Fast-Timing Digital Single Photon Readout for 5D Calorimetry

Proposal Category 1

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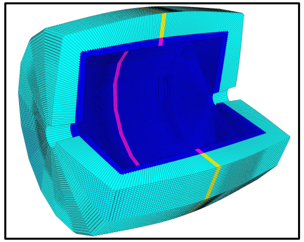
SLAC National Accelerator Laboratory

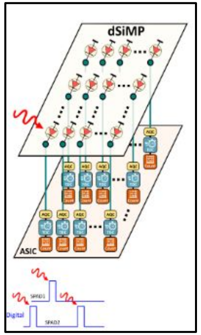
Stanford University | U.S. Department of Energy

FLASH: Digital Photon Readout for 5D Calorimetry

- **FLASH calorimeter concept**: ***F****ast-timing* ***L****ow-noise* ***A****dvanced* ***S****ingle-photon* ***H****igh-granularity*
- **FLASH realizes 5D calorimetry through direct time-resolved photon detection**: individual photons are detected and time stamped at the sensor front-end, **replacing analog waveforms with sparse, time-tagged photon hits**
- This architecture eliminates waveform digitization while enabling:
  - fine spatial granularity at the O(10 μm) scale
  - timing precision at the O(10–50 ps) level
  - reduced data volume and power consumption
  - scalable low-power implementation for future calorimeters
  - opens the path toward edge-level real-time processing and pattern recognition at the level of individual photons



IDEA High Granularity Dual Readout Calorimeter



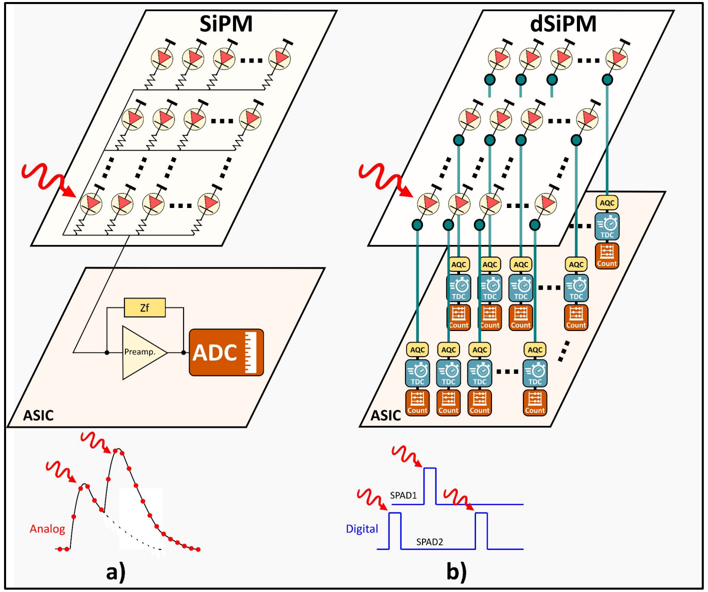
Pico-second timing single-photon digital readout (LDRD)

ML/AI online processing

Single-photon detectors: analog vs digital SiPMs

- **Analog SiPM:**
  - Sensor consists of several SPADs in parallel
  - One analog output: convolution of single-SPAD output with sensor+readout electrical circuit
  - Readout electronics: analog front-end + high-speed waveform digitizer
  - DSP to retrieve timing/number of photons
  - **Timing resolution with *N* photons is degraded**
  - **Scaling to large systems with sub-100ps is challenging:** power, calibration, data-rates, *etc*.
- **Digital SiPM:**
  - Several SPADs, each one has a ‘digital’ output
  - Timing: time-stamp each SPAD with in-pixel TDC
  - Energy/imaging: counter in each SPAD

Analog SiPM | Digital SiPM



~100 Gb/s
~100 mW
→
~ 10 Gb/s
~10 mW

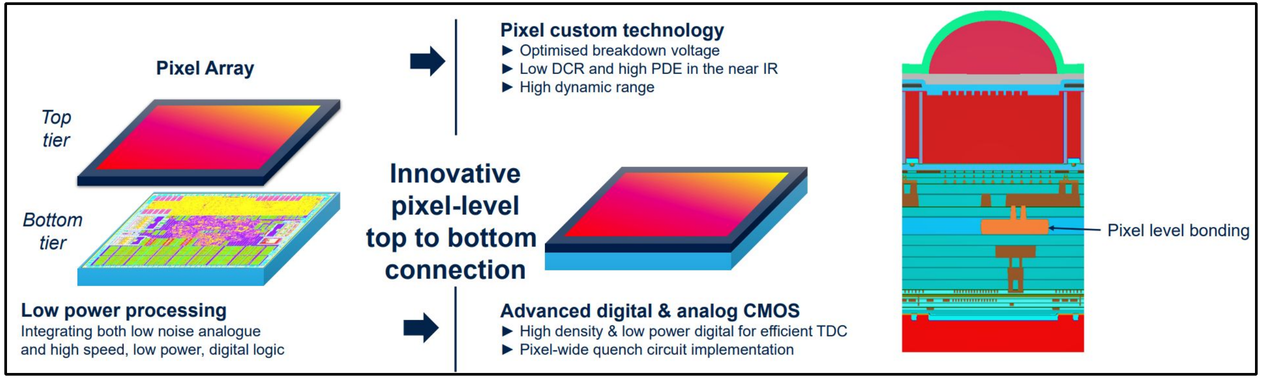
3D Stacking Technology

3D stacking at semiconductor foundries has become a well-established technology

We have identified a technology from ST Microelectronics that promises unprecedented performance in terms of PDE, pixel pitch (and thus dynamic range), and readout capabilities

This technology features a dedicated **top-tier pixel array of SPADs with a 10 µm pitch and near-100% fill-factor, connected via ultra-fine-pitch to a 40 nm CMOS die, where the readout electronics can be implemented**

What sets this technology apart is its feasibility for **fabricating small prototypes at a cost compatible with this proposal**

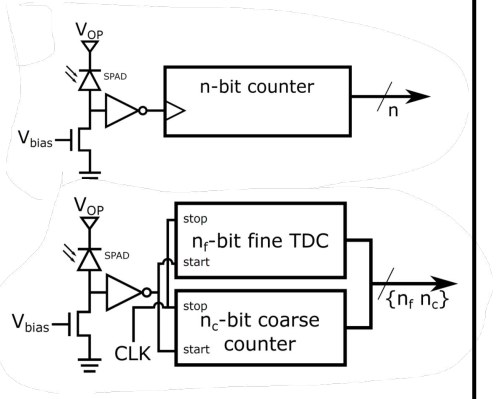


Proposed Development

- **Design and fabricate first dSiPM prototype**
  - Investigate Time-to-Digital Converter, target < 50 ps resolution
  - Evaluate implementation of both timing & photon counting mode
  - Size of first prototype: 3x3 mm2
  - Active imaging area: ~2x2 mm2, 200x200 pixels
- **Leverage existing infrastructure developed for LCLS-II 1 MHz detectors:**
  - FPGA readout boards and firmware, software (*rogue*)
  - Digital RTL logic for sparse readouts
- **The first prototype will serve as test vehicle for characterization in HEP environment, to be carried out in collaborations with TTU and UNM:**
  - Characterization of PDE, DCR vs temperature, Vbias, etc
  - DCR vs radiation hardness

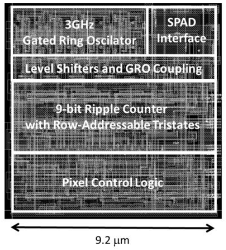
Readout circuitry for SPAD in photon counting (*top*) and timing mode (*bottom*)

10.1109/ICECS.2018.8617983



Example of in-pixel, 33 ps TDC implemented on 40 nm CMOS

10.1109/JSSC.2019.2905163



Anticipated Results and Deliverables

- **Y1Q1:**
  - **Define physics simulations to inform the requirements for the dSiPM system.**
  - **Define requirements and settling on the actual dSiPM ASIC architecture**
- **Y1Q2-Q4:**
  - Design of the ASIC containing SPADs and readout circuitry
- **Y2Q1:**
  - Submission to semiconductor fab for fabrication.
  - Design of PCB and supporting firmware/software for the characterization of the ASIC
- **Y2Q2-Q3:**
  - Test-bench characterization of the detector: QE, Timing, *etc*.
- **Y2Q4:**
  - Integrate device in a prototype of HG-DREAM dual-calorimetry system (w/ Texas Tech)

Next Steps: Simulations

- **dSIPM**:
  - Occupancy vs granularity, dynamic range, efficiency, deadtime, time resolution, need for lens? → Chip specifications
- **Longitudinal segmentation via timing:**
  - Do we need a double readout (back and front?) Or a single readout at the back works?
  - How do we correlated scintillating with Cherenkov light timing?
  - Can we identify space-time clusters and apply DR corrections at the cluster level? Or we need a jet-level ML approach?
  - How sensitive are we to the time during shower evolution? How does that impact longitudinal segmentation?
  - Can we access both segmentation and shower time development?
- **Integration of Dual readout Fiber HCAL, EM crystal, SiW layer, tracker, PID:**
  - How to best integrate Crystal with Fiber calorimeter? PID?
  - Reference time and calibration
- **5D Particle Flow:**
  - **The 5D Calorimeter concept enables the unification of PFA and DRO into a new type of ML/AI particle flow algorithm (yet to be developed!)** that combines high granularity fiber dual readout calorimetry with longitudinal segmentation via timing, tracks, and precision timing information

Backup

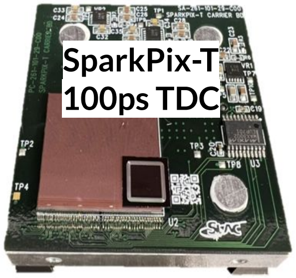
Readout ASIC

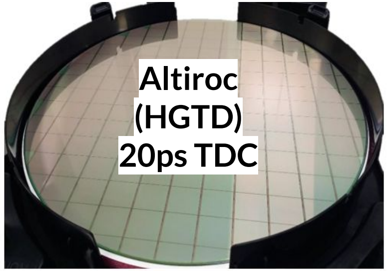
As part of our proposal we will design and fabricate a dSiPM readout-timing ASIC in the 40nm CMOS process from STMicroelectronics

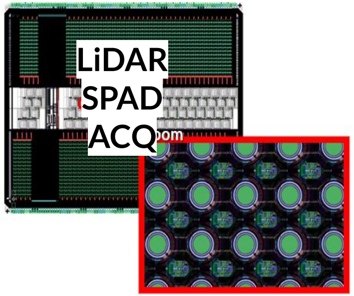
The ASIC will incorporate:

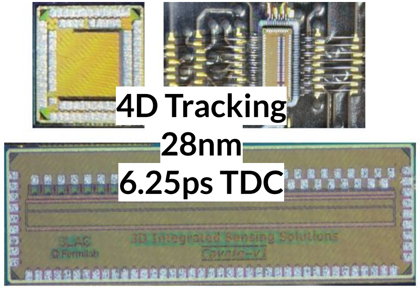
- Active quenching circuit (AQC) for SPAD readout and quenching
- ~10ps Time-to-Digital Converter (TDC) for time-of-arrival (TOA) measurements
- Counters for signal amplitude (energy) measurements
- Readout and configuration logic

The SLAC team has significant experience in designing high-precision timing detector ASICs as well as design of SPAD-based circuitry

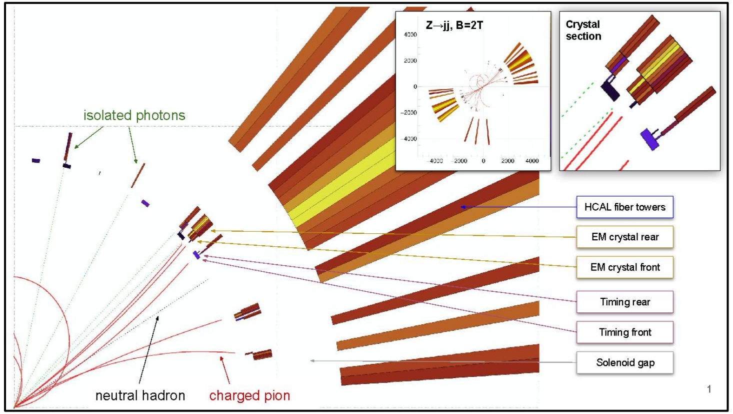


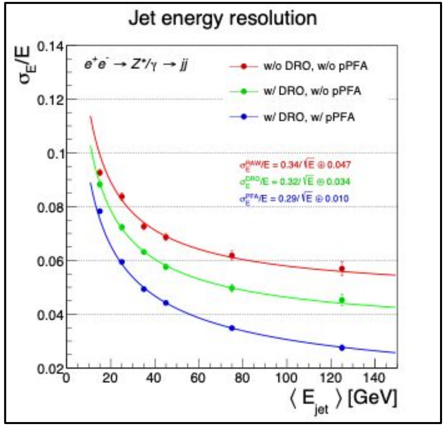






5D Imaging Dual Readout PFA Calorimetry





- **The 5D Calorimeter concept enables the unification of PFA and DRO into a new type of ML/AI particle flow algorithm (yet to be developed!)** that combines high granularity fiber dual readout calorimetry with longitudinal segmentation via timing, tracks, and precision timing information
- **Outstanding opportunity for students and postdocs**

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

A. Schwartzman[1], N. Akchurin[2], R. Bartoldus[1], Y. Feng[2], C. Madrid[2], B. Markovic[1], L. Rota[1], S. Seidel[3], D. Su[1], L. Wu[1]
[1]SLAC National Accelerator Laboratory [2]Texas Tech University [3]University of New Mexico

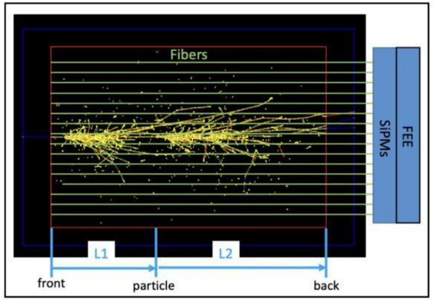
From Dual Readout to 5D Optical Calorimetry

Achieving the unprecedented precision required for jet, electron, and photon measurements at future Higgs factories such as FCC-ee place stringent requirements on calorimeter performance. Hadronic calorimetry remains fundamentally limited by fluctuations in shower development and by confusion effects in dense environments.

Combining high-granularity dual-readout calorimetry with precision timing has led to the emergence of **5D calorimetry** as a new reconstruction paradigm. In this framework, precision timing provides effective longitudinal segmentation, while fine spatial granularity enables the separation of overlapping energy deposits in both space and time. With this added information, dual-readout calorimetry can be naturally combined with particle-flow reconstruction to reduce confusion effects.

Traditional high-granularity calorimeters require many instrumented longitudinal layers, leading to large channel counts and major challenges in services, power, cooling, hermeticity, and detector accessibility. In 5D dual-readout calorimetry, the shower evolution can instead be reconstructed through timing using continuous fibers and a single readout layer at the back of the calorimeter. This architecture substantially simplifies detector services and electronics accessibility while preserving longitudinal shower information.

Longitudinal imaging through precision time projection instead of dense sampling segmentation



However, current photodetector and readout architectures do not scale to the requirements of 5D calorimetry

Current dual-readout calorimeter prototypes such as HG-DREAM use analog SiPMs followed by high-speed waveform digitization and deconvolution.

This approach provides timing for integrated calorimeter signals, but does not scale to future high-channel-density 5D calorimeters because of:

- power consumption from high-speed ADCs,
- large data volumes,
- calibration complexity,
- inaccessible embedded electronics,
- limited scalability of precision timing extraction.

As longitudinal granularity increases, the required services, cooling, and readout infrastructure become increasingly difficult to integrate within realistic detector systems.

FLASH: Digital Photon Readout for 5D Calorimetry

SLAC and Texas Tech University have introduced the **FLASH** calorimeter concept:

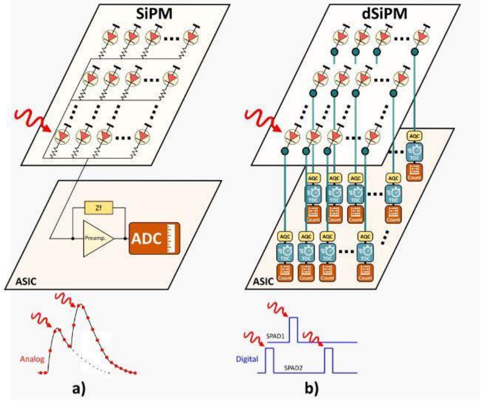
Fast-timing **L**ow-noise **A**dvanced **S**ingle-photon **H**igh-granularity

FLASH realizes 5D calorimetry through ***direct time-resolved photon detection***. Individual photons are detected and time stamped at the sensor front-end, replacing analog waveforms with sparse, time-tagged photon hits.

This architecture eliminates waveform digitization while enabling:

- fine spatial granularity at the $\mathcal{O}(10\,\mu\mathrm{m})$ scale,
- timing precision at the $\mathcal{O}(10\text{–}50\,\mathrm{ps})$ level,
- reduced data volume and power consumption,
- scalable low-power implementation for future calorimeters,
- opens the path toward edge-level real-time processing and pattern recognition at the level of individual photons.

Analog vs Digital SiPMs

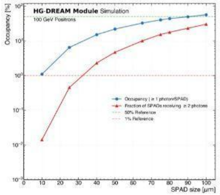


Analog SiPM	Digital SiPM
Summed microcell current	Individual SPAD-level response
Waveform digitization	Direct photon time stamping
Integrated analog signals	Sparse digital photon hits
High ADC power/data volume	Event-driven digital readout
Dense embedded services	Simplified scalable architecture
Data rate: ~150 Gb/s per SiPM	~25 Gb/s per dSiPM
Power consumption: 80 mW per ASIC	< 5 mW per ASIC
Timing precision: 1.1 ns FWHM	< 150 ps FWHM (50 ps RMS)

Occupancy and Deadtime

A key consideration for digital SiPMs is SPAD occupancy and deadtime. Simulation studies show that fine granularity strongly mitigates these effects:

- pitches $\lesssim$25 µm maintain low multi-photon occupancy,
- photon detection efficiency remains high under conservative deadtime assumptions,
- deadtimes of ~20 ns remain within a single bunch crossing.

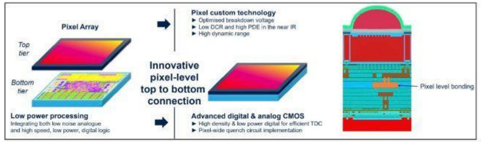


Enabling Technology: 3D SPAD–ASIC Sensor

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

HG-DREAM Validation Program at Texas Tech

The HG-DREAM calorimeter provides a mature, functional testbed for validating 5D optical calorimetry in a realistic detector environment.

Planned validation program:

- integrate FLASH sensors into HG-DREAM readout,
- evaluate photon-level timing performance in beam,
- benchmark against analog SiPM approaches,
- validate timing-based longitudinal reconstruction,
- connect device innovation to system-level calorimeter performance.

Impact and Outlook

FLASH provides a path toward the first experimental realization of 5D calorimetry, with IDEA at FCC-ee serving as a first high-impact application.

The technologies required for scalable 5D calorimetry are closely connected to modern pixel-detector, SPAD, and imaging architectures, leveraging SLAC's expertise in fast timing, ASIC development, 3D integration, and large-scale detector systems.

The program also aims at establishing SLAC, TTU, and UNM within the emerging international effort in photon-level calorimetry and digital SiPM development.

Broader applications include future collider calorimetry, EIC calorimetry and RICH detectors, photon science instrumentation, and neutrino detectors.

IDEA

DR fiber HCAL

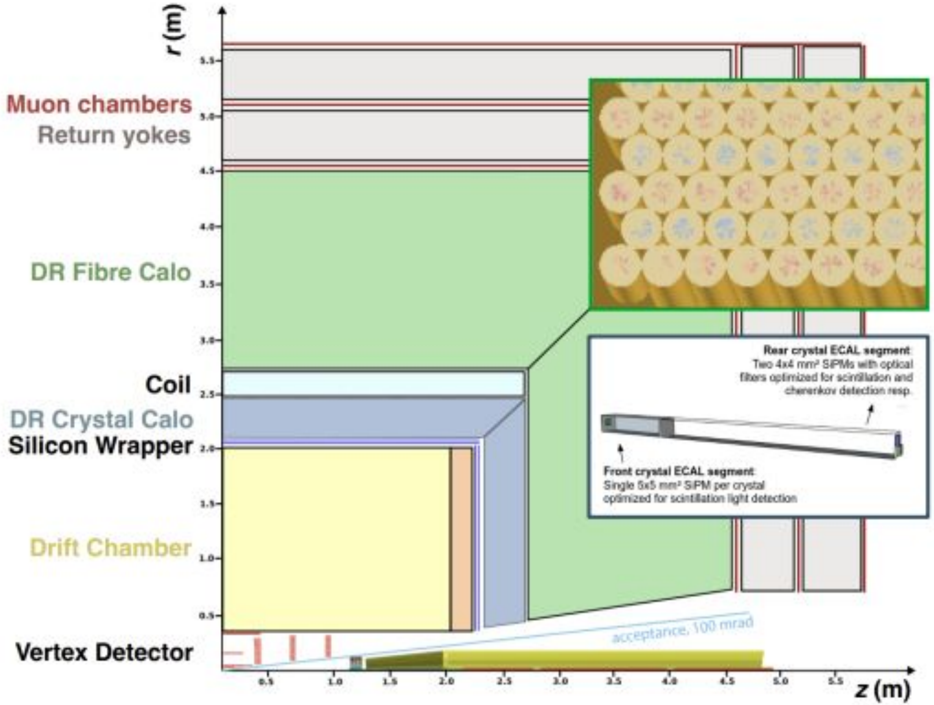
- Capillary tube w/ 2 mm diameter
- λ_{int} ~ 25 cm

DR crystal ECAL

- $PbWO_4$ crystals (baseline) w/ Cherenkov light detection using UV filters and/or timing differentiation
- 1x1 cm^2 for each front ($6X_0$) and rear ($16X_0$) end segments
- Moliere radius (ρ_M) ~ 2 cm

Solenoid

- $1.5X_0$ transparency based on arXiv:2502.21223
- (however, the actual implementation in k4geo is a thin Aluminum can with $0.75X_0$)
- 30 cm gap is allocated between the ECAL & HCAL
- For now, tracks are taken from the `TracksFromGenParticles` collection



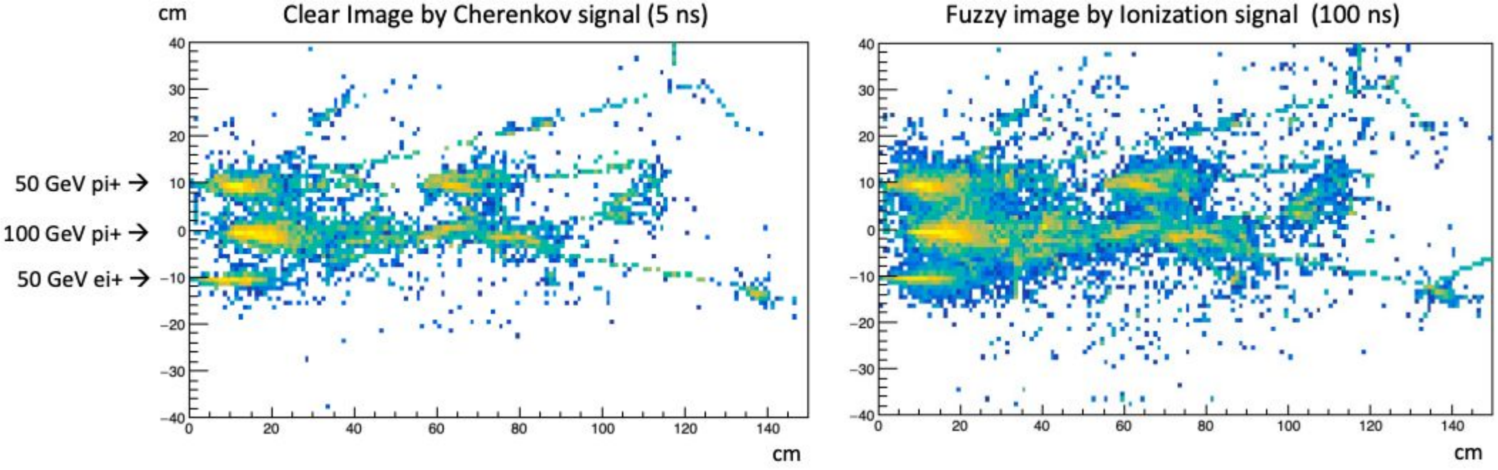
5D Dual Readout Imaging ML analysis

Clustering of Hits in Jet

Cherenkov signal produces clear and narrow image of hadronic shower comparing to ionization signal. AI/ML may use such clean shower images for 3D pattern recognition of complex event structure.

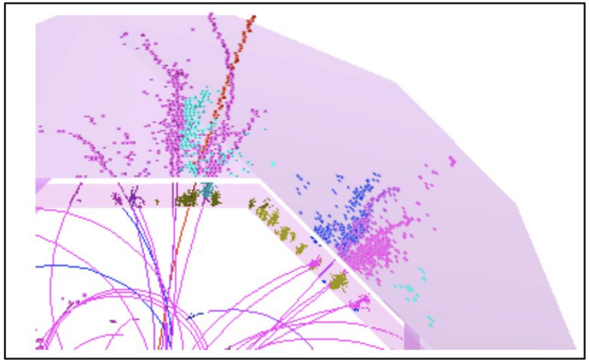
- reconstruction of individual particle in jet (then, link to inner tracks for particle flow reconstruction).
- analysis of jet substructure to identify boosted W/ Z / top / Higgs.

Below is an example of “pseudo jet”. Three particles hit a calorimeter at 10 cm apart. Assignment of “hits” to particle may be done in both cases (Cherenkov and Ionization), but the Ionization case becomes difficult once the separation get smaller.

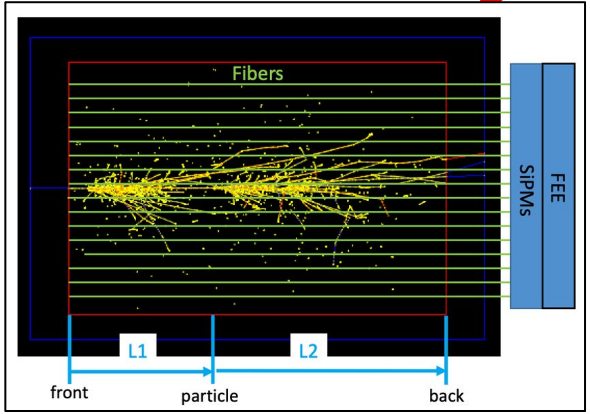


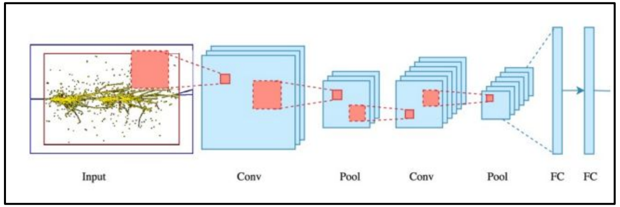
S. Kunori, 23-May-2024, Calor2024

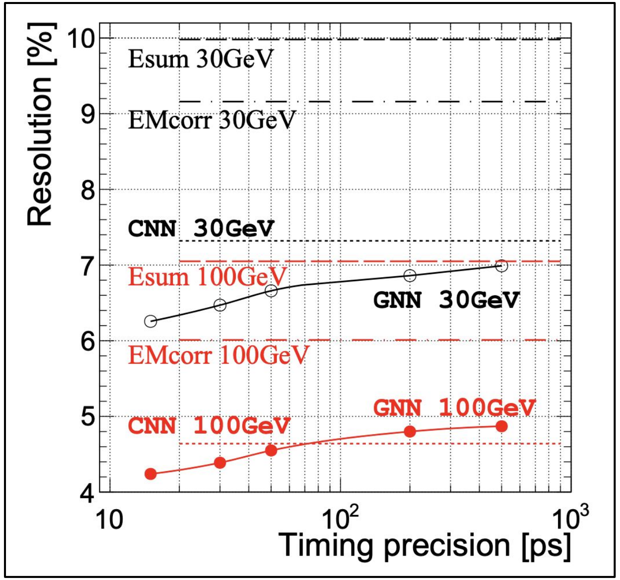
5D Calorimetry and PFA



[Akchurin, et. al.](#)

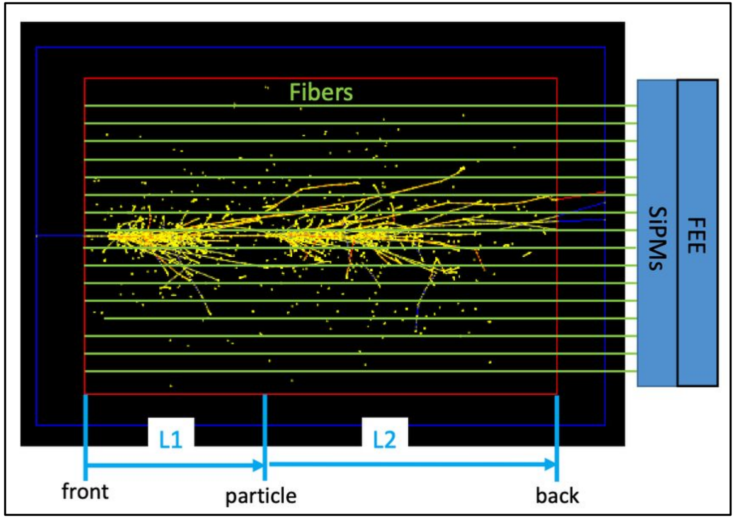


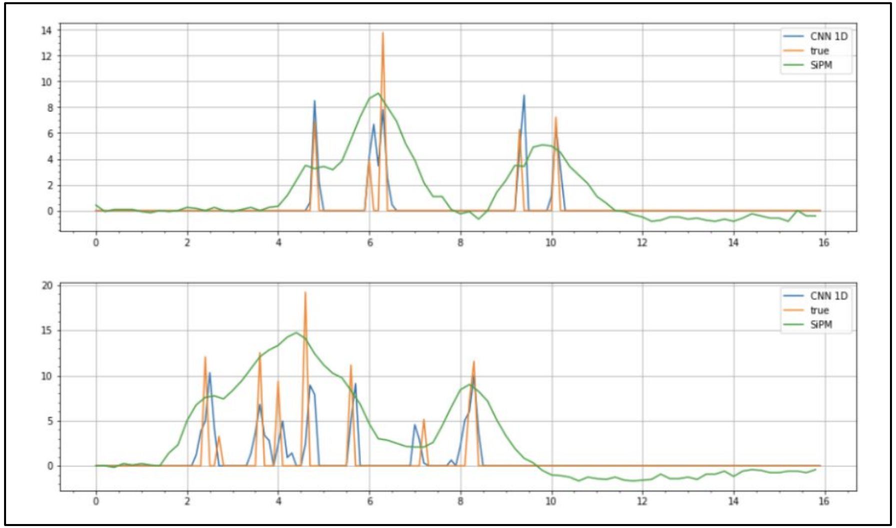




- **Performance of particle flow limited by the ability to accurately associate *tracks* to *calorimeter* clusters**
  - Challenging when showers overlap in space
- **Exploit the full space-time structure of showers to improve the jet energy resolution (5D PFA)**
- **Example: IDEA fiber dual-readout hadronic calorimeter**
  - 50ps time resolution for ~2cm depth segmentation
  - $t = L_1/c + L_2/(c/n)$, *with n=1.46*
- **Fast timing can also provide ToF for LLP and PID, and BIB suppression at muon colliders**

Timing Extraction





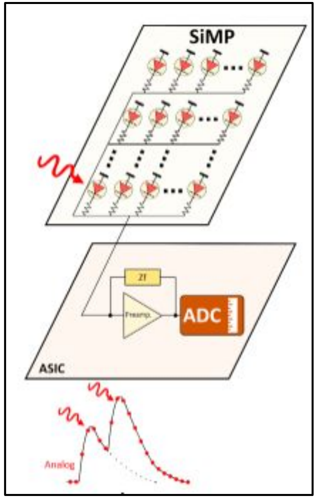
Current prototype based on ***analog SiPMs with fast-digitizer and processing***

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

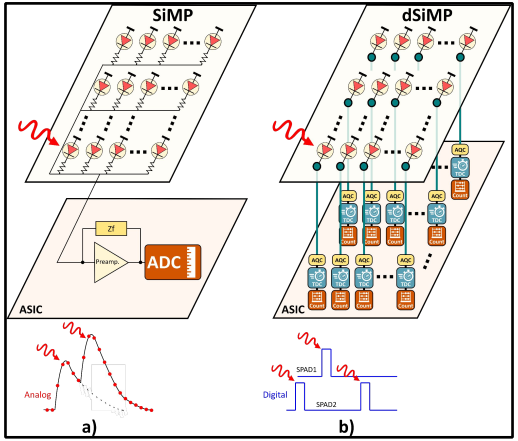
State of the Art Challenges

- Current concepts are based on conventional (analog) SiPMs and high-speed analog sampling and digitization (ADC conversion) of signal waveforms.
- Signal amplitude (energy) and time of arrival (TOA) extracted from the ADC samples
- **Challenging to scale** to channel sizes necessary for high-granularity calorimeters at future colliders
- High speed ADC sampling is **power hungry**
- Dealing with **large data volumes** is not trivial
- Extracting timing at 10ps precision from analog samples requires **intensive calibration** and **data processing**
- **All these issues become increasingly difficult to deal with as the number of channels increases**



In a conventional SiPMs, thousands of SPAD microcells are placed in parallel, summing all their currents and resulting in a device where output current is an analog waveform with amplitude proportional to the number of avalanche-triggered SPADs.

A New Approach: Next-gen dSiPM with 3D-stacked semiconductor imaging technology



- **Develop a fully-digital approach based on digital SiPM 3D stacked to a dedicated front-end ASIC incorporating high-precision TDCs for ~10ps time-tagging and counters for energy measurements**
- Unlike conventional SiPMs, in the dSiPM every SPAD microcell provides a separate output that can be treated by digital circuits: the signal amplitude is recovered by counting the number of triggered cells while the timing information is extracted from digital pulses employing high-precision TDCs.
- **Operating every SiPM microcell digitally and in-parallel offers many advantages:**

- **lower power consumption** as power hungry analog front-end and high-speed ADCs are avoided
- **lower data rates** as amplitude and time information are directly extracted in presence of the signal
- separate access to every microcell allows the use of the **fine spatial (tens of μm) information** as well as disabling of "hot" cells that exhibit elevated dark count rates, **improving noise performance**
- the all-digital system is robust and requires **minimal calibration**, making it **easily scale from a prototype to large systems**, *a step often not trivial for high-precision analog systems*

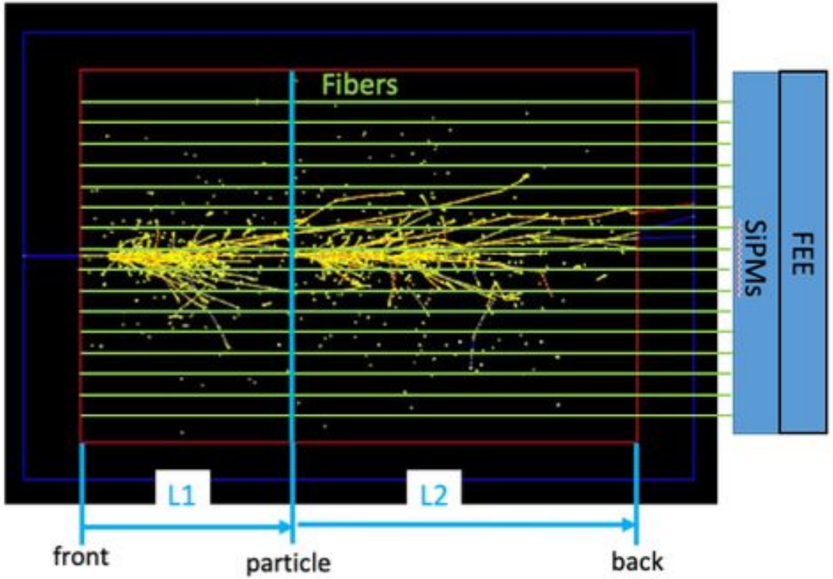
joint meeting rdc4-rdc9, February 19, 2025

1. Introductory remarks (Marina):
    a. reminder of the three main drivers of RDC9: 1. enhanced energy resolution (missing mass measurements, precision electroweak studies);2. time and/or spatial resolution to master high-occupancy, high-radiation exposure;3 3. ultrafast media to improve background rejection/mitigate pile-up.
    b. in terms of possible collaborations with the ASIC community, proposed challenges to be addressed in joint generic R&D effor: 1: energy resolution in a large dynamic range spanning the noise level until the highest shower energy to be processed; 2: readout for high-granularity/5D calorimetry: optimal techinques for high data volumes, including distributed processing, incorporating AI technieques, FPGA IP cores in ASICs;3: breaking the 10 ps barrier: fast TDCs, waveform sampling and feature extraction for ps timing, clock distribution.
    c. collaborative effort, although not a "blue-sky grant submission" may involve characterization of radiation hardness, assessment of performance at cryogenic temperature.

Google docs with the R&D themes described above have been created to be a forum for further discussion: https://drive.google.com/drive/folders/1jhf6dERrrhOYavOujnYK90l7XsS3wyX3?usp=sharing

CPAD RDC4-9 goal: US 5D-Calorimeter demonstrator

Longitudinal Segmentation with Timing



Signal time = L1/c + L2/v

c = velocity of particle

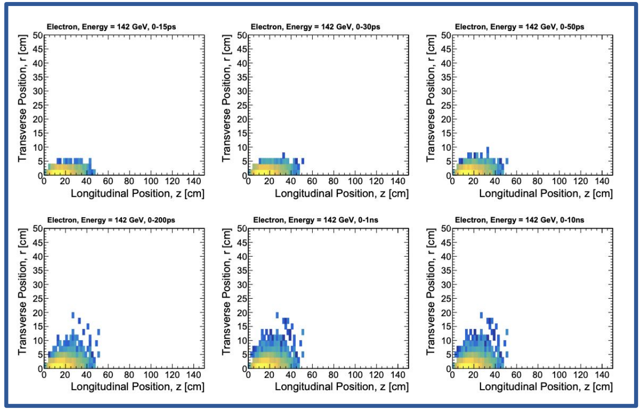
v = c/n, n = 1.46

ΔL = 2 cm ≈ 44 ps

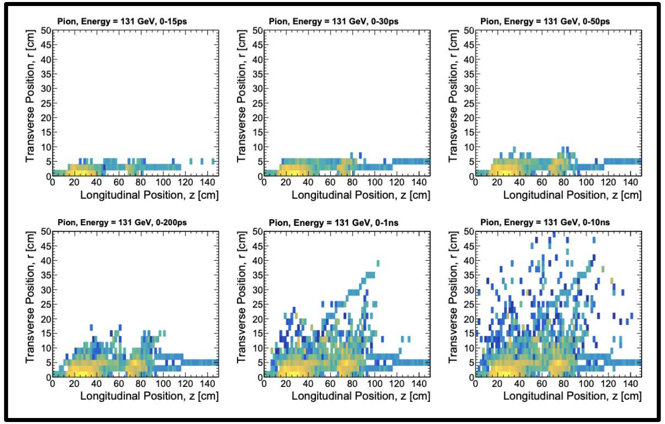
- 2D readout: fewer readout channels
- Effective 3D segmentation with timing
- Photo Detector and Front End Electronics (FEE) is on the back side of the detector, low radiations
- Easier signal collection
- The calibration is easier, no need to calibrate in depth

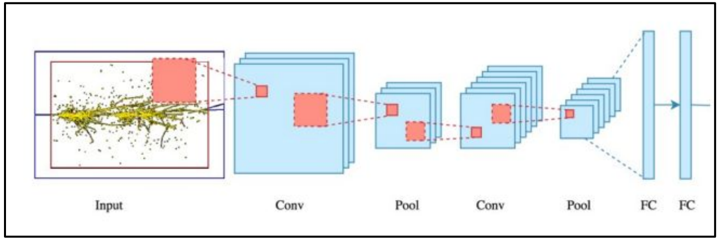
Fast-Timing + AI/ML 5D Calorimetry

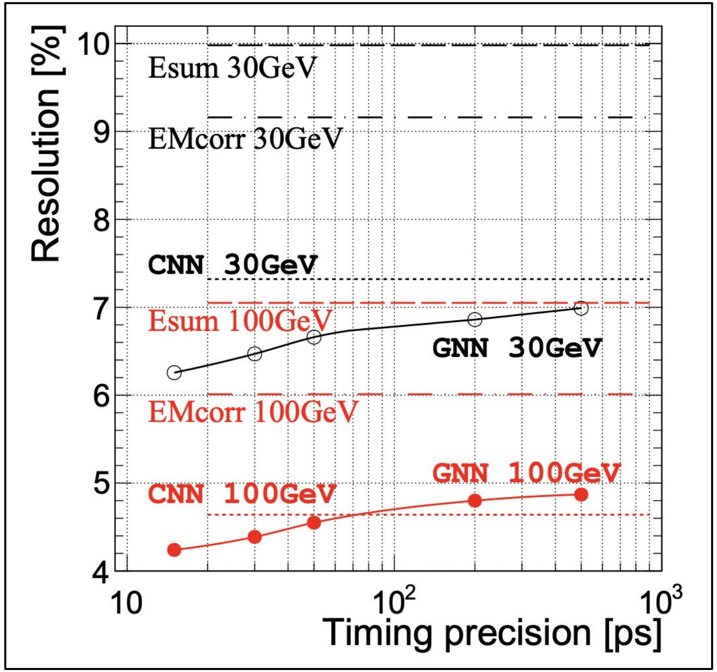
electron



charged pion

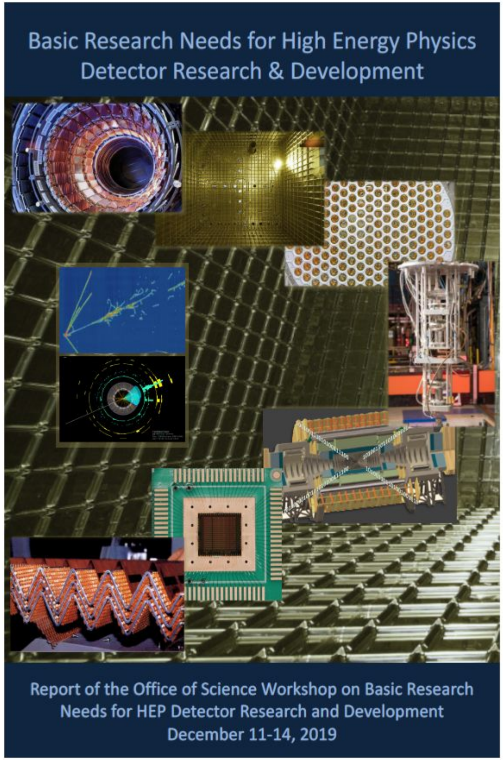






Fast timing: A Priority Research Direction

2019 DOE Basic Research Needs (BRN) Study on High Energy Physics Detector Research and Development



	PRD: Priority Research Direction	Grand Challenge
Calorimetry	PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements	1
	PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments	1,4
	PRD 3: Develop ultrafast media to improve background rejection in calorimeters and particle identification detectors	1,3,4
Photodetectors	PRD 7: Extend wavelength range and develop new single-photon counters to enhance photodetector sensitivity	1,3
	PRD 8: Advance high-density spectroscopy and polarimetry to extract all photon properties	2,3
	PRD 9: Adapt photosensors for extreme environments	2,4
	PRD 10: Design new devices and architectures to enable picosecond timing and event separation	1,2,4
	PRD 11: Develop new optical coupling paradigms for enhanced or dynamic light collection	1,2,3
SolidState	PRD 18: Develop high spatial resolution pixel detectors with precise high per-pixel time resolution to resolve individual interactions in high-collision-density environments	1,4
	PRD 19: Adapt new materials and fabrication/integration techniques for particle tracking	2,3
	PRD 20: Realize scalable, irreducible-mass trackers	2,3

EFCA Detector R&D Roadmap

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