R&D for Luminometers in e^+e^- Colliders

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on behalf of FCAL

HELMHOLTZ ASSOCIATION

DESY

FCAL R&D Collaboration

FCAL was founded in 2002

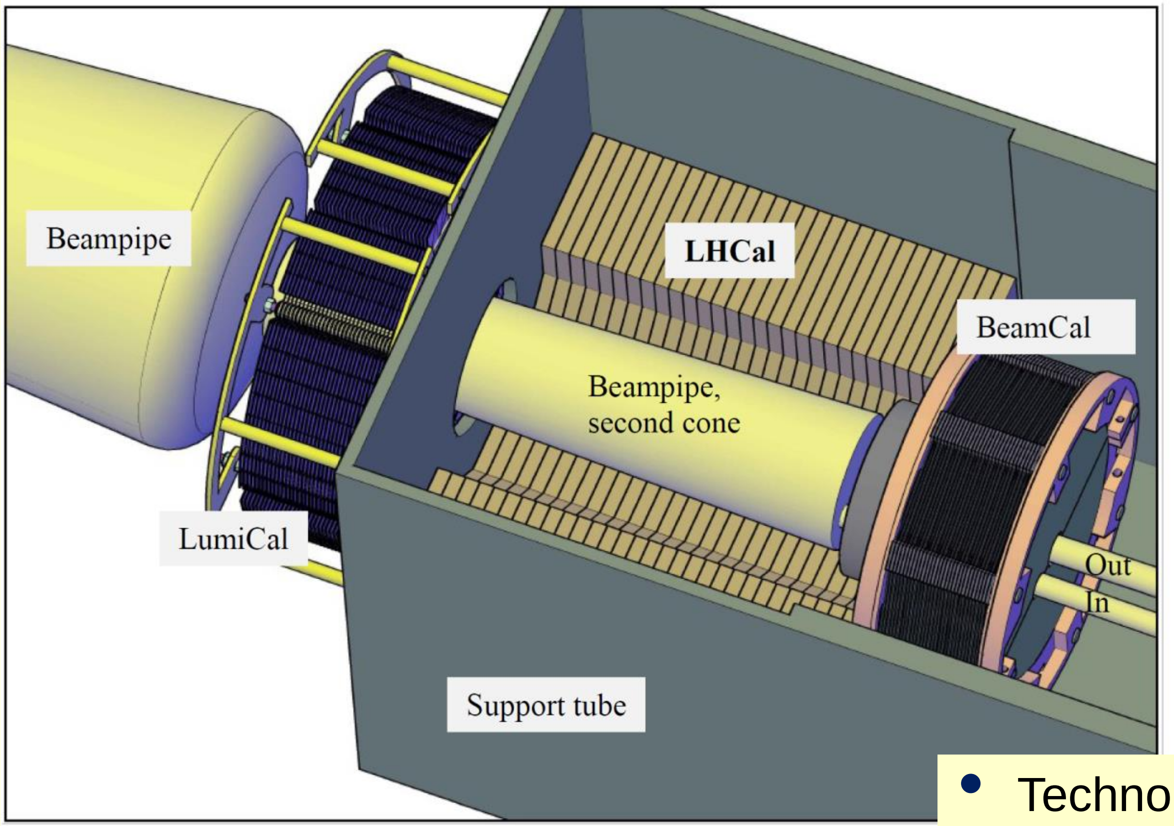
The mission was R&D for the instrumentation of the very forward region of detectors at future e^+e^- colliders, design, contruction and test of prototypes

In its best times:

- 70 physicists
- 15 Institutes, from Americas, Asia, Europe
- Contacts to ILD, SiD and CLICdp

Design of the very forward region

Forward region of an e^+e^- collider detector



- LumiCal for precise luminosity measurement (Counting Bhabhas)
- BeamCal for fast luminosity Measurement (using beamstrahlung)
- Both for large polar angle coverage (important for new particle searches)
- Technology choice: Si or GaAs/W sandwich calorimeters
- 1 X_0 absorber thickness, 20 (30) layers in ILC (CLIC)

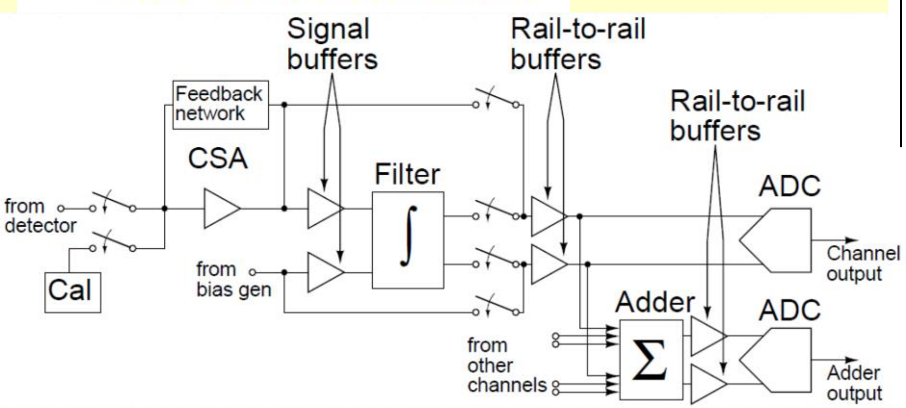
- Small Moliere radius
- High granularity

BeamCal Simulations

Fast readout of beamstrahlung pair depositions in areas after each bunch crossing
In addition energy of beamstrahlung photons (E_γ in GamCal)

- Fast luminosity estimate using beamstrahlung depositions (bunch-by-bunch at ILC)
- Beam parameter estimation
- Fast feedback to the machine

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.



JINST 3 (2008) P10004

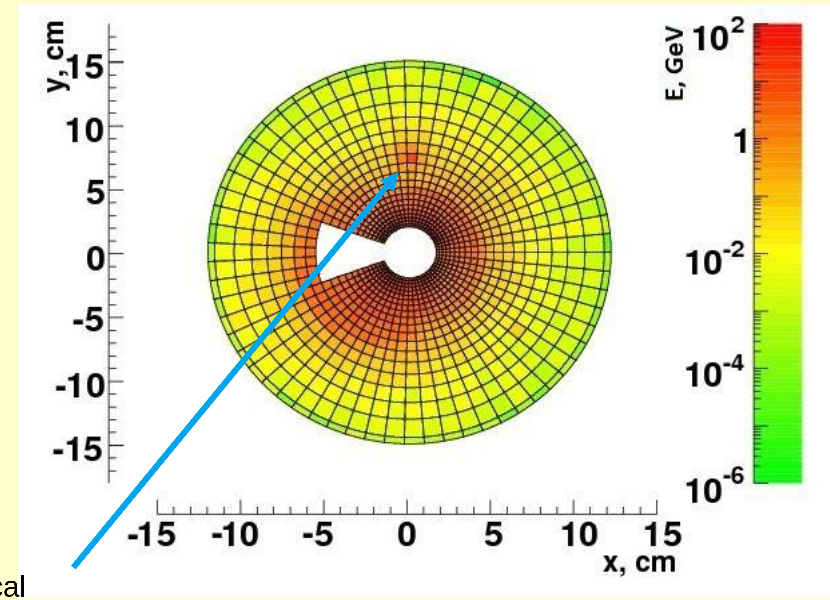
Dedicated ASIC development with fast AND to be used in the feedback system

Fast response to separate incoming machine induced background from beamstrahlung

Design done, no prototypes

BeamCal simulations

Detection of low angle electrons

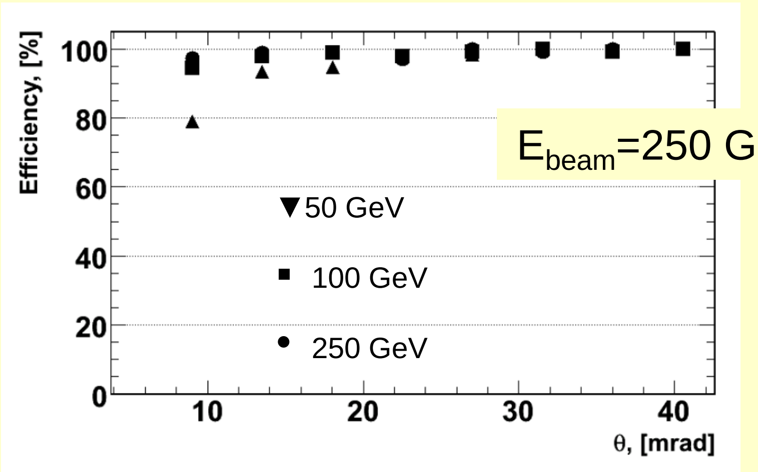


Local deposition of a single electron

- Average the background depositions for 10 BX per pad
- Subtract them from a signal event
- Search for a local shower in the remaining depositions

Efficiency of electron detection,

depends on the relative fraction of the depositions



LumiCal simulations

Luminosity is a key parameter in an experiment

$$N = \sigma \cdot L$$

Number of events — Cross section — Luminosity

Precision requirements on L derived from physics, expected statistics of $e^+ e^- \rightarrow f\,f\,(\gamma)$

O (10^{-3}) up to 500 GeV, e.g. ILC (few years of running, 500 fb^{-1})

O (10^{-2}) up to 3 TeV, e.g. CLIC

Better *O* (10^{-4}) for running at Z

The gauge process is low angle Bhabha scattering, $e^+e^- \rightarrow e^+e^-(\gamma)$

Strong requirements on the mechanical and position precision of LumiCal

JINST 5 (2010) P12002

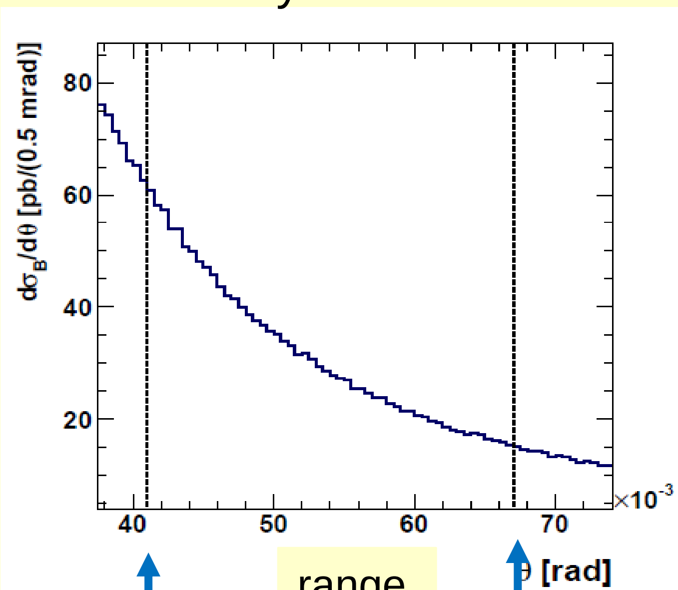
LumiCal

Luminosity measurement

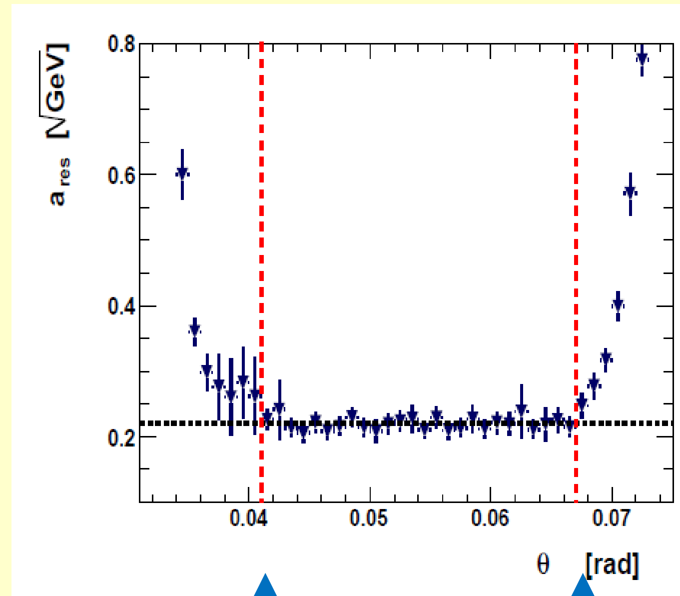
$$L = \frac{N_{BH}}{\sigma_{BH}}$$

Number of Bhabha events in a certain θ range

Bhabha cross section (from theory)



range



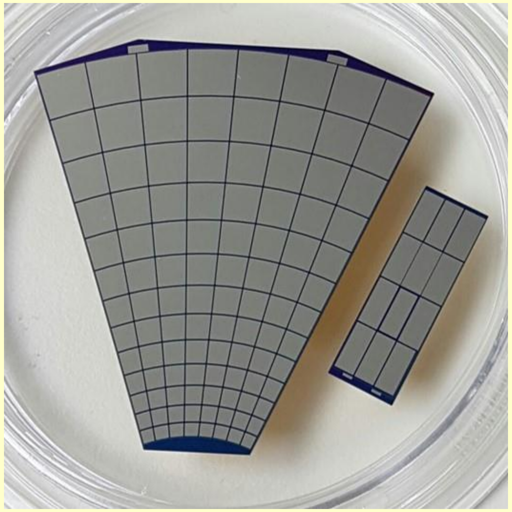
- Challenge is the control of the inner acceptande limit, *O* (10µm)
- A small range is important in case limited space available
- Bias on polar angle measurement

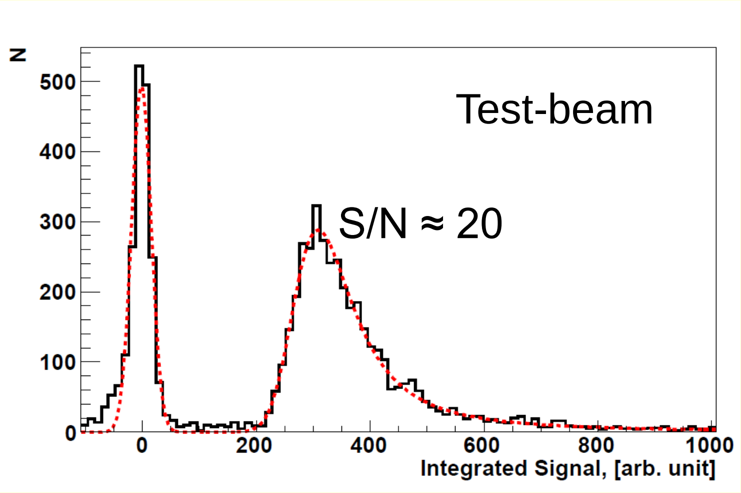
- Sharp edges
- Small leakage

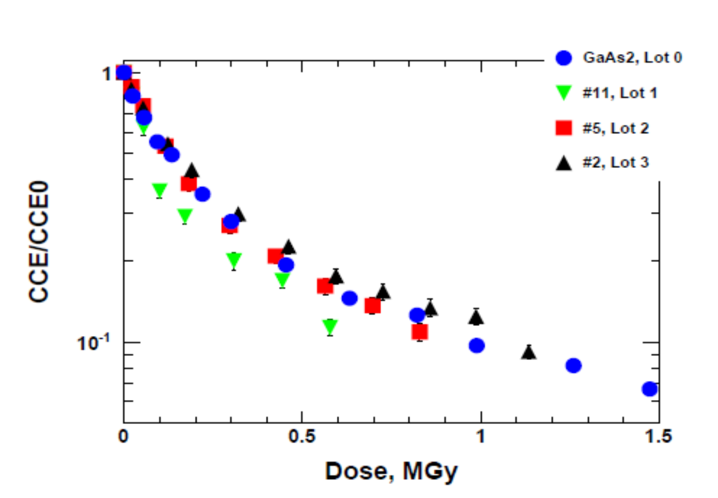
Requires small Moliere radius!

Sensor Technology BeamCal: GaAs

Development of high resistivity GaAs sensors with Tomsk State University







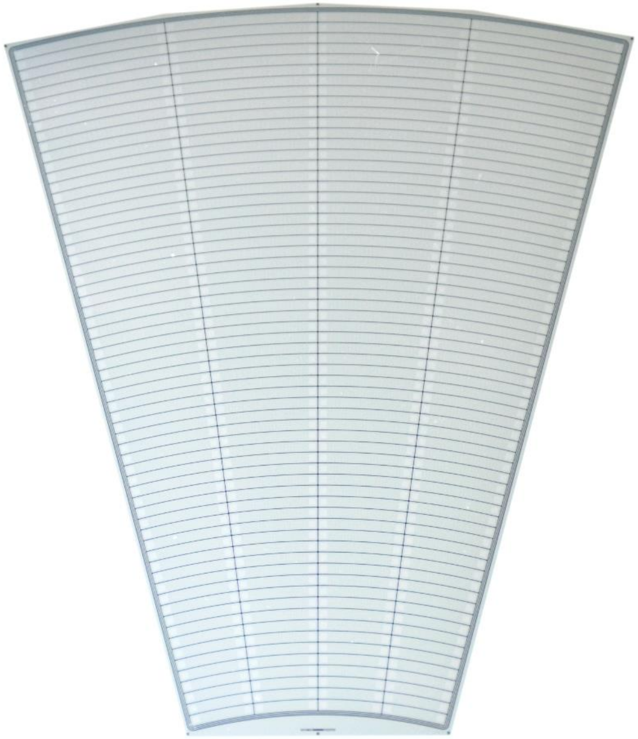
- Sensor thickness 500 µm
- Resistivity 10^9 Ωm
- Bias voltage 100 V
- Leakage current O(100nA) per pad
- Rad hard up to several MGy (electrons → beamstrahlung pairs)

JINST 7 (2012) P11022

Sensor Technolgy LumiCal: Silicon

Developed with Hamamatsu

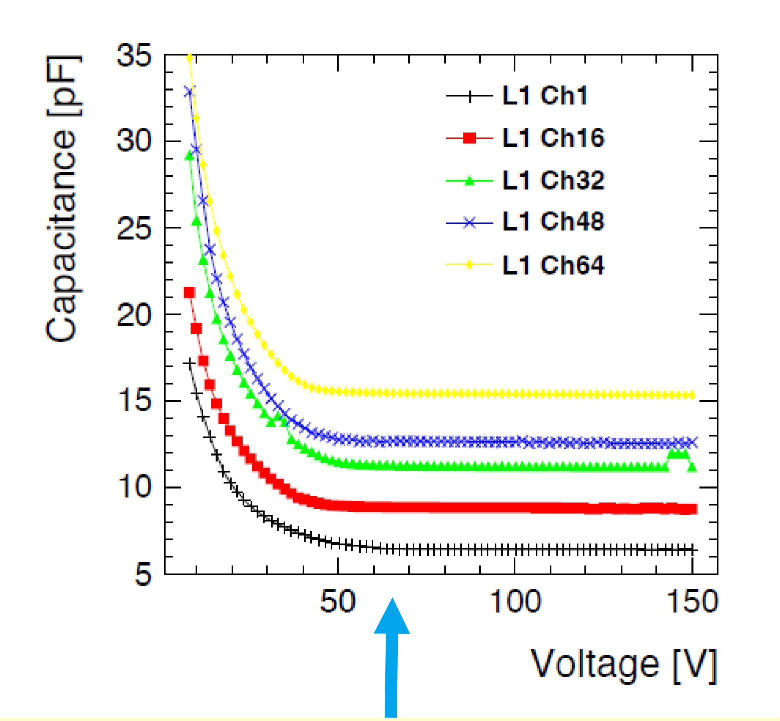
Outer active radius R = 195.2 mm



Inner active radius R = 80.0 mm

Si sensor prototype

- Thickness 320 µm
- p^+ in n
- DC coupled to FE

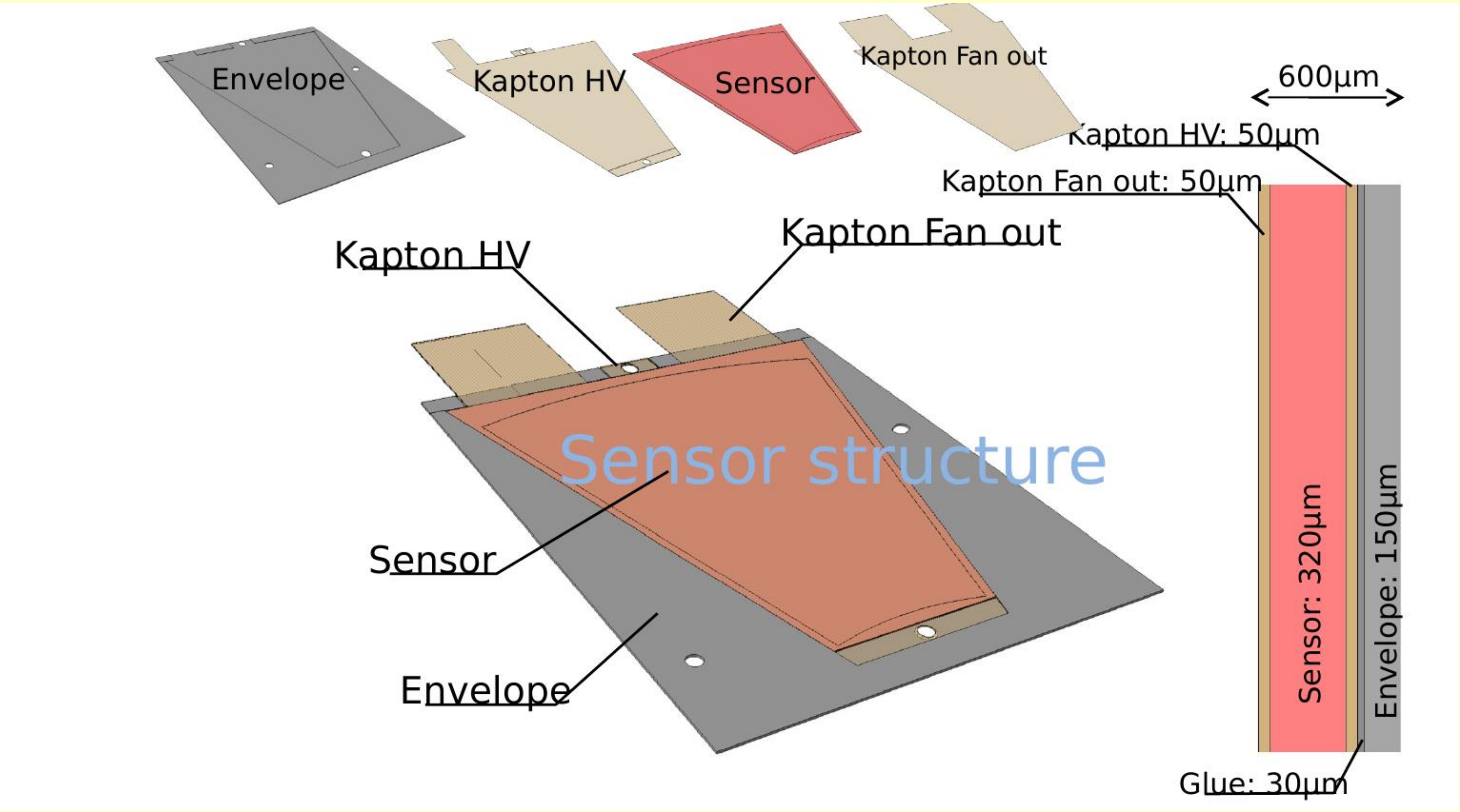


Full depletion at
60-70 V

Technology detector planes

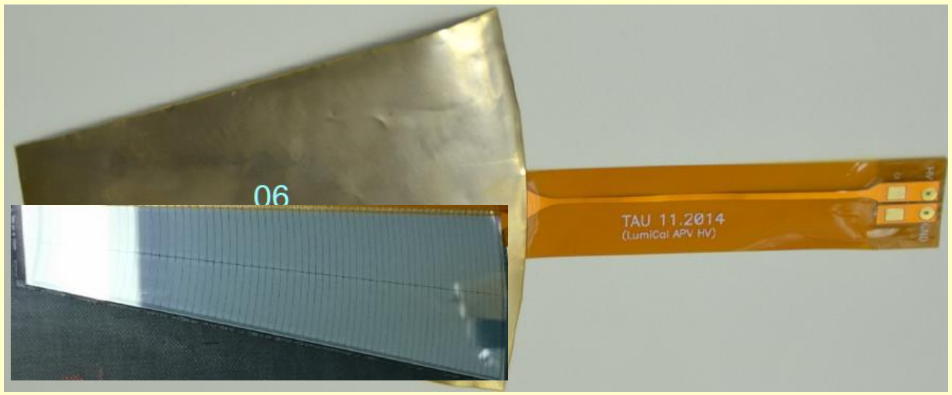
To keep the Moliere radius small:

- Thin sensor planes (< 1mm)
- Readout via copper traces on flexible Kapton PCB

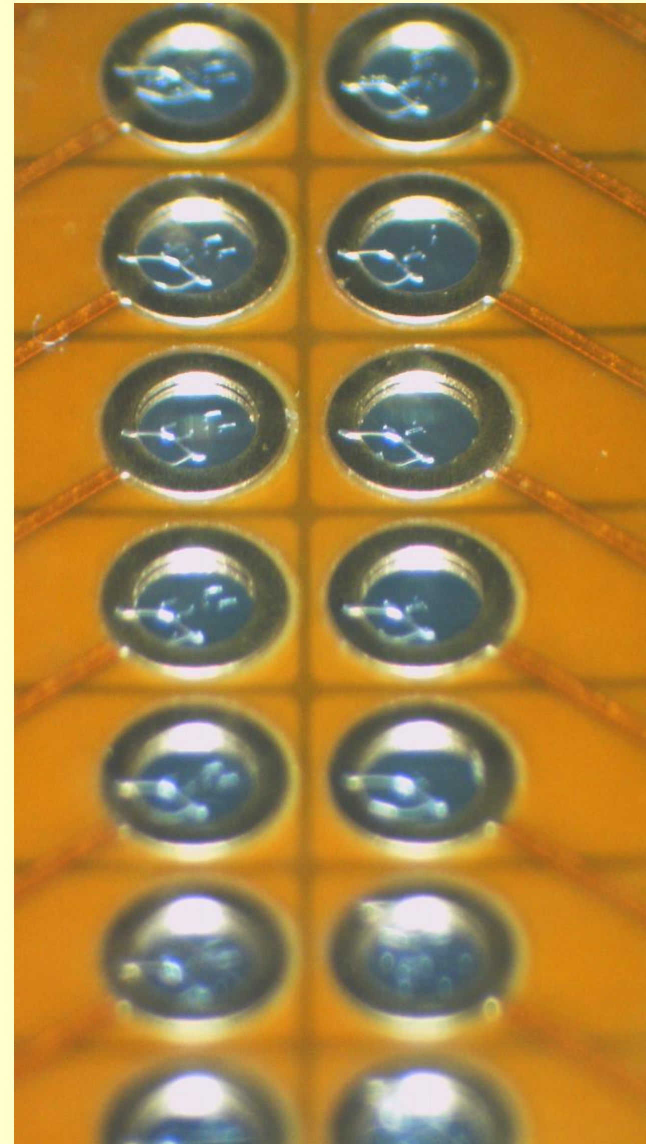


Technology detector planes

Connecting the sensor pads to copper traces
on Kapton fan-out

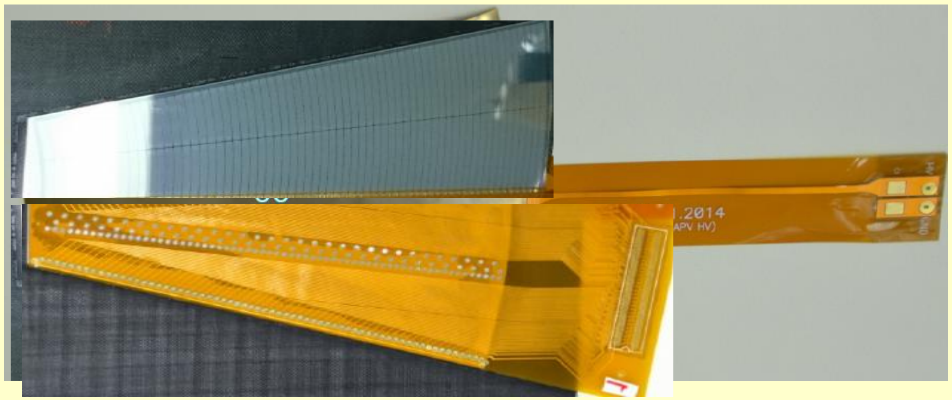


Keep bond loops
below 100 μm



Technology detector planes

Connecting the sensor pads to copper traces on Kapton fan-out



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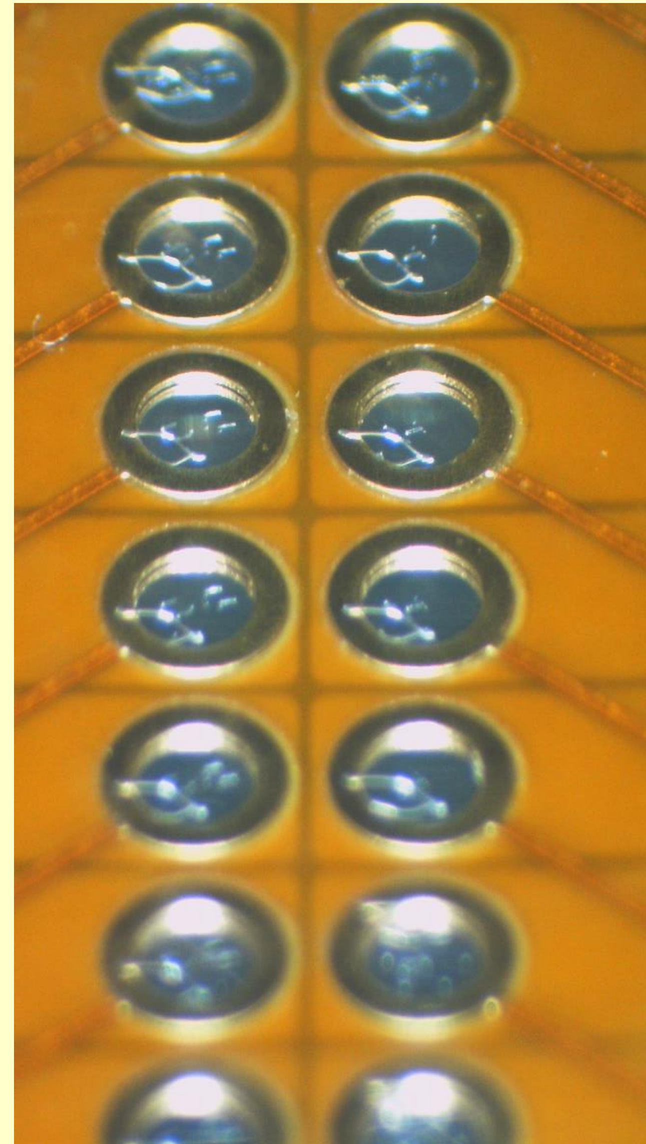


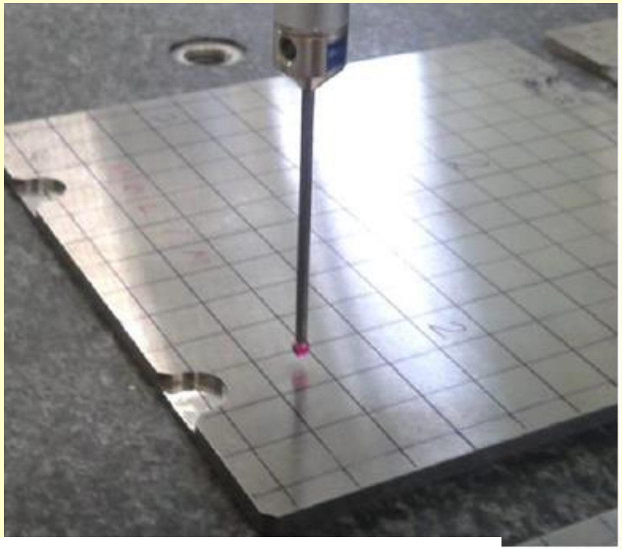
Technology W-Plates

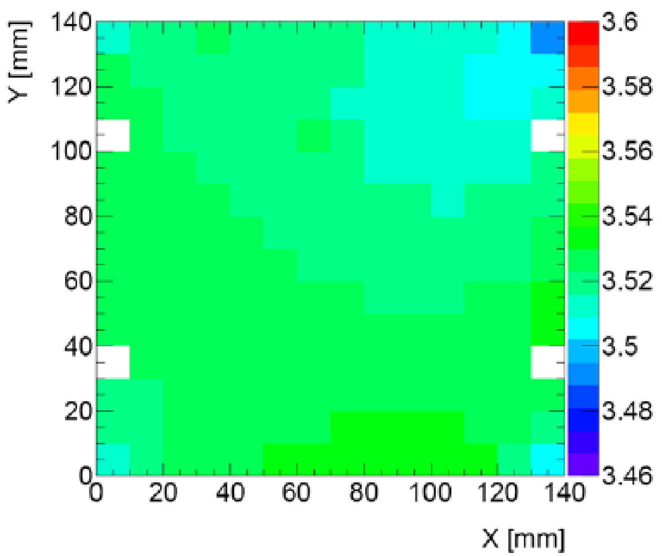
W-plates of high planarity

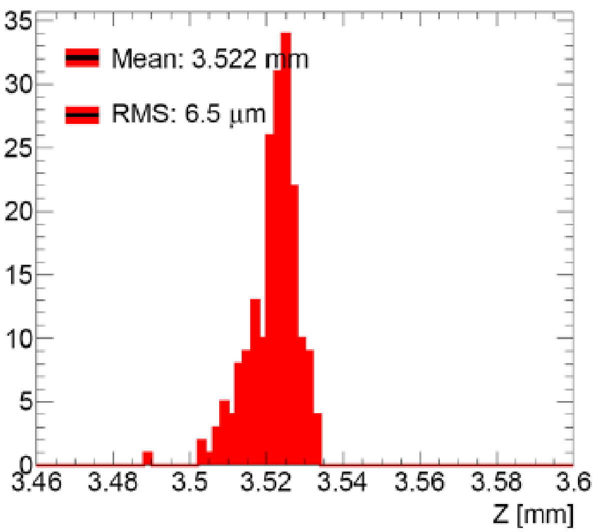
Max. deviation $O(10\mu m)$

Alloy: W (92.5%) Ni (5.25%), Cu (2.25%)

Density: 18 gcm^{-3}

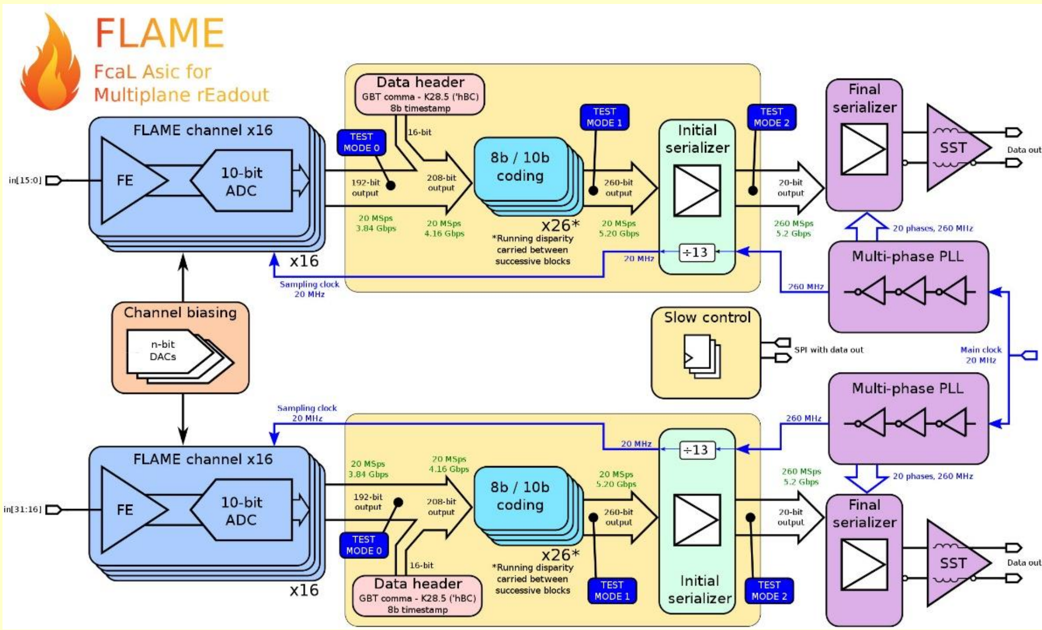






FE electronics

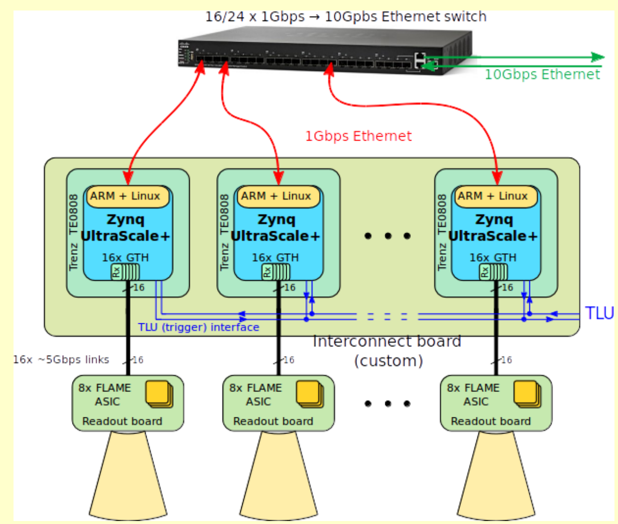
Dedicated FE electronics in 130 nm TSMC



- Variable gain (MiP sensitive)
- 10-bit SAR
- Peaking time 55 ns
- Power dissipation 2 mW per channel, power pulsing foreseen

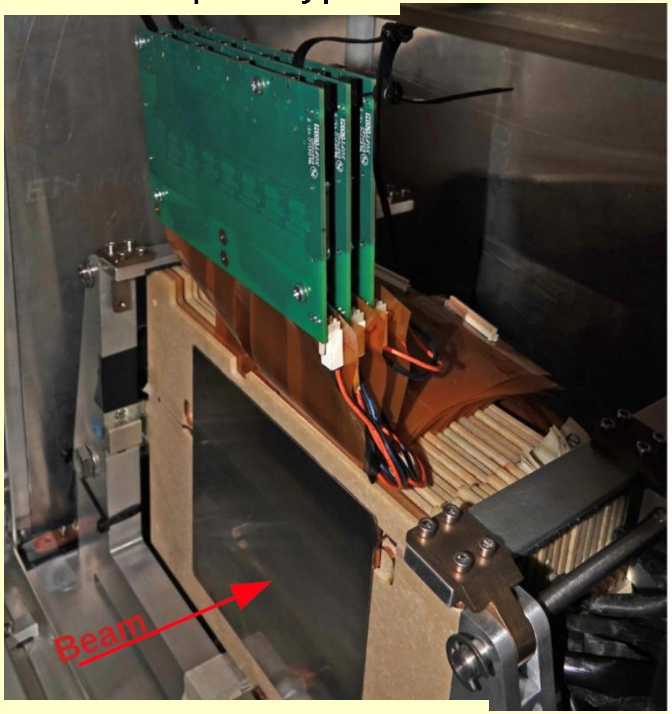
Signal processing using FPGA

JINST **10** C01018



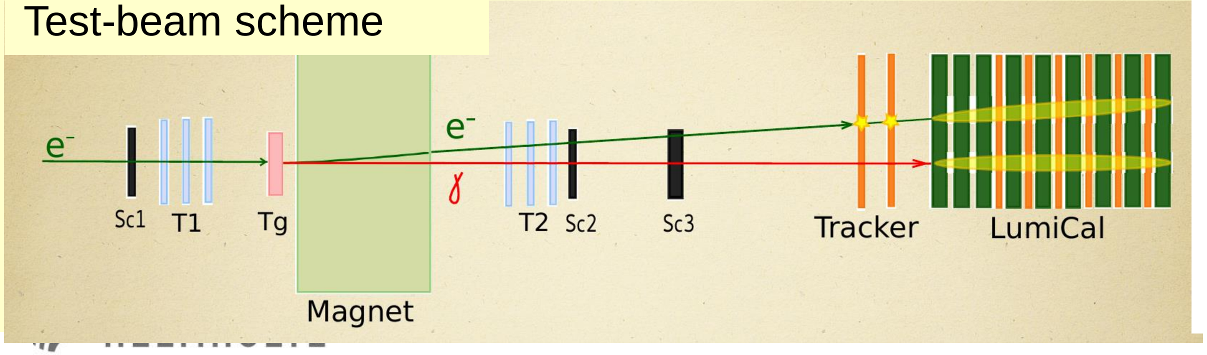
Prototype

LumiCal prototype

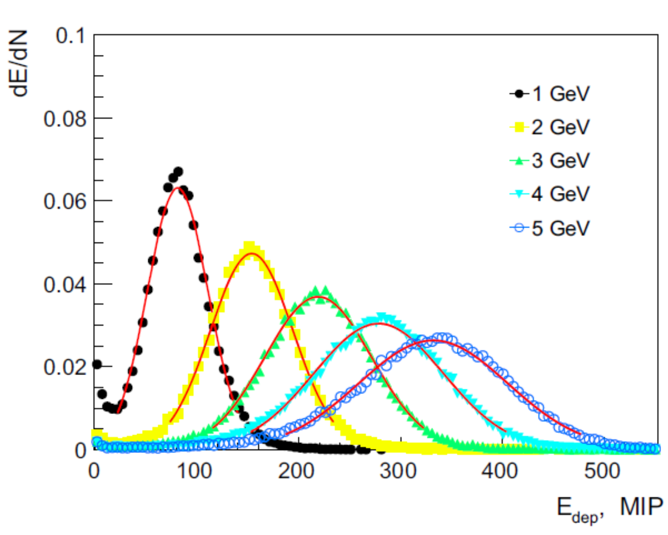


- 20 sensor/absorber planes available
- Partly instrumented with FLAME ASICs (remaining with APV25)
- TLU trigger box, EUDAQ (SRS from RD51)

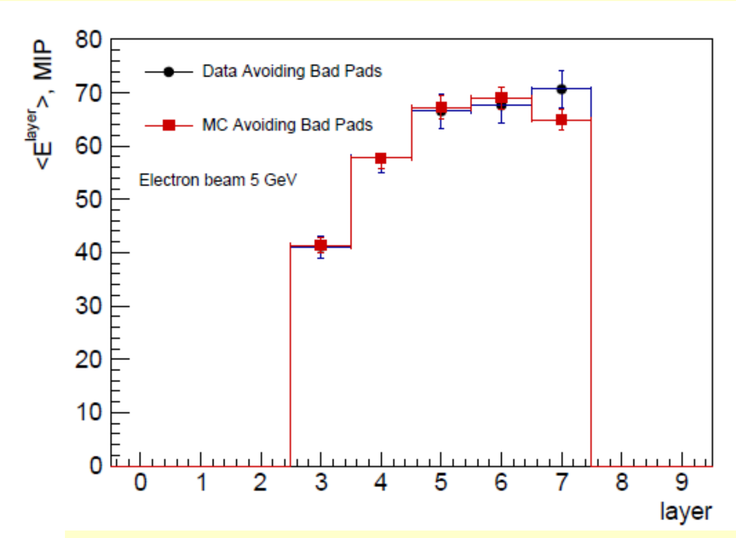
Test-beam scheme



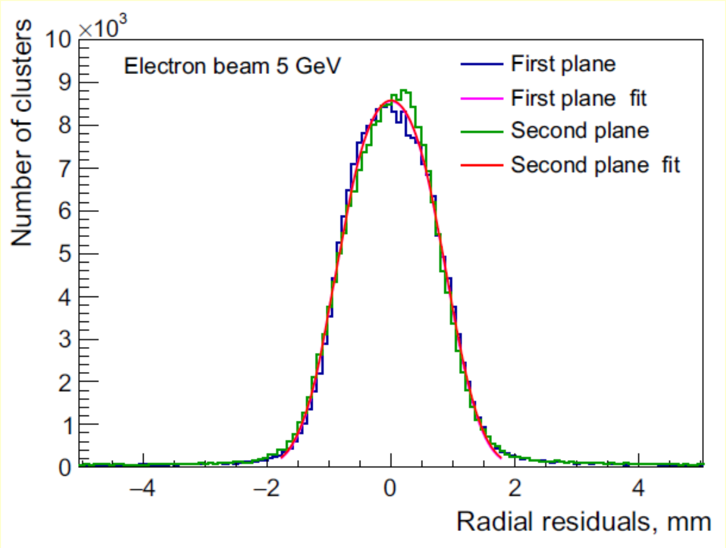
Energy deposited in the calorimeter



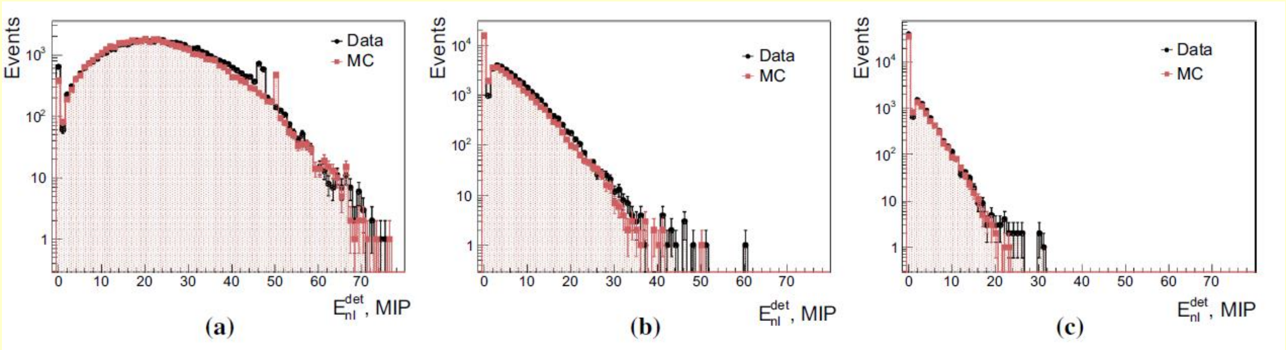
Test-beam results



Longitudinal shower development, data/MC comparison

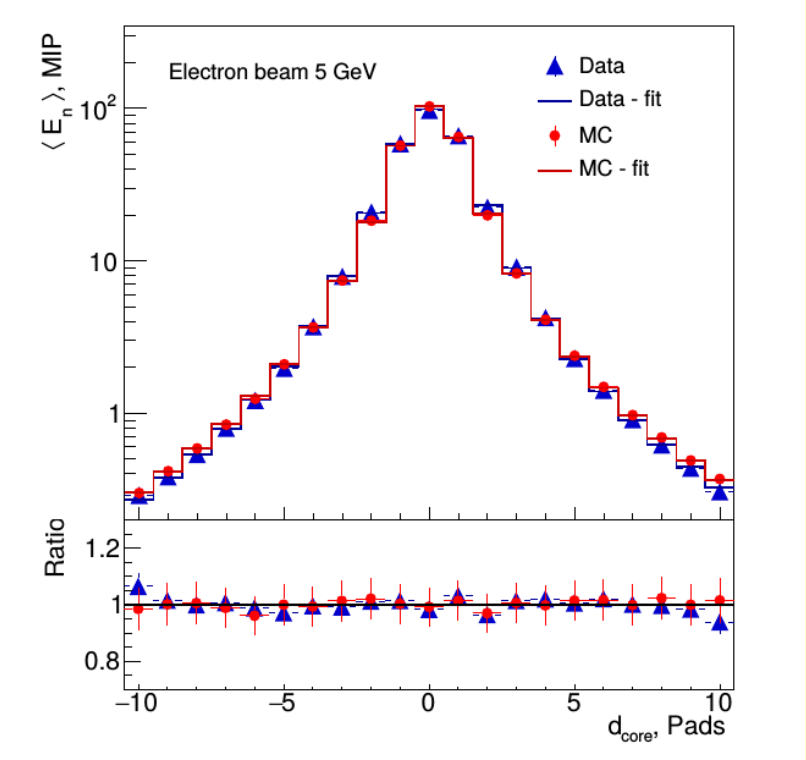


Shower position resolution 440 μm



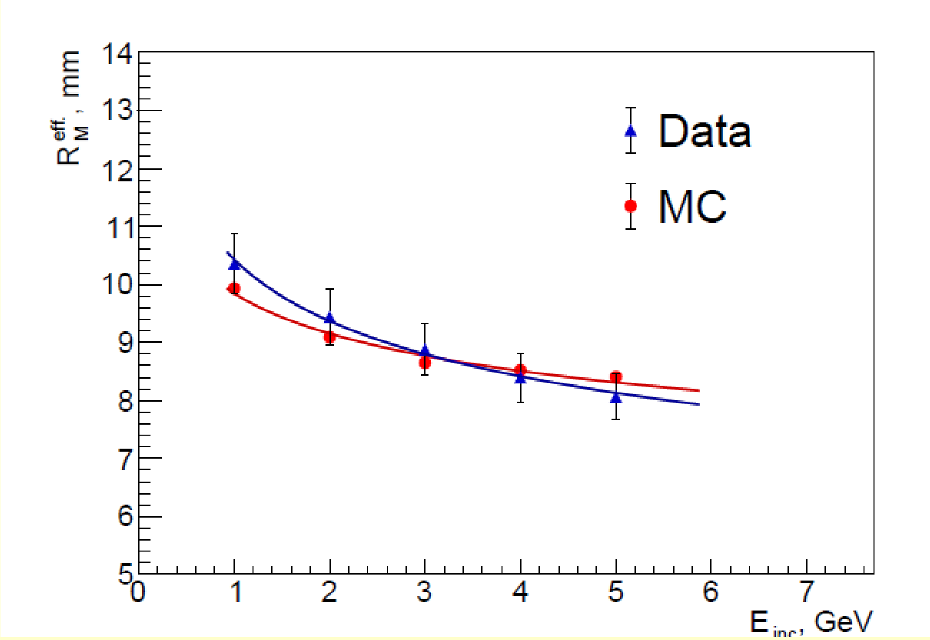
Transverse shower development, data/MC comparison (a) shower core, (b) 2 pads away, (c) 5 pads away, 7 X_0 upstream

Moliere radius



Projection of the energy depositio on the transverse plane

- Effective Moliere radius: ~ 8 mm (5GeV)
- approaching the technological limit



Energy dependence of R_M due to limited number of instrumented sensor planes (6)

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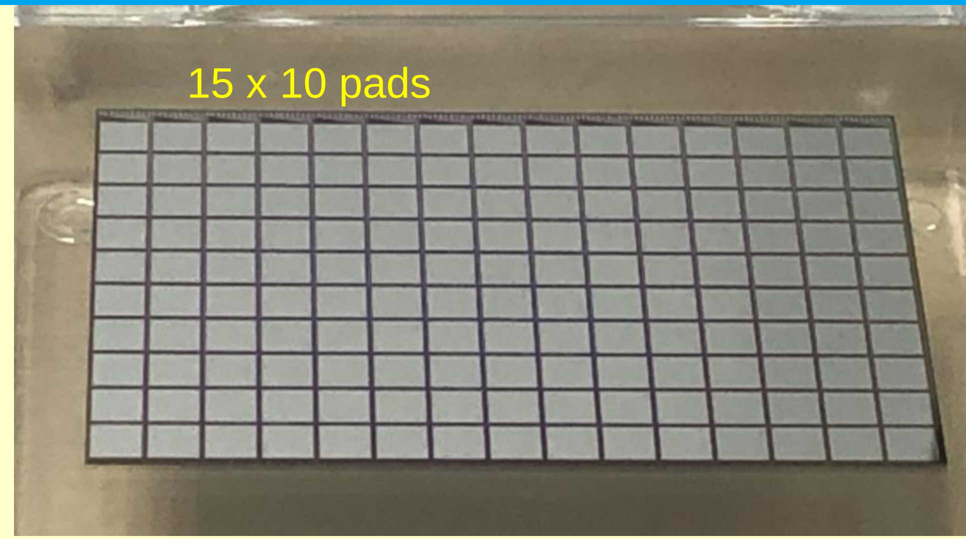
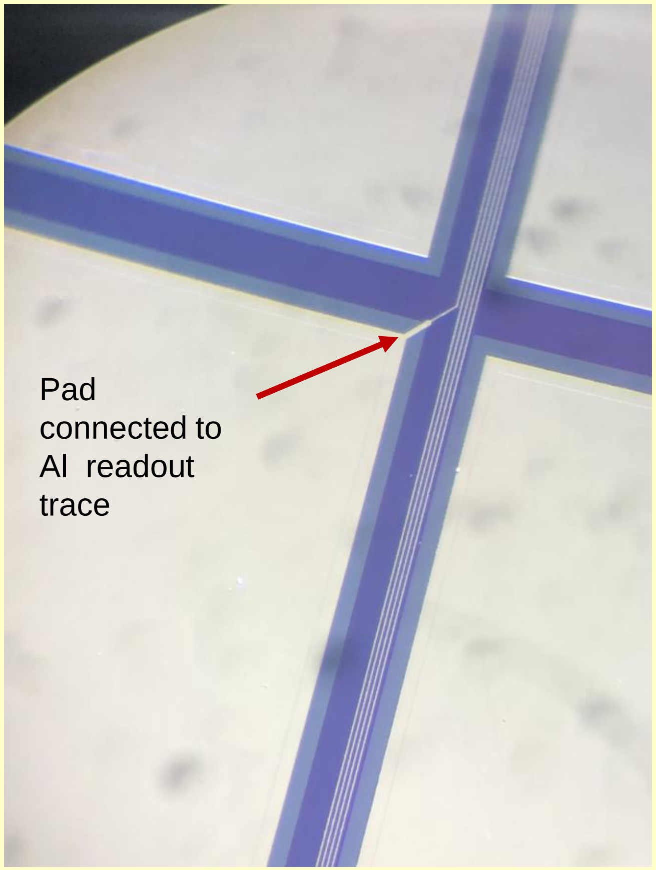
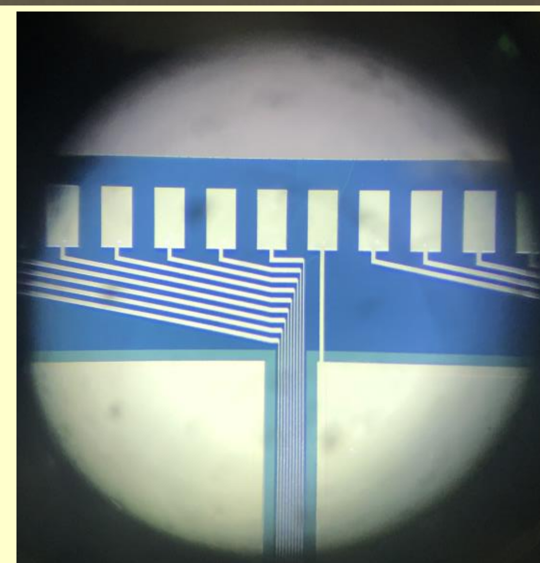
new technology GaAs sensors

New technology→Sensors, with signal routing integrated on the sensor



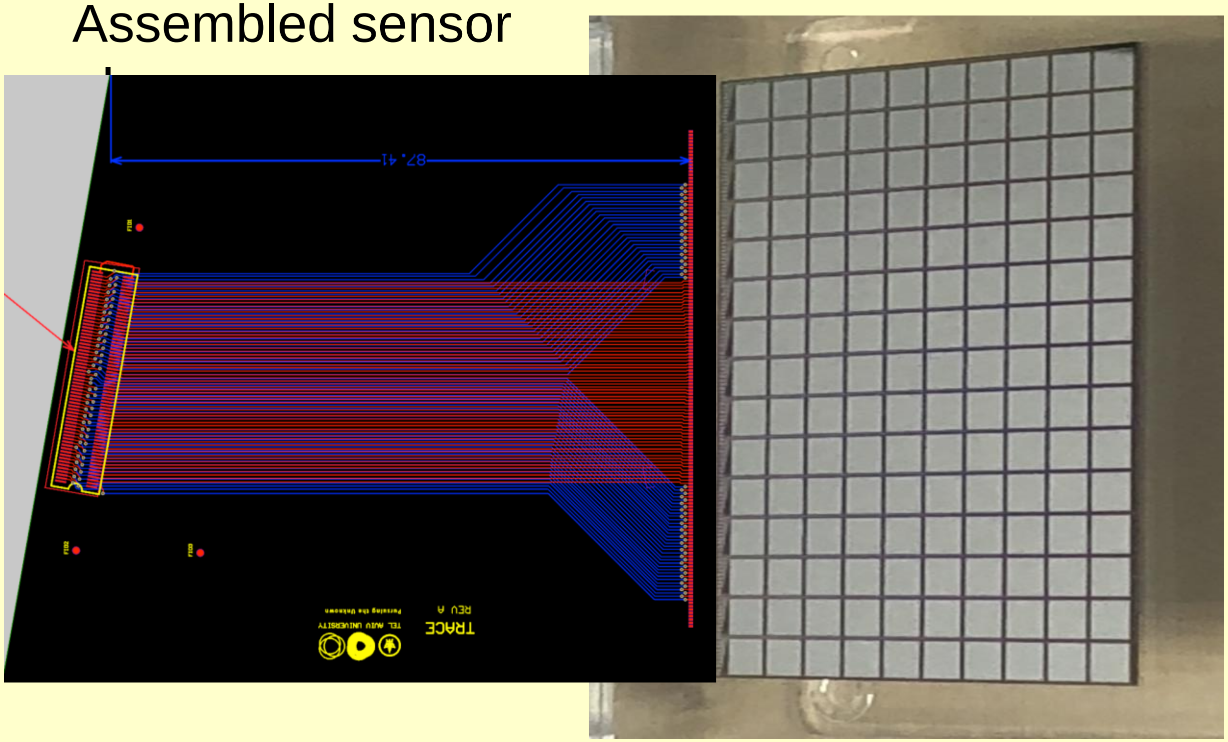


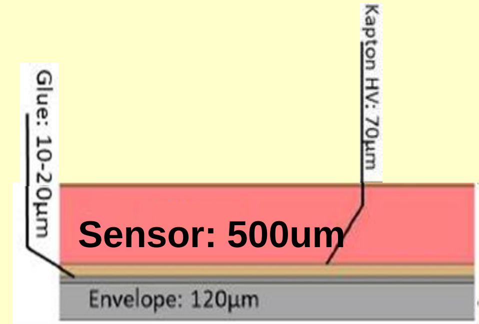
Bond pads at the upper sensor edge, To be connected to the FE ASIC



Read out connections

Assembled sensor





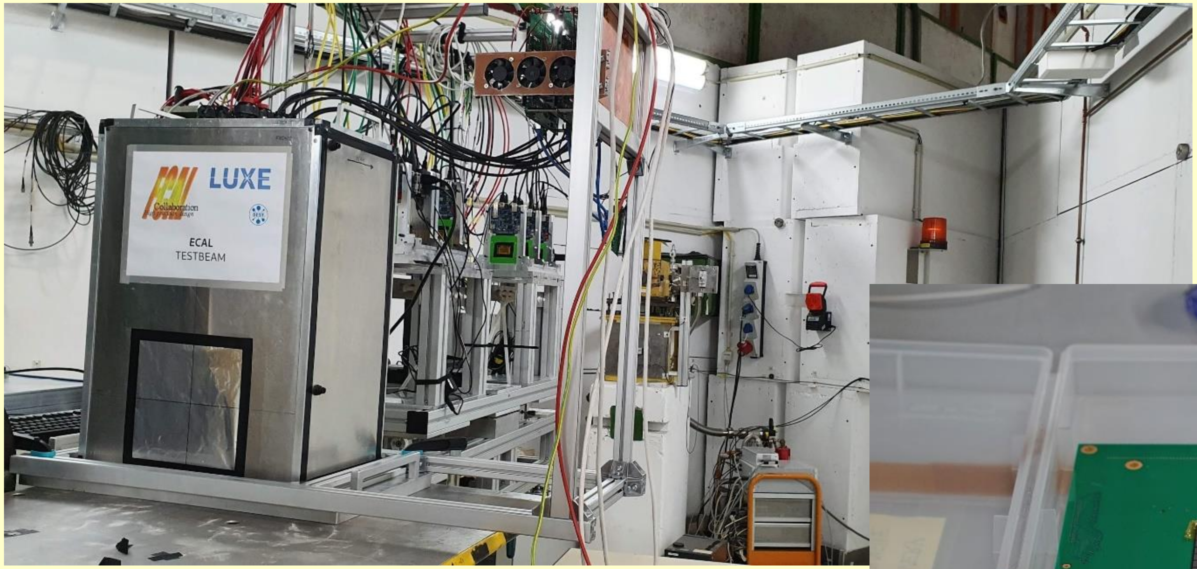
Thickness 710 µm

Details still to be designed for a robust and reliable connectivity scheme, Prototype below

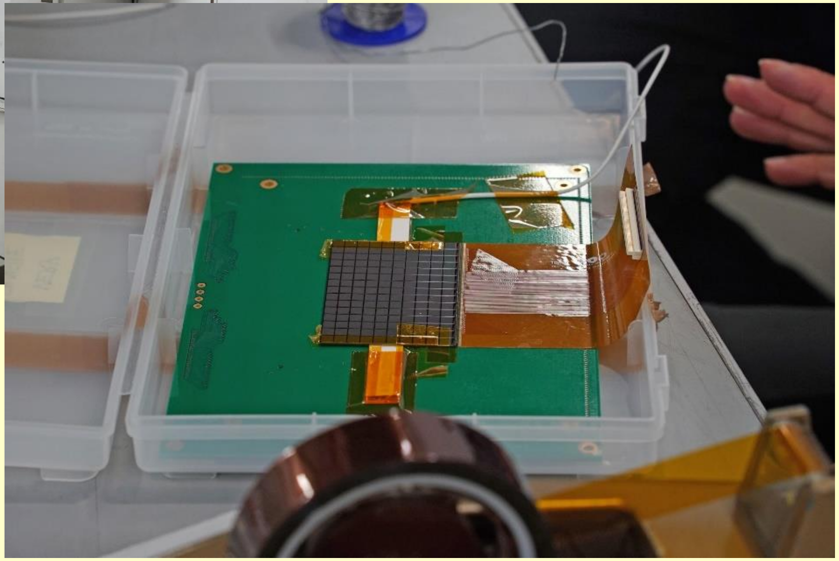
Testbeam

New signal routing technology on GaAs sensors

Beam test Nov. 8-14 at T24

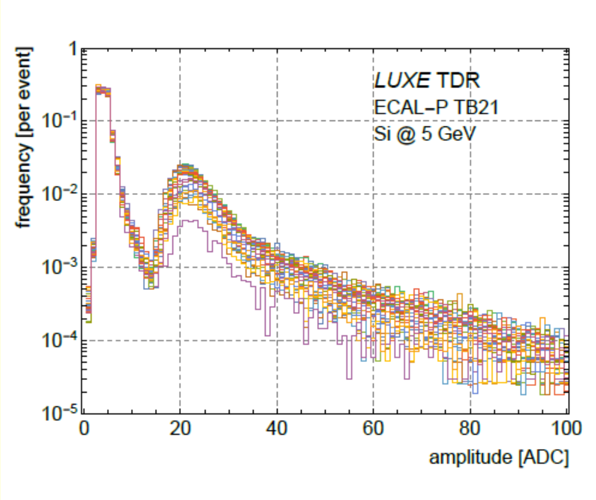


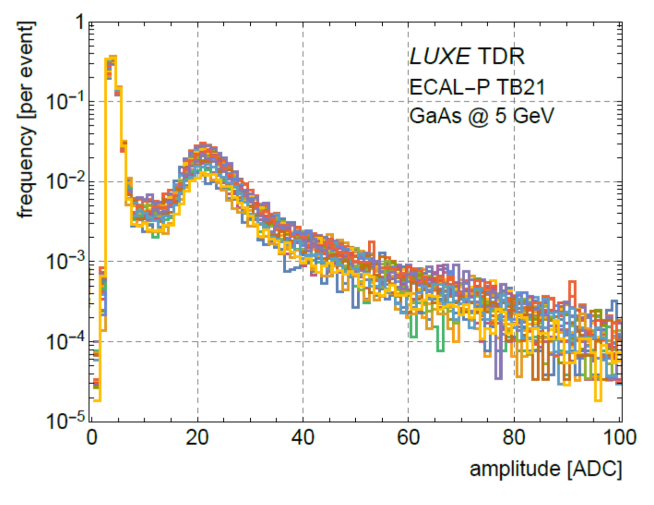
Sensor box (DUT) downstream of the beam talescope



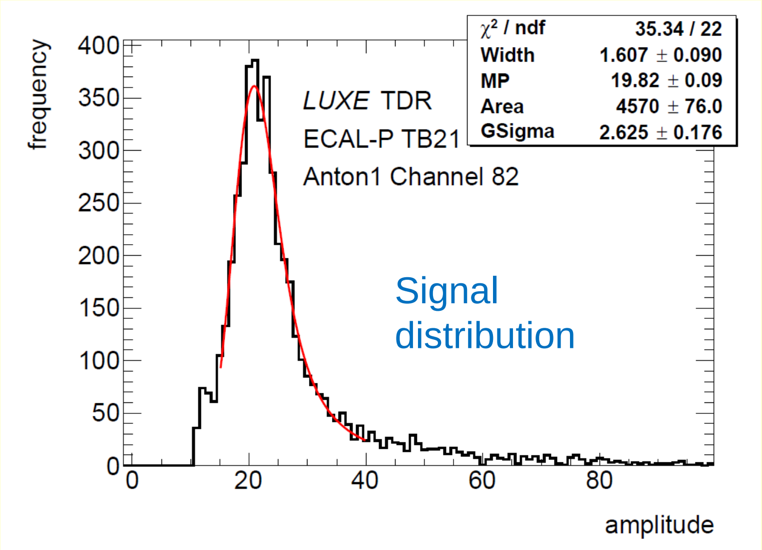
Two GaAs sensors (with new routing Al strips) and two Calice silicon sensors were prepared to be connected to FLAME readout

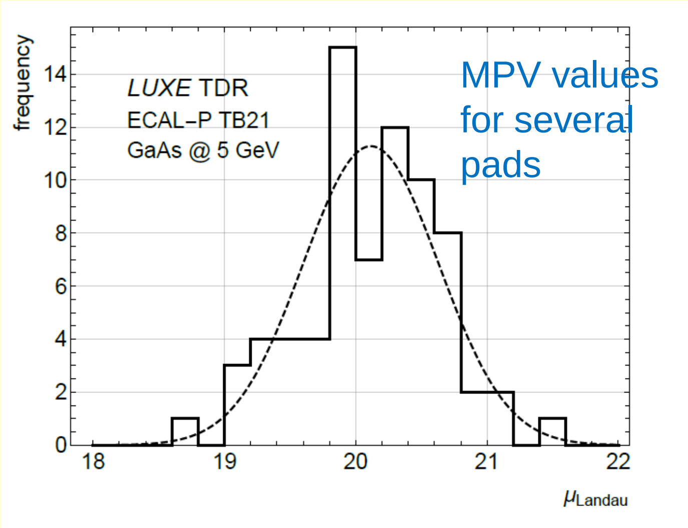
Test-beam results





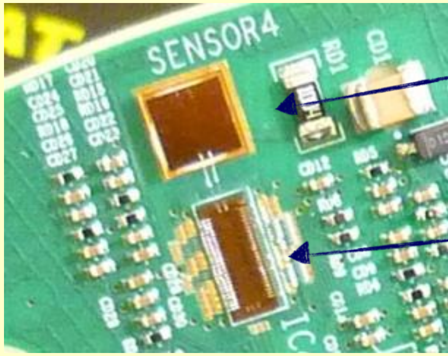
Signal size for Si and GaAs similar (due to very low hole mobility in GaAs)



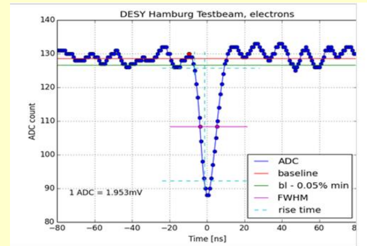


Spin-offs

Luminometer and Beam Condition Monitor for the CMS experiment



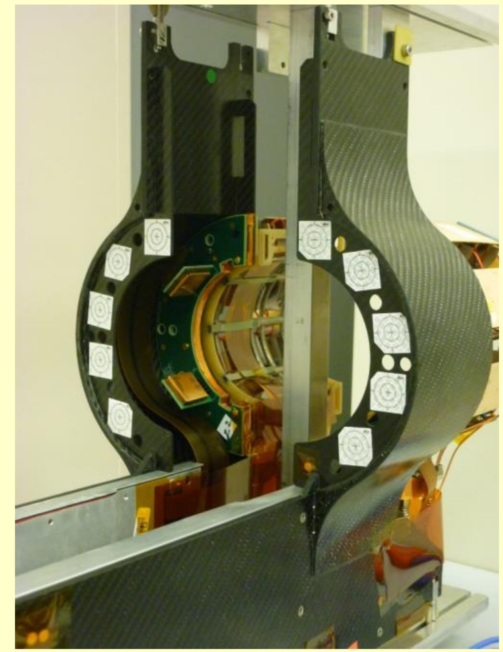
sensor pads (Si diodes or diamond)

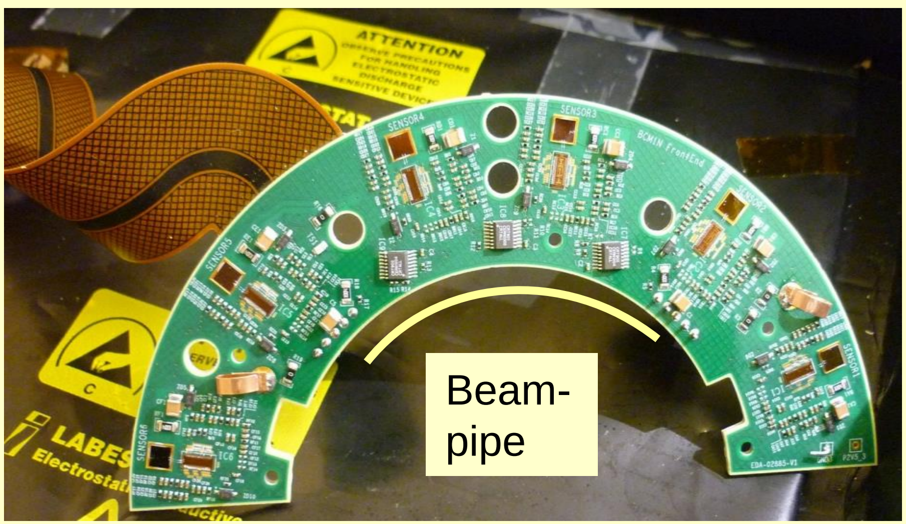


Front-end ASIC, supers-fast (sub-Nanosecond time measurement)

Designed in UST Krakow & CERN

Carbon fiber structure





Half ring with flexible Kapton PCB

Components of FLAME are used in the upgrade of the CMS HGCAL

Summary

- Two luminometers, BeamCal and LumiCal are designed for ILC or CLIC- like collider
- Fine-granular sensors and dedicated FE electronics were developed
- Assembled sensors planes of less than 1 mm thickness were build
- The transversal and longitudinal shower shape was measured in an electron beam up to 5 GeV, and compared with simulations, very good agreement found
- The effective Moliere radius was measured and approched the ‚technological limit‘
- GaAs sensors have been developed with signal routing traces integrated in the sensor
- Test-beam results show expected performance, signal size comparable to silicon
- The current political situation requires to reconsider the next steps
- FCAL has still millions of test-beam data. Person-power for analysis currently very small

Lessons for other colliders

- The polar angle range must be adapted to collect sufficient Bhabha event statistics (depends on available space, energy)
- Flame peaking time of 55 ns was set for ILC. Use at CLIC was possible thanks to low Bhabha rate per BX, and time resolution of a few ns.
- Data flux to be adapted to expected rates
- Background, beam-strahlung, bunch-charge density impact, polarisation to be considered.

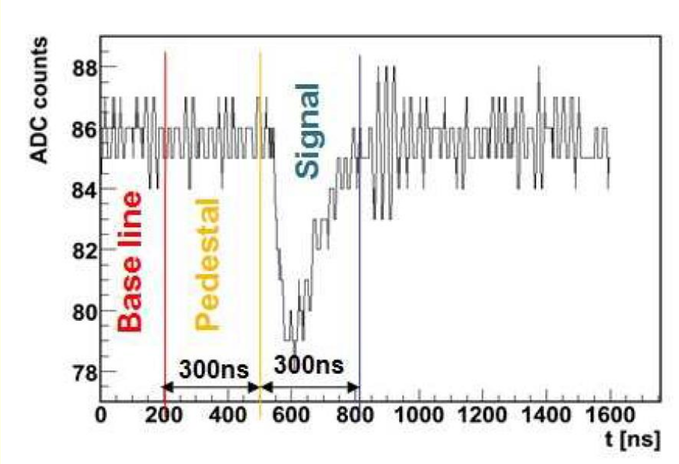
Beam-test campaign

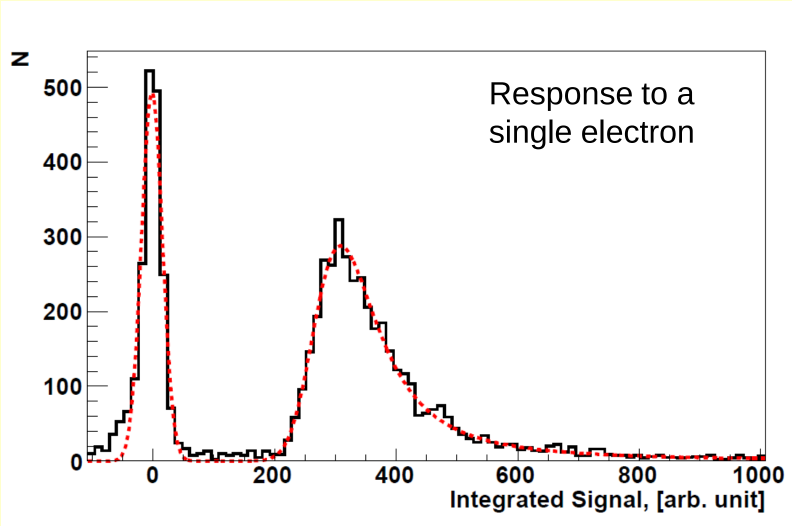
Participants from AGH-UST, ISS TAU

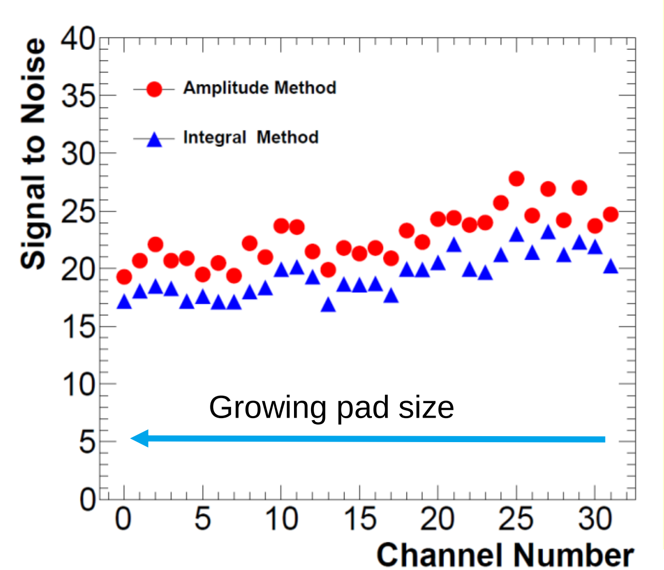
backup

GaAs sensors

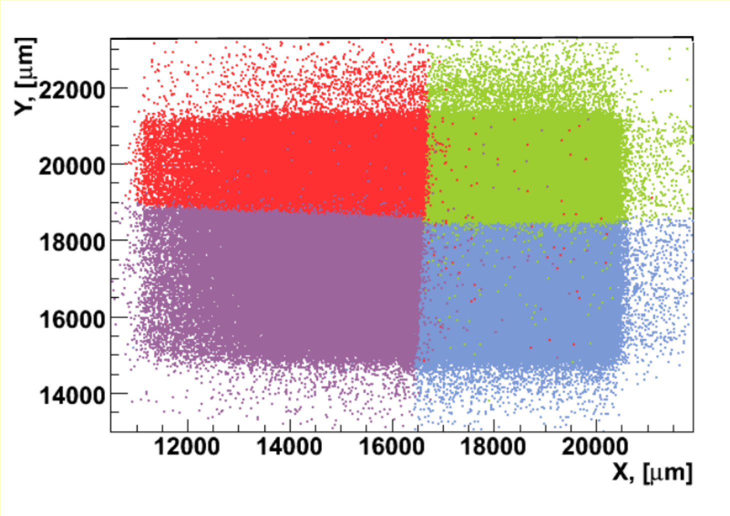
GaAs measurement results 2011



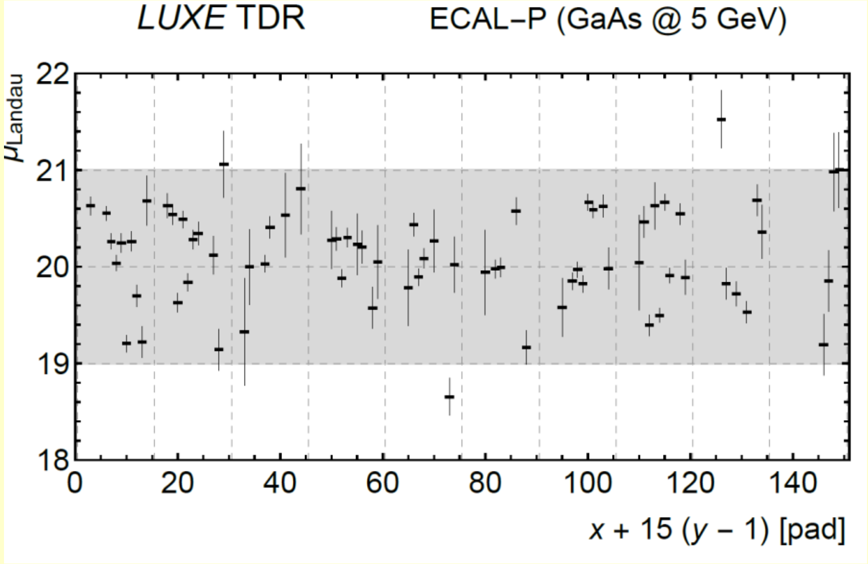


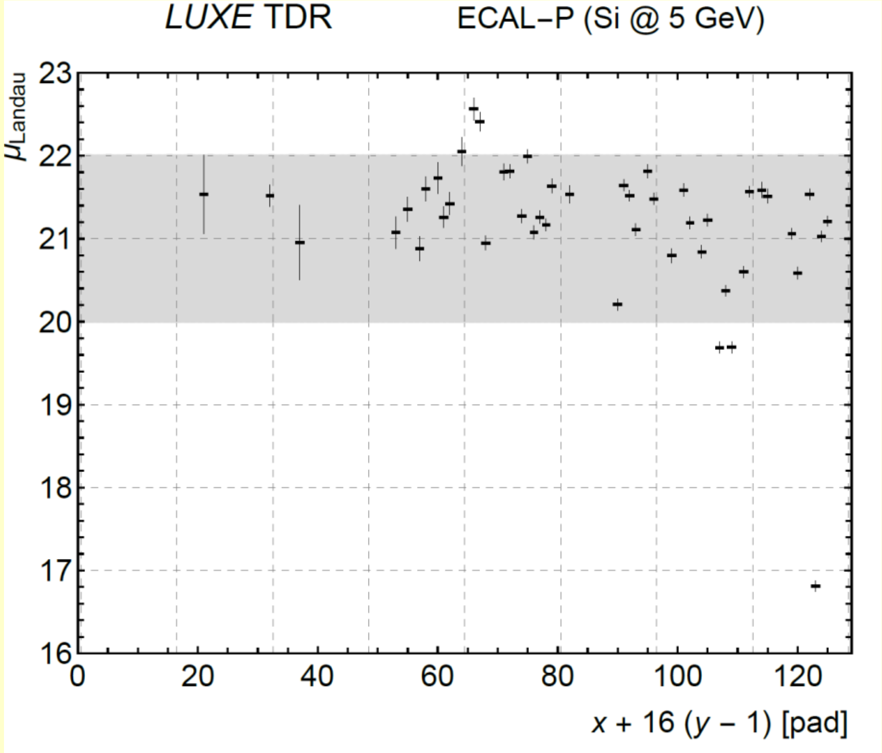


Using the information from the ZEUS beam telescope



Test-beam results





MPV as a function of the pad number

Similar for GaAs and silicon sensors,

Assuming 5% calibration uncertainty of the FE ASIC channels -> response is independent of the pad number

Quantitative study in the next test-beam