Luminometers for future collider experiments

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On behalf of the FCAL collaboration

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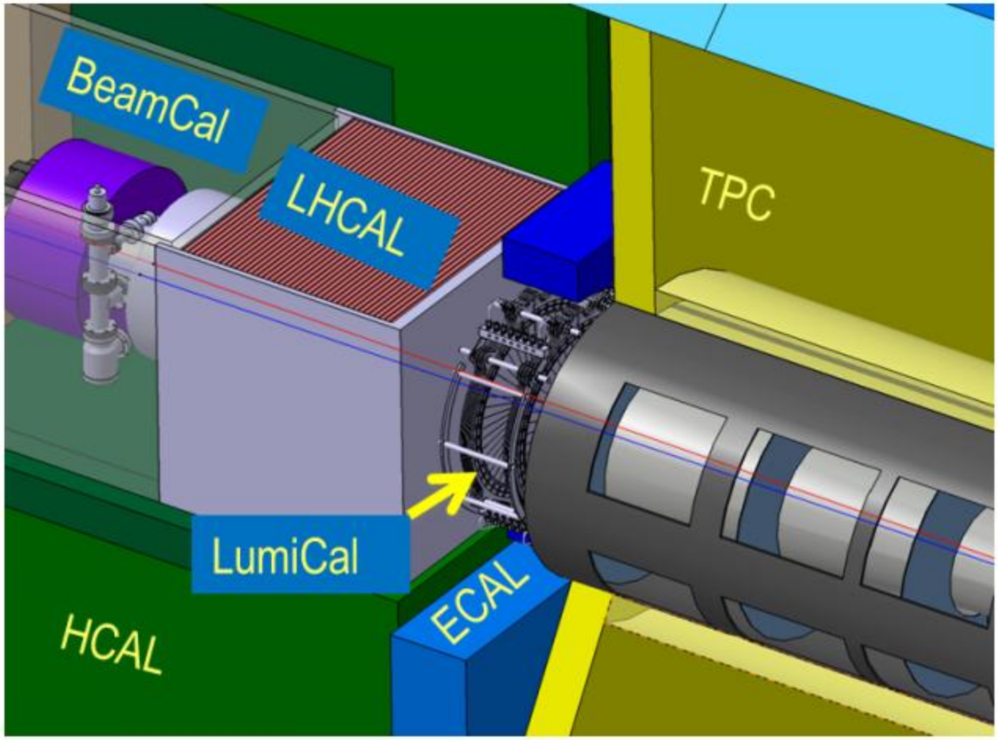


What’s all this “**collider luminosity**” stuff, anyhow?

- The instantaneous luminosity is *roughly* the quotient between the **rate of potential collisions** and the **effective cross section** of the interaction region

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

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

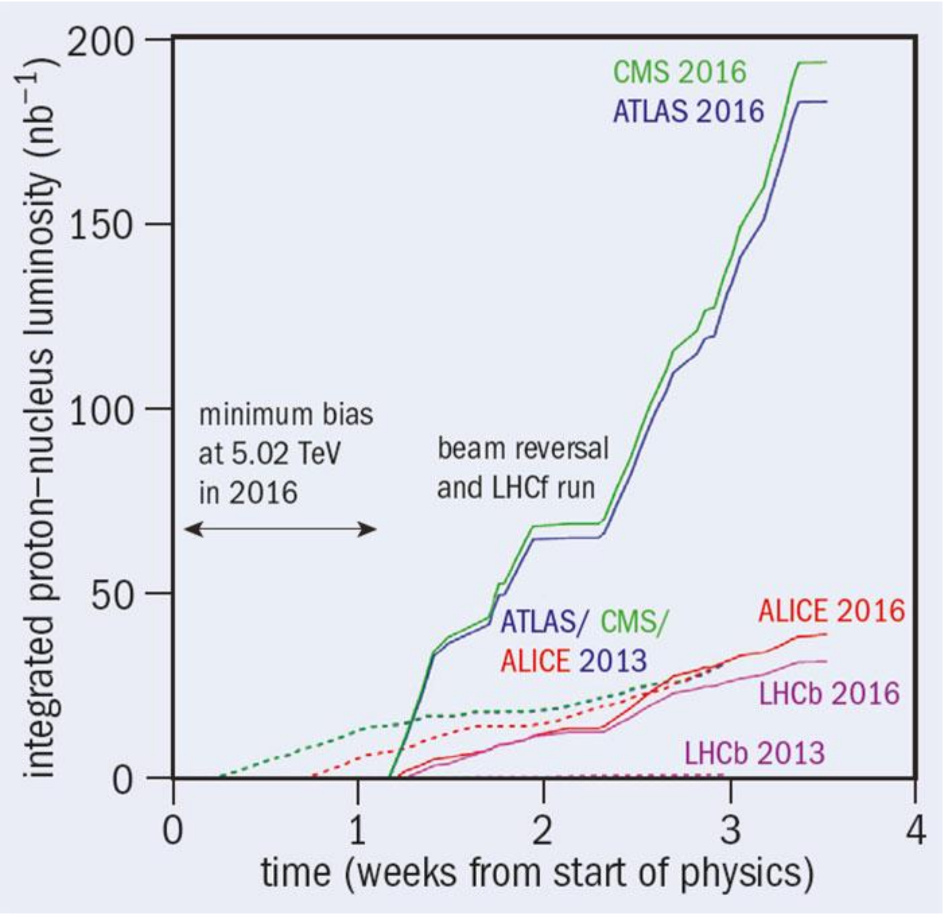
- Luminosity is related to the **beam parameters** such as size and intensity
- **Integrated luminosity** is *L* accumulated over the experiment data taking period

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

- 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 **normalize** the physics processes under study



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

Luminosity is difficult to estimate

- Luminosity is **process-independent**
  - Can be **inferred** from measured event rate and its known event cross section
  - Need a **well understood and measurable event**
- Luminosity estimations are complicated in hadron colliders
  - Uncertainty in the parton distribution functions (PDF) limit the precision

Outline of this talk

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

So what’s next?

- Luminosity measurements
- LumiCal and BeamCal design
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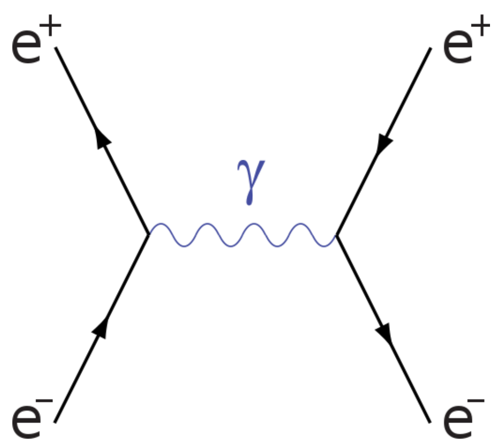
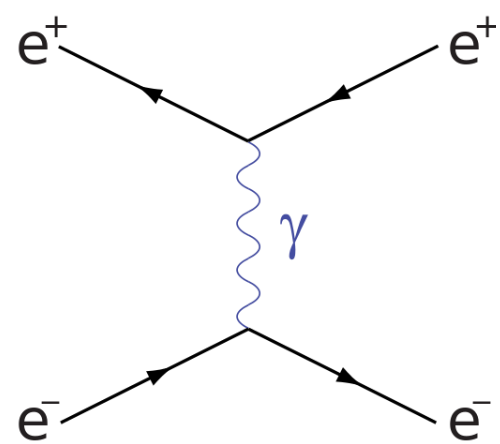
Precision luminometry in $e^+ e^-$ colliders

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

- High production rate
- Theoretically well understood



annihilation



scattering

Why small angle Bhabha scattering?

- The differential cross section of Bhabha scattering can be calculated from theory:

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

arXiv:1009.2433

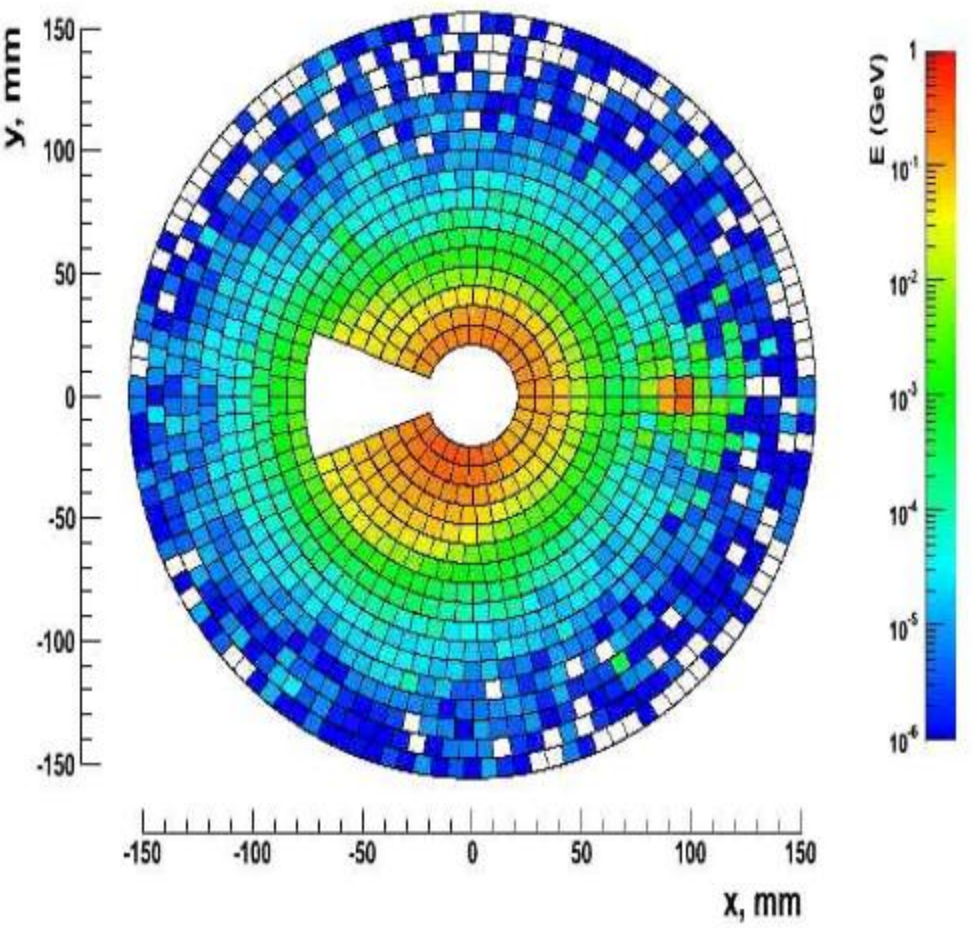
- Then the luminosity can be estimated:

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

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

The total energy and shape of the bunch-by-bunch deposition on small polar angle allows the estimation of beam parameters

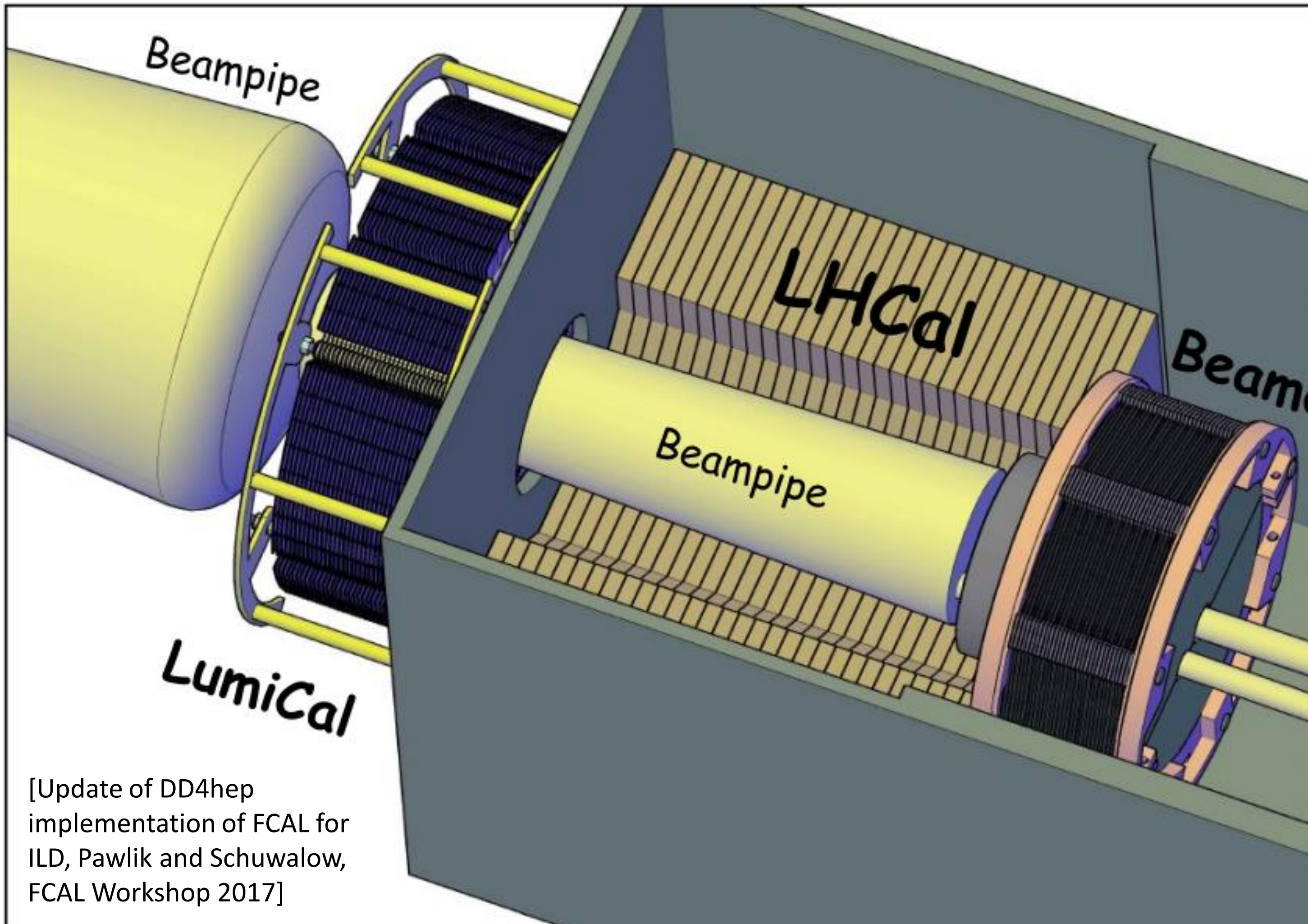
arXiv:1009.2433



Luminometry requirements for future linear colliders

- Precision better than 10^{-3} for 500-GeV CME
  - Challenges in electronics, mechanics and position control
- Instantaneous luminosity estimation
- High occupancy
- High radiation environment in low polar angle (~MGy per year) – beamstrahlung
- Hermeticity
- Small Molière Radius
- Shield tracker by reducing backscattering

Example of forward calorimeters: current layout for ILD detector @ILC



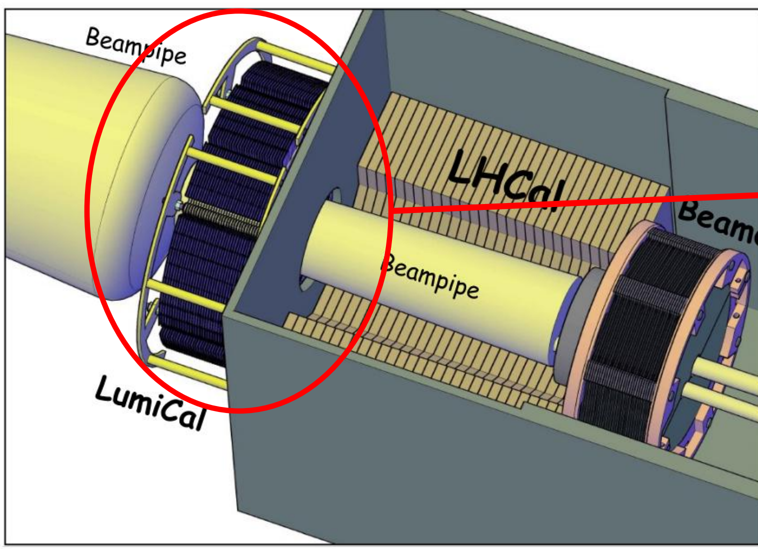
[Update of DD4hep implementation of FCAL for ILD, Pawlik and Schuwalow, FCAL Workshop 2017]

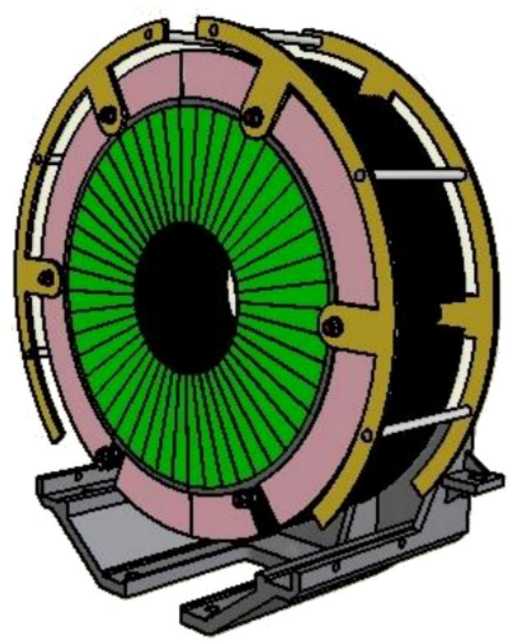
So what’s next?

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

LumiCal design

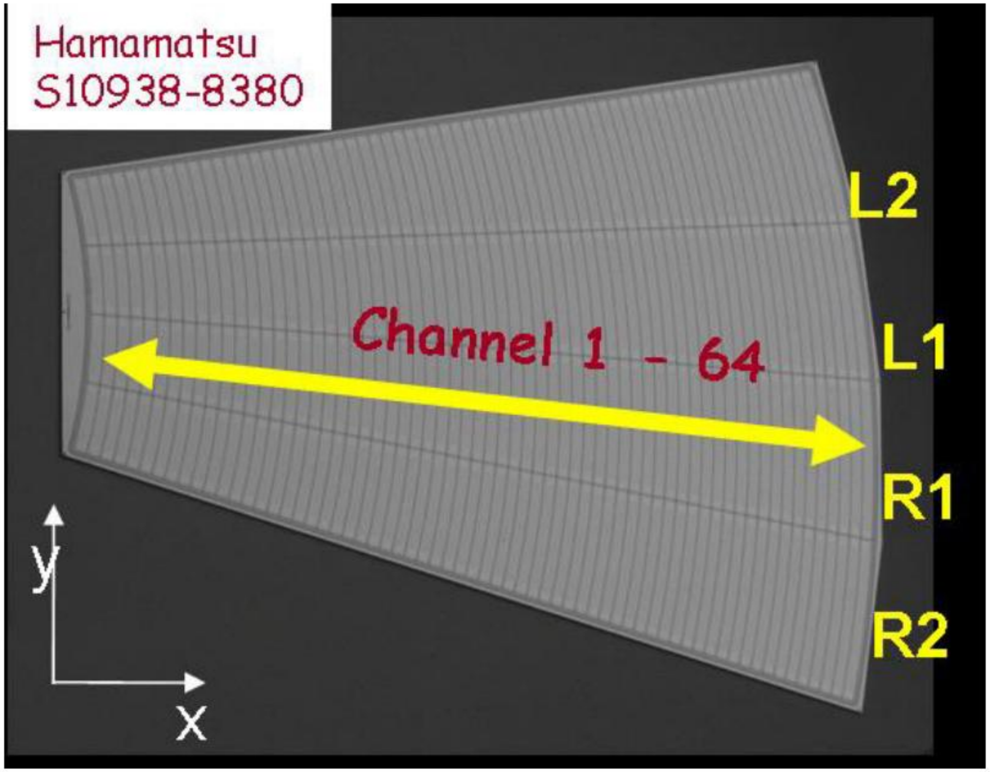
- Sampling (sandwich) Si-W calorimeter
- 30 **precise** layers at ILC (40 at CLIC), one radiation length each
- 42–67 mrad at ILC (38–110 mrad at CLIC)
- **Compactness** for ~1cm Molière radius



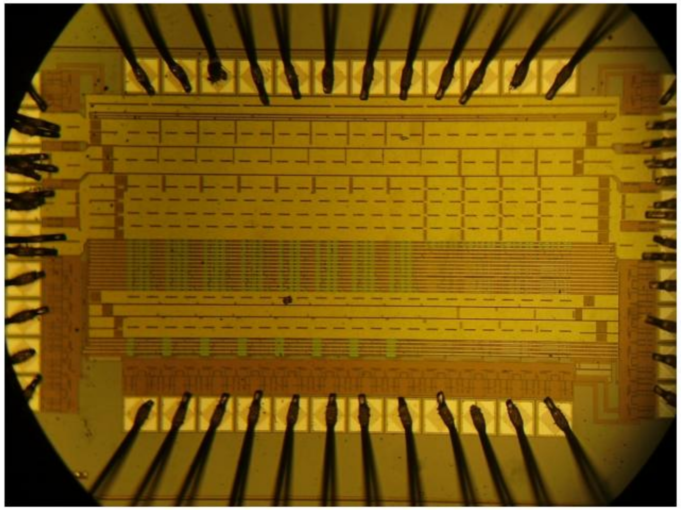


http://inspirehep.net/record/1386724/files/v46p1297.pdf

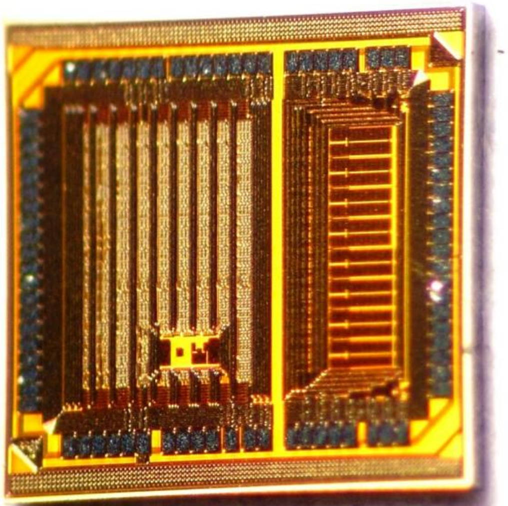
LumiCal sensor plane and ASICs



arXiv:1411.4924



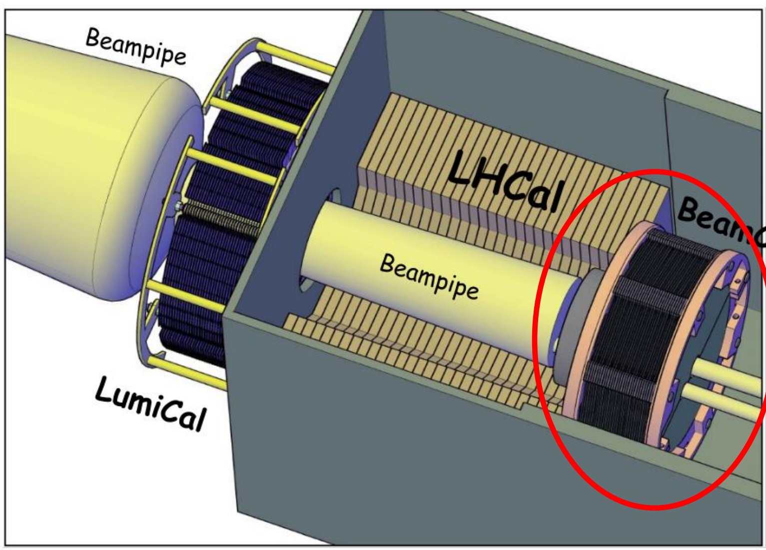
https://doi.org/10.1016/j.nima.2009.06.059

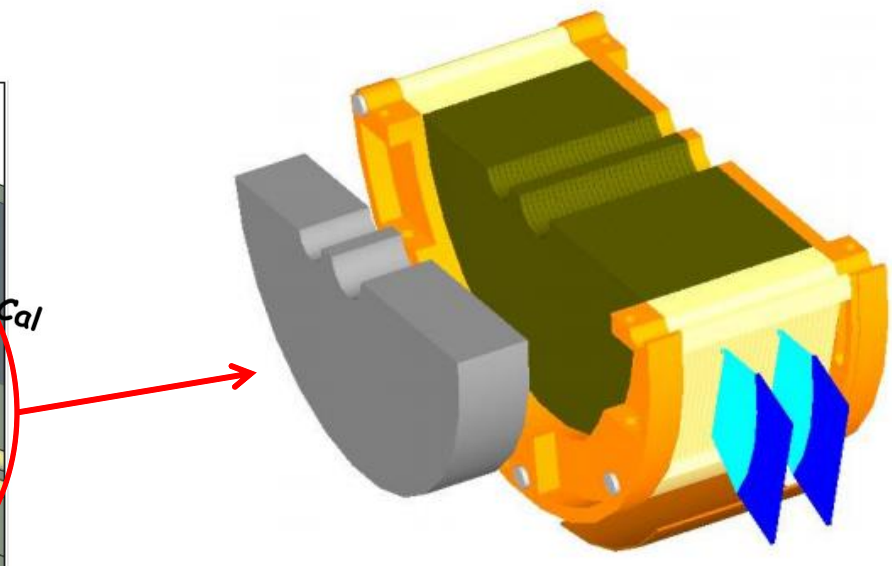


doi:10.1088/1748-0221/10/11/P11012

BeamCal design

- Sampling **?**-W calorimeter
  - Sapphire, CVD diamond and GaAs are 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

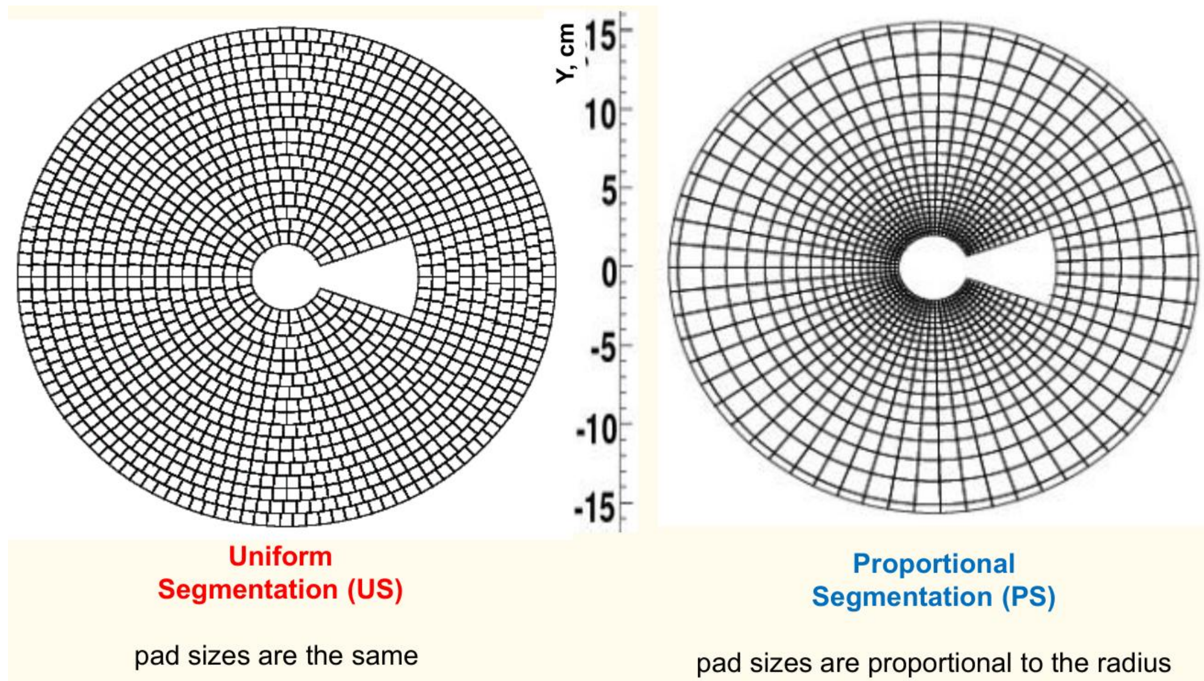




BeamCal sensor planes – GaAs option

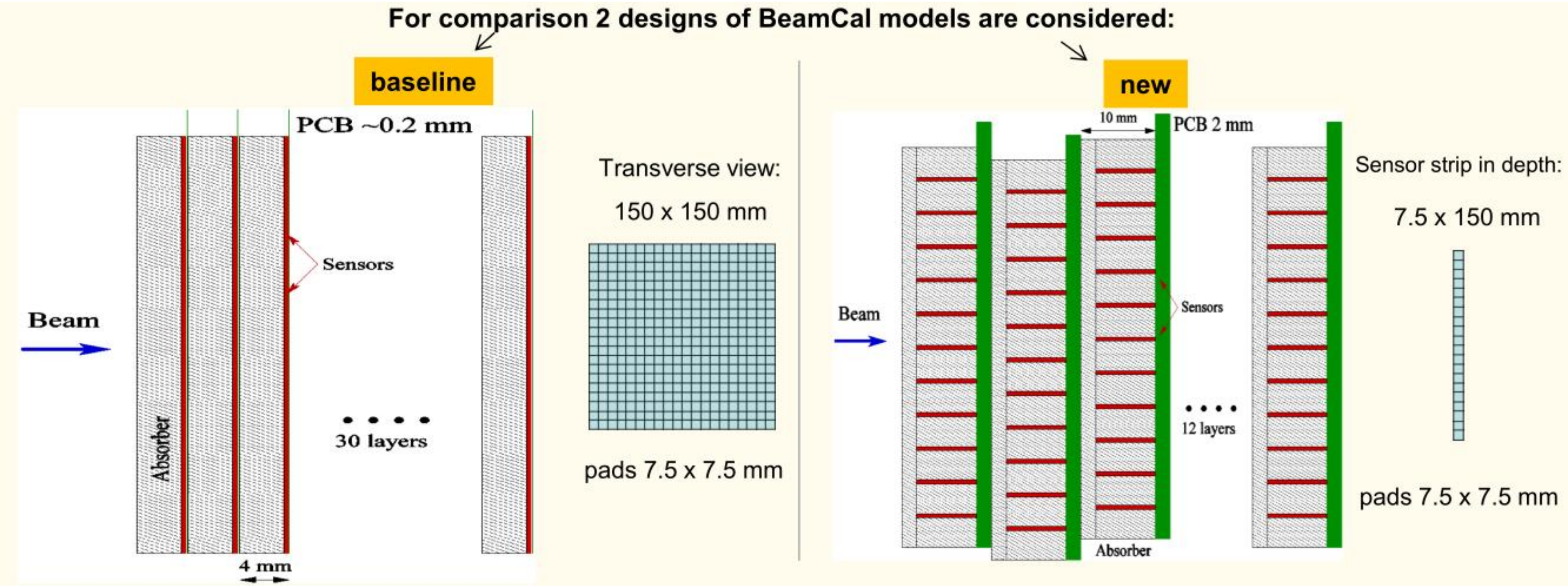
Preliminary design, two segmentation options

arXiv:1411.4924v2



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

BeamCal sensor planes – Sapphire option



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

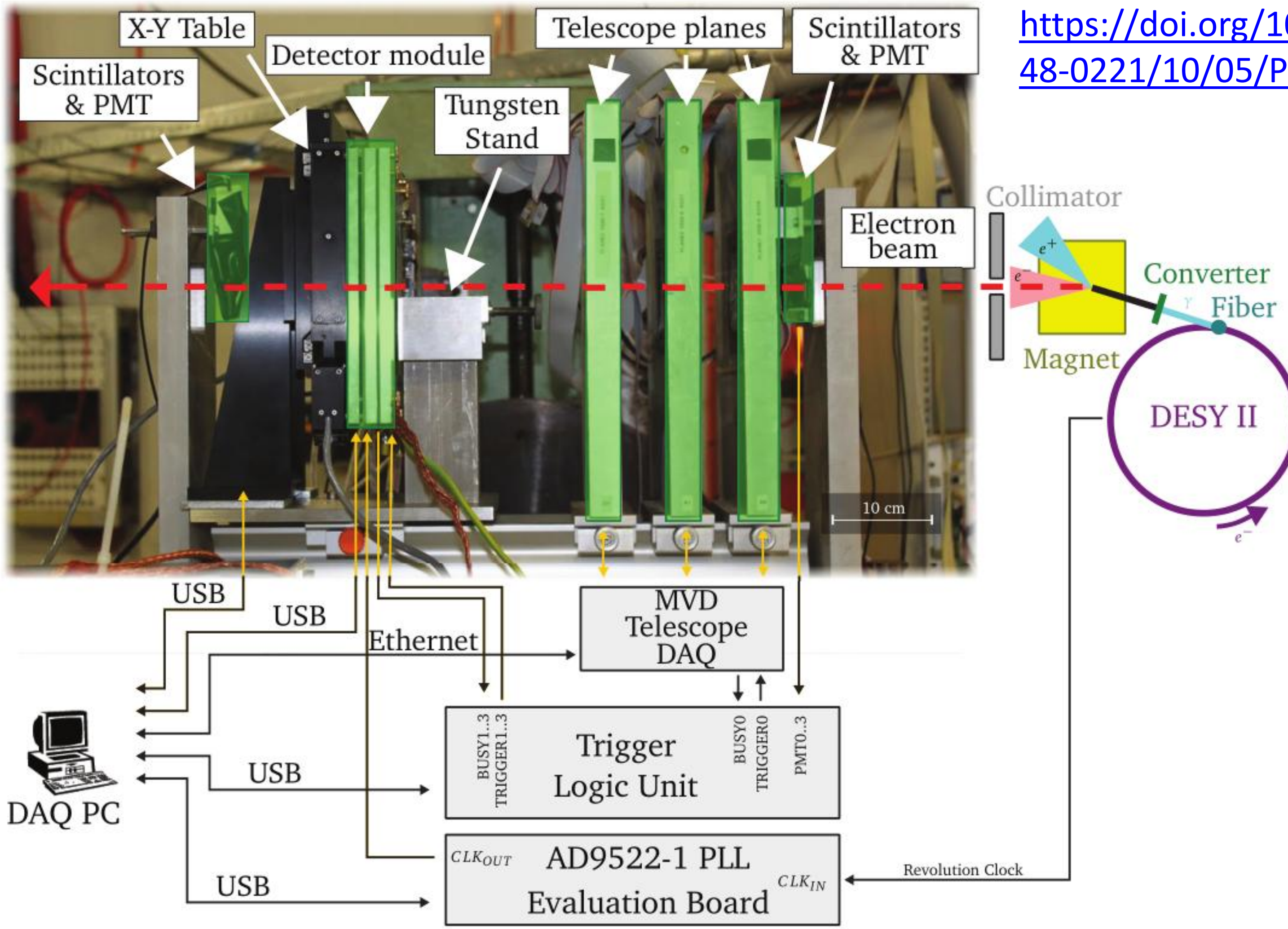
- Sapphire is cheap and less sensitive to radiation; smaller signals
- New design is more sensitive to MIPs, less DR required
- Non-standard assembly procedure

So what's next?

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

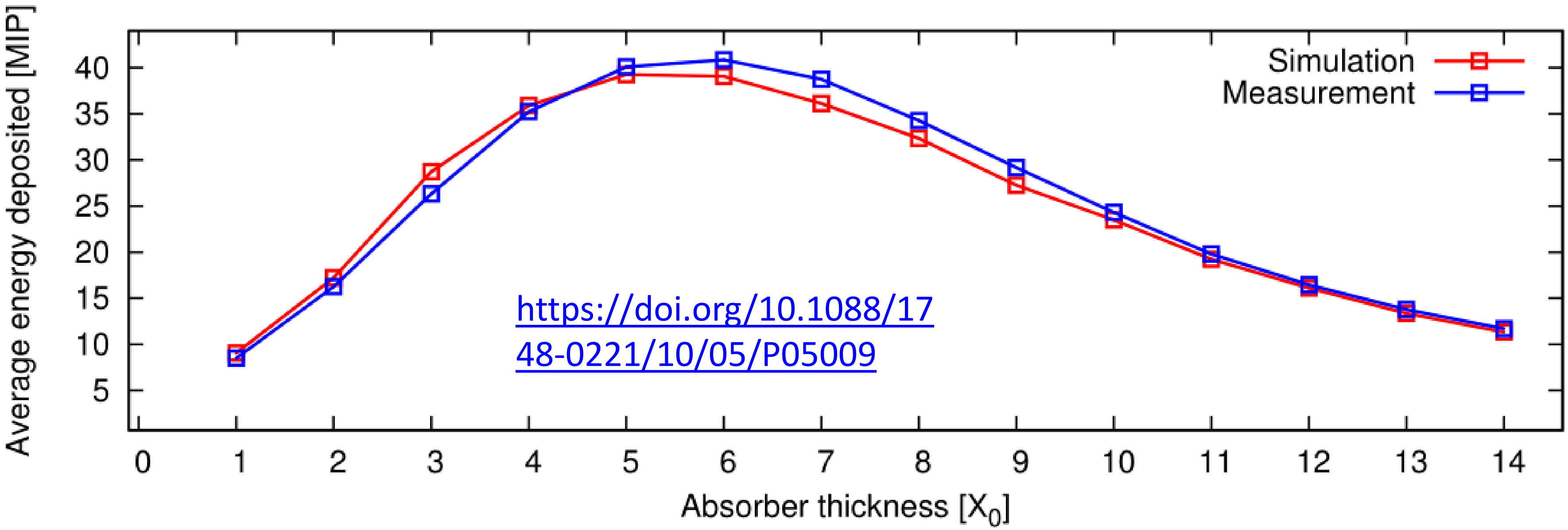
DESY-II Synchrotron 2011

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



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

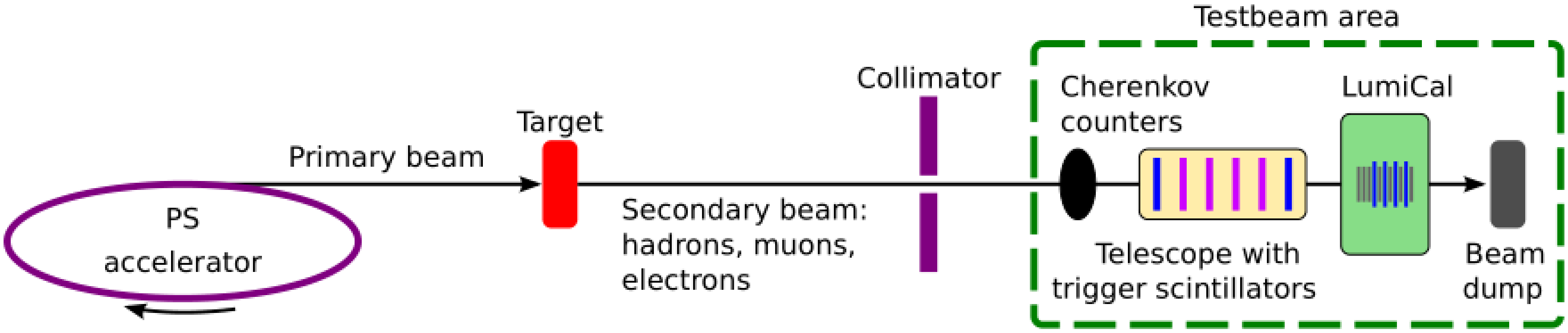
Results: shower development, Si sensor



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

CERN PS accelerator, T9 beam 2014

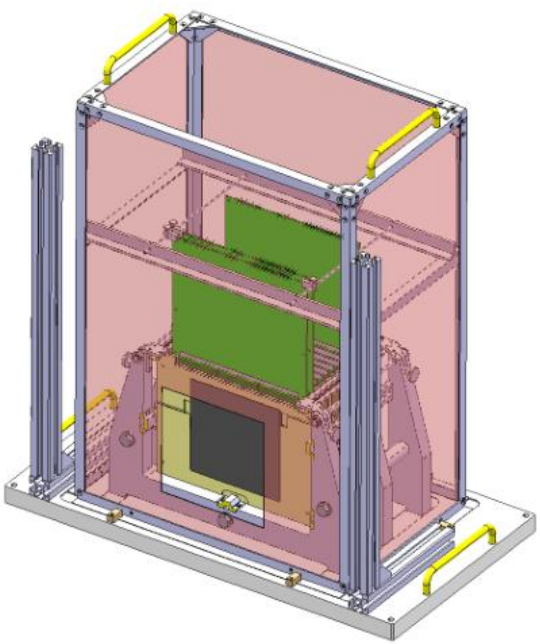
- Beam parameters:
  - Particles (mainly e^- and μ) with ~5GeV energy
  - 400ms spills every 33.6s
- Objectives:
  - Demonstrate multiplane W-Si operation
  - Study EM shower and estimate Molière radius

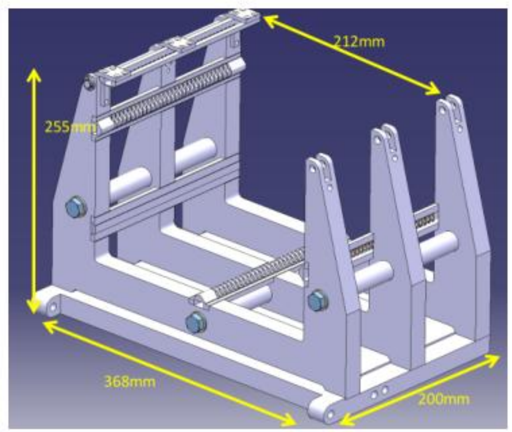


[*Measurement of shower development and its Molière radius with a four-plane LumiCal test set-up*, submitted to the Eur. Phys. J. C]

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

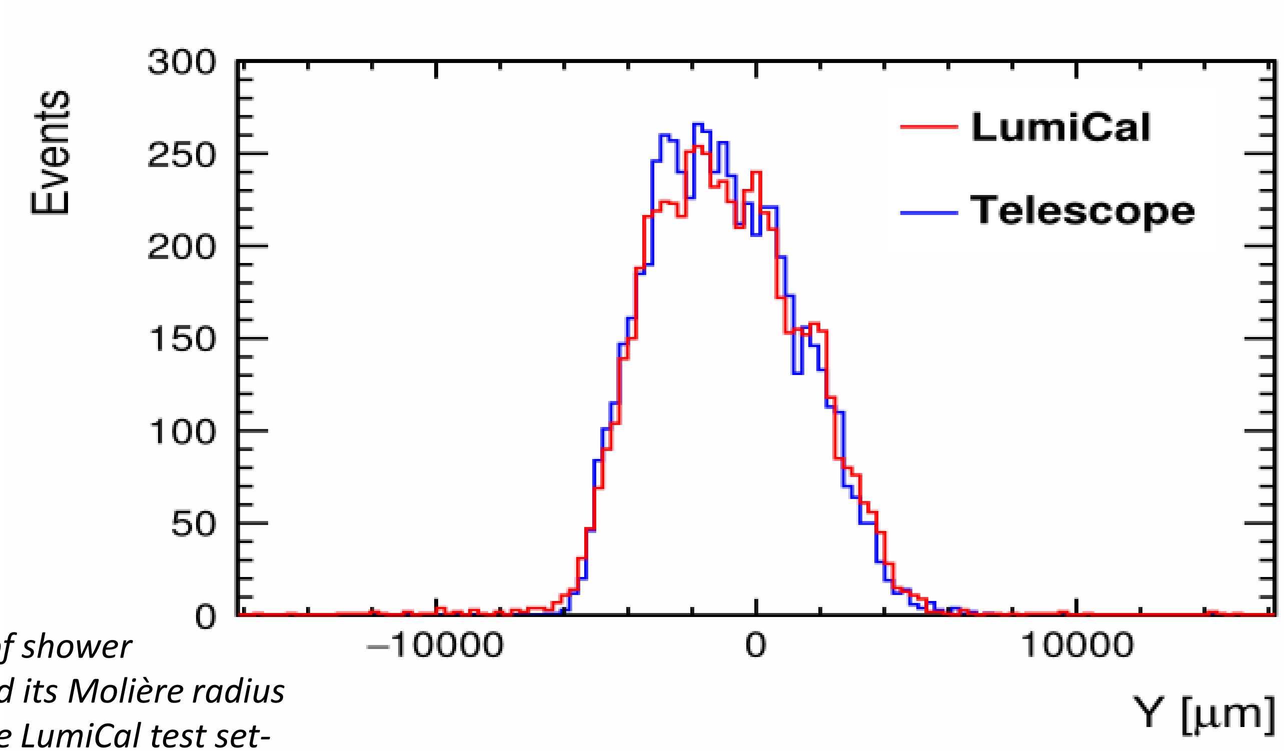




[*Measurement of shower development and its Molière radius with a four-plane LumiCal test set-up*, submitted to the Eur. Phys. J. C]

Results

Distribution of radial shower position – Lumical vs. tracker

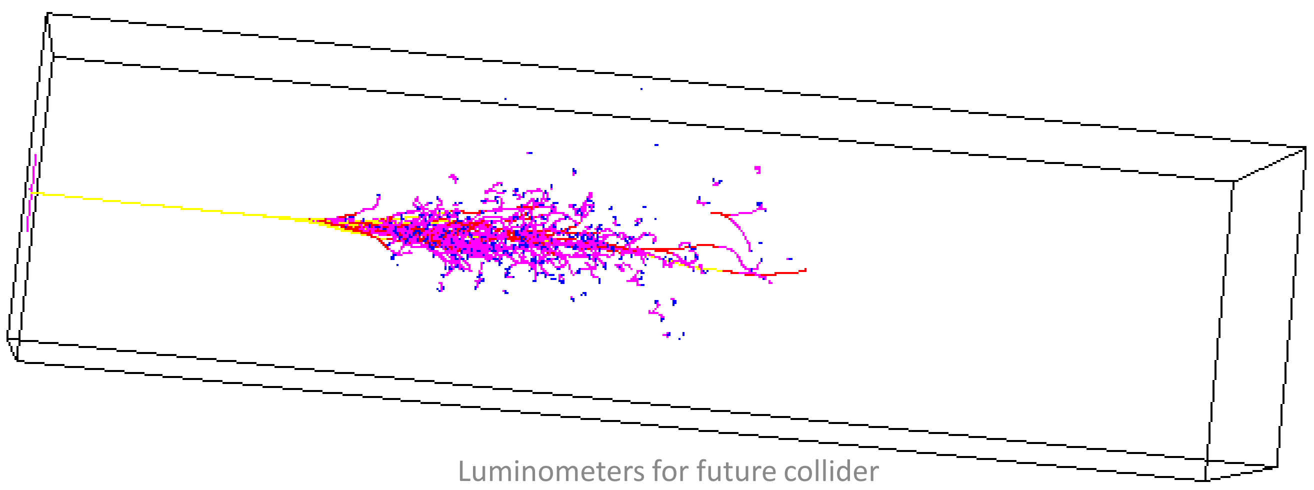


[*Measurement of shower development and its Molière radius with a four-plane LumiCal test set-up*, submitted to the Eur. Phys. J. C]

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

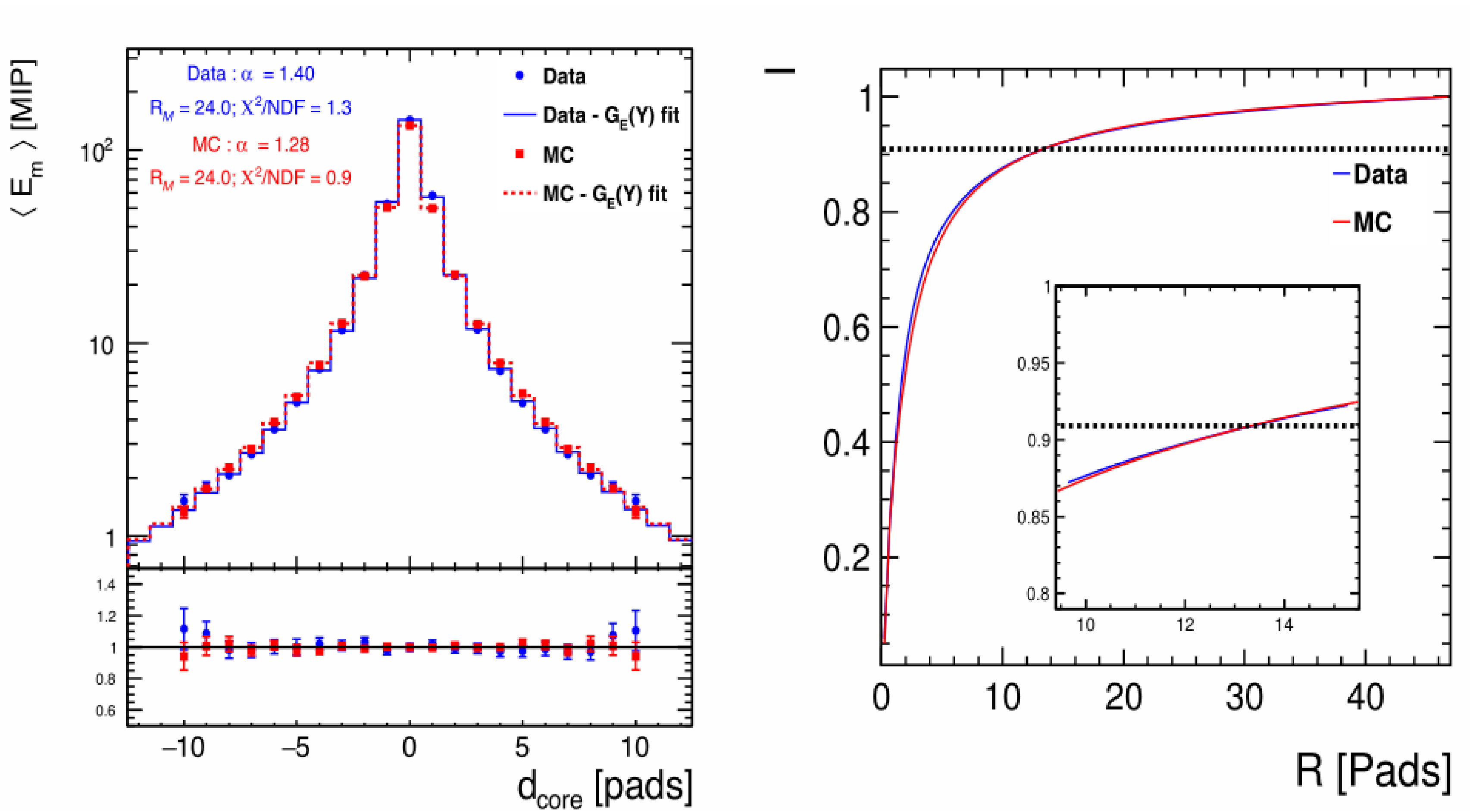
- Radius of a cylinder that contains 90% of the energy deposition of the shower
  - A small $R_{\mathcal{M}}$ facilitates reconstruction of high energy e^-
- It is a **constant of the material** or target **stack**
  - E.g., an air gap in the stack increases $R_{\mathcal{M}}$

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



Molière radius results

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



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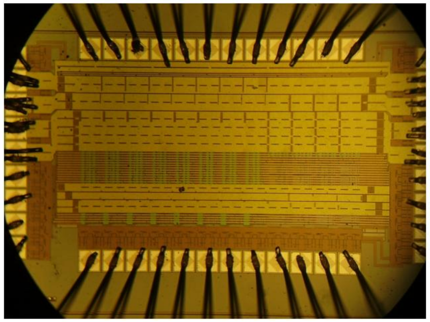
Prior art:
FCAL-related ASICs overview



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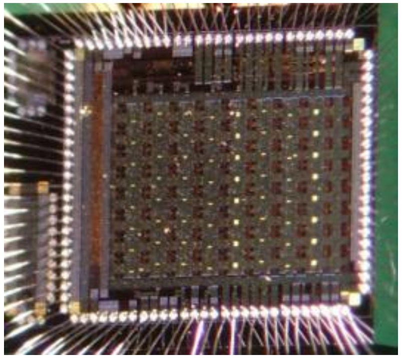
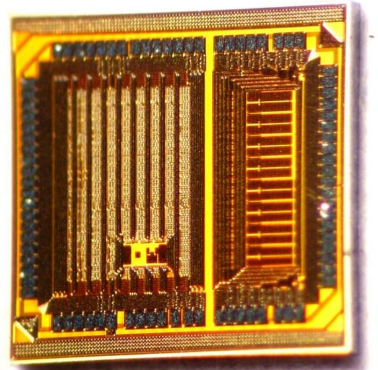


JINST, 6 P01004, 2011



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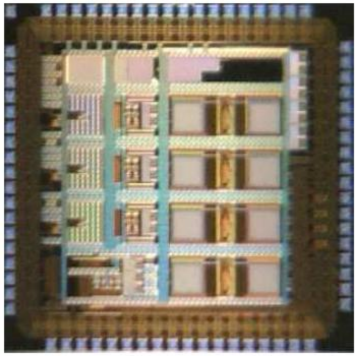
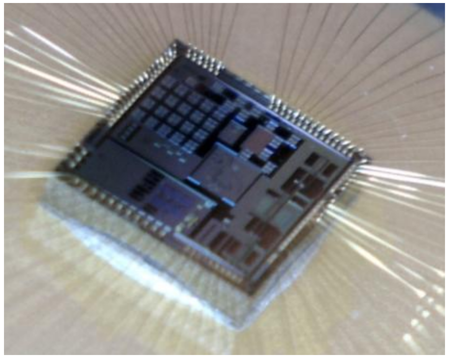
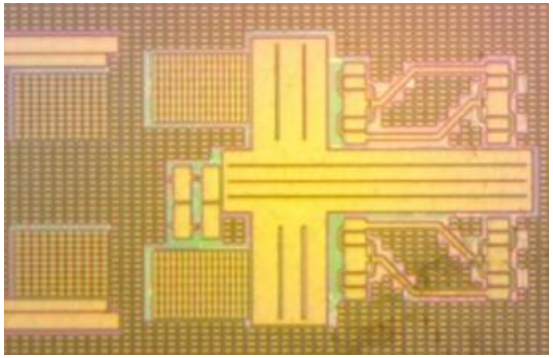


DOI: 10.1109/TNS.2012.2194308

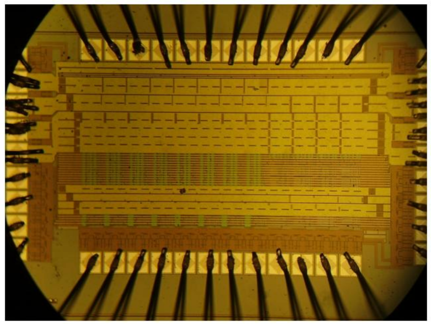


DOI: 10.1016/j.mejo.2015.06.005



LumiCal FE and multichannel ADC

Served both TB campaigns mentioned earlier



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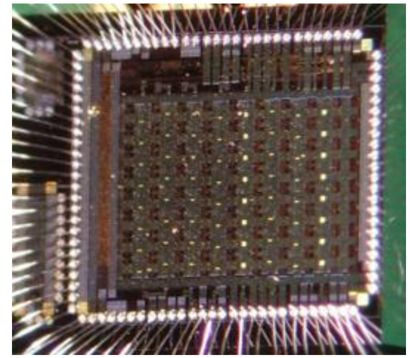
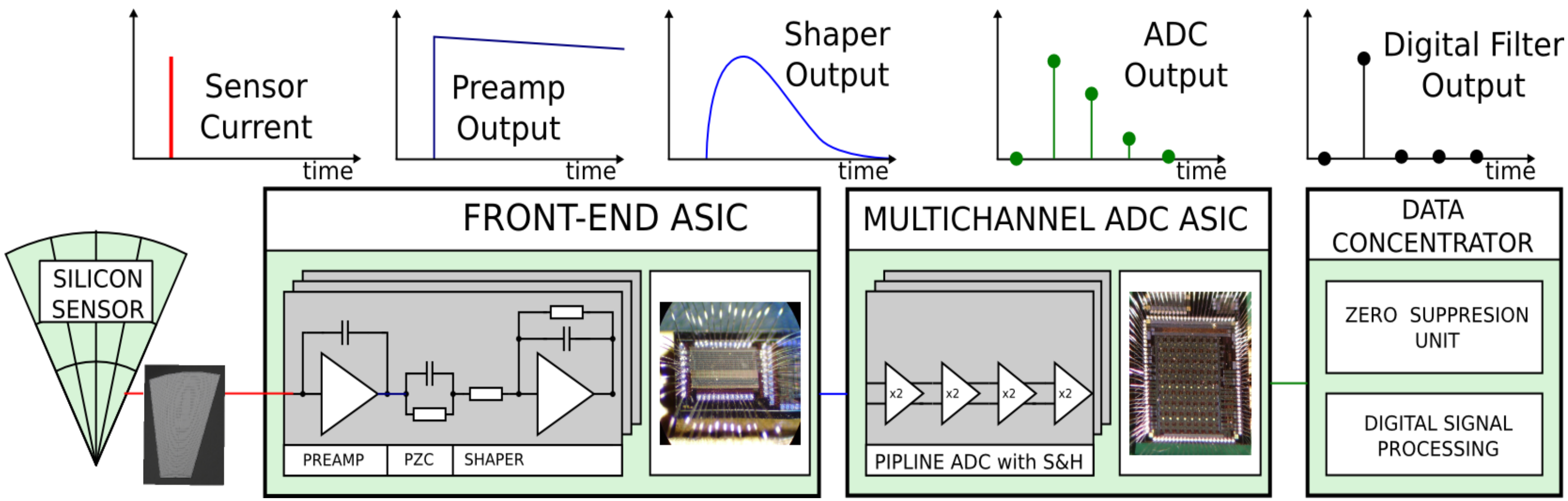
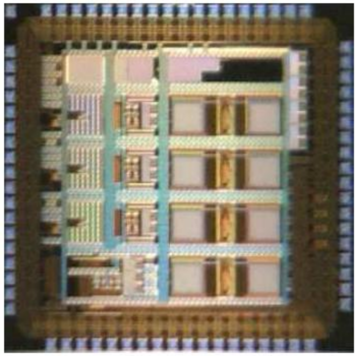


JINST, 6 P01004, 2011

Served during the first TB campaign mentioned earlier



Bean V1



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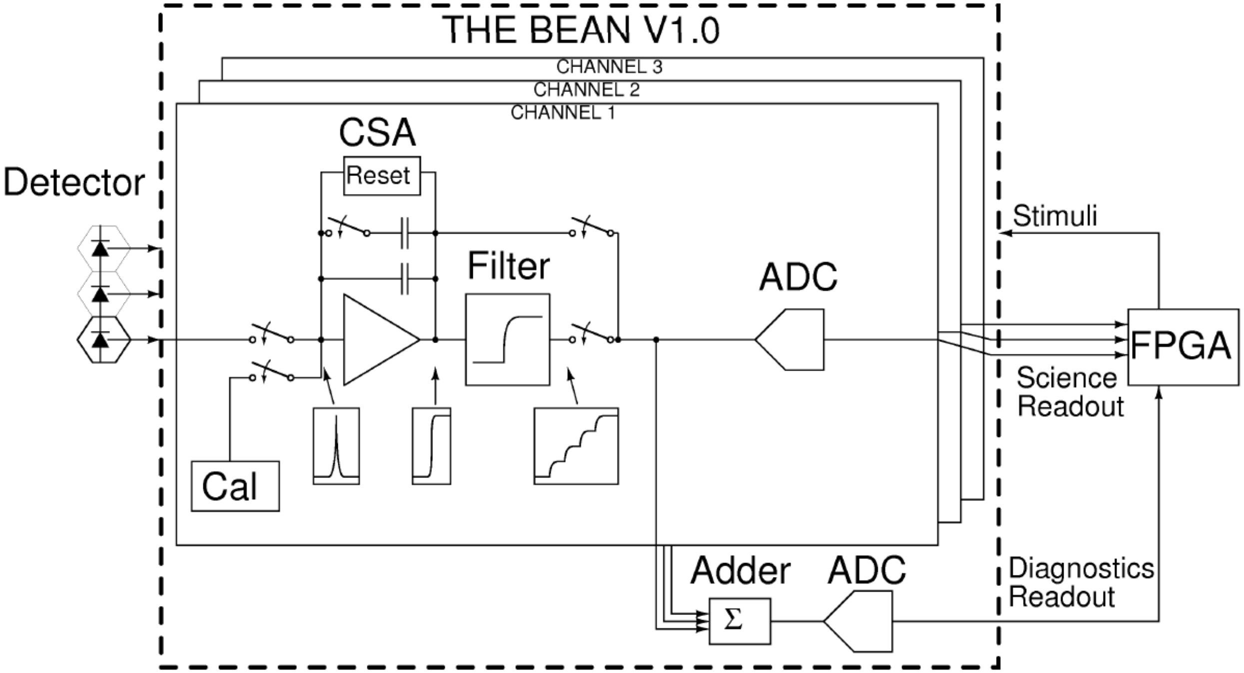
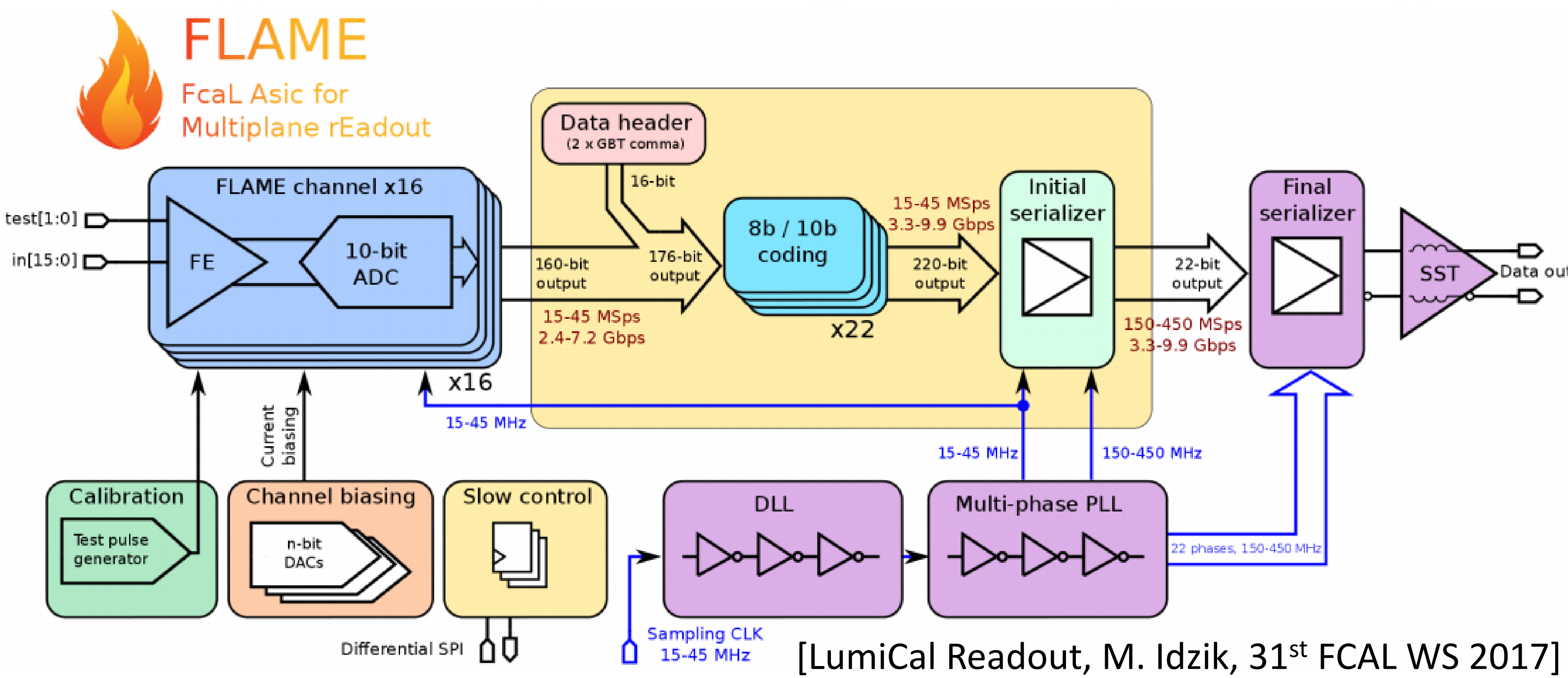


Recent development

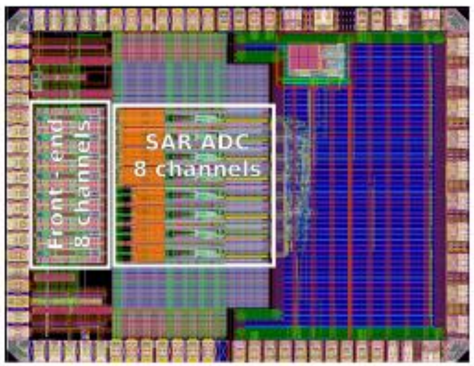
- For very compact calorimeter we need an ultra low-power SoC
- FLAME: 16-channel readout ASIC in 130nm CMOS, includes FE & ADC, fast SER and Data Tx

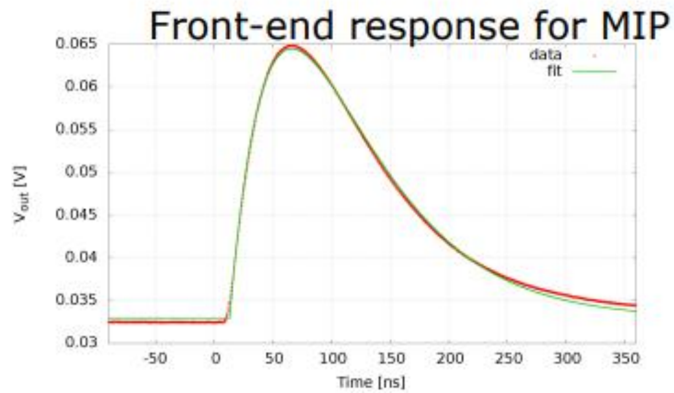


[LumiCal Readout, M. Idzik, 31st FCAL WS 2017]

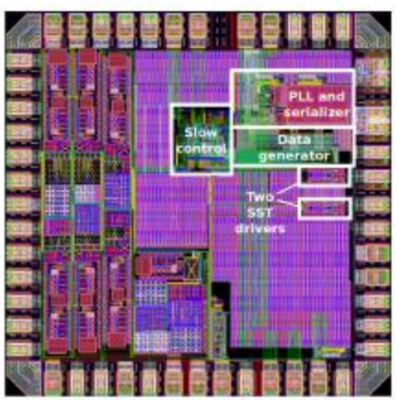
FLAME and Serializer ASIC

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

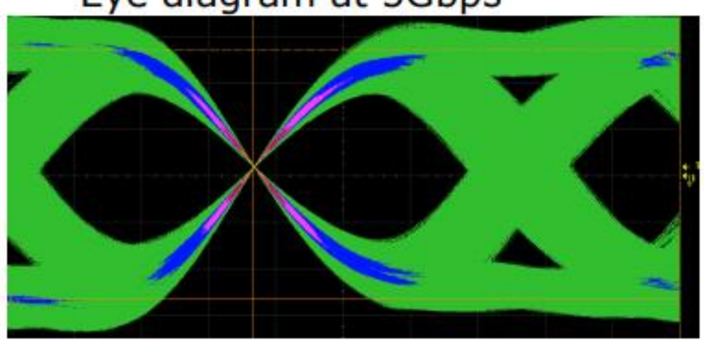




- **Prototype serializer ASIC**



Eye diagram at 5Gbps



First tests performed

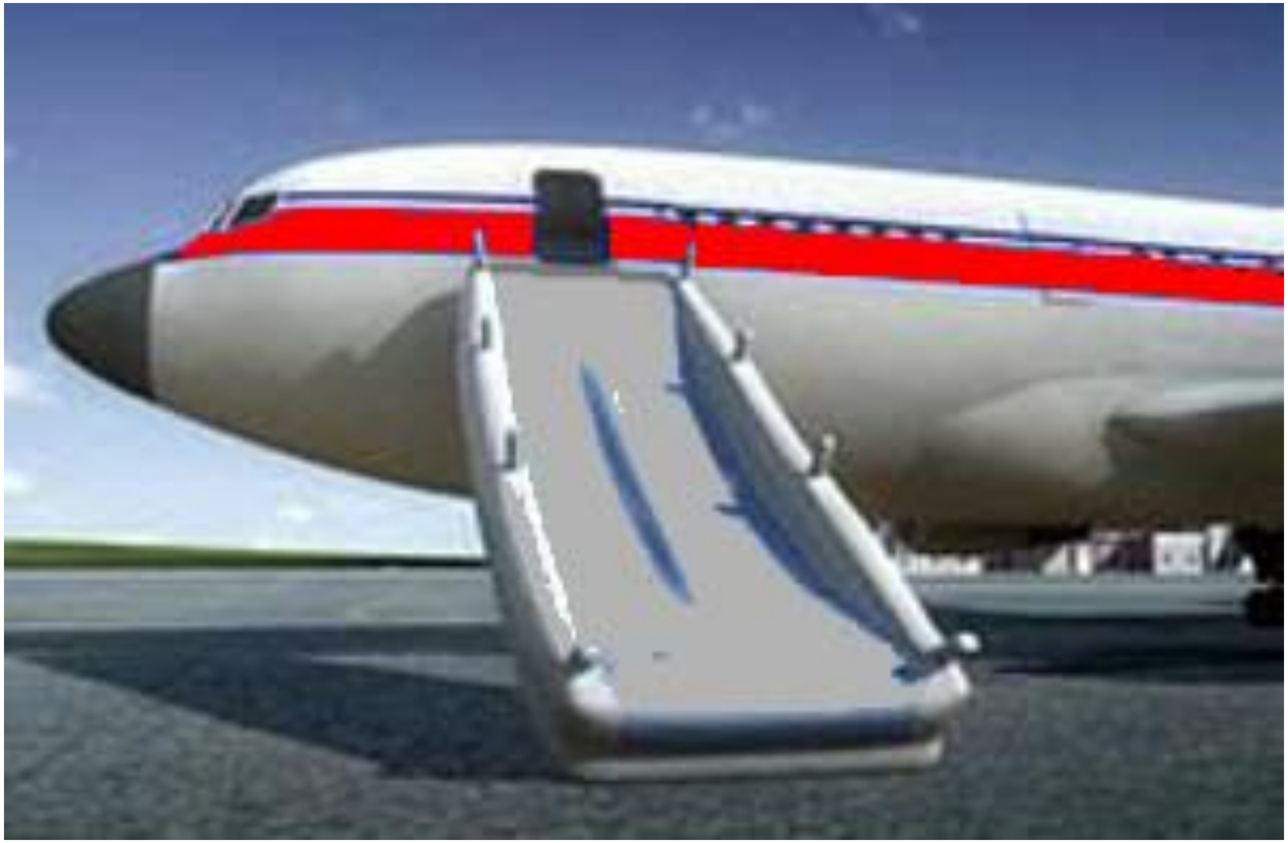
- PCB produced
- Front-end: **OK**
- ADC: **OK**
- Serializer: **OK**
- Ongoing work…

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

Concluding remarks

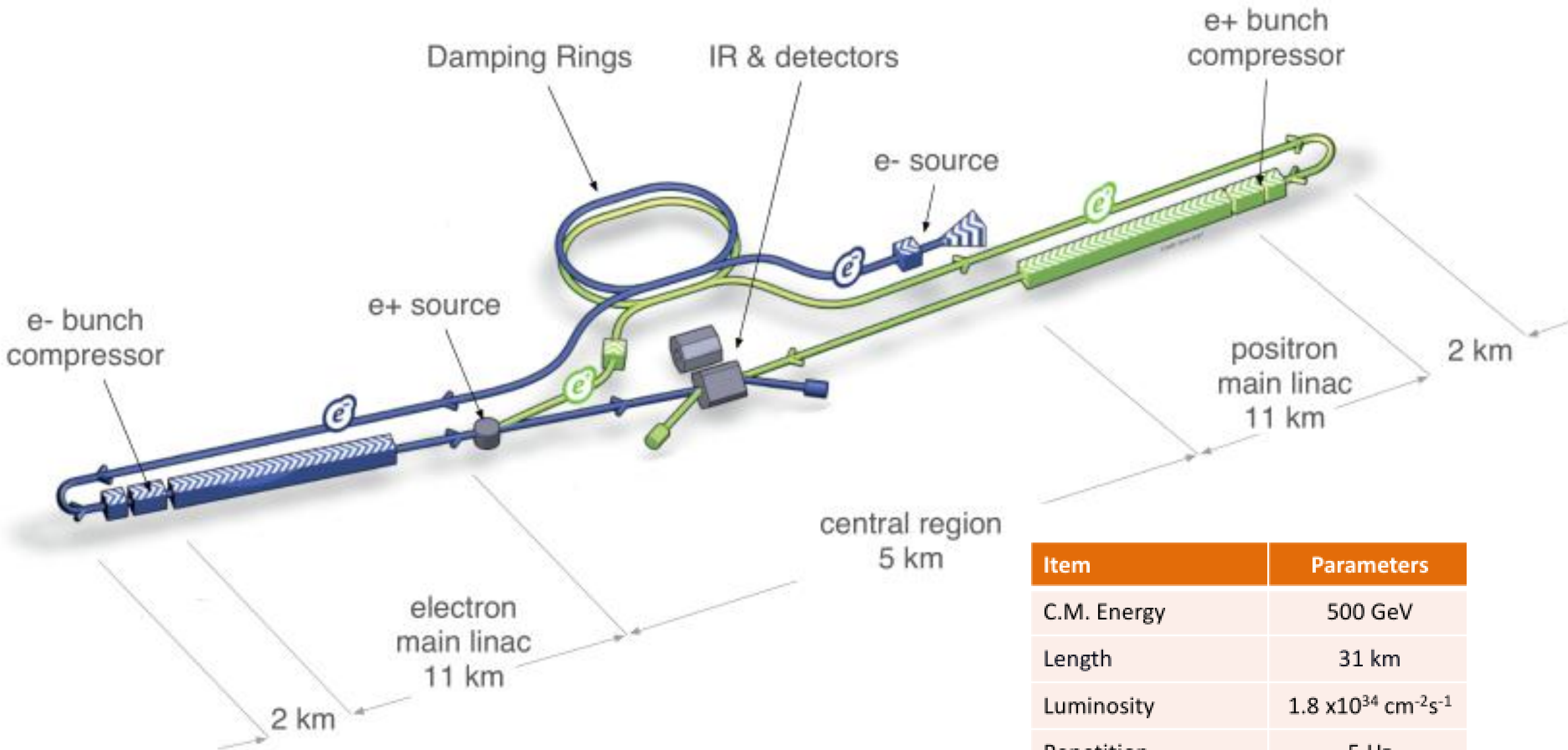
- Luminosity numbers are important
- Luminosity estimations are difficult
- Two luminosity concepts presented
  - Precise estimation from Bhabha scattering
  - Fast measurement from Beamstrahlung pairs
- Current development includes
  - ASICs
  - Testbeam results

THANKS FOR YOUR ATTENTION



EMERGENCY 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]

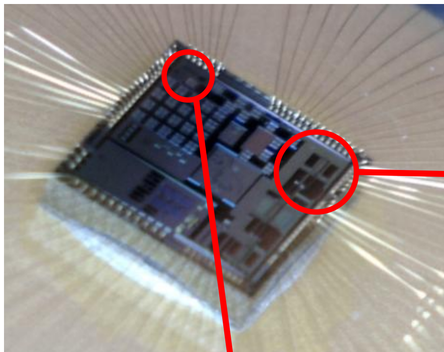
Luminosity formula

$$\mathcal{L} = F\frac{k_b N_b^2 f_{\mathrm{rev}} \gamma}{4\pi \epsilon_n \beta^*}, \tag{12.7}$$

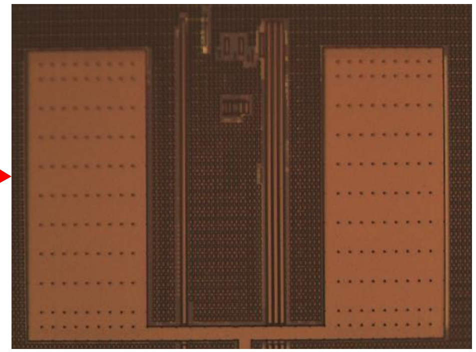
where k_b is the number of bunches per ring, N_b the number of protons per bunch, f_{rev} the revolution frequency, ϵ_n the normalized r.m.s. transverse emittance (assumed to be the same in both planes), β^* the beta-function at the collision point, and $F \leq 1$ is a reduction factor caused by the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

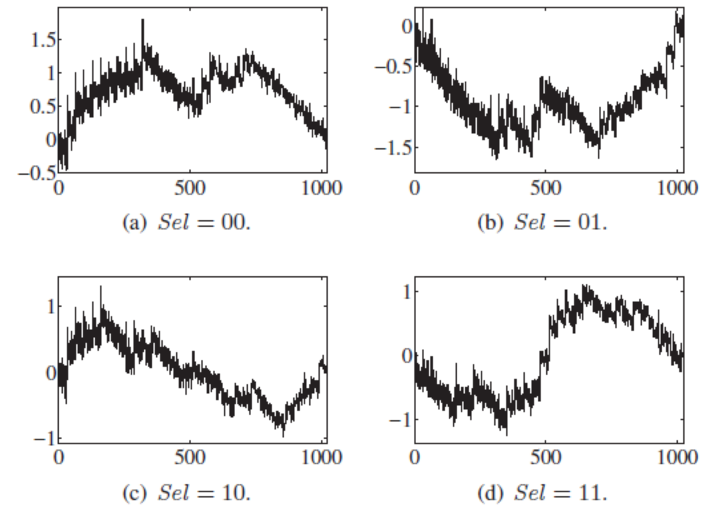
[Induction Accelerators, Takayama and Briggs (editors), Springer 2011]

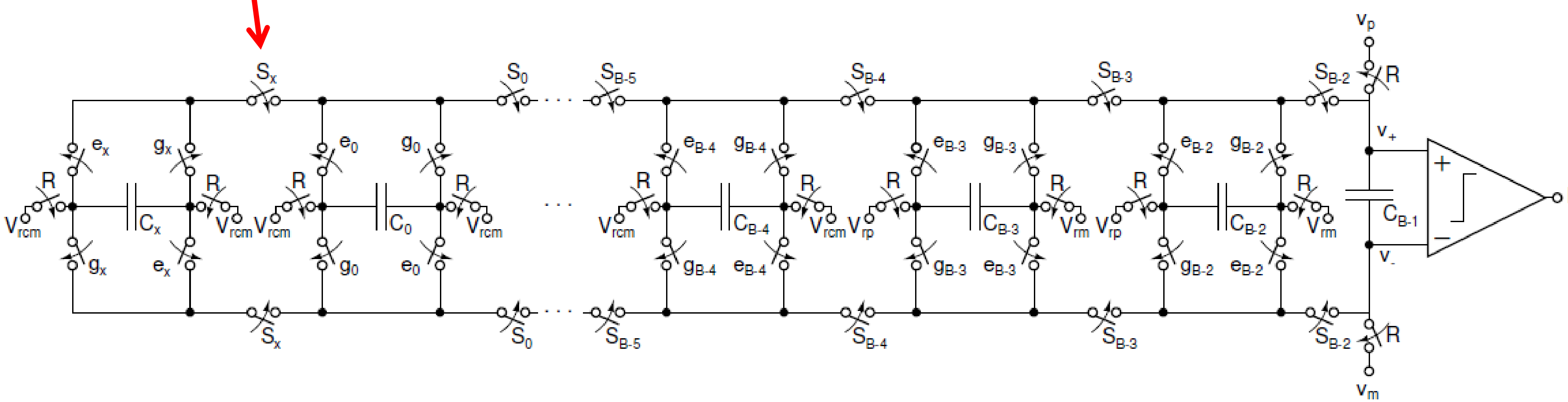
Prufpilo: Low power ADC and nonlinear ADC



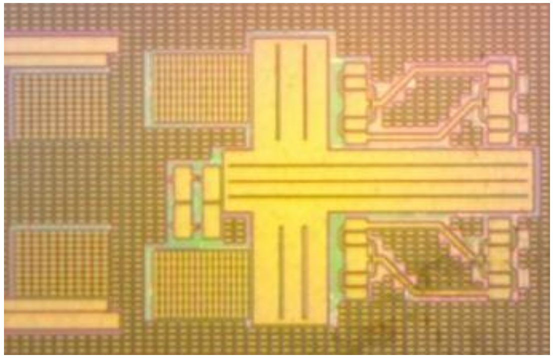
DOI: 10.1016/j.mejo.2015.06.005

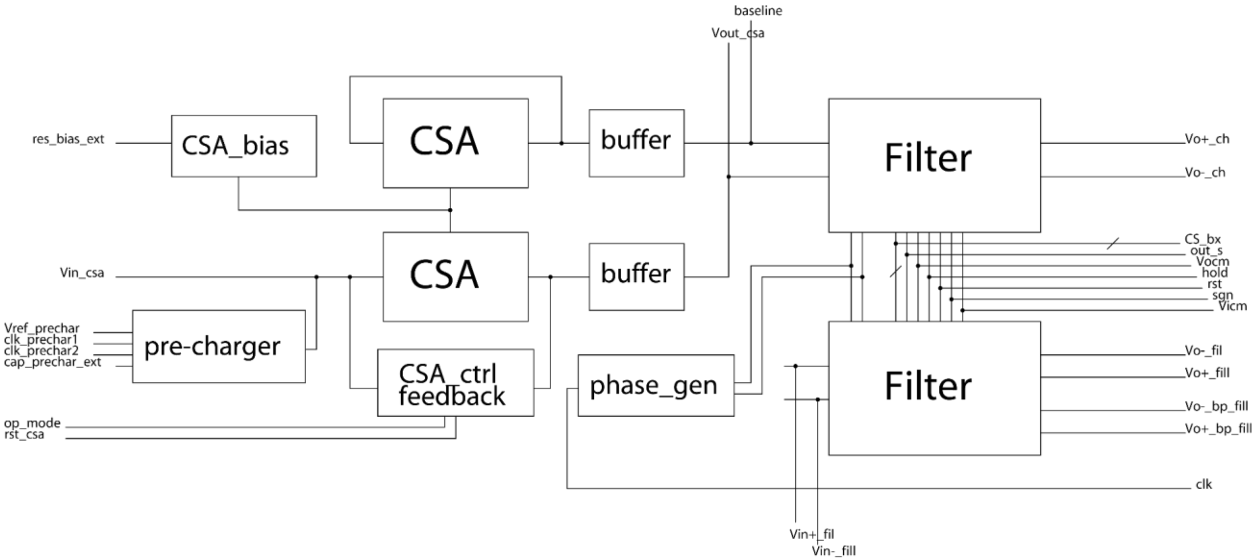




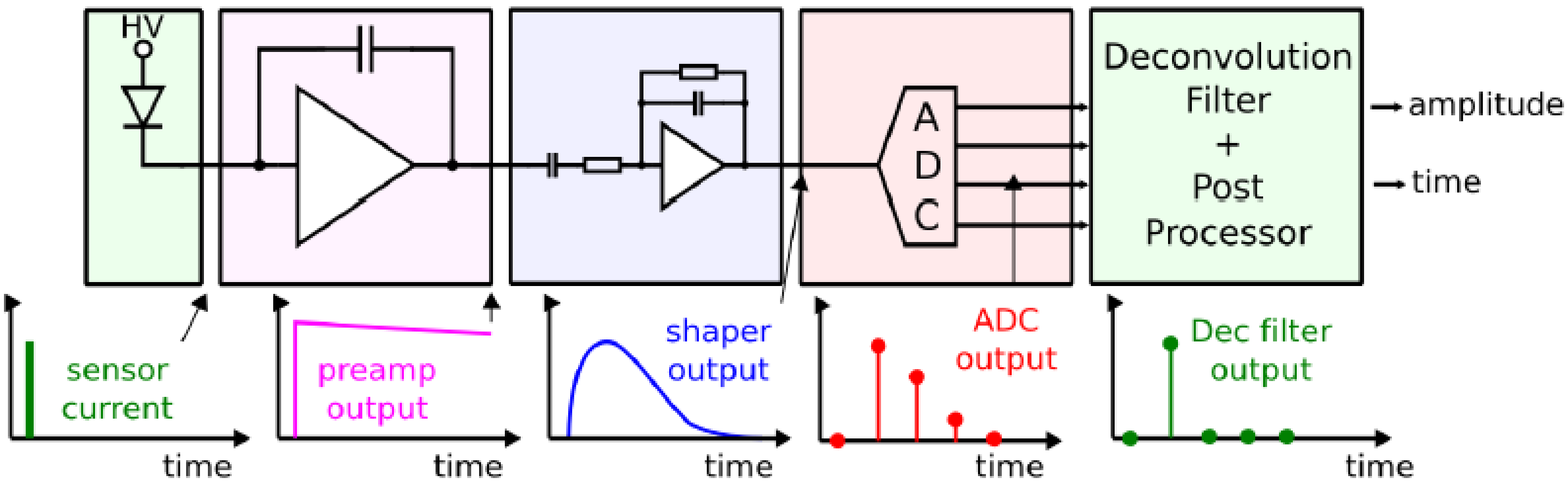


Bean V2:
arbitrary weighting function generation





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

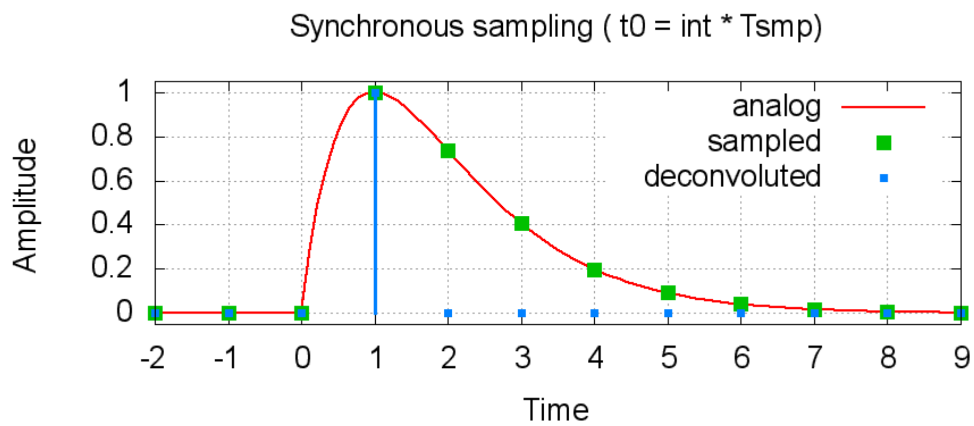
$$d_i = s_i + w_1 s_{i-1} + w_2 s_{i-2}$$

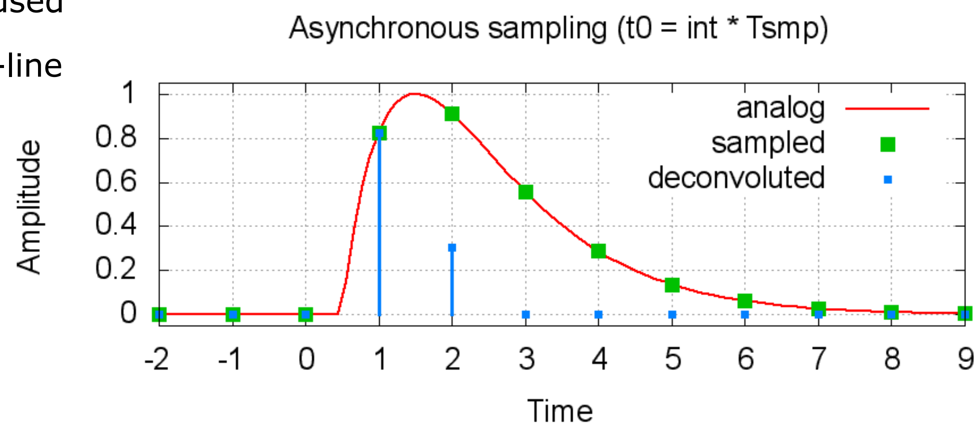
CR-RC, $T_{smp} = T_{peak} = 1$, amp = 1

- 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...**