Forward silicon vertex/tracking detector design and R&D for the future Electron-Ion Collider

Xuan Li (xuanli@lanl.gov)

on behalf of the

Los Alamos National Laboratory EIC team

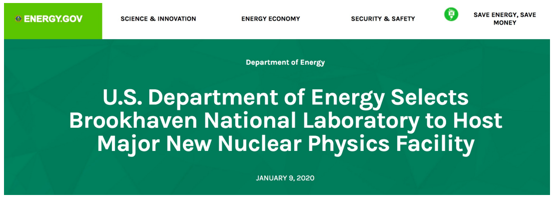
This work is supported by LANL LDRD 20200022DR project!

Outline

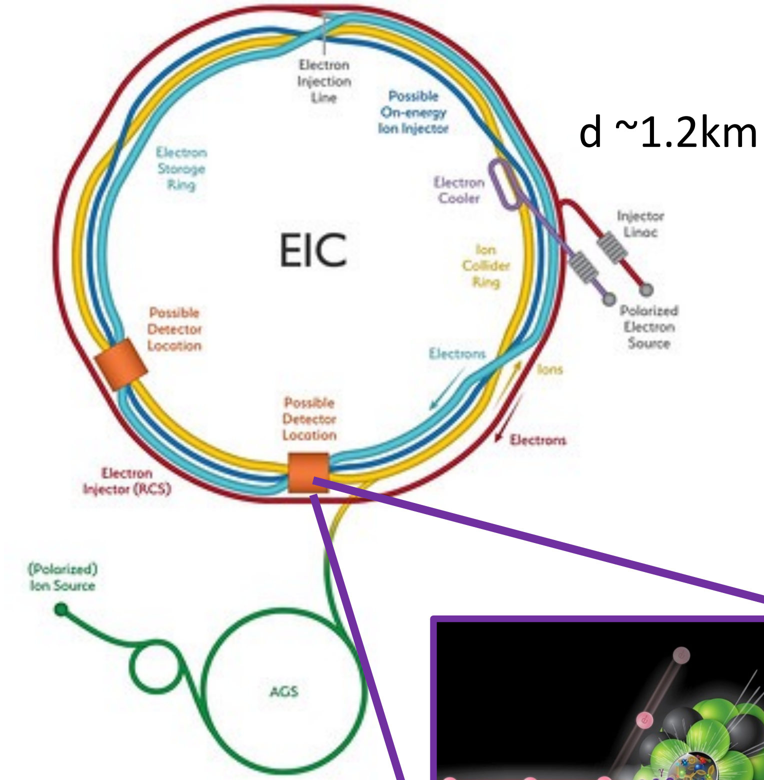
- Introduction to the Electron-Ion Collider (EIC).
- The proposed Forward Silicon Tracker (FST) design and simulation studies.
- Detector R&D setup and results.
- Summary and Outlook.

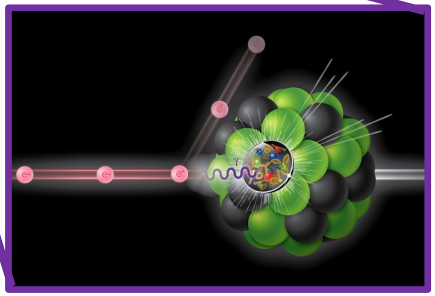
Introduction to the Electron-Ion Collider (EIC)

- The proposed Electron-Ion Collider (EIC) CD0/1 has been announced and the site is selected to be BNL.



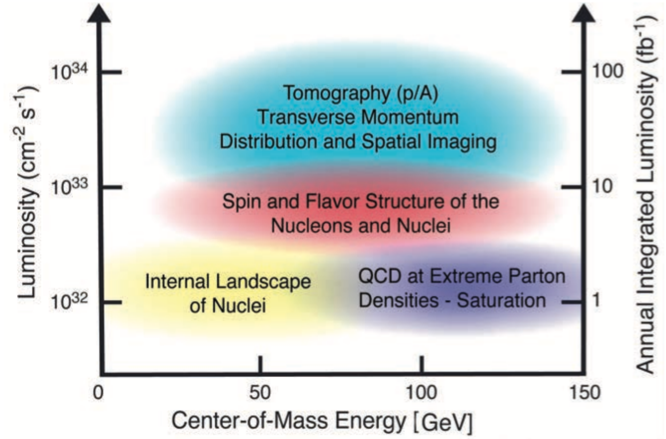
- e-p collisions at the EIC:
  - (Polarized) p, d/^{3}He beams at 41-275 GeV.
  - (Polarized) e beam at 5-18 GeV.
  - Instant luminosity L_{int} ~ $10^{33\text{-}34}$ cm^{-2}sec^{-1}. A factor of ~1000 higher than HERA.
  - Bunch crossing rate: 1-10 ns.
- e-A collisions at the EIC:
  - Multiple nuclear species (A=2-208) and variable center of mass energies.
  - Instant luminosity L_{int} ~ $10^{33\text{-}34}$ cm^{-2}sec^{-1}.
  - Bunch crossing rate: 1-10 ns.

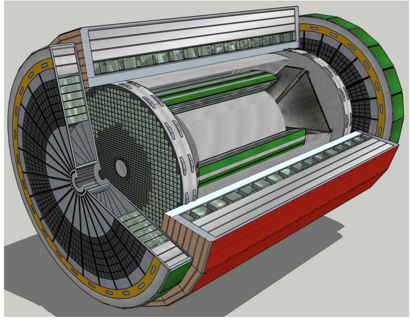


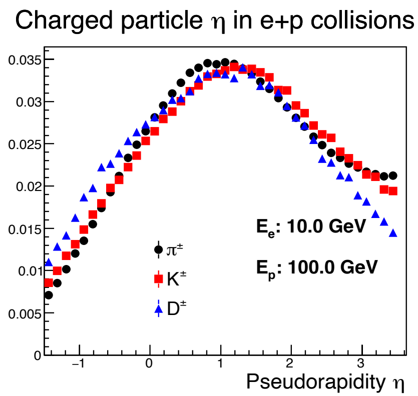


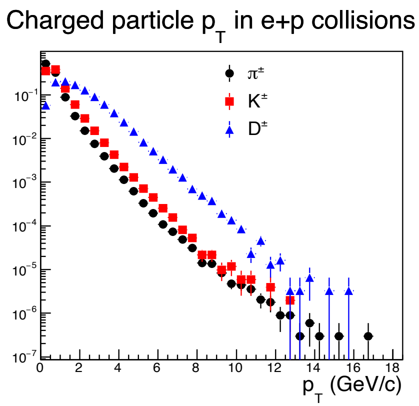
High Precision Detector is Required at the EIC

- The future EIC will utilize high luminosity high energy electron and proton (nucleus) collisions to solve several fundamental questions in the nuclear physics field.







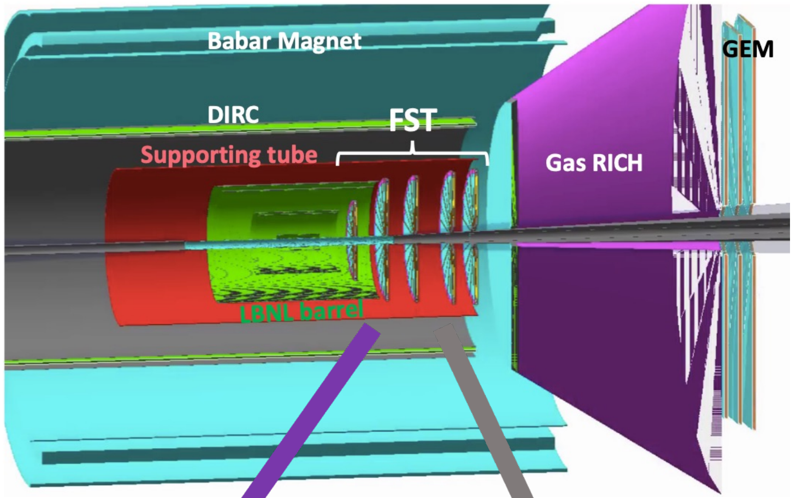


- The EIC detector is required to have large granularity in tracking, especially in the forward region.
- A silicon vertex/tracking detector with low material budgets and fine spatial resolution is needed. Fast timing (1-10ns readout) capability allows the separation of different collisions and suppress the beam backgrounds.

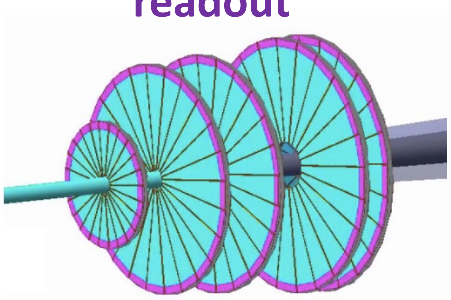
The Proposed Forward Silicon Tracker Design

- The current Forward Silicon Tracker (FST) design consists of 5 disks with the pseudorapidity coverage from 1.2 to 3.5.

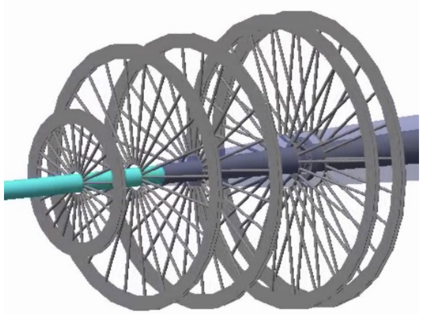
LANL FST implemented in GEANT4



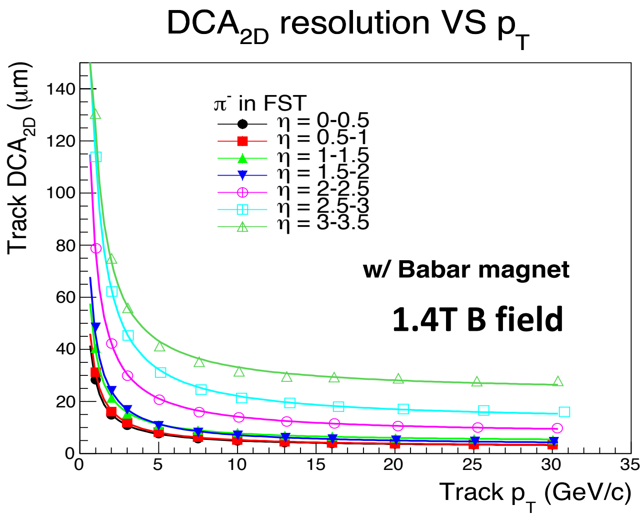
Silicon wedge and readout



Support and cooling



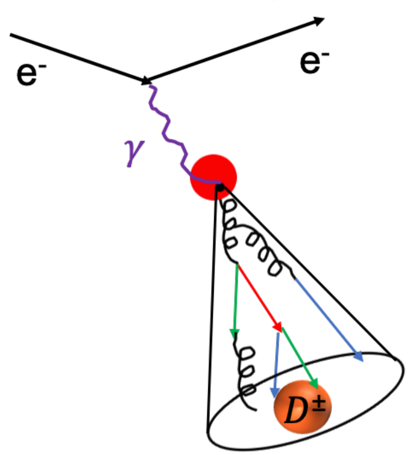
- Detector geometry fully implemented in GEANT4 (Fun4All framework).
- Initial tracking performance evaluated. arXiv: 2009.02888
- Recent updates with estimated support structure and cooling.

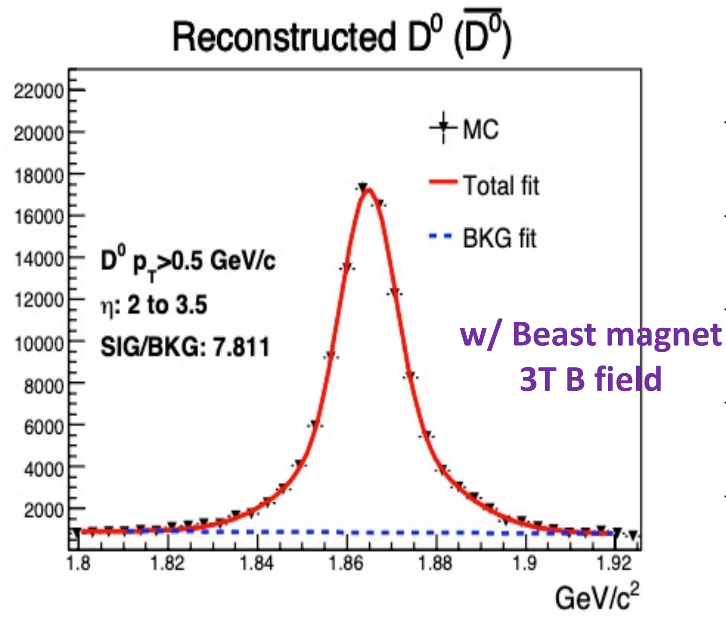


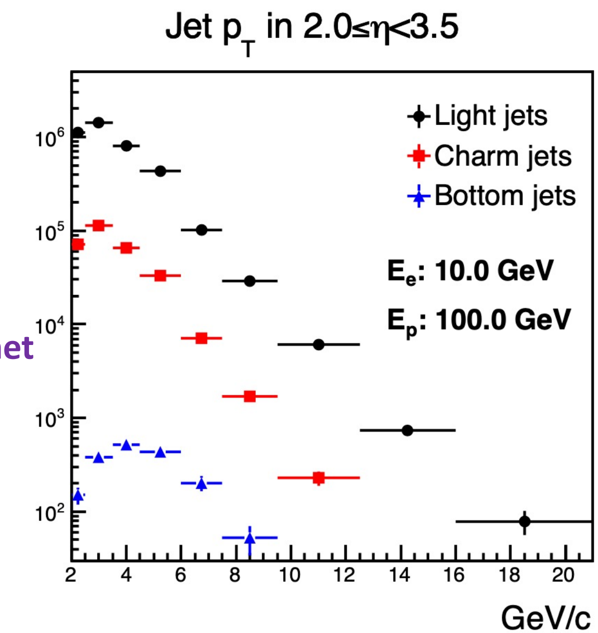
New Physics Observables Enabled by the Silicon Vertex/Tracking Detector

- Simulation studies of heavy flavor hadron/jet reconstruction with the proposed silicon vertex/tracking detector in 63.2 GeV electron+proton collisions .

$e^- + \mathrm{p} \rightarrow e^- + jet(D^{\pm}) + X$







- Clear heavy flavor hadron/jet signals can be achieved in the forward pseudorapidity region, which helps exploring the nucleon/nuclei structure and the hadronization process in the poorly constrained kinematic region.

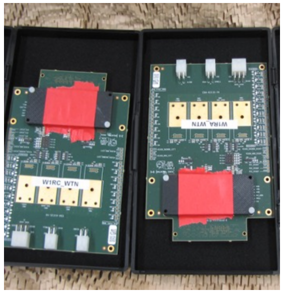
The Proposed Forward Silicon Tracker Technology Candidates

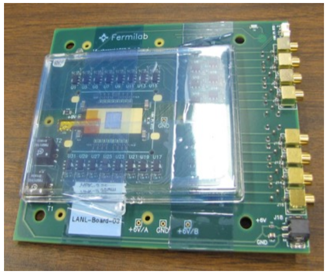
- Technology candidates:
  - ~10 μm pixel pitch Monolithic Active Pixel Sensor (MAPS) technology, e.g., ITS-3.
  - DMAPS technology: e.g., 36.4 μm pixel pitch MALTA.
  - Low Gain Avalanche Diode (LGAD), e.g., AC-LGAD.

Name	Technique	Pixel Size	Integration Time	Thickness per layer
Monolithic Active Pixel Sensor (MAPS)	180 nm (future 65 nm) Tower Jazz	~ 10 X 10 μm^2	~ 2 μs	< 0.3%X_0 per layer
Radiation hard MAPS (MALTA)	180 nm Tower Jazz	36.4 X 36.4 μm^2	< 5 ns	< 0.5%X_0 per layer
AC-LGAD	Low Gain Avalanche Diode	500 X 500 μm^2	< 100 ps	< 1%X_0 per layer

Monolithic Active Pixel Sensor (MAPS) sensor

DMAPS (MALTA) sensor

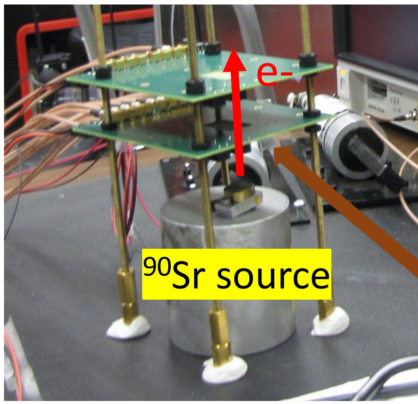




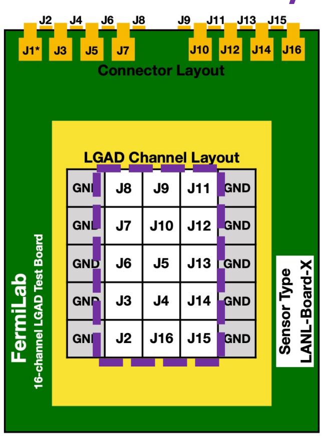
LGAD/AC-LGAD sensor

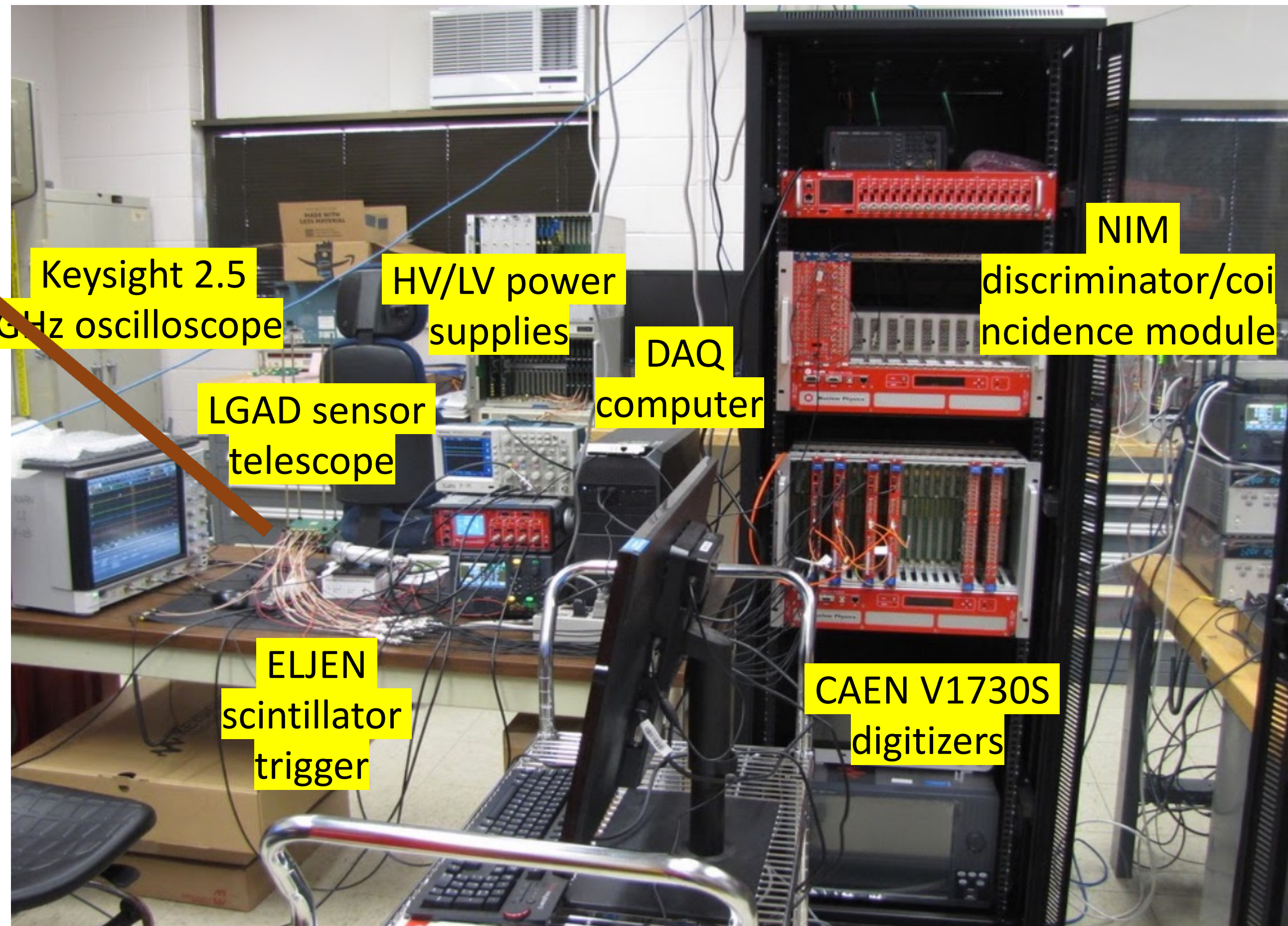
LGAD Test Bench Configuration

- LGAD bench testing starts with a single LGAD sensor with a ^{90}Sr source. Then a two-layer LGAD (AC-LGAD) telescope is setup.



LGAD pixel map (15 are connected)

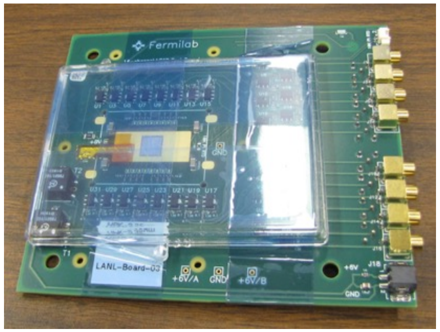




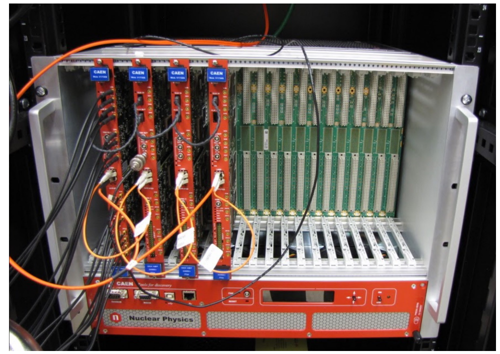
LGAD Sensor Data Processing Flow

- Data flow chart:

LGAD sensor

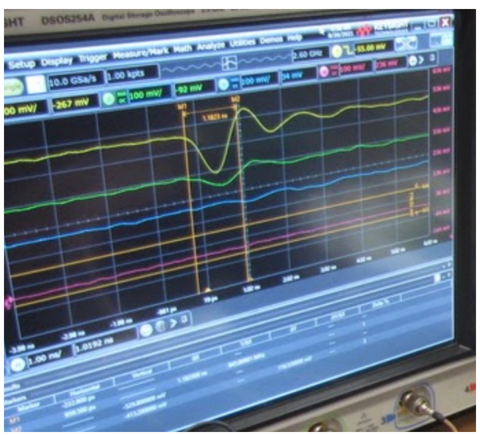


CAEN 1730s digitizer

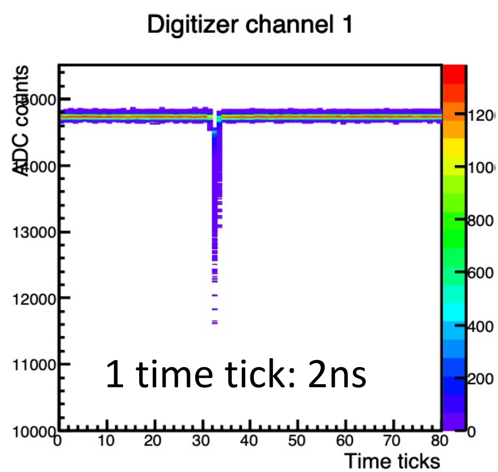


DAQ computer

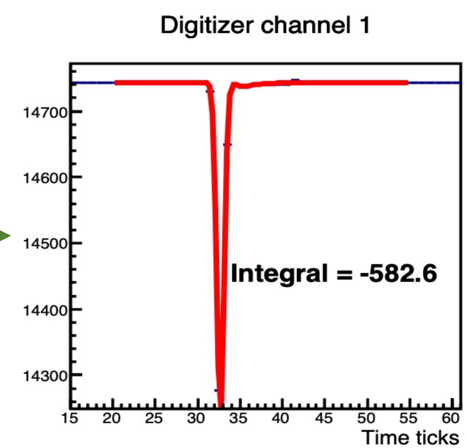
Raw analog signal



Accumulated pulse distribution



Extracted average pulse shape and charge



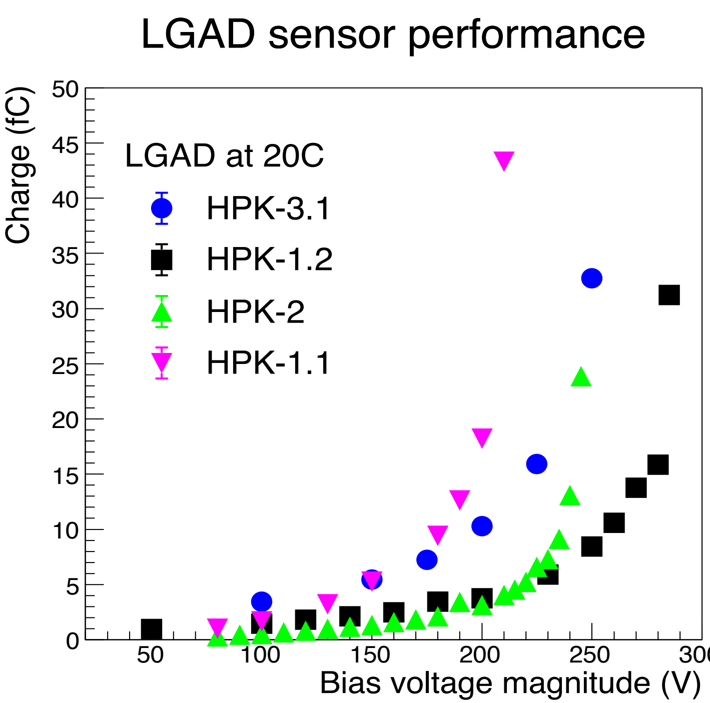
Pulse width: ~500ps, Pulse amplitude: ~-100mV

LGAD Single Sensor ^{90}Sr Source Tests

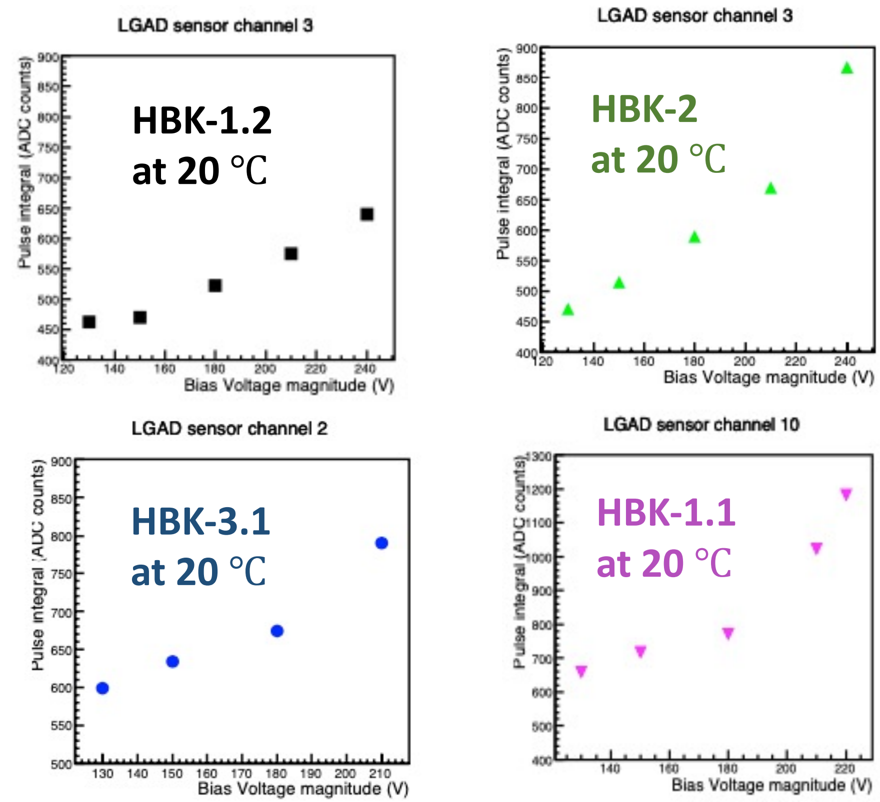
- The LGAD sensor has the capability to tune the charge collection gain by varying the bias voltage.
- Different types of LGAD sensors have different sensitivities to the bias voltage variation.

Consistent gain curves!

Test with laser pulse on sensor

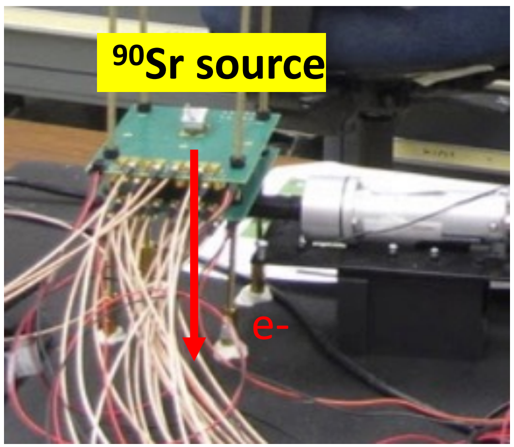


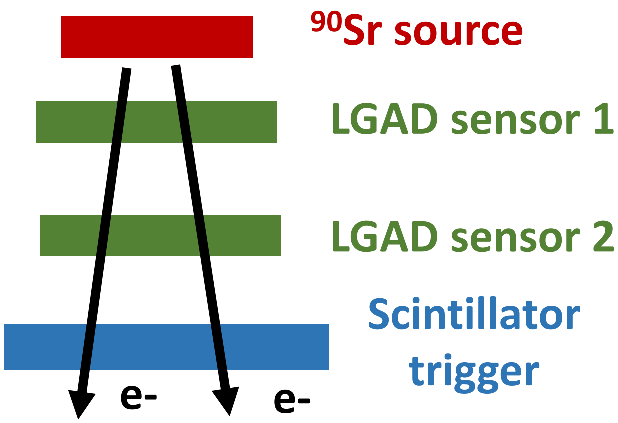
Analyzed results from the LANL bench test



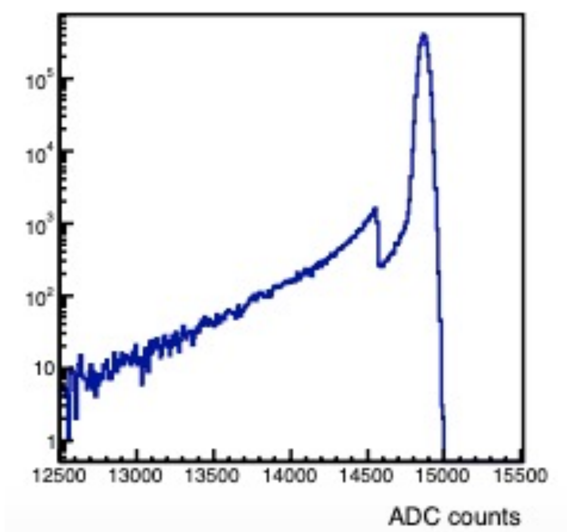
LGAD Two-layer Telescope ^{90}Sr Source Tests

- Use two HBK-1.2 LGAD sensors to build a 2-layer telescope.
- Use self trigger and the external trigger from a scintillator placed underneath the bottom LGAD sensor.

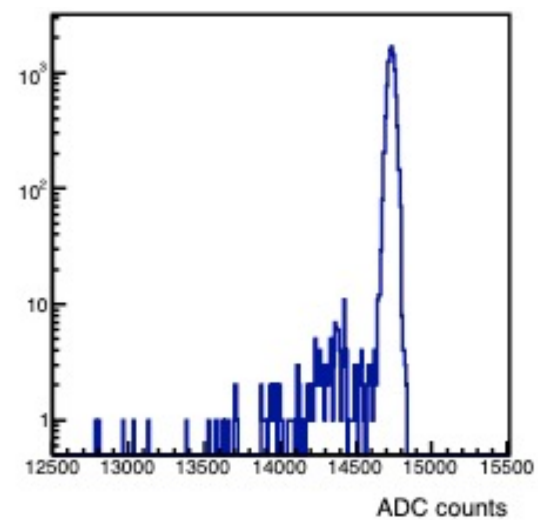




ADC distribution for sensor 1



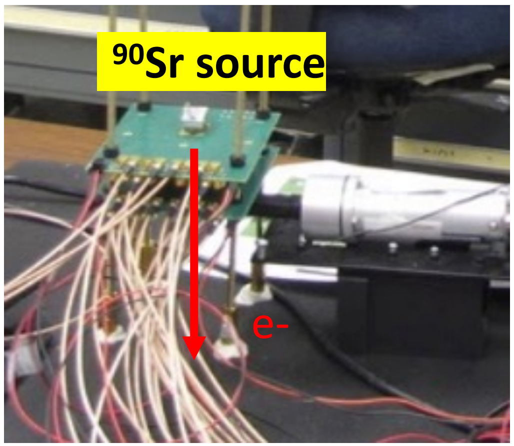
ADC distribution for sensor 2



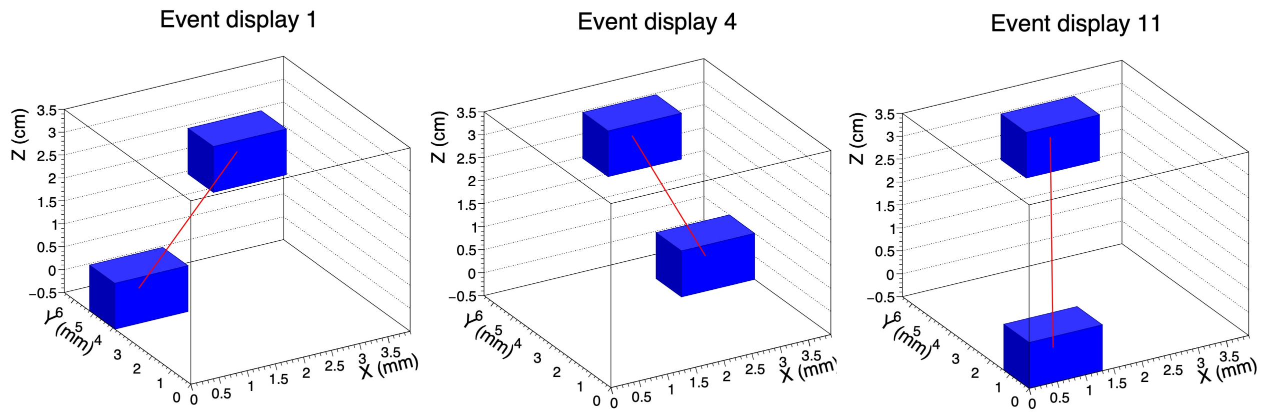
- 2 orders of magnitude higher electron yields measured in the top sensor than in the bottom sensor as most electrons are absorbed in the top sensor.

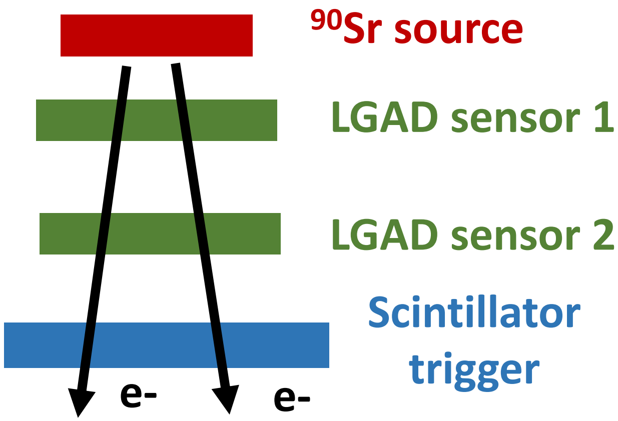
LGAD Two-layer Telescope ^{90}Sr Source Tests

- Use two HBK-1.2 LGAD sensors to build a 2-layer telescope.
- Use self trigger and the external trigger from a scintillator placed underneath the bottom LGAD sensor.



Event display of the ^{90}Sr telescope tests

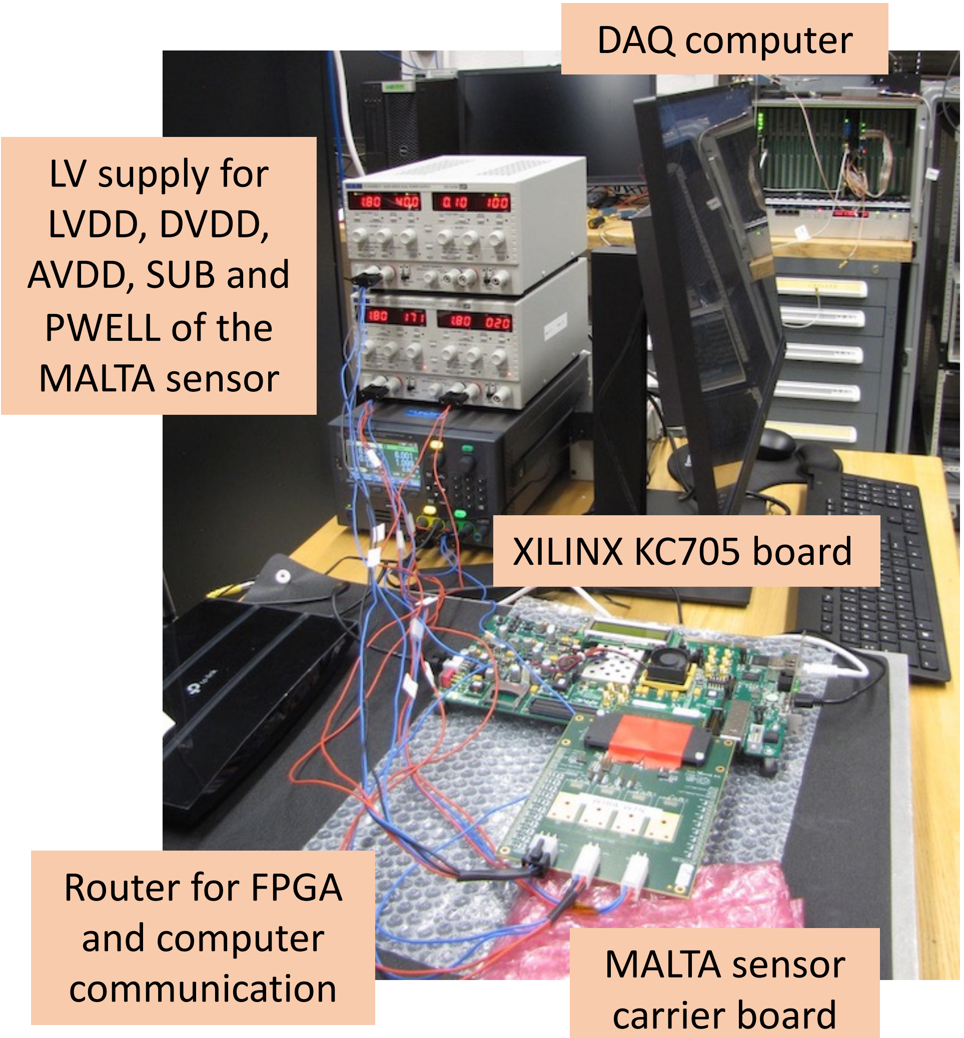




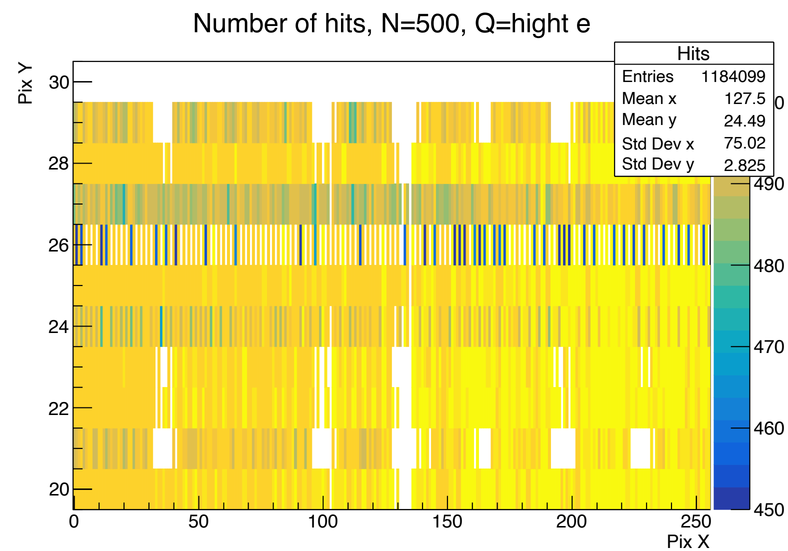
- Found hits from both layers belong to the same electron track.
- Track fit is under development.
- Will use AC-LGAD sensors to verify the fine spatial resolution.

MALTA Sensor Test Setup

- Single sensor bench test has been setup at LANL.



Example of analog scan of part of the MALTA sensor

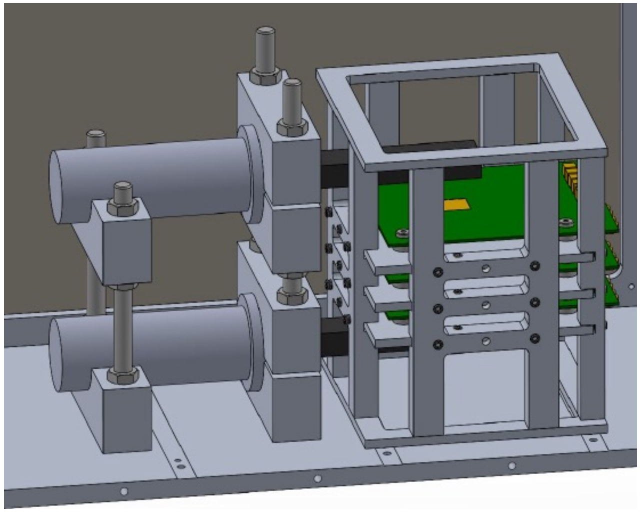


- Threshold/noise scan tests are underway.
- Will setup the source (cosmic ray) tests for the hit/tracking performance evaluation.

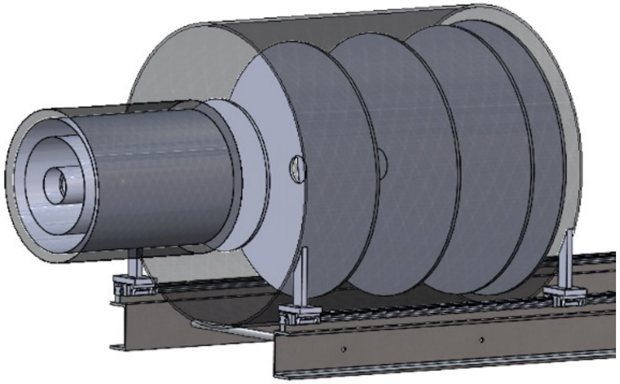
Next Steps

- LGAD test:
  - Expand the telescope studies to AC-LGAD.
  - Will carry out the irradiation tests using the LANL LANSCE facility.
  - Plan to use a GHz laser scan system to test the timing resolution.
- MALTA test:
  - We will setup a MALTA telescope and carry out the ^{90}Sr source and cosmic ray tests.
- Detector conceptual design:
  - Will optimize the detector conceptual design and implement the service parts based on the R&D results.

3-layer silicon sensor telescope mechanical structure design

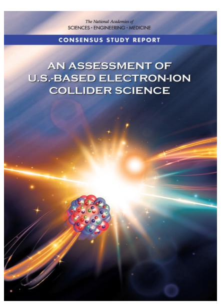


Engineer drawing of the FST conceptual design

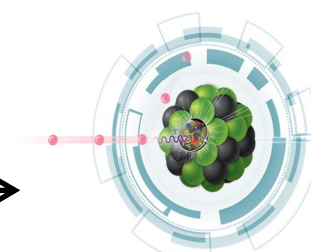


Summary and Outlook

- The future EIC requires advanced silicon detectors to realize high precision particle tracking and identification measurements.
- The initial design of the proposed forward silicon vertex/tracking detector meets the EIC heavy flavor physics requirements.
- R&D work for the silicon detector candidates: LGAD and MALTA has achieved bench test results at LANL.
- We look forward to collaborate with more institutions toward the detector developments and construction for the EIC.



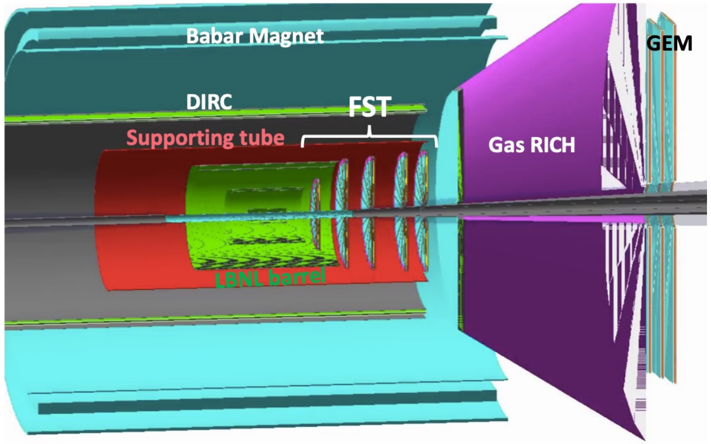
NAS review	EIC CD0	EIC CD1	EIC CD2	EIC CD3	EIC CD-4a	EIC CD-4
2018	2020	2021	2023	2024	2030	2033

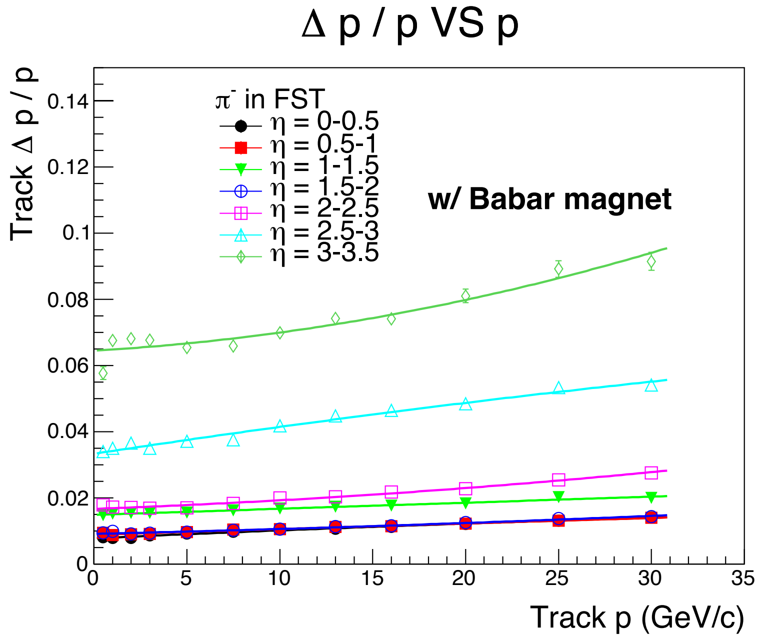


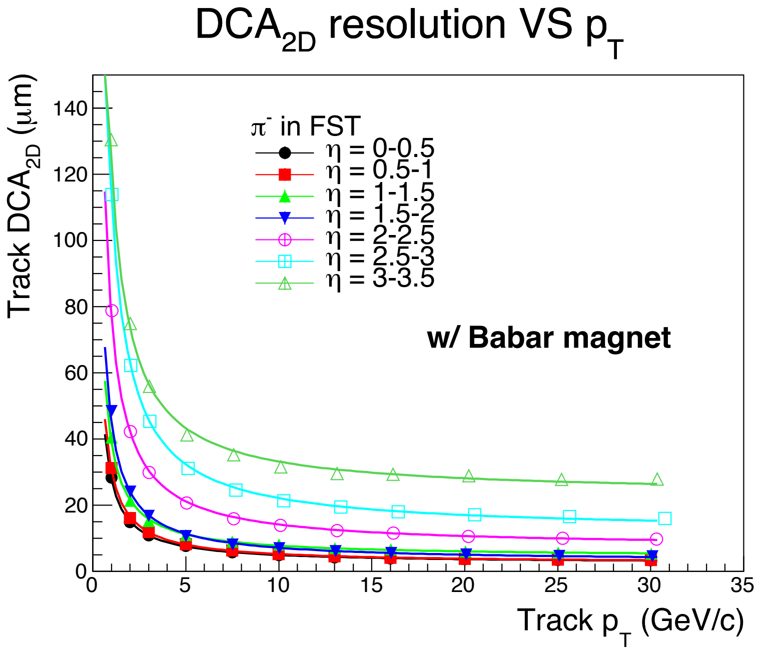
Backup

Tracking Performance w/ Babar Magnet

- Tracking momentum resolution (left) and track transverse DCA (DCA_{2D}) resolution in different pseudorapidity regions.

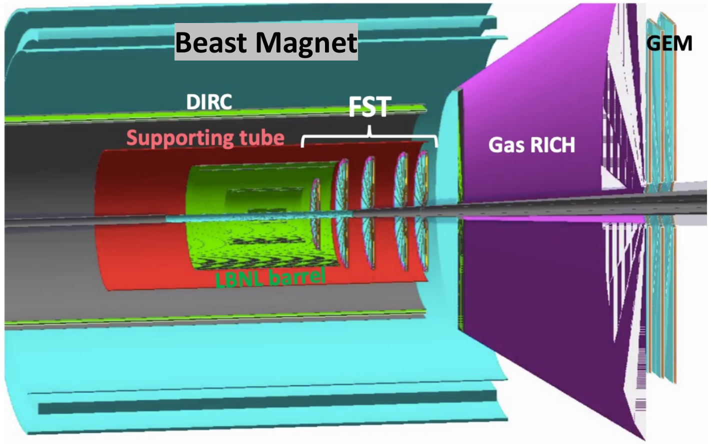


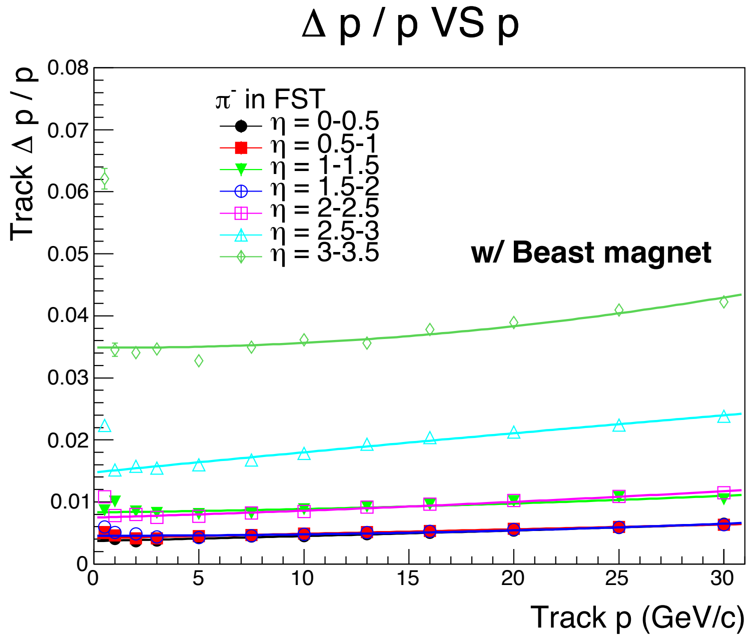


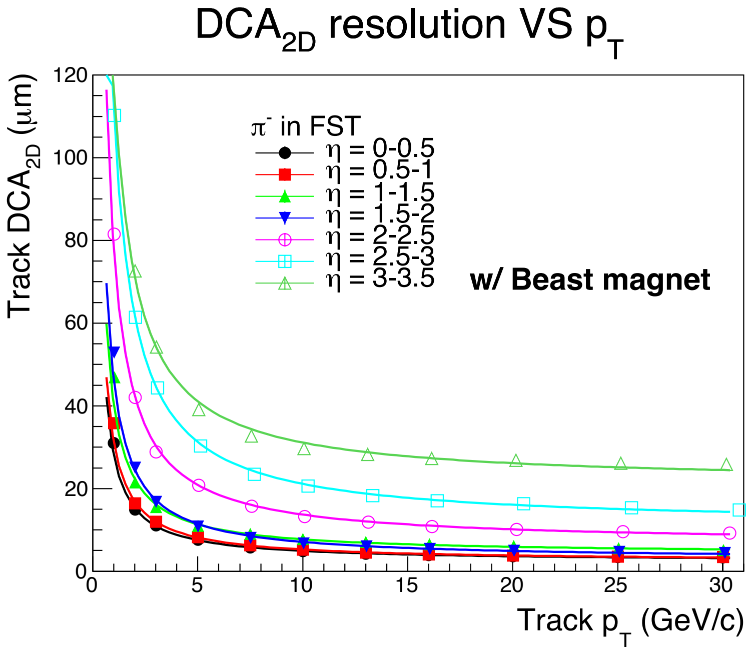


Tracking Performance w/ Beast Magnet

- Tracking momentum resolution (left) and track transverse DCA (DCA_{2D}) resolution in different pseudorapidity regions.

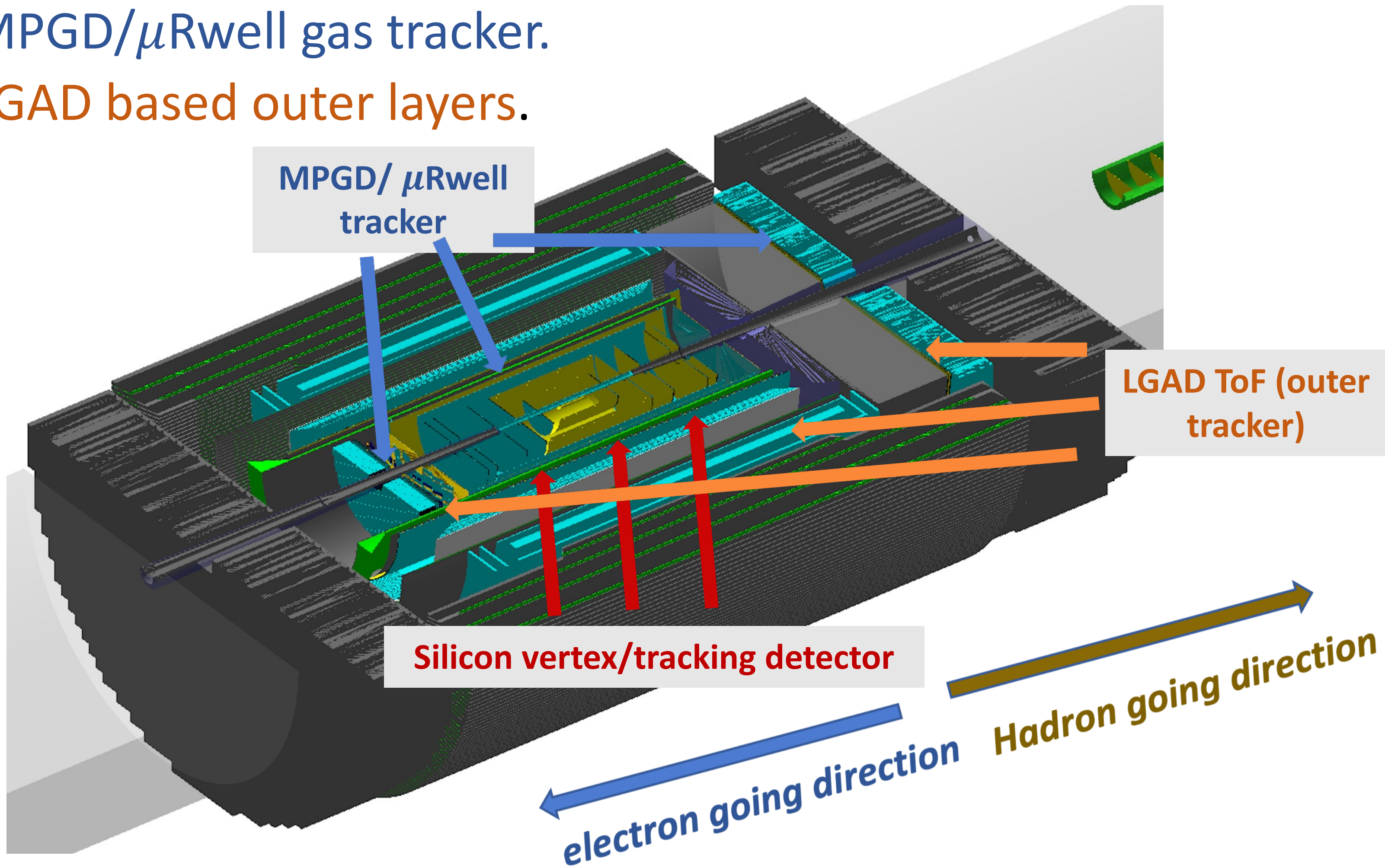






Integrated ECCE Detector implemented in Fun4All

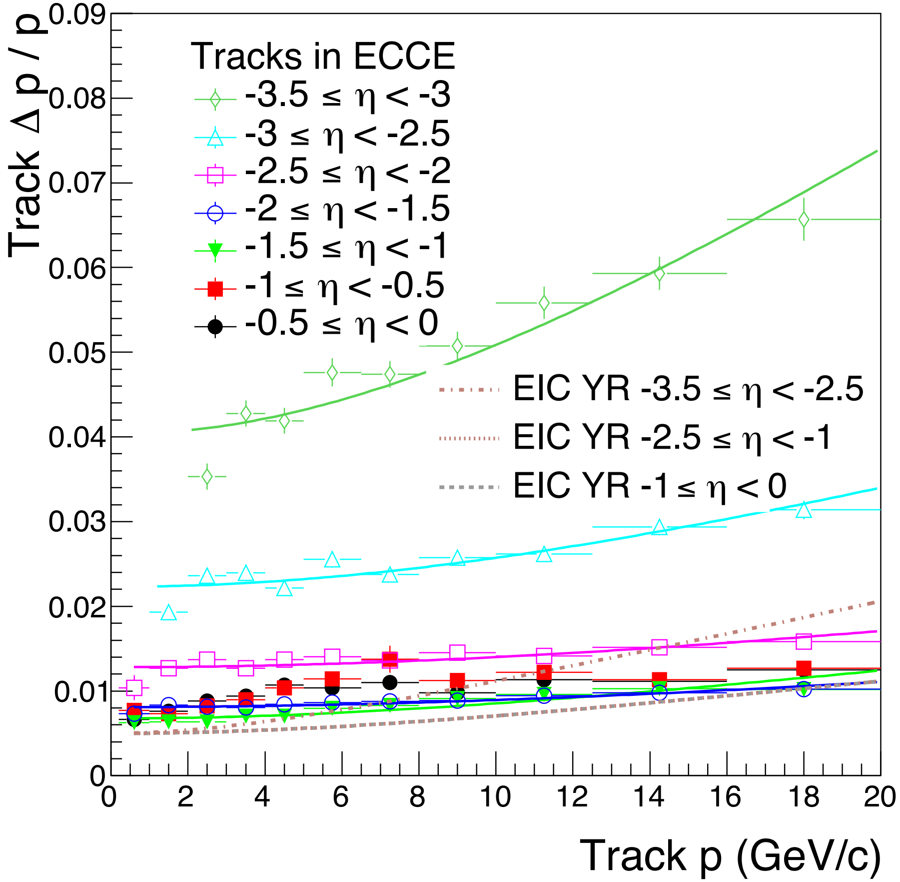
- July concept ECCE tracking detector consists of
  - MAPS based silicon vertex/tracking layers/planes.
  - MPGD/μRwell gas tracker.
  - LGAD based outer layers.



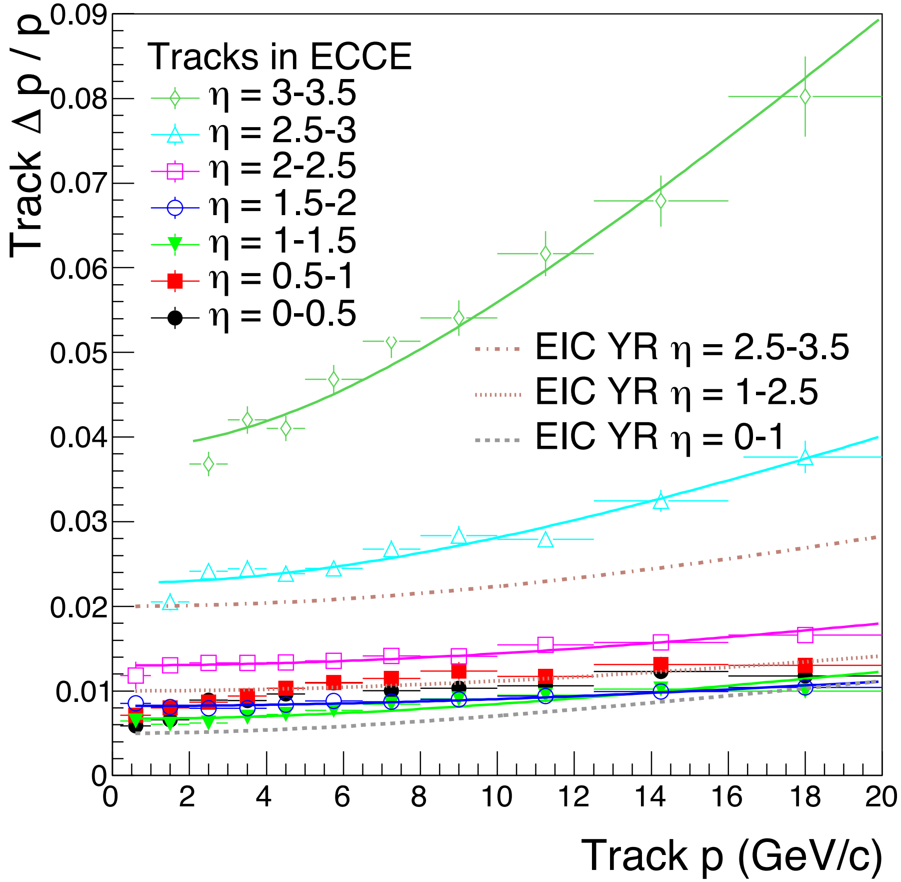
ECCE Detector Tracking Performance: Momentum resolution

- The tracking momentum resolution of the current ECCE design is not far from the EIC Yellow Report requirements.

$\Delta p / p$ VS p in $-3.5 \leq \eta < 0$



$\Delta p / p$ VS p in $0 \leq \eta < 3.5$



ECCE Detector Tracking Performance: DCA_{2D} resolution

- The tracking DCA_{2D} resolution of the current ECCE design meets the EIC Yellow Report requirements.