Los Alamos NATIONAL LABORATORY

Forward silicon tracking detector developments for the future Electron-Ion Collider

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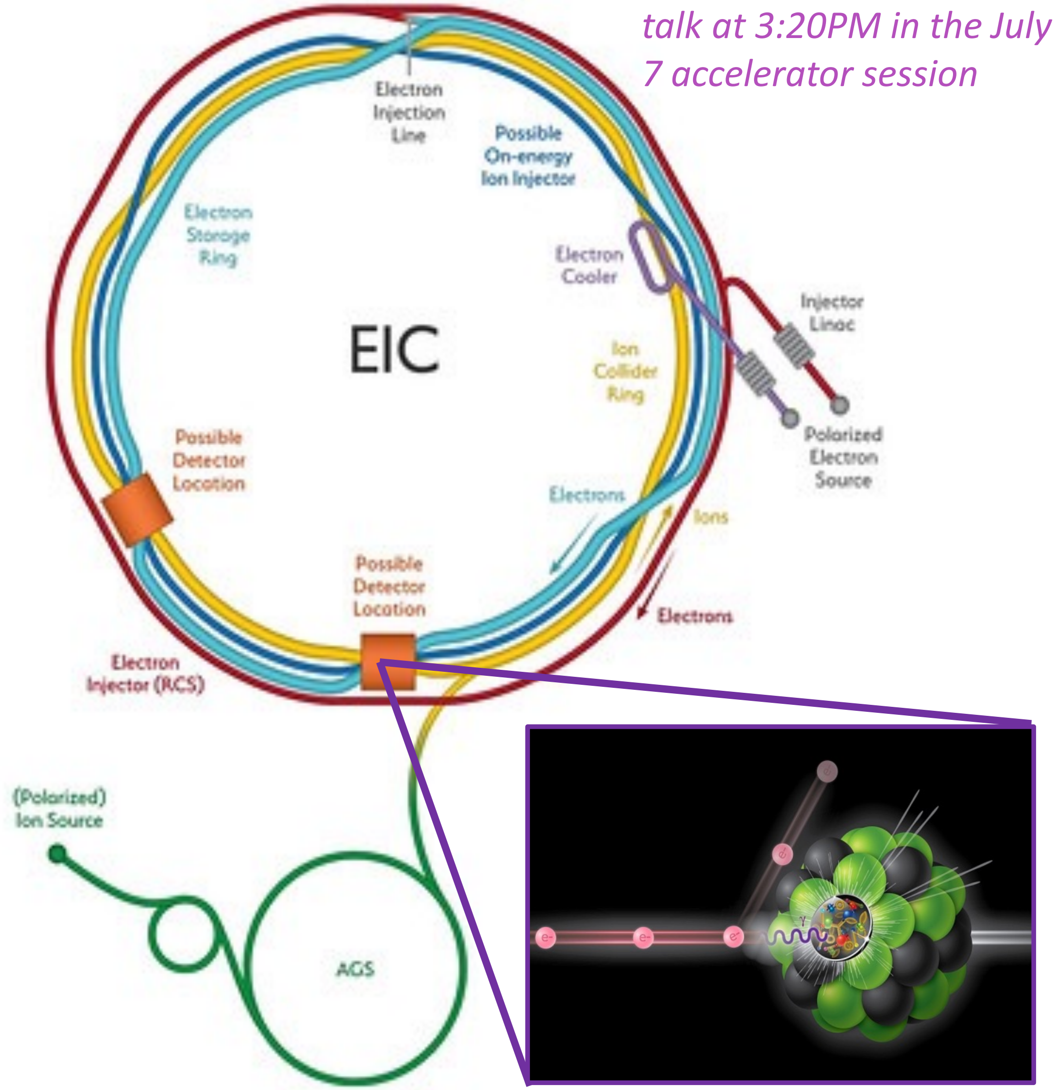
Outline

- Introduction to the Electron-Ion Collider (EIC) and the EIC detector.
- The Forward Silicon Tracking (FST) detector design and performance.
- Advanced silicon detector R&D progress for the FST and generic EIC detector.
- Summary and Outlook.

Introduction to the future Electron-Ion Collider (EIC)

- The future Electron-Ion Collider (EIC) will utilize high-luminosity high-energy e+p and e+A collisions to solve several fundamental questions in the nuclear physics field.
- The project has received CD1 approval from the US DOE in 2021 and will be built at BNL.
- The future EIC will operate:
  - (Polarized) p and nucleus beams at 41-275 GeV.
  - (Polarized) e beam at 5-18 GeV.
  - Instant luminosity $L_{int} \sim 10^{33\text{-}34}\ cm^{-2}sec^{-1}$. A factor of ~1000 higher than HERA.
  - Bunch crossing rate: ~10 ns.

See Silvia Verdú-Andrés' talk at 3:20PM in the July 7 accelerator session

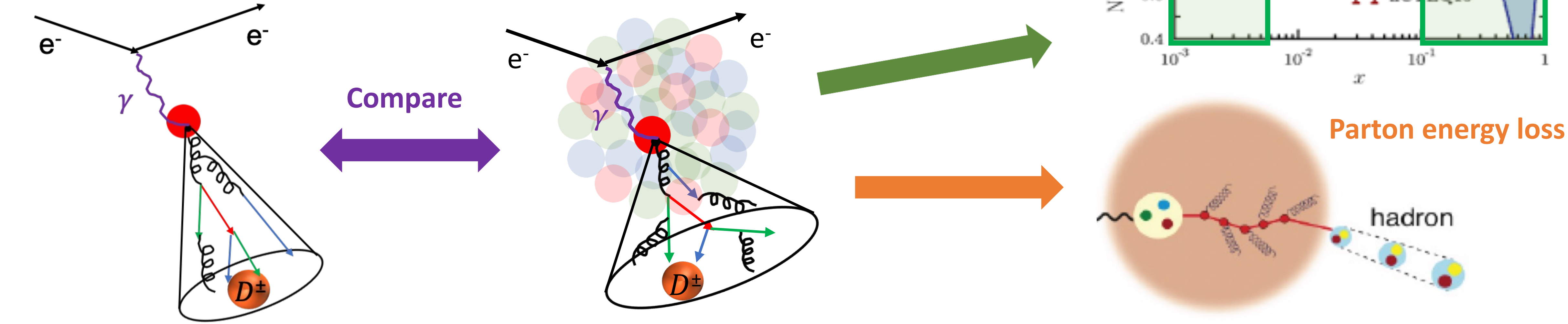


Heavy flavor measurements can enrich the EIC physics program

- Heavy flavor hadron and jet measurements at the future EIC can help study its science focuses and play a significant role in exploring
  - Nuclear modification on the initial nuclear Parton Distribution Functions (nPDFs) especially in the high and low Bjorken-x (x_{BJ}) region.
  - Final state parton propagation inside nuclear medium and hadronization processes in vacuum and nuclear medium.

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

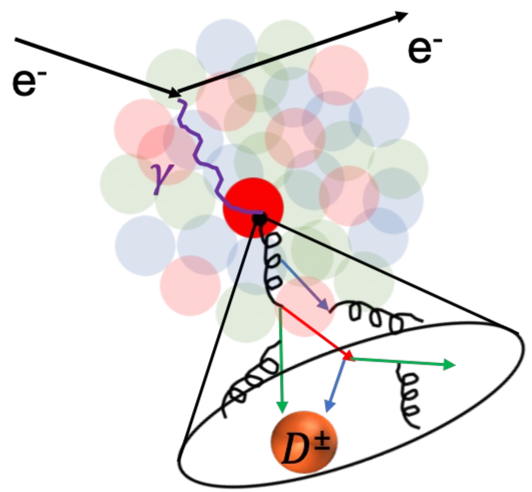
$e^- + \mathrm{Au} \to e^- + jet(D^{\pm}) + X$

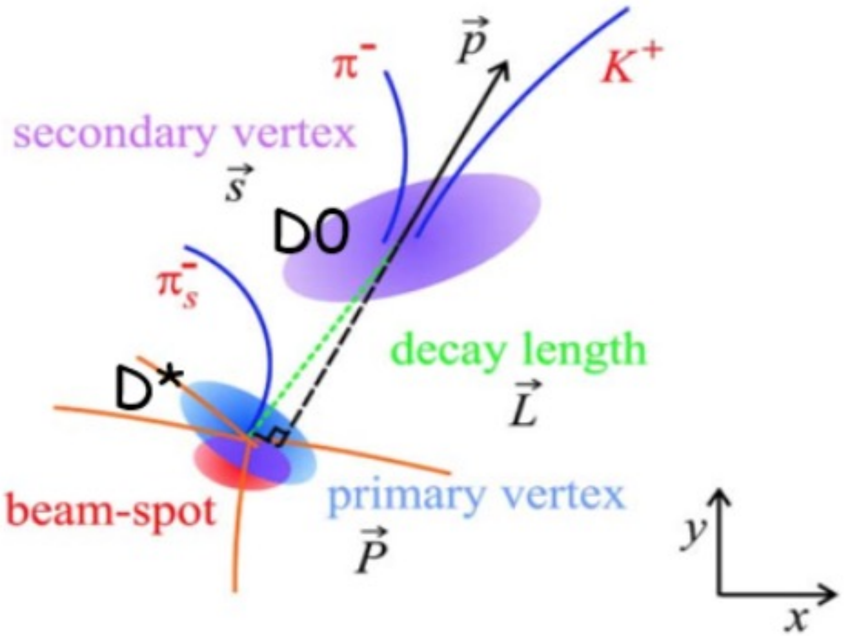


High precision vertex/tracking detector is required to measure HF products

- Heavy flavor hadrons usually have a short lifetime compared to light flavor hadrons. They can be identified by detectors using their unique lifetime and masses.

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





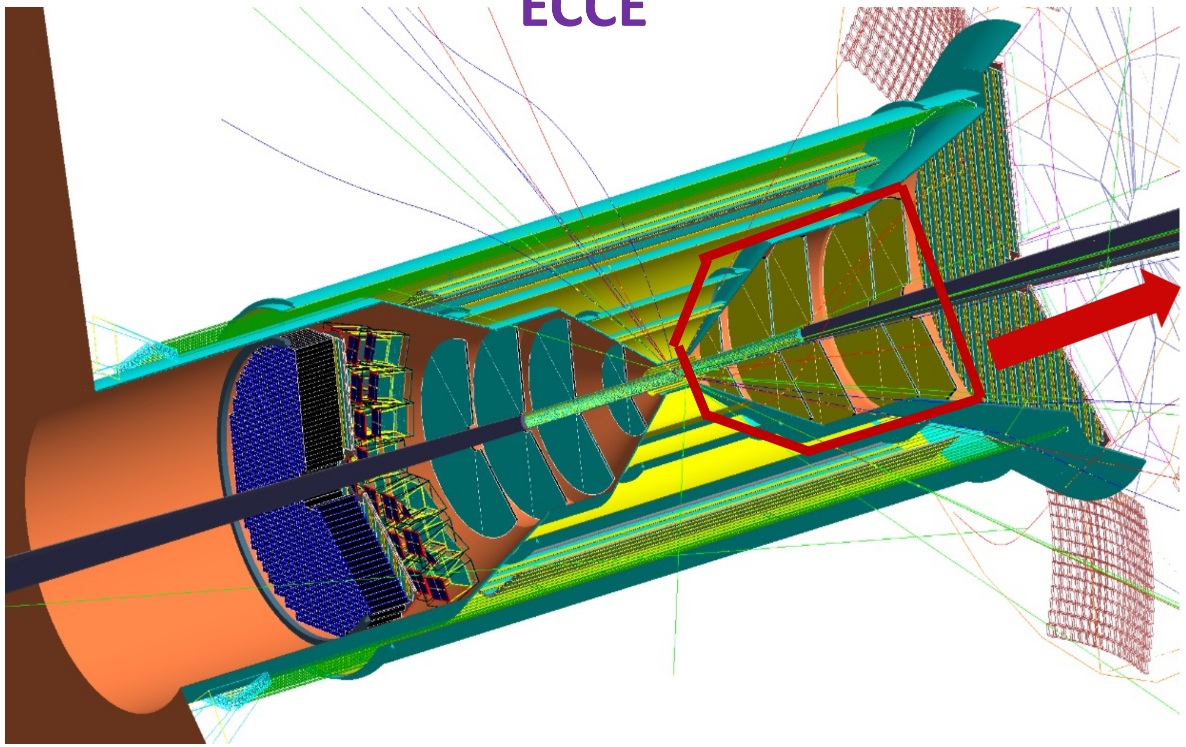
Particle	Mass (GeV/c^2)	Average decay length
$D^{\pm}$	1.869	312 micron
D^0	1.864	123 micron
$B^{\pm}$	5.279	491 micron
B^0	5.280	456 micron

- Heavy flavor physics-driven detector performance requirements:
  - Fine spatial resolution (<100 μm) for displaced vertex reconstruction.
  - Fast timing resolution to suppress backgrounds from neighboring e+p/A collisions.
  - Low material budgets to maintain fine hit resolution.

Forward Silicon Tracker design implemented in the ECCE detector

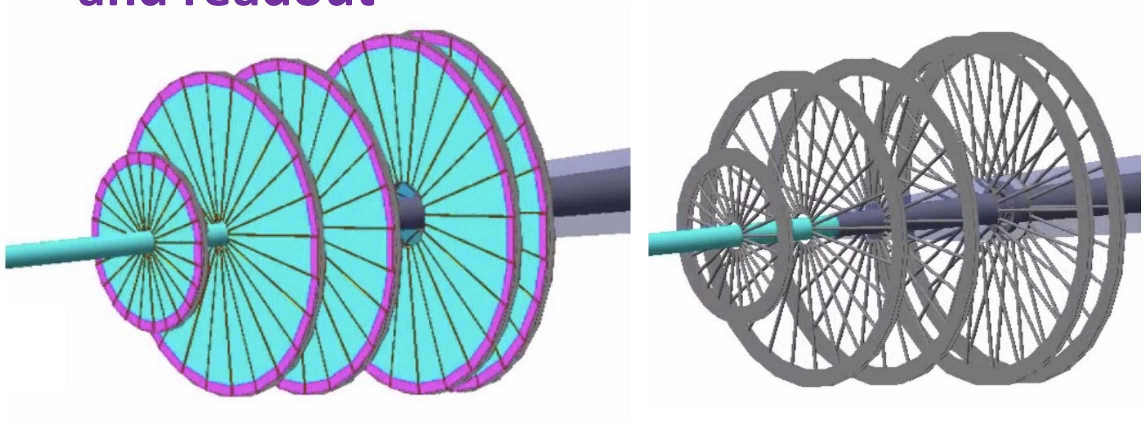
- The Monolithic Active Pixel Sensor based Forward Silicon Tracker (FST) design consists of 5 disks with the pseudorapidity coverage from 1.2 to 3.5, ~10B pixels and ~2.2 m^2 active area.

LANL led FST detector design implemented in the EIC reference detector: ECCE



Silicon wedge and readout

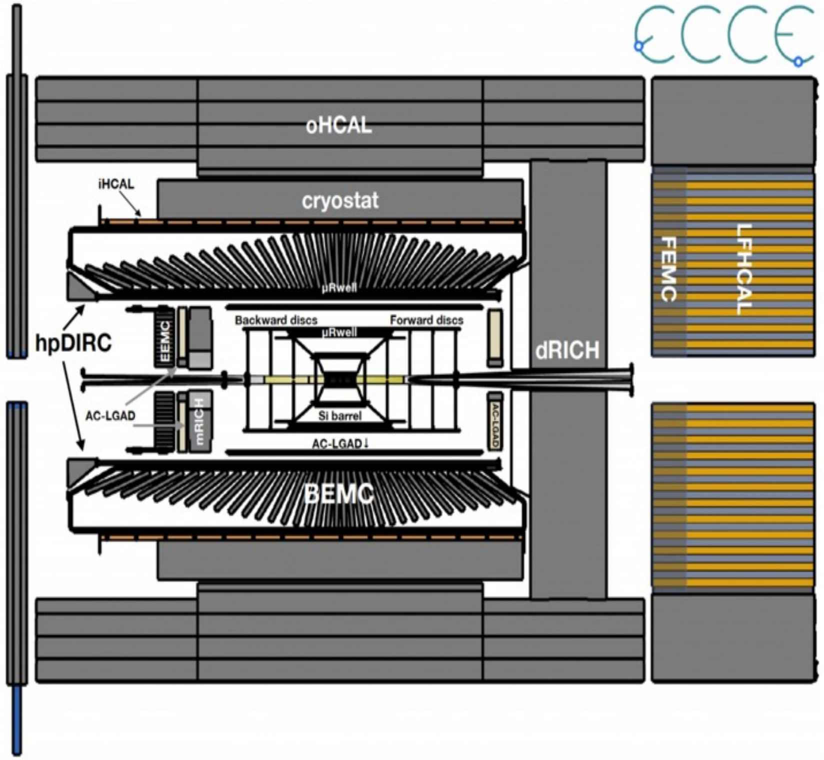
Support and cooling

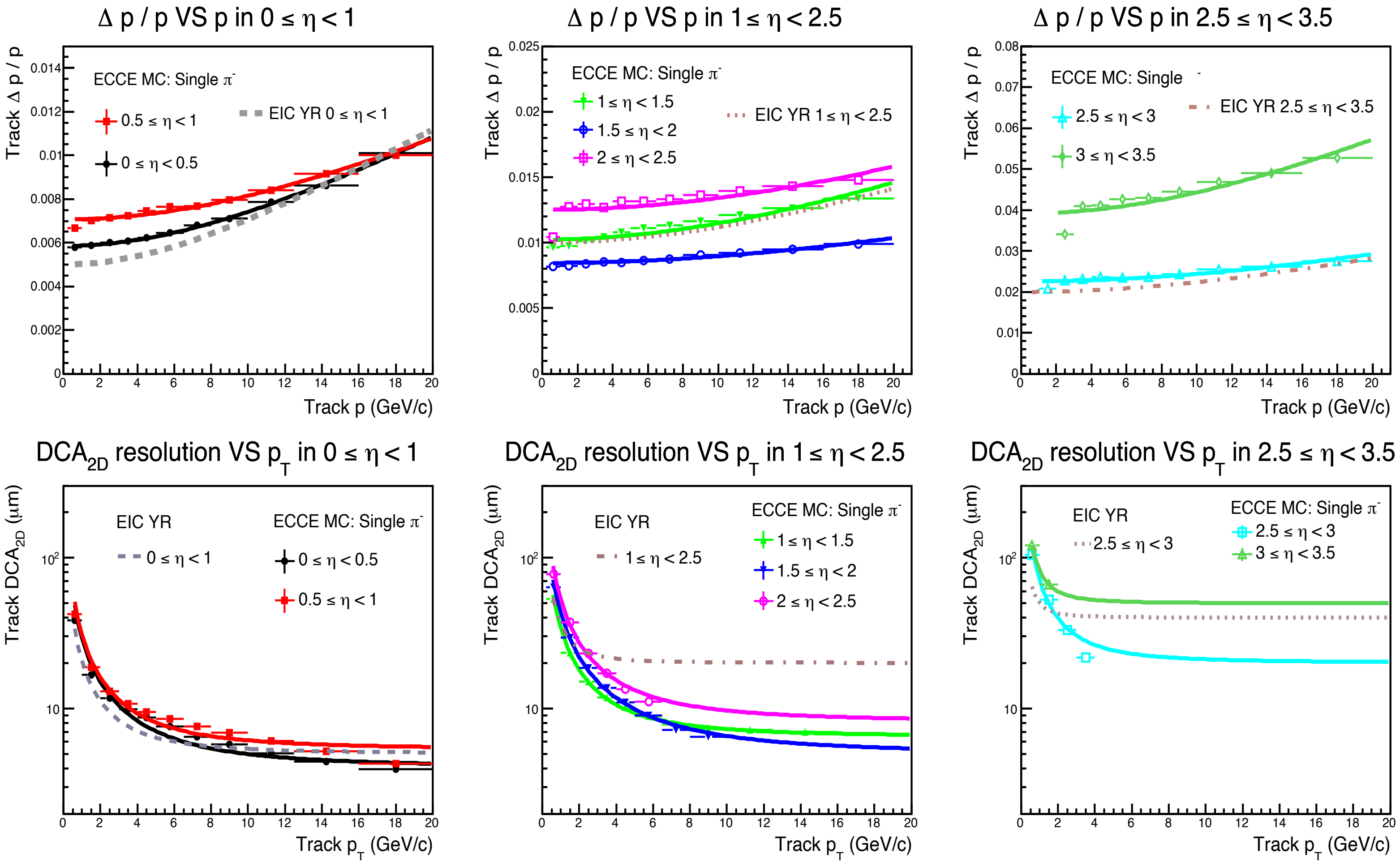


- Detailed detector layout (segmentations, readout units, cooling and support structures) have been implemented in GEANT4 simulation.

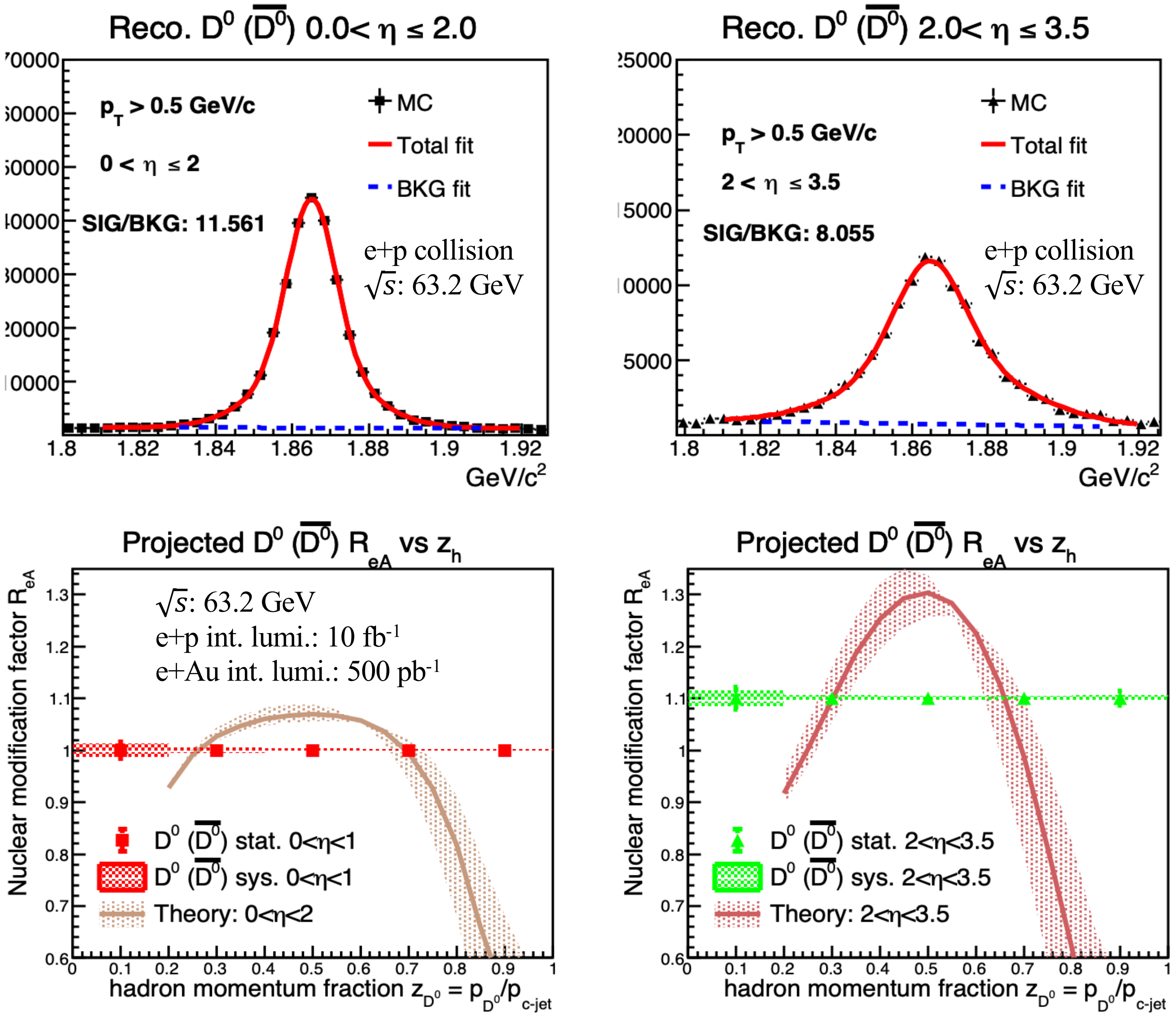
Tracking performance of the EIC reference design in GEANT4 simulation

- Integrated MAPS, MPGD (e.g., μRwell) and AC-LGAD tracking detectors of the EIC reference design (ECCE) provide precise momentum and transverse DCA_{2D} resolutions.





Forward heavy Flavor physics enabled by the FST



- Clear and pronounced $D^0(\overline{D^0})$ signals have been found in 10+100 GeV e+p simulation with the latest EIC accelerator and detector design.

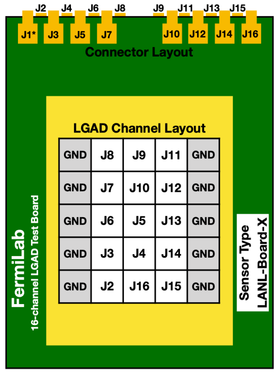
Theory: Phys. Lett. B 816 (2021) 136261

- The associated reconstructed D meson in charm jets nuclear modification factor (R_{eA}) shed light on exploring the hadronization in different nuclear medium conditions with better precisions than theoretical predications.

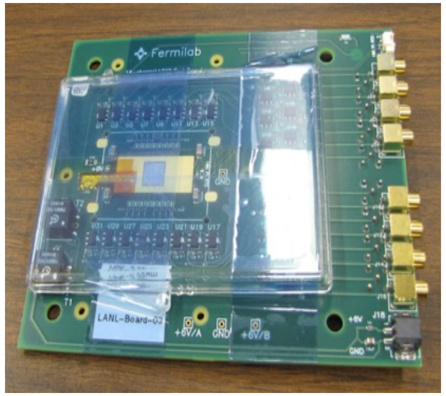
Advanced silicon technology candidates for the EIC silicon tracker

- Several advanced silicon technologies are under characterization at LANL.

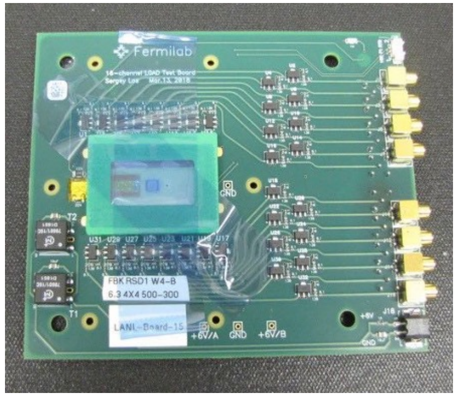
LGAD pixel map
3X5 Matrix



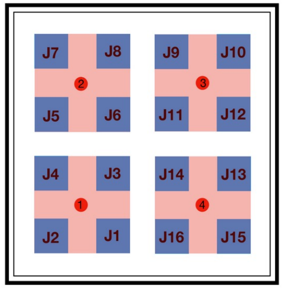
LGAD Carrier Board



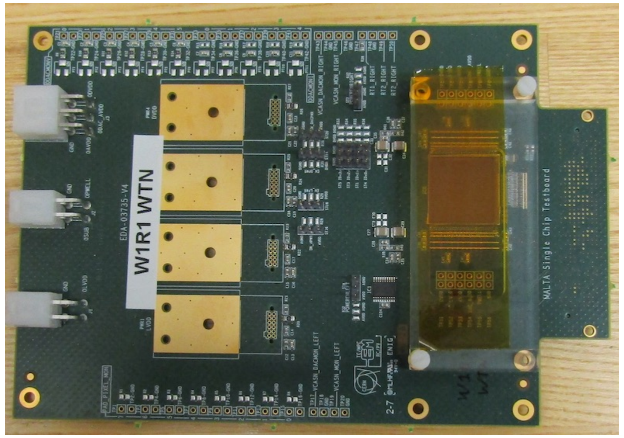
AC-LGAD Carrier Board



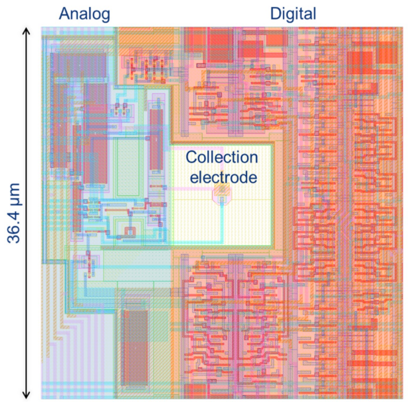
AC-LGAD
pixel map
4X4 Matrix



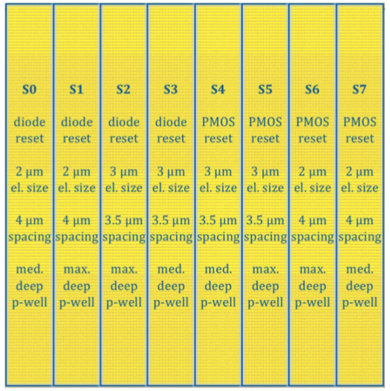
MALTA Carrier Board



MALTA Pixel diagram



MALTA sensor diagram
512X512 Matrix



in collaboration with BNL, JLab, UCSC, CERN, FNAL, Rice Univ., UM, UNM, ANL, KIT, LGAD Consortium, UC Consortium

Low Gain Avalanche Detector (LGAD) and AC-Coupled LGAD (AC-LGAD)

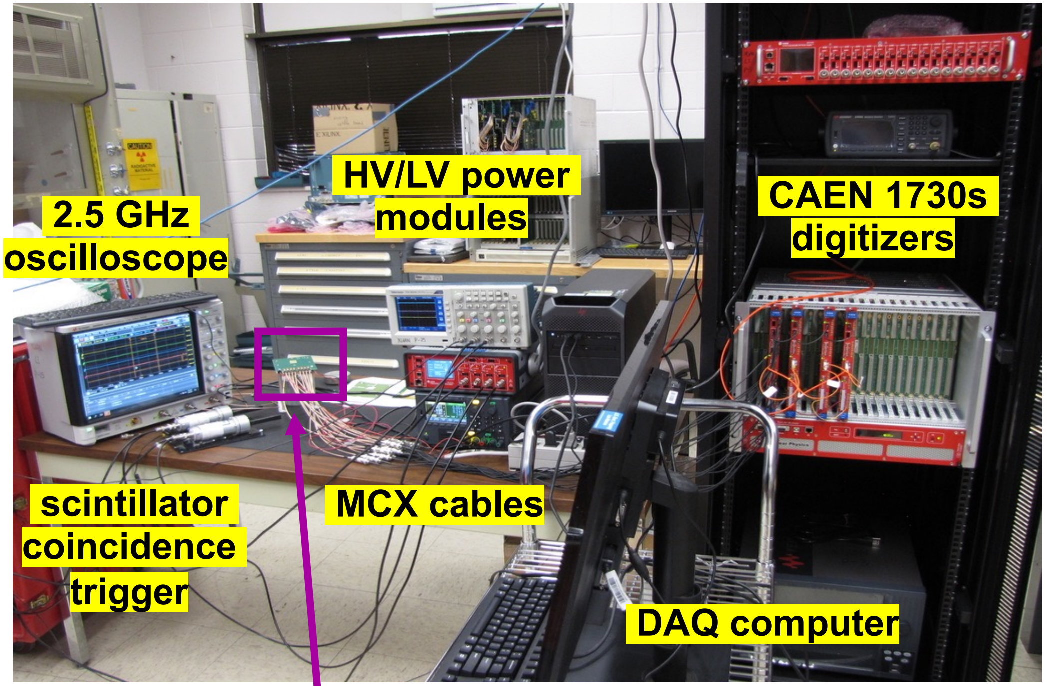
Pixel size: 0.5 to 1.3 mm
Spatial resolution: ~30 μm
Time resolution: <30 ps

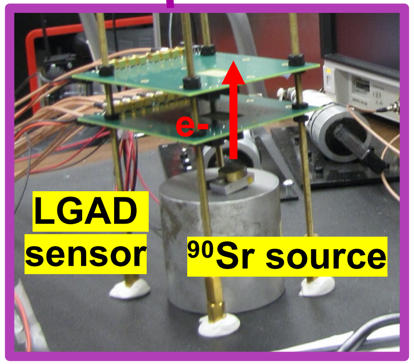
Depleted Monolithic Active Pixel Sensor (e.g., MALTA)

Pixel size: 36.4 μm
Spatial resolution: ~7 μm
Time resolution: ~2 ns

Advanced silicon technology R&D setup for EIC silicon tracker

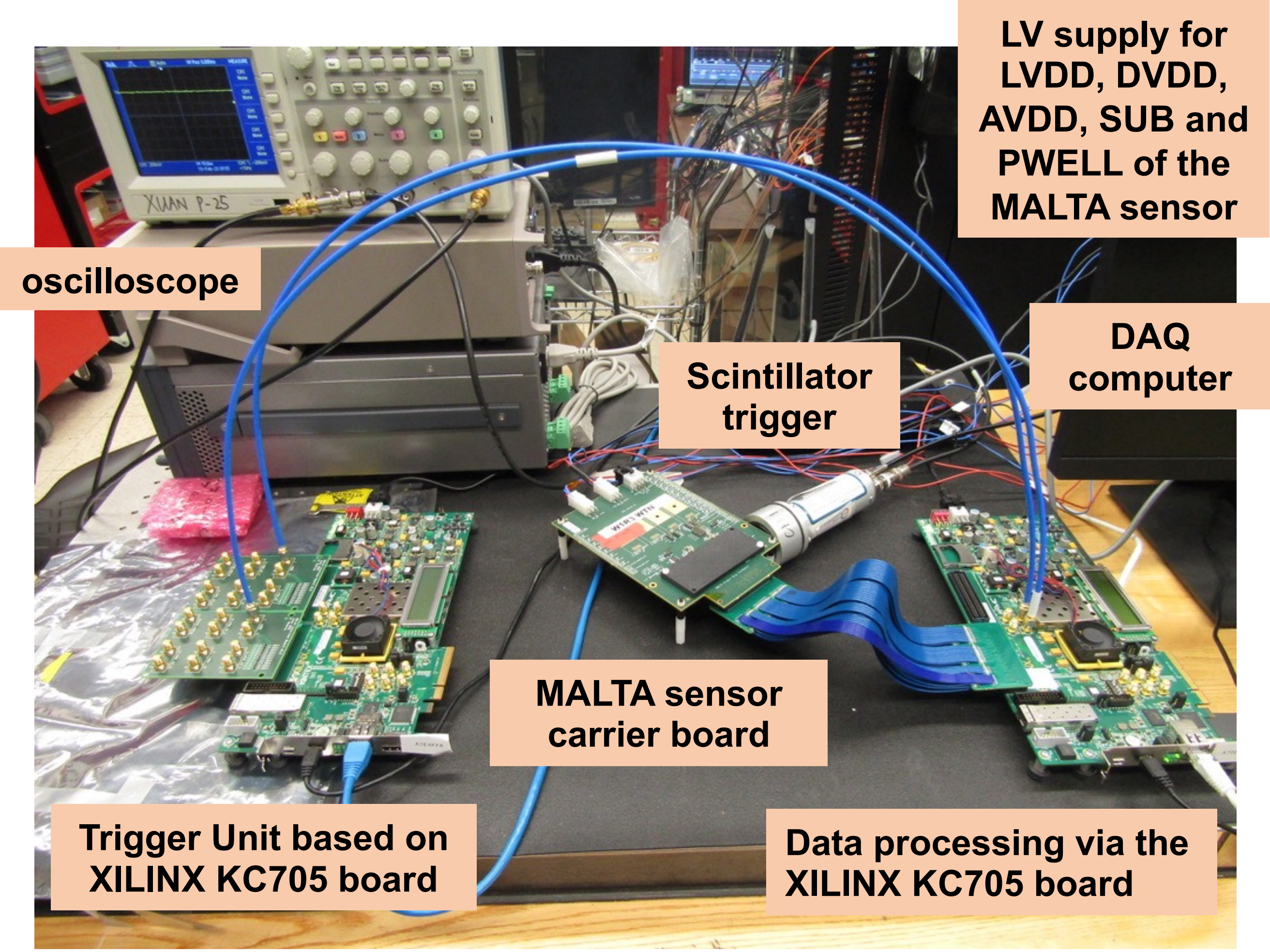
LGAD (AC-LGAD) characterization with the ^{90}Sr source test





2-layer LGAD telescope

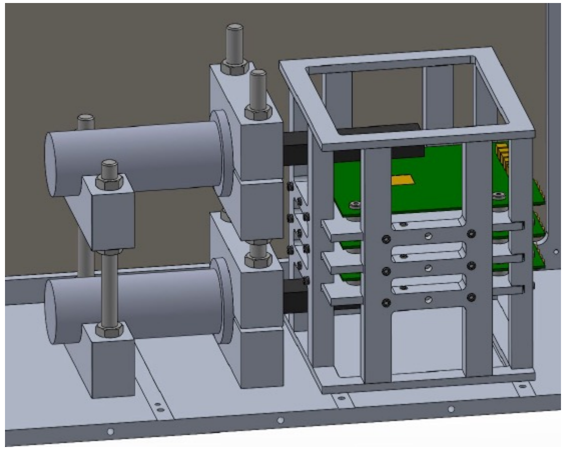
MALTA sensor characterization test bench



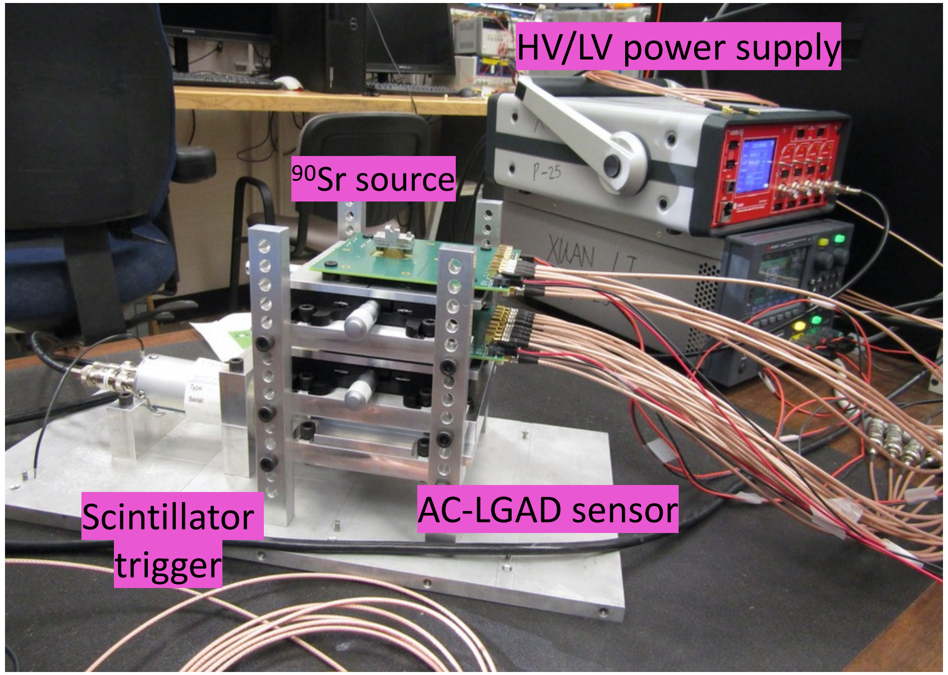
LGAD and AC-LGAD R&D test results

- Feasibility tests of a two-layer AC-LGAD telescope using a ^{90}Sr source.

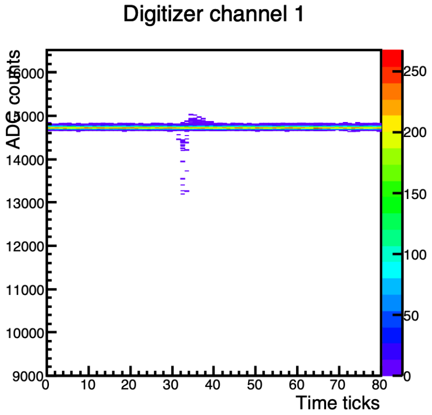
Mechanical design of 3-layer LGAD (AC-LGAD) telescope



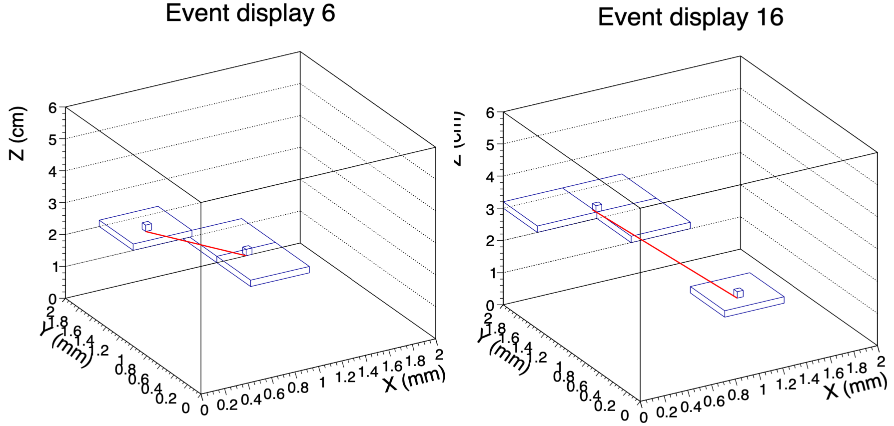
3-layer AC-LGAD telescope ^{90}Sr test setup with 2 sensors connected to the readout



Digitized pulse shape VS time tick (2ns) for individual pixel from the ^{90}Sr source tests.



Event display of reconstructed electron tracks

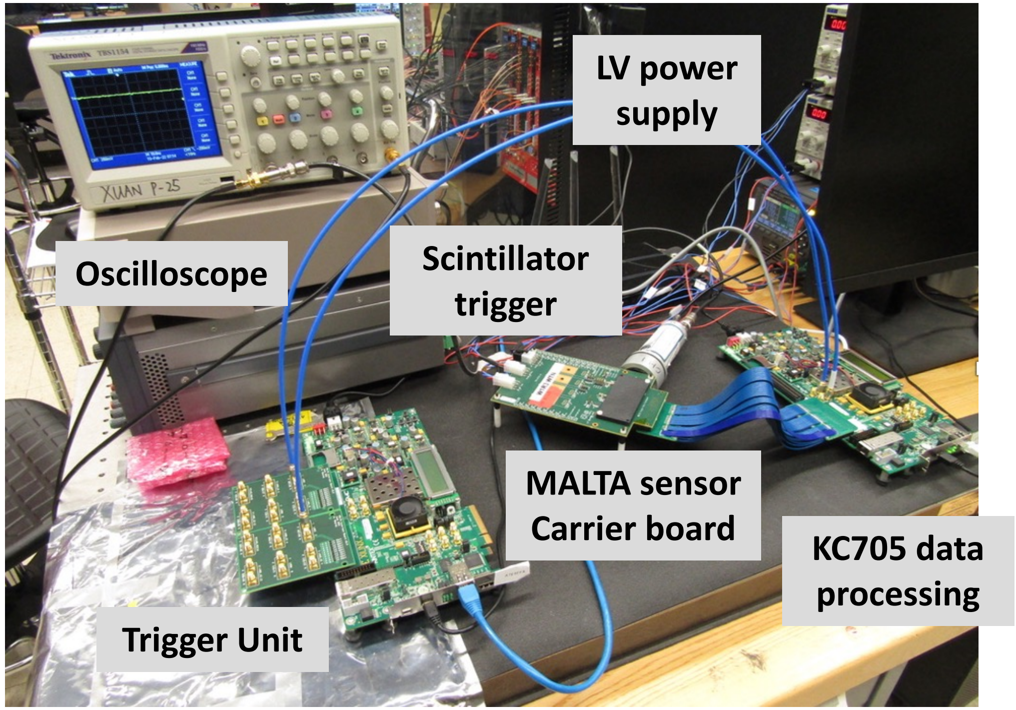


- Tracking performances such as efficiency, spatial and temporal resolutions are under study with the 3-layer telescope configuration.

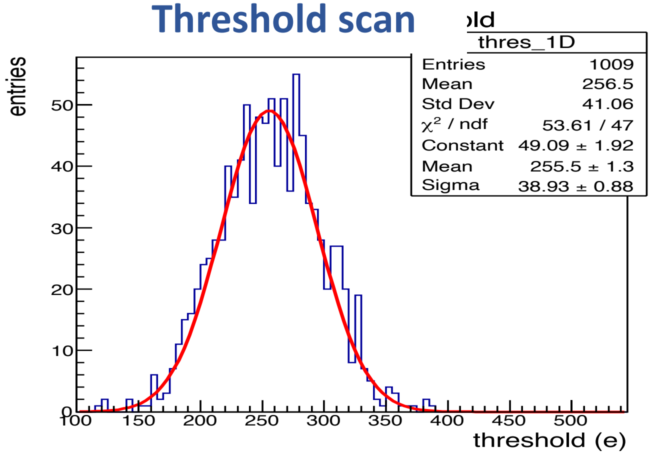
MALTA R&D test results

- Threshold and noise scan has been performed.
- Successfully suppressed the noise hits and the hit occupancy has been studied with the ^{90}Sr source tests.

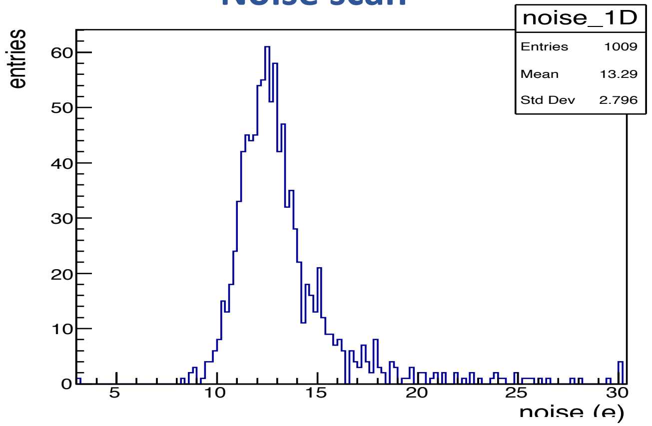
MALTA prototype sensor test setup



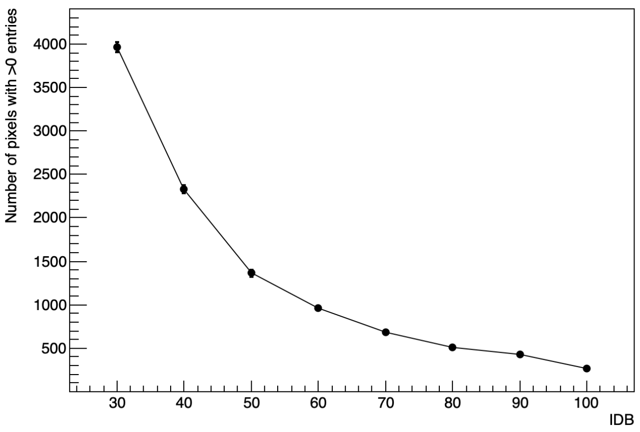
Threshold scan



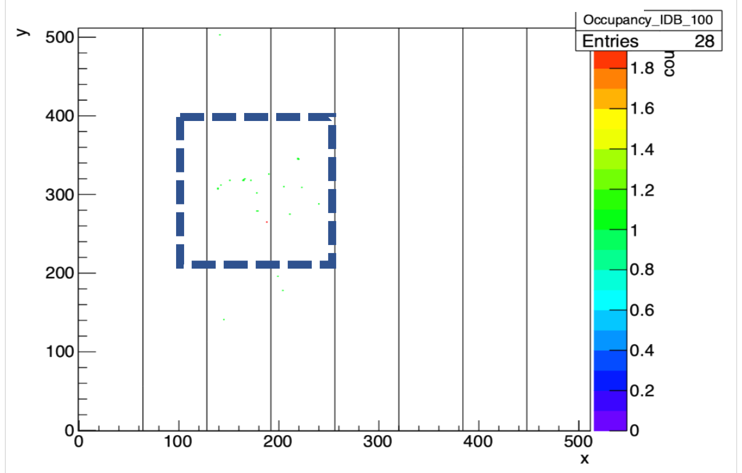
Noise scan



Noisy pixel rate VS IDB value

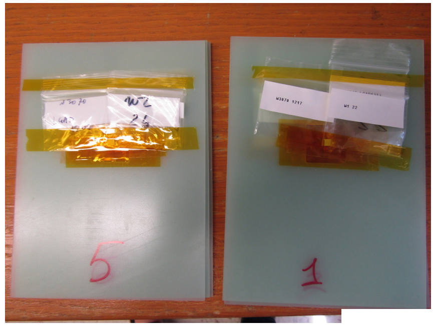


^{90}Sr source hit occupancy



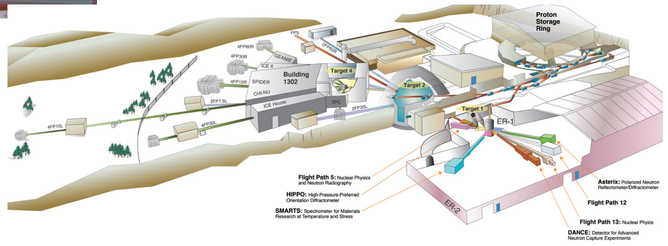
EIC Silicon detector design and R&D path forward

- Irradiation tests scheduled with the LANL LANSCE facility to test the radiation hardness for LGAD and AC-LGAD prototype sensors with 10^{13}-10^{16} $n_{eq}cm^{-2}$ doses.
- Telescope bench tests ongoing at LANL and planed beam tests in collaboration with other institutions.
- Work towards the EIC detector 1 technical design.
  - The EIC detector 1 proto-collaboration formed in April 2022, is working on the detector technology down selection and the detector design optimization and updates for the CD2 approval scheduled in 2023.

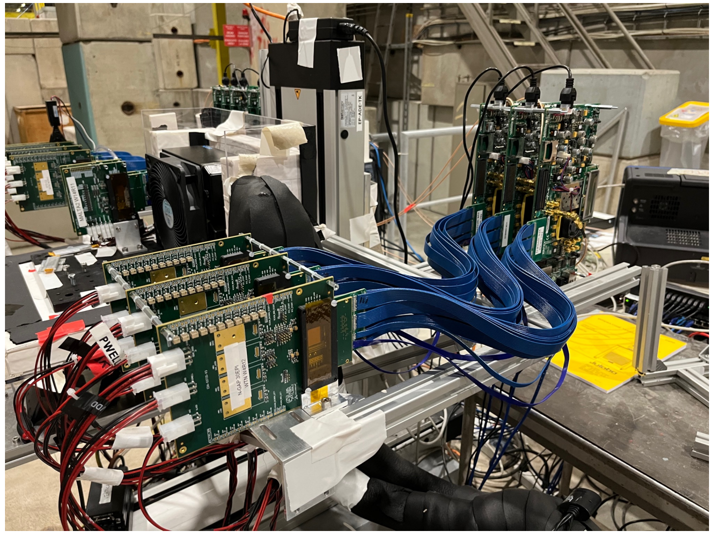


LGAD and AC-LGAD test samples under irradiation tests at LANL.

LANL LANSCE



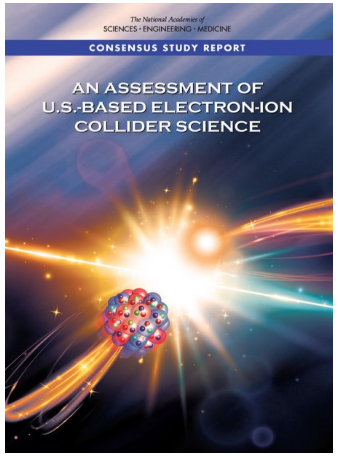
MALTA telescope beam tests at CERN SPS

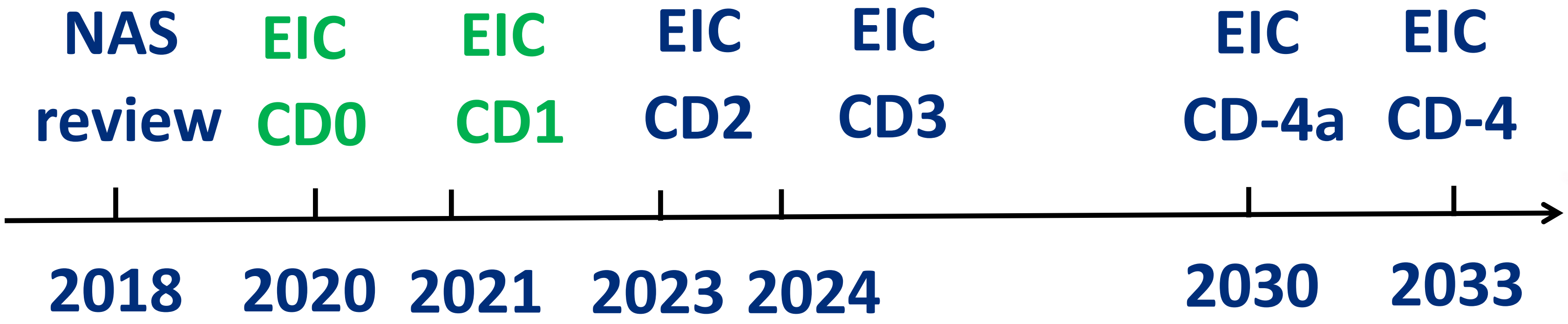


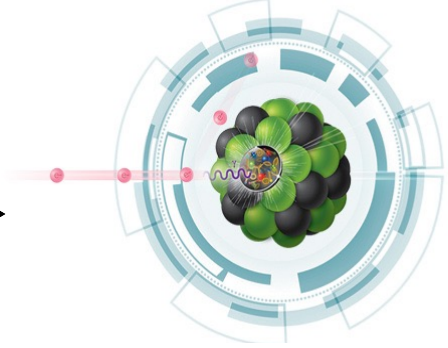
ATLAS EXPERIMENT

Summary and Outlook

- Great progresses have been achieved for the EIC silicon detector R&D, design and associated physics developments.
- The FST has been integrated into the selected EIC detector reference design.
- As we are moving towards the EIC CD2/3 approval, we look forward to work with more collaborators for the EIC detector/experiment realization.

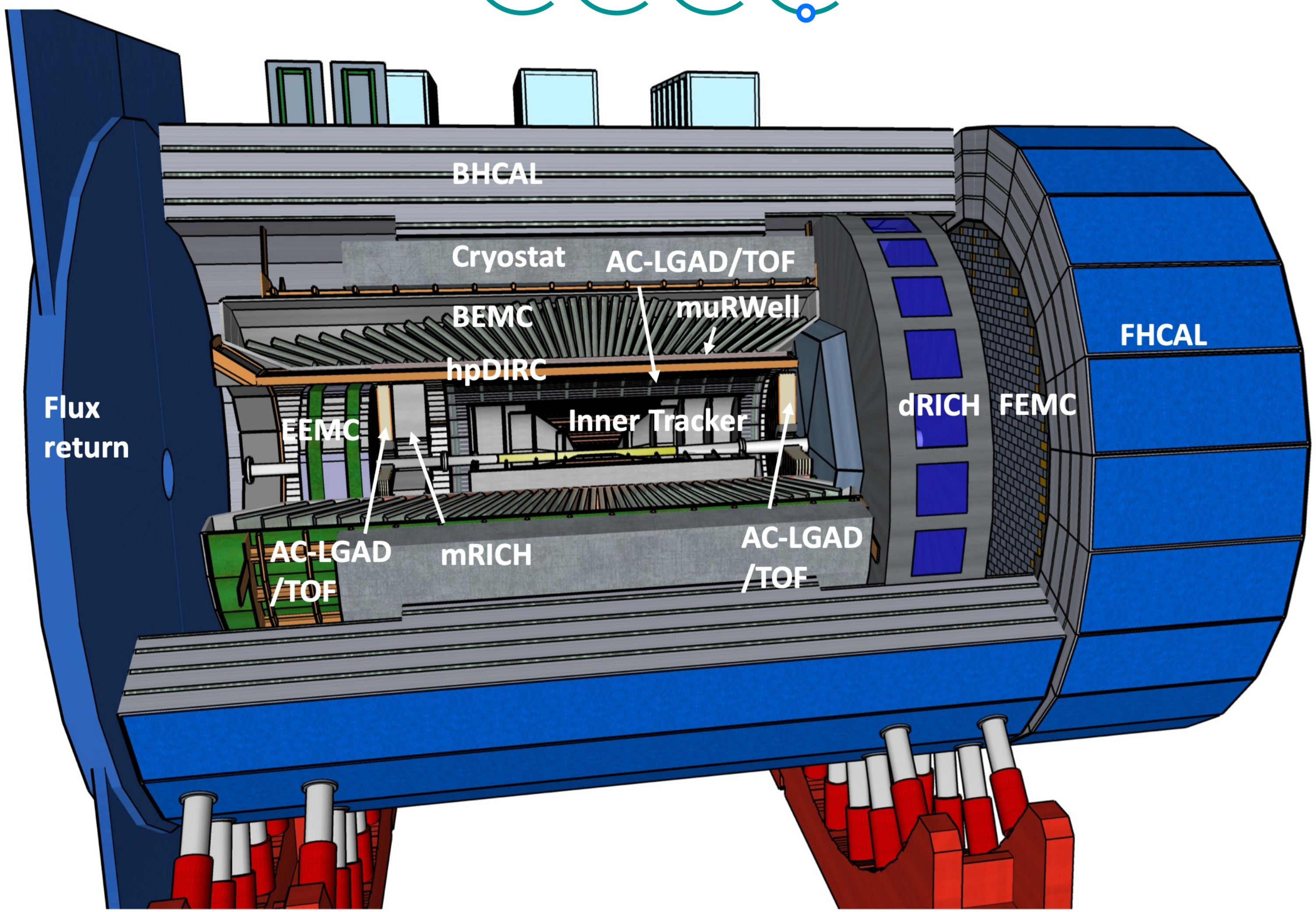




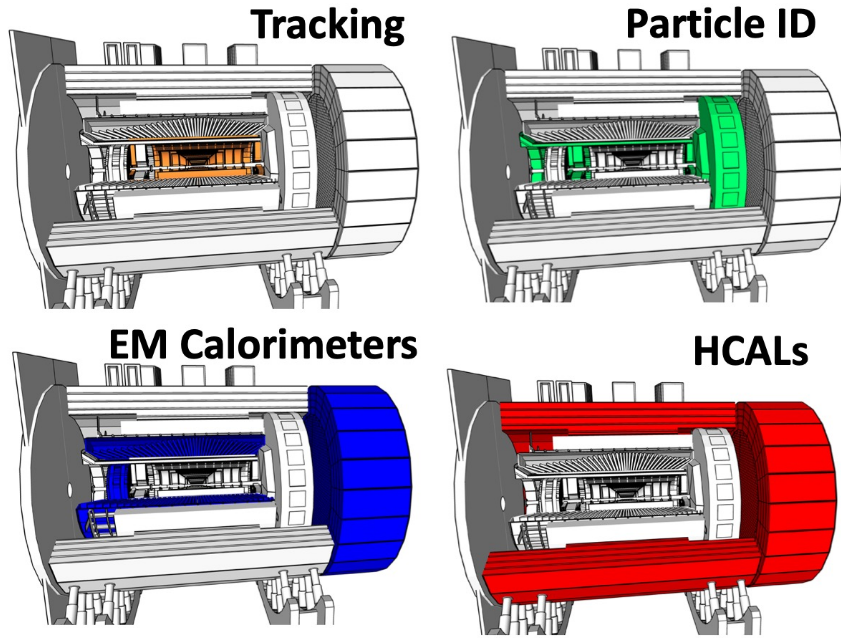


Backup

ECCE detector layout

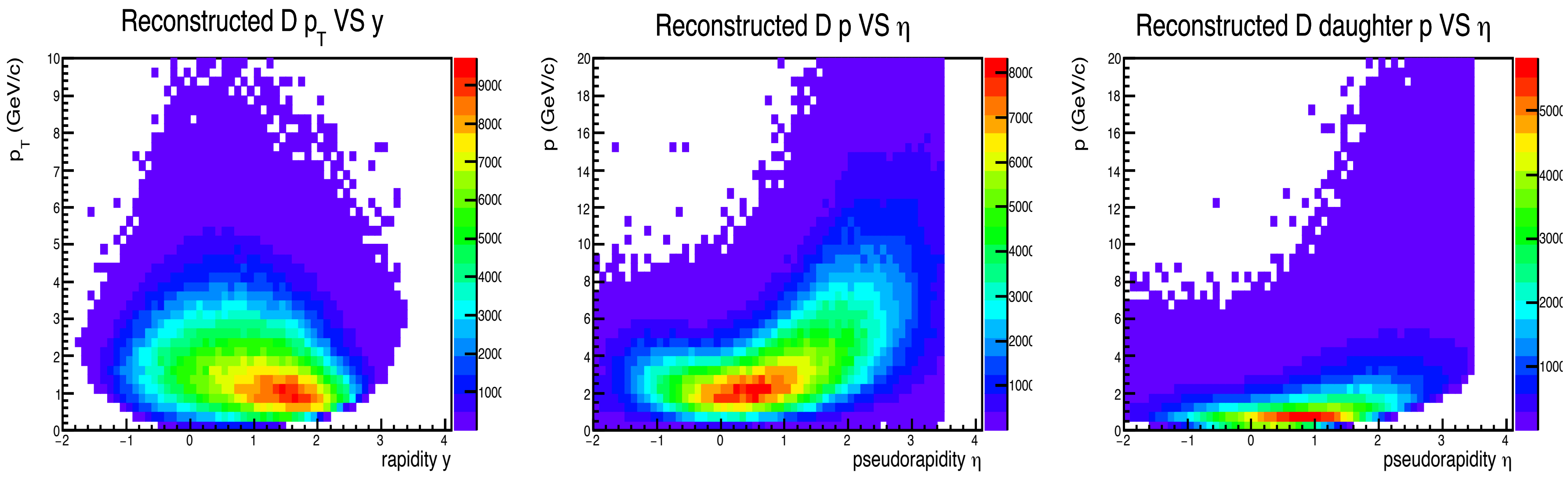


- The proposed ECCE detector consists of Tracking, Particle ID, EM Calorimeters and Hadronic Calorimeter subsystems.



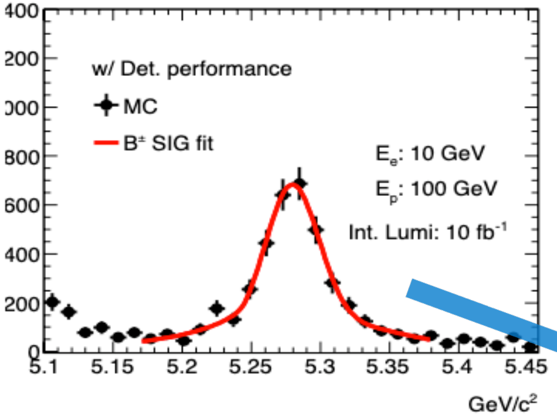
EIC detector requirements for a silicon vertex/tracking detector

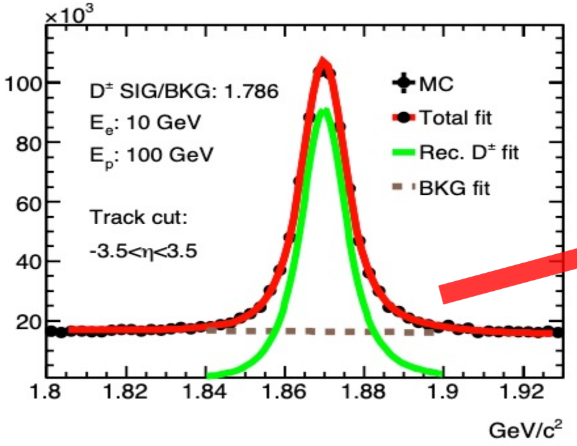
- To meet the heavy flavor physics measurements, a silicon vertex/tracking detector with low material budgets and fine spatial resolution is needed.
- Particles produced in the asymmetric electron+proton and electron+nucleus collisions have a higher production rate in the forward pseudorapidity. The EIC detector is required to have large granularity especially in the forward region.

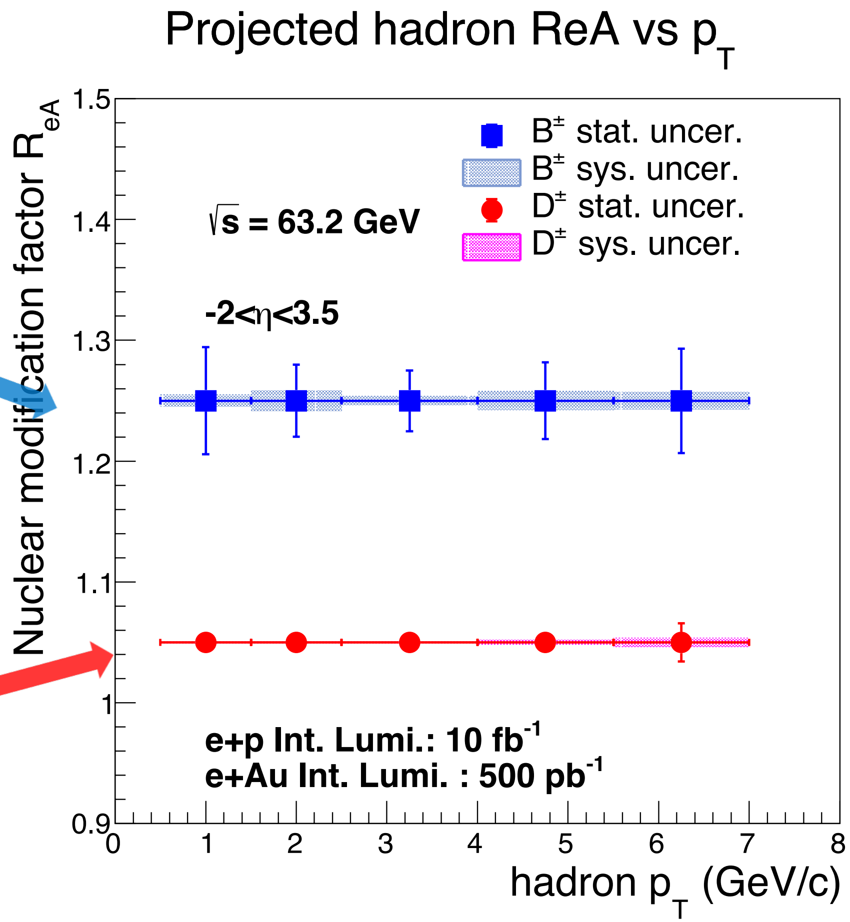


- Fast timing (1-10ns readout) capability allows the separation of different collisions and suppress the beam backgrounds.

Flavor dependent nuclear modification factor projections (I)







Nuclear modification factor:

$$R_{eA} = \frac{\sigma_{eA}}{A\sigma_{ep}}$$

Systematic uncertainty:

- Different magnet options (Babar or Beast).
- Different detector geometries.
- Jet cone radius selection.

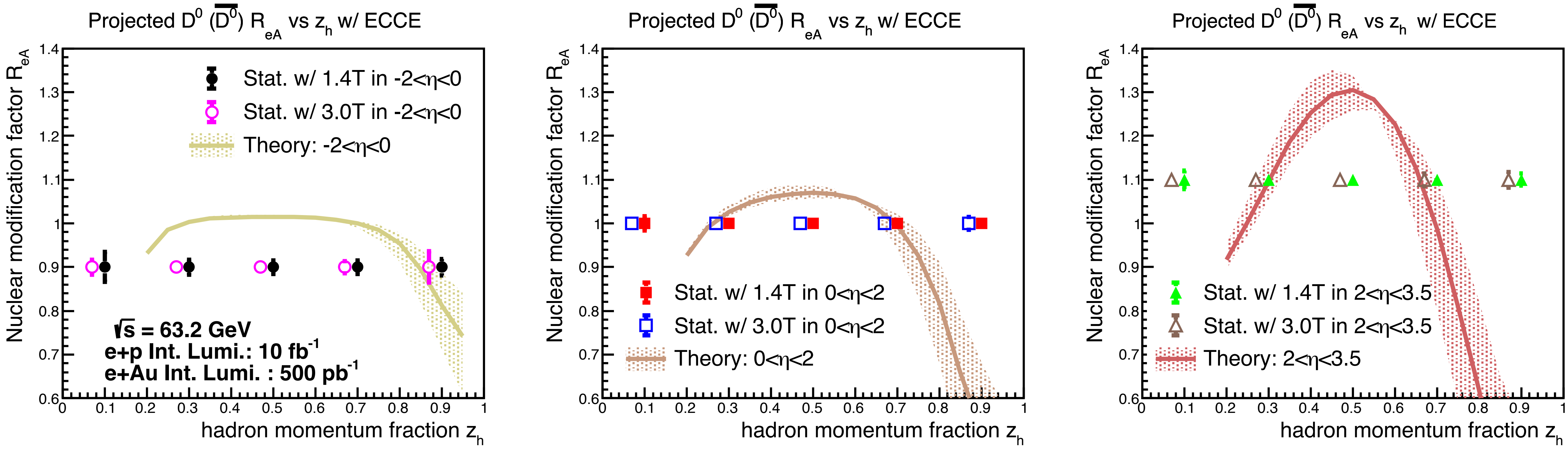
- Good precision can be provided by future EIC reconstructed heavy flavor hadron measurements within the low p_T region to explore the hadronization process in nuclear medium.

Pseudorapidity dependent HF nuclear modification factor projections (II)

Nuclear modification factor:

$$R_{eA} = \frac{\sigma_{eA}}{A\sigma_{ep}}$$

Theoretical calculations with projections normalized by inclusive production: H. T. Li, Z. L. Liu and I, Vitev, Phys. Lett. B 816 (2021) 136261.



- Good statistical uncertainties can be provided by both the 1.4T and 3.0T magnetic fields to constrain the theoretical predications especially in the high hadron momentum fraction region.

Ongoing irradiation tests for LGAD (AC-LGAD) sensors

- Attach the Al foil to the surface of the LGAD (AC-LGAD) sensor to monitor the accumulated doses.