Precision Timing in Calorimeters

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TTU

Introduction

Evolution in calorimetry

1. Compensation (*e/h=1*) using slow neutrons (~40 years ago)
2. Event-by-event compensation in dual read-out $f_{em} \sim Q/S$ (~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*)

Precision timing (O(10) 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)

In this talk, I will focus on \`timing' in as relates to calorimetry with some details on sensors, radiators, and electronics

To-Do List & remarks

What does 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
- σ_t < 10-20 ps (*e.g*. long-lived particles)

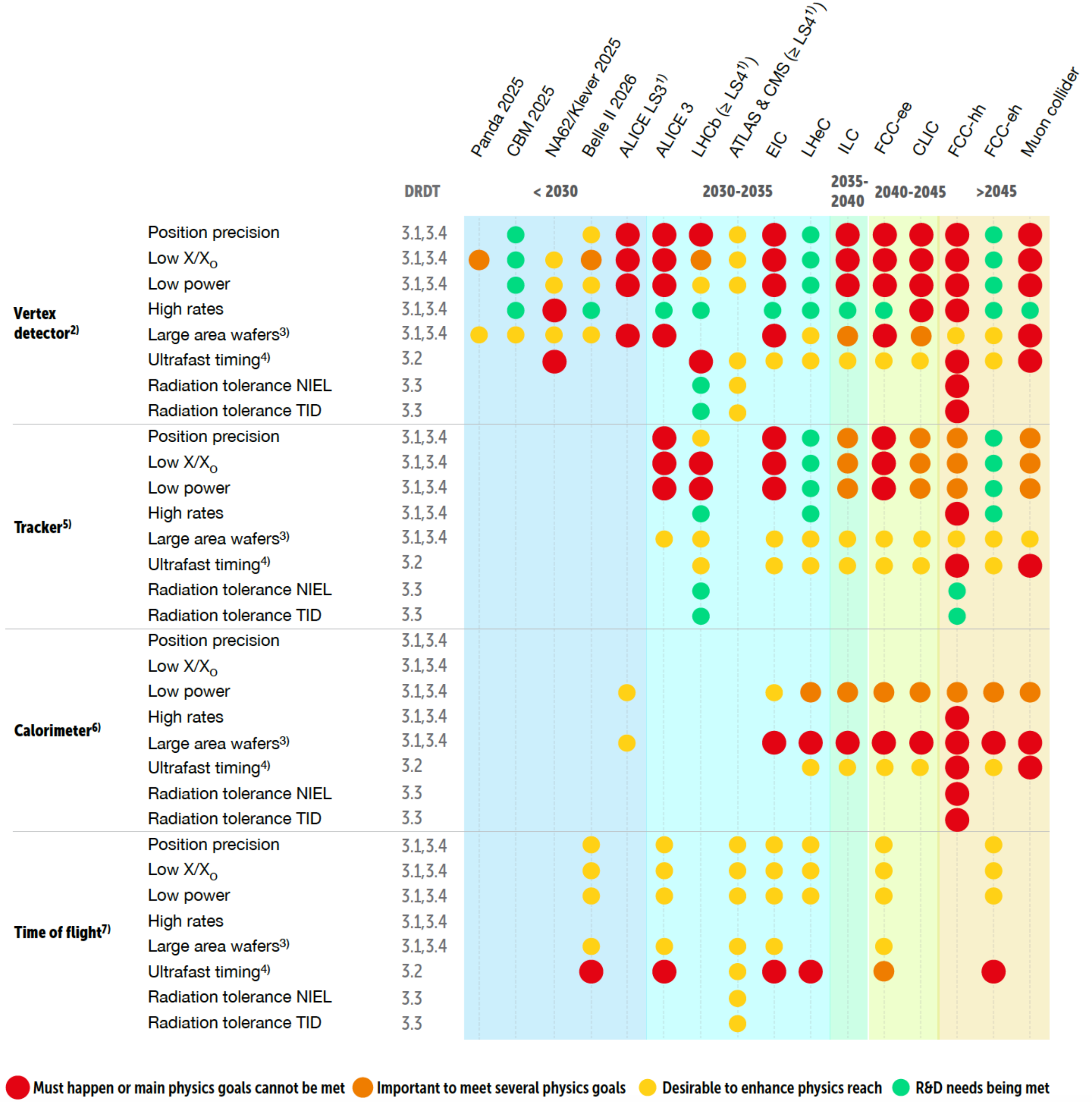
In >20 years, high precision (5D) calorimetry in *hh* machines:

- 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
- σ_t < 5-10 ps (*e.g*. pile-up suppression and PID)

Ultrafast calorimetry

- Ultra-high-rate experiments
- Special detector elements (granular, rad-hard, fast radiators, sensors, and readout electronics…)
- σ_t ~ 1-5 ps

In all cases, fast readout, AI/ML reconstruction, some on-detector intelligence will be needed



HEP community plans reflect the anticipated role of timing at the future colliders:

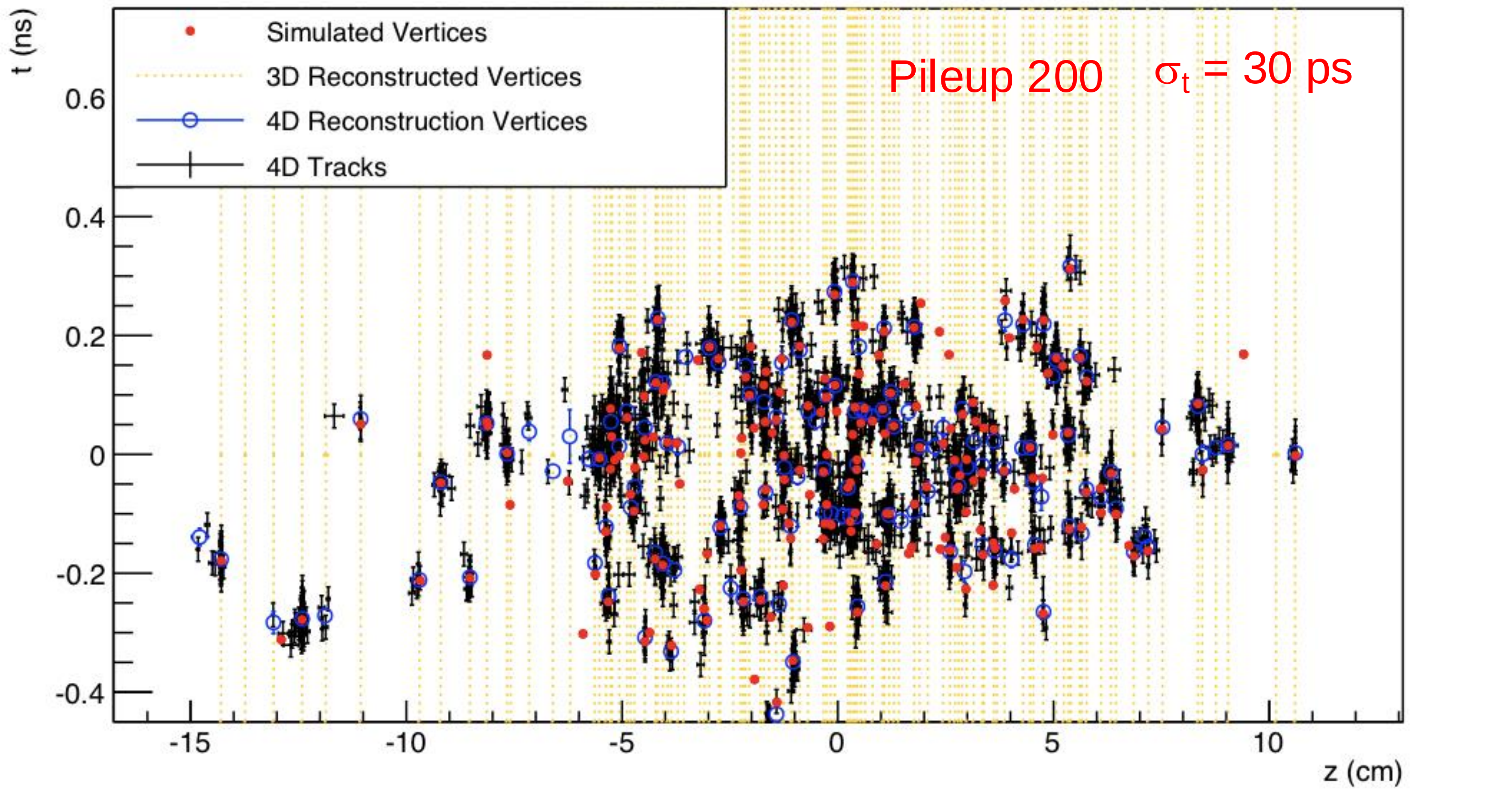
Basic Research Needs for HEP Detector Research and Development (2019)

ECFA Detector R&D Roadmap Process Group (2021)

EPS-HEP 2023 ECFA Session

Power of Precise Time Measurement – Pileup 200

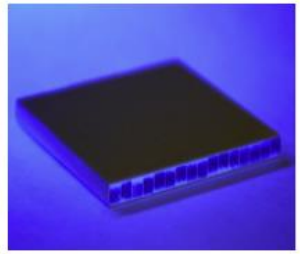
Technical Report CERN-LHCC-2019-003. CMS-TDR-020



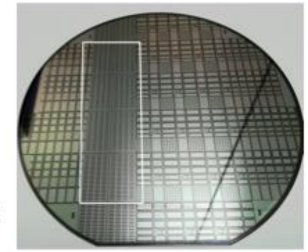
The simulated vertices are the red dots. The vertical yellow lines indicate 3D-reconstructed (*i.e.* no use of timing information) vertices, with instances of vertex merging visible throughout. The black crosses and the blue open circles represent reconstructed tracks and vertices, respectively, using 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.

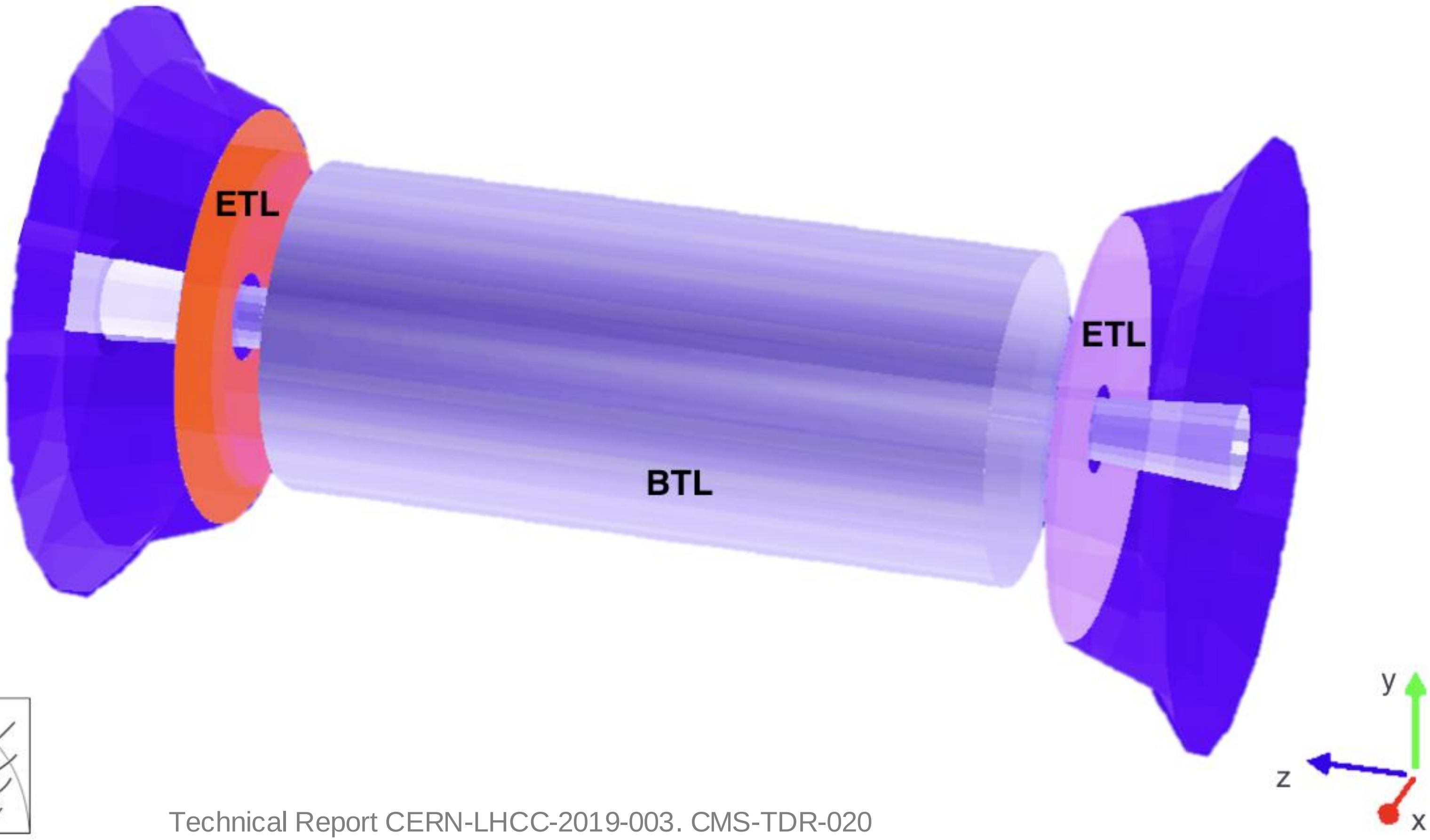
Example: CMS MIP Timing Detector (MTD)

BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: $|\eta| < 1.45$
- 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



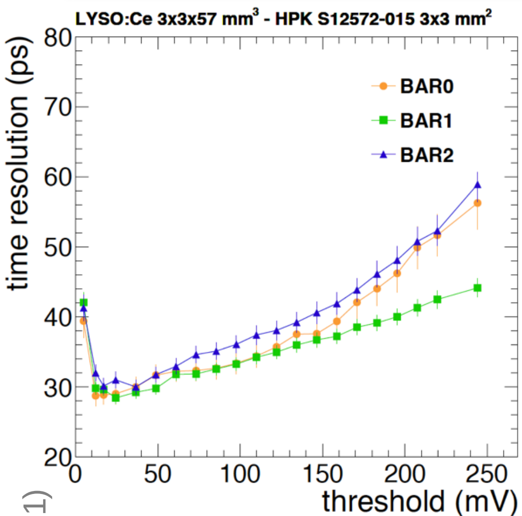
ETL: Si with internal gain (LGAD):
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2

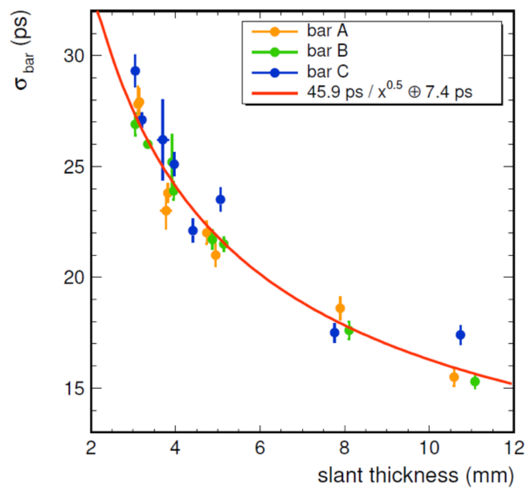


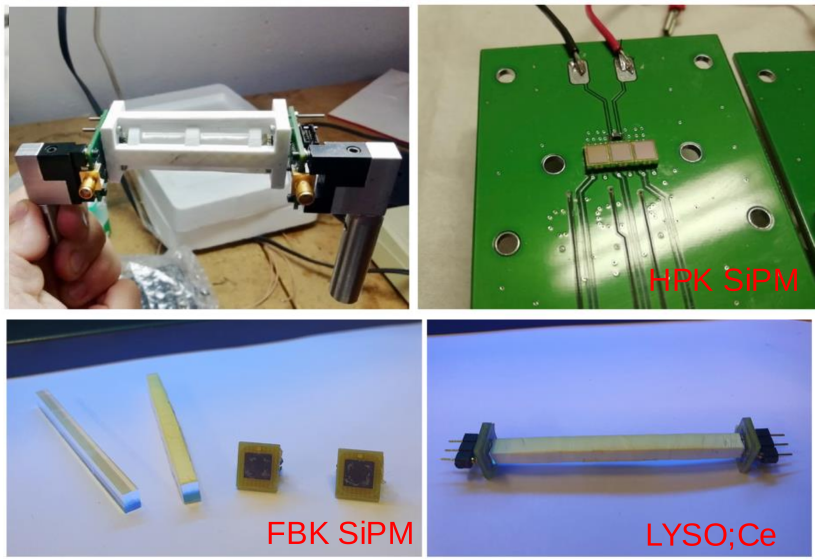


Technical Report CERN-LHCC-2019-003. CMS-TDR-020

Barrel Timing Layer (BTL) Test Beam Results







σ_t^{min}= 28.4±0.4 ps

Two contributions to time resolution as a function of threshold:

arXiv:2104.07786v1

- 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

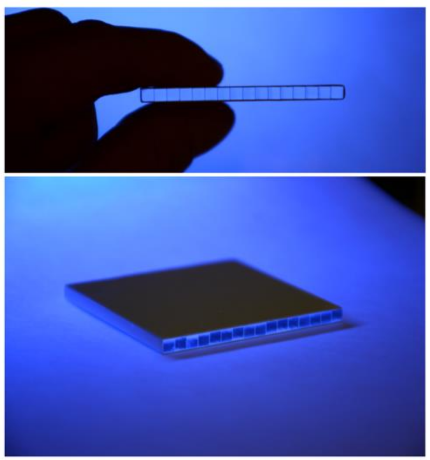
R. Abbott et al (CMS MTD) ArXiv:2104.07786 (2021)

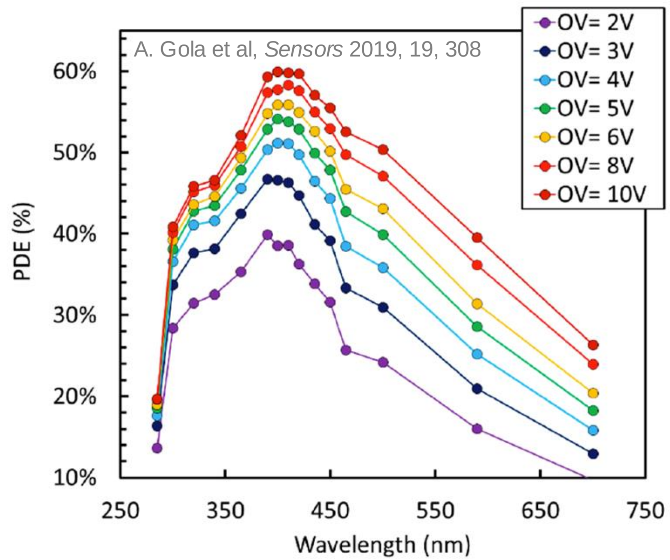
What Matters: Timing Resolution Drivers (Photons)

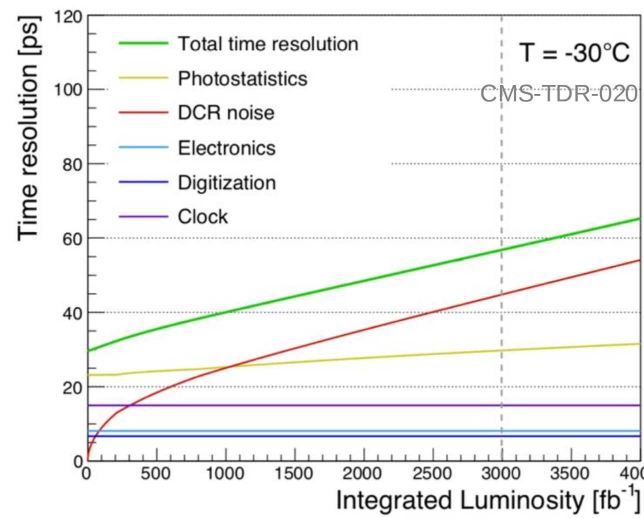
$$\sigma_{\rm t} = \sigma^{\rm phot} \oplus \sigma^{\rm clock} \oplus \sigma^{\rm elec} \oplus \sigma^{\rm digi} \oplus \sigma^{\rm noise} \oplus \ldots$$

$\boxed{\sigma^{\rm phot} \approx 25\ {\rm ps}}$ $\boxed{\sigma^{\rm clock} \approx 15\ {\rm ps}}$ $\boxed{\sigma^{\rm elec} \approx 8\ {\rm ps}}$ $\boxed{\sigma^{\rm digi} \approx 7\ {\rm ps}}$ $\boxed{\sigma^{\rm noise} \approx 50\ {\rm ps\ after}\ 3{,}000\ {\rm fb}^{-1}}$

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



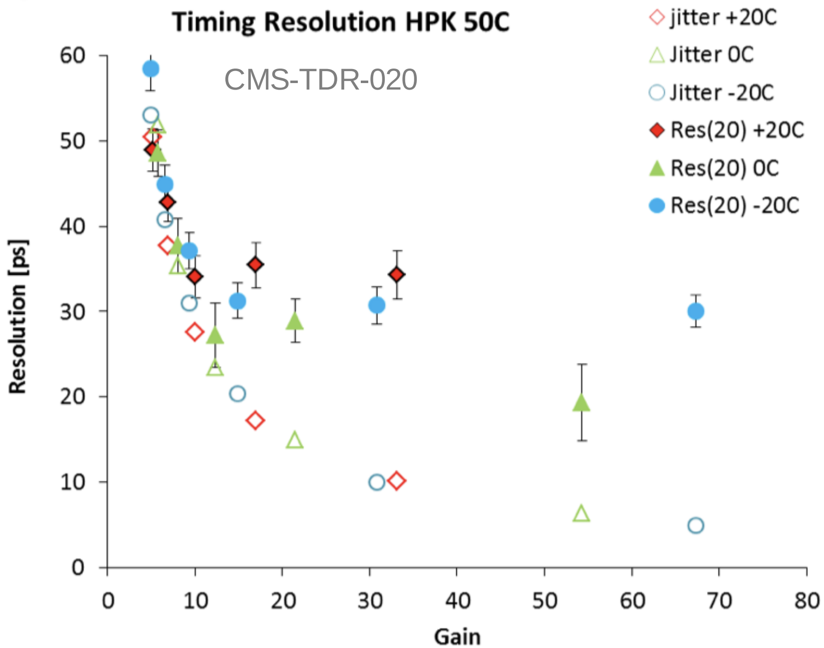


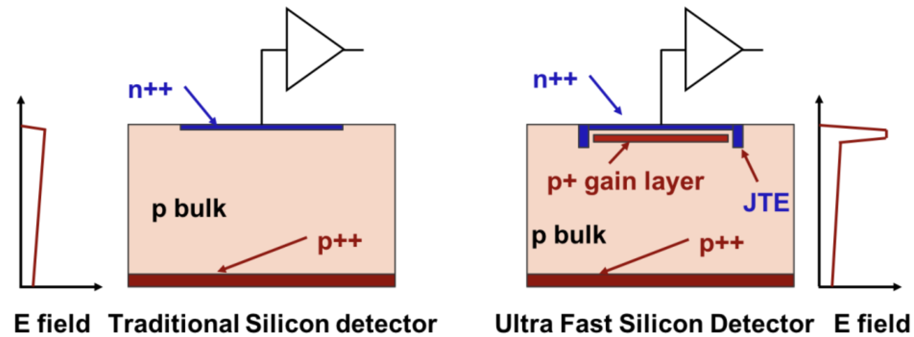


LYSO:Ce is a bright scintillator with 30,000 ph/MeV, 420 nm peak emission, decay time <43 ns, rise time <200 ps, density 7.4 g/cm^3, 9.55 MeV/cm, and refractive index 1.82

CMS MTD: 4.8~68 MRad, 2.5×10^{13}~2.1×10^{14} p/cm^2 and 3.2×10^{14}~2.4×10^{15} n_{eq}/cm^2

What Matters: Timing Resolution Drivers (Charge)





$$\sigma_t = \sigma^{\text{jitter}} \oplus \sigma^{\text{ionization}} \oplus \sigma^{\text{distor}} \oplus \sigma^{\text{TDC}} \oplus \ldots$$

$$\sigma^{\text{jitter}} = \frac{N}{dV/dt} \propto \frac{e_n C_d}{Q}\sqrt{t_r}$$

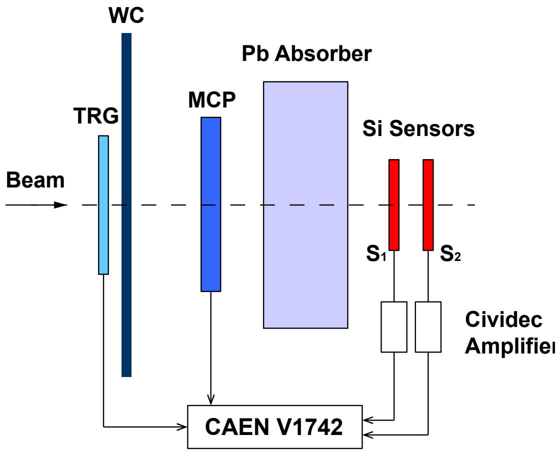
$$\sigma^{\text{ionization}} = \sigma^{\text{Total}} + \sigma^{\text{Local}}$$

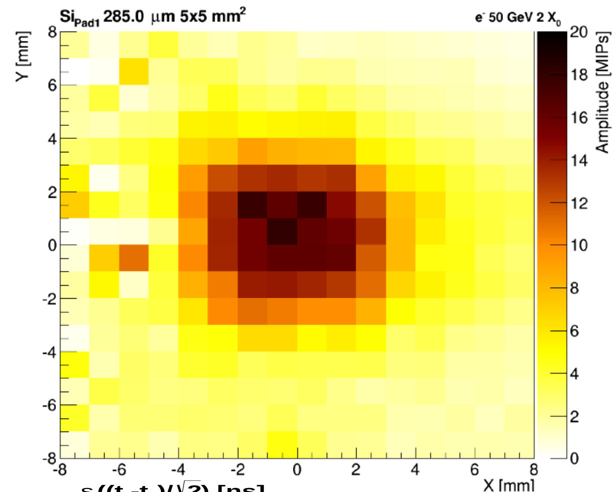
The jitter and total time resolution as a function of gain for a Hamamatsu 50-μm thick UFSD sensor: the jitter term decreases with gain, while the total time resolution flattens around σ_t = 30 ps

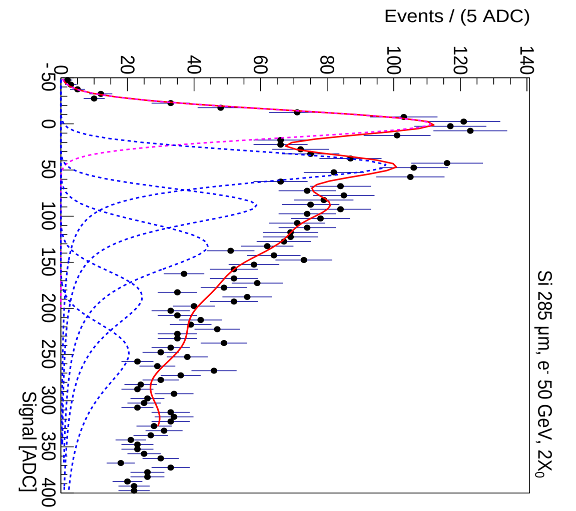
Non-uniform charge deposition determines the intrinsic time resolution; this is a function of the sensor thickness and is about $\sigma_t \approx$ 25 ps for 50-μm thick sensors

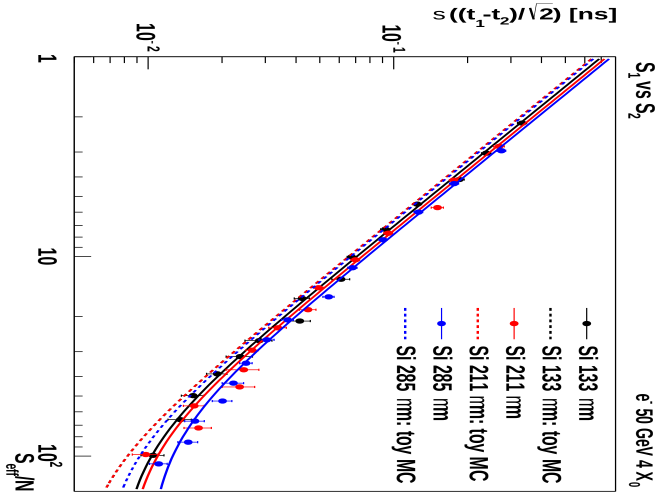
The time resolution σ_t = 30–40 ps will degrade to 40–50 ps at a fluence of 3 $\times$ 10^{15} n_{eq}/cm^2

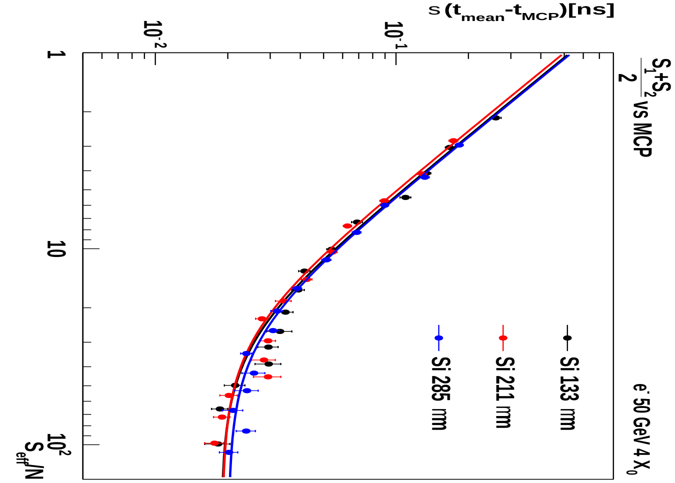
Timing Performance of Thin Planar Silicon Sensors









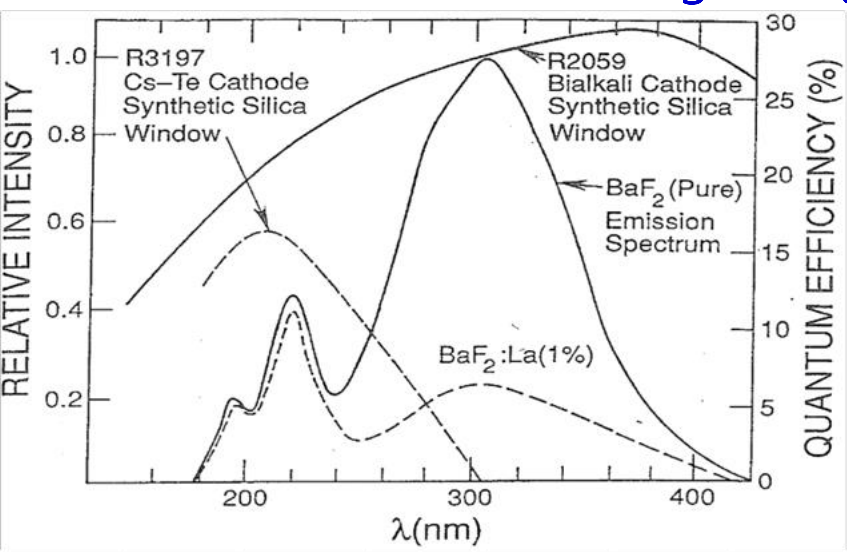


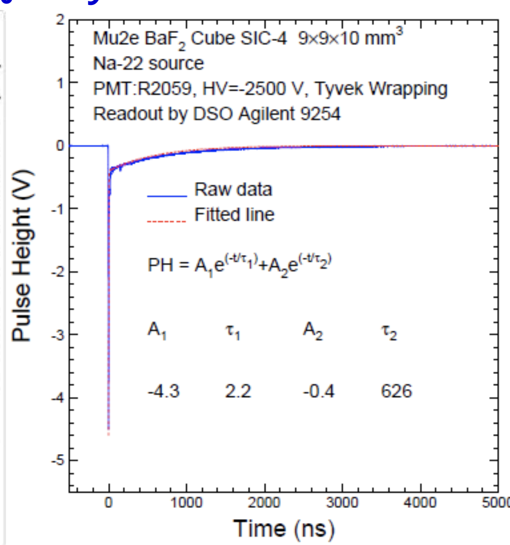
NIMA 859 (2017) 31-36

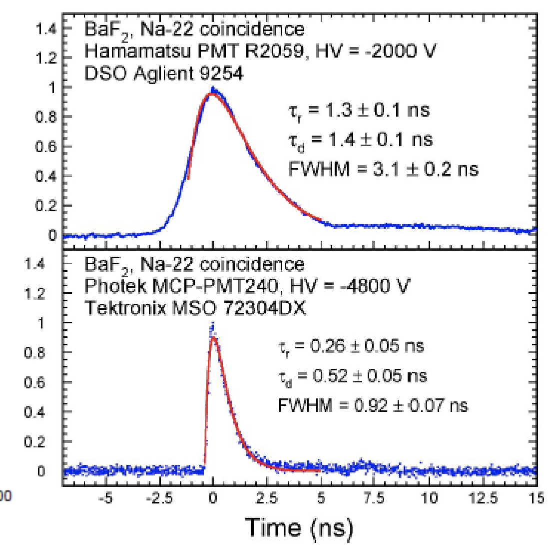
Three different silicon planar sensors, with thicknesses 133, 211, and 285 μm. The measurements and simulations show better than 20 ps timing resolution for signals larger than a few tens of MIPs

BaF_2 - Fast and Slow Light

- BaF_2 has been known to HEP since the SSC days
- BaF_2 has a cross-luminescence component at 220 nm with ~0.5 ns decay time (~1,500 ph/MeV). It has also a factor of 5 brighter slow component at 300 nm with 600 ns decay time
- Slow component suppression may be achieved by rare earth (Y (next page), La and Ce) doping, and/or solar-blind photo-detectors, *e.g.* Cs-Te, K-Cs-Te and others
- BaF_2 shows saturated damage from 10 kRad to 100 MRad, indicating good radiation resistance against γ-rays



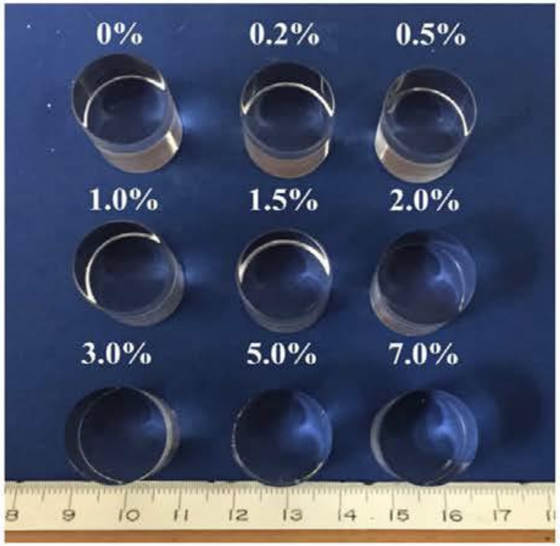


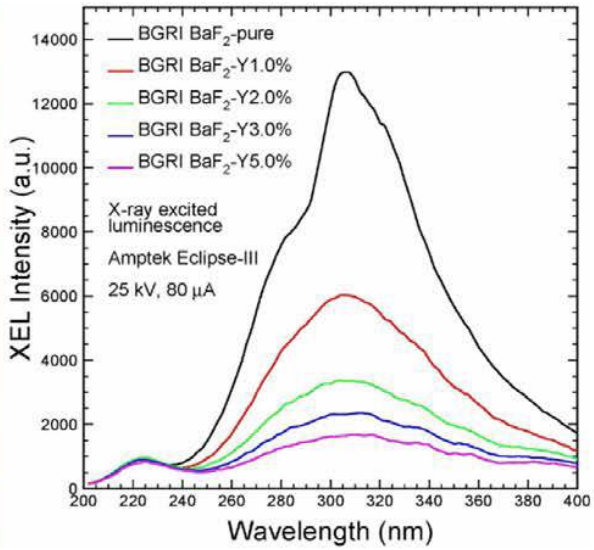


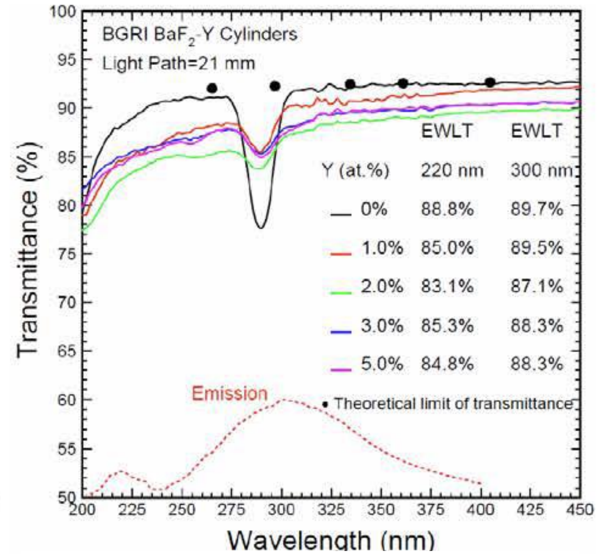
R. Y. Zhu et al, NIMA 340 (1994) 442-457

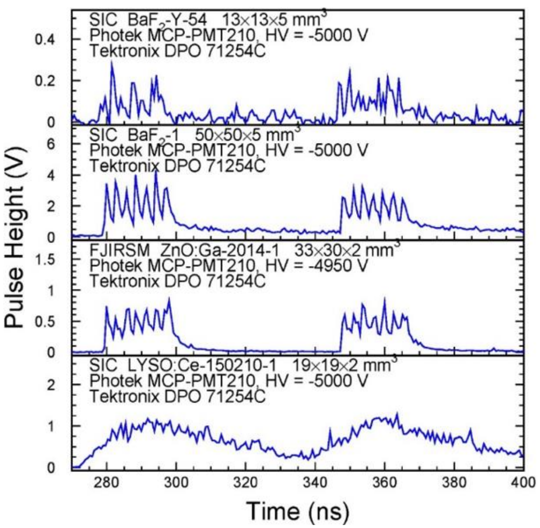
IEEE TNS NS 67, No 6 (2020) 1014-1019

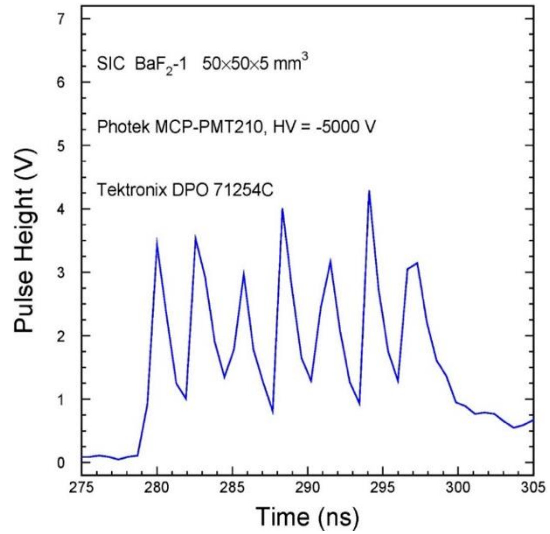
BaF_2:Y for Ultrafast Calorimetry

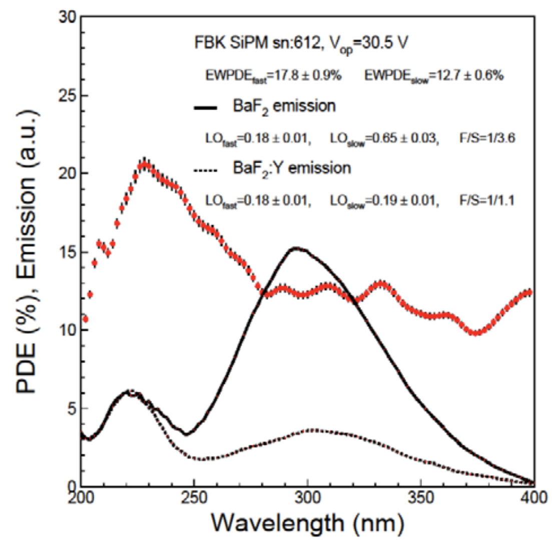










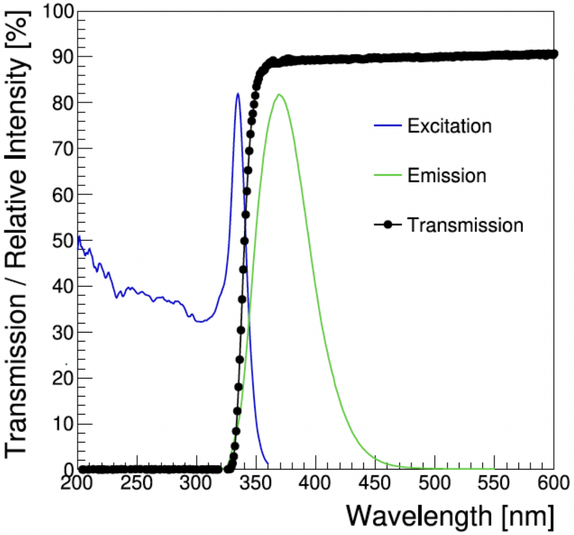


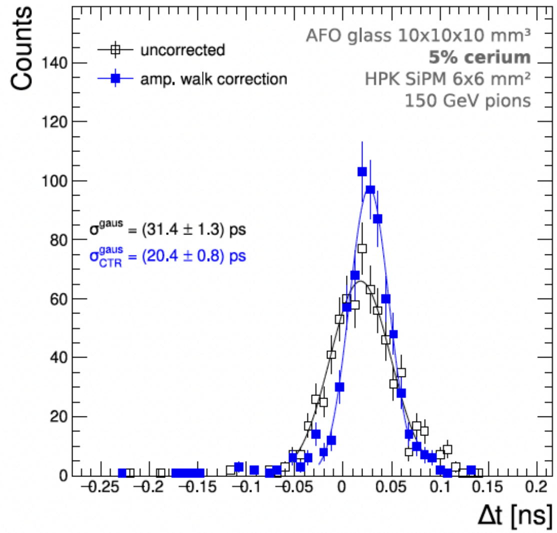
NIMA 240 (2019) 223-239
D. Hitlin et al CPAD 2021

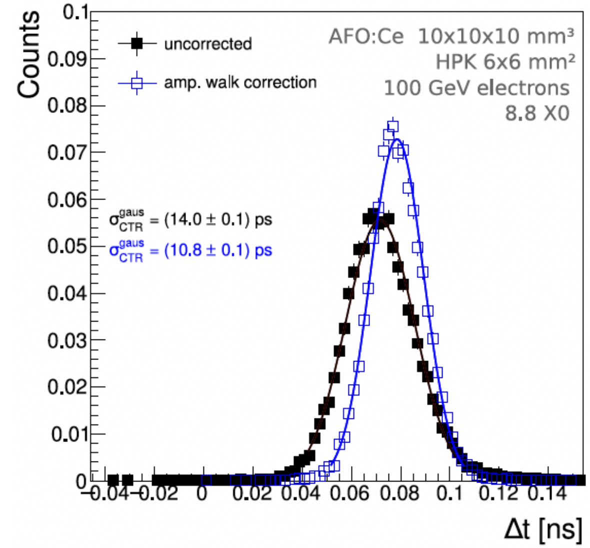
X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals for hard X-ray imaging

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

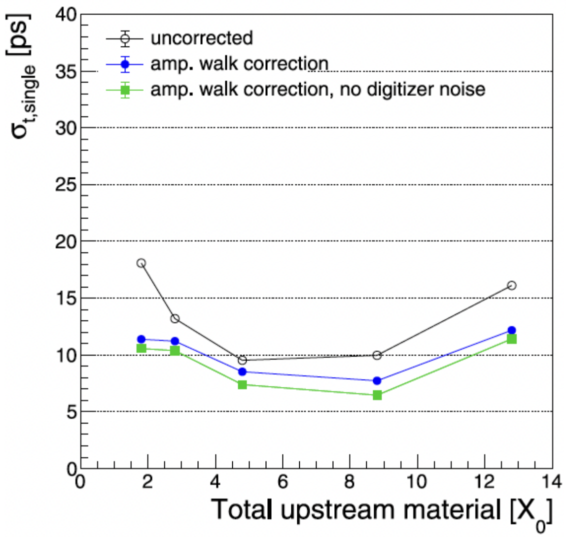
AFO (cerium-doped Alkali Free Fluorophosphate) scintillating glass with 5% Ce





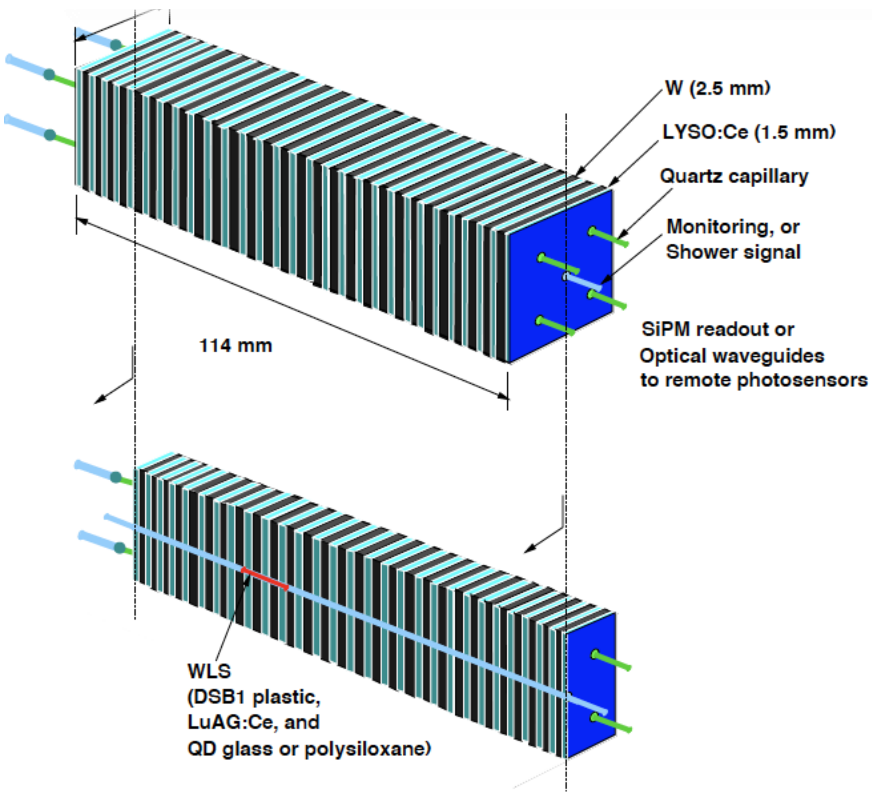


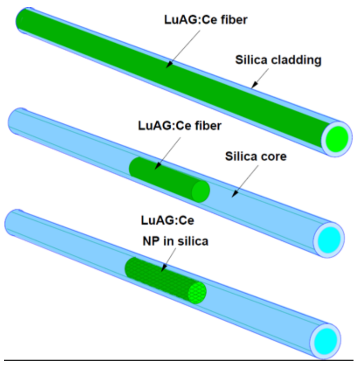
M. T. Lucchini et al et NIM A 1051 16214 (2023)

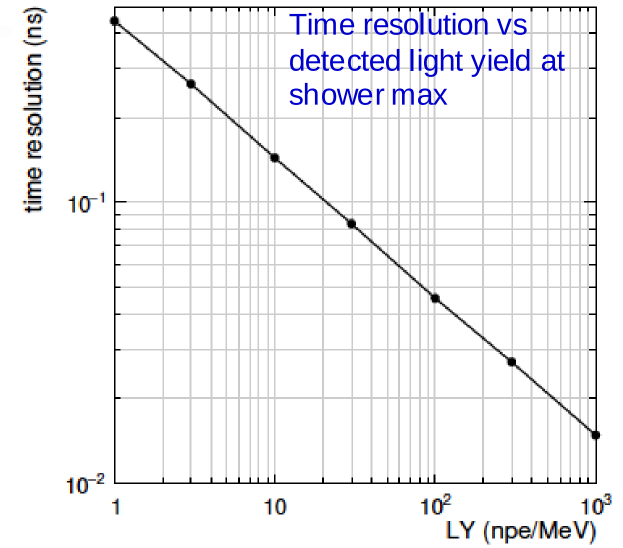


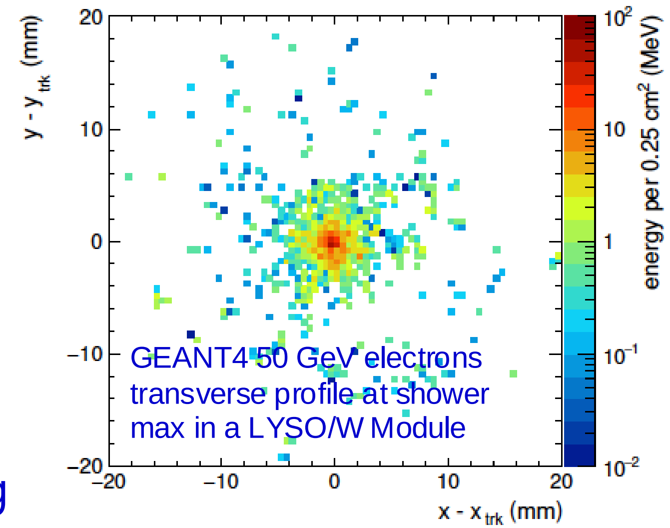
The black open circles (left) represent the time resolution before amplitude walk corrections, blue after amplitude walk corrections and green is the time resolution of the devices after subtracting in quadrature the contribution from the CAEN V1742 digitizer electronic noise.

Shower Max Timing with RADiCAL





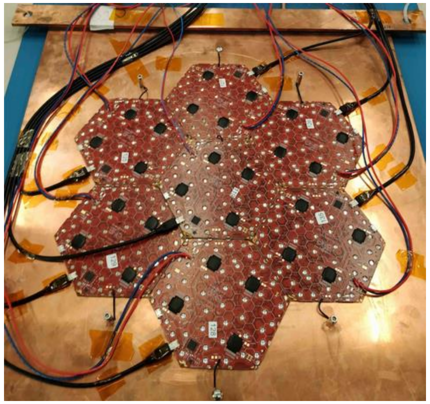


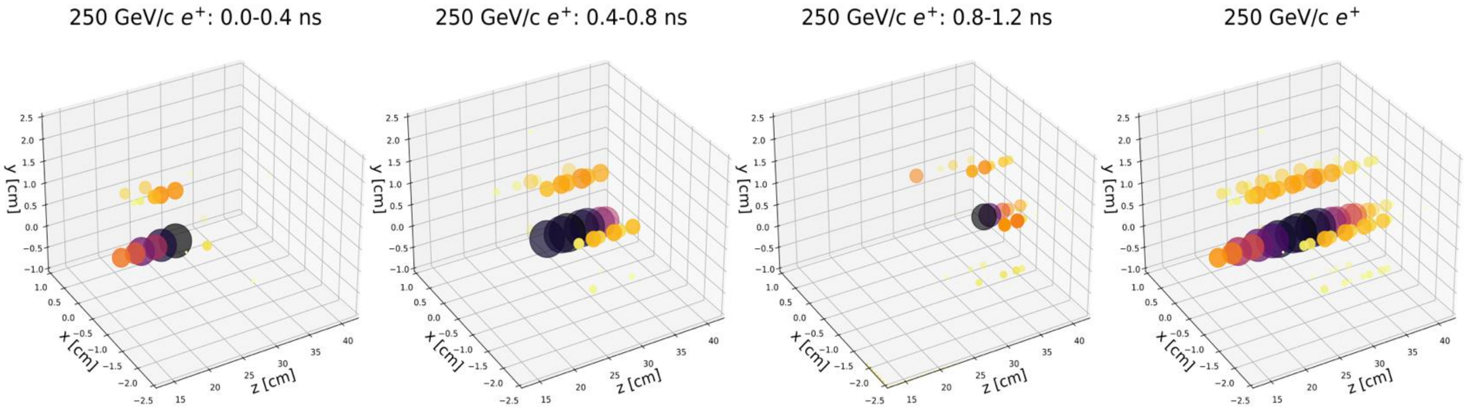


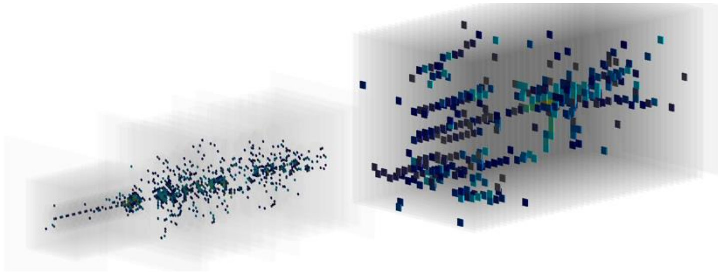
- Positioning of WLS filaments at shower max for timing studies
- Incorporation of dual readout for both scintillation and Cherenkov measurement – including for timing with quartz rods and the WLS capillary structures which are predominantly quartz material

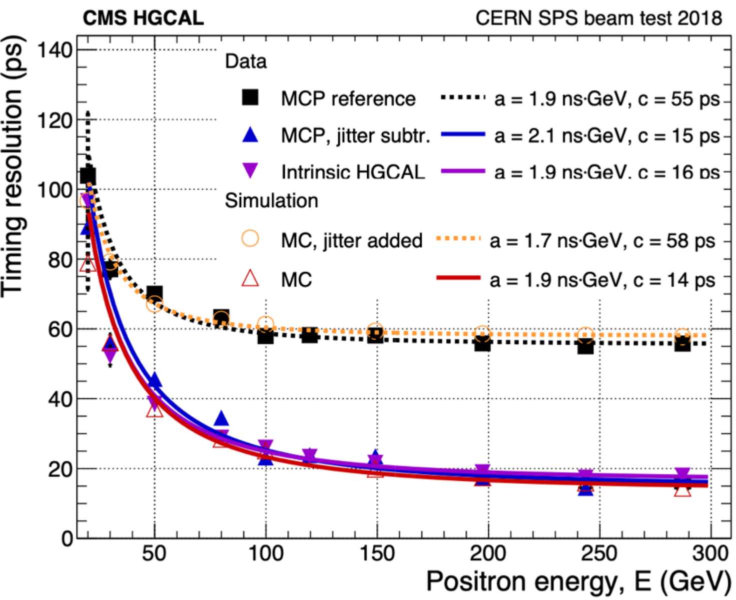
R. Ruchti et al CPAD 2021,
DRD6 Workshop (2024)

CMS HGCAL Timing Performance





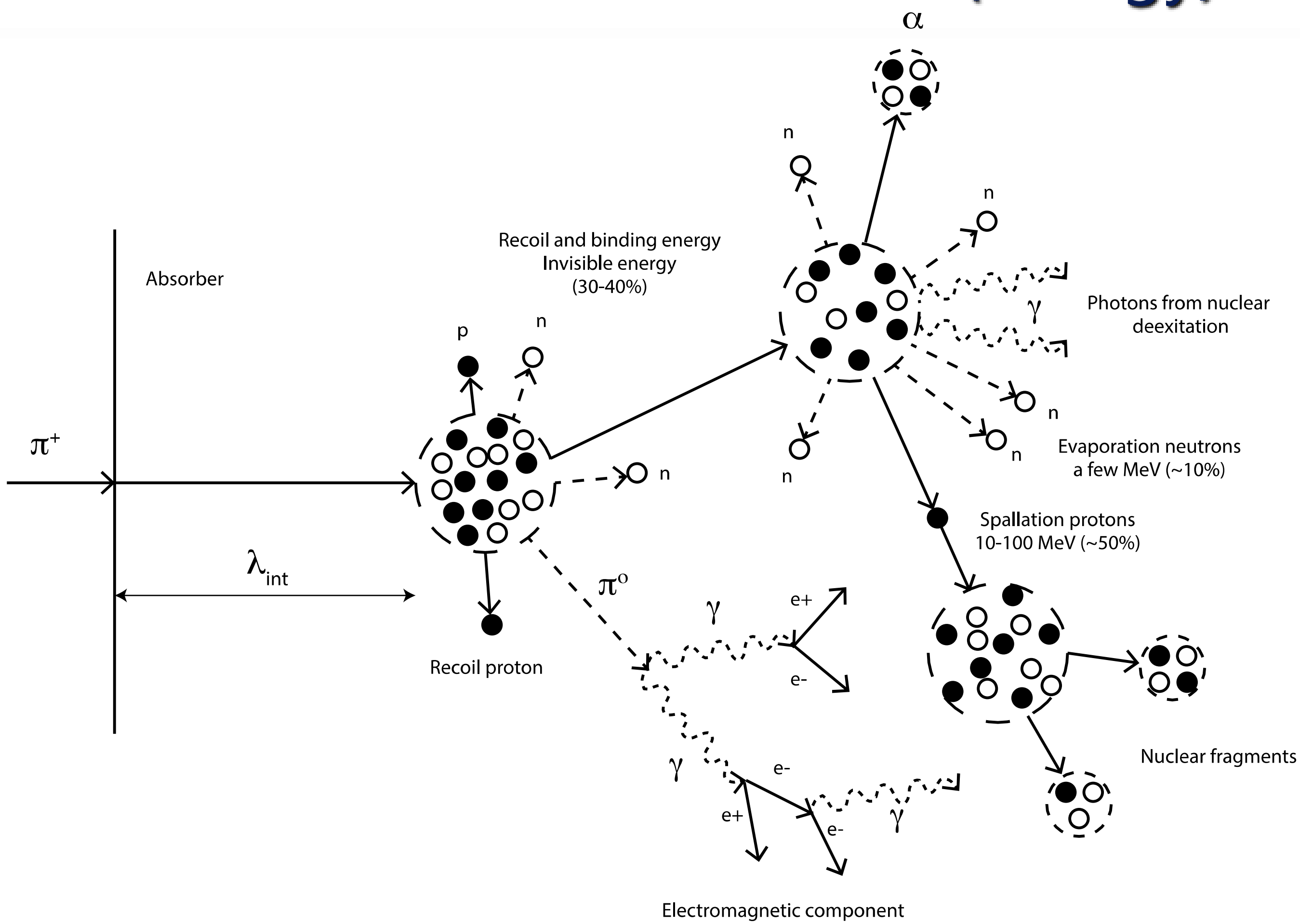




The timing resolution is measured for all layers using the MCP as a reference (black squares) as well as using only half the layers with respect to the other half and assuming they have identical resolution (purple triangles). Other measurements in the figure allow to cross-check and confirm the hypothesis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

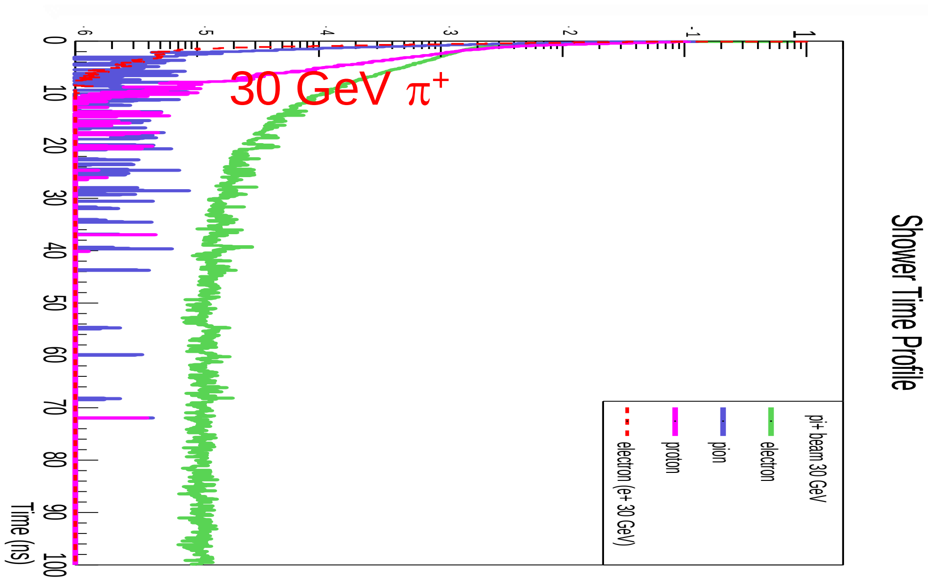
B. Acar et al (CMS HGCAL) ArXiv:2211.04740 (2023) and ArXiv:2312.14622v1 (2023)

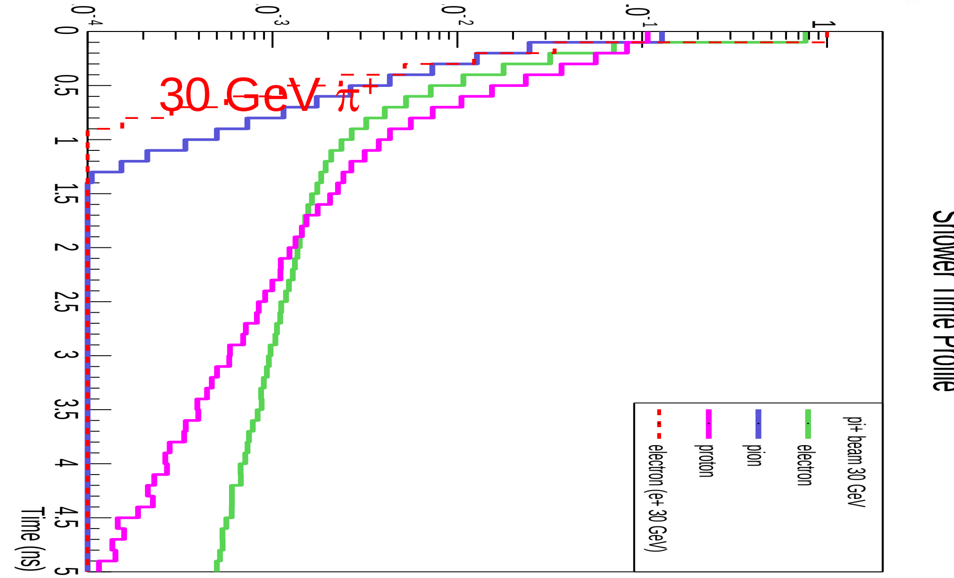
Hadronic Interaction Cartoon (energy) - I



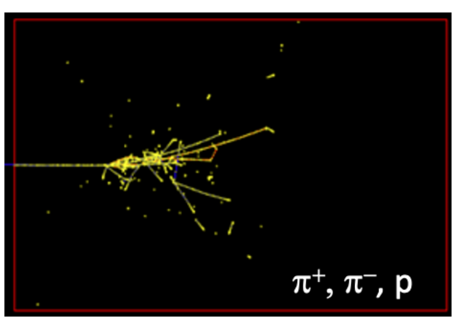
The energy and time spectra of the hadronic shower particles are wide. The percentages above refer to the fractions of the non-electromagnetic energy component. The fluctuations in the electromagnetic and invisible energy fractions (part of energy loss that does not generate a signal) degrade hadronic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

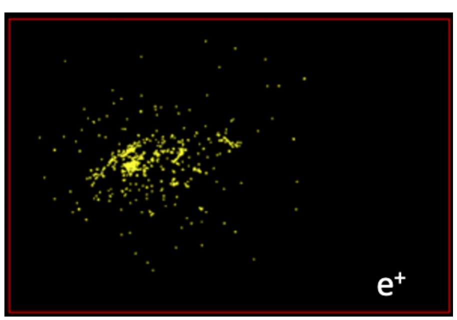
Time Evolution of Hadronic Shower

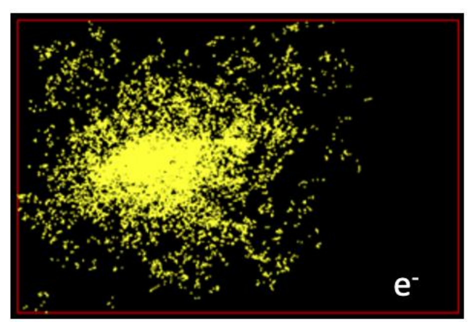


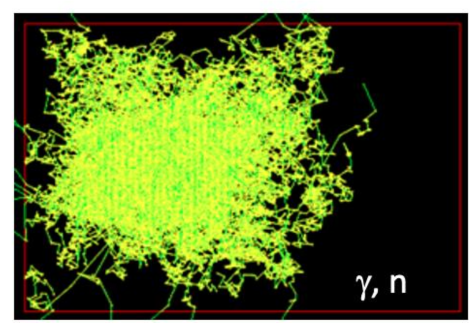


Time structure in a sampling calorimeter (17 mm Cu and 3 mm Si). The times are given in local time $t=t_{G4} - z/c$ to correct for the travel time along the z-axis.





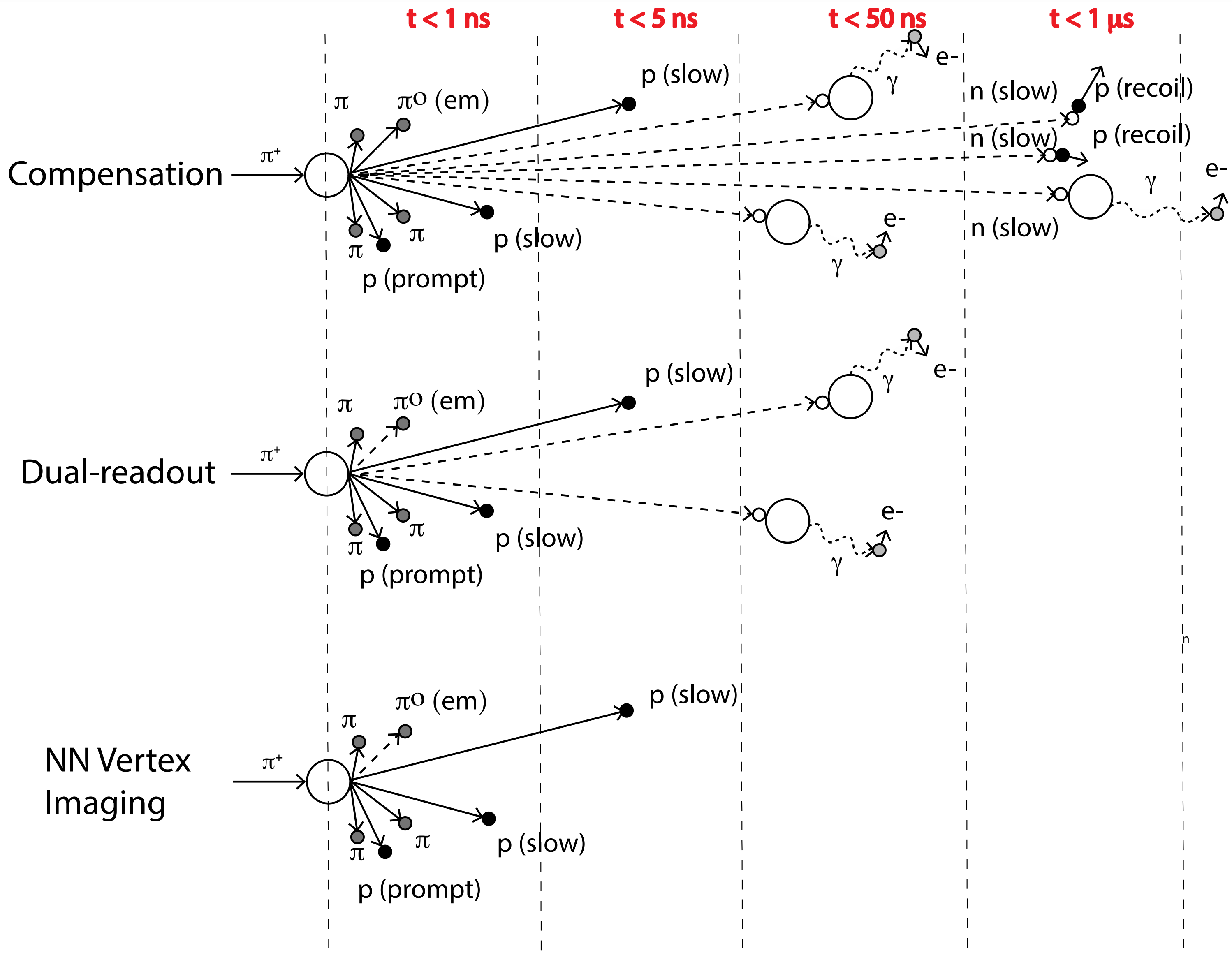




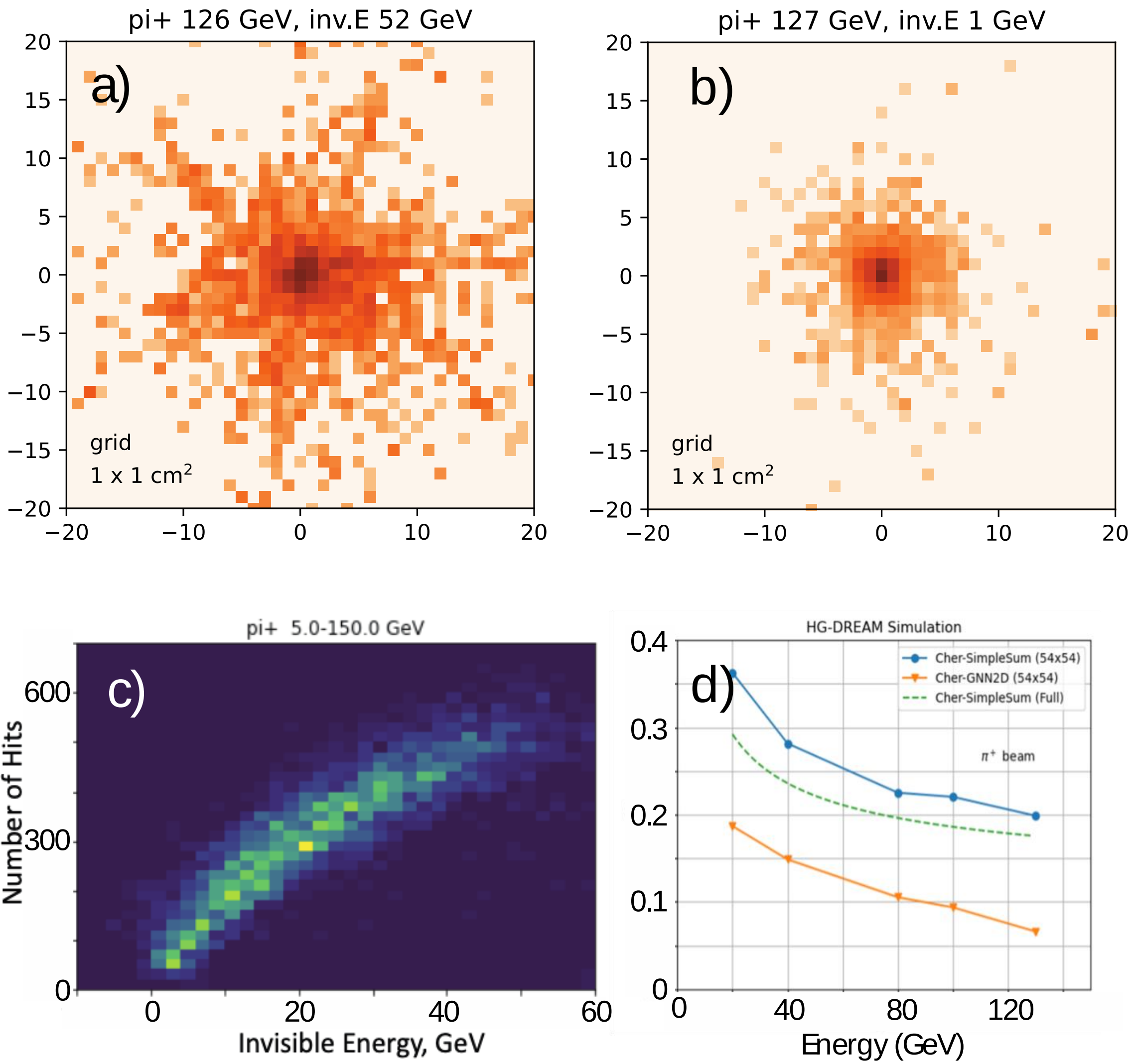
Fast Component < 5 ns

Slow Component > 10 ns

Hadronic Interaction Cartoon (time) - II



Example: HG-DREAM Cherenkov GNN 2D Simulation



Left: Cherenkov signal with large (52 GeV) invisible energy (true-measured) where the color shading is in log(*E*)

Right: Cherenkov signal with small (1 GeV) invisible energy

The correlation between the invisible energy and the number of hits is strong and energy-independent. The "image" recognition by the network in this way enables better energy reconstruction and results in improved energy resolution and response linearity compared to more traditional (summing) reconstruction methods

Expect better performance in 3D reconstruction?

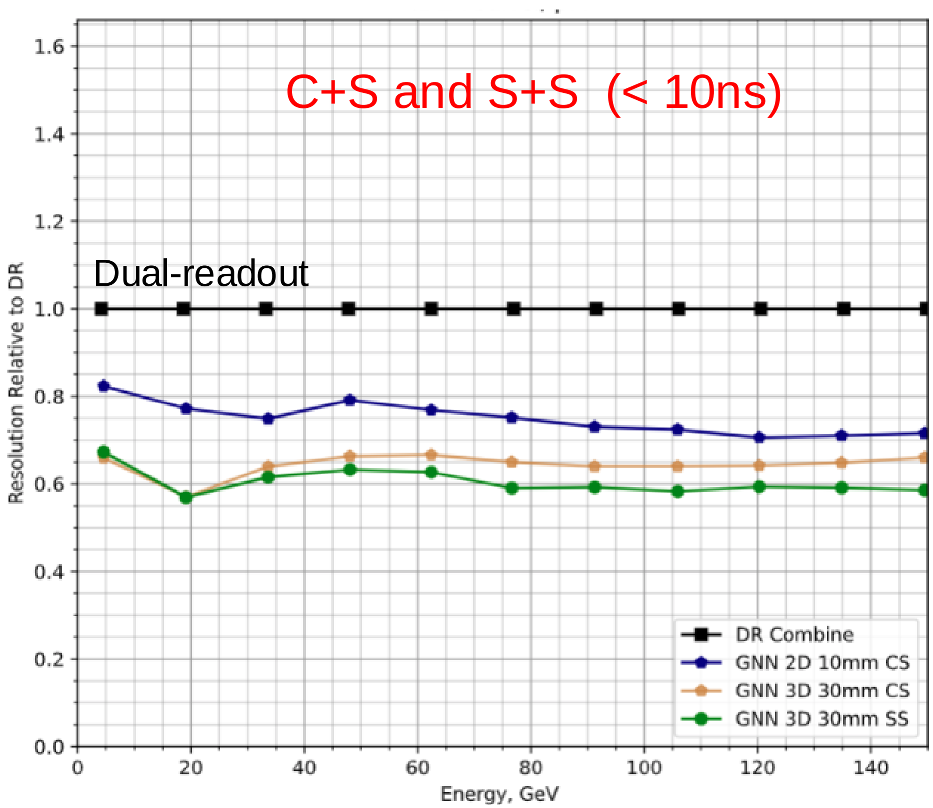
Example: GNN with a Fiber Calorimeter

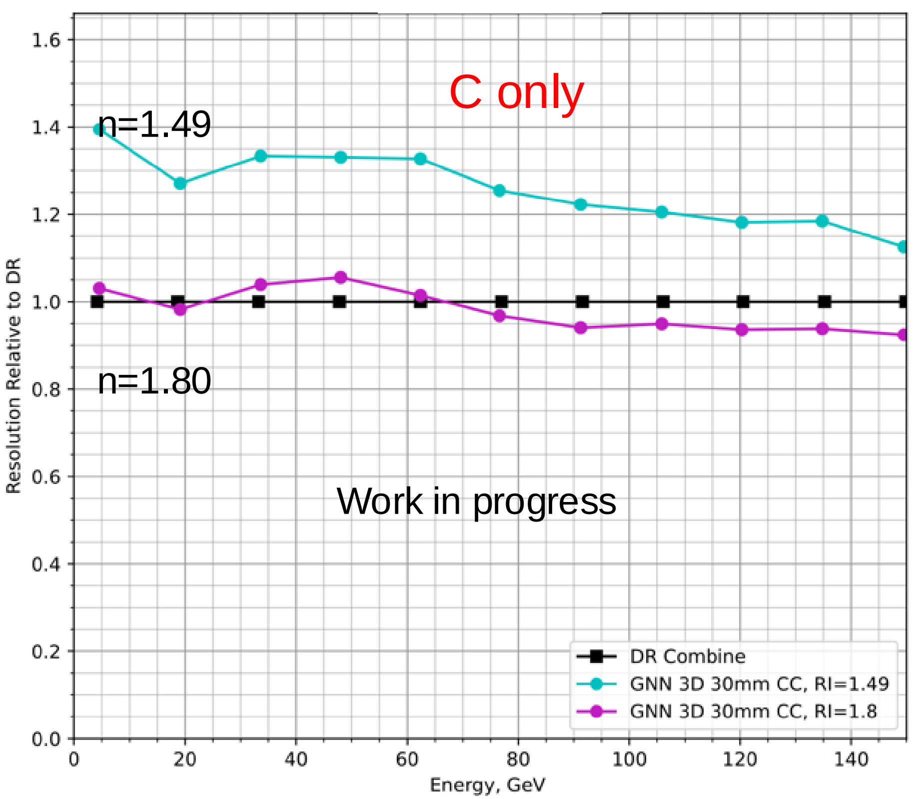
Cu absorber with 1 mm diameter fibers spaced at 1.5 mm

Segmentation 1x1 cm^2 for 2D and 3x3x3 cm^3 for 3D analysis

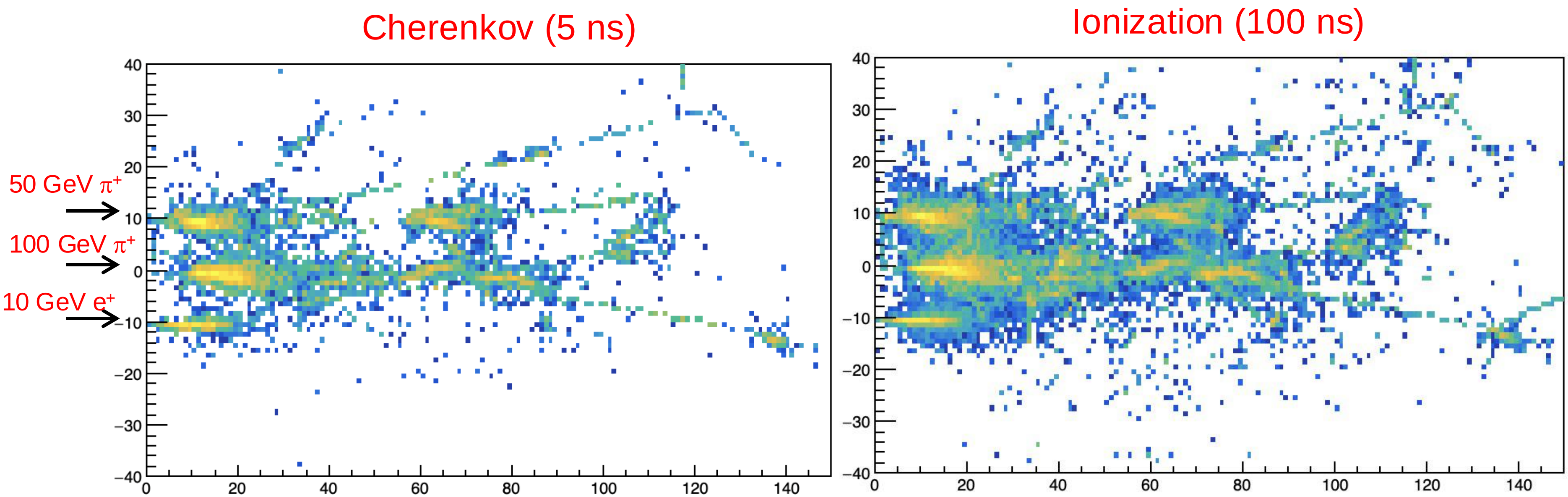
Signal integration time 10 ns

Dual-readout as reference $0.31/\sqrt{E} + 0.008$





Shower Images – Cherenkov *vs* Ionization

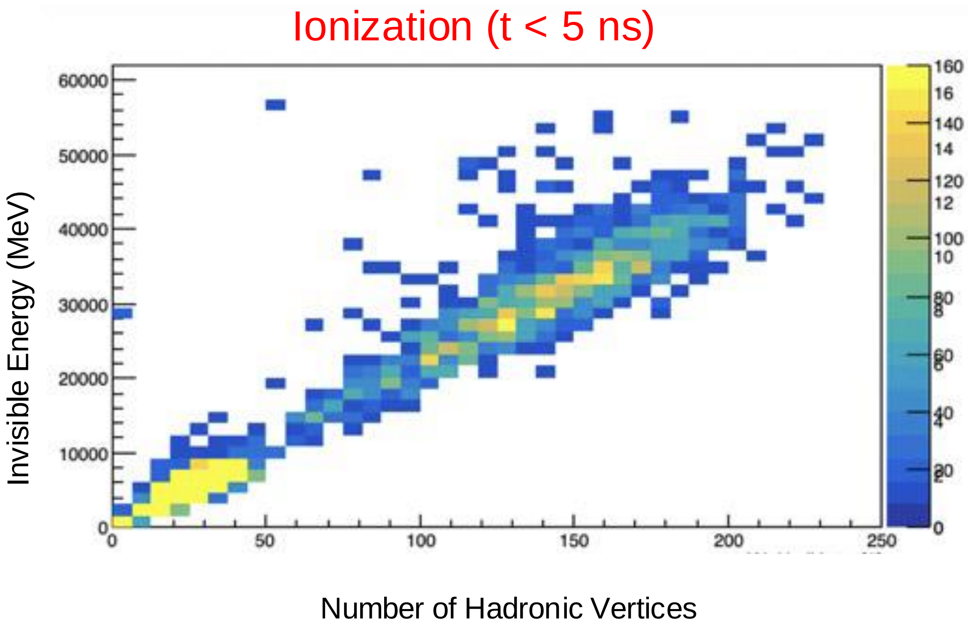


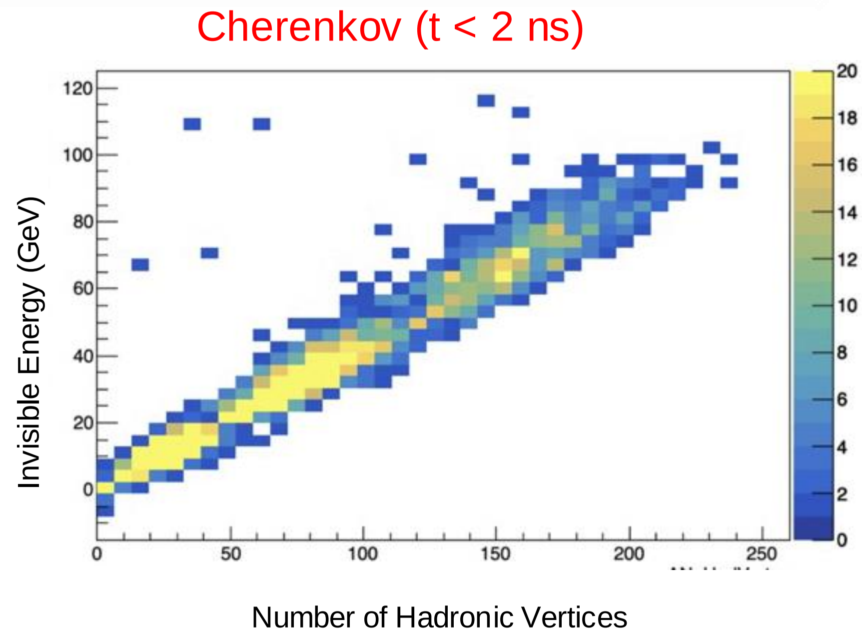
Shower image generated by the Cherenkov signal is sharper compared to that of the image generated by the ionization signal, making it more advantageous for AI/ML pattern recognition of complex event structures

- Reconstruction of individual particles in jets and associating them with tracks for particle flow algorithms
- Analysis of jet substructure to identify boosted *W/Z/H/t*

"Pseudo-jet" has three particles 10 cm apart interacting with a calorimeter

Counting Hadronic Vertices in Short Times



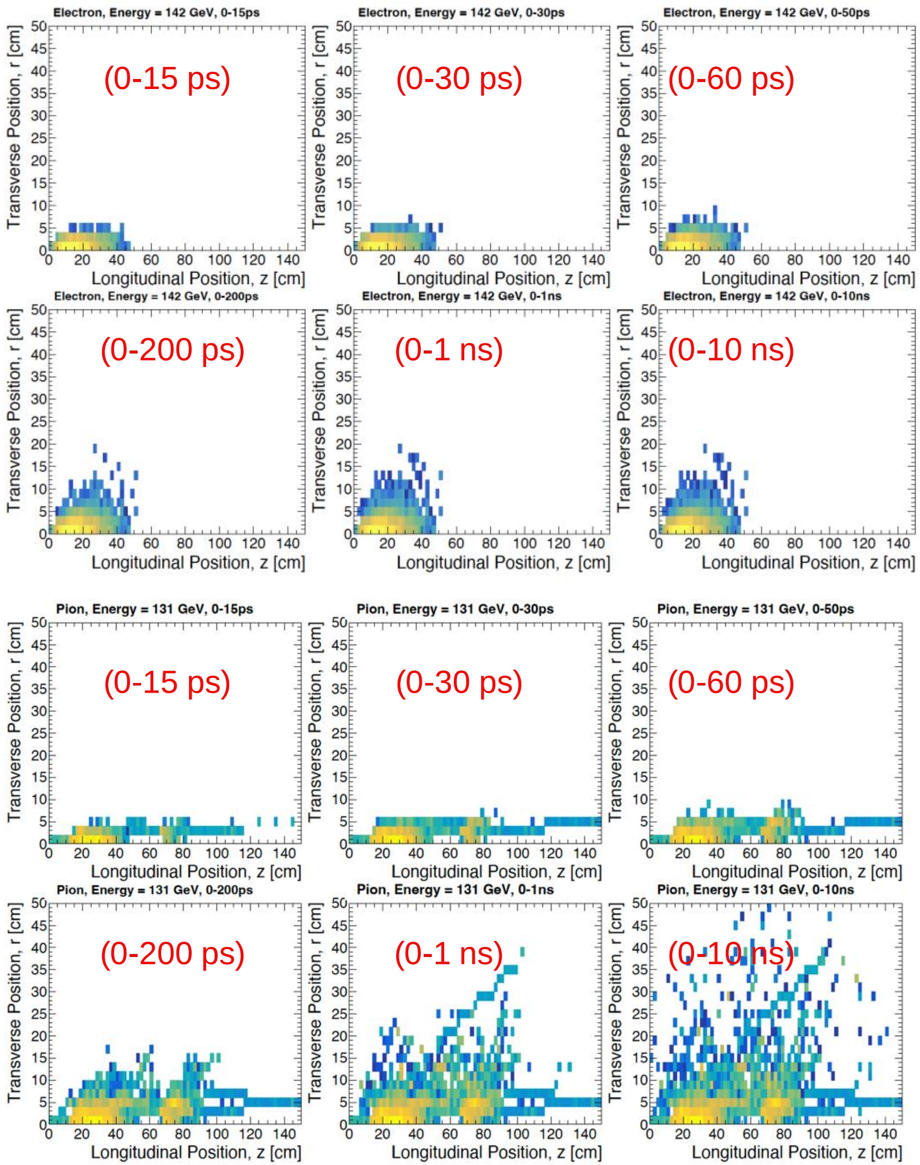


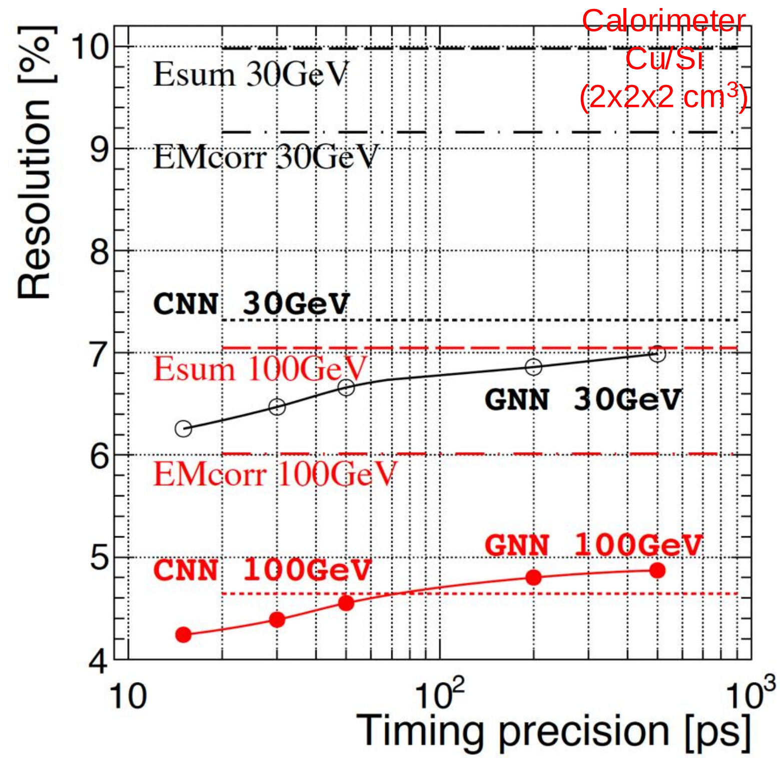
Counting or imaging the number vertices in a highly granular calorimeter will likely improve the hadronic energy resolution when measured event-by-event because of strong correlation with the invisible energy

Feature	Simulation	Consideration
Fast	Integration time <5 ns	High collision rate
High granularity (3D)	$2\times2\times2$ cm^3 cell	ρ_M~1.6 cm (Cu)
Less neutrons	Copper absorber	Least binding loss

Energy Resolution with Timing Information Using NNs

N. Akchurin et al JINST 17 P12036 (2021)





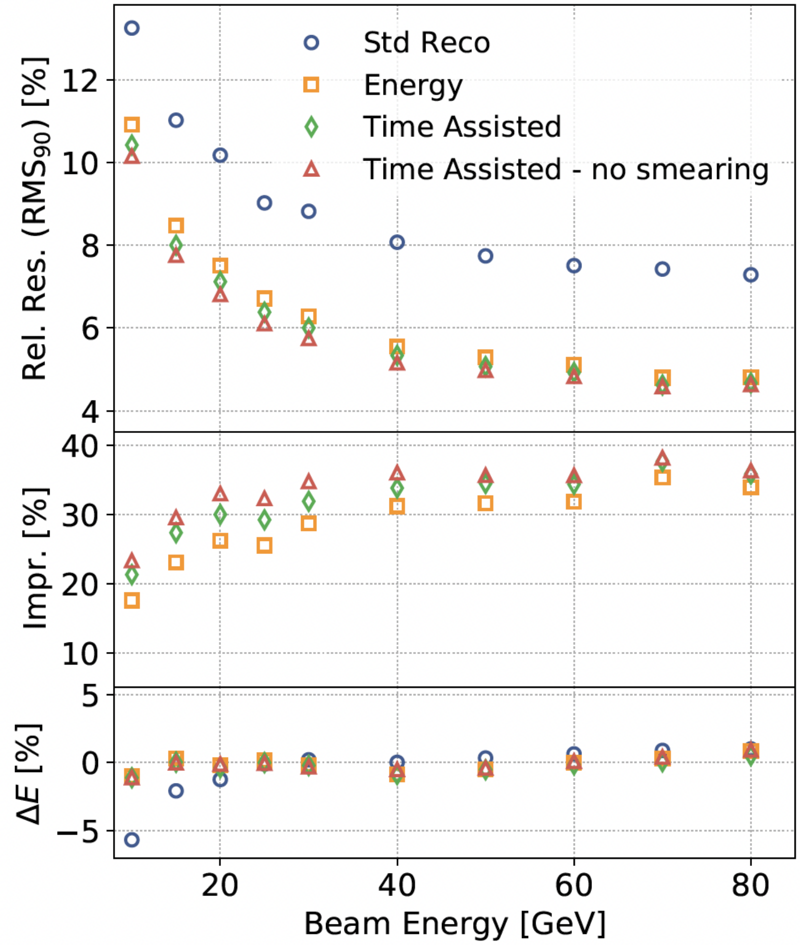
- GEANT4 FTFP-BERT 2x2x2 cm^3 Cu 1.7 cm, Si 0.3 cm 4-150 GeV charged pions
- CNN: input (x,y,z,E) per cell in 5 ns, target (beam energy)
- GNN: input (x,y,z,E,t) per cell in 6 time-windows
- CNN trained only pions achieves marked improvement over the conventional approaches
- GNN, with edge convolution (PointNet), with shower development timing information further improves energy resolution when shorter time slices are included
- Next try Cherenkov signal

Time-assisted Software Compensation

- 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

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

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

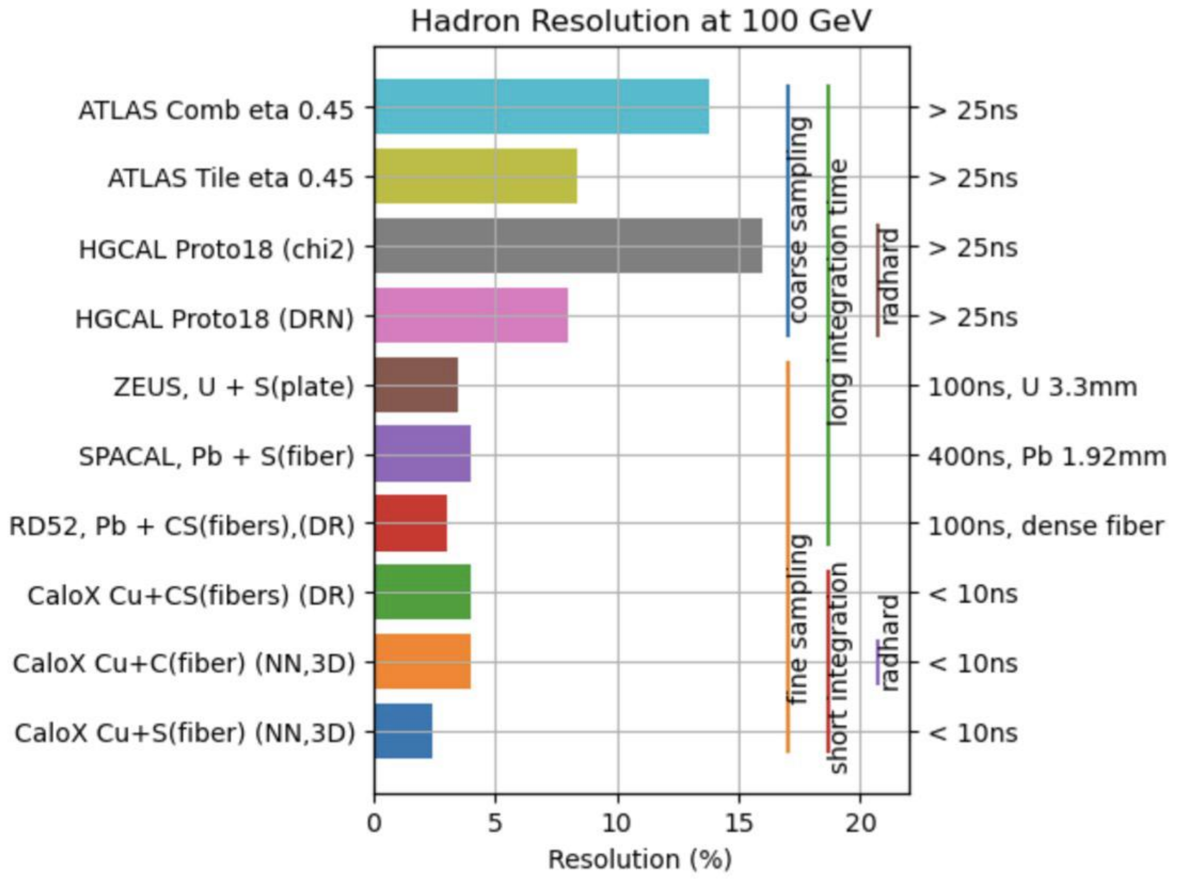


C. Graf and F. Simon, JINST 17 P08027 (2022)

Sampling and Integration Time

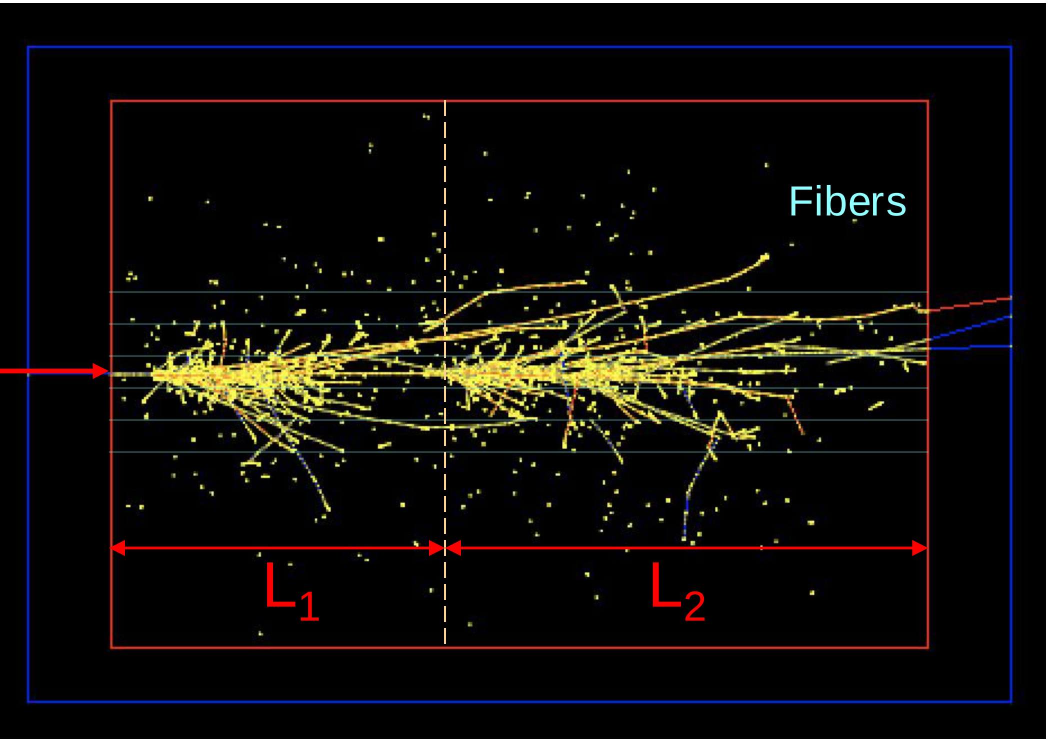
Key features of a high-performance calorimeter at the future high-rate collider experiments:

- Fine sampling
- Short integration time
- Radiation hardness
- Absorber material (Cu or Fe over Pb, W, or U)



Longitudinal Segmentation with Timing

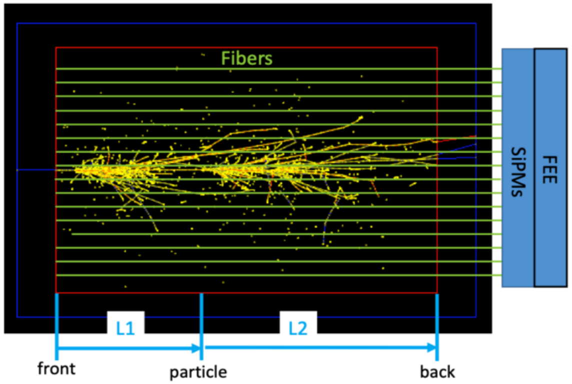
Fiber calorimeters generate and efficiently transport light. With appropriate timing ("sampling/strobing"), it may be possible to effectively segment the calorimeter in depth

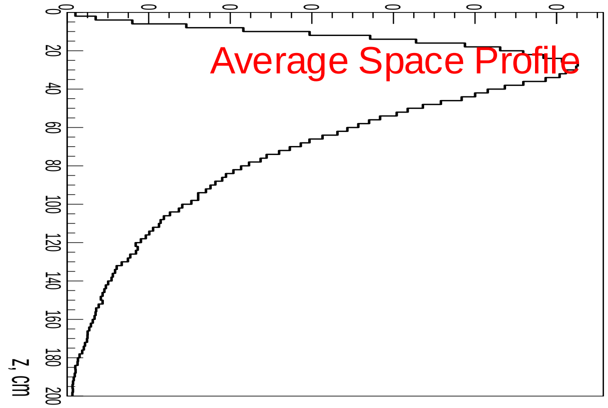


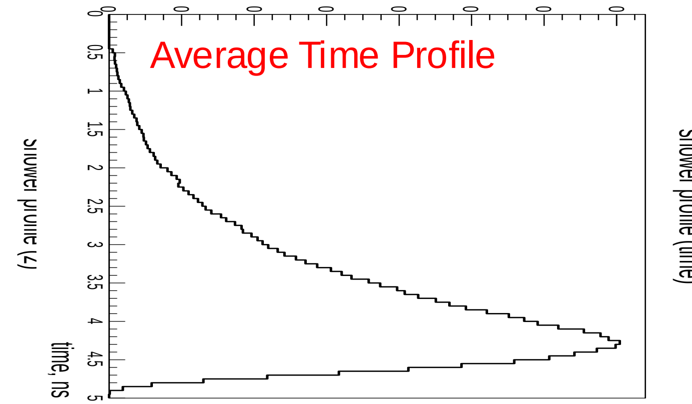
Signal time = $L_1/c + L_2/(c/n)$,
(c/n) = velocity of light in fiber (n~1.45)
~20 cm/ns or ~1 cm/50 ps

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

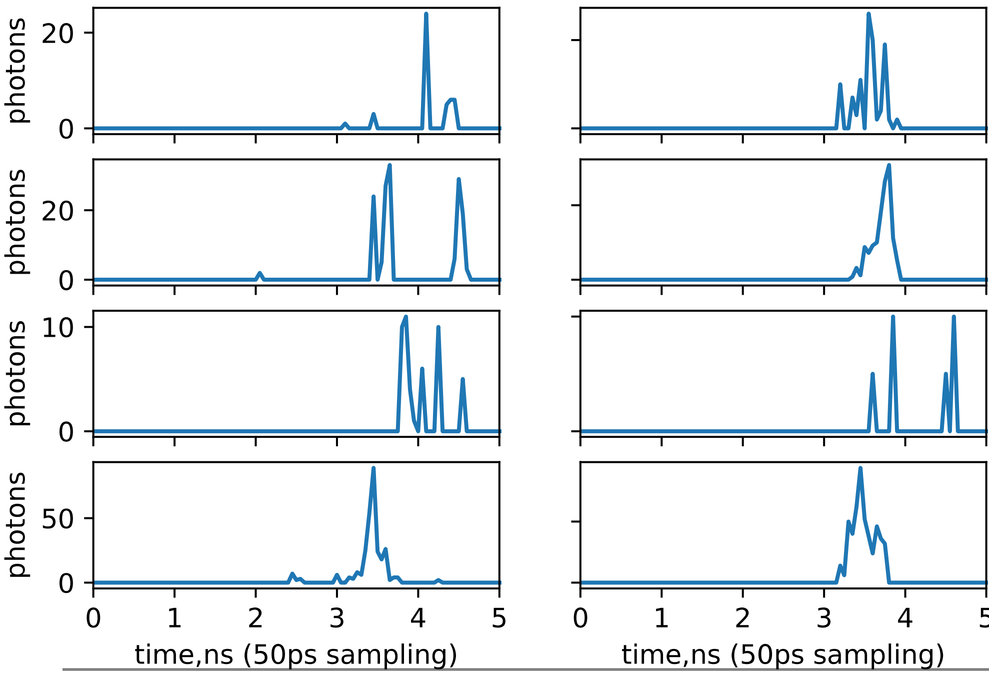
Simulations/Estimates with HG-DREAM



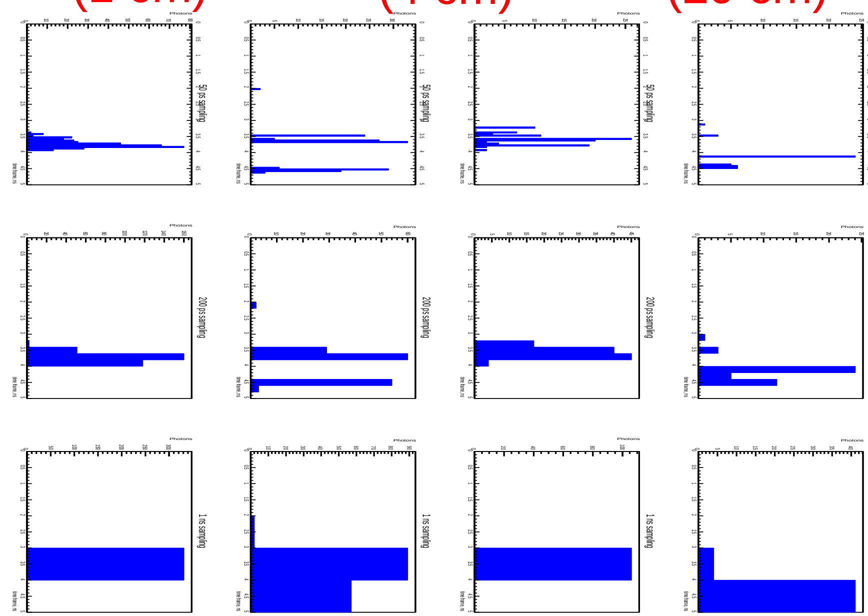




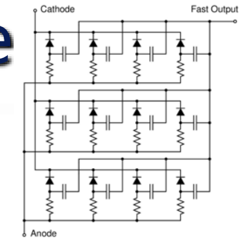
50 GeV π^+ in 1.2 cm x 1.2 cm tower



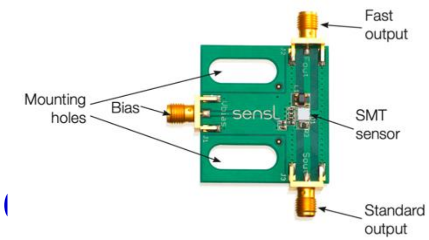
0.05 ns (1 cm) 0.2 ns (4 cm) 1 ns (20 cm)



Separation of Two Signals Close in Time



SiPMs are excellent photon counting devices and have potential to map time structure of showers in calorimeter when used with high performance waveform digitizer

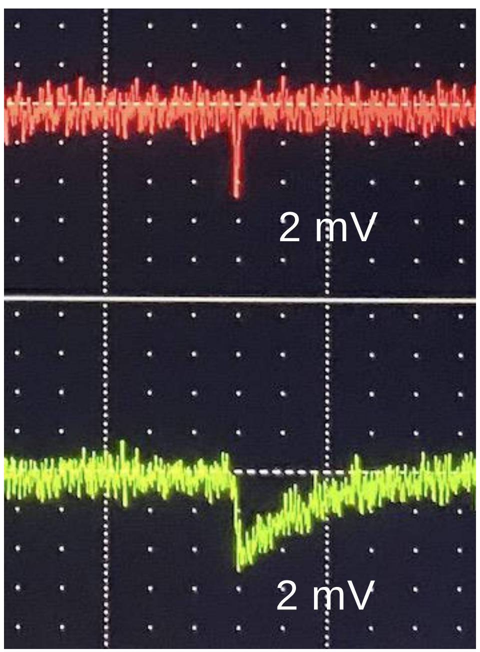


OnSemi (MicroFC-30020SMT) SiPMs have fast an standard outputs

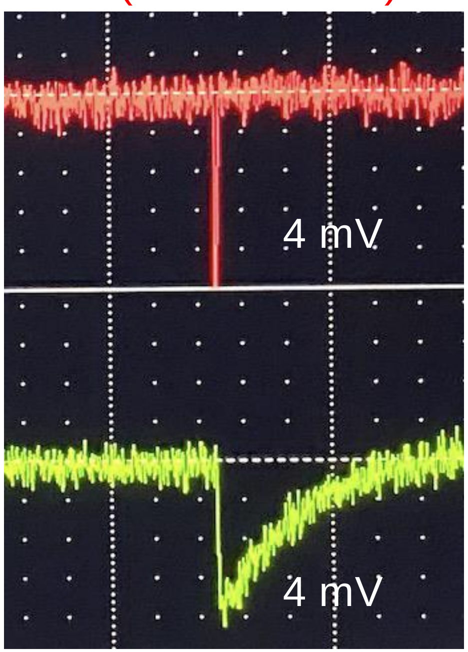
One photon event

Fast Out (2 mV/photon)

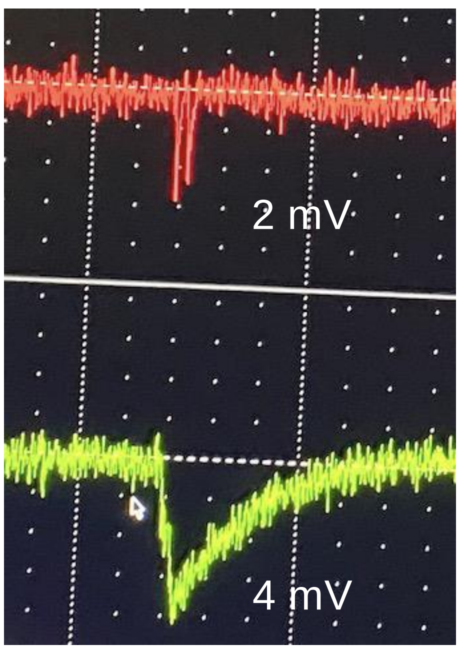
Std Out (2 mV/photon)



Two photon event (simultaneous)

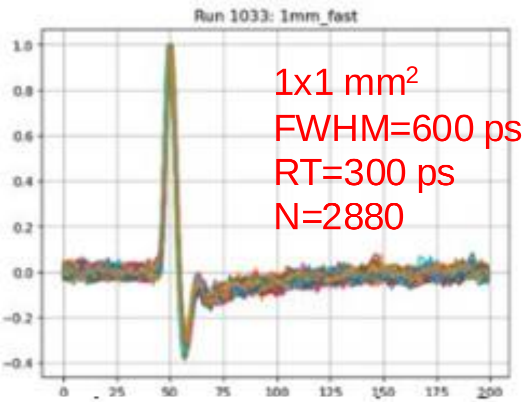


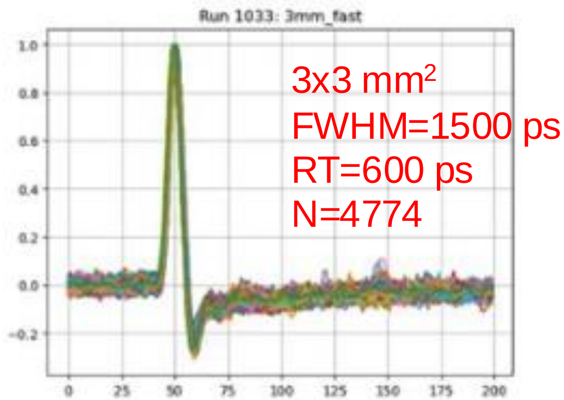
Two photon event (5 ns apart)

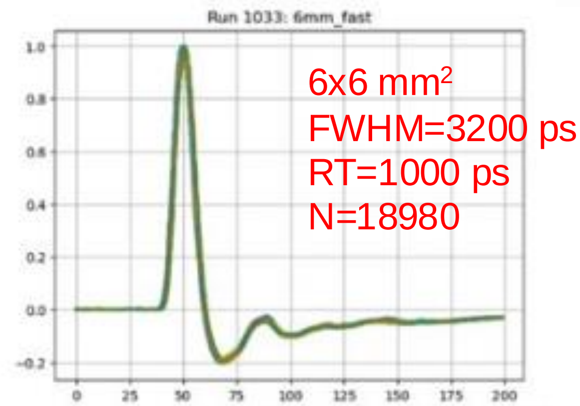


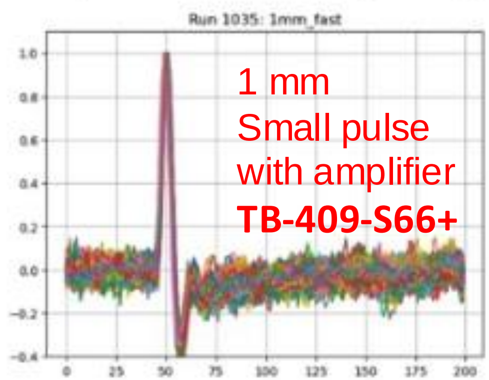
S. Kunori et al CPAD 2021

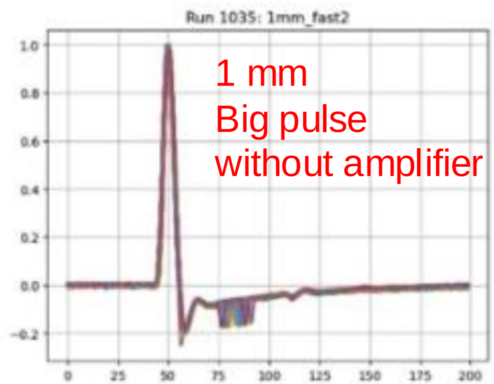
Fast Pulse Shape Studies (OnSemi SiPM C-Series)











Bench tests using a fast laser (~140 ps pulse)

1,000 pulses in each plot

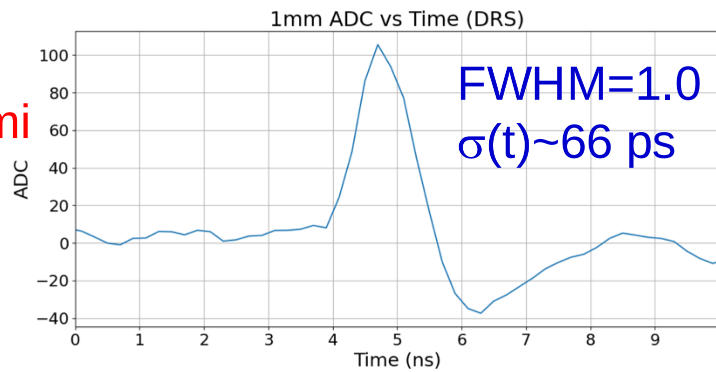
Stable pulse shapes lend themselves for reliable deconvolution

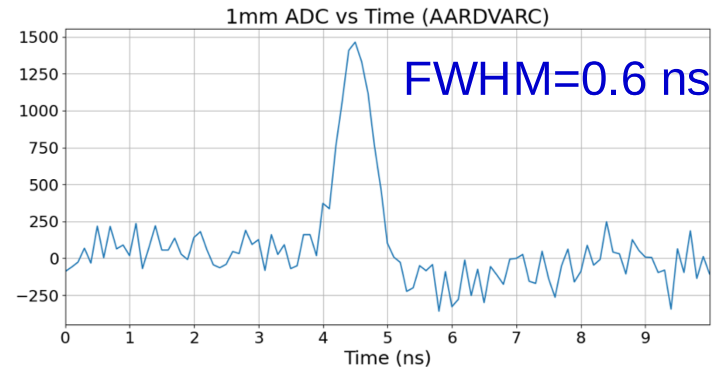
Fast Pulse Shape with DRS and AARDVARCv3

CAEN V1742
(DRS)
Input BW ~ 0.5 GHz
Sampling = 5 GS/s

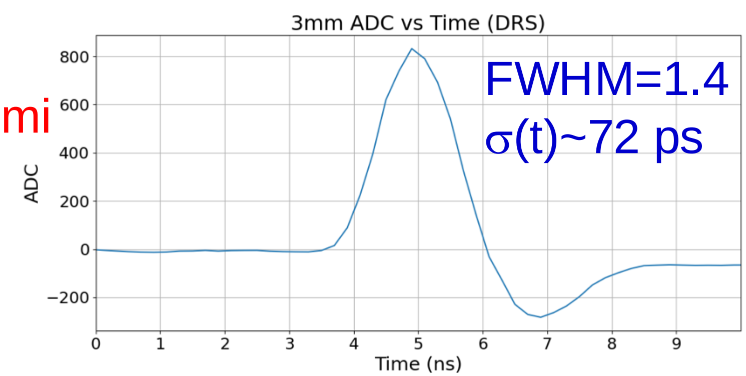
NALU AARDVARC3
(Evaluation Board)
Input BW > 1 GHz
Sampling = 10-14 GS/s

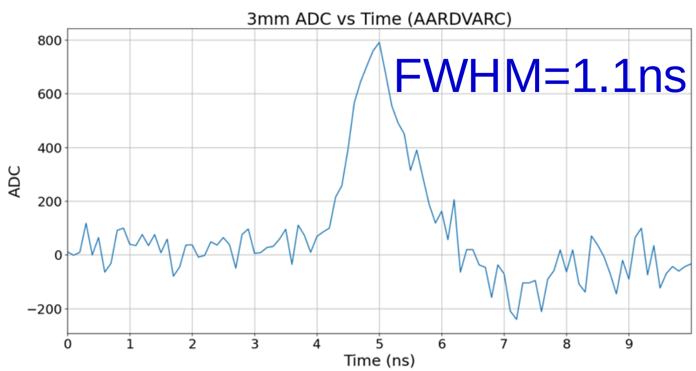
1x1 mm^2 OnSemi
FWHM=0.6 ns





3x3 mm^2 OnSemi
FWHM=1.5 ns

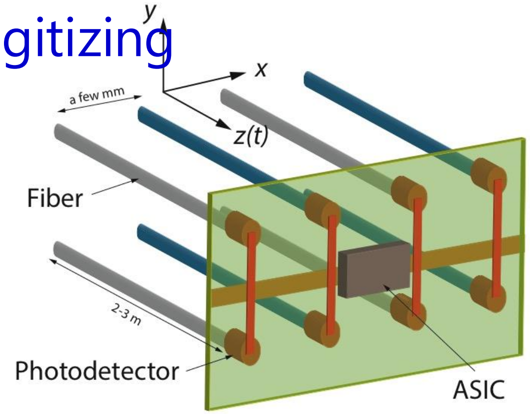


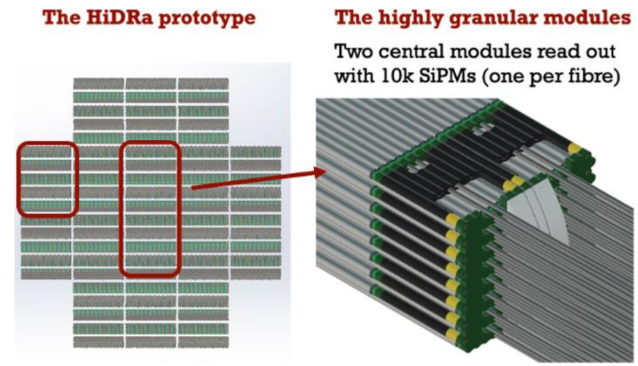


- DRS FWHM for 1 mm^2 is wider than datasheet value, likely due to the limited bandwidth of the DRS
- σ(t) is the *rms* of t(SiPM)-t(laser trigger)

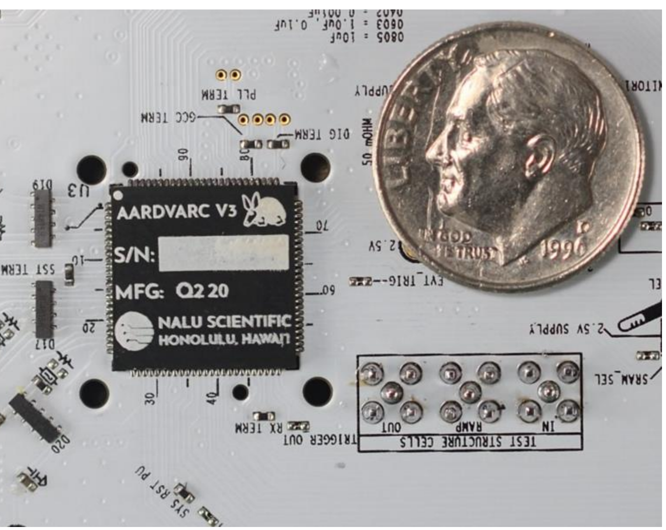
Example: Enabling Digitizer NALU AARDVARC V3

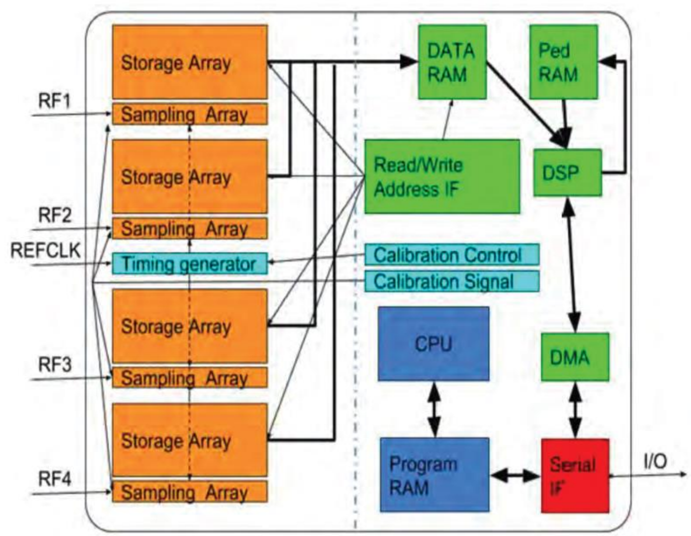
- Compact, high performance waveform sampling and digitizing
  - Sampling rate 10-14 GS/s,
  - 12 bits ADC,
  - 4-8 ps timing resolution,
  - 32 k sampling buffer,
  - Bandwidth 2 GHz,
  - System-on-Chip (CPU)
- Higher channel density per chip desired/planned?

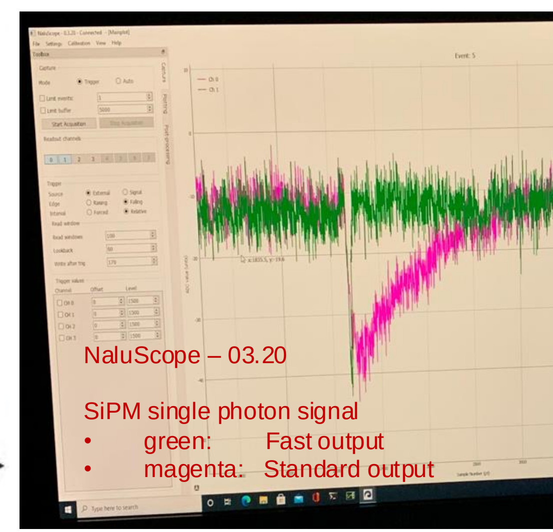




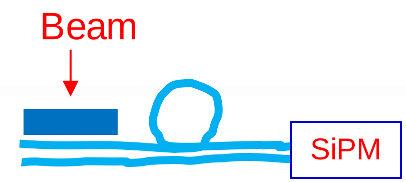
HiDRa prototype (IDEA) INFN…







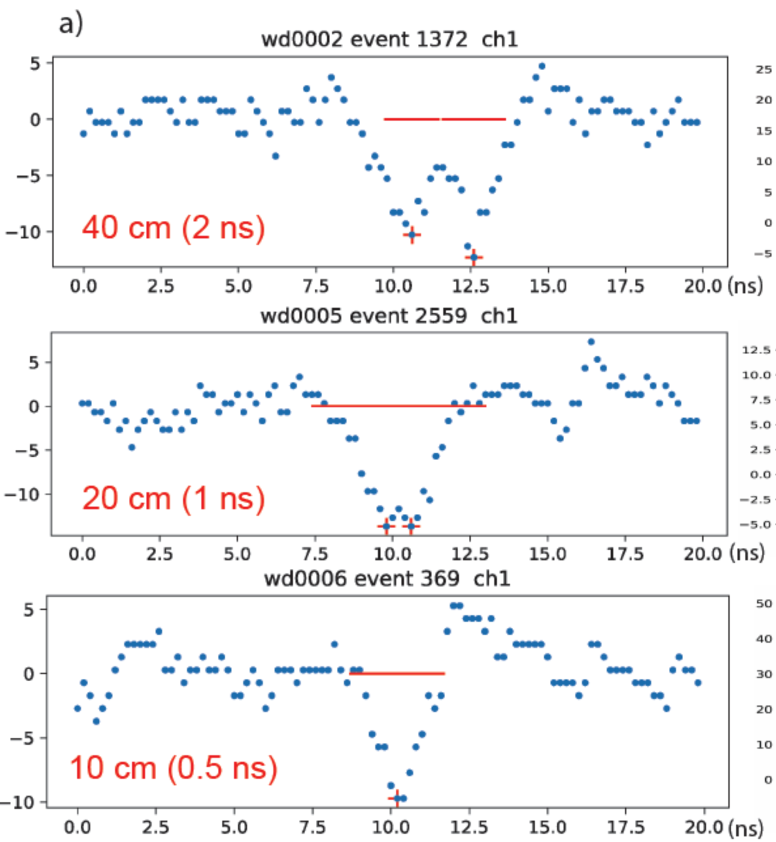
Pulse Train Studies - I

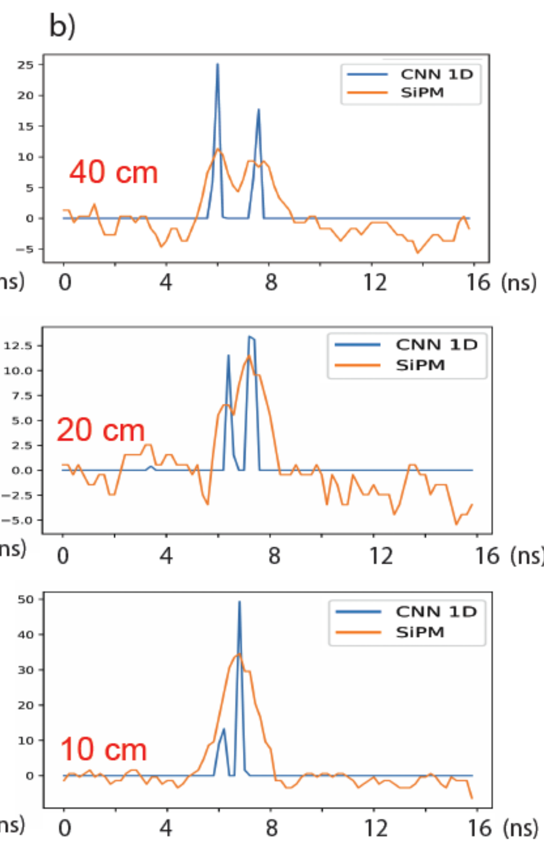


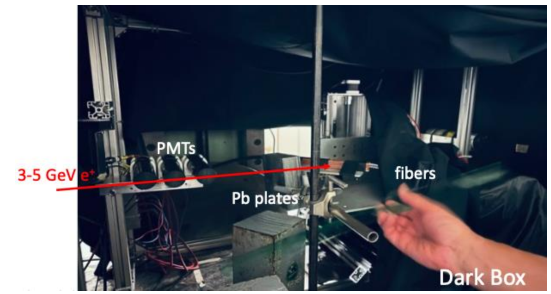
TB23 Data
Cherenkov Signal
(1 photon = 10 ADC counts)
3x3 mm^2 SiPM with a 10x amplifier

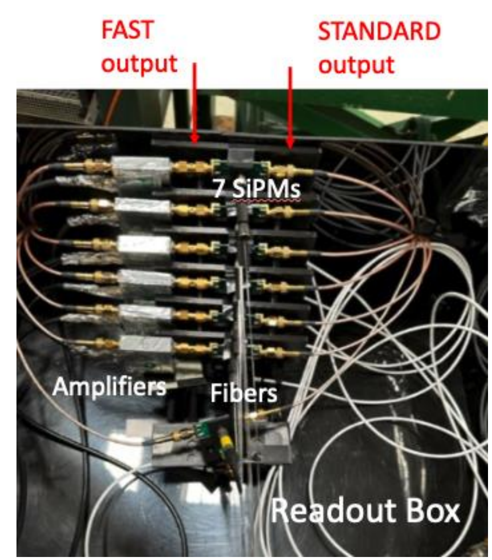
CNN reconstruction
DRS (noisy) data

TB23 Setup at
CERN PS T9

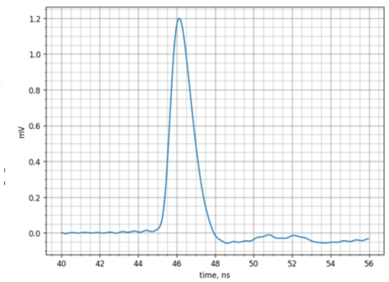




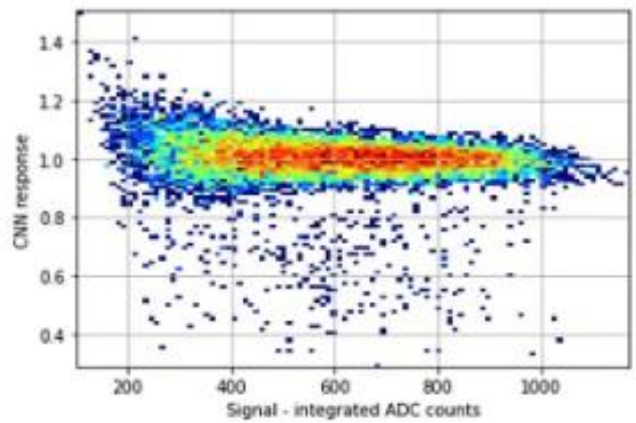


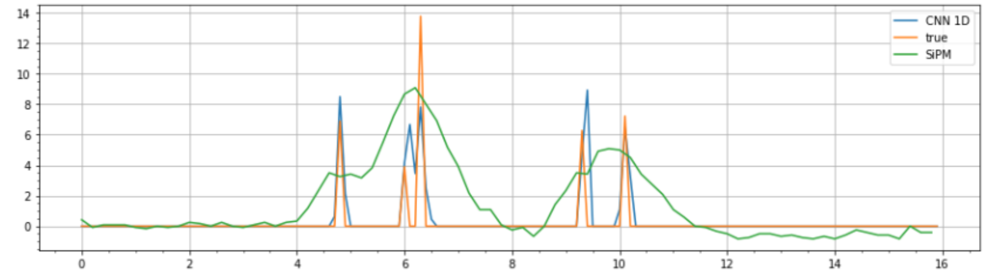


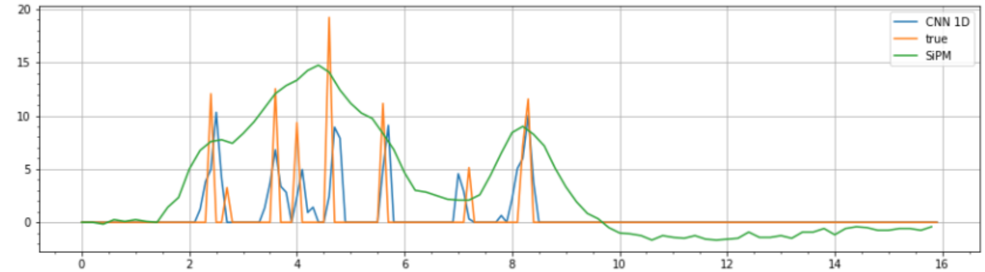
Pulse Train Studies - II

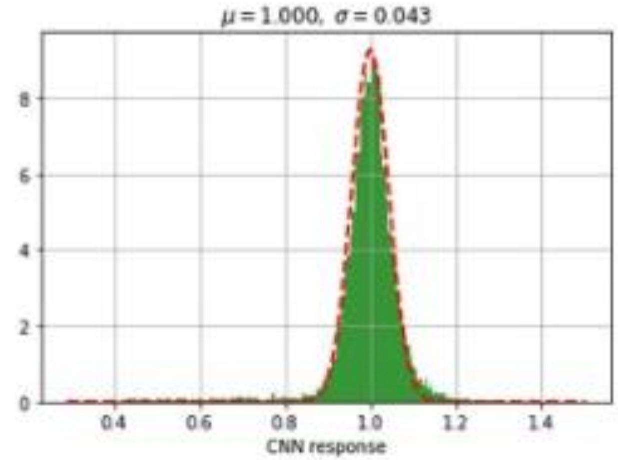


- SiPM pulse shape is extracted from TB23 data
- Pseudo-data are produced by overlapping pulses and added Gaussian noi
- The amplitude is varied
- Time separation between pulses ranged 0-2.6 ns
- Overall arrival time is varied bv ±0.8 ns





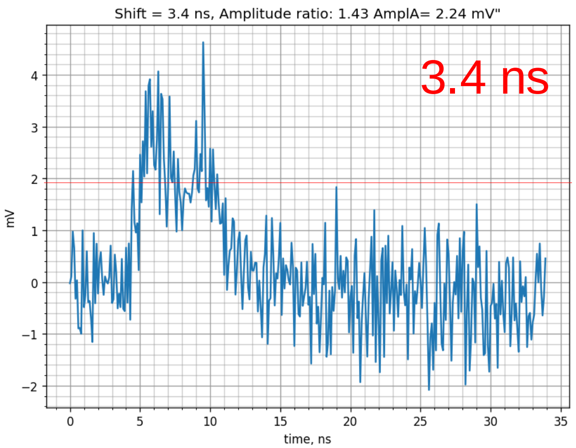


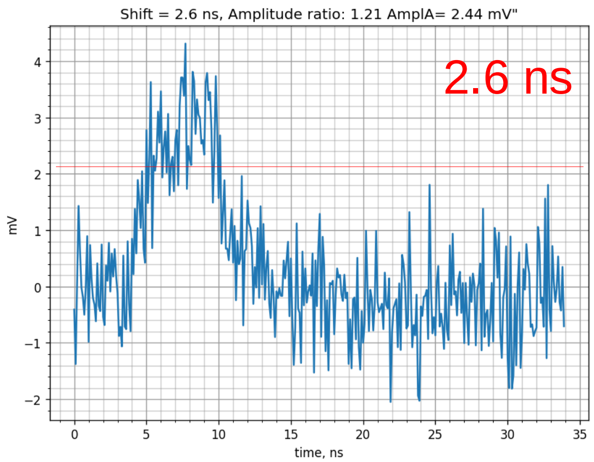


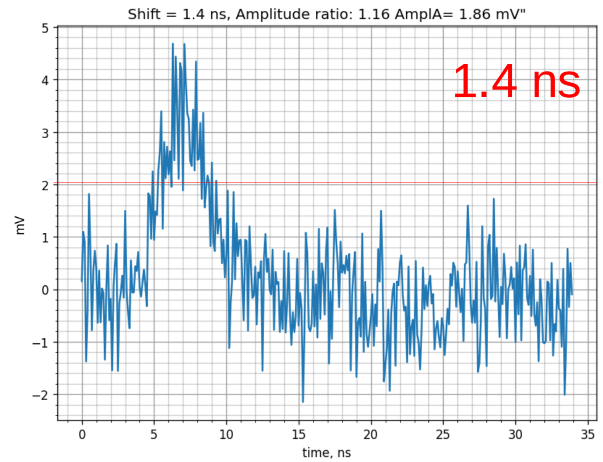
It seems possible to deconvolve overlapping SiPM (Cherenkov) pulses to reveal the true distribution of shower components using CNN:

- Green: Convoluted SiPM pulse train
- Blue: Deconvoluted SiPM pulse train
- Orange: True pulse train

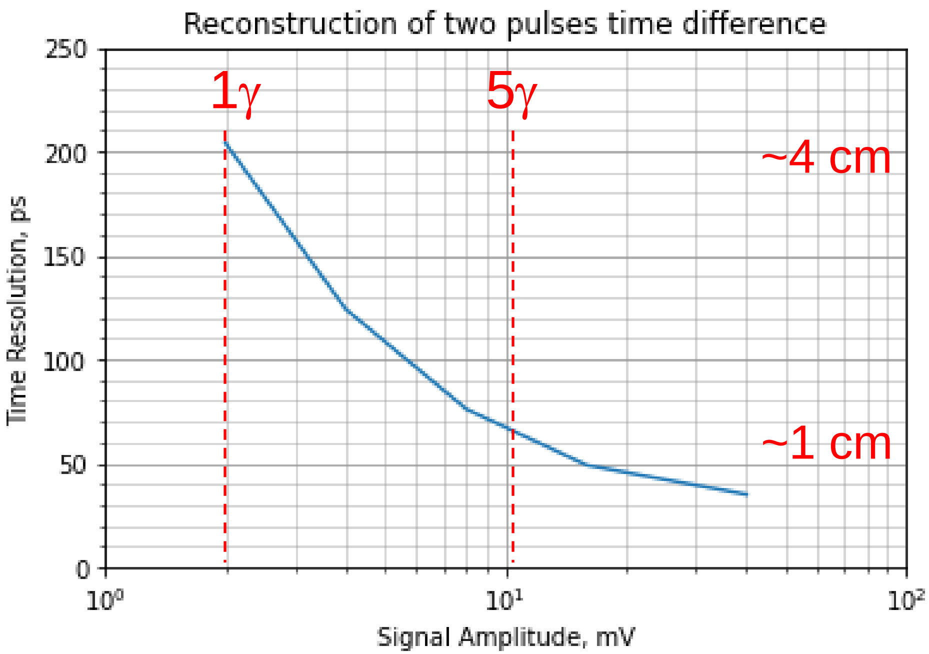
Timing Resolution at Single Photon Level
Separation of Two Signals



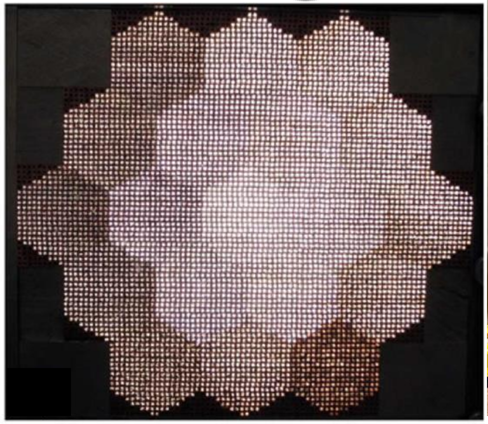


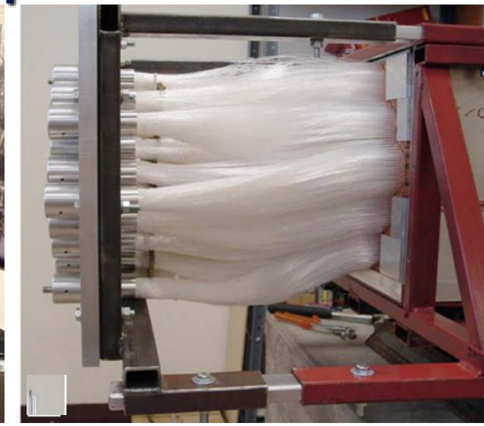


- Pulse shape of single photon signal from SensL/OnSemi SiPM was measured with NALU's AARDVARC V3 and used to simulate waveforms of convoluted pulses of two photon events
- Recurrent Neural Network (RNN) was used to reconstruct the timing of two photons
- Resolution of 4 cm (1 cm) seem possible for 1 (5) photon-equivalent signal on bench tests. Significant R&D needed for future applications



The Original DREAM Prototype



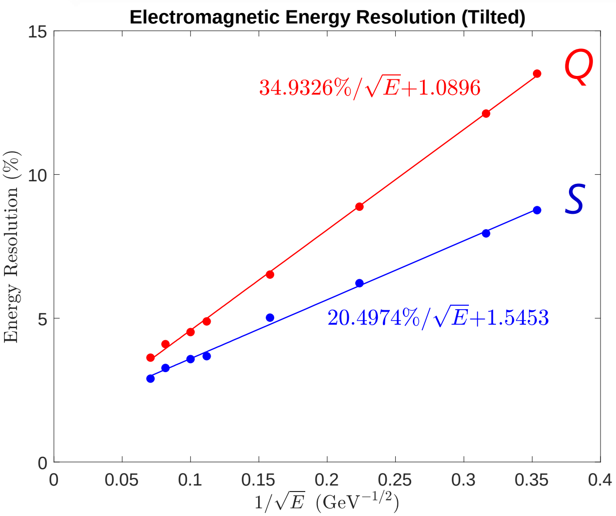


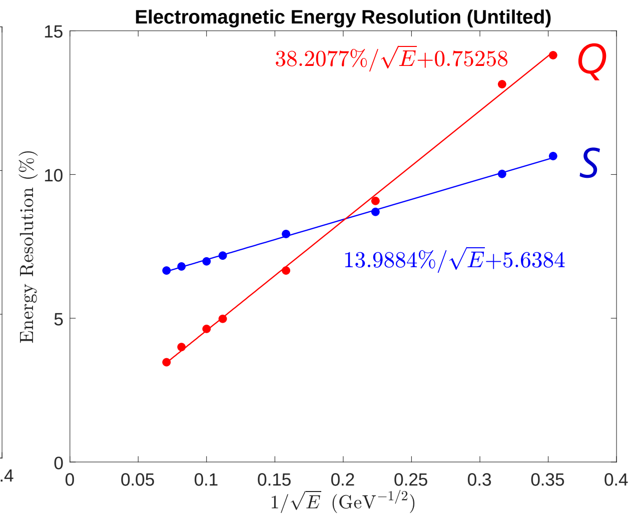
DREAM module was built at TTU and exposed to beams at CERN starting in 2003 in several campaigns

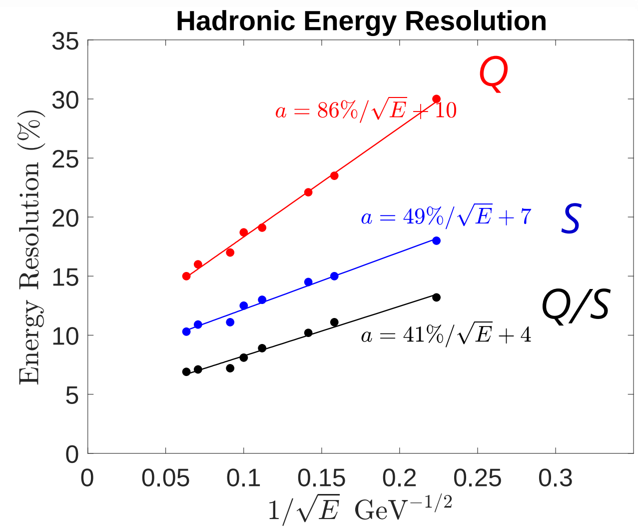
The motivation was to explore the simultaneous measurement of showers using scintillation (*S*) and Cherenkov (*Q*) signals for event-by-event compensation because $Q/S \sim f_{em}$

- X_o ~20.1 mm, ρ_M~ 20.4 mm, λ_I~ 200 mm, and weight ~ 1,030
- Scintillating fiber: SCSF-81J Kuraray
- Clear/Cherenkov fibers: QP Polymicro, Raytela PJR-FB750 Tora
- 69.3% Cu, 9.4% Scintillator, 12.6% Cherenkov, and 8.7% air
- f_{samp} $(Cu/S)_{MIP}$ ~ 2.1%
- 19 Scintillating and 19 Cherenkov towers of *r* ~ 37.1 mm
- PMT R580 10-stage with gain 3.7E5 at -1250 V

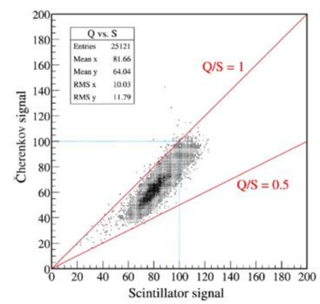
DREAM Performance in a Nutshell



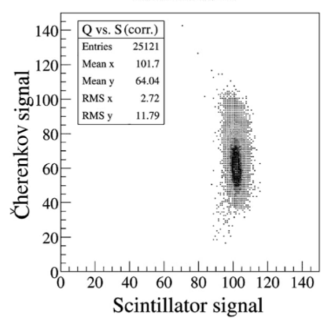


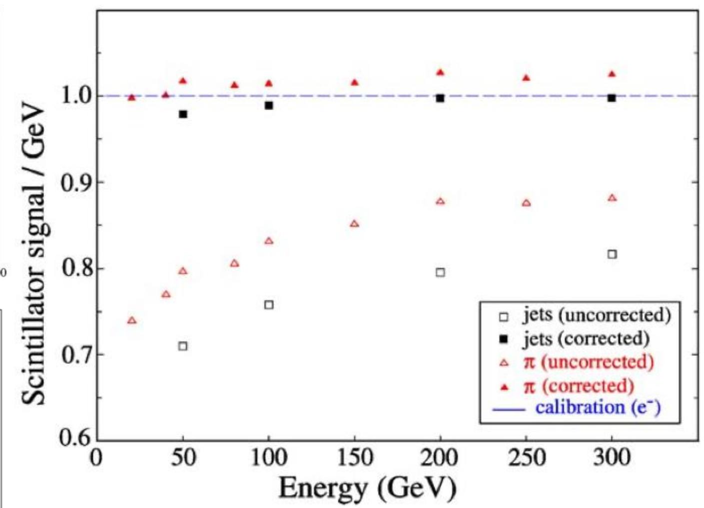


The photoelectron yield was 8 pe/GeV for Cherenkov with fused-silica (Polymicro), 18 pe/GeV for clear plastic (Toray), and 33 pe/GeV for scintillator fibers (Kuraray).

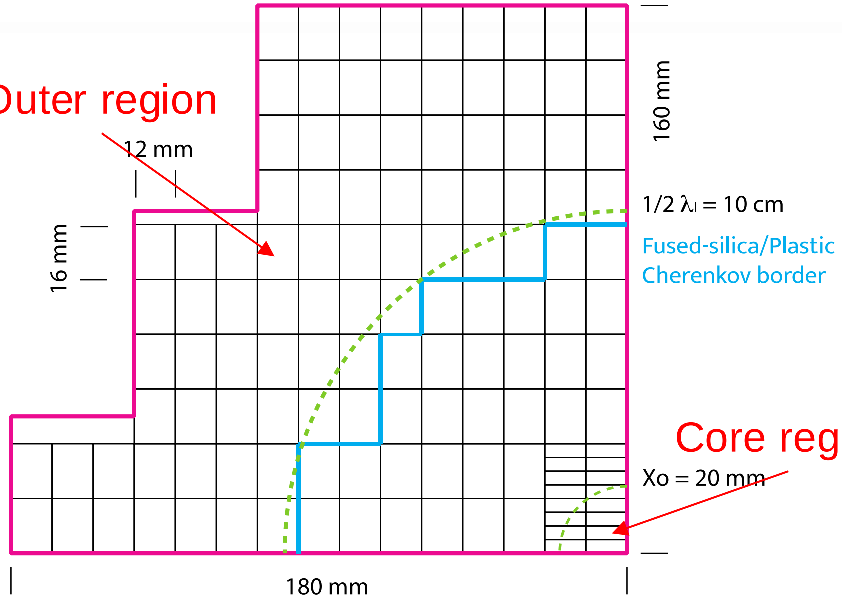


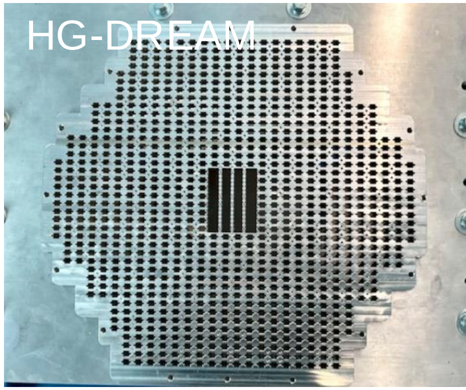
The hadronic energy resolution improves with *Q/S* correction (essentially a rotation in *Q vs S* plane), and the hadronic response linearity is attained as well





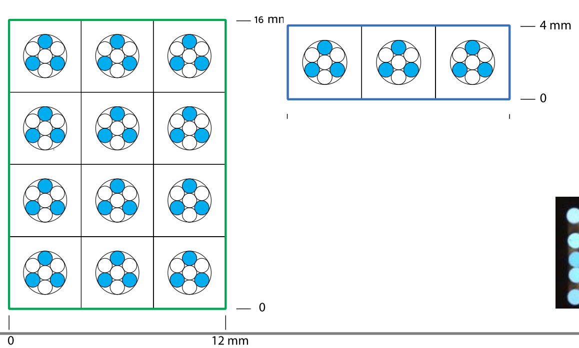
HG-DREAM Segmentation - I

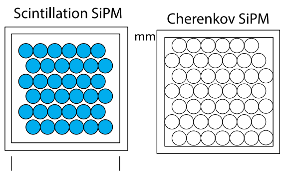


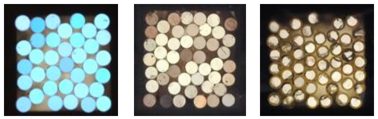


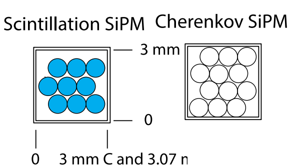
Segmentation increases by x24

	Tower size (mm^2) (No of rods)	No. S/C fibers	SiPM area (mm^2)	No. of units
Outer region	12x16 (12)	36 S, 48 C	6x6	440
Core region	12x4 (3)	9 S, 12 C	3x3	64

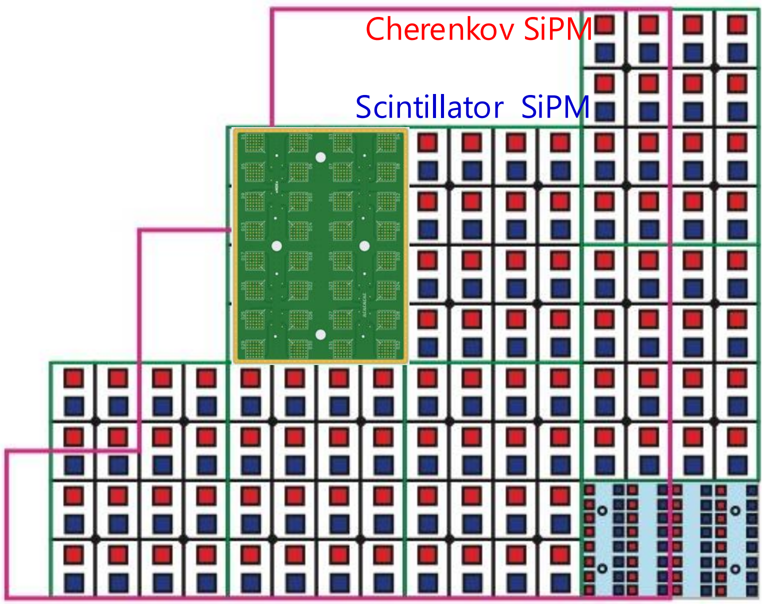


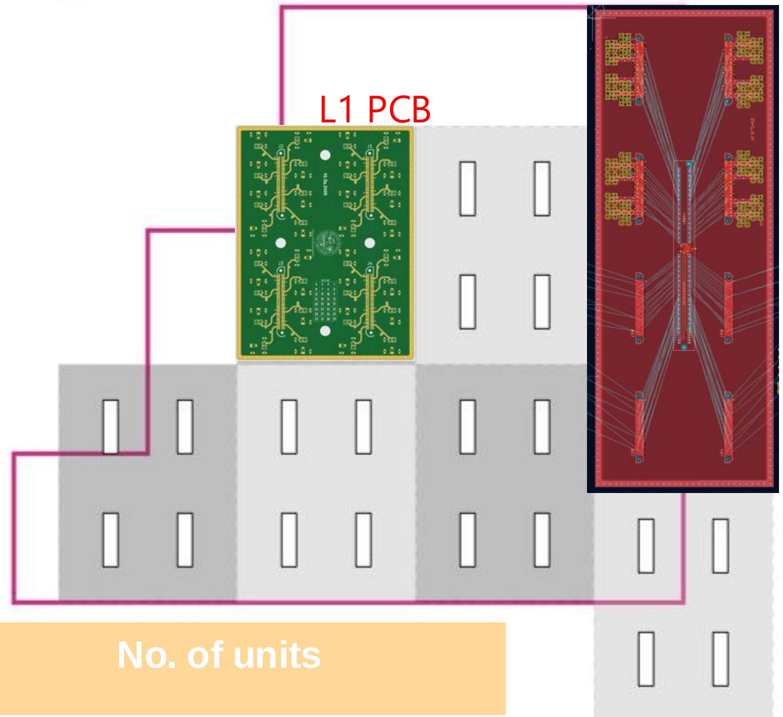






HG-DREAM Segmentation - II

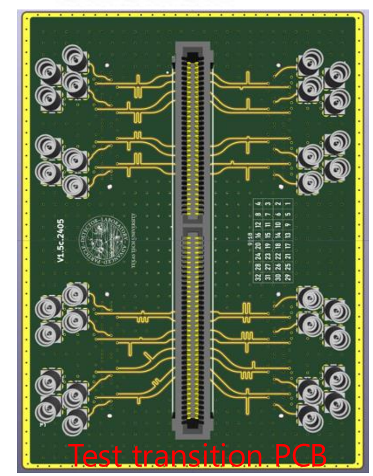




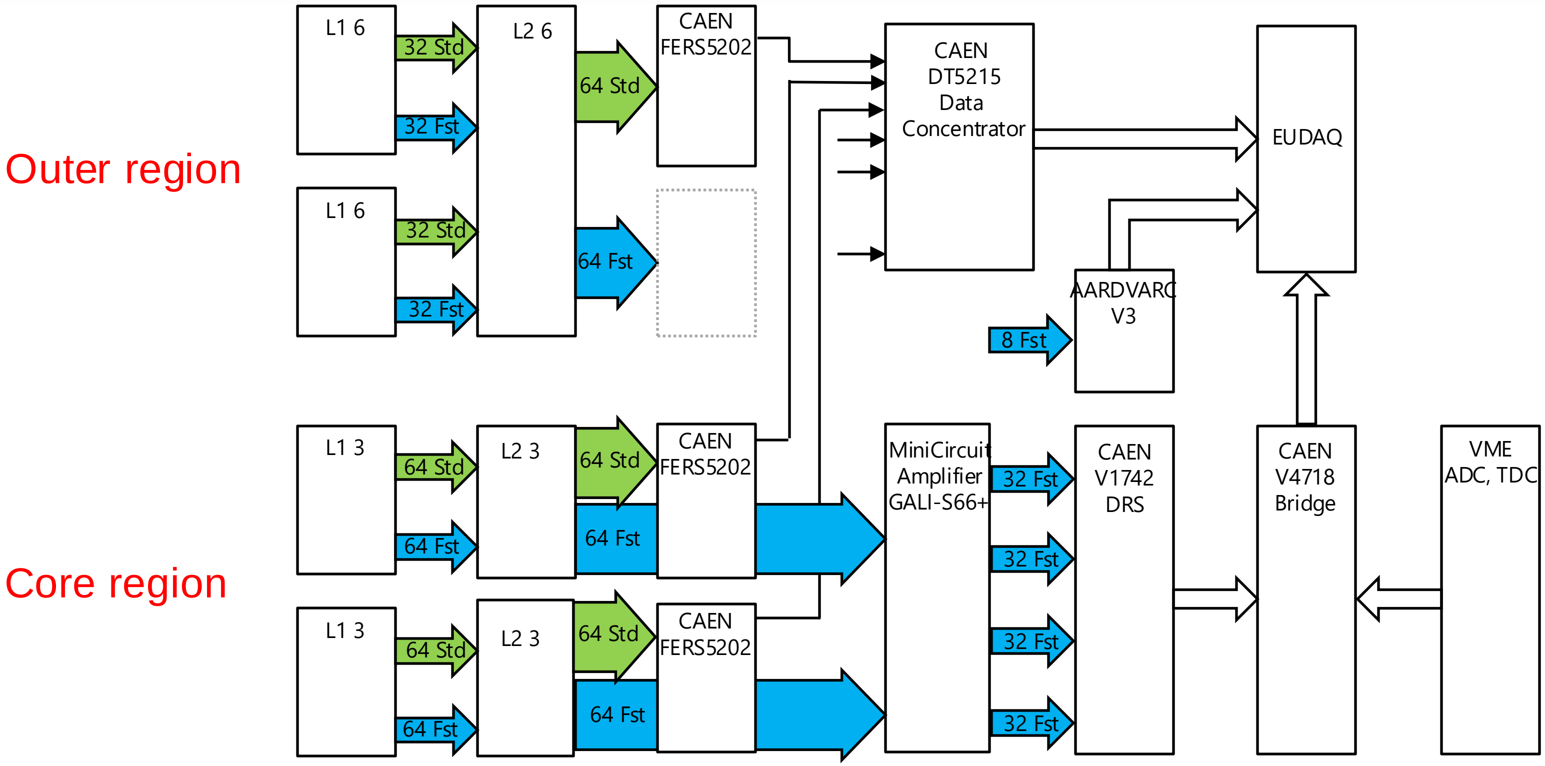
	L1 PCB	No. L1	No. L2	No. of units
Outer region	32 SiPMs	24	12	768 Std (FERS) 768 Fst
Core region	64 SiPMs	2	1/2	128 Std (FERS) 128 Fst (DRS)

L1 and test transition PCBs are designed

1. OnSemi SiPM C- and J-series SiPMs require different designs
2. Trace lengths are kept short: Std 15-18mm and Fst 6-10 mm (tested coplanar waveguide with ground (CPWG) and strip-lines (buried traces) in 6-layer boards)
3. For Std & Bias HSEC8-170-01-S-DV (edge connect to A5202)
4. For Fst MMCX Jack (female direct to amplifier or waveform digitizer)



HG-DREAM Readout Configuration



- Different types of information from a large number of channels need to be integrated and collected in a unified manner (EUDAQ)
- Expected data size ~220 kB/event for DRS and ~1.7 kB/event f FERS
- The data transfer rate 70-200 MB/s depending on link type
- There is much room for data size optimization but need for on-detector processing becomes evident

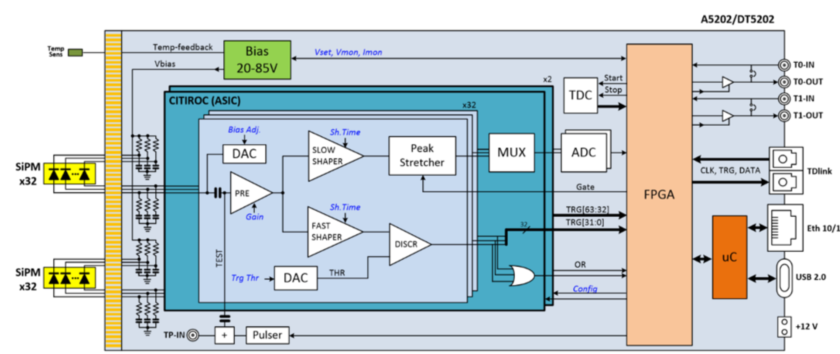
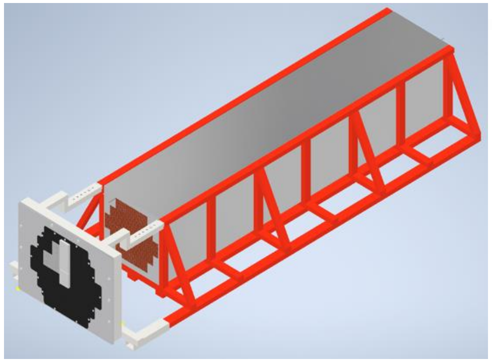
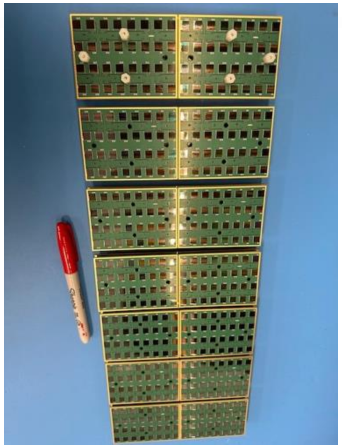
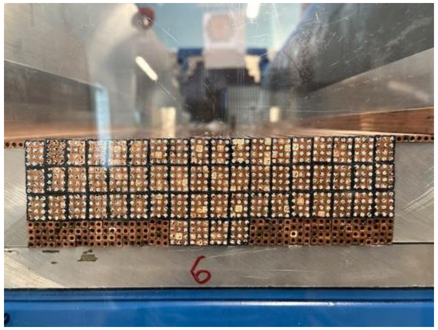


Fig. 1.1: Simplified block diagram of the A5202 FERS-5200 unit.

Status of HG-DREAM Assembly







Individual towers (12x16 mm^2) are constructed using fixtures

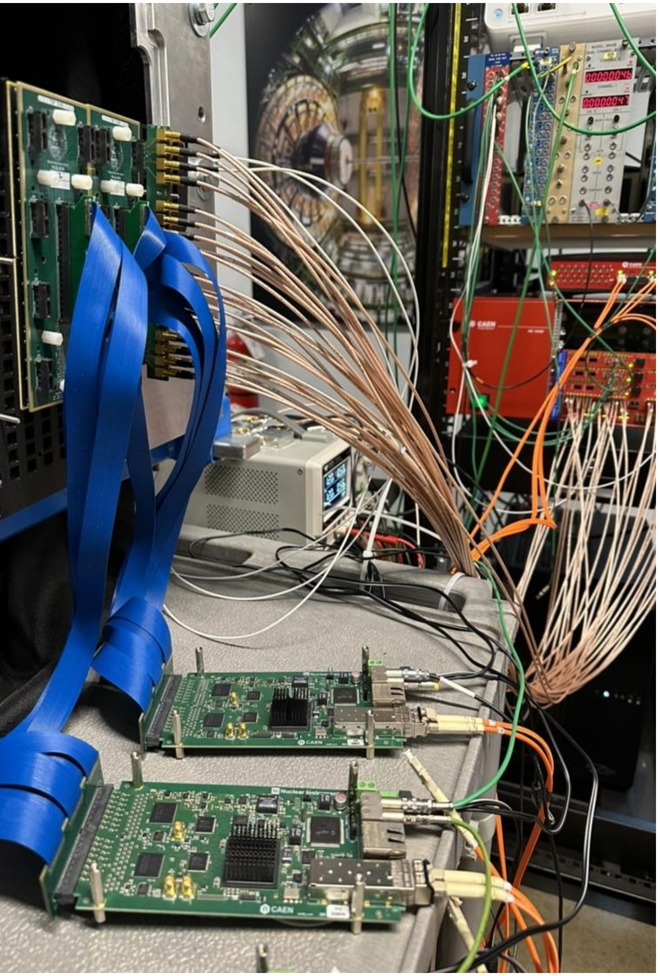
Aluminum endplate and fiber bundles with 3D-printed fiber connectors are done

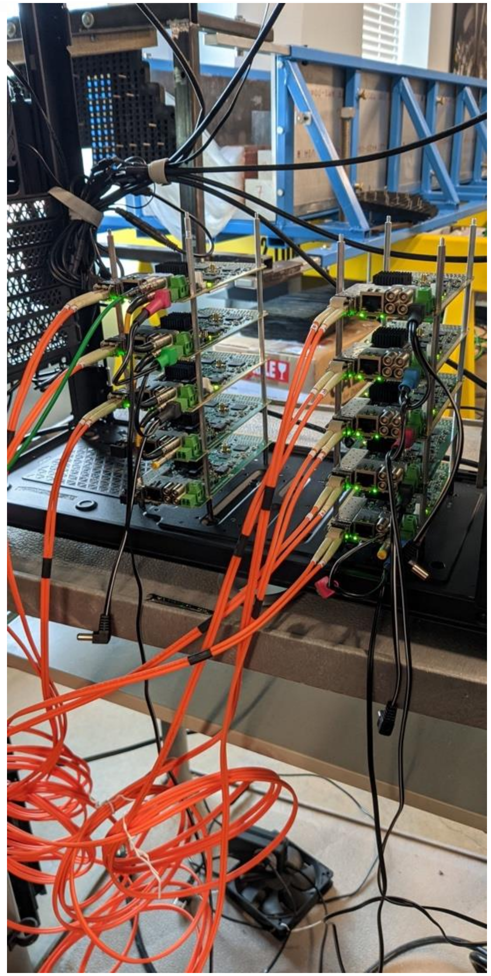
Now machining/testing filter plate to hold yellow filters (scintillation)

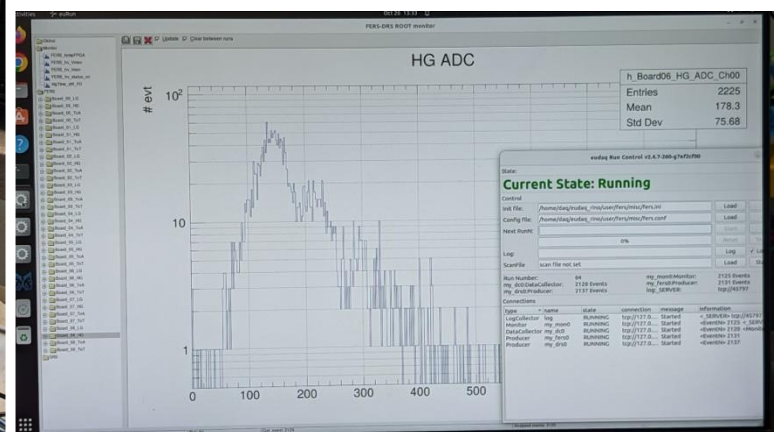
EUDAQ integrates FERS, DRS, and ancillary units (QDC, TDC)

HG-DREAM module beam test will take place in summer 2025 at CERN

Progress on EUDAQ for HG-DREAM

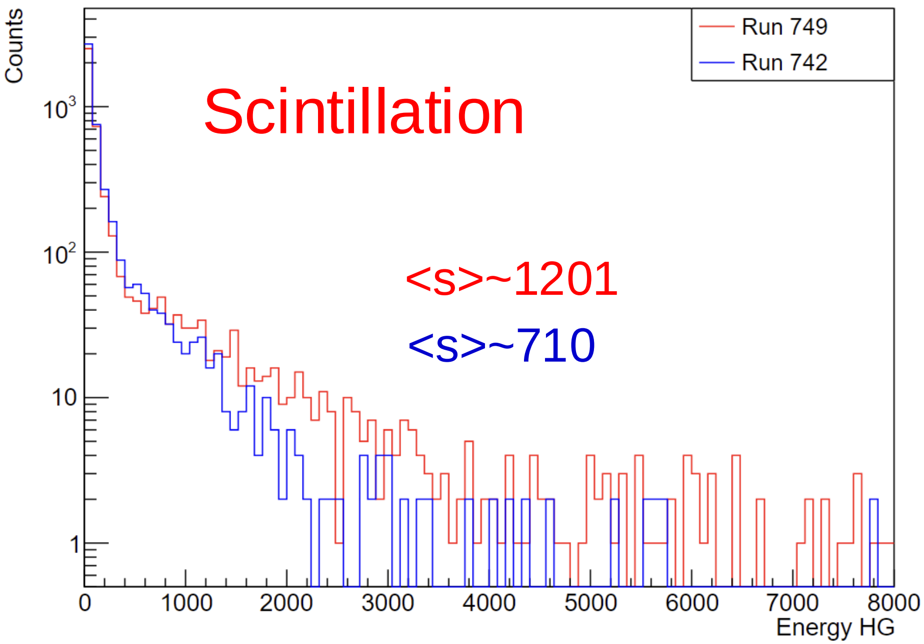


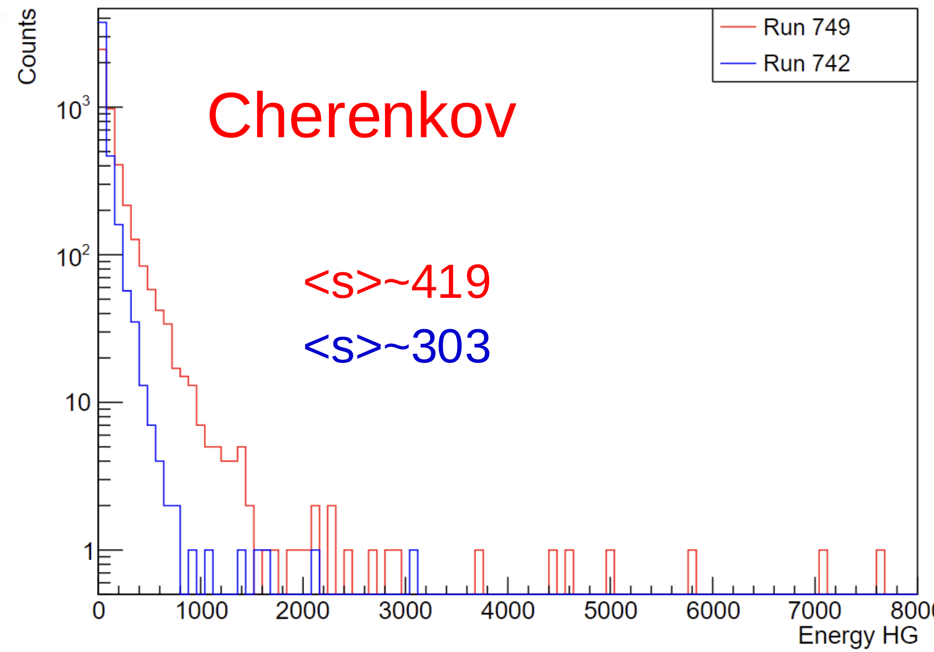


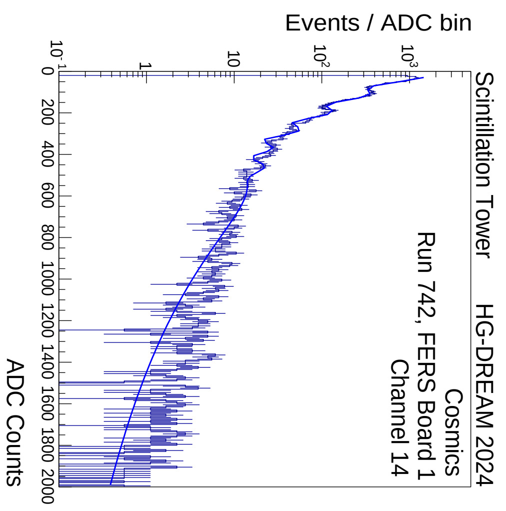


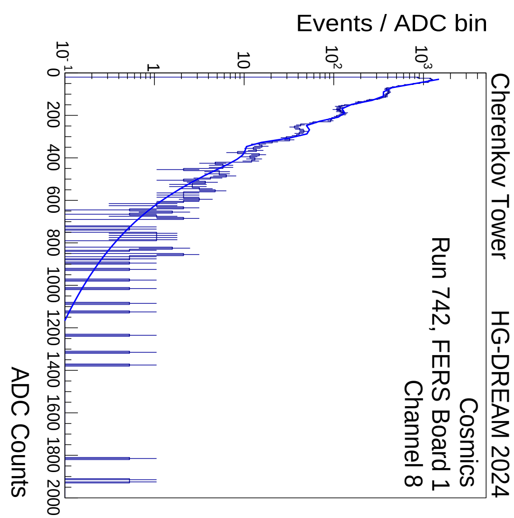
We run 11 FERS (A5202) and 6 DRS (V1742) without synchronization failures. We will have 14 FERs and 6 DRS boards in the final configuration.

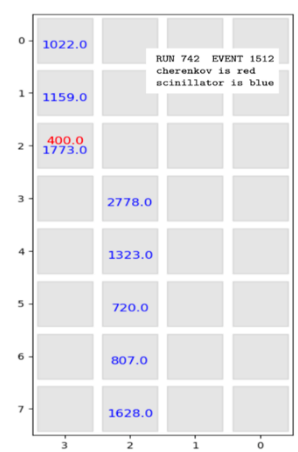
Cosmic Muon Runs with HG-DREAM



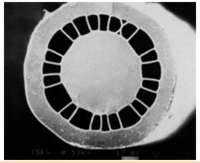




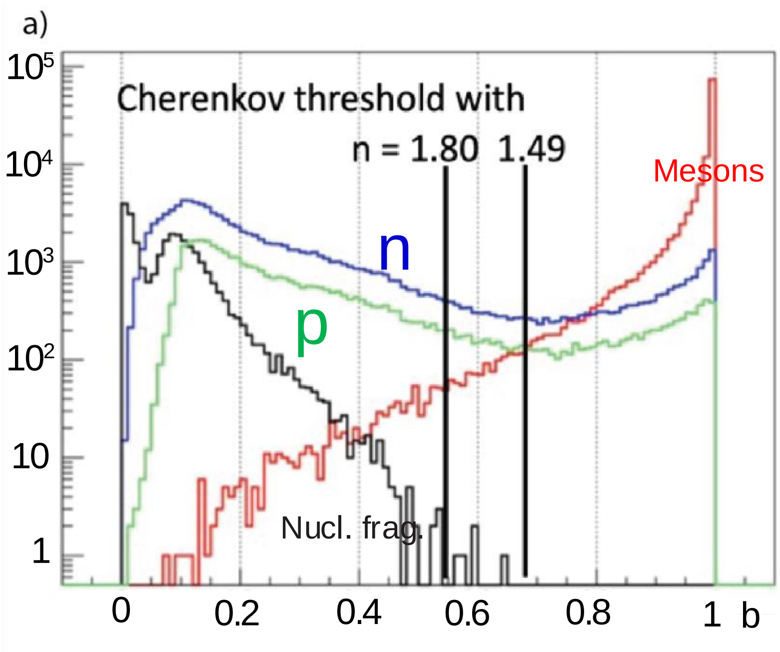


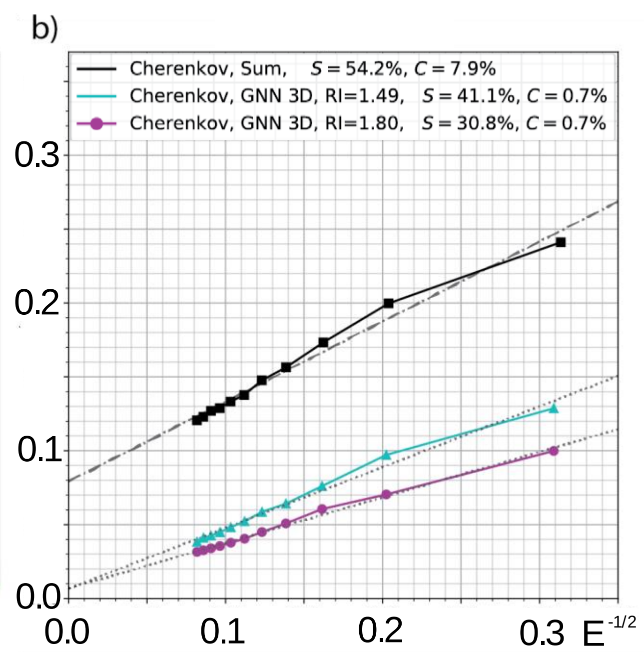


Optical Fibers

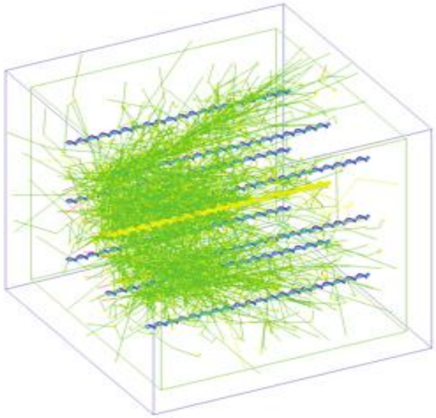


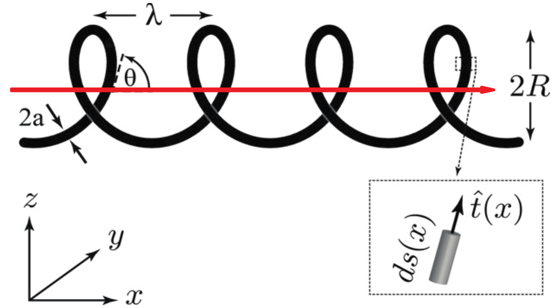
	QQ	QP	Plastic	Sapphire	Air-clad
NA $\quad \mathrm{NA} \approx \sqrt{n_{\mathrm{core}}^2 - n_{\mathrm{clad}}^2}$	0.22	0.37	0.55		~0.9
n_{core}	1.46	1.46	1.5	1.77	1.46
f_{trap} $\quad f_{\mathrm{trap}} \approx \left(\frac{\mathrm{NA}}{2n_{\mathrm{core}}}\right)^2$	0.57%	1.61%	3.36%		9.5%
$T_{electron}$	190 keV	190 keV	174 keV	108 keV	190 keV
T_{proton}	350 MeV	350 MeV	321 MeV	199 MeV	350 MeV

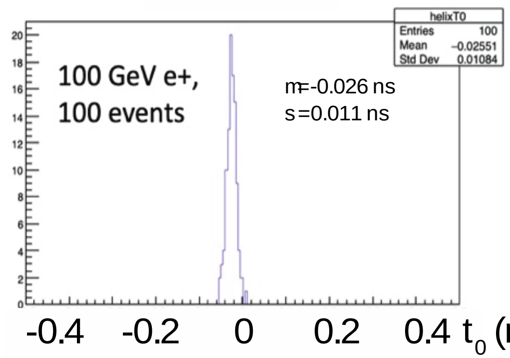


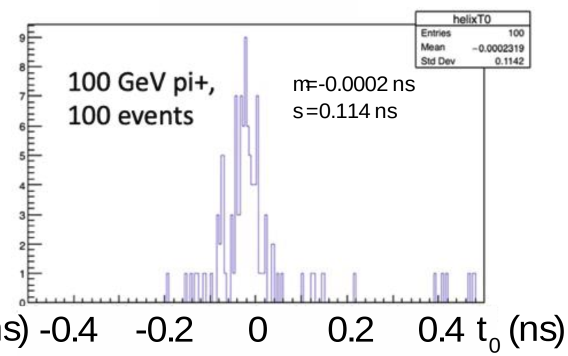


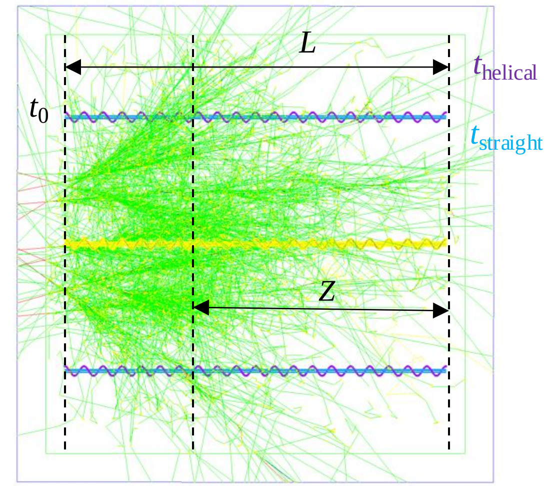
Shaped (Helical) Fibers











$$t_{\text{straight}} = t_0 + Z/c + (L - Z)/(c/n)$$
$$t_{\text{helical}} = t_0 + Z/c + h(L - Z)/(c/n)$$
$$L = \sqrt{(2\pi R)^2 + \lambda^2}$$
$$h = L/\lambda = 1.38$$
$$\Delta t = t_{\text{helical}} - t_{\text{straight}} = (h-1)[(L-Z)/(c/n)]$$

Helical fibers offer unique features for calorimeters:

1. More favorable Cherenkov light capture
2. Signal arrival time difference between the straight and helical fibers is a measure of where the signal is produced (*Z*) in the calorimeter using the calorimetry information alone
3. $2R$ = 1.8 mm, λ = 6.0 mm give h=1.38 (a = 225 µm)

To Do List & Remarks

1. Longitudinal segmentation by timing of otherwise unsegmented (fiber) calorimeter
   - enables position, energy, and time (5D) reconstruction of showers
   - reduces channel count (n^3 *vs* n^2)
2. Improved calorimeter performance by Cherenkov light alone
   - becomes possible when high-granularity is combined with NNs and fast (short integration times) calorimetry (polarization?)
3. Precision timing coupled with NNs
   - seems to improve energy regression
   - adds a new and independent observable to NN reconstruction algorithms
4. Absolute timing by calorimeter alone
   - introduces a new capability for pileup mitigation, TOF/PID measurements, jet substructure analysis by using different shaped fibers and/or refractive indices
5. Data processing on detector (*e.g.* AI/ML algorithms)

HG-DREAM is designed for high-granularity, precision timing with fast SiPMs (dSiPMs) and electronics (>10 GS/s), integration of NNs, and exploration of new fibers/materials ("designer meta-materials")

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