A detector system to push the 1 picosecond barrier.

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Goal:

Building a detector system to measure time with high precision requires all the elements of the system to work with even higher precision.

Each of the separate elements of a system need to be optimized for this purpose.

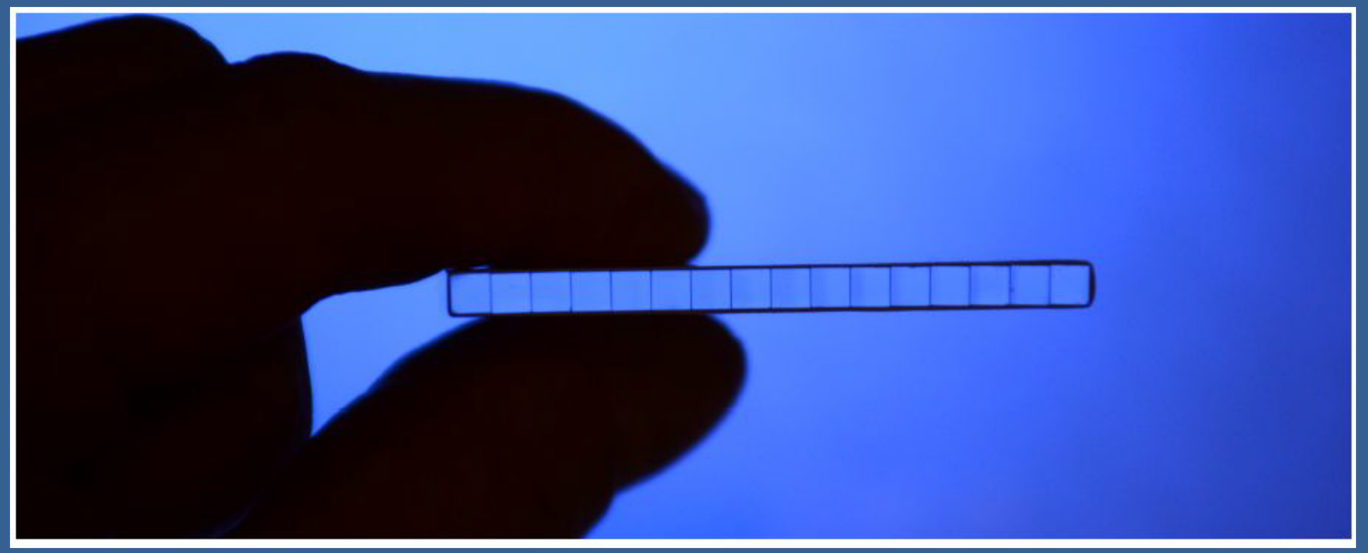
We include the signal source, the photodetector, the front-end amplifier, the TDC and the clock reference distribution.

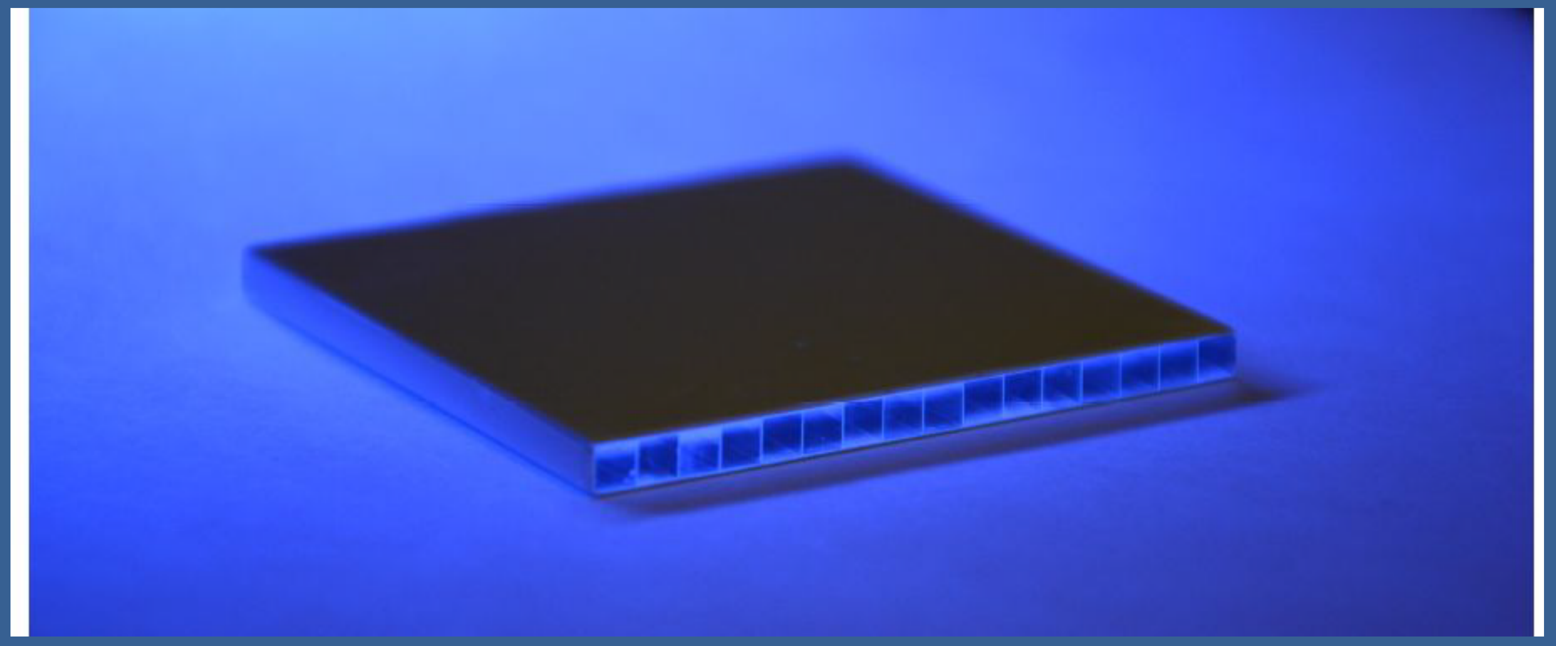
Each of these will need to operate with high precision across a detector for the system to achieve the optimum performance.

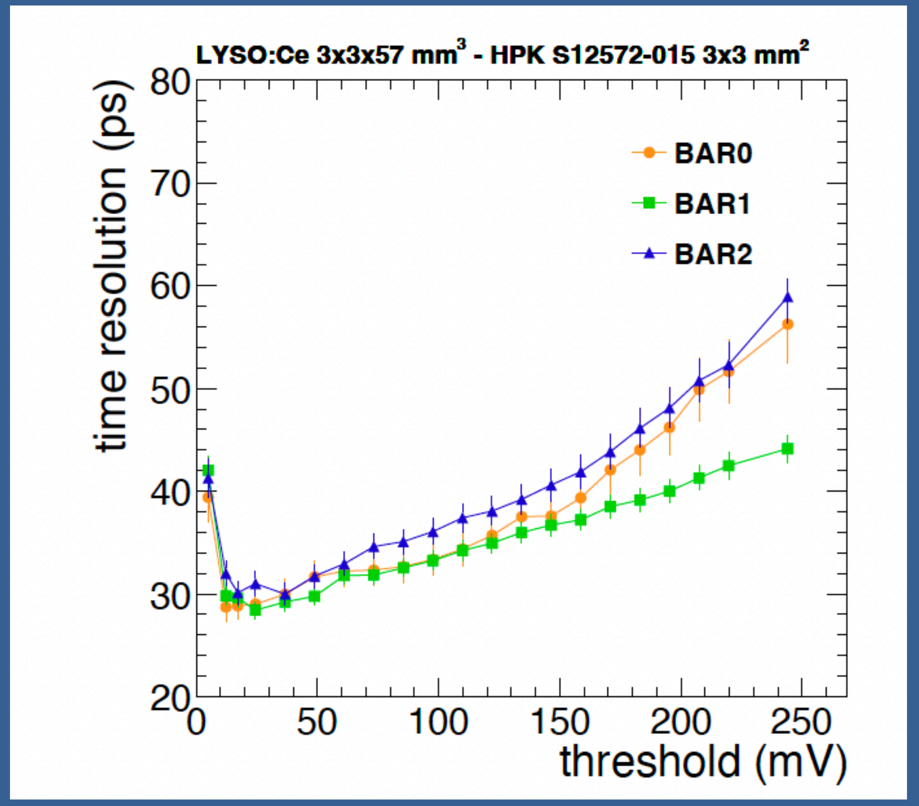
$$\sigma_t = \sigma_{ck} \oplus \sigma_{digi} \oplus \sigma_{ele} \oplus \sigma_{phot} \oplus \sigma_{dark}$$

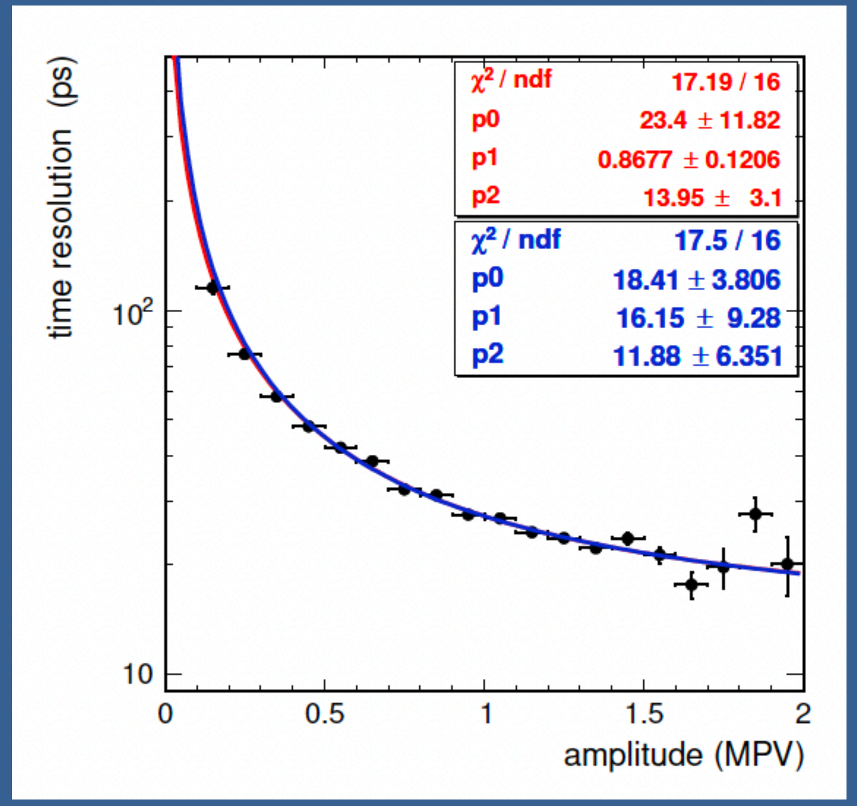
State of the Art

CMS and ATLAS Mip Timing Detectors:









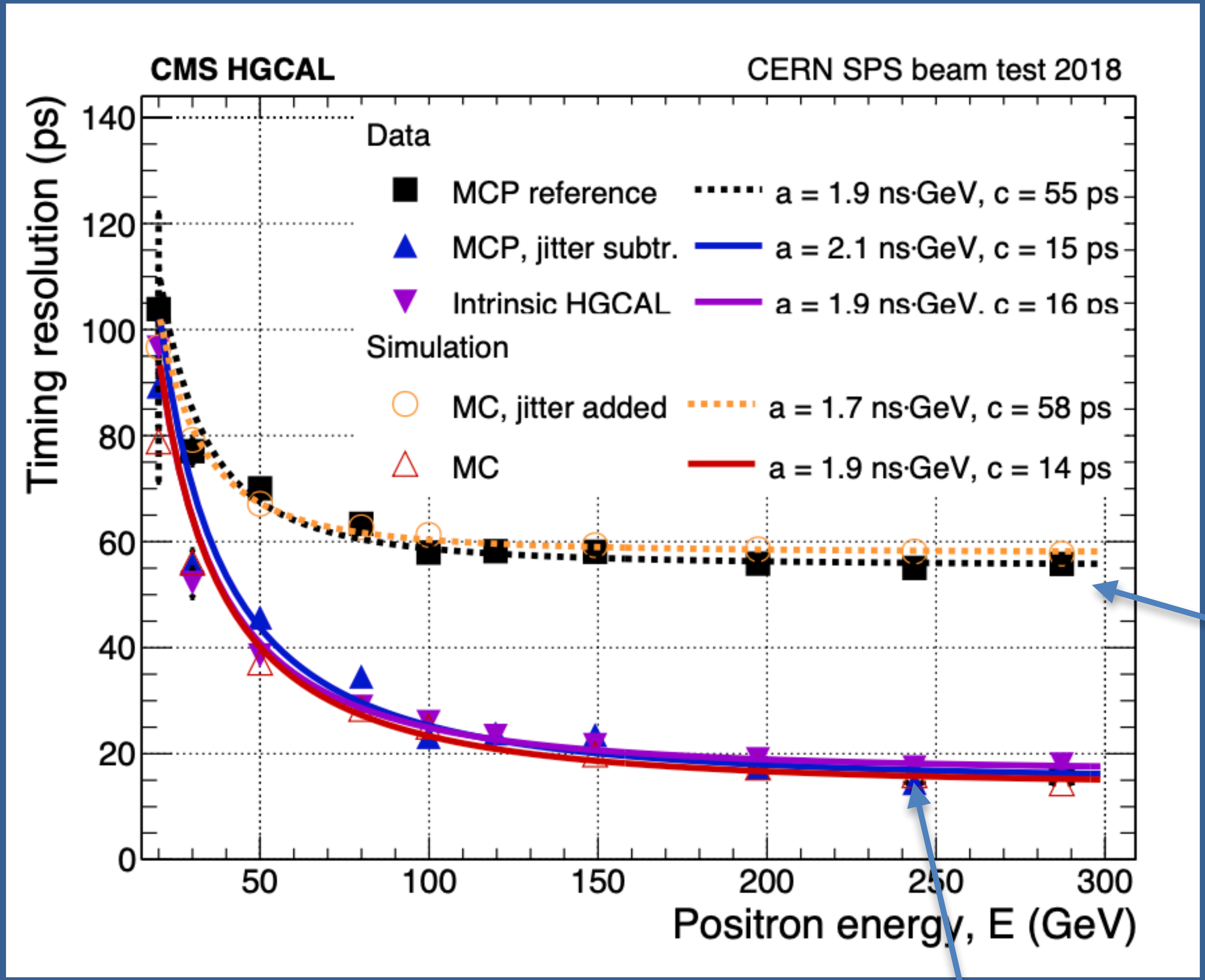
CMS barrel detector:

- Short LYSO crystals readout at both ends with 4 mm^2 SiPMs — $\sigma_t \approx 30ps$.

Endcap detector:

- Low Gain Avalanche detectors. Large area silicon diodes with impact ionization at the p-n junction — $\sigma_t \approx 40ps$

HGCAL prototype — Timing in electron showers



Difference due to jitter in the time from the reference MCP

Precision derived from difference in signal times in two halves of the detector.

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To get the best resolution everything matters:

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Low jitter stable clock ~0.5 ps

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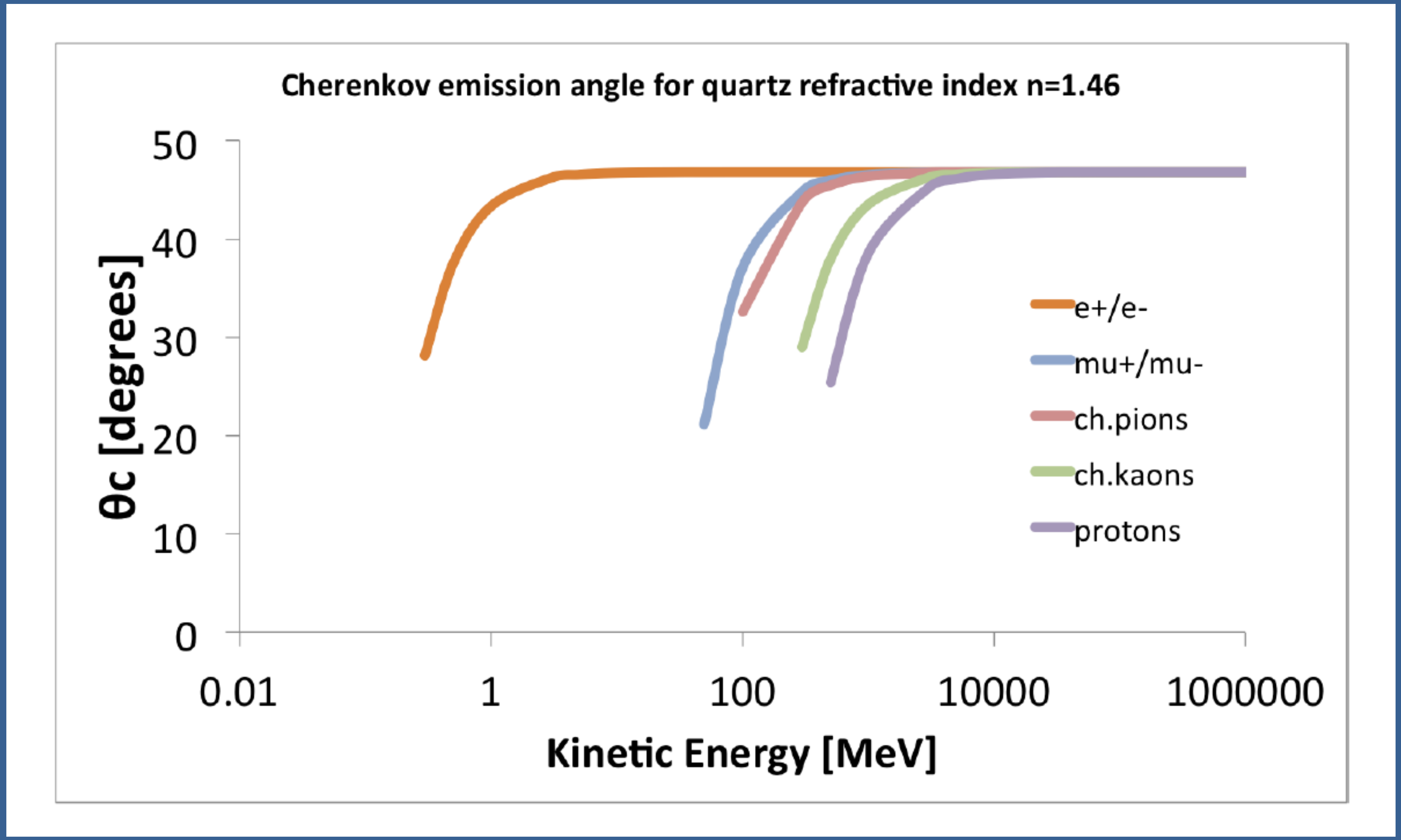
Cherenkov Radiation

A truly prompt signal is Cherenkov Radiation.

Quartz (silica) is a low-cost material with an index of 1.46 and good transmission in the UV.

Cherenkov threshold is 0.68c

- Electrons: 161 keV
- Muons: 33 MeV
- Protons: 296 MeV
- Kaons: 155 MeV
- Pions: 44 MeV.



Cherenkov Signal

Number of photons per unit length is given by:

$$\frac{dN}{dx} = 2\pi\alpha \sin^2\theta \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2}$$

$$\cos\theta_c = \frac{1}{\beta n}$$

Or:

$$\frac{dN}{dx} = 2\pi\alpha \sin^2\theta \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_1} \right)$$

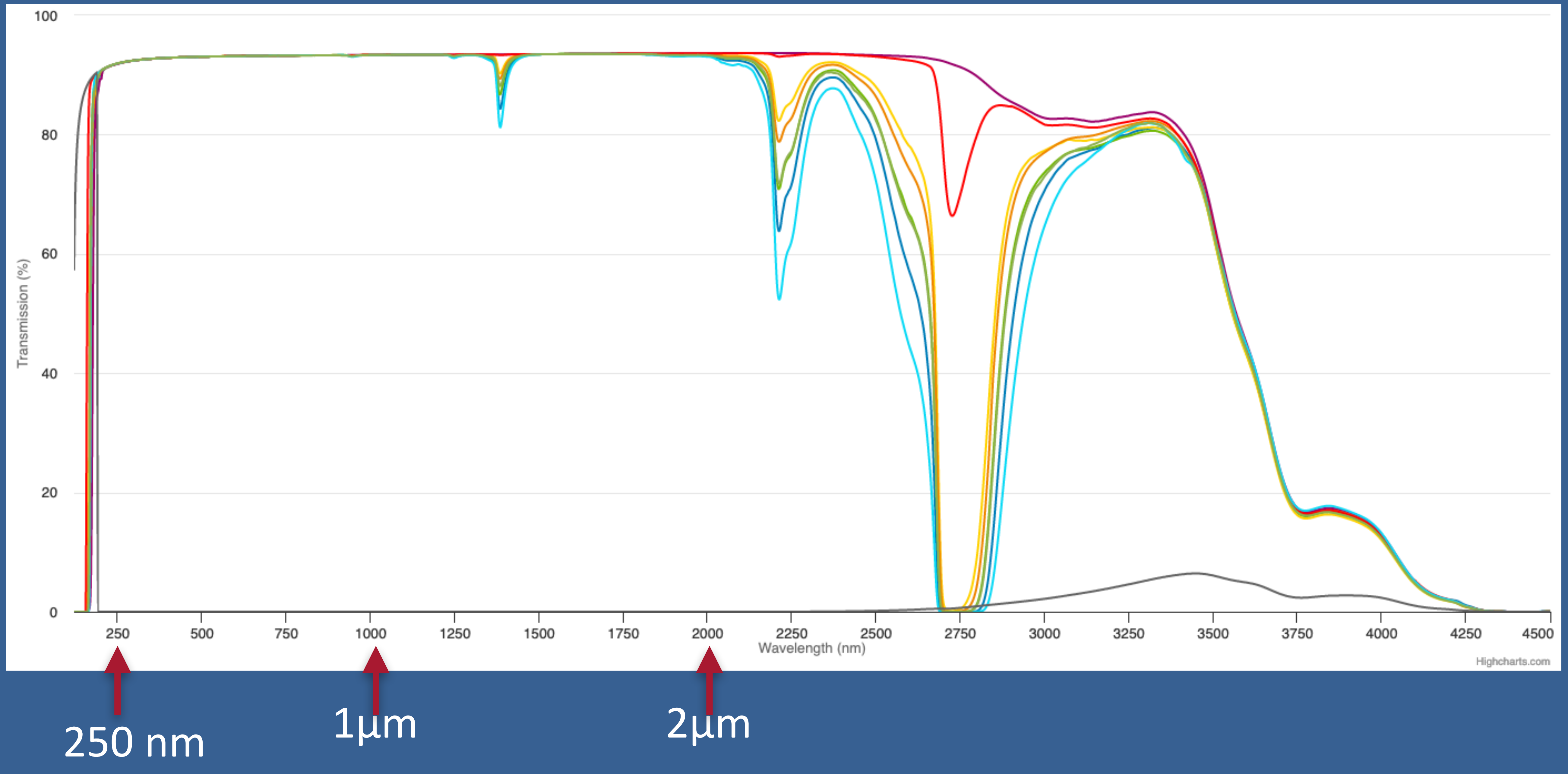
For silica with $\beta = 1$, θ_c = 0.8 radians.

α is the fine structure constant.

For a particle with β = 1 the number of photons produced in a 5mm quartz rod with a wavelength between 200 and 600 nm is 400.

Radiator

High purity fused silica has an index of 1.46 is transmissive in the UV.



Dispersion in the arrival time of the photons: $\Delta t_{max} = \frac{d}{c\beta}(\beta^2 n^2 - 1)$

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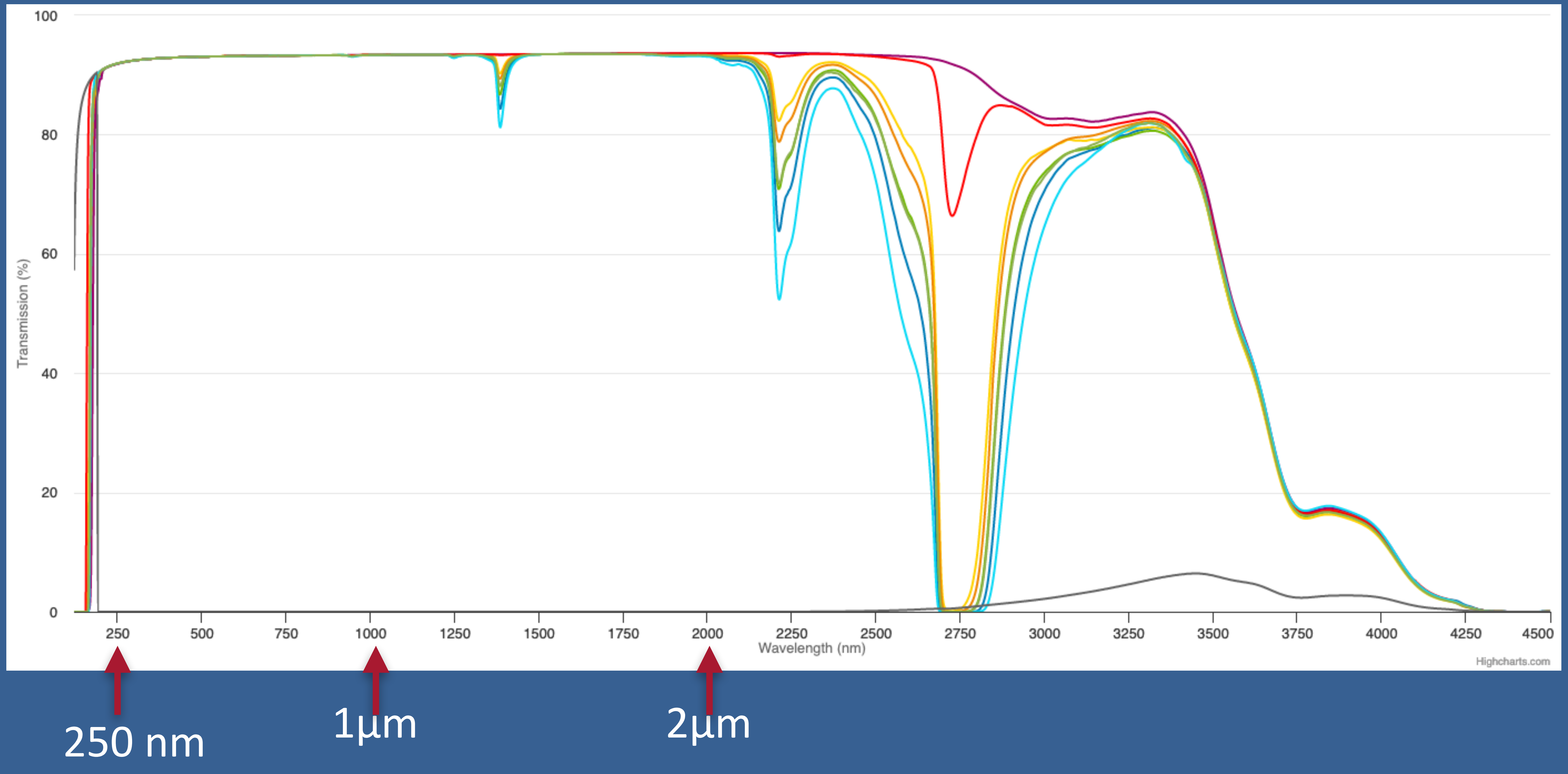

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~400 photons arrive at end of rod in interval of 19 ps

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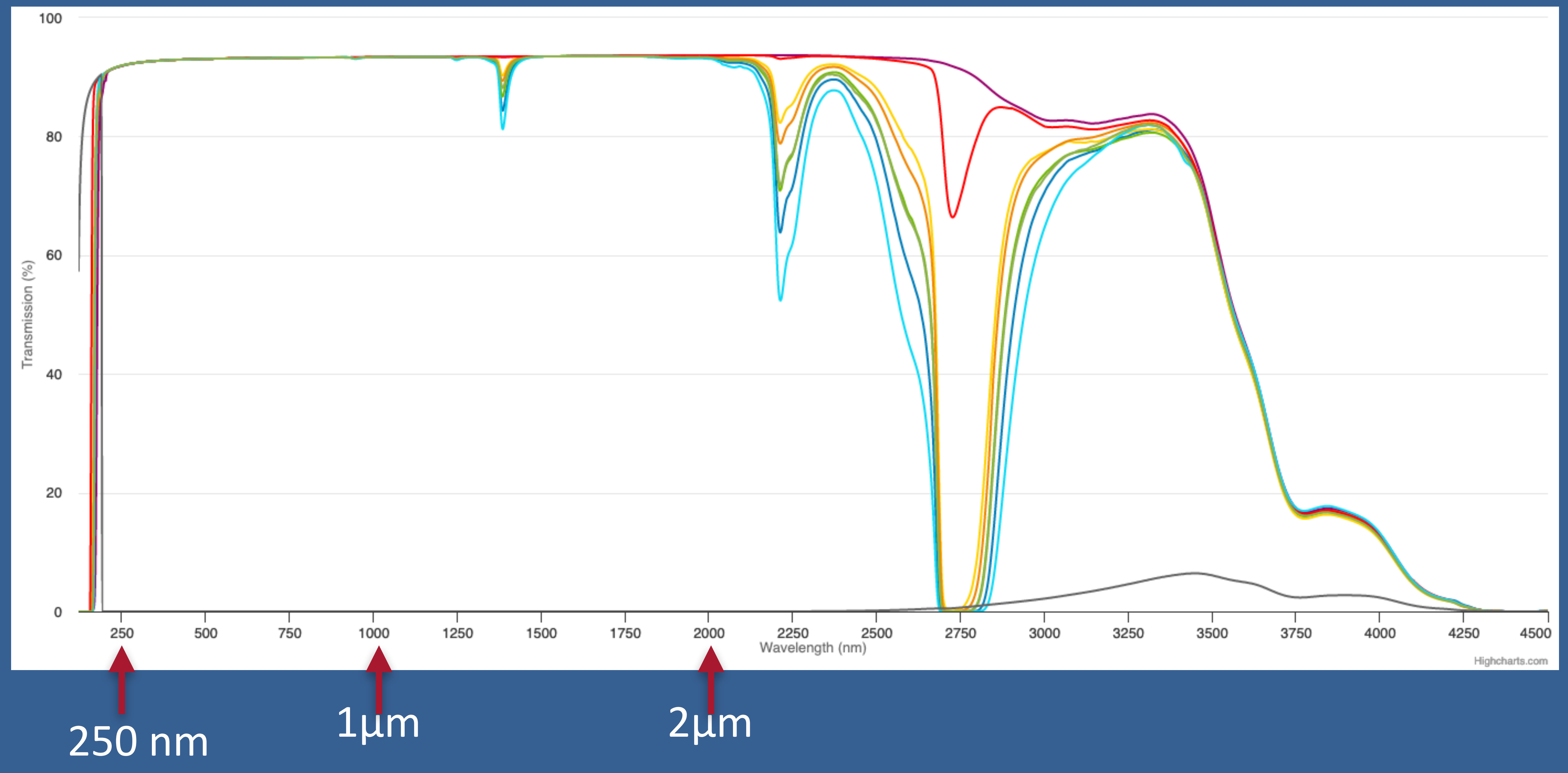

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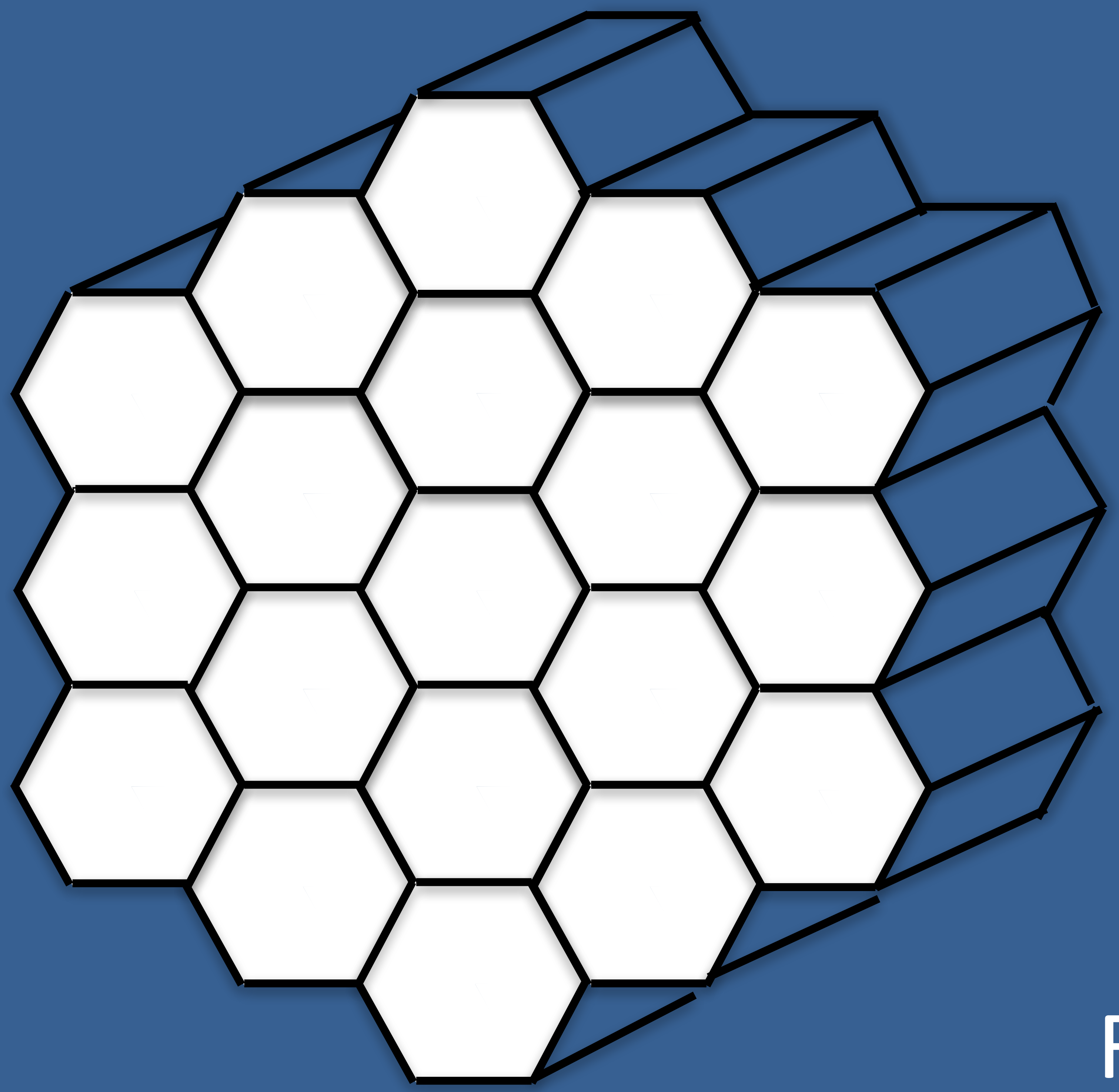
There is a trade off between the index and the thickness and number of photons and the signal dispersion

Detector Concept

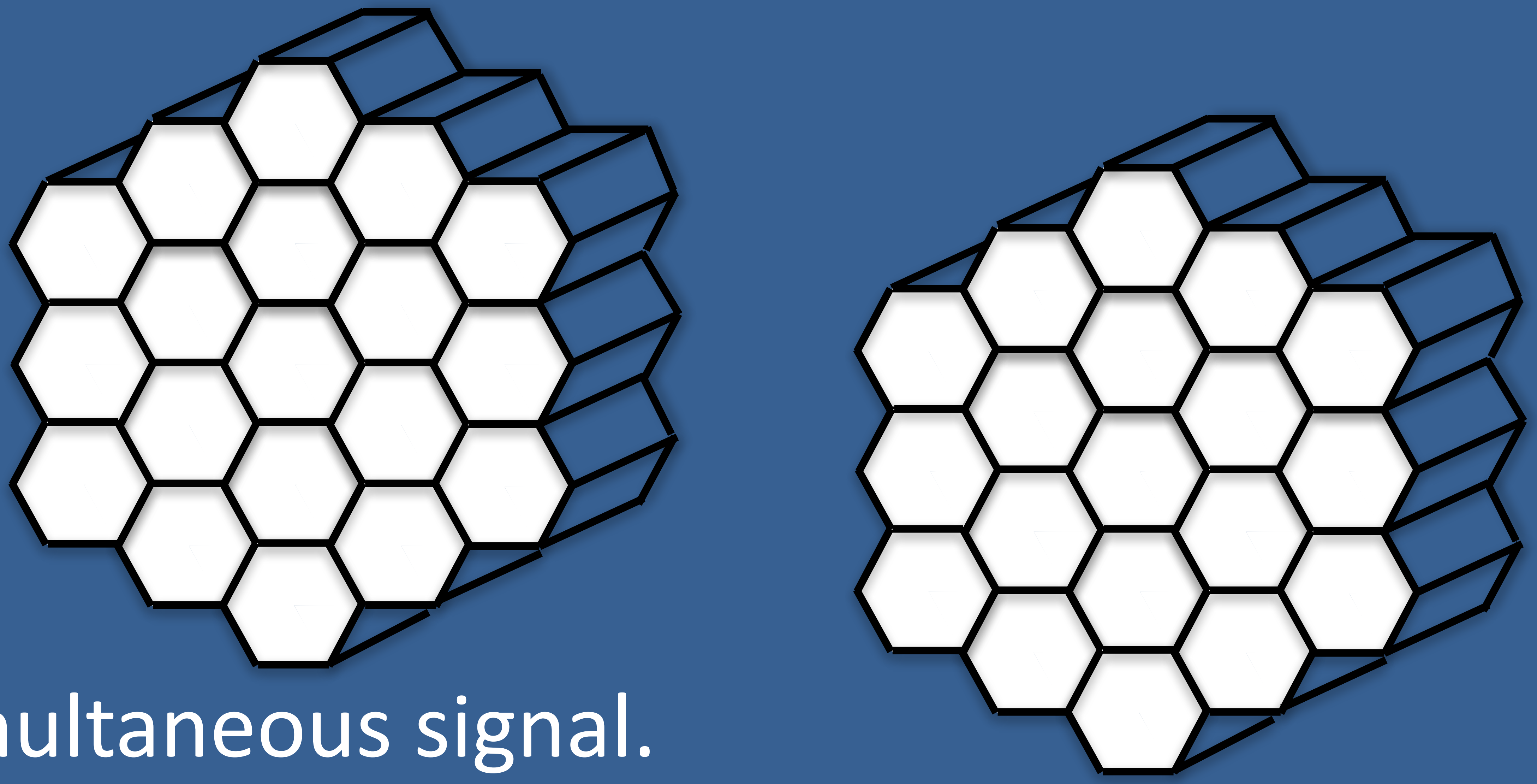


Hexagonal stack of 5 mm long quartz rods read out by SiPMs.

Readout using a high precision TDC vernier phase delay or time difference amplifier

Test in a beam:

Two detector matrices use to detect decay products in a beam line.



Could use π^{o-}decays K-decays to get simultaneous signal.

Could use two single-channel detectors in sequence in a beam line.

Photodetector:

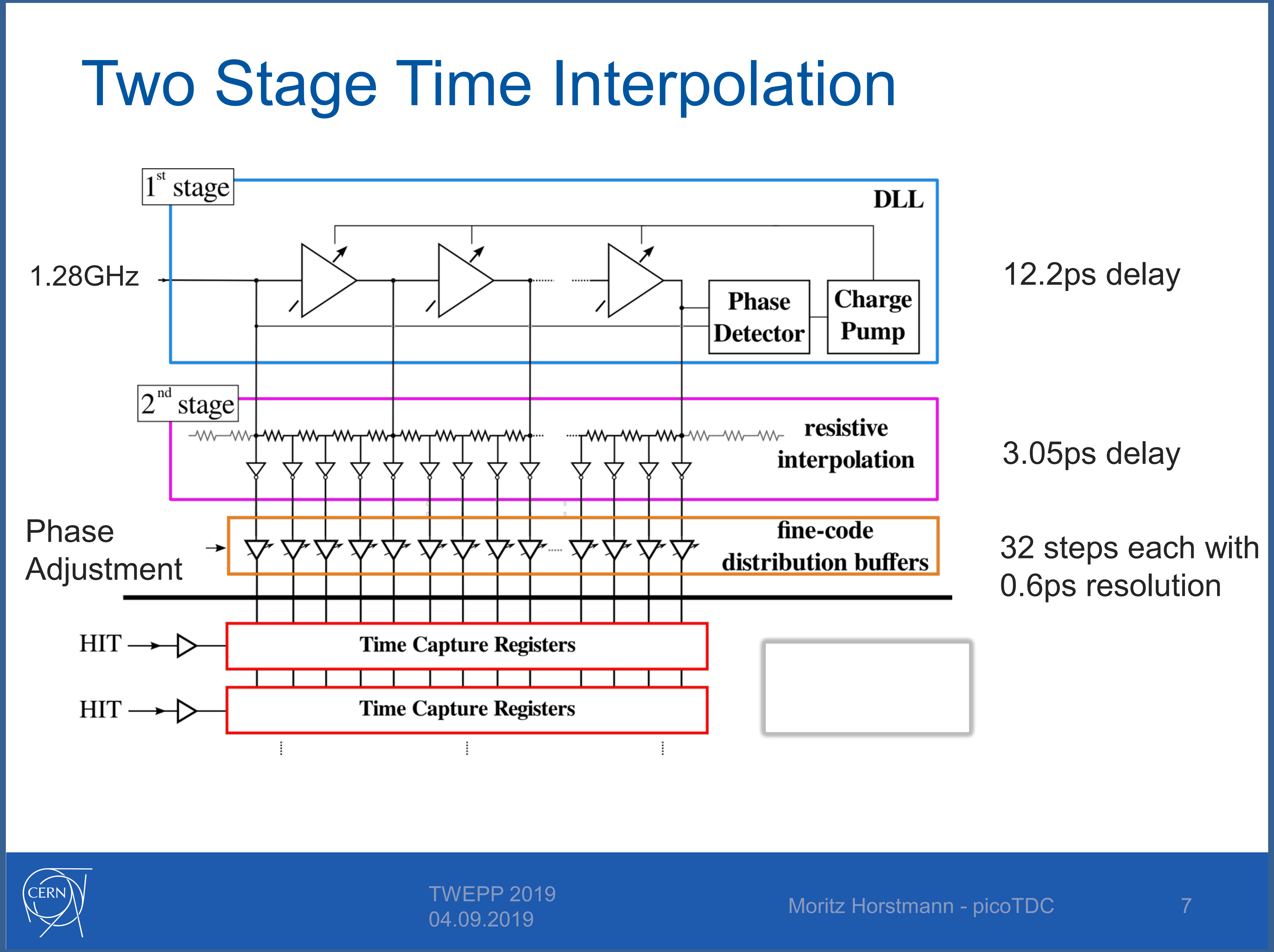
- SiPMs
  - Low cost, well understood technology
  - Dispersion of signal due to low-filed region at the surface.
- LAPDs
  - Cost/mm^2
  - Dispersion in signal due to variations in phot-electron path length and signal formation in the micro channels.
- SNSPDs
  - Ultra fast cryogenic devices.
  - Large area?
    - Is there a trade-off with signal dispersion?

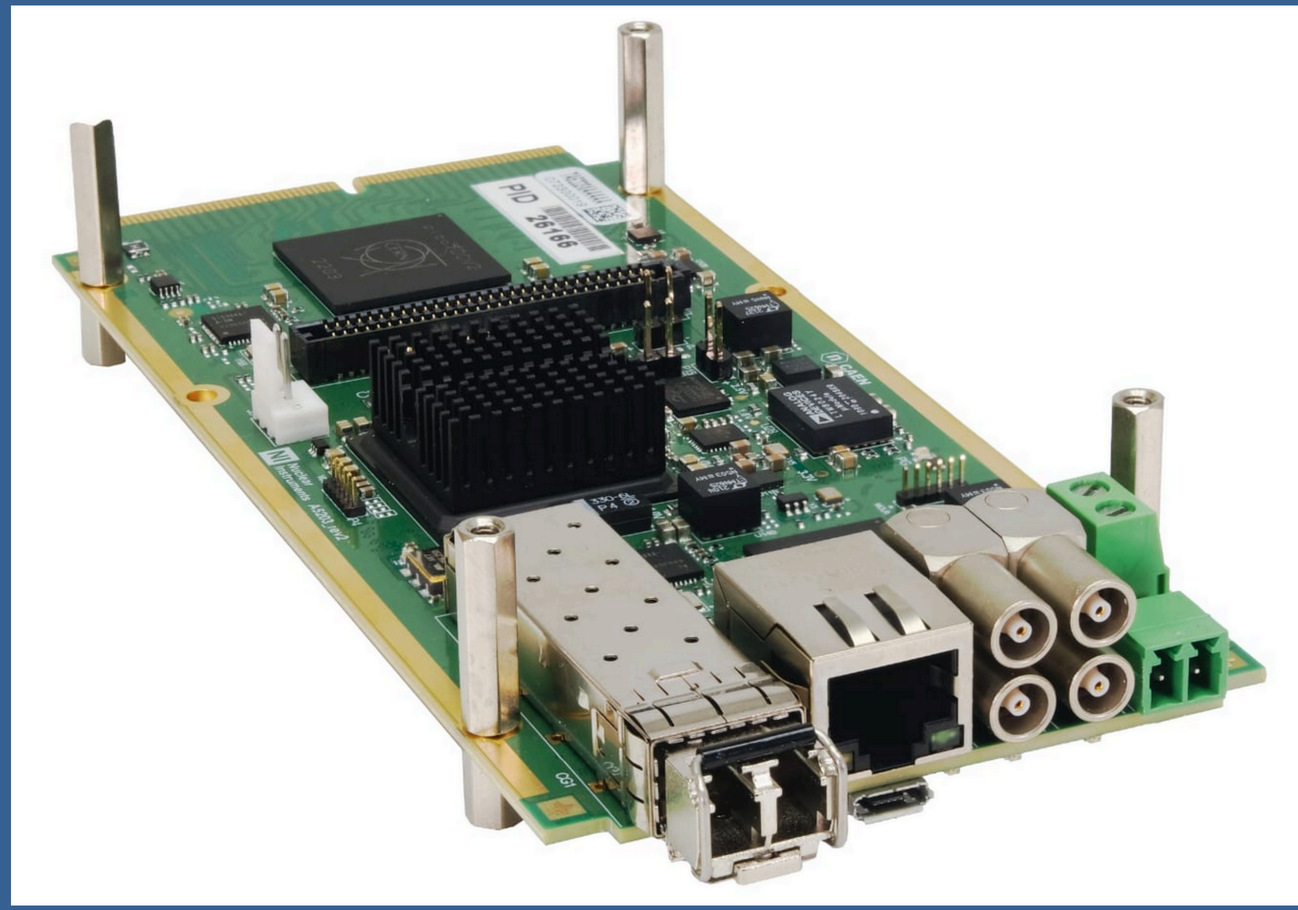
No obvious solution — requires investigation

TDC:

Assume we will use SiPMs.

Vernier TCDs





CAEN A5203

Calibration between devices and linearity.

TDC — Time Difference Amplifier

A Linear High Gain Time Difference Amplifier Using Feedback Gain Control

Wenlan Wu[1, 2], R. Jacob Baker[1], Phaneendra Bikkina[2], Fred Garcia[2] and Esko Mikkola[2]
[1]University of Nevada-Las Vegas, Las Vegas, Nevada
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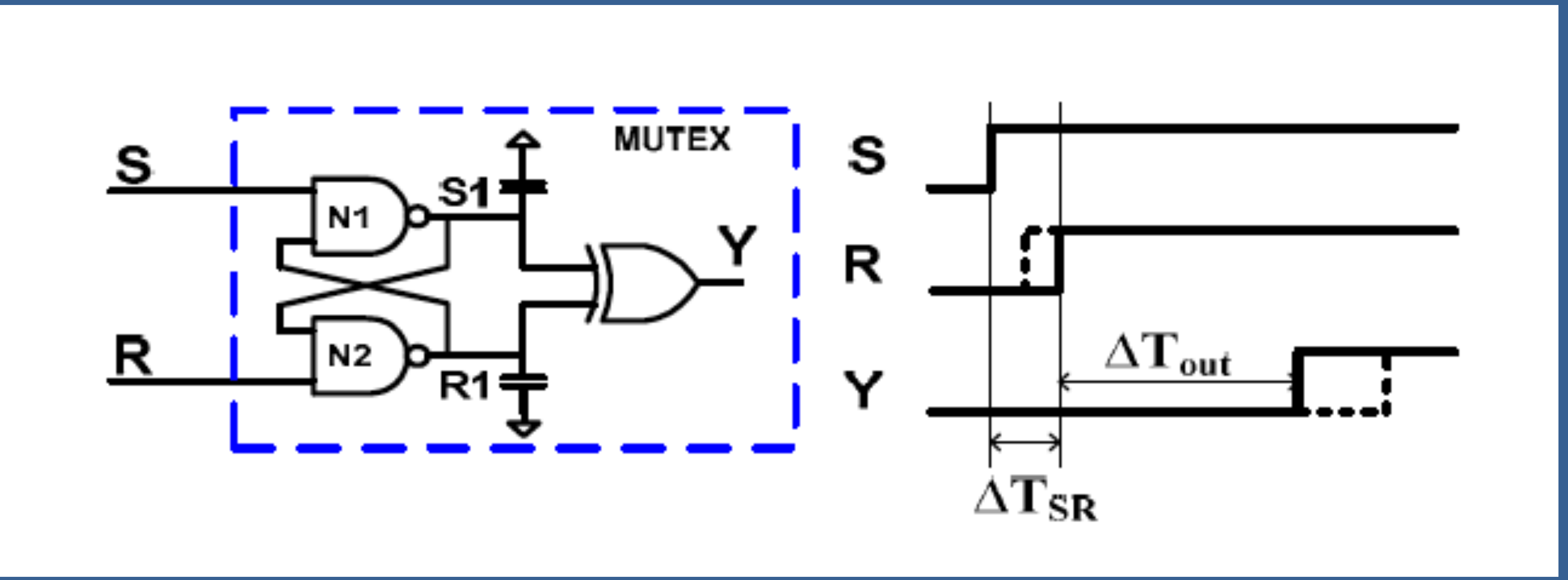
Paper link



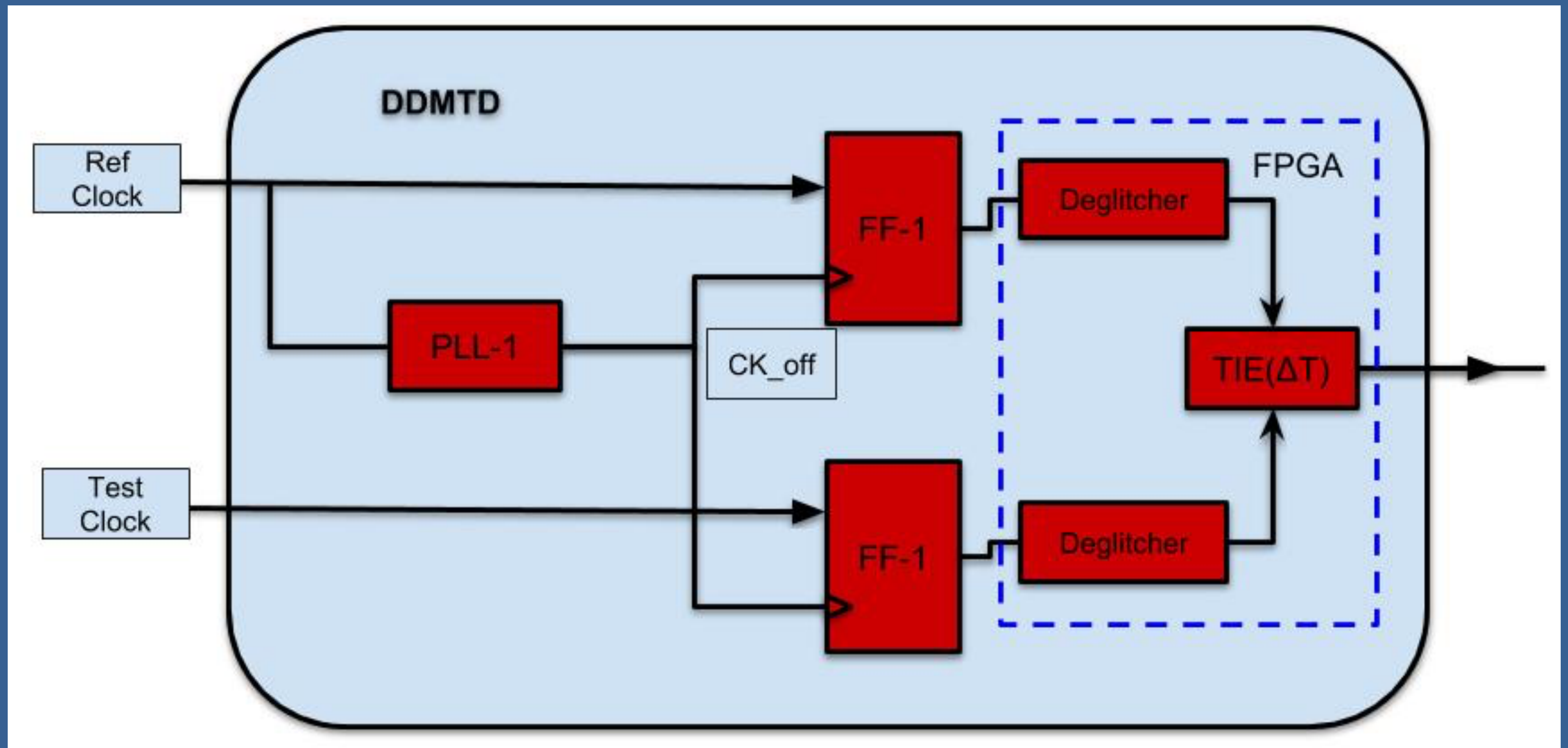
MUTEX circuit that exploits metastability of an SR latch.

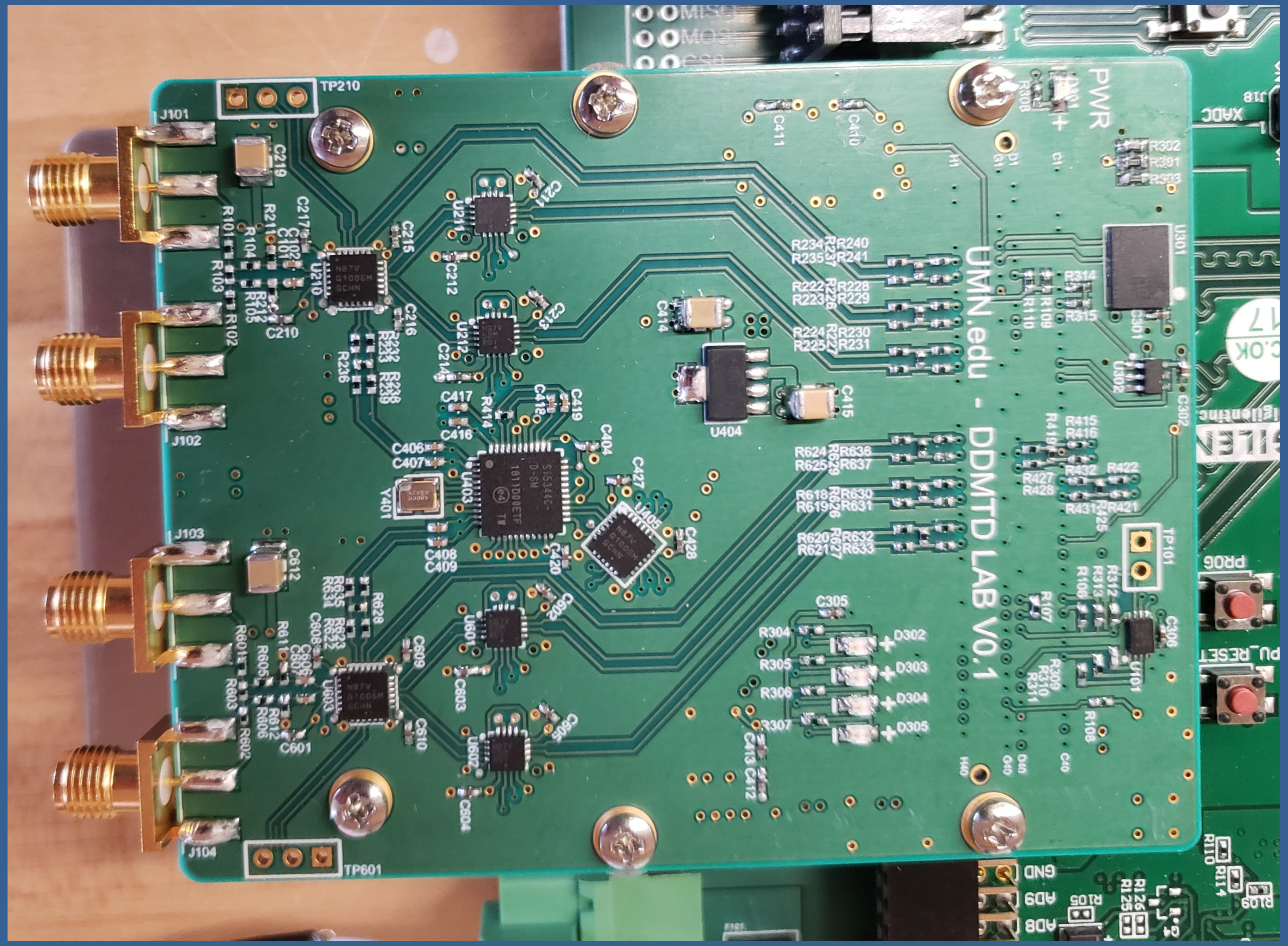
Interesting circuit that includes feedback in the SR latch to achieve linearity of TDC gain.

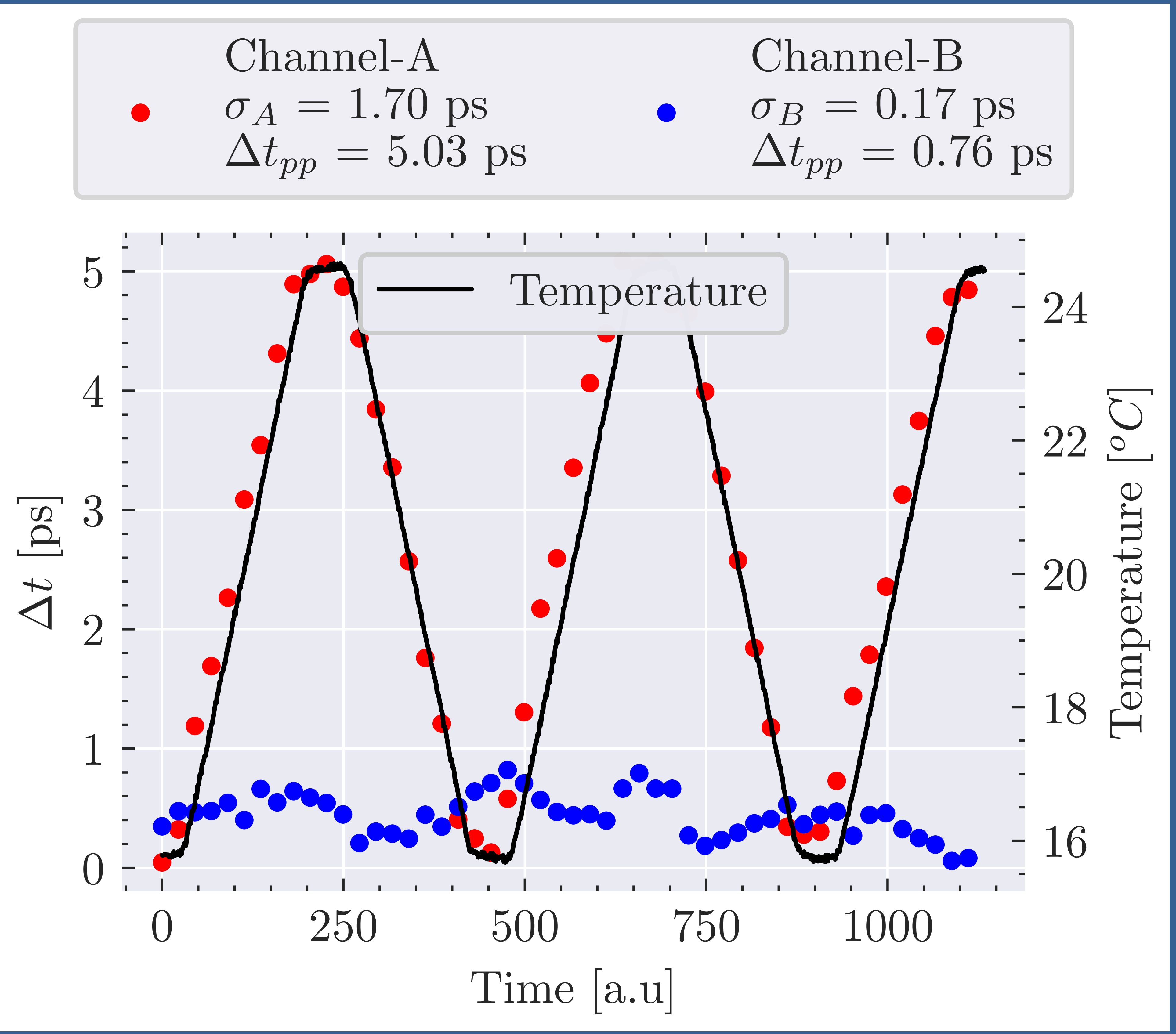
Othe options: Optical circuitry?

Clock Stabilization

Use clock with phase stabilization using DDMTD and DCPS ASIC







Questions:

- Best material:
  - What is the best material large value of *n* or low value?
  - Optimum geometry to minimize the optical dispersion.
- Best photodetector
  - Optimize for low latency, signal size and low dark count rate.
  - Is it feasible to use SNSPDs
    - Cryogenics?
- Readout:
  - Design of front-end preamp.
- Digitization:
  - Can we do better than 3 ps digitization?
  - Rad tolerant PLL with sub-picosecond jitter.

Potential to collaborate with multiple RDCs (and DRDs) - we would welcome new groups interested in any, or all of these questions.

Backup:

Beam Halo Monitor in CMS