Particle by Time-Of-Flight

A detector system to push the 1 picosecond barrier.

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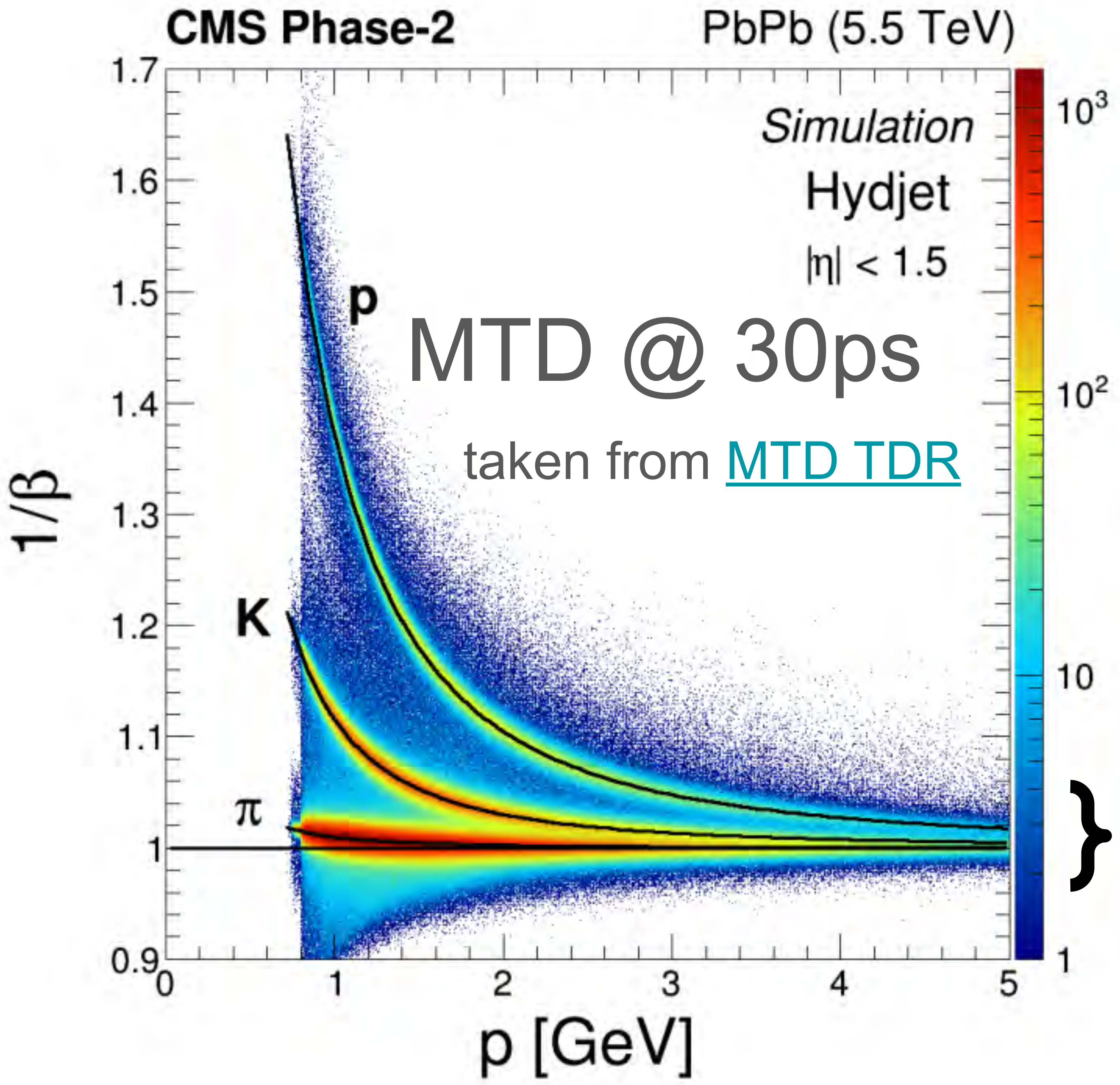
Primary Goal

We are proposing to investigate techniques to achieve an order-of-magnitude improvement in the performance of detector timing resolution, with the physics motivation the need to identify individual particles within jets

Applications

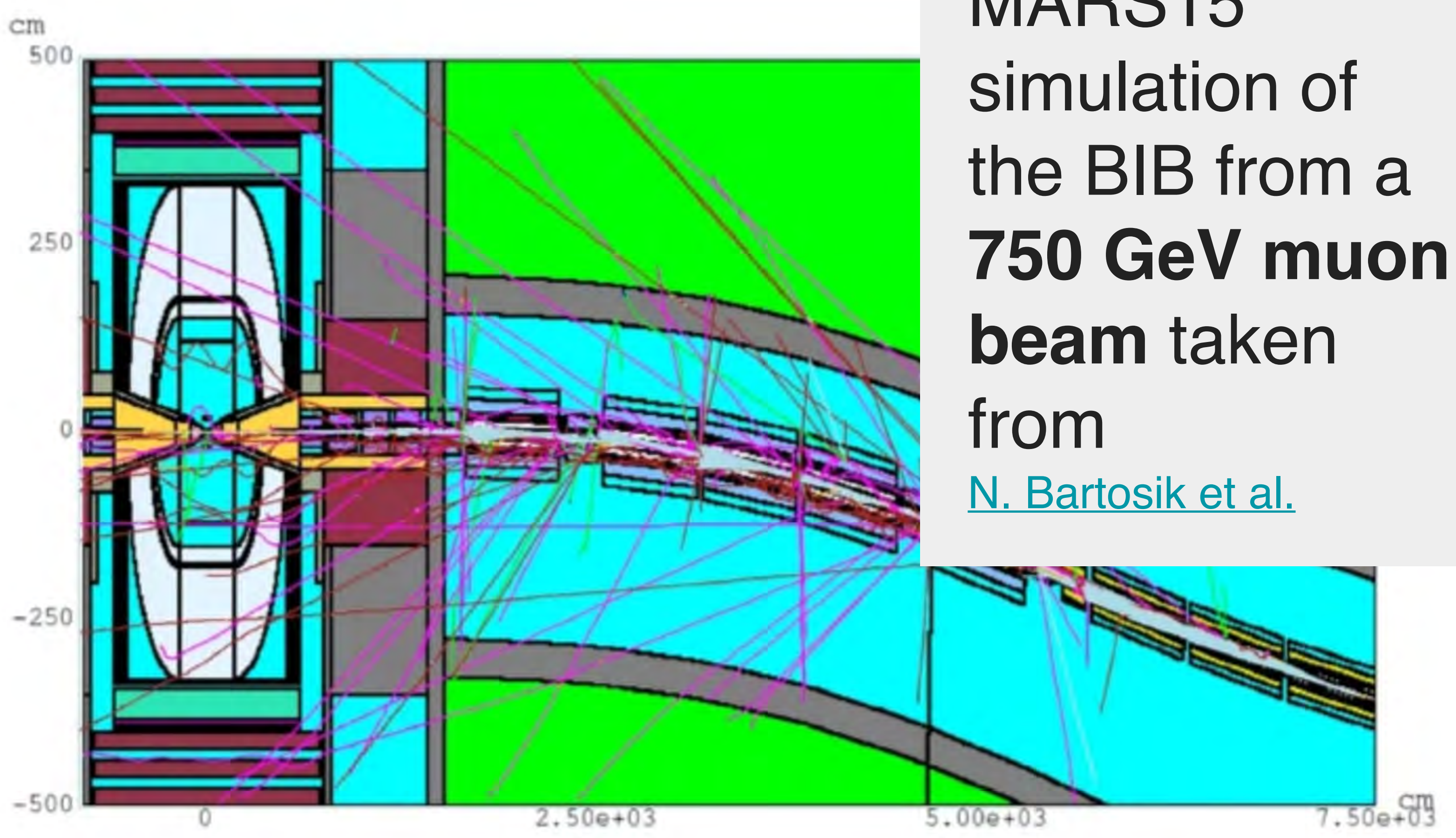
Particle Identification



To resolve bands at higher energies

p, K, π separation in high energy jets.

BIB & Pileup Discrimination

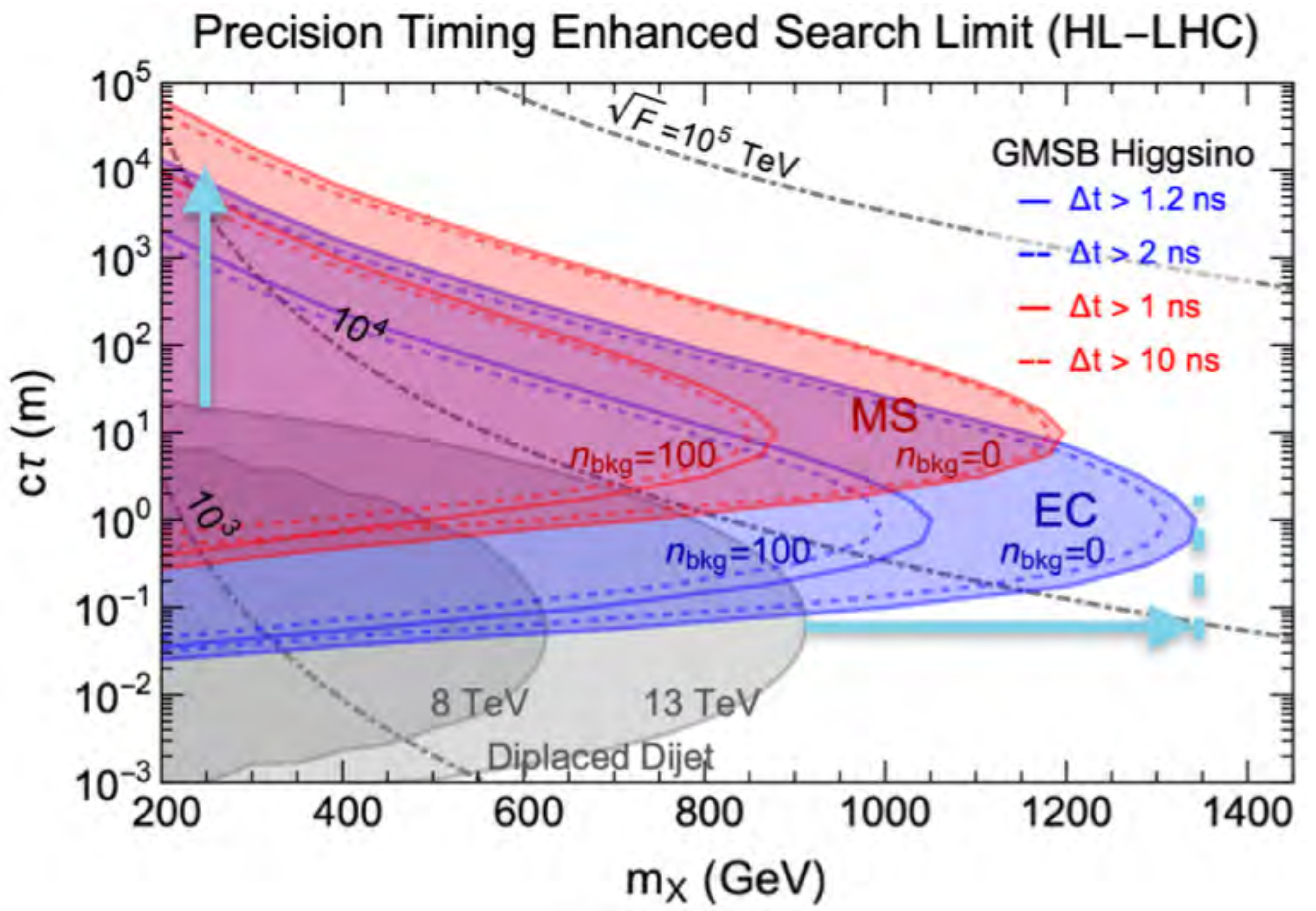


MARS15 simulation of the BIB from a **750 GeV muon beam** taken from N. Bartosik et al.

Separation of beam induced background[1] and better pile-up rejection for future detectors

1 Exploiting directionality and timing of the detector

Rare & Exotic Searches

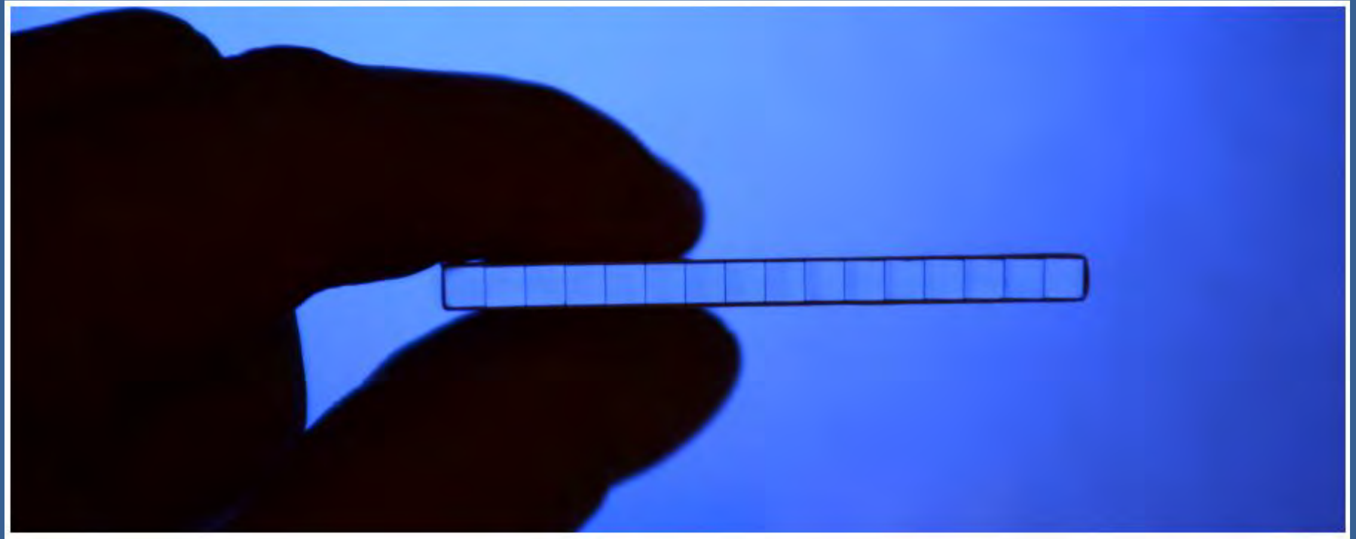


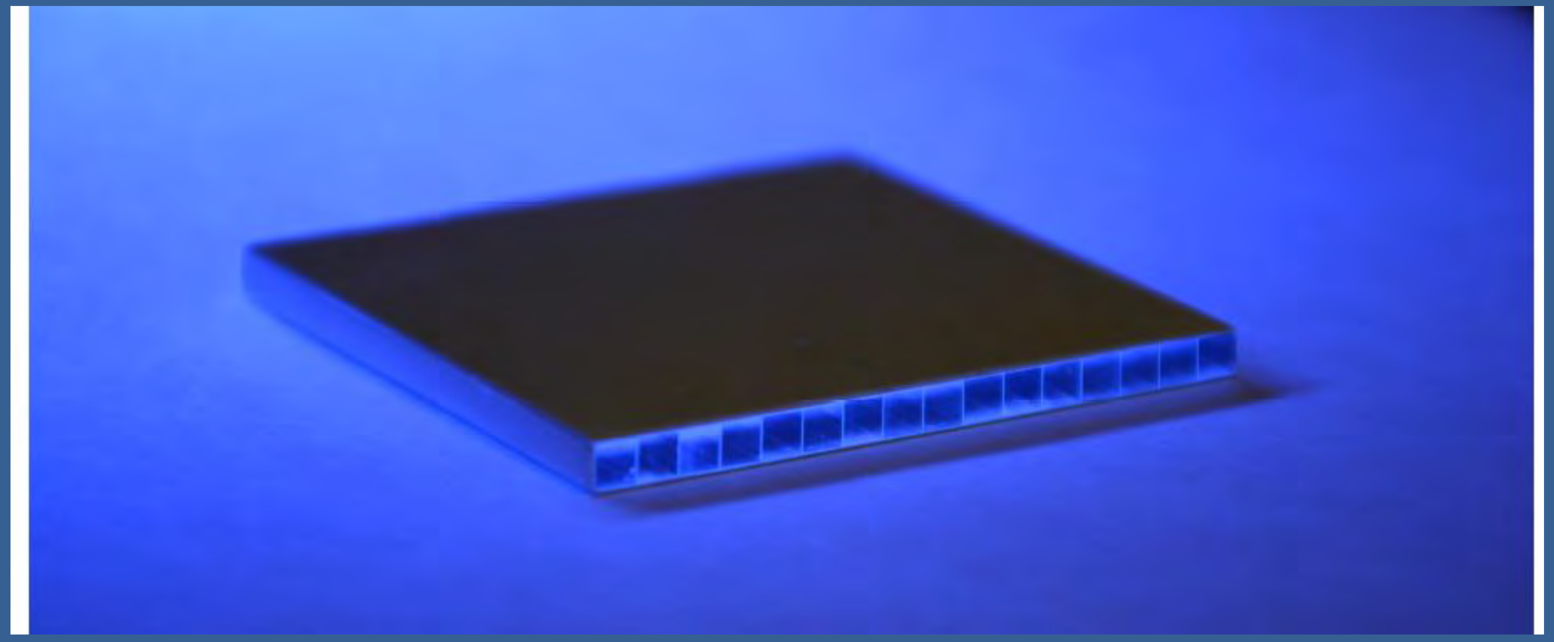
taken from a study on LLP by Zhen Liu et. al

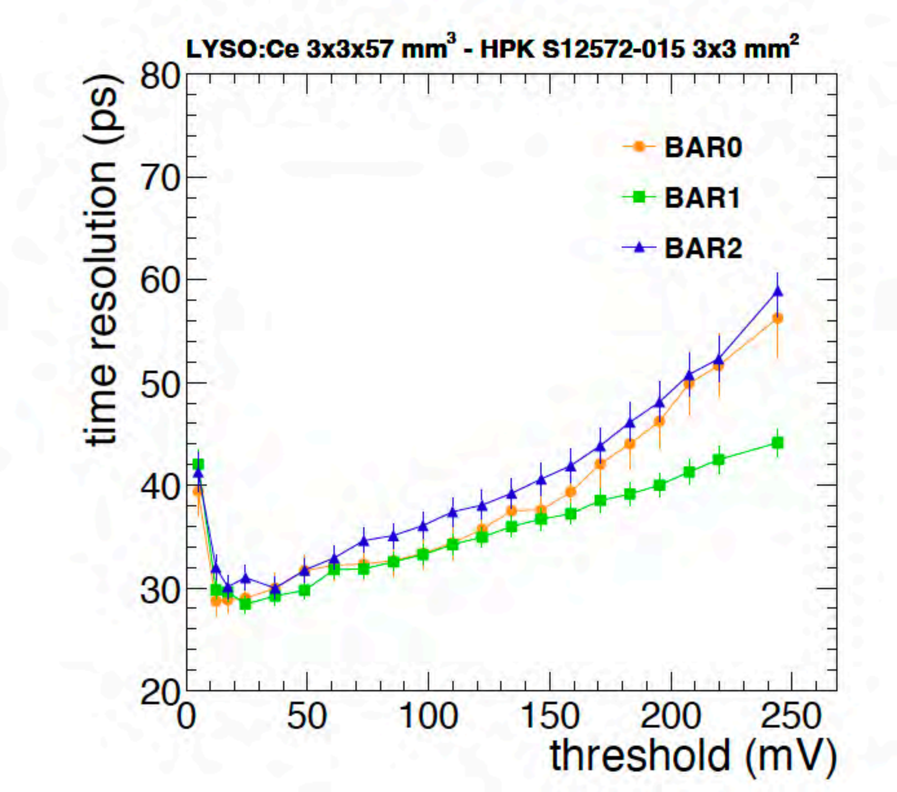
Improvements in timing improves the mass, lifetime reach and suppresses SM background

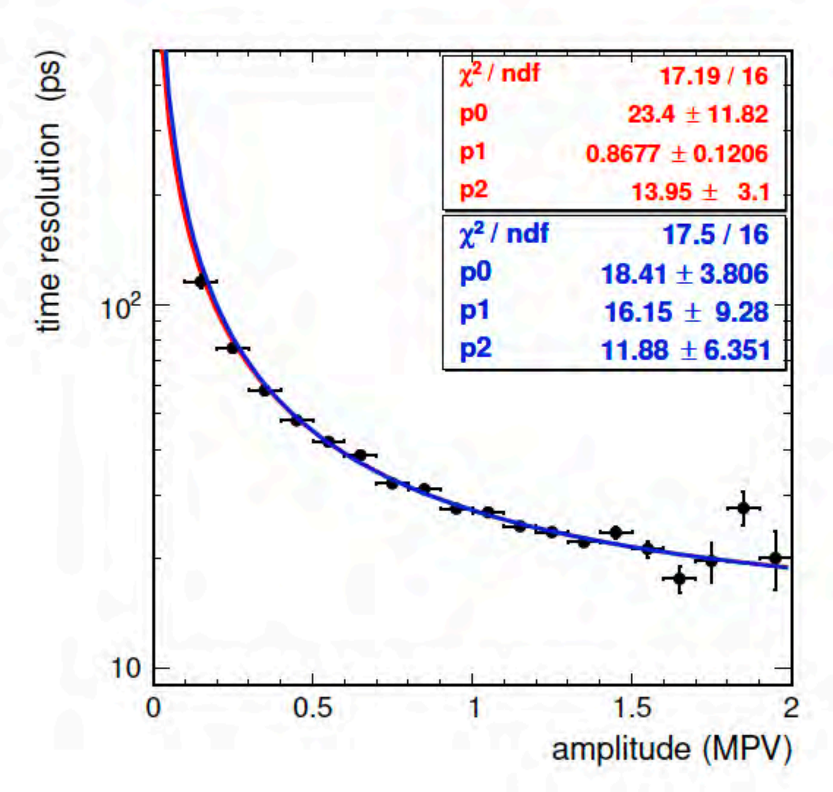
State of the Art

CMS and ATLAS Mip Timing Detectors:









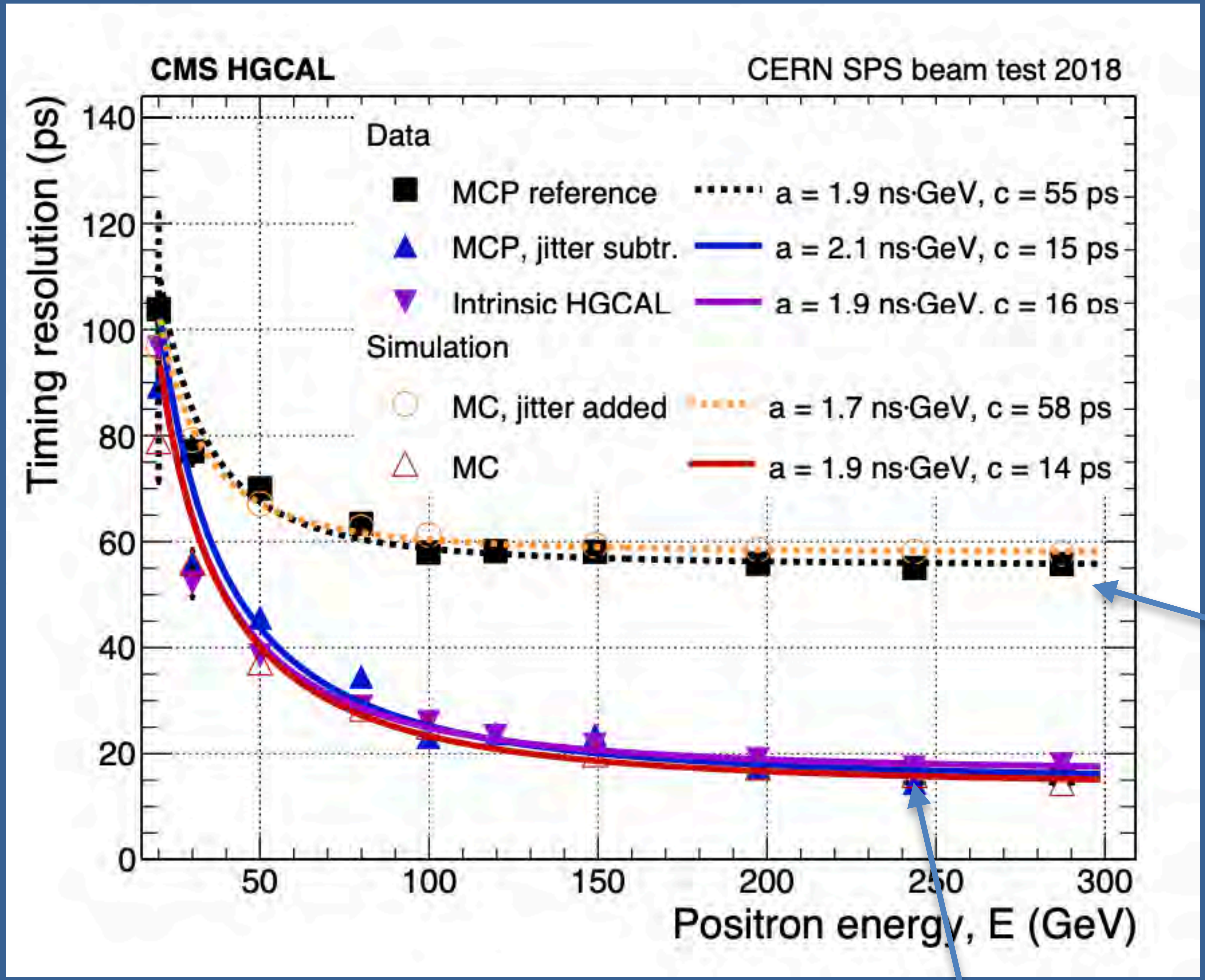
CMS barrel detector:

- Short LYSO crystals readout at both ends with 4 mm² SiPMs — $\sigma_t \approx 30ps$.

Endcap detector:

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

Calorimetry— 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.

Program

Build a detector *system* to measure time with very high timing precision (~1 ps) requires all the elements of the system to work with even higher precision.

Base system on the precision detection of Cerenkov radiation.

Requires:

- Cerenkov Radiator
- UV-enhanced, low-jitter photodetector
- Fast preamplifier.
- High precision TDC.
- Precision reference clock distribution
- Mechanical assembly of system.

Areas of Investigation

Initial Detector Concept using current state-of-the art:

- Cerenkov Radiator
  - Fused silica - high UV-transmission, low cost.
- Photodetector:
  - UV-sensitive SiPM (or LAPPD)
  - Low jitter is essential requirement.
- Front-end electronics:
  - High-precision TDC with ~ 3 psec registration.
- Precision Clock Distribution
  - Use Minnesota's Digitally Controlled Phase Shifter and DDMTD.

We foresee this as a longterm program to create a framework to establish the technologies for precision timing in future detectors.

As there is progress in individual elements these can be incorporated

Questions:

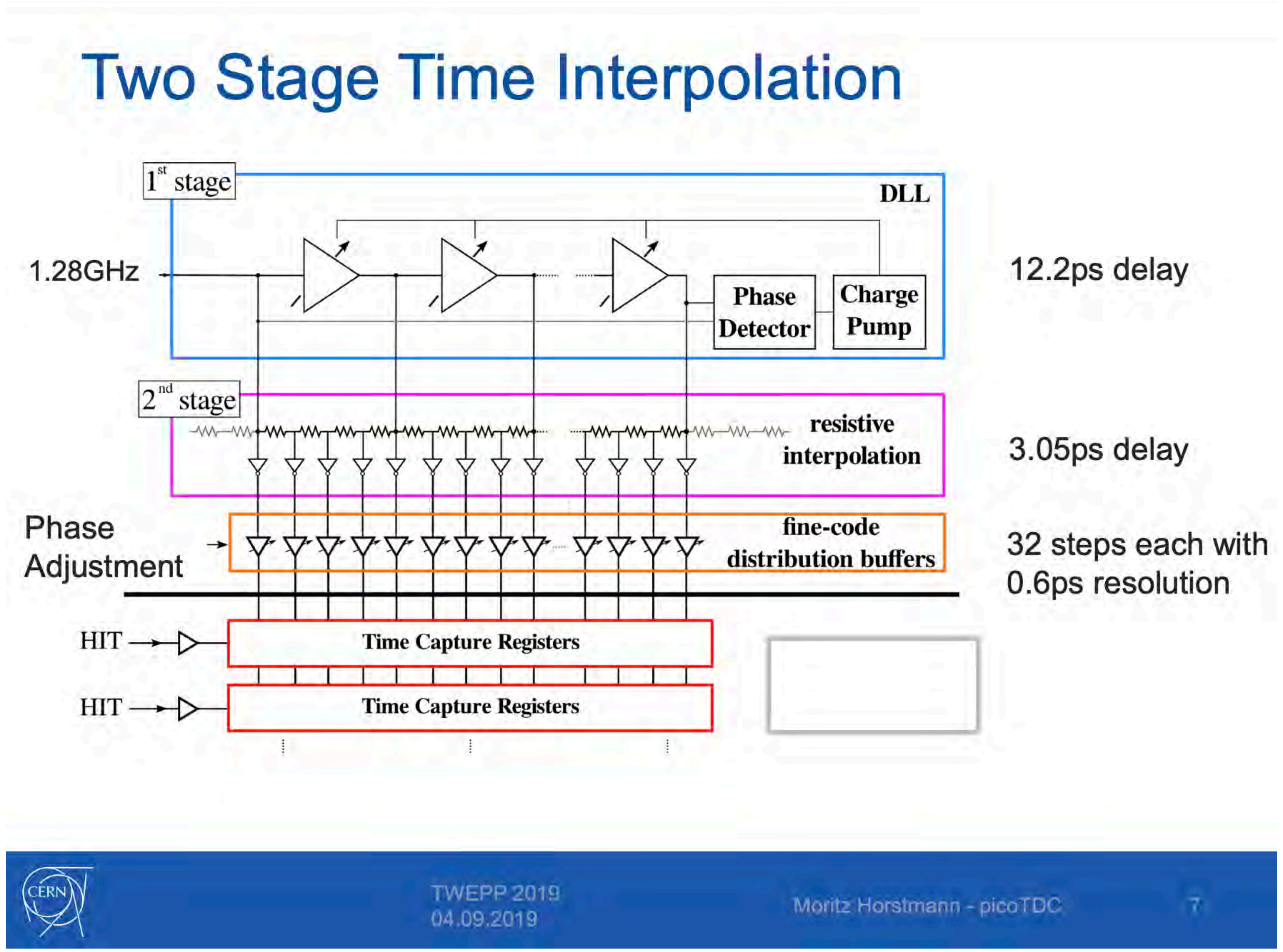
- Best material:
  - What is the best material large value of *n* or low value?
  - Optimum geometry to minimize the optical dispersion.
- Best photodetector
  - Optimize for low latency, signal size and low dark count rate.
  - Is it feasible to use SNSPDs
    - Cryogenics?
- Readout:
  - Design of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

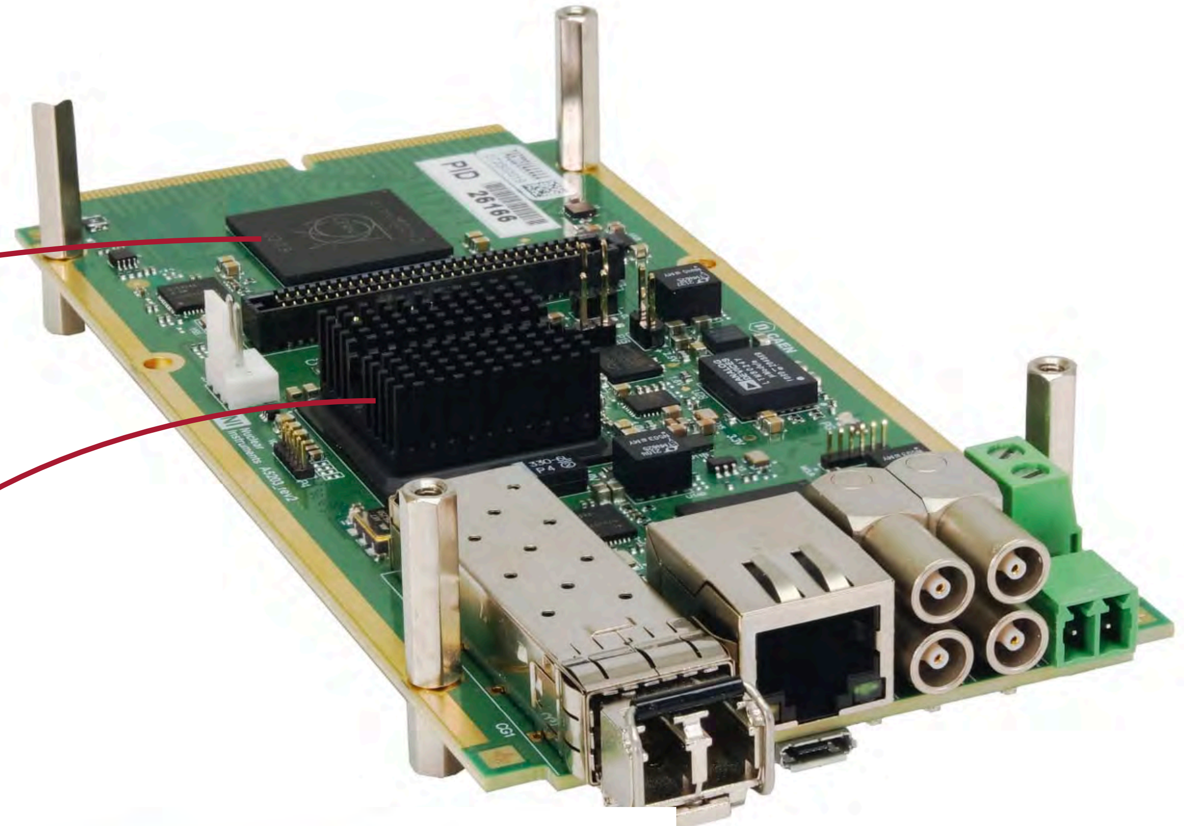
Potential to collaborate with multiple RDCs (and DRDs) - we would welcome new groups interested in any, or all of these questions.

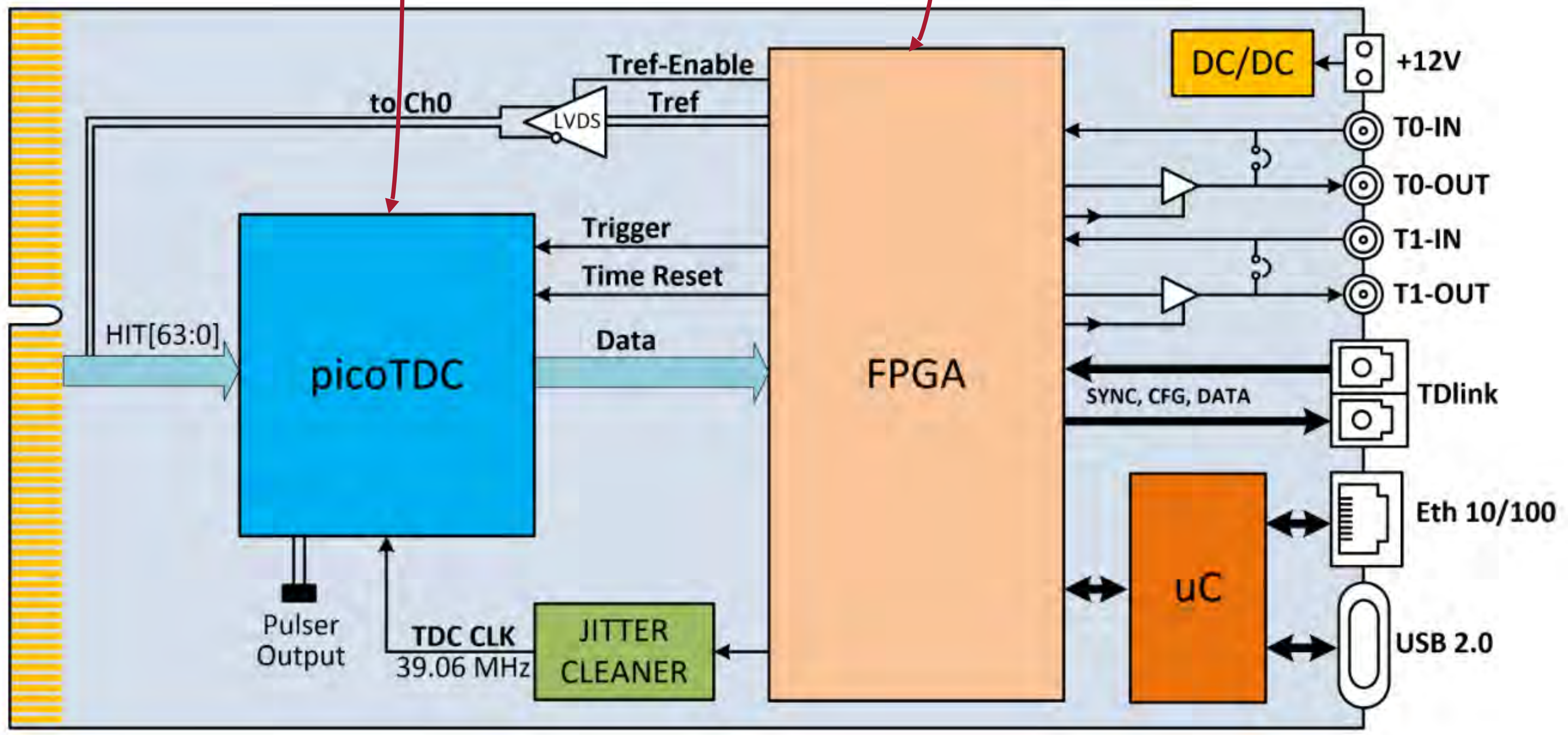
Digitization of Signal: TDC

Assuming we will use SiPMs

Vernier TCDs







Can we do better?

CAEN A5203

LSB = 3.125 ps, RMS typ. ~ 7 ps

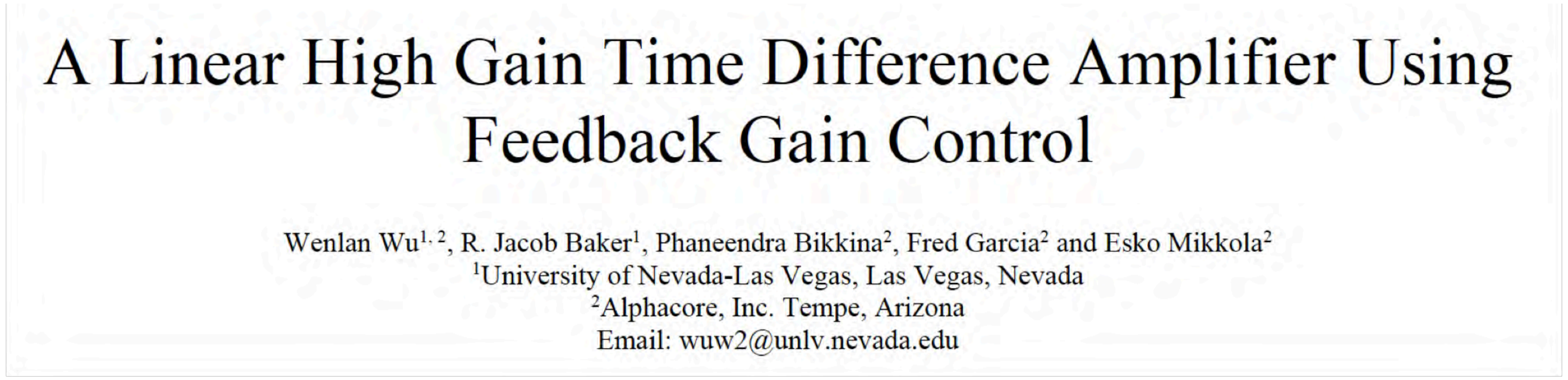
64/128-ch TDC unit

TDC dynamic range: up to 26 bit (~ 210 μs)

(can be extended)

Require calibration to account for process variation and temperature

Digitization of Signal: TDC


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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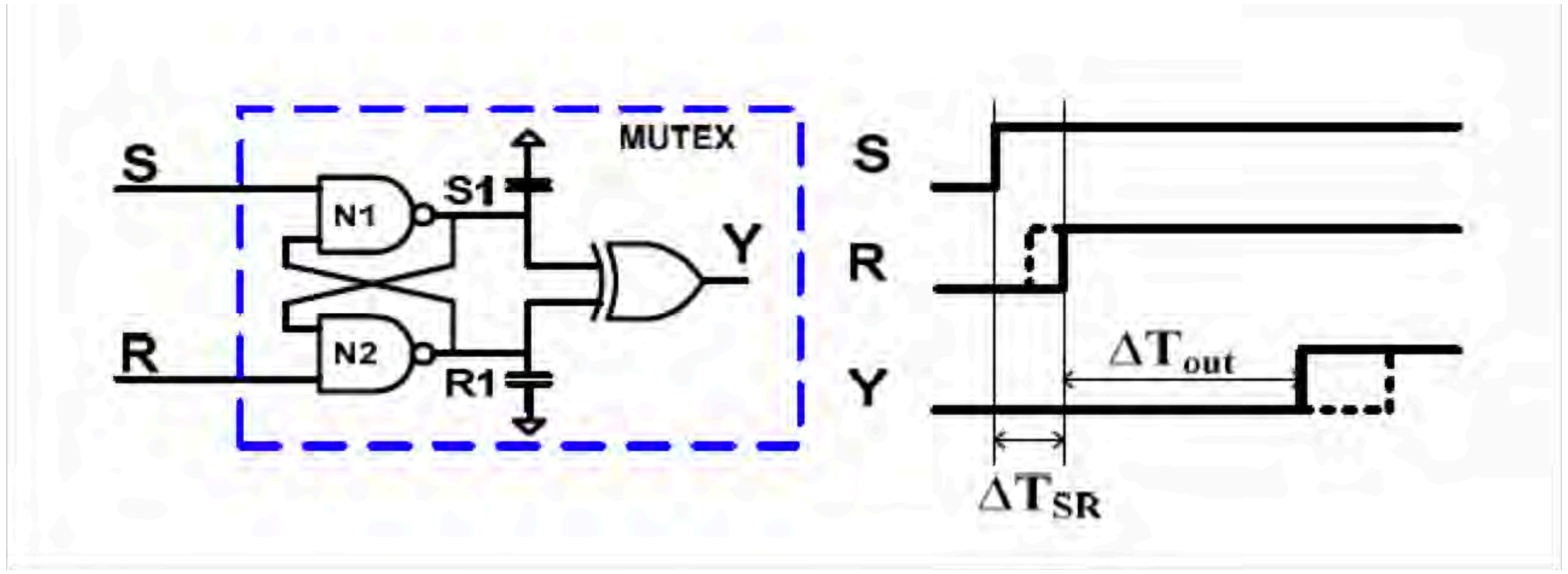
Paper link

Paper link



MUTEX circuit that exploits metastability of an SR latch to amplify the time difference

Extended circuit that includes feedback to the SR latch to achieve *linearity of time-difference gain*.

Other options: Optical circuitry?

Need to account for effects from **process, voltage & temperature**

Ref. Clk Distribution: Stabilize clocks to sub-

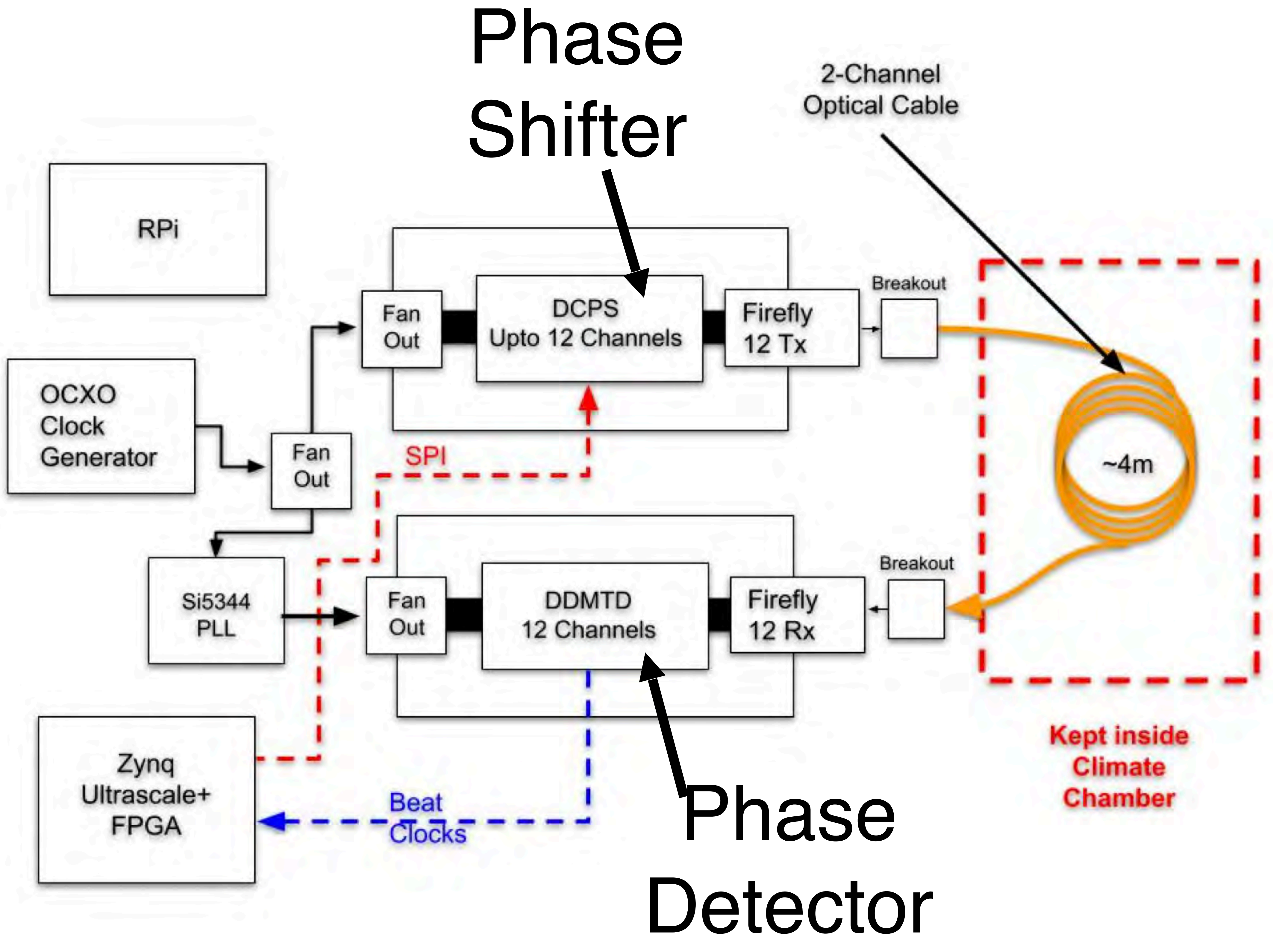
We have developed a system that corrects for **wander** with sub-picosecond stability

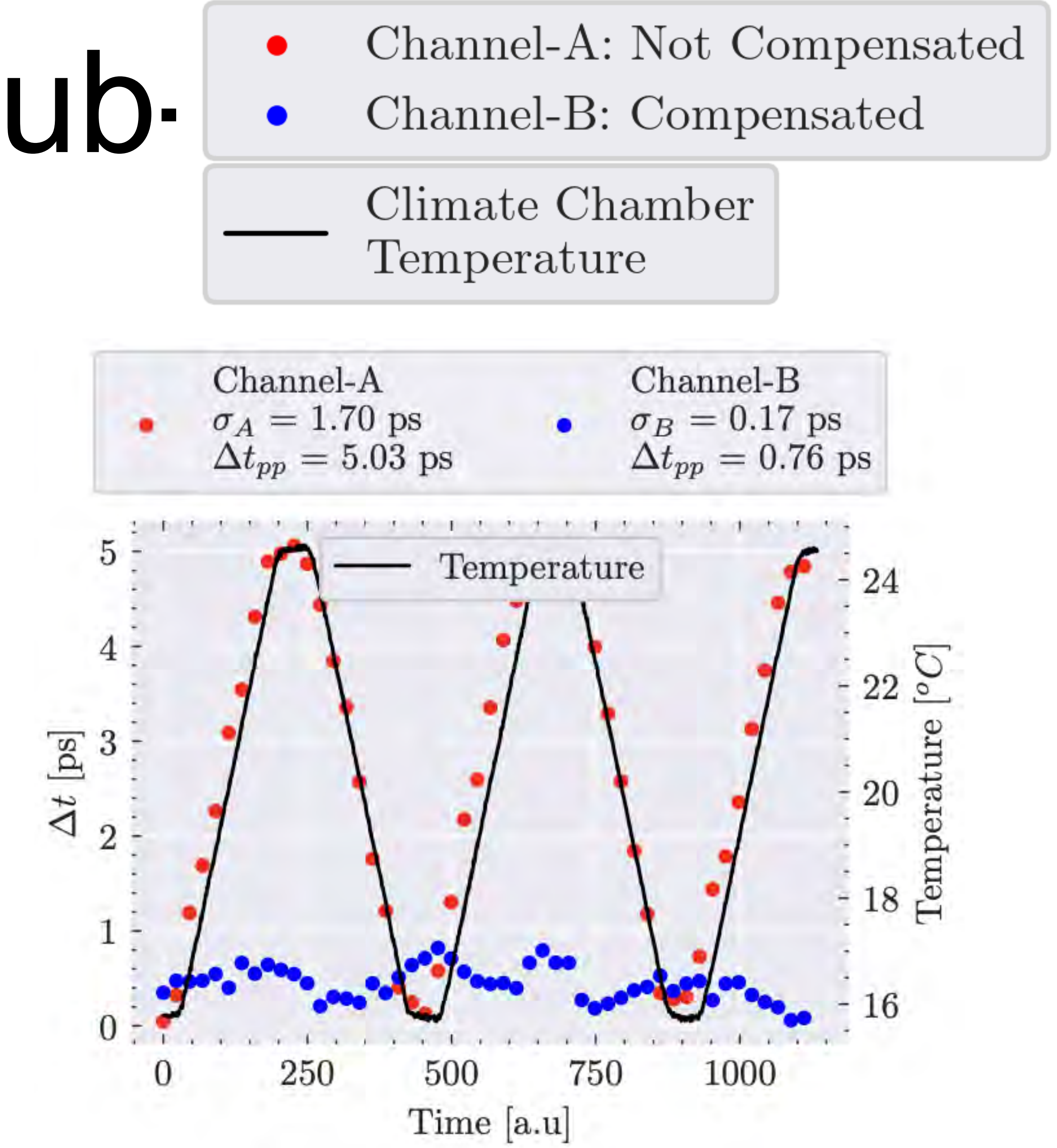
Uses:

➔ Phase Detector
- DDMTD with precision of **~100fs**
- Sensitive to wander **< 1.6kHz**

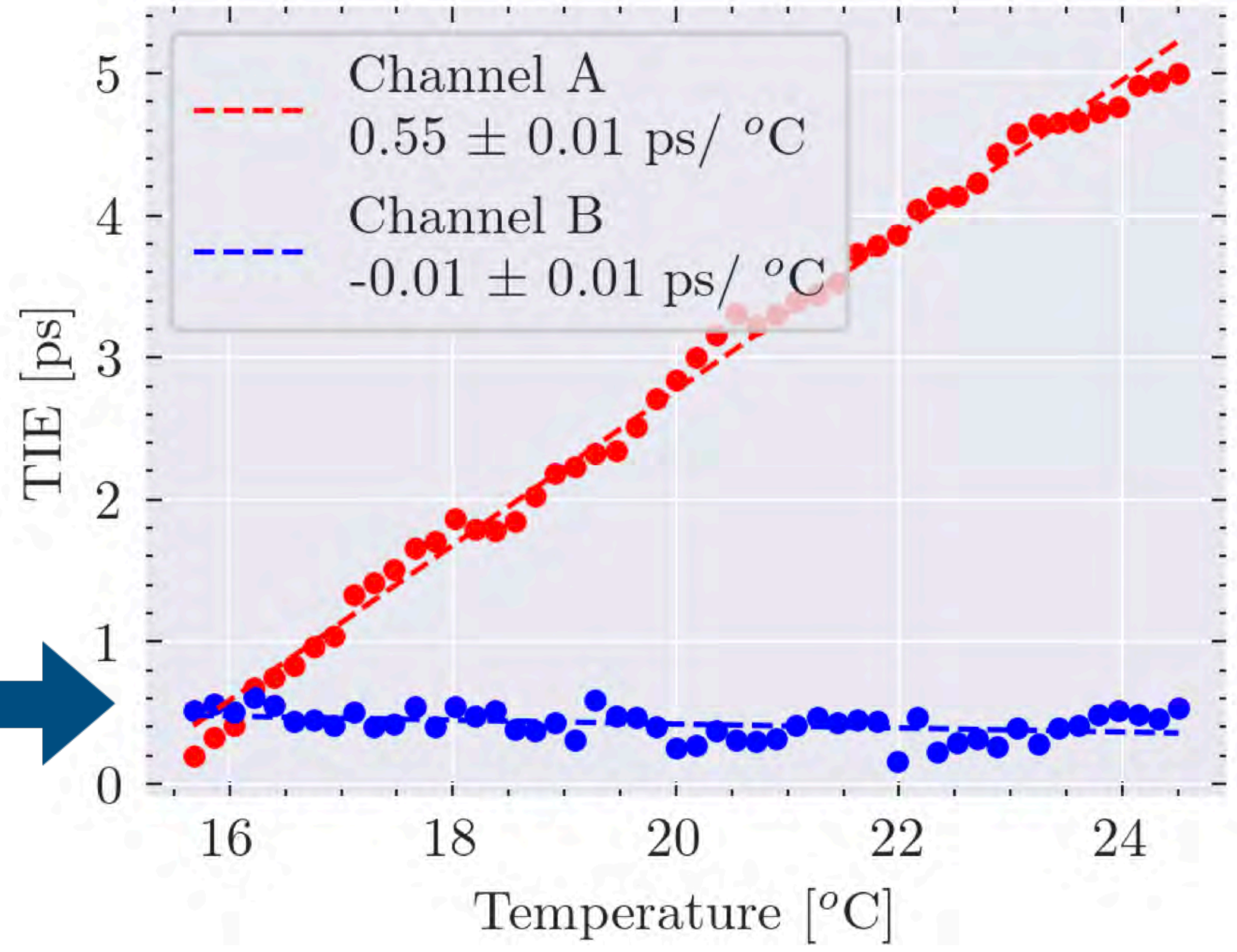
Paper:
DOI 10.1088/1748-0221/18/01/T01003

➔ Phase Shifter
- Custom ASIC with resolution of **~280fs**
- Dynamic Range of **~230ps**
- Bandwidth b/w **~500MHz - 5GHz** depending on the dynamic range
- **Radiation tolerant (20MRads for gamma)**





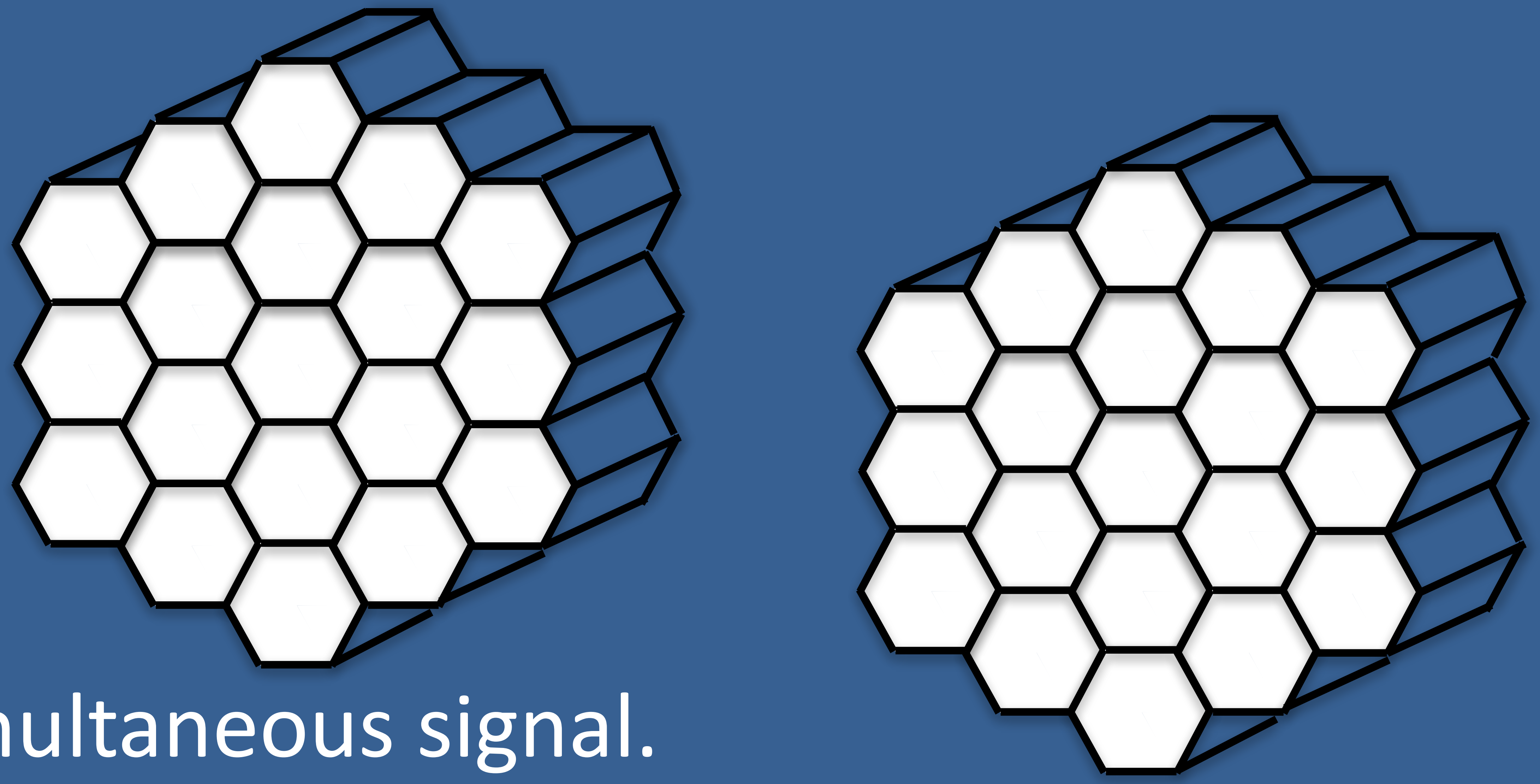
Compensated channel stabilizes clock to sub-picosecond precision



Paper:
DOI 10.1088/1748-0221/19/04/C04060

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.

Who is Doing What - 1?

Boston University – Electronic systems, simulation, prototype assembly and testing.

BNL – BNL leading the development of many of the new detector technologies needed for the future experiments at the EIC. BNL's contribution to this R&D project will be in the areas of radiator design, UV-enhanced photodetector development, and streaming readout electronics. BNL has significant capabilities to develop and test these systems, including an ultra fast femtosecond laser that can deliver extremely narrow light pulses (< 1 ps),

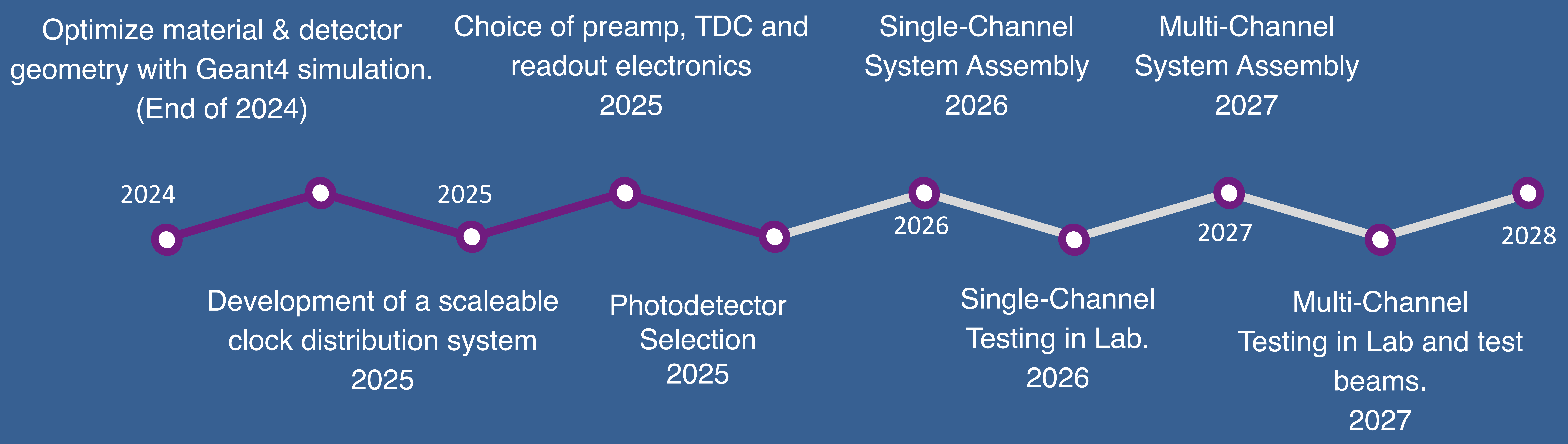
Who is Doing What - 2?

MIT - MIT Bates Research and Engineering Center has the interest and capabilities to contribute to designing and manufacturing the mechanical support structure for the test detector and future applications.

Minnesota - System design and clock distribution. Electronics, system design and testing.

TIFR India - Irradiation studies as needed for the project with reactor neutrons and gamma sources. The evaluation of photodetector timing performance after irradiation. They will also contribute to the GEANT4 simulations as needed by the project, and provide technical and engineering support.

Project Plan:



Overlaps With RDCs.

This proposal is couched in the precision timing RDC - 11

We have significant overlap and shared interest with:

- RDC - 2 Photodetectors
- RDC - 4 Electronics and ASICs

And overlap of interest with:

- RDC - 5 Trigger DAQ
- RDC - 9 Calorimetery

And possibly with:

- RDC - 8 Quantum/Superconductors

The intent is to create a collaborative framework to develop ultra-high precision timing detector capabilities.

Backup:

Timing Resolution:

To get the best resolution everything matters:

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

Clock

Digitization

Electronics

Photostatistics

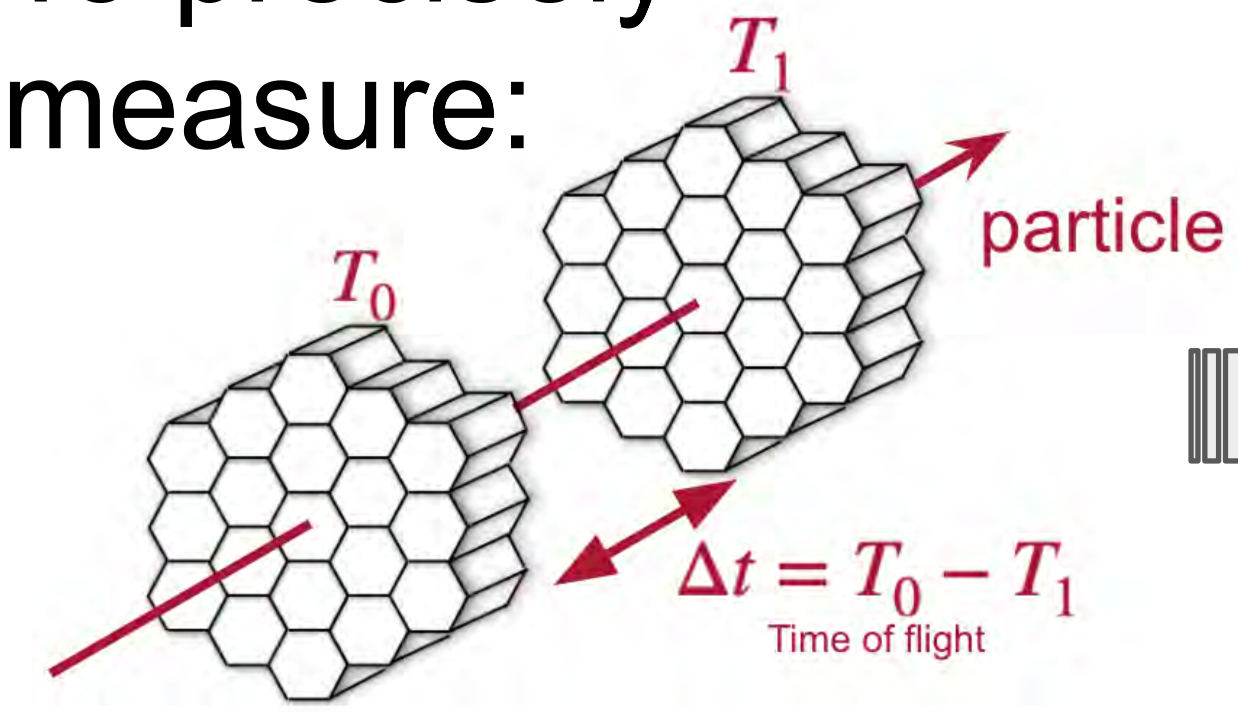
Dark Current

Low jitter stable clock ~0.5 ps

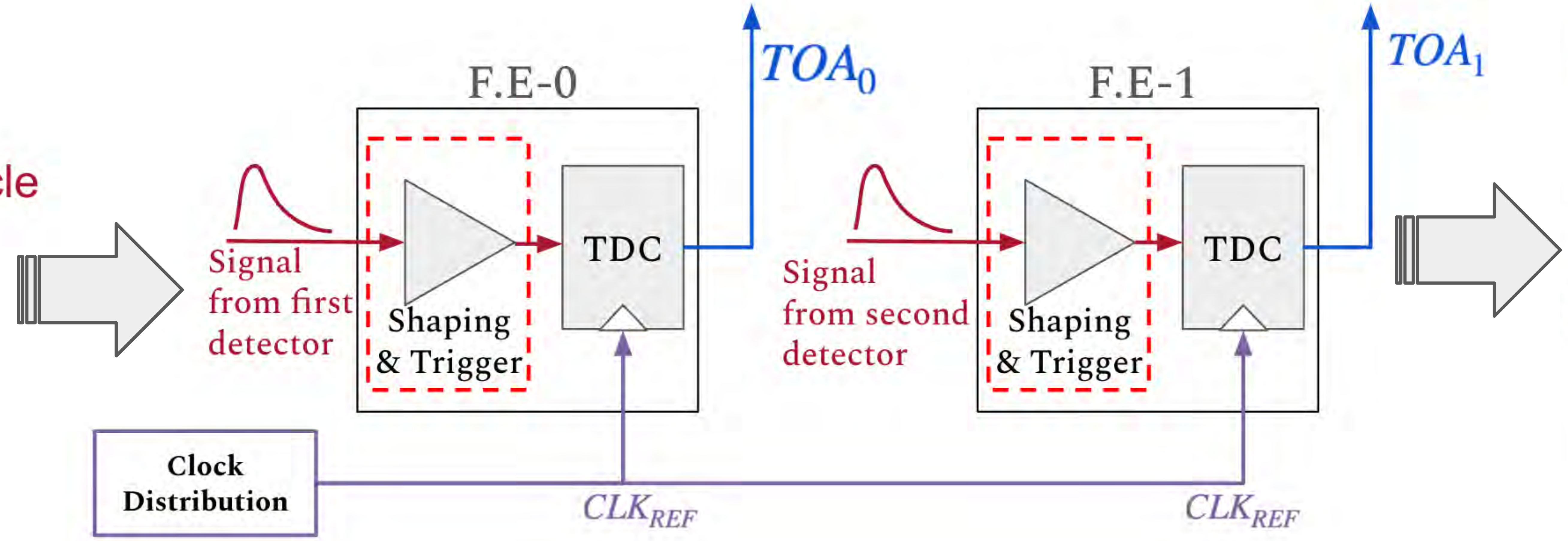
Off-the-shelf > 3 ps
Can we do better?

Cooled SiPMs or even SNSPDs.

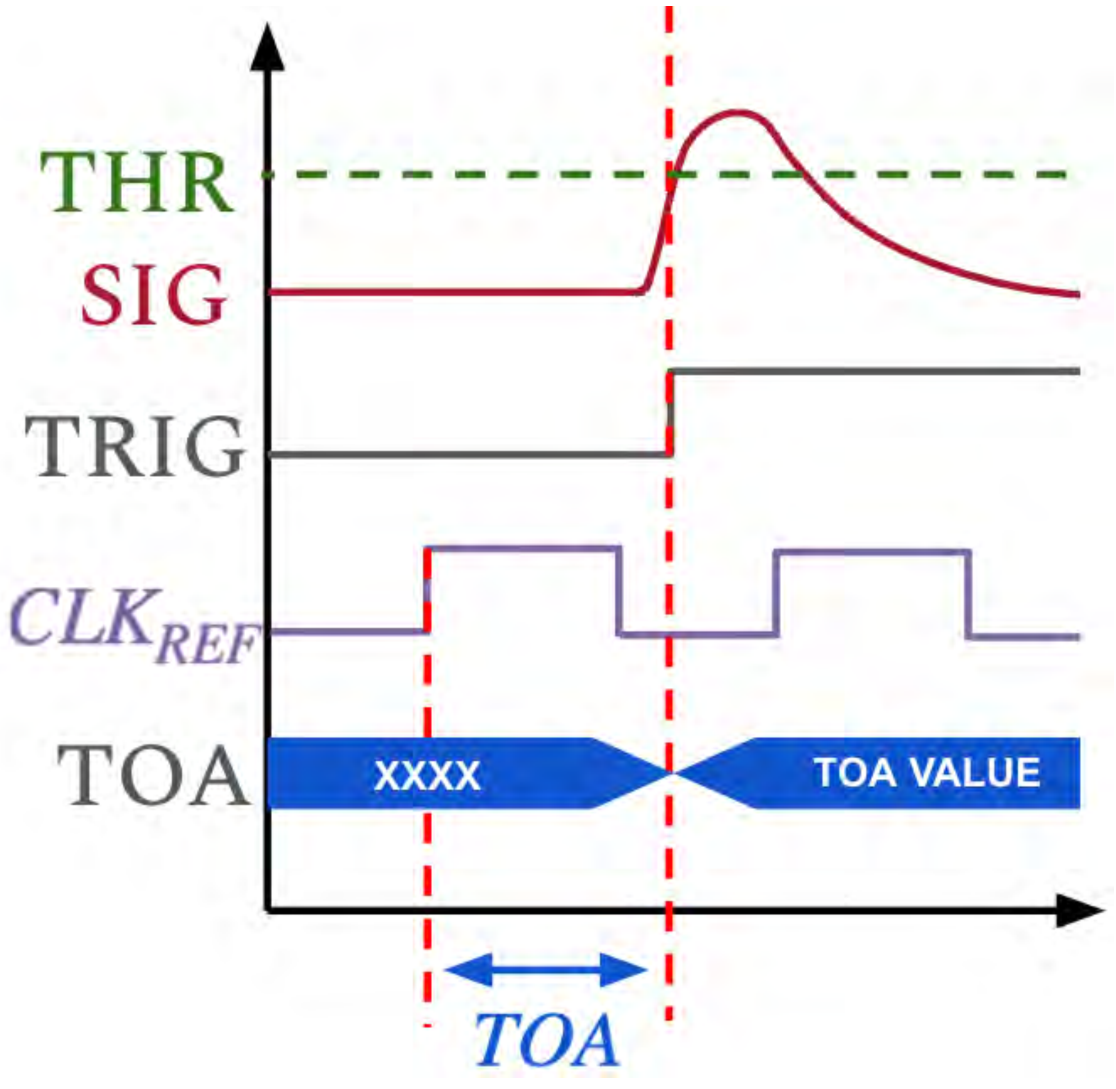
To precisely measure:



Digitisation & Electronics



Measured against a reference clock



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

Signal Source

Ref.Clock

Digitization of Signal

Electronic Noise

Photostatistics & Dark Current

Time Resolution

Cherenkov Signal

Number of photons per unit length is given by:

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

Or:

$$\frac{dN}{dx} = 2\pi\alpha \sin^2\theta \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)$$

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

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.

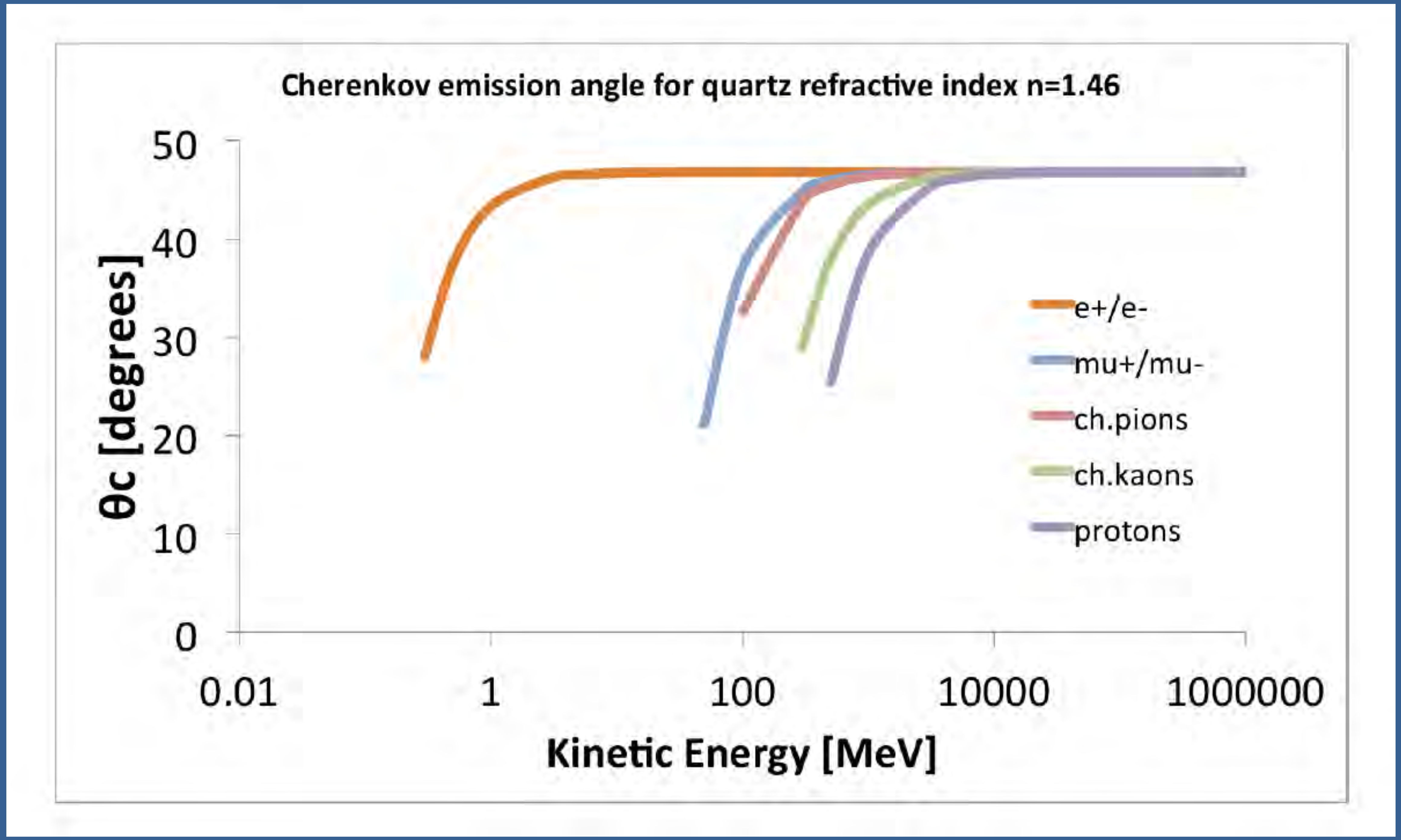
Cherenkov Radiation

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.

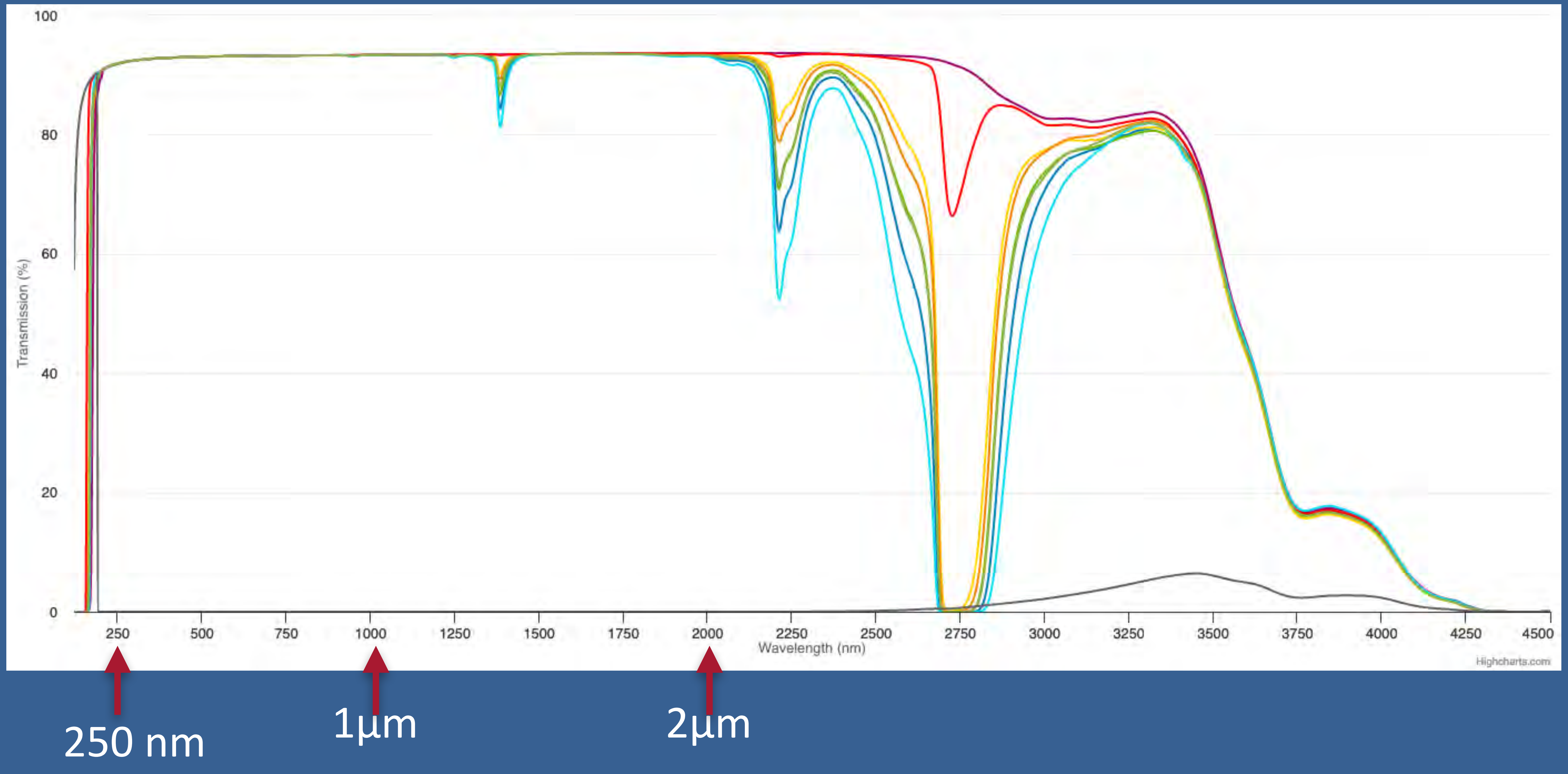
Cherenkov threshold is 0.68c

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



Radiator

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



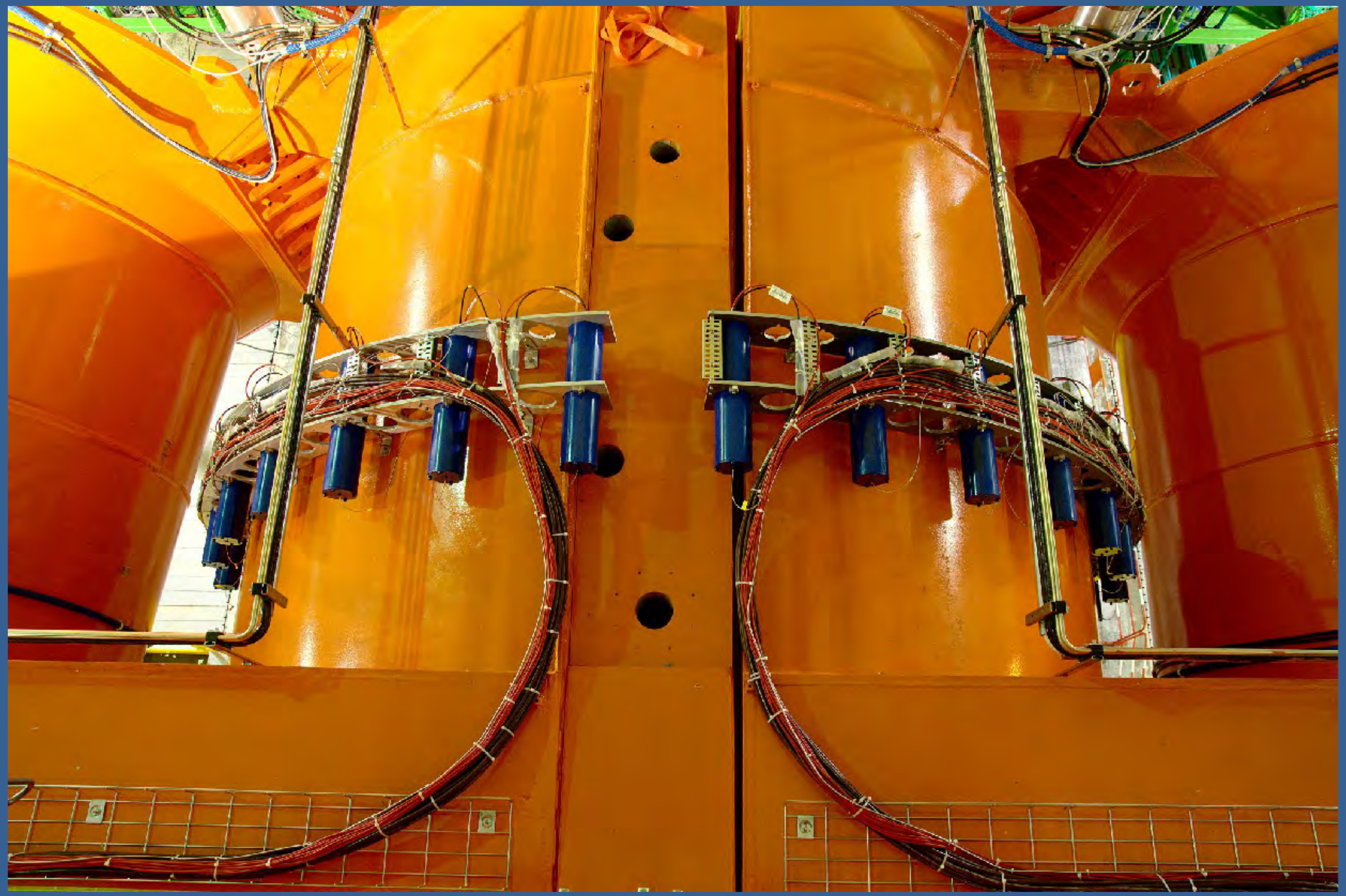
Dispersion in the arrival time of the photons: $\Delta t_{max} = \frac{d}{c\beta}(\beta^2 n^2 - 1)$

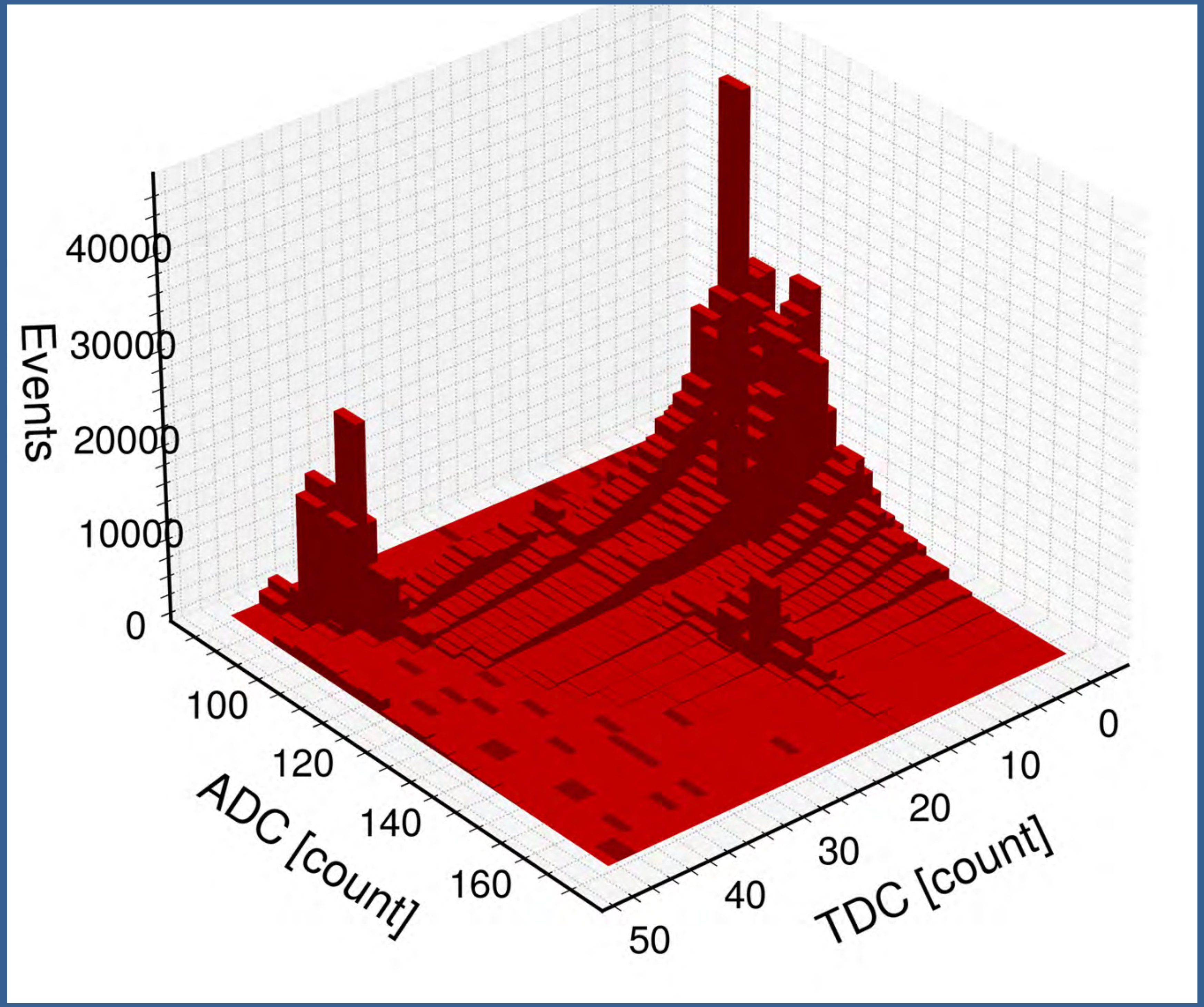
For β = 1, d = 5 mm, n = 1.46,

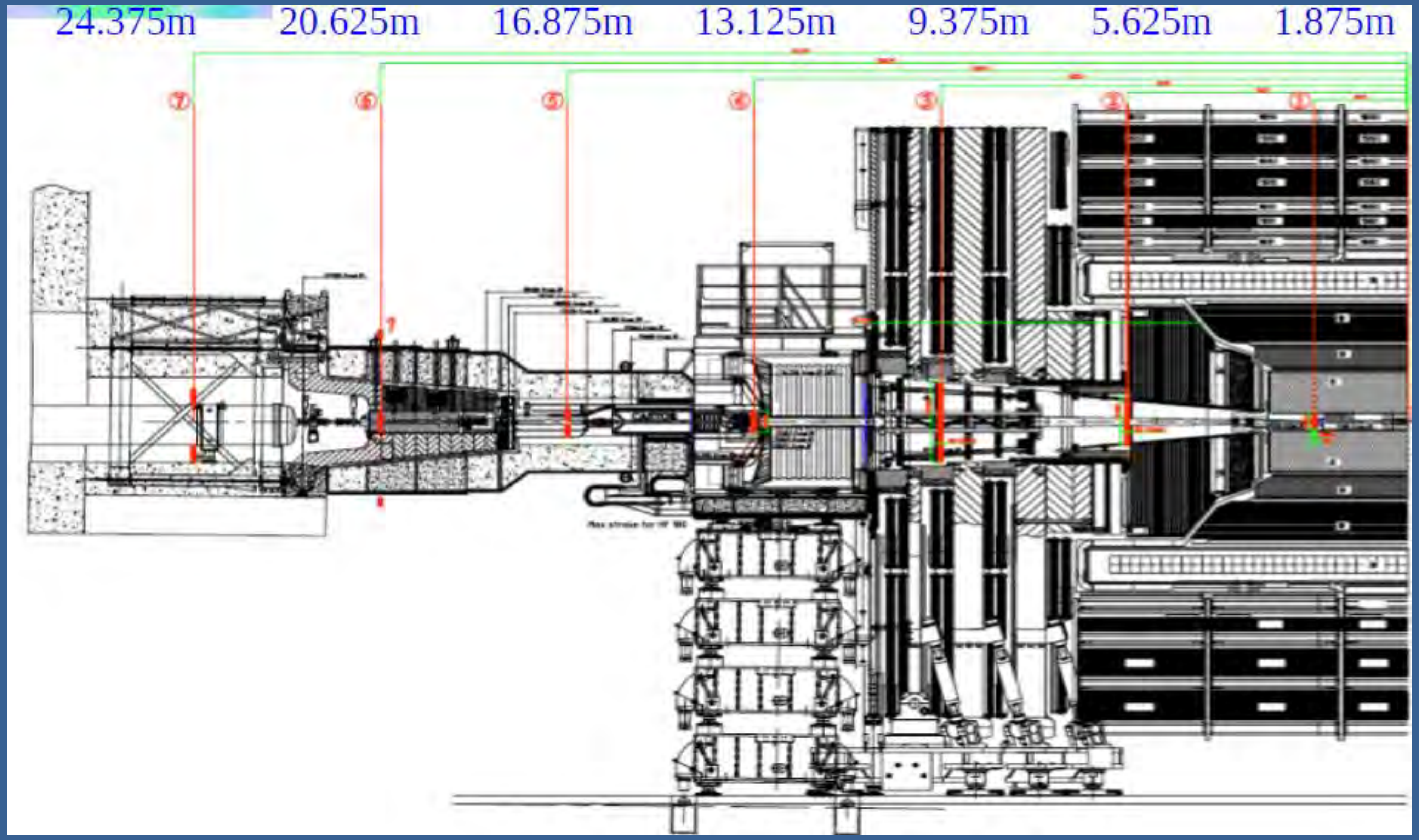
~400 photons arrive at end of rod in interval of 19 ps

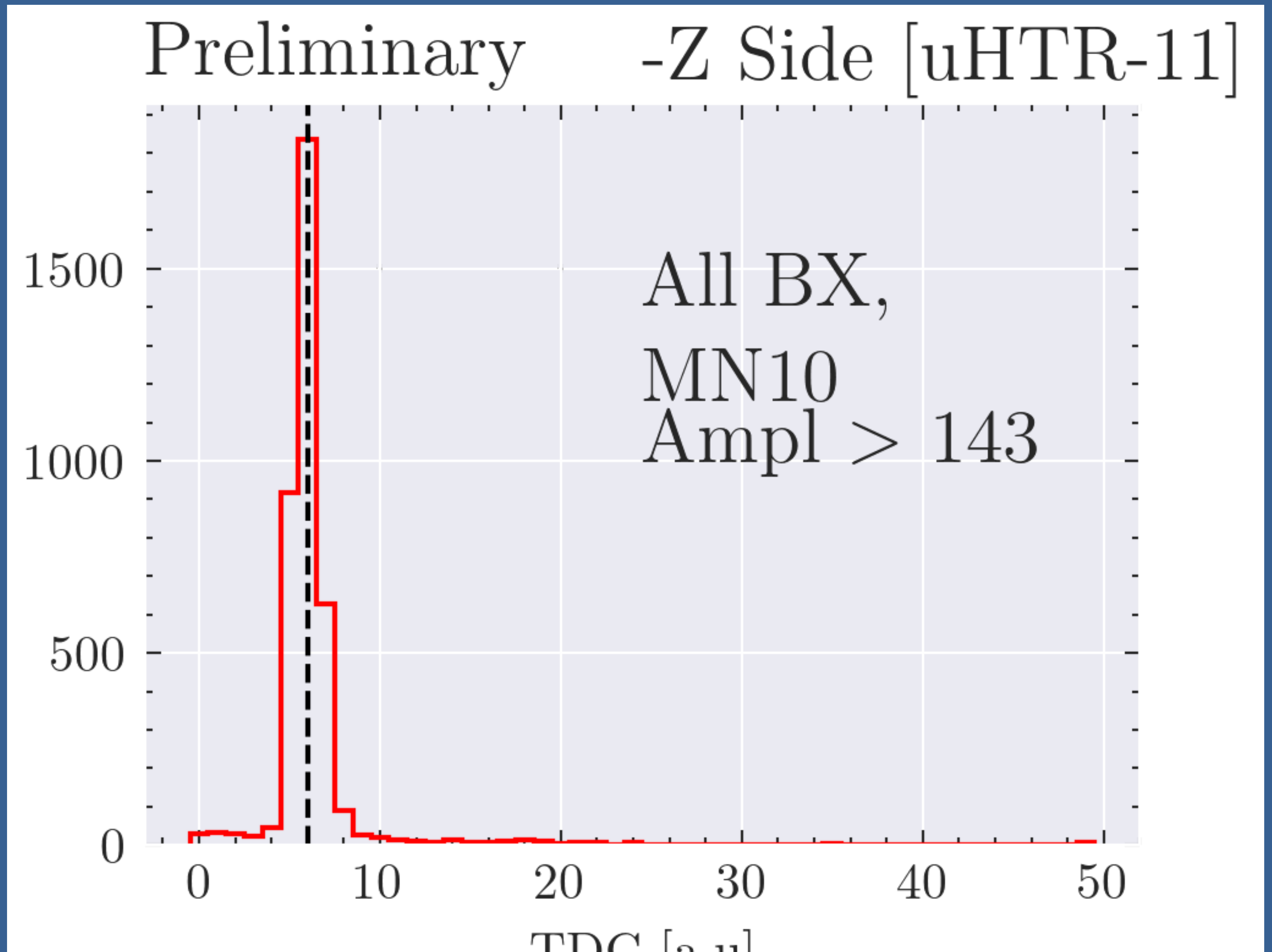
There is a trade off between the index and the thickness and number of photons and the signal dispersion

Beam Halo Monitor in CMS









Photodetector Options:

- 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

Irradiation facilities available

The irradiation facilities that are available include those present in the TIFR, Mumbai campus as well as those from sister institutes of our parent organization.

EM irradiation :

– Co-60 source with a "strength" of ~ 4-5 kGray/hour

– 5-10 MeV electron beam can deliver a comparable doses as the Co-60 source

Neutron irradiation :

A neutron irradiation facility from the Apsara-U reactor at BARC. This is a swimming pool type reactor with a total power of 2 MW.

→ Dose depends on distance from the core.

Irradiation with 1 MeV neutron equivalents to ~10^{16} n/cm^2 per day is possible.

TIFR pelletron facility :

20 MeV proton beam with a flux of 10^10 particles /s/cm2