Luminometers for future linear collider experiments

Angel Abusleme*
On behalf of the FCAL collaboration

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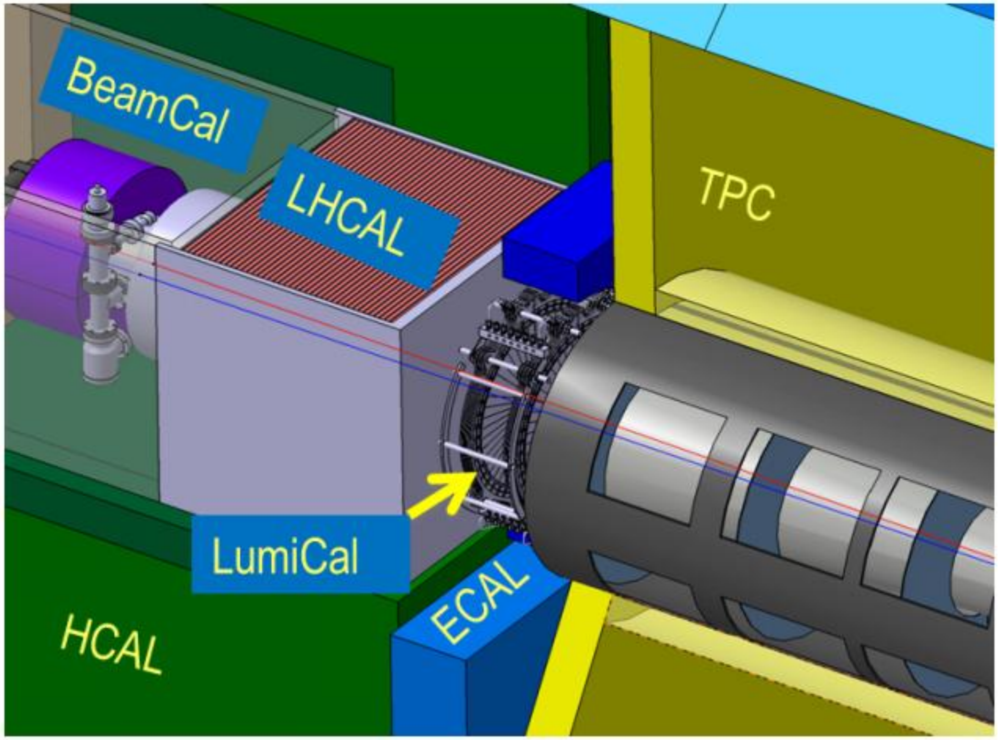
* Pontificia Universidad Católica de Chile - Centro Científico Tecnológico de Valparaíso



Collider luminosity in a nutshell

- The instantaneous luminosity of a collider is the quotient between the **rate of a certain event or group of events** and the **effective cross section of the processes involved**

$$L = \frac{1}{\sigma}\frac{dN}{dt}\left[b^{-1}s^{-1}\right]$$

e.g. $L = 10^{34}\ cm^{-2}\ s^{-1}$

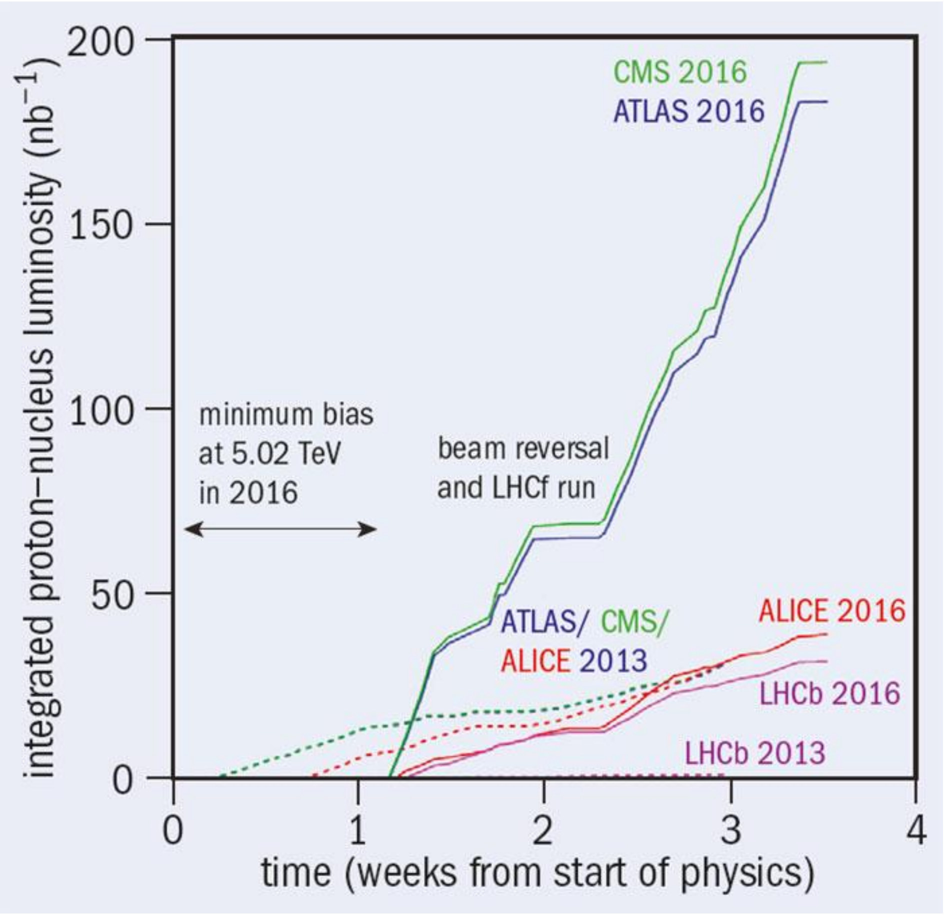
- Luminosity is a **machine parameter** related to the **beam features** such as size and intensity
  - Luminosity is **process-independent**
  - Can be **inferred** from measured event rate and its known event cross section
  - Need a **well understood and measurable process**
- **Integrated luminosity** is *L* accumulated over the experiment data taking period

$$L_{\text{int}} = \int L\text{dt}\left[b^{-1}\right]$$

- Integrated luminosity is related to the **total data** produced by an experiment

L and L_{int} are **very important**

- *L* is necessary to **monitor the accelerator performance**
- The higher L_{int}, the higher the number of unlikely events to show up in the experiment
  - E.g., for 7TeV LHC, only **one Higgs** is produced **every 10G** events!
- L_{int} is necessary to **measure the process cross section**



http://cerncourier.com/cws/article/cern/67435

Luminosity in $e^+ e^-$ colliders

- Luminosity measurements are **crucial** in a collider physics program
- Luminosity **precision** goals in $e^+ e^-$ colliders are **more ambitious** than in hadron colliders
- **One luminosity instrument** concept for **two linear colliders** under study
  - ILC (SCRF cavities)
  - CLIC (conventional cavities)

Outline of this talk

- Luminosity measurements
- LumiCal and BeamCal design
- Recent testsbeam results
- Thin detector planes development
- Sensor radiation damage studies
- ASIC development

So what’s next?

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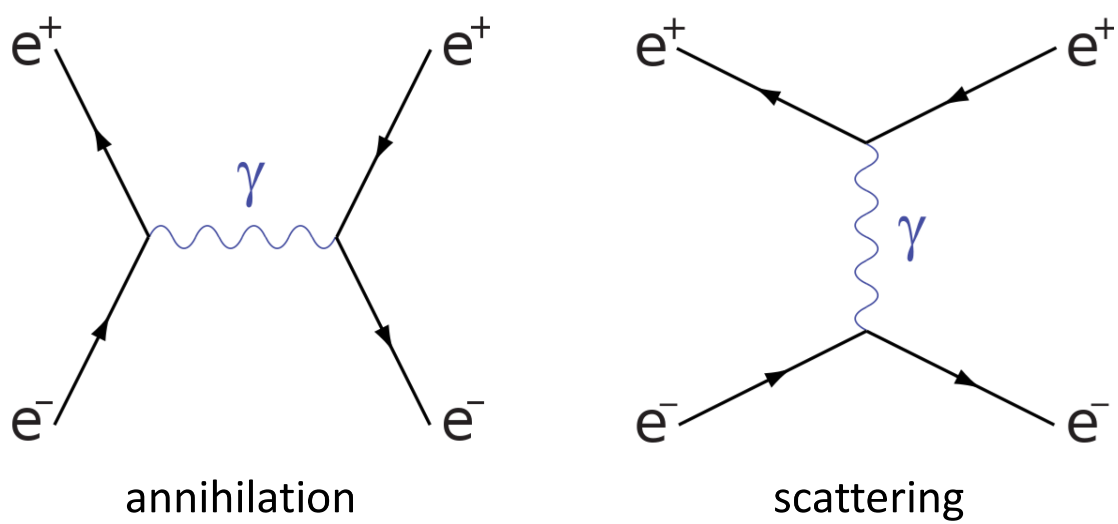
Precision luminometry in $e^+ e^-$ colliders

Small-angle elastic $e^+ e^-$ scattering (**Bhabha** process) is used for precision luminosity measurements

- High production rate
  - Almost pure QED
- Theoretically well understood



How **precise**?

- Required precision: 10^{-3}
- The differential cross section of Bhabha scattering can be calculated from theory:

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

arXiv:1009.2433

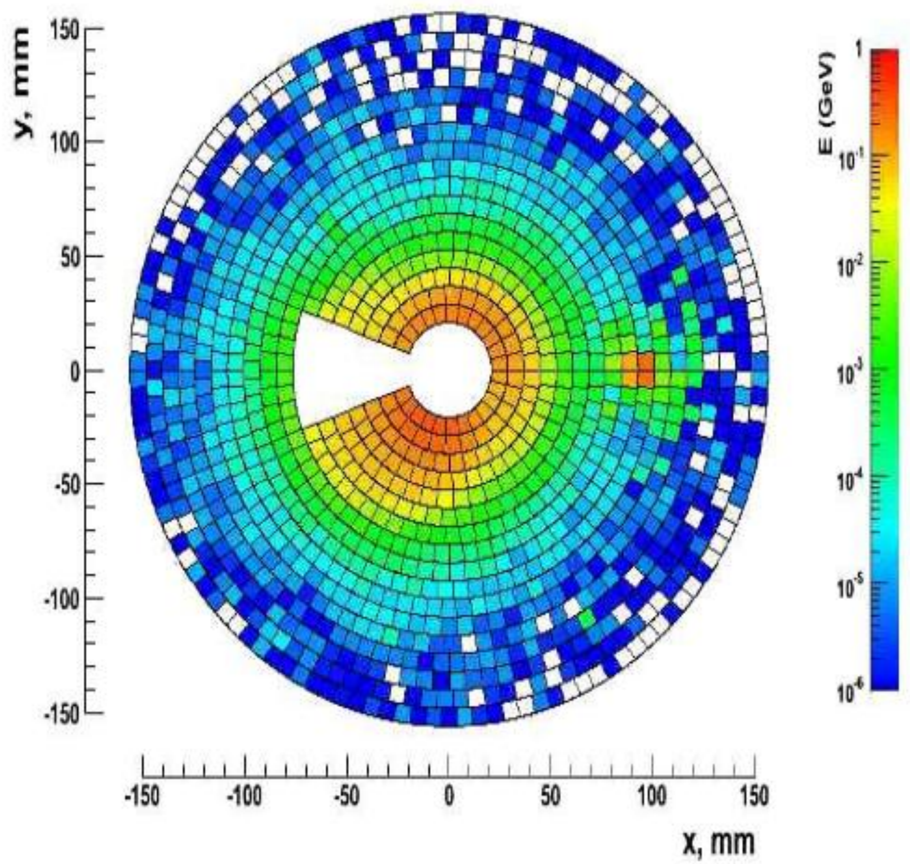
- Then the luminosity can be estimated:

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

Instantaneous luminometry in $e^+ e^-$ colliders

- **Instantaneous luminosity measurement** based on e^+e^- pairs originating from **beamstrahlung**
  - Depends on beam-beam alignment at interaction point
- Smaller polar angles than those for Bhabha scattering
- **Fast**, but not as precise as estimations from Bhabha process

arXiv:1009.2433



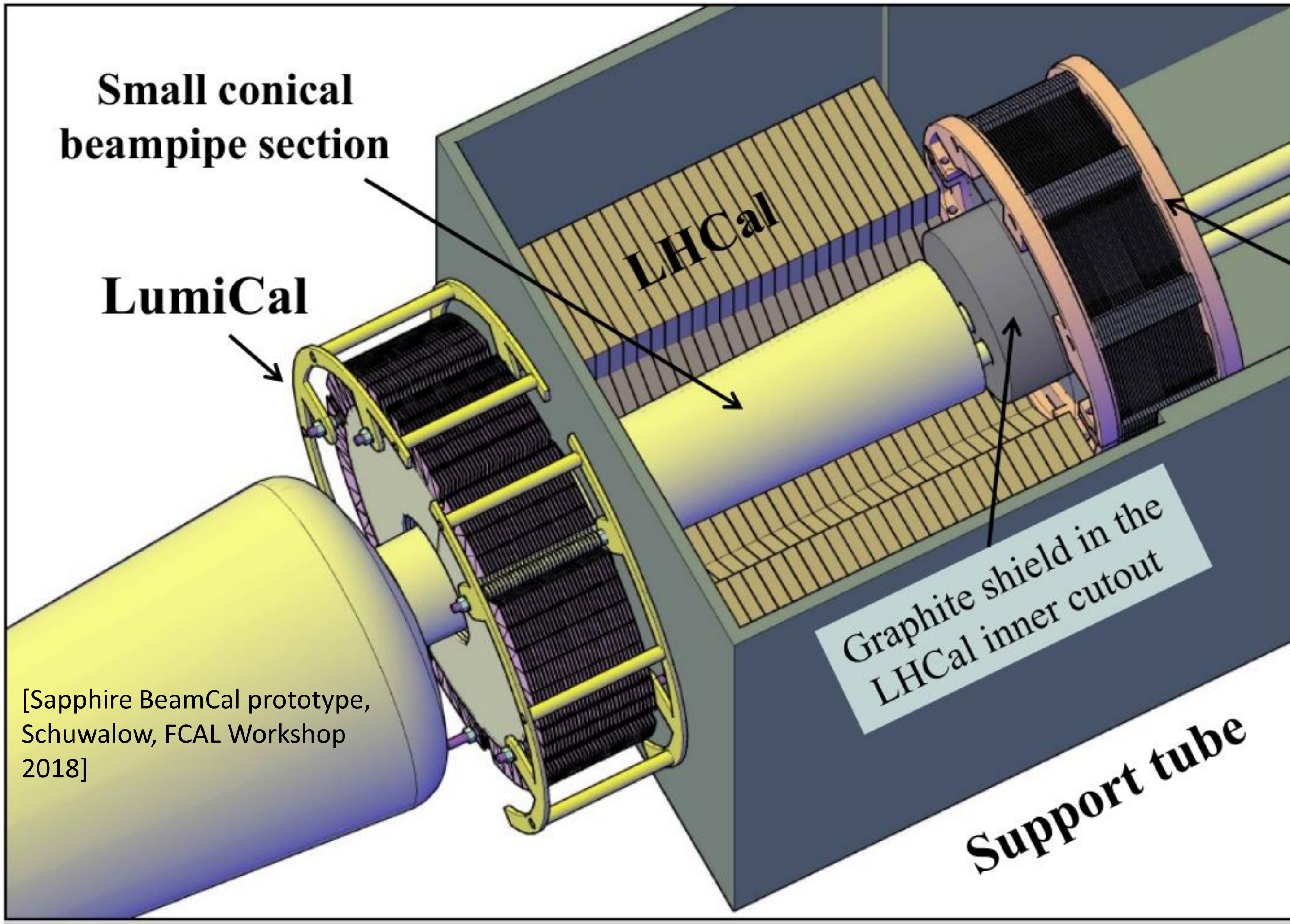
Distribution of the energy deposited by beamstrahlung pairs after one bunch crossing in a the sensor covering small angle

Twofold luminometry requirements and challenges for future linear colliders

- **Precise** measurements
  - Precision better than 10^{-3} for 500-GeV CME
    - Challenges in electronics, mechanics and position control; non-trivial luminosity spectrum due to beam-beam effects
  - Small spread of shower for better reconstructability
- **Instantaneous** measurements
  - High occupancy
  - High radiation environment (~MGy per year) due to beamstrahlung
  - Shield tracker by reducing backscattering

- These requirements call for **two complementary instruments** in the collider forward region:
  - **Lumical** for precise luminosity measurements
  - **BeamCal** for instantaneous luminosity measurements

Example of forward calorimeters: layout for ILD detector @ILC



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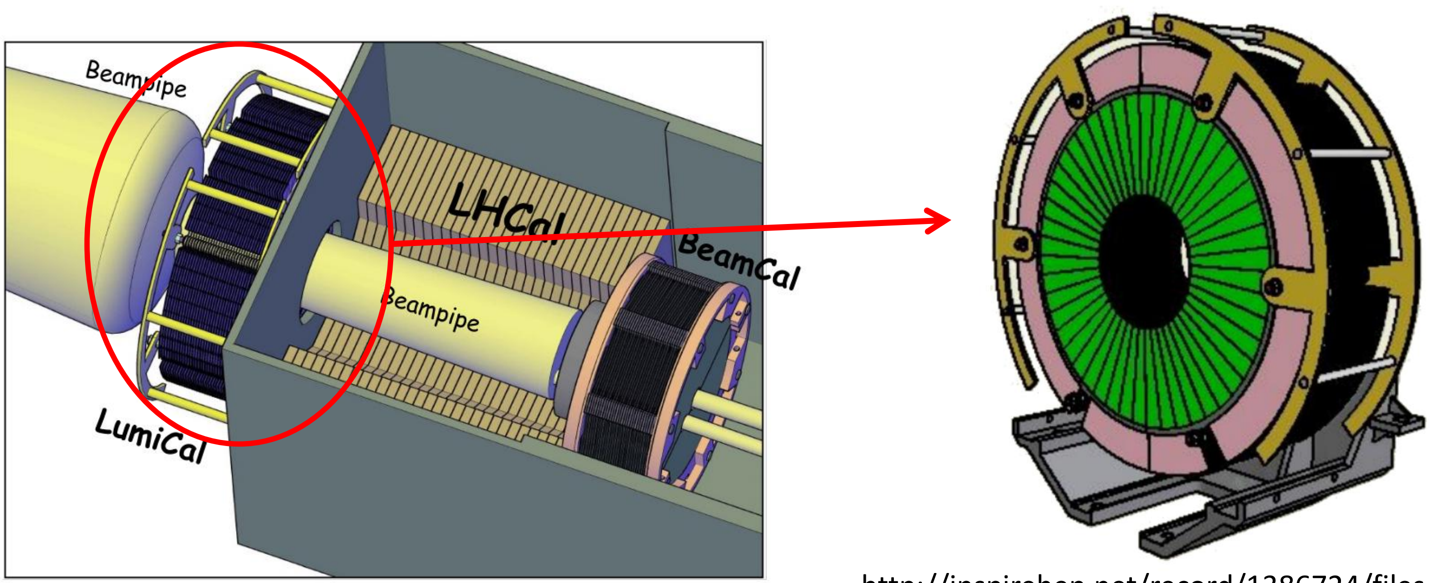
LumiCal design

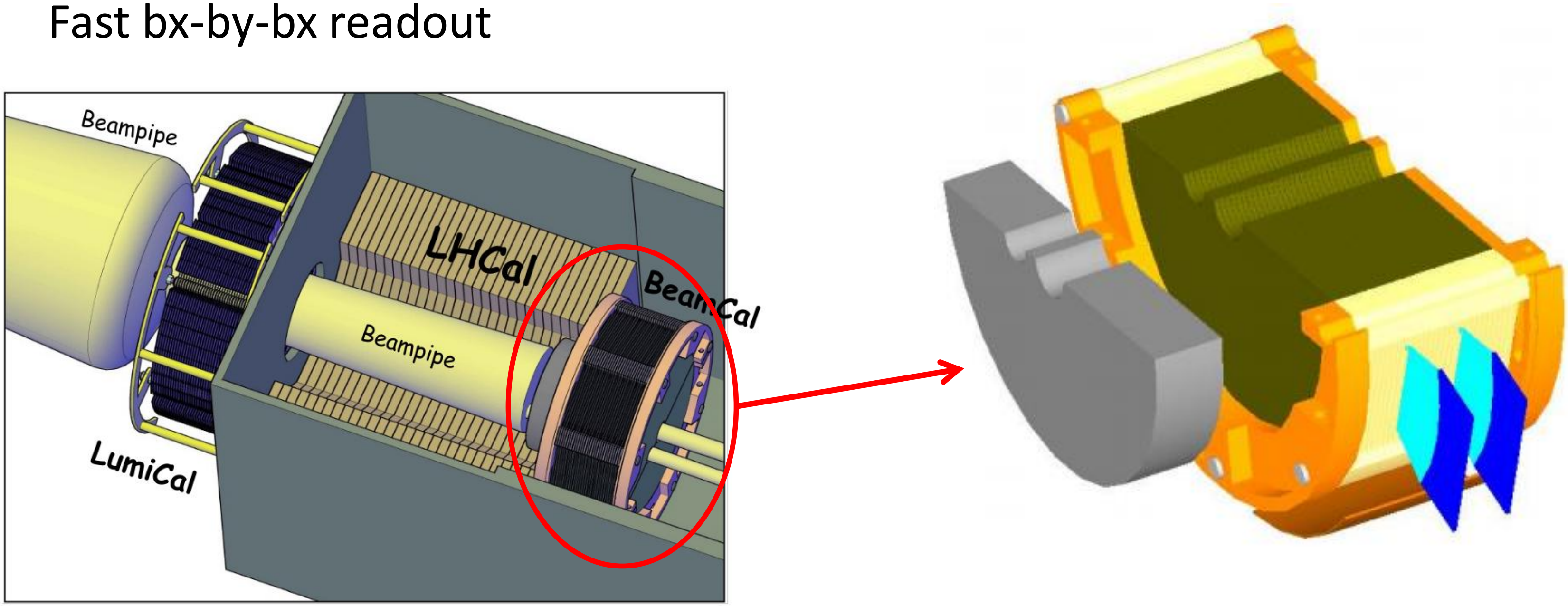
- Sampling (sandwich) Si-W calorimeter
- 30 **precise** layers at ILC (40 at CLIC), one radiation length each
- 42–67 mrad at ILC (38–110 mrad at CLIC)
- **Compactness** for transverse size of shower around ~1 cm



http://inspirehep.net/record/1386724/files/v46p1297.pdf

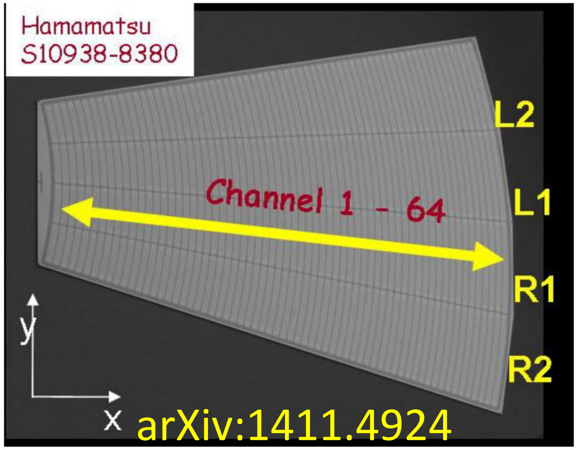
BeamCal design

- Sampling **?**-W calorimeter
  - Thorough research on Sapphire, CVD diamondGaAs and Si as possible candidates
- 30 **precise** layers at ILC (40 at CLIC), one radiation length each
- 5–45 mrad at ILC (15–38 mrad at CLIC)
- High radiation tolerance
- Fast bx-by-bx readout

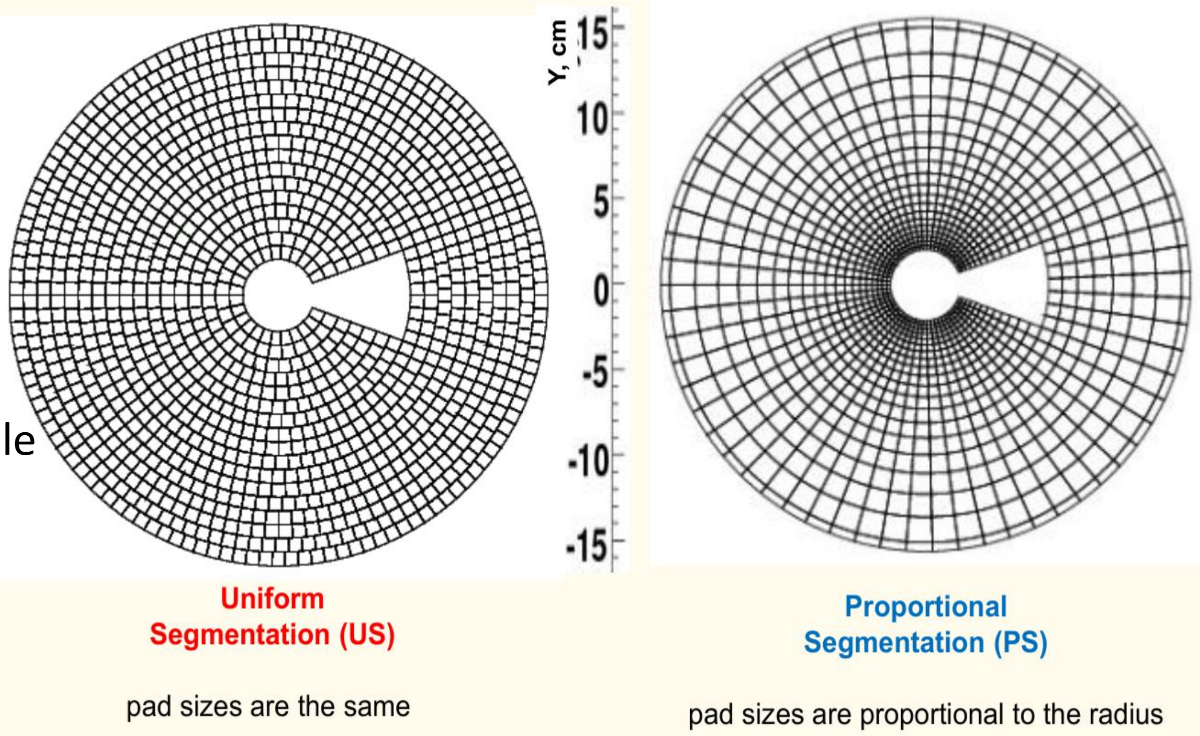


FCAL sensor planes

LumiCal sensor plane sector

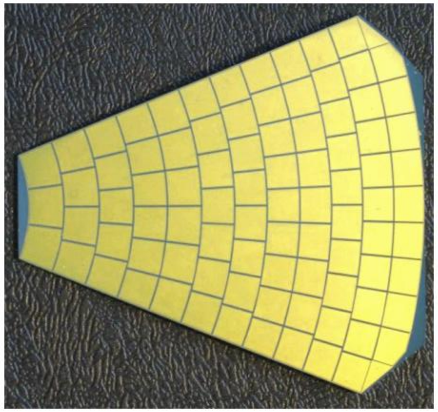


BeamCal segmentation options



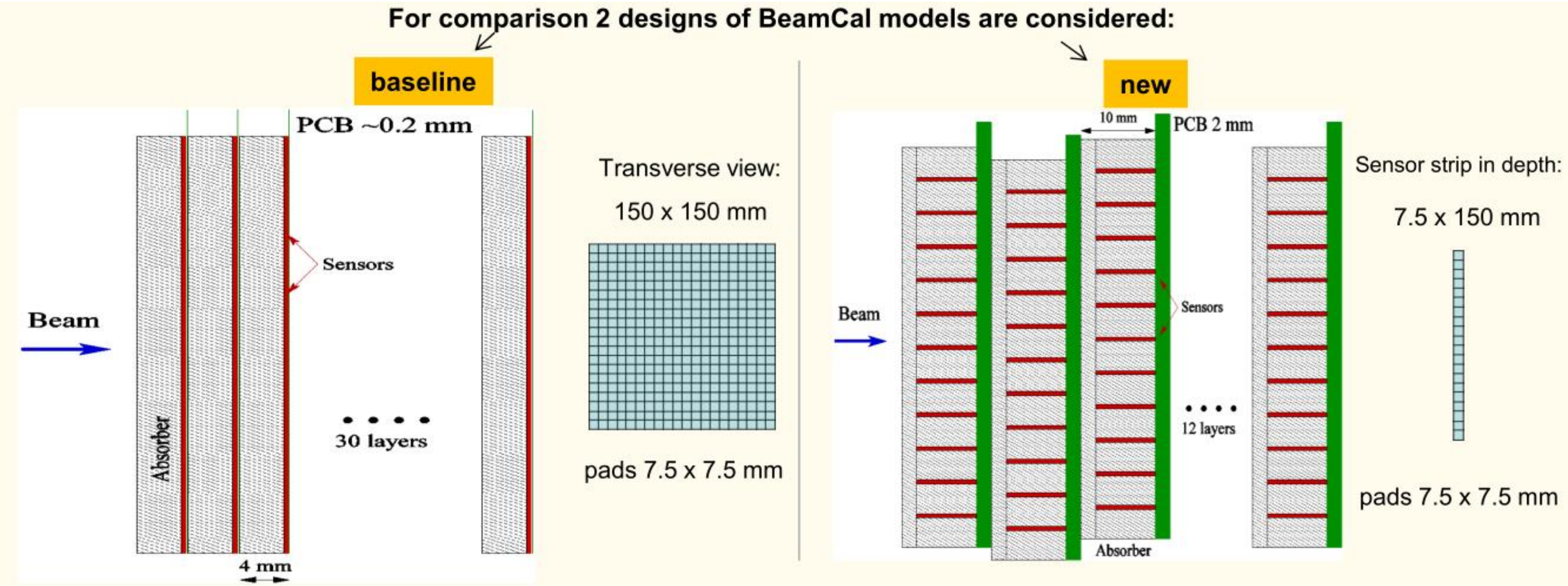
[Optimization of the BeamCal Design, L. Bortko, LCWS 2014]

BeamCal sensor plane sector example



arXiv:1411.4924v2

BeamCal sensor planes – Sapphire option



[Optimization of the BeamCal Design, L. Bortko, LCWS 2014]

- Sapphire is cheap and less sensitive to radiation; smaller signals
- New design is more sensitive to MIPs, smaller DR required
- Non-standard assembly procedure
- Worse energy resolution

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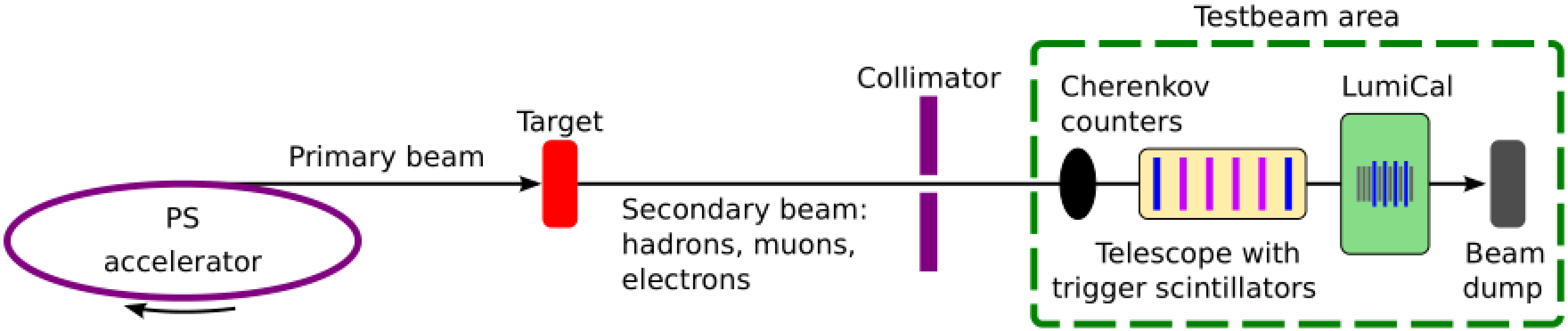
CERN PS accelerator, T9 beam 2014

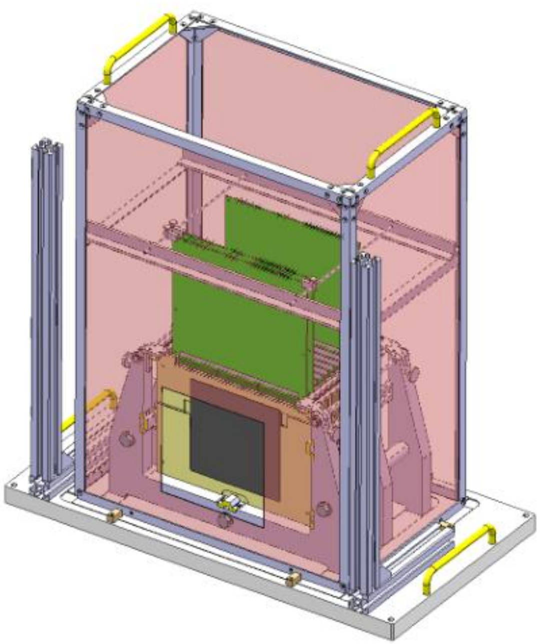
- Beam parameters:
  - Particles (mainly e^- and μ) with ~5GeV energy
  - 400ms spills every 33.6s
- Objectives:
  - Demonstrate multiplane W-Si operation
  - Study EM shower and estimate Molière radius

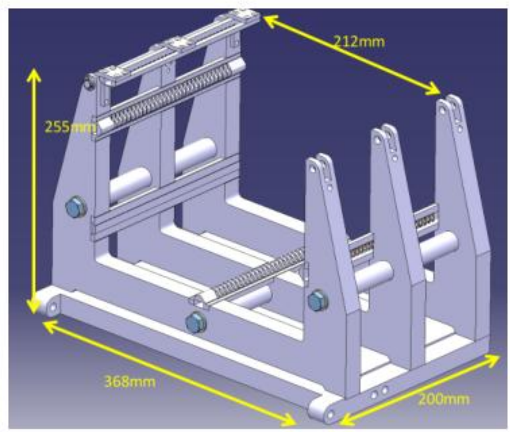


[*Measurement of shower development and its Molière radius with a four-plane LumiCal test set-up*, submitted to the Eur. Phys. J. C]

Experimental setup

- 4-layer tracker using MIMOSA-26 chips
  - Custom DAQ based on NI PXI crate
- Scintillation counters for trigger
- Few electrons per second were recorded
- 4-layer detectors, 32 channels/layer
  - FPGA-based DAQ

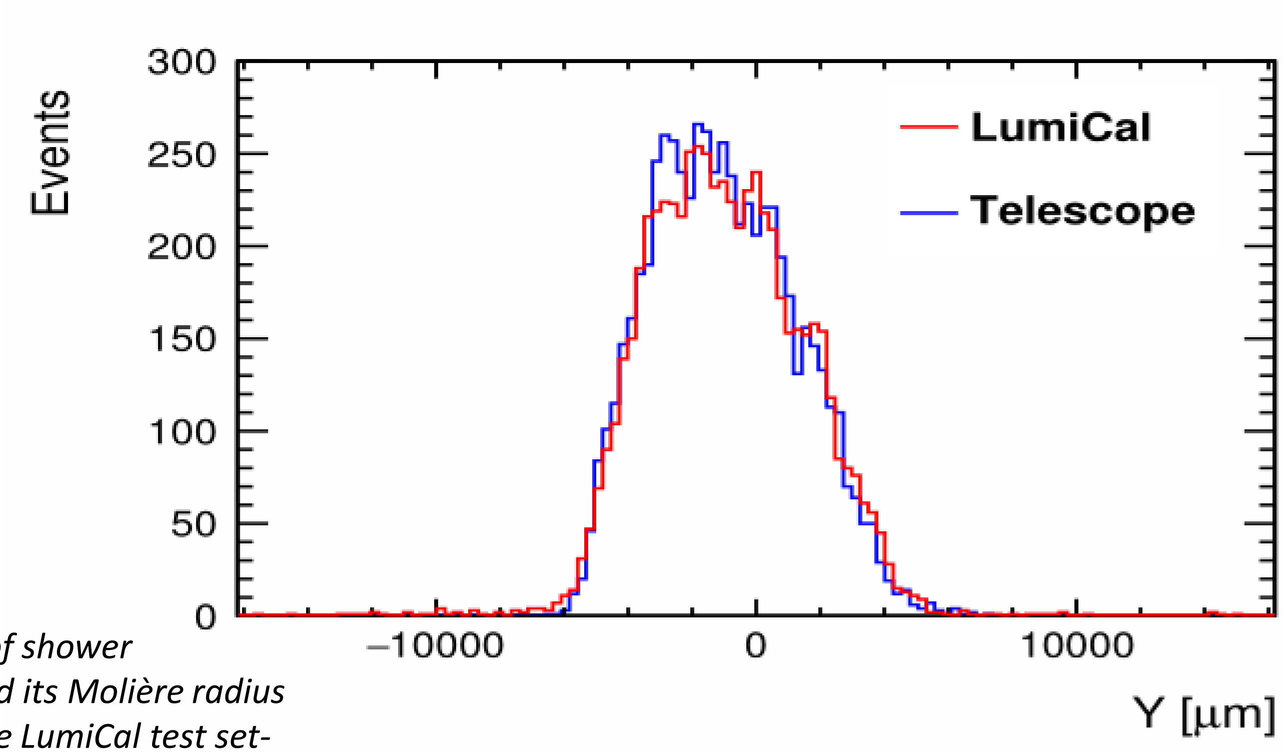




[*Measurement of shower development and its Molière radius with a four-plane LumiCal test set-up*, submitted to the Eur. Phys. J. C]

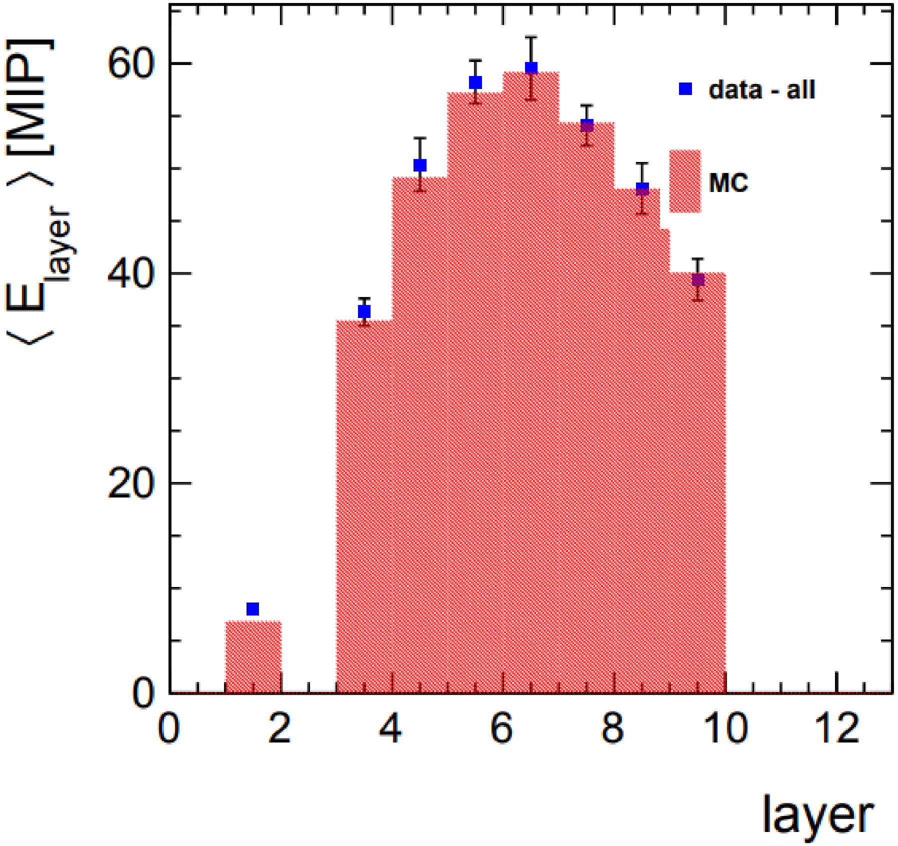
Results: distribution of radial shower position

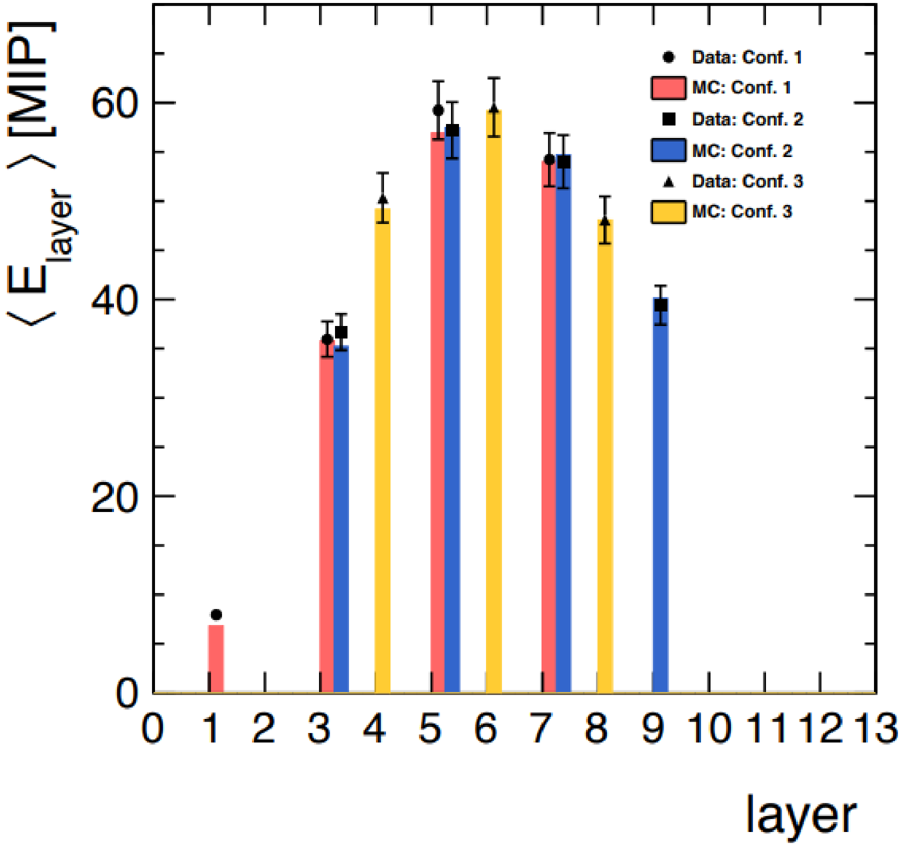
Distribution of radial shower position – Lumical vs. tracker



[*Measurement of shower development and its Molière radius with a four-plane LumiCal test set-up*, submitted to the Eur. Phys. J. C]

Results: Energy per layer

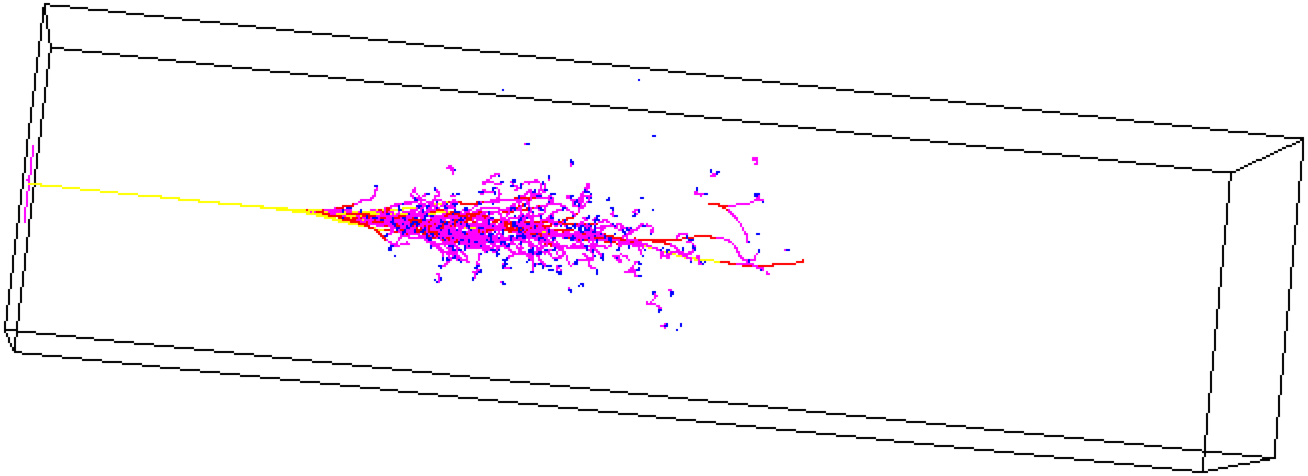




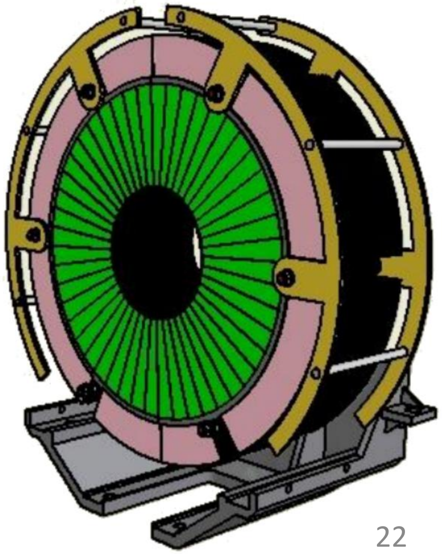
arXiv:1705.03885

Molière radius in a nutshell

- Radius of a cylinder that contains 90% of the energy deposition of the shower
  - A small R_M facilitates reconstruction of high energy e^-
- It is a **constant of the material** or target **stack**
  - E.g., an air gap in the stack increases R_M



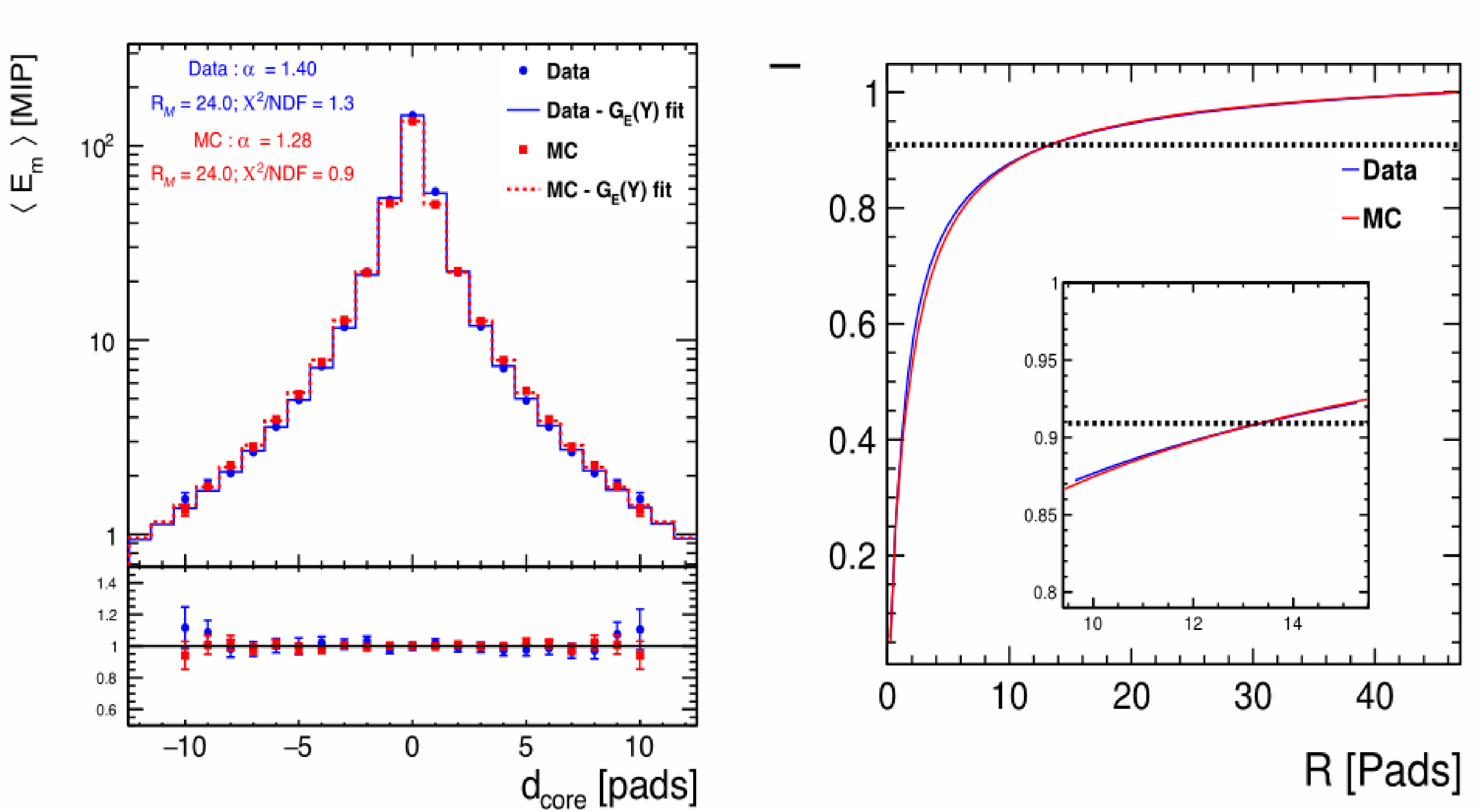
Example: EM shower simulation, 10GeV e^- on opal, https://goo.gl/Vb38eZ



Molière radius results

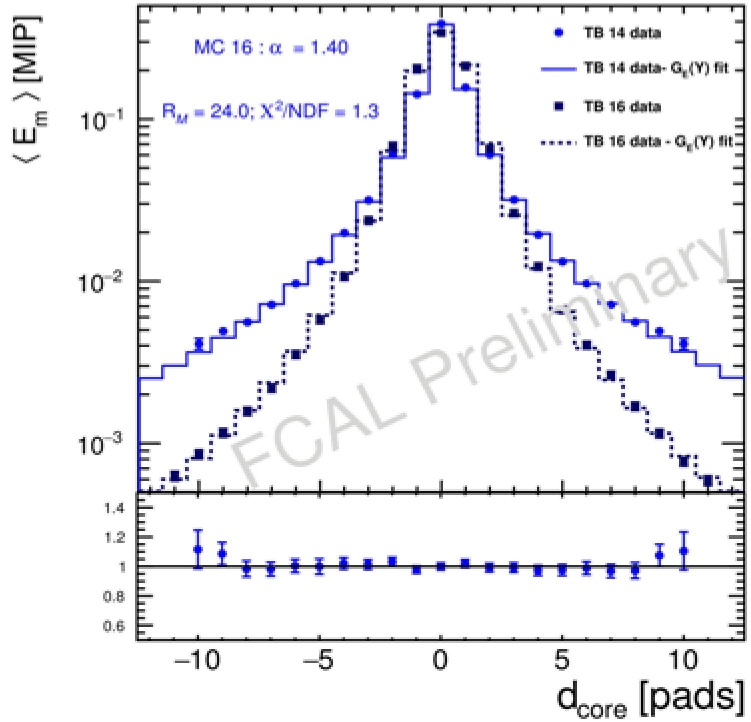
$R_M = 24.0 \pm 0.6(\text{stat.}) \pm 1.5(\text{syst.})$ [mm]

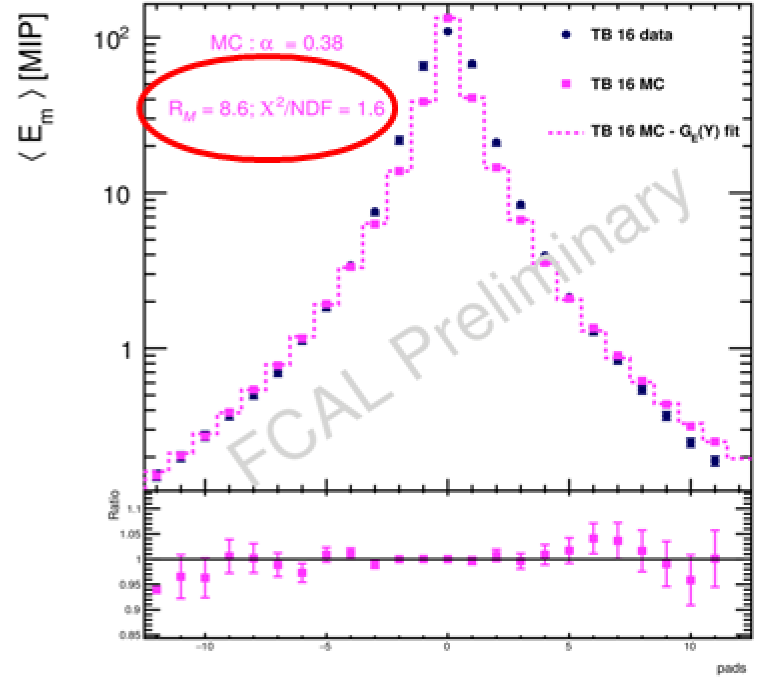
Air gaps in detector assembly explain the small discrepancies

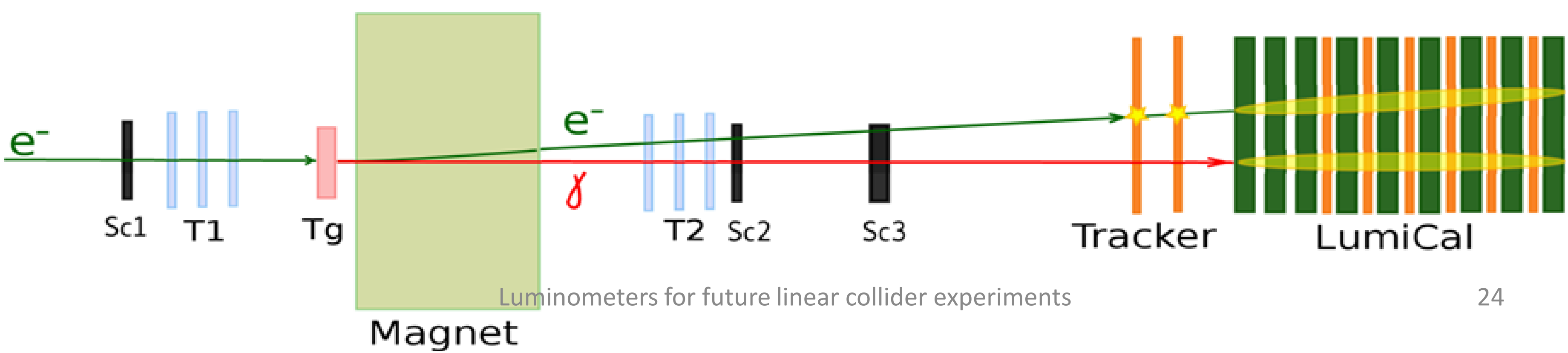


Molière radius results, TB2016

Comparison of transverse shower in TB2016 with TB2014







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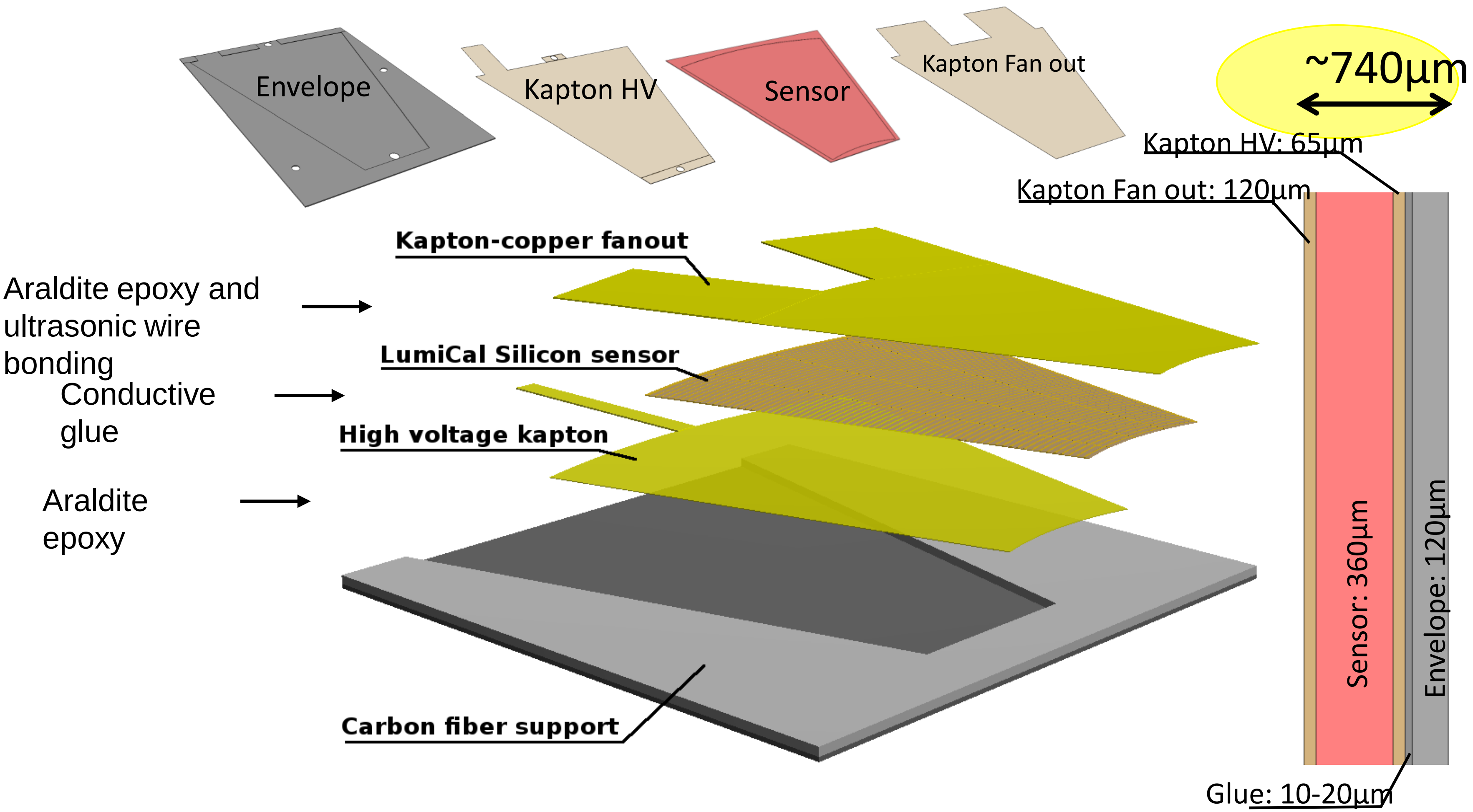
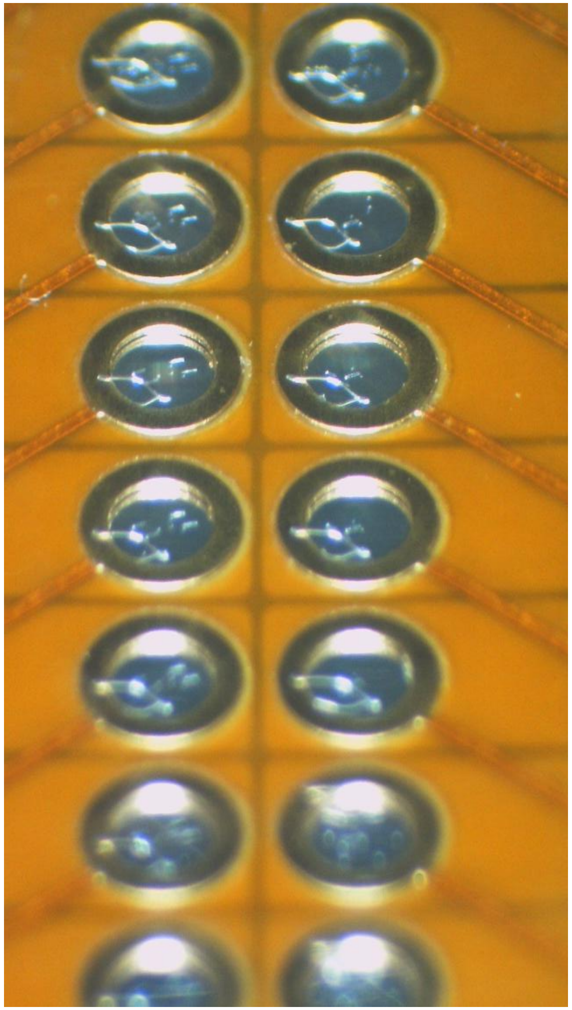
Design of the **thin** Lumical module

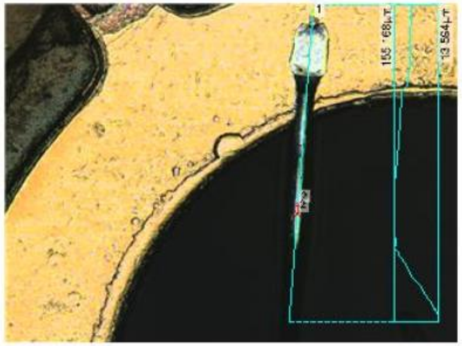


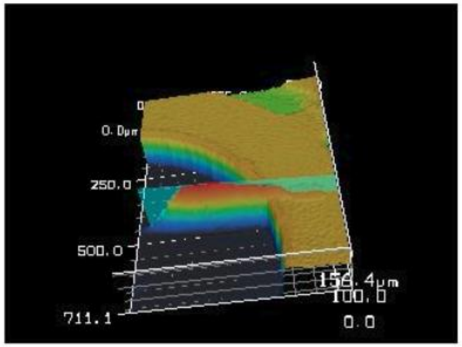
Wedge wire-bonding for FE contact

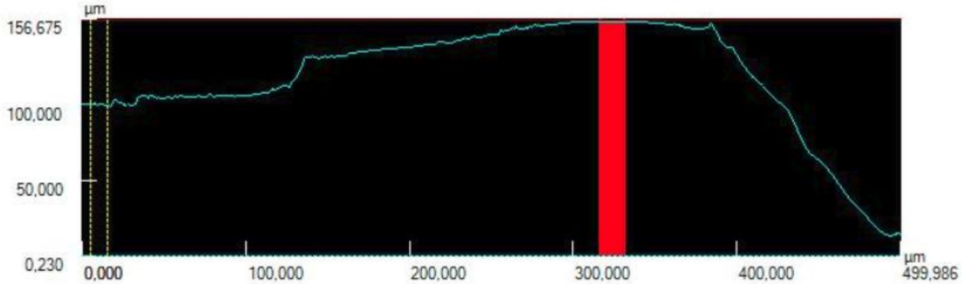


Achievable size of the bonding loops is in the range 50 μm – 100 μm.

Bonding loop measured with 3D laser scanning confocal microscope at DESY Zeuthen.

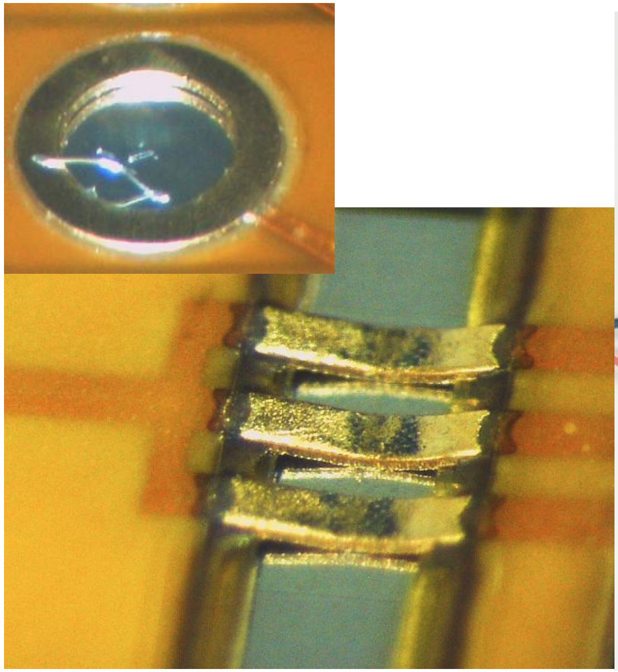


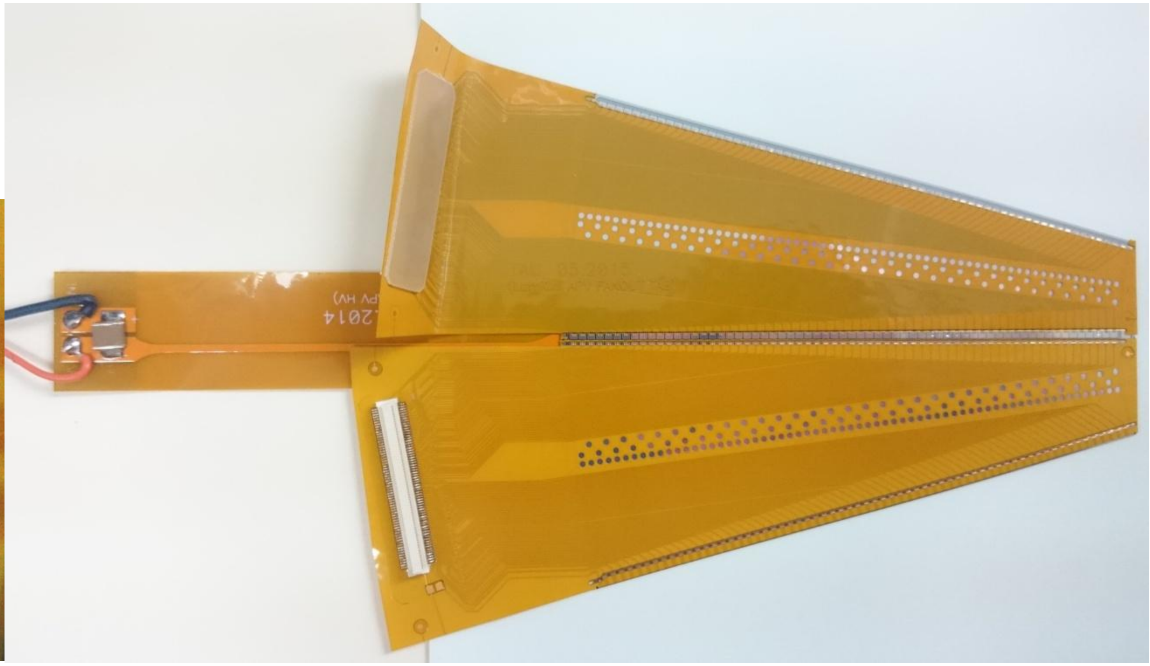




TAB technology for FE contact

Search for **long-term stable contact** between sensor and readout electronics which meets LumiCal geometrical (compactness) requirement





Single point Tape Automated Bonding (TAB):

- No wire loop, the bond can be covered by the glue for better protection
- One LumiCal module is assembled and tested using TAB technology

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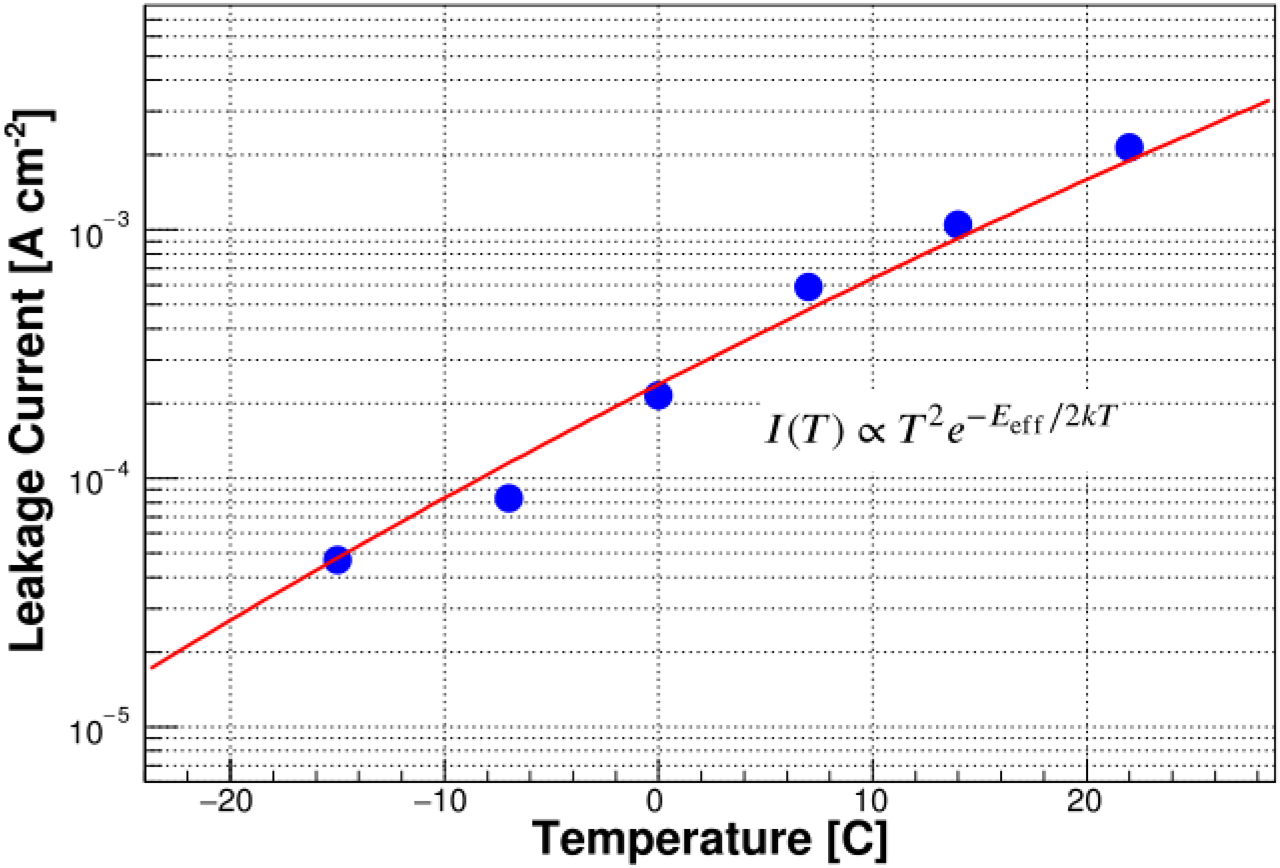
Procedure

- Radiation damage experimental data from
  - T506 experiment
  - RD48 collaboration
- FLUKA simulations to extrapolate radiation damage experiments results
- Assumption: bulk damage dominated by non-ionizing energy loss (NIEL)

T506 leakage after 270Mrad exposure

- 600 V bias
- After several annealing steps



[Schumm and Smithers, https://doi.org/10.1016/j.nima.2018.08.024]

BeamCal simulation in FLUKA

$e^+ e^-$ | Neutrons

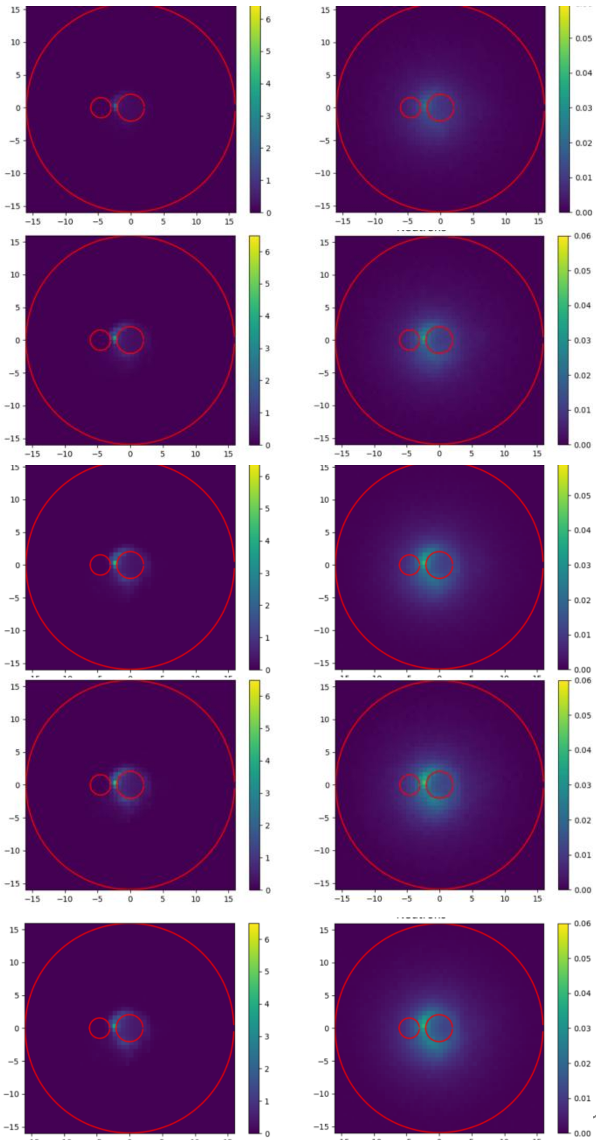
Layer 2

Layer 4

Layer 6

Layer 8

Layer 10



Radiation damage studies results

- Under the **conservative assumption** that leakage in BeamCal is mostly due to **neutron radiation damage**, power draw accumulation for operation at -10^{o}C is less that 100 W per year of operation
- Si sensors are feasible at BeamCal, but cooling is necessary to limit leakage current
- Charged particle TID (2.5krad/year) at the front-end location (BeamCal periphery) is not a concern for the electronics

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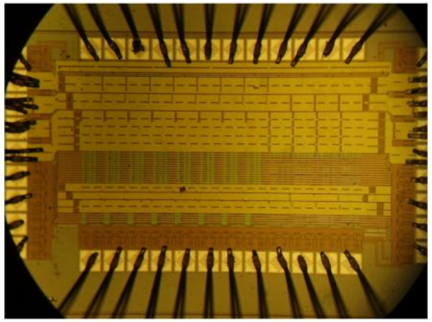
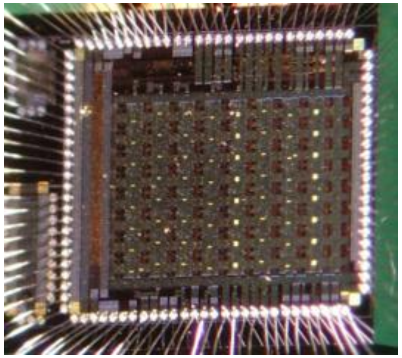
Prior art:
FCAL-related ASICs overview

350 nm CMOS



https://doi.org/10.1016/j.nima.2009.06.059

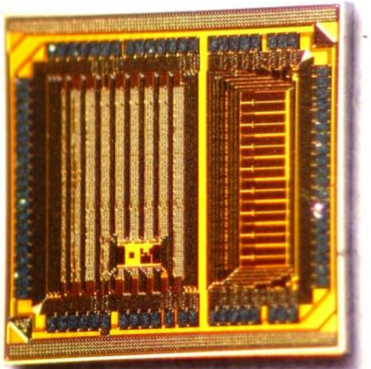
350 nm CMOS



JINST, 6 P01004, 2011

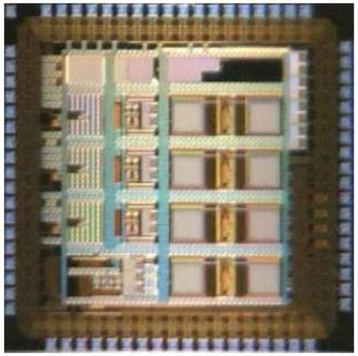
High speed,
Low power

130 nm CMOS



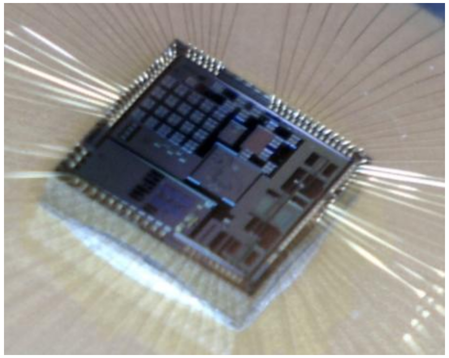
doi:10.1088/1748-0221/10/11/P11012

180 nm CMOS



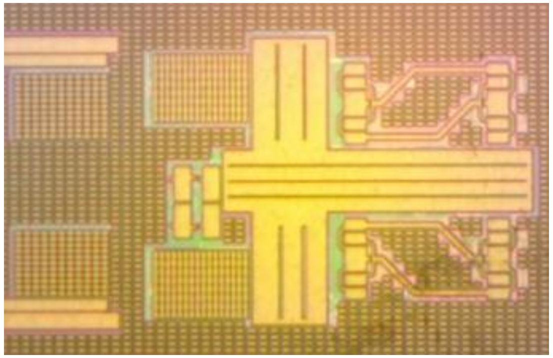
DOI: 10.1109/TNS.2012.2194308

180 nm CMOS



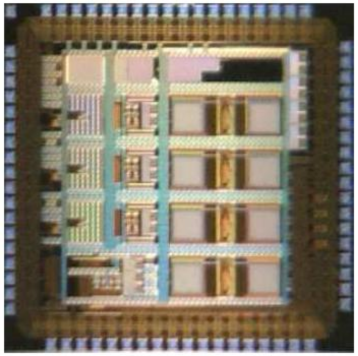
DOI: 10.1016/j.mejo.2015.06.005

180 nm CMOS

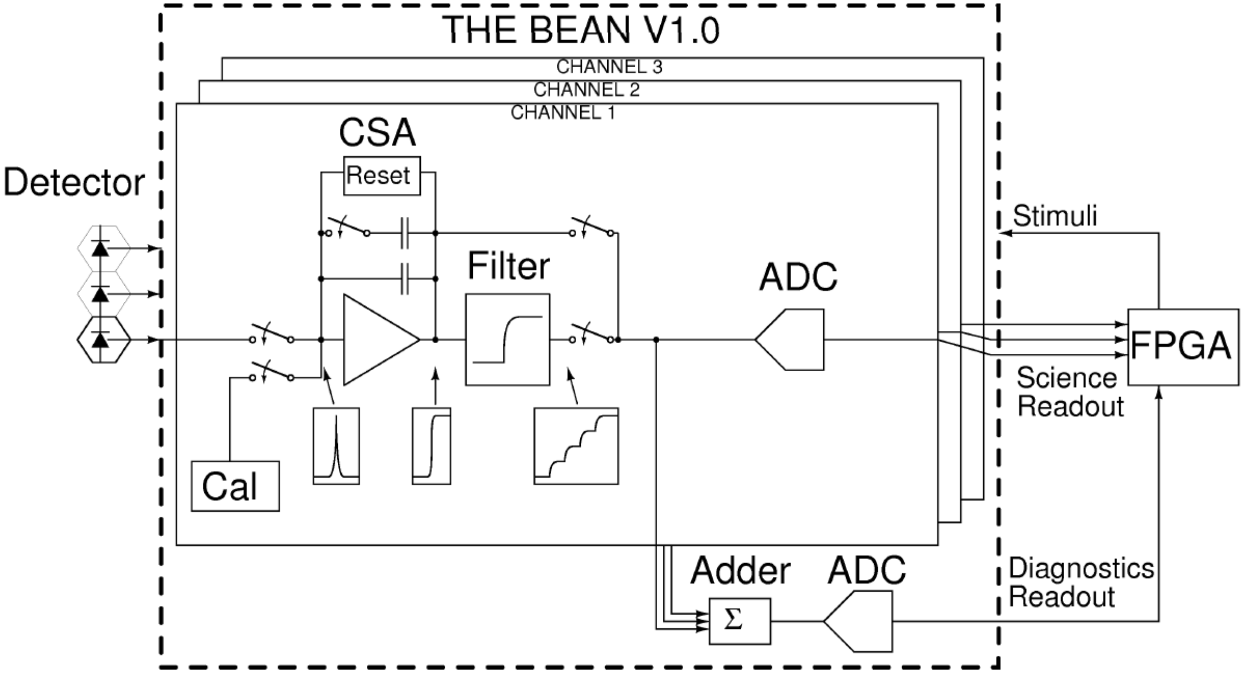


Why do we need a **dedicated readout** for our luminometers?

Bean V1 and fast readout



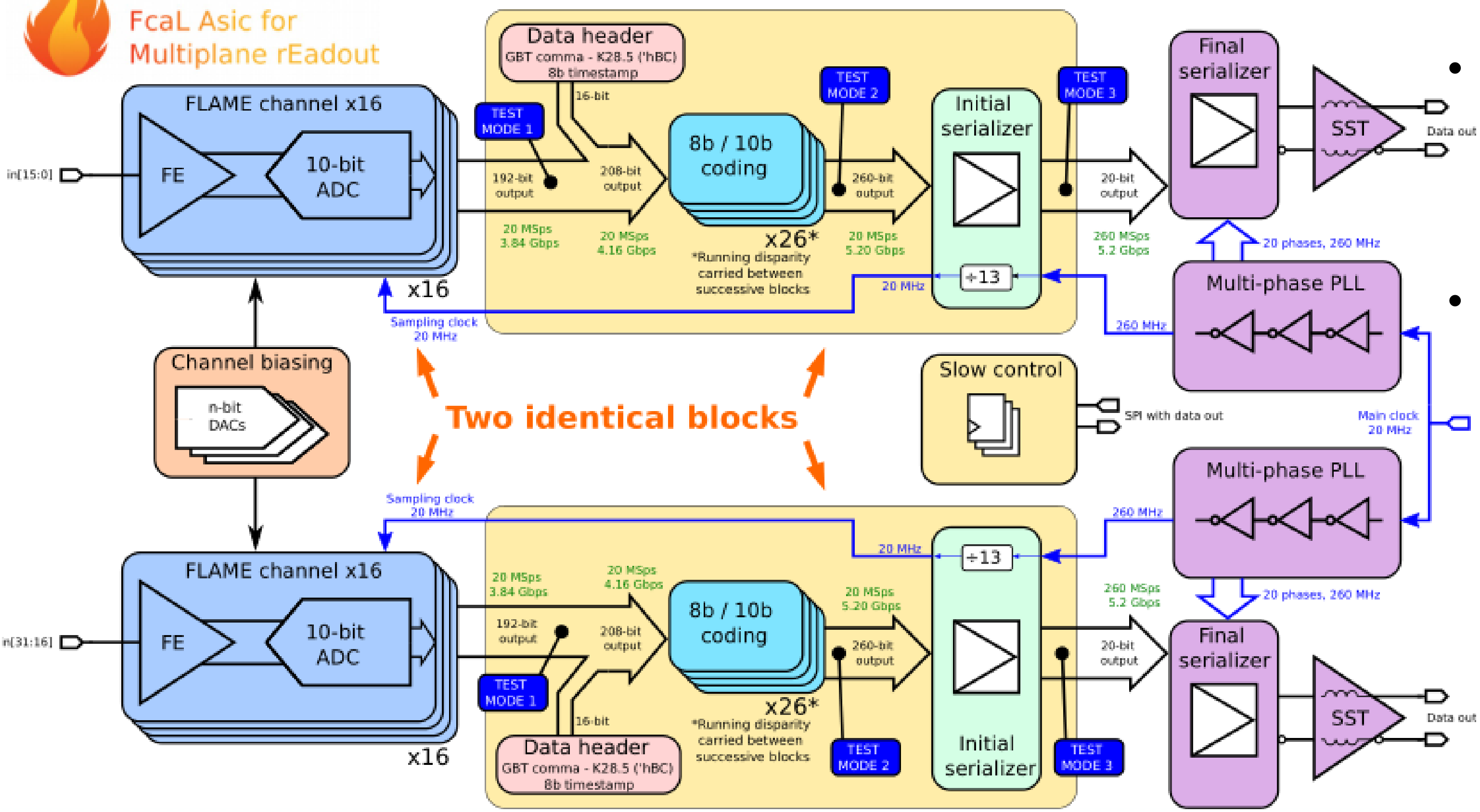
DOI: 10.1109/TNS.2012.2194308



Recent development

FLAME
FcaL Asic for Multiplane rEadout

- Two complete 16-channel blocks in one padring to save the PCB area and maximize the instrumented sensor area. CMOS 130 nm process.

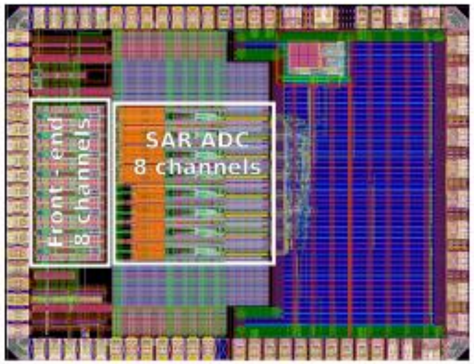


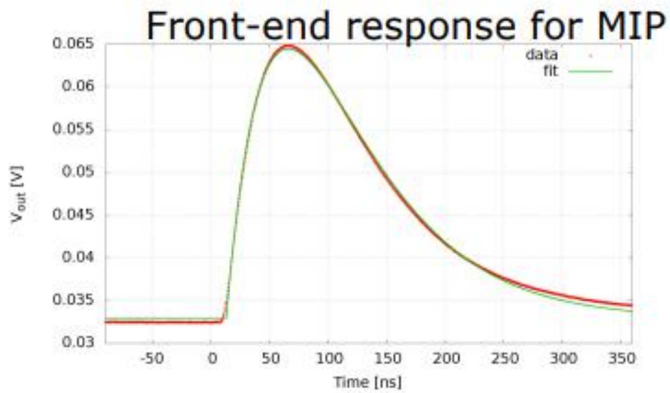
- For **very compact calorimeter** we need an **ultra low-power** SoC
- FLAME: 2x16-channel readout ASIC in 130nm CMOS, includes FE & ADC, fast SER and Data Tx

[Status of FLAME development, Moron et al, 33rd FCAL WS 2018]

FLAME and Serializer ASIC

- **Prototype 8-channel FE+ADC ASIC**



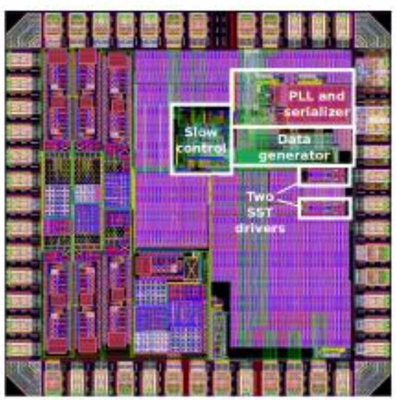


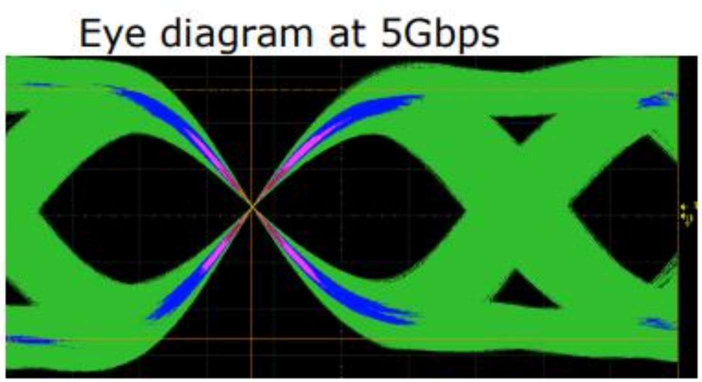
130-nm CMOS process

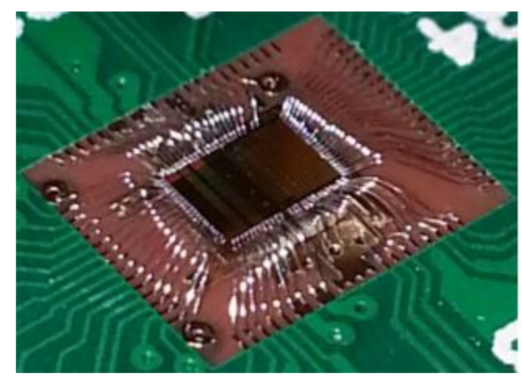
First tests performed

- PCB produced
- Front-end: **OK**
- ADC: **OK**
- Serializer: **OK**

- **Prototype serializer ASIC**

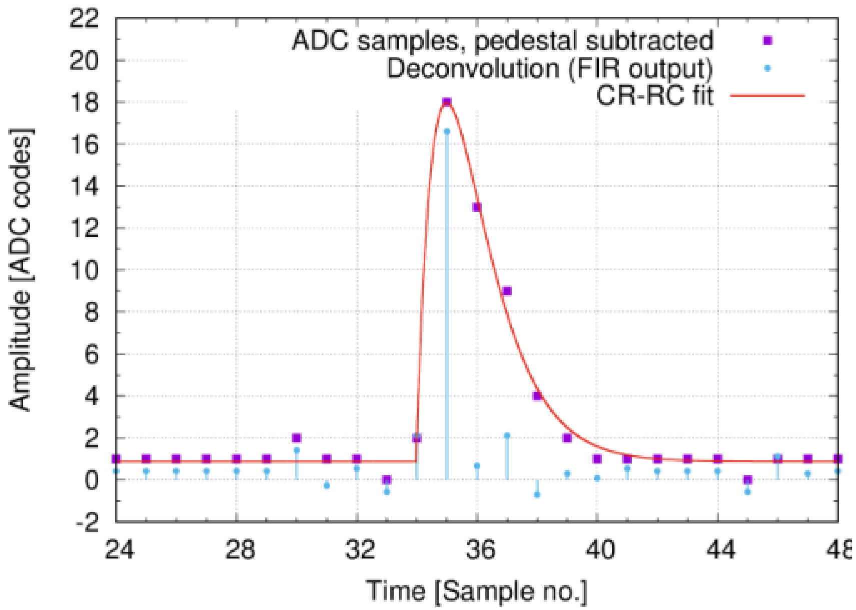


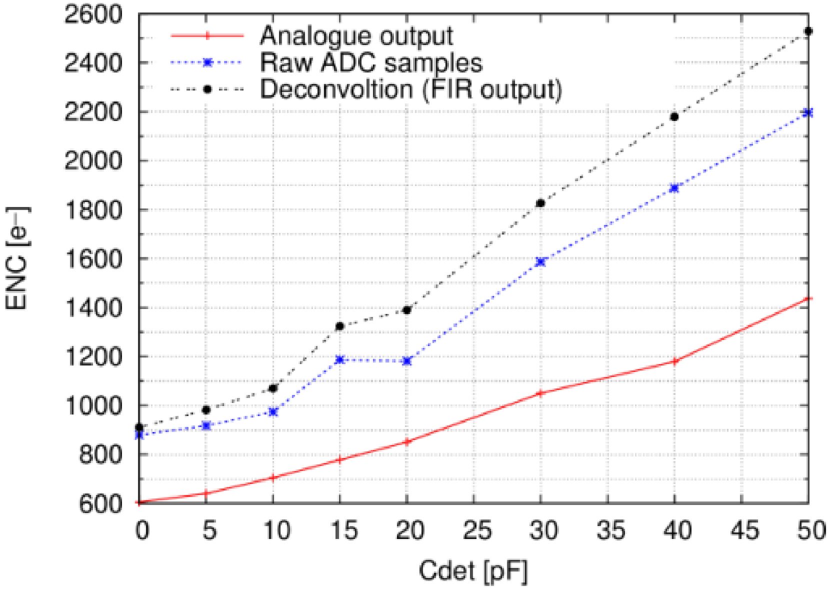




[LumiCal Readout, M. Idzik, 31^{st} FCAL WS 2017]

FLAME preliminary results





- Amplitudes from FE+ADC reconstructed by deconvolution (3-sample FIRfilter) for 1 MIP input signal at 20 MSps sampling rate
- Noise levels for Gain 0 as a function of detector capacitance as expected

Concluding remarks

- **Two luminosity concepts** presented
  - **Precise** estimation from Bhabha scattering
  - **Fast** estimation from Beamstrahlung pairs
- Current development includes
  - ASICs
  - Thin sensor planes
- Radiation damage studies provide important data
  - Si sensors are not ruled out for BeamCal
  - Radiation damage at BeamCal periphery (electronics) is not a concern
- Testbeam experiments show promising results
  - Verified functionality of existing setup
  - Performance of EM shower reconstruction is in agreement with MC simulations

Major components for a luminometer to be used at a future experiment at CLIC or ILC, developed by the FCAL collaboration, can be operated as a system.

THANKS FOR YOUR ATTENTION