Argonne NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

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TOPSiDE Detector

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Science and Instrumentation of the 2nd Interaction Region for the EIC

Outline

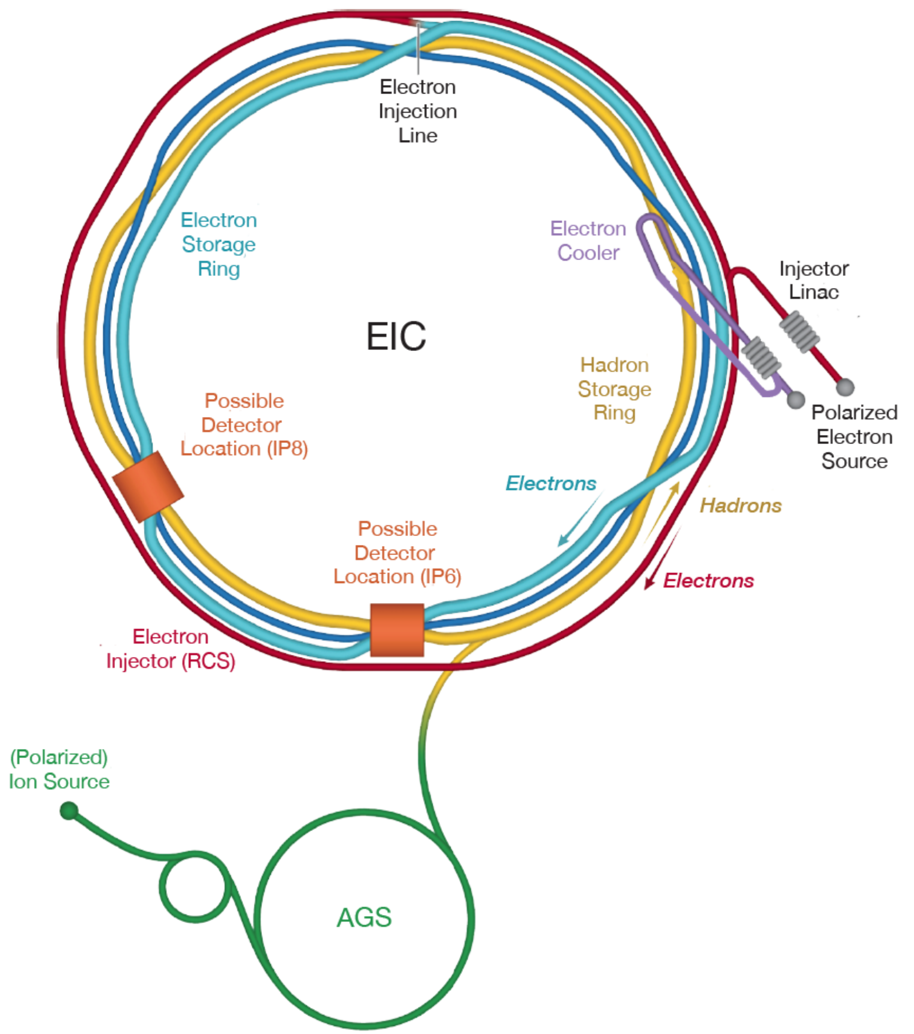
- EIC Detector Requirements
- TOPSiDE Detector
- Development of Key Technologies for TOPSiDE
- Simulation Toolkit

What Will EIC Do?

Key Science Questions to be Addressed

EIC Yellow Report
EIC White Paper

- Emergence of nucleon mass and spin
- Multi-dimensional parton distributions
- Quark, gluon, and jets interactions with a nuclear medium
- Emergence of confined hadronic states and nuclear bindings.
- Gluon density in nuclei and dense gluonic matter



Measurements at EIC

EIC Yellow Report

Physics	Process	Measurement Challenges
Origin of Nucleon Spin	Polarized DIS	Precise electron measurement Good hardon measurement Control of radiative corrections
Origin of Nucleon Mass	Quarkonium production	High luminosity Precise measurement of electrons at low-Q^2 Recoil proton detection (very forward angles)
Multi-Dimensional Imaging of the Nucleon	Semi-Inclusive DIS	$\pi/K/p$ separation
Transverse Spatial Distributions of Partons	Exclusive process (DVCS, DVMP, …)	Forward proton, e, γ measurements
Nucleus' sea quark and gluon structure	Inclusive, semi-inclusive DIS on nuclei	Good tracking and forward calorimetry Very forward measurement of diffractive process
Nuclear PDFs	Inclusive DIS on nuclei Charm production	Good impact parameter resolution
Passage of Color Charge Through Cold QCD Matter	Jets	High center-of-mass energy Good tracking and calorimetry Good hardonic energy resolution at forward region
Many More ...		

Requirements for EIC Detector

Requirement	Detector
Tracking and Vertexing Barrel $\mathbf{0.02}\boldsymbol{p} \oplus \mathbf{5}\,\%$; Backward and Forward $\mathbf{0.02}\boldsymbol{p} - \mathbf{0.1}\boldsymbol{p} \oplus \mathbf{1} - \mathbf{2}\,\%$	**Vertex detector** **Central tracker and solenoid**
Electron identification and measurement **-4 < η < +4** Forward $3\sigma\ e/\pi$ $\boldsymbol{p} \leq$ **15 GeV/c**; Barrel **1:10^{-2}**; Backward up to **1:10^{-4}** Good energy resolution	**Central tracker and solenoid** **Calorimeter**
Hadronic jet measurement Excellent energy resolution, kinematic reconstruction	**Central tracker and solenoid** **Calorimeter**
Pion/kaon/proton separation Barrel $\boldsymbol{p} \leq$ **6 GeV/c**; Forward $\boldsymbol{p} \leq$ **50 GeV/c**; Backward $\boldsymbol{p} \leq$ **10 GeV/c**	**Central tracker and solenoid** **Forward dipole/toroid** **TOF or Čerenkov**
Forward proton/ion detection and measurement	**Roman pots with timing**
Forward neutron detection and measurement	**0^0 calorimeter**

TOPSiDE for EIC

Measure (E, x, y, z, t) for every hit in tracker + calorimeter

Silicon pixel vertex + strip tracker
Sampling calorimeter
Superconducting solenoid (3T)
Forward gaseous RICH + silicon disks + calorimetry
Backward silicon disks + crystal calorimeter

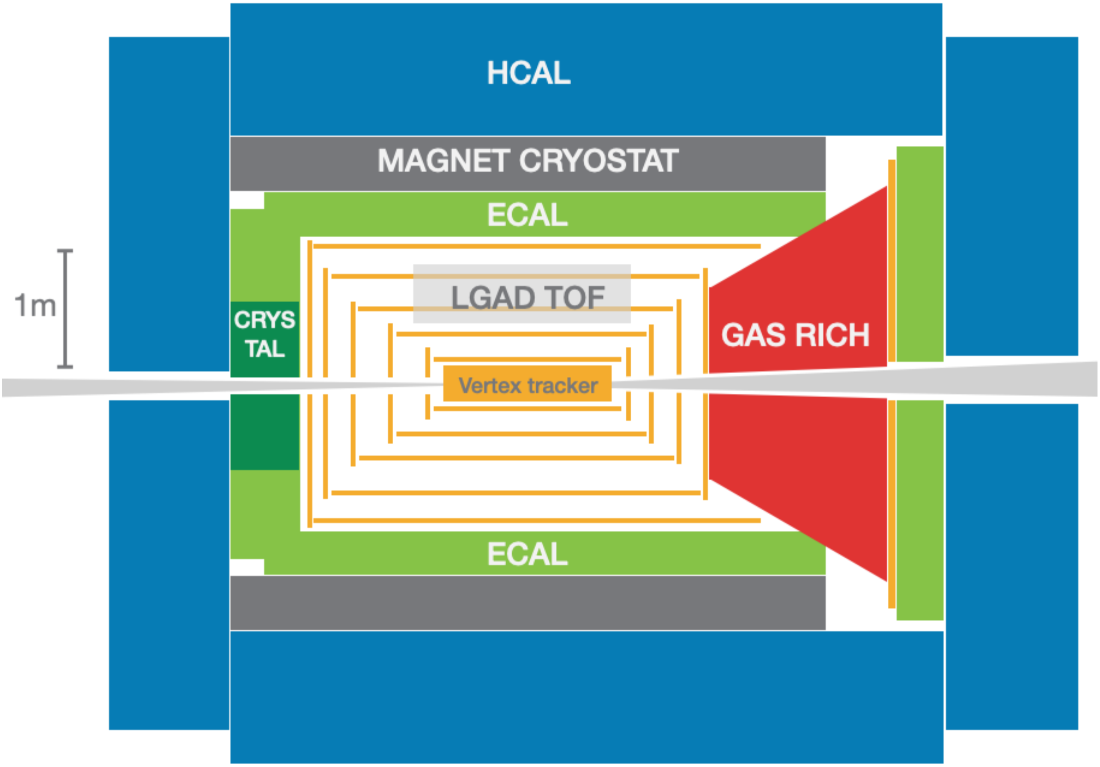
Particle identification ($\pi/K/p$ separation)

Particle momenta < 7 GeV/c for central barrel with trackers + calorimeters
Trackers + Forward RICH for forward/backward region
Ultra-fast silicon sensors with **time resolution of about 10 ps**

Minimizes

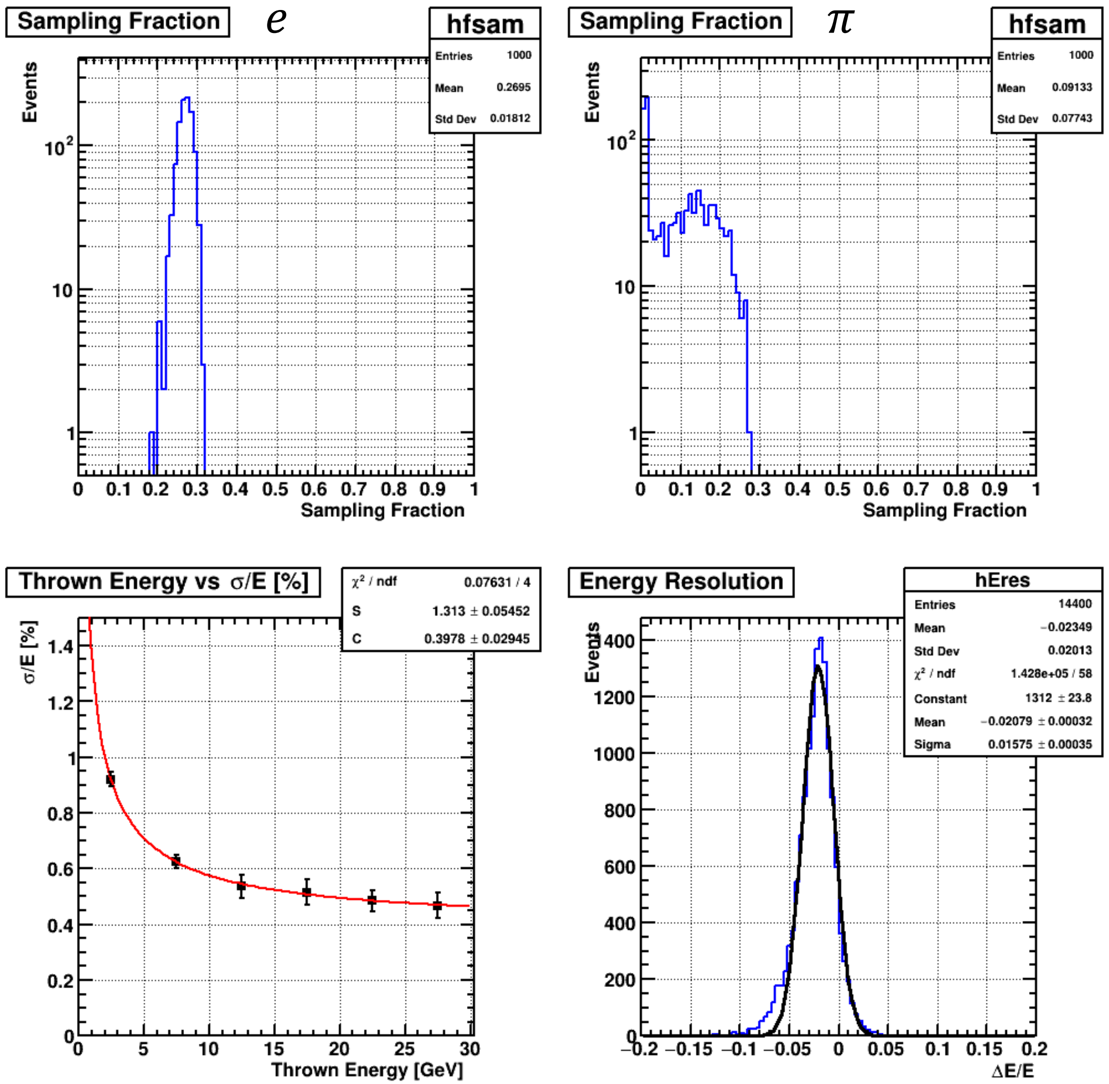
The material between vertex and ECal,
The number of subsystems

Time-of-flight Optimized PID Silicon Detector



Calorimetrers

- Sampling EM calorimeter for central barrel
  - Good energy resolution
  - Excellent spatial resolution
  - Energy deposit profiling, PID between electron/hadron
- Homogeneous crystal calorimeter for backward end-cap
  - Excellent energy resolution
  - Good spatial resolution
- Preshower Calorimeter, Hadron Calorimeter, …



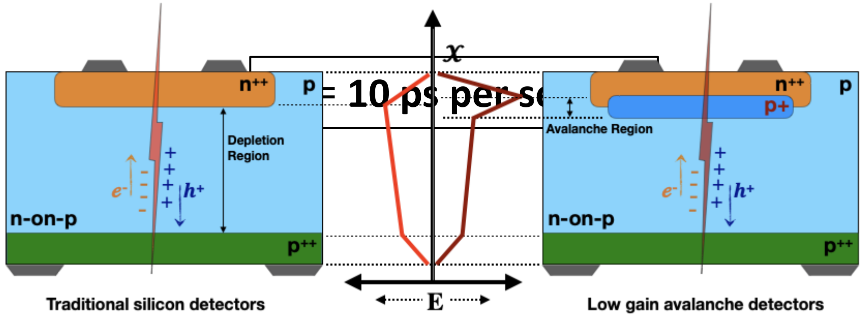
Ultra-fast Silicon Sensors

M. Jadhav *et al.*, Arxiv:2010.02499
H. F-W Sadrozinski *et al.*, 2018 *Rep. Prog. Phys.* **81** 026101

Development of Low Gain Avalanche Diodes (LGADs)

LGAD Consortium: Argonne, BNL, and UC Santa Cruz
Additional p-layer close to anode
Modest multiplication by factor of 10 – 50

⟶ Amplification of electrons close to pixel (minimal drift)
⟶ **Improvement in time resolution**

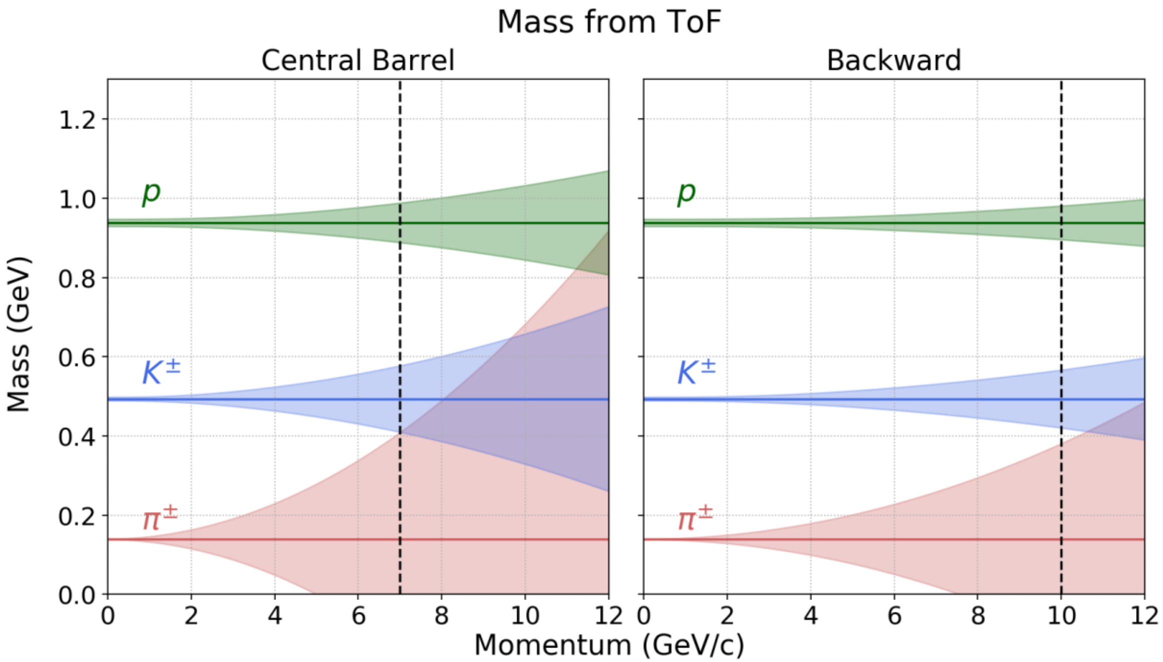


Can be used in

EM calorimeter and tracker for Particle ID
(π – K – p separation)

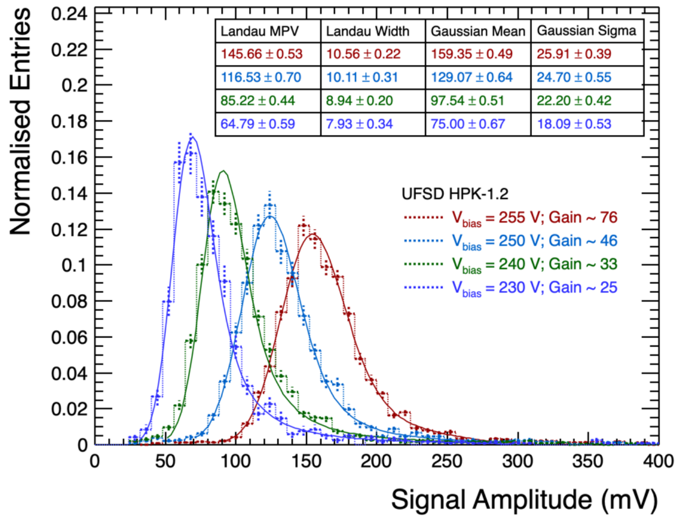
Full detector simulation

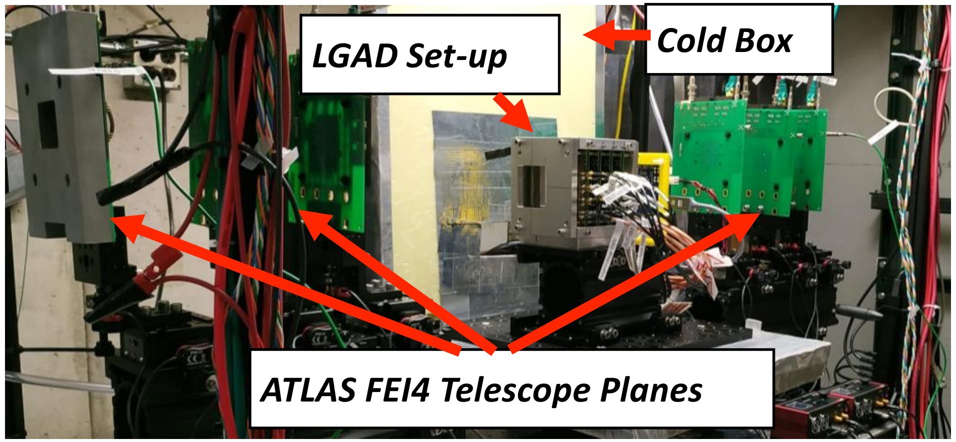
Single particles in barrel region
GEANT4, digitization, reconstruction
Reconstructed mass $\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta p}{p}\right)^2 + \gamma^4\left[\left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta l}{l}\right)^2\right]$
Resolution of 10 ps per sensor ⟶ separation up to ~ 7 GeV/c

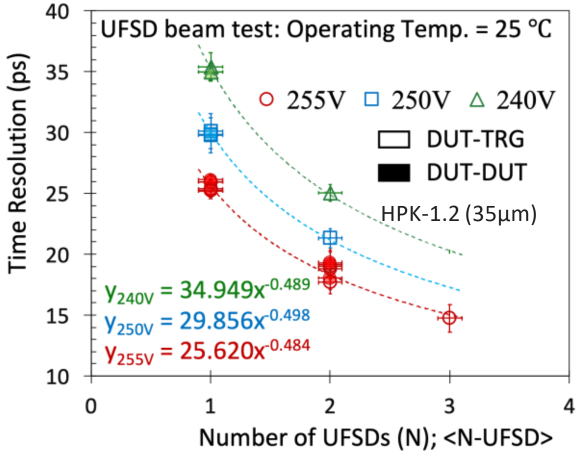


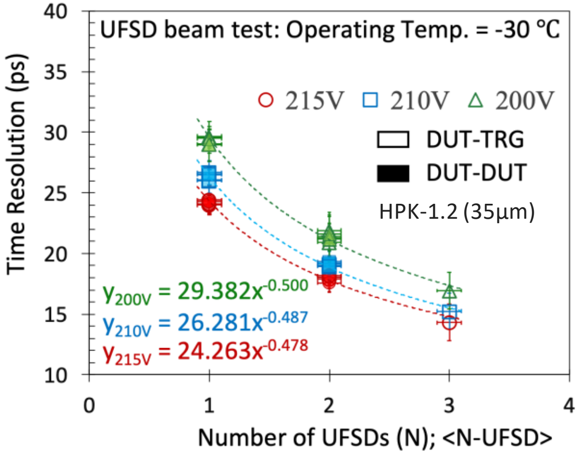
LGAD Achievement

- LGADs beam test at the Fermilab Test Beam Facility
- Achieved **timing resolution of 14.31 ± 1.52 ps**
- Normalized signal amplitude vs. Bias Voltage
- Very short rise time of ~350-400 ps were obtained
- Signal Amplitude, Signal to Noise Ratio, Jitter, Rise Time as function of voltage bias and temperature
- M. Jadhav *et al.*, arXiv:2010.02499; Accepted at JINST

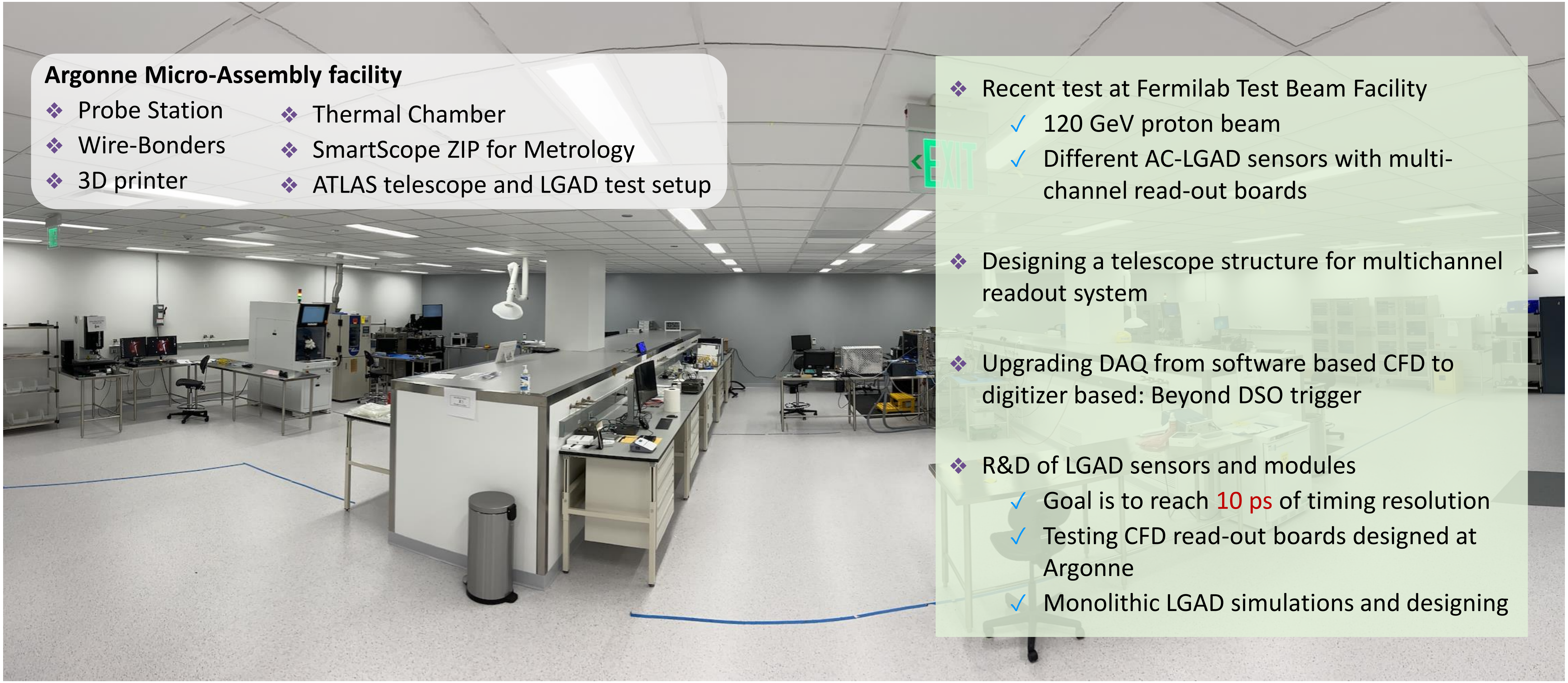








LGAD Development Ongoing



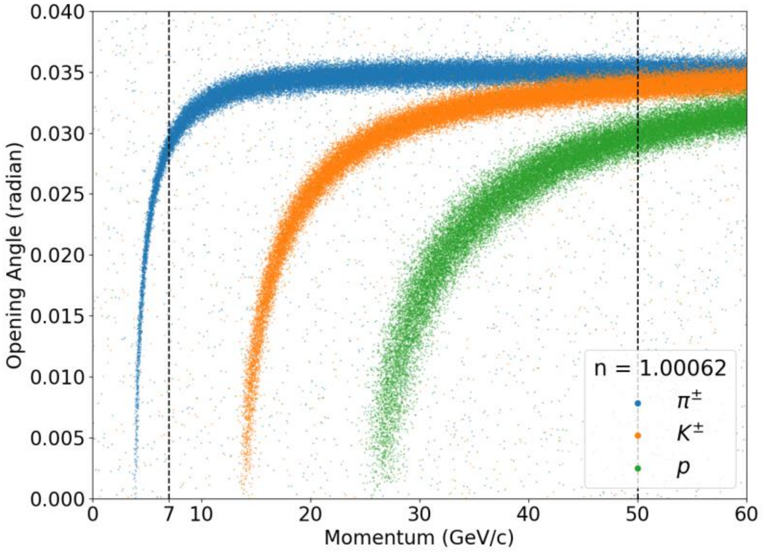
Argonne Micro-Assembly facility

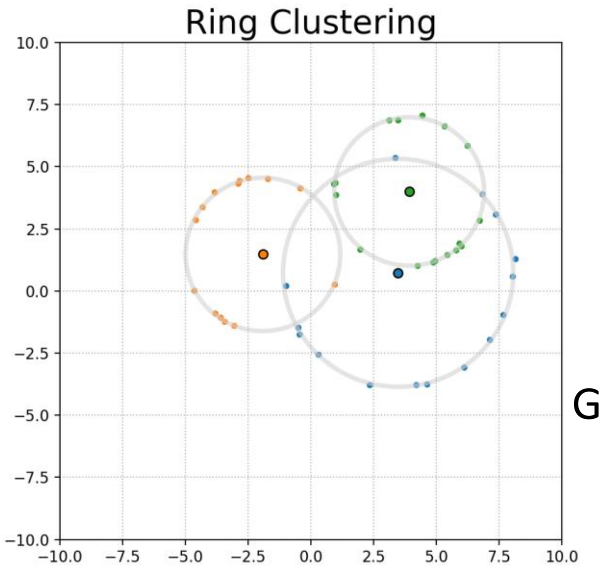
- Probe Station
- Wire-Bonders
- 3D printer
- Thermal Chamber
- SmartScope ZIP for Metrology
- ATLAS telescope and LGAD test setup

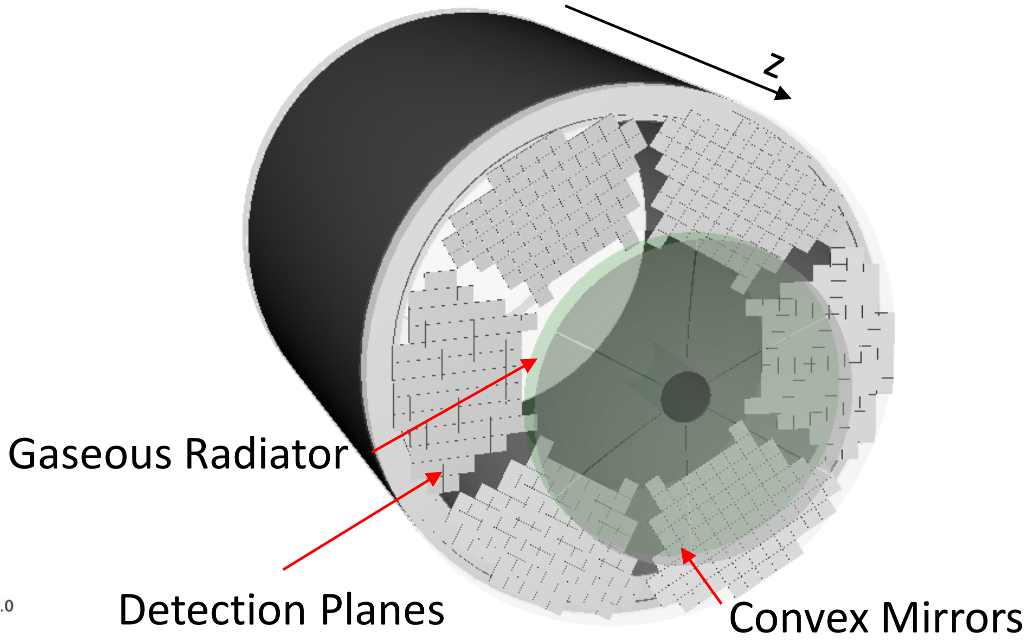
- Recent test at Fermilab Test Beam Facility
  - ✓ 120 GeV proton beam
  - ✓ Different AC-LGAD sensors with multi-channel read-out boards
- Designing a telescope structure for multichannel readout system
- Upgrading DAQ from software based CFD to digitizer based: Beyond DSO trigger
- R&D of LGAD sensors and modules
  - ✓ Goal is to reach 10 ps of timing resolution
  - ✓ Testing CFD read-out boards designed at Argonne
  - ✓ Monolithic LGAD simulations and designing

Gaseous Ring imaging Cherenkov Detector

- Forward Pion/Kaon/Proton Separation with Imaging of Cherenkov Light Cones
- Gaseous radiator, PID for high energy hadrons (ToF for low energy)
- Photon detection by MCP-PMTs with Pixelated Readout
- Optimizing design with end-to-end simulation toolkit





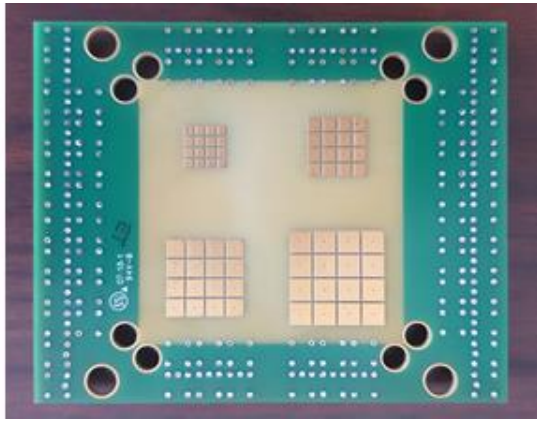


MCP-PMT for RICH

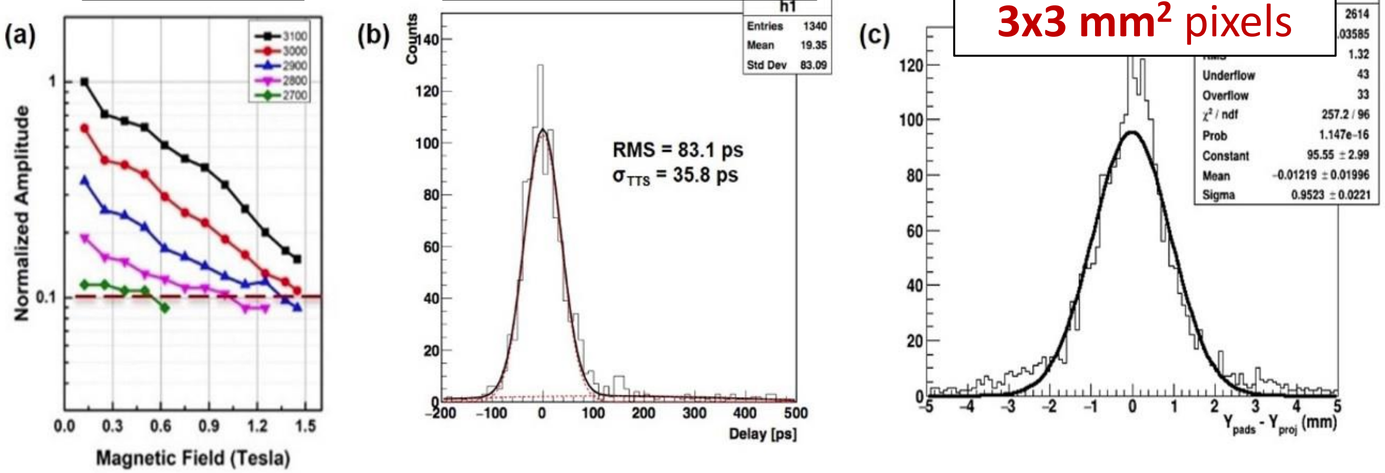
MCP-PMTs

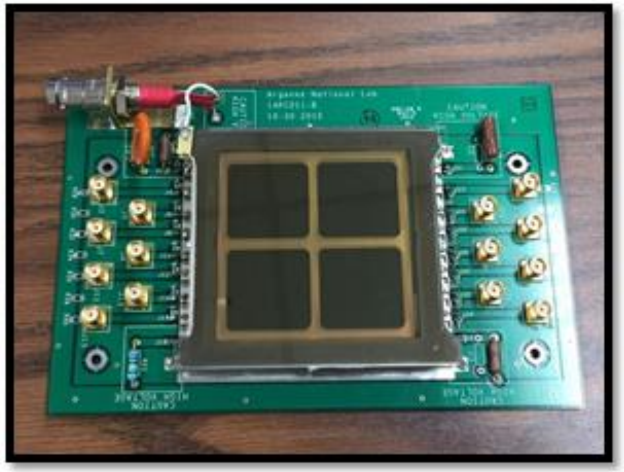
- Based on Microchannel Plates
- High-resolution (spatial + timing), strong magnetic fields tolerance
- Developed by Argonne, UChicago, UC Berkeley
- Tested 6x6 cm^2 MCP-PMTs with different pixel sizes

4 different pixel sizes (2x2,3x3,4x4 and 5x5 mm^2) implemented for testing



1.5 T field | **83.1 ps** timing res. | **0.9 mm** res. with **3x3 mm^2** pixels

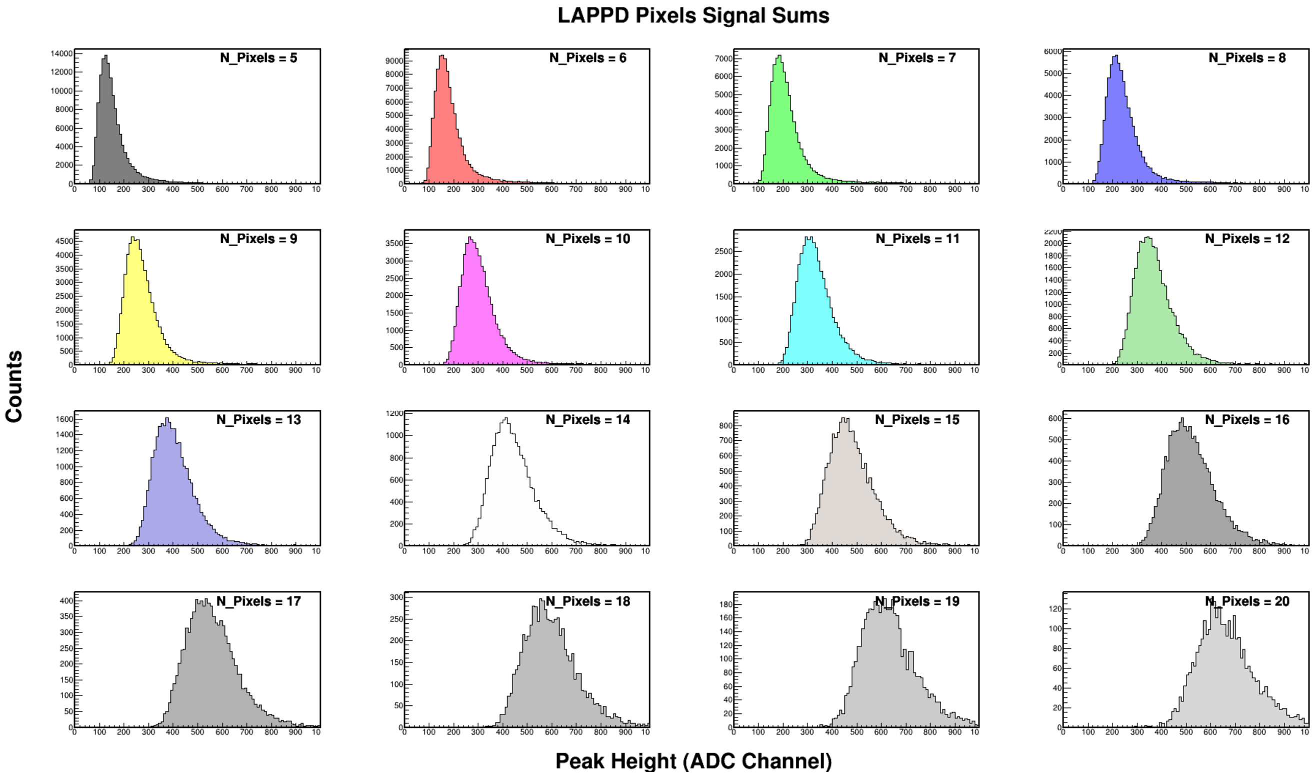


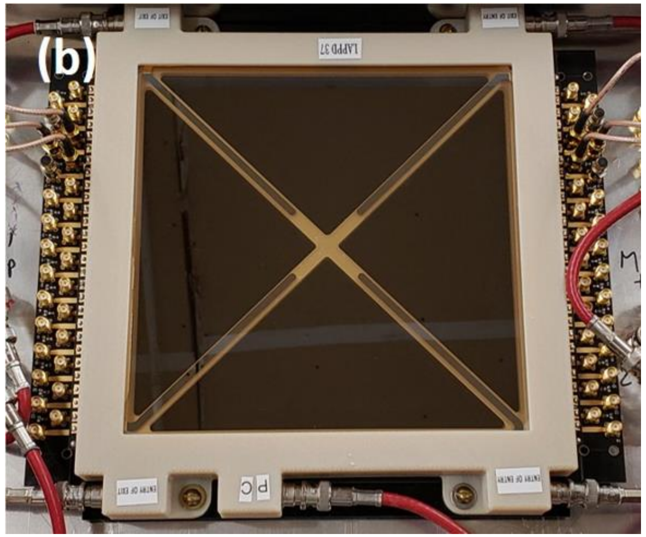


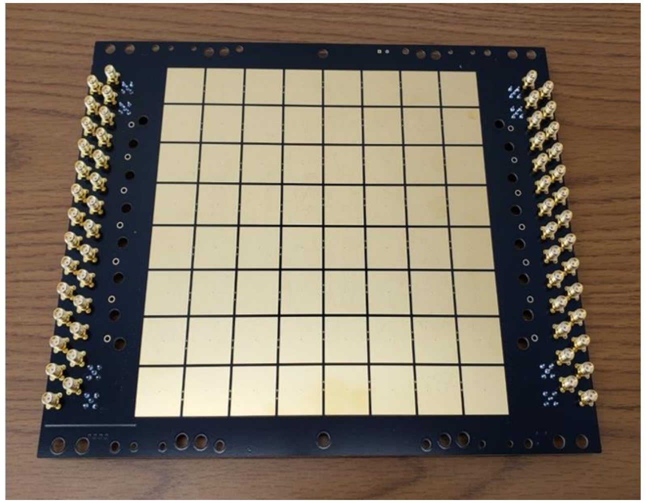
J. Xie *et al.*, 2020 *JINST* **15** C04038

Large Area Picosecond Photo Detectors (LAPPD™)

- Now being commercialized by INCOM, Inc.
- Coarse pixelized (25x25 mm^2) for Telescope Cherenkov Prototype
- Beam test at Hall C, LAPPD and MaPMTs
- Publication for the first test: arXiv:2011.11769



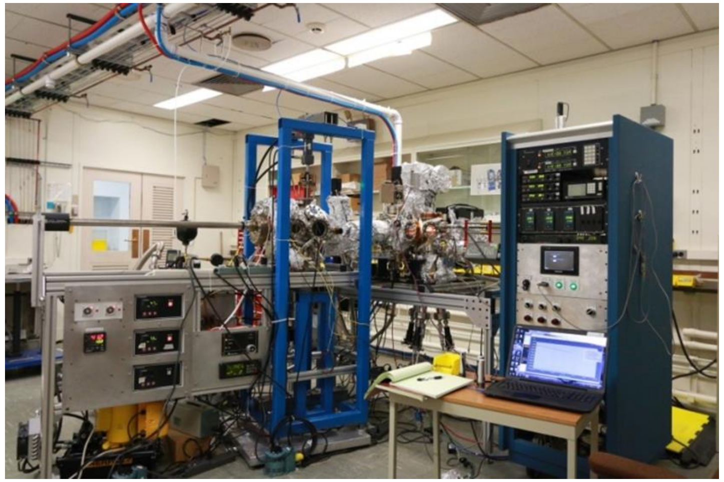


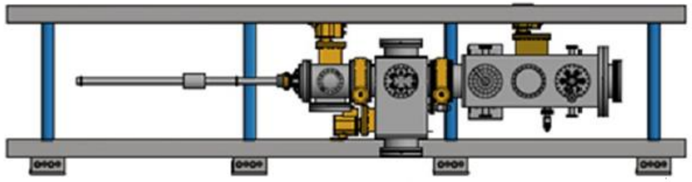


MCP-PMT Development Ongoing

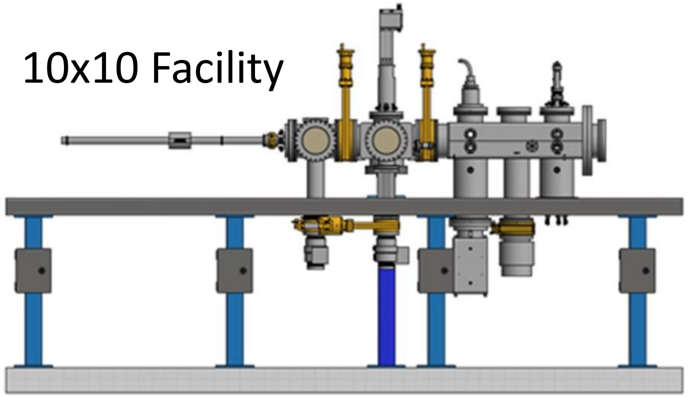
- Transition to fabrication of 10x10 cm^2 MCP-PMT
  - 6x6 cm^2 MCP-PMT was fabricated by an existing facility
  - Building new R&D fabrication facility
  - Commissioning the fabrication facility
  - Fabricate and evaluate several 10x10 cm^2 MCP-PMTs this summer
  - New facility will serve the **EIC community**

- Gas-RICH prototype
  - Construct gas-RICH prototype using MCP-PMT as photodetector
  - Evaluate the gas-RICH prototype in beamline

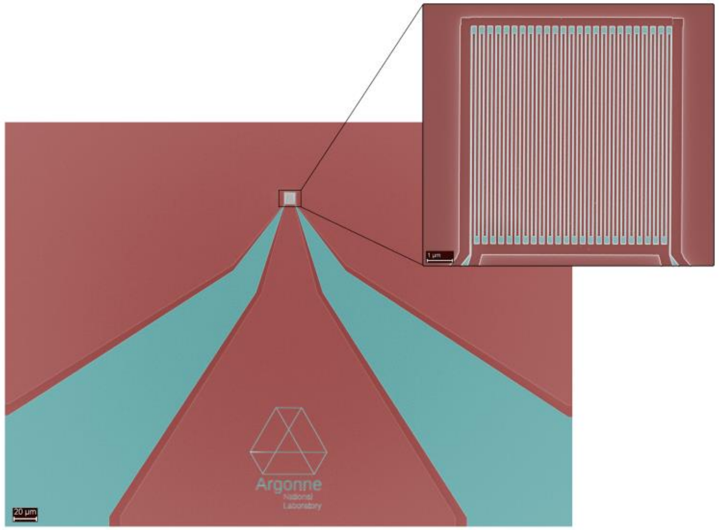


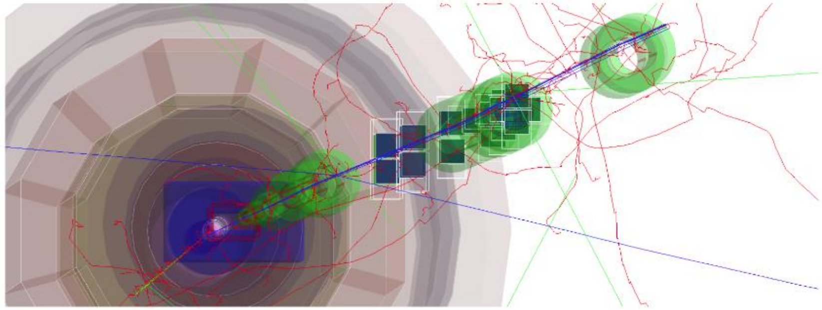


10x10 Facility



Superconducting Nanowire for Far-forward Hadron Detector



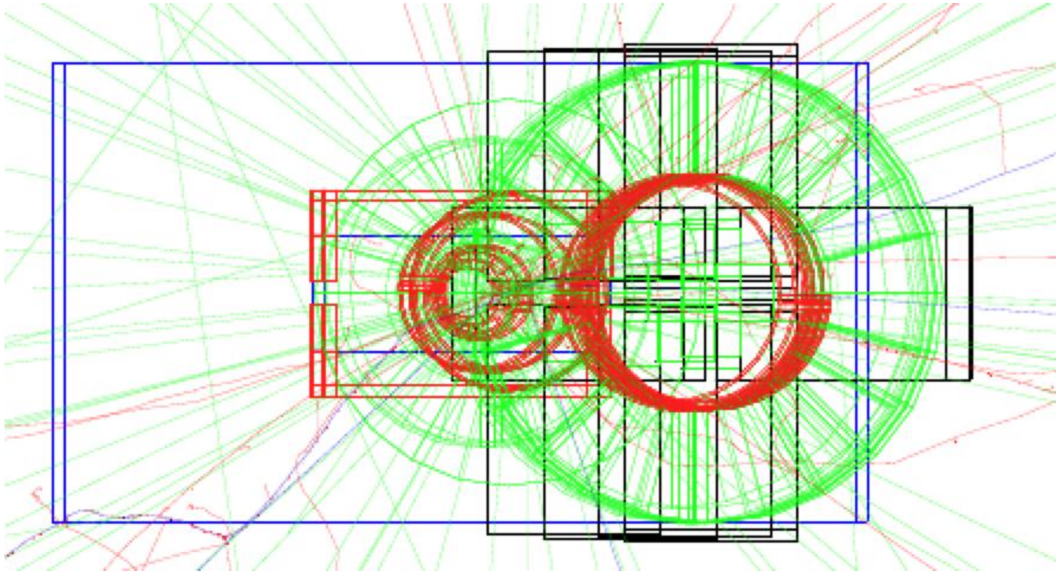


Efficient, fast sensors for a high-radiation, high-field environment.

- Sensors can operate in fields up to (at least) 7T, can operate inside of magnets.
- Novel concept for high-resolution rad-hard detector based around superconducting nanowires (early R&D stage), good potential for near-beamline detector for tagging in the far-forward region.
- Capability to fabricate nanowire sensors on-site.
- Developing readout electronics for cold environments, collaborating with Fermilab and Nalu Scientific.

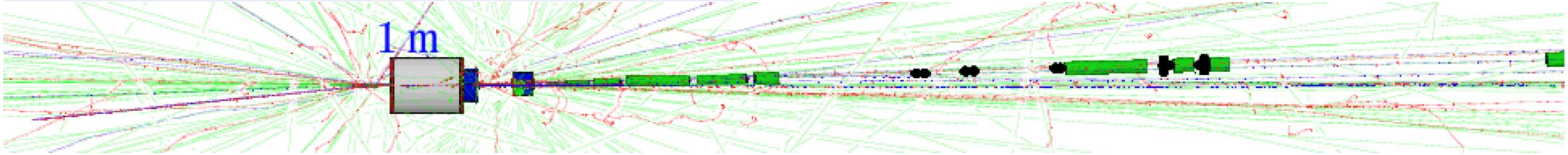
Simulation for TOPSiDE

- Modern tool chain for end-to-end simulation
  - DD4Hep, ACTS, Gaudi, …
- Automized workflow for simulation, digitization, and reconstruction (**W. Armstrong's talk on Friday**)



Task	Tool
Generate collision events	lAger, Lepto, PYTHIA8, Milou, …
Transport of particles through matter	GEANT4
Digitizing the response	Gaudi Framework
Reconstruct tracks	ACTS
Reconstruct particles	Gaudi Framework
Data Model	PodIO
Analyze events	Root
Geometry/Event display	Web-based UI, DAWN, …

- Validating and optimizing TOPSiDE design with simulation
  - Forward RICH, sampling calorimeter, silicon trackers, …



Summary

- EIC environment/physics poses specific challenges to the detector design

- TOPSiDE is a concept detector being developed to address the challenges
  - Minimizes the mass before ECal
  - Reduces the number of subsystems

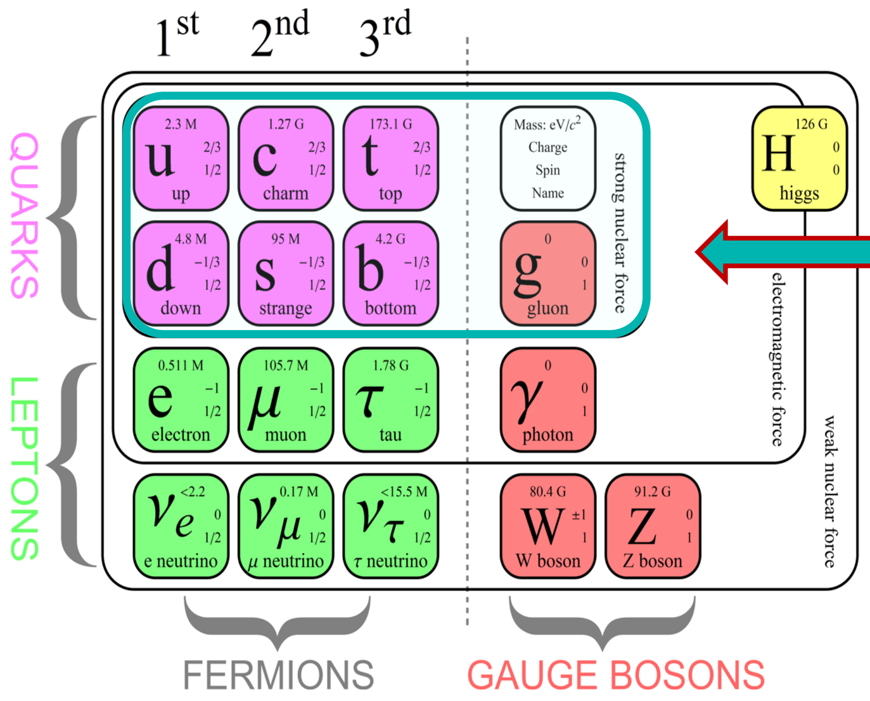
- Novel Ideas for colliding beam detectors
  - 5D measurement with sampling calorimetry + LGADs
  - Gaseous RICH with MCP-PMTs

- End-to-end simulation toolkit

Thank you!

Back-up Slides

Standard Model of Particle Physics



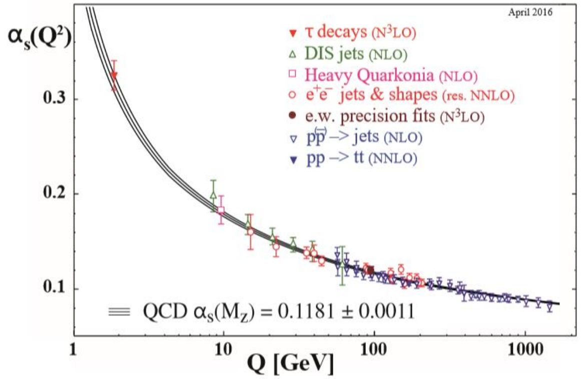
Emphasis of the Electron-Ion Collider

Strong force described by

Quantum Chromodynamics (QCD)

- High-energy regime/short distances

  Exact calculations (perturbative)
  Tested in countless experiments



Strong coupling constant

- Low-energy regime /long distances

  Large coupling (non-perturbative)
  More difficult to calculate
  Interactions described by models or on the lattice
  Much less explored

Study physics with		Generic requirements
• Inclusive process	→	• Electron PID; Precise angle/energy; Tracking, EM and hadronic calorimetry
• Semi-inclusive process	→	• Hadron PID; Full 2π tracking; Vertexing
• Exclusive process	→	• Excellent tracking; End-cap hadronic calorimetery; Very forward detectors; Zero-degree neutron detection

Time Resolution of Silicon Detectors

Hartmut F-W Sadrozinski *et al.*, 2018 *Rep. Prog. Phys.* **81** 026101

$$\boxed{\sigma_t^2 = \sigma_{\text{Time Walk}}^2 + \sigma_{\text{Landau Noise}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{TDC}}^2}$$

Contribution from RO electronics
$\longrightarrow$ Minimized with careful design

Dependence on signal noise: $\sigma \approx t_{rise}/\left(\frac{S}{N}\right)$
$\longrightarrow$ Minimized with fast signals and large S/N

Dependence on drift velocity
$\longrightarrow$ Minimize with uniform electric fields

Dependence on uniformity of electron/hole pair production
$\longrightarrow$ Minimized by decreasing sensor thickness

Dependence on signal size
$\longrightarrow$ Minimize using e.g. constant fraction discriminators