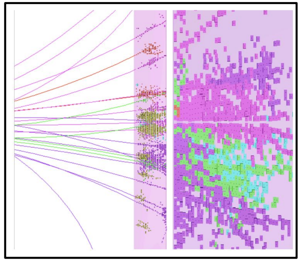
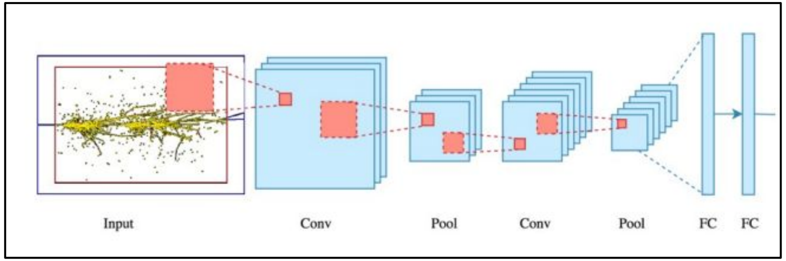
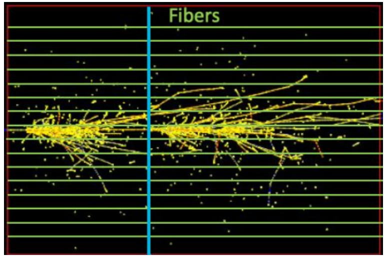
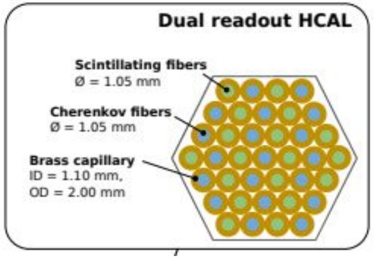








Dual Readout 5D Calorimetry at SLAC

Ariel Schwartzman, Su Dong, Rainer Bartoldus, Julia Gonski, Lorenzo Rota, Bojan Markovic, Larry Ruckman, Chris Kenney + University Collaborators

SLAC NATIONAL ACCELERATOR LABORATORY

Fast-Timing Digital Single Photon Readout for 5D Calorimetry

Proposal Category 1

Lead Investigator: Ariel Schwartzman

Collaborators: Bojan Markovic, Lorenzo Rota, James Sinclair, Christopher Kenney, Rainer Bartoldus, Su Dong

Date: 10-June-2026

LDRD awarded: outstanding opportunity for the whole SLAC ATLAS group to lead key elements of both detector hardware and software and play a major role within US-FCC and DRD

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

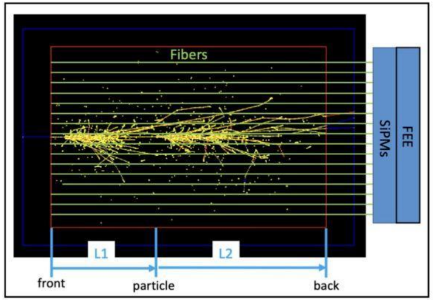
From Dual Readout to 5D Optical Calorimetry

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:

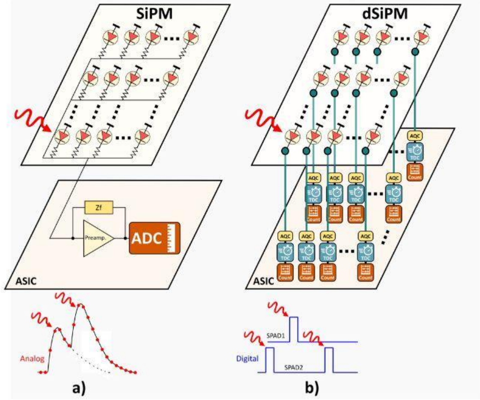
Fast-timing **L**ow-noise **A**dvanced **S**ingle-photon **H**igh-granularity

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

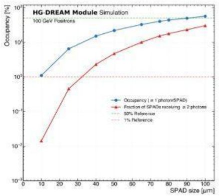


Analog SiPM	Digital SiPM
Summed microcell current	Individual SPAD-level response
Waveform digitization	Direct photon time stamping
Integrated analog signals	Sparse digital photon hits
High ADC power/data volume	Event-driven digital readout
Dense embedded services	Simplified scalable architecture
Data 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 $\lesssim 25\,\mu$m maintain low multi-photon occupancy,
- photon detection efficiency remains high under conservative deadtime assumptions,
- deadtimes of ~20 ns remain within a single bunch crossing.

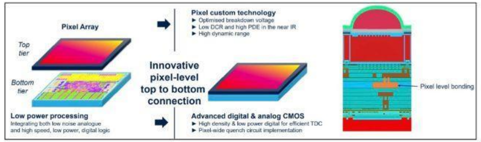


Enabling Technology: 3D SPAD–ASIC Sensor

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.

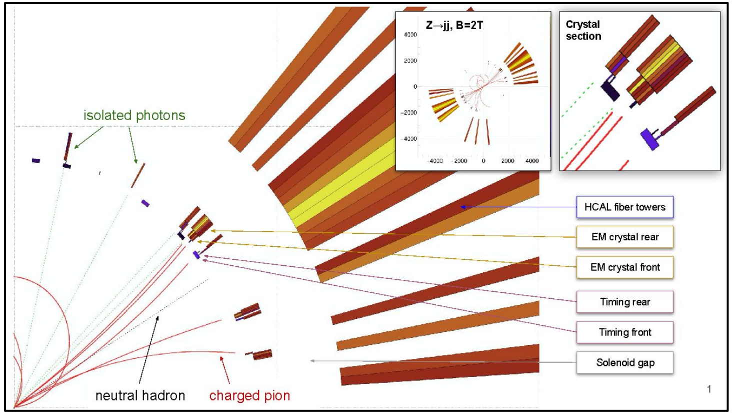
Anticipated Results and Deliverables

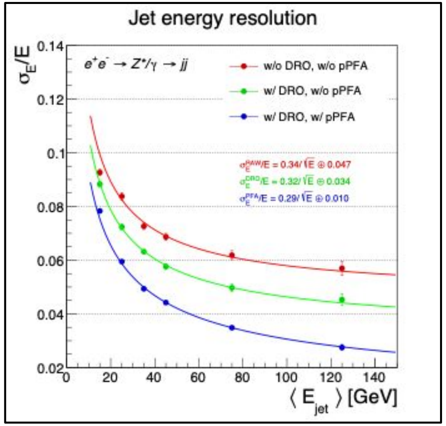
- **Y1Q1:**
  - **Define physics simulations to inform the requirements for the dSiPM system.**
  - **Define requirements and settling on the actual dSiPM ASIC architecture**
- **Y1Q2-Q4:**
  - Design of the ASIC containing SPADs and readout circuitry
- **Y2Q1:**
  - Submission to semiconductor fab for 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 (I): Simulations

- **dSIPM:**
  - Occupancy vs spatial/time granularity, dynamic range, efficiency, deadtime, time resolution → Chip specifications
  - Cherenkov vs Scintillating light requirements
  - Number of bits to transmit
- **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?

Next Steps (II):
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 SLAC! utilizing our whole breadth of expertise and interests in jets, tracking, timing, readout, FPGA, machine learning, and synergistic with ATLAS. Huge cutting-edge scientific and technical opportunities for students, postodcs, and scientists/faculty/engineers**

Next Steps (III): Readout

- **Test board for prototype**
  - Start from existing chip designs rather than building everything from scratch – Work with TID to verify functionality of the board
- **Readout for test beam**
  - Interface between TTU group, TID, and calorimeter concept
  - Measurements, mechanical integration, data analysis
- **Fully-digital readout scheme for full IDEA calorimeter**
  - Layout scheme
  - Synchronization, calibration, data volumes and rates
  - Single vs. double readout
  - Bunch spacing
  - eFPGE edge processing? clustering, noise-reduction, DR corrections? Fast calibrations?
  - Z-pole vs Higgs running
  - …

Next Steps (IV): Overall Concept

- **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, systematic uncertainties
    - Full FCC-ee IDEA simulations
    - Focus on aspects/questions that would most influence dSIPM requirements
- **AI/ML Detector design**
    - Evaluate impact of detector choices on physics performance
    - Leverage AI/ML efforts at SLAC

Next Steps (V)

- **Weekly SLAC/TTU/UNM meetings:**
  - https://indico.slac.stanford.edu/category/154/
  - 5d-calorimetry@slac.stanford.edu
  - https://www.when2meet.com/?38007945-2t82H

- **SLAC 5D Calorimetry meetings** (off-week FPD Higgs Factory meetings, same date/time:
  - https://indico.slac.stanford.edu/category/168/
  - 5d-calorimetry-slac@slac.stanford.edu
  - Co-organized by Julia and Ariel

- Plan presentations in US-FCC, CalVision, CPAD, DRD to update community and grow effort with university collaborators

Many opportunities

1. Simulations

dSIPM Specs & Timing:

- Analyze occupancy vs granularity, dynamic range & deadtime.
- Determine longitudinal segmentation via timing parameters.
- Correlate scintillating with Cherenkov light timing.
- Assess space-time clustering and shower time development.

2. 5D PFLOW

Algorithm & Integration:

- Unify PFA & DRO into a novel ML/AI particle flow algorithm.
- Integrate high granularity fiber readout with longitudinal timing.
- Leverage cross-departmental SLAC expertise (ATLAS synergy).

Michael Kagan

3. Digital Readout

Readout Scheme & DAQ:

- Define synchronization, calibration, and rate volumes.
- Evaluate single vs. double readout architectures.
- Develop eFPGA edge processing (clustering, noise-reduction).
- Adapt for Z-pole vs. Higgs running environments.

Julia Gonski
Su Dong

4. Overall Concept

Integration & AI/ML:

- Integrate Crystal with Fiber HCAL, tracker & PID.
- Address reference time, calibration & systematics.
- Evaluate detector choice impact on physics.
- Leverage AI/ML design efforts at SLAC.