Precision Timing in Calorimeters

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Preamble - I

Precision timing (<50 ps) capability offers myriad advantages in future collider experiments

1. Resolve complicated events at high pile-up with 4D trackers
2. Suppress out-of-time beam induced background in muon colliders
3. Enable PID at low momenta
4. Expand searches for new physics (*e.g.* long-lived particles)
5. Improve calorimeter performance (*e.g.* energy/shower reconstruction)

Preamble - II

Evolution in calorimetry

1. Compensation (*e/h=1*) using slow neutrons (~40 years ago)
2. Event-by-event compensation in dual read-out f_{em} ~*Q/S* (~20 years ago)
3. Particle flow combined high-granularity calorimeter and tracker information (~20 years ago)
4. High-granularity combined with AI/ML tools (~5 years ago) for position, energy, and time measurements (5D) = (*x, y, z, E, t*)

In this talk, focus on `timing’ in general terms first but emphasize specifically the aspects related to calorimetry with little detail on sensors and active materials

Some remarks

What's the Landscape Look Like?

In ~10-20 years, high precision 5D *(x, y, z, E, t)* calorimetry in e^+e^- machines:

- Energy scale is set by Z-boson and Higgs decays with no pileup
- 10%/√E + 1% EM and ~35%/√E HAD energy resolutions
- $\sigma_t < 10\text{-}20$ ps (*e.g.* long-lived particles)

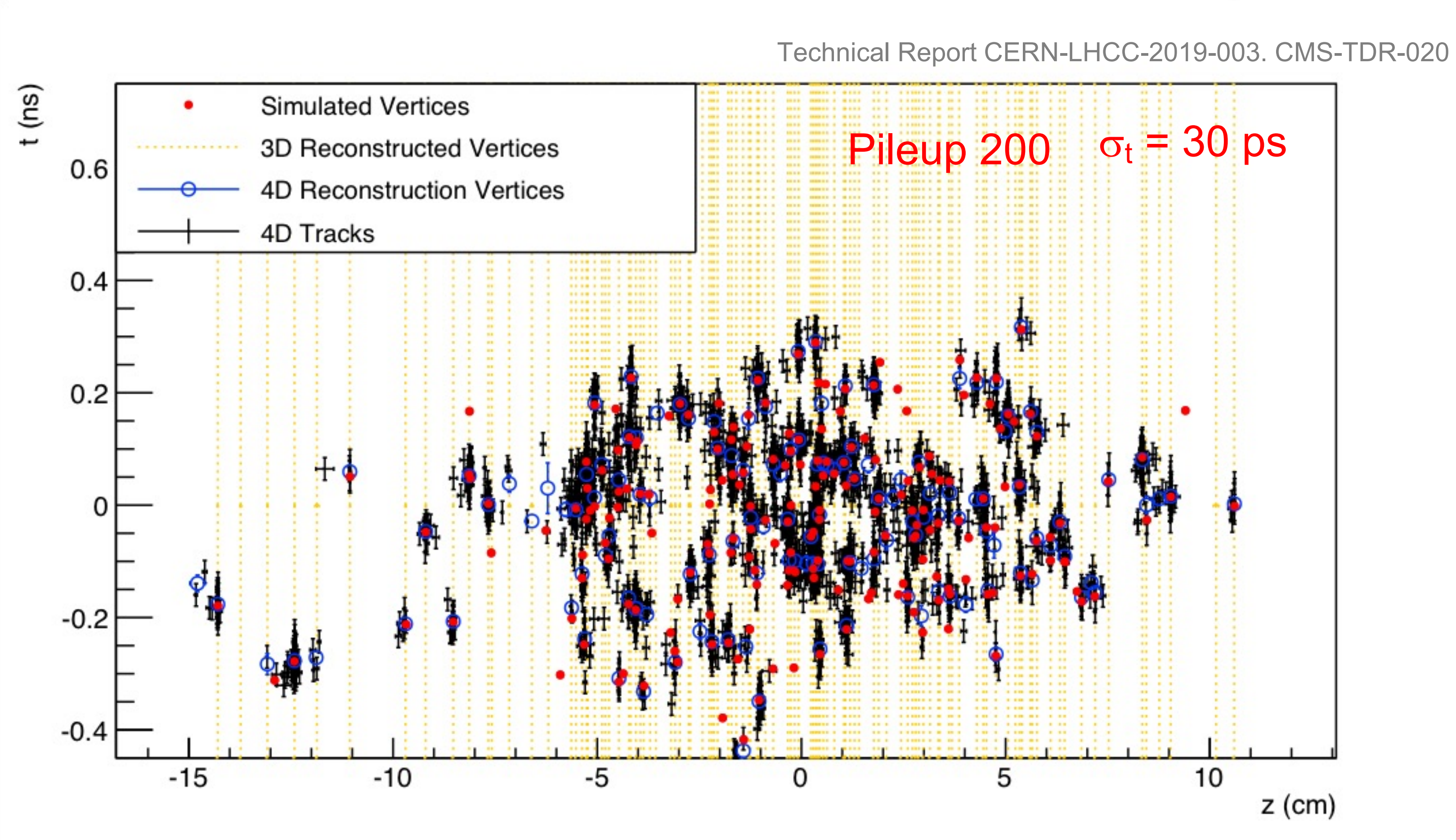
In >20 years, high precision (5D) calorimetry in *hh* machines:

- Energy scale is from <1 TeV to >20 TeV with ~1,000 pile-up
- Higgs self-coupling, Higgs invisible, new physics searches
- Radiation levels of ~ 1 GigaGray and ~10^{17} n_{eq}/cm^2
- <10%/√E EM and <30%/√E HAD energy resolutions
- $\sigma_t < 5\text{-}10$ ps (*e.g.* pile-up suppression and PID)

Ultrafast calorimetry

- Cope with ultra-high-rates
- Special detector elements (*e.g.* granular, radiation-hard, new fast active media and readout…)
- $\sigma_t \sim 1\text{-}5$ ps

Power of Precise Time Measurement – Pileup 200

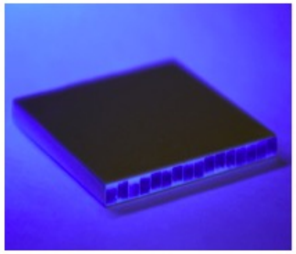


The simulated vertices are the red dots. The vertical yellow lines indicate 3D-reconstructed (*i.e.* no use of timing information) vertices, with instances of vertex merging visible throughout. The black crosses and the blue open circles represent reconstructed tracks and vertices, respectively, using a method that includes the time information and is therefore referred to as "4D." Many of the vertices that appear to be merged in the spatial dimension are clearly separated when time information is available.

Example: CMS MIP Timing Detector (MTD)

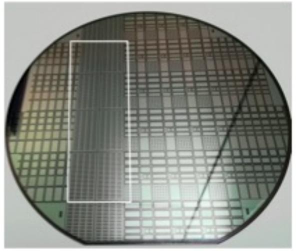
BTL: LYSO bars + SiPM readout:

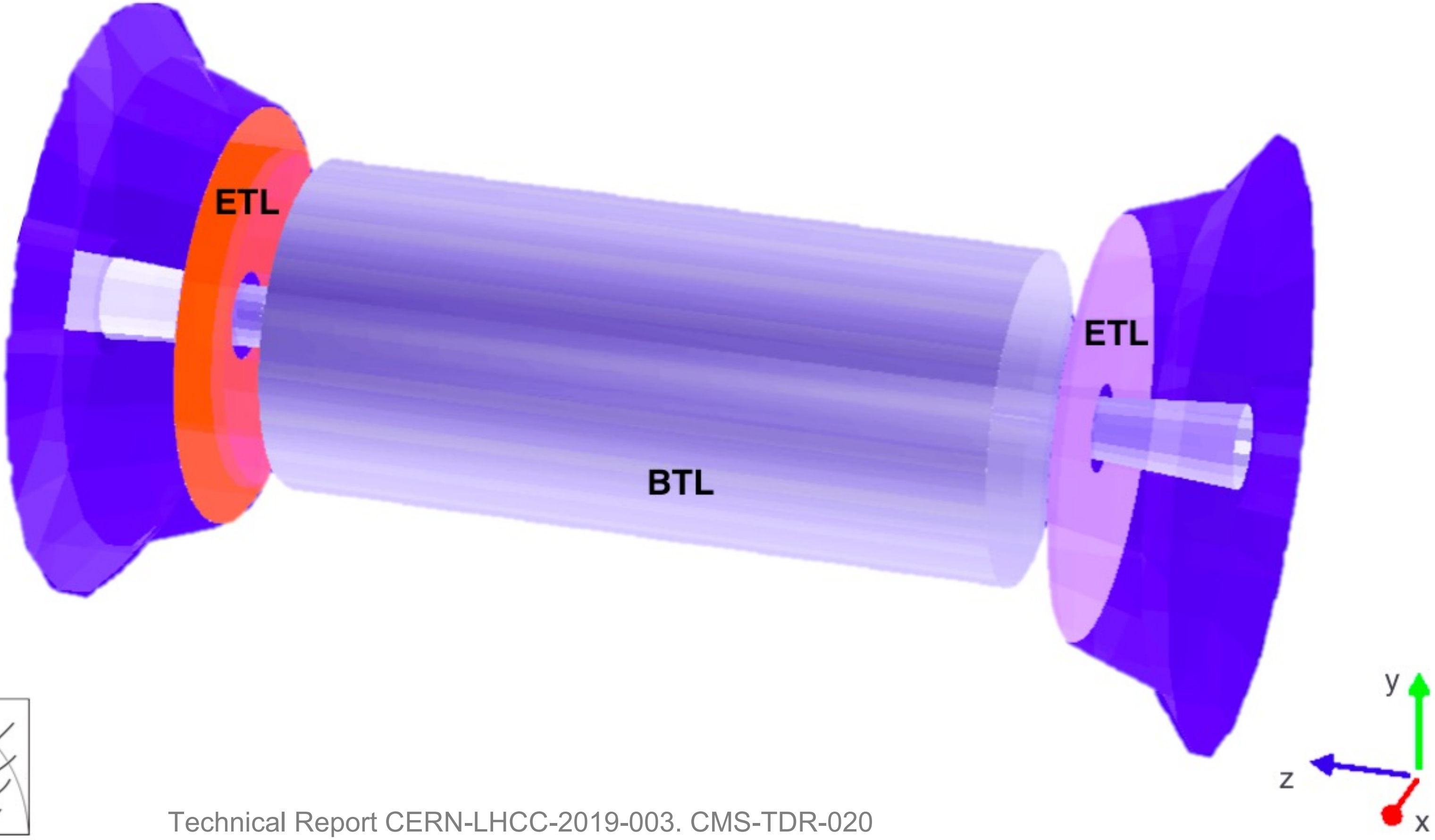
- TK / ECAL interface: |η| < 1.45
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2×10^{14} n_{eq}/cm^2



ETL: Si with internal gain (LGAD):

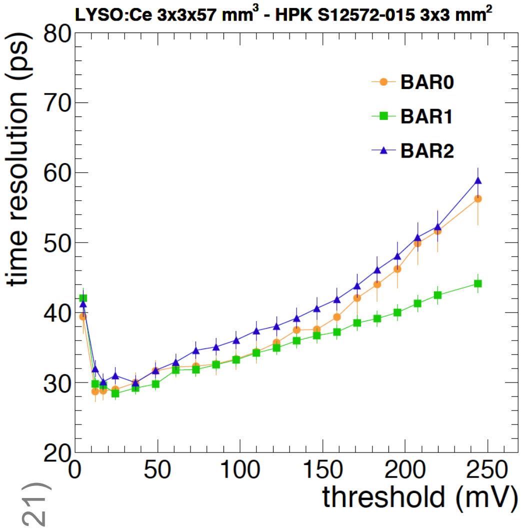
- On the CE nose: 1.6 < |η| < 3.0
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2

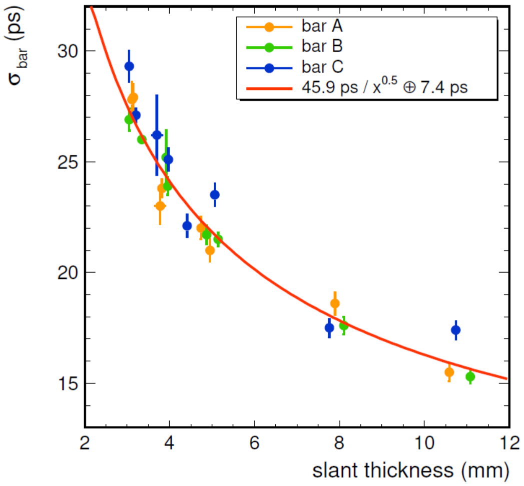


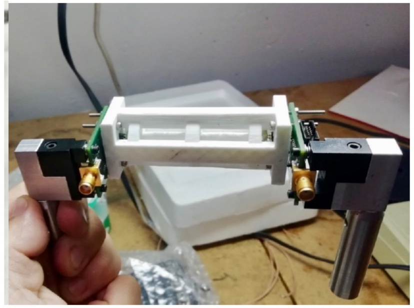


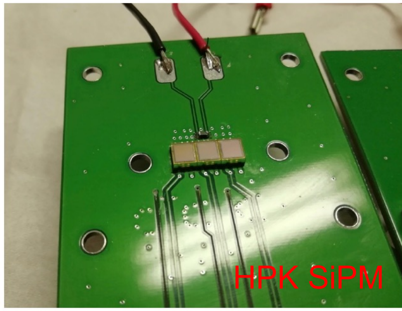
Technical Report CERN-LHCC-2019-003. CMS-TDR-020

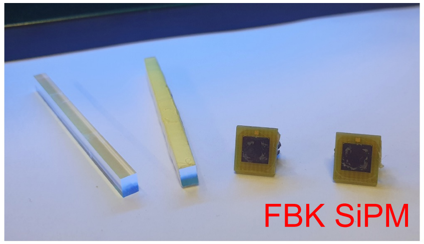
Barrel Timing Layer (BTL) Test Beam Results

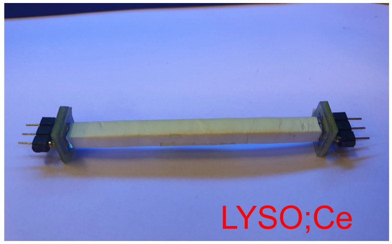












$\sigma_t^{min} = 28.4 \pm 0.4$ ps

arXiv:2104.07786v1

Two contributions to time resolution as a function of threshold:

- stochastic fluctuations in the time of arrival of the photons increase as a function of the threshold
- the noise decreases with increasing threshold; the contribution from the noise $\sigma_V/dV/dt$, reduces at larger thresholds because the derivative dV/dt is larger
- the combination of the two contributions results in a minimum in the time resolution which corresponds to the optimal operating threshold

R. Abbott et al (CMS MTD) ArXiv:2104.07786 (2021)

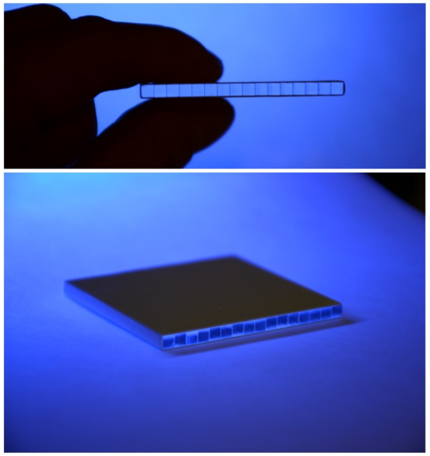
What Matters: Timing Resolution Drivers (Photons)

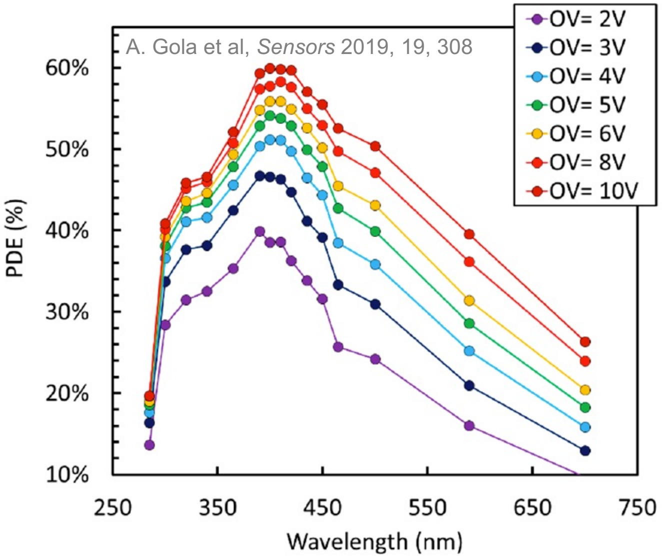
$$\sigma_{\mathrm{t}} = \sigma^{\mathrm{phot}} \oplus \sigma^{\mathrm{clock}} \oplus \sigma^{\mathrm{elec}} \oplus \sigma^{\mathrm{digi}} \oplus \sigma^{\mathrm{noise}} \oplus \ldots$$

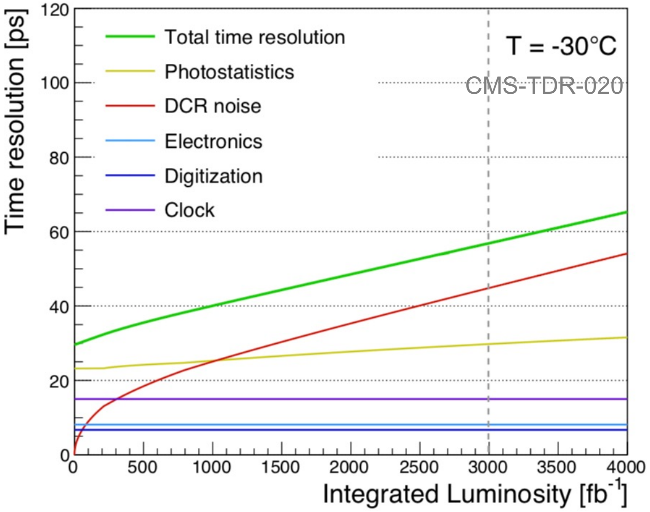
$\boxed{\sigma^{\mathrm{phot}} \approx 25\ \mathrm{ps}}$ $\boxed{\sigma^{\mathrm{elec}} \approx 8\ \mathrm{ps}}$ $\boxed{\sigma^{\mathrm{noise}} \approx 50\ \mathrm{ps\ after\ } 3,000\ \mathrm{fb}^{-1}}$

$\boxed{\sigma^{\mathrm{clock}} \approx 15\ \mathrm{ps}}$ $\boxed{\sigma^{\mathrm{digi}} \approx 7\ \mathrm{ps}}$

$$\sigma^{\mathrm{phot}} \propto \sqrt{\frac{\tau_{\mathrm{rt}}\tau_{\mathrm{ft}}}{N_{\mathrm{pe}}}} \approx \sqrt{\frac{\tau_{\mathrm{rt}}\tau_{\mathrm{ft}}}{E_{\mathrm{dep}}(LY)\epsilon_{\mathrm{LC}}(PDE)}}$$



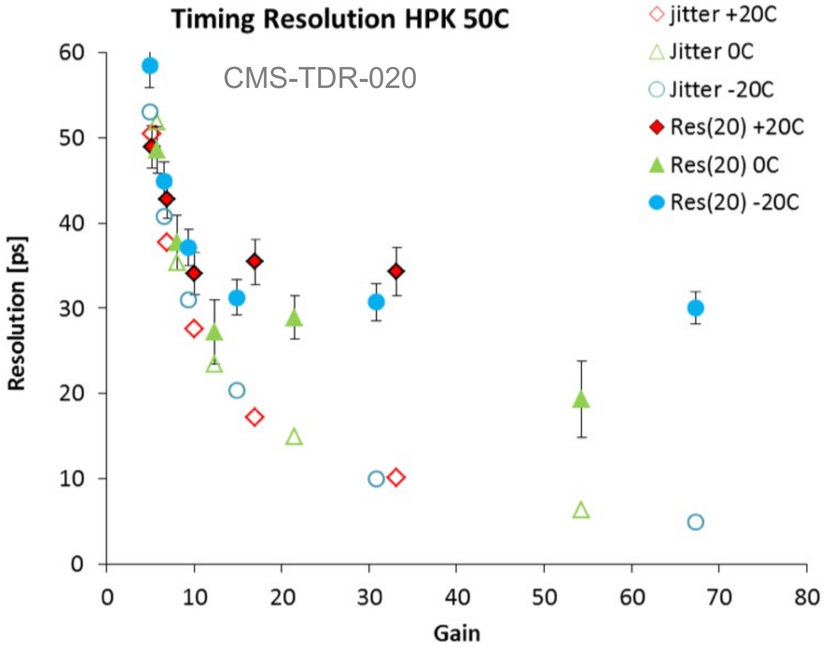


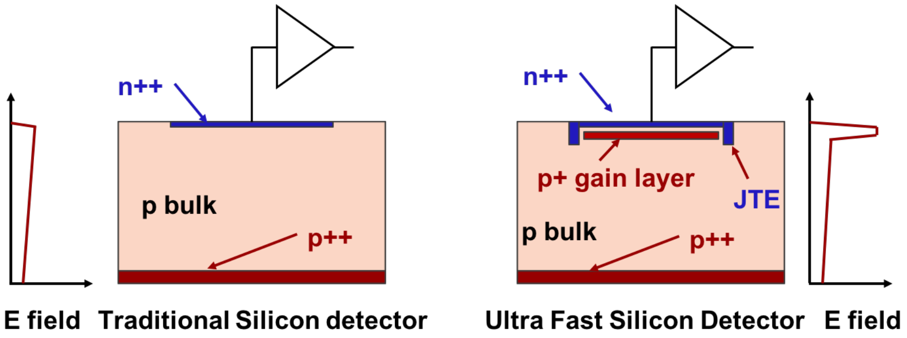


LYSO:Ce is a bright scintillator with 30,000 ph/MeV, 420 nm peak emission, decay time <43 ns, rise time <200 ps, density 7.4 g/cm^3, 9.55 MeV/cm, and refractive index 1.82

CMS MTD: 4.8~68 MRad, 2.5x10^{13}~2.1x10^{14} p/cm^2 and 3.2x10^{14}~2.4x10^{15} n$_{eq}$/cm^2

What Matters: Timing Resolution Drivers (Charge)





$$\sigma_{\mathrm{t}} = \sigma^{\mathrm{jitter}} \oplus \sigma^{\mathrm{ionization}} \oplus \sigma^{\mathrm{distor}} \oplus \sigma^{\mathrm{TDC}} \oplus \ldots$$

$$\sigma^{\mathrm{jitter}} = \frac{N}{dV/dt} \propto \frac{e_{\mathrm{n}} C_{\mathrm{d}}}{Q} \sqrt{t_{\mathrm{r}}}$$

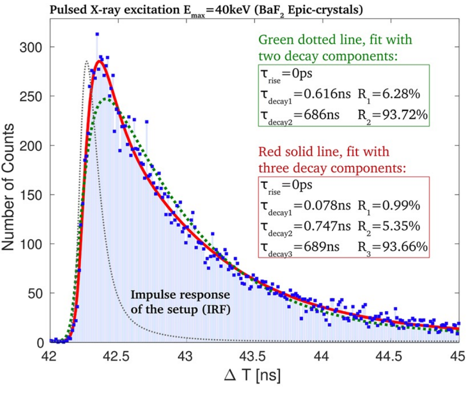
$$\sigma^{\mathrm{ionization}} = \sigma^{\mathrm{Total}} + \sigma^{\mathrm{Local}}$$

The jitter and total time resolution as a function of gain for a Hamamatsu 50-μm thick UFSD sensor: the jitter term decreases with gain, while the total time resolution flattens around $\sigma_t = 30$ ps

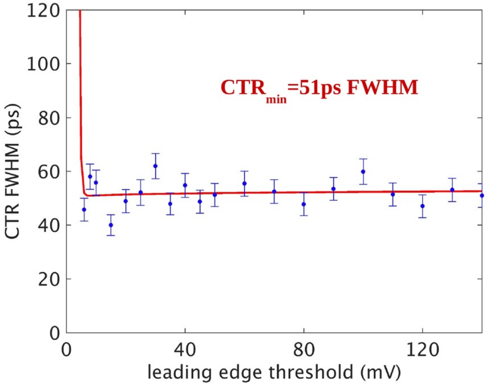
Non-uniform charge deposition determines the intrinsic time resolution; this is a function of the sensor thickness and is about $\sigma_t \approx 25$ ps for 50-μm thick sensors

The time resolution $\sigma_t = 30$–40 ps will degrade to 40–50 ps at a fluence of 3×10^{15} n_{eq}/cm^2

Status of Some Timing Studies



(a)



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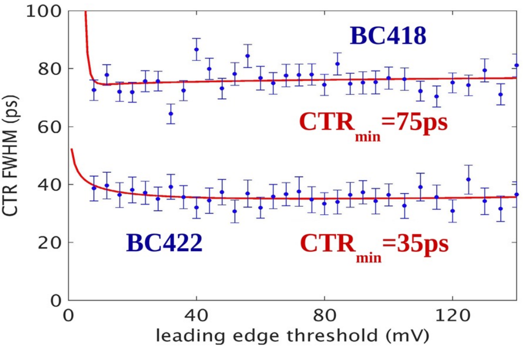
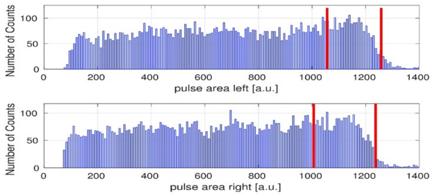
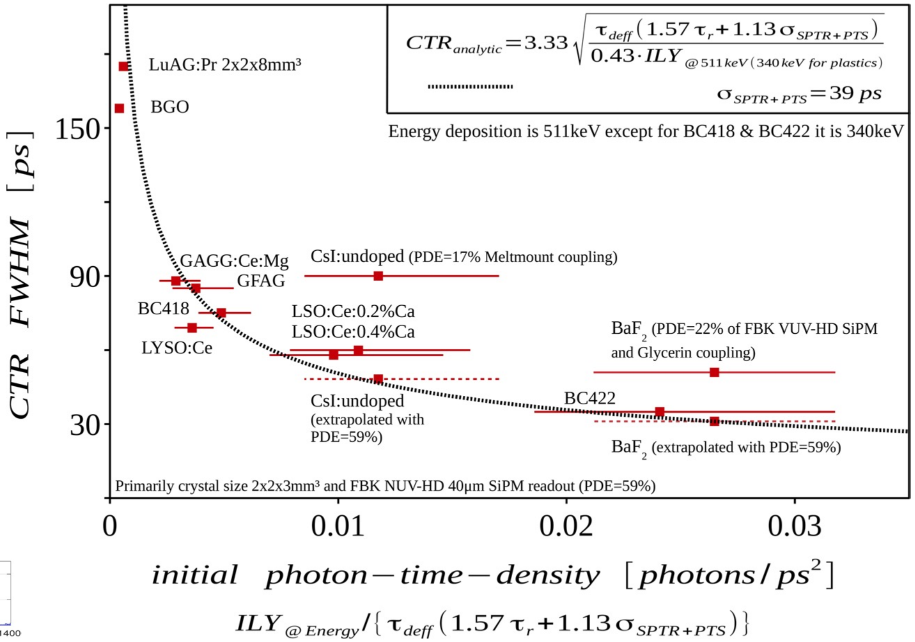


Energy selection on pronounced Compton-edge with **340keV**.

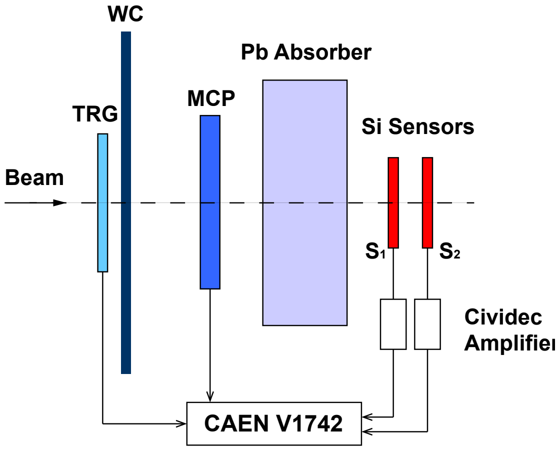


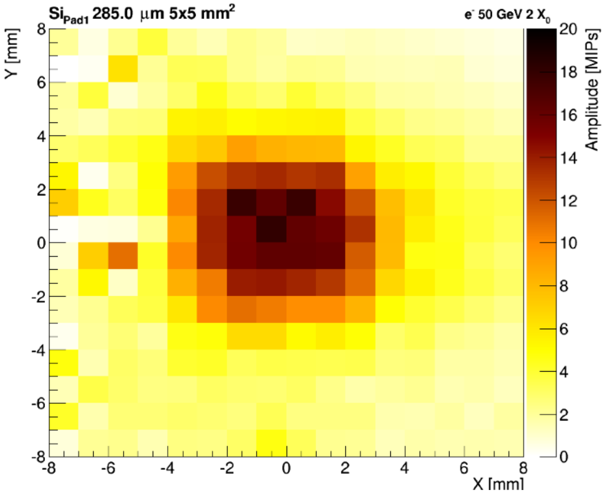


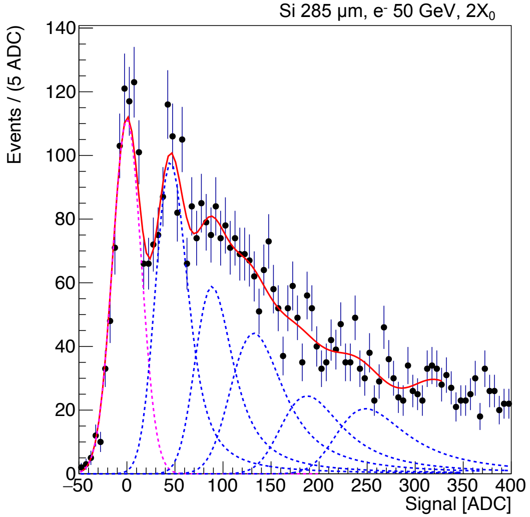
S. Gundaker et al, Phys. Med. Bio. (2019) 64:055012,
S. Gundaker et al, Phys. Med, Bio. (2020) 65:025001

Understanding of CTR is maturing and provides good guidance (Vinagradov 2018) for high-rate sampling readout systems. Typically, these studies are carried out in small samples (2x2x3 mm^3). BaF$_2$ and BC422 emerge as a good candidates

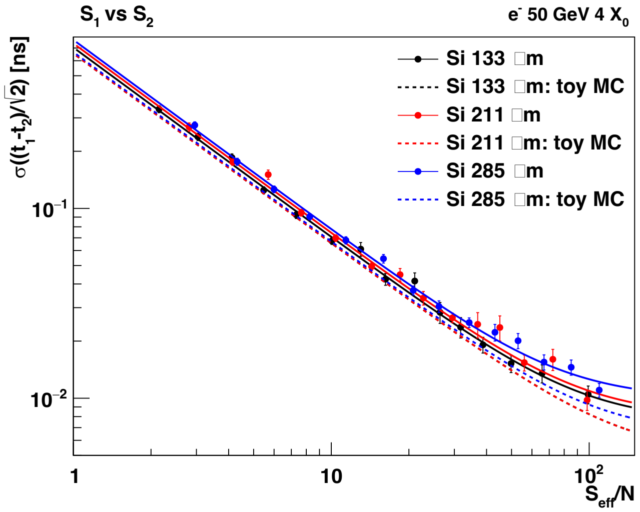
Timing Performance of Thin Planar Silicon Sensors

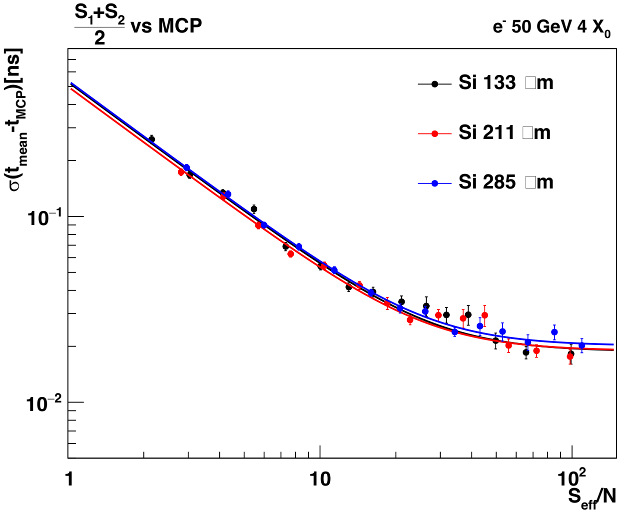






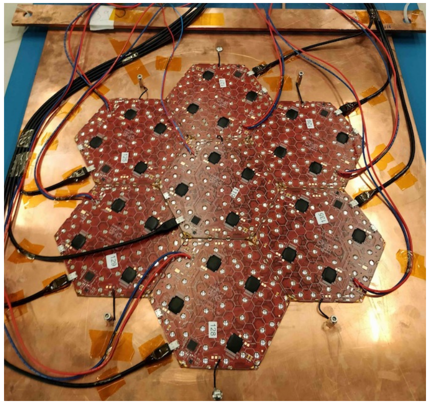
NIMA 859 (2017) 31-36

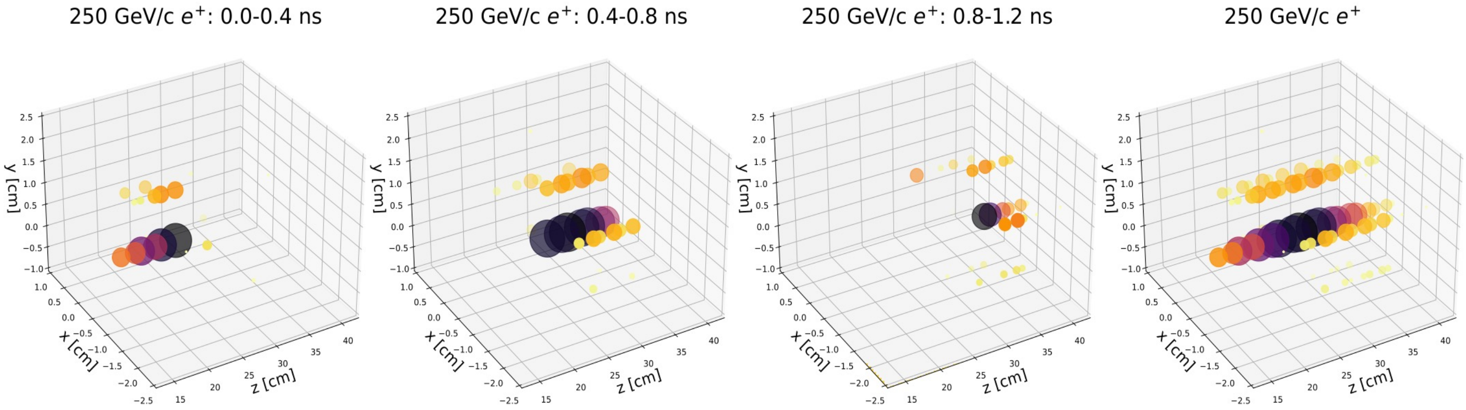


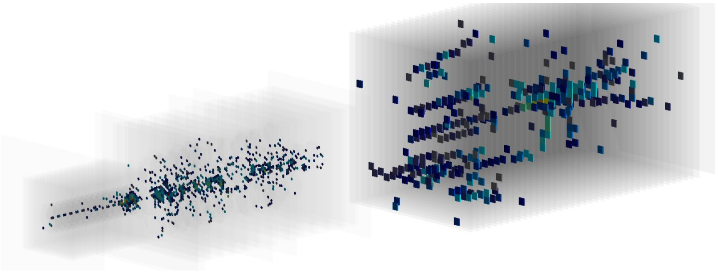


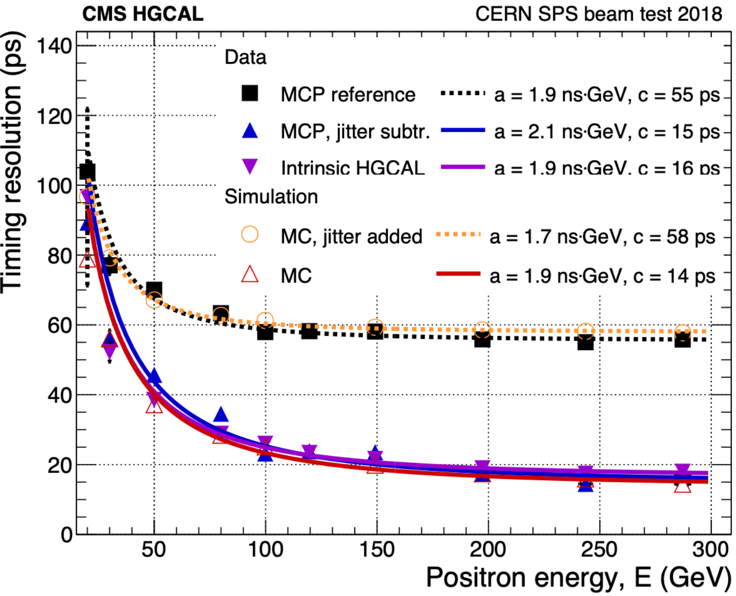
Three different silicon planar sensors, with depletion thicknesses 133, 211, and 285 μm. The measurements and simulations show better than 20 ps timing resolution for signals larger than a few tens of MIPs

CMS HGCAL Timing Performance





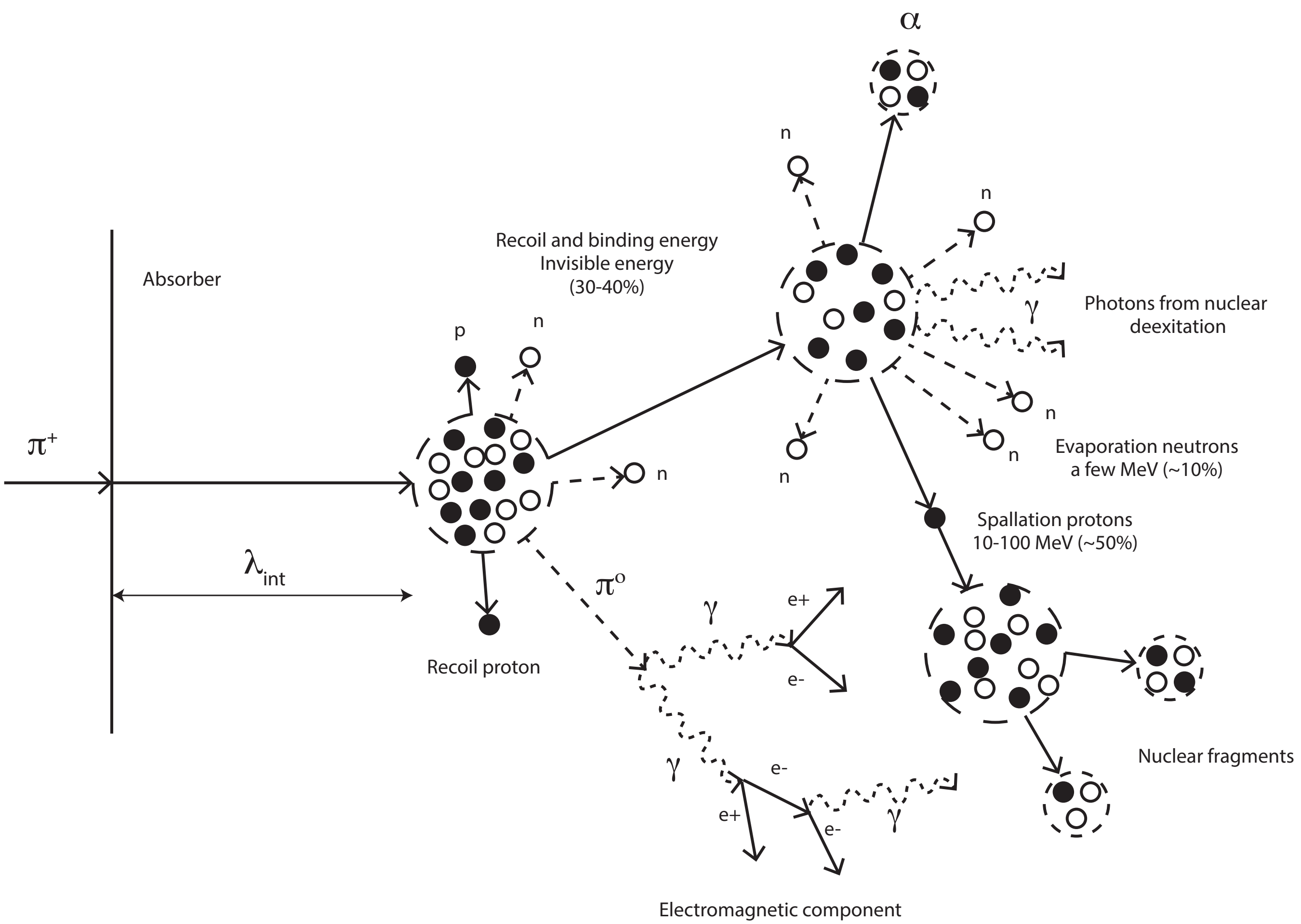




The timing resolution is measured for all layers using the MCP as a reference (black squares) as well as using only half the layers with respect to the other half and assuming they have identical resolution (purple triangles). Other measurements in the figure allow to cross-check and confirm the hypothesis that a global jitter between the MCP and HGCAL systems was present in the measurements

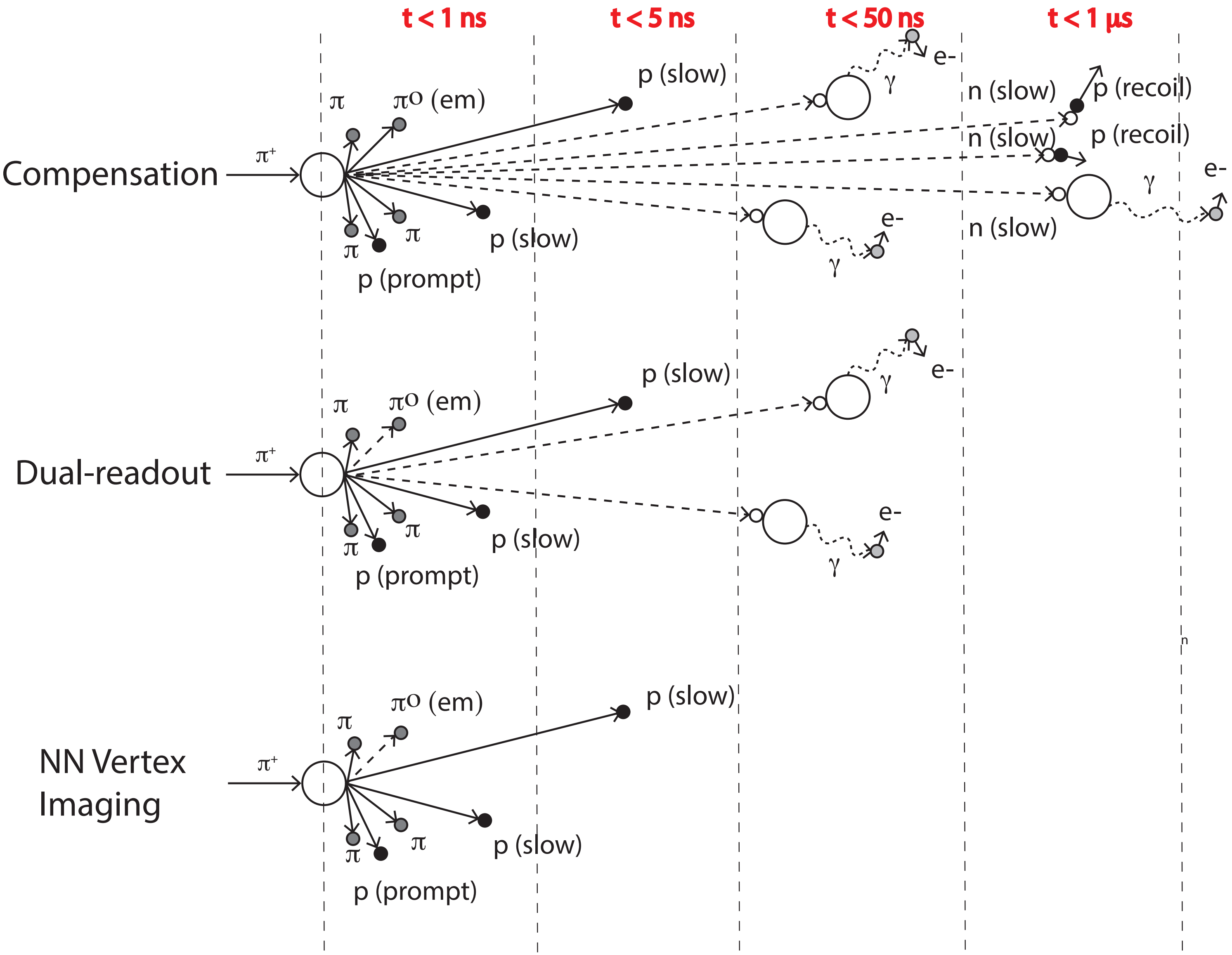
B. Acar et al (CMS HGCAL) ArXiv:2211.04740 (2023) and ArXiv:2312.14622v1 (2023

Hadronic Interaction Cartoon - I

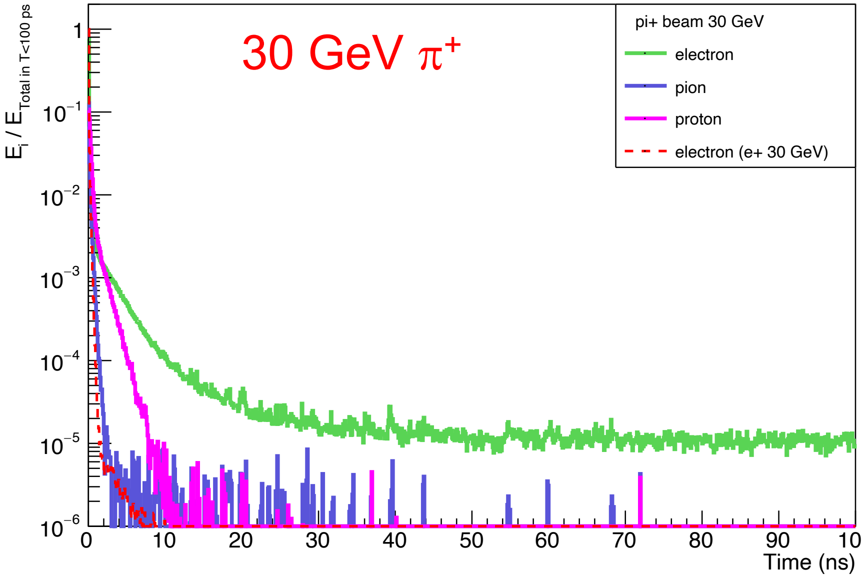


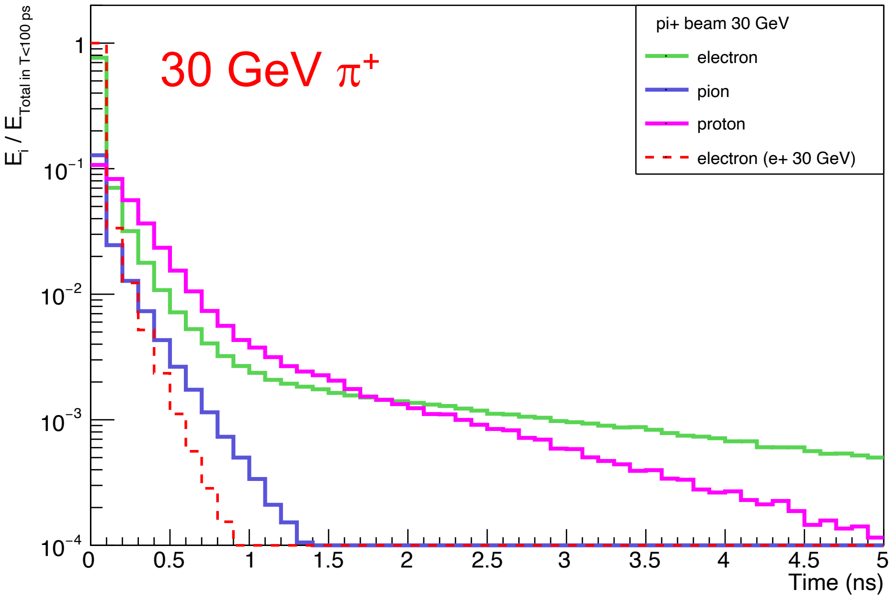
The energy and time spectra of the hadronic shower particles are wide. The percentages above refer to the fractions of the non-electromagnetic energy component. The fluctuations in the electromagnetic and invisible energy fractions (part of energy loss that does not generate a signal) degrade hadronic energy resolution

Hadronic Interaction Cartoon (time) - II

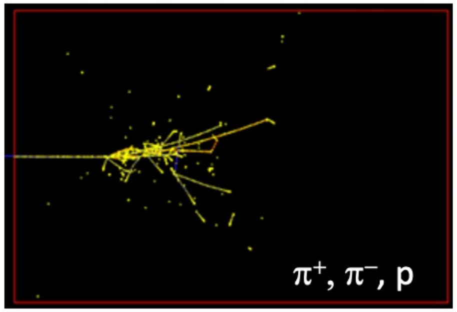


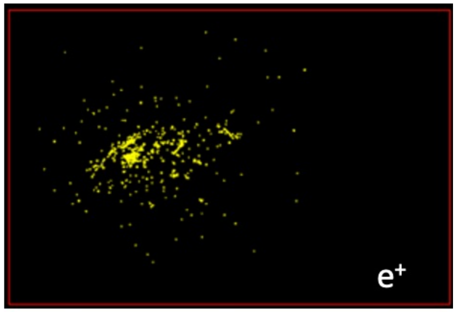
Time Evolution of Hadronic Shower



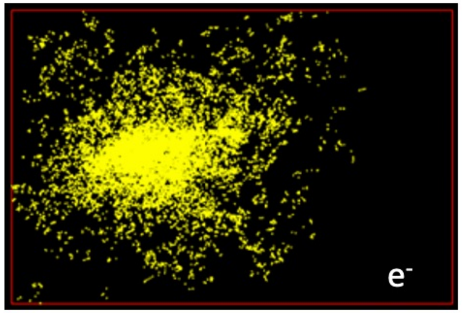


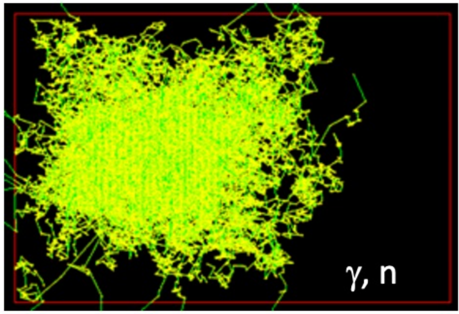
Time structure in a sampling calorimeter (17 mm Cu and 3 mm Si). The times are given in local time $t = t_{G4} - z/c$ to correct for the travel time along the z-axis.





Fast Component < 5 ns

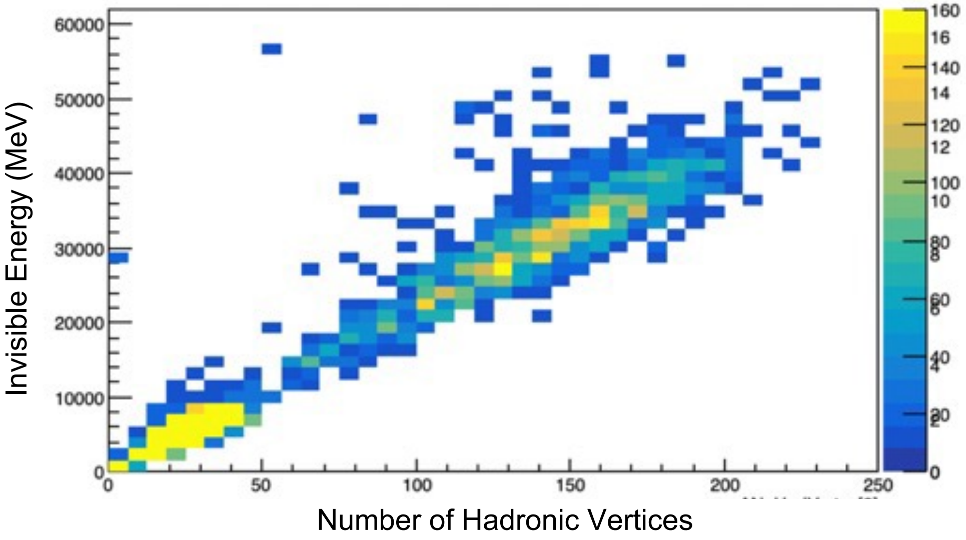




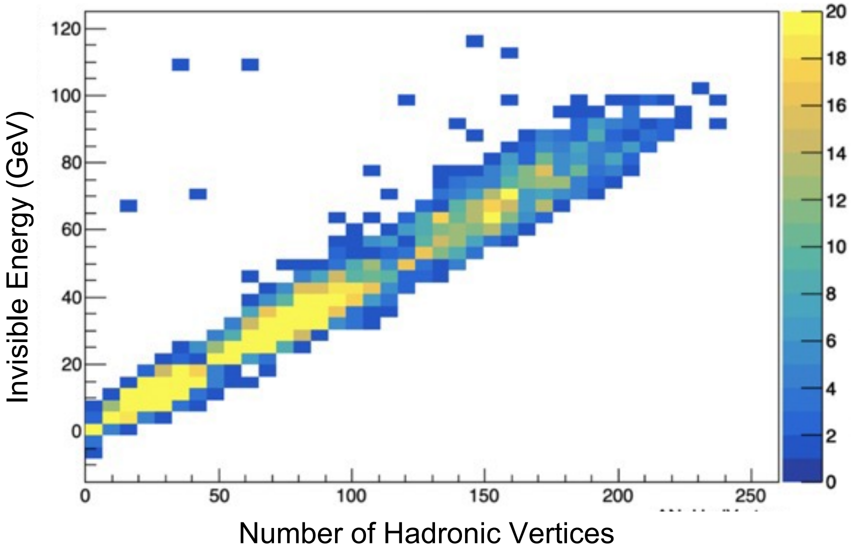
Slow Component > 10 ns

Counting Hadronic Vertices in Short Times

Ionization (t < 5 ns)



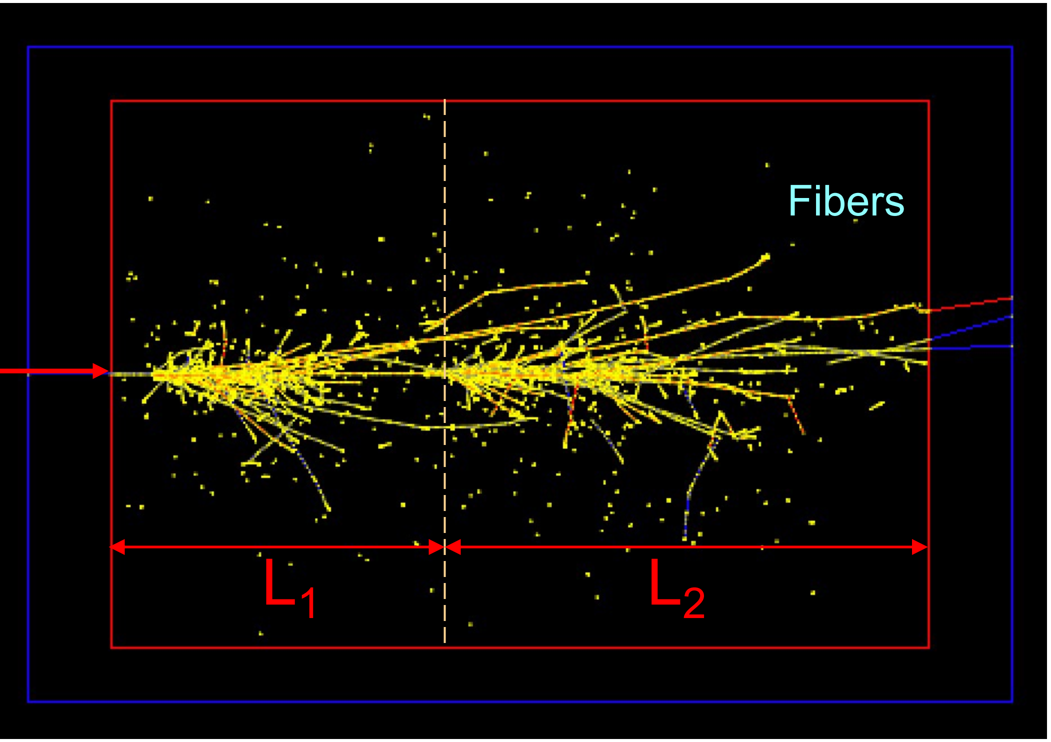
Cherenkov (t < 2 ns)



The invisible energy in a hadronic shower scales with the number of hadronic vertices. Counting or imaging the number vertices in a highly granular calorimeter will likely improve the hadronic energy resolution when measured event-by-event

Longitudinal Segmentation with Timing

Fibers in spaghetti calorimeters generate and efficiently transport light. With sufficient timing resolution, it may be possible to effectively segment the calorimeter in depth



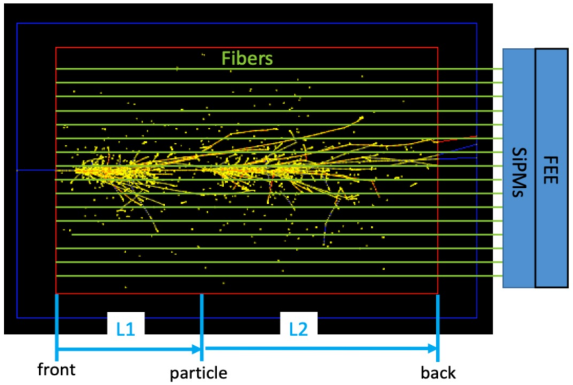
Signal time = $L_1/c + L_2/(c/n)$,

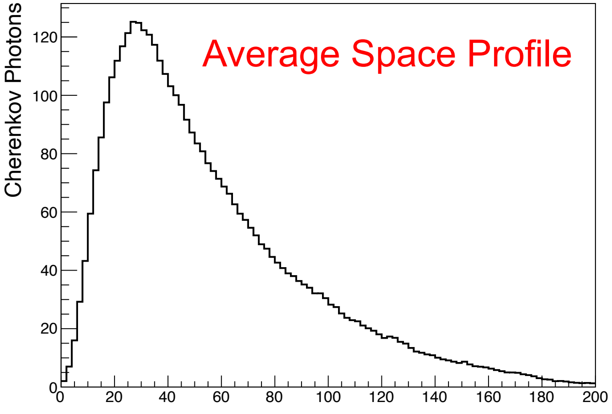
(c/n) = velocity of light in fiber (n~1.45)

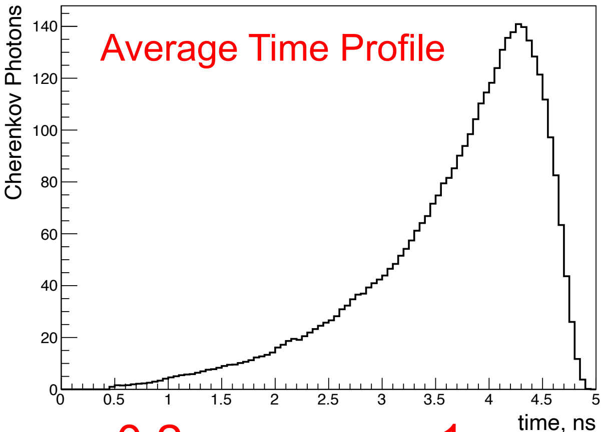
~20 cm/ns or ~1 cm/50 ps

There is significant savings in channel count (and calibration) as one fiber bundle represents many channels along the depth of calorimeter.

Simulations/Estimates with DREAM Module





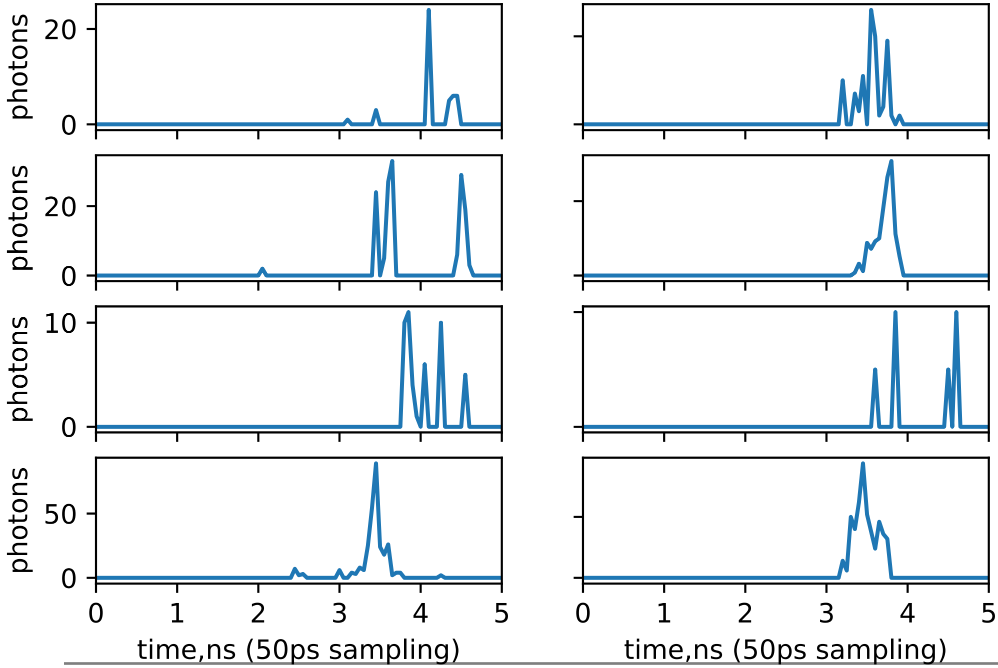


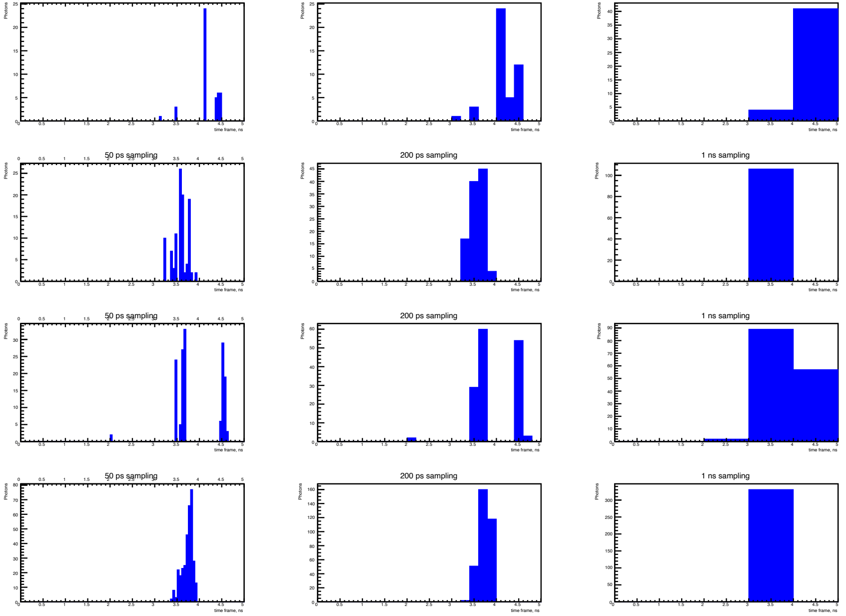
50 GeV π^+ in 1.2 cm x 1.2 cm tower

0.05 ns (1 cm)

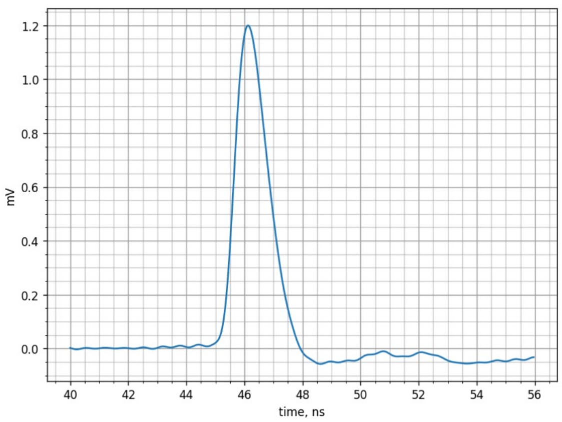
0.2 ns (4 cm)

1 ns (20 cm)

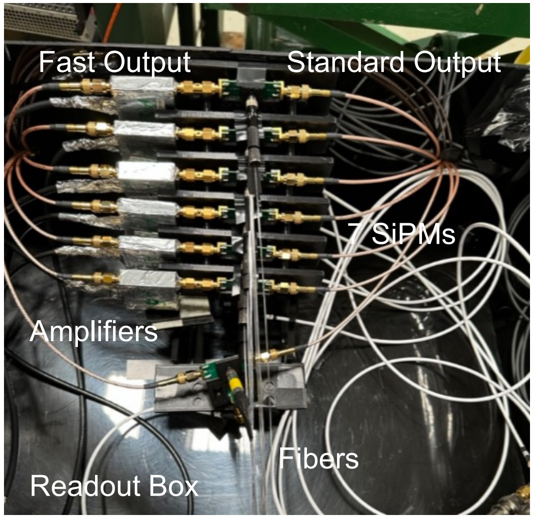


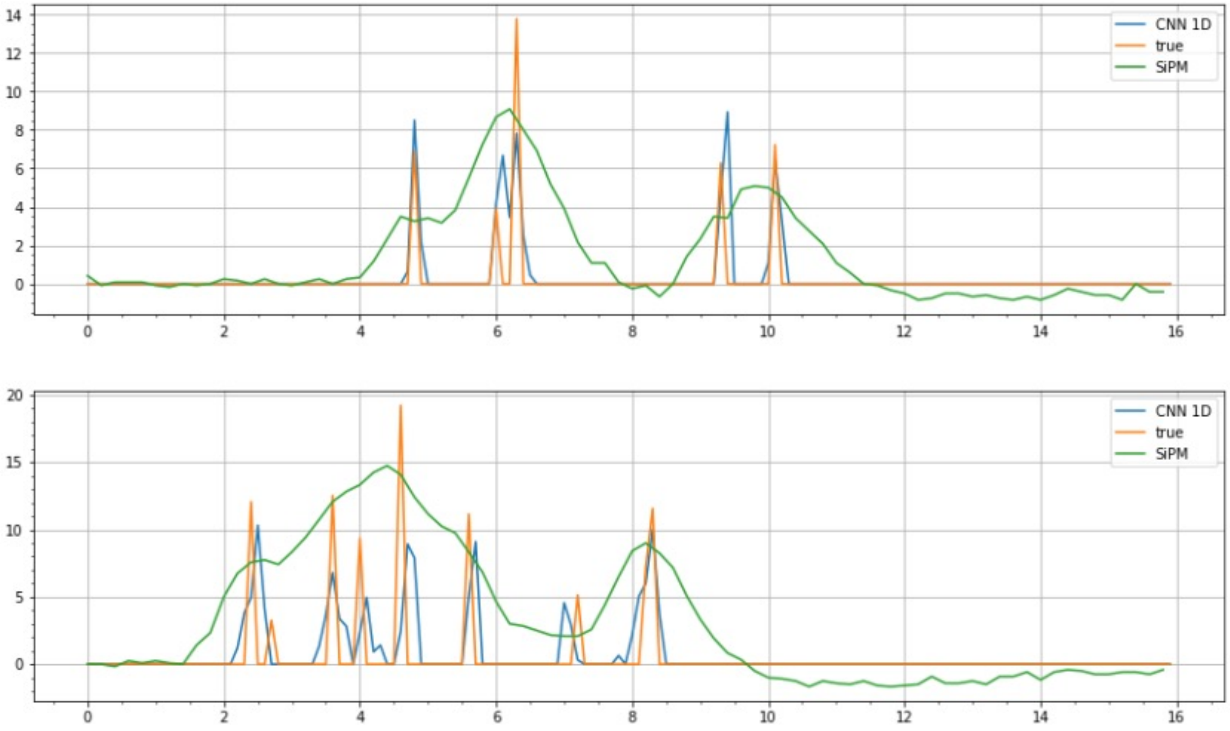


Deconvolution of Pulse Train with CNN



Single Cherenkov photon SiPM (OnSemi Fast output) pulse obtained in 2023 beam test





It seems possible to deconvolute overlapping SiPM (Cherenkov) pulses to reveal the true distribution of shower components using CNN:

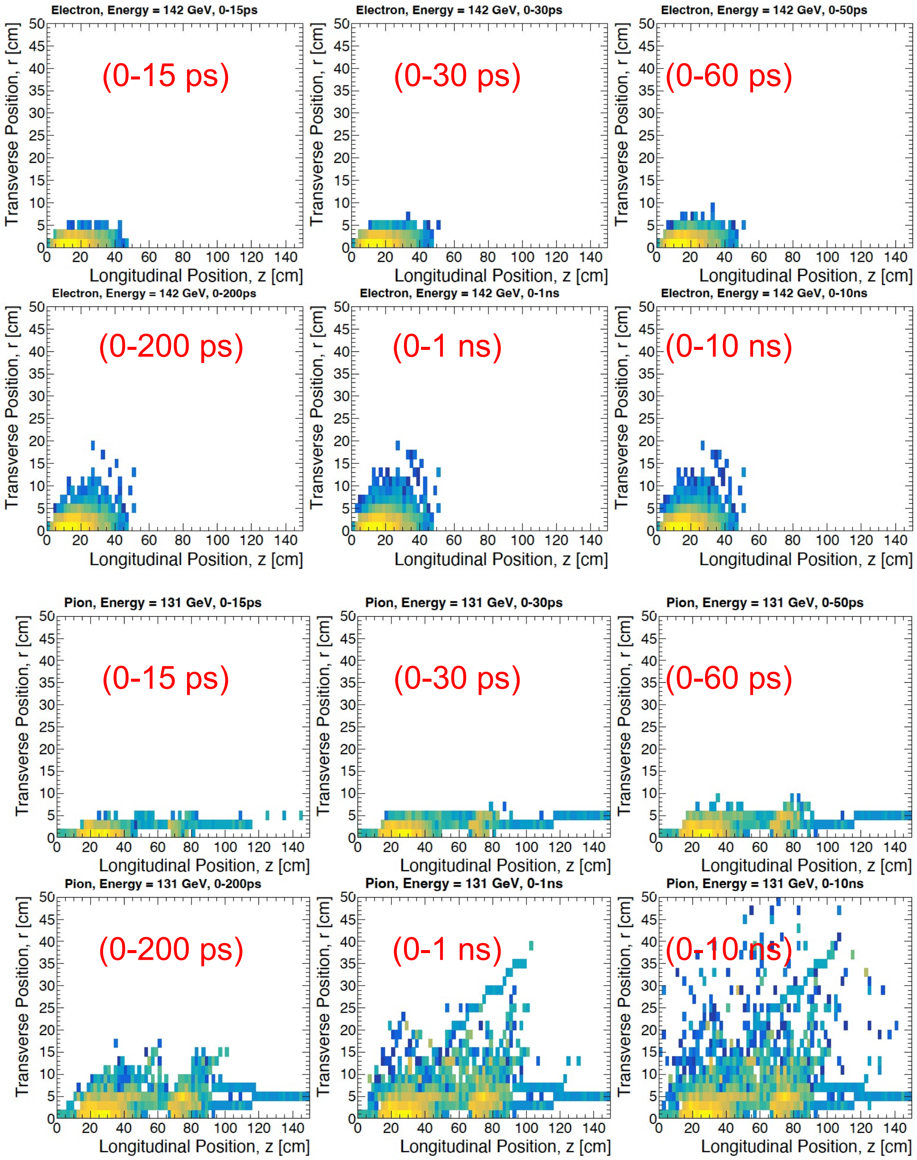
Green: Convoluted SiPM pulse train

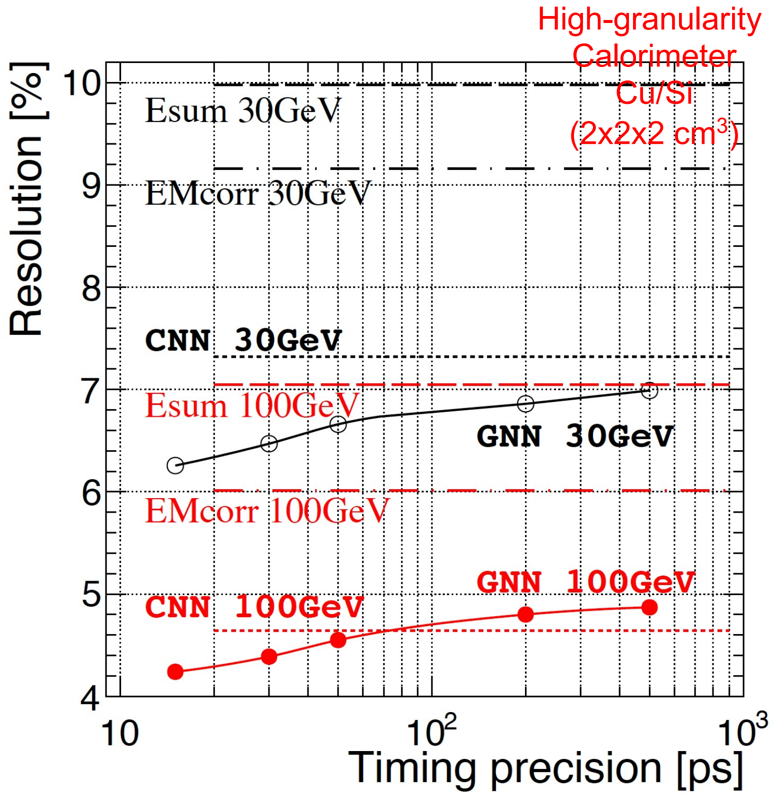
Blue: Deconvoluted SiPM pulse train

Orange: True pulse train

Energy Resolution with Timing Information Using NNs

N. Akchurin et al JINST 17 P12036 (2021)





- CNN trained only pions achieves marked improvement over the conventional approaches while maintaining the performance for photon reconstruction (pure EM showers)
- GNN, with edge convolution (PointNet), with shower development timing information further improves energy resolution when shorter time slices are included
- GNN is a good candidate tool for energy reconstruction in granular or multi-readout fibers calorimeters because it can perform energy regression in a single step by combining the multi-layer 2D energy and timing information with minimal pre-processing of the raw signal from the detector

Time-assisted Software Compensation

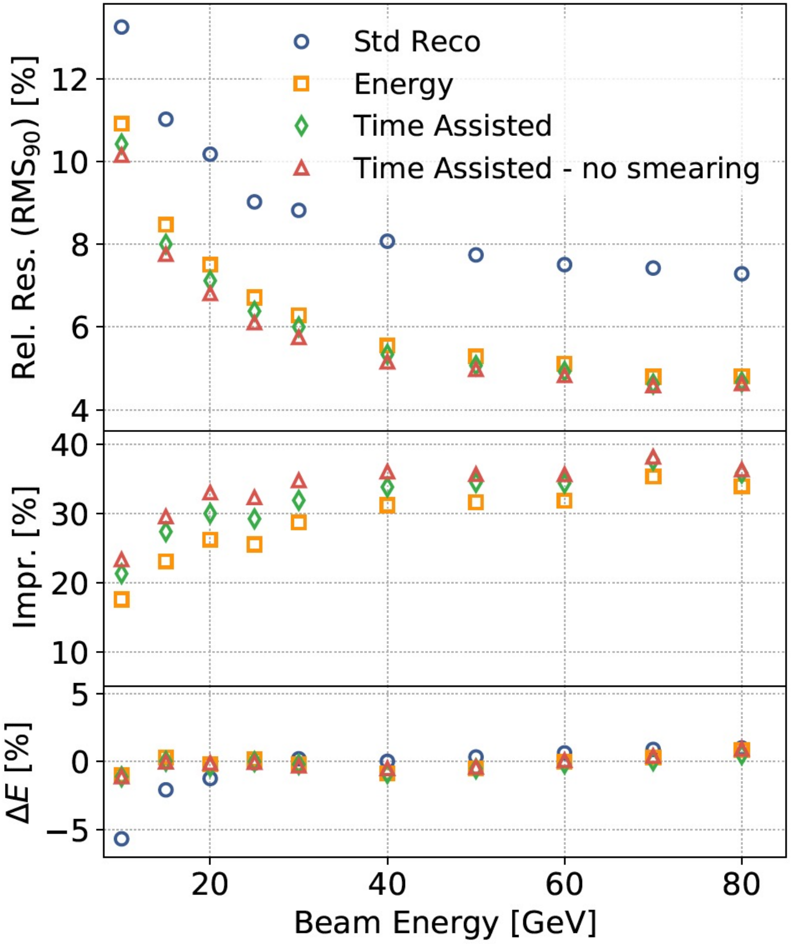
C. Graf and F. Simon, JINST 17 P08027 (2022)

5D reconstruction of the shower includes time measurement on a cell-by-cell basis

Local energy reconstruction is weighted bin-by-bin using a parametrization and the weights are calculated by minimization of a loss function

$$E^{\mathrm{local}}_{\mathrm{reco}} = \sum_{j\,\in\,\mathrm{hits}} e_j \cdot w(e_j, E_{\mathrm{std}}).$$

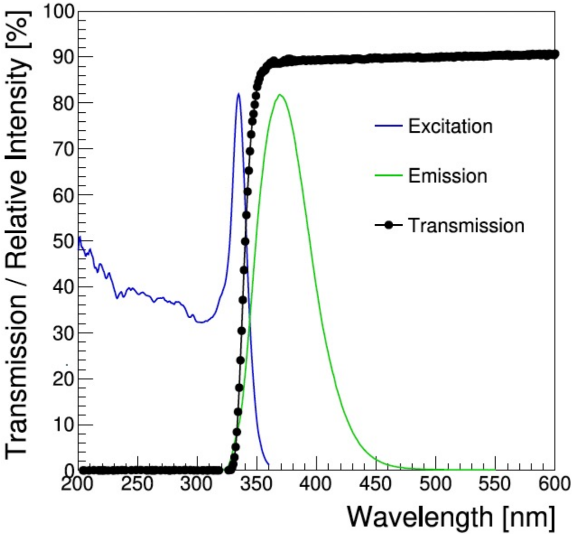
Local timing information, assuming 1 ns resolution, employing a simple algorithm in a highly granular calorimeter improves hadronic energy resolution

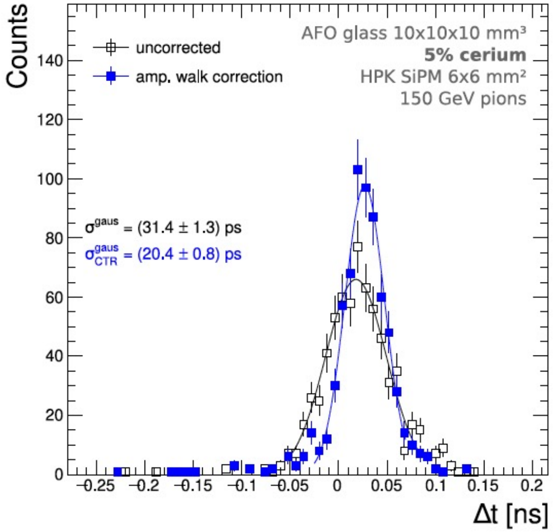


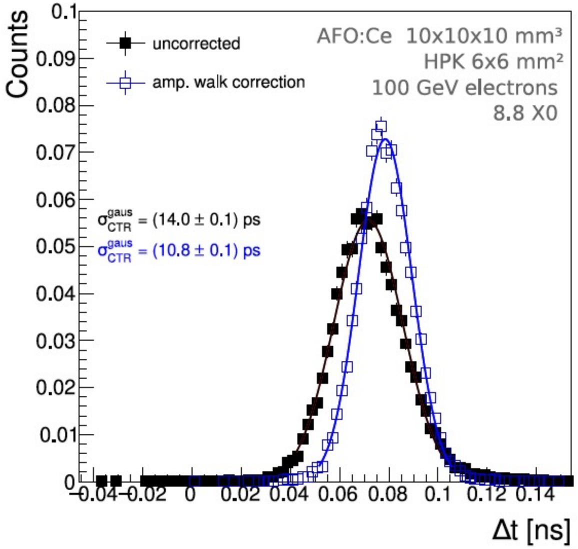
Tagging EM Showers (Sub-10 ps) with Scintillating Glasses

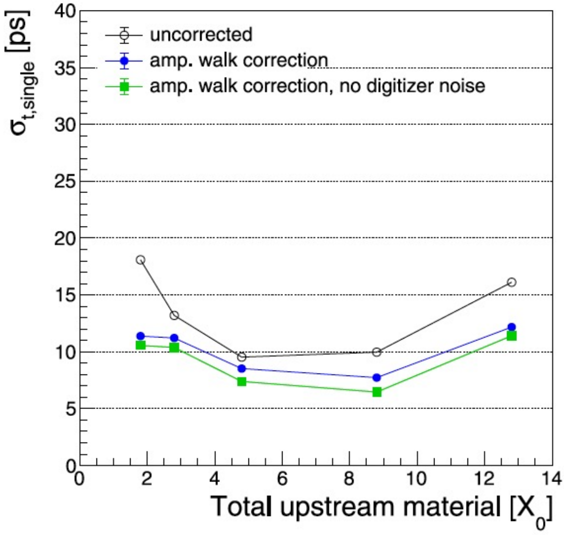
AFO (cerium-doped Alkali Free Fluorophosphate)
scintillating glass with 5% Ce

M. T. Lucchini et al et NIM A 1051 16214 (2023)



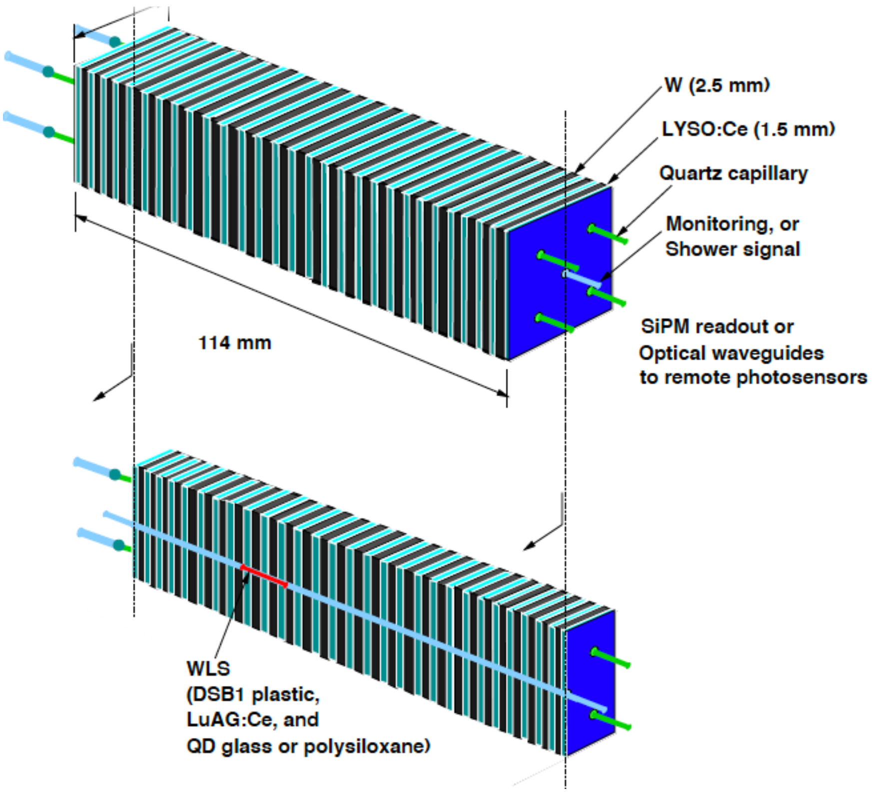


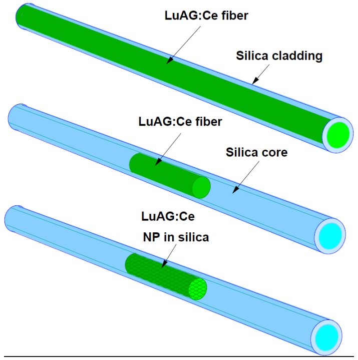


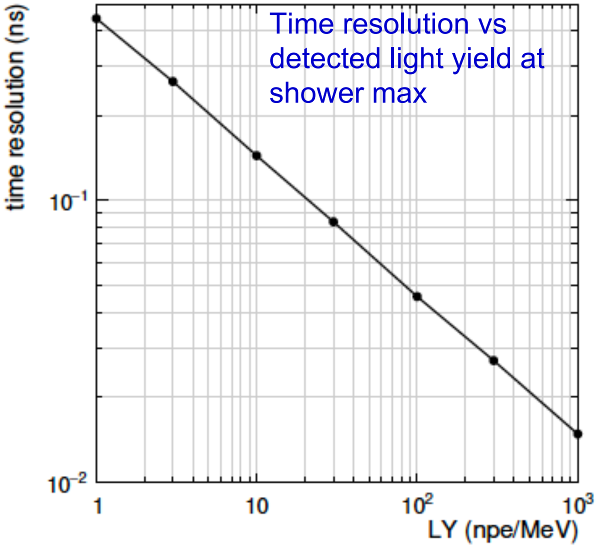


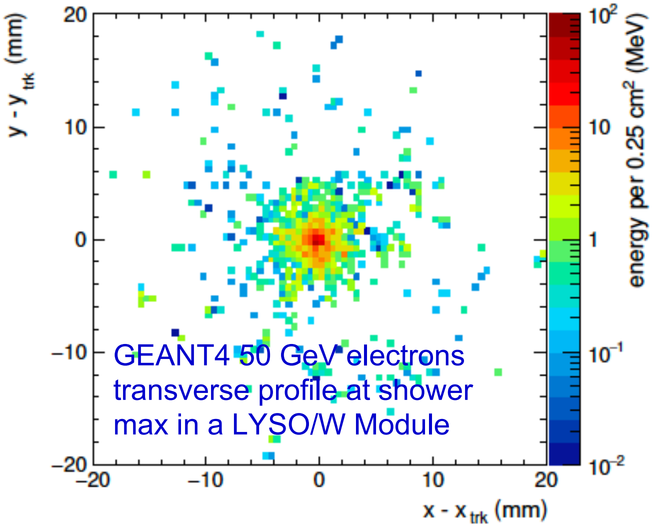
The black open dots represent the time resolution before amplitude walk corrections, blue after amplitude walk corrections and green is the time resolution of the devices after subtracting in quadrature the contribution from the CAEN V1742 digitizer electronic noise

Shower Max Timing with RADiCAL






Time resolution vs detected light yield at shower max

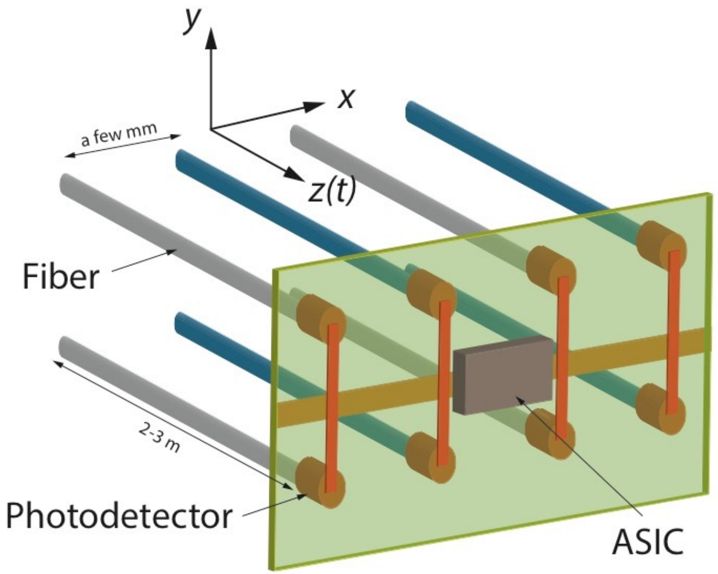

GEANT4 50 GeV electrons transverse profile at shower max in a LYSO/W Module

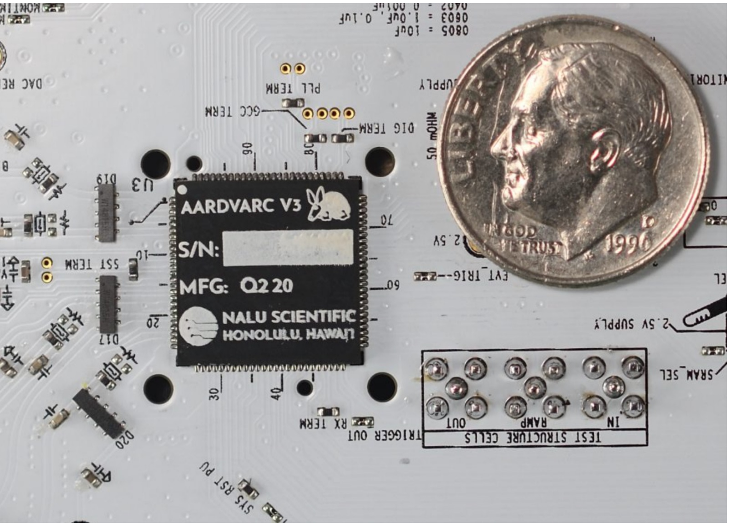
- Positioning of WLS filaments at shower max for timing studies
- Incorporation of dual readout for both scintillation and Cherenkov measurement – including for timing with quartz rods and the WLS capillary structures which are predominantly quartz material

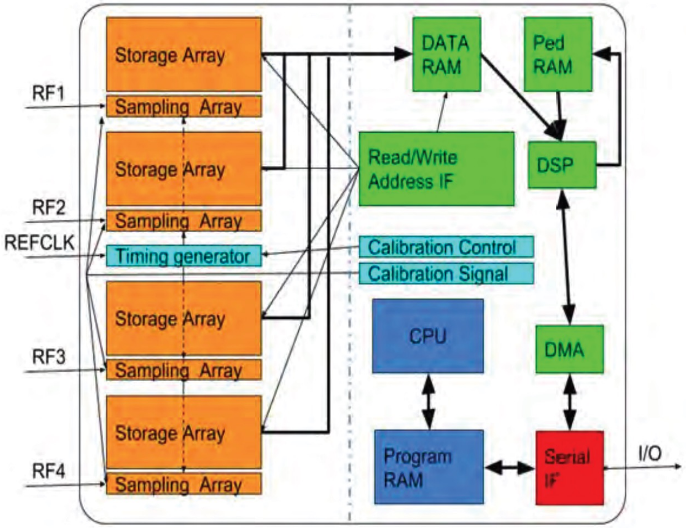
R. Ruchti et al CPAD 2021

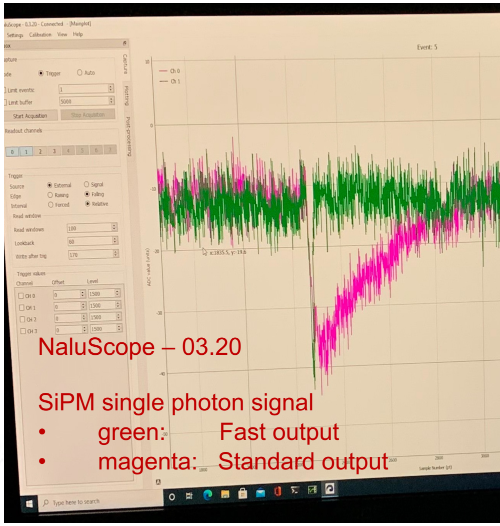
Example: Enabling Digitizer NALU AARDVARC V3

- Compact, high performance waveform sampling and digitizing
  - Sampling rate 10-14 GS/s,
  - 12 bits ADC,
  - 4-8 ps timing resolution,
  - 32 k sampling buffer,
  - bandwidth 2 GHz,
  - System-on-Chip (CPU)
- Higher channel density per chip planned





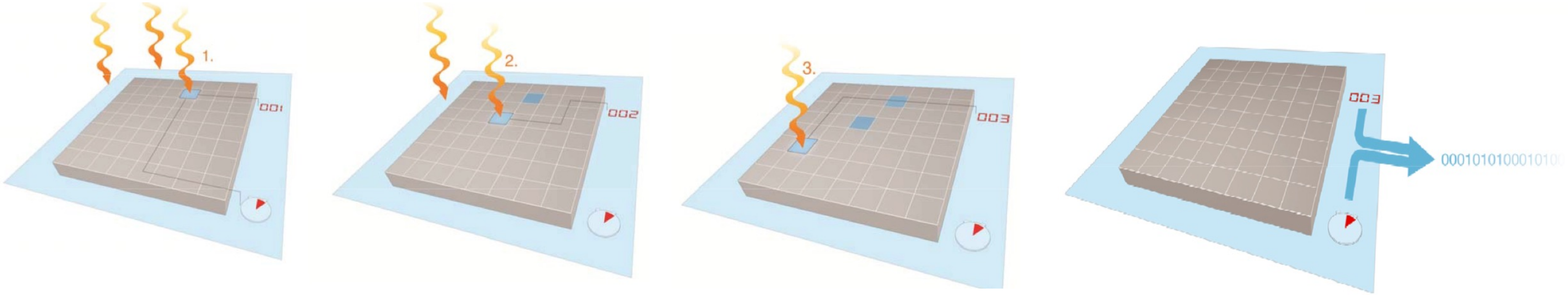




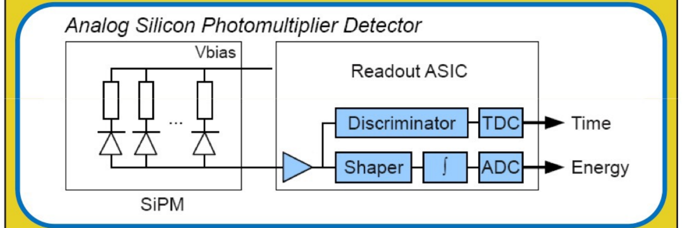
NaluScope – 03.20

SiPM single photon signal
- green: Fast output
- magenta: Standard output

Digital Sensors (dSiPM) for Timing in Calorimetry

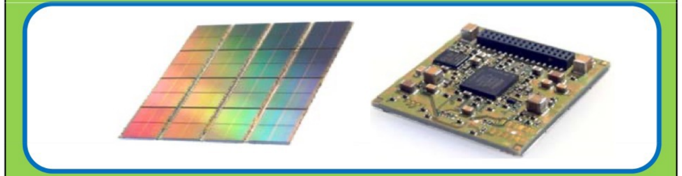


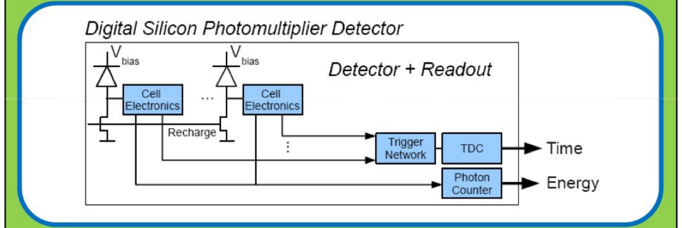
Analog SiPM



- discrete, limited integration
- analog signals to be digitized
- dedicated ASIC needed
- difficult to scale

Digital Photon Counter





- fully integrated
- fully digital signals
- no ASIC needed
- fully scalable

NIM-A 809 31-52 (2016)

https://indico.cern.ch/event/192695/contributions/353376/attachments/277251/387863/TIPP2014_Amsterdam_lecture_Philips_Haemisch_pub.pdf
https://indico.fnal.gov/event/46746/contributions/209928/attachments/141285/177855/Pratte_CPAD2021_v4.pdf

Some Remarks

Much has been achieved in improving timing measurements in recent years (σ_t~30-100 ps) at “large” systems. Many different scientific, technical, and conceptual aspects need to coherently come together to make progress (σ_t~1-10 ps) in the next decades

We need advancements in all areas:

1. Fast, bright, and radiation-hard active materials (glasses, crystals, fibers, metamaterials, …)
2. Innovative waveguide structures accommodating different types of photons (Cherenkov, scintillating, cross-luminescence light, …)
3. Fast, miniature, and radiation-hard photodetectors
4. Multi-GHz, low power, high-density, compact waveform digitizers
5. Precise clock distribution (LpGBT-v0 random jitter 2.2 ps)
6. AI/ML tools taking advantage of timing for better calorimeter performance (hardware/software)