

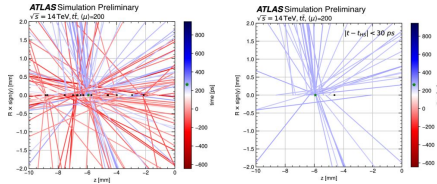
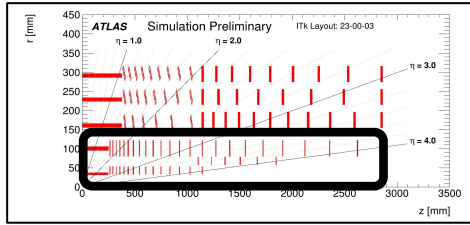
Toward a US Collaboration for 4D Tracking

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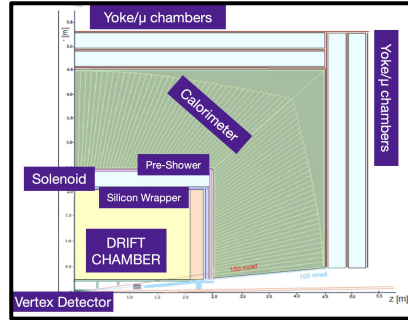
Artur Apresyan, Davide Braga, Timon Heim, Christopher Kenney, Bojan Markovic, Simone Mazza, Lorenzo Rota, Larry Ruckman, Bruce Schumm, Julie Segal, Maria Spiropulu



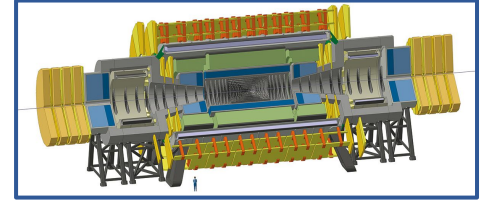
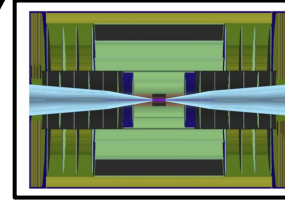
4D Trackers with picosecond timing



HL-LHC: (2035)
4D tracker inner system replacement



FCCee/ILC: (2040)
Timing layers for flavor tagging, particle ID, and LLP searches



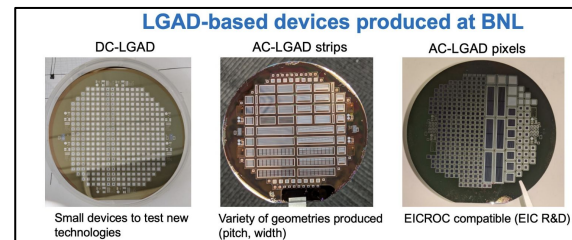
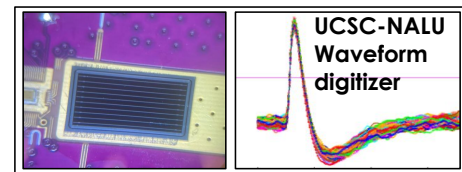
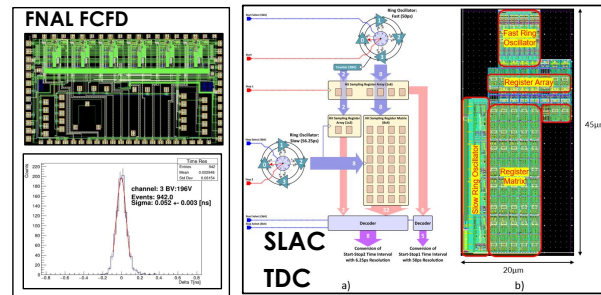
10 TeV muon and hadron colliders (2050+)

Full 4D tracker for BIB rejection (μ C) and pileup suppression (FCC-hh) at extremely high radiation environments

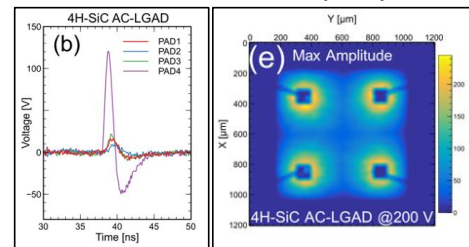
- Leap in detector technology that will enable new physics capabilities
- High priority identified by DOE BRN for detector R&D and CPAD

Major Open Challenge

- With major advances and many collaborative efforts within the US over the last decade in fast-timing sensors, LGADs, 28nm ASICs, and hybrid-bonding approaches, **the field has now reached a transitional moment**
- The major challenge is no longer to show that an individual sensor or ASIC can be fast and time-stamp a pulse with picosecond resolution but to demonstrate that these elements can be **integrated into a detector system**
 - synchronizable at the required level
 - calibrated across channels and time
 - operable in a beam environment
- **Identify the dominant bottlenecks and develop solutions and architectures that are extensible to reticle-scale and wafer-size detector systems**



4H-SiC LGADs: LBNL/NC/BNL



US-Collaborative Program

**Four-plane 4D
tracking telescope**

**System level validation
platform** for synchronization,
packaging, calibration, and
detector-electronics
co-design studies

Beyond **demonstration**, it
provides an experimental
setup to **address the
dominant limitations of
scalable 4D trackers**

**Next generation
timing ASIC
architectures**

Informed directly by
detector-system
measurements and
operational constraints

**Emphasis on innovations in the
context of integrated detector
operation**, including gated
front-end concepts,
timing-aware local processing,
and scalable sync. strategies

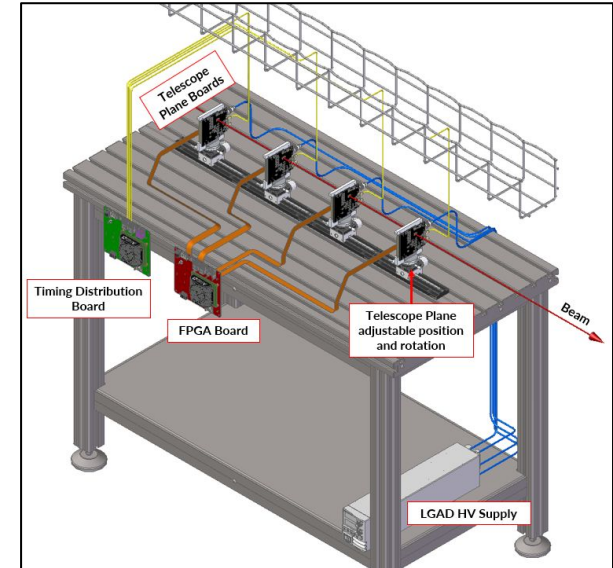
**Advanced
hybrid-bonding
approaches**

**Reduce sensor-to-ASIC
interconnect parasitics**
beyond the limits of
bump-bonding

Demonstrate die-to-wafer
hybrid bonding as a
practical, near-term route to
heterogeneous 4D detector
integration

4D Tracking Telescope

- Integrate fast-timing sensors, advanced pixel ASICs, synchronization infrastructure, mechanical support, DAQ, and calibration and reconstruction software into a single detector platform
 - Address key questions on what limits system-level 4D tracking performance at scales relevant for future colliders
- **4 planes utilizing existing state-of-the-art LGAD sensors and 28nm readout ASICs**
 - Time distribution board for picosecond-jitter clock distribution
 - FPGA board for control and DAQ



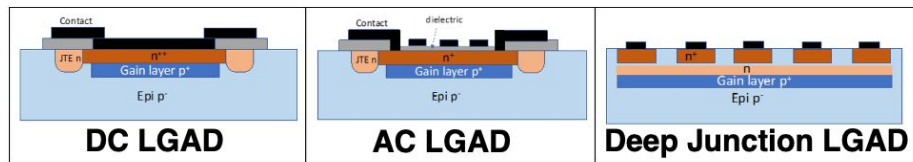
4-planes enable track formation, inter-plane synchronization, time distribution, alignment, and cluster-level timing validation

Sensors and ASIC

3D Integrated Sensing Solutions:

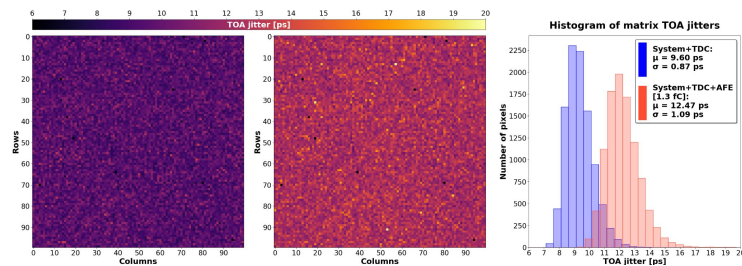
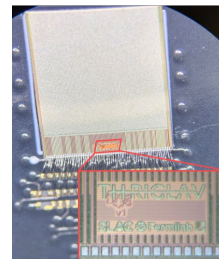
LGAD Development

- Development in partnership with Tower Semiconductor
- Full wafer run on 12" process (first LGAD process on 12" wafers)
- ~50 separate sensor structures: **pixel** arrays (50, 100 μm pitch); **strip** arrays (20, 40, 60, 80, 100 μm pitch); device and guard ring **test structures**
- LGAD variants: **AC**, **Deep Junction (DJ)**, **Reach Through (RT)**



THRIGLAV (THRee-d InteGrated LgAd driVer)

- (5x6mm²) with 100x100 50 μm pitch pixel array
- Analog FE
- TDC: TOA 11-bit, 6.25ps | TOT 8-bit, 50ps
- Sparsified readout logic
- Hierarchical timing-signal distribution (H-tree)



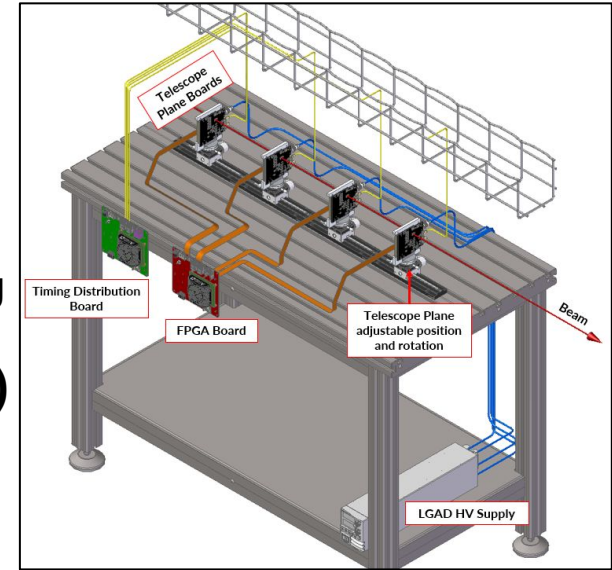
Telescope Integration

- **Mechanical integration (Fermilab)**

- Low mass mechanical structure will provide precise and stable positioning minimizing material and preserving flexibility for future integration studies
- Adjustable plane spacing and rotation, services and clock-distribution lines, thermal stabilization
- Evaluate impact of mechanical tolerances, thermal gradients, and vibration stability on timing precision

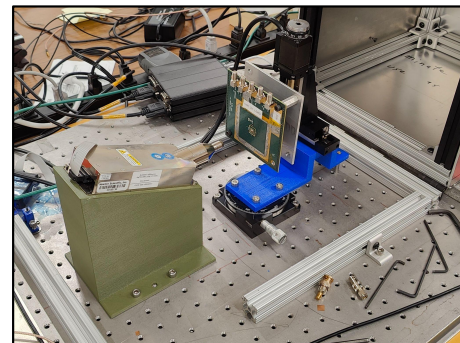
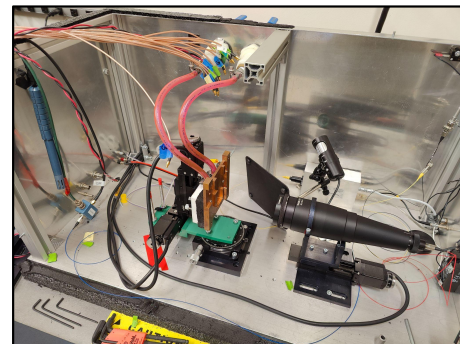
- **Electrical integration and Synchronization (SLAC)**

- DAQ framework to register synchronized hit data, environmental data, metadata, and calibration information
- Common clock-distribution architecture and a fast external reference chain for validating hit-time performance at the 10ps level



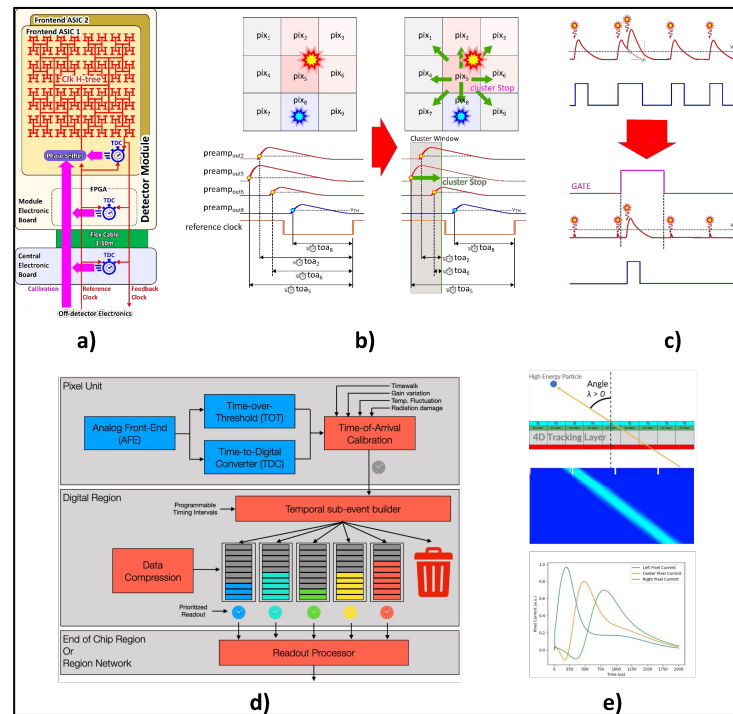
Laboratory Characterization, Beam Tests, and Calibration and Reconstruction Software

- **Laboratory tests (SCIPP, Caltech):**
 - Threshold scans, noise, occupancy, timing uniformity, reference distribution stability, and environmental dependencies
 - Radioactive sources, laser system, X-ray gun for charge injection testing
- **Beam tests (LESA @ SLAC)**
 - first facility to provide beams with picosecond bunch length
- **Calibration and Reconstruction (SCIPP, Caltech)**
 - Software to decode raw data, align planes, combine hit times into clusters, quantify timewalk, threshold dispersion, reference clock distribution
 - New Kalman Filter 4D Tracking reconstruction module compatible with existing MIMOSA telescope at SLAC

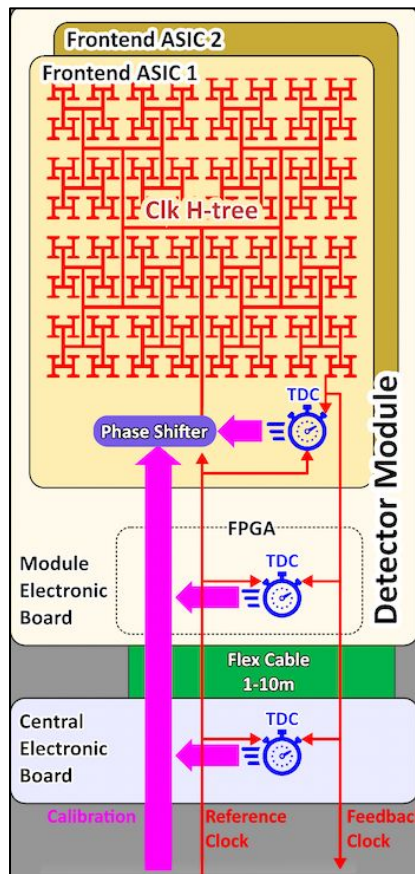


Next-Generation 4D Tracking ASIC

- Start the design of the next generation ASIC in parallel with the 4D telescope construction
- **Combine lessons from building the telescope with new instrumentation ideas and innovations for applications at future colliders**
- 3 broad goals:
 - preserve time precision at the system level under realistic detector operation (informed by the telescope data)
 - control power and bandwidth
 - support physics use cases in environments of high occupancy such as muon colliders

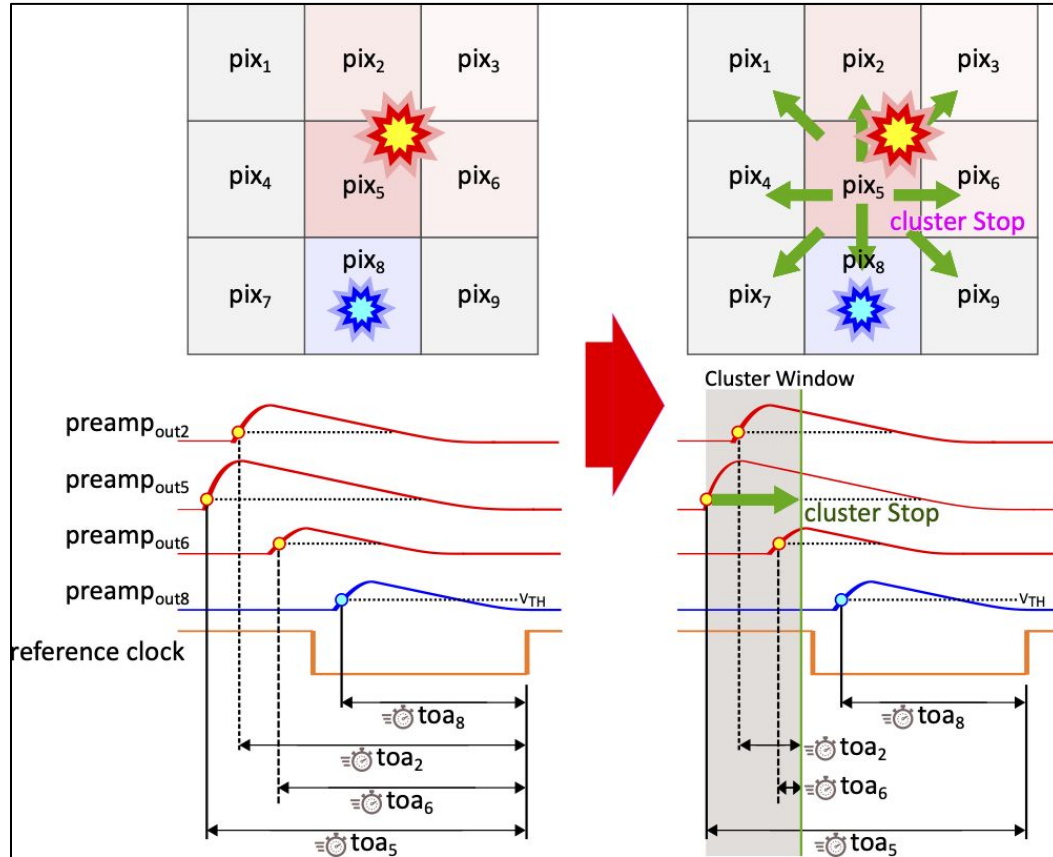


Clock Stability and Drift Compensation



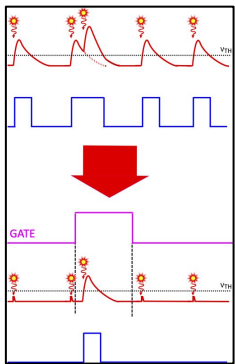
- **Maintain picosecond-level synchronization despite clock distribution delays and environmental drift**
- 4D Tracking telescope operation will inform specifications based on measured effects of clock drift with environmental factors
- Measure the skew between the ASIC input clock and the clock delivered to a pixel (through hierarchical H-tree) using a high precision TDC (FPGA-based) and adjust the clock phase shifter settings to cancel the skew at the ASIC level

Power reduction and Time-aware Readout

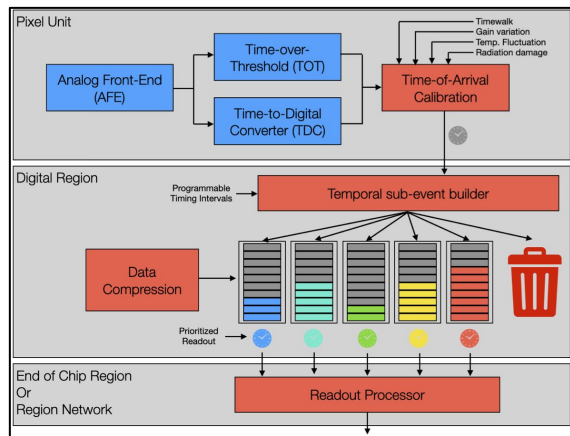


- THRIGLAV TDCs are activated only in the presence of a particle hit $\rightarrow$ power is weighted by occupancy
- Once the hit occurs, TDC power is proportional to the time interval being measured $\rightarrow$ **Measure relative times within cluster hits**
 - only the first hit is measured relative to the reference clock
 - shorter time intervals $\rightarrow$ power reduction

Nanosecond Gated Front-End and On-chip Time-Aware Data Processing

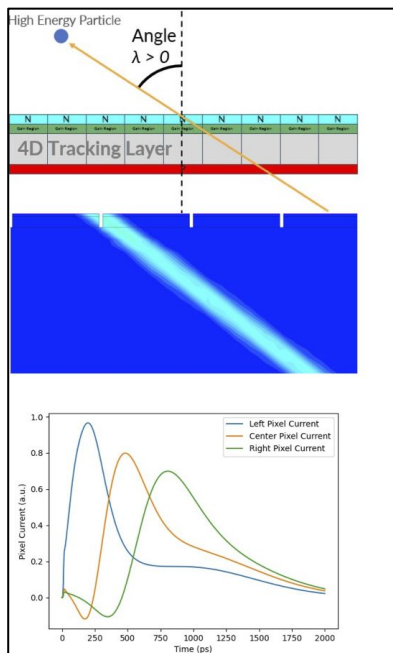


- Powerful way to suppress beam induced backgrounds at a muon collider by rejecting signals that arrive outside the time window associated with collision particles
- New capability for collider pixel ASICs
- Investigate front-end concepts that can rapidly discharge unwanted charge outside the gating window



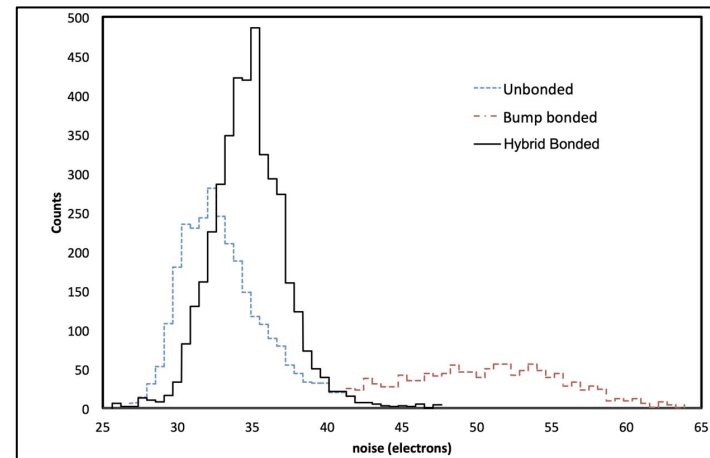
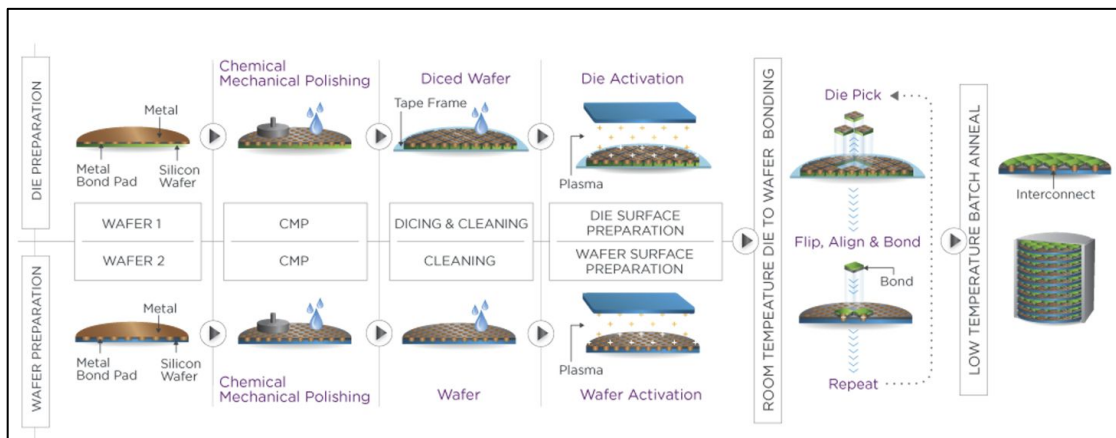
- 4D Trackers generate large data volumes that can become difficult to manage
- Investigate pixel-region and cluster-region processing strategies that can operate locally, reducing redundant timing information
- Temporal clustering, rejecting hits outside specific temporal windows (on-chip sub-event building)

Forward-Looking Extensions: 6D Tracking



- Local time difference among neighboring LGAD pixels encode directional information from a single layer (see [Victor Turbiner's talk](#))
- New capability that can transform single-tracking layers into double-like layers providing new handles for triggering, background suppression, and pattern recognition
- The 4D telescope will enable track-angle measurements and studies (using fine-step rotation of telescope planes)

Hybrid-Bonding



- Conventional interconnect parasitics limit front-end performance
- Fine-pitch (Cu-Cu) **hybrid bonding between LGAD sensors and ASIC electronics provides a route to reduce capacitance at the amplifier input and improve time resolution**
- The goal is to demonstrate and characterize die-to-wafer LGAD-ASIC (THRIGLAV) integration

Reconstruction and Physics Impact

An Integrated 4D tracker enables new measurements that will help evaluate how timing precision impacts track reconstruction and physics performance at future colliders:

- Time-aware seeding and tracking
- Suppression of out-of-time beam-induced backgrounds at a muon collider using nanosecond gating and directional (6D Tracking) information
- Time-aware local processing architectures to improve reconstruction in very dense environments

The proposed program addresses not only the realization of the 4D Tracking hardware, but also the broader reconstruction paradigm enabled by precision space-time tracking

Summary

- **4D tracking detectors represent a major leap in instrumentation** that will enable transformative physics capabilities at future collider experiments
- While recent advances in LGADs, fast 28nm readout ASICs, and hybrid-bonding technologies have proven that **precision timing is achievable at the component level**, translating these advances into a scalable and synchronized detector architecture remains a challenge
- **We propose a coordinated program to close the gap between component-level R&D and scalable 4D tracking systems**
 - Four-plane telescope, next generation ASIC architectures, and advanced hybrid bonding
- Starting point for a broader U.S. collaboration, bringing together complementary expertise in sensors, ASICs, detector integration, and reconstruction, and providing opportunities for new groups to participate
- **If successful, this effort can help establish a framework for future detector developments and RD53-class collaborative efforts towards 4D Tracking**