Development and performance of compact LumiCal prototype calorimeter for future linear collider experiments

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VIRTUAL CONFERENCE

Dr. Borysova Maryna

KINR & DESY

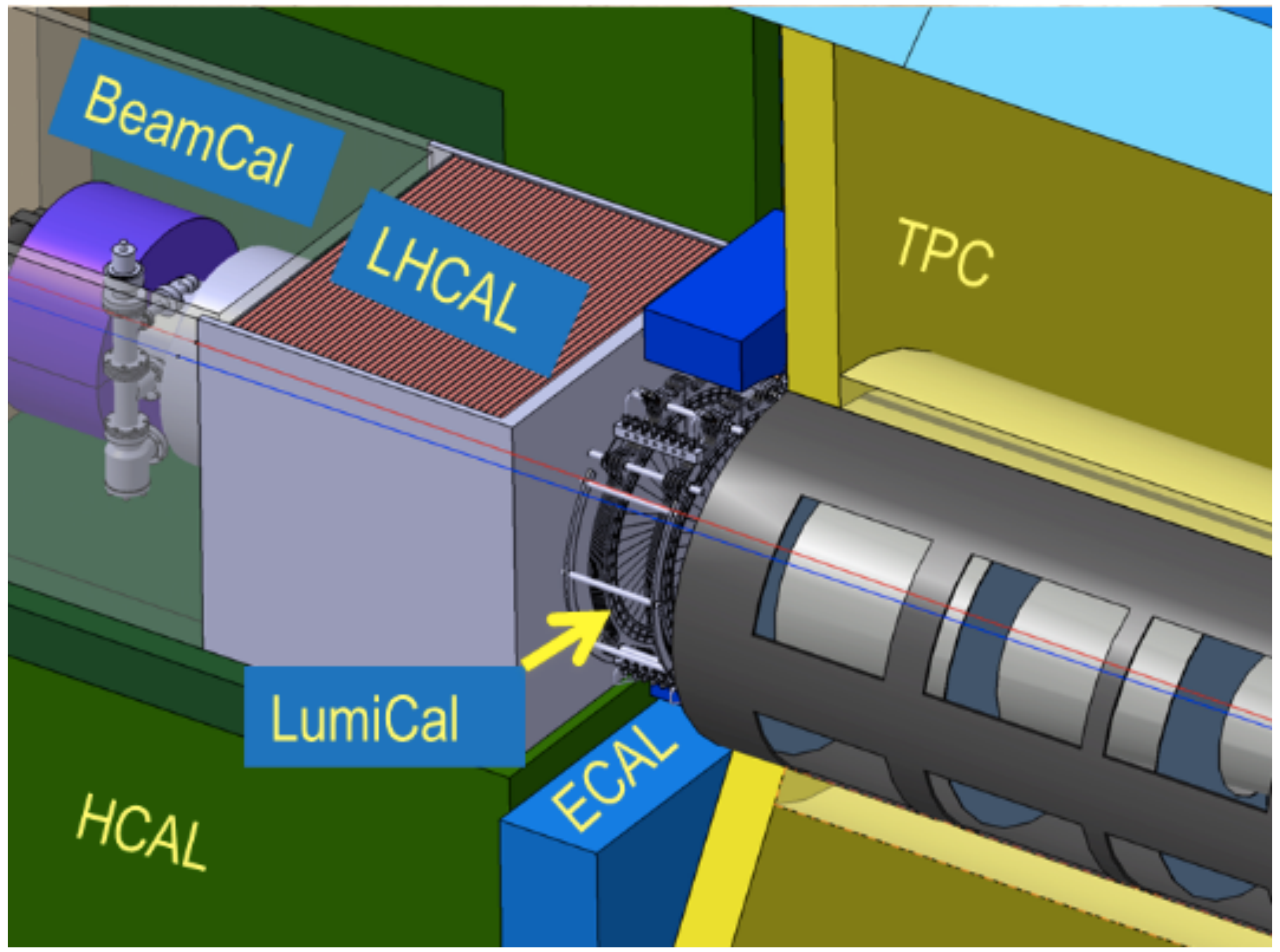
On behalf of the FCAL collaboration

July, 31, 2020

Outline

- Design of the very forward region of e+e- collider experiments
- LumiCal design optimisation in simulations
- Assembly of thin detector module
- FLAME - dedicated readout ASIC for LumiCal
- Performance tests of LumiCal prototype in the beam
- Summary & Outlook

FCAL detectors in LC Experiments



LumiCal

- Precise integrated luminosity measurement;
- 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 absorbers with 1 mm gap for silicon sensors;
- two arms symmetrically on both sides at ~2.5 m (ILD) from the interaction point.

BeamCal

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

LHCal

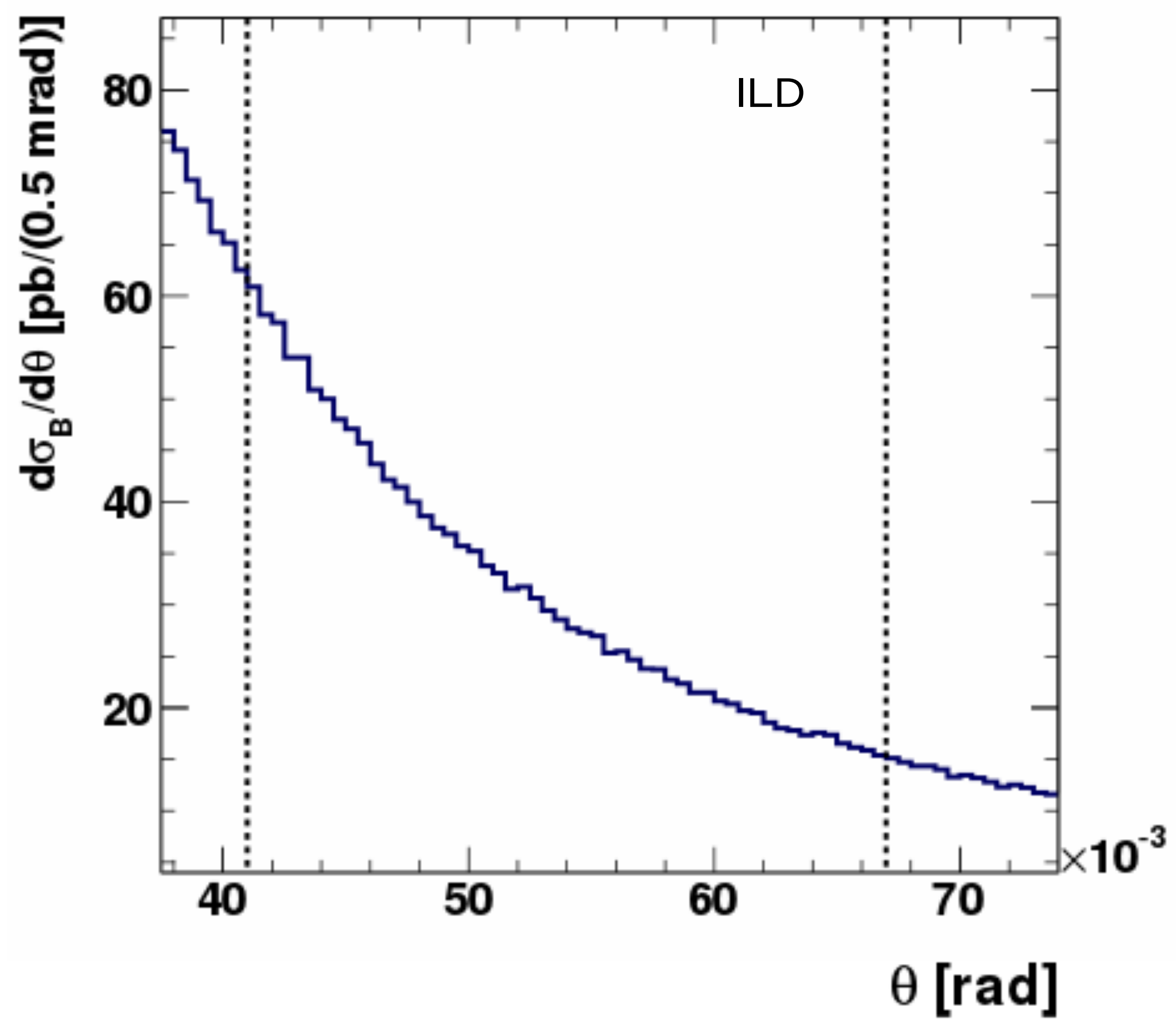
- extends the coverage of HCAL;
- Sampling calorimeter
- 29 layers, silicon sensors, tungsten or iron absorbers of about 16mm thickness.

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: $41 < \theta < 67$ mrad

The cross section of the Bhabha process can be precisely calculated.

In leading order:

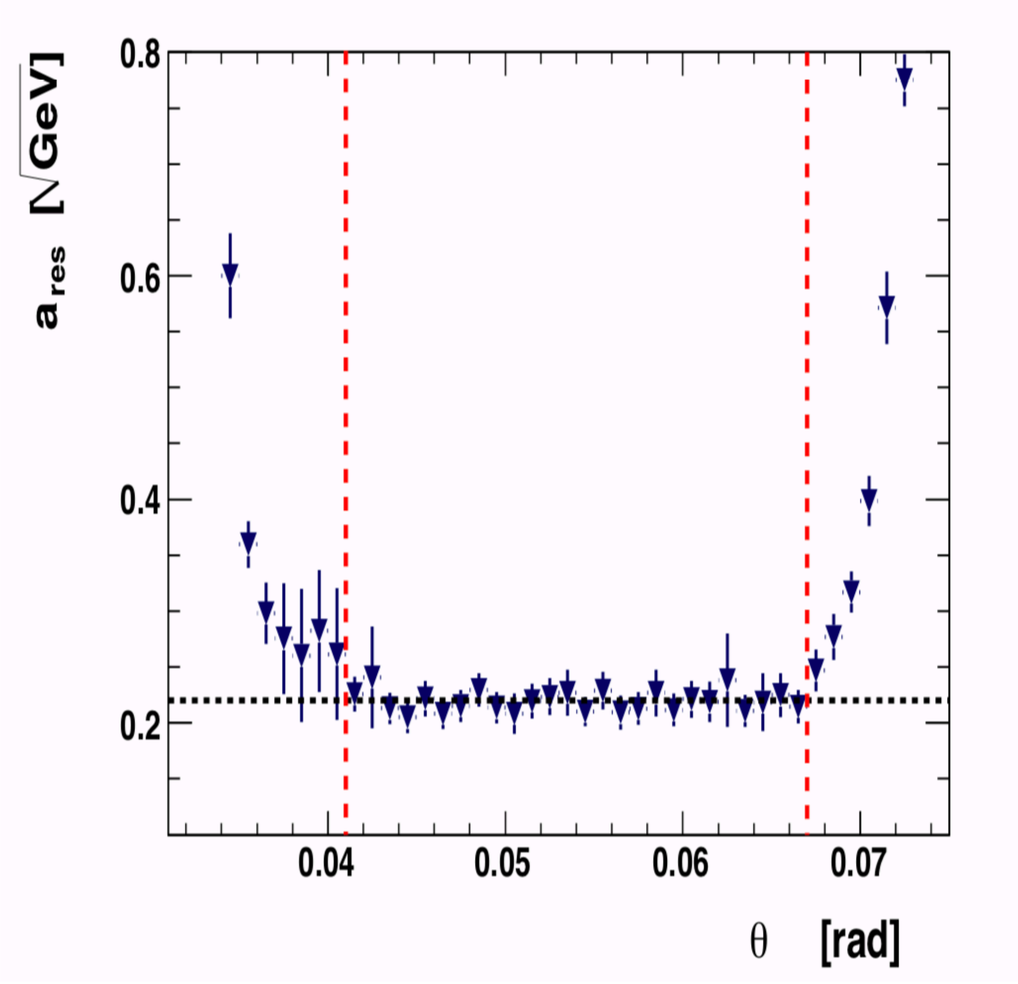
$$\frac{d\sigma_B}{d\theta} = \frac{2\pi\alpha_{em}^2}{s}\frac{\sin\theta}{\sin^4(\theta/2)} \approx \frac{32\pi\alpha_{em}^2}{s}\frac{1}{\theta^3},$$

the approximation holds at small θ.

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

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



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

$$a_{res} = (0.21 \pm 0.02)\ \sqrt{GeV}$$

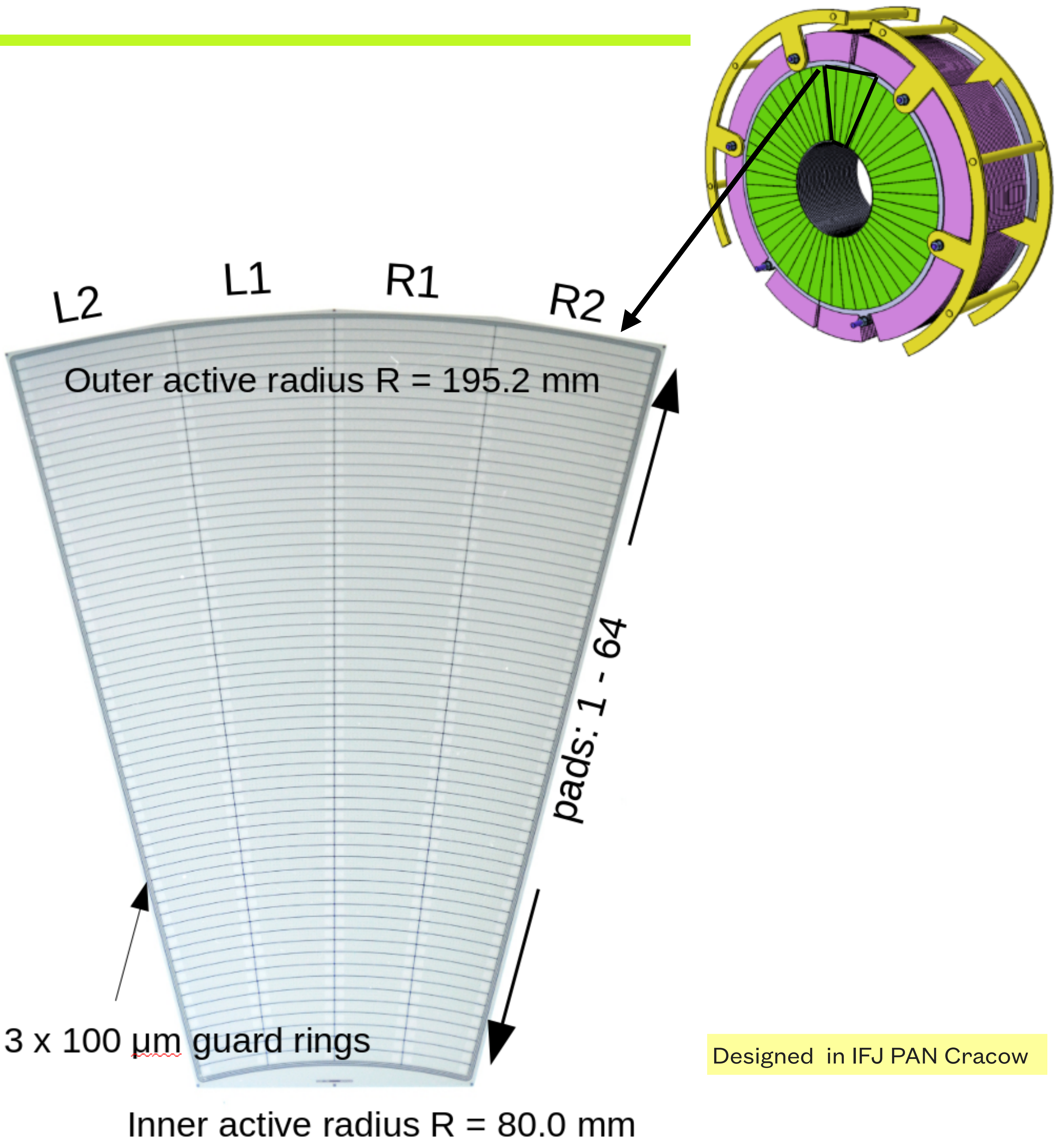
- Bigger fiducial volume => higher statistics on Bhabha events
- The smaller Molière Radius => the bigger fiducial volume
- Compact Calorimeter => Smaller Molière Radius
- High energy resolution to correctly identify Bhabha events
- Smaller Molière Radius => higher efficiency of electron detection over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

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

LumiCal silicon sensor

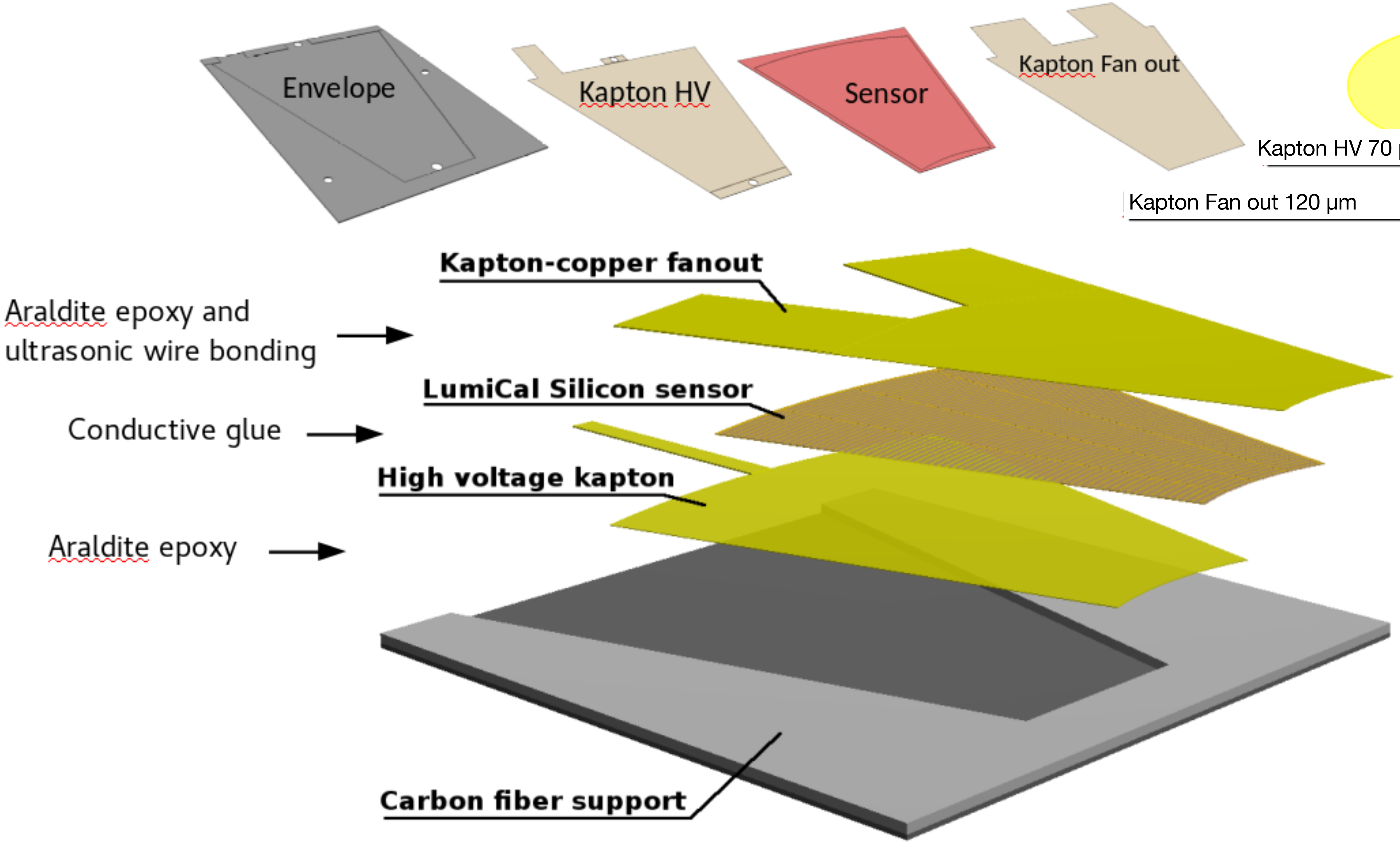
Silicon pad sensor prototype is designed for ILD; produced by Hamamatsu

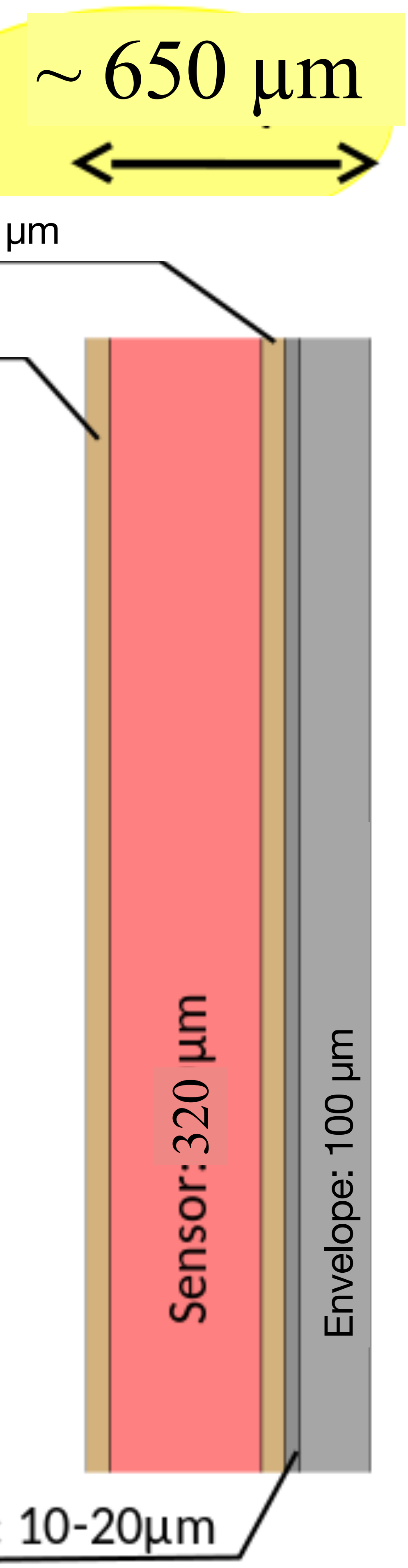
- thickness 320 µm
- DC coupled with readout electronics
- p+ implants in n-type bulk
- 64 radial pads, pitch 1.8 mm
- 4 azimuthal sectors in one tile, each 7.5°
- 12 tiles make full azimuthal coverage



Designed in IFJ PAN Cracow

LumiCal thin module prototype assembly





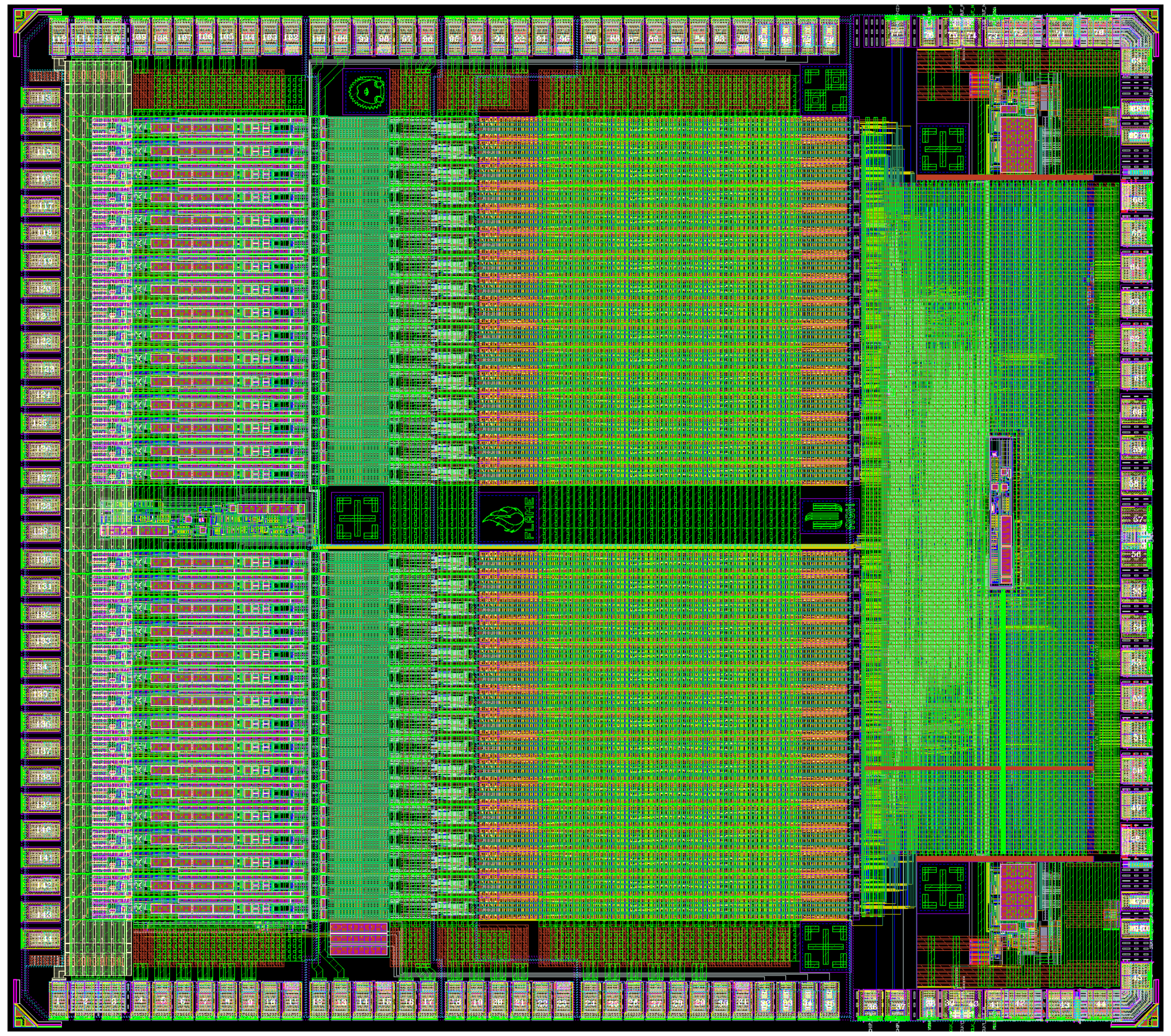
- Compactness is an essential requirement to provide small Molière radius/accurate shower position reconstruction.
- In current LumiCal conceptual design the space between absorbers is 1 mm!
- Carbon fiber support facilitate handling and mounting on tungsten planes

Designed at TAU

FLAME - Readout ASIC for LumiCal

Architecture of FcaL Asic for Multiplane rEadout

FLAME layout: the size is 3.7mm x 4.3mm



Complete readout ASIC integrating whole functionality (biasing, calibration, etc.)

32 mix-mode channels comprising:

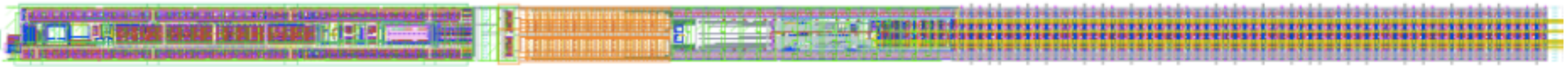
- Variable gain front-end
- 10-bit SAR ADC with sampling rate up to 50 MSps
- Ultra low power consumption (Front-end + ADC <2mW/chan)

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)

Single FLAME channel: 2350 µm x 80 µm:

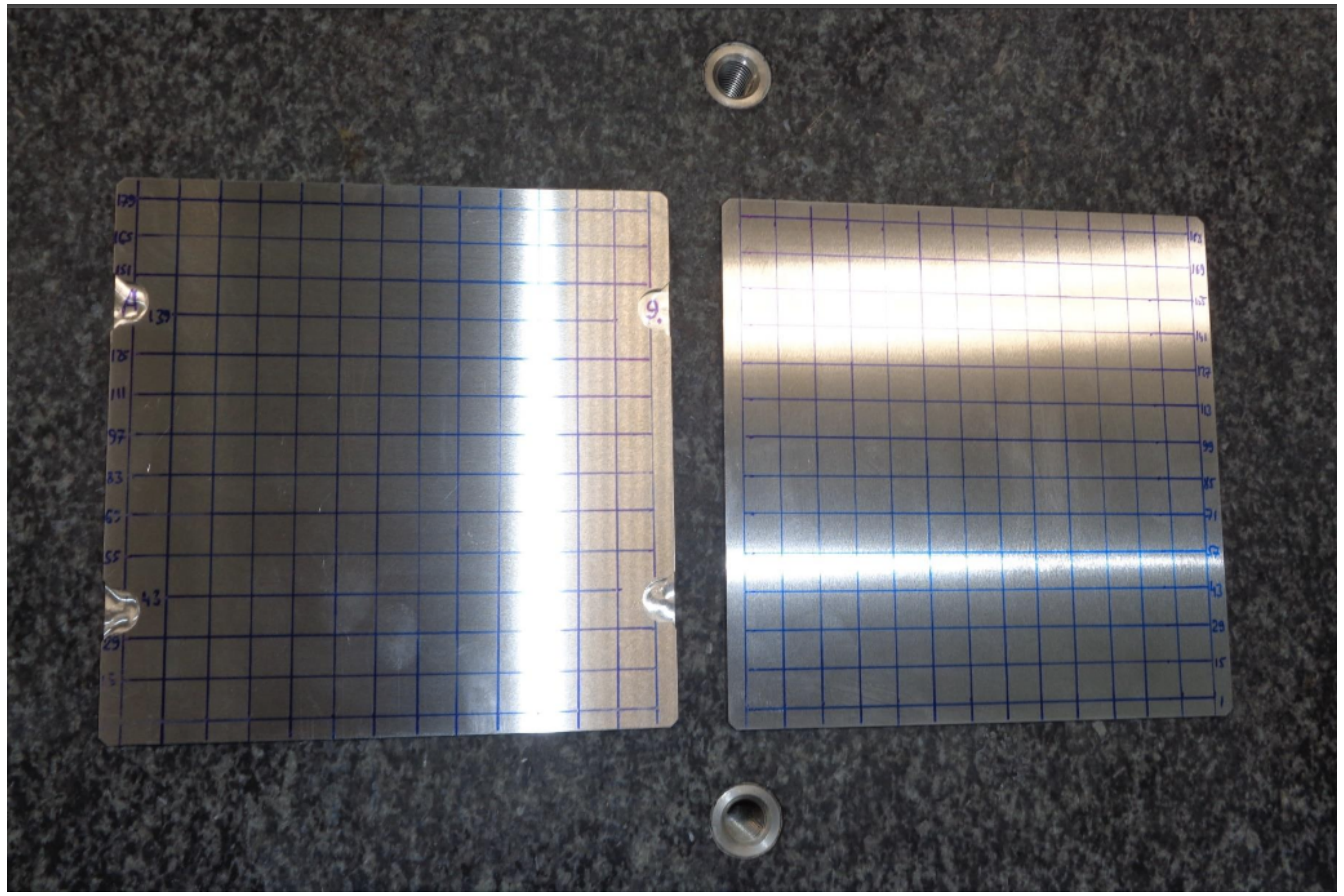


Designed in UST Krakow

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

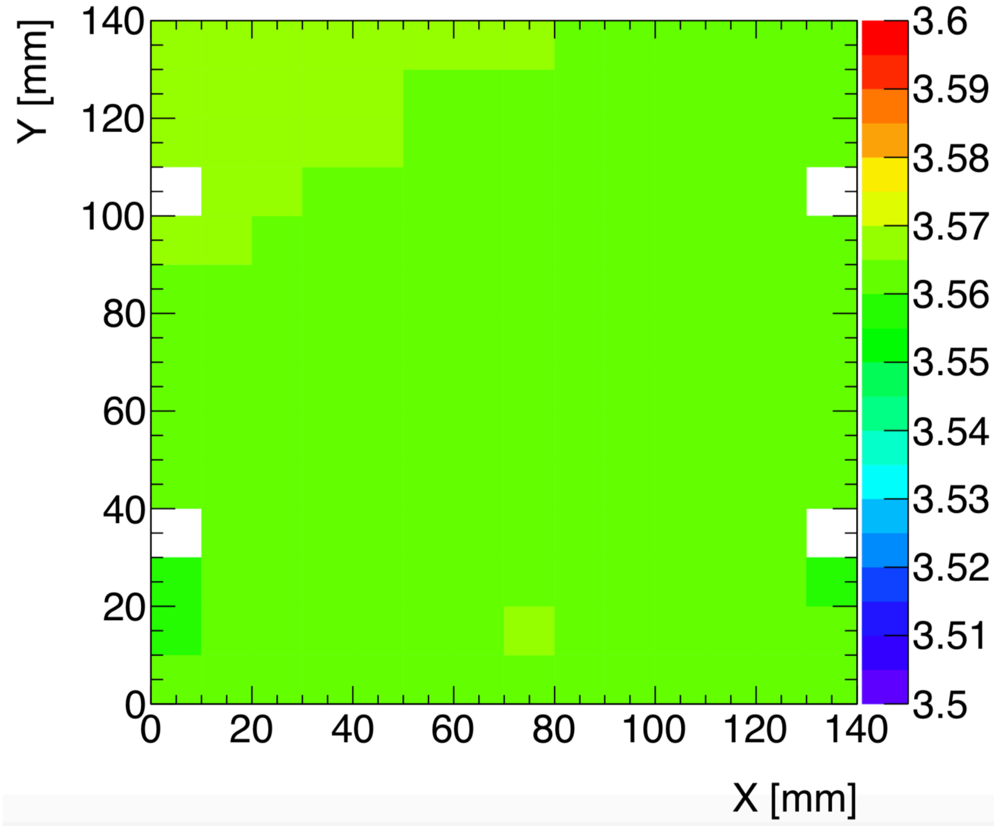
Tungsten plates

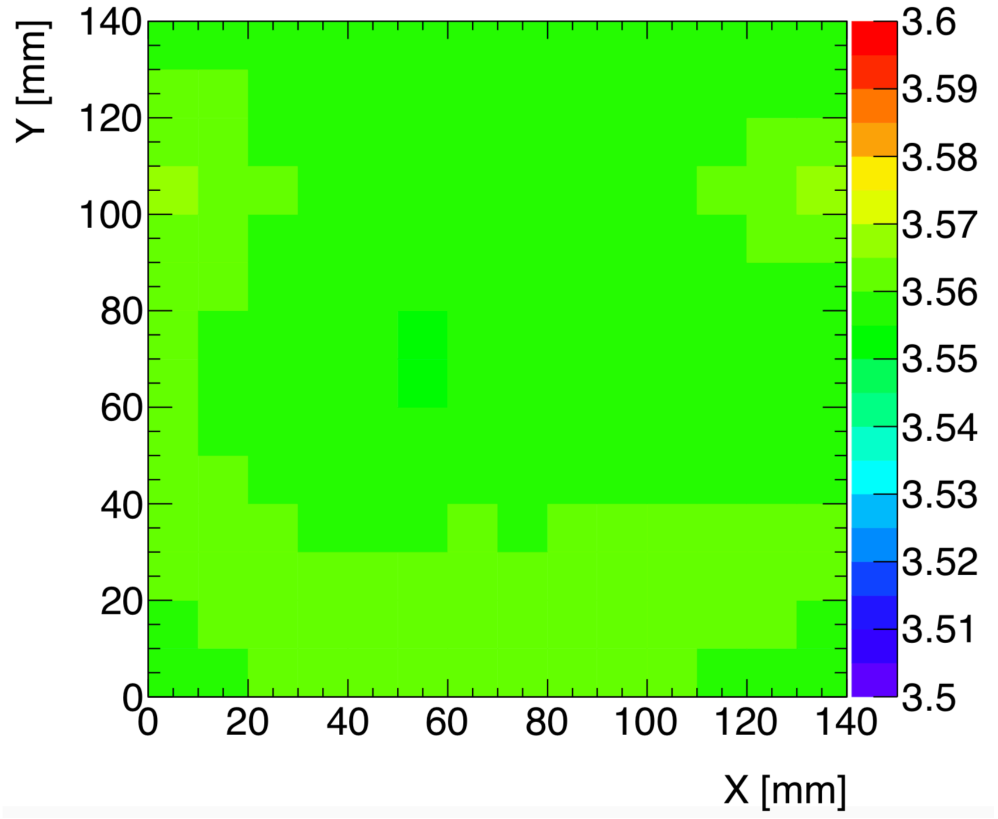
- 10 new tungsten absorber plates
- High requirements to geometrical accuracy (~50 μm for thickness) make it difficult to use pure W.
- the absorber alloy : 93% tungsten, 5% nickel & 2% copper.
- Good flatness ~30 μm observed
- Glued to permaglass frame
- Used in assembled calorimeter in 2019/2020 beam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



Dimensions 140x140x3.5 mm

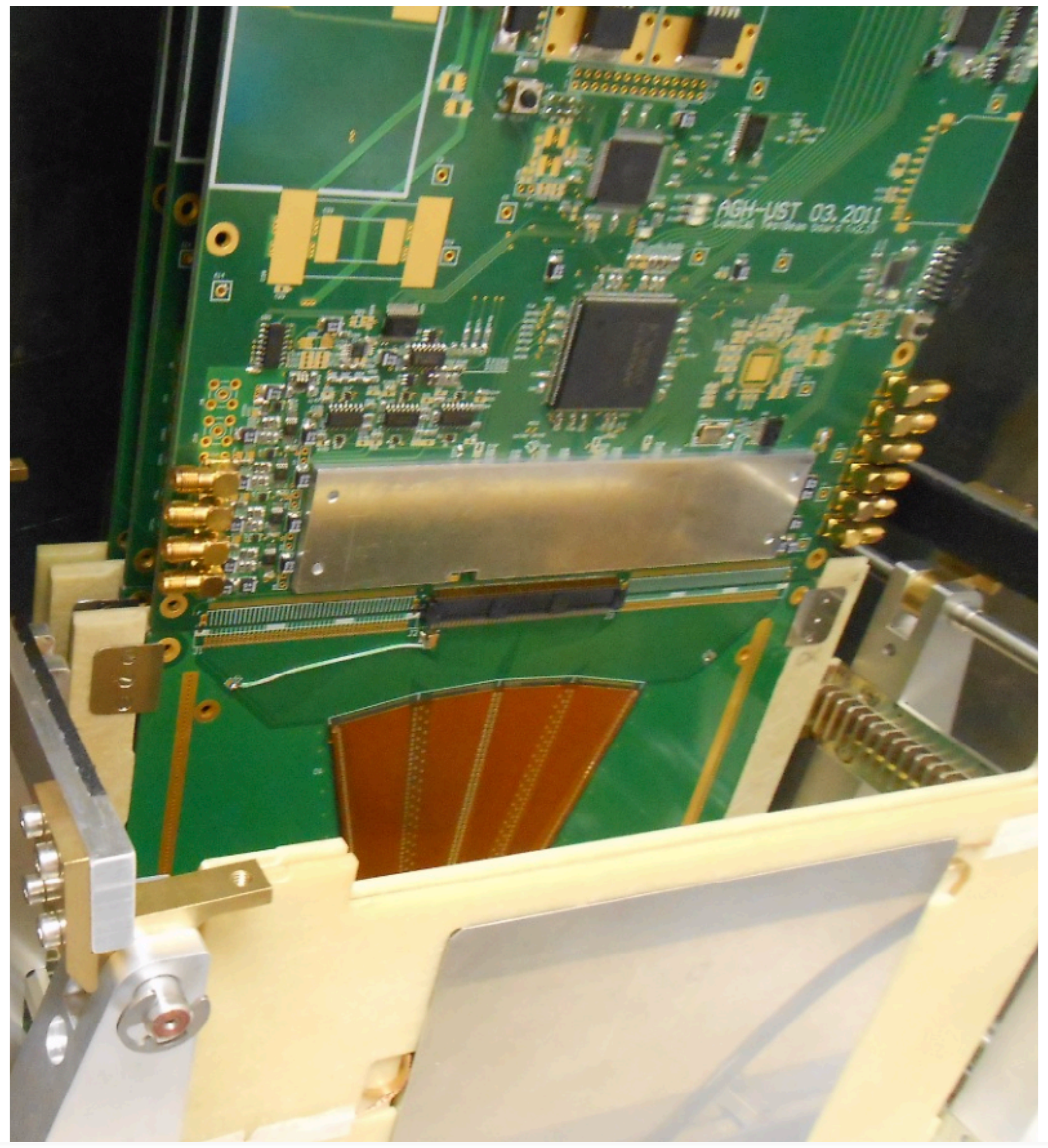
Designed in JINR Dubna





Performance tests of LumiCal prototype in the beam

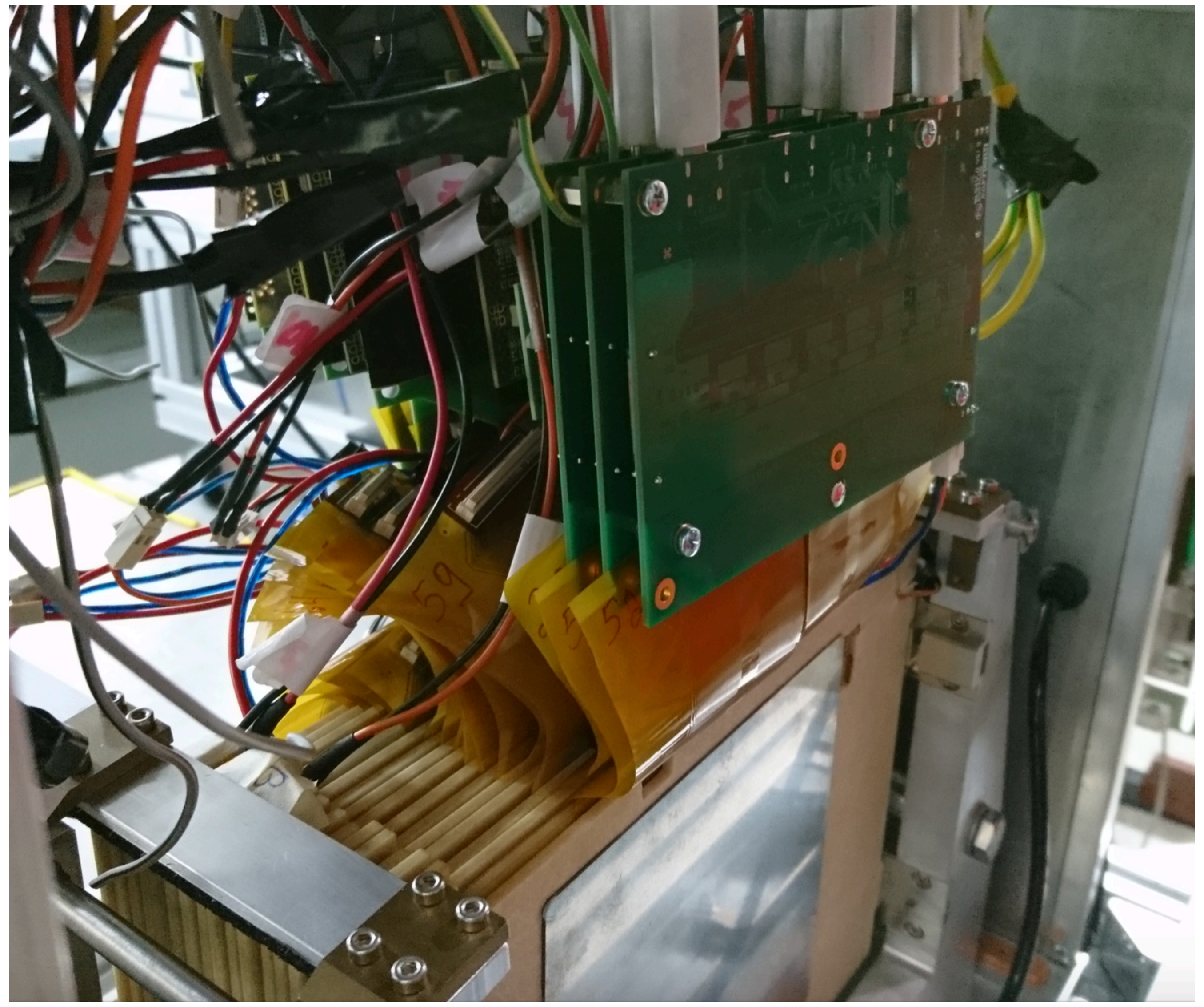
beam test 2014



beam test 2016

First Test of multi-layer compact design
- 8 LumiCal detector planes equipped
- with adapted APV25 readout
- 1 mm between tungsten plates
- Tested in test beam at DESY with 1-6 GeV e-

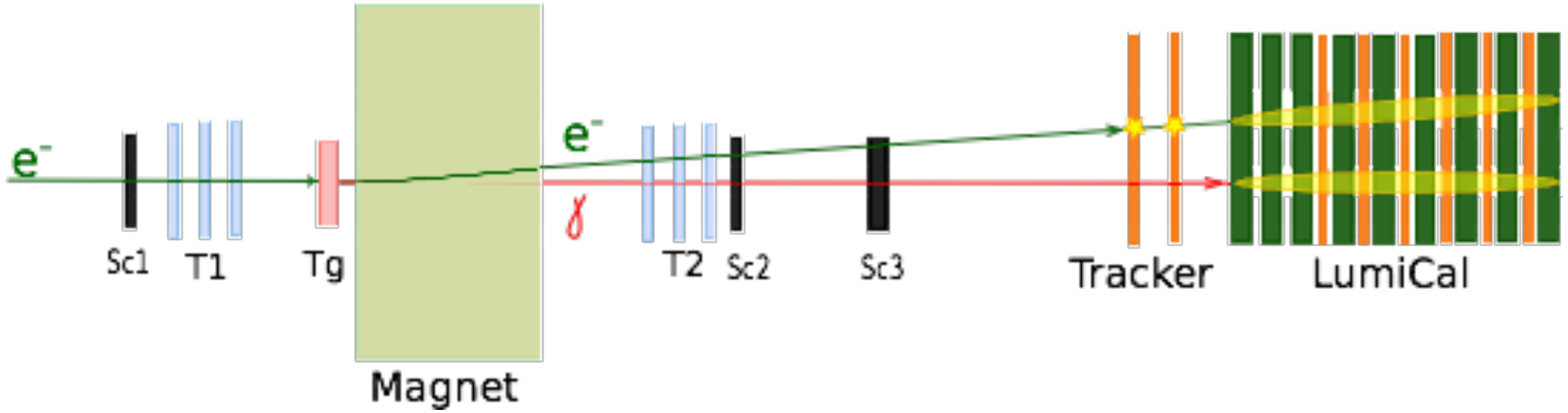
beam test 2020



First Test of multi-detector plane operation
- 4 LumiCal detector planes
- 32 channels per plane
- 4.5 mm between tungsten plates
- Tested in test beam at CERN PS with 5 GeV e-/μ

Test of 15-layer compact design with FLAME
- 15 LumiCal detector planes equipped
- with adapted APV25 and FLAME
- 1 mm between tungsten plates
- Tested in test beam at DESY with 1-5 GeV e-

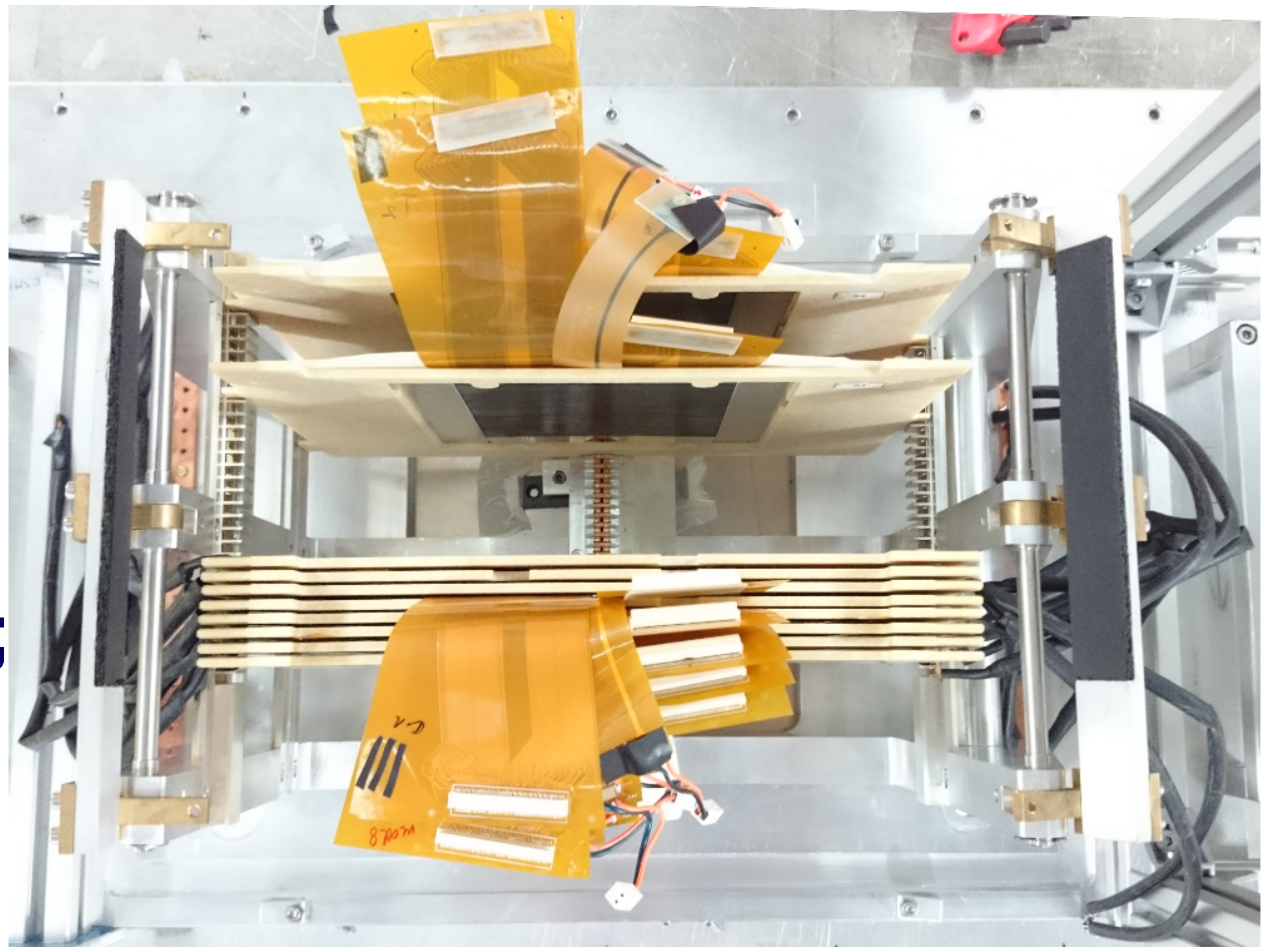
2016 Test Beam at DESY



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 – 6 GeV;
- Dipole magnet 1 – 13 kGs;

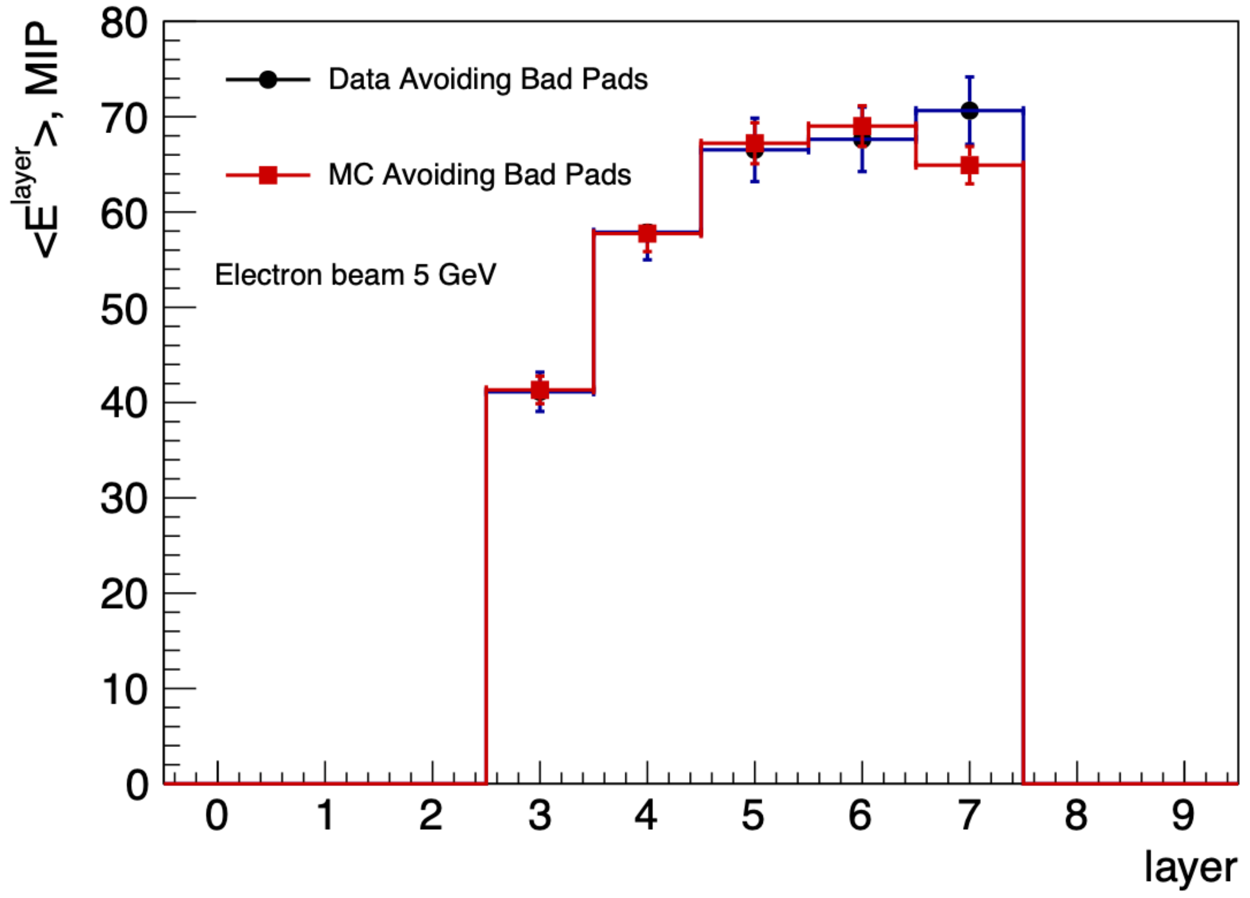
- 8 (256 channels) thin LumiCal modules (> 2k channels);
- 2 - used as a tracker / tagger for e/γ separation;
- 6 - in calorimeter (3 - 8 X0) installed in 1 mm gaps between absorbers;
- DAQ : SRS system, designed by RD51 collaboration;
- EUDET / AIDA beam Telescope : 6 planes with MIMOSA chip;



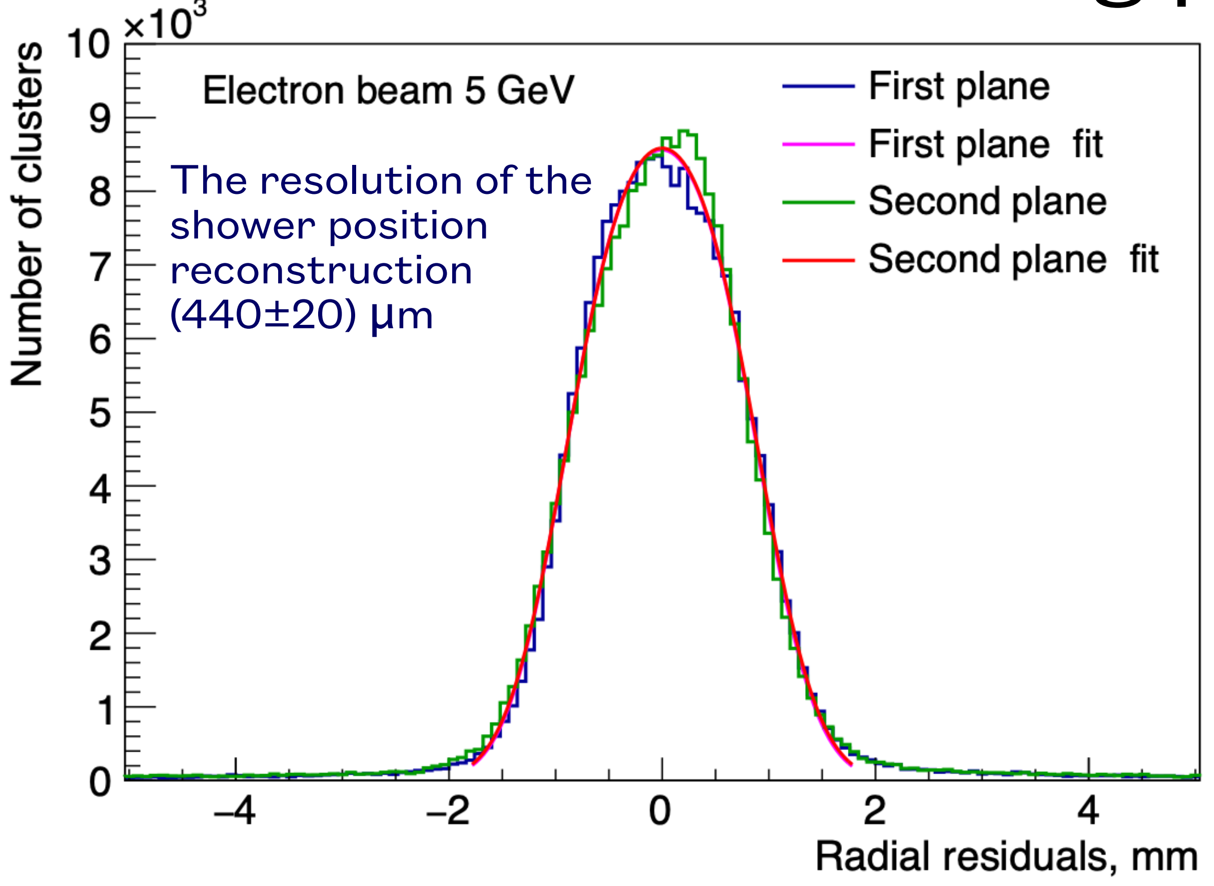
mechanical frame designed at CERN

Shower Study for 5 GeV electrons 2016 test beam

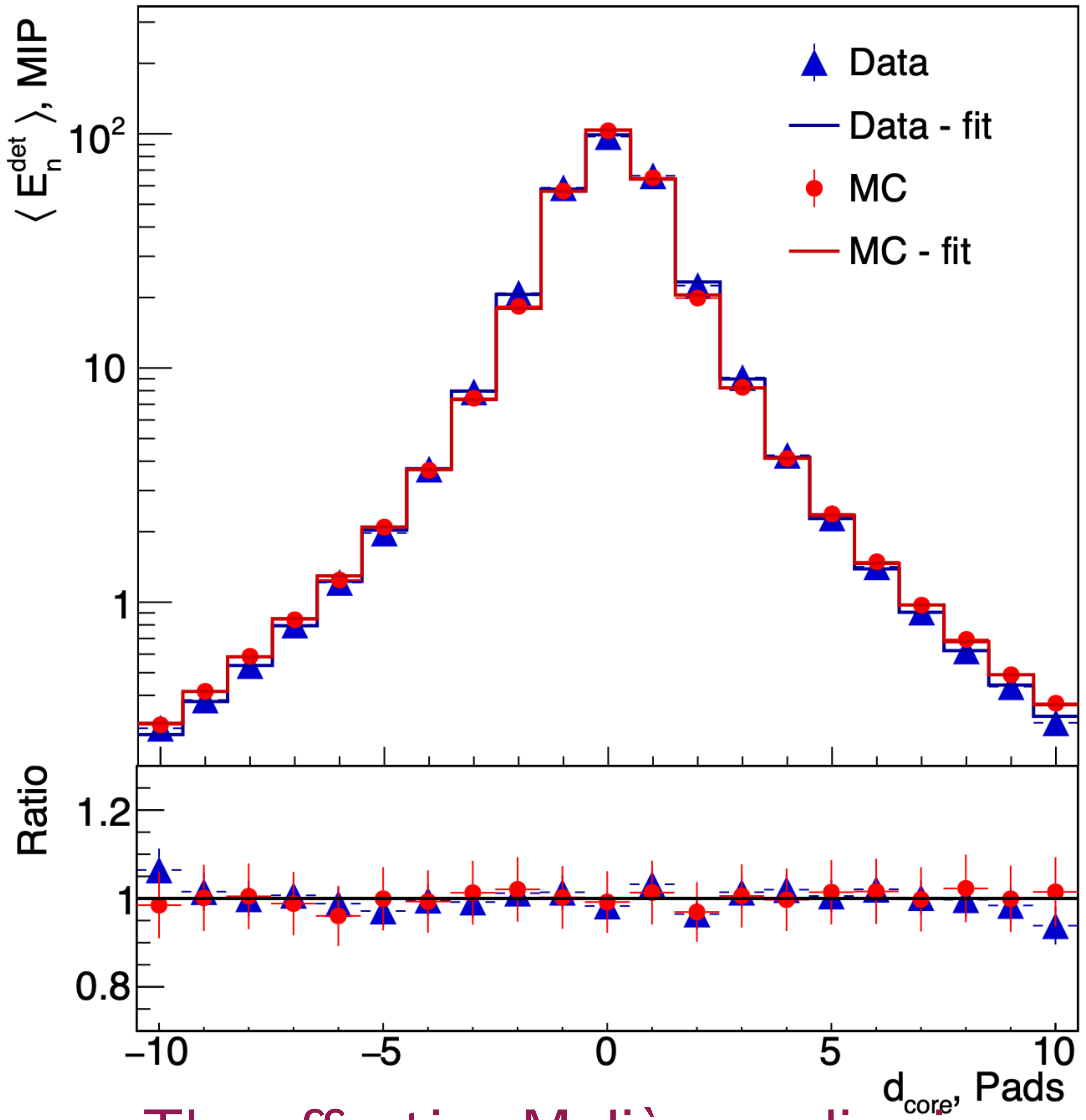
longitudinal shower



radial position residuals between the calorimeter and tracking planes



transverse shower



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

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

Shower parametrisation in radial direction:

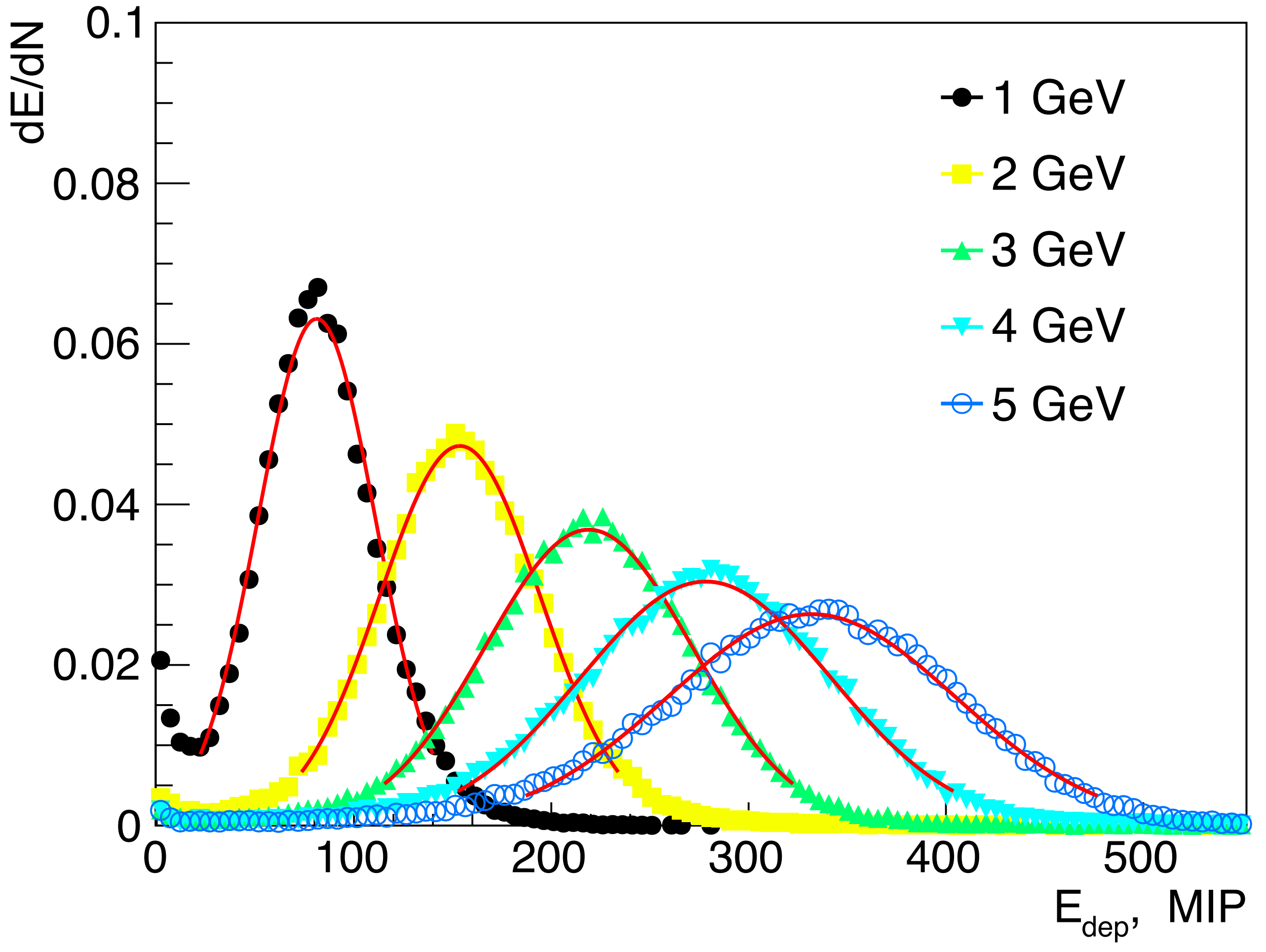
$$F_E(r) = A_C e^{-\left(\frac{r}{R_C}\right)^2} + A_T \frac{2r^{\alpha} R_T^2}{(r^2 + R_T^2)^2}$$

Parameters are found by fitting to data after integration over the area corresponding to sensor pads.

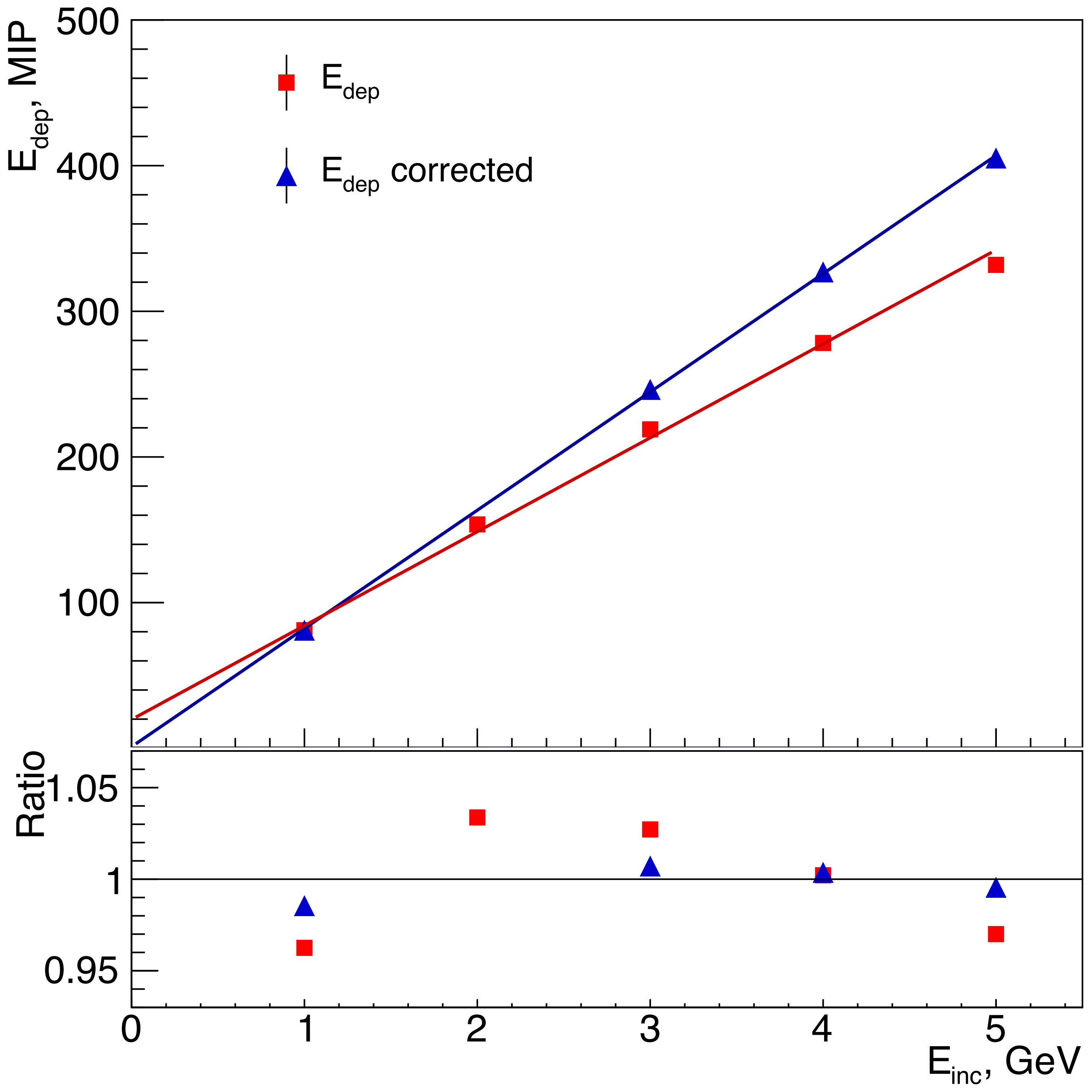
Molière radius $R_{\mathscr{M}}$ can be found from the equation:

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

LumiCal Energy Response

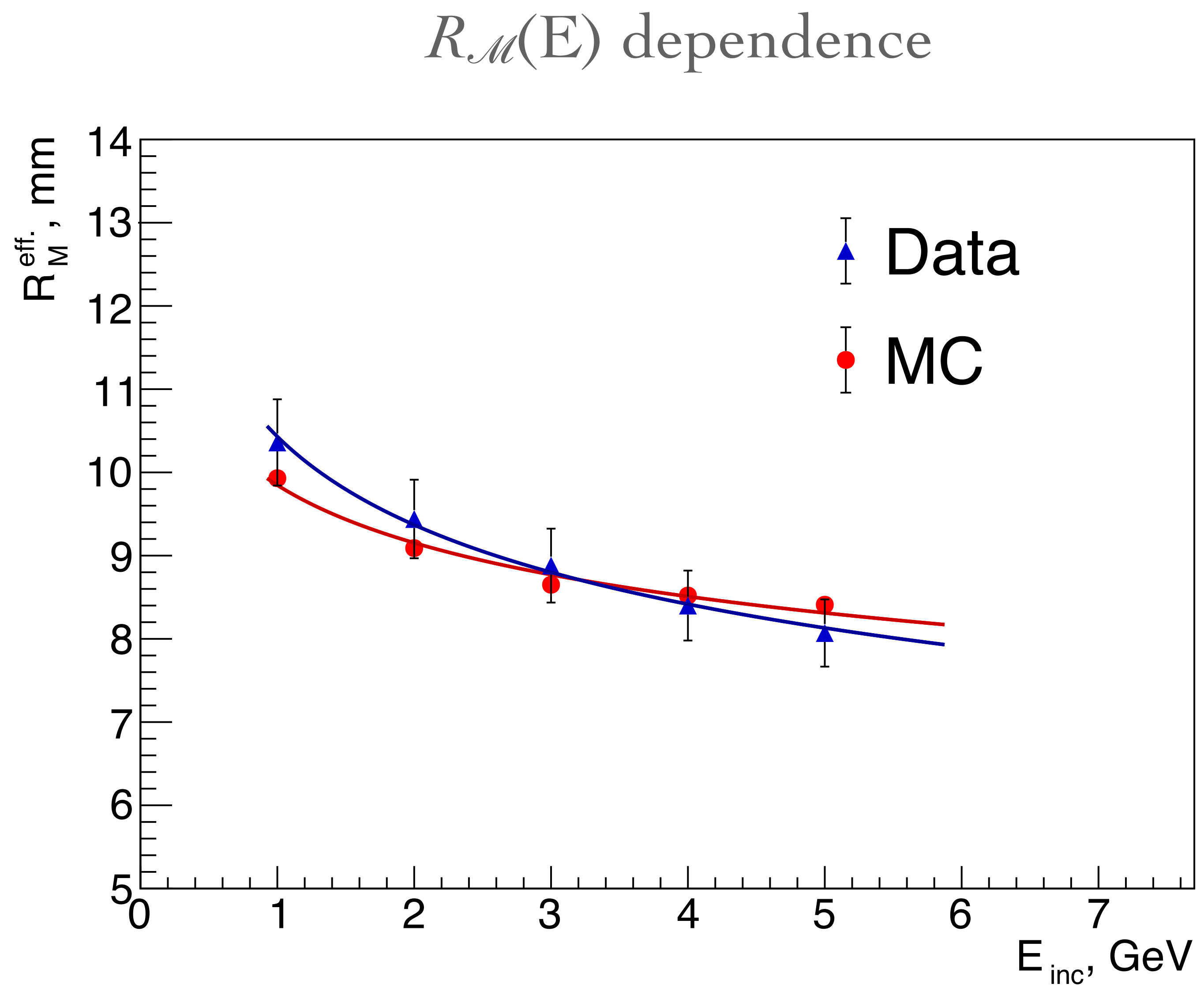


LumiCal prototype demonstrates good linear response to the beam of 1 – 5 GeV.



Small nonlinearity is explained by limited number of sensitive planes.

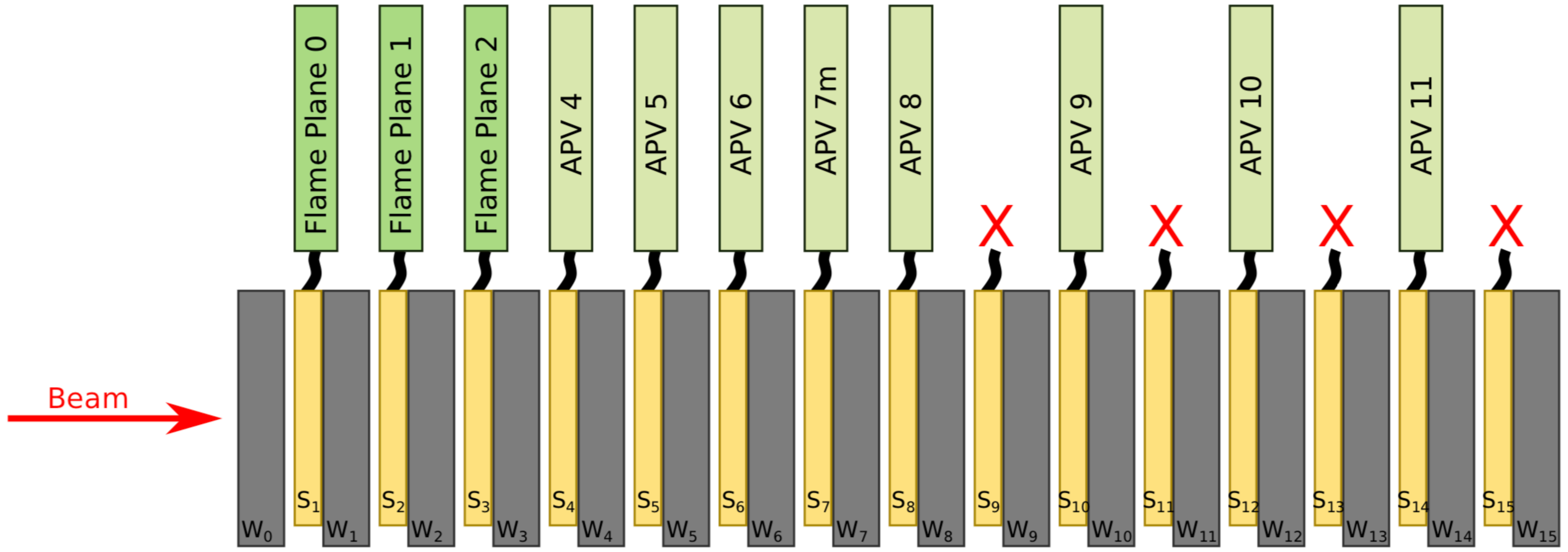
Tested and corrected in MC.



Observed slight dependence of $R_{\mathscr{M}}$ 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

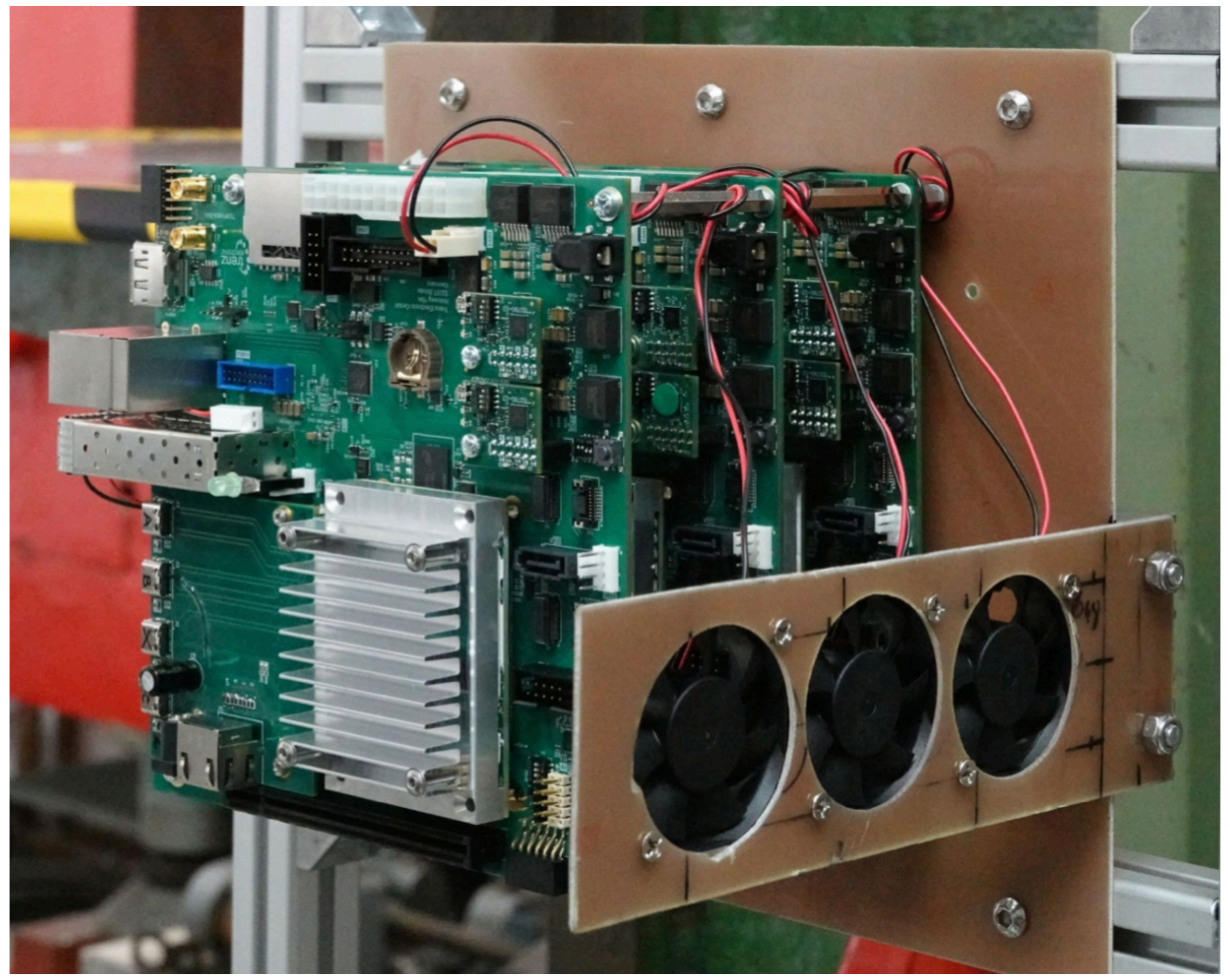
FLAME – in beam test 2020 at DESY

- LumiCal prototype with 15 sensitive sensor layers
- 3 planes equipped with FLAME dedicated LumiCal Readout
- 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



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



- 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…

Summary and Outlook

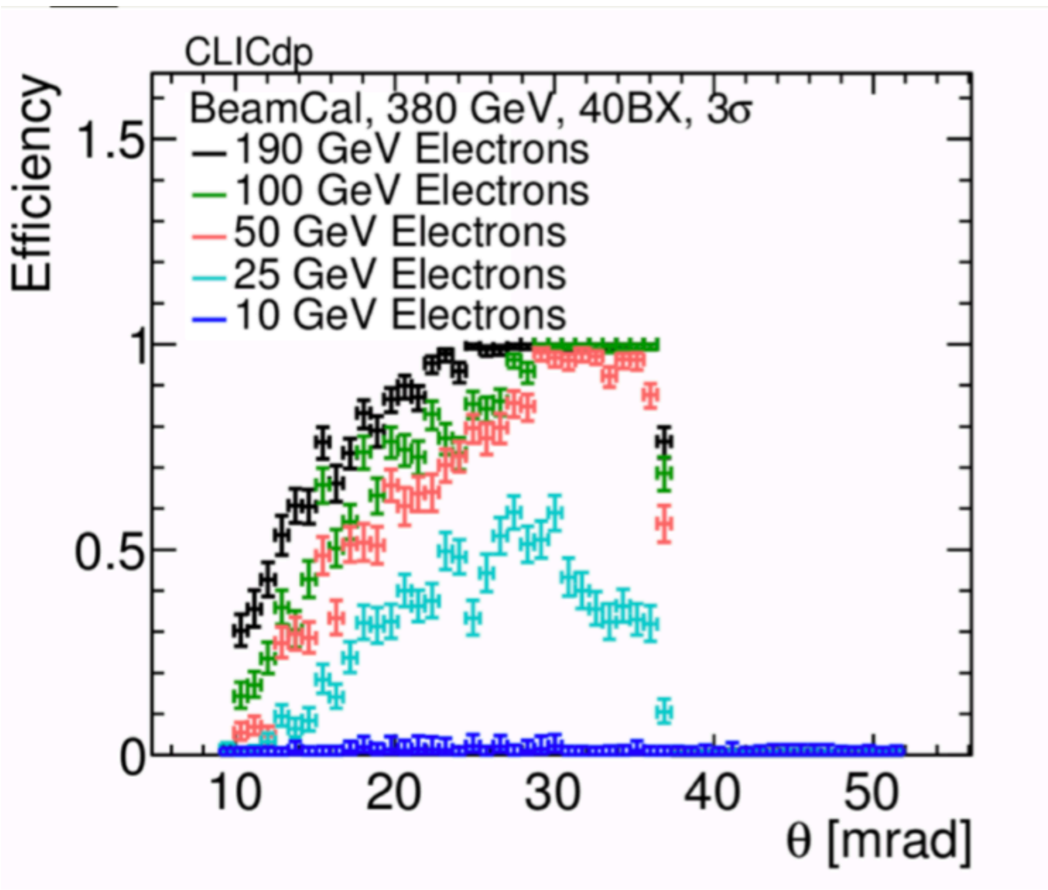
- FCAL has developed a design for the very forward region for experiments at e+e- colliders
- Three compact calorimeters are foreseen:
    - LumiCal for precise measurement of the integrated luminosity.
    - BeamCal for bunch-by-bunch luminosity measurement and electron tagging
    - LHCal to extend the coverage of HCAL
- Sensors for prototype of 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 at 5 GeV);
- Simulations are confirmed by the measurements
- Technologies developed in FCAL are applied in other experiments, e.g. CMS, XFEL and considered for LUXE at DESY.

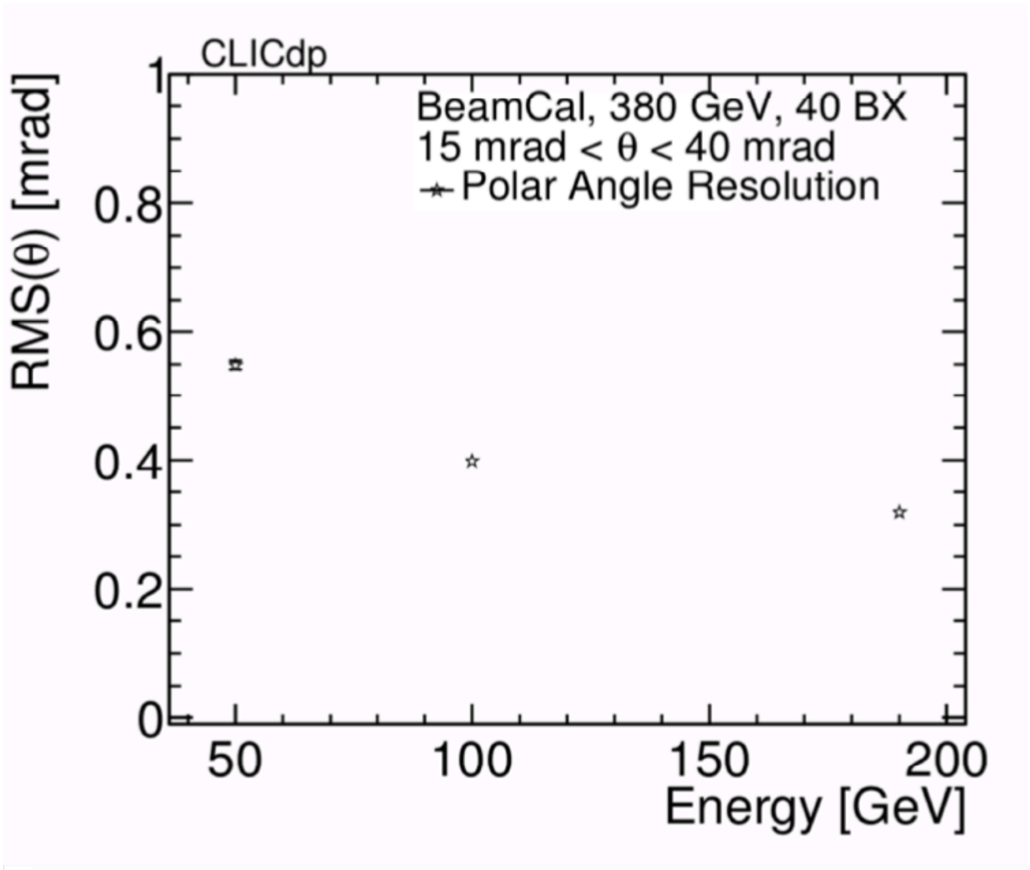
Thank you for attention!

Back up

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

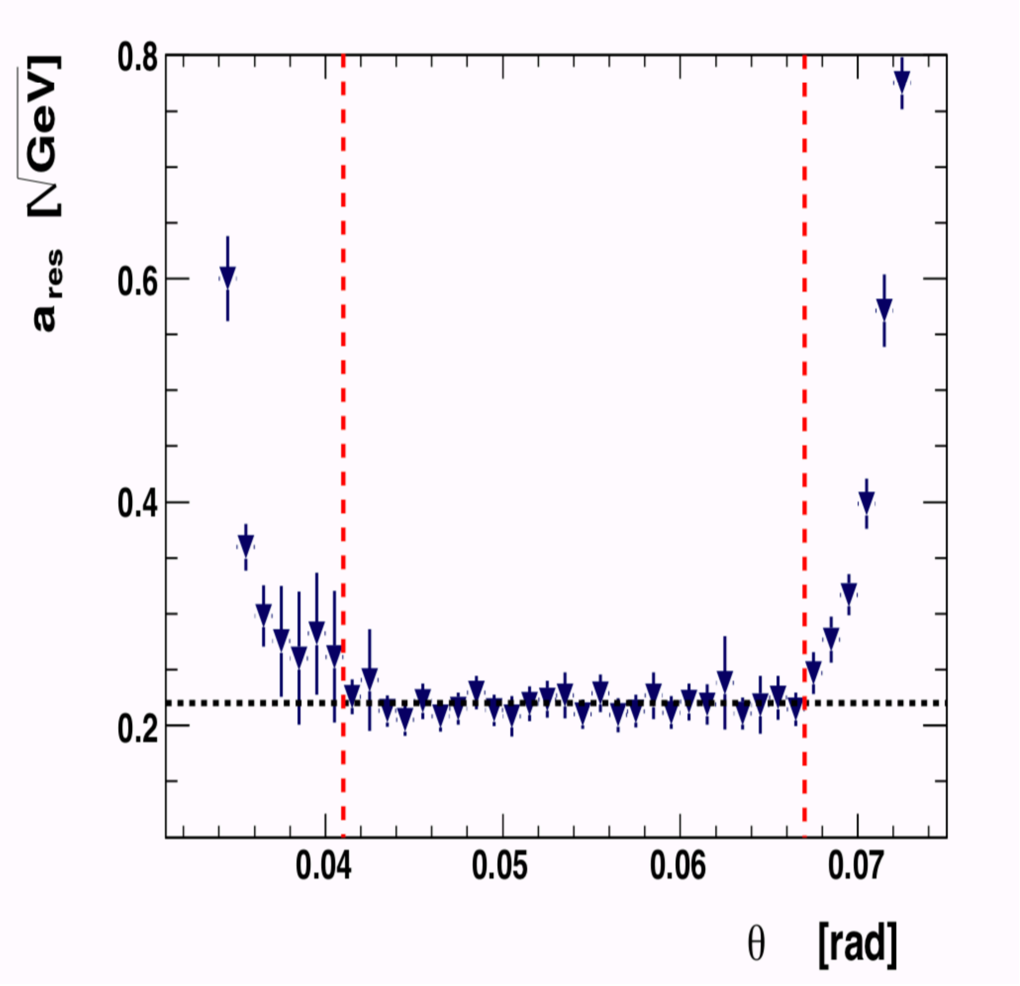
CLICdp-Note-2018-005





- **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

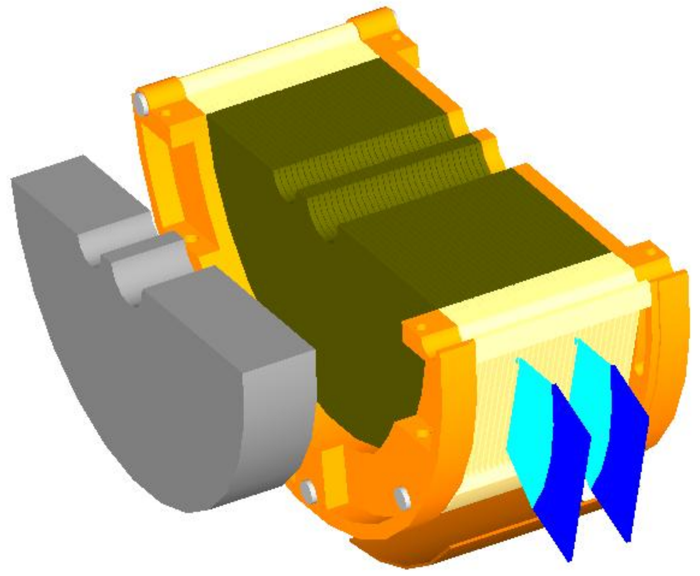
- **LumiCal**
  - Cover the angles between 41 mrad to 67 mrad (ILC)
  - Sensor segmentation is optimised to obtain the given precision of luminosity measurement



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

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

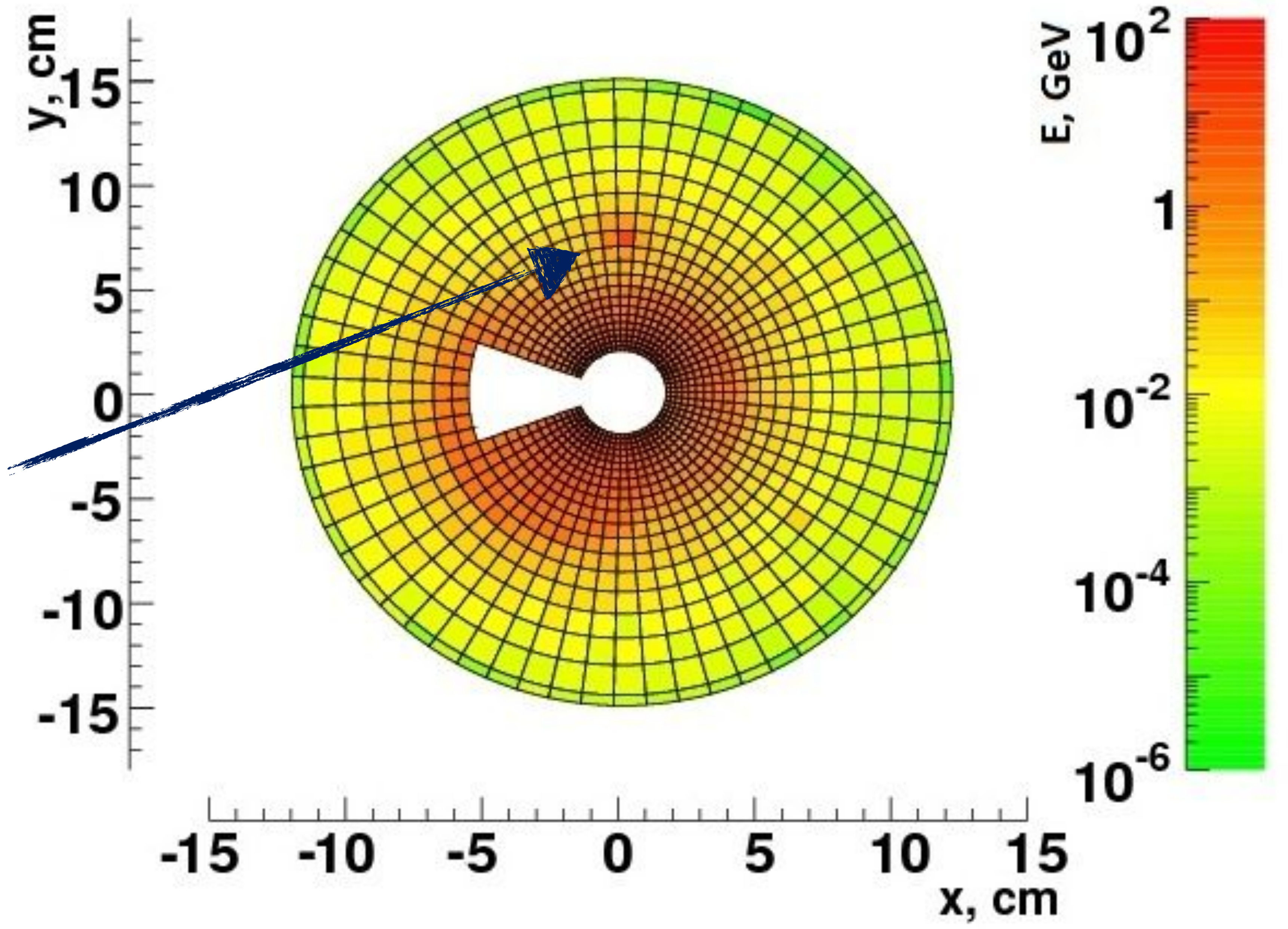
BeamCal



Beamstrahlung at linear colliders (due to nm bunch sizes)

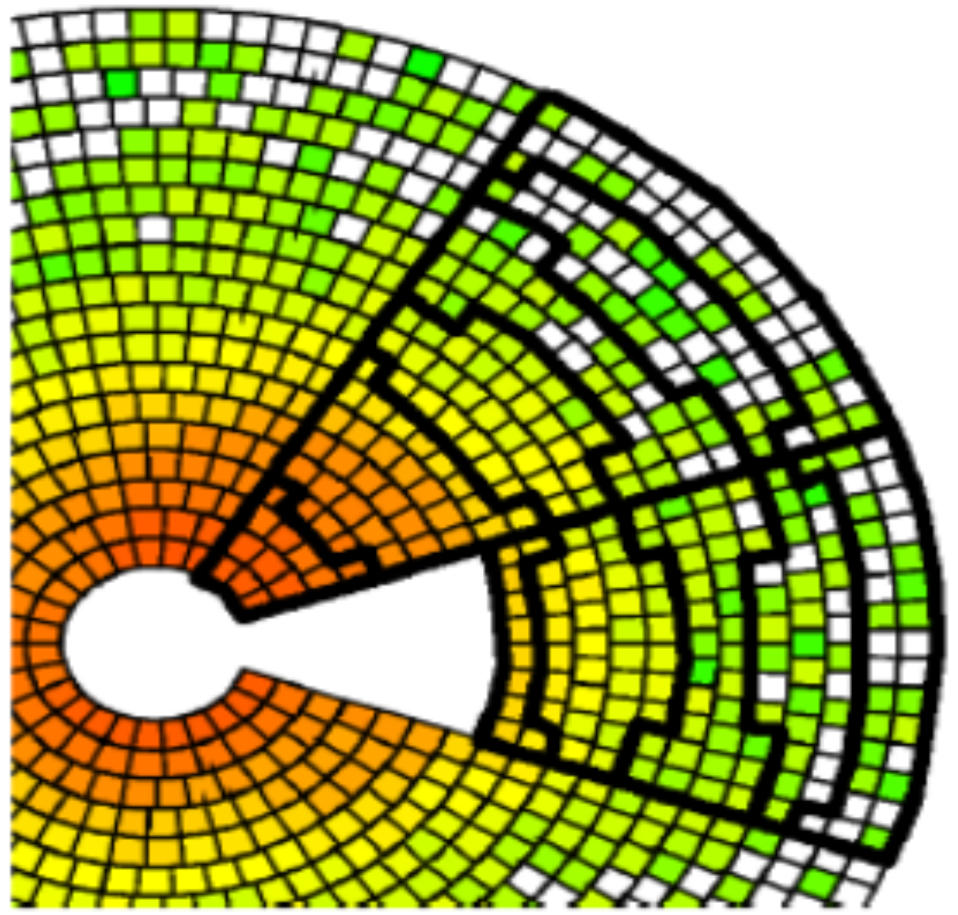
Low energy electron deposition per BX

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

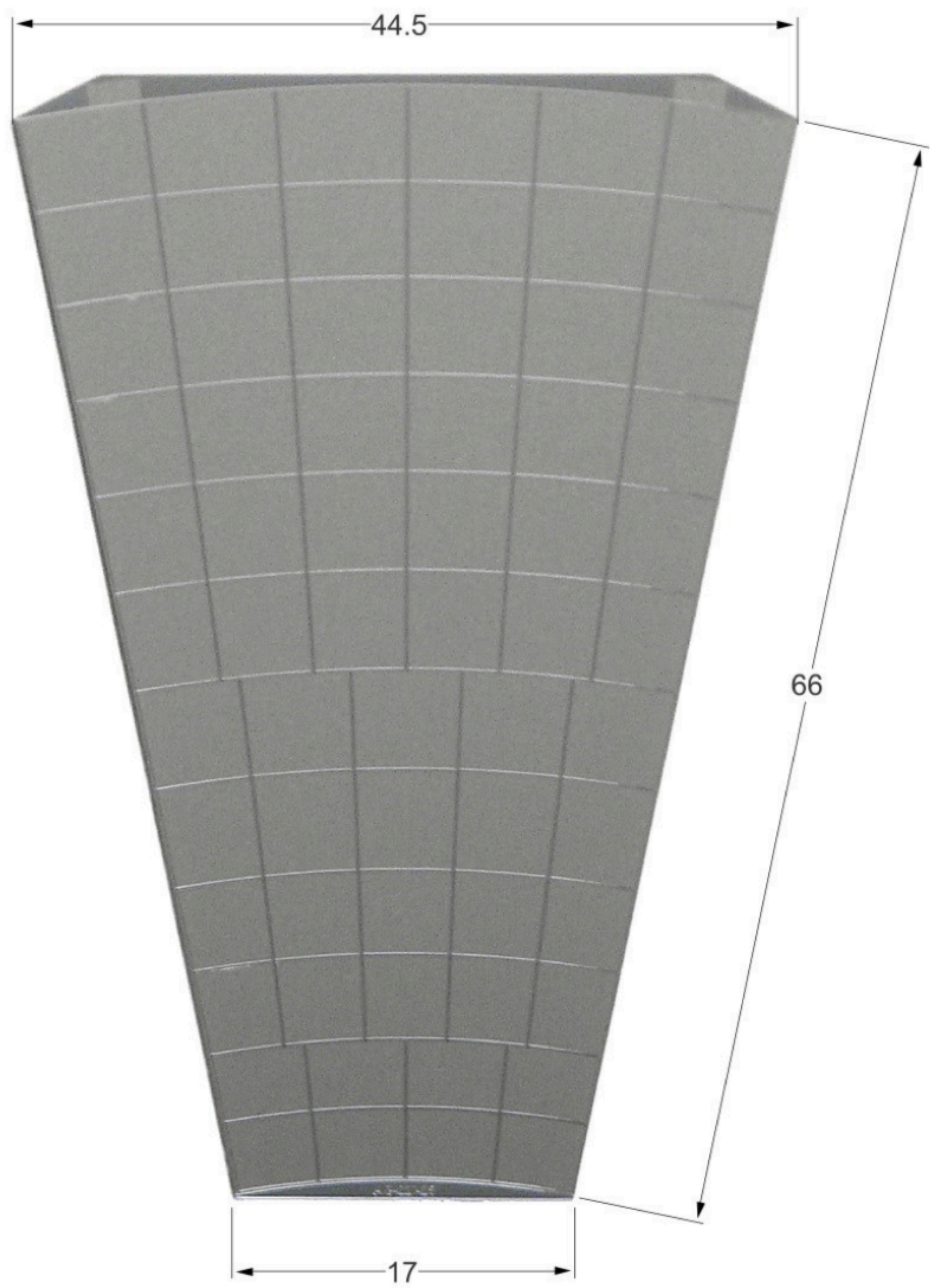


Beam parameters and luminosity measurement

beam parameter	unit	nom.	resolution, 14 mrad no E_γ	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

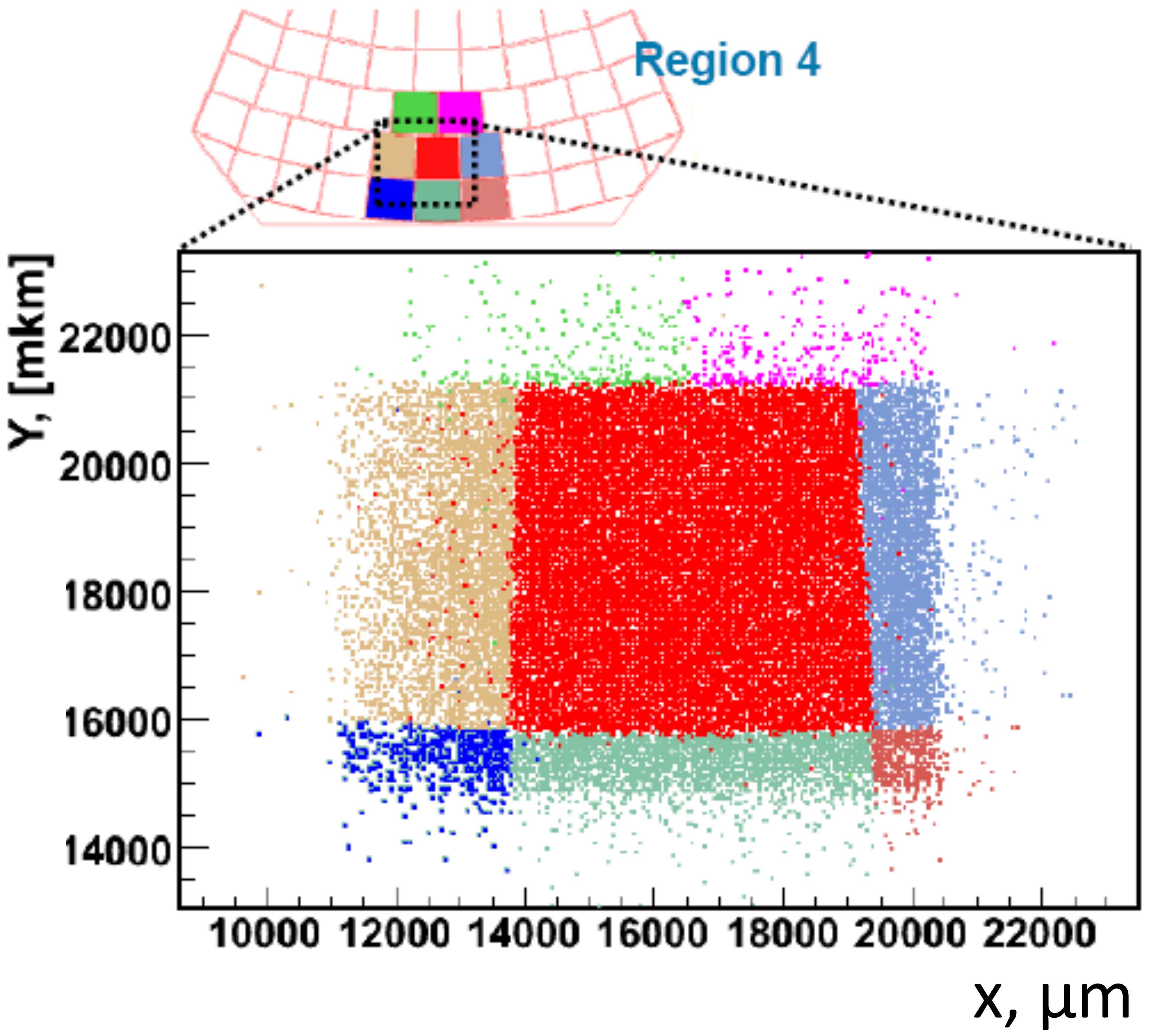
Baseline sensor: GaAs

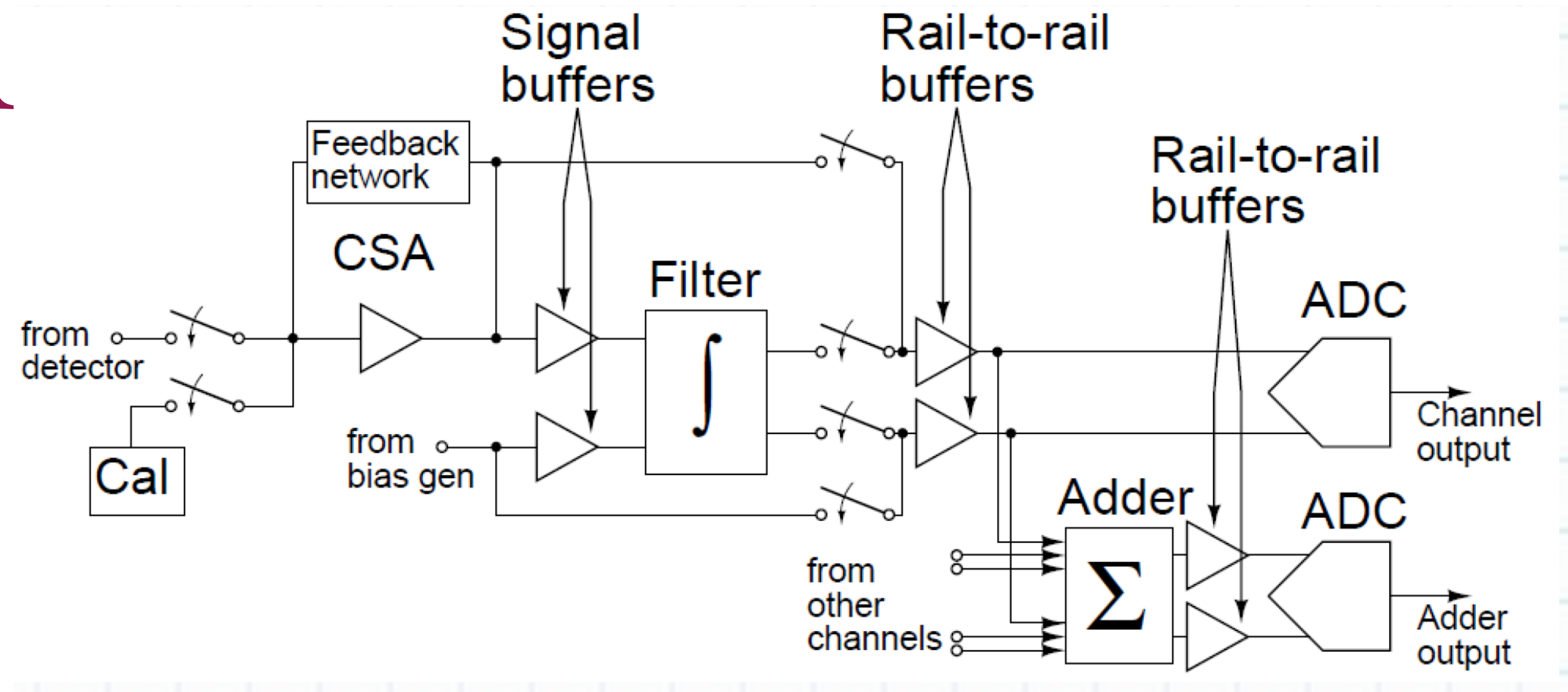


Designed in JINR Dubna

Test-beam fully instrumented detector plane

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



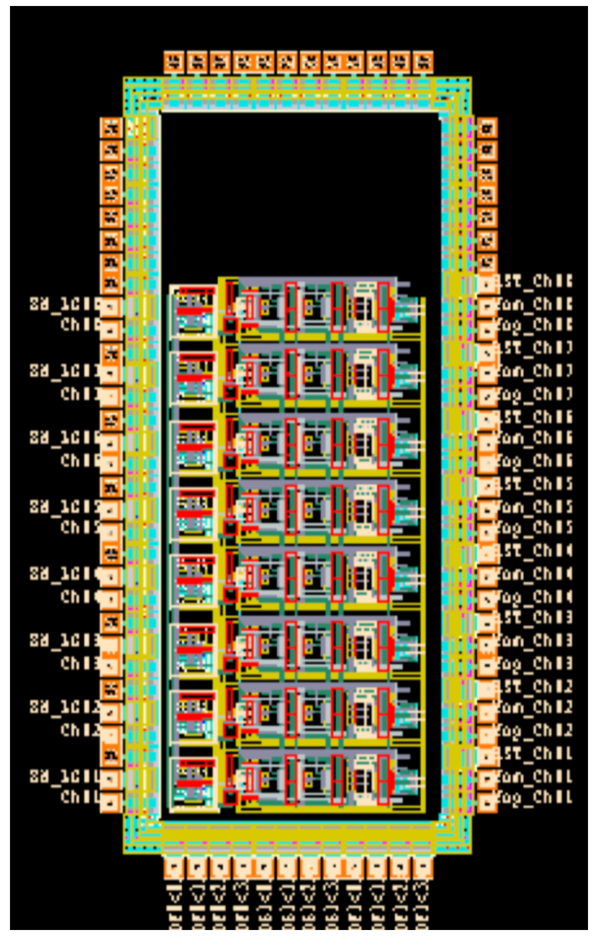


Dedicated ASIC development with fast OR to be used in the feedback system

BeamCal ASIC v3 Design

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

Designed at Pontificia Universidad Católica de Chile



Shower Study in Transverse Plane for 2014

The sensor geometry does not allow direct measurement of transverse shower development

Shower parametrisation in radial direction:

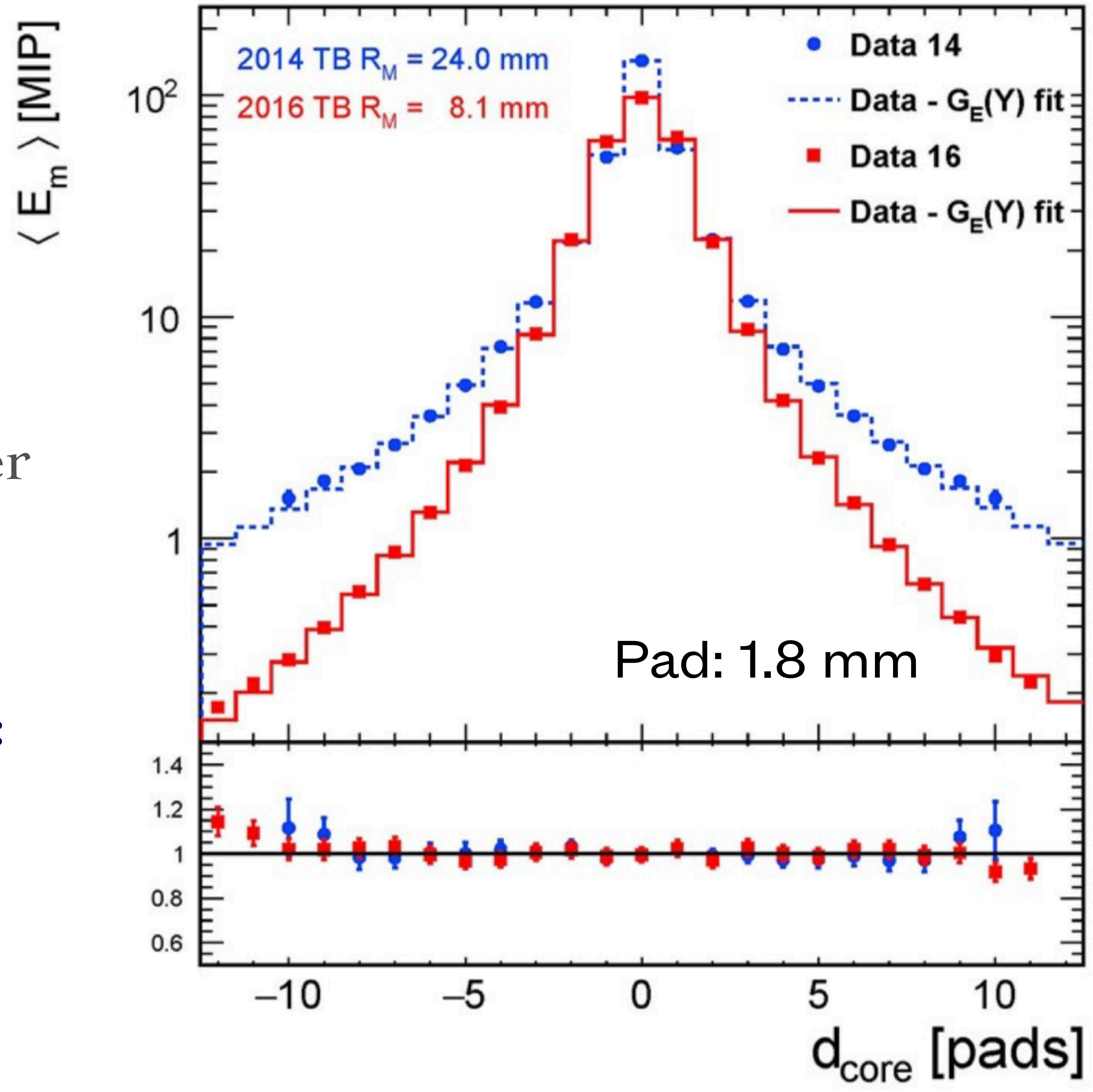
$$F_E(r) = A_C e^{-\left(\frac{r}{R_C}\right)^2} + A_T \frac{2r^\alpha R_T^2}{(r^2 + R_T^2)^2}$$

Parameters are found by fitting to data after integration over the area corresponding to sensor pads.

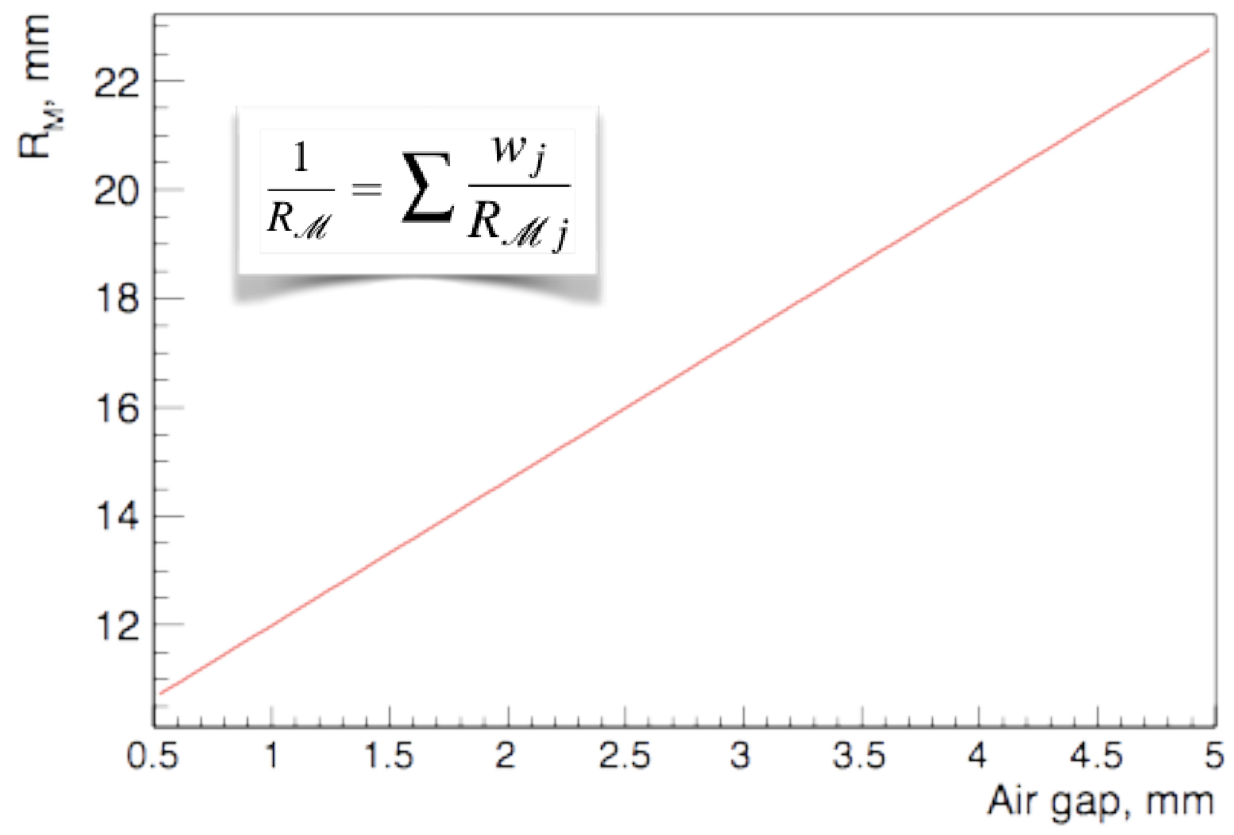
Molière radius $R_{\mathcal{M}}$ can be found from the equation:

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

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.)



$R_{\mathcal{M}}$ as function of the air gap between 4.5 mm thick tungsten plates



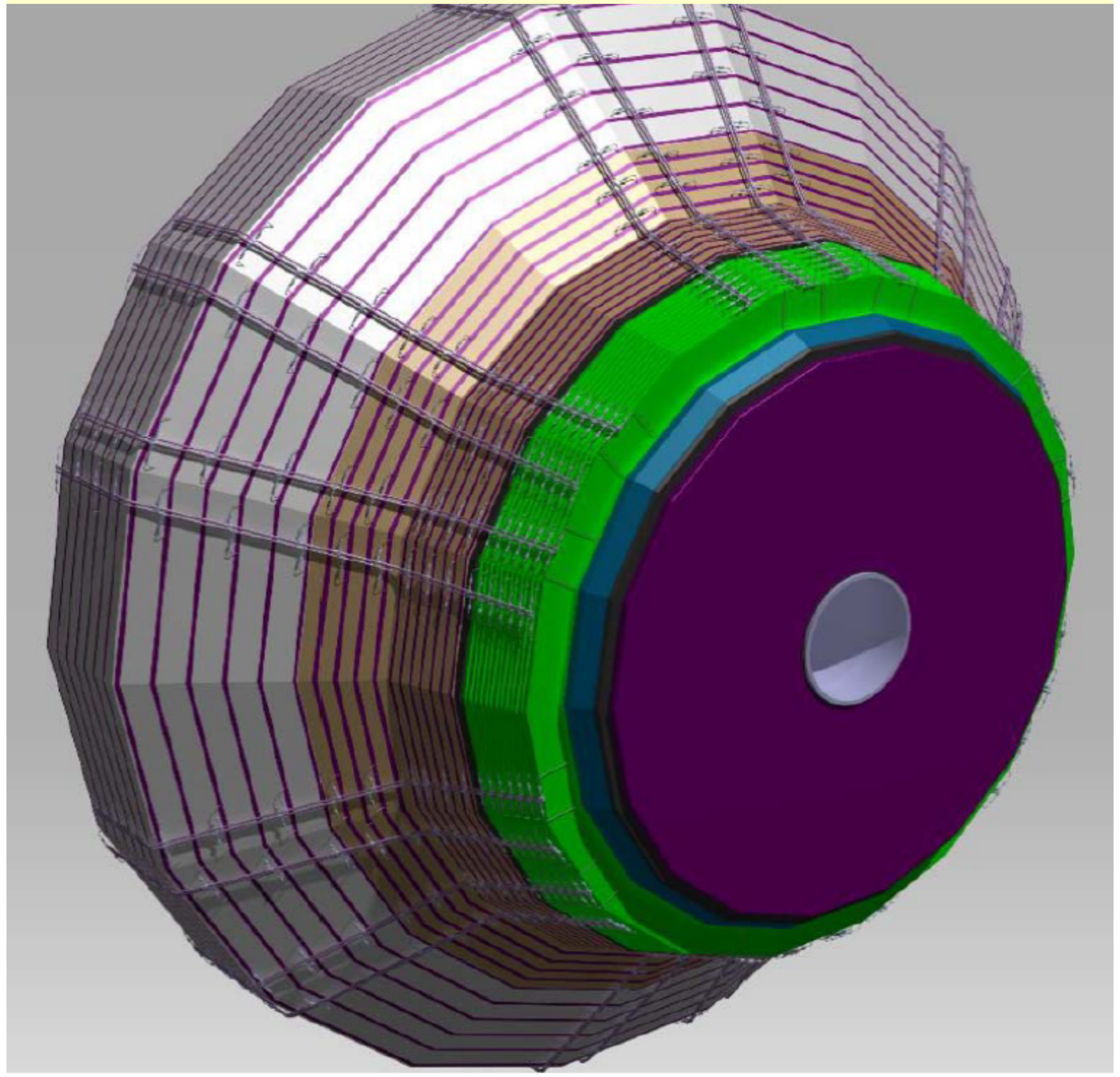
$$\frac{1}{R_{\mathcal{M}}} = \sum \frac{w_j}{R_{\mathcal{M}j}}$$

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

Spin offs from FCAL technologies

FLAME is used for the HL upgrade of the CMS detector

High Granularity Calorimeter



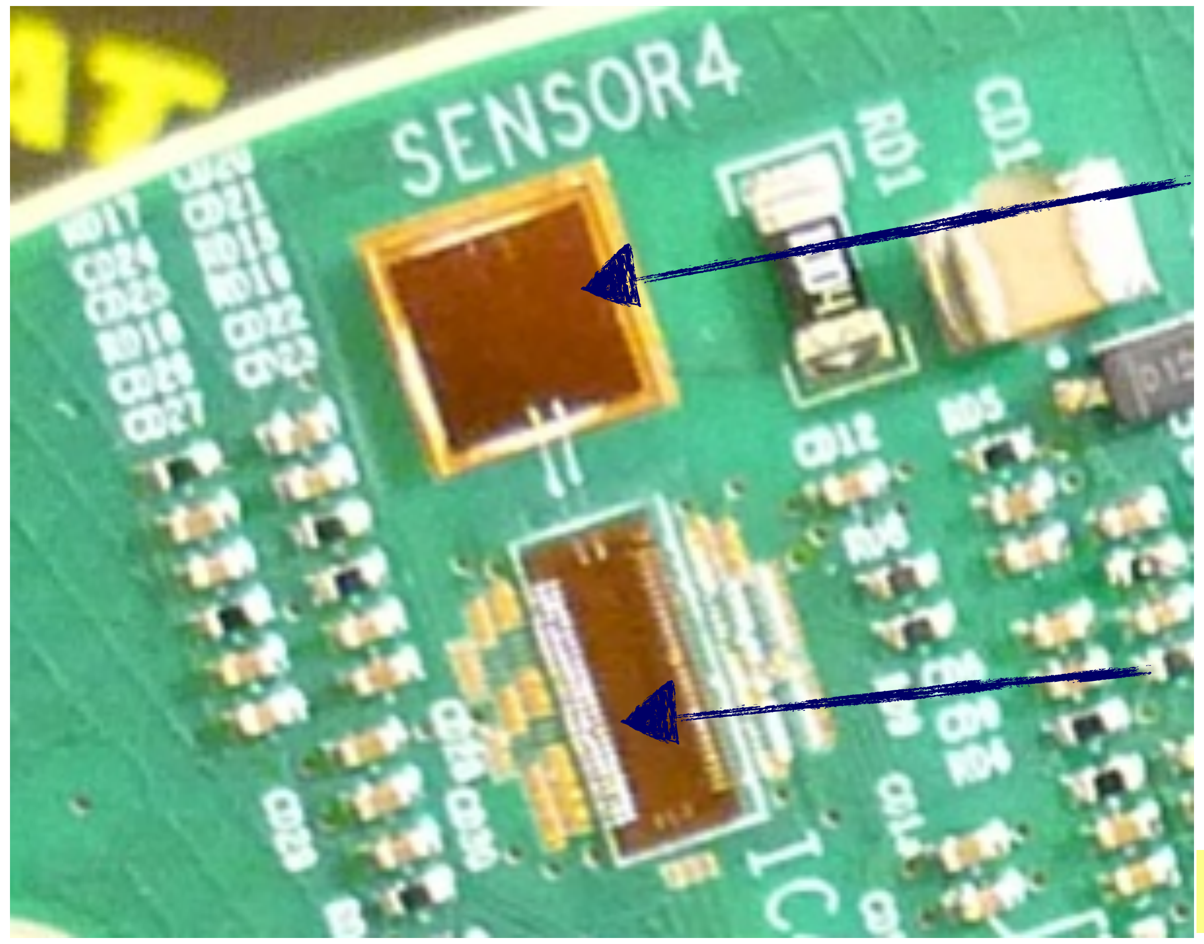
ECAL: SiW sandwich
HCAL: Si/Sc steel sandwich
6.5 x 10^6 readout channels

fast Mip Timing Detector MTD

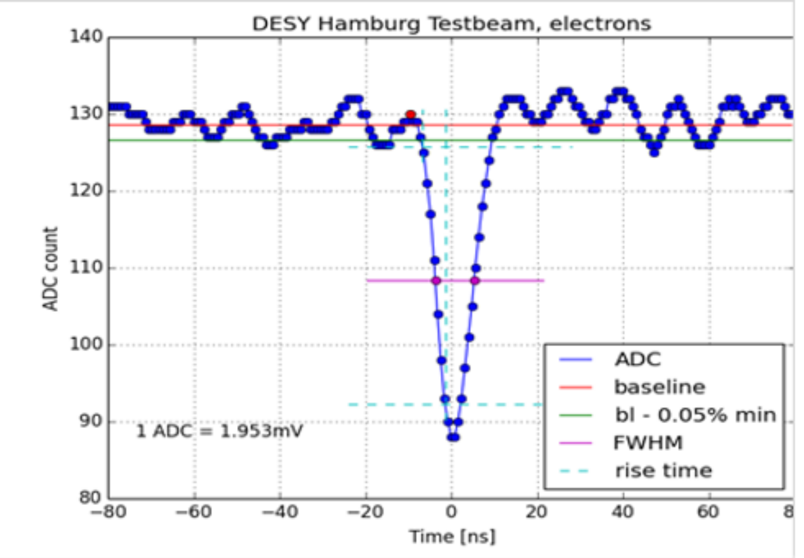
Lyso:Cr crystals, read out with SiPMs

Spin offs from FCAL technologies

Luminometer and Beam Condition Monitor for the CMS experiment

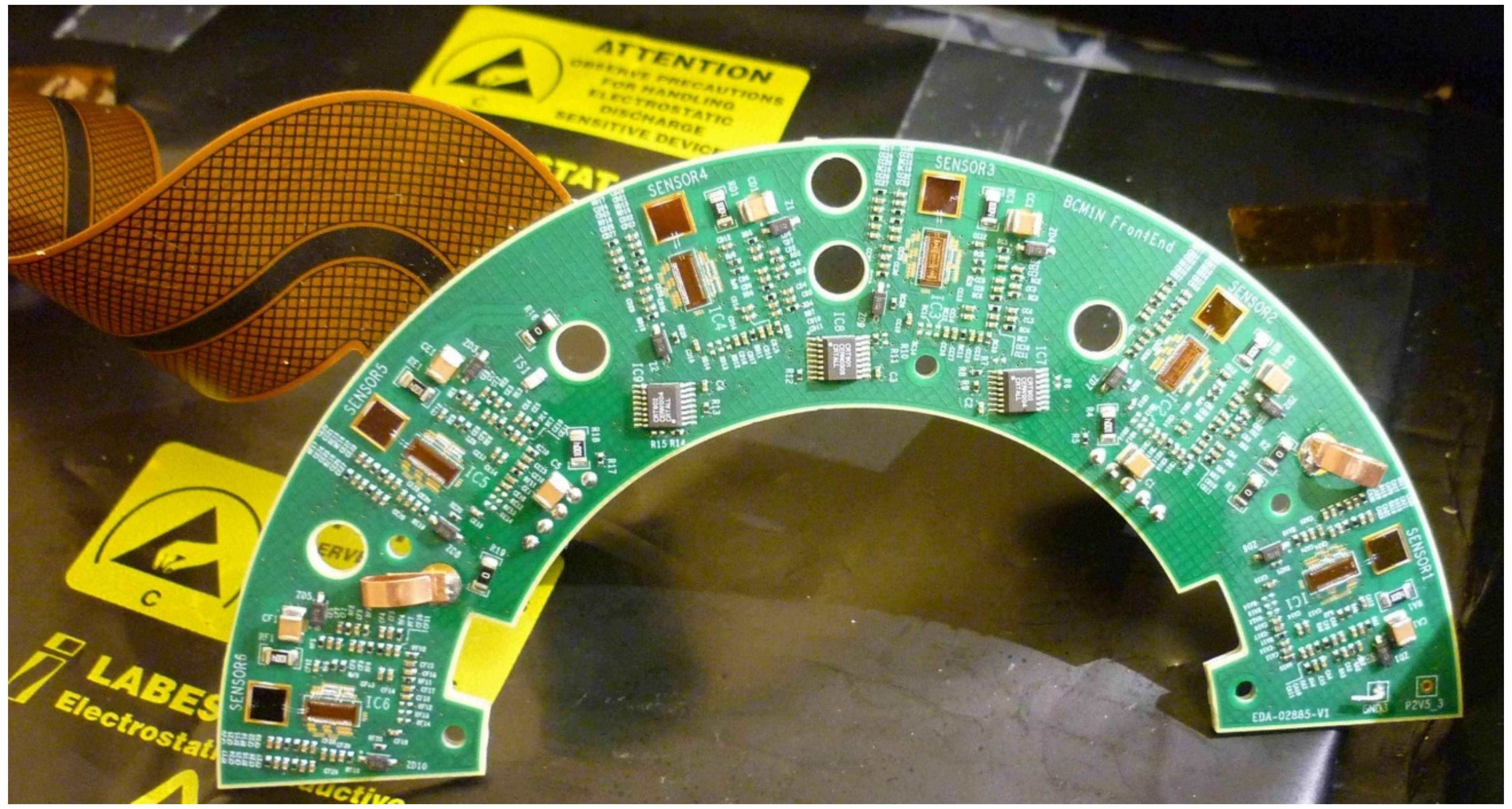


sensor pads (Si diodes)



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

Designed in UST Krakow



Half ring with flexible Kapton PCB

Carbon fiber structure