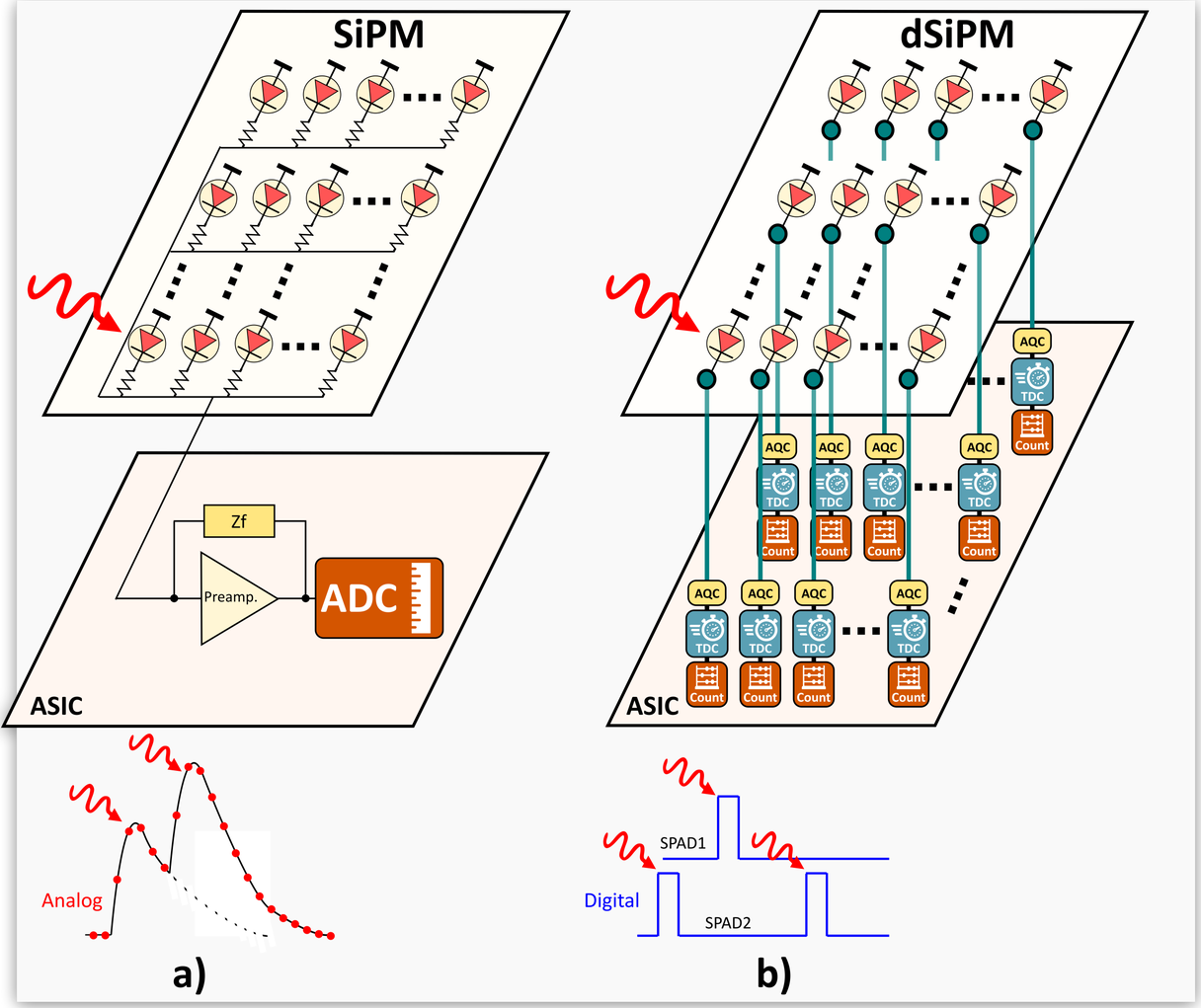
FLASH: Photon-Level Time-Resolved Calorimetry with Digital SiPMs

N. Akchurin, R. Bartoldus, Y. Feng, **C. Madrid**, B. Markovic, L. Rota,
A. Schwartzman, S. Seidel, D. Su, L. Wu

CPAD 2026, Seattle Washington
October 20, 2026

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Single Photon-level readout with FLASH



- Industry continues to push the development of 3D optical devices
  - Leverage current development
- FLASH architecture aims to deliver dense channel multiplicity with precision timing per photon
- Wide range of applications
  - Focusing on optical fiber calorimetry for this talk
- On-going SLAC LDRD with expected first devices produced in 2027
  - Initial studies shown at CPAD 2025 (L. Wu)
  - CALOR2026 (A. Schwartzman)

Motivation

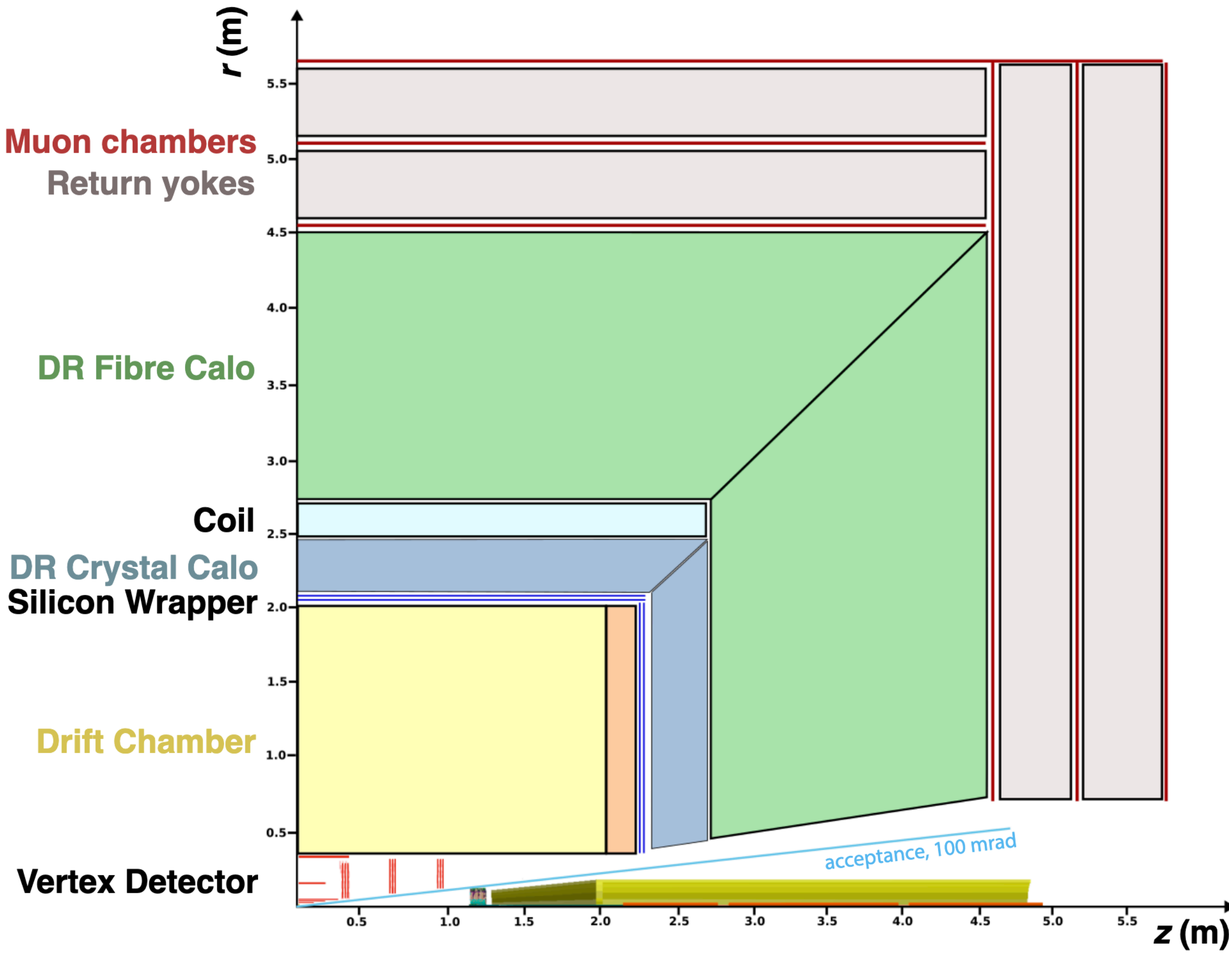
- Physics goals for future e^+e^- colliders include needed jet resolution to separate W, Z, and Higgs hadronic decays
  - Requiring ~30%/$\sqrt{E}$ for jets

- Dual Readout (DR) fiber based calorimetry shown to be a viable option
  - DREAM, RD52, CalVision

- **Can we achieve better results with advanced readout electronics?**

- **Pushing the development of next**

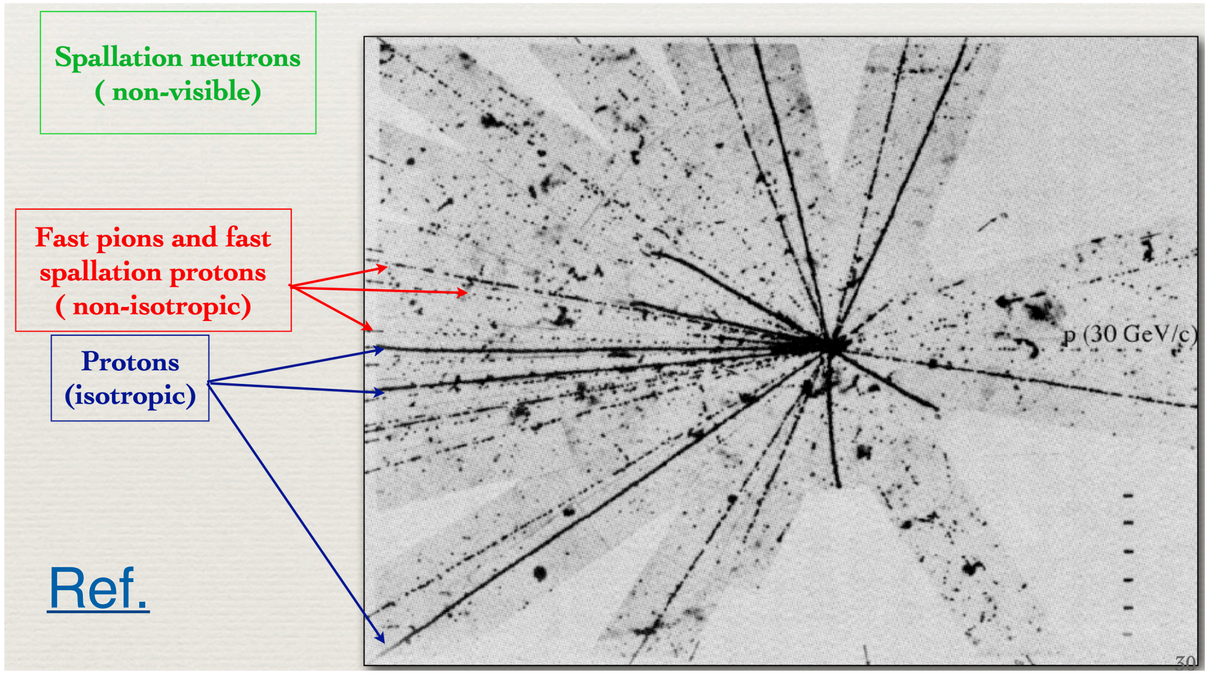
IDEA Detector Concept

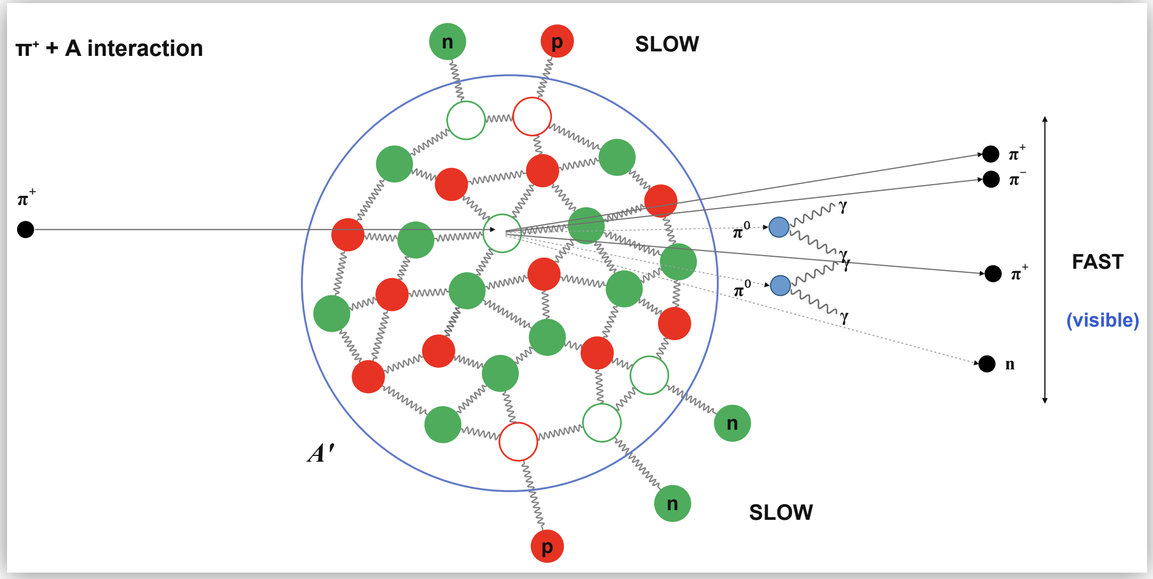


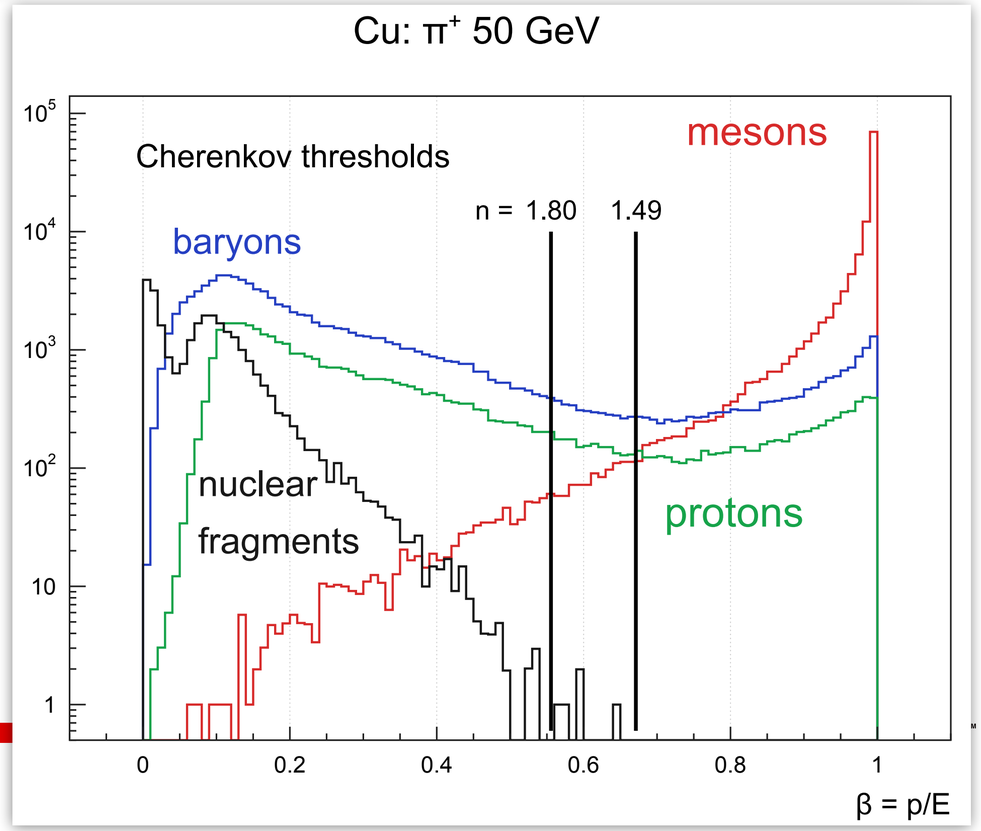
arXiv:2502.21223

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Hadron Showers

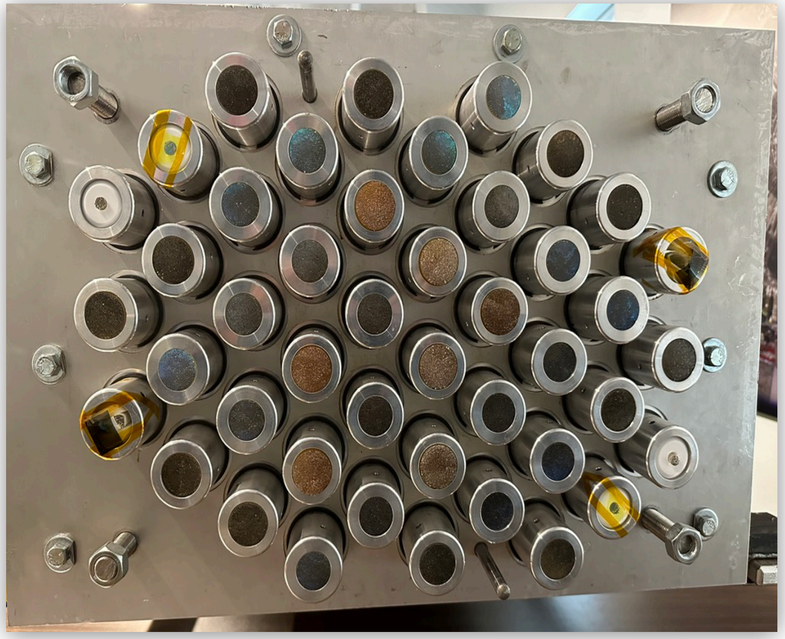


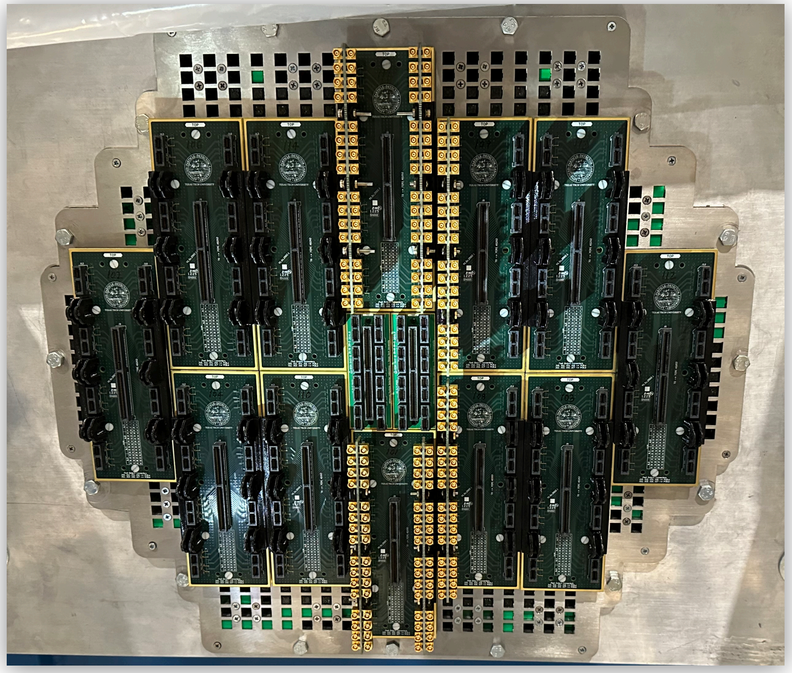


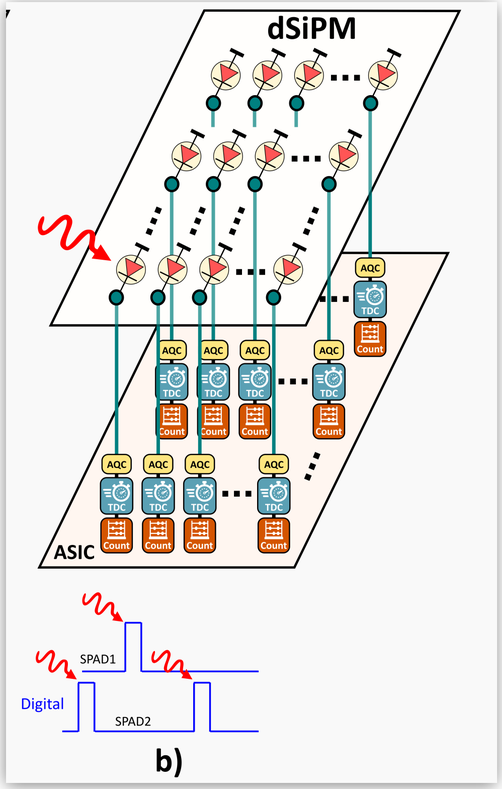


- Hadronic showers produce a large variety of particles
  - Estimating energy loss to invisible processes is critical
- DR approach developed to understand the fluctuations in electromagnetic energy fraction per event
  - DREAM collaboration effort started ~20 years ago
  - Can we do better today? (See **Y. Feng's HG-DREAM talk**)

The next stage of Dual Readout Calorimetry?







Original DREAM

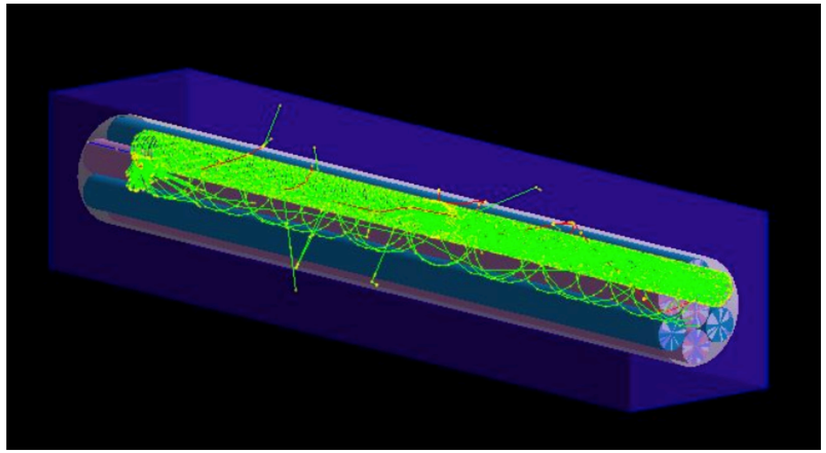
HG-DREAM

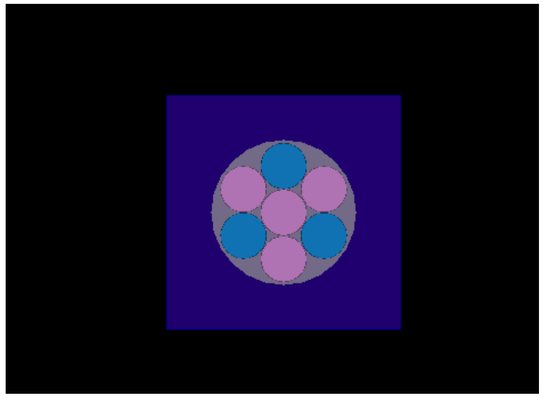
DREAM with FLASH

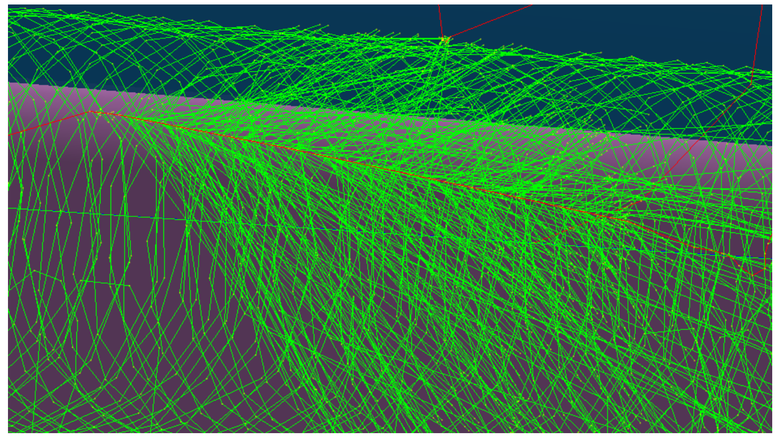
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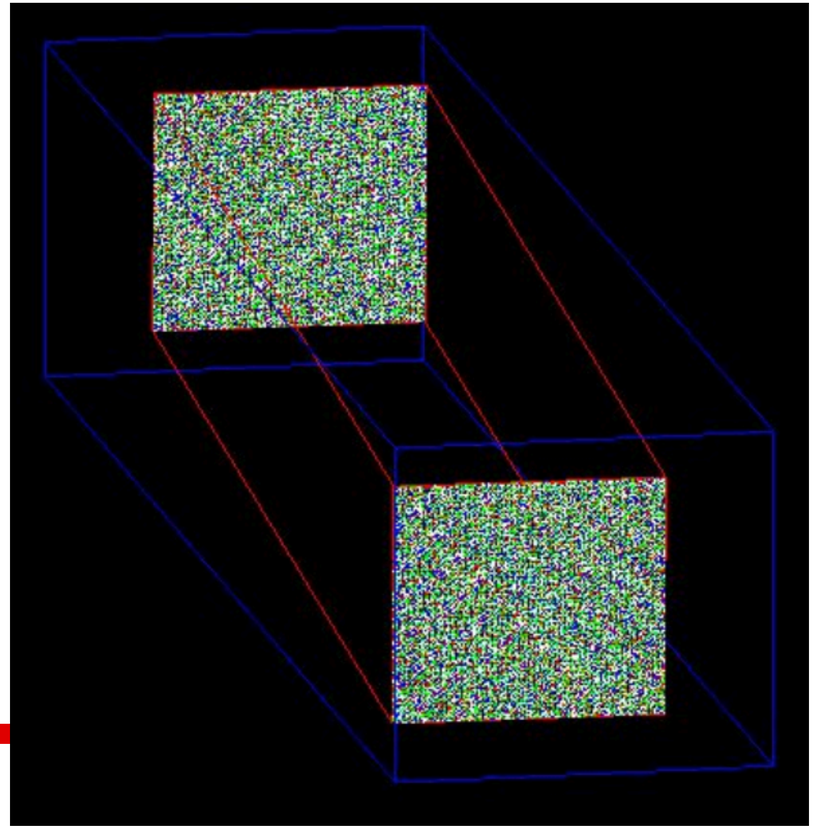
Optical Fiber Simulation

- Current FLASH simulation studies based on Geant4





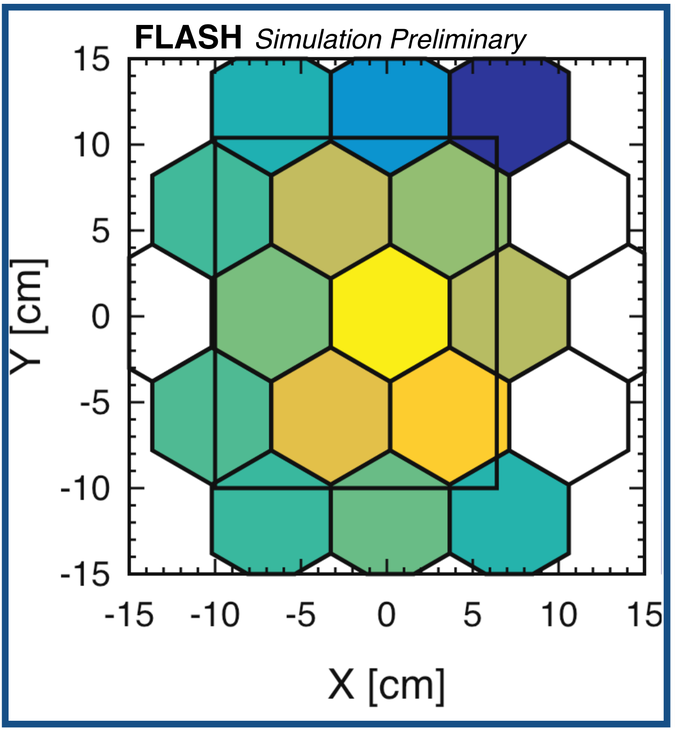


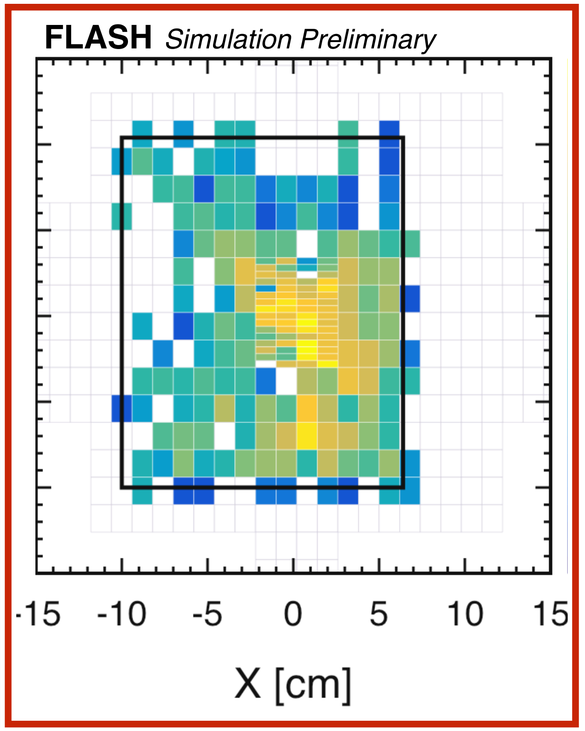


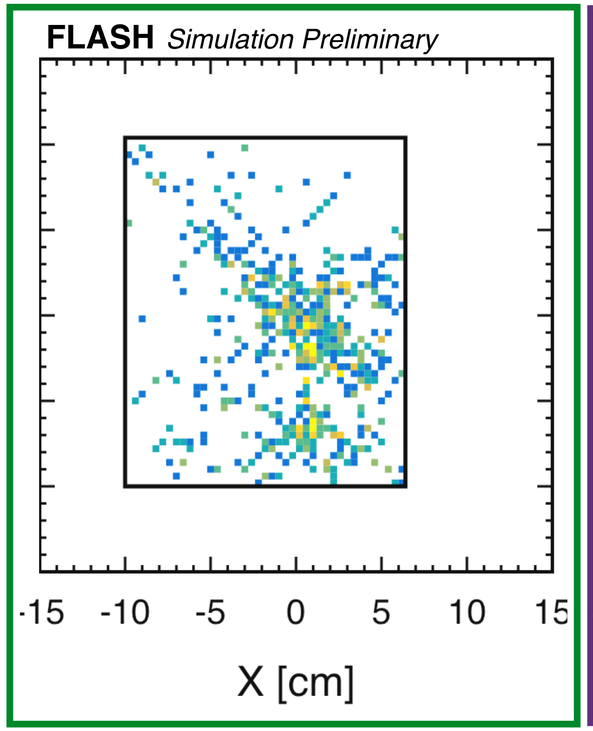
- Working on studying the hadronic shower developments and optical photon propagations in the fibers
  - **Focusing on the timing properties**

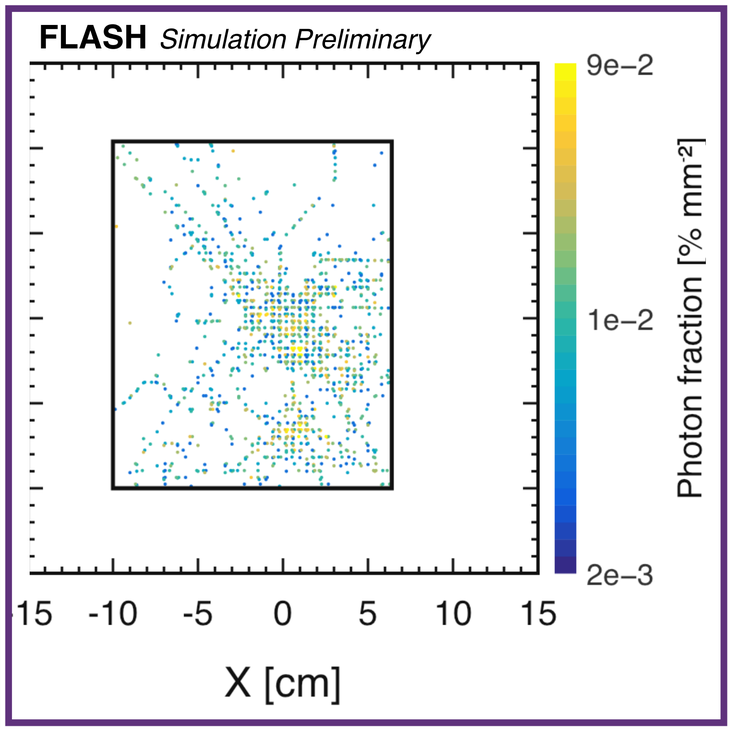
- Exploring different fiber parameters (size, multi-cladding, helical, etc in order to improve photon capturing efficiency
- **Currently working on full detector simulation**

Comparing different DREAM readout





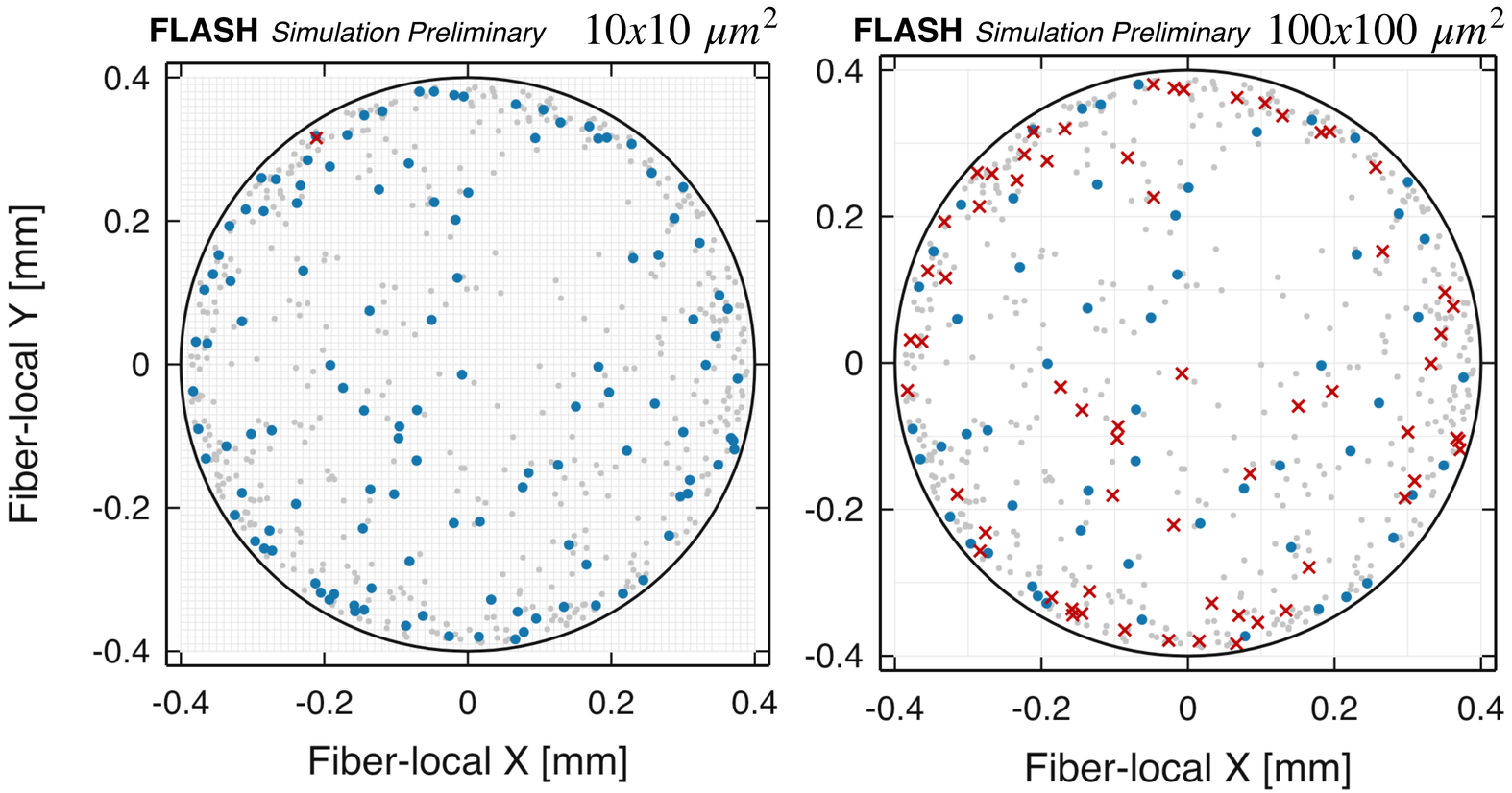




Original DREAM **HG-DREAM** **DREAM with FLASH** **Simulated Truth**

- Comparing the same individual 100 GeV Pion simulated event across different readout
  - **Original DREAM (19x ch.)**, **HG-DREAM (896x ch.)**, and **DREAM with FLASH (~10k)**
- **The FLASH sensor readout approaches Truth level information**

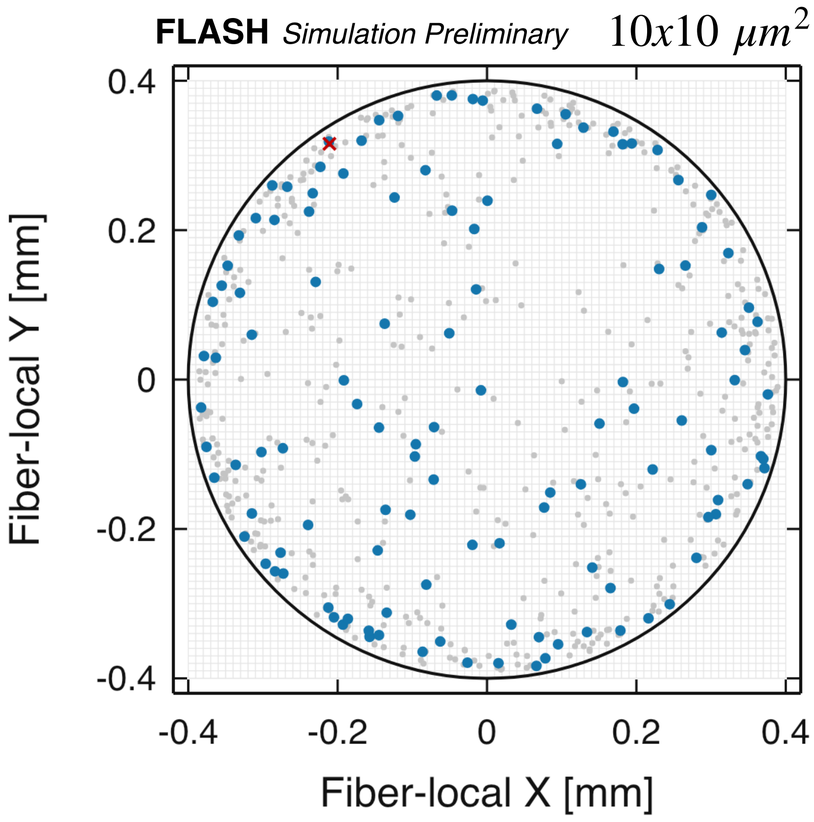
Improving photon detection with SPAD size

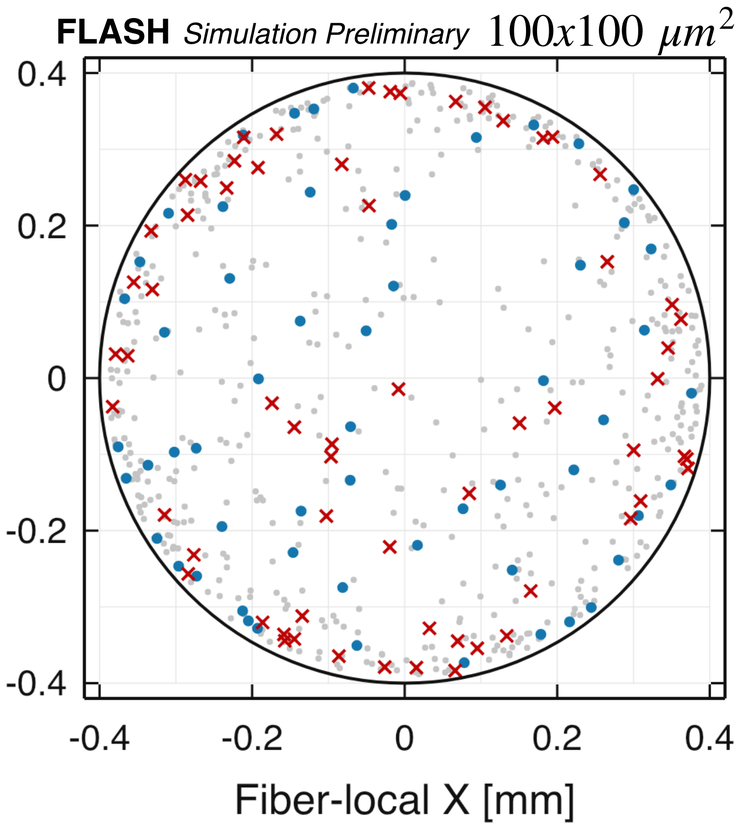


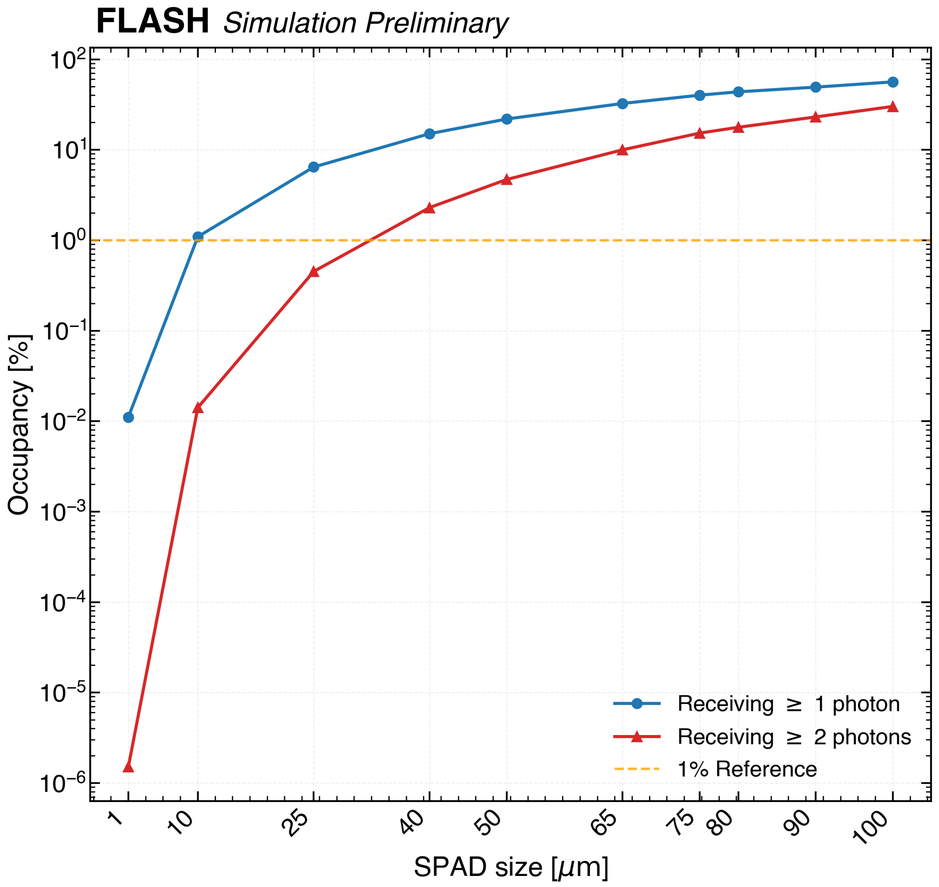
- The number of Cherenkov photons we receive per fiber is already low
  - Can't afford to miss one due to SPAD/channel size

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Improving photon detection with SPAD size





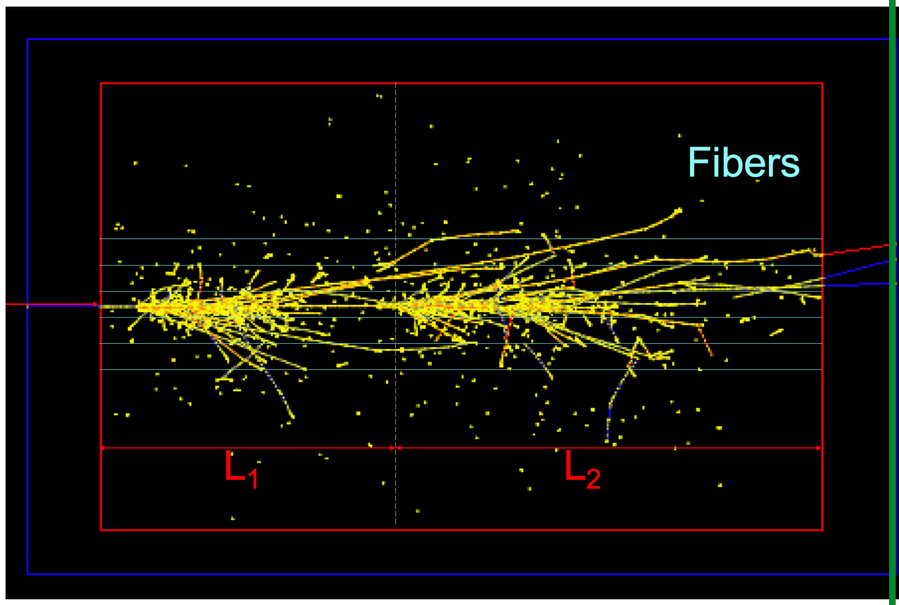


- The number of Cherenkov photons we receive per fiber is already low
  - Can't afford to miss one due to SPAD/channel size
- Occupancy approaches single photon per channel with $10x10\ \mu m^2$ or less SPAD size

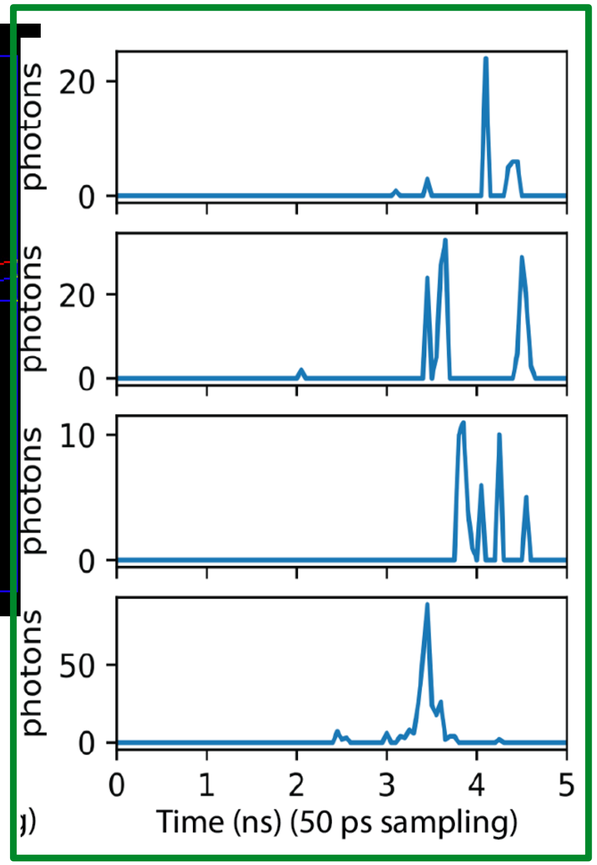
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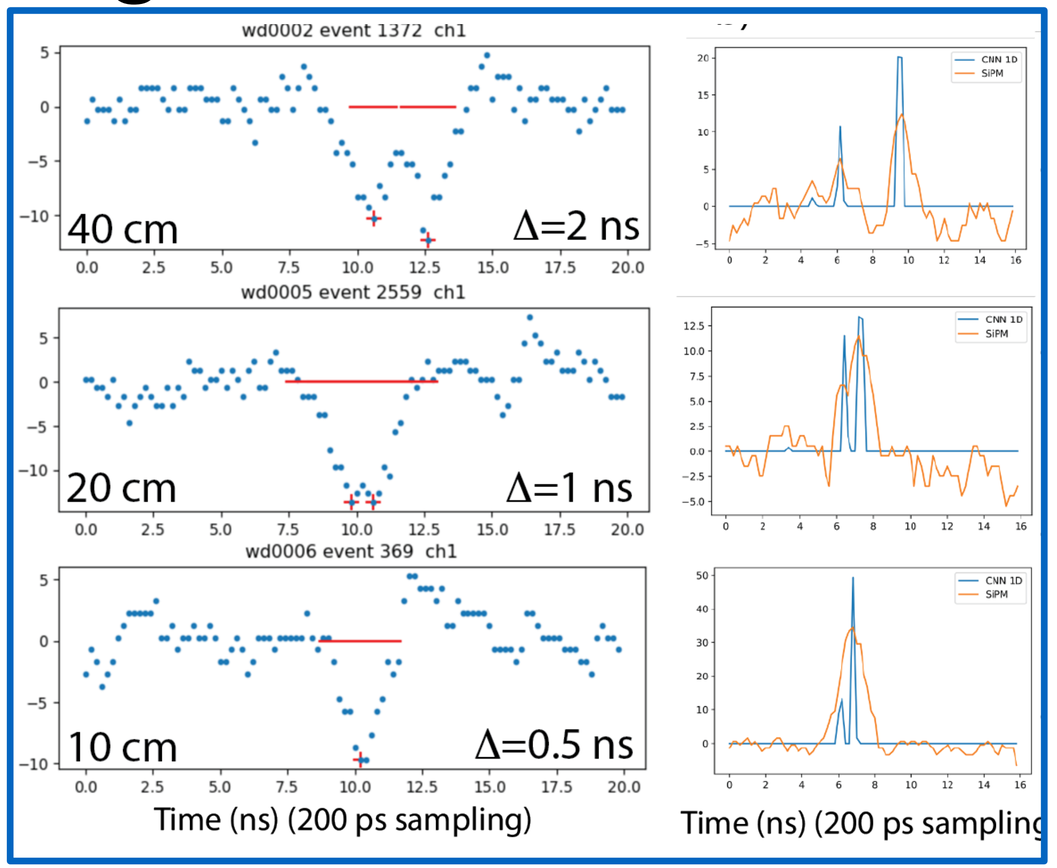
Longitudinal Segmentation with Timing

arXiv:2408.15430



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

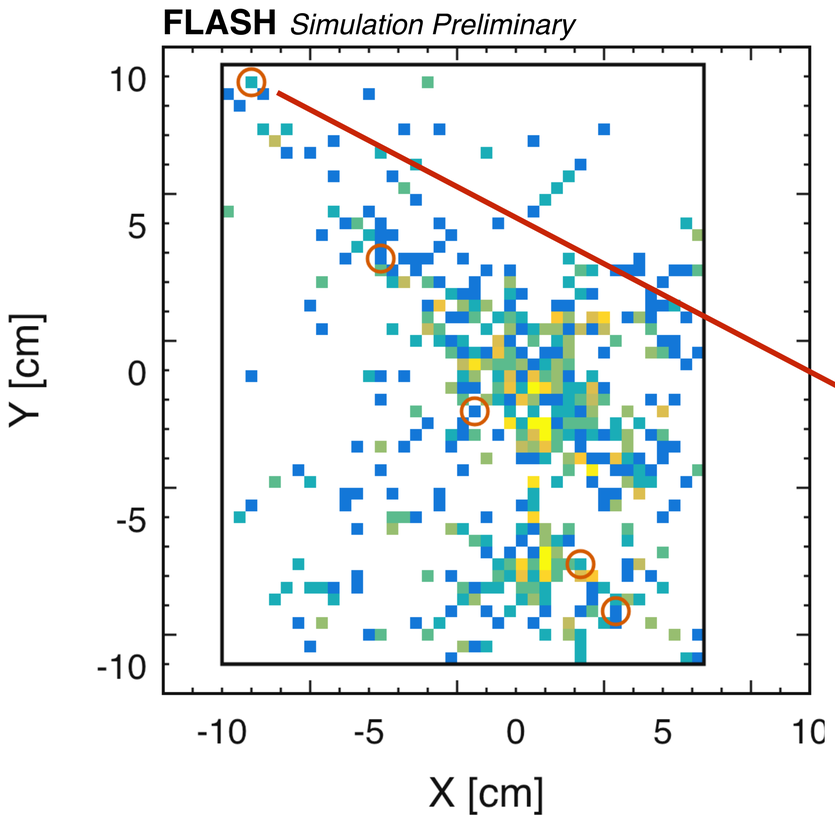


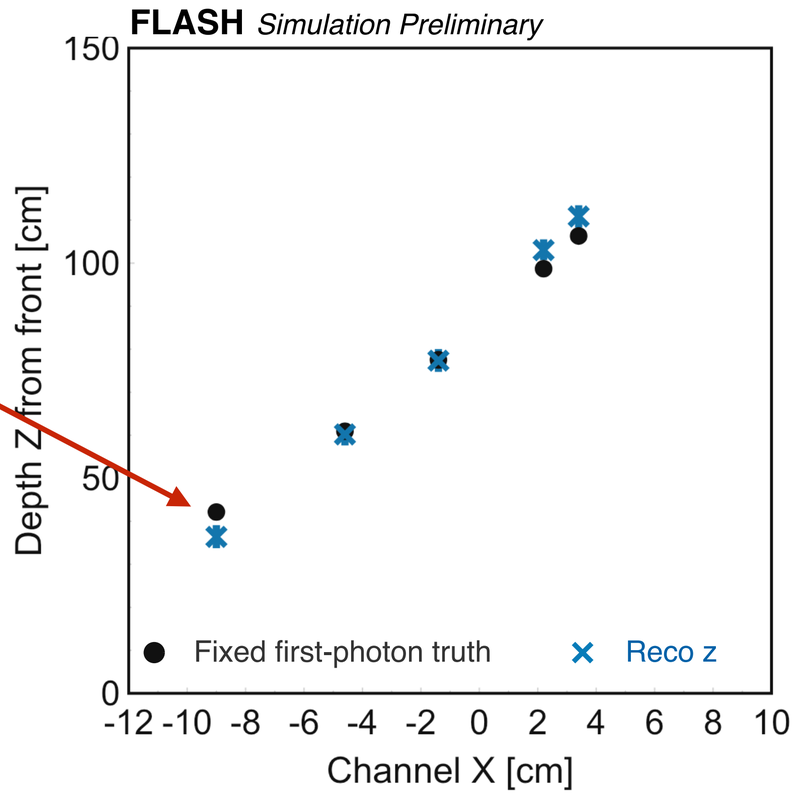


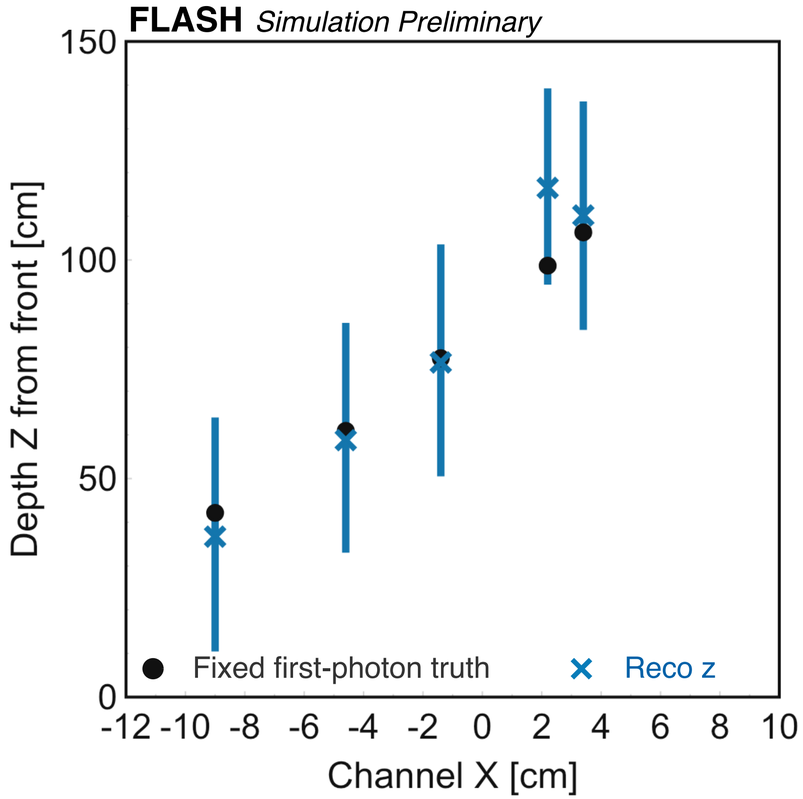
- **Hadronic showers can vary dramatically from event to event as shown in green**
- **With the use of a CNN we have demonstrated you can reconstruct signals resolving position dependence of hits using the timing information**
  - **Providing longitudinal segmentation to ~10 cm resolution**

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Using time to reconstruct position along fiber

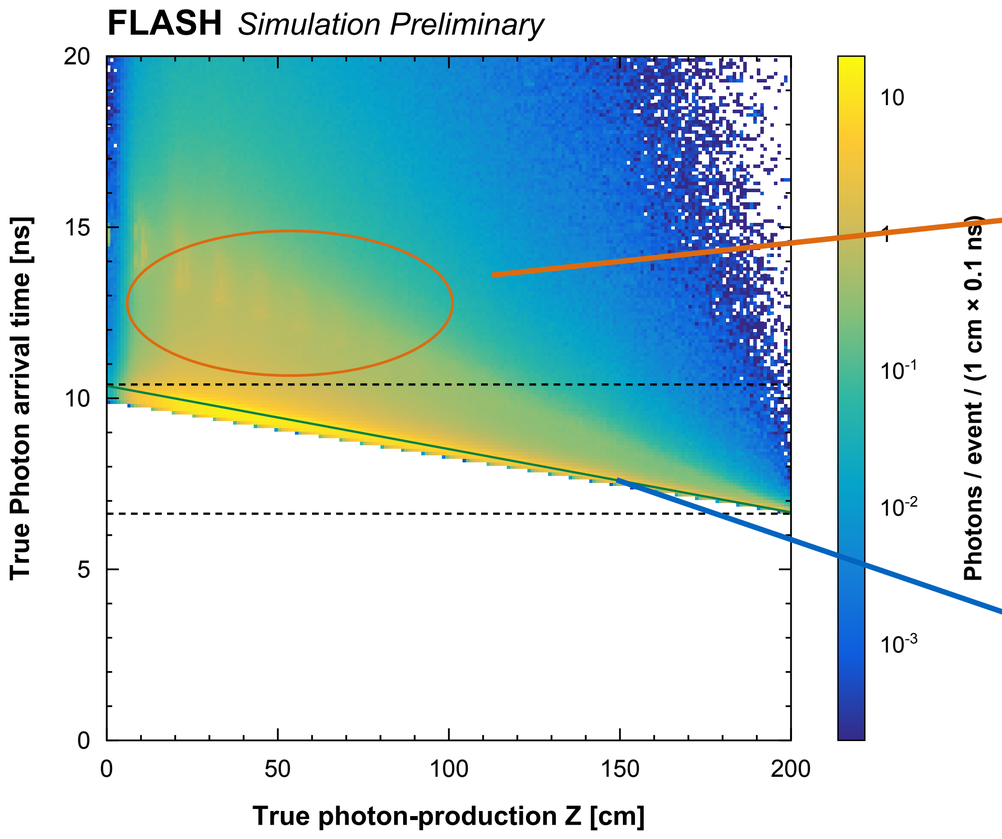






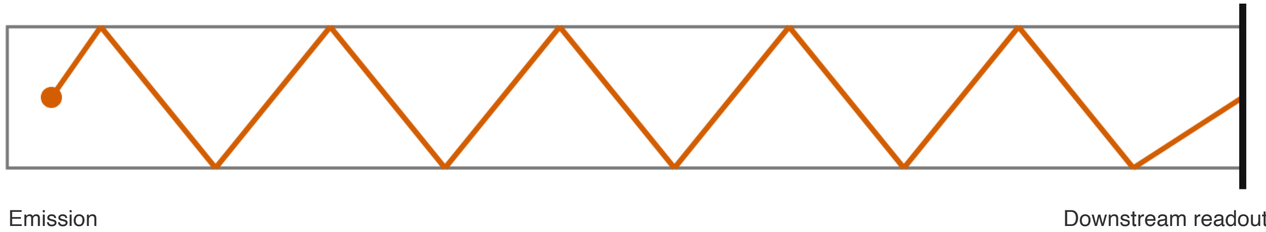
- Five cherry picked channels illustrate the z position reconstruction idea
  - 50 ps timing → ~1 to 10 cm z-position resolution
  - 500 ps timing → ~50 to 100 cm z-position resolution
- Large dependence on FLASH timing performance

Timing variation from shower and light propagation



More oblique light: longer path

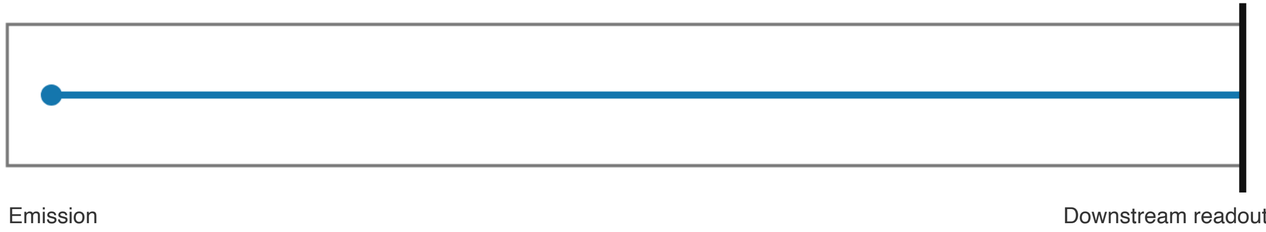
Same emission position and time. Same light speed in both cases.



Longer path gives a later arrival

More axial light: shorter path

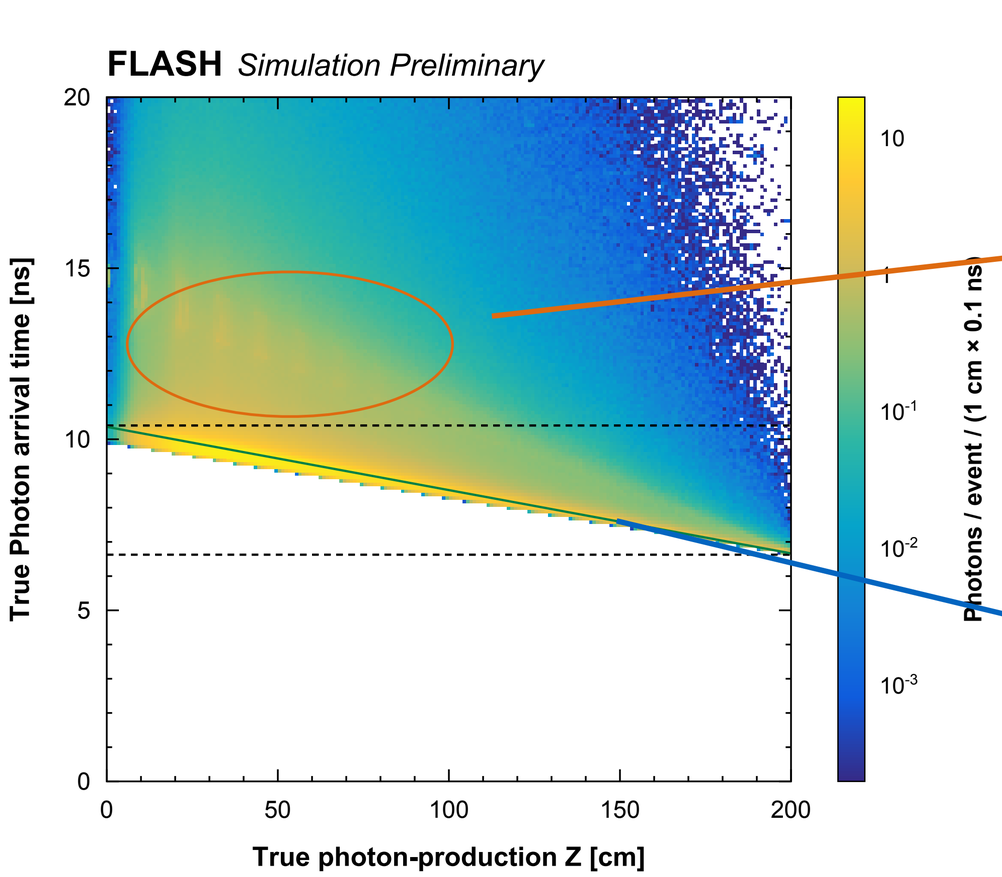
Same emission position and time. Same light speed in both cases.

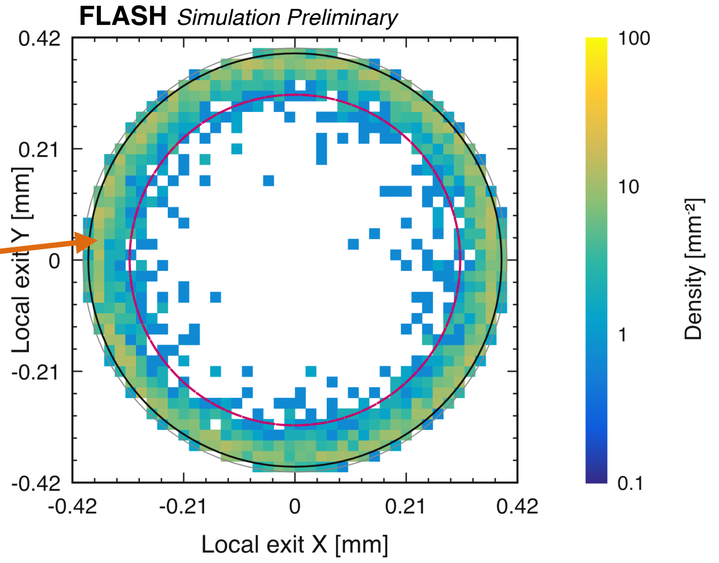


Shorter path gives an earlier arrival

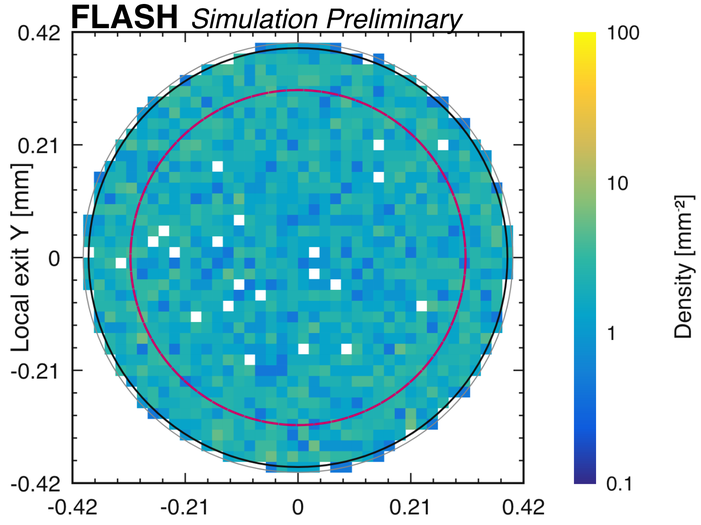
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Timing variation from shower and light propagation





- Photons with longer paths come at high fiber radius



- Expect to recover optical path variation with the small channel size provided by the FLASH sensor

Summary

- FLASH aims to retain individual photon-hit positions and arrival times for fiber calorimetry
- Simulations show how finer segmentation improves photon acceptance and allows for transverse shower reconstruction
- Spatially resolved readout provides a possible handle on late photons
- Next steps are to finalize device design and produce first version for initial testing

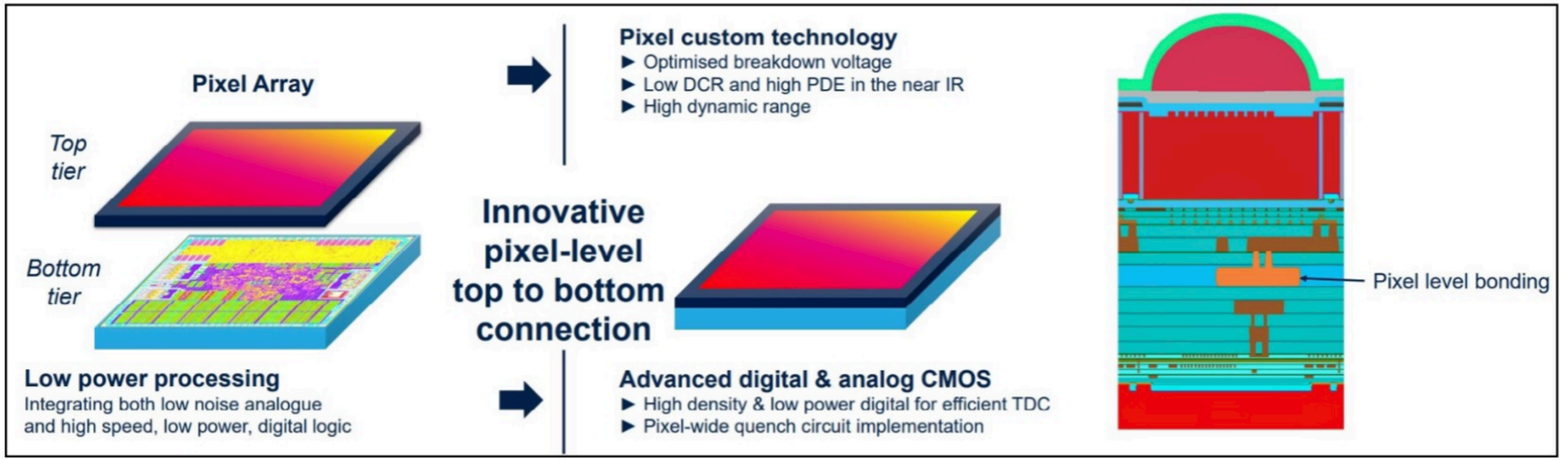
Backup

Enabling Technology: 3D SPAD–ASIC Sensor

The enabling technology is a **3D-integrated SPAD–ASIC device** combining:

- high-efficiency SPAD sensing layer (PDE$>$20%),
- custom fast-timing ASIC for pixel-level photon time stamping with timing precision at the $\mathcal{O}(10\text{–}50\,\mathrm{ps})$ level,
- dense vertical interconnects,
- fine pitch at the $\mathcal{O}(10\,\mu\mathrm{m})$ scale,

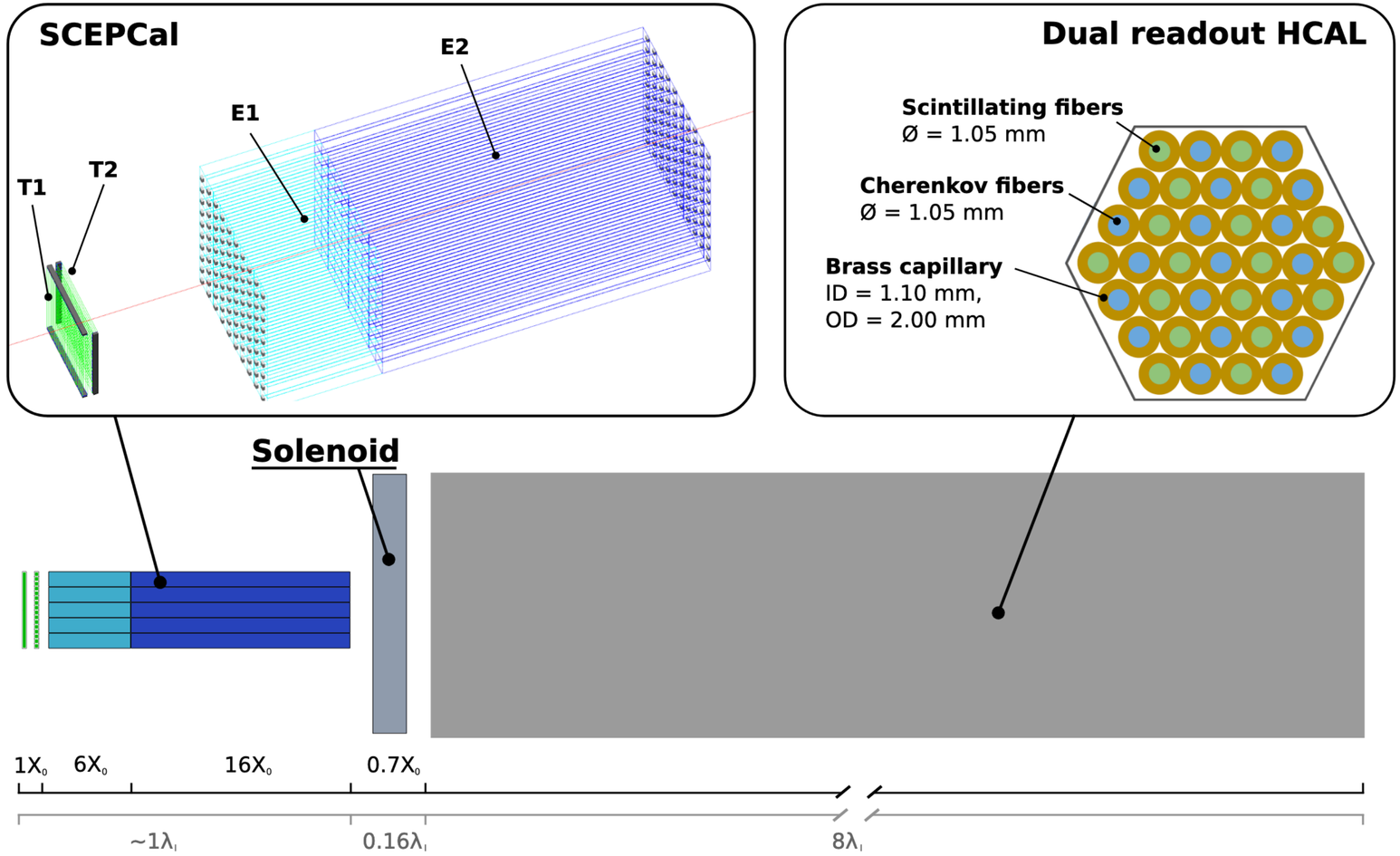
3D integration enables independent optimization of sensing and readout layers while preserving high fill factor and scalability to future calorimeter systems.



Picture from S. Pellegrini and B. Rae, International SPAD Sensor Workshop, 13th June 2022

Dual Readout Calorimetry

- Detector concepts are being developed
  - With extensive simulation studies
- IDEA detector concept includes DR calorimetry
  - Both Crystal and fiber based
- Fiber calorimetry active R&D collaborations
  - CalVision, HiDRa
  - DRD6, RDC9

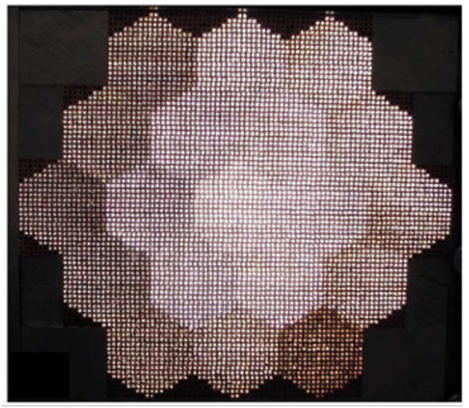


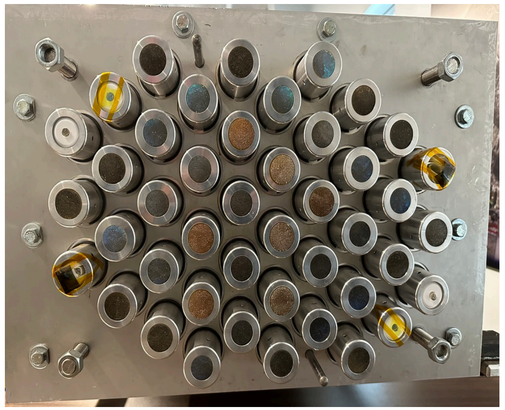
arxiv:2008.00338

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The Original DREAM Prototype







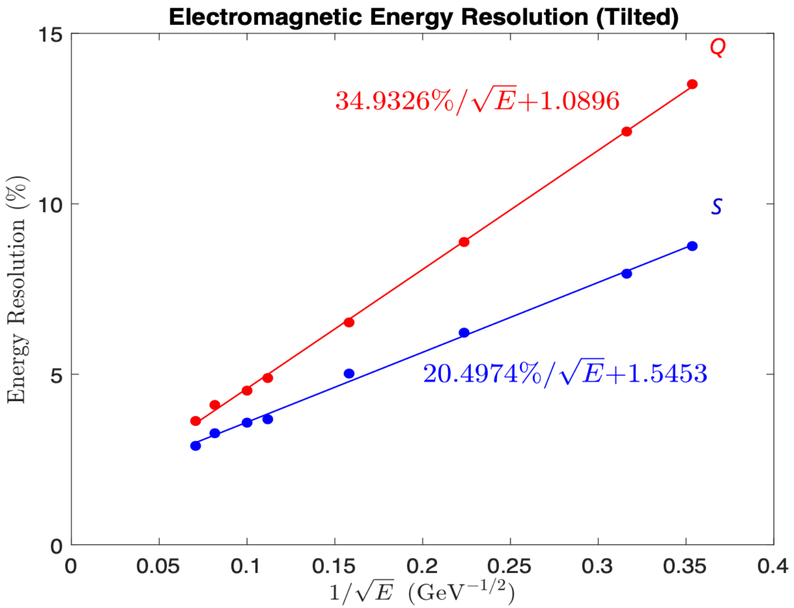


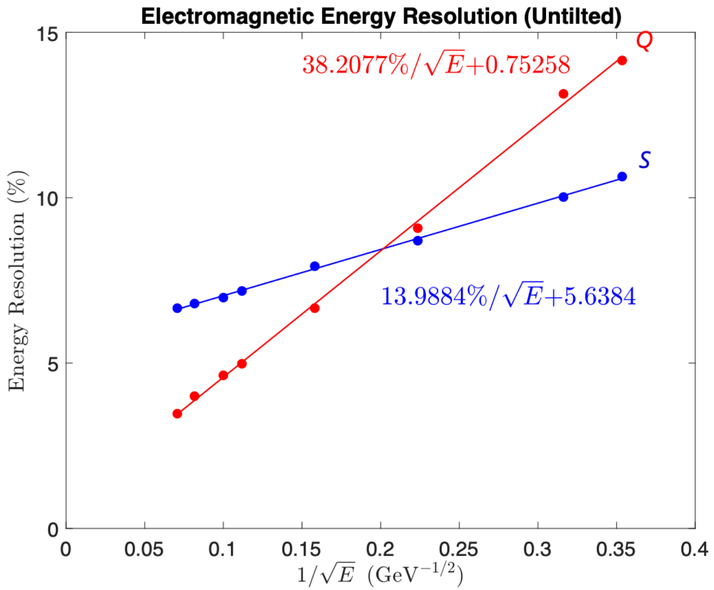
- DREAM module was built at TTU and exposed to beams at CERN starting in 2003 in several campaigns
- The motivation was to explore the simultaneous measurement of showers using scintillation (S) and Cherenkov (Q) signals for event-by-event compensation because Q/S ~ fem
- Specifications:
  - X_0 ~20.1 mm, ρ_M~ 20.4 mm, λ_I~ 200 mm, and weight ~ 1,030 kg
  - Scintillating fiber: SCSF-81J Kuraray
  - Clear/Cherenkov fibers: QP Polymicro, Raytela PJR-FB750 Toray
  - 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

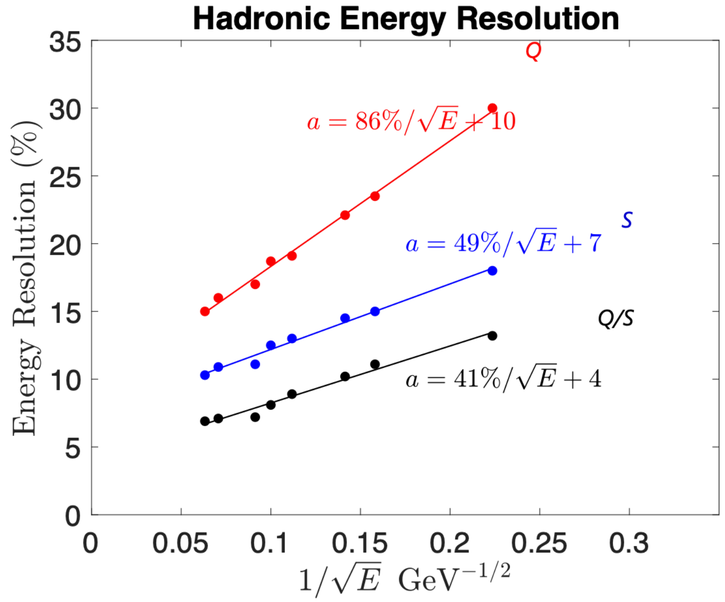


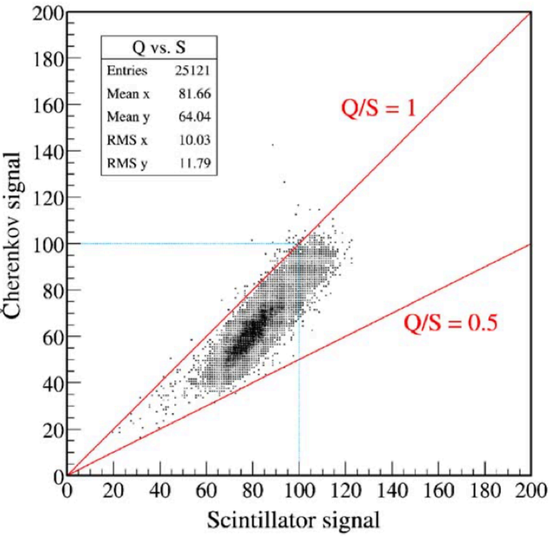
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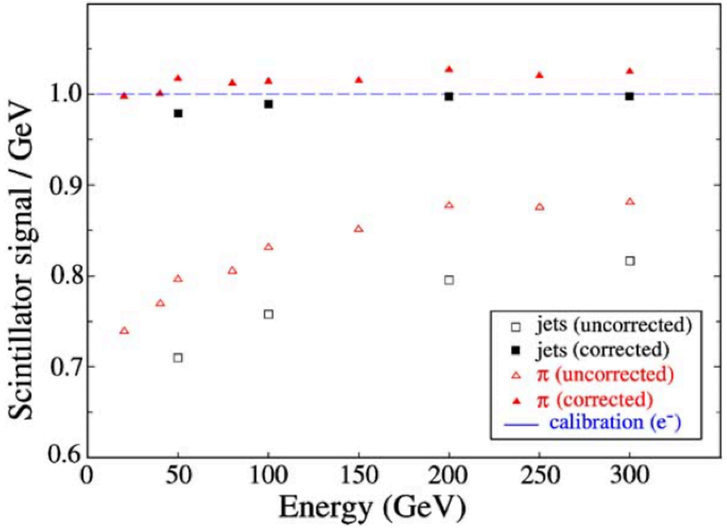
DREAM Performance in a Nutshell





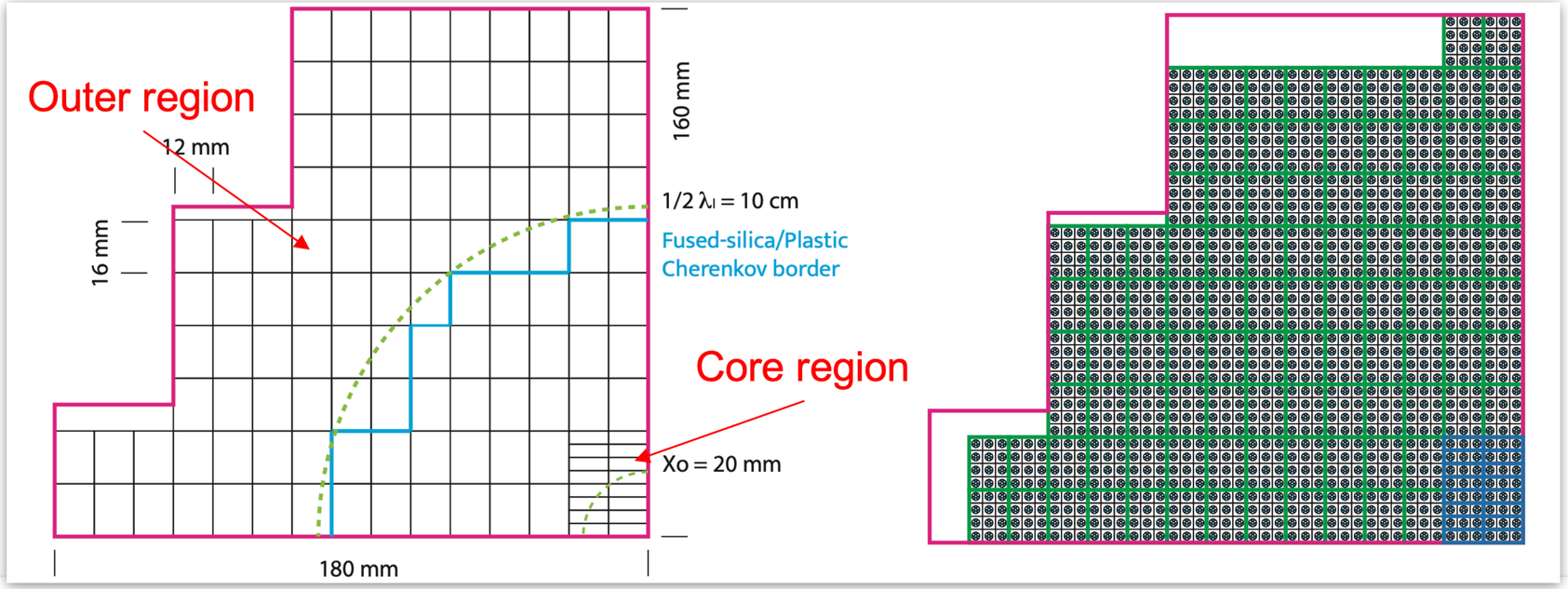




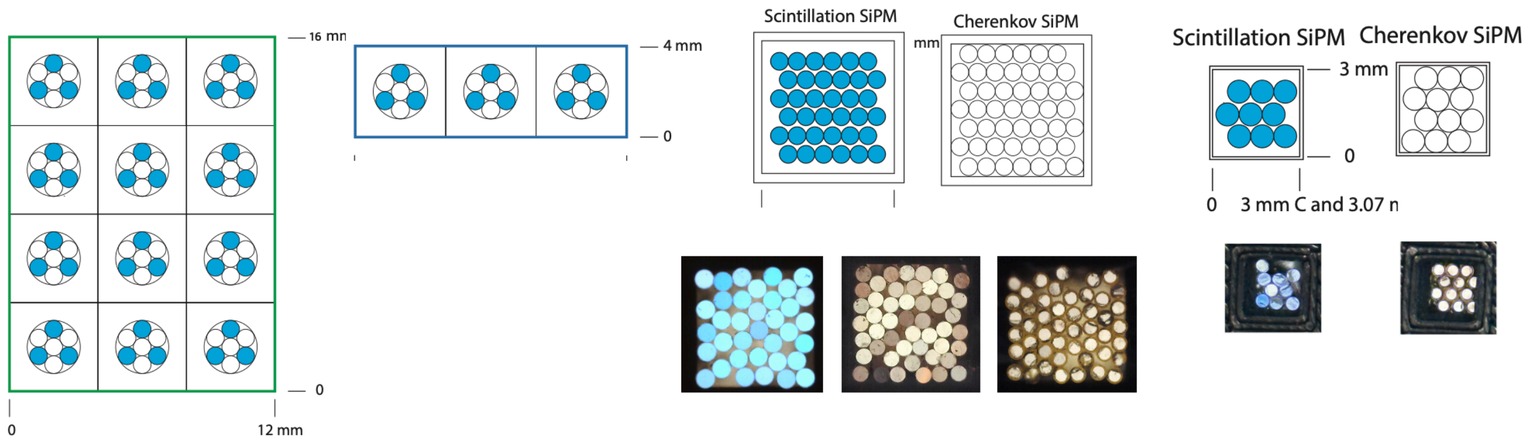


- The photoelectron yield was 8 pe/GeV for Cherenkov with fused-silica (Polymicro), 18 pe/GeV for clear plastic (Toray), and 33 pe/GeV for scintillator fibers (Kuraray).
- The hadronic energy resolution improves with Q/S correction (essentially a rotation in Q vs S plane), and the hadronic response linearity is attained

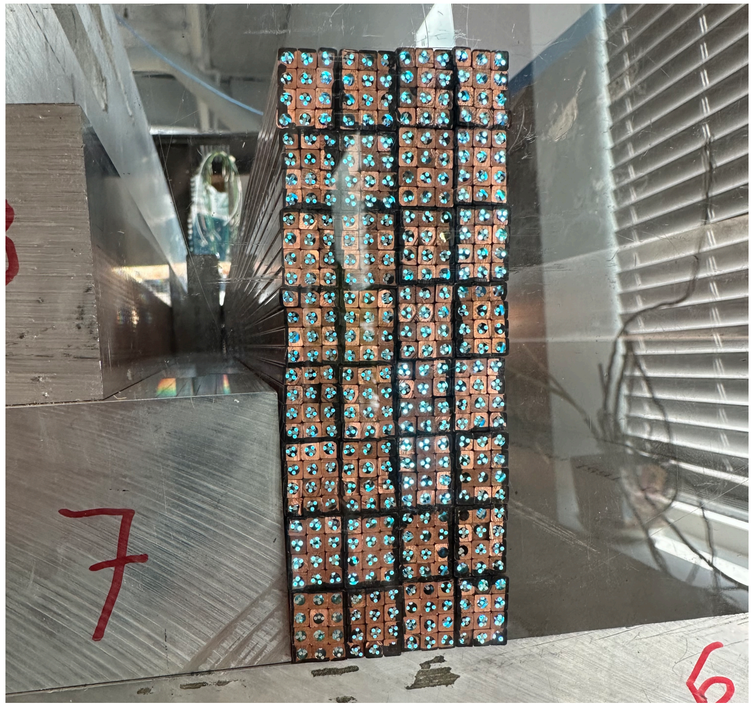
HG-DREAM

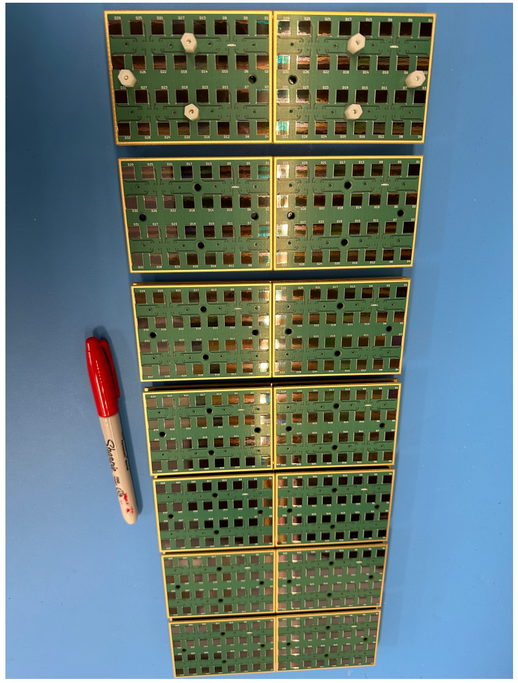


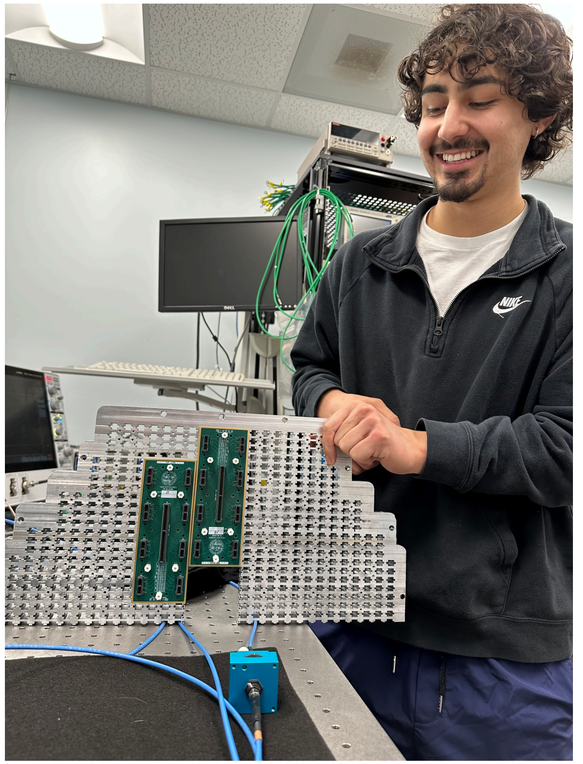
	Tower size (mm^2) (No of rods)	No. S/C fibers	SiPM area (mm^2)	No. of units
Outer region	12x16 (12)	36 S, 48 C	6x6	440
Core region	12x4 (3)	9 S, 12 C	3x3	64

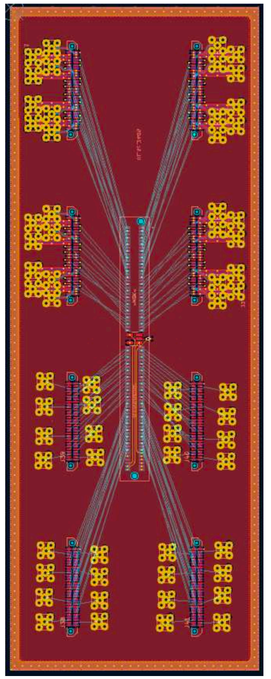


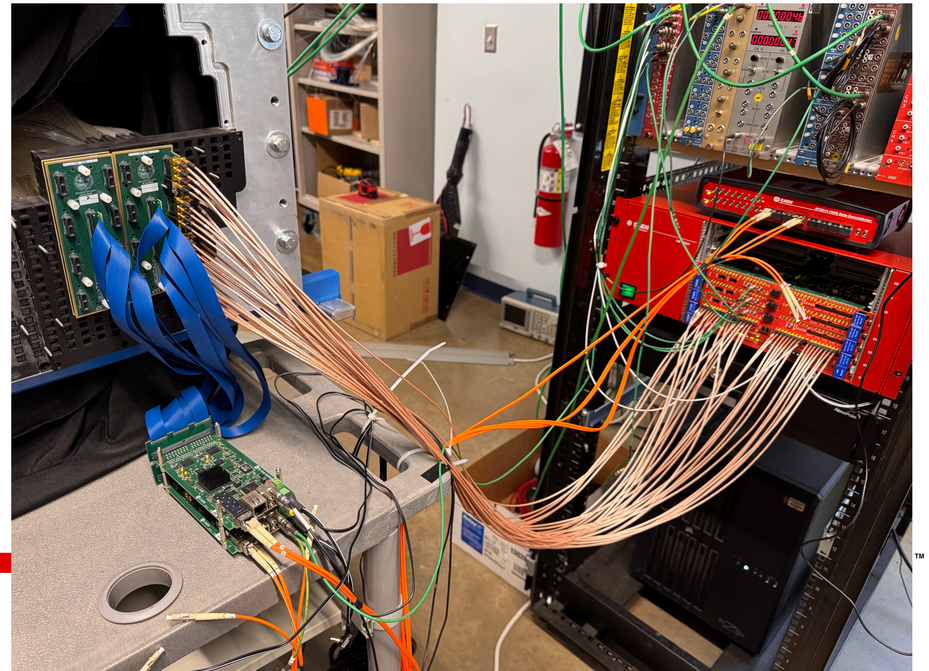
HG-DREAM Readout





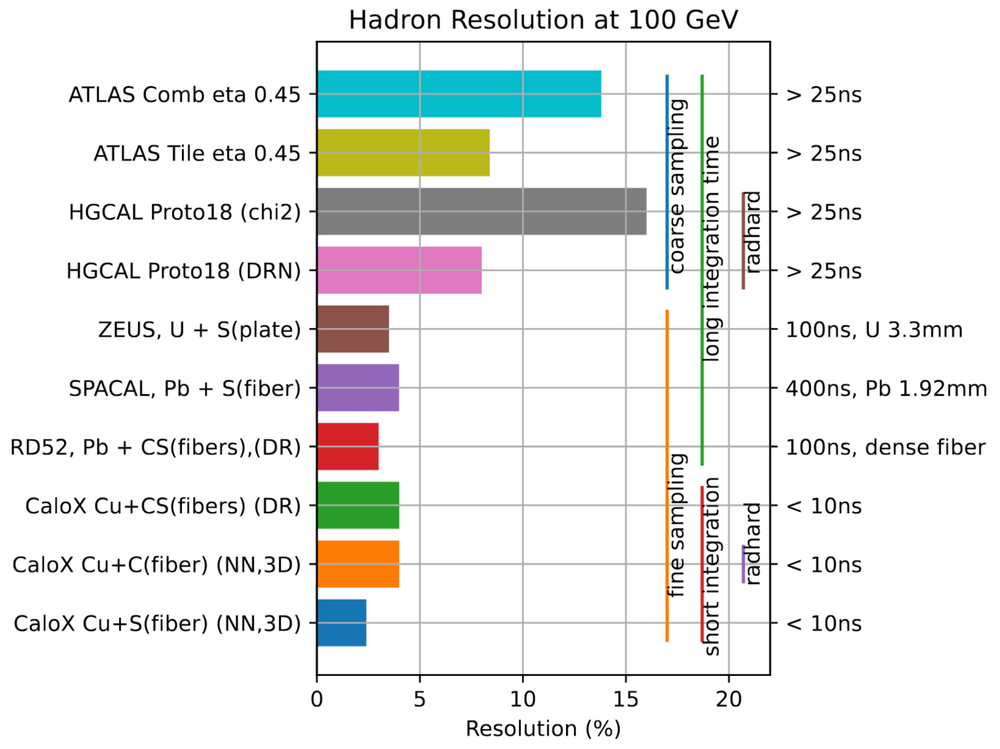


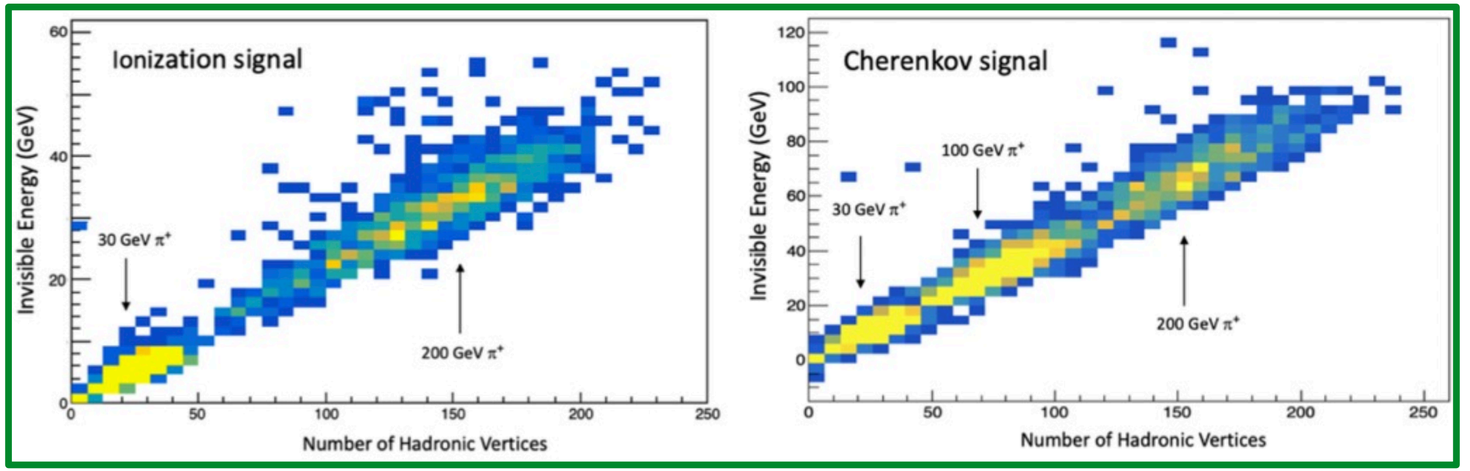


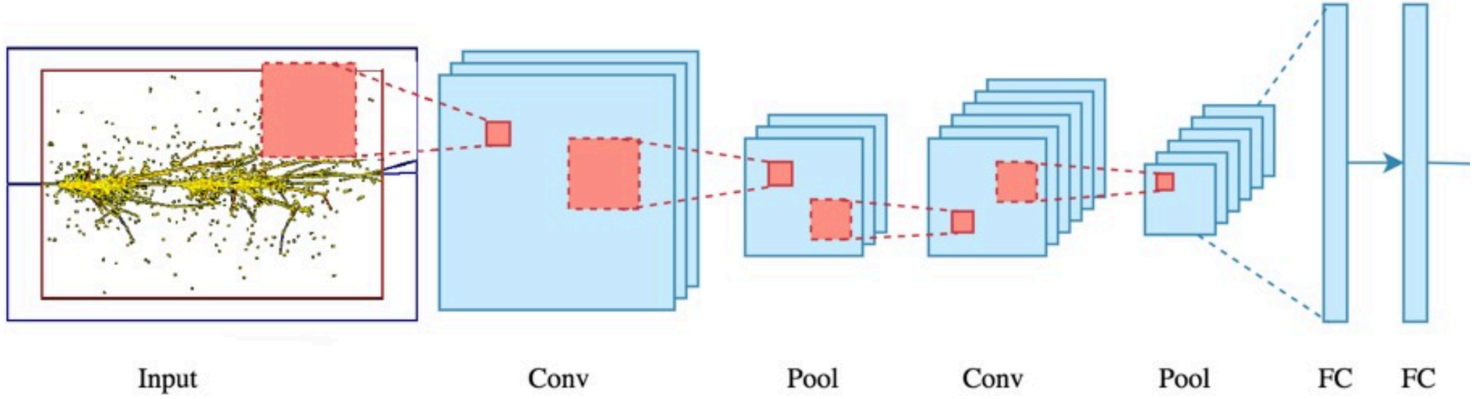


- The SiPM signal will be readout by either a FERS or DRS
  - FERS provides an ADC for each event
  - DRS provides a waveform for pulse shape reconstruction

Reconstruction with ML





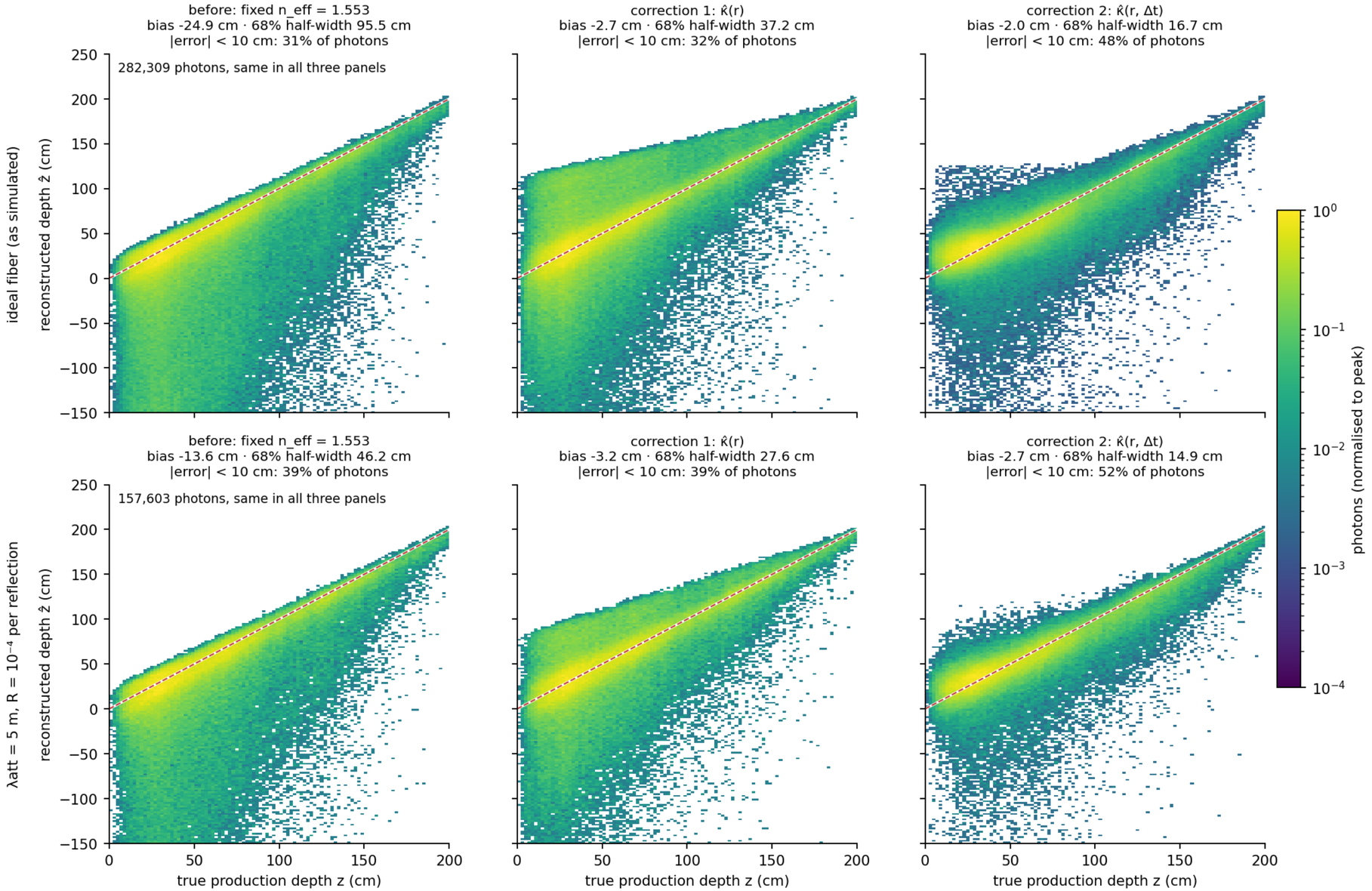


arxiv:2408.15385

- Useful information in the shower profile
  - **Counting number of vertices is highly correlated with amount of invisible energy**
- Implies ML techniques should improve overall performance
  - Initial studies of HG-DREAM with GNN trained on simulation are promising

TEXAS TECH

No selection. 100 GeV π⁺ test half (108 events), 50 ps timing, 10 µm SPADs, 20% PDE. Δt = arrival time after the first photon in the same rod channel.



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