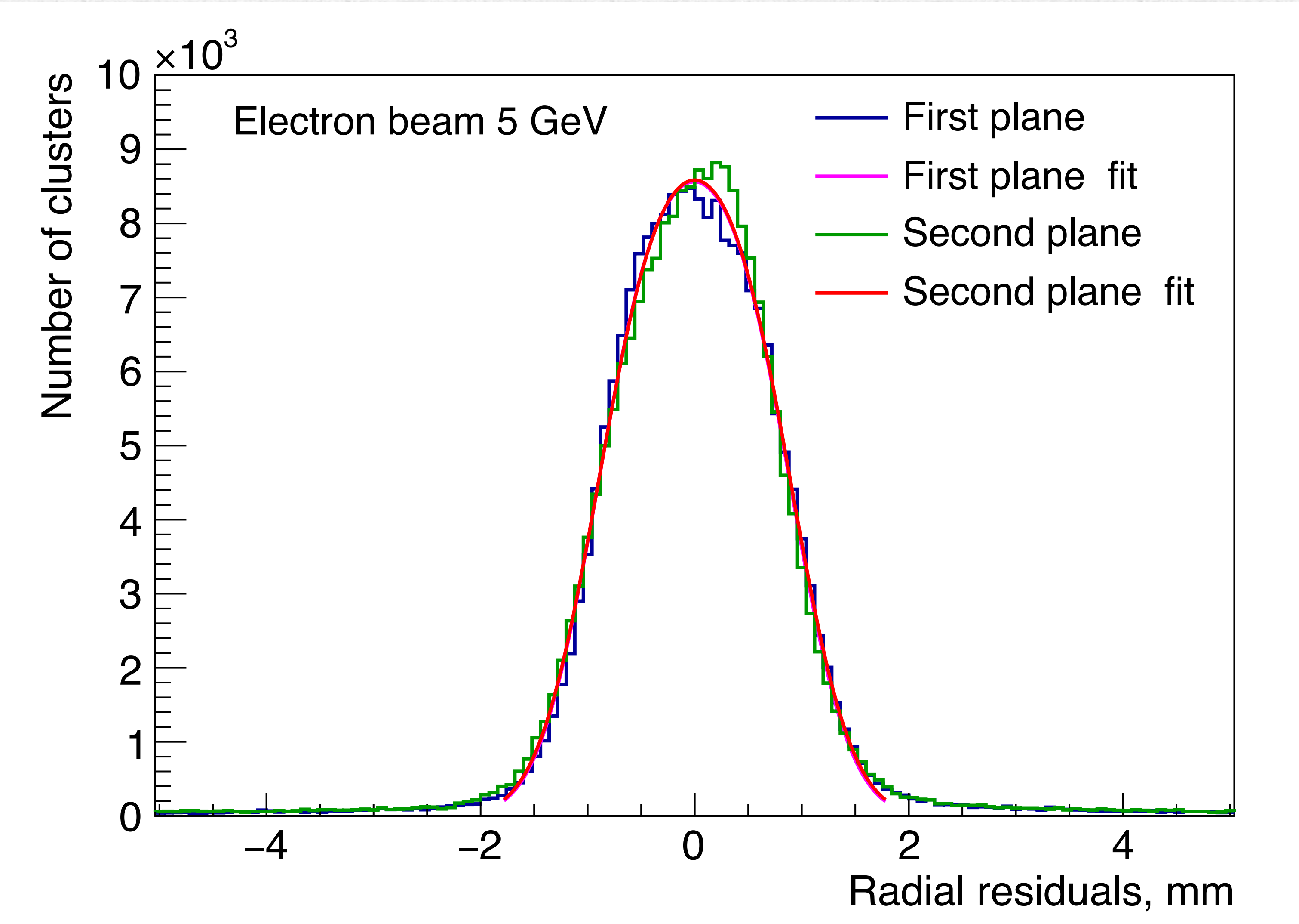
transverse shower



The effective Molière radius is 8.1 ± 0.1 (stat) ± 0.3 (syst) mm

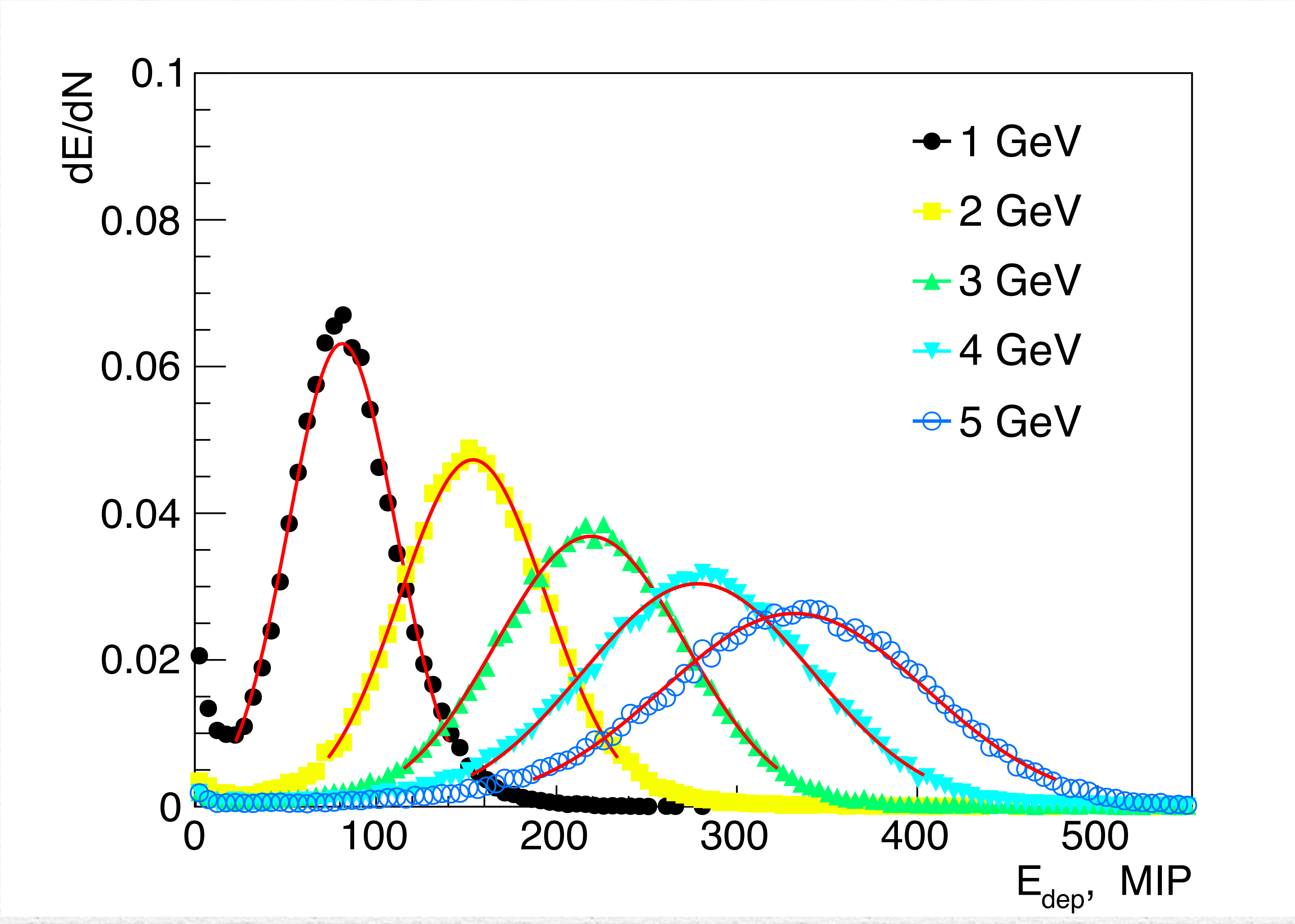
Eur.Phys.J. C79 (2019) no.7, 579

radial position residuals between the calorimeter and tracking planes

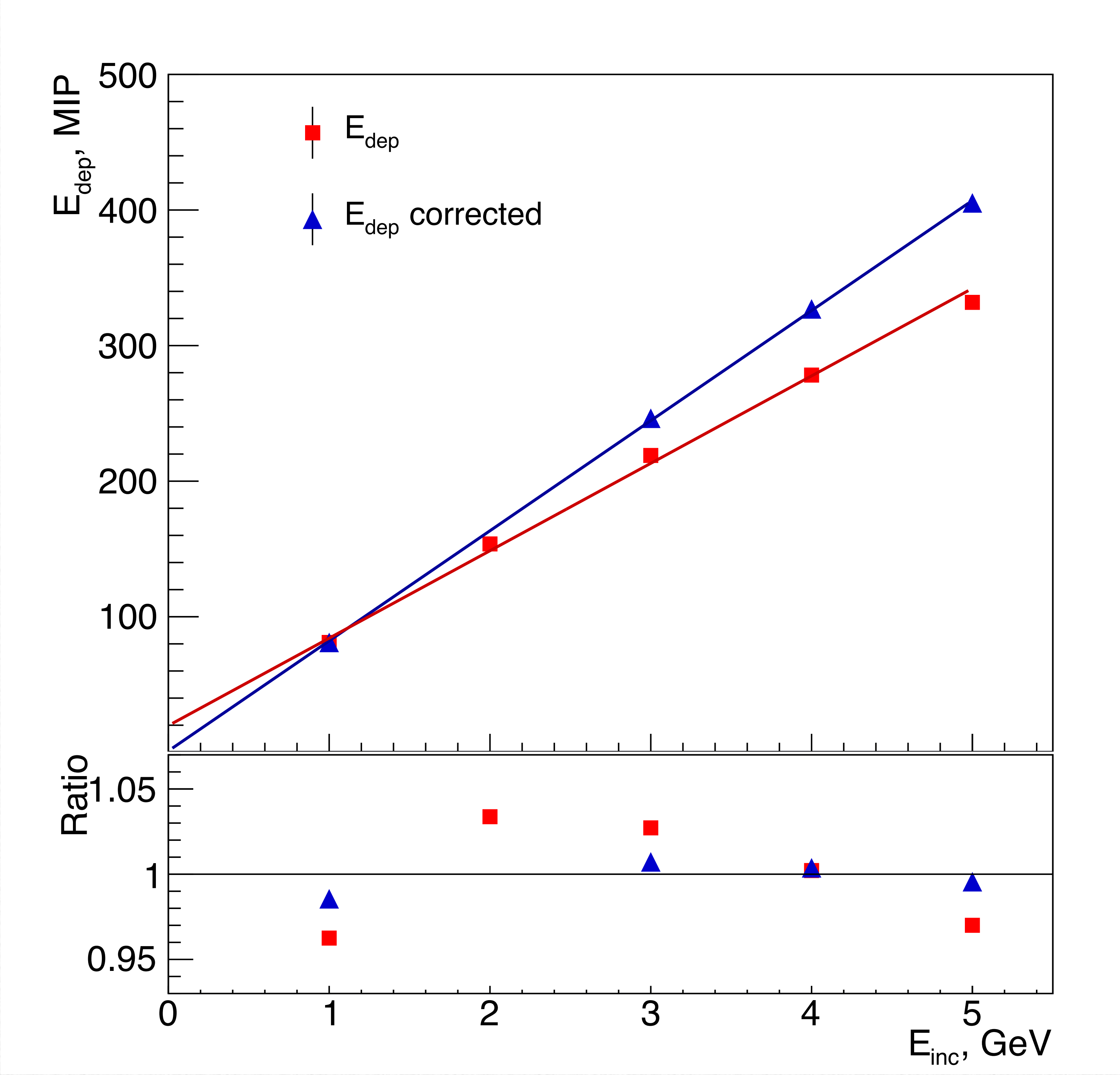


The resolution of the shower position reconstruction (440±20) μm

LumiCal Energy Response



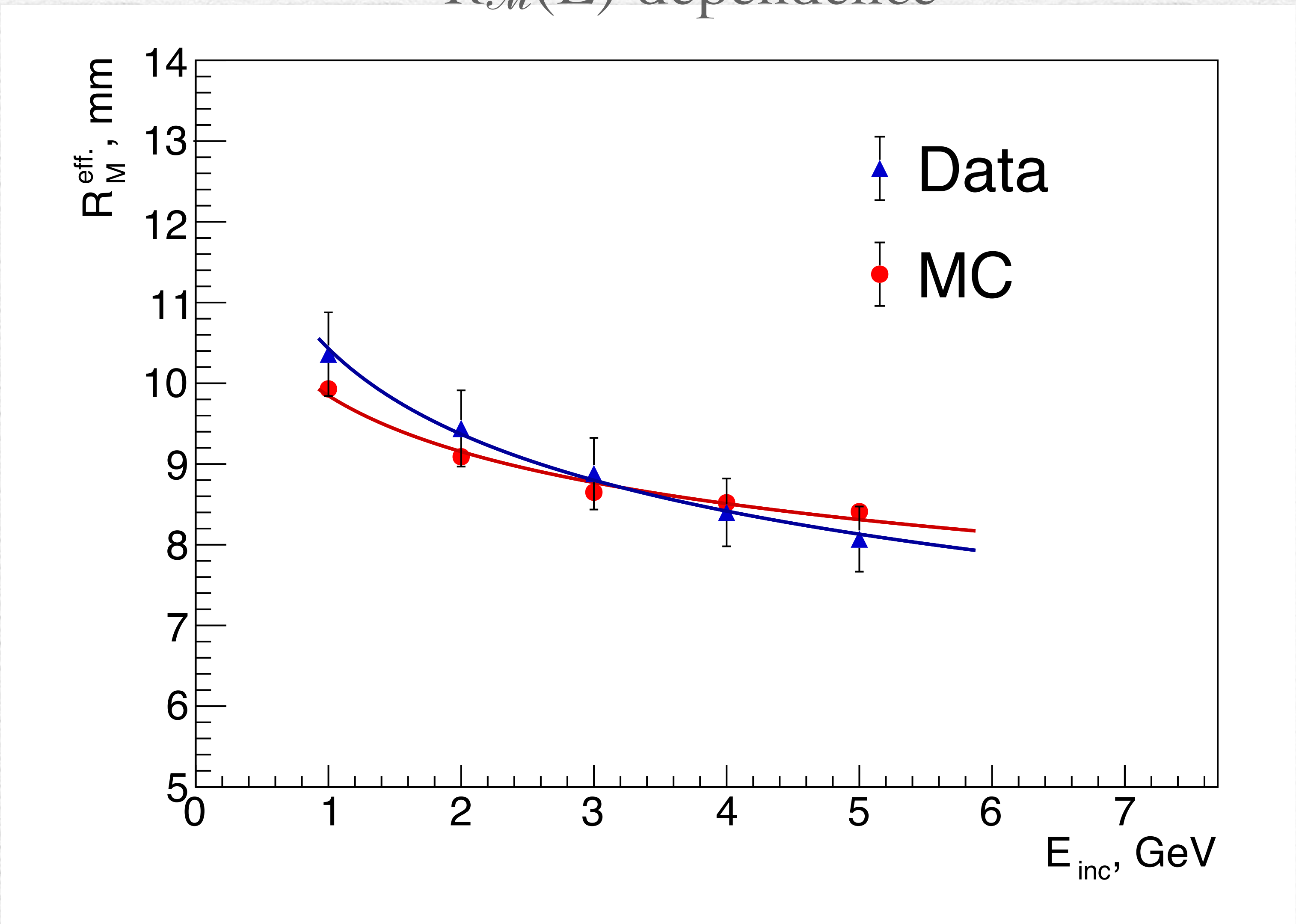
LumiCal prototype demonstrates good linear response to the beam of 1 – 5 GeV.



Small nonlinearity is explained by limited number of sensitive planes.

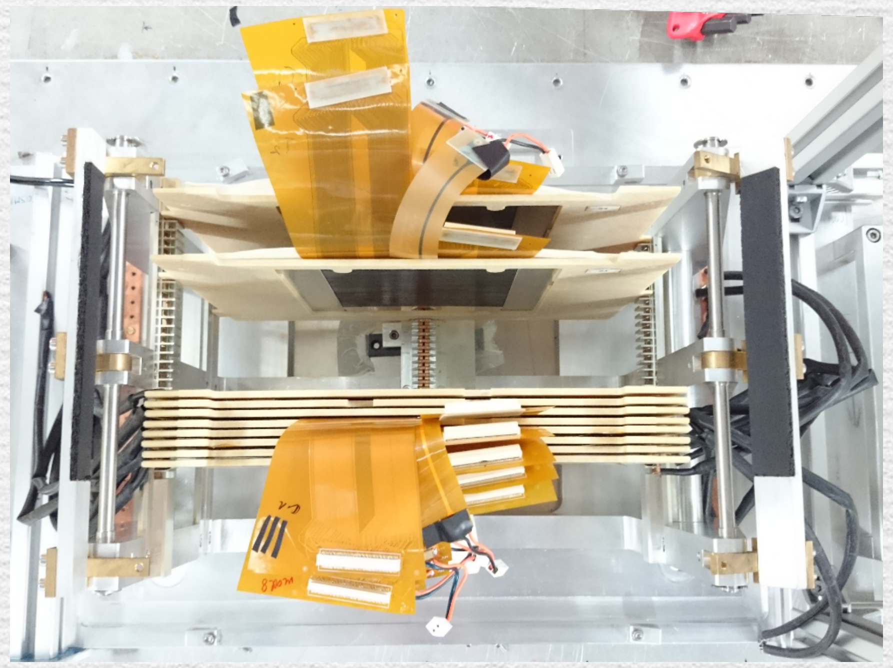
Tested and corrected in MC.

$R_{\mathscr{M}}$(E) dependence

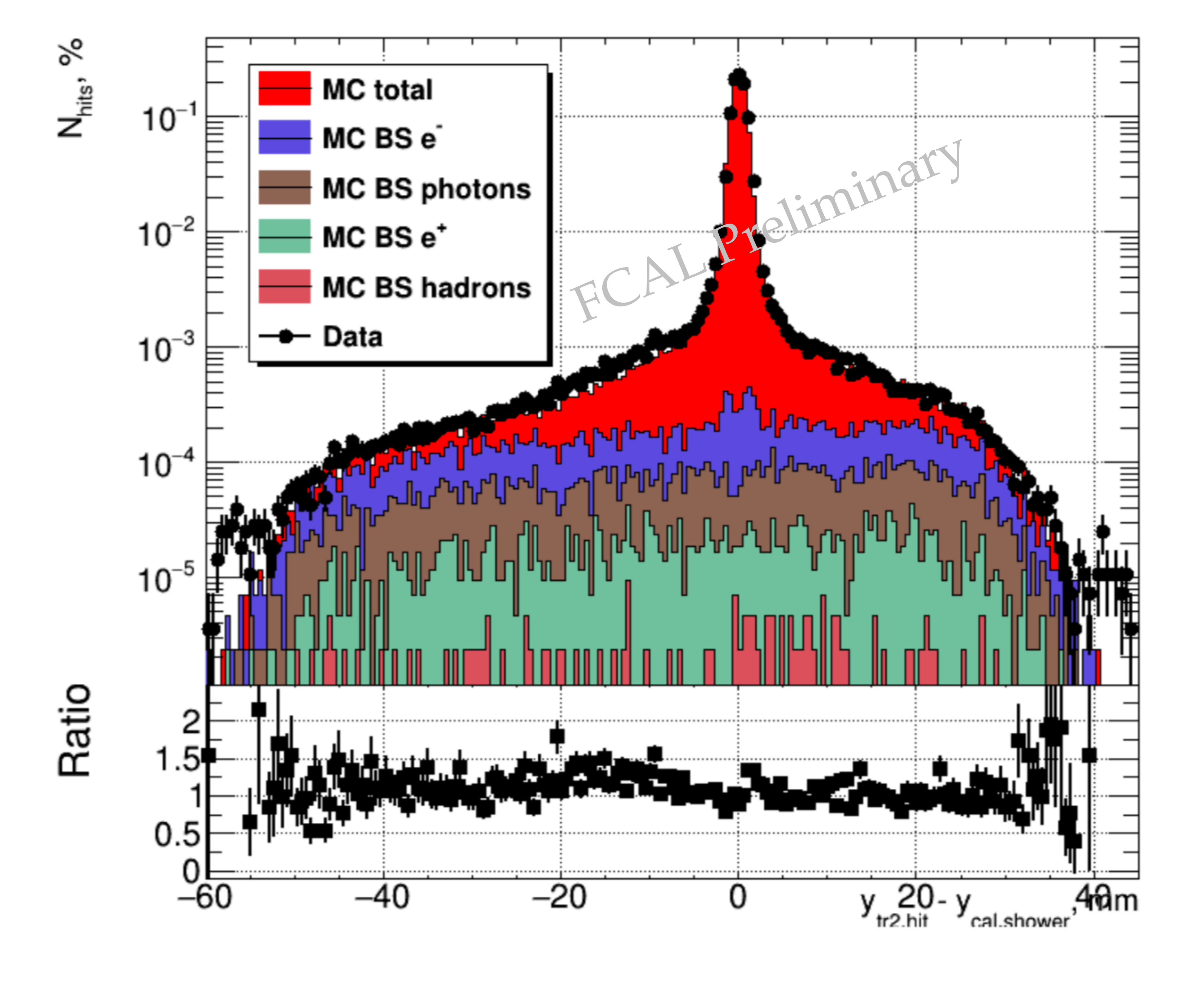


$R_{\mathscr{M}}$ shows slight dependence on E is explained by the fact that for higher energies smaller fraction of the shower is deposited in calorimeter with only 6 working layers

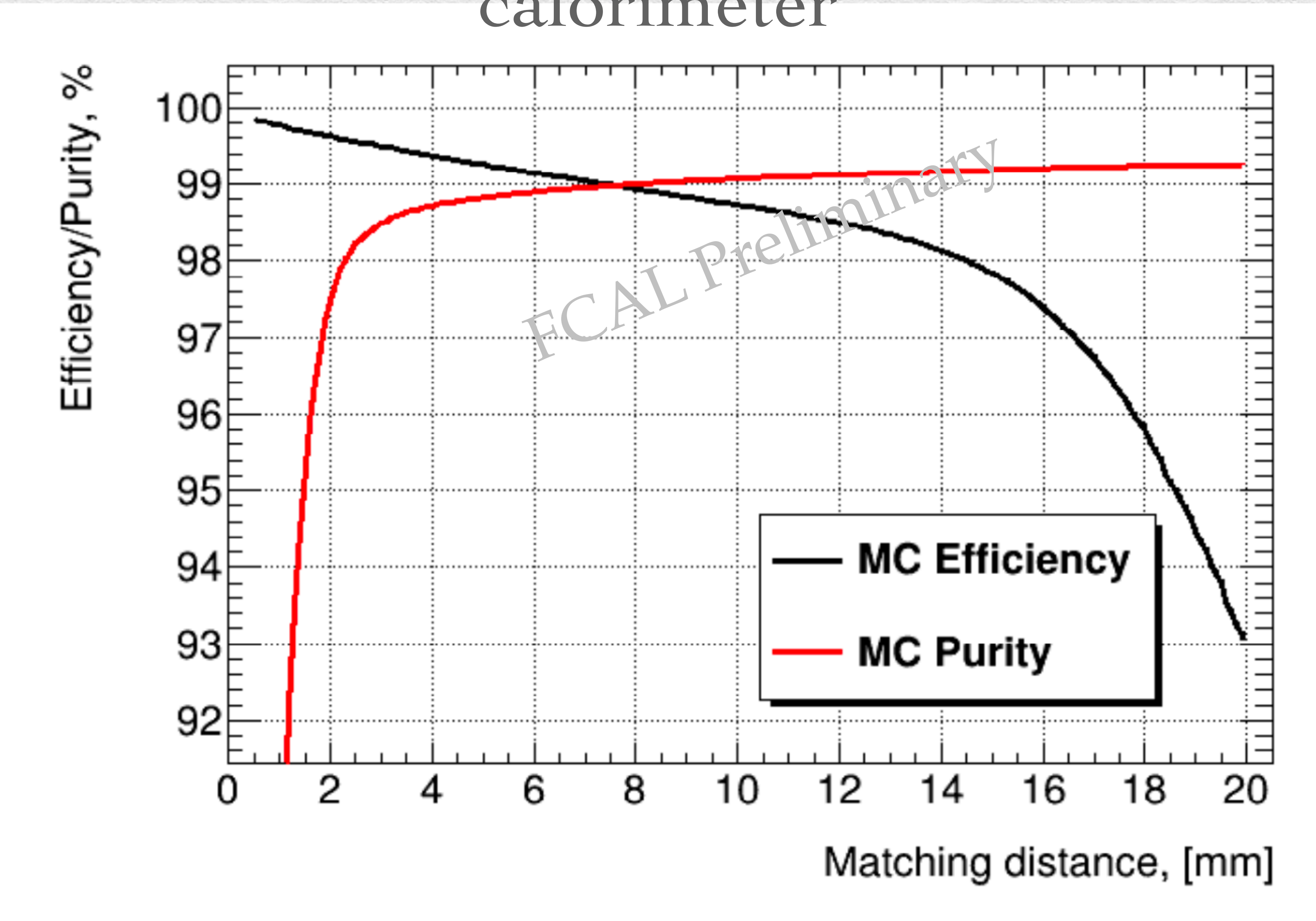
Electron-photon identification in tracking layers in front of LumiCal



The composition of back scatters observed in tracking planes

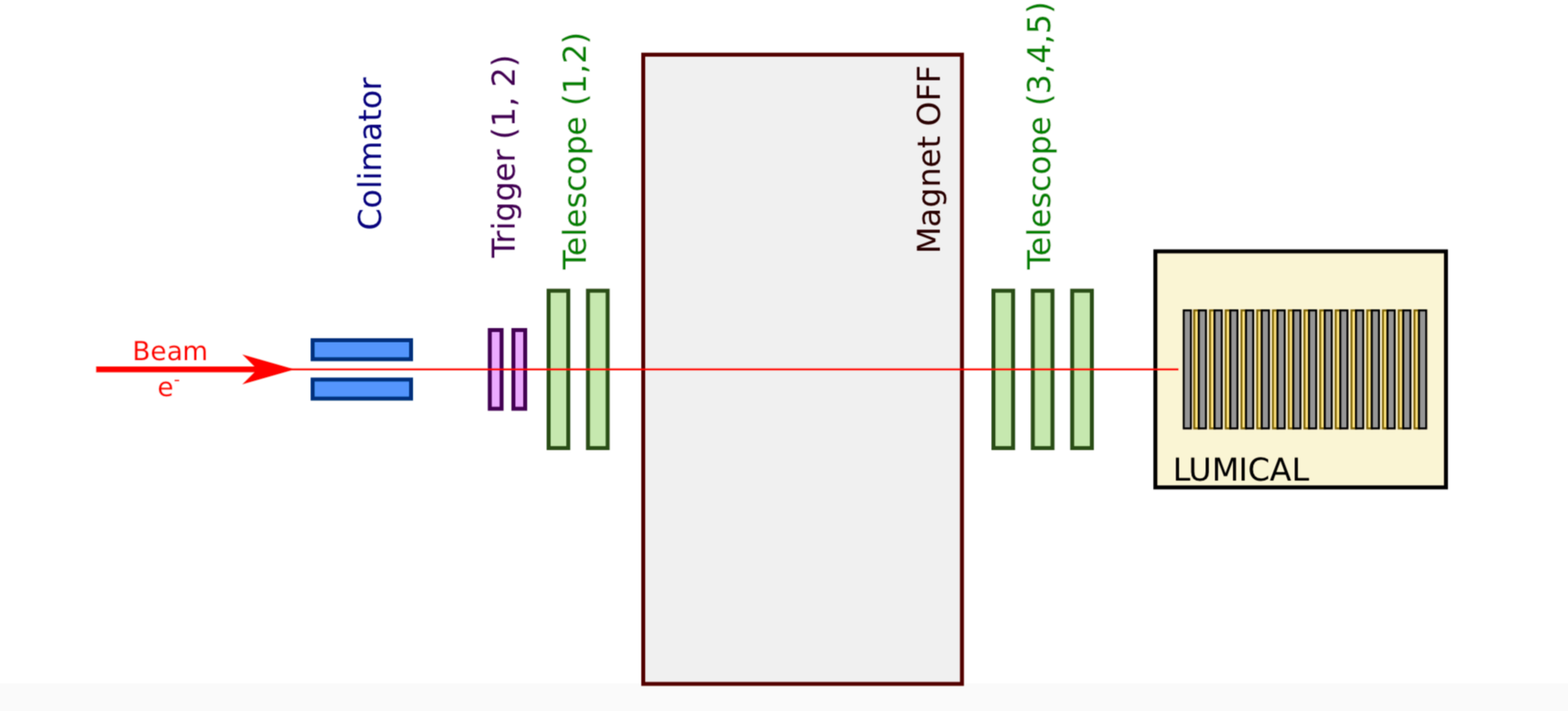


Efficiency and the purity of photon ID as a function of distance between the hits in tracking planes and shower position in calorimeter

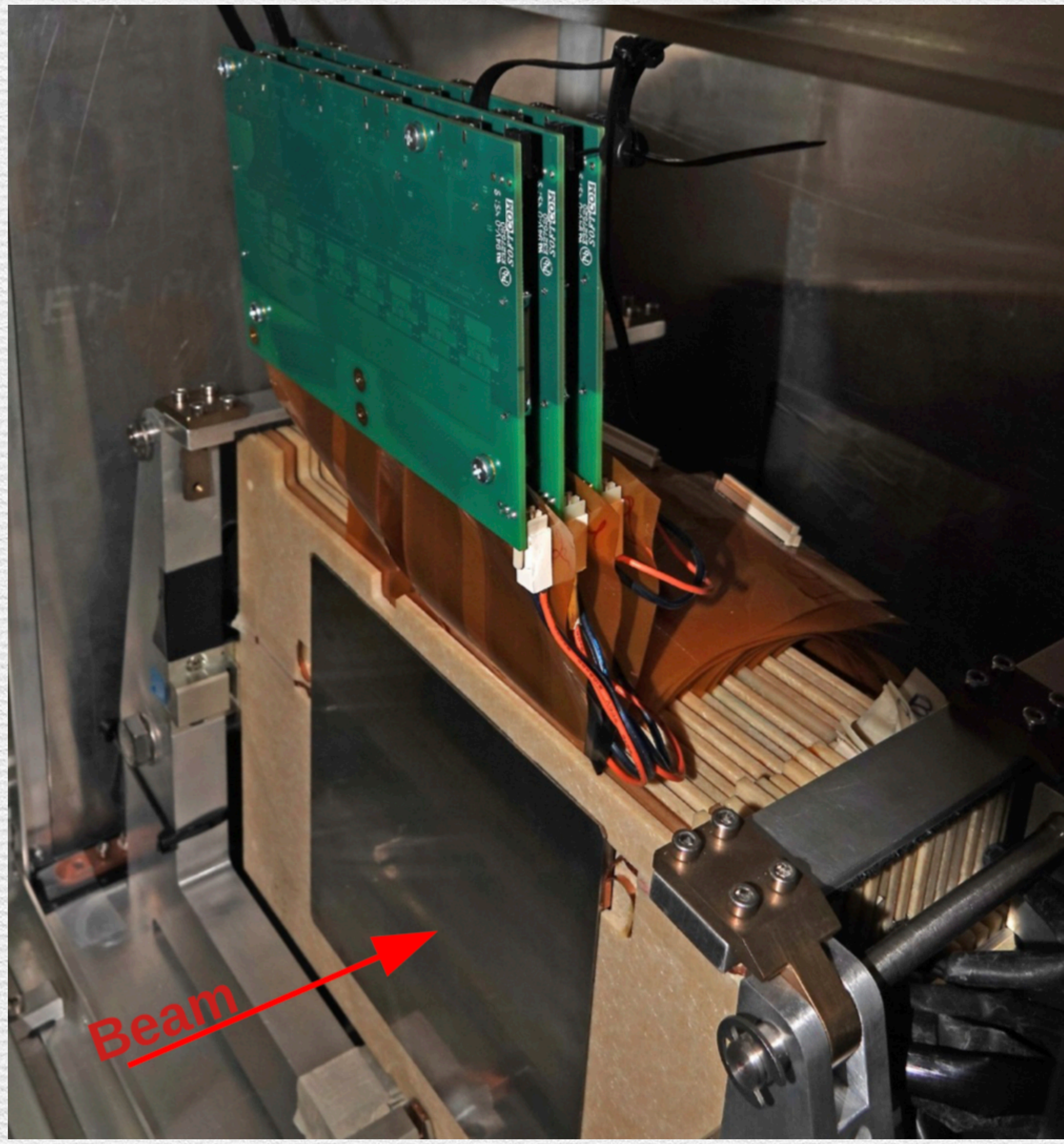


photon / electron identification efficiency more than 90% at 2.5 mm matching distance

2020 Test Beam Campaign at DESY



DESY test beam facilities:
- Electron beam 1 – 5 GeV;
- Dipole magnet 1 – 13 kGs;

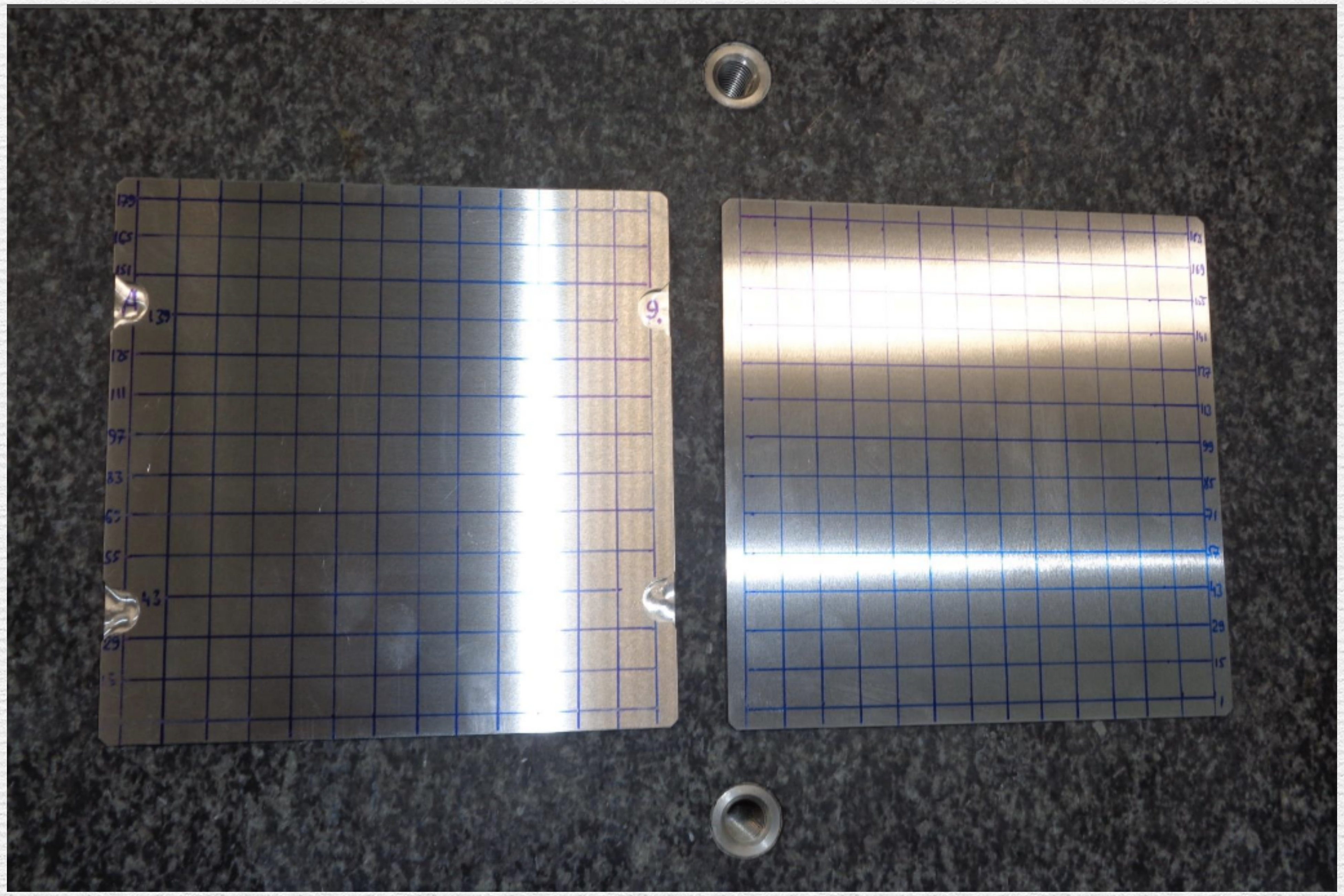


- LumiCal prototype with 15 sensitive sensor layers
- 3 planes equipped with FLAME dedicated LumiCal Readout (Slides 23-24)
- Others - with double gain readout using APV25
- Edge scan for fiducial volume study
- Data collection with tilted calorimeter to study bias in position reconstruction
- Test electron/gamma response

- Data Analysis is in progress….

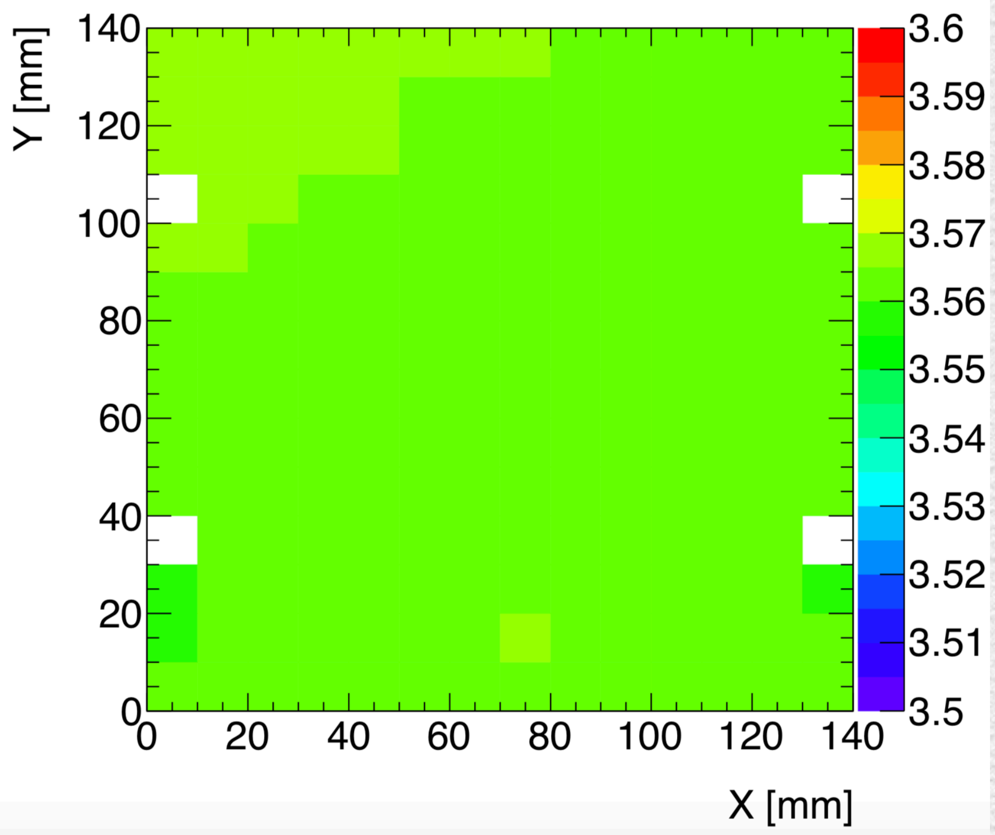
Tungsten plates

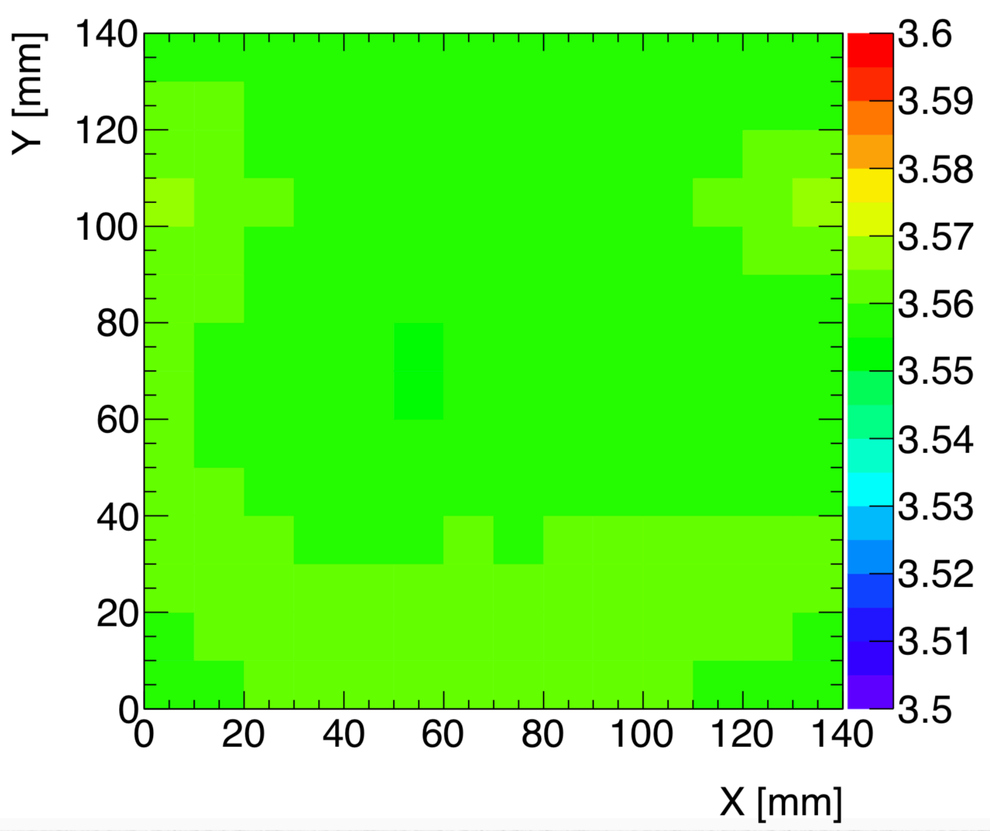
- 10 new tungsten absorber plates
- High requirements to geometrical accuracy (~50 μm for thickness) make it difficult to use pure W.
- the absorber alloy : 93% tungsten, 5% nickel & 2% copper.
- Good flatness ~30 μm observed
- Glued to permaglass frame
- Used in assembled calorimeter in 2019/2020 beam test campaigns



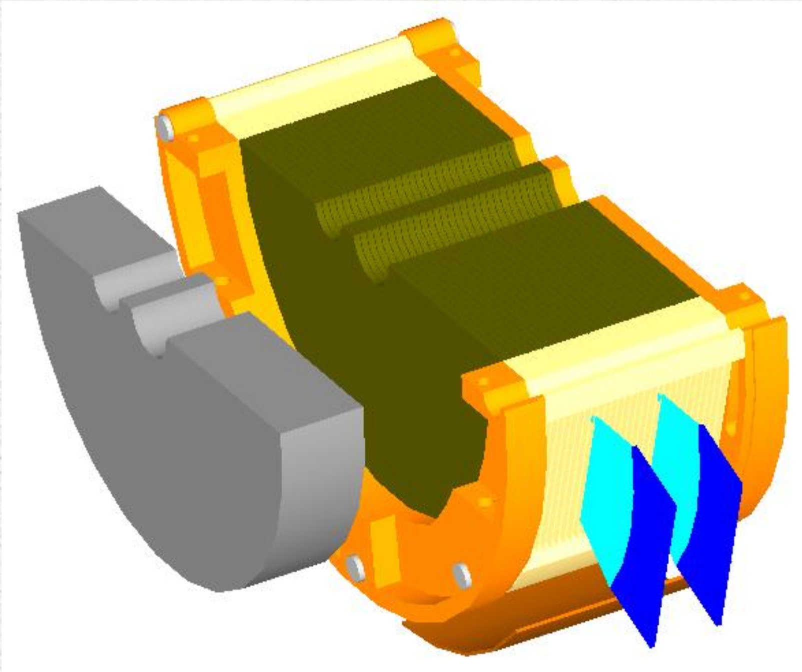
Dimensions 140x140x3.5 mm

Designed in JINR Dubna





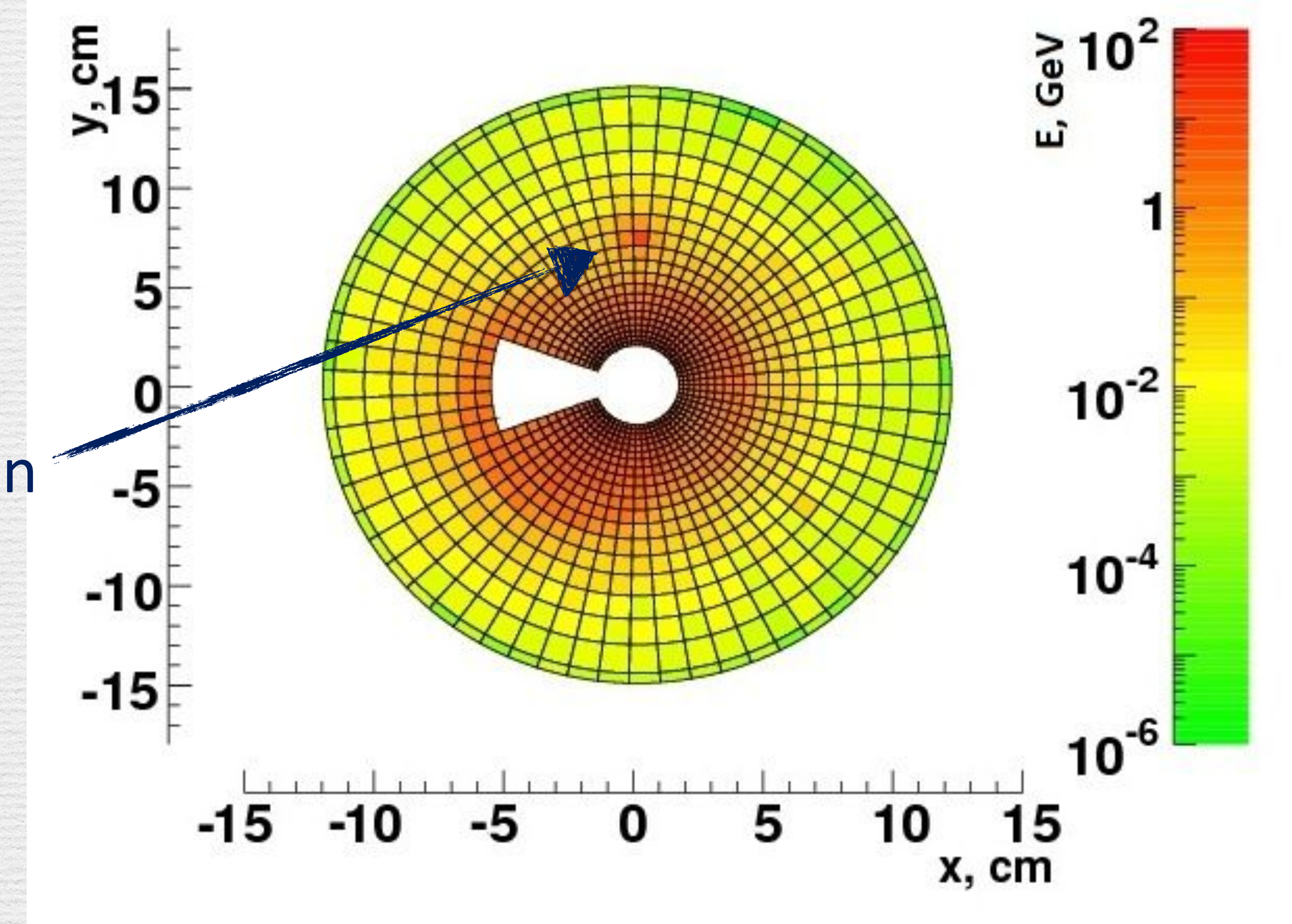
BeamCal



Beamstrahlung at linear colliders (due to nm bunch sizes)

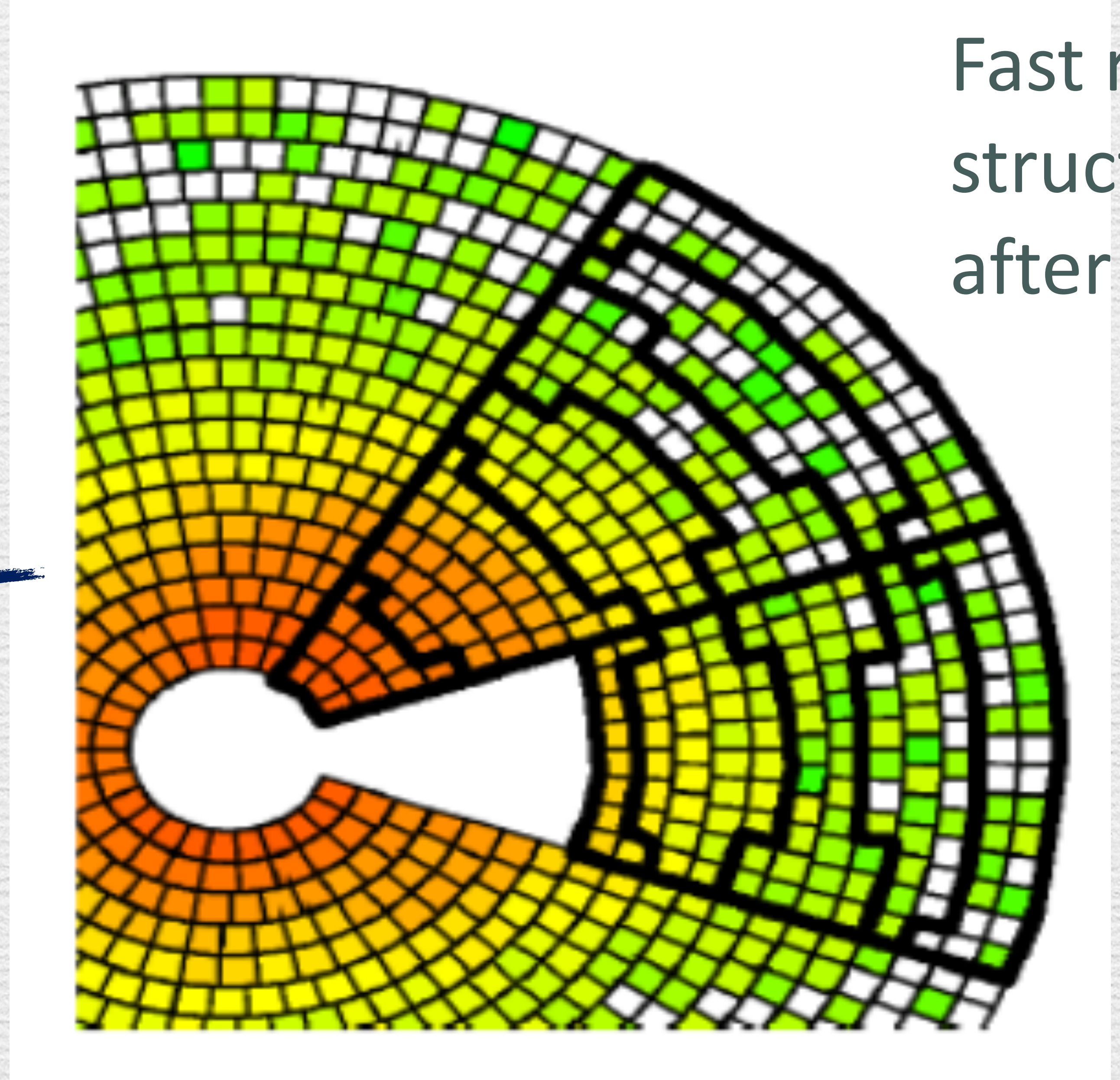
Low energy electron deposition per BX

Single high energy electron



- Fast luminosity estimate using beamstrahlung (bunch-by-bunch at ILC)
- Beam parameter estimation
- Fast feedback to the machine
- Low angle electron tagging

Fast readout of structured areas after each BX

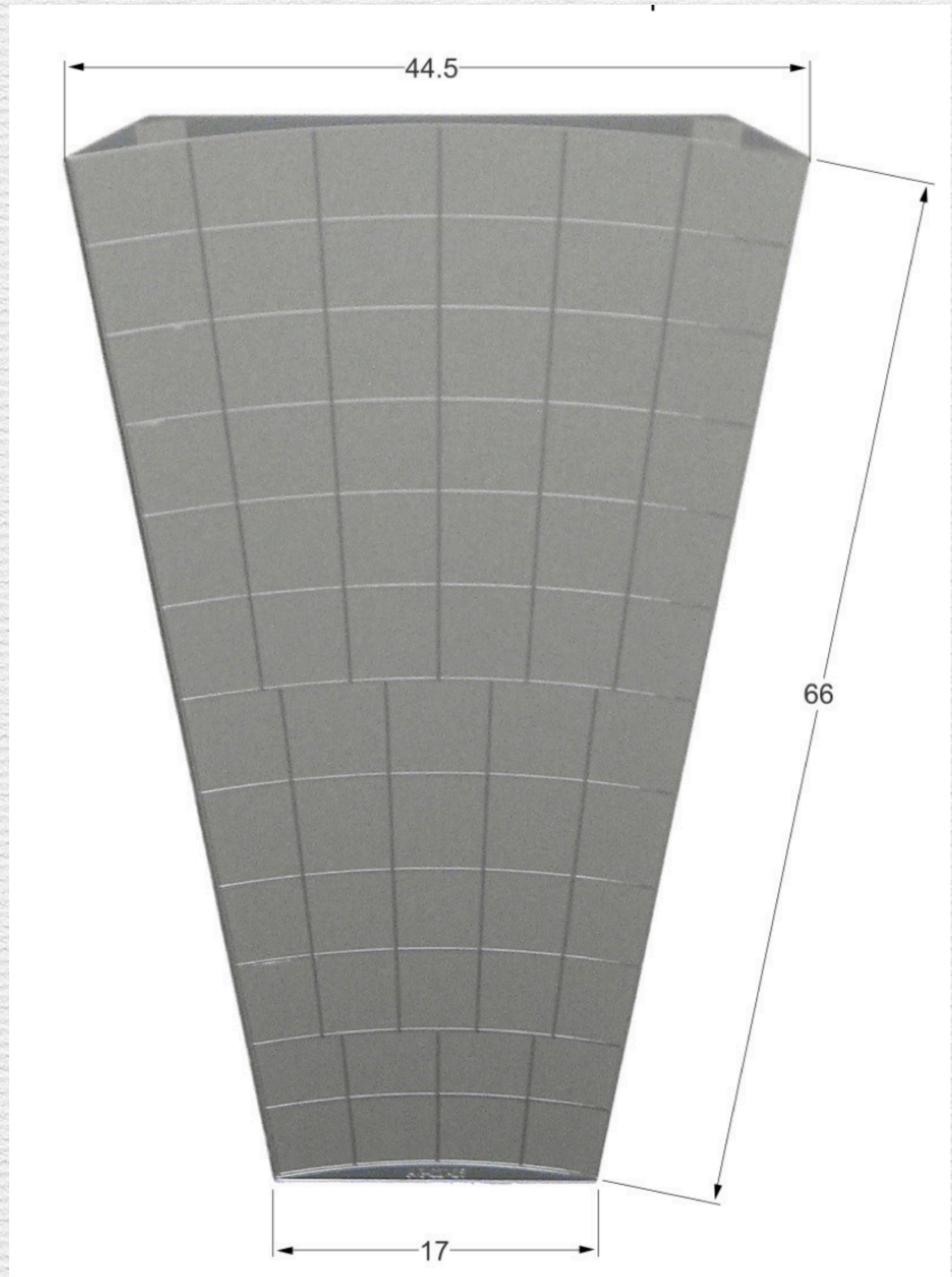


Beam parameters and luminosity measurement

beam parameter	unit	nom.	resolution, 14 mrad: no E_γ	resolution, 14 mrad: with E_γ
σ_x	nm	655.0	700. ± 49.	660. ± 43.
$\Delta\sigma_x$	nm	0.0	7. ± 30.	17. ± 20.
σ_y	nm	5.7	5.8 ± 7.1	5.1 ± 2.7
$\Delta\sigma_y$	nm	0.0	-0.53 ± 0.97	0.26 ± 0.80
σ_z	μm	300	331. ± 67.	295. ± 31.
$\Delta\sigma_z$	μm	0.0	3. ± 56.	4. ± 35.

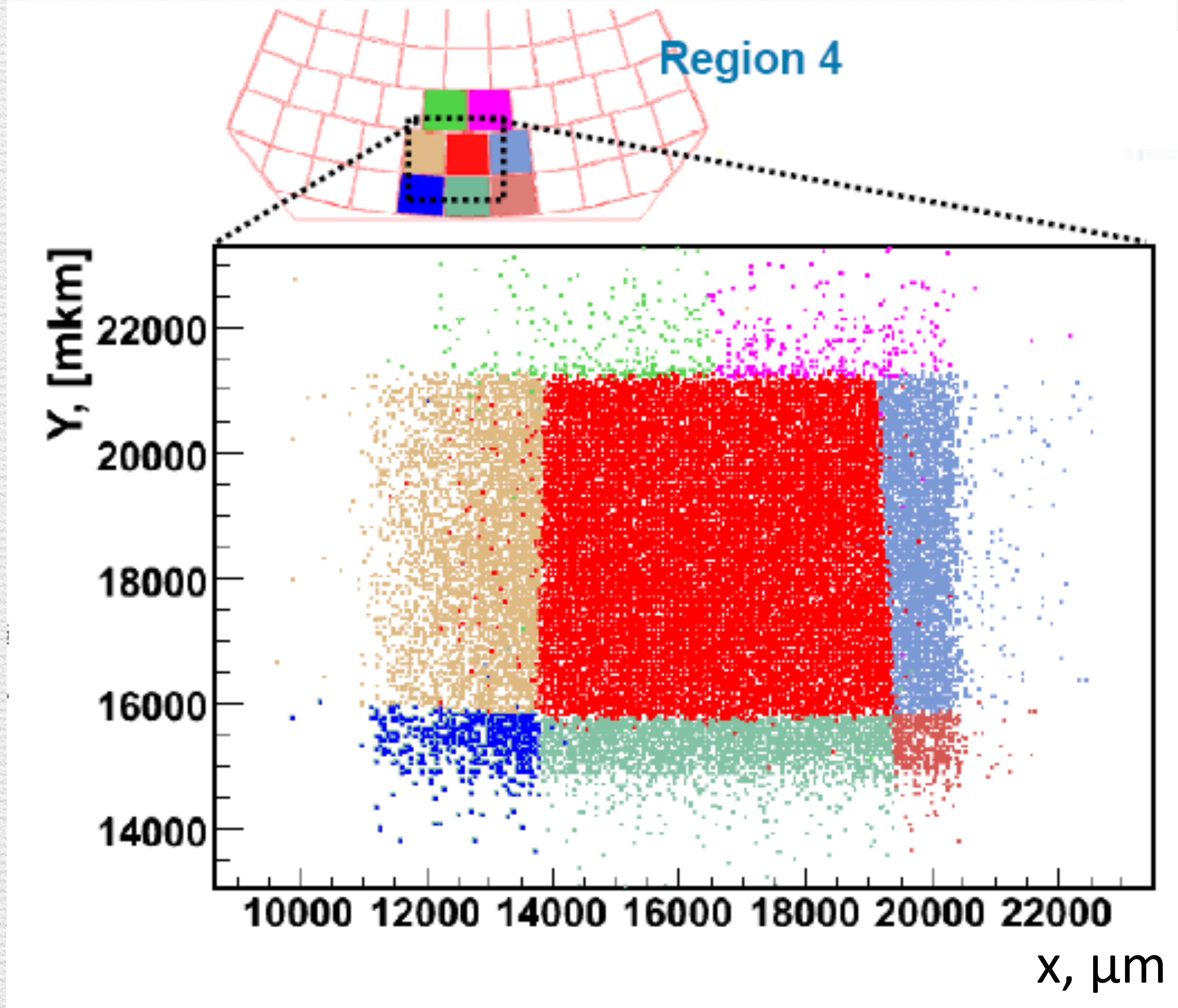
BeamCal

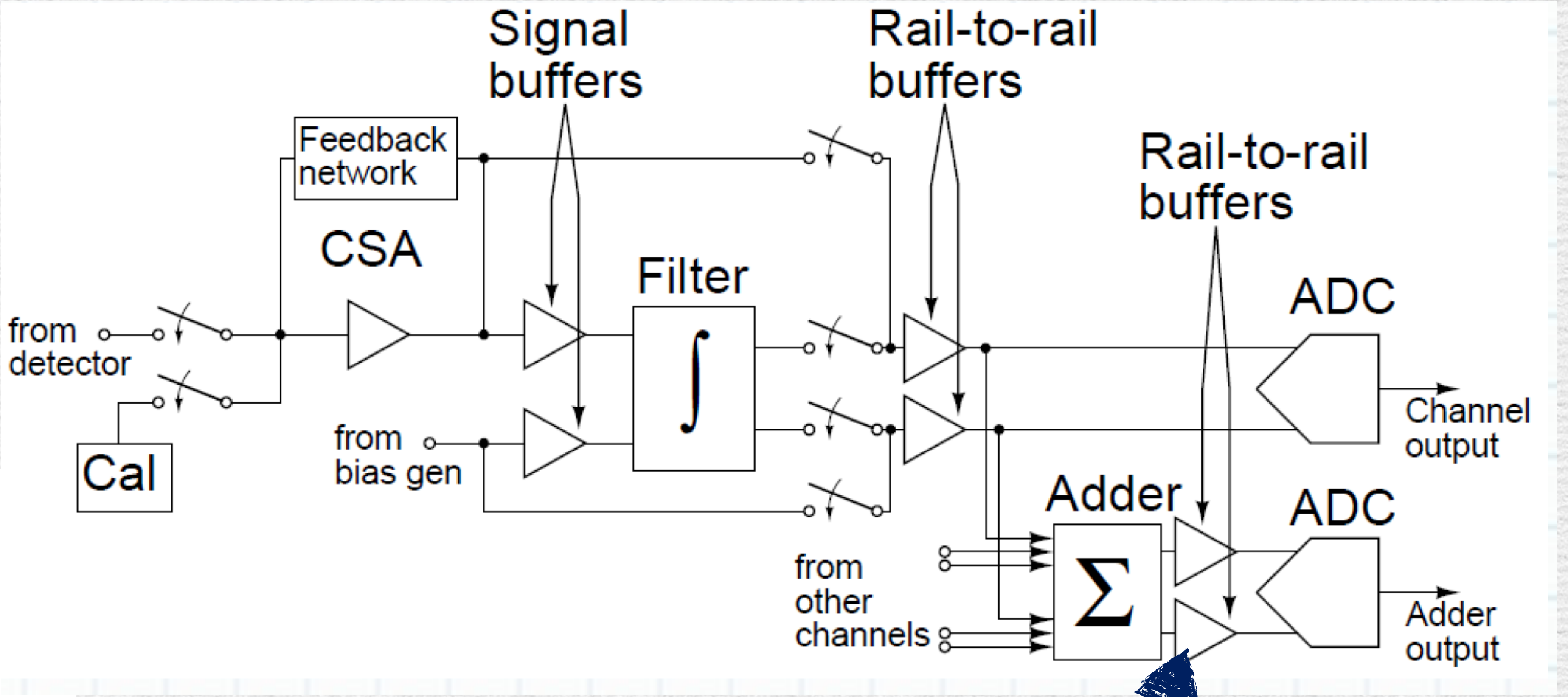
Baseline sensor: GaAs



Designed in JINR Dubna

Thickness 500 µm
High resistivity (10^7 Ωm)
S/N for MiPs ≈ 20





Dedicated ASIC development with fast OR to be used in the feedback system

Test-beam fully instrumented detector plane

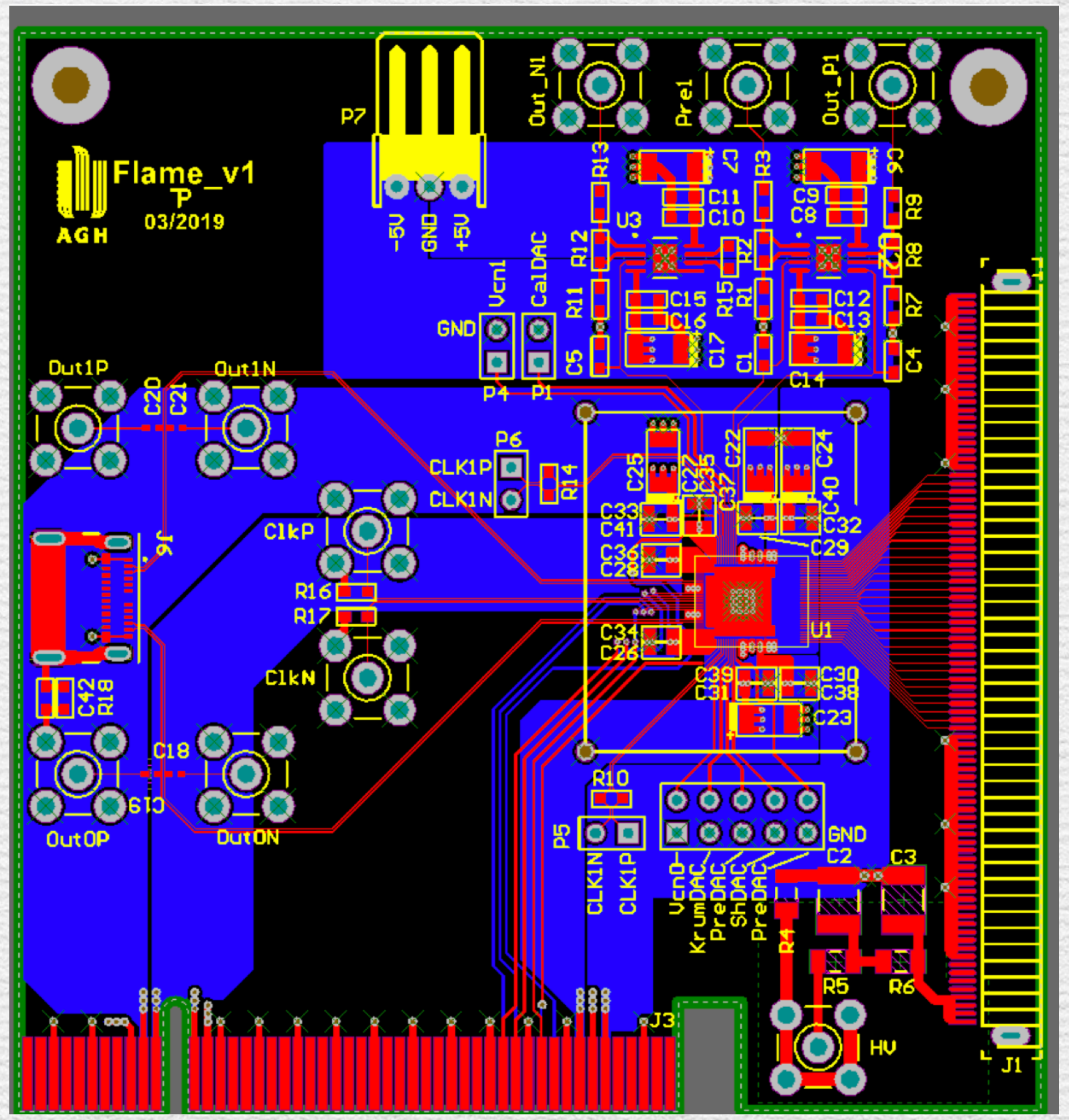
dedicated front-end and ADC ASICs

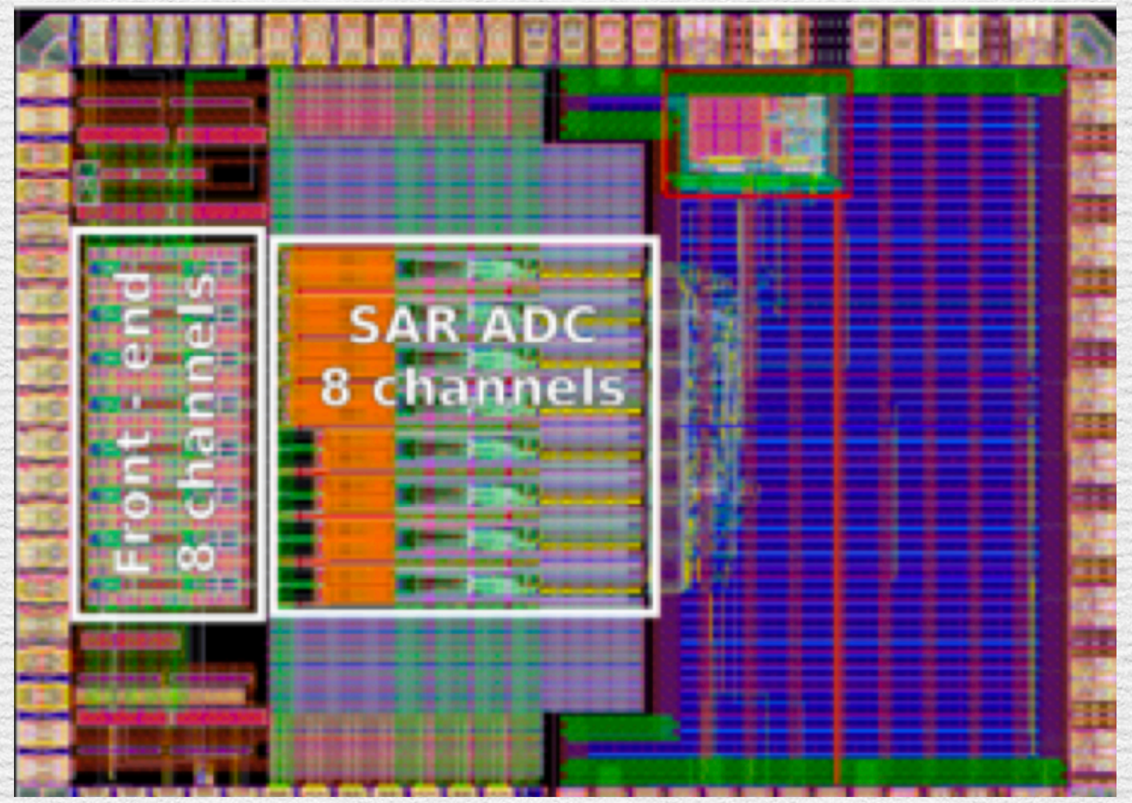
New readout ASIC for LumiCal -FLAME

FcaL Asic for Multiplane rEadout
ASIC architecture

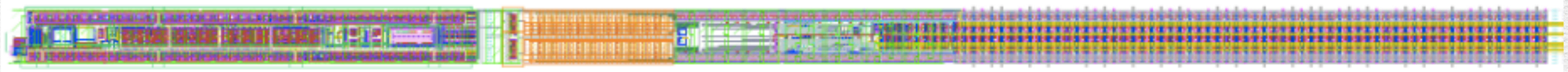
Complete readout ASIC integrating whole functionality (biasing, calibration, etc.)
32 mix-mode channels comprising:
Variable gain front-end
10-bit SAR ADC
Data encapsulation and 8b/10b coding (according to the Xilinx MGT specification)
Multi-phase PLL based fast serializer (up to 8 Gbps)
Fast SST driver (up to 8 Gbps)

Mix-mode FLAME part:
~2.5 mm x~3.5 mm





Single FLAME channel: 2350 µm x 80 µm:



- Development of new readout ASIC for LumiCal – FLAME – is done
- Chip has been manufactured and assembled to PCB

Designed in UST Krakow

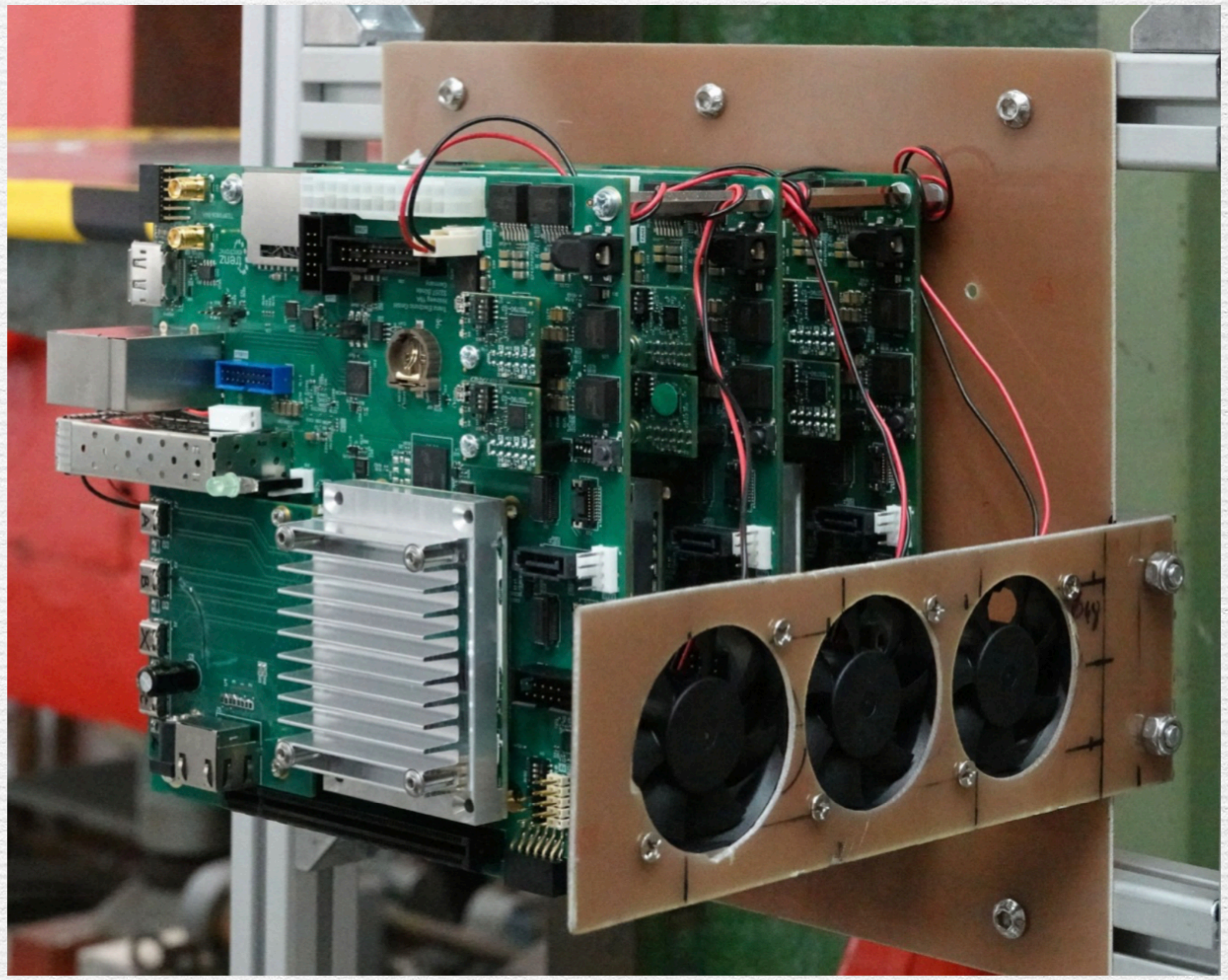
FLAME – in beam test 2020 at DESY

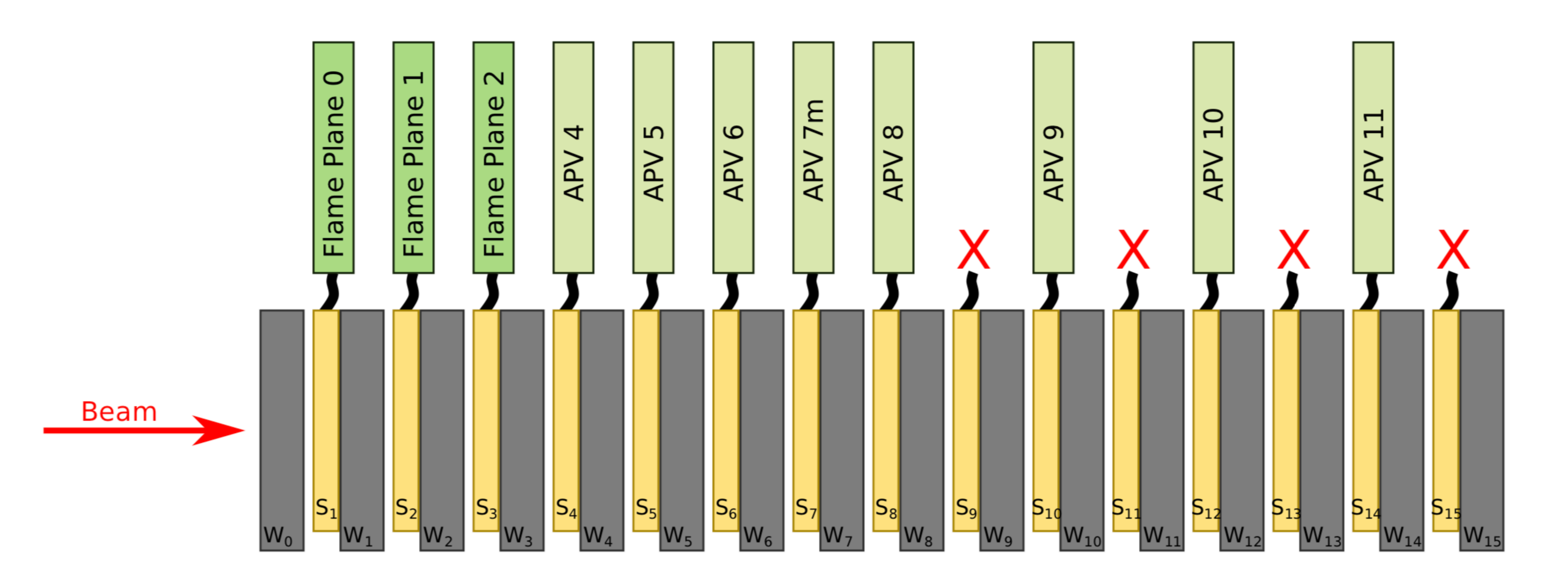
Analogue front-end comprising:

- Charge sensitive preamplifier with variable gain:
- High gain – for test beam - up to 200 fC with MIP sensitivity
- Low gain – for shower development (up to 6 pC)
- Differential CR-RC shaper with 50ns peaking time

10-bit multichannel SAR ADC

- Sampling rate up to 50 MSps
- DNL, INL < 0.5 LSB
- ENOB > 9.5
- Ultra low power consumption (below 1 mW per channel at 40 MSps)

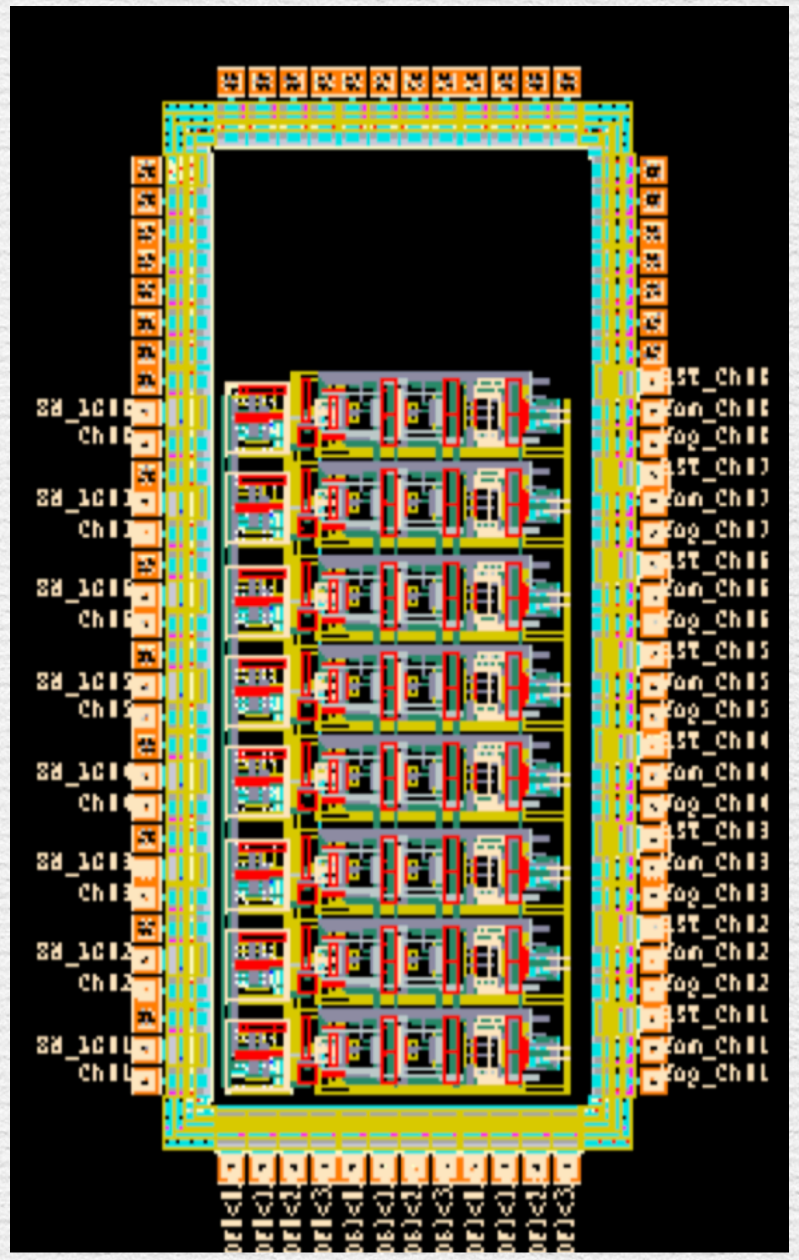




- 3 complete readout cards with 128 channels each
- Stack (15 sensor layers (S1 - S15)) was scanned by connecting consecutively each three sensors

First Test-Drive was successful!
Data analysis is in progress…

BeamCal ASIC v3 Design



Designed at Pontificia Universidad Católica de Chile

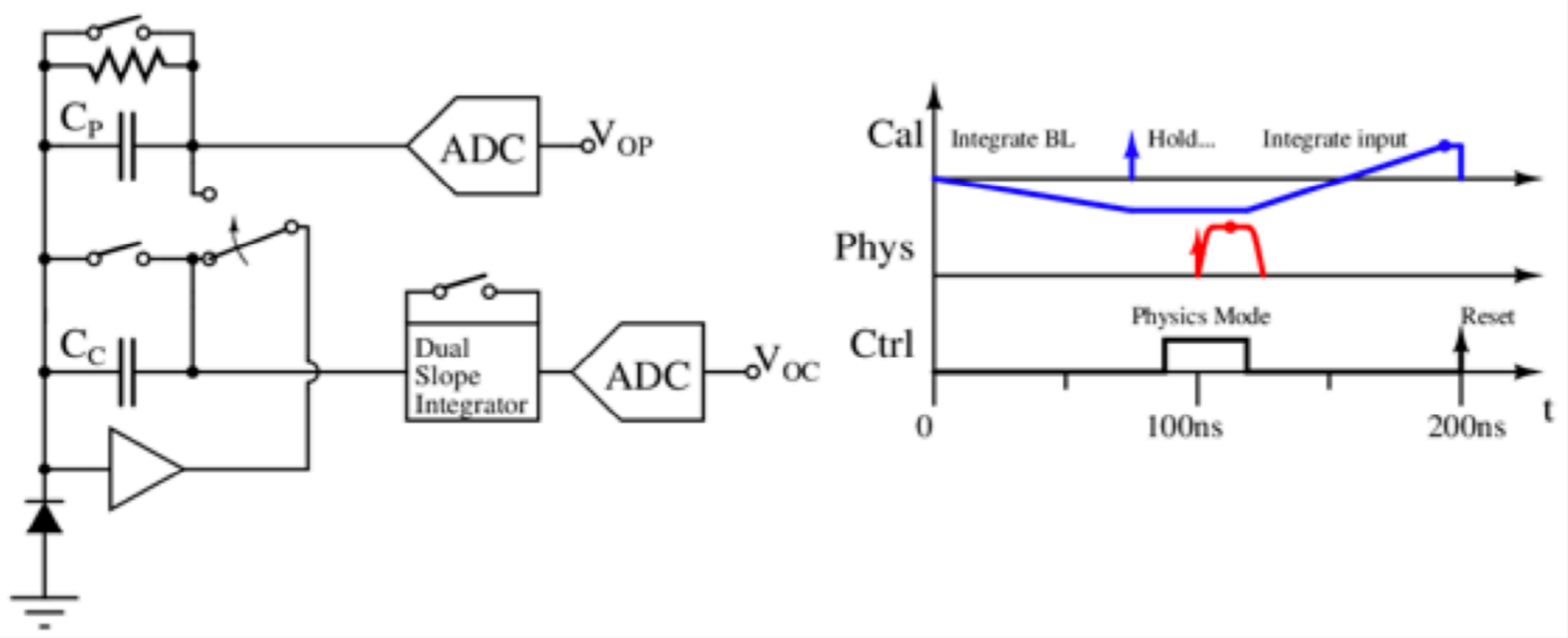
Different sensor materials: GaAs, Si, Diamond, Sapphire;
Different sensor segmentation – input capacitance;
Different MIP response and maximum signal: 0.8 pC – 30 pC.

Specification	Value
Q_{in}	> 2.8 fC
ENC	< 1000 - 1500 e^- rms
Number of channels	8
Maximum input rate	1 / 554ns
Baseline restoration	1%

- Firstly, BeamCal is hit by beam halo (muons)
  - – MIP deposition, low noise electronics
  - – Clean environment
  - – Good for calibration
- ~25ns later, BeamCal is hit by collision scattering
  - – Large deposit energy
  - – Physics readout

- Pad Capacitance: ~20pF (New Sapphire Design)
- Programmable time constant
- Active baseline restoration
- Programmable baseline restoration current

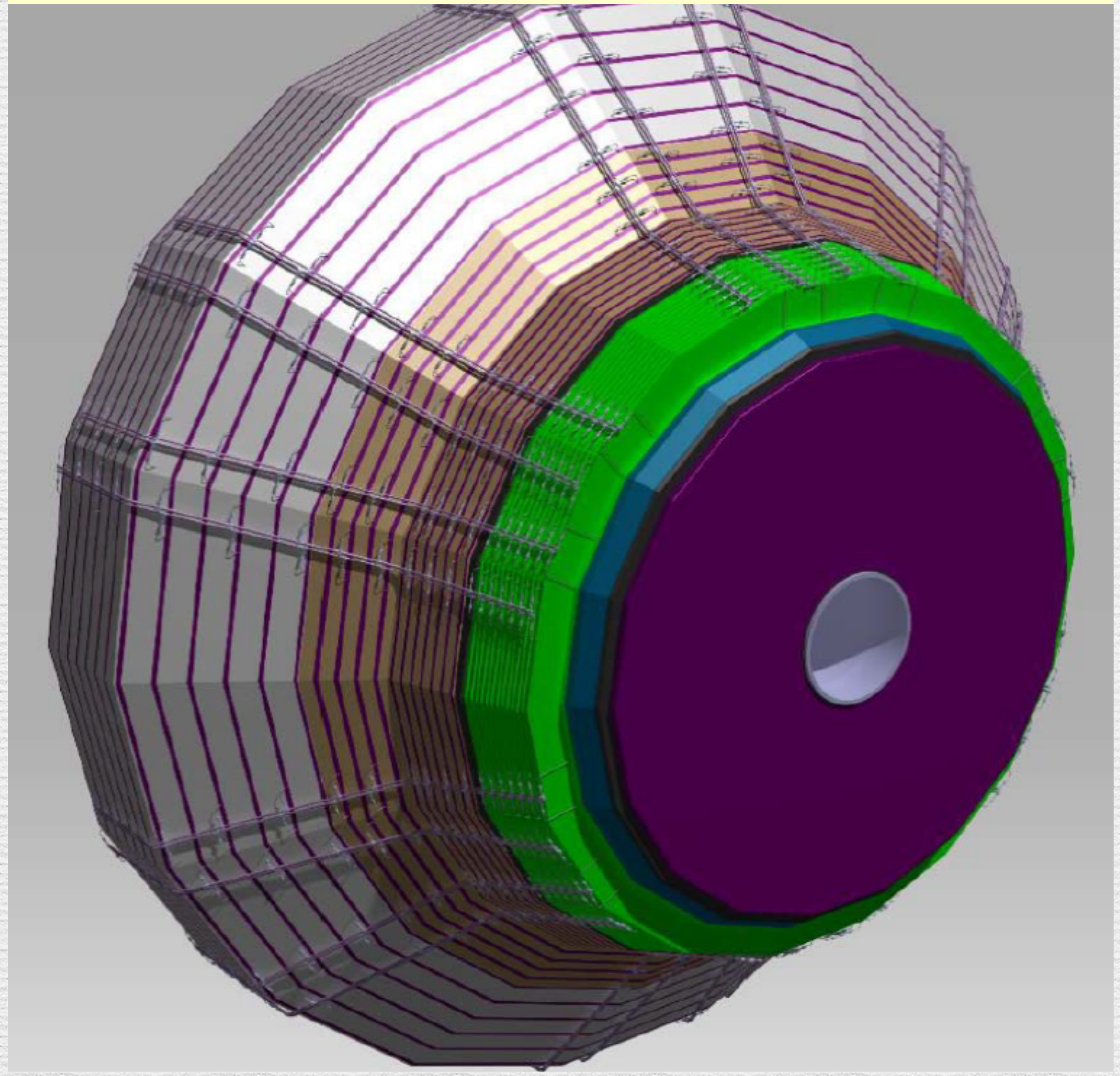
Dual slope integrator for calibration signal



Spin offs from FCAL technologies

FLAME is used for the HL upgrade of the CMS detector

High Granularity Calorimeter



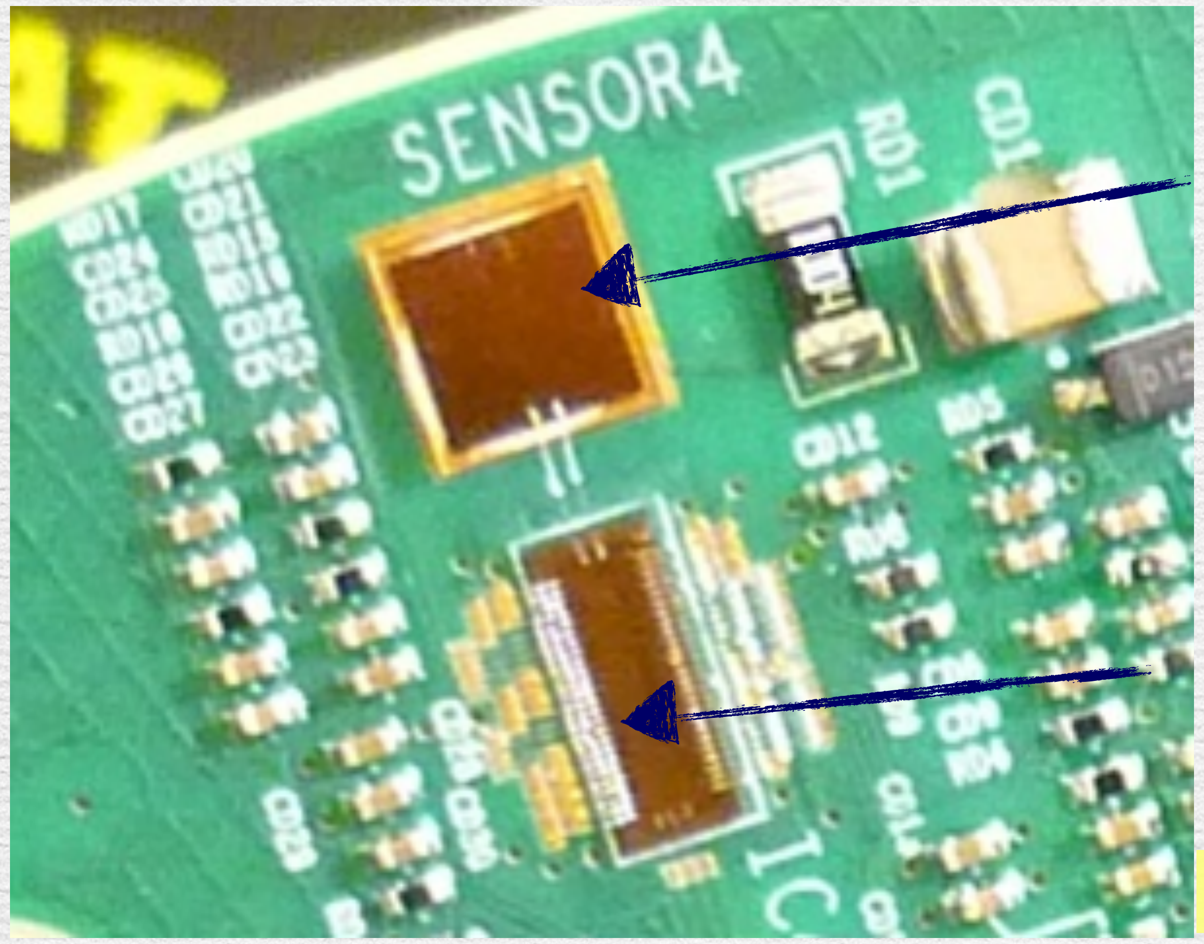
ECAL: SiW sandwich
HCAL: Si/Sc steel sandwich
6.5 x 10^6 readout channels

fast Mip Timing Detector MTD

Lyso:Cr crystals, read out with SiPMs

Spin offs from FCAL technologies

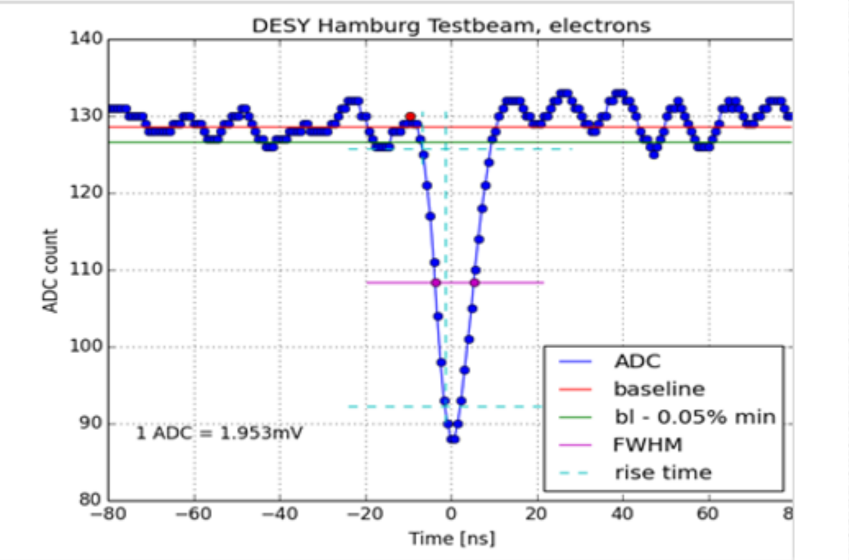
Luminometer and Beam Condition Monitor for the CMS experiment



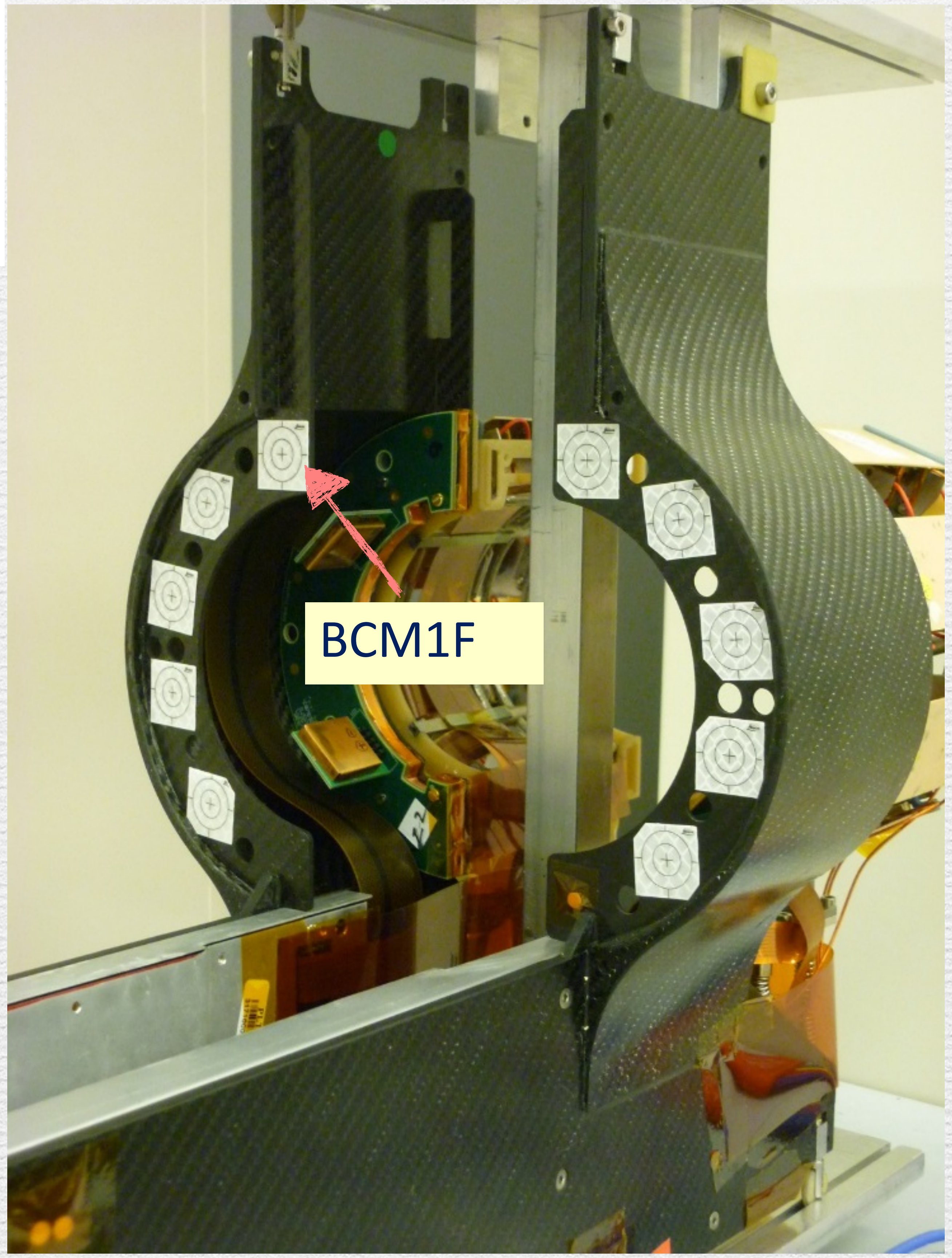
sensor pads (Si diodes)

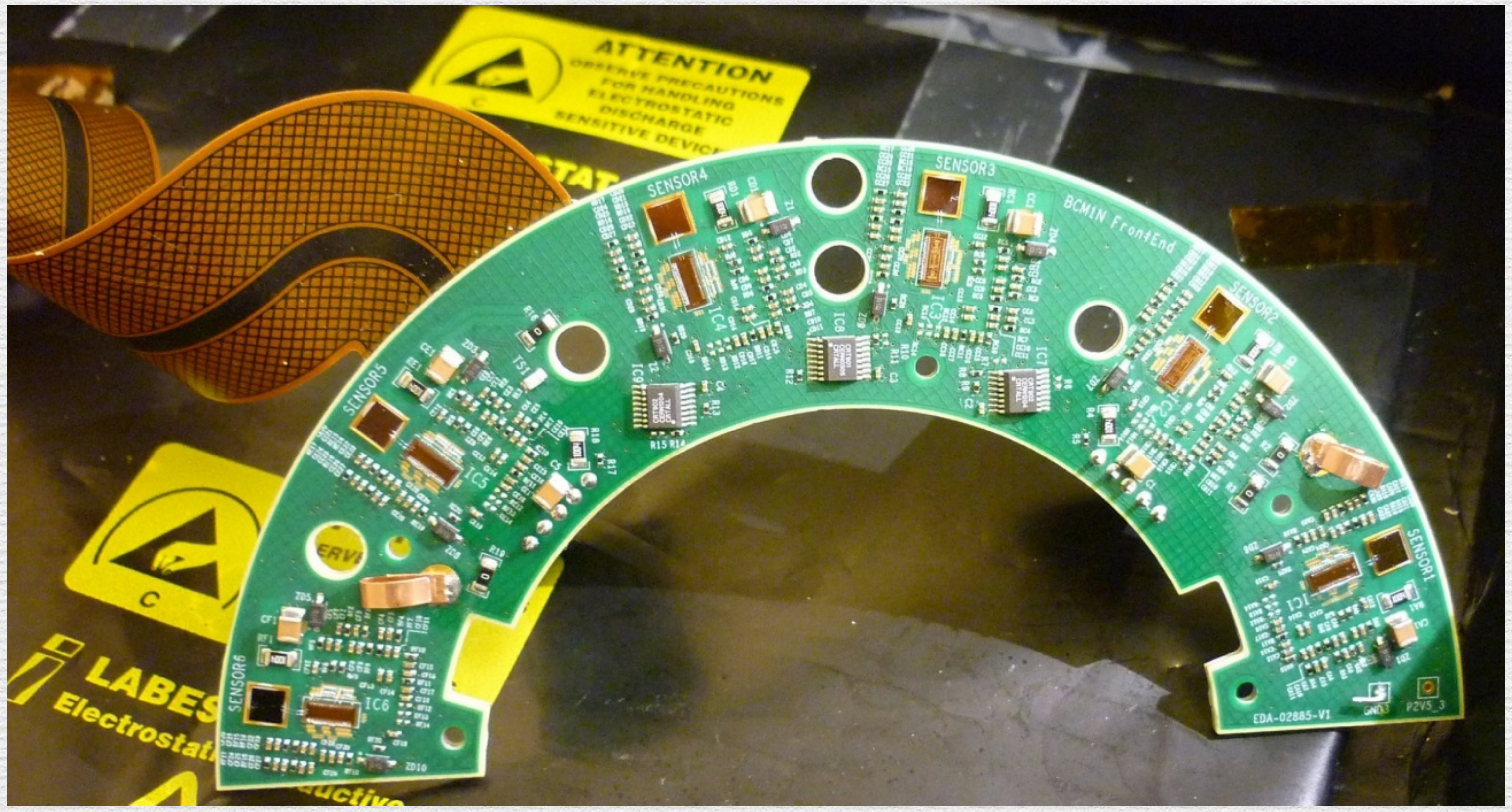
Front-end ASIC, supers-fast (sub-Nanosecond time measurement)

Designed in UST Krakow



Carbon fiber structure





Half ring with flexible Kapton PCB

Summary and Outlook

- FCAL has developed a design for the very forward region of a detector at an e+e- collider
- Three compact calorimeters are foreseen:
  - BeamCal for bunch-by-bunch luminosity measurement and electron tagging
  - LumiCal for precise measurement of the integrated luminosity.
  - LHCal to extend the coverage of HCAL
- Sensors for prototypes of BeamCal and LumiCal are designed and fabricated
- Dedicated FE ASICs are designed and fabricated in 130 nm CMOS technology
- Prototypes of fully instrumented sensor planes are built and tested
- A prototype of a highly compact calorimeter was studied in test-beams at CERN and DESY
  - the measurement of the effective Molière radius ($R_{\mathcal{M}}$ = 8 mm);
  - the measurement of the shower position reconstruction (440 µm resolution);
  - the measurement of the longitudinal shower shape.
- Simulations are confirmed by the measurements
- Technologies developed in FCAL are used in a luminometer for CMS and for CMS upgrades

Thank you for attention!

Back up

The forward region of the CEPC detector

- Instrumented with a luminometer (LumiCal), aiming to measure integrated luminosity with a precision of 10^{-3} in e+e- collisions for Higgs production at the center-of-mass energy of 240 GeV

- The precision requirements on the integrated luminosity measurement are motivated by the CEPC physics program, intended to test the validity scale of the Standard Model through precision measurements in the Higgs and the electroweak sectors with 10^6 Higgs and up to 10^{12} Z bosons.
- Many sensitive observables depend on the uncertainty of the integrated luminosity.