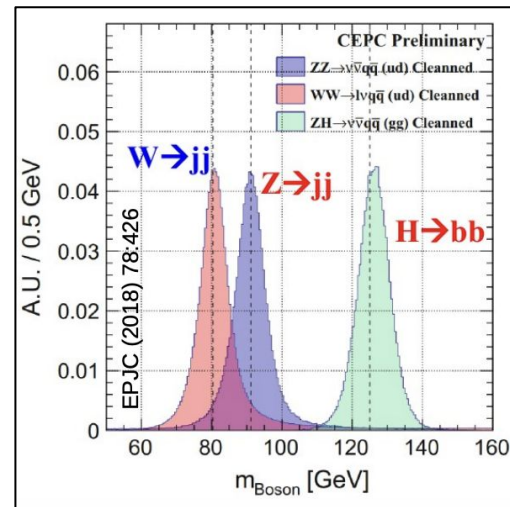
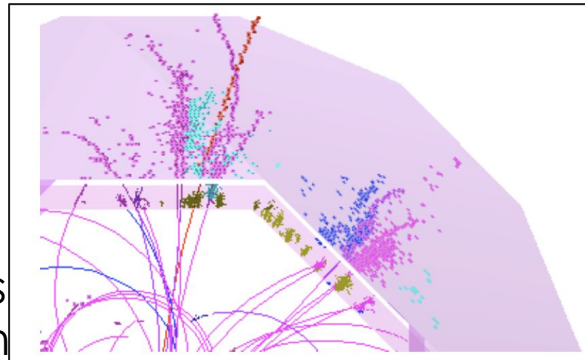


Dual Readout 5D Calorimetry at SLAC

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

Calorimetry at Future Colliders

- **The Calorimeter is one of the critical components of a Higgs Factory detector**
 - essential for the precision measurement of jets, and it represents the dominant component of the overall cost
- The Calorimeter is also the sub-detector that exhibits the greatest variation among proposed designs with two opposing approaches: **Particle Flow** (PFA) (tracking plus high granularity calorimetry) and **Dual Readout** (DRO) (Scintillating and Cherenkov light for e/h compensation)
- **Higgs boson precision measurements require unprecedented jet energy resolution to separate hadronic W's, Z's, and H's**
- 3-4% $\Delta E/E$ at 100 GeV
 - Very difficult to achieve with traditional calorimetry



Calorimetry Approaches

~40 years ago

Software compensation

Weight calorimeter depositions (clusters, cells) based on local information (E density, segmentation)

Example: ATLAS Local Hadron Calibration

~20 years ago

Particle Flow

Replace charged hadron energy depositions by tracks

Limited by confusion term (overlapping showers)

Non-linear response and resolution due to fluctuations in charged particle content jet-by-jet

~20 years ago

Dual Readout

Use Cherenkov and Scintillating light to measure e/h event-by-event and correct the hadronic response

Better suited for particle flow due to better cluster resolution → improved track-cluster matching

~5 years ago

5D

High granularity DR
+ **timing** + **ML** + PFlow

Very high granularity dual readout combined with AI/ML for 5D measurements: (x, y, z, E, t)

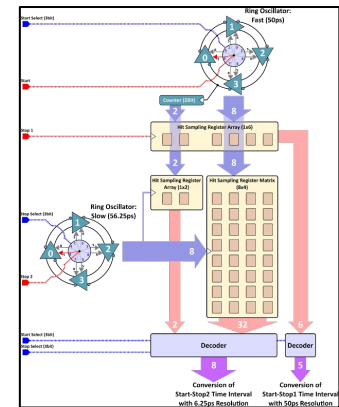
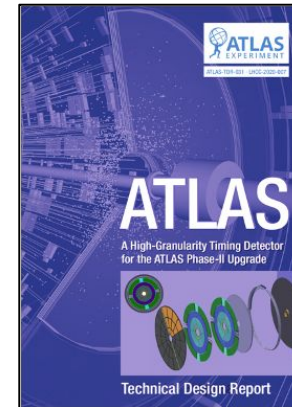
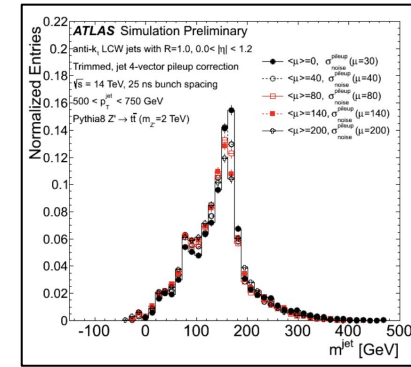
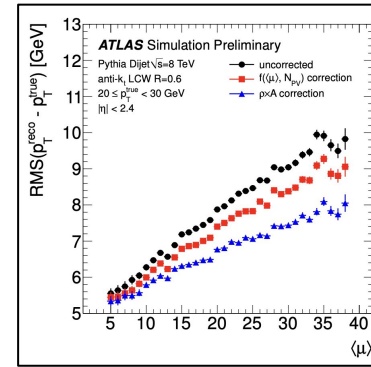
New handles to improve energy resolution: better separation of nearby showers for improved particle flow

- Long Lived Particles
- Jet substructure

SLAC's ATLAS Global Sequential Calibration
(inspired by DRO) + **Track-based reconstruction**

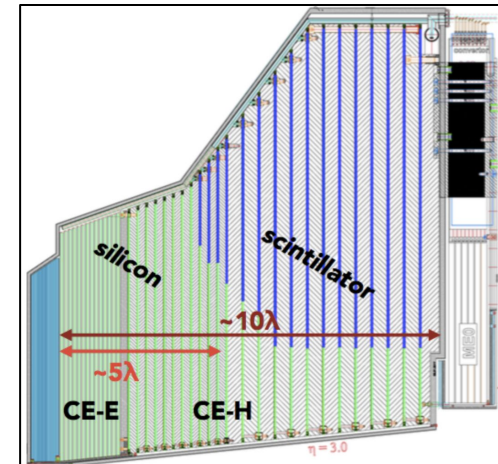
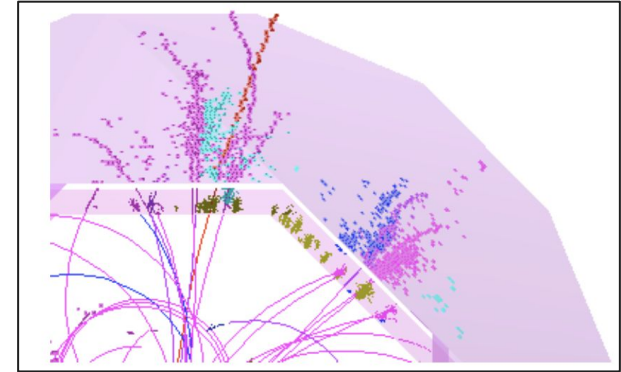
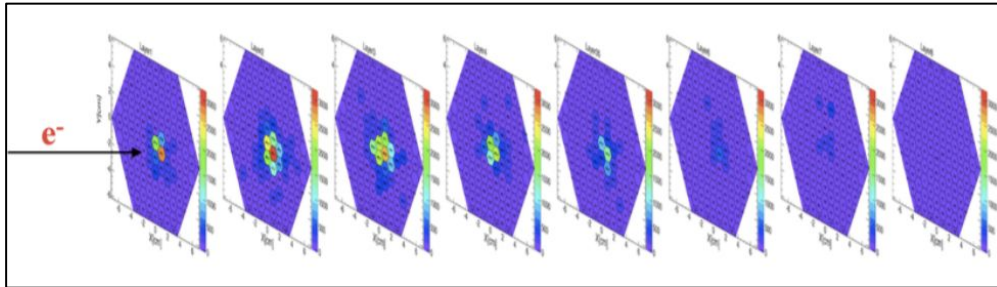
ATLAS Calorimetry and Timing

- Major contributions in the development of jet reconstruction and calibration and combining tracking with calorimetry
- Pioneered the HGTD detector since the start until the TDR, designing the core ASIC electronics
- Many lead roles: Jet/ETmiss, Upgrade physics, HTGD physics and simulation
- More recently pioneering combining HGTD with LAr timing in ATLAS
- SLAC is a well established Institution with two decades of leadership in calorimeter reconstruction, fast-timing, and readout electronics as a launch platform towards FCC-ee Calorimetry**
- Extremely synergistic with pixel detector and AI/ML expertise: key for FCC-ee high granularity calorimetry + overall Particle Flow design!**

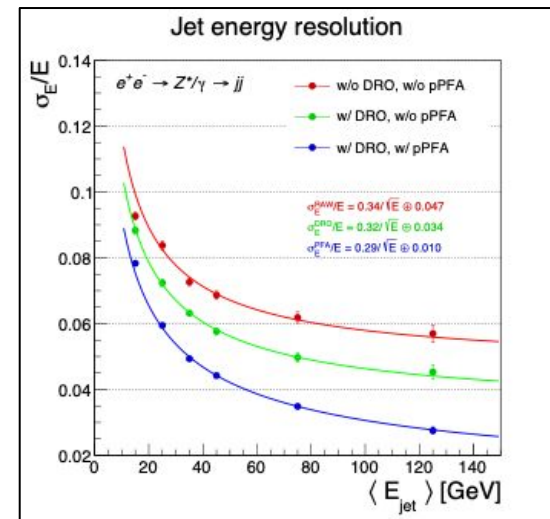
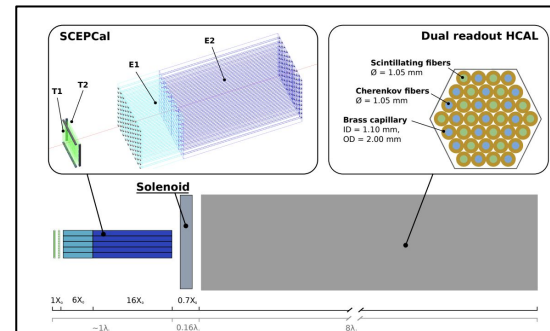
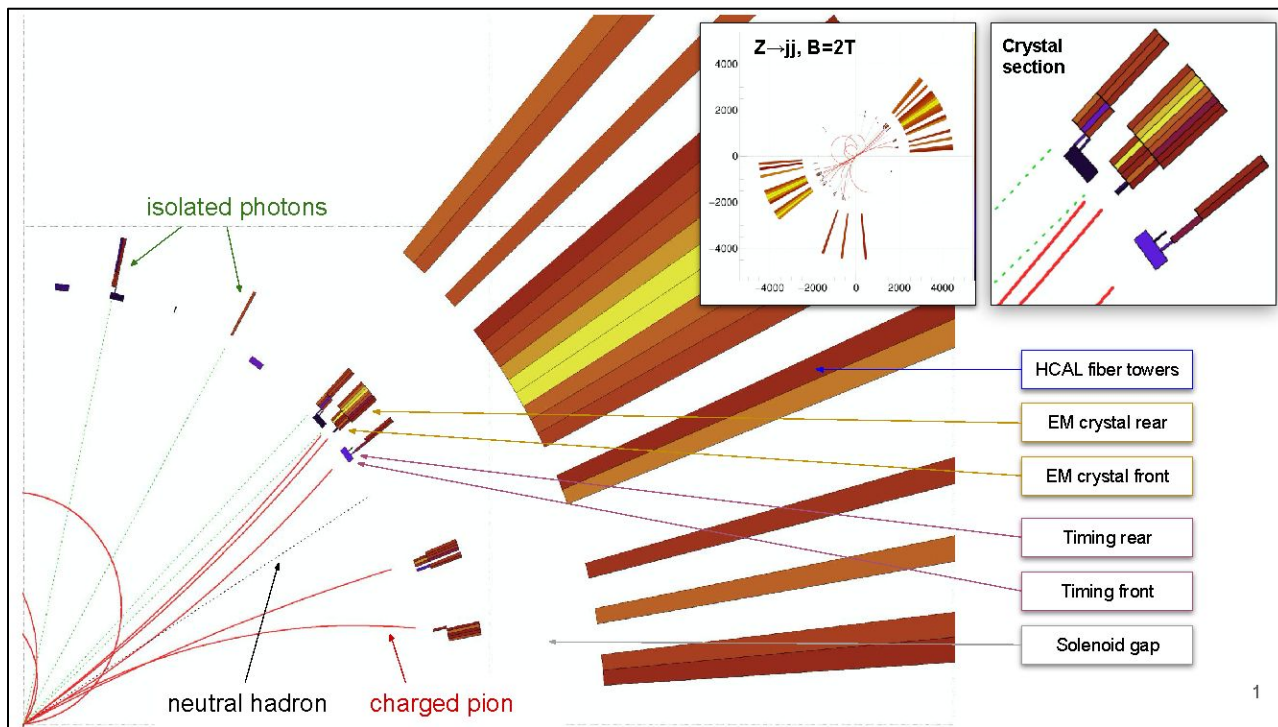


Calorimetry Challenges

- Hadronic calorimetry remains fundamentally limited by fluctuations in shower development and by confusion effects in dense environments
- 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



IDEA Calorimeter Concept

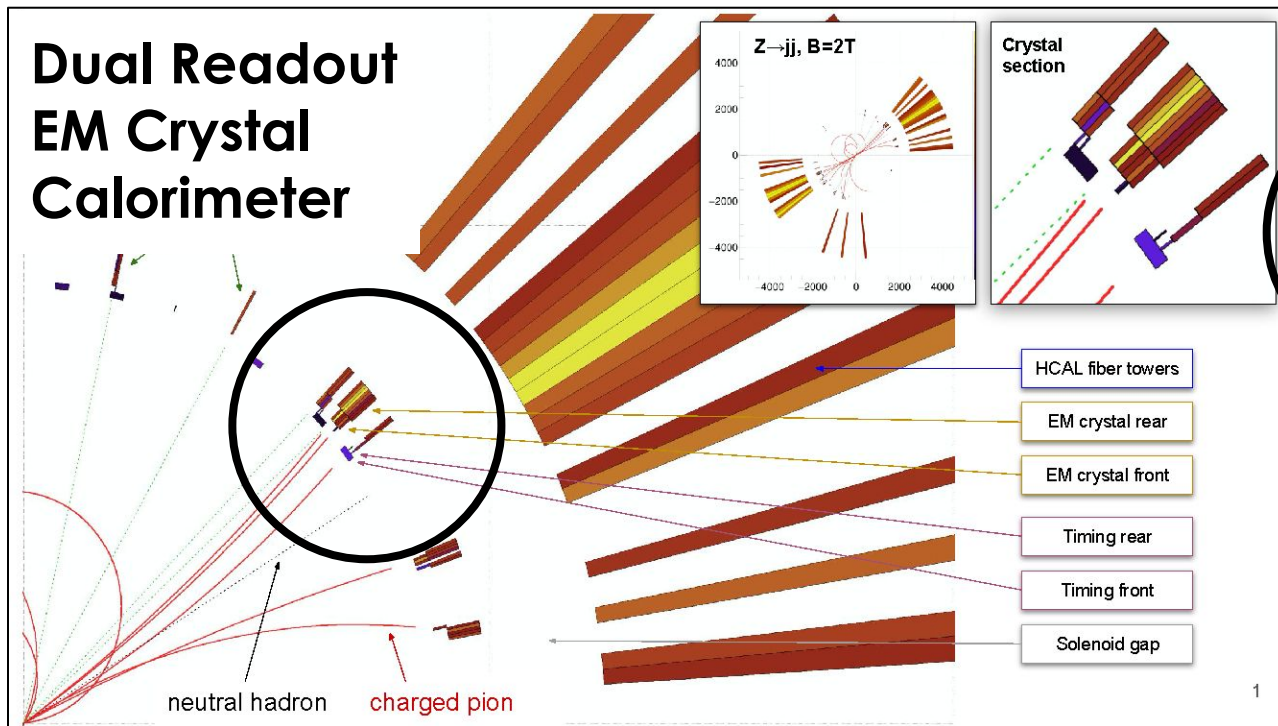


Dual Readout 5D Particle Flow:

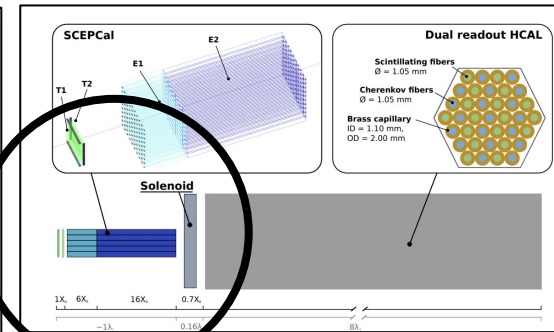
Combine Scintillating and Cherenkov light, (timing), and tracks

Dual Readout IDEEA Concept

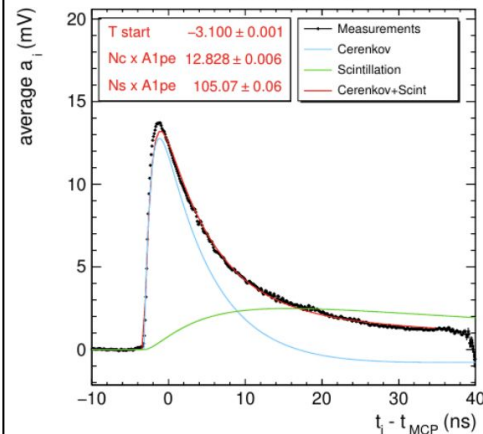
Dual Readout EM Crystal Calorimeter



Excellent EM resolution, but worse e/h $\rightarrow$ C/S extraction
front-end electronics SiPM design

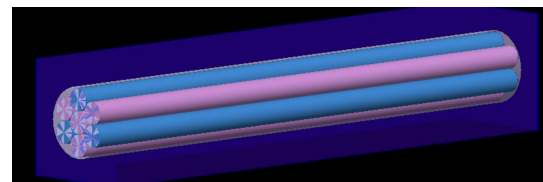
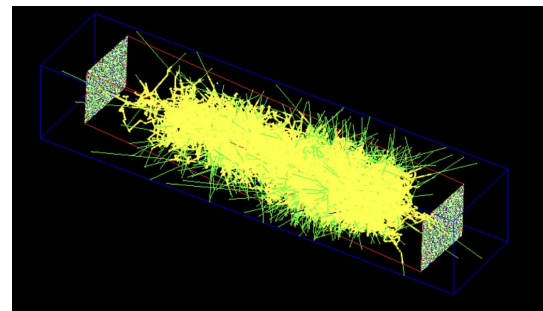
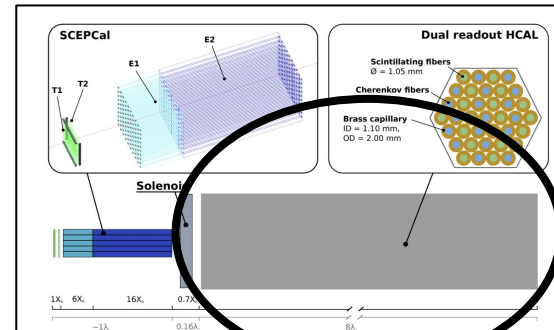
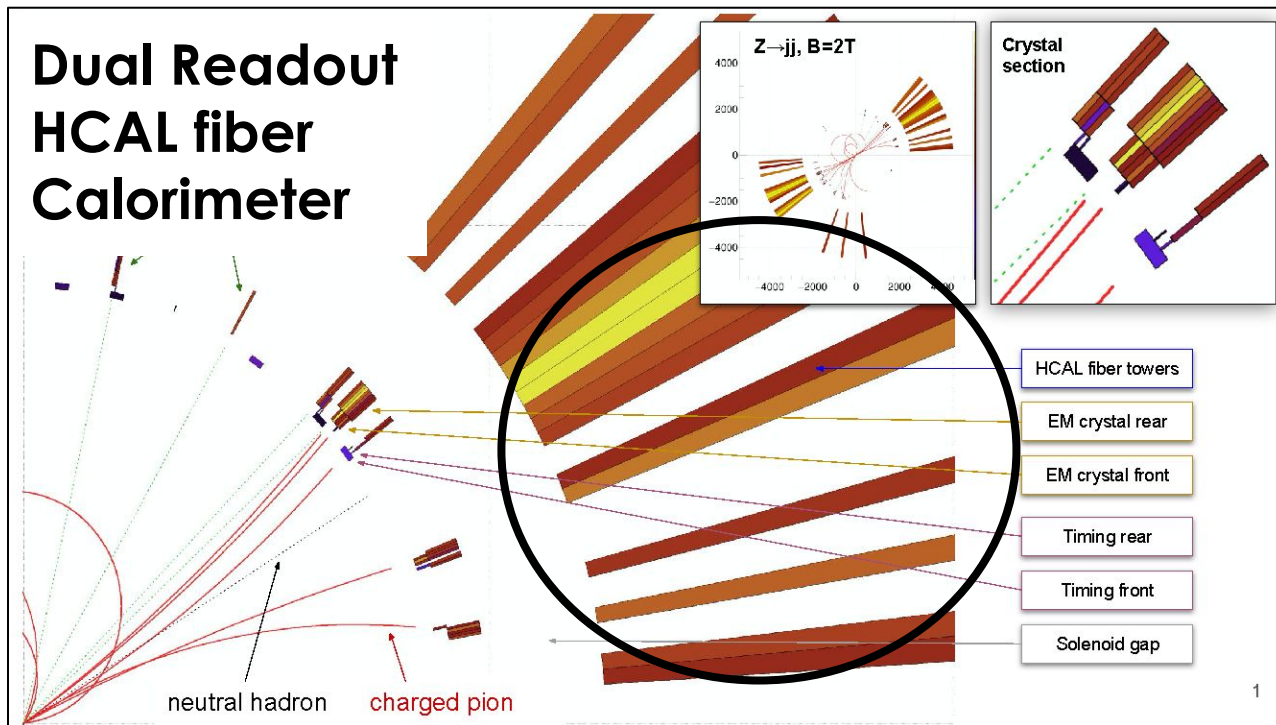


Back SiPM (U330 filter)



Dual Readout IDEA Concept

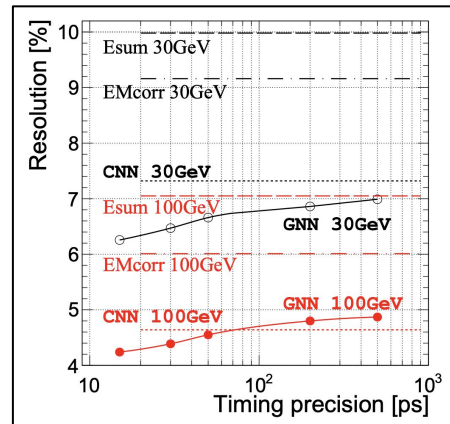
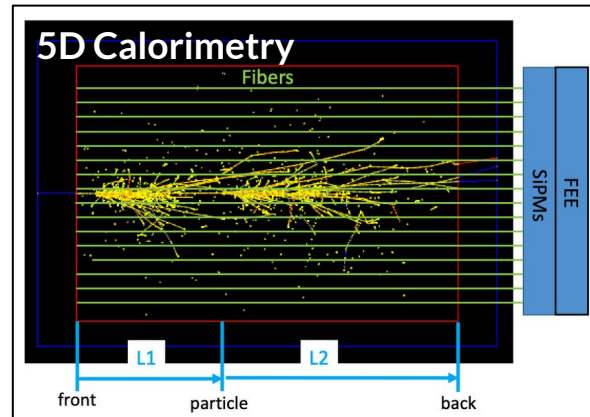
Dual Readout HCAL fiber Calorimeter



5D concept: longitudinal segmentation via fast-timing
Cherenkov+ML for full space-time shower reconstruction
Digital SiPM R&D

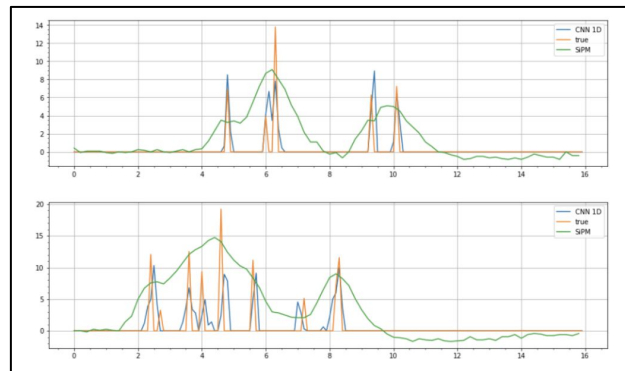
5D Dual Readout Calorimetry

- 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.
- In 5D dual-readout calorimetry, the shower evolution is reconstructed through timing using continuous fibers and a single (or double) readout layer at the back (and front) of the calorimeter. This architecture substantially simplifies detector services and electronics accessibility while preserving longitudinal shower information.
- This represents a quantum leap in calorimetry for the FCC-ee IDEA Calorimetry**



5D Dual Readout Calorimetry

- However, a 5D calorimeter cannot realistically be implemented simply based on today's photodetectors and readout electronics:
 - SiPMs with waveform digitization create severe scaling challenges in power, data volumes, calibration complexity, and system cost as the channel count grows
- The next generation of 5D calorimeters will require a new class of single-photon sensitive detectors with fast timing and ultra-high granularity
- A major objective of SLAC's current efforts is to build and demonstrate the core enabling sensor technology towards 5D calorimetry: a **fully-digital SPAD-based photon detector (digital SiPM)**, that combines single-photon detection with 50 ps timing, high fill factor, and fine pitch $O(10\text{ }\mu\text{m})$

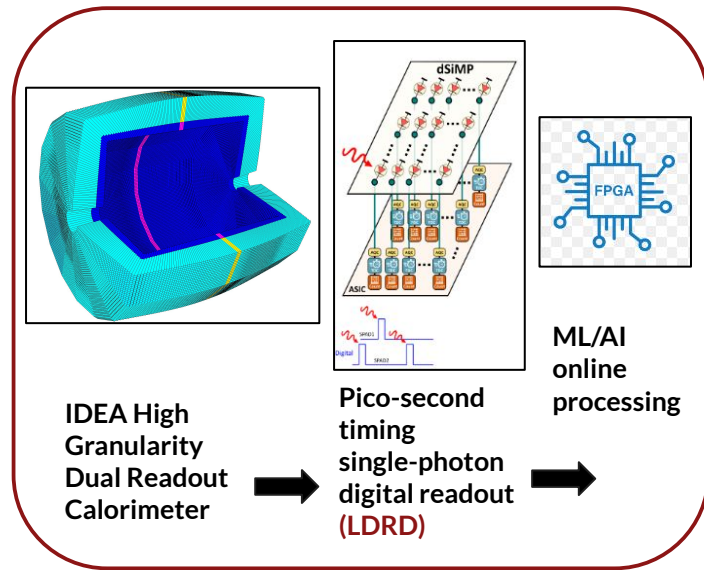


**Heavy computation
needed to retrieve
timing of individual
pulses from digitized
SiPM waveform!**

(Investigating within KA-29)₁₀

FLASH: Digital Photon Readout for 5D Calorimetry

- SLAC and Texas Tech University have introduced the **FLASH calorimeter concept**: *Fast-timing Low-noise Advanced Single-photon High-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 $O(10\ \mu\text{m})$ scale
 - timing precision at the $O(10\text{--}50\ \text{ps})$ 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



If successful, this technology will place SLAC at the forefront of 5D calorimetry for FCC-ee, leveraging our unique capabilities in ASIC and SPAD design, calorimetry, readout systems, and strengthening our collaboration with Texas Tech University

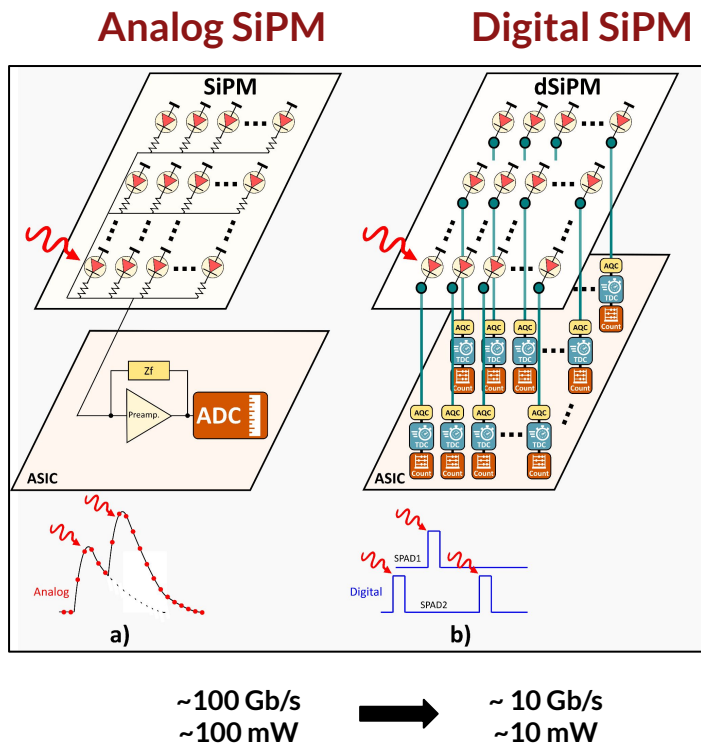
Single-photon detectors: analog vs digital SiPMs

- **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



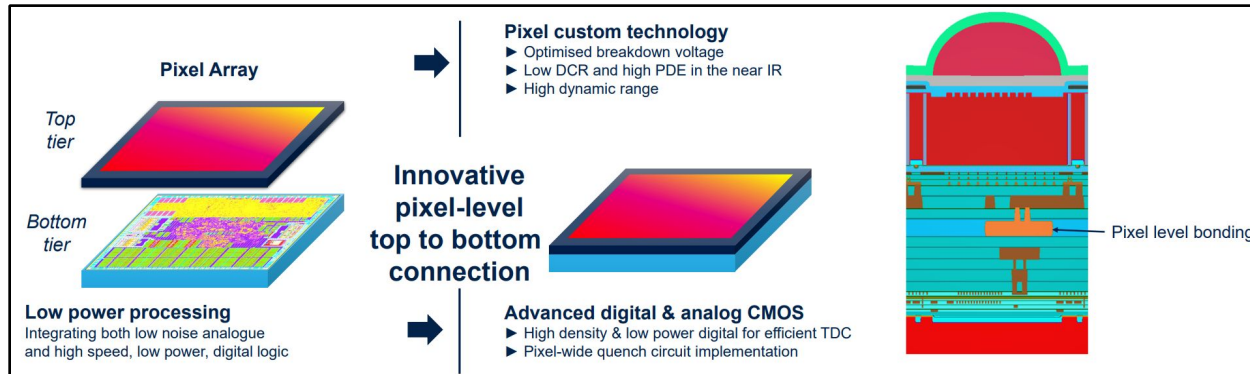
3D Stacking Technology

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**



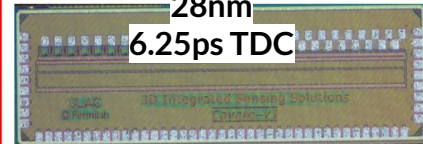
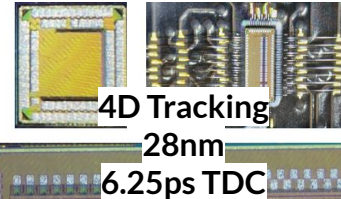
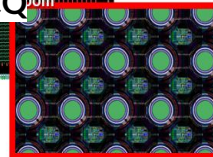
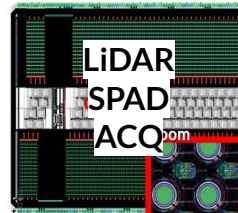
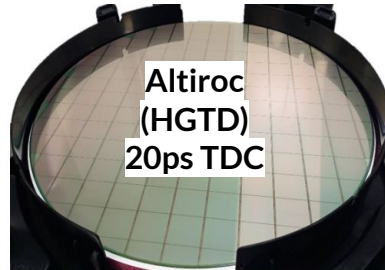
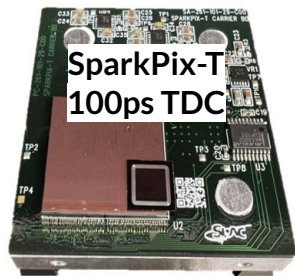
Readout ASIC

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

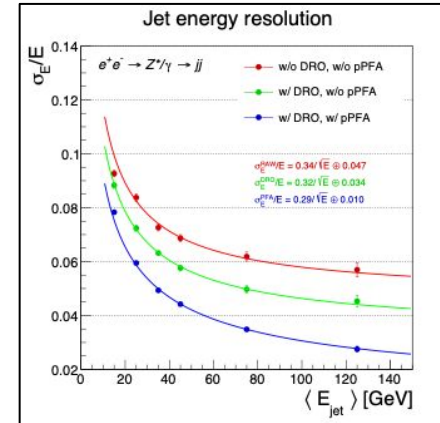
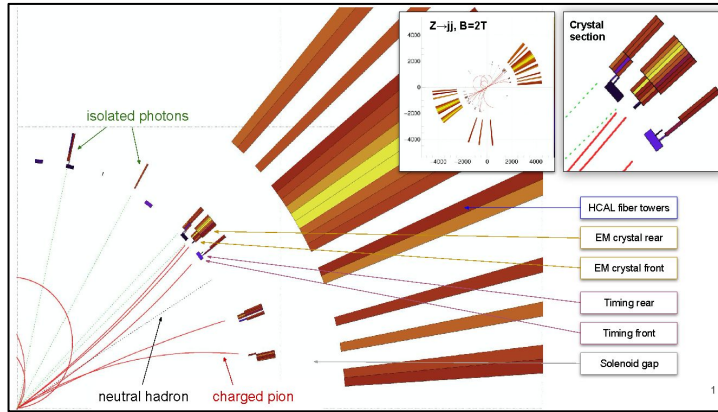
The ASIC will incorporate:

- 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 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, postdocs, and scientists/faculty/engineers

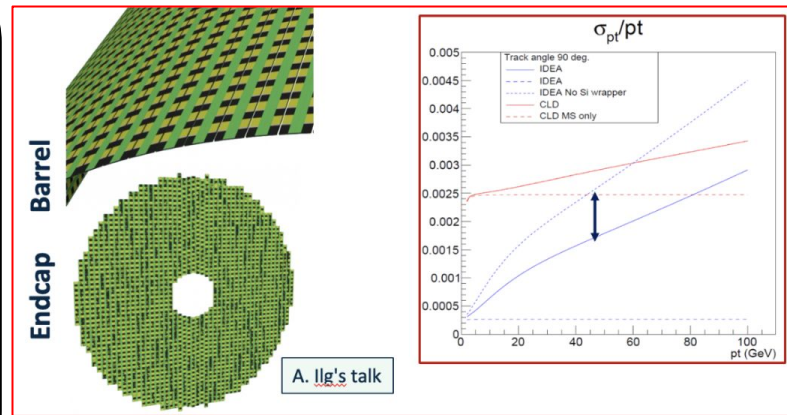
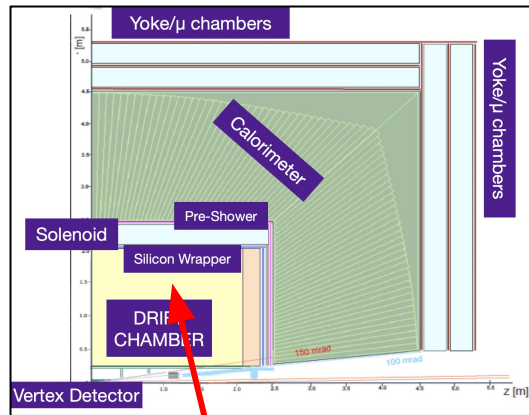
FCC-ee Timing Layers

ALLEGRO



Silicon Wrapper

IDEA



IDEA

- Precision silicon layer around the central tracker
 - Two barrel and two disks, $\sim 100\text{m}^2$ of total covered area
 - $10\mu\text{m}$ hit spatial resolution to Improve track momentum resolution
 - Time of flight for particle identification and long lived particle searches
 - Time reference for 5D Calorimetry
- Interest and expertise in tracking, electronics, LGAD sensors, and interplay between timing layer and calorimeter timing, including vertex t_0

Landscape

Next 10-20 years: 5D Calorimetry (x,y,z,E, t) and silicon wrapper in e^+e^- Higgs Factory

- 35%/√E hadronic energy resolution
- 10-20ps resolution for long lived particles
- 10ps for Time of Flight PID

CPAD goal: US
5D-Calorimeter
demonstrator

20+ years: 5D Calorimetry in 10 TeV muon/hadron colliders

- 5ps resolution for 1,000 pileup suppression and 20-60 ps for BIB suppression
- high radiation environment
- Full 4D tracking + 5D calorimeter

This research direction expands a decade of SLAC expertise and leadership in timing detector development (photon science, HEP timing-layers and 4D tracking) to the next leap in HEP calorimetry, and positions SLAC to have a major role in the IDEA detector concept at FCC-ee

4D Tracking and 5D Calorimetry are one of the most innovative elements for all future collider concepts. **Optimizing the Higgs factory physics potential requires the combined optimization of fast timing in the tracker and the calorimeter for 5D Particle Flow: ideal scope for a National Lab**

Status and Next steps (I)

- Establish SLAC+Texas Tech as leaders in 5D Calorimetry within the international community
 - **Digital SiPMs**
 - FLASH LDRD proposal to fabricate ASIC and test in beam
 - Meeting and discussing with IDEA and DRD groups in Europe interested in this technology, as well as CalVision in the US
 - **EM Crystal:**
 - eFPGA for C/S extraction and Fiber photon timing: analog SiPM / waveform digitizer (or dSiPM)
 - **Simulations**
 - Need extensive studies to fully **demonstrate longitudinal segmentation and timing** capabilities and set requirements for ASIC and detector design
Outstanding opportunity for students and postdocs!
 - Integration of Dual readout Fiber HCAL, EM crystal, SiW layer, tracker, and PID
 - How to best integrate Crystal with Fiber calorimeter? PID?
 - Reference time and calibration
 - Combined Particle Flow detector optimization
 - ML/AI detector design

LDRD

KA-29

US-FCC

Status and Next steps

- Establish SLAC+Texas Tech as leaders in 5D Calorimetry within the international community
 - **On-chip processing**
 - Current work by Julia's group for EM Crystal Calorimeter based on analog SiPMs / Extend to 5D Fiber time extraction
 - Investigate opportunities to process time-ordered sequence of photons for noise reduction, clustering, Dual-readout corrections, other new ideas?
 - Strengthen connection with CalVision
 - **5D Particle Flow with AI/ML**
 - How to best integrate single-photon time-resolved counts for Cherenkov, Scintillating light, and tracks, within a foundation model for 5D Particle flow
 - Leverage our expertise in jet/ETMiss and AI/ML in ATLAS
 - Huge opportunity for innovation at the cutting-edge of detector technology and physics performance

How to advance this vision

- **LDRD (and follow-up) funding to fabricate FLASH sensor is critical**
 - Led by TID
 - Student, postdoc, scientists contributions to beam tests and lab testing
 - Continue to position SLAC within the international community
- **eFPGA processing + calorimeter readout architecture**
 - Major activity with TID
- **Simulations**
 - Critical
 - Need engagement from students and postdocs and grow presence within CalVision and DRD
- **ML/AI 5D Particle Flow**
 - Outstanding opportunity for students, postdocs, and everyone!
- **Overall detector design**
 - EM Crystal + HAD Fiber, timing, tracking, Silicon Wrapper, PID, readout

Summary

- **IDEA 5D Dual Readout Calorimetry is an outstanding opportunity for SLAC ATLAS/TID: Very large, innovative project that leverages our National Lab expertise in large detector systems, fast-timing and ASIC electronics, dSIPMs, tracking, pixel detectors, DAQ, machine learning, jet physics and calorimetry**
 - Innovative core technologies for this calorimeter (pixels, timing, dSIPMs, eFPGA, readout) are an ideal fit for SLAC, exploits our core capabilities, and can put us at the forefront of DR-5D calorimetry
- **SLAC can become a lead lab to develop the key technologies to enable a large-scale 5D Calorimeter concept for FCC-ee, involving the combined strengths of the ATLAS group and TID**

Backup

IDEA

DR fiber HCAL

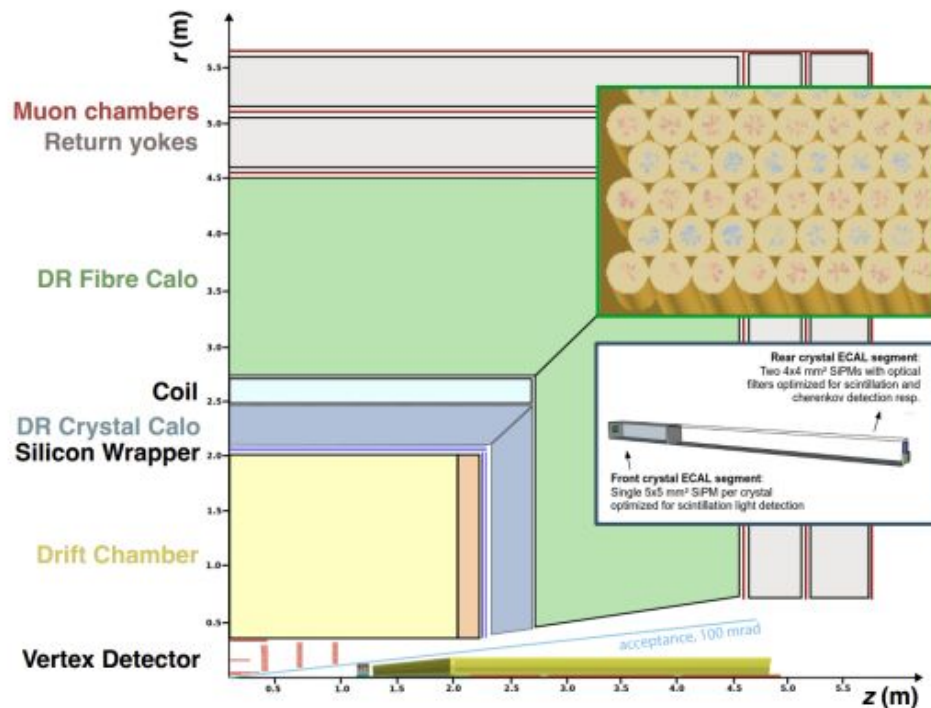
- Capillary tube w/ 2 mm diameter
- $\lambda_{\text{int}} \sim 25 \text{ cm}$

DR crystal ECAL

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

Solenoid

- $1.5X_0$ transparency based on [arXiv:2502.21223](https://arxiv.org/abs/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



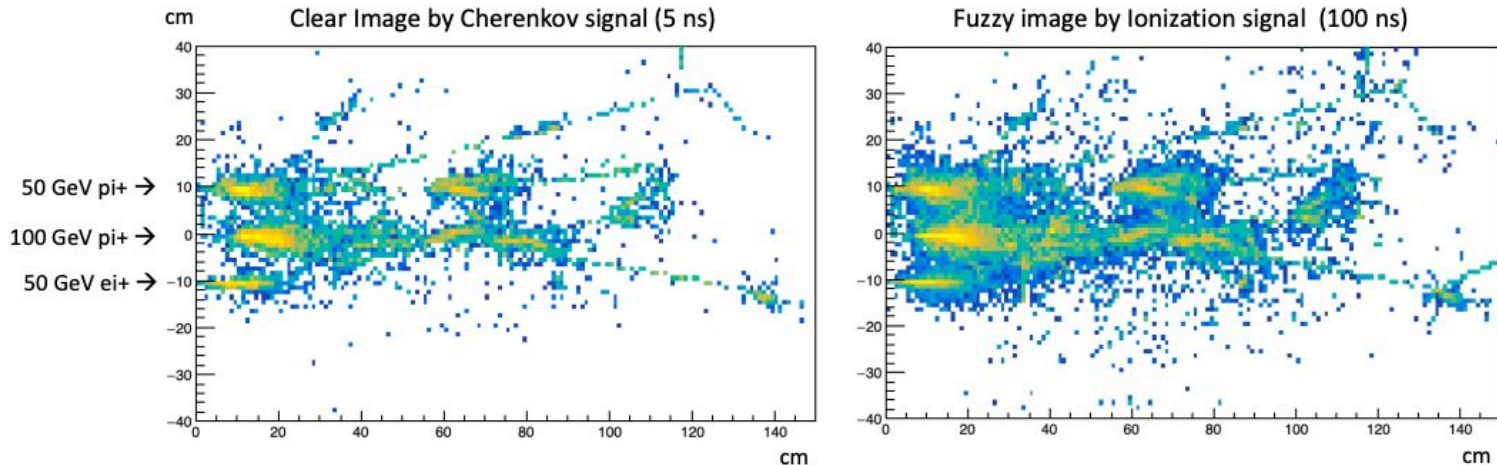
5D Dual Readout Imaging ML analysis

Clustering of Hits in Jet

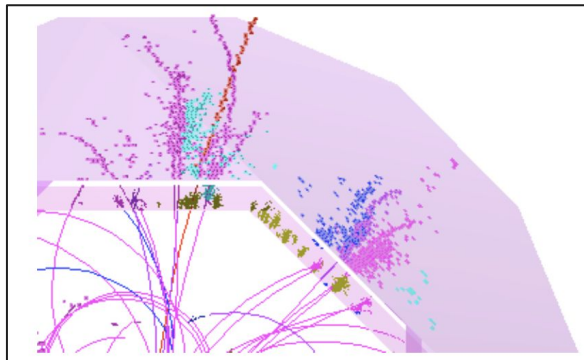
Cherenkov signal produces clear and narrow image of hadronic shower comparing to ionization signal. AI/ML may use such clean shower images for 3D pattern recognition of complex event structure.

- 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.

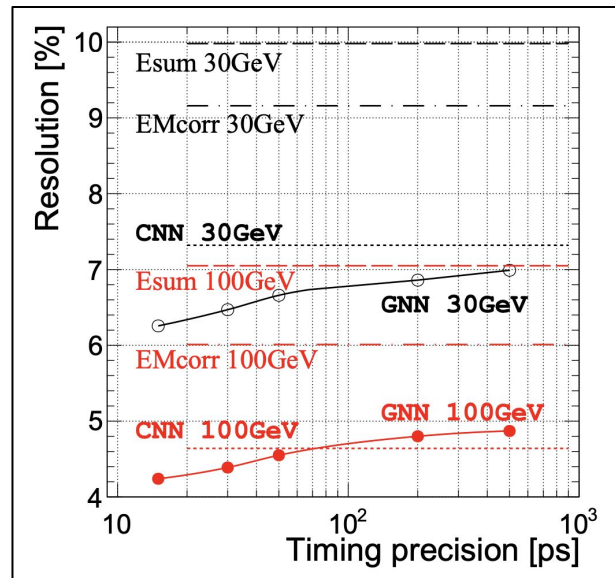
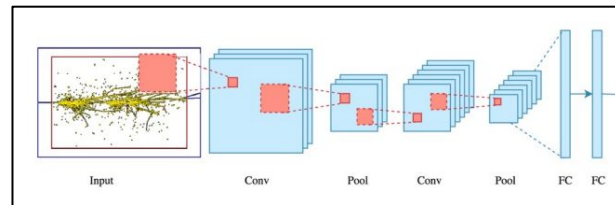
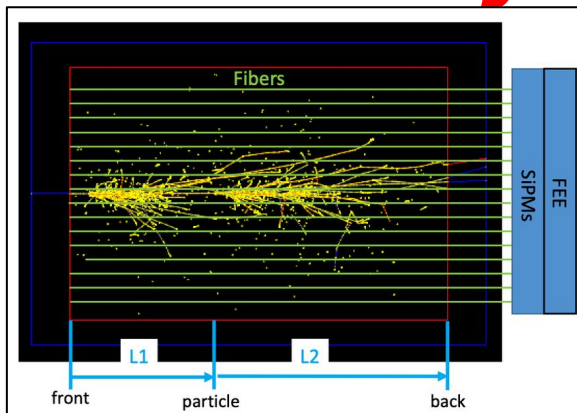
Below is an example of “pseudo jet”. Three particles hit a calorimeter at 10 cm apart. Assignment of “hits” to particle may be done in both cases (Cherenkov and Ionization), but the Ionization case becomes difficult once the separation get smaller.



5D Calorimetry and PFA

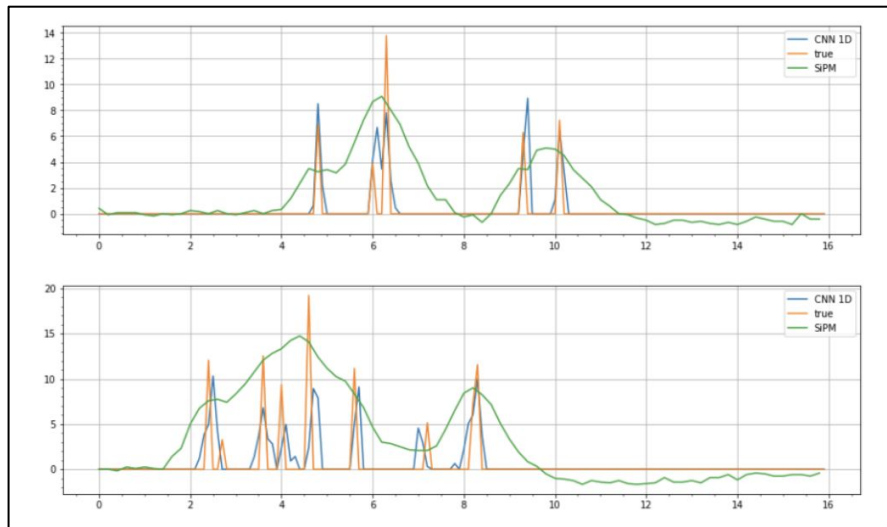
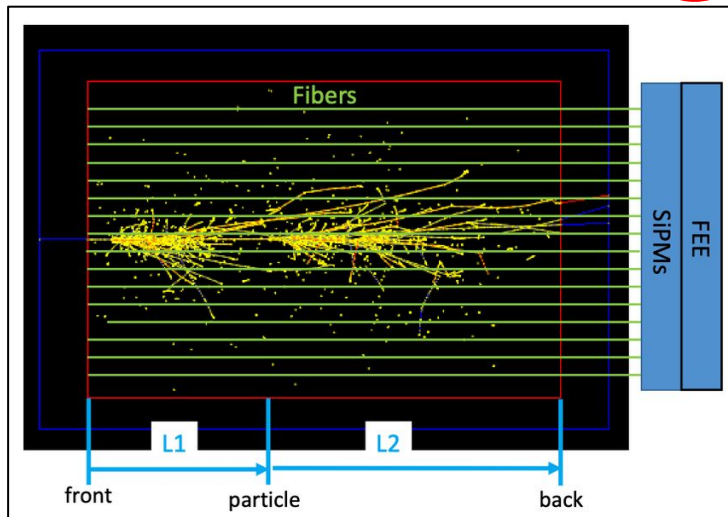


[Akchurin, et. al.](#)



- 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



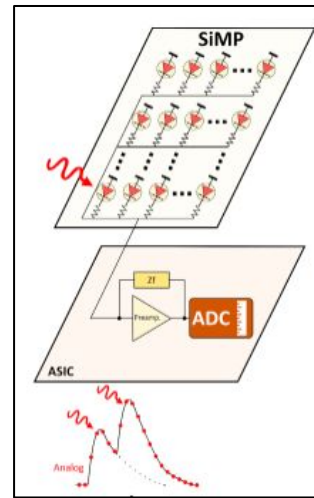
Current prototype based on ***analog SiPMs with fast-digitizer and processing***

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

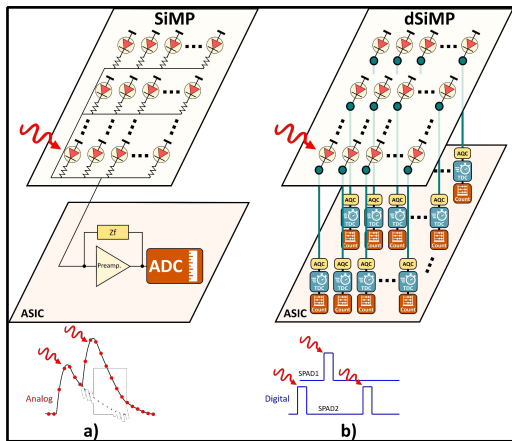
State of the Art Challenges

- 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

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

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. 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 effort: 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 techniques for high data volumes, including distributed processing, incorporating AI techniques, 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/1jhf6dERrrhOYavOujnYK90I7XsS3wyX3?usp=sharing>

R&D Directions

Electronics / Demonstrator

5D calorimetry demonstrator composed of stacked dSiPM die and a ~10ps timing and data-processing ASIC design:

- Fully digital: low-power consumption and suitable for high-granularity implantations,
- Dedicated dSiPM and ASIC dies allow for best detection (fill-factor, PDE, etc.) and electronics (time-resolution, power, ...) performance
- Leveraging SLACs expertise in high precision timing and SPAD (dSiPM cell)

Calvision EM Crystal:

- Front-end readout design
- C/S extraction on-chip

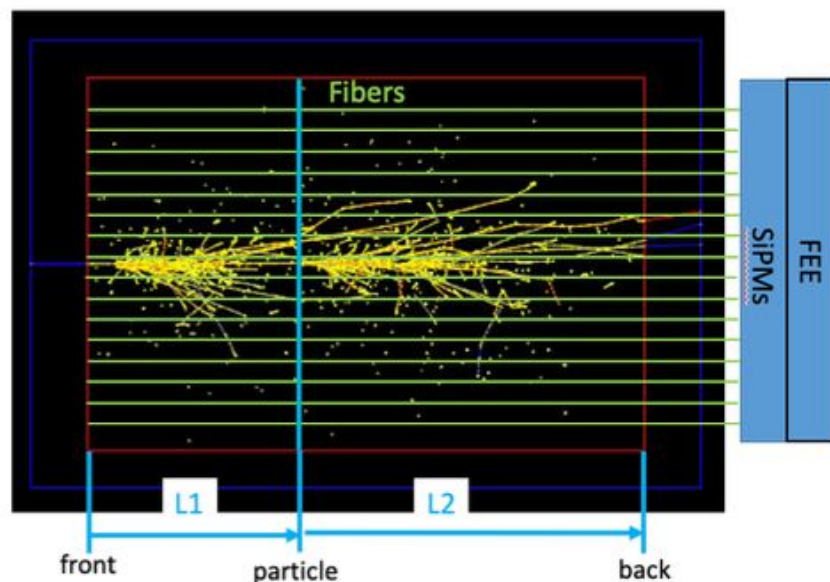
Overall detector concept / Simulations / Reconstruction

- jet performance
- ML reconstruction
- Use of tracks: DRO 5D Particle Flow: CalVision/IDEA
- Many ideas!

<https://docs.google.com/document/d/1YS5TLTkFvyR5cSLgGVjXCa6frOxDjehykXrVpyQ0cUU/edit?tab=t.0#heading=h.6evh2cl176kl>

Many exciting opportunities for detector design, software, ML reconstruction, test beams, and electronics (with TID) for **students and postdocs** to work towards developing the **next generation of calorimeters for future colliders!**

Longitudinal Segmentation with Timing

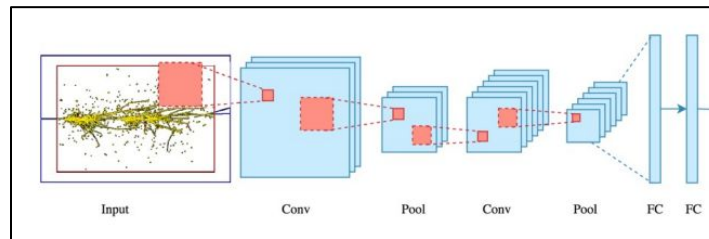
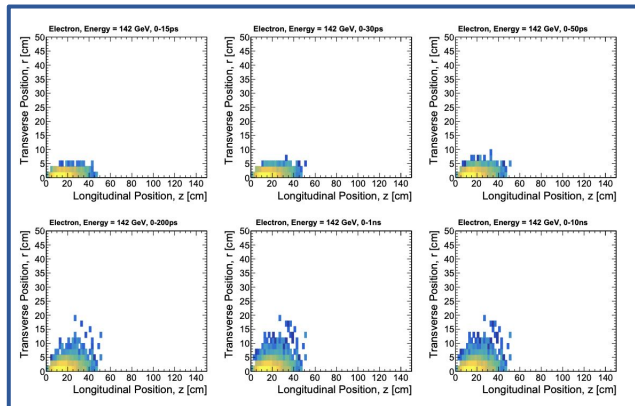


$$\begin{aligned}\text{Signal time} &= L1/c + L2/v \\ c &= \text{velocity of particle} \\ v &= c/n, n = 1.46 \\ \Delta L &= 2 \text{ cm} = 44 \text{ ps}\end{aligned}$$

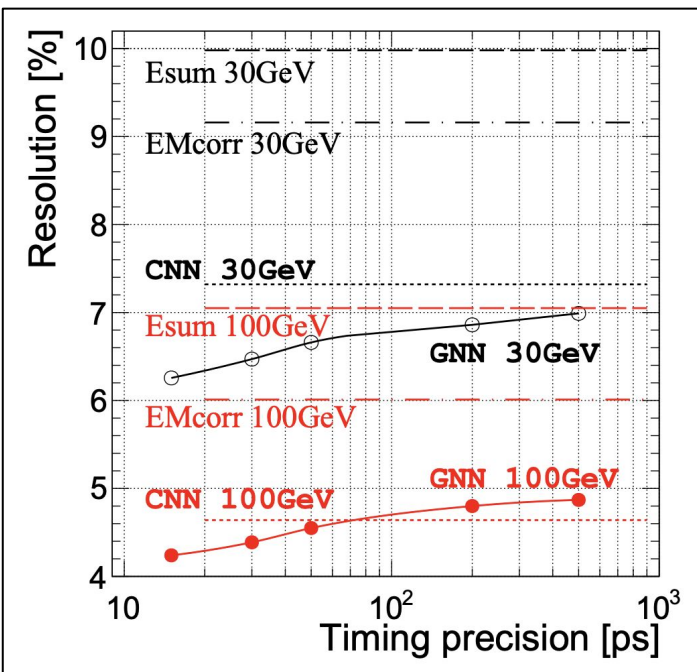
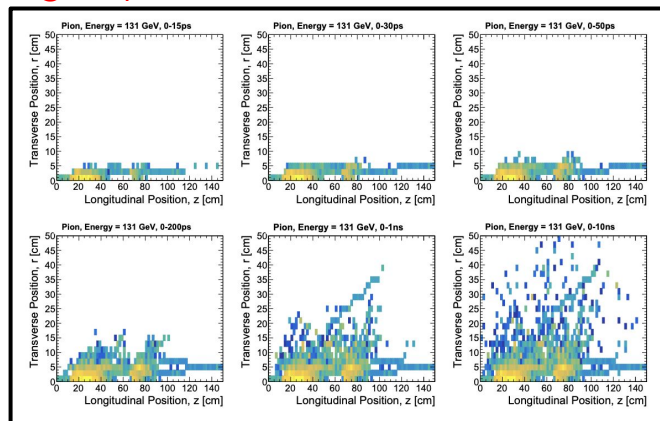
- ❖ 2D readout: fewer readout channels
- ❖ Effective 3D segmentation with timing
- ❖ Photo Detector and Front End Electronics (FEE) is on the back side of the detector, low radiations
- ❖ Easier signal collection
- ❖ The calibration is easier, no need to calibrate in depth

Fast-Timing + AI/ML 5D Calorimetry

electron



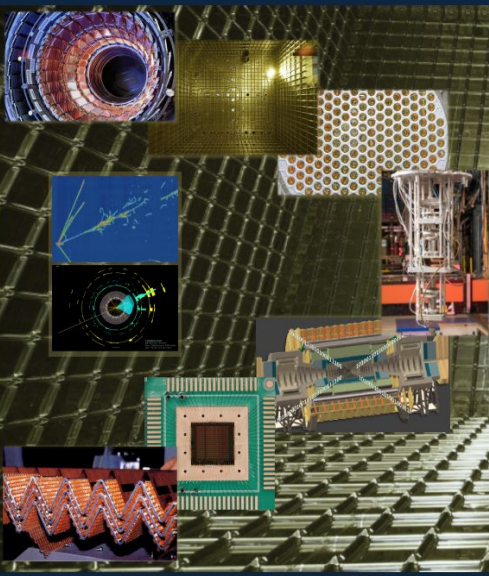
charged pion



Fast timing: A Priority Research Direction

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

Basic Research Needs for High Energy Physics Detector Research & Development

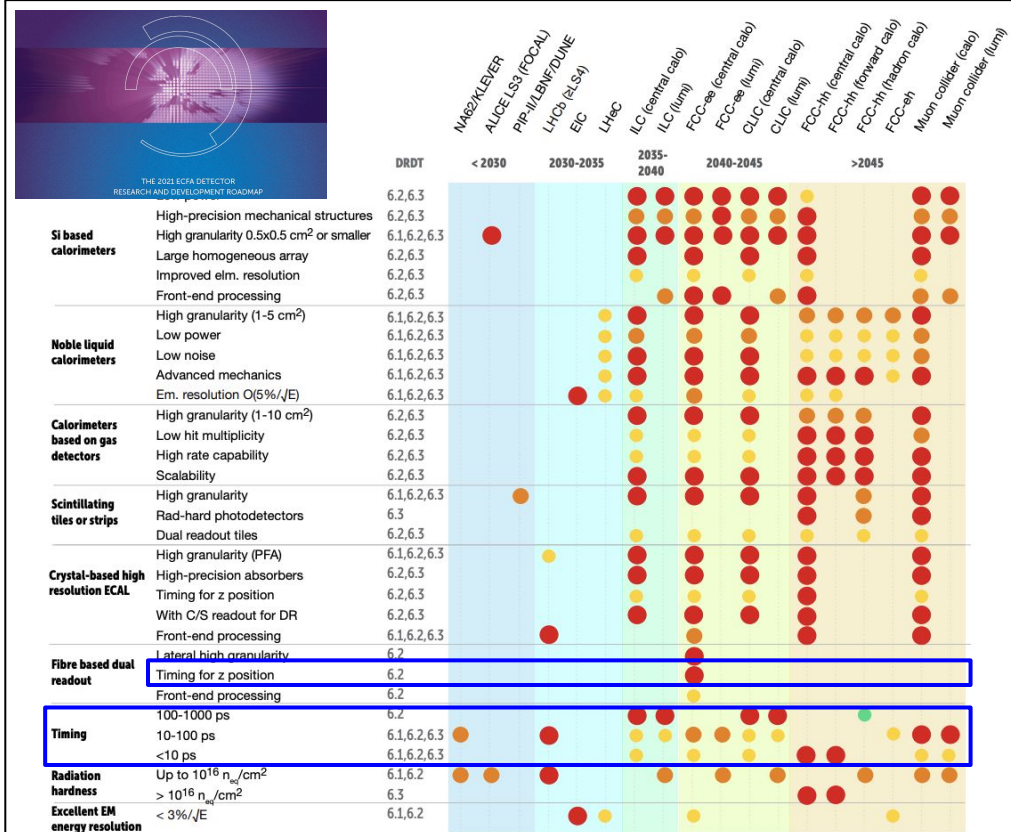
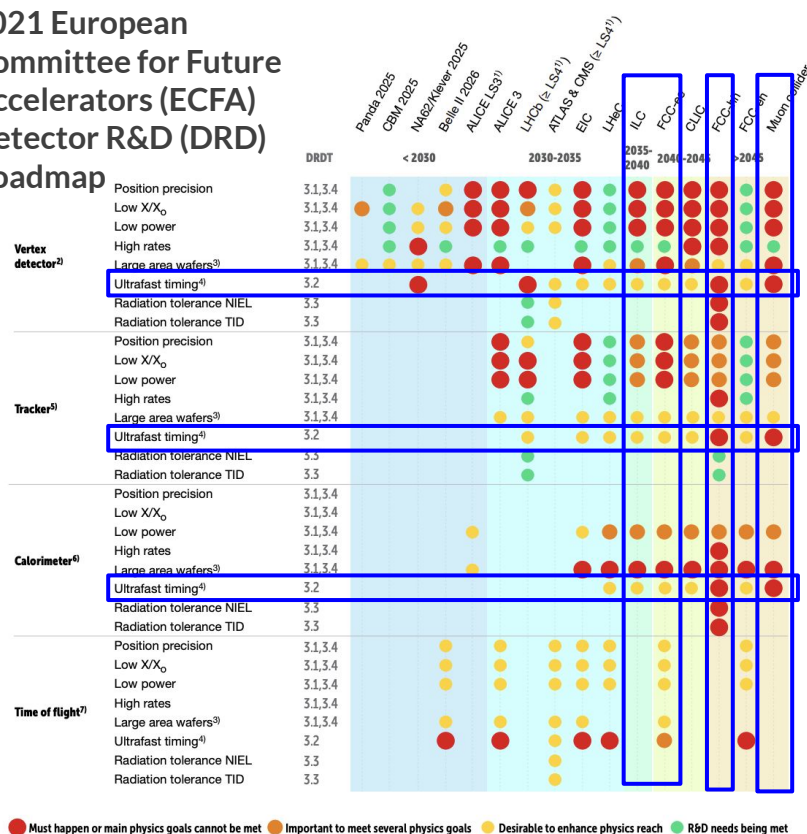


Report of the Office of Science Workshop on Basic Research Needs for HEP Detector Research and Development
December 11-14, 2019

	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

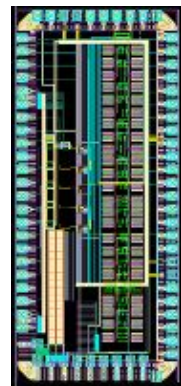
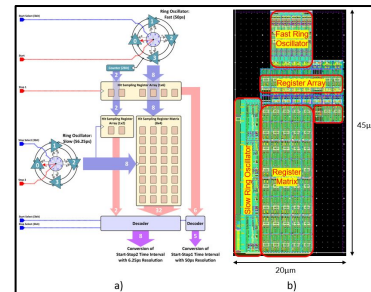
EFCA Detector R&D Roadmap

2021 European Committee for Future Accelerators (ECFA) Detector R&D (DRD) Roadmap

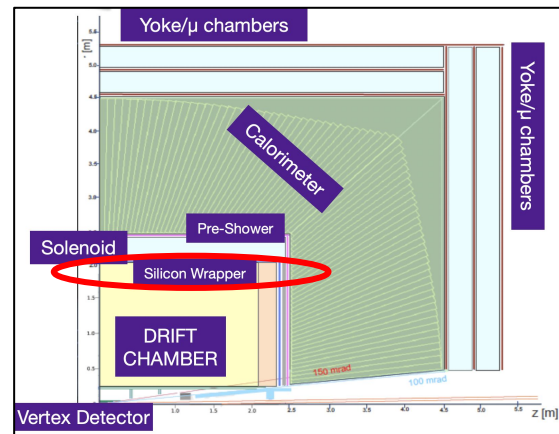


Fast timing at SLAC

- Pioneered the **High Granularity Timing Detector (HGTD)** at ATLAS
 - Designed the 20ps TDC of the ASIC chip (**Bojan Markovic**)
 - HGTD Physics and Simulation convenership for 6 years (**Ariel Schwartzman**)
- Currently developing **4D tracking** detectors for future HL-LHC upgrades beyond Run 4, and future colliders
- Within DOE's HEP Detector R&D program funding, we developed a low-power **TDC architecture in 28nm CMOS** that achieves **6.25ps timing resolution** within core area of **45μm x 20μm**
- DOE's Accelerate Innovations in Emerging Technologies - **3D Integrated Sensing Solutions project** (SLAC, Fermilab, LLNL)
 - **Develop technologies for 3D-integration of 4D tracking detectors with 28nm CMOS read-out chips and LGAD sensors in 12 inch wafers** (65nm) in partnership with Tower. The goal is to enable a new generation of particle detectors using 3D-integration



IDEA Detector FCC-ee



Broad Impacts

- **Neutrino experiments:**
 - replacing analog SiPMs with dSiPM could reduce power, increase spatial/temporal resolution
- **Medical imaging:**
 - PET scanners
- **Develop SLAC know-how in stacked imaging technology will benefit photon science applications requiring ultra-fast imaging:**
 - Soft X-ray detectors (LCLS-II)
 - Ultra-fast imaging with $< \text{ns}$ shutter (MEC)
 - Time-of-Flight spectrometer (LCLS-II)
 - Diagnostics in fusion reactors

Widespread 4D + 5D Applications

High Energy Density Science HEDS:

- Sensors and systems that can survive large neutron fluences are needed for inertial and magnetic confinement studies at NIF, MEC-U, ITER, etc. Into 4 pi, NIF can produce 1×10^{18} neutrons in 10s of ps.
- Example call - FUSION INNOVATION RESEARCH ENGINE (FIRE) DE-FOA-0003361
- **Ultra-fast picosecond imaging is enabling for future HEDS research**

Nuclear Energy

- Sensors and systems must operate under intense neutron fluxes near reactor cores

Space Science

- Intense Jovian radiation belts surround Io, Europa, and Ganymede

Neutron Imaging

- Neutron imaging whether using standard radiography or associated particle imaging (API) must tolerate high neutron fluences. Detector temporal resolution limits API. (NNSA/DNN)