# Precision Timing and Its Application in Calorimetry

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TTU

# Topics for this Talk

There have been recent paradigm shifts in calorimetry

1. Particle flow (combined calorimeter and tracker information)
2. Dual-readout (event-by-event compensation, *e/h* =1)
3. High-granularity segmentation (energy (*E*), position measurements *(x, y, z))*
4. Precision timing (motivated by need for pile-up suppression (*t*))

US DOE Basic Research Needs activity in Dec 2019

Focus on precision timing

1. briefly in the context of pile-up suppression and
2. (mostly) in calorimetry (but hard to fully separate the two)

What's being done with a few selected examples

1. LHC and HL-LHC activities in timing (~5 years)
2. Future collider outlook (~10 years)
3. Really cool stuff (20+ years)

Some "obvious" remarks

# DOE Basic Research Needs Study in HEP Dec 2019

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

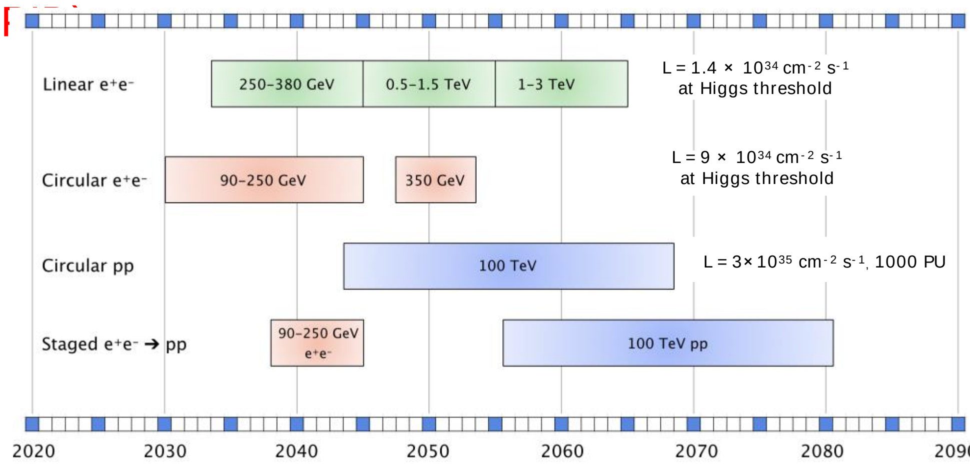
- Energy scale is set by Z-boson and Higgs decays with no pileup
- Ready by ~2030?
- 10%/√E + 1% EM and ~35%/√E hadronic energy resolutions
- $\sigma_t$ < 10 ps (*e.g.* long-lived particles)

## 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 ~$10^{17}$ $n_{eq}/cm^2$
- Ready by ~2045?
- <10%/√E EM and <30%/√E hadronic energy resolutions
- $\sigma_t$ < 5 ps (~1 ps pile-up suppression and P

## Ultrafast calorimetry

- Special detectors
- $\sigma_t$ ~ 1 ps



# DOE Basic Research Needs Study in HEP Dec 2019

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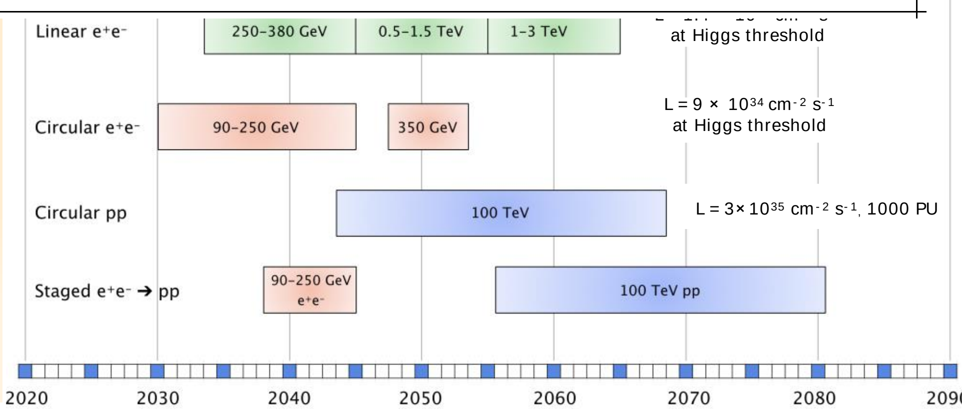
| | **PRD: Priority Research Direction** |
|---|---|
| Calorimetry | PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements |
| | PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments |
| | PRD 3: Develop ultrafast media to improve background rejection in calorimeters and particle identification detectors |

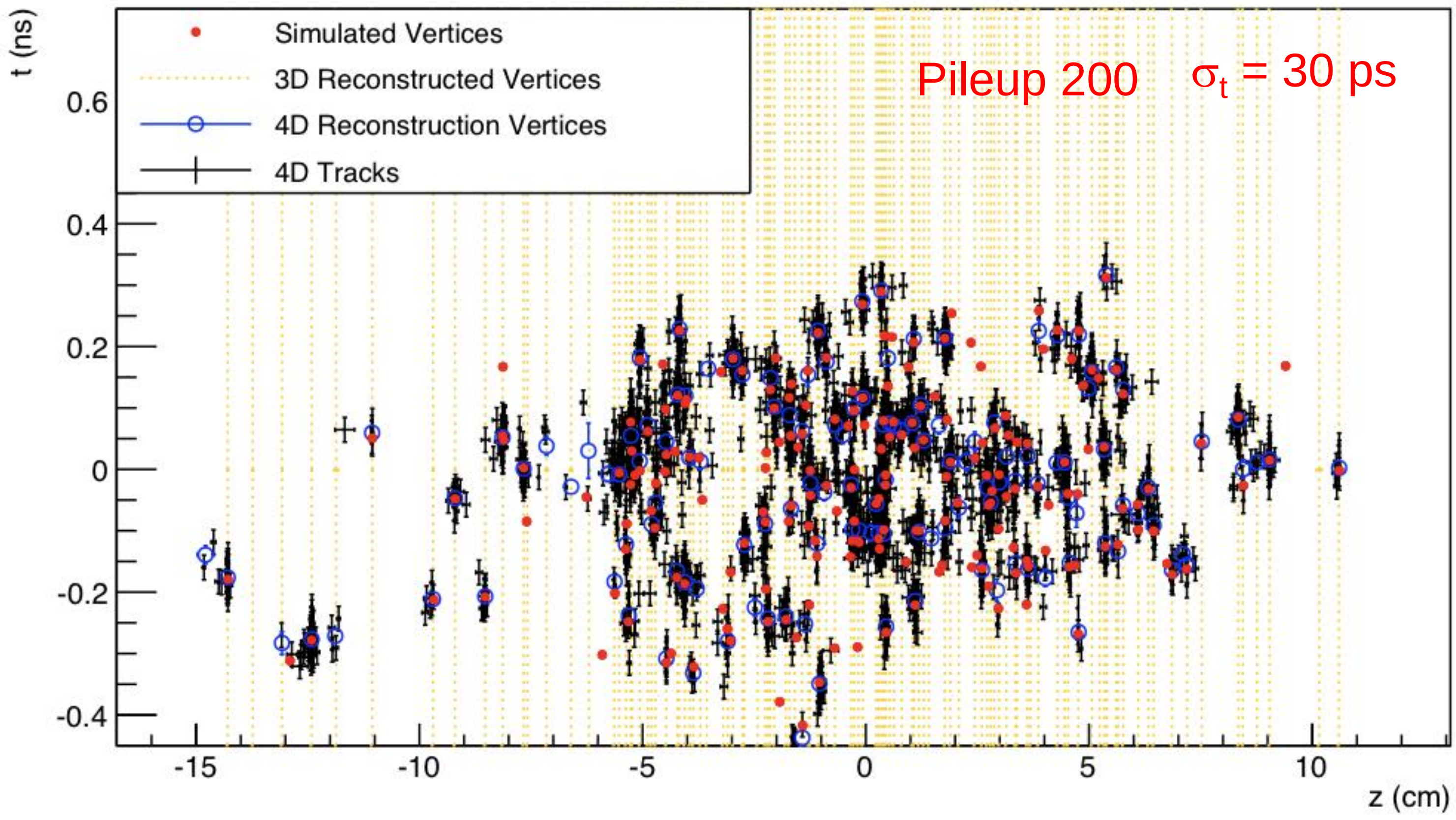
## Ultrafast calorimetry

- Cope with ultra-high rate experiments
- Special detectors
- $\sigma_t$ ~ 1 ps



# Power of Precise Time Measurement – Pileup 200

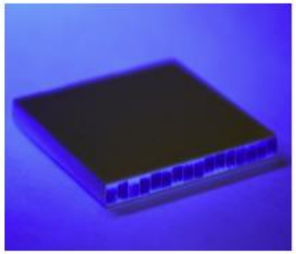
Technical Report CERN-LHCC-2019-003. CMS-TDR-020



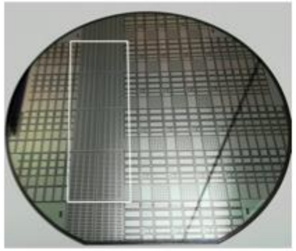

The simulated vertices are the red dots. The vertical yellow lines indicate 3D-reconstructed (*i.e.* no use of timing information) vertices, with instances of vertex merging visible throughout the display. The black crosses and the blue open circles represent tracks and vertices reconstructed using a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

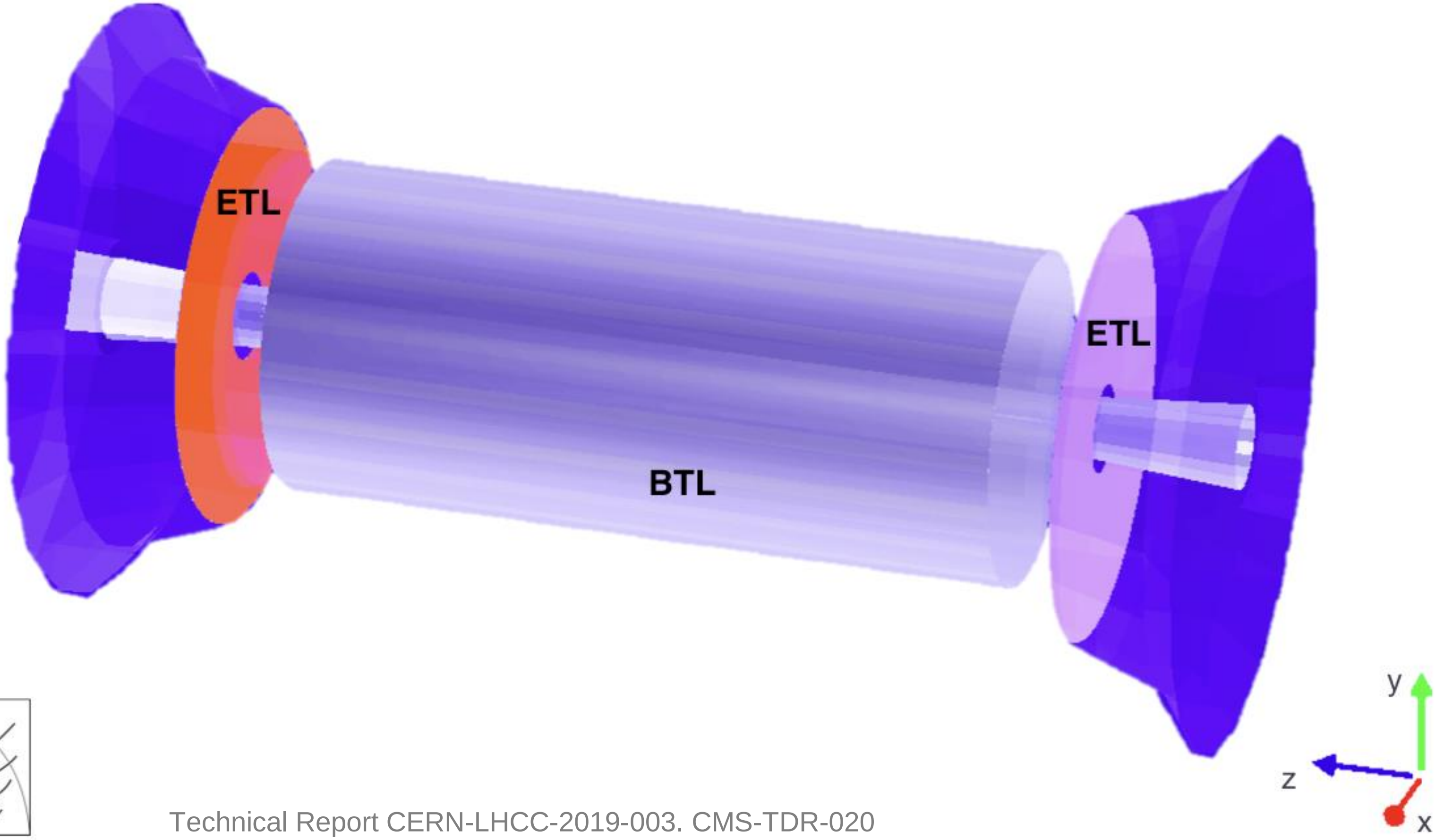
# Example: CMS MIP Timing Detector (MTD)

**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 $ab^{-1}$: $2\times10^{14}$ $n_{eq}/cm^2$



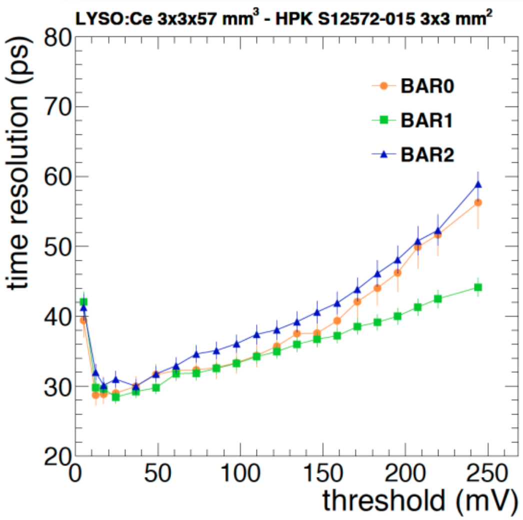
**ETL: Si with internal gain (LGAD):**
- On the CE nose: 1.6 < |η| < 3.0
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 $m^2$; ~8.5M channels
- Fluence at 4 $ab^{-1}$: up to $2\times10^{15}$ $n_{eq}/cm^2$



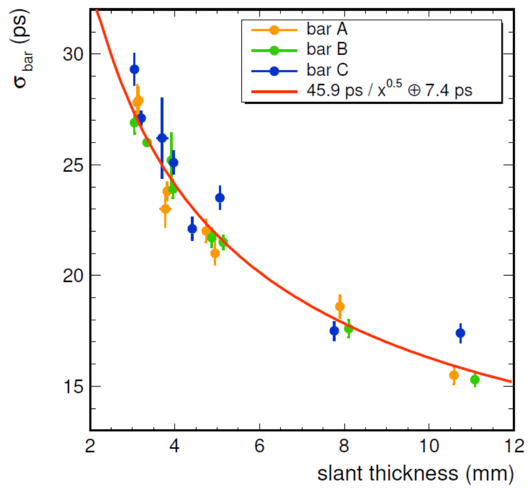


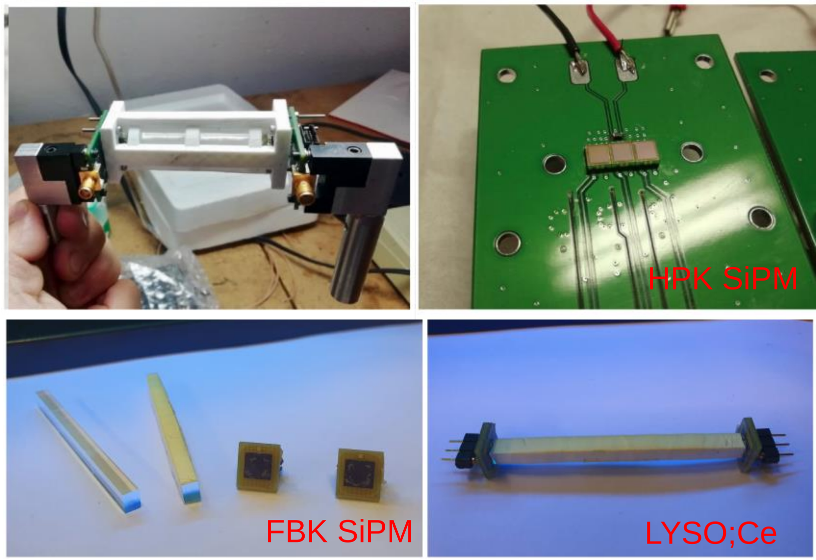

Technical Report CERN-LHCC-2019-003. CMS-TDR-020

# Barrel Timing Layer (BTL) Test Beam Results




$\sigma_t^{min}$= 28.4±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

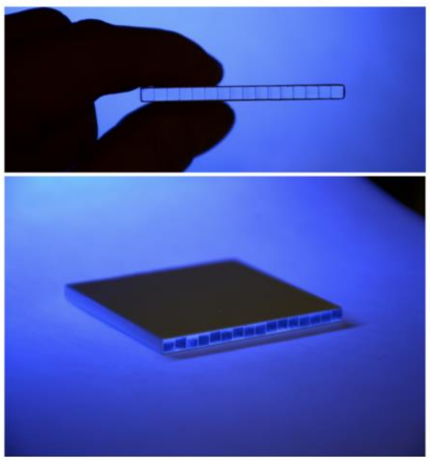
# What Matters: Timing Resolution Drivers (Photons)

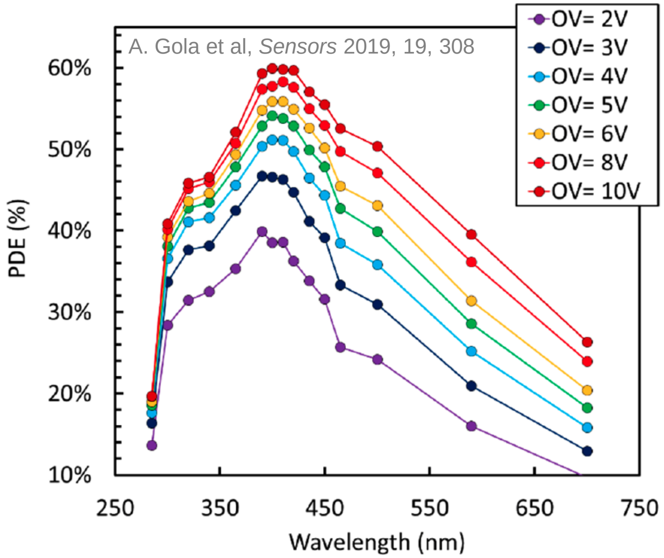
$$\sigma_t = \sigma^{\mathrm{phot}} \oplus \sigma^{\mathrm{clock}} \oplus \sigma^{\mathrm{elec}} \oplus \sigma^{\mathrm{digi}} \oplus \sigma^{\mathrm{noise}} \oplus \ldots$$

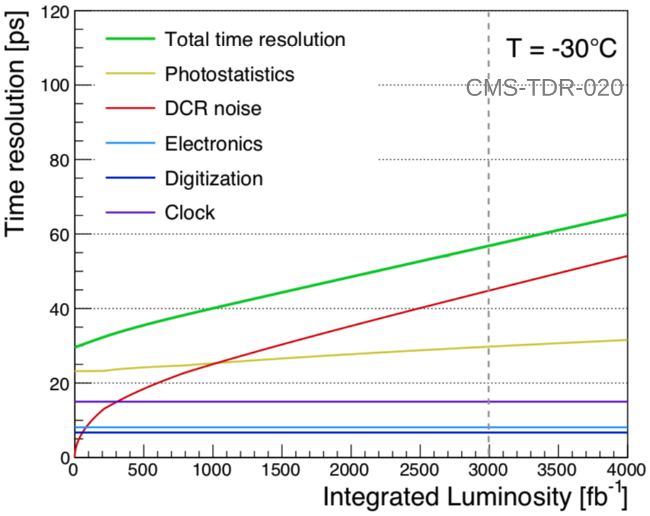
$\sigma^{\mathrm{phot}} \approx 25$ ps  $\sigma^{\mathrm{elec}} \approx 8$ ps  $\sigma^{\mathrm{noise}} \approx 50$ ps after $3{,}000$ fb$^{-1}$

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

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

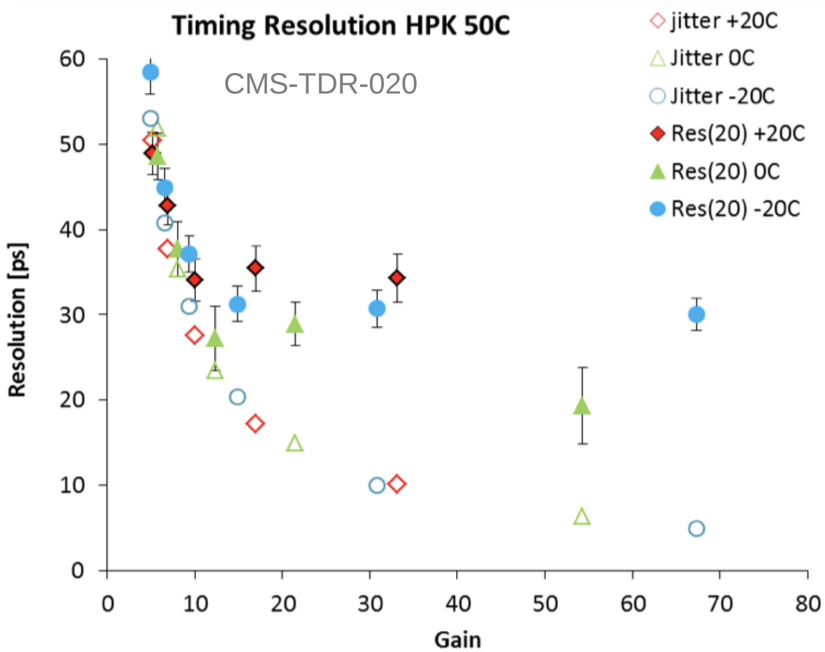


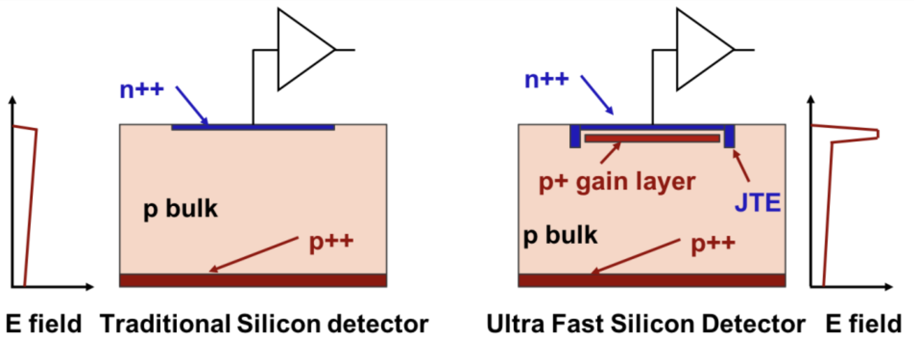



- LYSO:Ce is a bright scintillator with 30,000 ph/MeV, 420 nm peak emission, decay time <43 ns, rise time <200 ps, density 7.4 g/cm$^3$, 9.55 MeV/cm, and refractive index 1.82
- CMS MTD: 4.8~68 MRad, 2.5x10$^{13}$~2.1x10$^{14}$ p/cm$^2$ and 3.2x10$^{14}$~2.4x10$^{15}$ n$_{eq}$/cm$^2$

# What Matters: Timing Resolution Drivers (Charge)




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

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

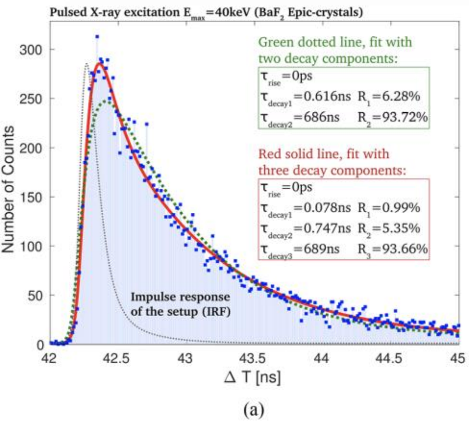
$$\sigma^{\mathrm{ionization}} = \sigma^{\mathrm{Total}} + \sigma^{\mathrm{Local}}$$

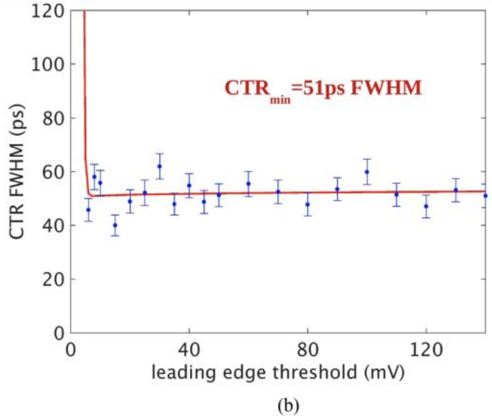
The jitter and total time resolution as a function of the UFSD gain for a Hamamatsu 50-$\mu$m thick UFSD sensor: the jitter term decreases with gain, while the total time resolution flattens around $\sigma_t$ = 30 ps

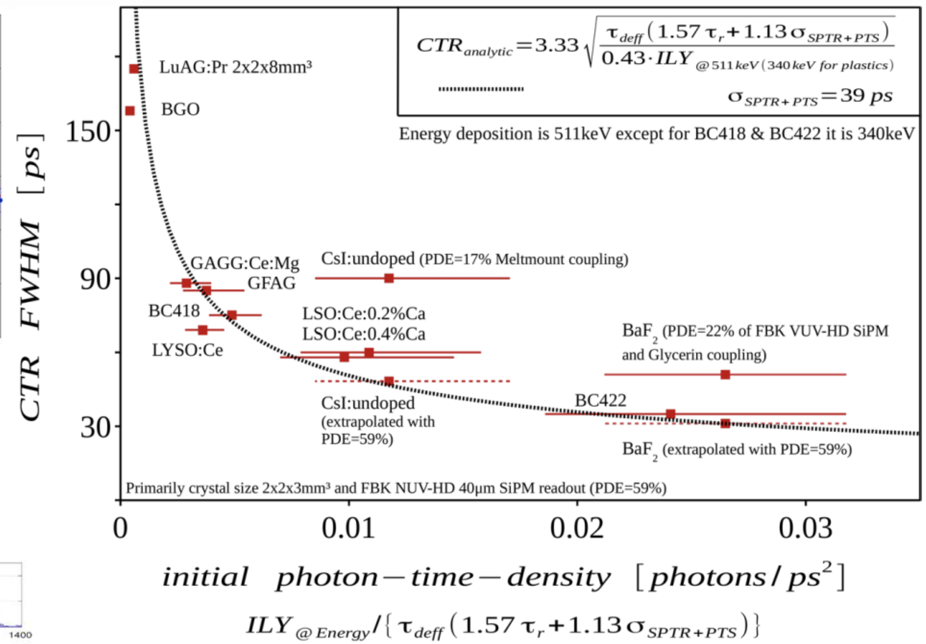
Non-uniform charge deposition determines the intrinsic time resolution; this limit is a function of the sensor thickness and is about $\sigma_t \approx$ 25 ps for 50-$\mu$m thick sensors

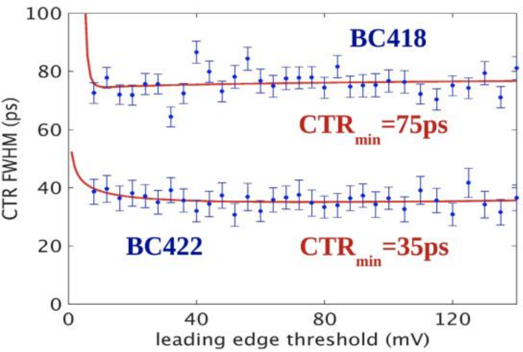
The time resolution $\sigma_t$ = 30–40 ps will degrade to 40–50 ps at a fluence of 3 × $10^{15}$ $n_{eq}/cm^2$

# Status of Some Timing Studies

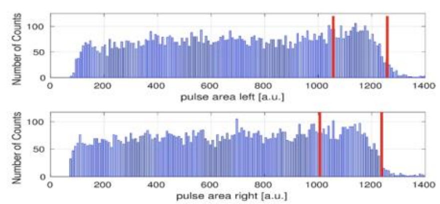



Energy selection on pronounced Compton-edge with **340keV**.




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 $mm^3$). $BaF_2$ emerges as a good candidate, as well as BC422

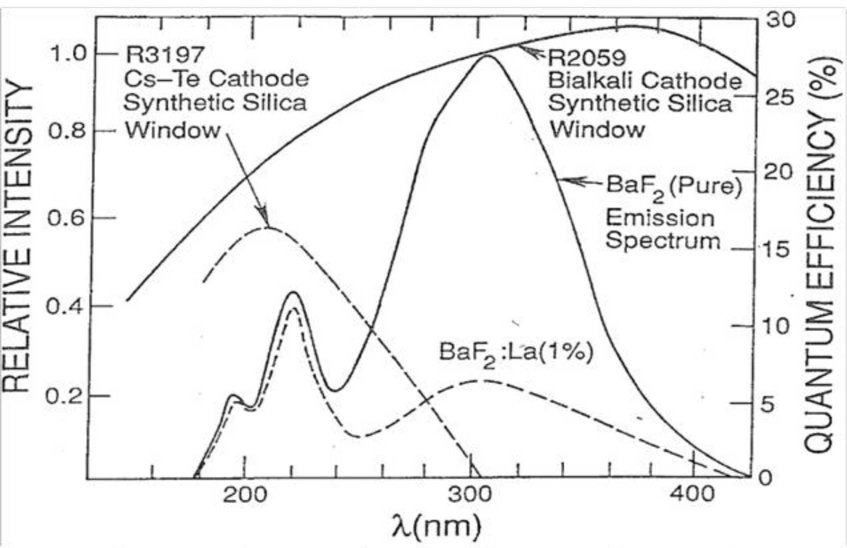
# $BaF_2$ - Fast and Slow Light

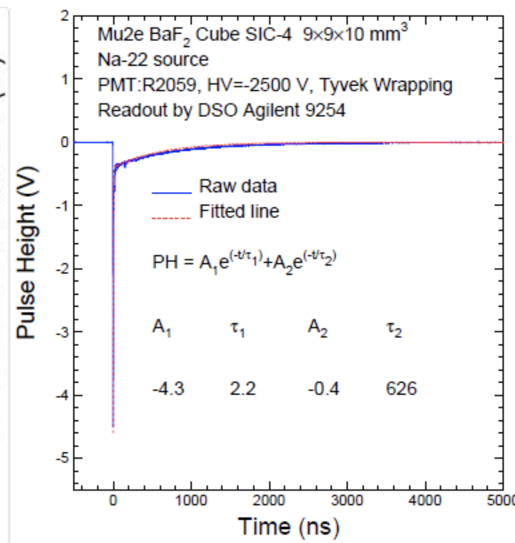
$BaF_2$ has been known to HEP since the SSC days

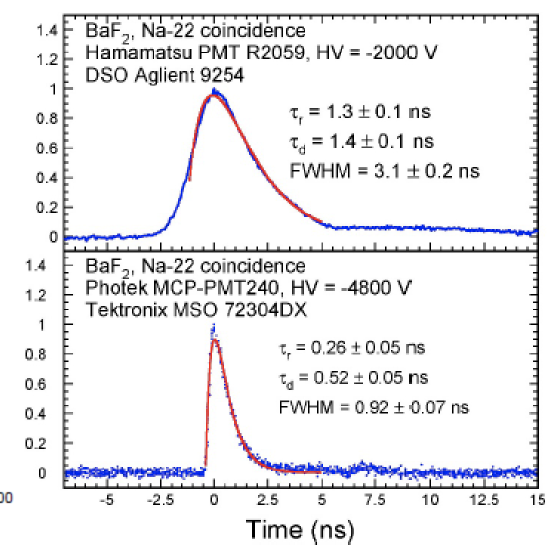
$BaF_2$ has a cross-luminescence component at 220 nm with ~0.5 ns decay time (~1,500 ph/MeV). It has also a factor of 5 brighter slow component at 300 nm with 600 ns decay time

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 ɣ-rays



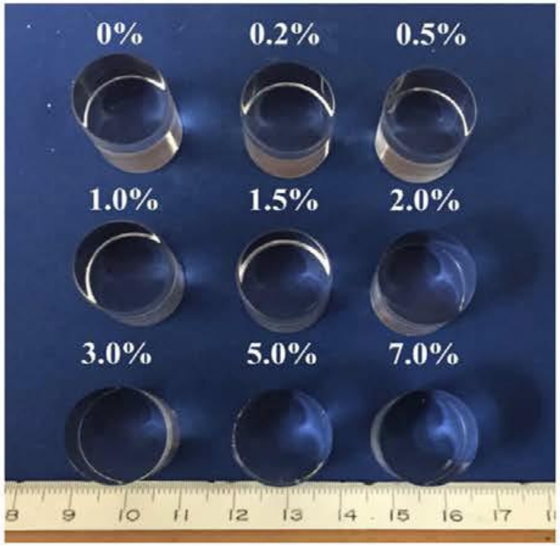



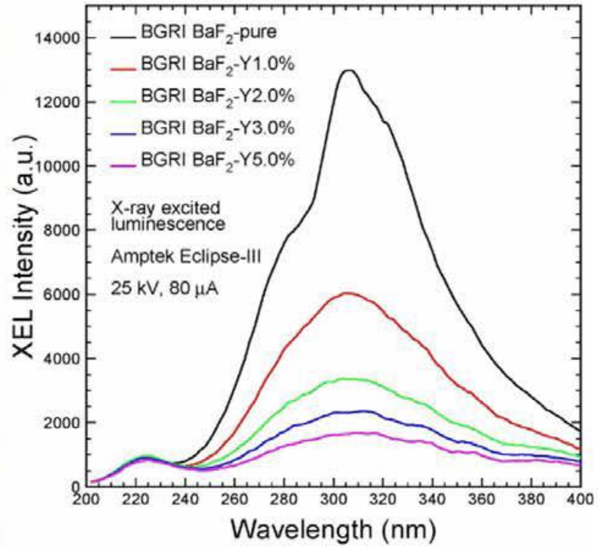



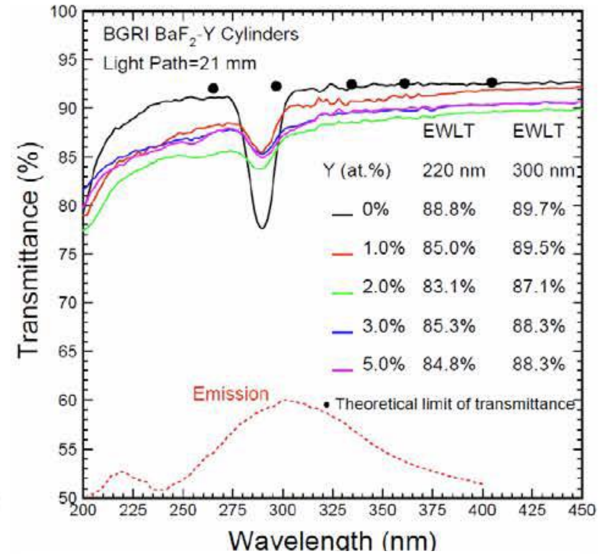

R. Y. Zhu et al, NIMA 340 (1994) 442-457

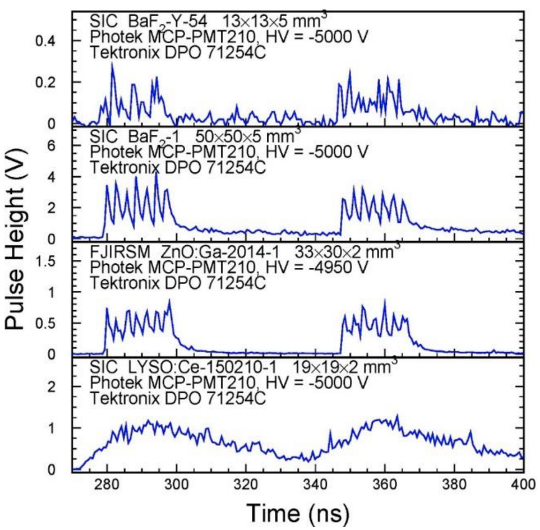
IEEE TNS NS 67, No 6 (2020) 1014-1019

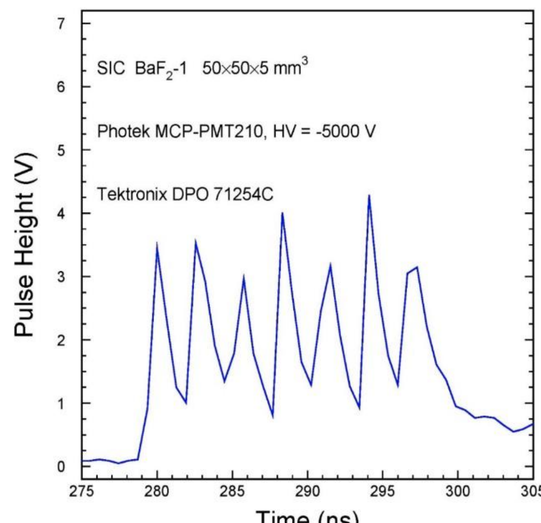
# $BaF_2$:Y for Ultrafast Calorimetry

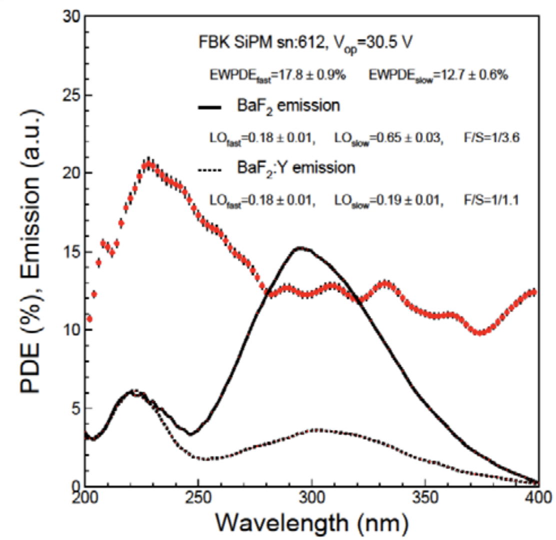


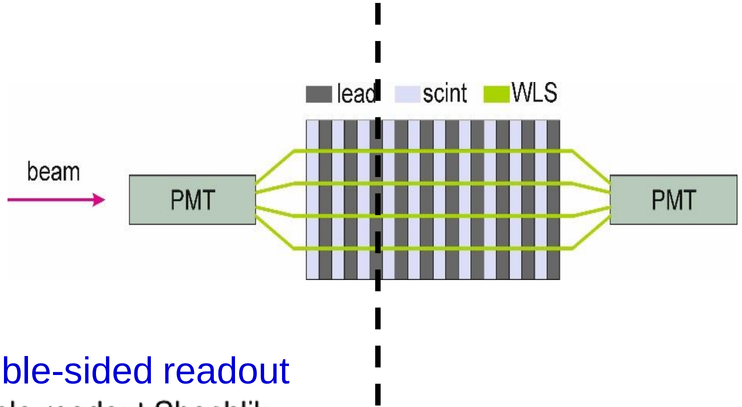




X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast $BaF_2$:Y and $BaF_2$ crystals for hard X-ray imaging

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

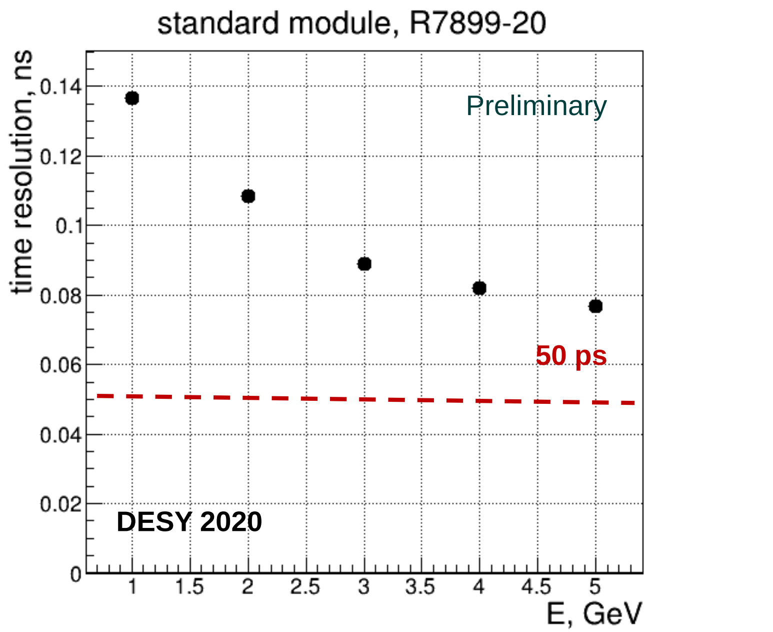
# LHCb Shashlik : ECAL Performance Upgrade II

- Better than 50 ps achieved at energies of 4 - 5 GeV with double-sided readout
  - Expected to improve at higher energies
- Use better PMT (small transit time spread and transit time uniformity over the photocathode)
  - R7899-20 (TTS ≈ 1-2 ns)
  - R7600U-20 (TTS ≈  0.35 ns)
- Use WLS fibers with shorter decay time
  - Y11 decay time ≈ 7 ns
  - Research work is ongoing in KURARAY aiming to develop faster WLS fibers with good light yield
  - New KURARAY WLS:  YS-2 (≈ 2.7 ns)

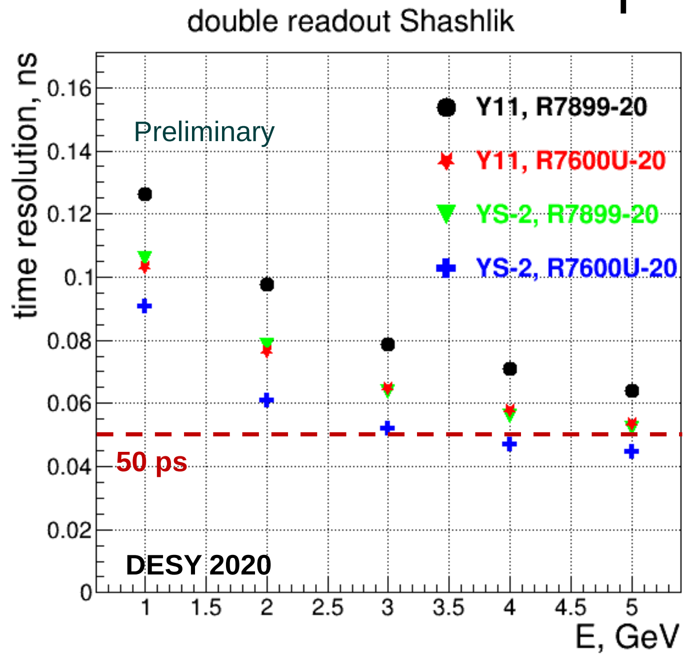



SPACAL R&D Group

Standard module, single-sided readout, R7899-20

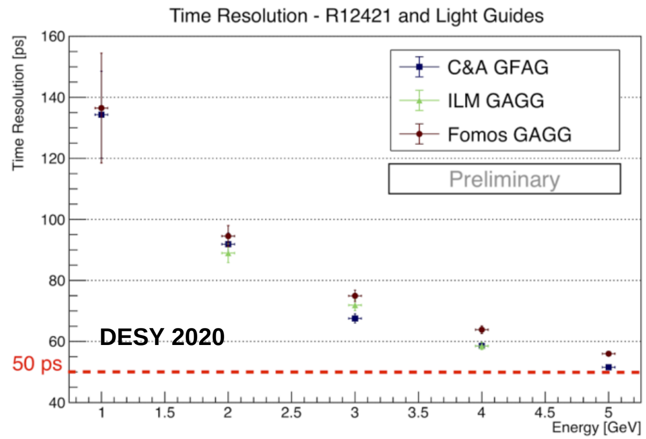


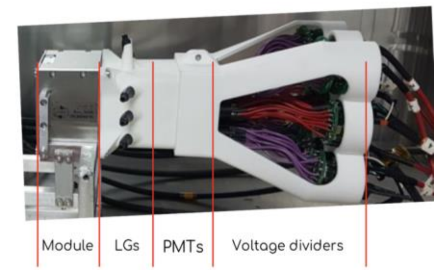

Double-sided readout



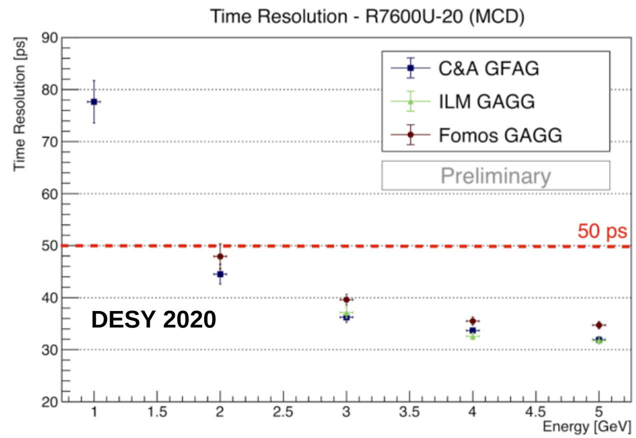
# LHCb SPACAL-W : Time Resolution

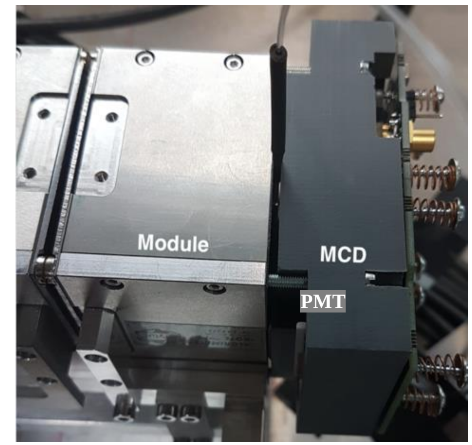
- Time resolution measured at DESY for GAGG samples with electrons at an incidence angle of 3° vertically and 3° horizontally
- Time resolution of 51 ps @ 5 GeV for R12421 and light guides
- Time resolution of 32 ps @ 5 GeV for R7600U-20 and direct coupling
  - Improvement thanks to higher light detection efficiency and better time transit spread homogeneity
- Expected time resolution of order 10 ps at 100 GeV (from simulation)
- SPACAL-W with polystyrene fibers is also tested at DESY



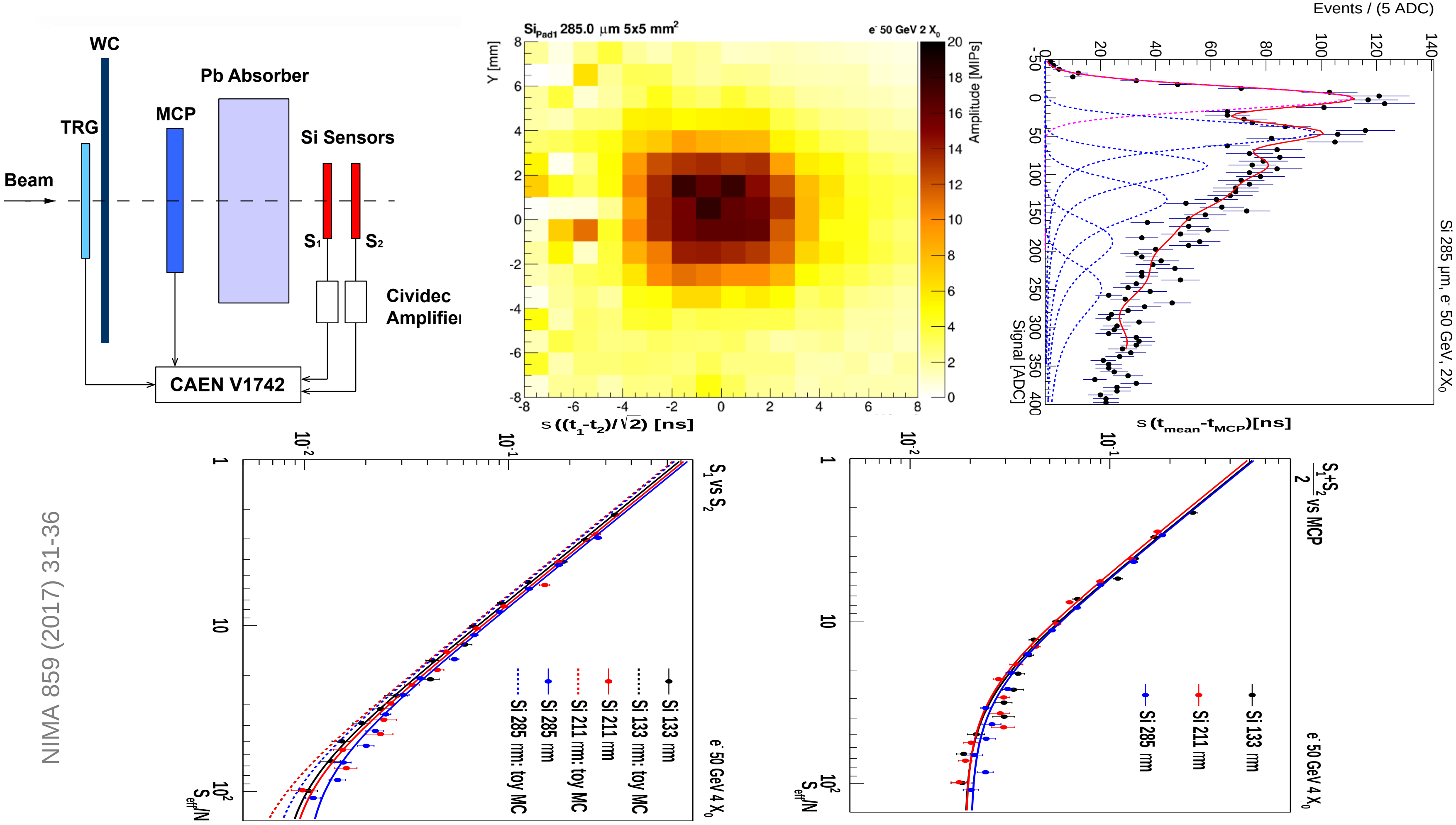

Time Resolution - R7600U-20 (MCD) - direct optical contact




SPACAL R&D Group

# Timing Performance of Thin Planar Silicon Sensors

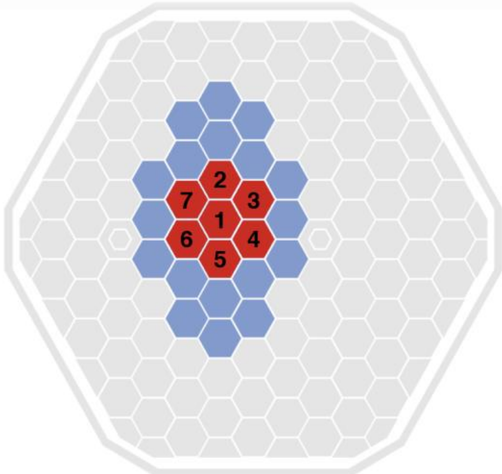


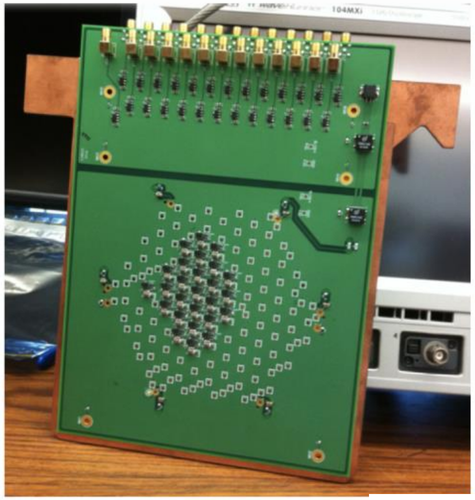

NIMA 859 (2017) 31-36

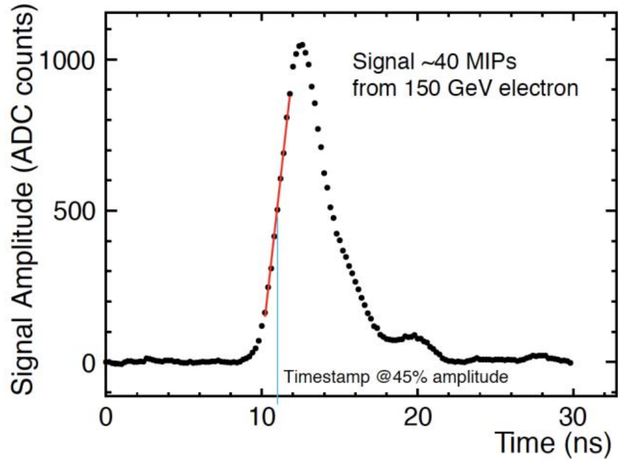
Three different silicon planar sensors, with depletion thicknesses 133, 211, and 285 μm. The measurements and simulations show better than 20 ps timing resolution for signals larger than a few tens of MIPs

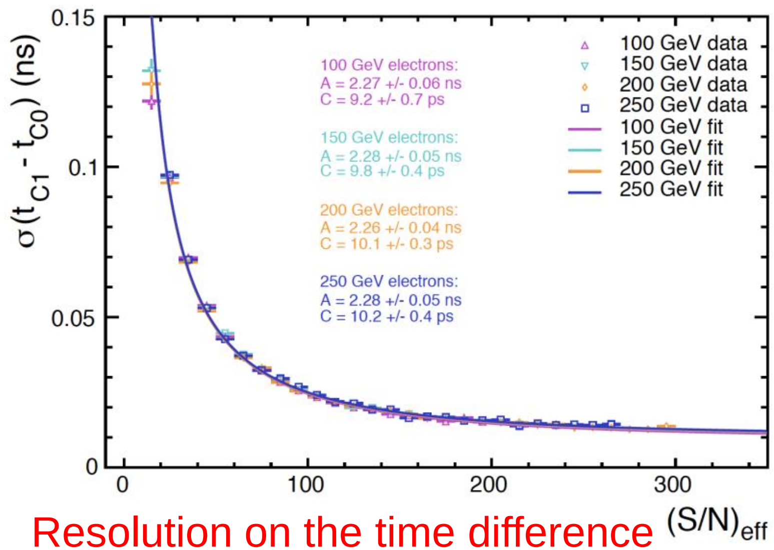
# Timing Performance of CMS HGCAL Prototype

JINST 13 (2018) P10023

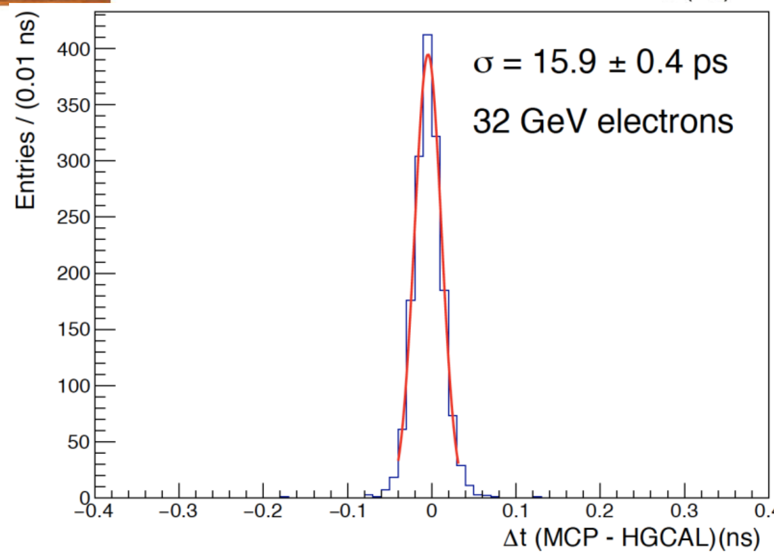




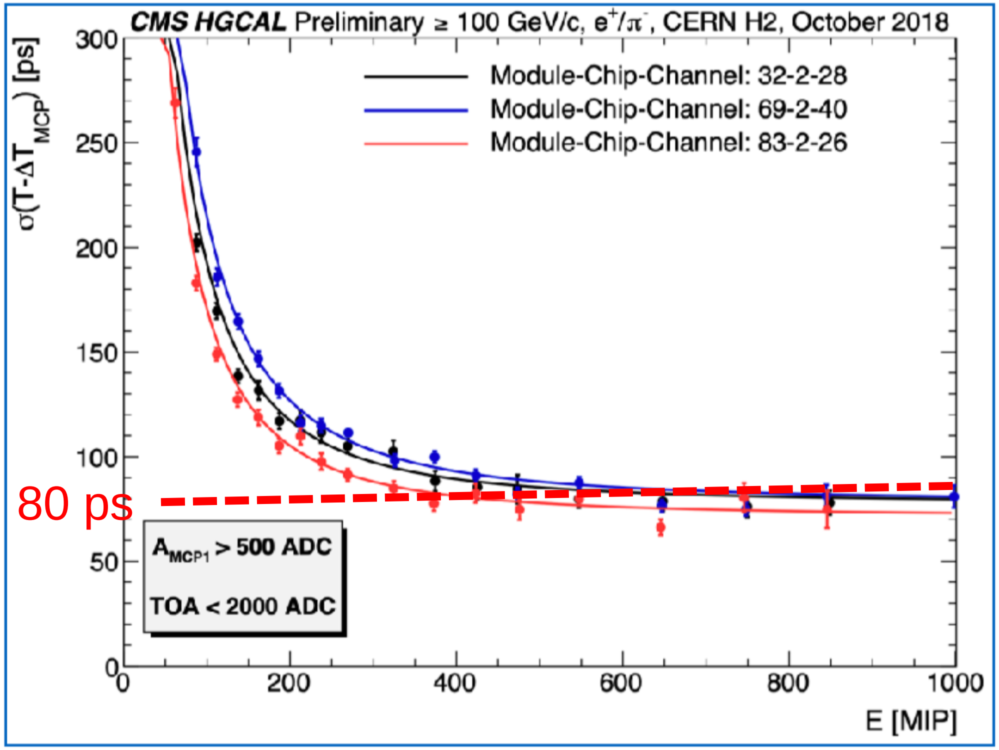




Resolution on the time difference between neighboring hexagonal cells of a 300-um thick hexagonal silicon sensor

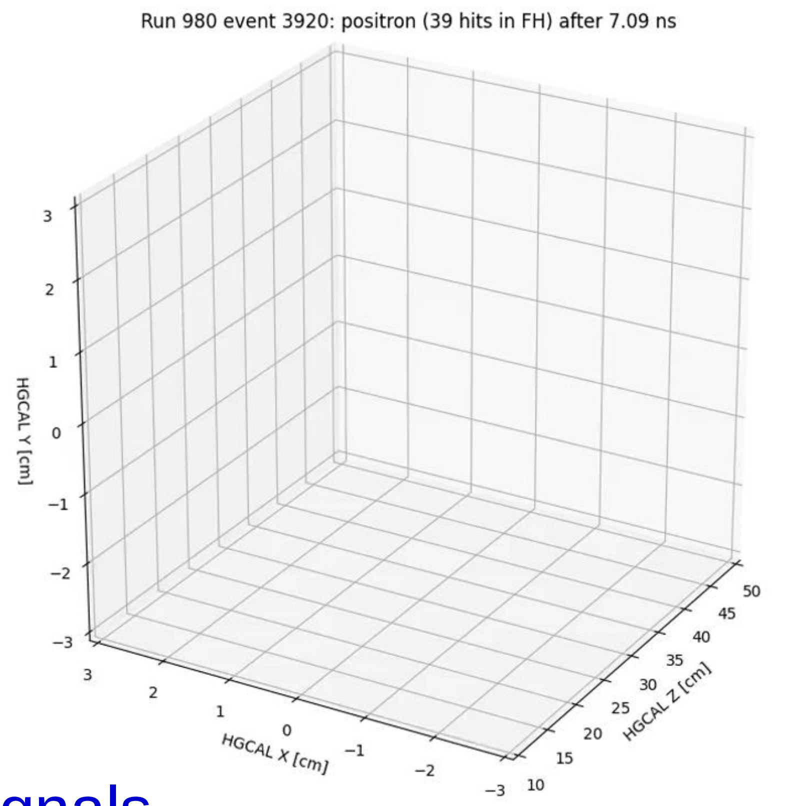



MCP-PMT and HGCAL with $6X_0$ tungsten absorber, information from all 7 cells was combined

# Timing Performance of CMS HGCAL Prototype




Time evolution of a positron shower in the HGCAL

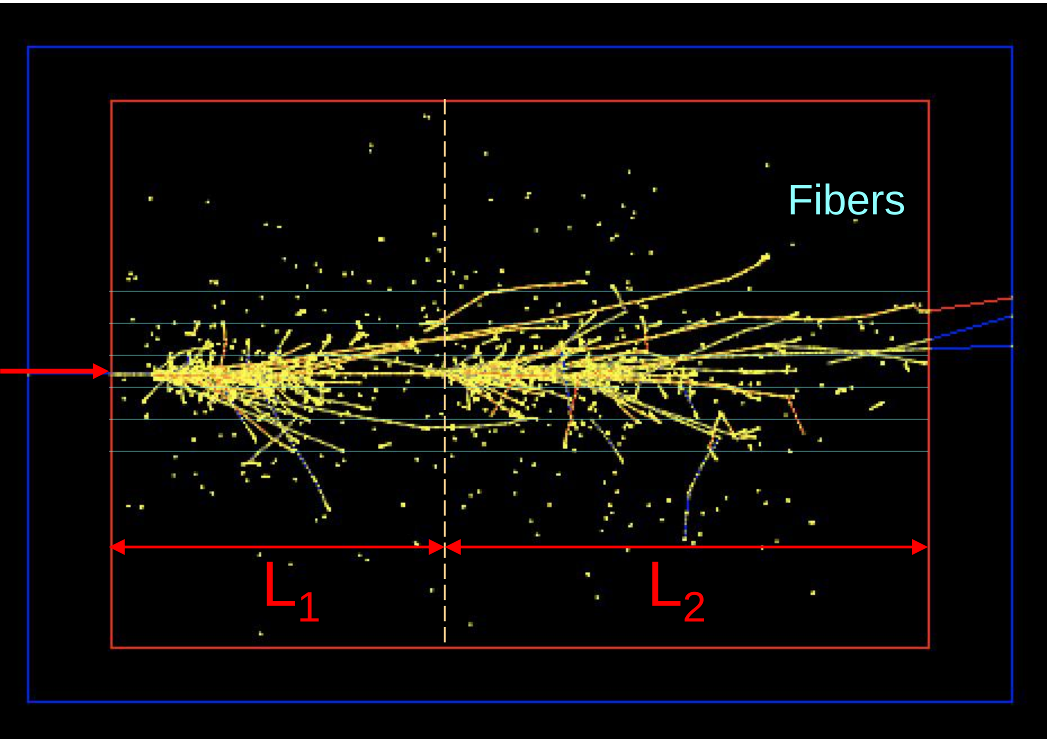



Can measure time of arrival of big signals to ~80 ps precision

Courtesy: D. Barney and T. Quast

# Longitudinal Segmentation with Timing

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



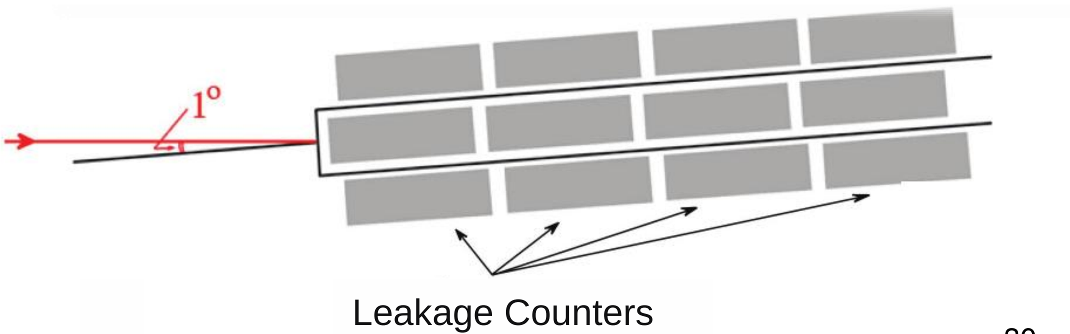

Signal time = $L_1/c + L_2/(c/n)$,

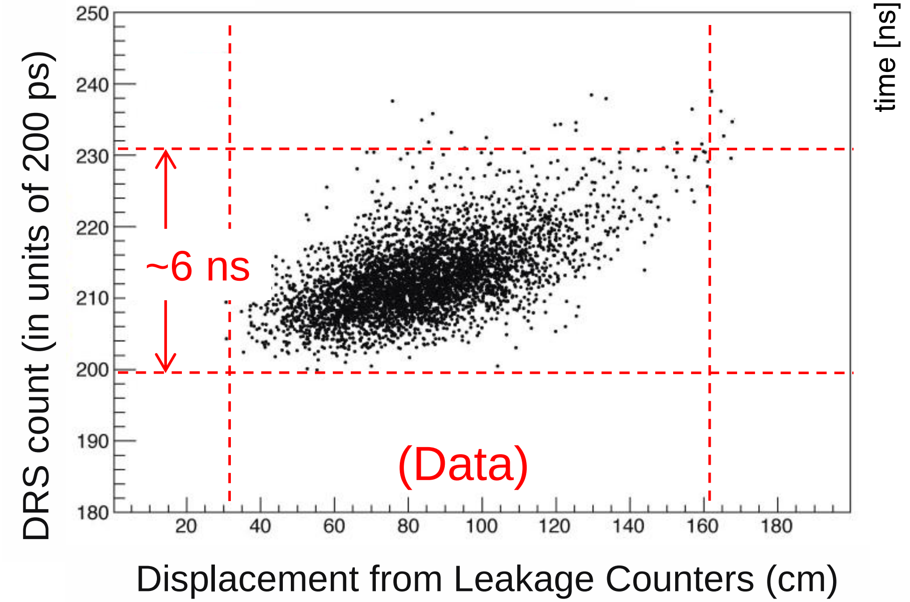
($c/n$) = velocity of light in fiber (n~1.45)

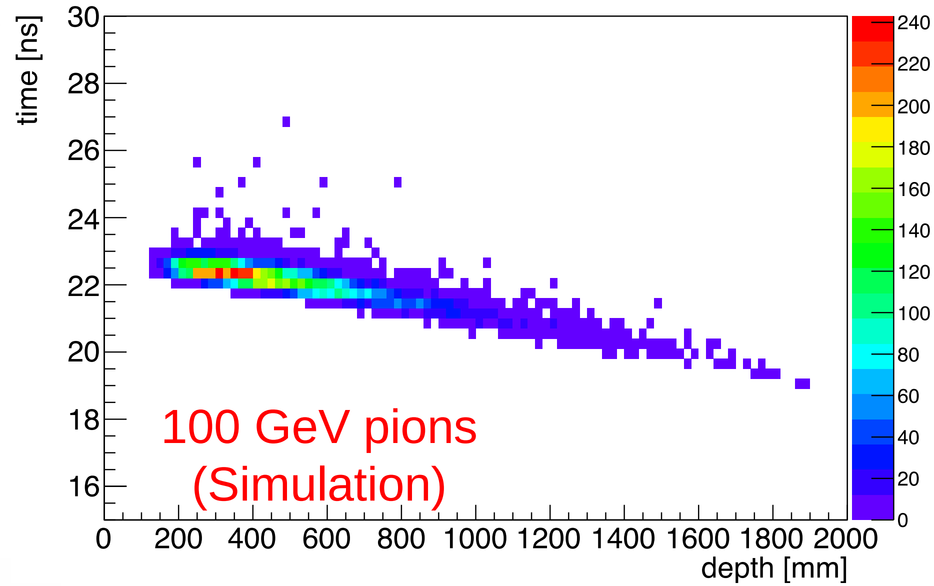
~20 cm/ns or ~1 cm/50 ps

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

# Time *vs* Displacement Measurements with Beam

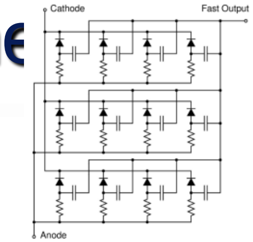


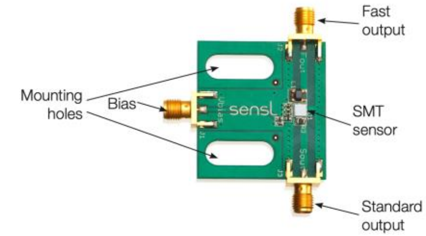




DREAM/RD52 measured the correlation between the gravity of ‘light’ in a calorimeter and the time of arrival of photons. The precision by which the signal shape is measured determines the effective longitudinal segmentation

# Separation of Two Signals Close in Time



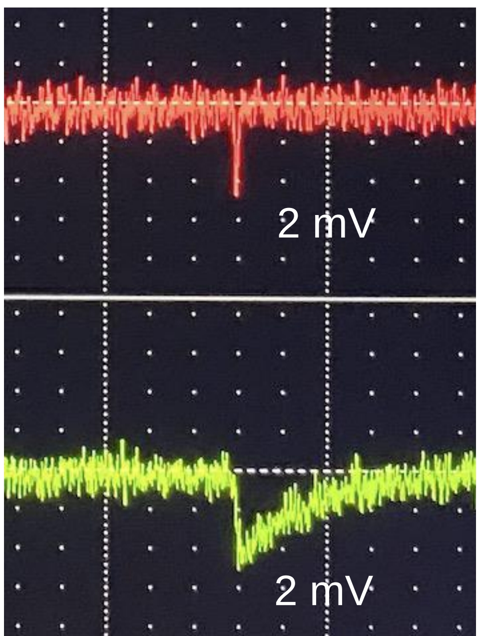

- SiPMs are excellent photon counting devices and have potential to map time structure of showers in calorimeter when used with high performance waveform digitizer
- SensL (MicroFC-30020SMT) SiPMs have fast an standard outputs



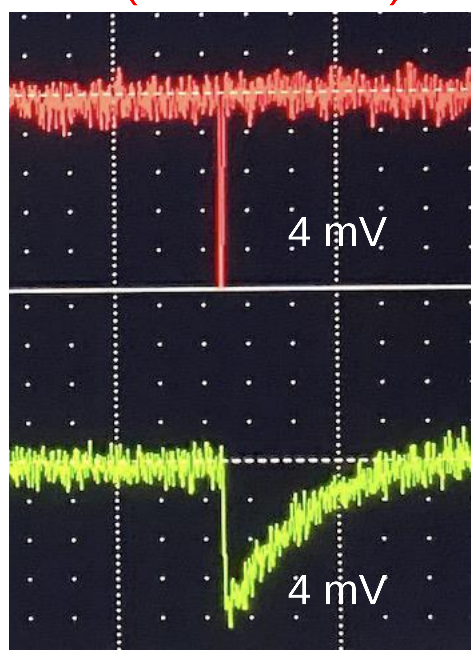

Fast Out (2 mV/photon)

Std Out (2 mV/photon)

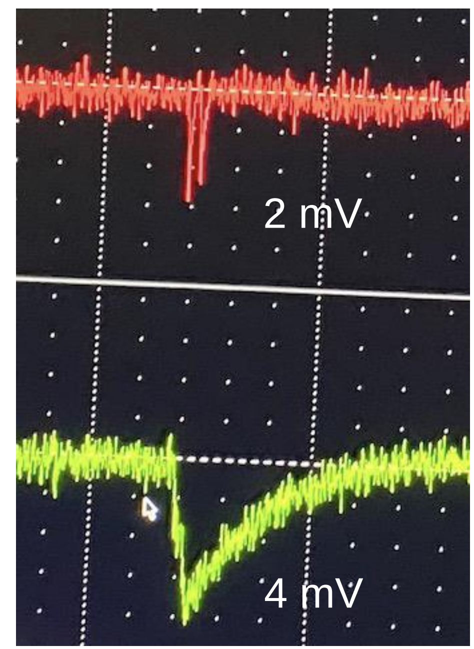
One photon event




Two photon event (simultaneous)

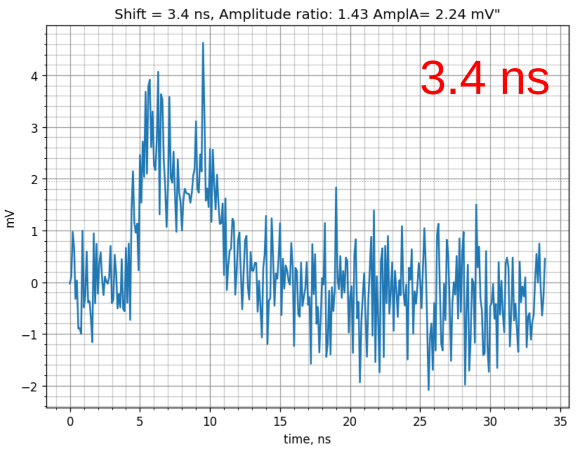


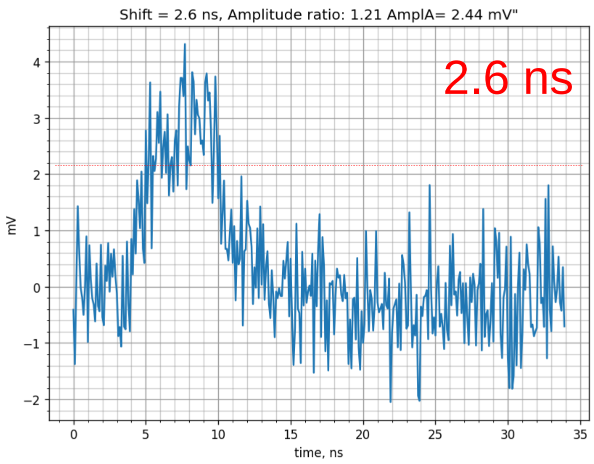

Two photon event (5 ns apart)

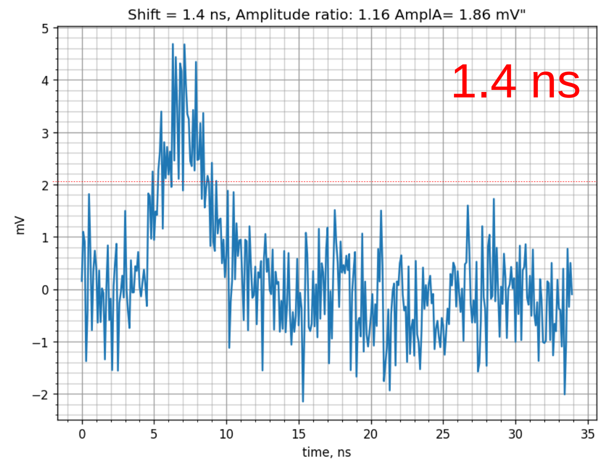



S. Kunori et al CPAD 2021

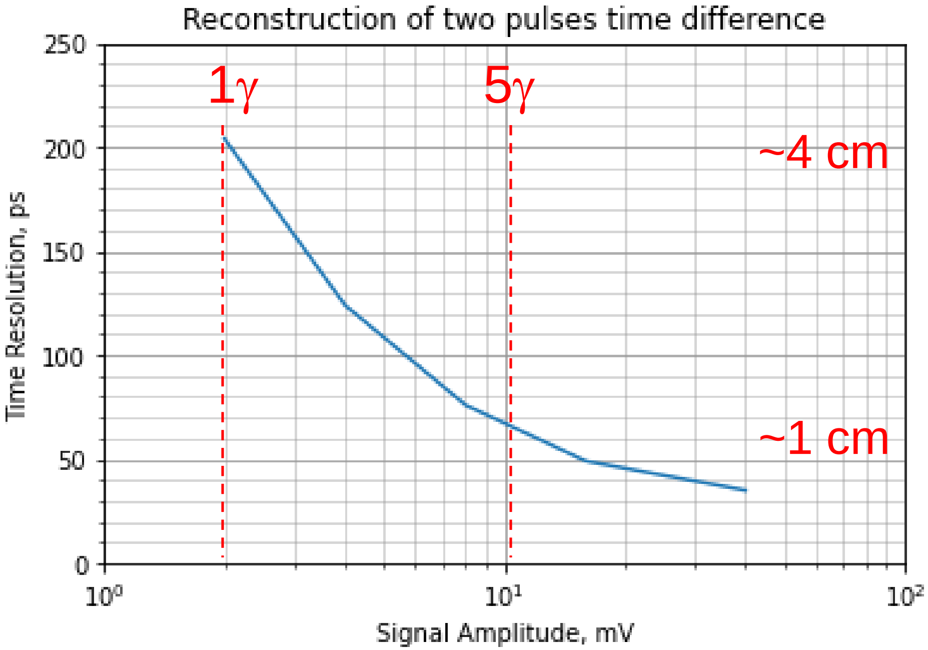
# Timing Resolution at Single Photon Level
# Separation of Two Signals



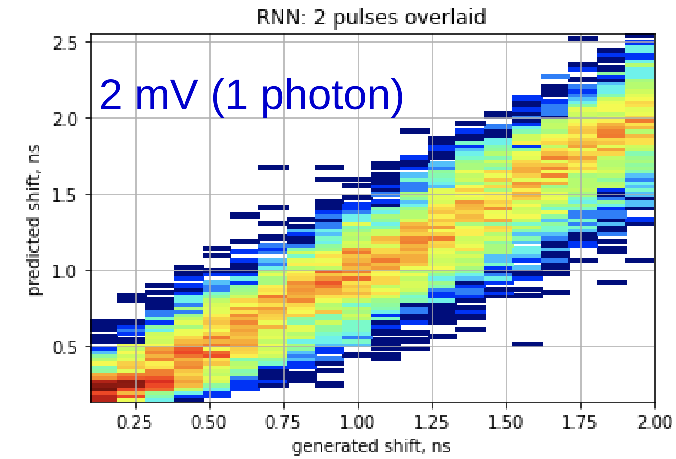



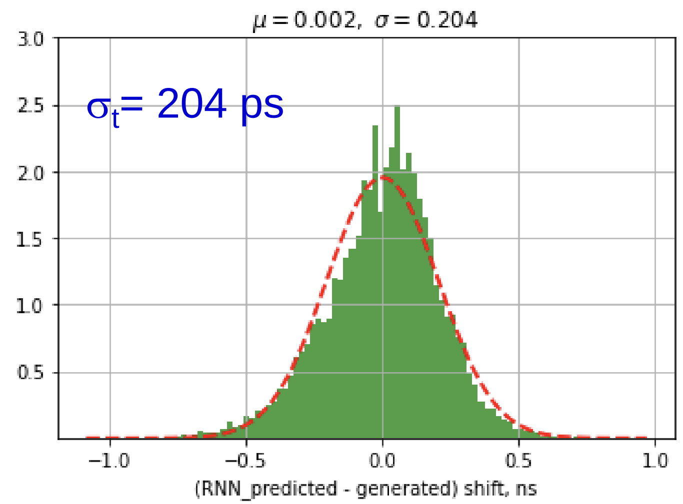



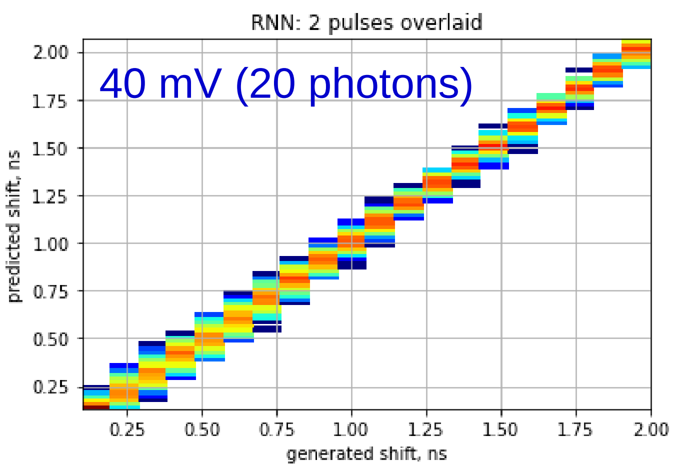

- Pulse shape of single photon signal from SensL SiPM was measured with NALU's AARDVARC V3 and used to simulate waveforms of convoluted pulses of two photon events
- Recurrent Neural Network (RNN) was used to reconstruct the timing of two photons
- Resolution of 4 cm (1 cm) seem possible for 1 (5) photon-equivalent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

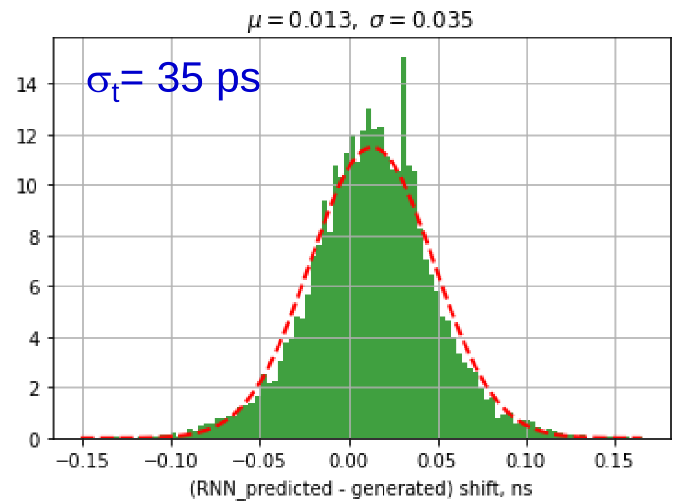


# Timing Resolution at Single Photon Level
# Impact of Machine Learning



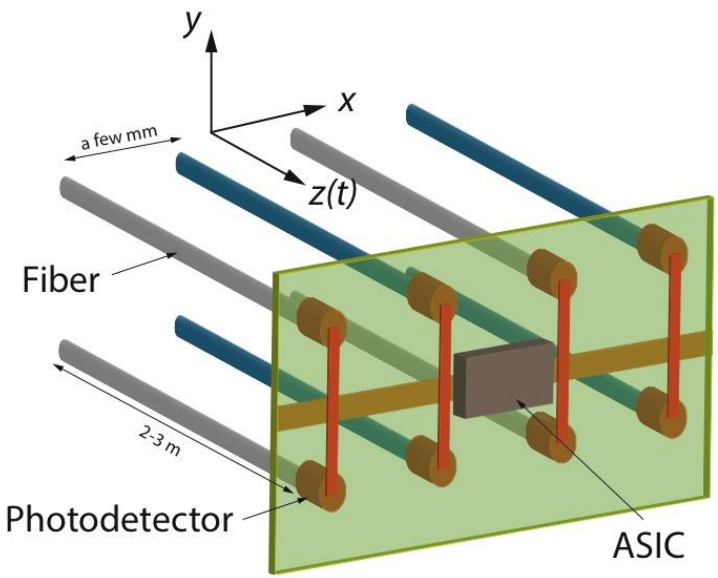



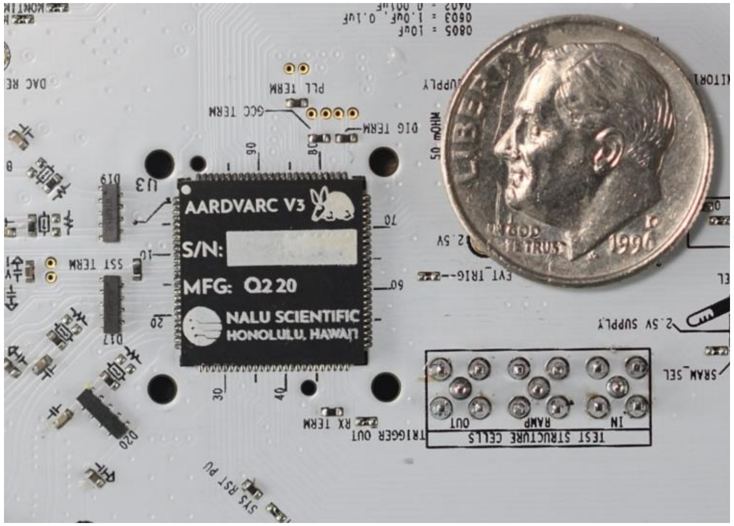



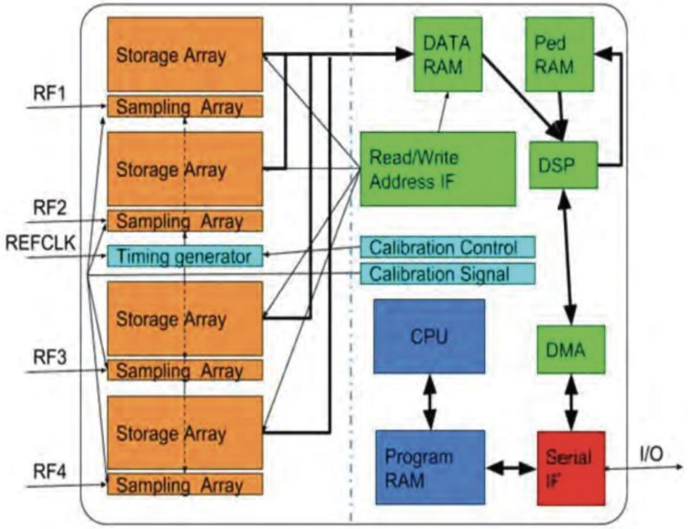

- Recurrent Neural Network (RNN) adds significant resolving power in timing resolution
- Clearly, more investigations are essential. It may be possible to implement these techniques in hardware in the future as appropriate

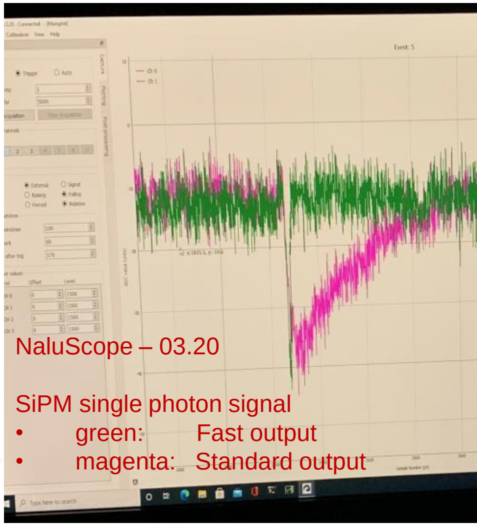
# Example: Enabling Digitizer AARDVARC V3

- Compact, high performance waveform sampling and digitizing
  - Sampling rate 10-14 GSa/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

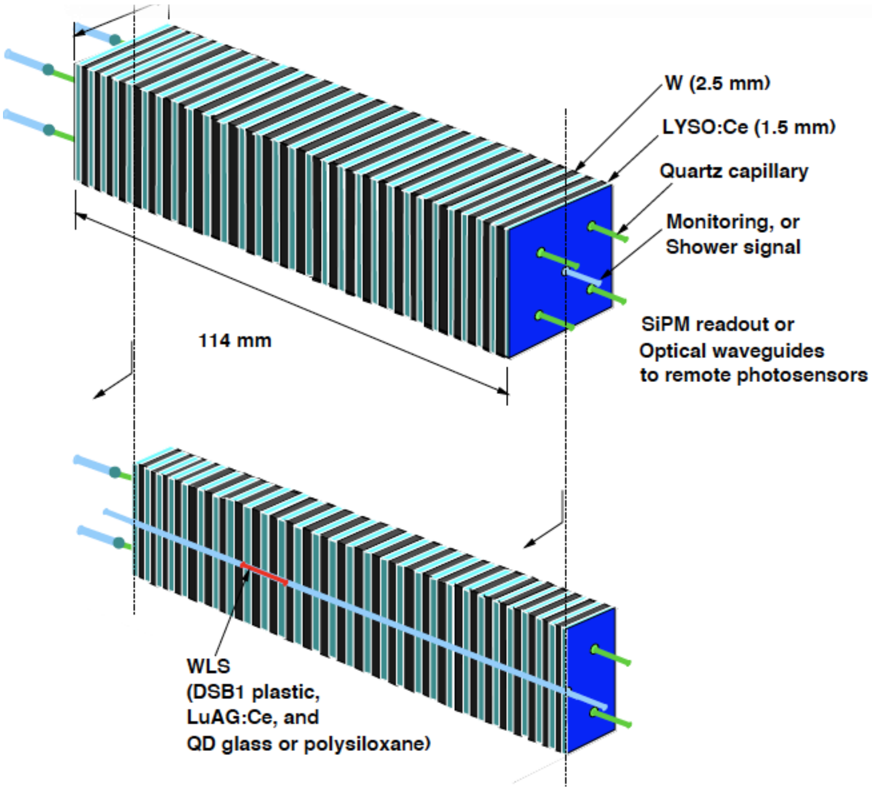


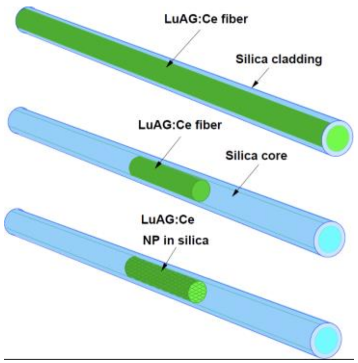



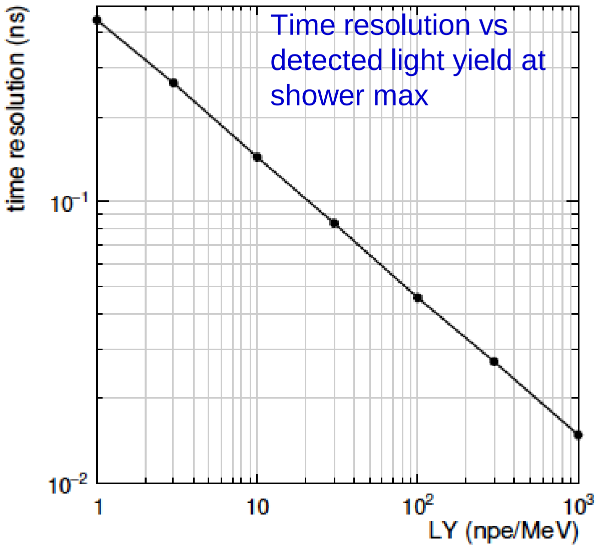



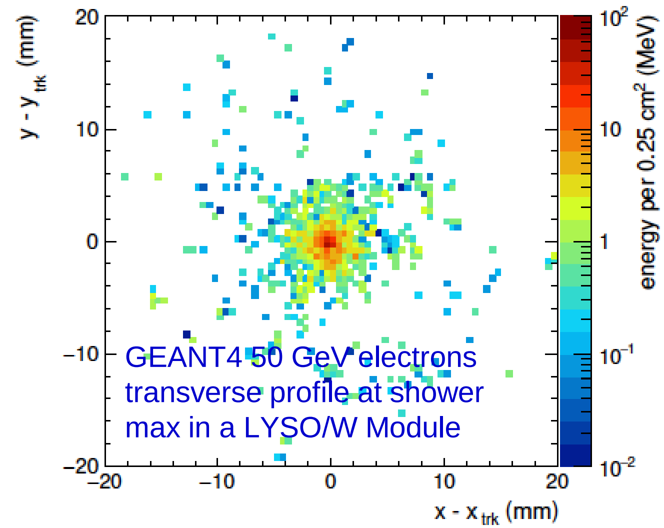



# Show Max Timing with RADiCAL



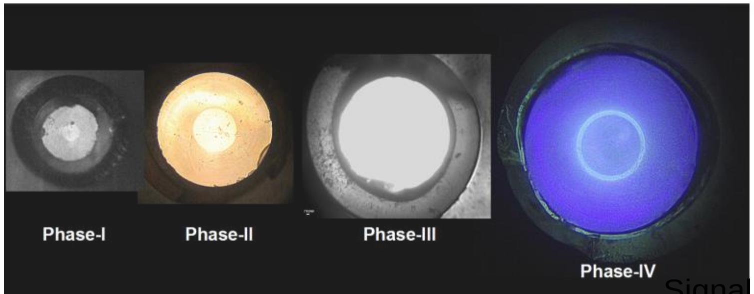



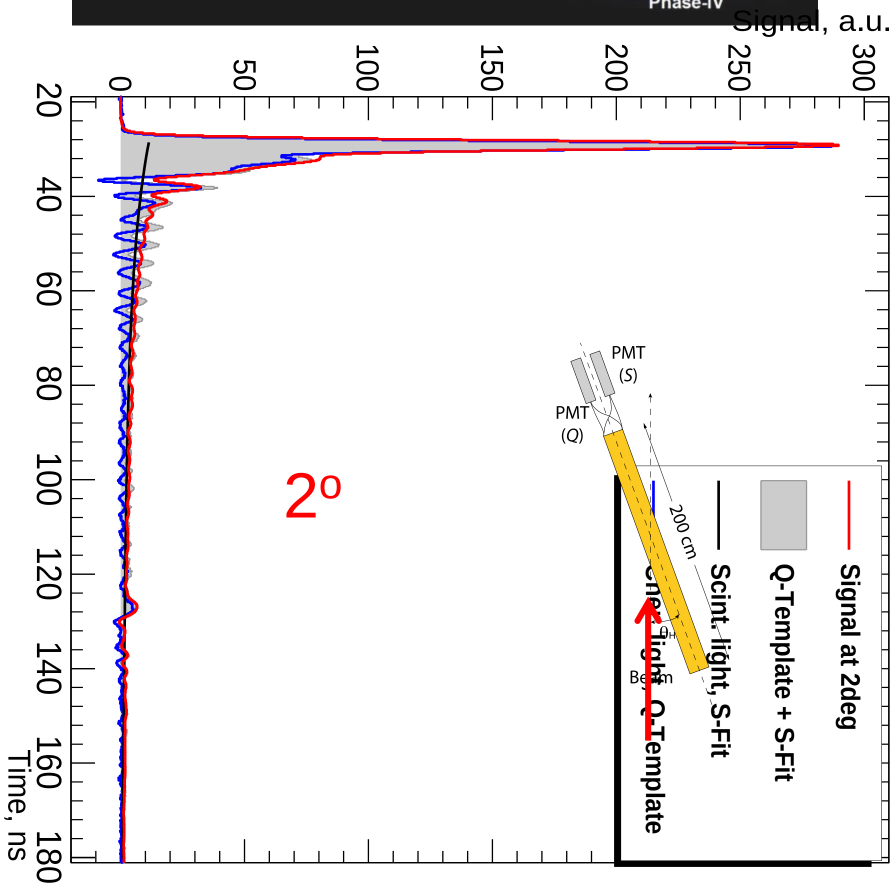

- Positioning of WLS filaments at shower max for timing studies
- Incorporation of dual readout for both scintillation and Cherenkov measurement – including for timing with quartz rods and the WLS capillary structures which are predominantly quartz material

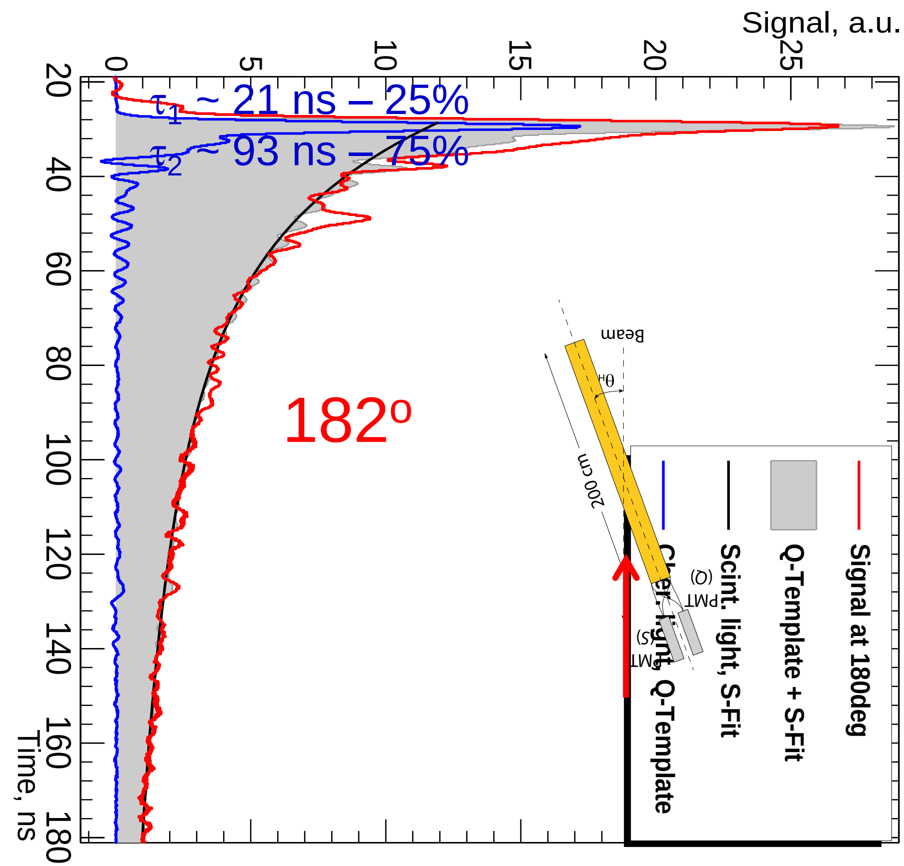
R. Ruchti et al CPAD 2021

# Scintillation/Cherenkov Light in a Single Fiber



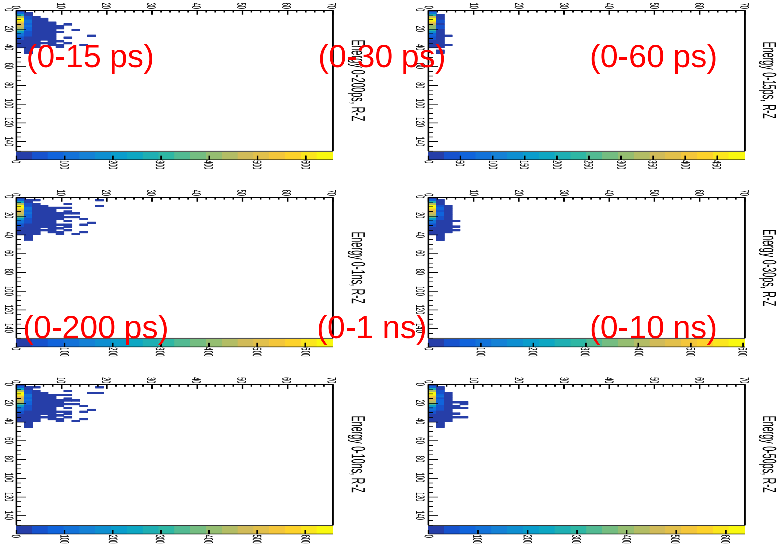

The Cherenkov ($SiO_2$) and scintillation ($SiO_2:Ce^{3+}$) light coexist in a single fiber and the balance between the two types of light can be "tuned." Cherenkov light can be used for timing purposes



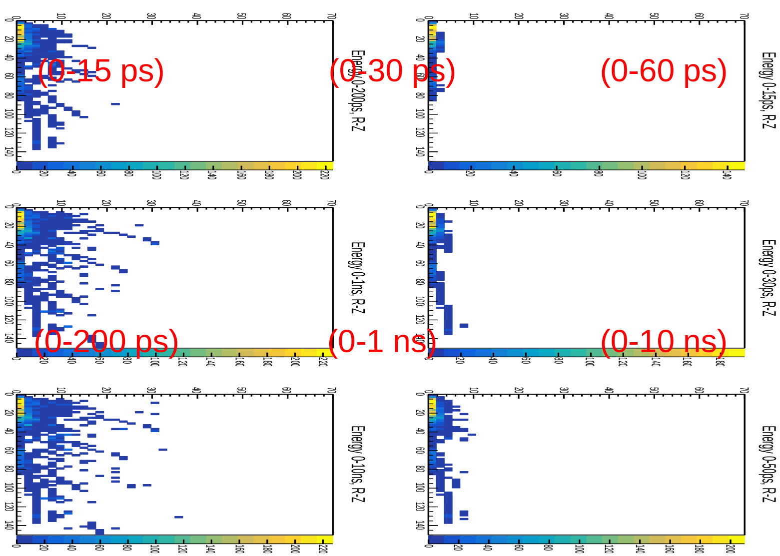



# Enhancement in Performance Fast Timing in NN

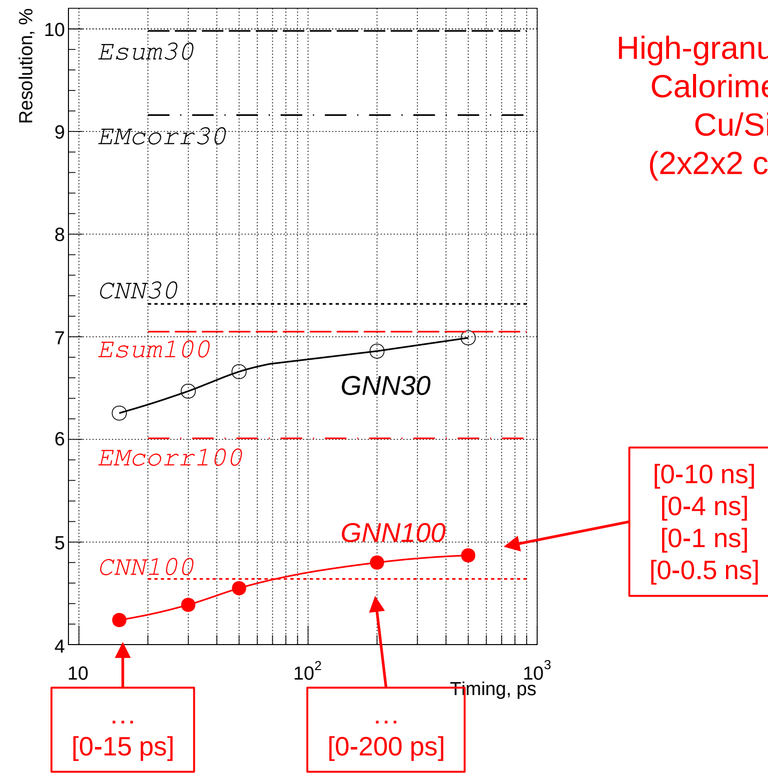
## 73 GeV Electron




## 121 GeV Pion

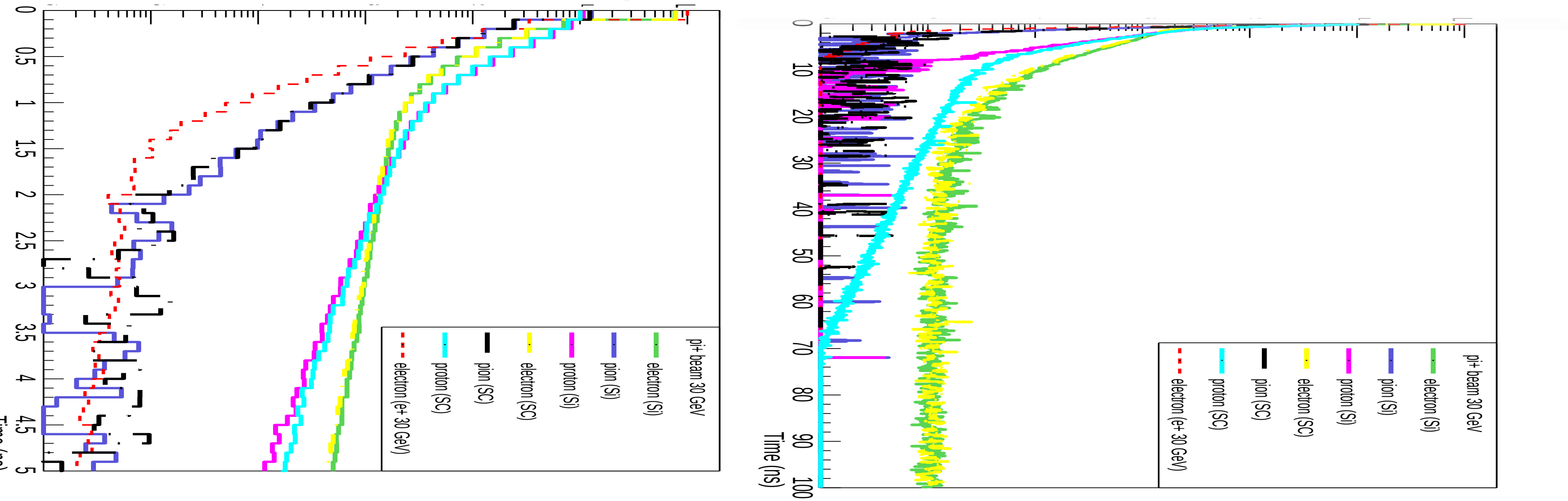



High-granularity Calorimeter Cu/Si ($2x2x2\ cm^3$)




- 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 Spectrum of A Shower

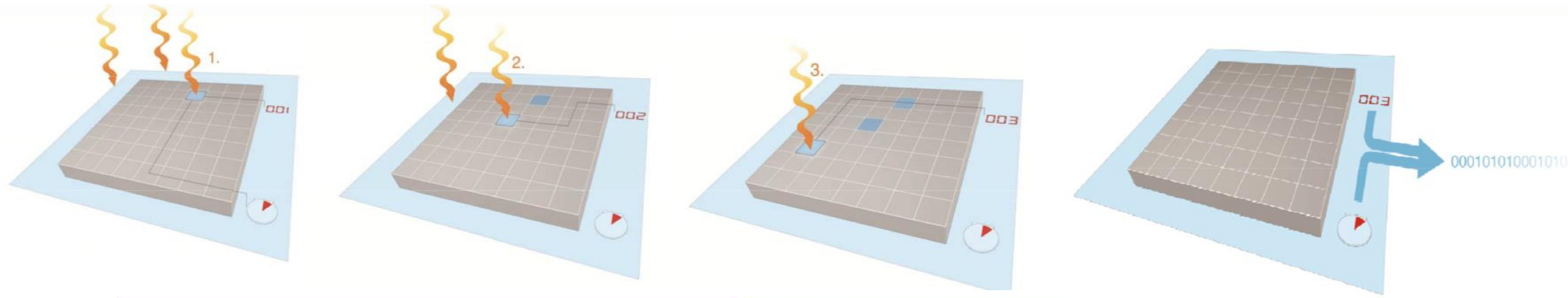



There is little difference in the way that a hadronic shower develops for a 30 GeV pion in silicon- or scintillator-based calorimeter in the first ~5 ns

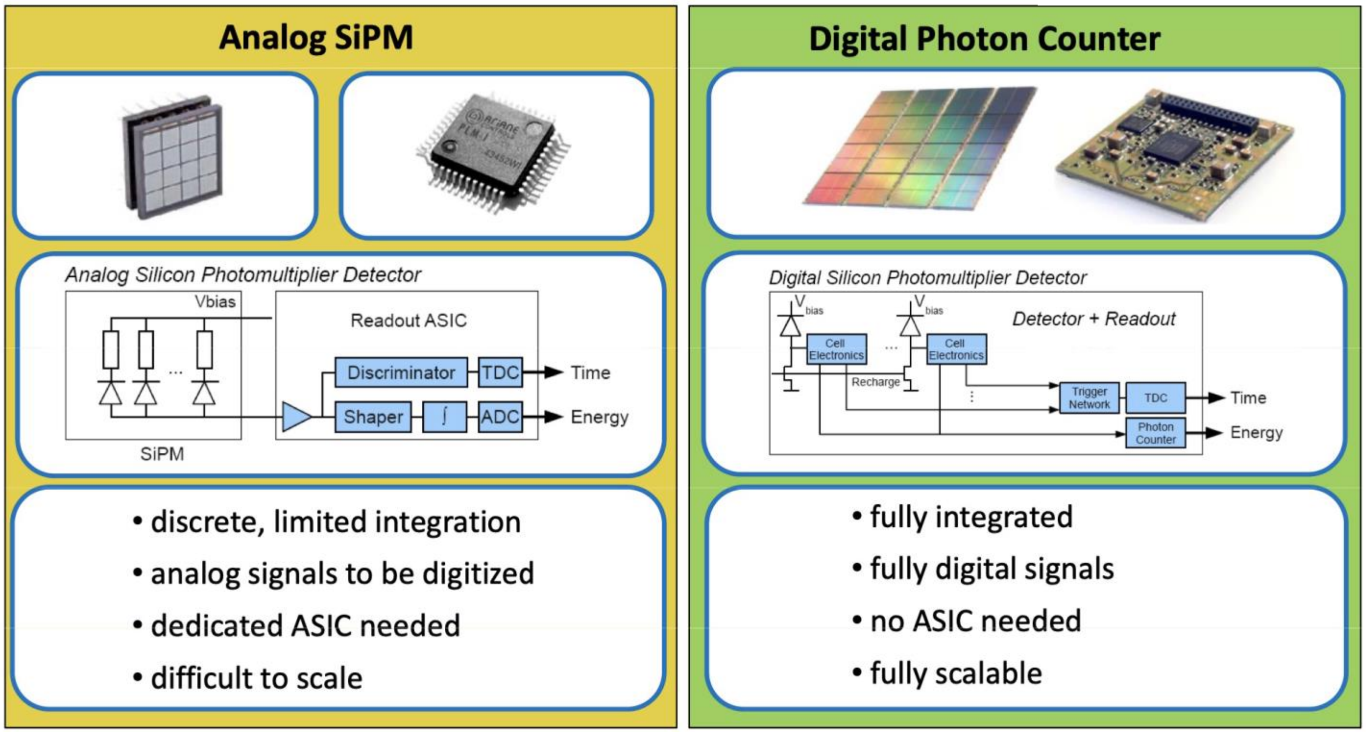
Significant difference starts emerging >10 ns when “free” protons contribute to the signal in scintillators

In proton distribution roughly three time scales appear: prompt/hard scattering (<1 ns), nuclear evaporation (<10 ns), and n+p interactions (>10 ns)

# Emerging Digital Sensors for Timing in Calorimetry



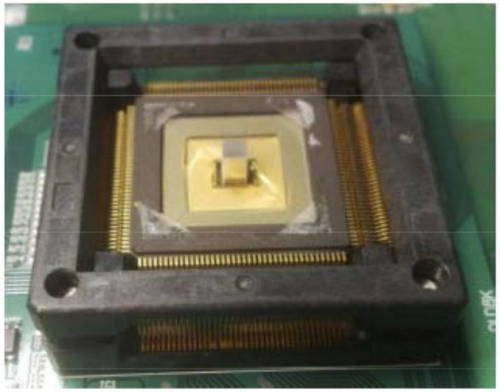

NIM-A 809 (2016), 31-52



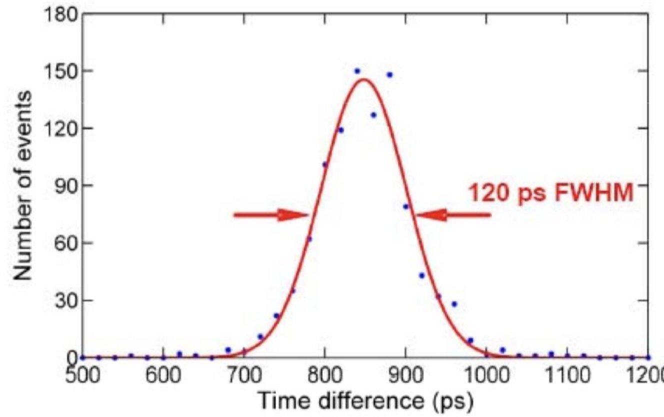

https://indico.cern.ch/event/192695/contributions/353376/attachments/277251/387863/TIPP2014_Amsterdam_lecture_Philips_Haemisch_pub.pdf
https://indico.fnal.gov/event/46746/contributions/209928/attachments/141285/177855/Pratte_CPAD2021_v4.pdf

# Example: Timing with Ca-codoped LSO:Ce + dSiPM

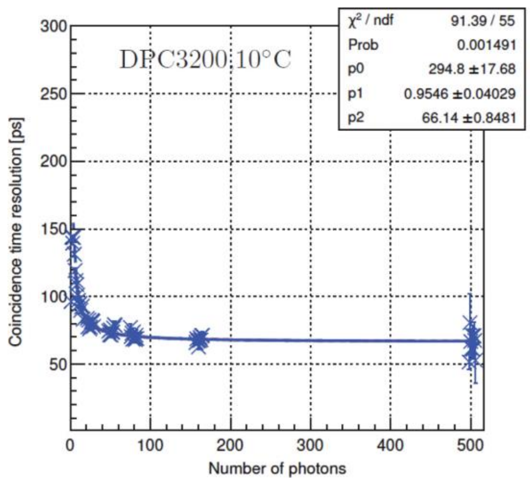
D. R. Schaart et al, MSS-MIC 2011, MIC15.S-137

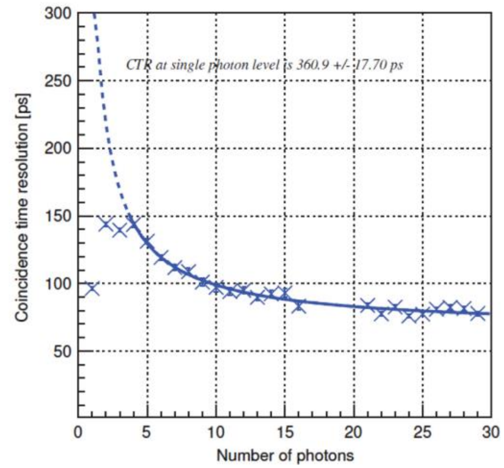


Photograph of Ca co-doped LSO:Ce crystal mounted on dSiPM demonstrator chip




- Time difference spectrum measured with a Na-22 point source
- CRT = 120 ps FWHM (for two detectors in coincidence) at room temperature



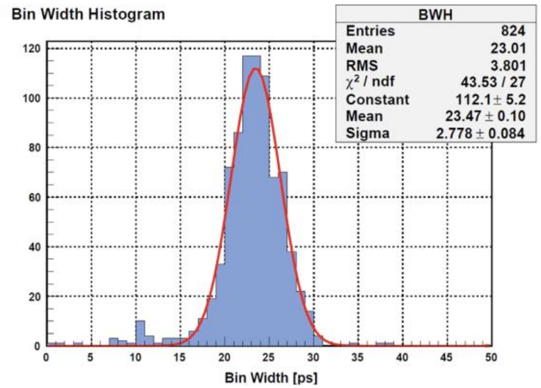



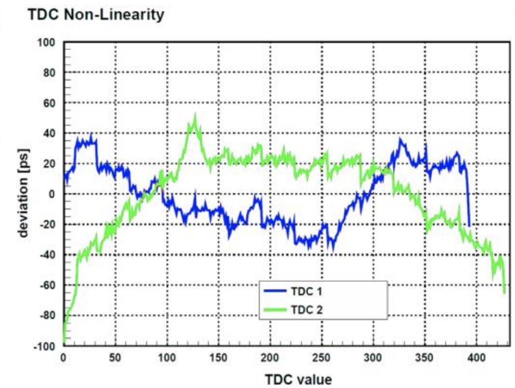

Coincidence time resolution of the DCP3200-22 sensor chip for femtosecond laser pulses

# Digital SiPM

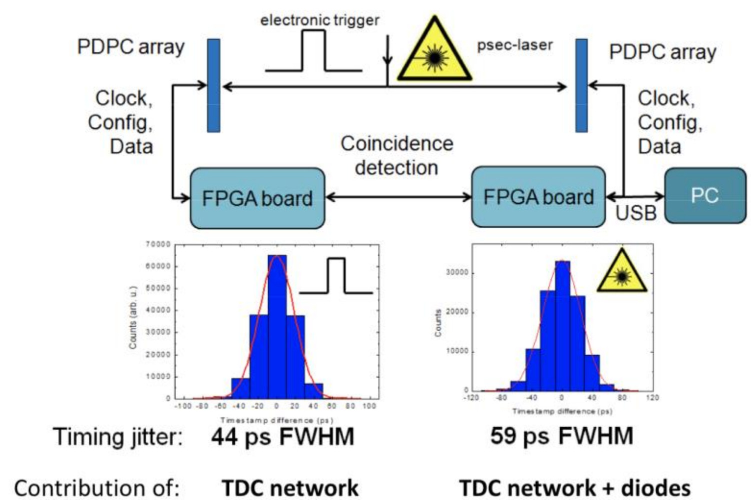
Advantages of digital photon counting *vs* analog detection (SiPM)

- Better intrinsic <u>timing resolution</u> due to integrated TDCs (~ factor 5)
- Better linearity (& correction)
- Significantly reduced temperature sensitivity (~$10^{-1}$)
- Active quenching reduces after-pulsing & crosstalk (~$10^{-1}$)
- Individually addressable cells enable DC control
- No analog electronics, no ADCs, no ASICs




TDC bin width distribution (left) and linearity (right) of the DLD8K demonstrator chip. The integral non-linearity is corrected in the read-out FPGA using calibration look-up tables




On-chip integration of TDC

# Some Remarks

Much has been achieved in improving timing measurement precision in the recent years ($\sigma_t$~30-100 ps) at "large" systems. Many different scientific, technical, and conceptual aspects need to coherently come together to make additional progress ($\sigma_t$~1-10 ps) in the next decade.

We need advancements in all areas:

1. Fast, bright, and radiation-hard radiators (blocks, crystals, fibers, …)
2. Innovative waveguide structures accommodating different types of photons (*e.g.* Cherenkov, scintillating, cross-luminescence light, …)
3. Radiator media for multiple-readout
4. Multi-GHz, low power, compact waveform digitizers
5. Precise clock distribution (LpGBT-v0 random jitter 2.2 ps)
6. Fast, miniature and radiation-hard photodetectors
7. Machine learning tools applied to timing (on- and off-line)
8. …