Heavy flavor physics studies and silicon detector R&D for the future Electron-Ion Collider

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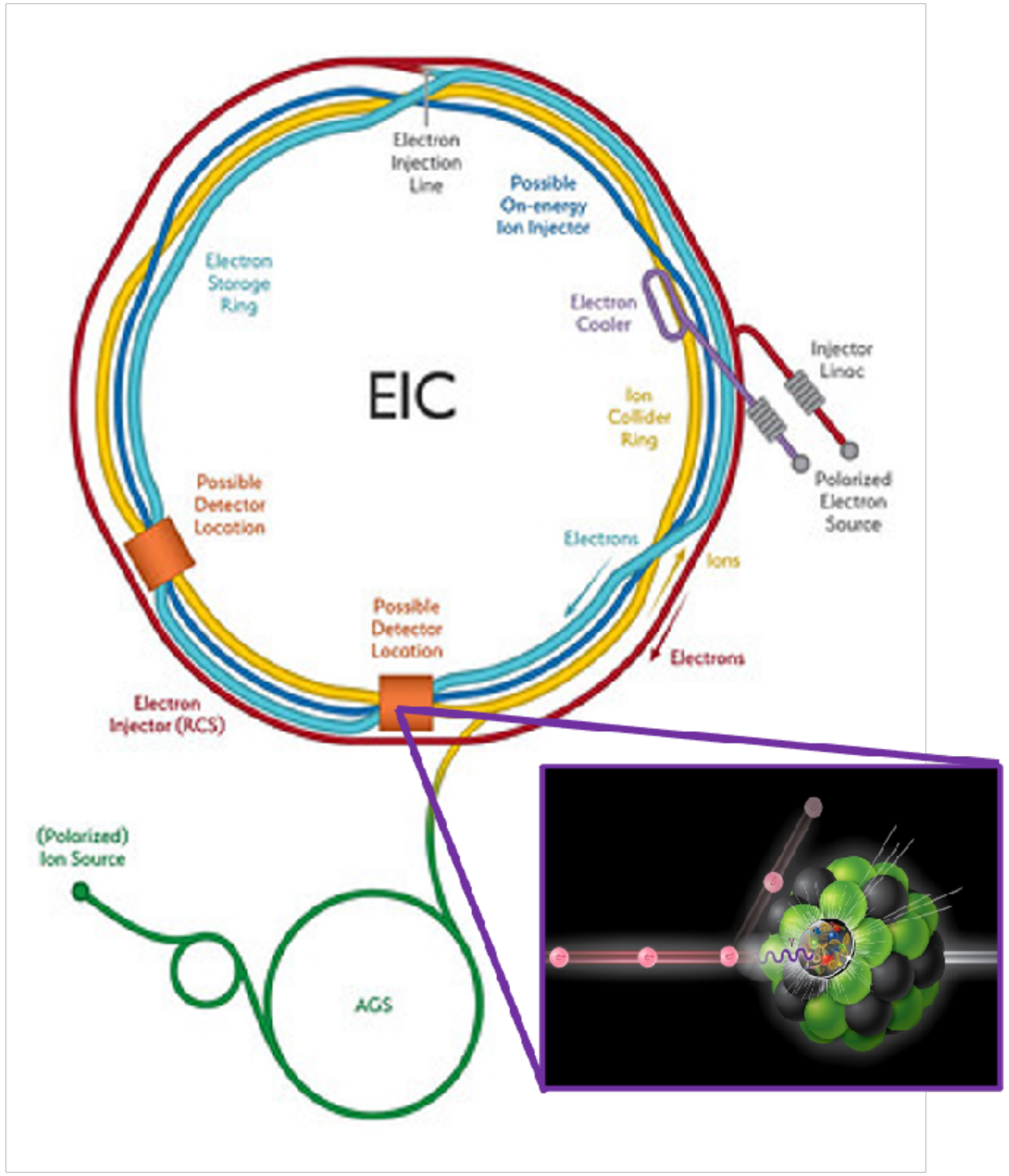
Los Alamos National Laboratory

The Electron-Ion Collider (EIC)

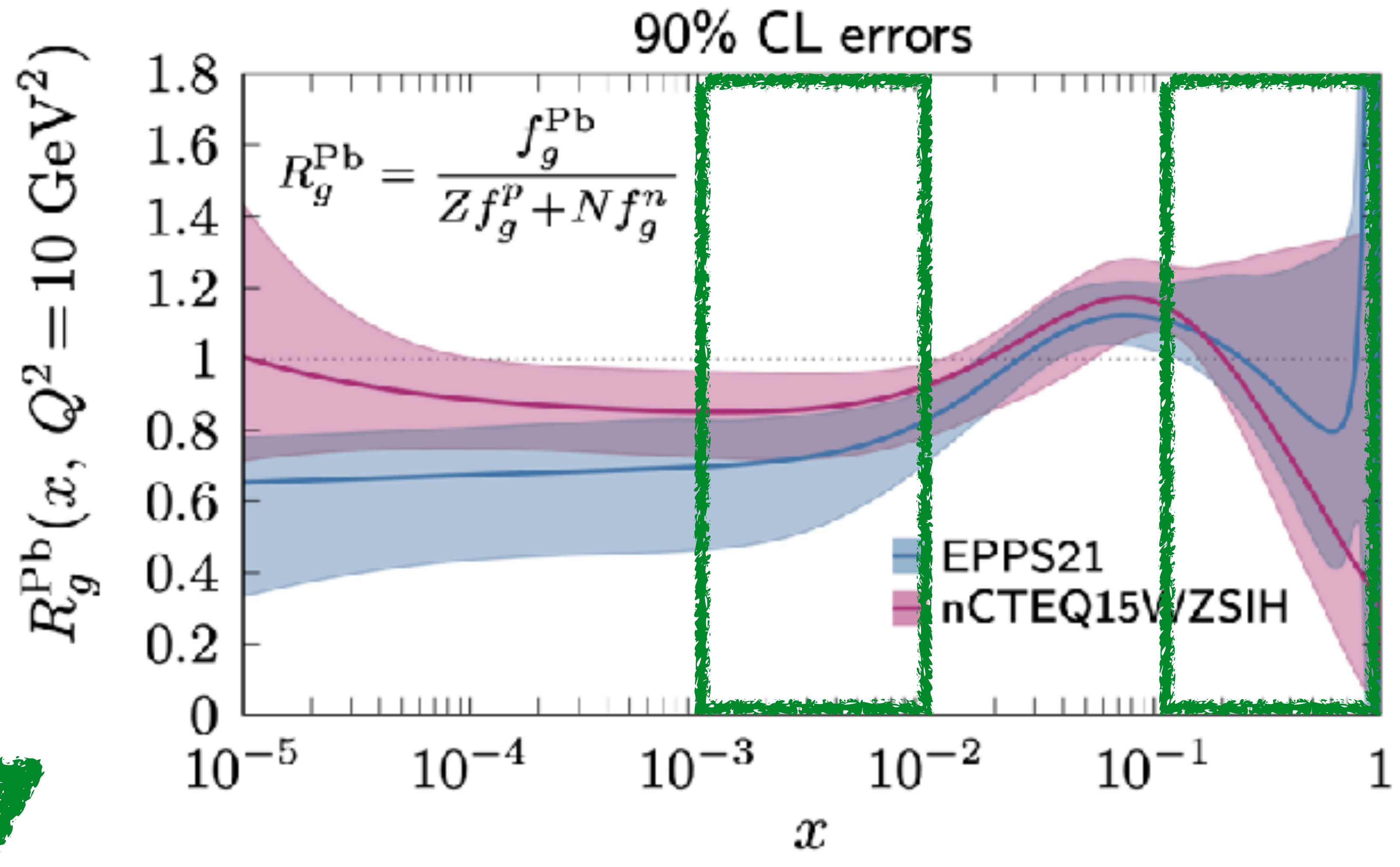
- The future Electron-Ion Collider (EIC) will utilize high-luminosity high-energy e+p and e+A collisions to solve several fundamental questions in the nuclear physics field.
- The project has received CD1 approval from the US DOE in 2021 and will be built at BNL.
- The future EIC will operate:
  - (Polarized) 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.

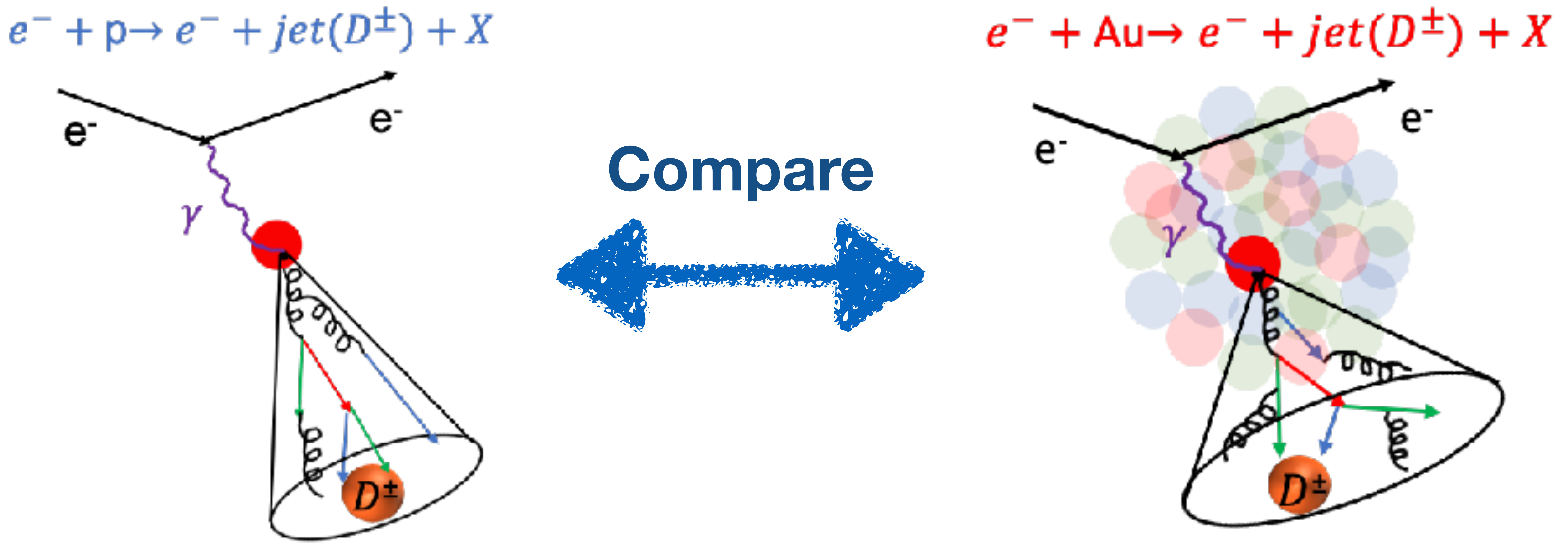


Heavy flavor measurements at EIC physics program

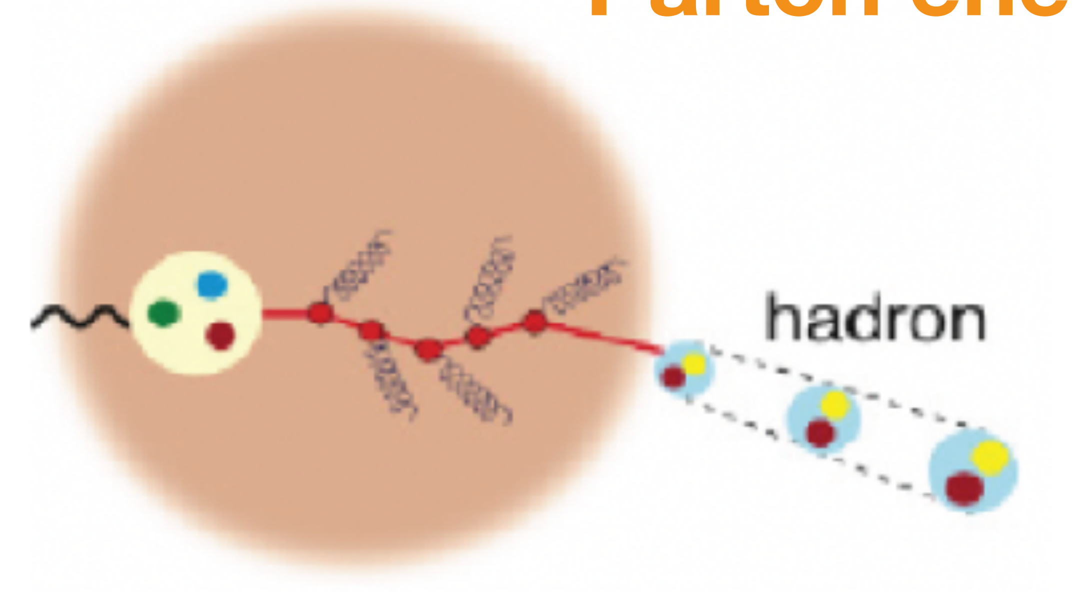
- Heavy flavor hadron and jet measurements at the future EIC can help solve the listed science problems and plays a significant role in exploring:
  - Nuclear modification on the initial nuclear Parton Distribution Functions (PDFs) especially in the high and low Bjorken-x (x_{BJ}) region.
  - Final state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

nPDF modification



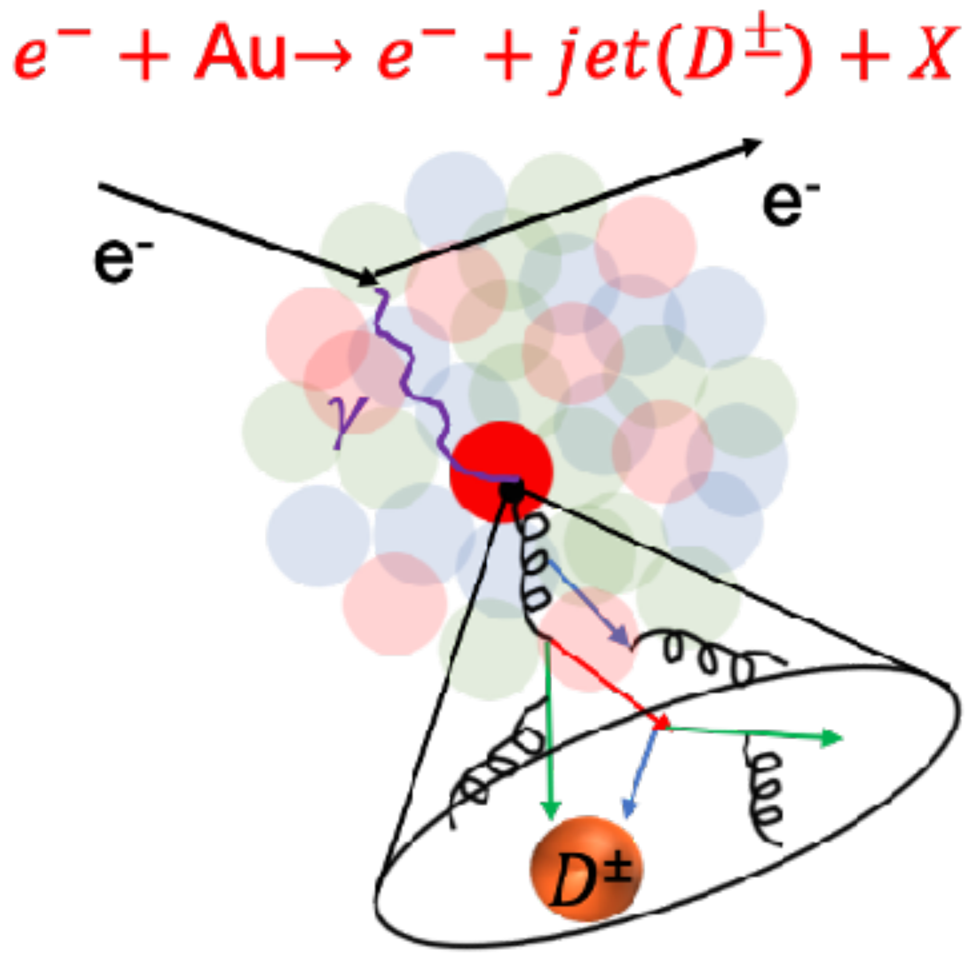


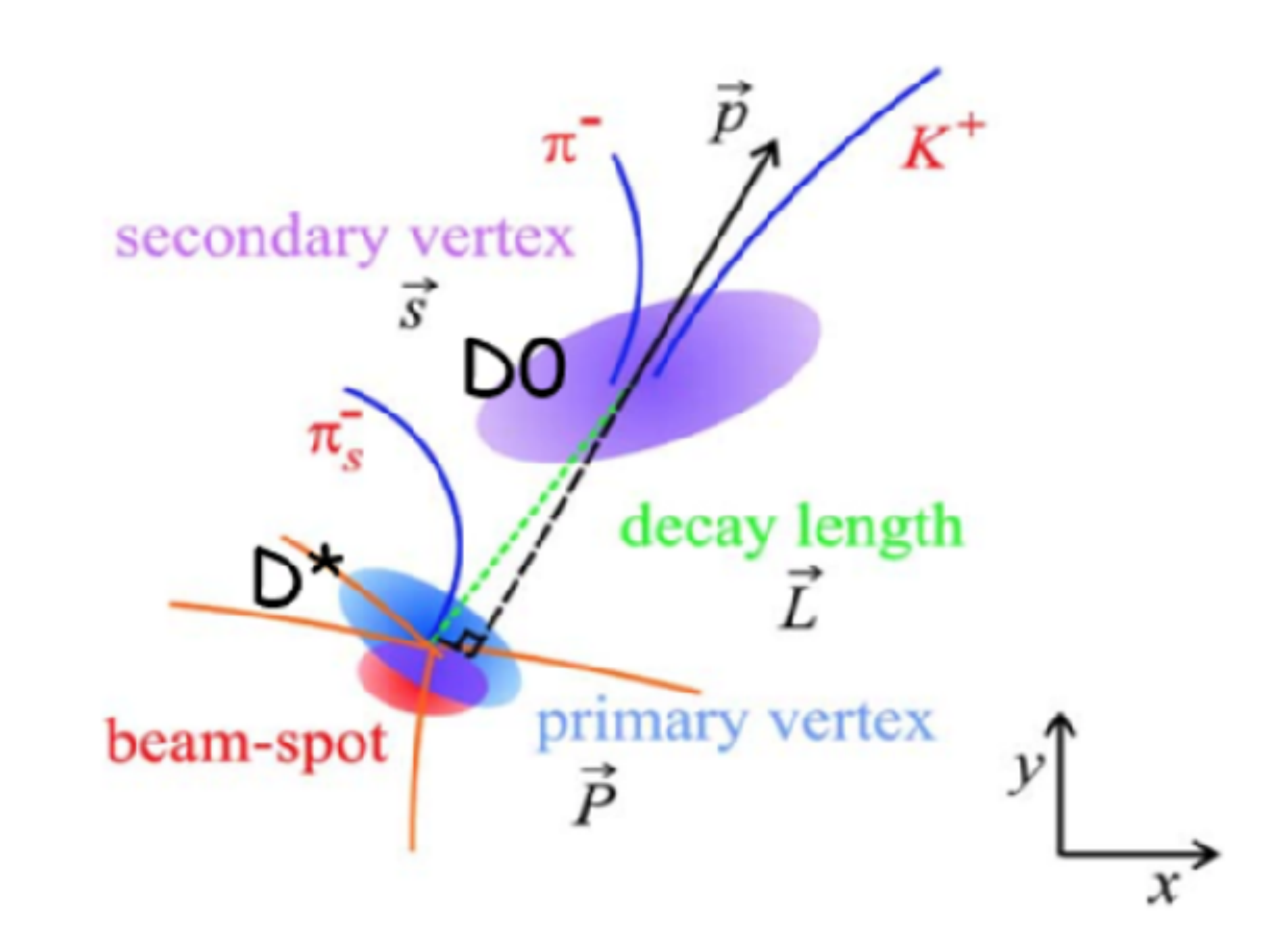
Parton energy loss



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.





Particle	Mass (GeV/c²)	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 collisions.
  - Low material budgets to maintain fine hit resolution.

Forward Silicon Tracker design implemented in the ECCE detector

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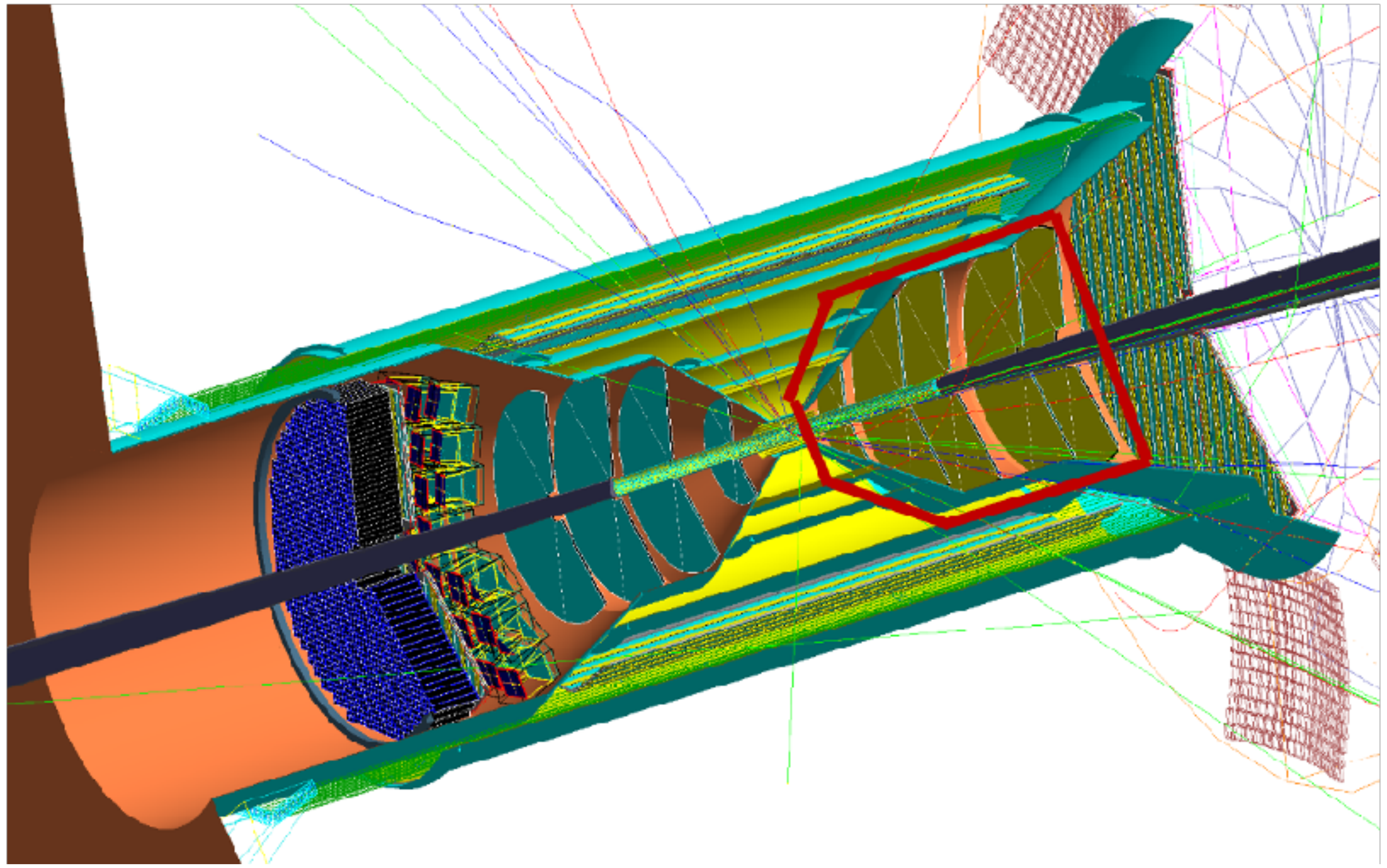
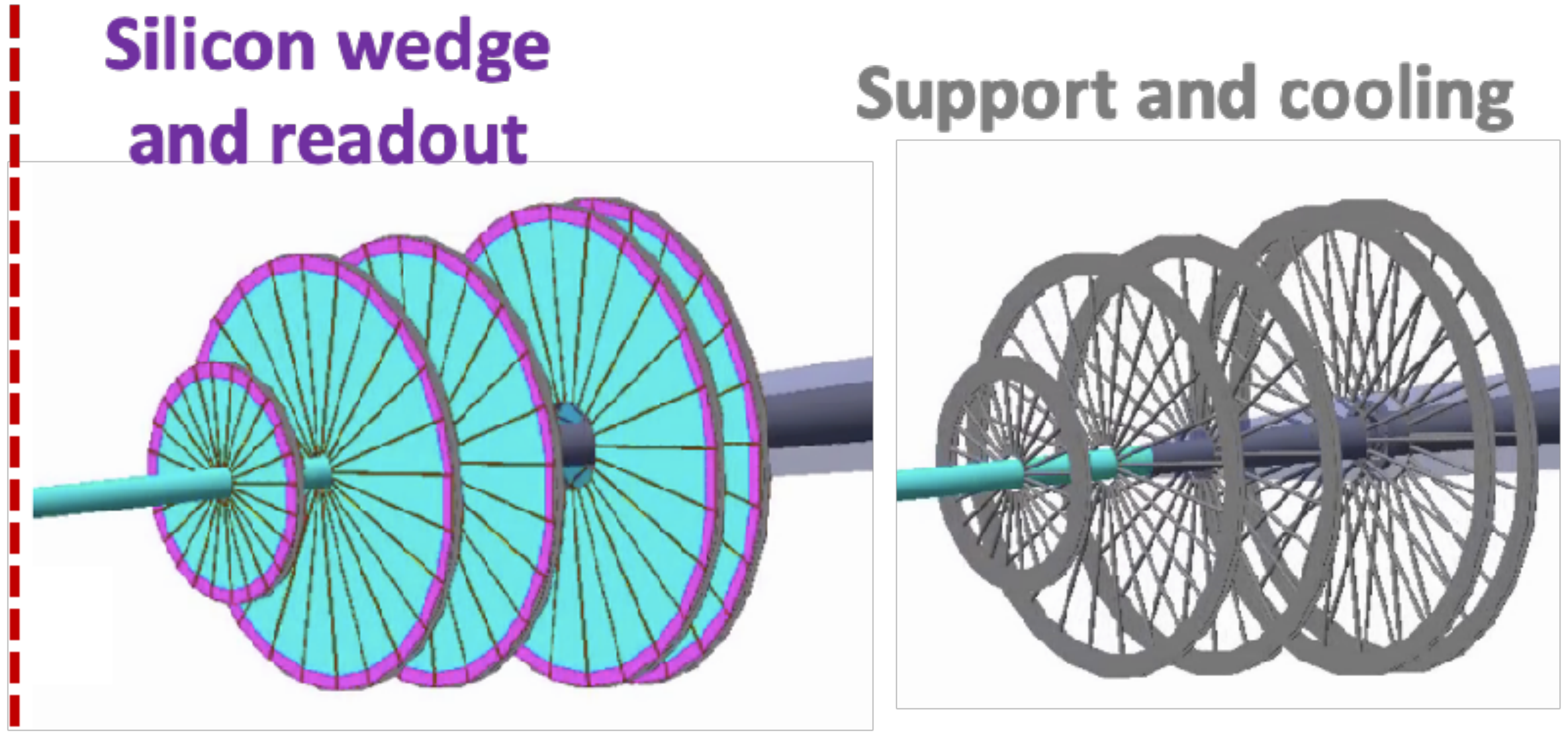
- ➢ The Monolithic Active Pixel Sensor based Forward Silicon Tracker (FST) design consists of 5 disks with the pseudorapidity coverage from 1.2 to 3.5, ~10B pixels and ~2.2m^2 active area.

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



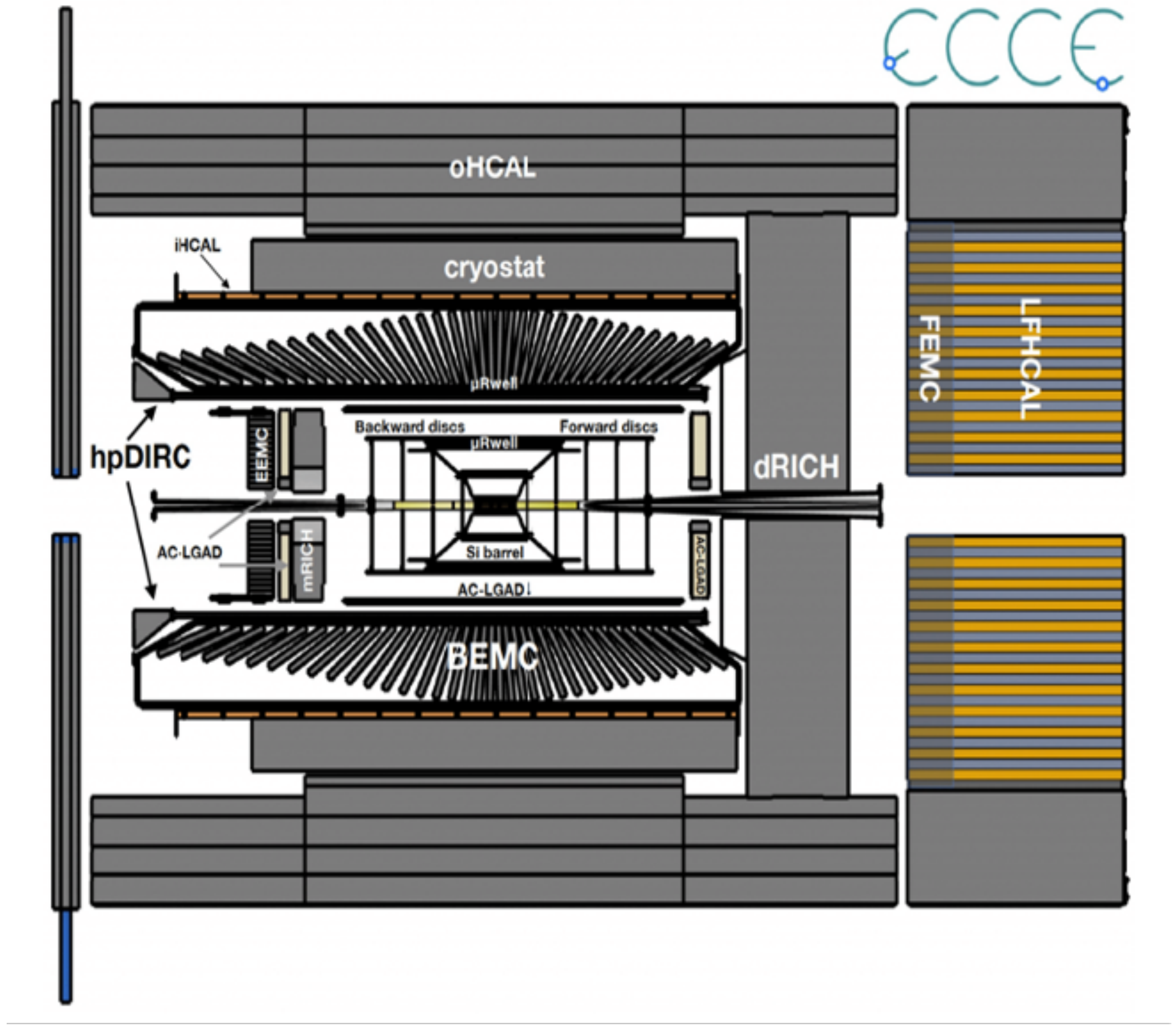


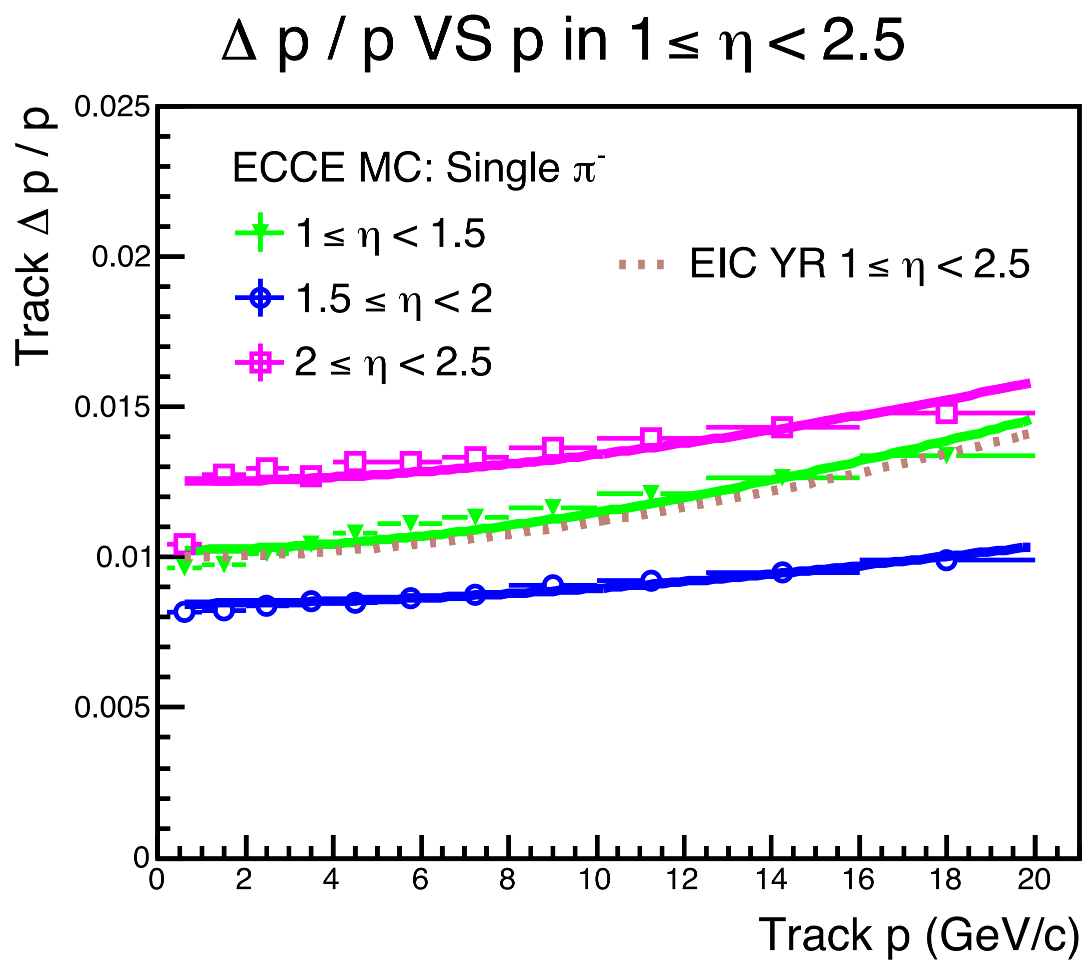
supported by LANL LDRD

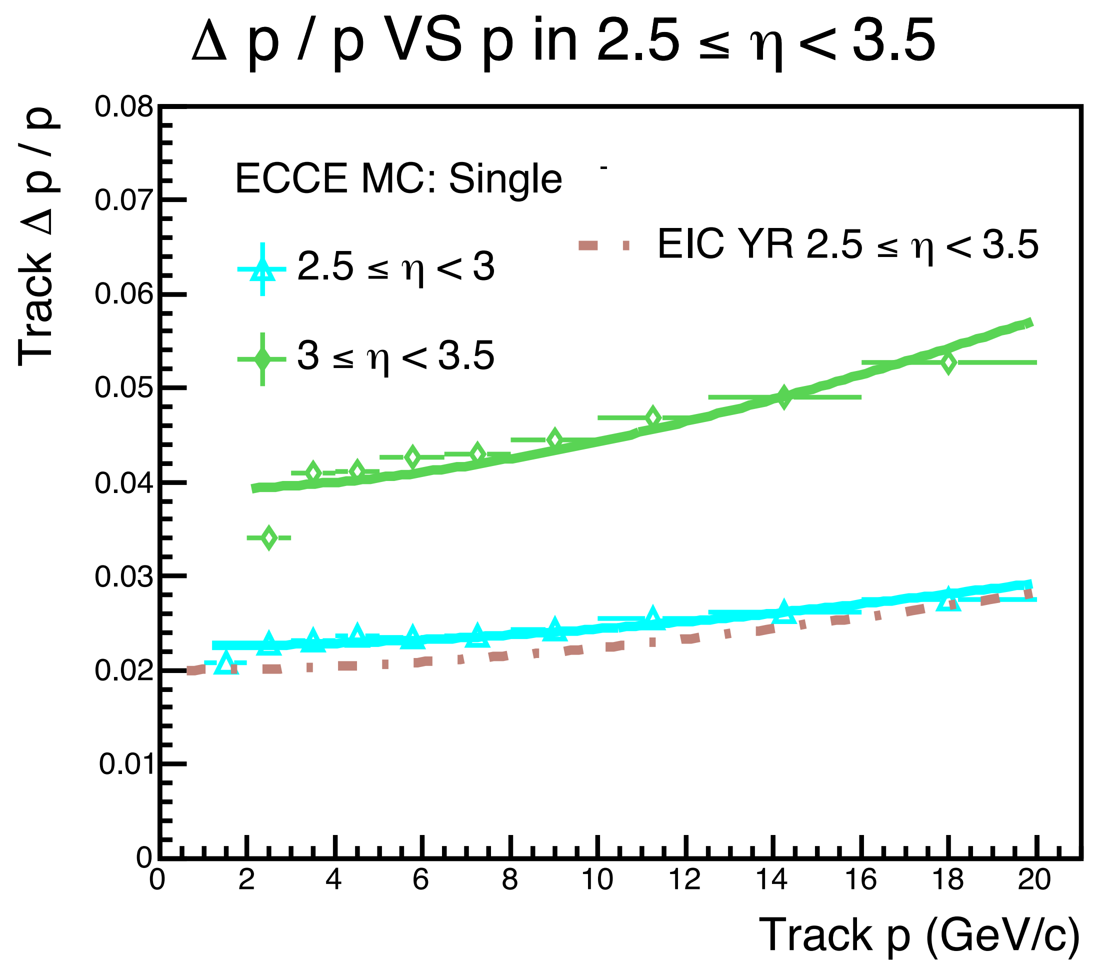
Detailed detector layout (segmentations, readout units, cooling and support structures) have been implemented in GEANT4 simulation.

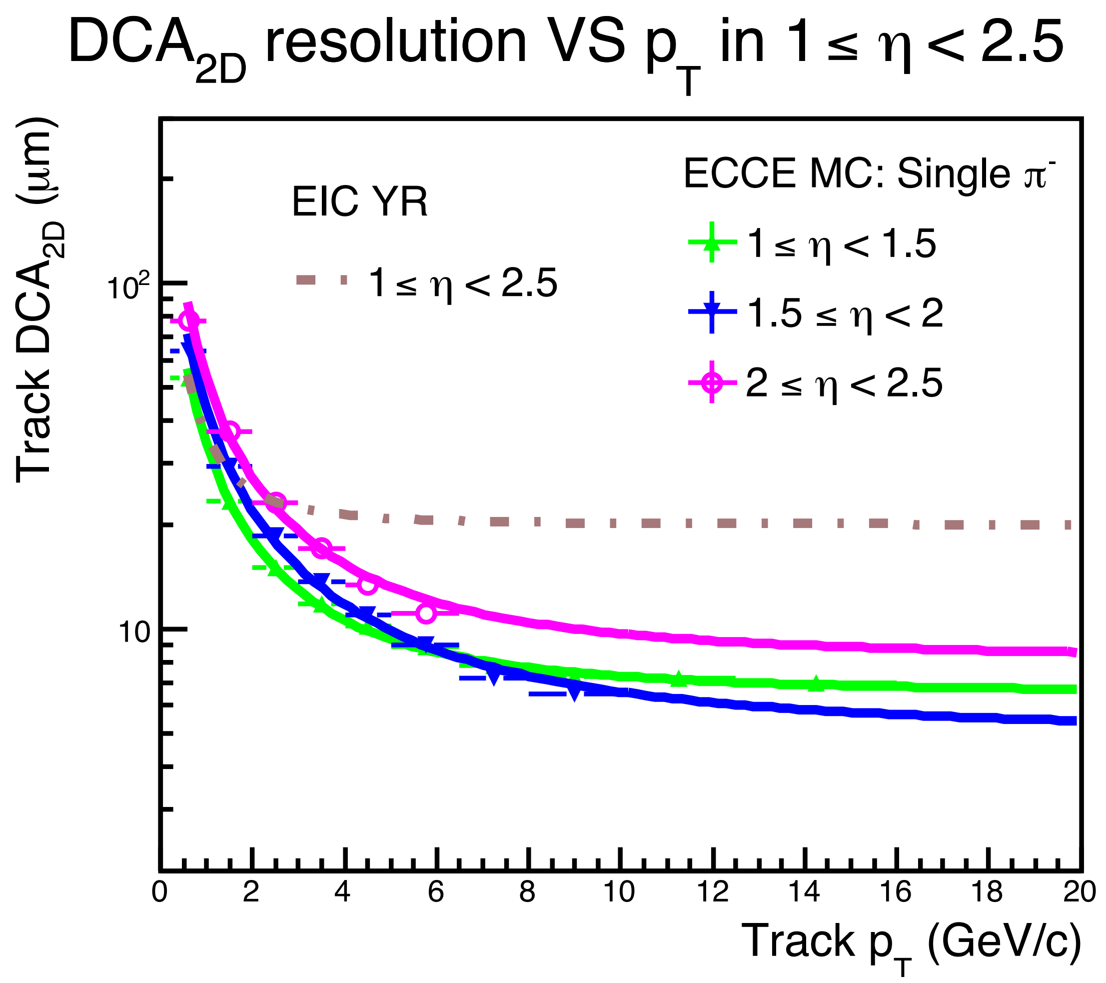
Tracking performance evaluated in GEANT4 simulation

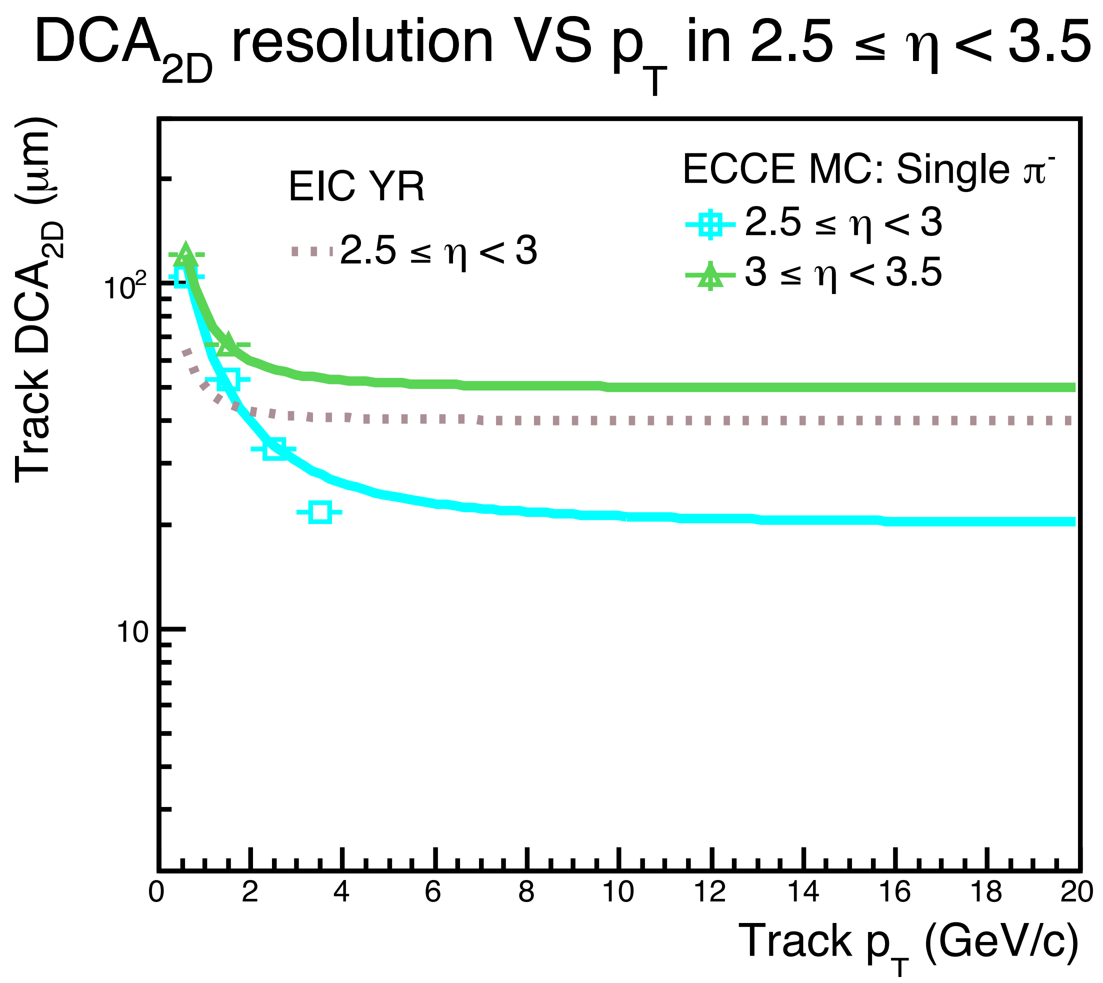
- ➢ Integrated MAPS, μRwell and AC-LGAD tracking detectors at ECCE provide precise momentum and transverse DCA_{2D} resolutions.





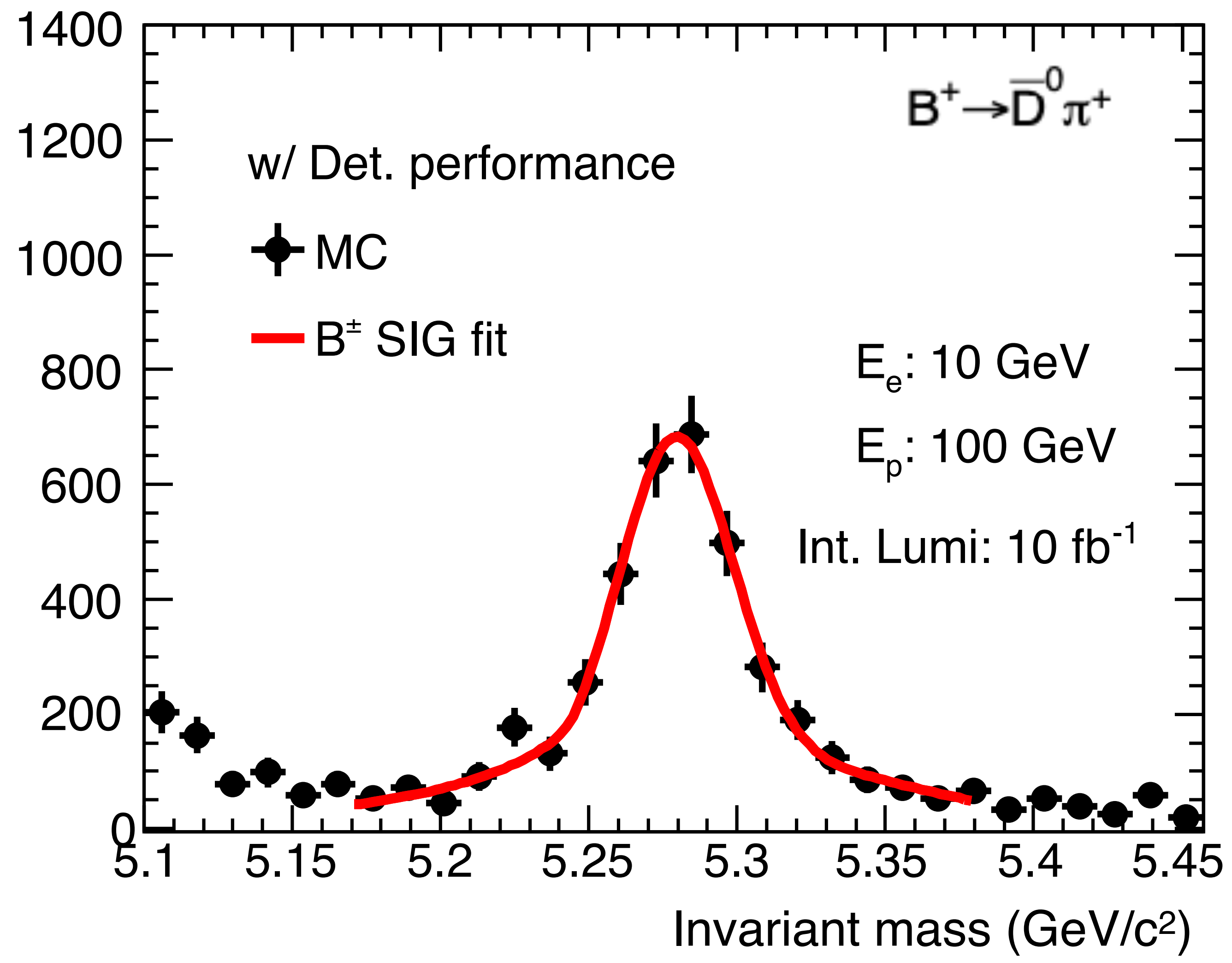


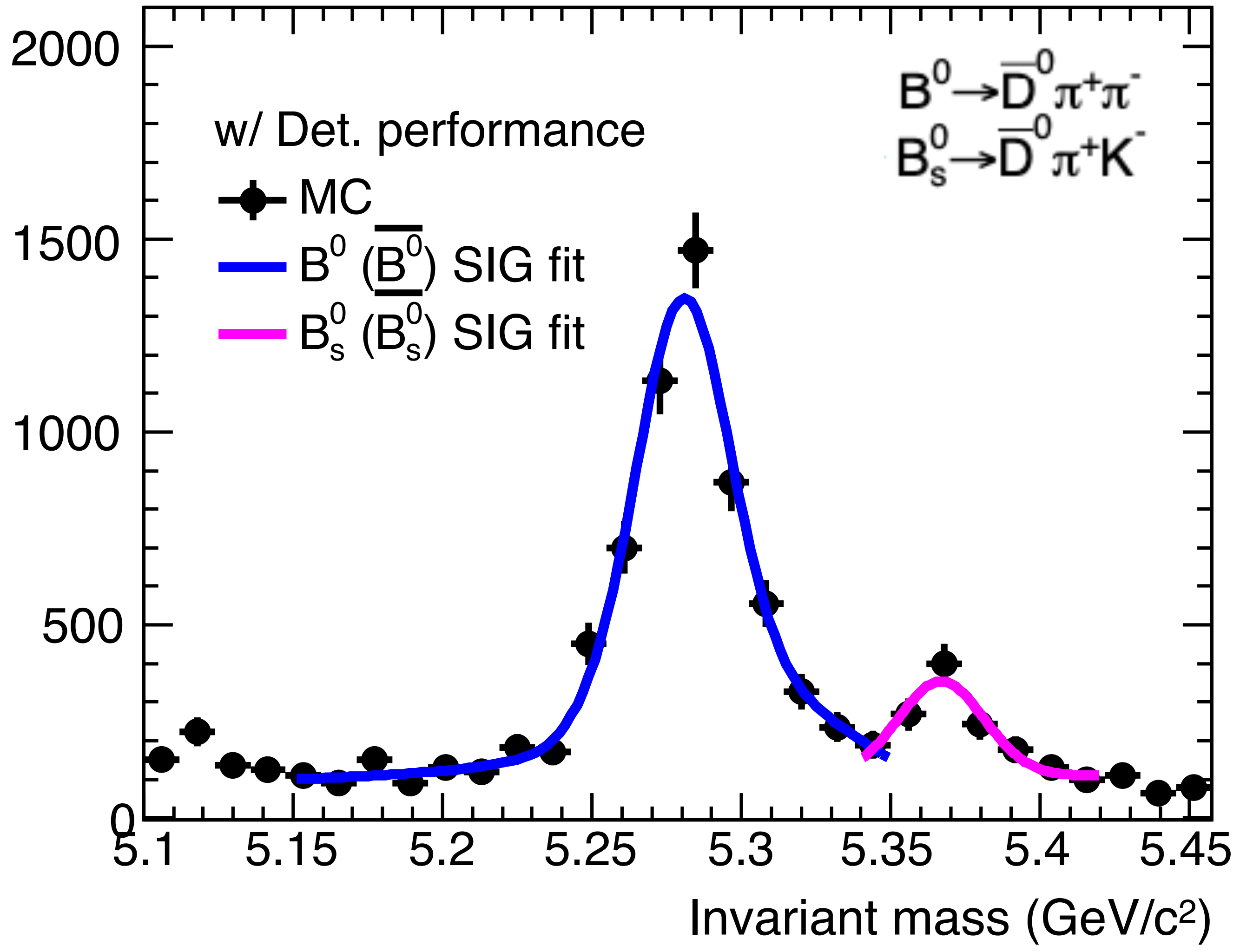




Reconstruction of open heavy flavor hadron in e+p simulation

- The full analysis framework which includes the event generation (PYTHIA), ECCE detector response in GEANT4 simulation, beam remnant & QCD background, and hadron reconstruction algorithm have been setup.
- Mass distributions of reconstructed bottom hadrons using the ECCE detector performance inside the Babar magnet in 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 fb^{-1}.

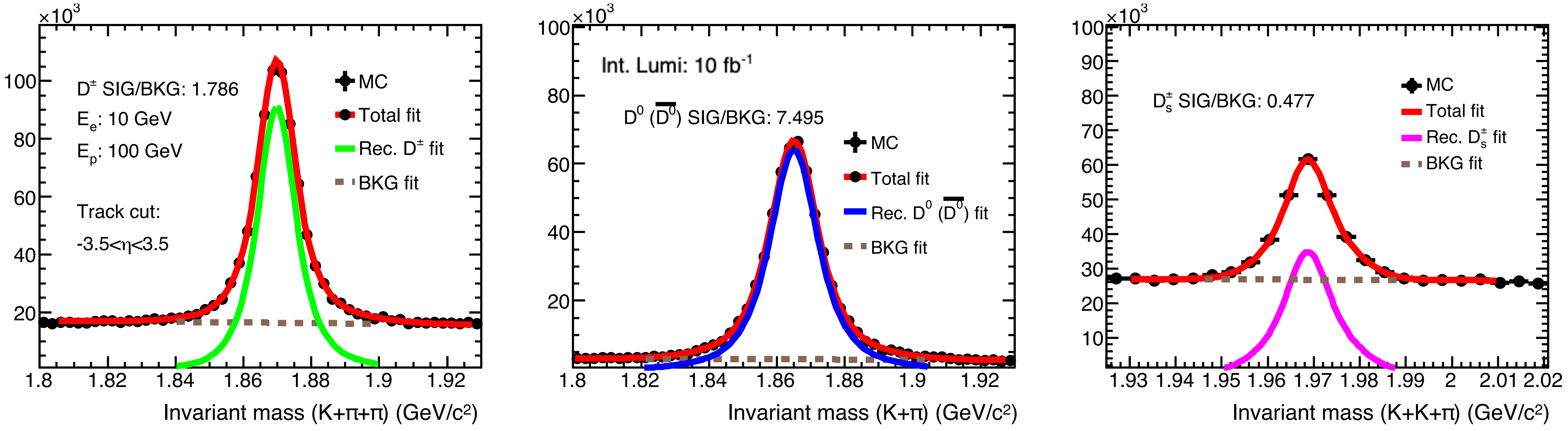




DCA_{2D} matching and angular cuts to suppress the background

Reconstruction of open heavy flavor hadron in e+p simulation

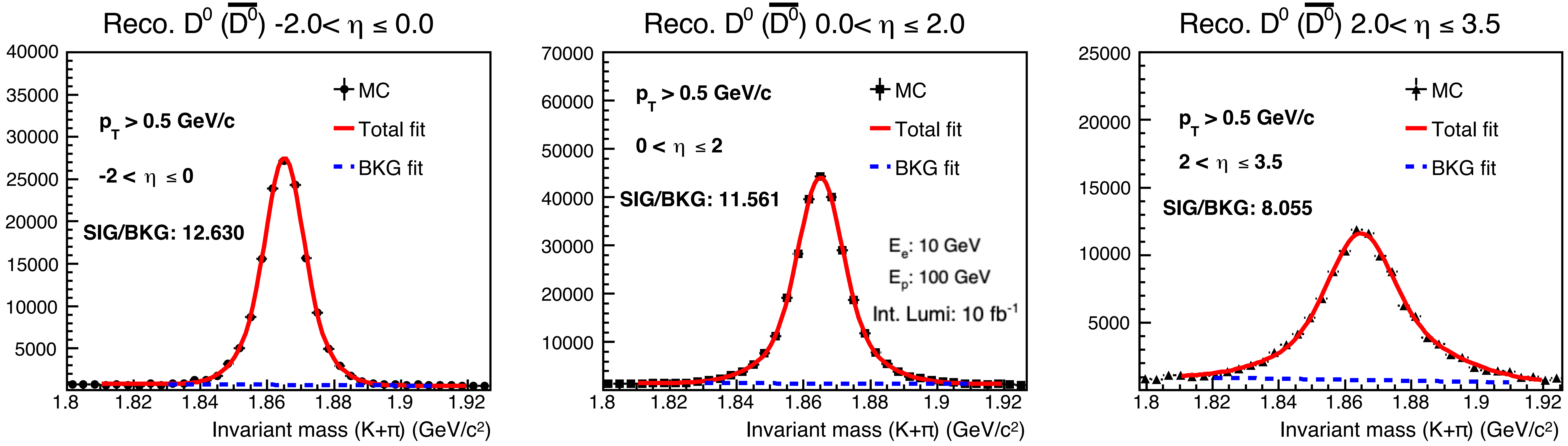
- ➢ The full analysis framework which includes the event generation (PYTHIA), ECCE detector response in GEANT4 simulation, beam remnant & QCD background, and hadron reconstruction algorithm have been setup.
- ➢ Mass distributions of reconstructed charm hadrons using the ECCE detector performance inside the Babar magnet in 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 fb^{-1}.



DCA$_{2D}$ matching and angular cuts to suppress the background

Pseudorapidity dependent D^0 meson reconstruction

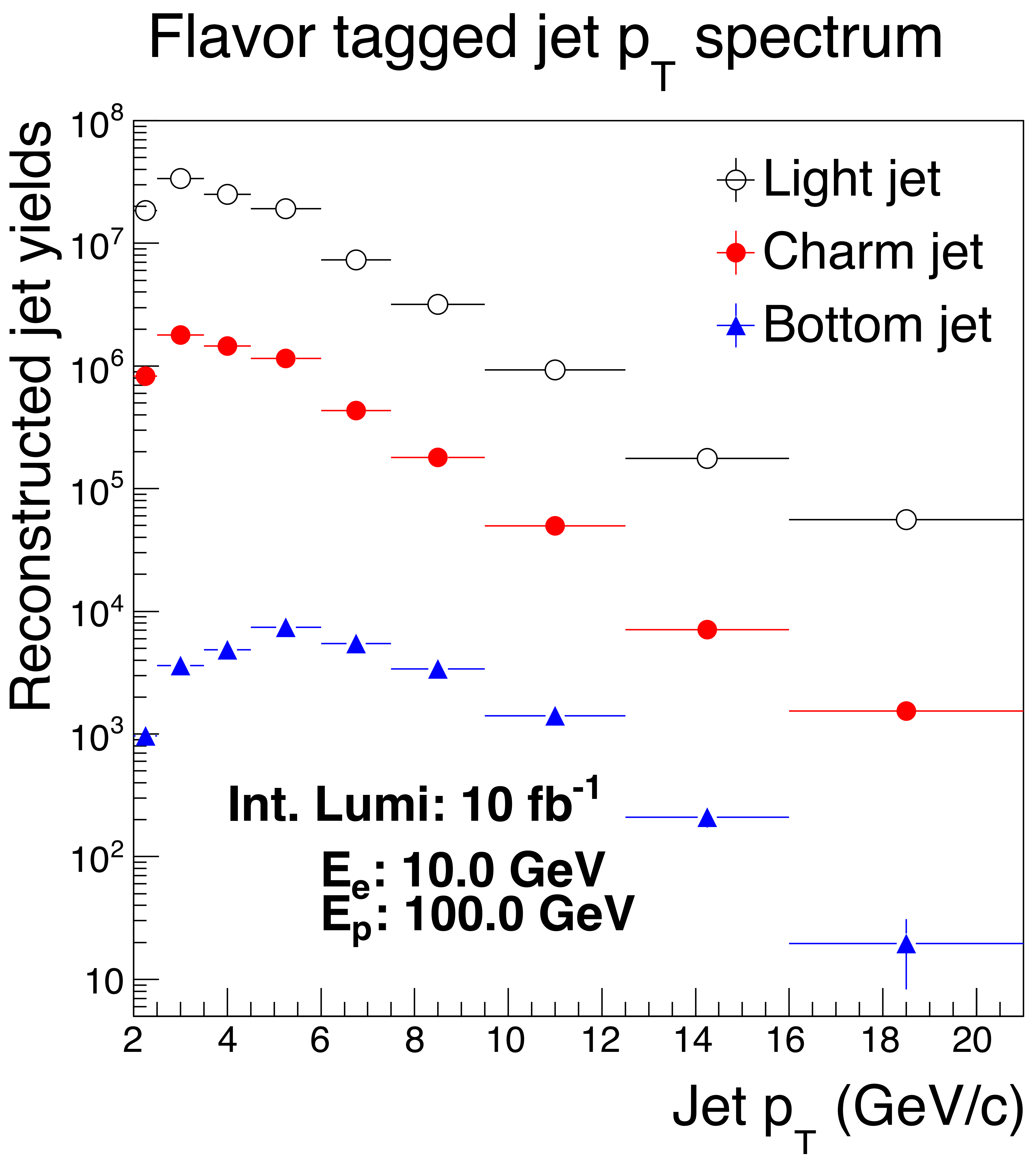
- Heavy flavor production in different pseudorapidity regions can access different initial and final state effects.



- Compared to heavy ion measurements, better signal over background ratios can be achieved by reconstructed $D^0\,(\bar{D}^0)$ mesons at the future EIC over a wide pseudorapidity region.

Reconstructed heavy flavor jets in e+p simulation

- Heavy flavor jets can treat as the surrogate of the initial heavy quarks.
- P_t spectrum of reconstructed jets with the ECCE detector response in simulation in 10 GeV electron and 100 GeV proton collisions with 10 fb^{-1} integrated luminosity.
- Jet algorithm: Anti-k_T with cone radius at 1.0.
- Tagging charm-jets (bottom-jets) with the associated displaced vertex.
- Reconstructed jet yields without the reconstruction efficiency and purity corrections.

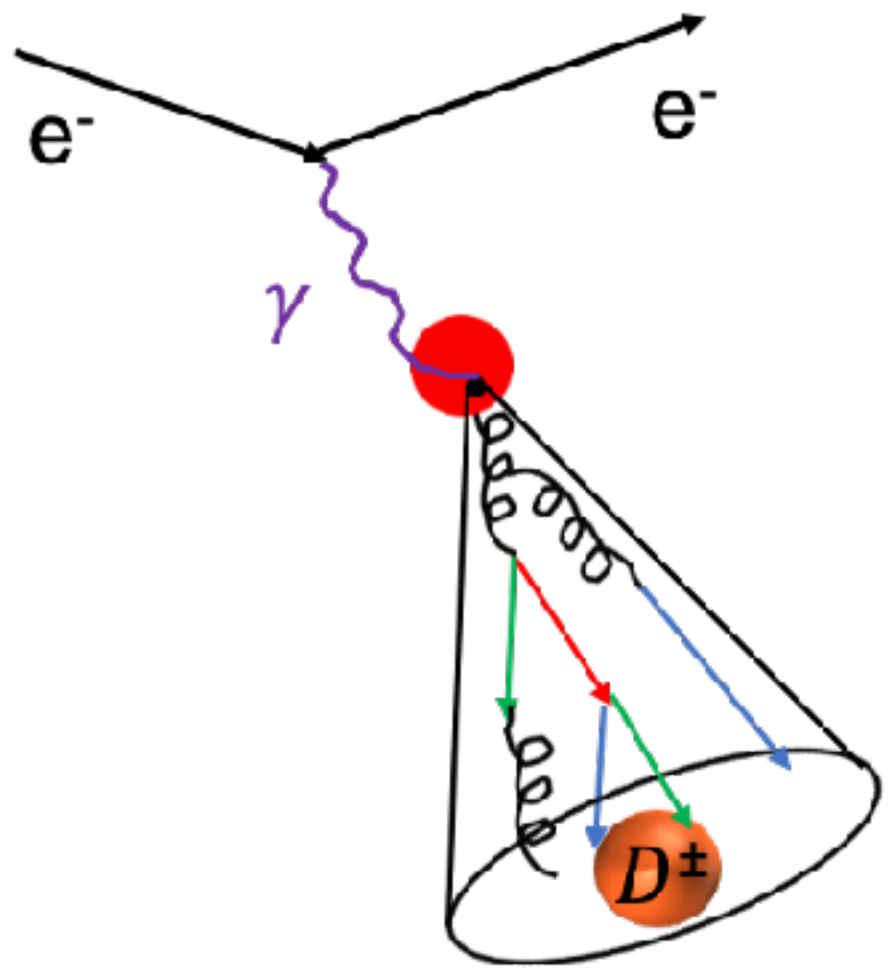


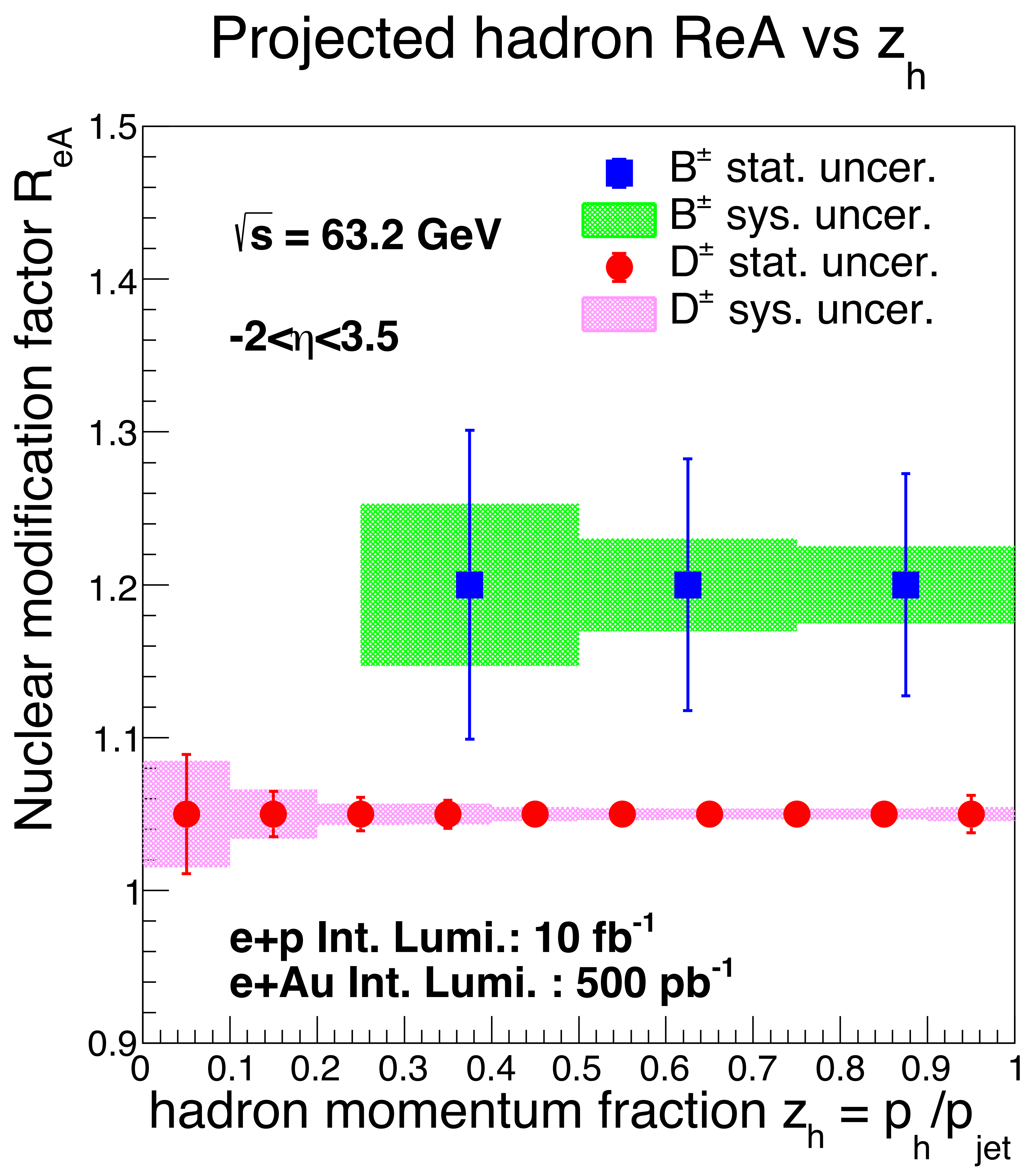
Flavor dependent nuclear modification factor projections

Nuclear modification factor:

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

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





Systematic uncertainty:

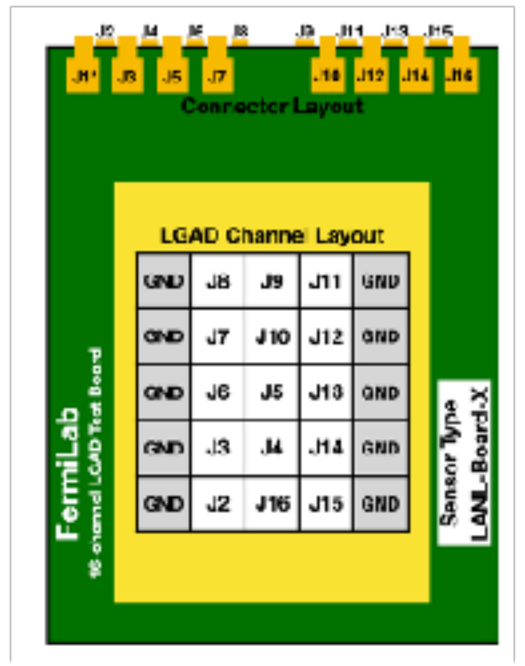
- ➢ Different magnet options (Babar or Beast).
- ➢ Different detector geometries.
- ➢ Jet cone radius selection

➢ The future EIC heavy flavor hadron inside jet measurements can provide great constrains on the fragmentation function in the high z_h region.

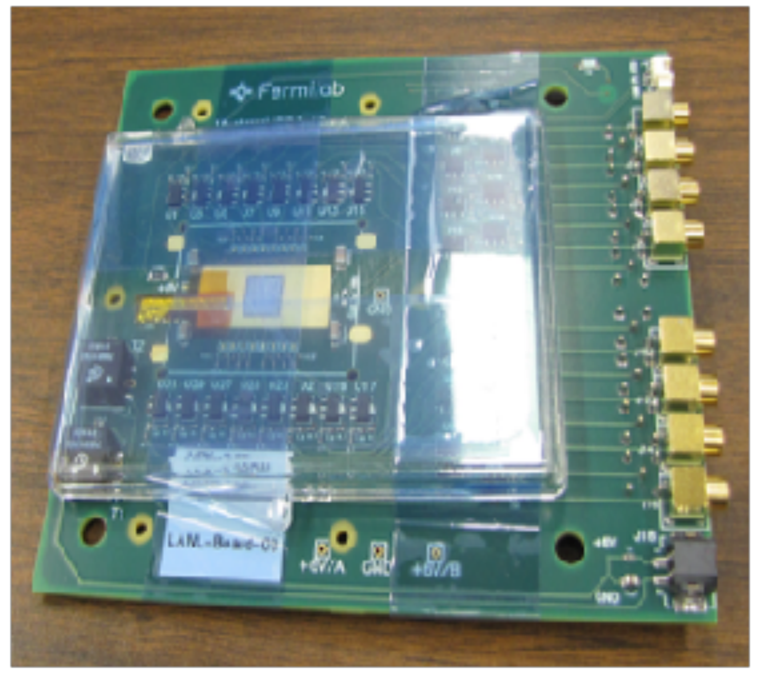
Advanced silicon technology candidates for EIC silicon tracker

➢ Several advanced silicon technologies are being tested at LANL.

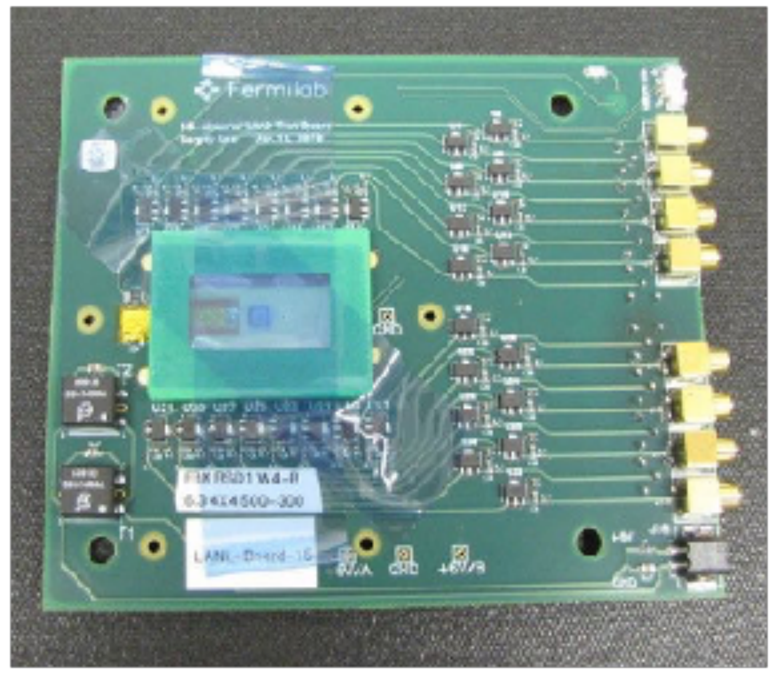
LGAD pixel map
3X5 Matrix



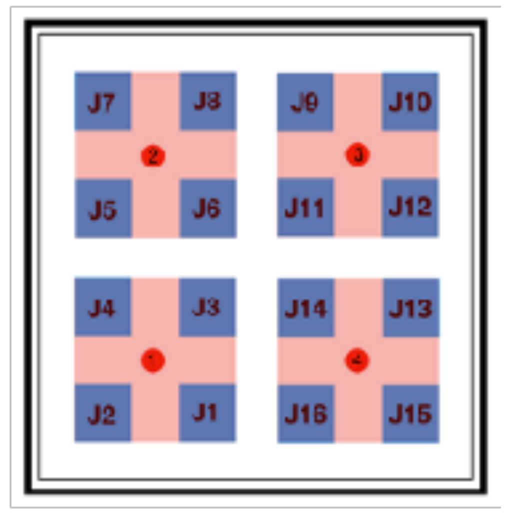
LGAD Carrier Board



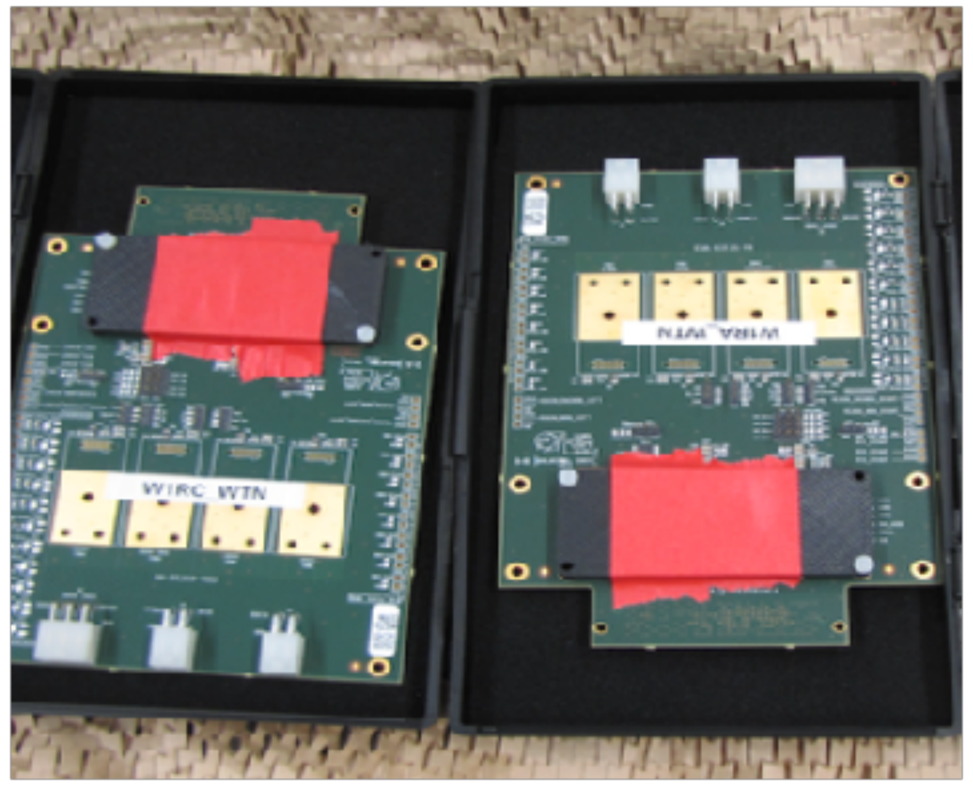
AC-LGAD Carrier Board



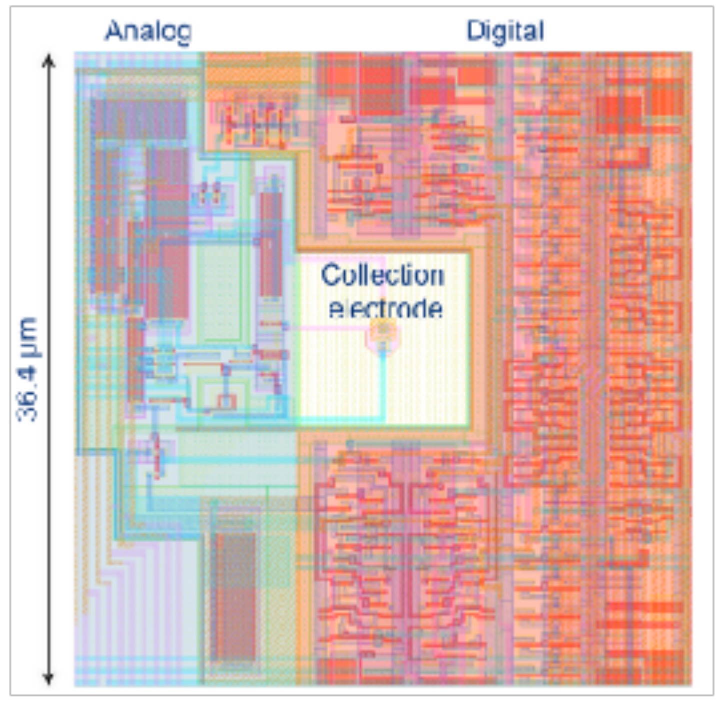
AC-LGAD
pixel map
4X4 Matrix



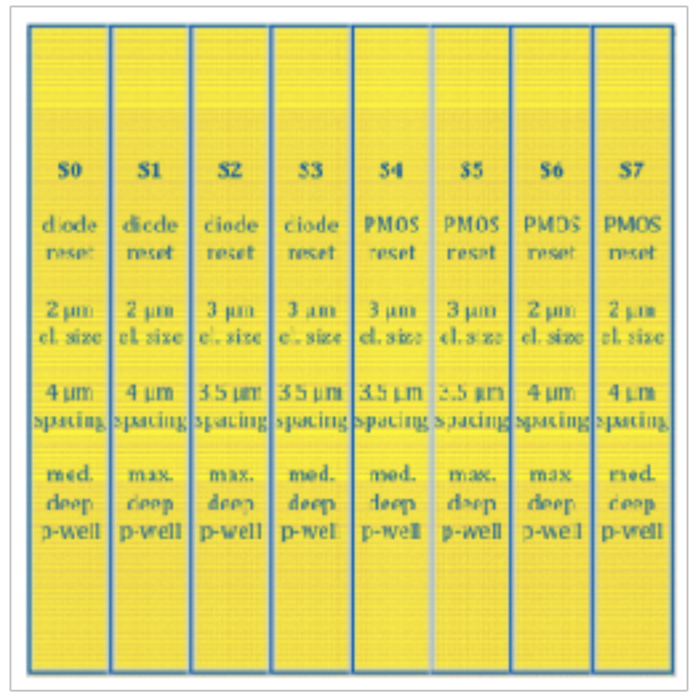
MALTA Carrier Board



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: 1.3 to 0.5 mm

Spatial resolution: ~30 μm

Time resolution: <30 ps

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

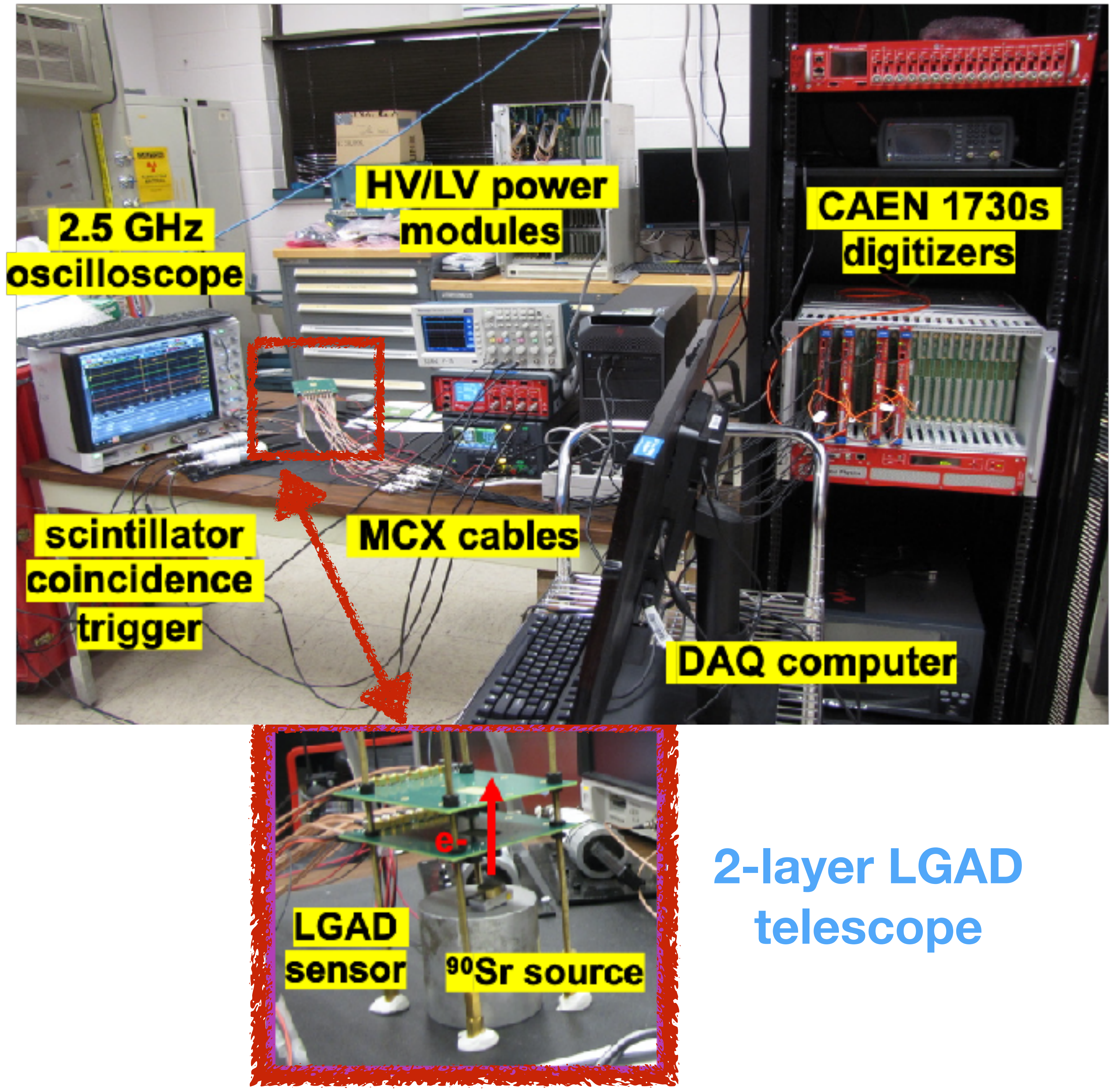
Pixel size: 36.4 μm

Spatial resolution: ~7 μm

Time resolution: ~2 ns

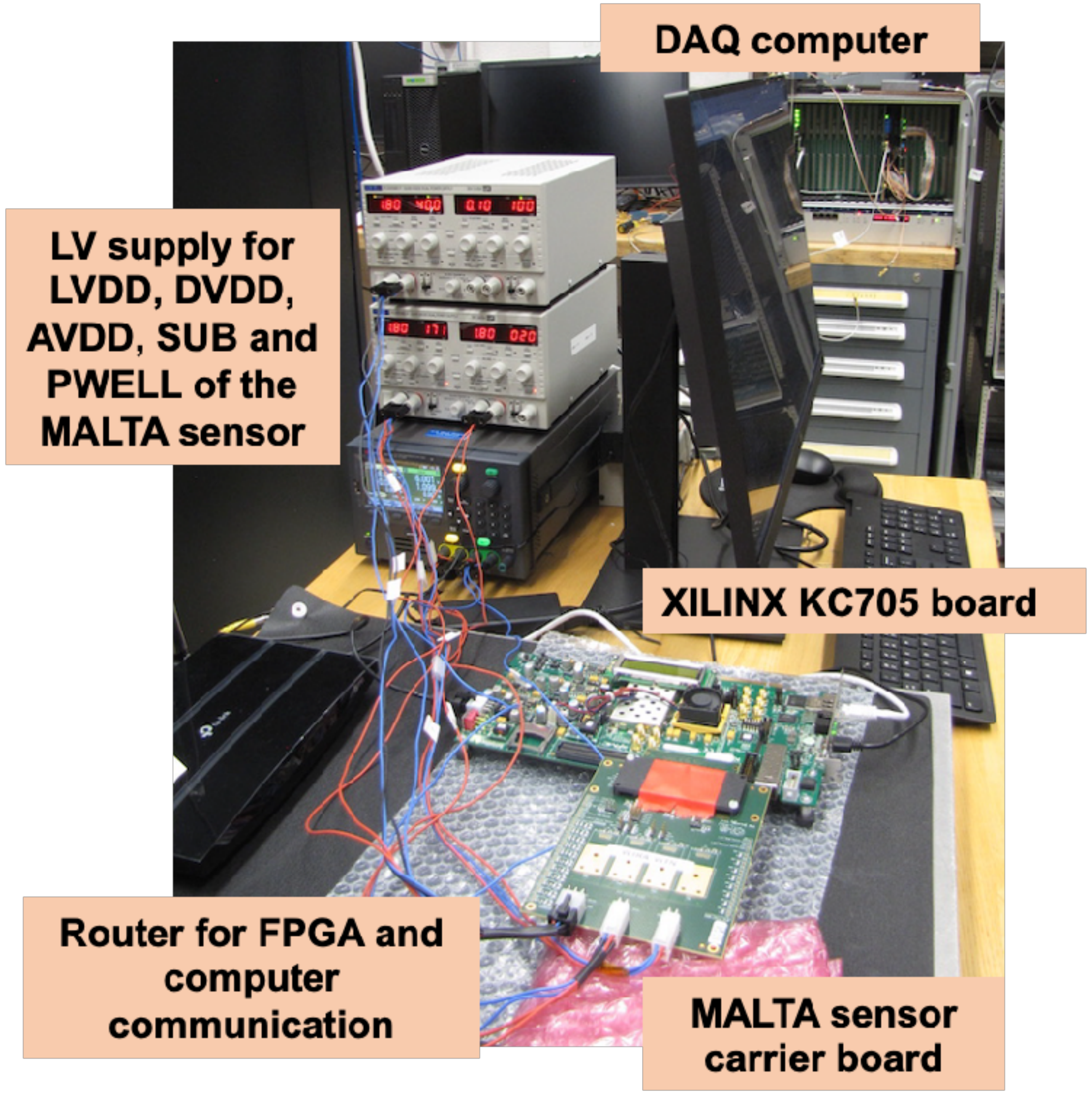
LGAD and AC-LGAD R&D test configuration

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



2-layer LGAD telescope

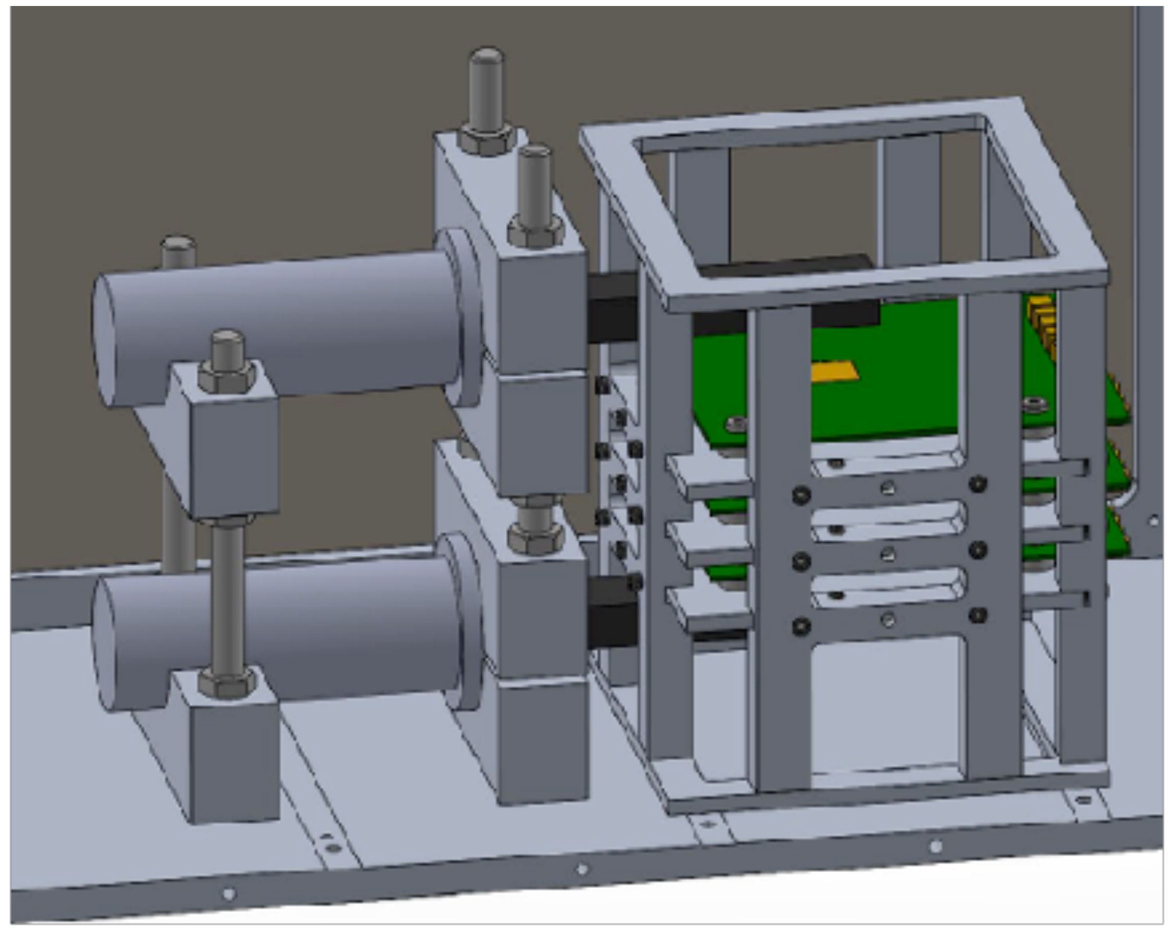
MALTA sensor characterization test bench



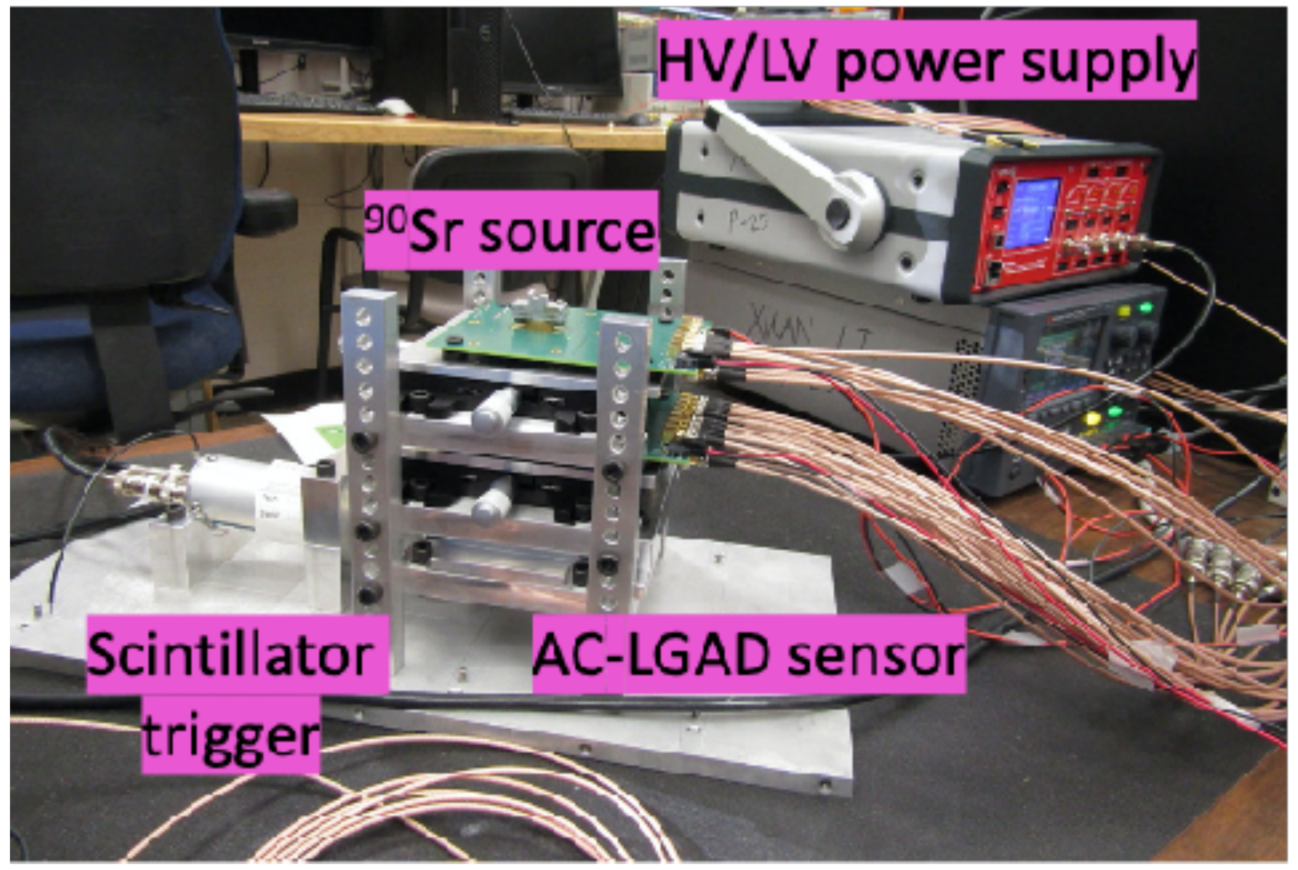
Advanced silicon technology candidates for EIC silicon tracker

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

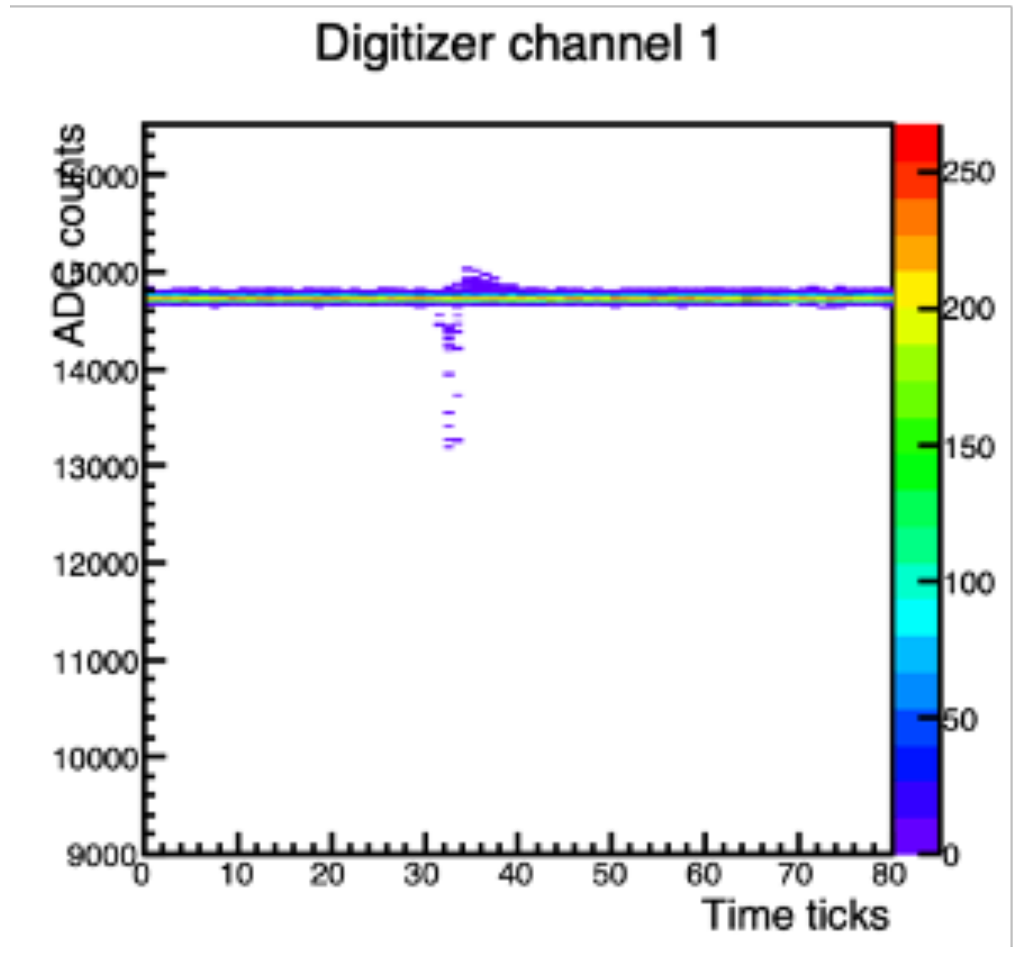
Mechanical design of 3-layer LGAD (AC-LGAD) telescope



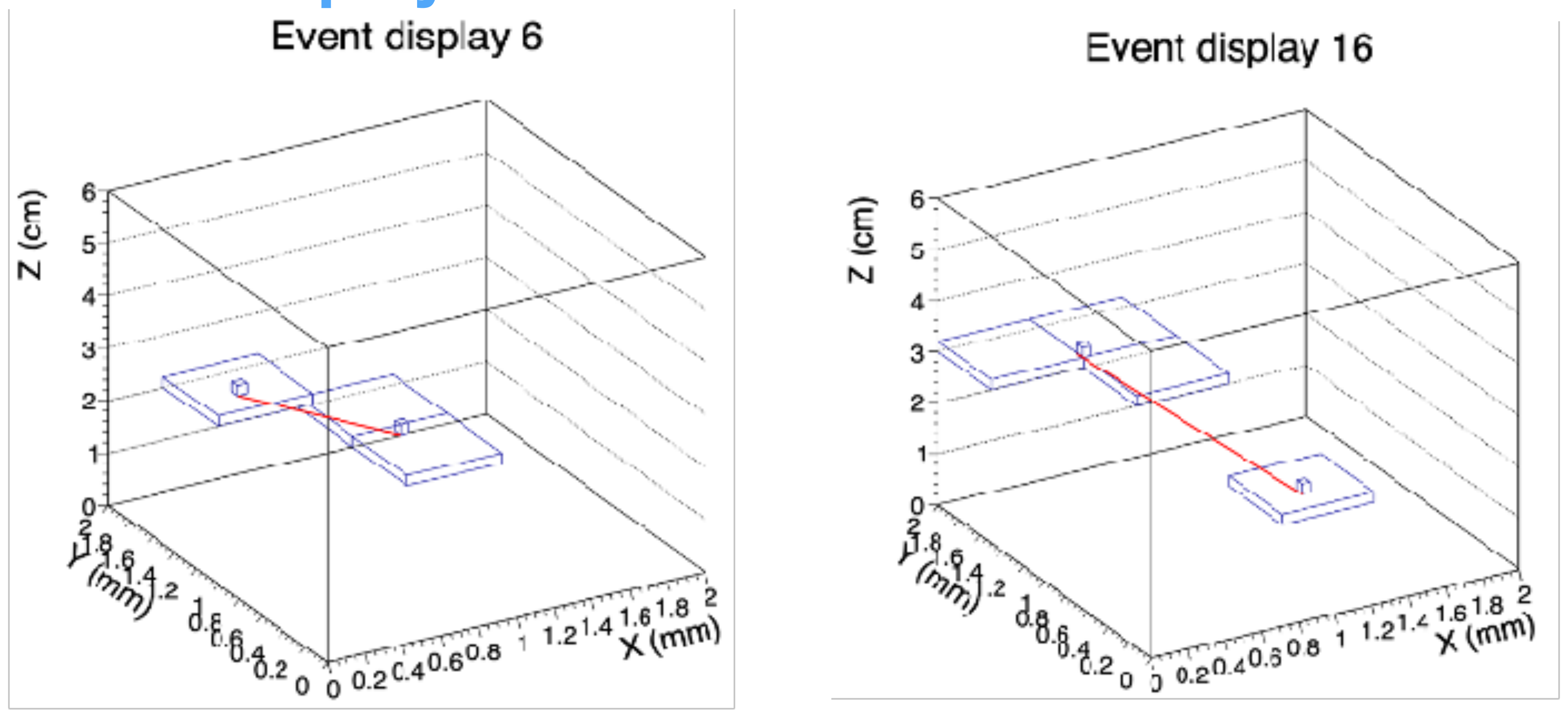
2-layer AC-LGAD telescope ^{90}Sr test setup



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



Event display of reconstructed electron tracks

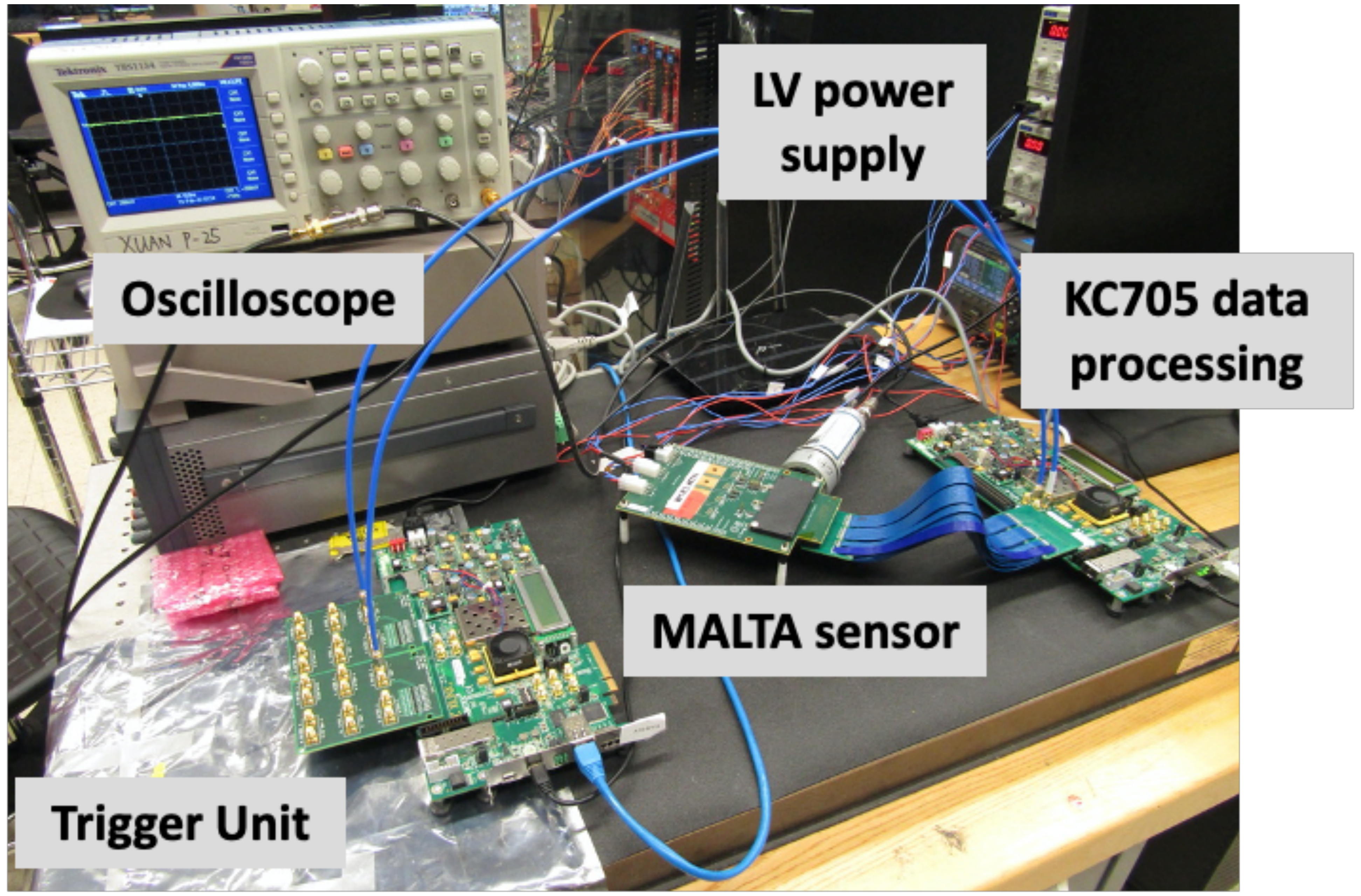


➢ Tracking performances such as efficiency, spatial and temporal resolutions are under study with the 3-layer telescope configuration.

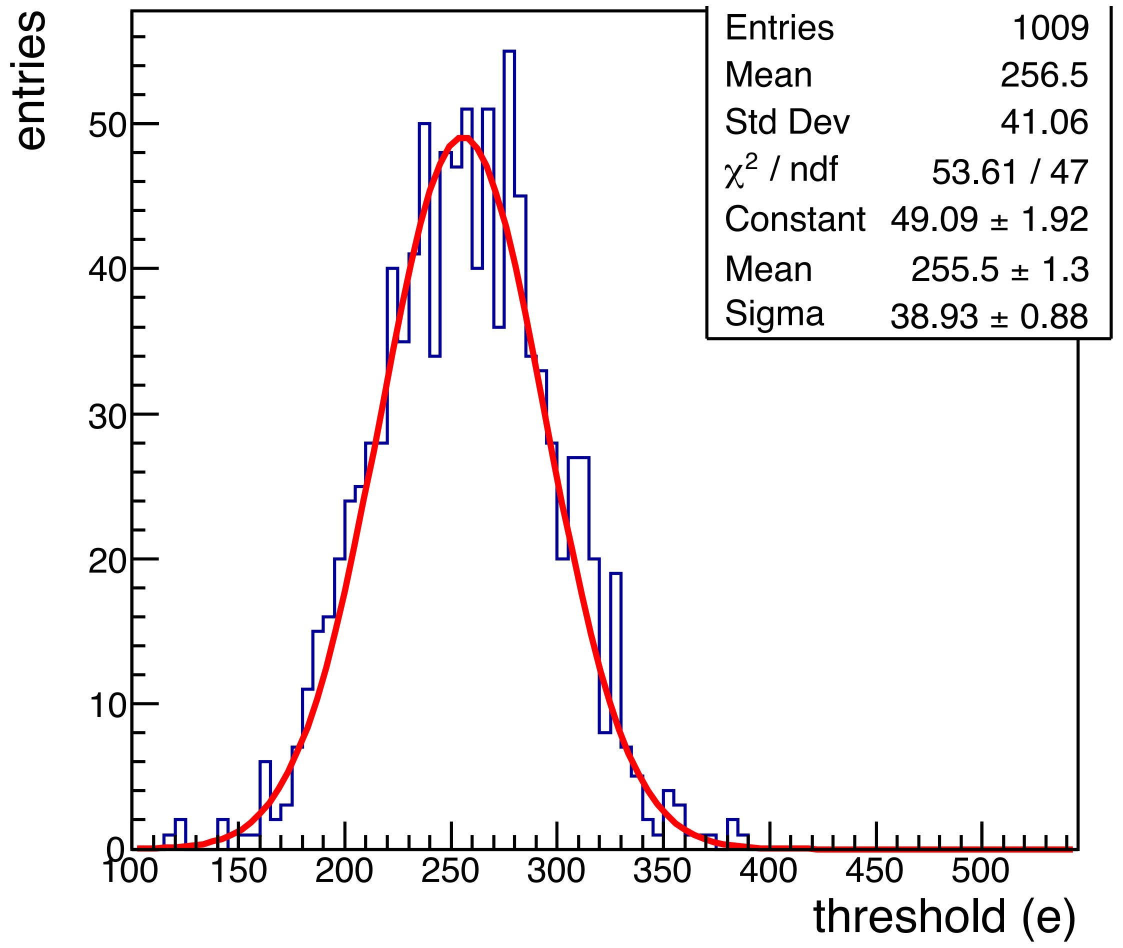
MALTA R&D test results

- Threshold and noise scan has been performed
- Hit occupancy has been studied with the ^{90}Sr source.

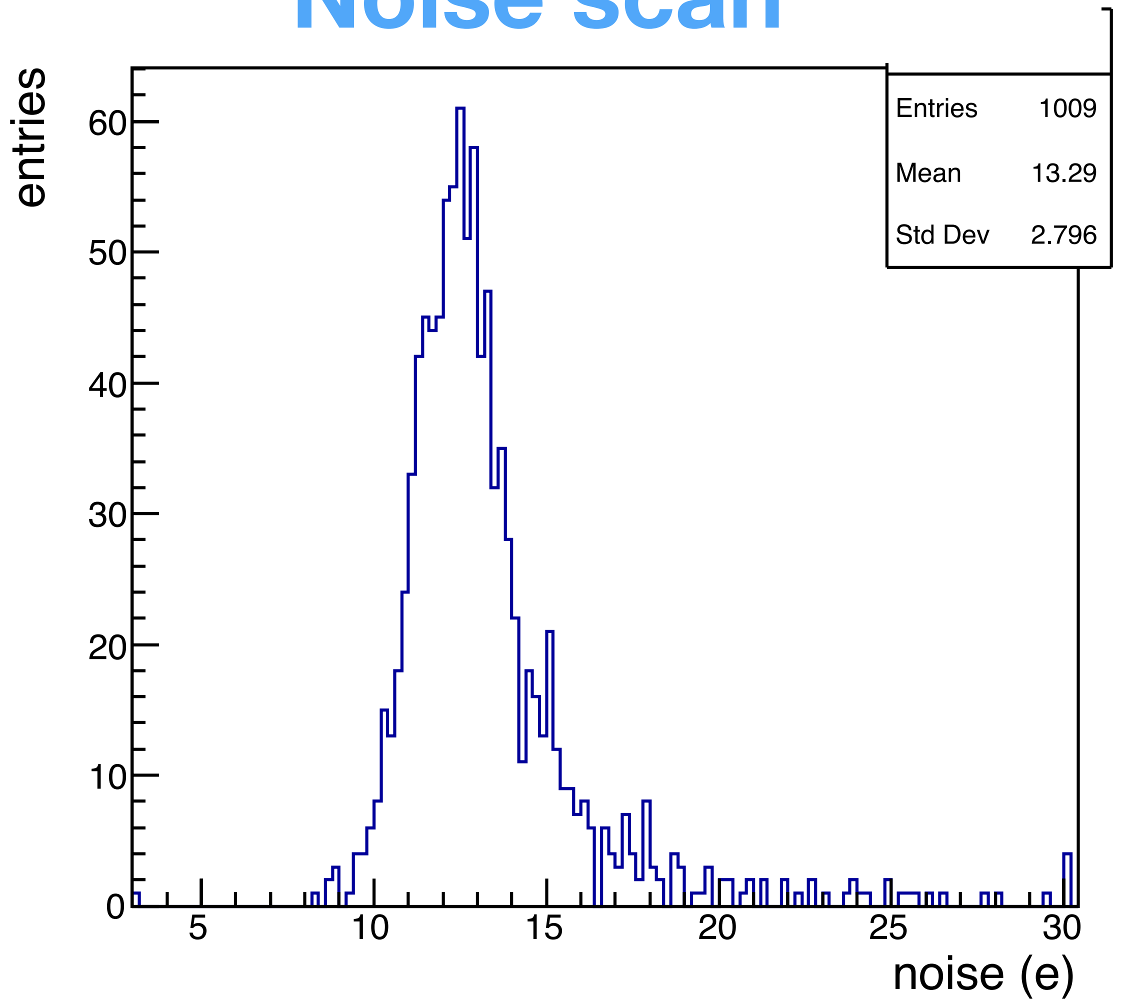
MALTA prototype sensor test setup



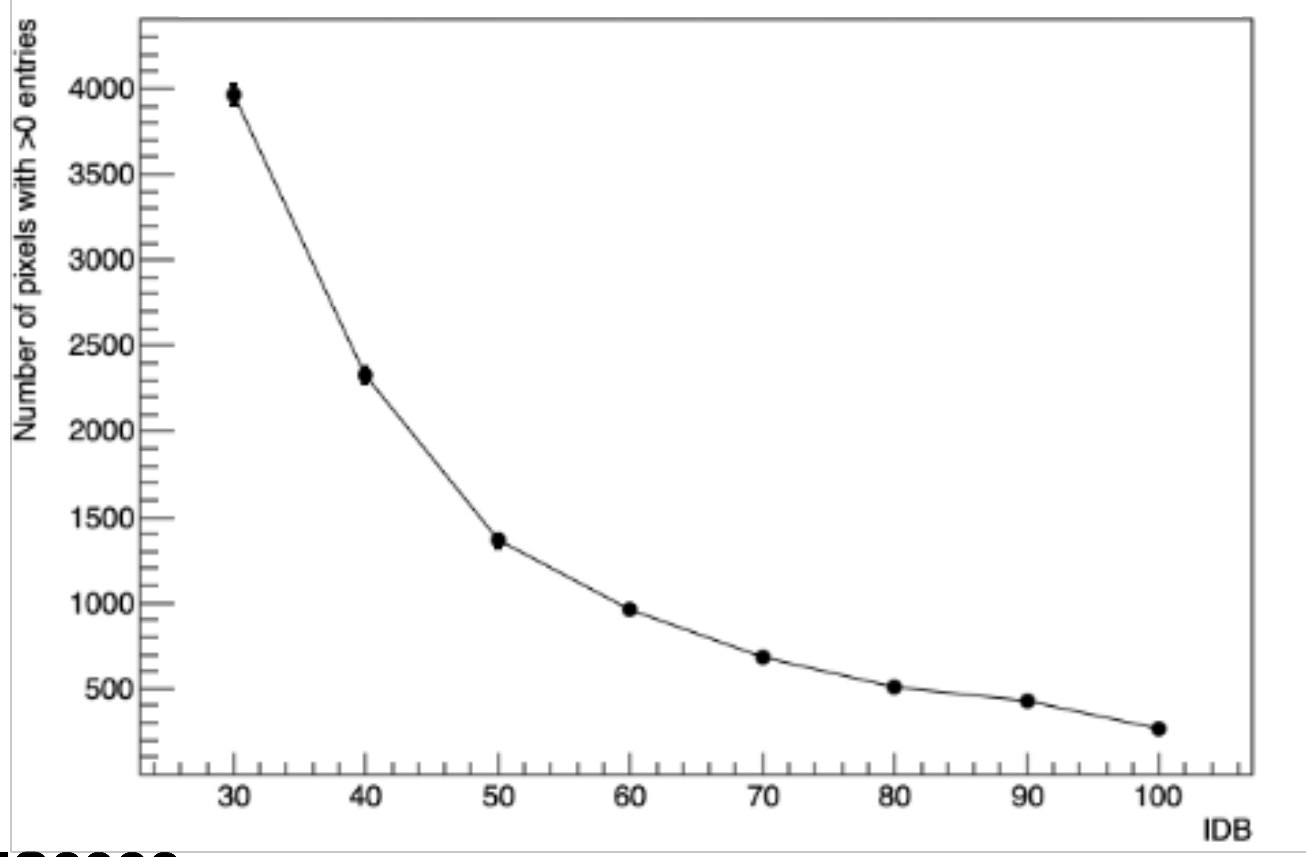
Threshold scan



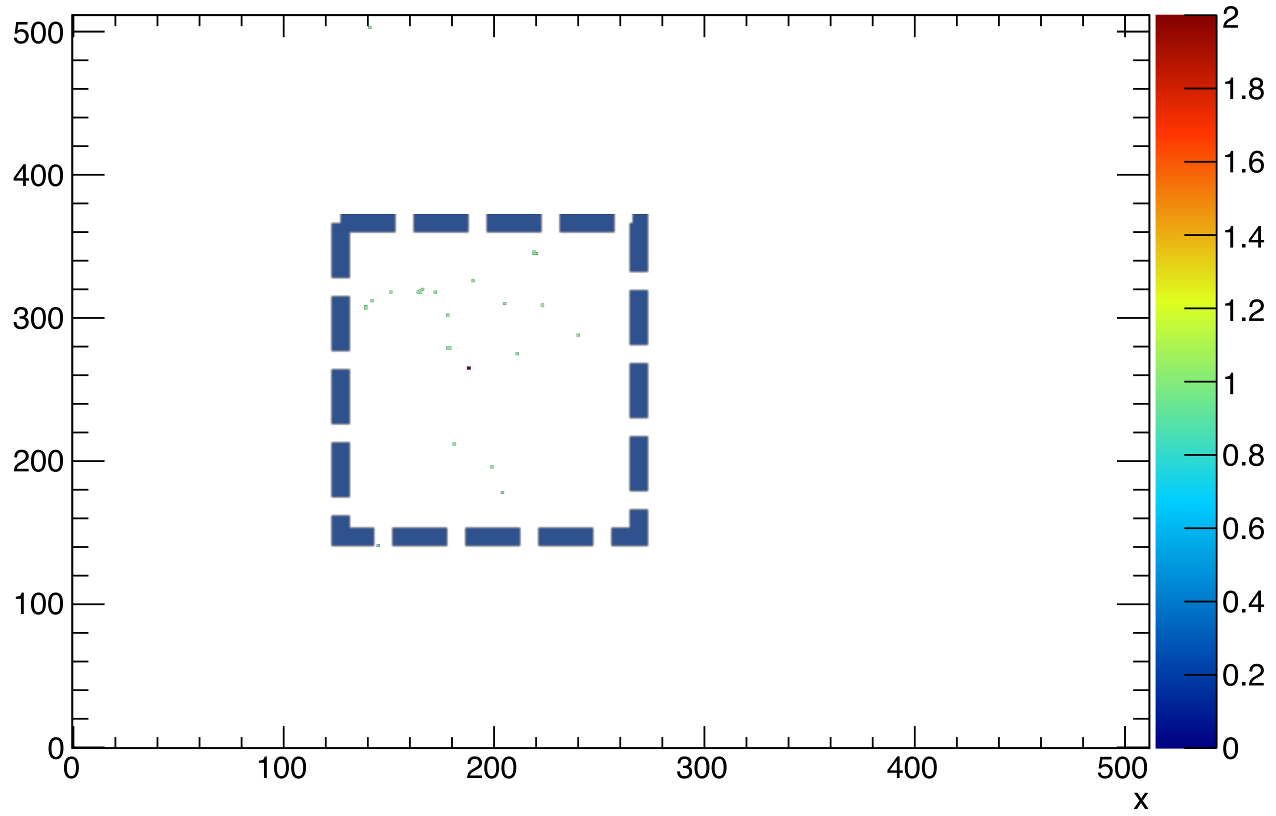
Noise scan



Noise pixel rate vs IDB

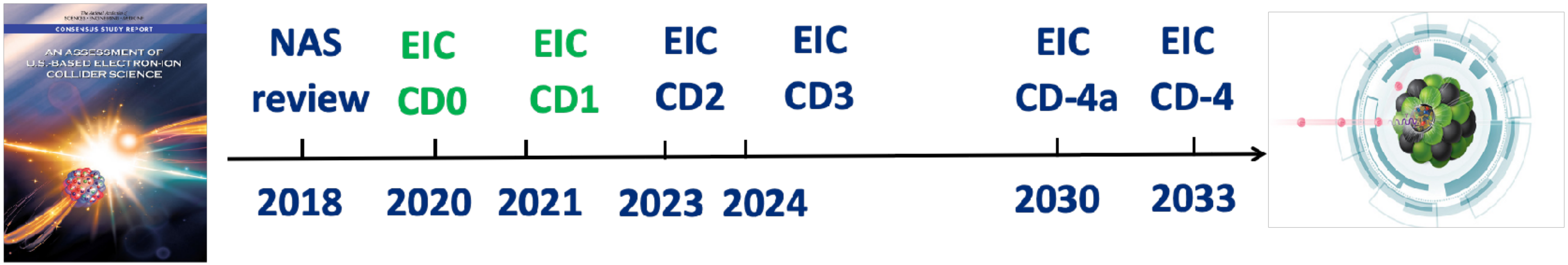


^{90}Sr source hit occupancy

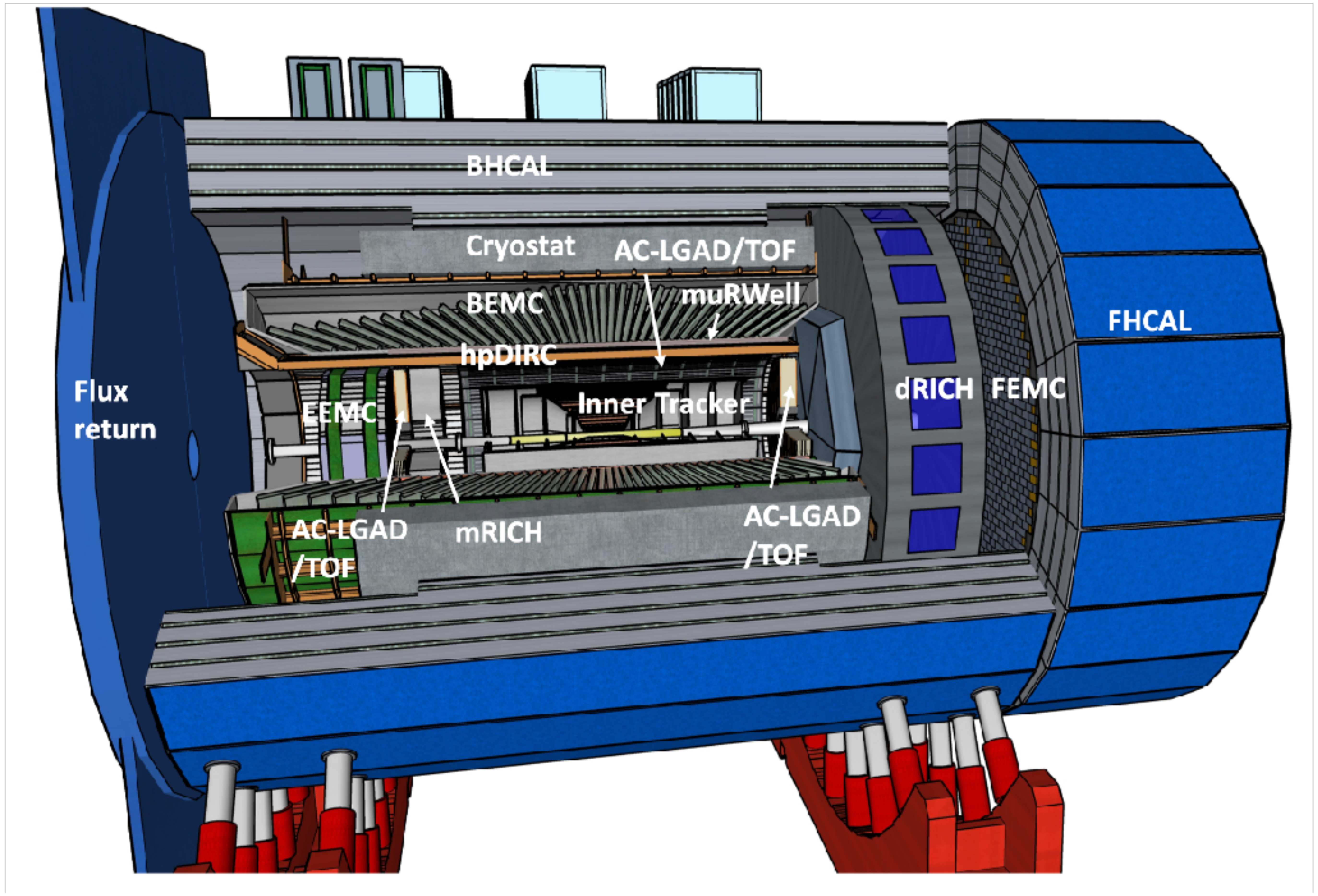


Summary and Outlook

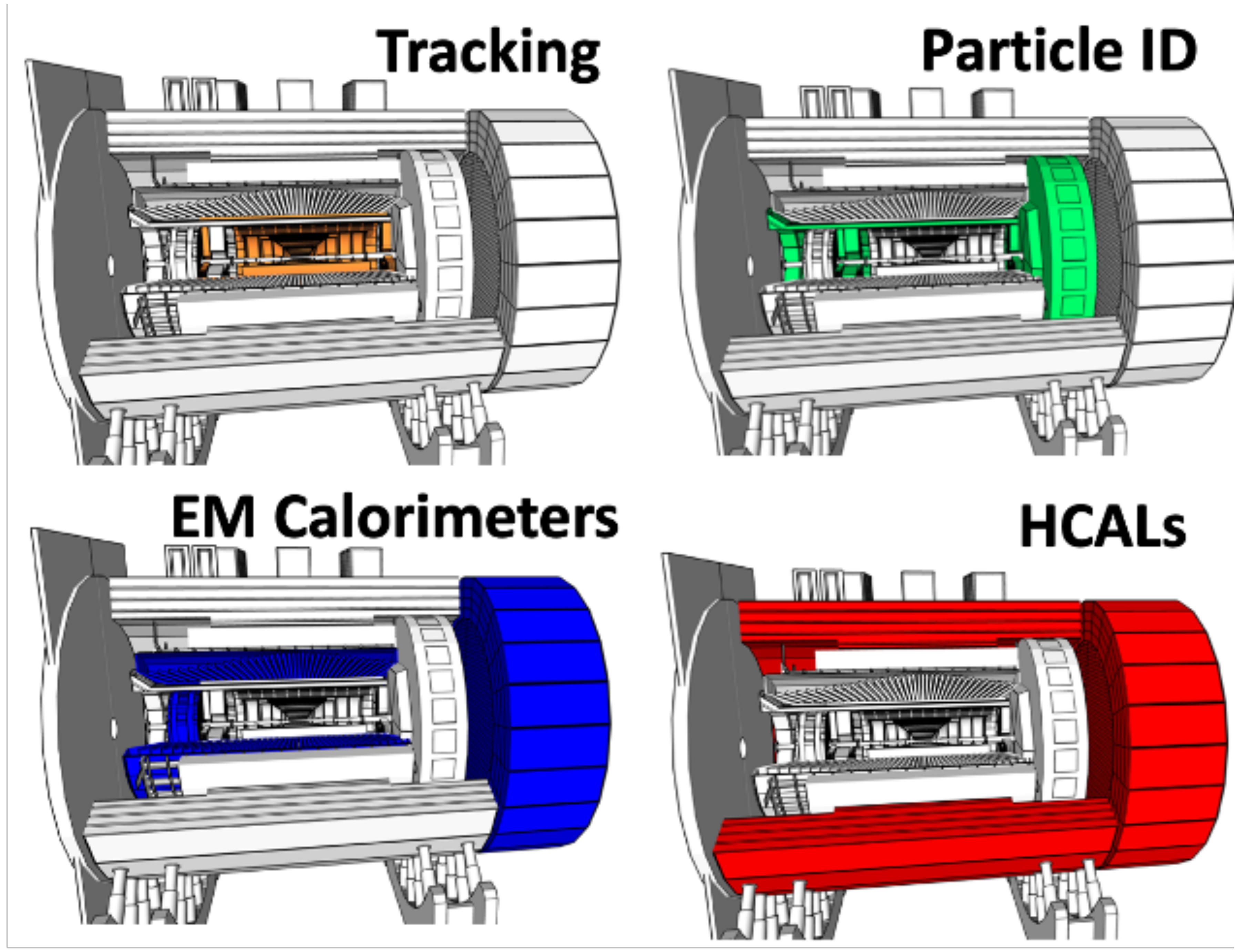
- The new heavy flavor and jet program for the EIC will explore the flavor dependent parton energy loss in medium and the hadronization processes in the poorly constrained kinematic region.
- Good progresses and results have been achieved in the EIC heavy flavor and jet studies with detector performances evaluated in full simulation.
- Promising results achieved from ongoing Silicon technology R&D towards detector design and construction.



Backup Slides

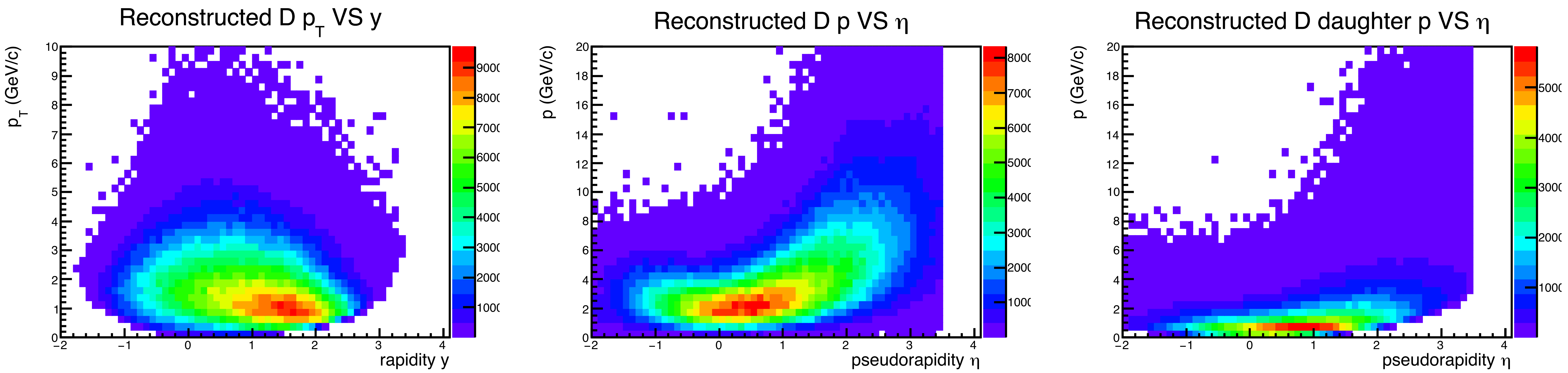


- ➢ The proposed ECCE detector consists of Tracking, Particle ID, EM Calorimeters and Hadronic Calorimeter subsystems.

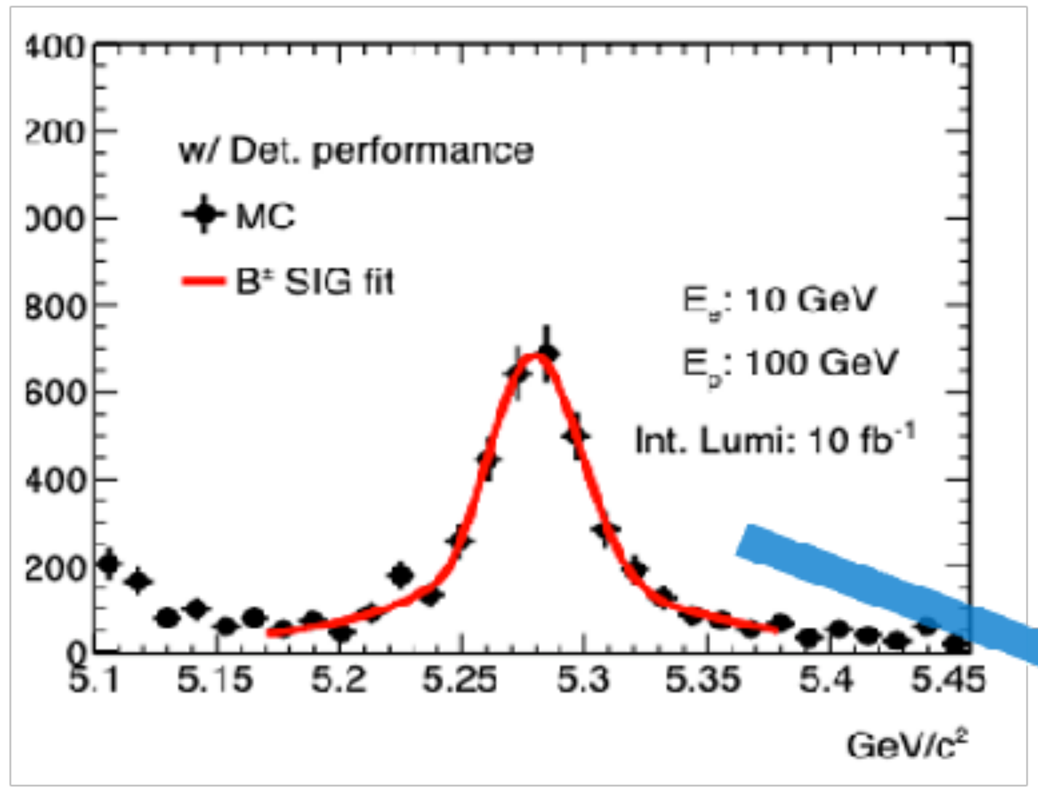


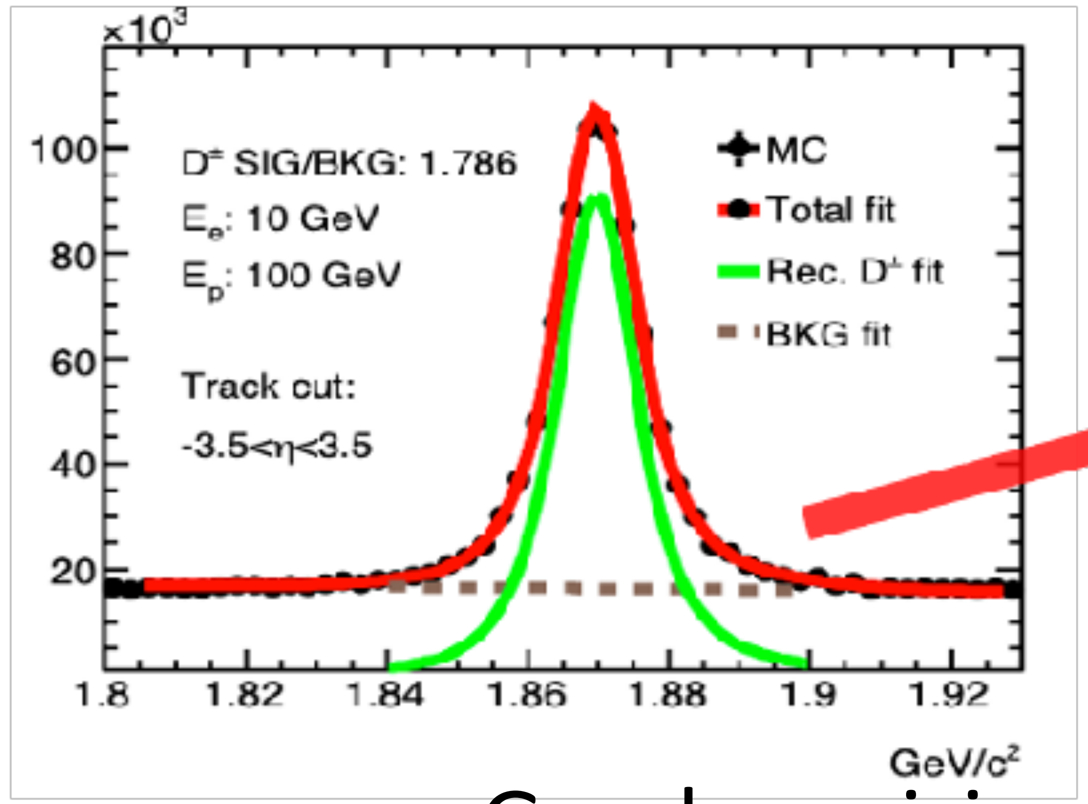
•To meet the heavy flavor physics measurements, a silicon vertex/tracking detector with low material budgets and fine spatial resolution is needed.

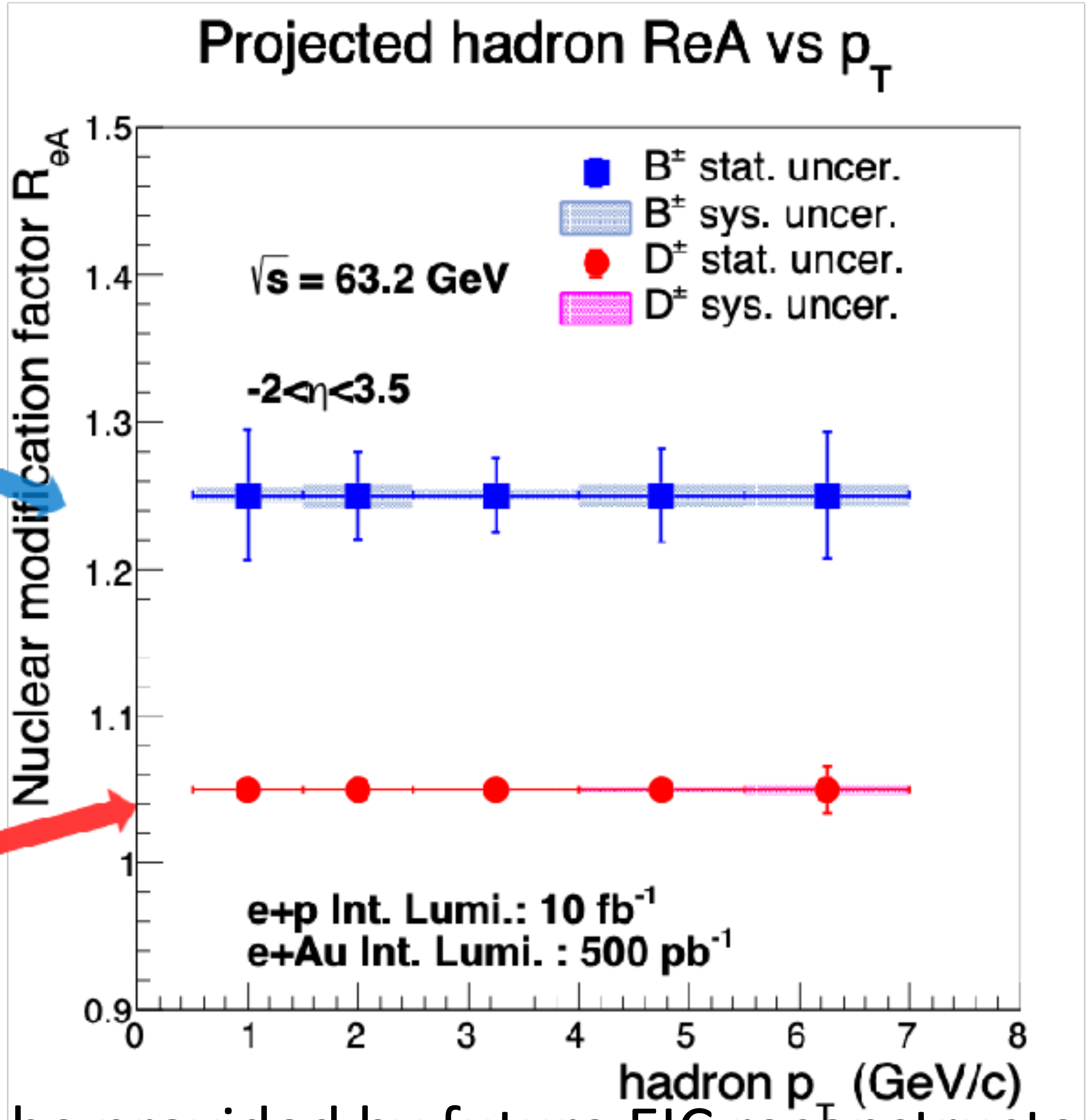
•Particles produced in the asymmetric electron+proton and electron+nucleus collisions have a higher production rate in the forward pseudorapidity. The EIC detector is required to have large granularity especially in the forward region.



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







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.

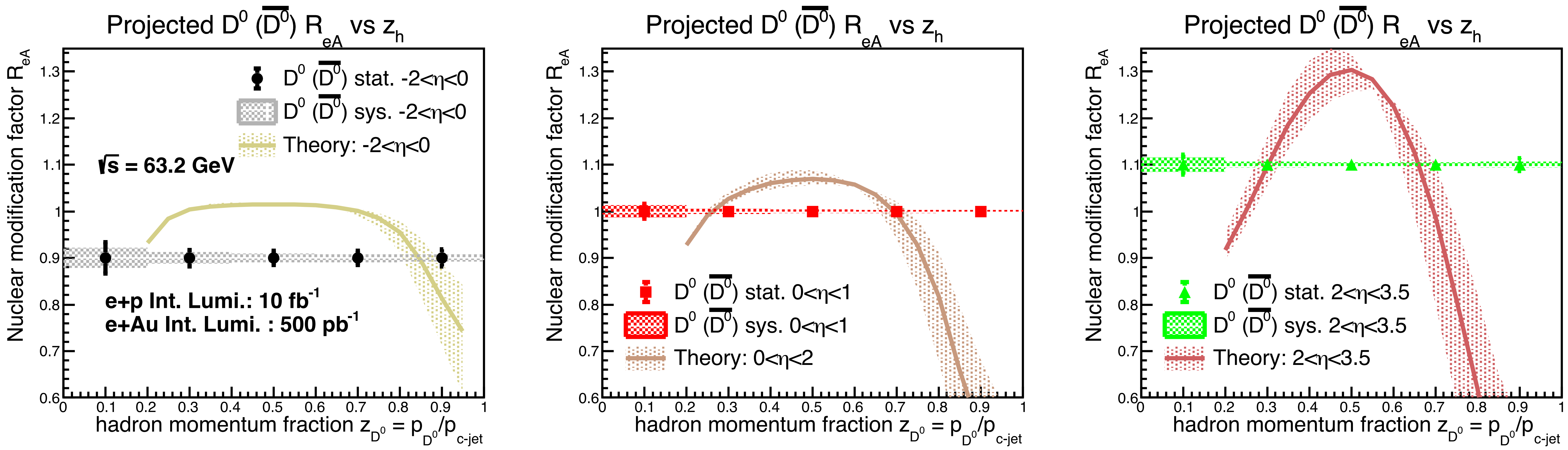
•Good precision can be provided by future EIC reconstructed heavy flavor hadron measurements within the low p_T region to explore the hadronization process in nuclear medium.

Pseudorapidity dependent HF nuclear modification factor projections

Nuclear modification factor:

R_eA=σ_eA/(Aσ_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 discriminating power in separating different model calculations on the heavy flavor production in a nuclear medium can be provided by future EIC heavy flavor measurements over a wide pseudorapidity region.

Outline

- ➢ Introduction to the Electron-Ion Collider (EIC) and the EIC detector.
- ➢ Heavy flavor hadron and jet reconstruction in simulation and physics projection.
- ➢ Advanced silicon detector R&D progress at LANL
- ➢ Summary and Outlook