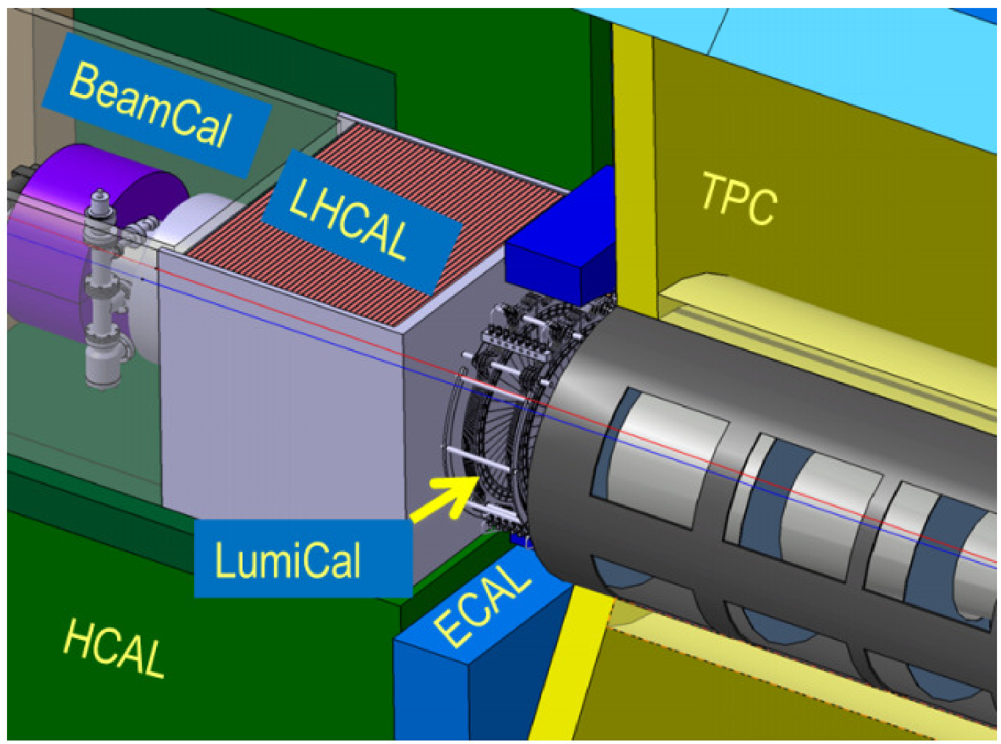
Luminometers for future e^+e^- collider experiments

Angel Abusleme*
On behalf of the FCAL collaboration

7th International Conference on High Energy Physics in the LHC Era, **HEP 2018**
January 8-12, 2018, UTFSM, Valparaíso, Chile

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



What’s all this “**collider luminosity**” stuff, anyhow?

- 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}

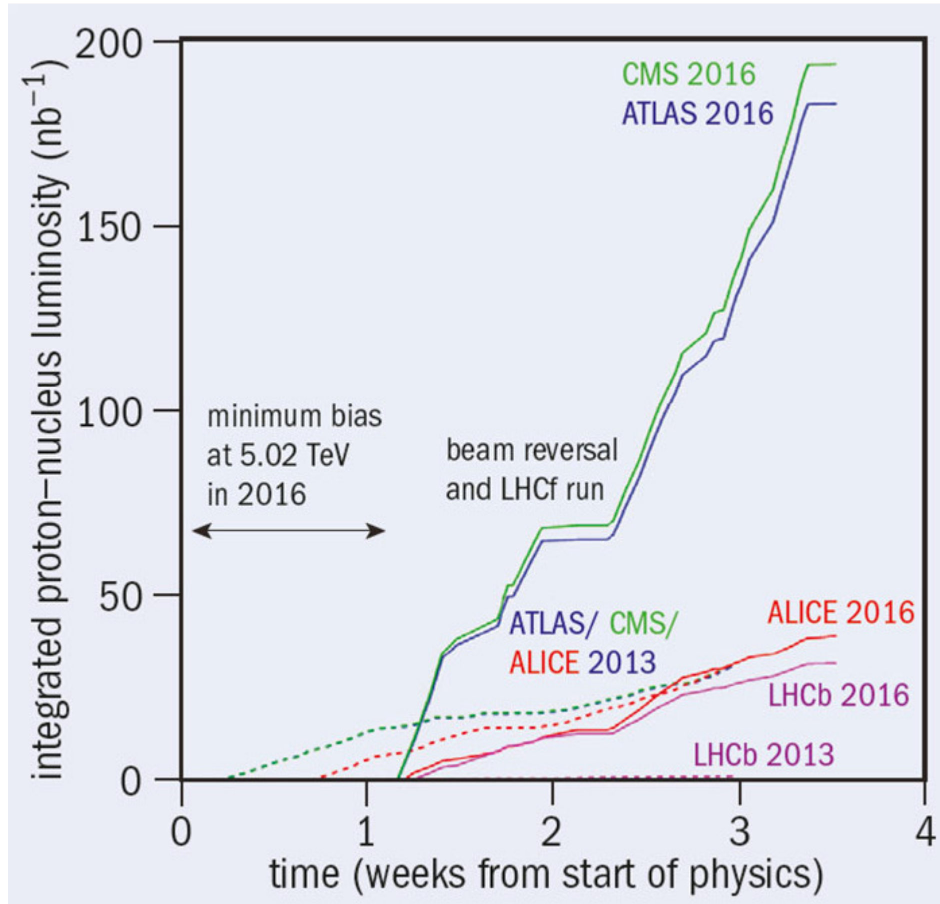
- Luminosity is a **machine parameter** related to the **beam features** such as size and intensity
  - Luminosity is **process-independent**
  - Can be **inferred** from measured event rate and its known event cross section
  - Need a **well understood and measurable process**
- **Integrated luminosity**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

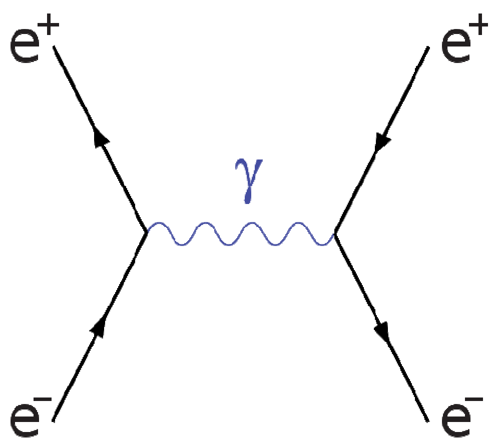
So what's next?

- Luminosity measurements
- LumiCal and BeamCal design
- Recent testsbeam results
- Thin detector planes development
- ASIC development

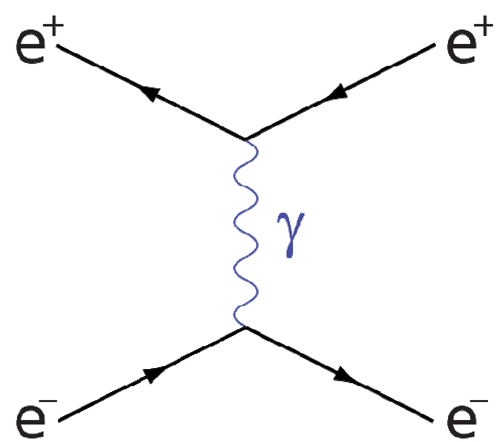
Precision luminometry in $e^+ e^-$ colliders

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

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



annihilation



scattering

How precise?

- Required precision: 10^{-3} for initial design, 10^{-2} for scaled design
- 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

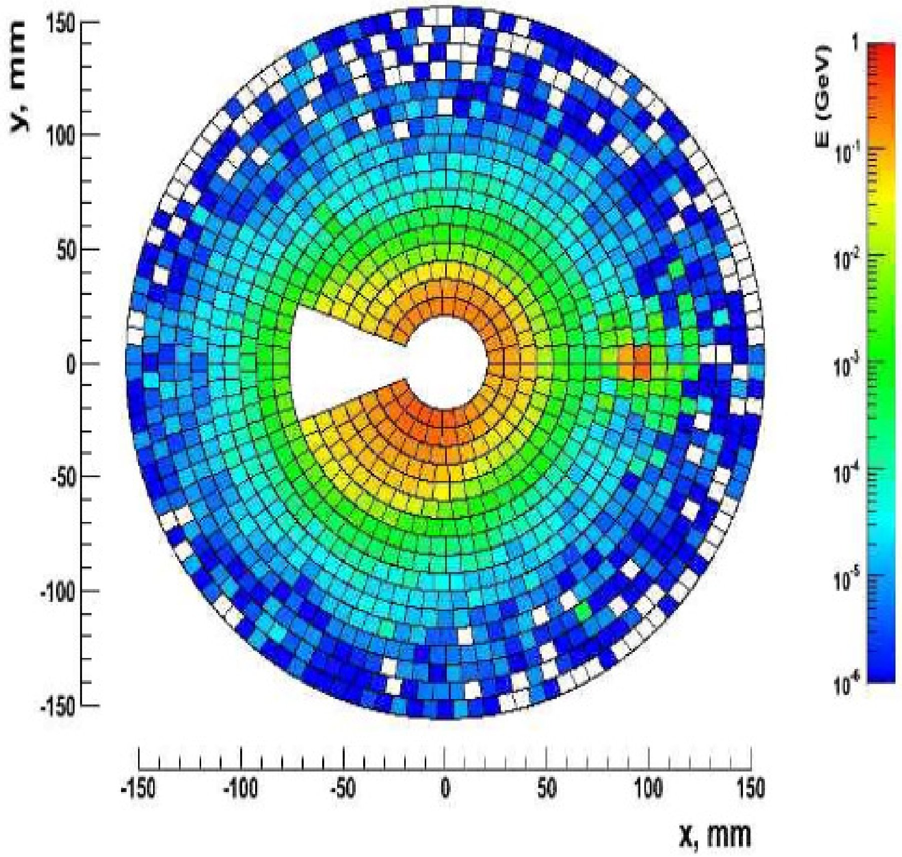
- Then the luminosity can be estimated:

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

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



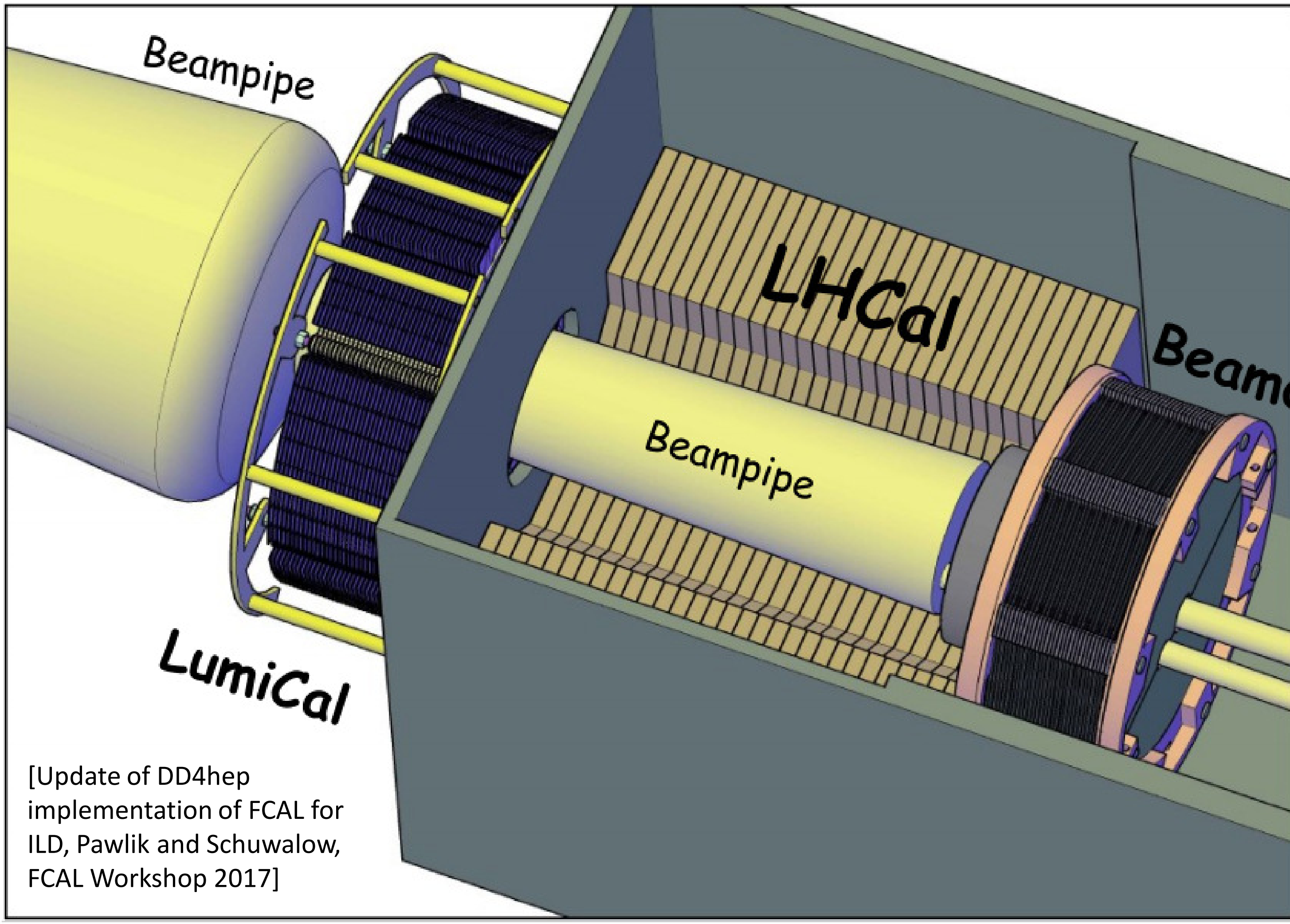
Distribution of the energy deposited by beamstrahlung pairs after one bunch crossing in a the sensor covering small angle

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



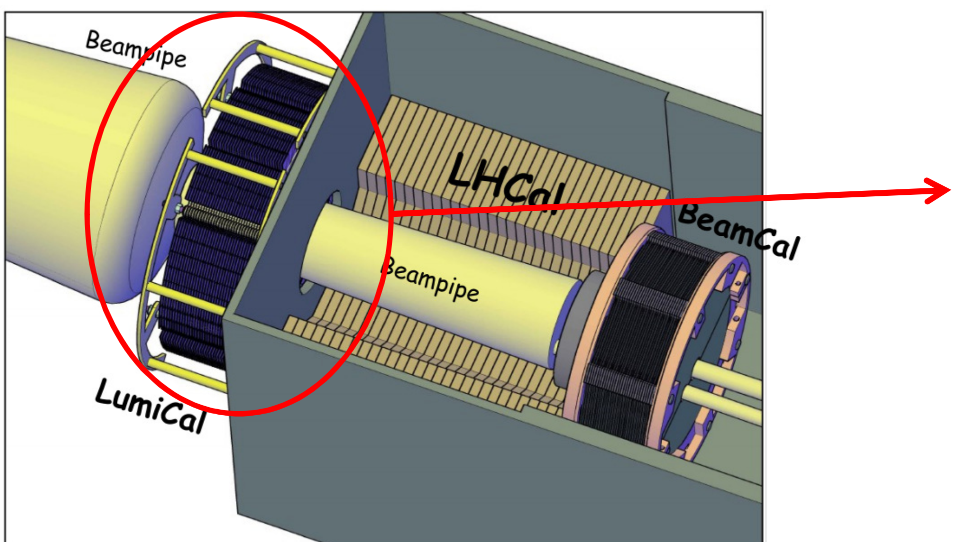
[Update of DD4hep implementation of FCAL for ILD, Pawlik and Schuwalow, FCAL Workshop 2017]

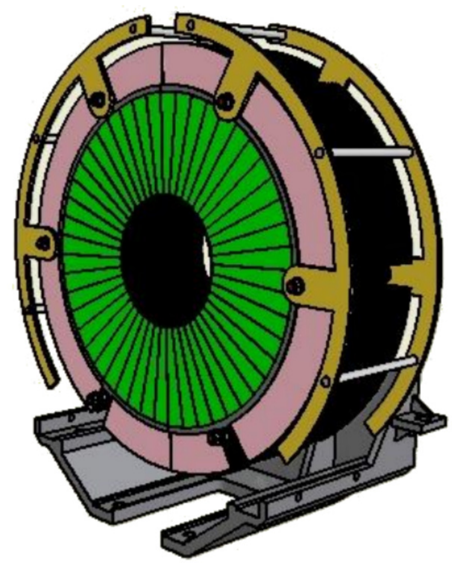
So what’s next?

- Luminosity measurements
- LumiCal and BeamCal design
- Recent testsbeam results
- Thin detector planes development
- ASIC development

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

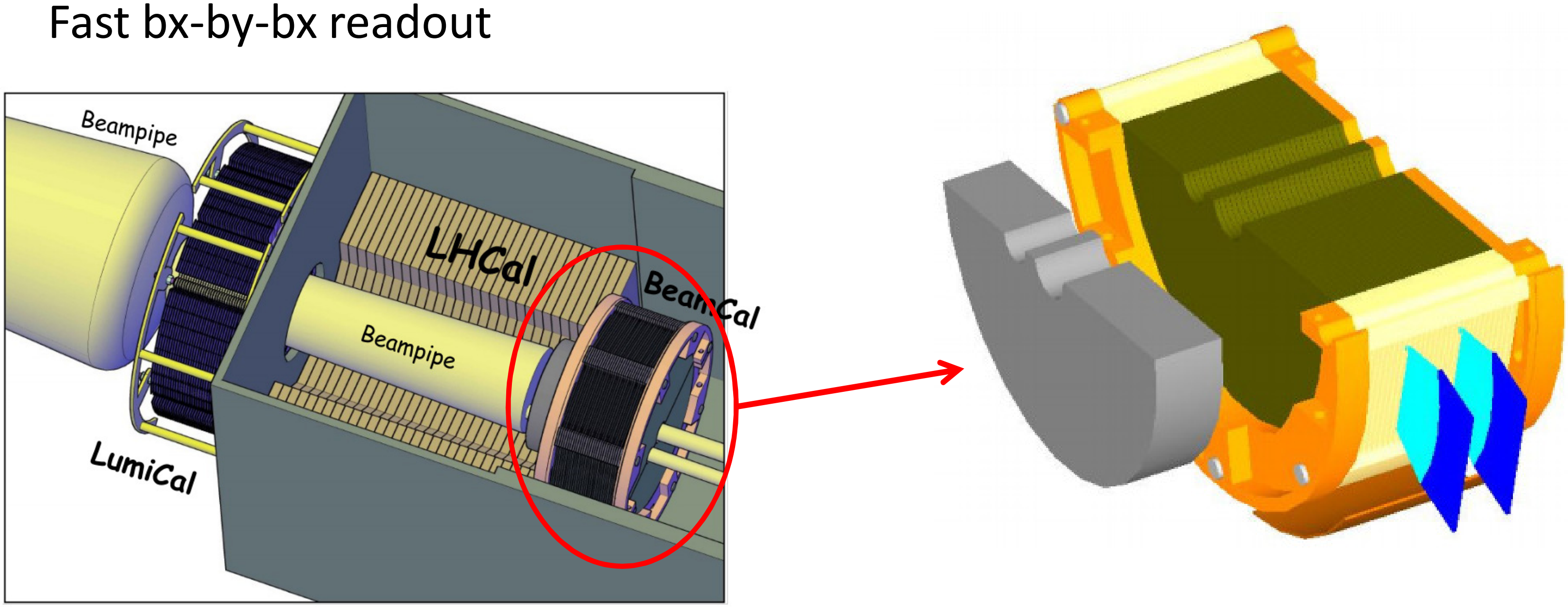




http://inspirehep.net/record/1386724/files/v46p1297.pdf

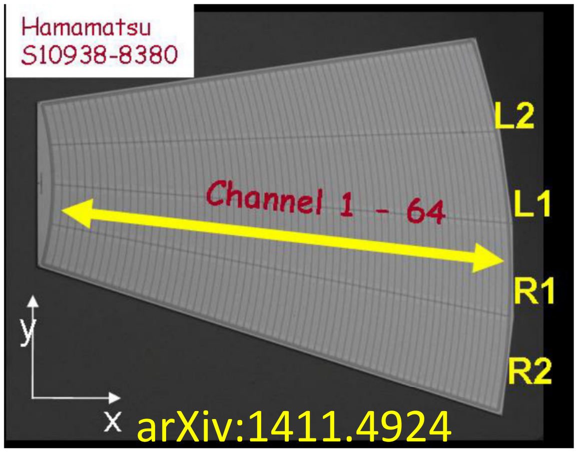
BeamCal design

- Sampling **?**-W calorimeter
  - Thorough research on Sapphire, CVD diamond and GaAs 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

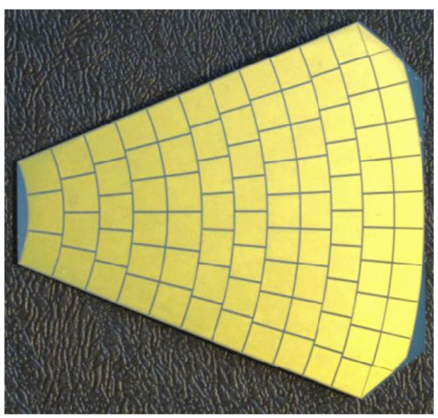


FCAL sensor planes

LumiCal sensor plane sector

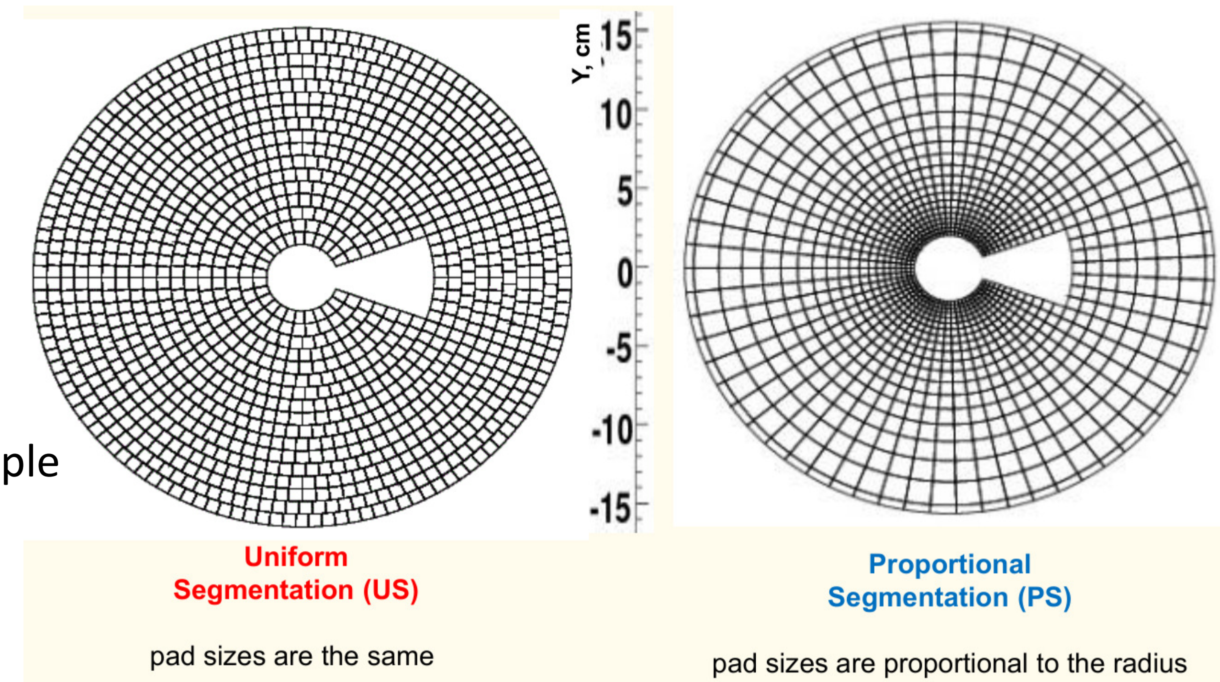


BeamCal sensor plane sector example



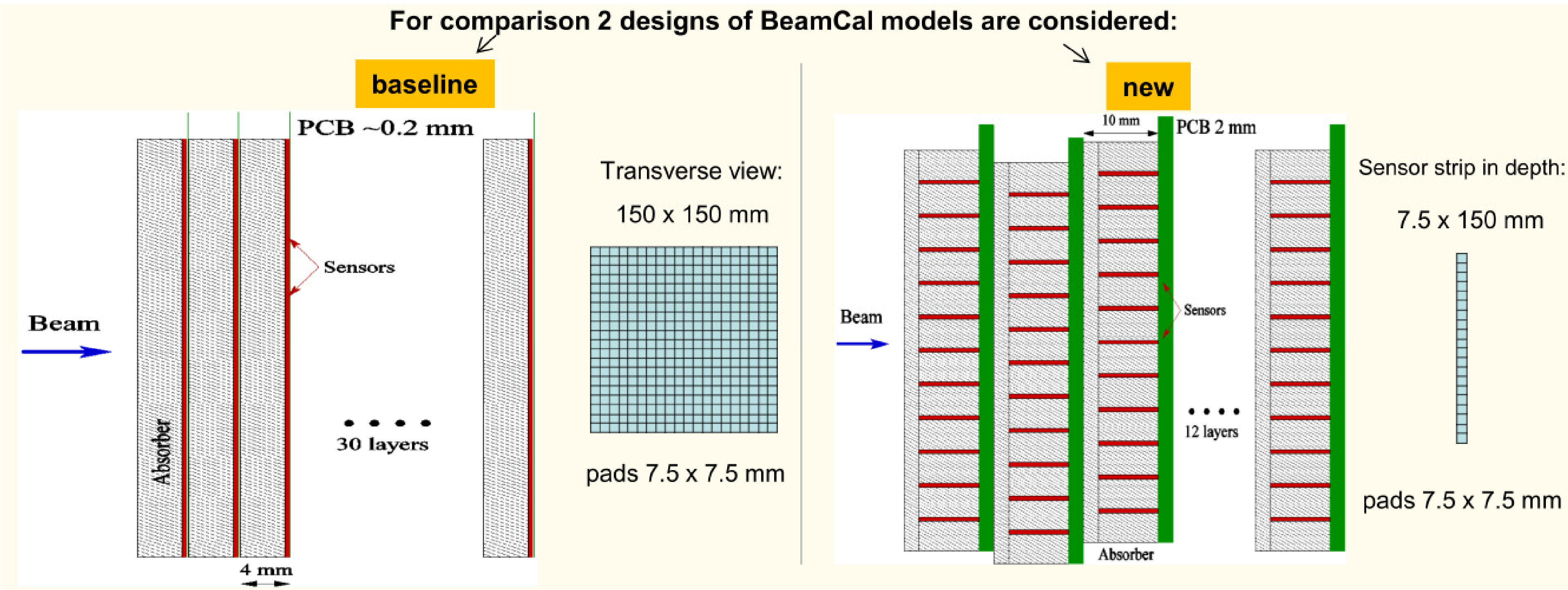
arXiv:1411.4924v2

BeamCal segmentation options



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

BeamCal sensor planes – Sapphire option



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

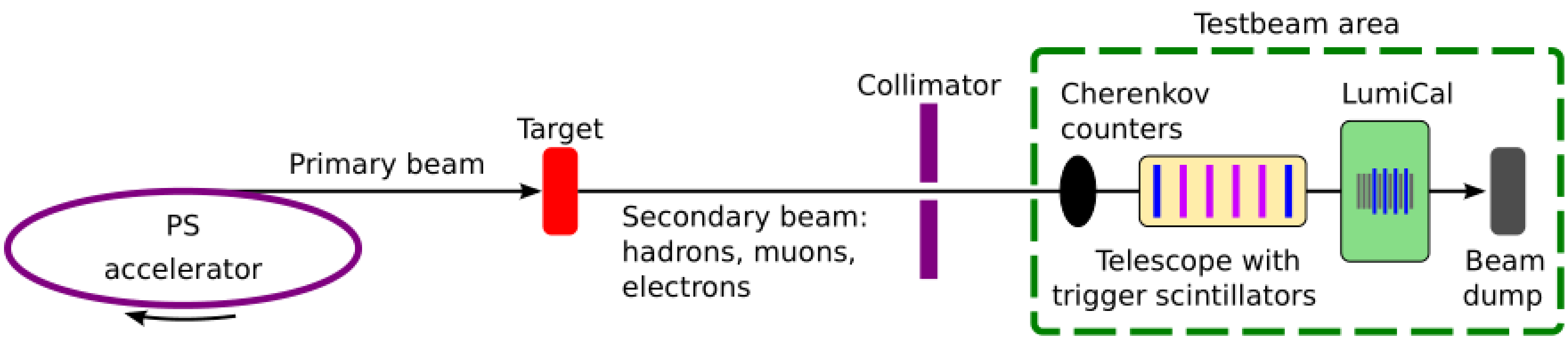
- Sapphire is cheap and less sensitive to radiation; smaller signals
- New design is more sensitive to MIPs, less DR required
- Non-standard assembly procedure

So what’s next?

- Luminosity measurements
- LumiCal and BeamCal design
- Recent testsbeam results
- Thin detector planes development
- ASIC development

CERN PS accelerator, T9 beam 2014

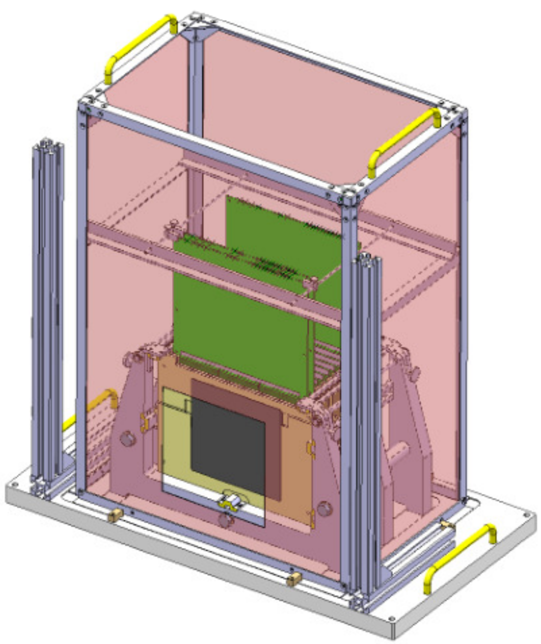
- Beam parameters:
  - Particles (mainly e^- and μ) with ~5GeV energy
  - 400ms spills every 33.6s
- Objectives:
  - Demonstrate multiplane W-Si operation
  - Study EM shower and estimate Molière radius

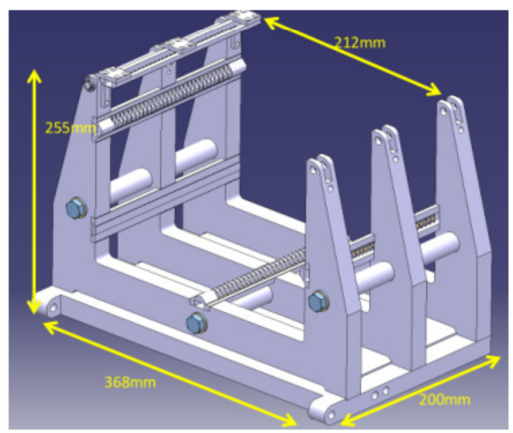


[*Measurement of shower development and its Molière radius with a four-plane LumiCal test set-up*, submitted to the Eur. Phys. J. C]

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

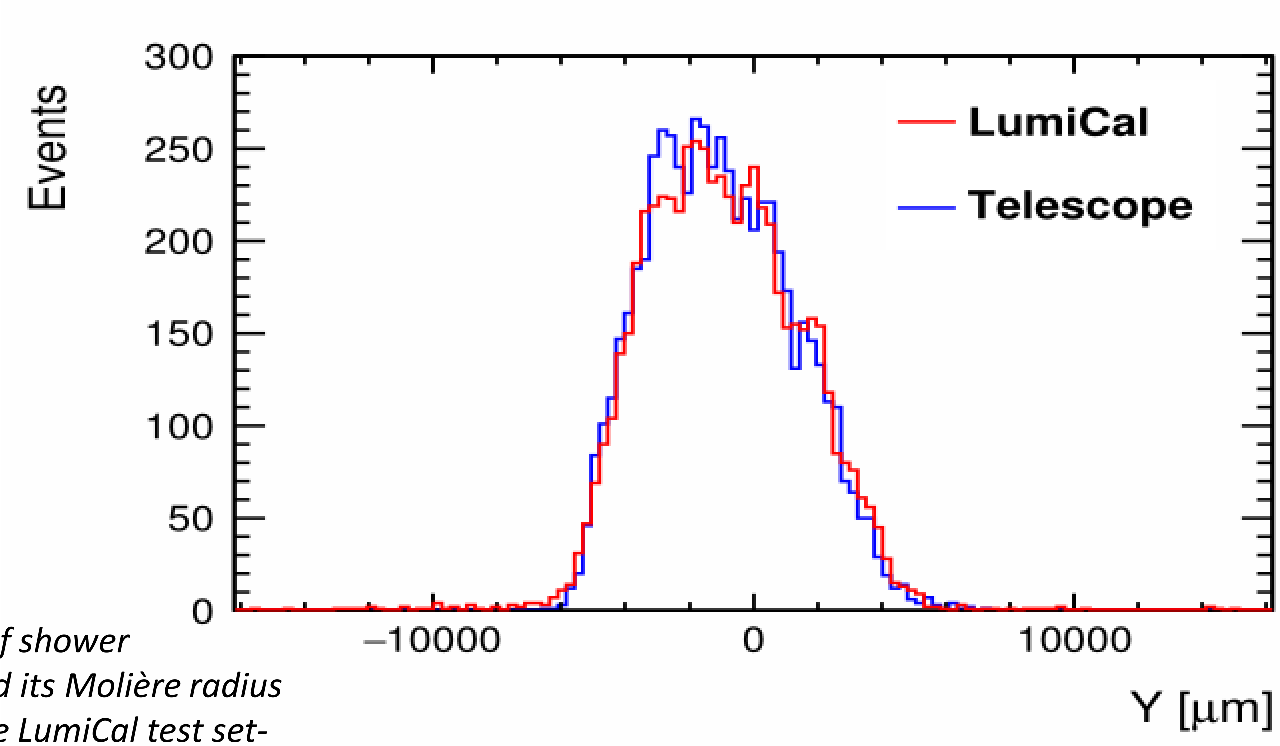




[*Measurement of shower development and its Molière radius with a four-plane LumiCal test set-up*, submitted to the Eur. Phys. J. C]

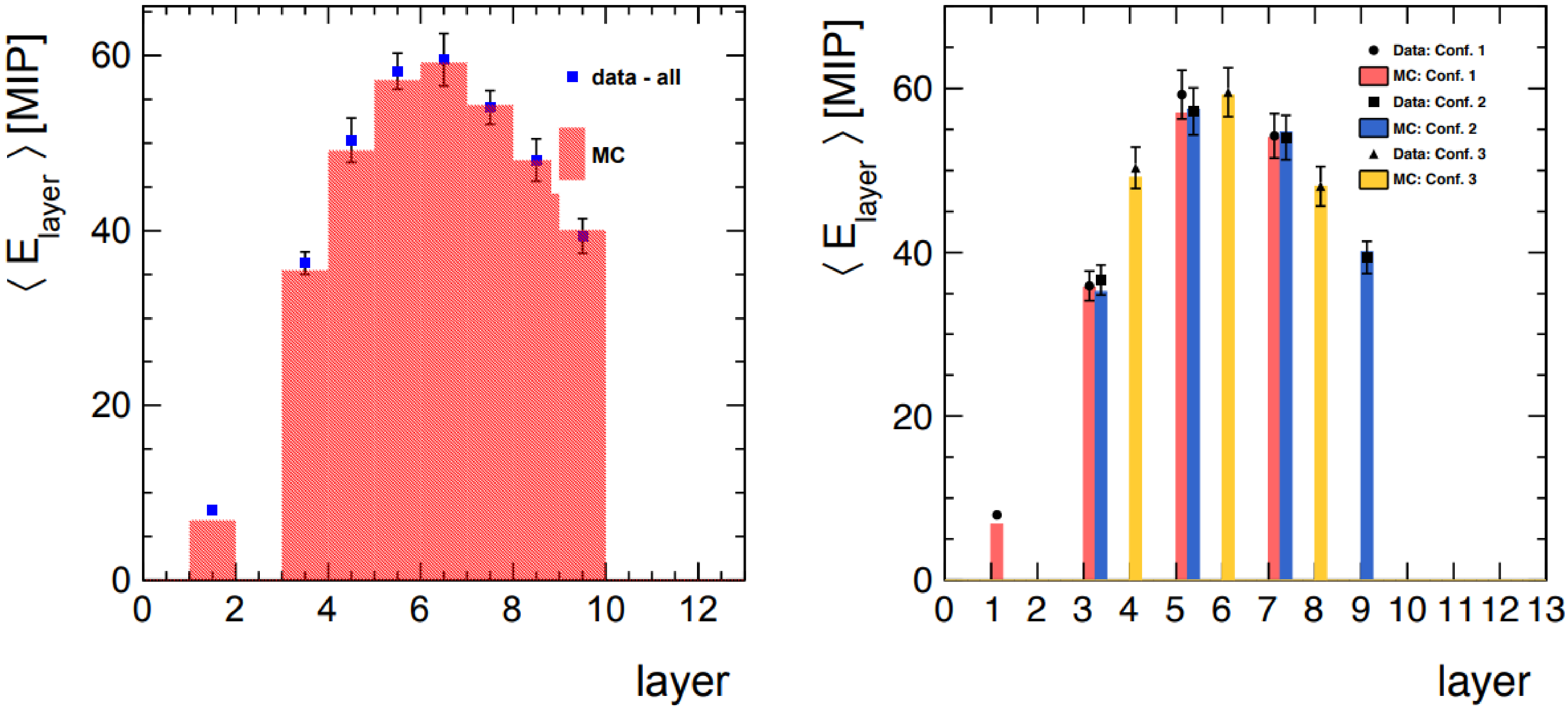
Results: distribution of radial shower position

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]

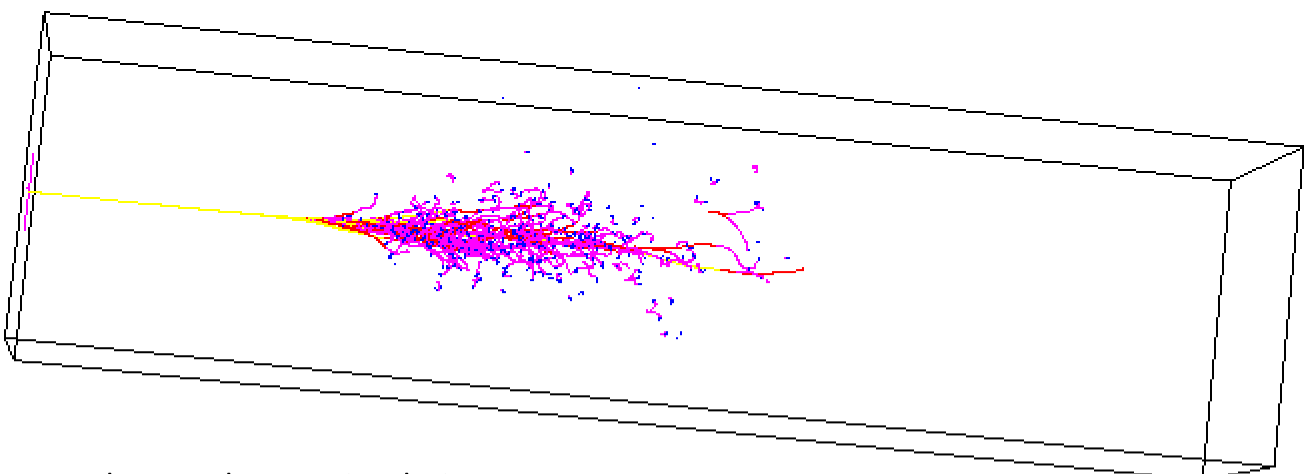
Results: Energy per layer



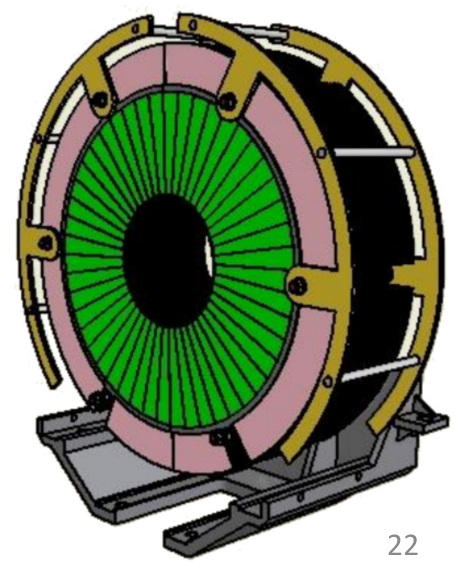
arXiv:1705.03885

What's all this "**Molière radius**" stuff, anyhow?

- 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



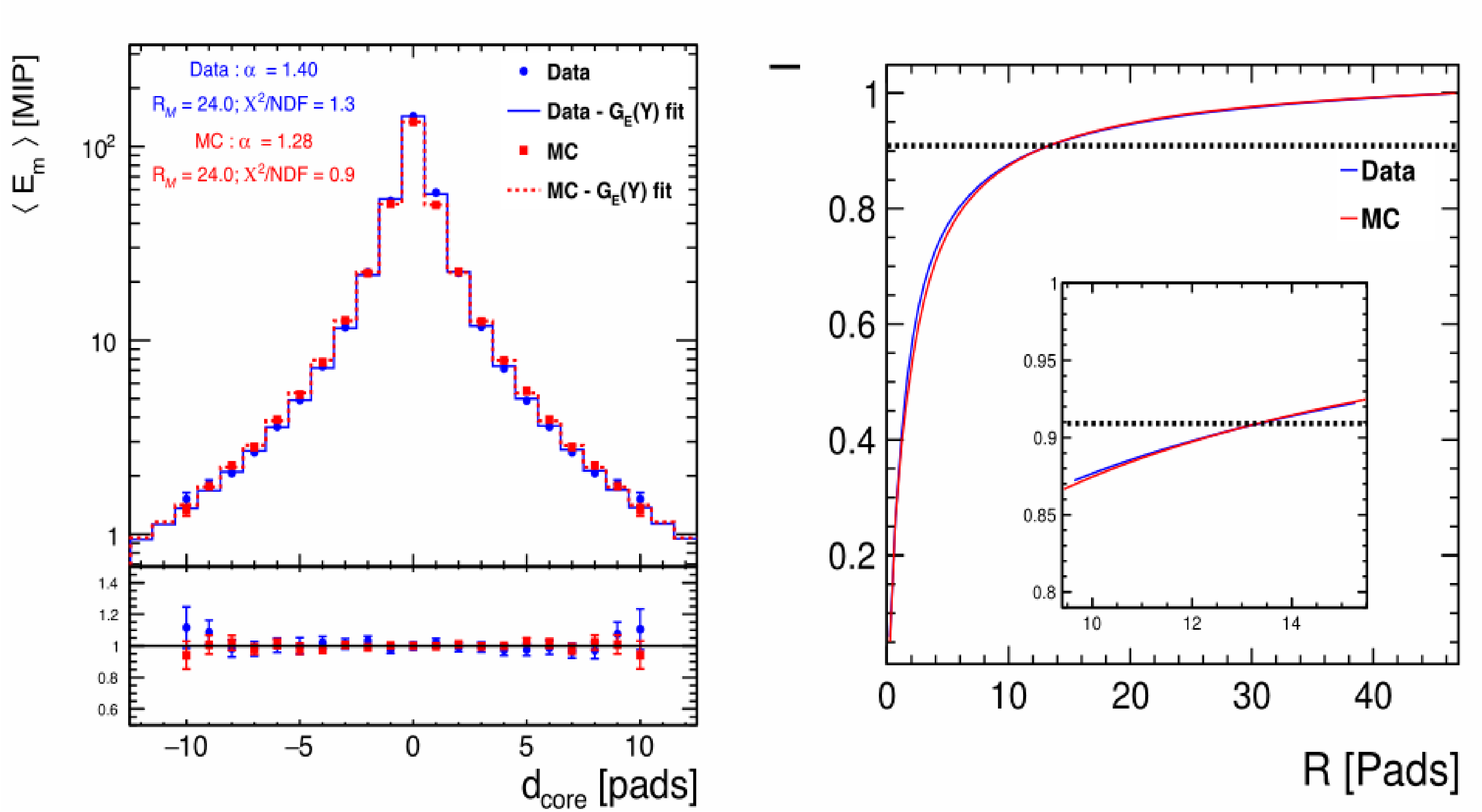
Example: EM shower simulation, 10GeV e^- on opal, https://goo.gl/Vb38eZ



Molière radius results

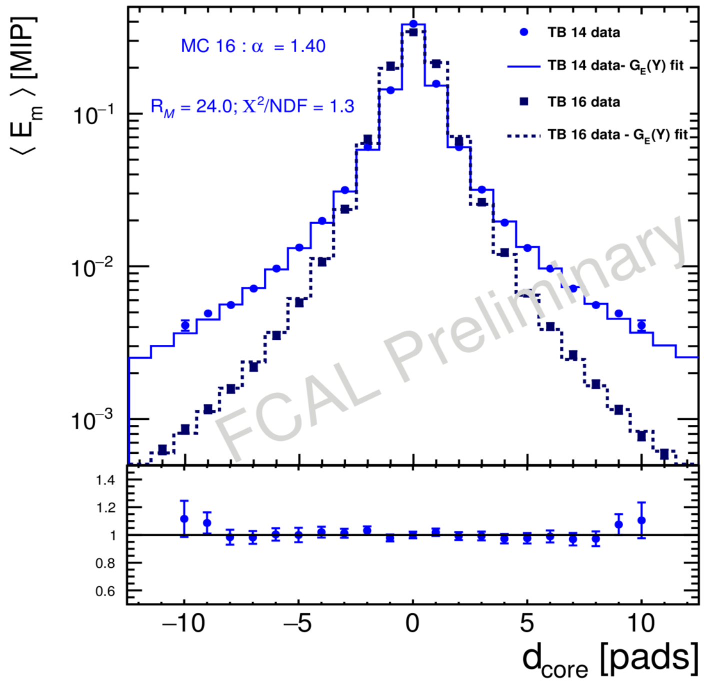
$R_M = 24.0 \pm 0.6(\text{stat.}) \pm 1.5(\text{syst.})$ [mm]

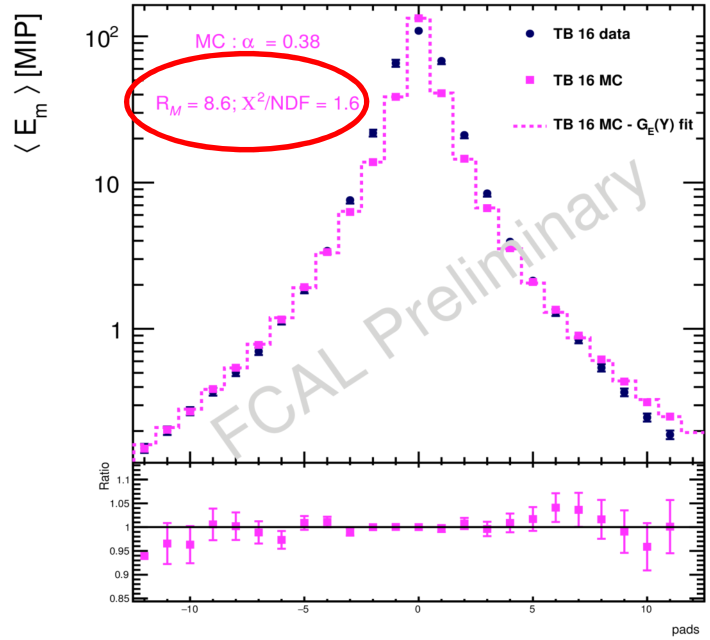
Air gaps in detector assembly explain the results

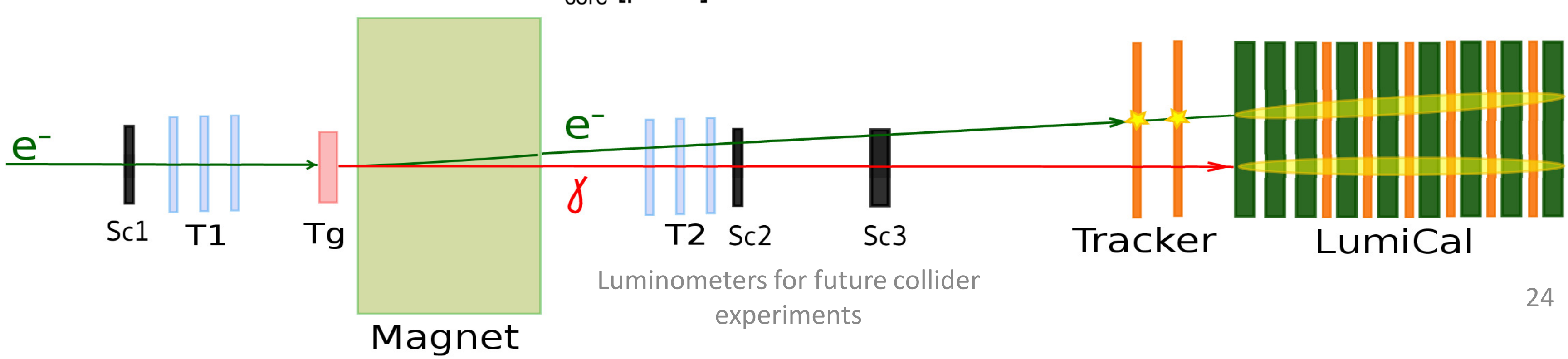


Molière radius results, TB2016

Comparison of transverse shower in TB2016 with TB2014



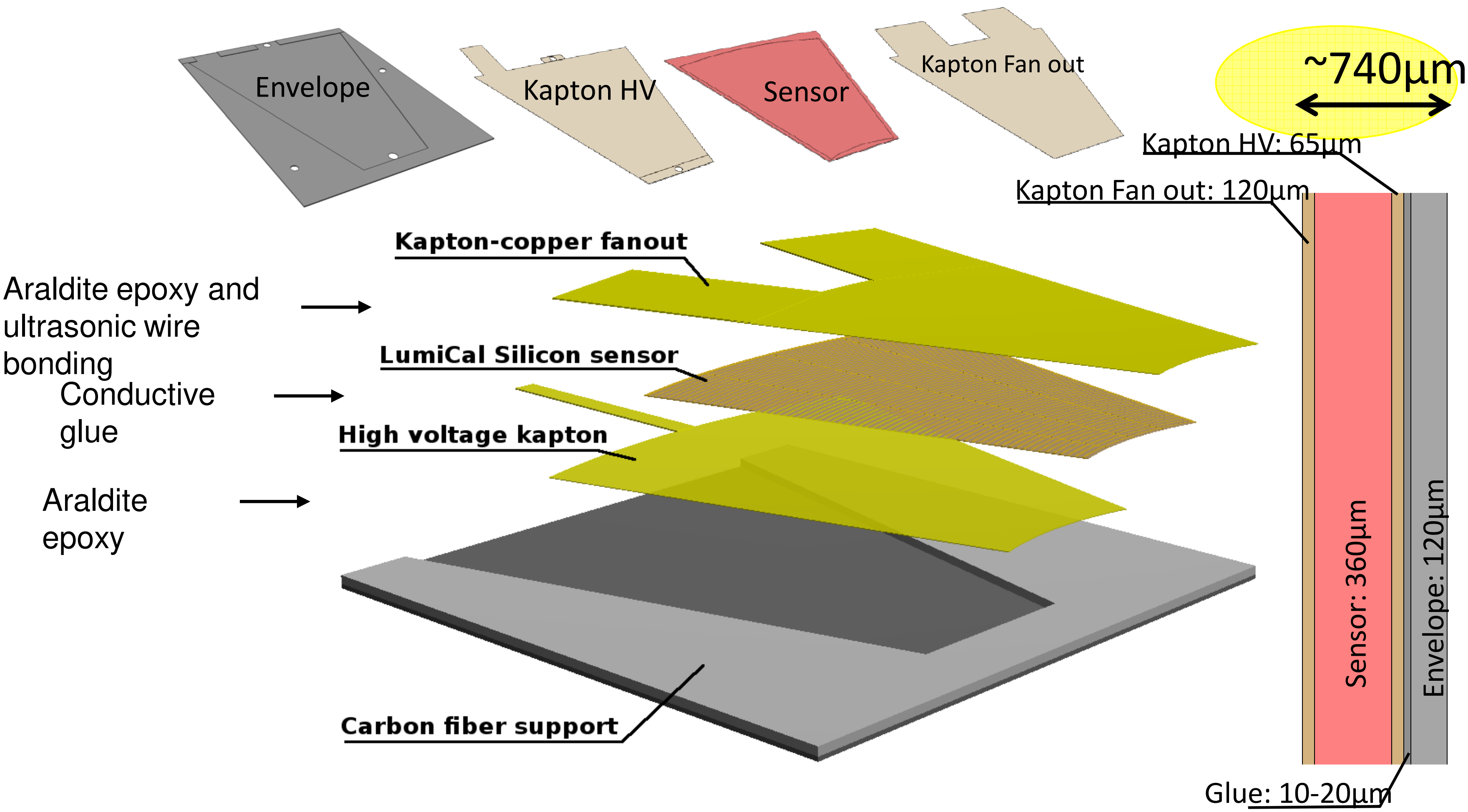




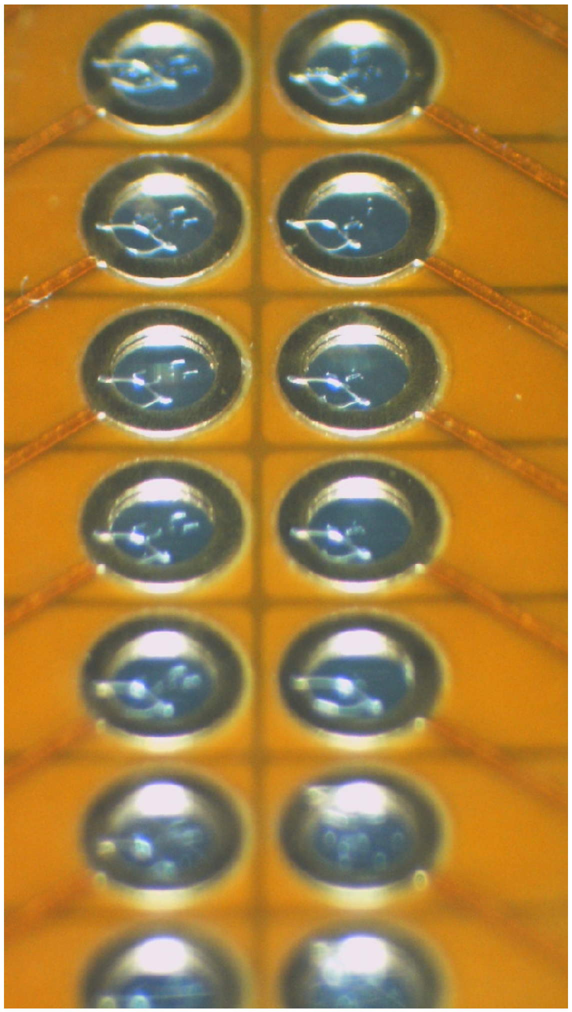
So what’s next?

- Luminosity measurements
- LumiCal and BeamCal design
- Recent testsbeam results
- Thin detector planes development
- ASIC development

Design of the **thin** Lumical module

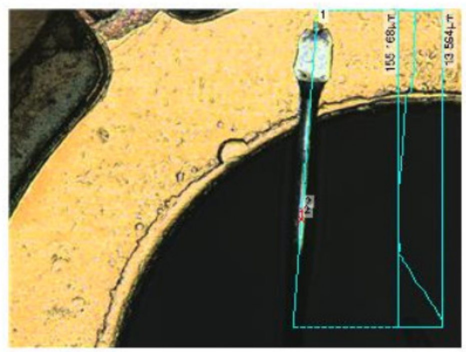


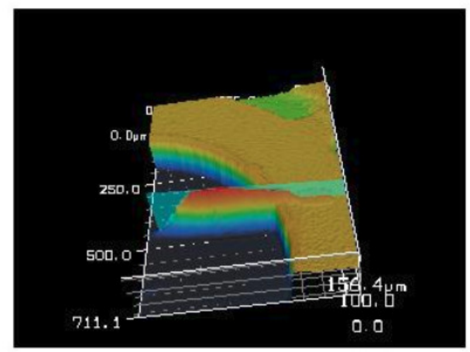
Wedge wire-bonding for FE contact

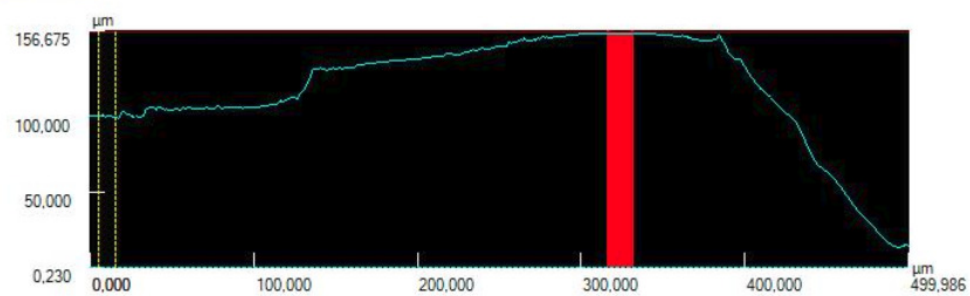


Achievable size of the bonding loops is in the range 50 μm - 100μm.

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

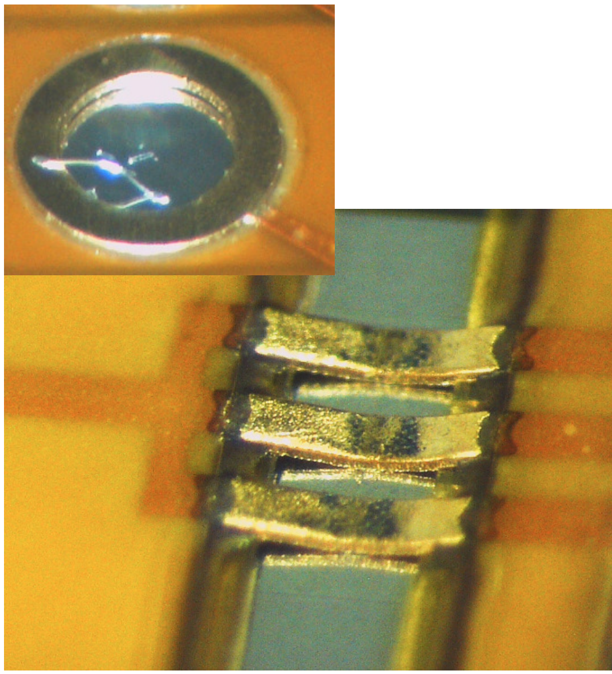


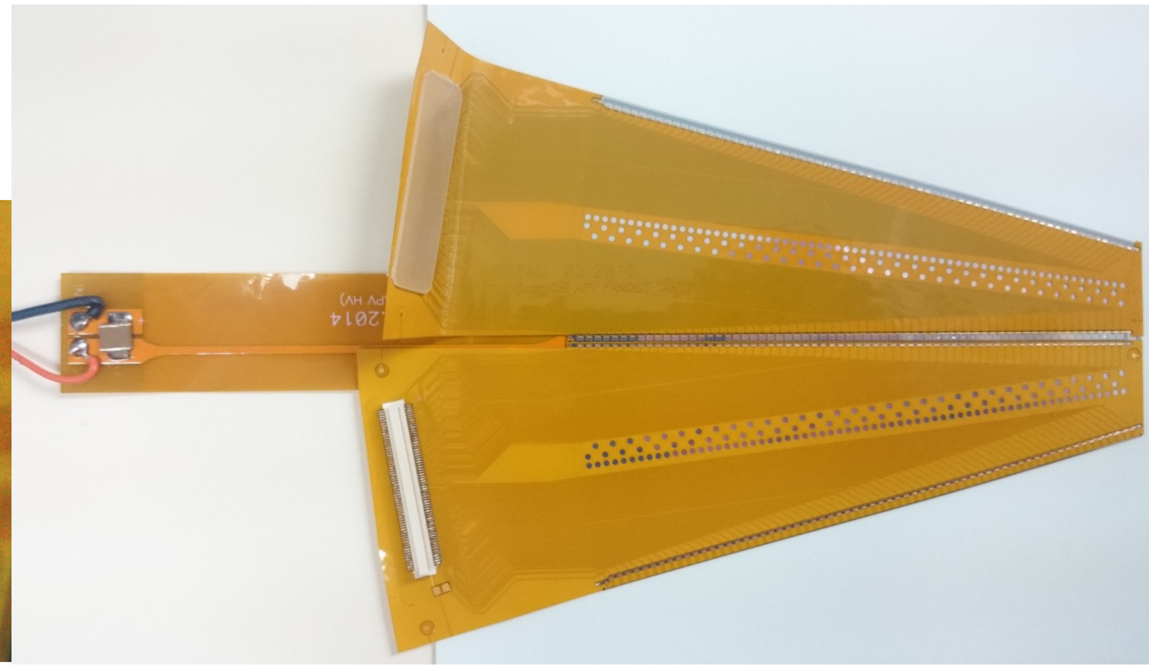




TAB technology for FE contact

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





Single point Tape Automated Bonding (TAB):

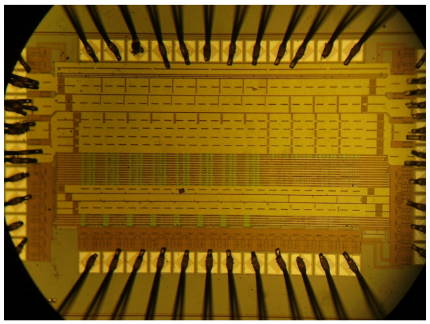
- No wire loop, the bond can be covered by the glue for better protection;
- One LumiCal module is assembled and tested using TAB technology.

So what's next?

- Luminosity measurements
- LumiCal and BeamCal design
- Recent testsbeam results
- Thin detector planes development
- ASIC development

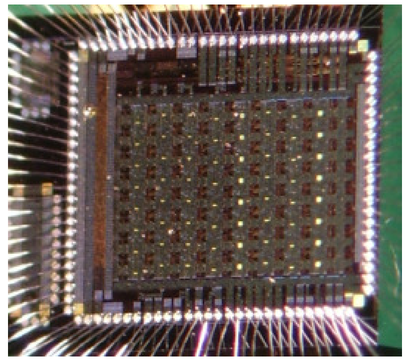
Prior art:
FCAL-related ASICs overview

350 nm CMOS



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

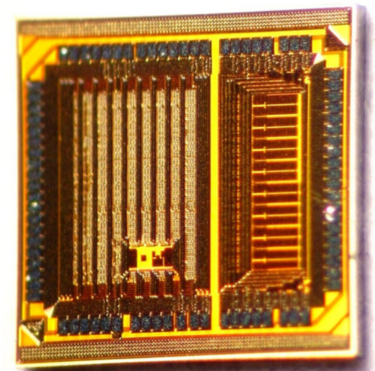
350 nm CMOS



JINST, 6 P01004, 2011

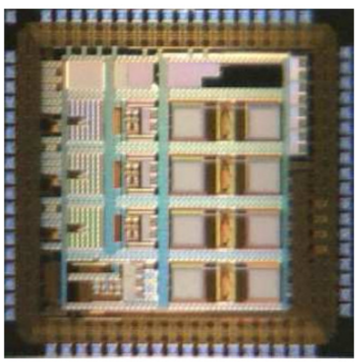
High speed,
Low power

130 nm CMOS



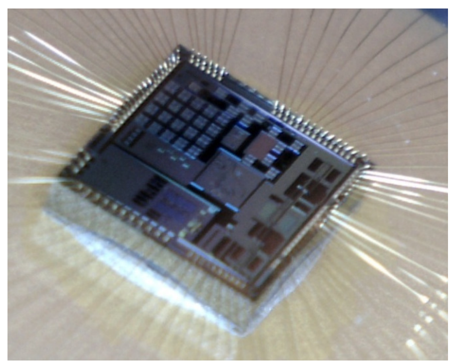
doi:10.1088/1748-0221/10/11/P11012

180 nm CMOS



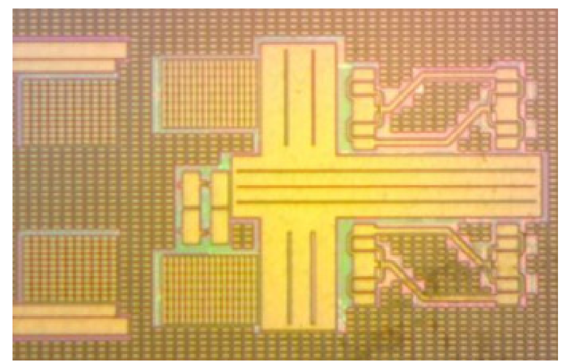
DOI: 10.1109/TNS.2012.2194308

180 nm CMOS



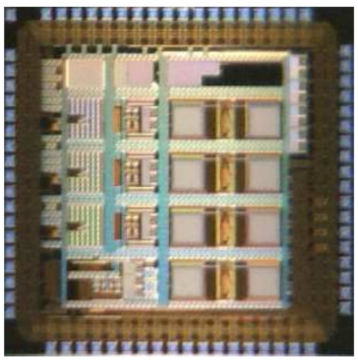
DOI: 10.1016/j.mejo.2015.06.005

180 nm CMOS

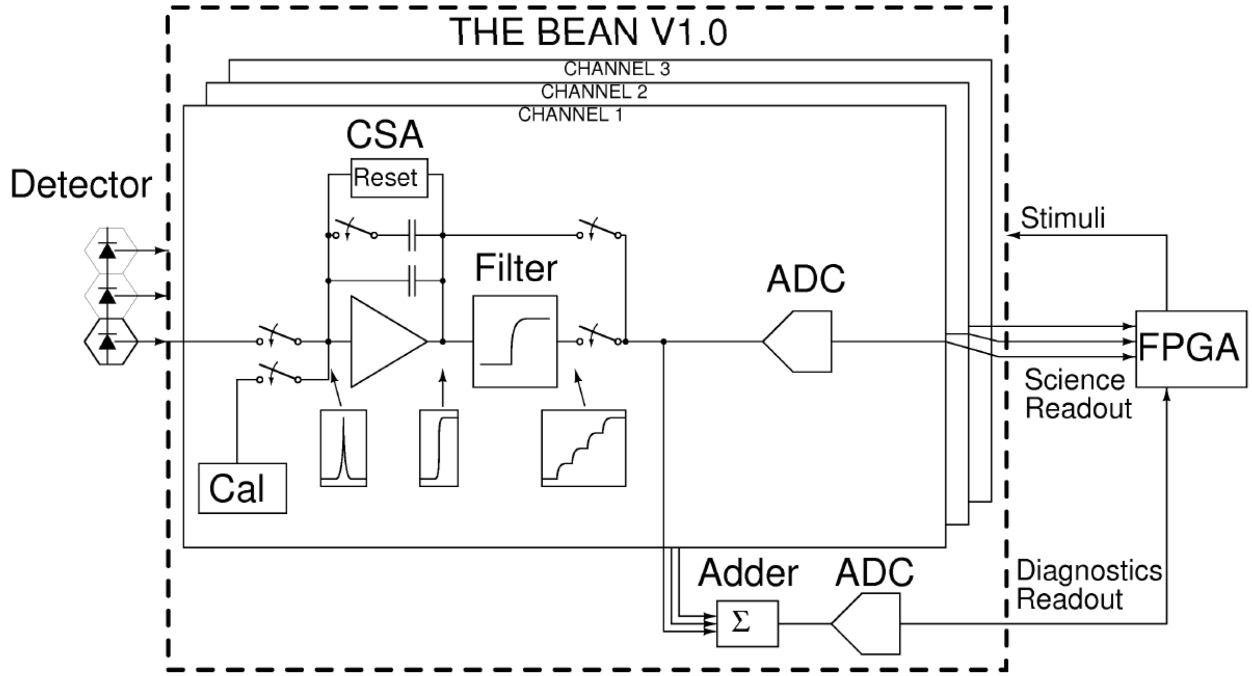


Why do we need a **dedicated readout** for our luminometers?

Bean V1 and fast readout

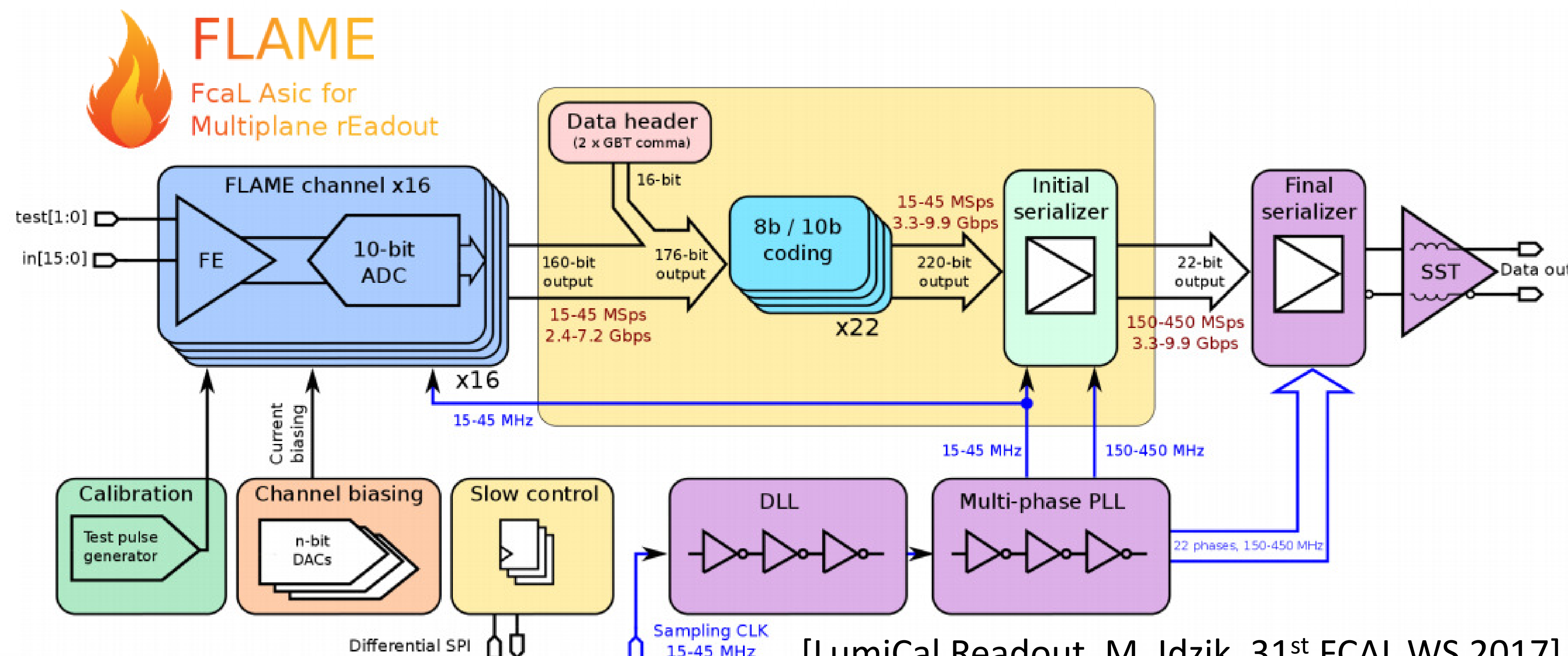


DOI: 10.1109/TNS.2012.2194308



Recent development

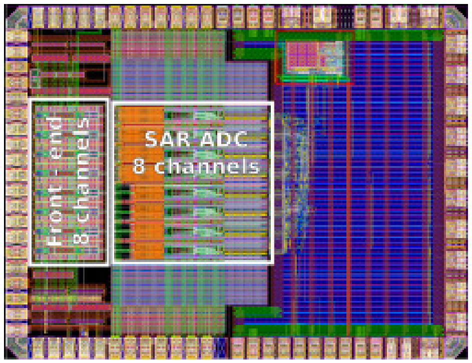
- For **very compact calorimeter** we need an **ultra low-power** SoC
- FLAME: 16-channel readout ASIC in 130nm CMOS, includes FE & ADC, fast SER and Data Tx

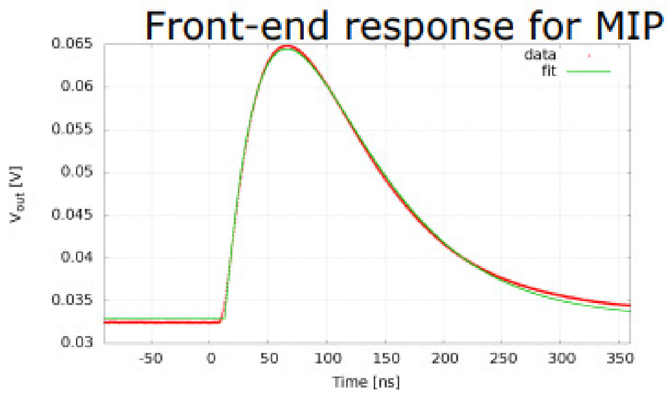


[LumiCal Readout, M. Idzik, 31st FCAL WS 2017]

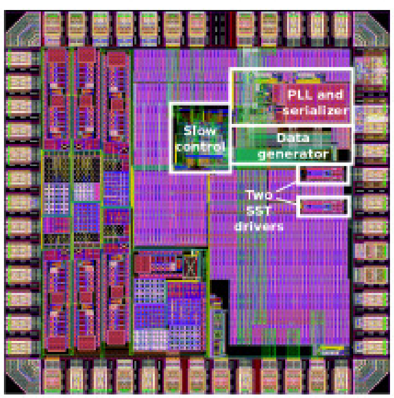
FLAME and Serializer ASIC

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

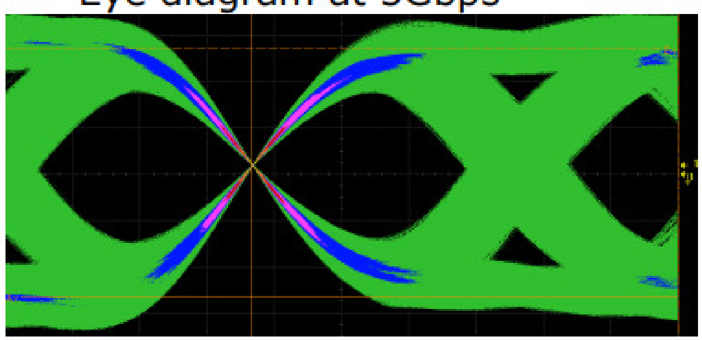




- **Prototype serializer ASIC**



Eye diagram at 5Gbps



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

130-nm CMOS process

First tests performed

- PCB produced
- Front-end: **OK**
- ADC: **OK**
- Serializer: **OK**
- Ongoing work…

Concluding remarks

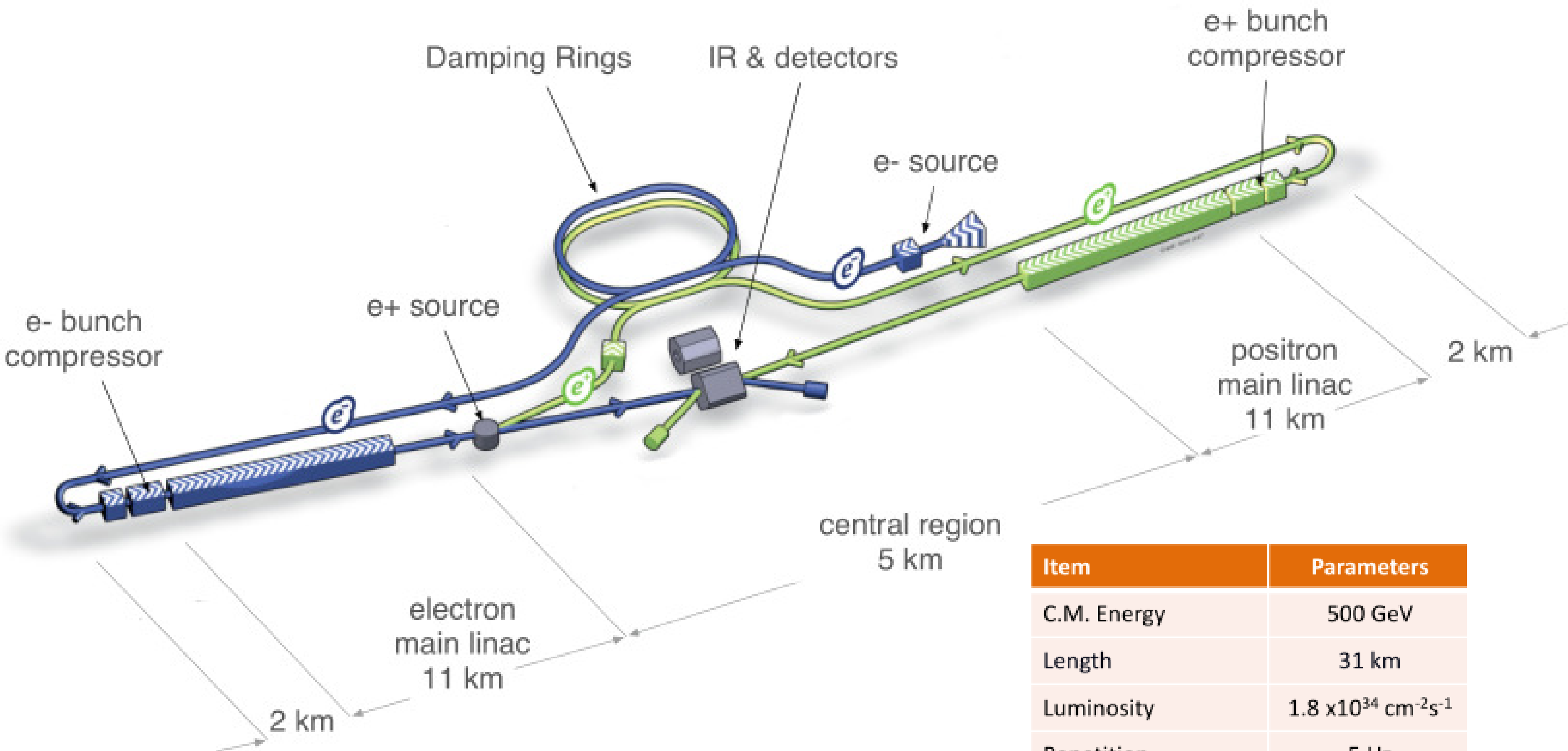
- Luminosity numbers are important
- Two luminosity concepts presented
  - Precise estimation from Bhabha scattering
  - Fast estimation from Beamstrahlung pairs
- Current development includes
  - ASICs
  - Thin sensor planes
- Testbeam results show promising results
  - Verified functionality of existing setup
  - Performance of EM shower reconstruction is in excellent 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

BACKUP SLIDES

ILC layout



Item	Parameters
C.M. Energy	500 GeV
Length	31 km
Luminosity	1.8 x10^{34} cm^{-2}s^{-1}
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	5.9 nm
SRF Cavity G. Q_0	31.5 MV/m Q_0 = 1x10 ^{10}

[ILC TDR 2013]

Luminosity formula

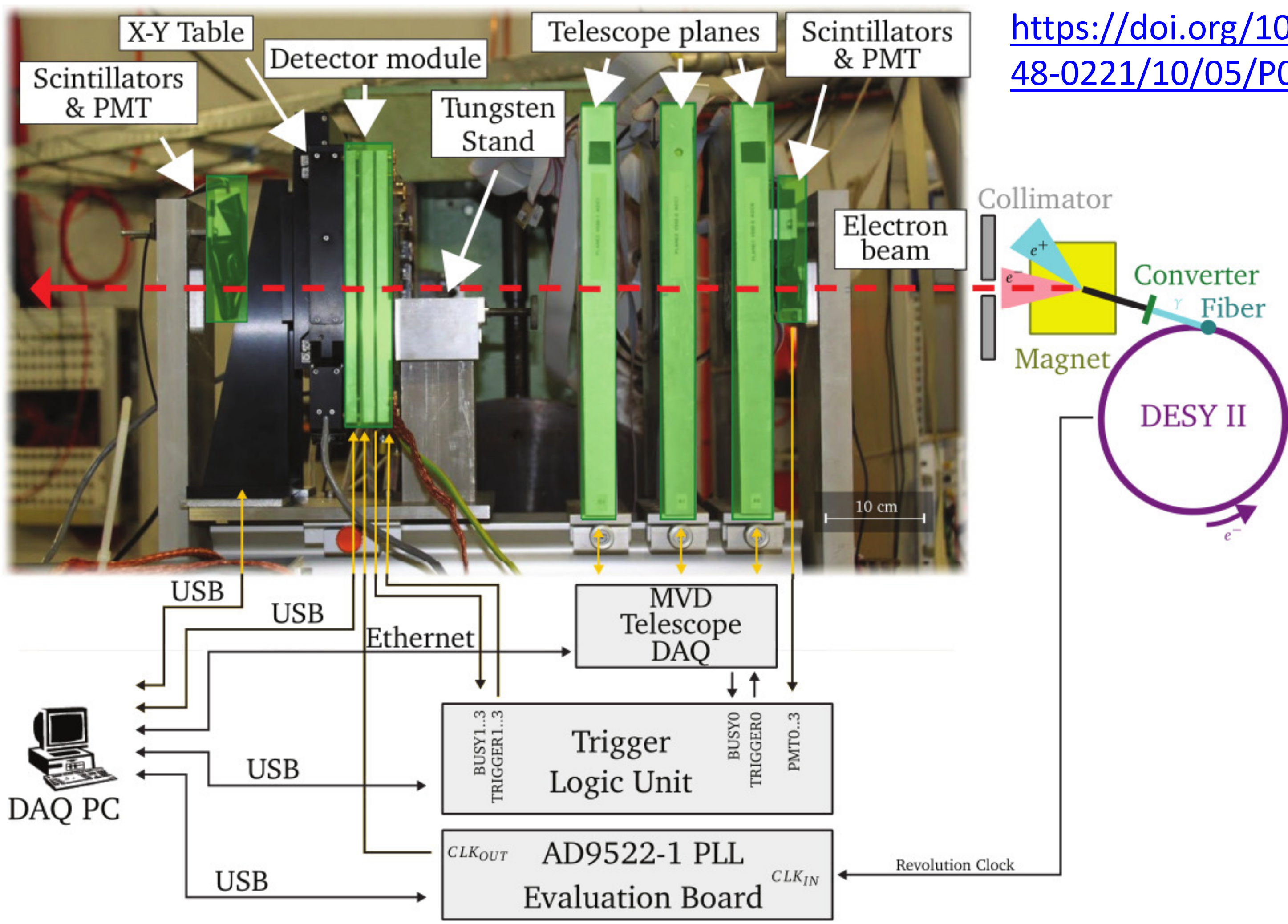
$$\mathcal{L} = F\frac{k_b N_b^2 f_{\rm rev}\gamma}{4\pi\,\epsilon_n\beta^*}, = F\frac{N_1 N_2 f_{rev} N_b}{4\pi\sigma_x\sigma_y} \qquad (12.7)$$

where k_b is the number of bunches per ring, N_b the number of protons per bunch, $f_{\rm rev}$ the revolution frequency, ϵ_n the normalized r.m.s. transverse emittance (assumed to be the same in both planes), β^* the beta-function at the collision point, and $F \le 1$ is a reduction factor caused by the finite crossing angle Φ.

[Induction Accelerators, Takayama and Briggs (editors), Springer 2011]

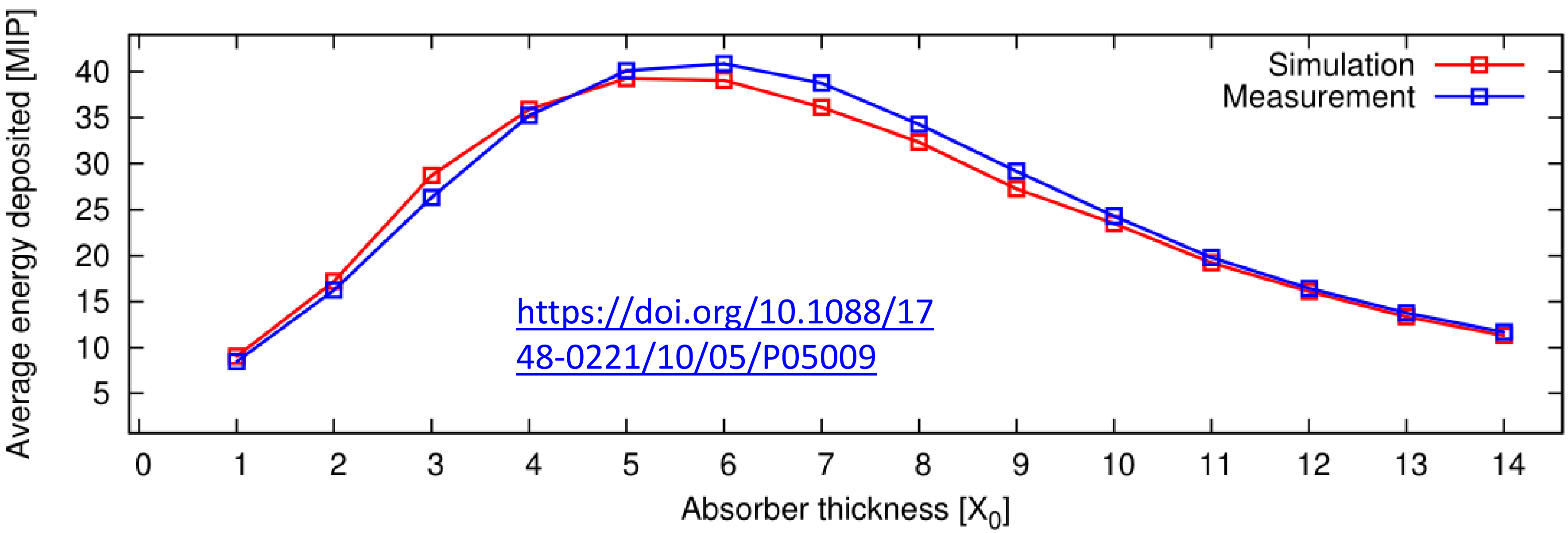
DESY-II Synchrotron 2011

e⁻ beam 2-4.5GeV, 100's particles per second



https://doi.org/10.1088/1748-0221/10/05/P05009

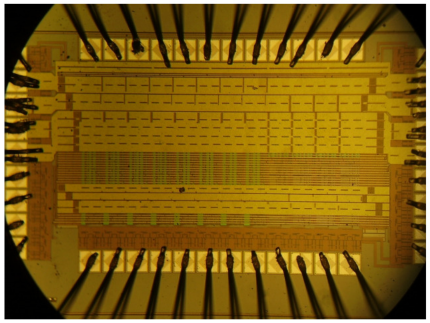
Results: shower development, Si sensor



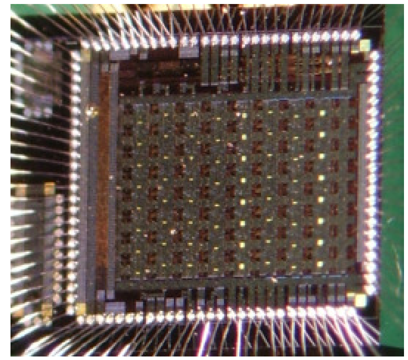
- Full functionality of sensor planes
- SNR between 20 and 30
- Next step: multiplane tests

LumiCal FE and multichannel ADC

Served both TB campaigns mentioned earlier

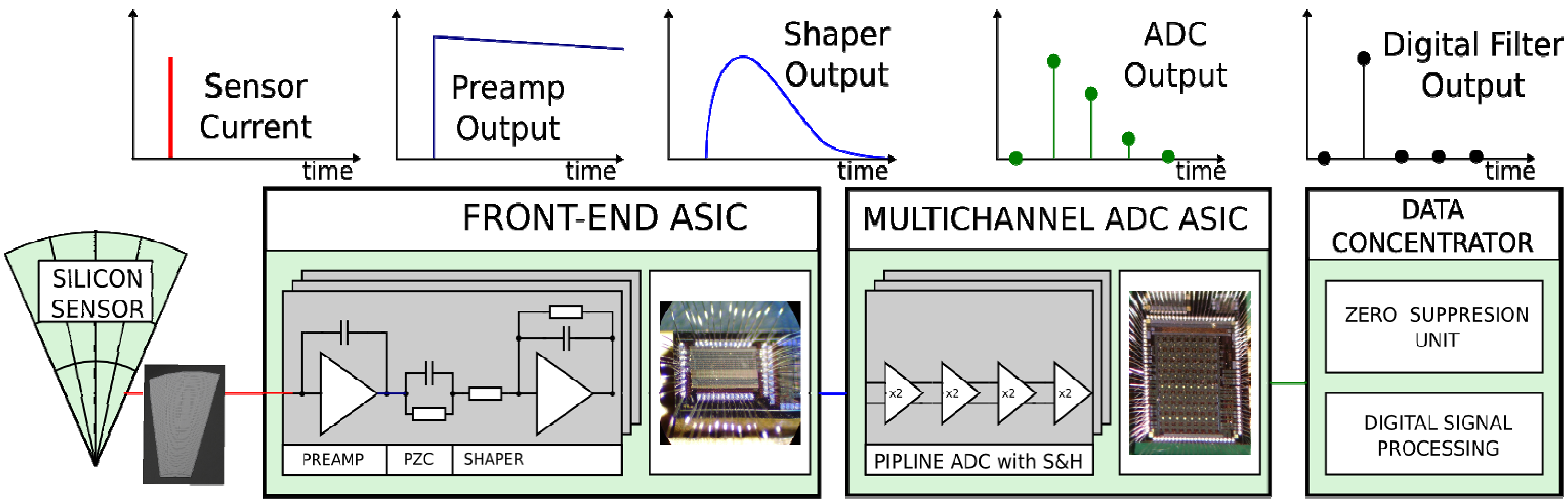


https://doi.org/10.1016/j.nima.2009.06.059

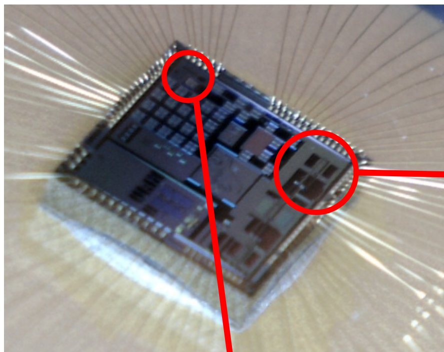


JINST, 6 P01004, 2011

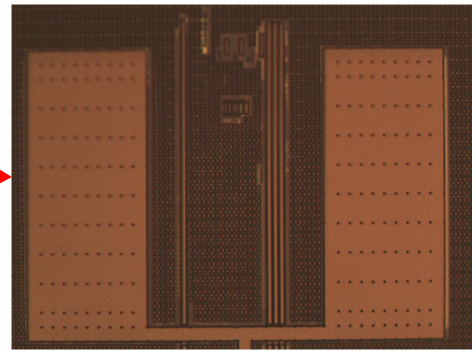
Served during the first TB campaign mentioned earlier

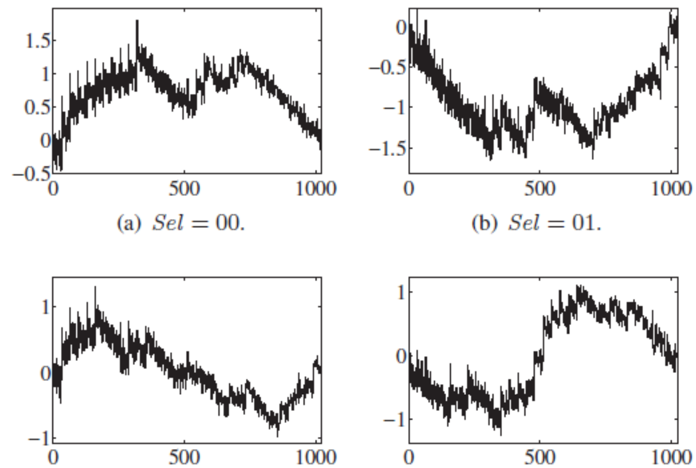


Prufpilo: Low power ADC and nonlinear ADC

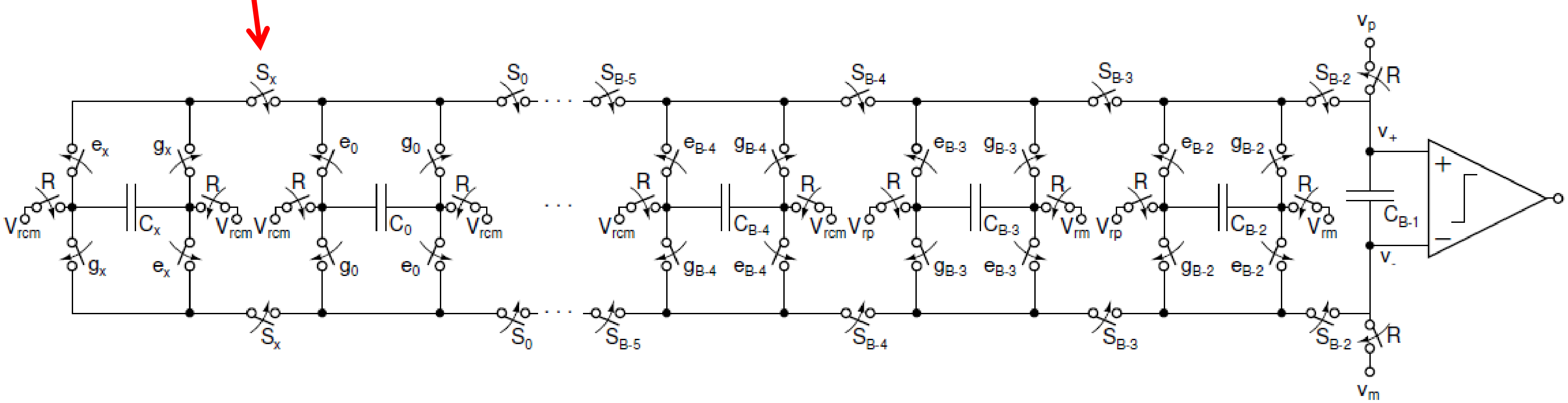


DOI: 10.1016/j.mejo.2015.06.005

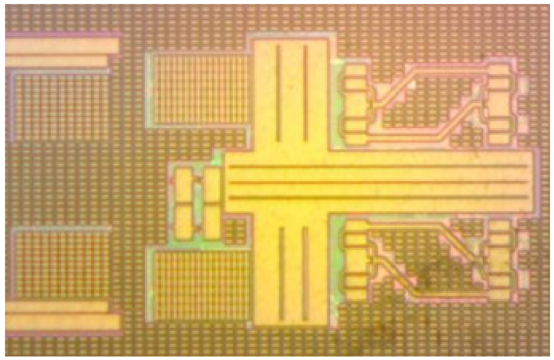


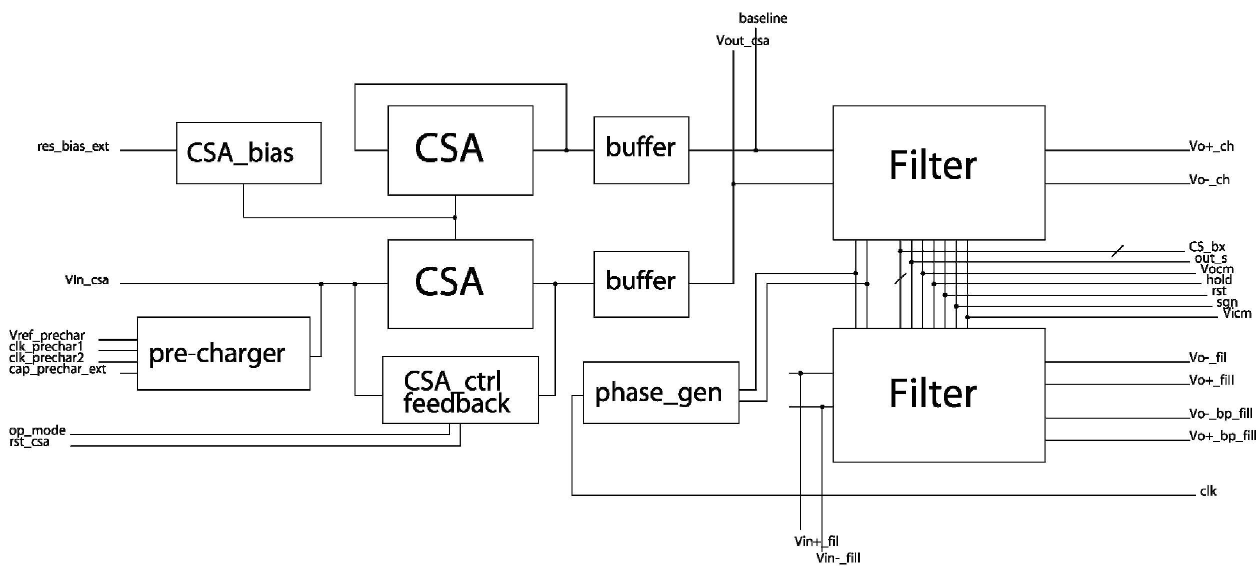


(a) $Sel = 00$. (b) $Sel = 01$. (c) $Sel = 10$. (d) $Sel = 11$.

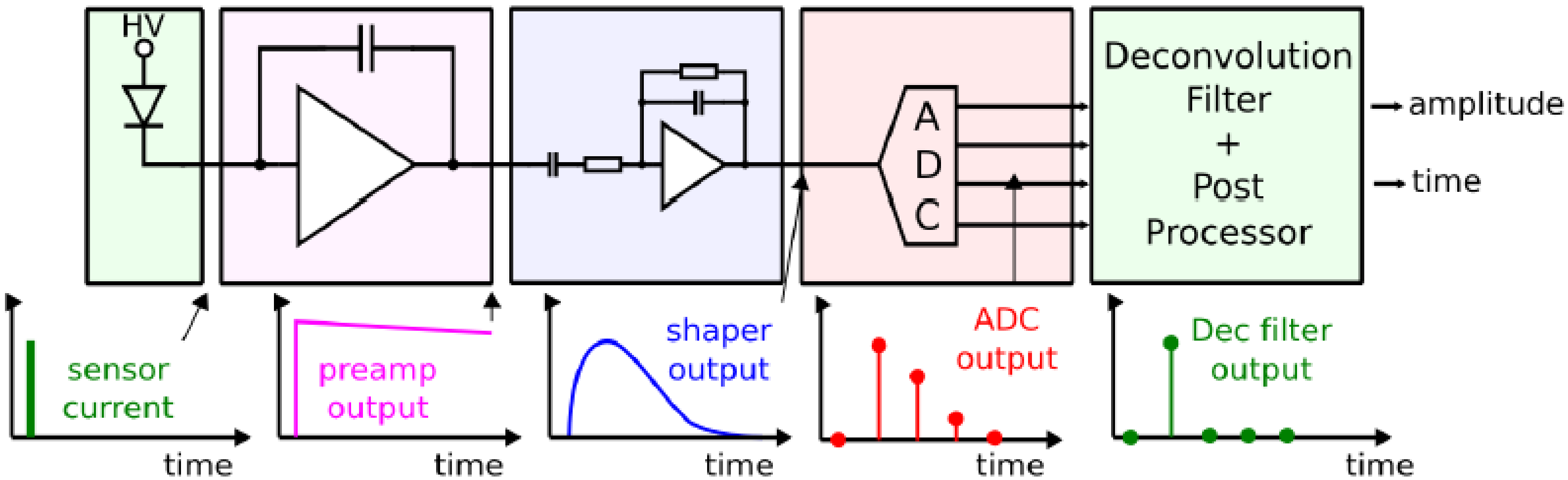


Bean V2:
arbitrary weighting function generation





LumiCal readout electronics diagram – Deconvolution theory



- Pulse at output of shaper v(t) is convolution of input signal (current from sensor – s(t)) and impulse response of readout chain h(t):

$$v(t) = \int_{-\infty}^{+\infty} h(t-x)\, s(x)\, dx$$

- Using data from continuously running ADC and taking advantage of known pulse shape one can perform invert procedure – **deconvolution** – to get information about event time and amplitude

Deconvolution for CR-RC shaping - Theory

$$d_i = s_i + w_1 s_{i-1} + w_2 s_{i-2}$$

CR-RC, $T_{smp} = T_{peak} = 1$, amp =1

- Only two multiplications and three additions (very fast and light !)

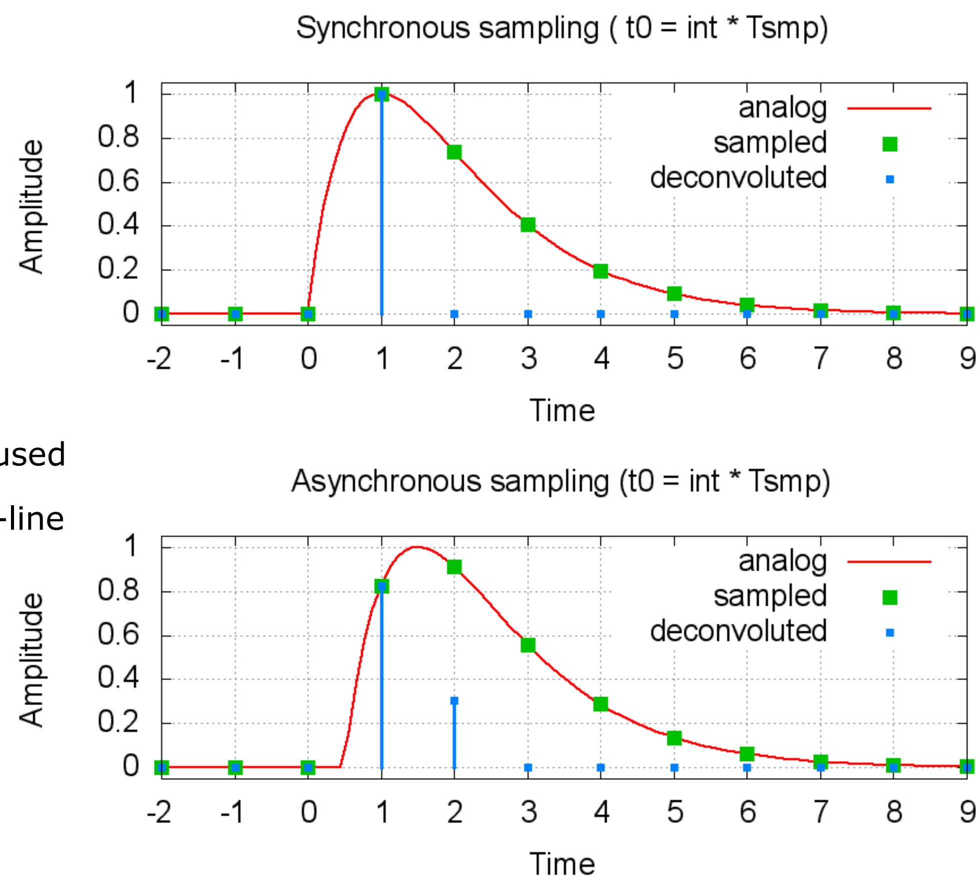
- Deconvolution produces non-zero data only when one or two first samples are on baseline,
and second/third is on pulse

- **Initial time** of pulse is found from ratio of those samples

- **Amplitude** is found from sum of those samples, multiplied by time dependent correction factor

} Look Up Tables used
Can be done off-line

- Deconvolution reduces (infinite number) of CR-RC pulse samples to 1 or 2 non zero samples !



Deconvolution for CR-RC shaping
Real, averaged, FE pulses

- Real pulse (1 MIP) deconvoluted for various phase shift t0 between the Front-End pulse and ADC sampling
- Deconvolution done for different sampling periods (12.5, 25 and 50 ns are presented)
- **Amplitude reconstruction** (top plot) – deconvoluted to real pulse amplitude ratio
  - Error is below 2% except 12.5 ns sampling period
- **Time reconstruction** (bottom plot) – difference between reconstructed and real pulse peak position
  - Constant offset of around 2 ns except 50 ns sampling period
- **S/N after deconvolution still to be measured...**