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Heavy Flavor Physics at the EIC with the ECCE detector

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on behalf of the ECCE proto-collaboration

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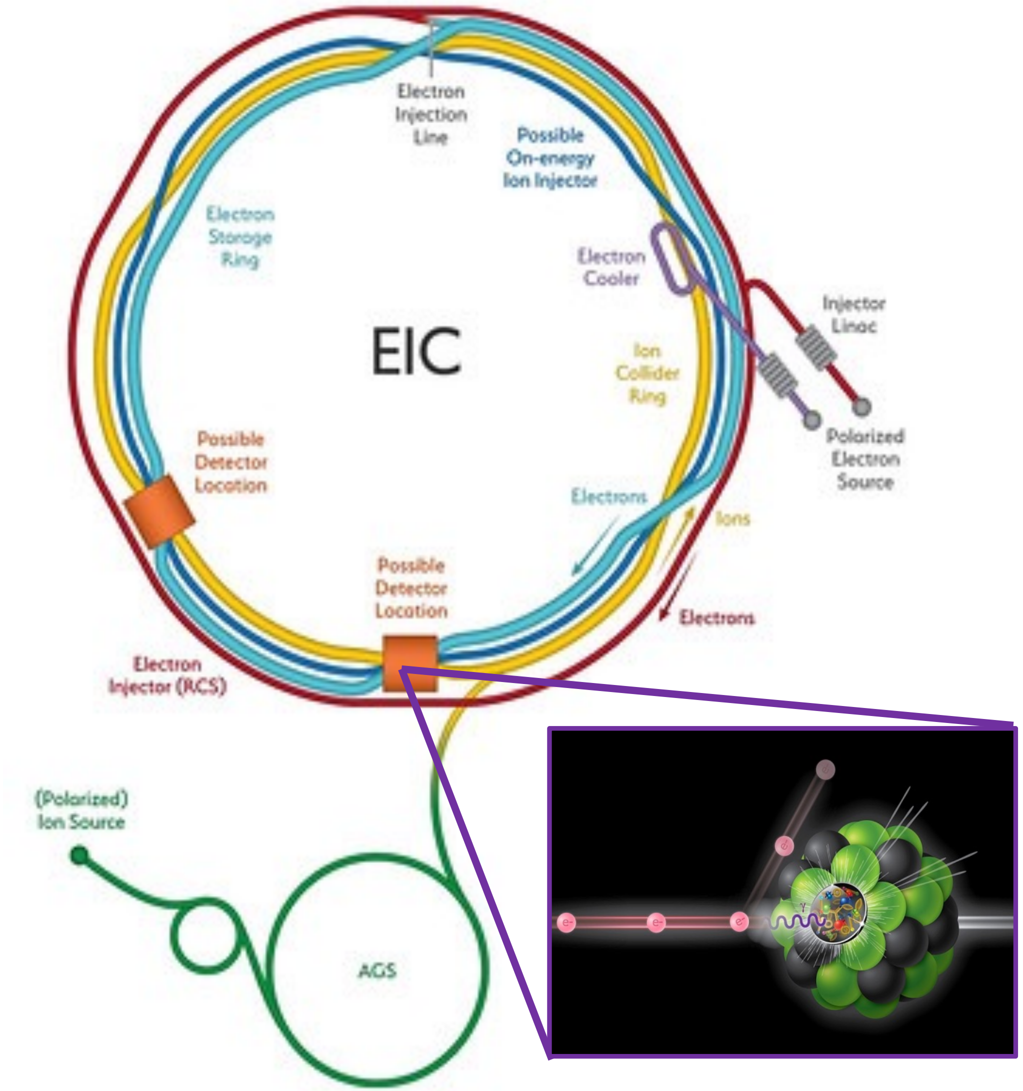
Outline

- Introduction to the Electron-Ion Collider (EIC) and the ECCE detector.
- Heavy flavor hadron and jet reconstruction with the ECCE detector performance in e+p simulation.
- Projections of open and closed heavy flavor measurements at the EIC.
- Summary and Outlook

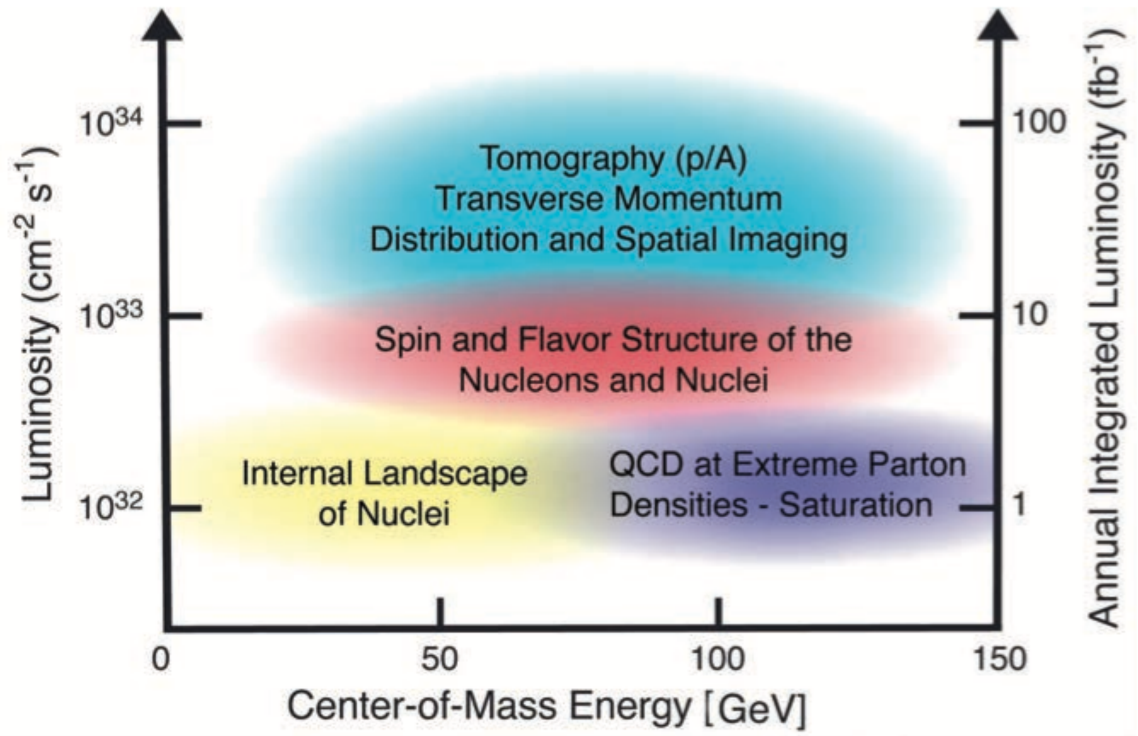
Introduction to the future Electron-Ion Collider (EIC)

- 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.

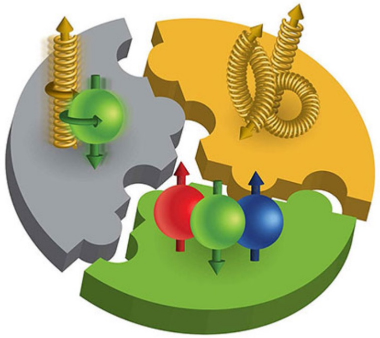


EIC science objectives

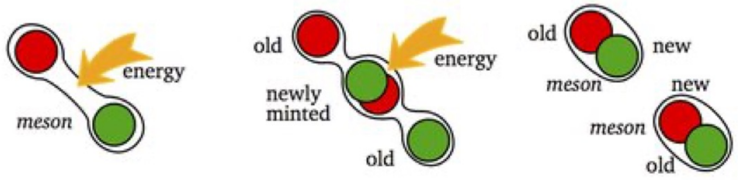
- With a series of e+p and e+A collisions at different center of mass energies and luminosities, the proposed EIC will
  - precisely study the nucleon/nuclei 3D structure.
  - help address the proton spin puzzle.
  - explore the nucleon/nuclei parton density extreme – gluon saturation.
  - explore how quarks and gluons form visible matter inside the vacuum/medium, which is referred to as the hadronization process.
  - Study the quark/gluon kinematics inside a nucleus.



Proton spin crisis



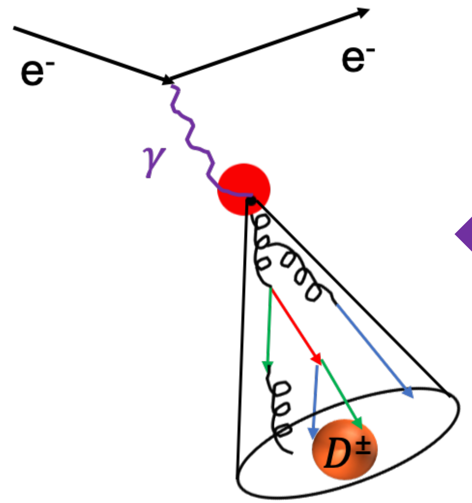
Quark confinement



Heavy flavor measurements can enrich the EIC physics program

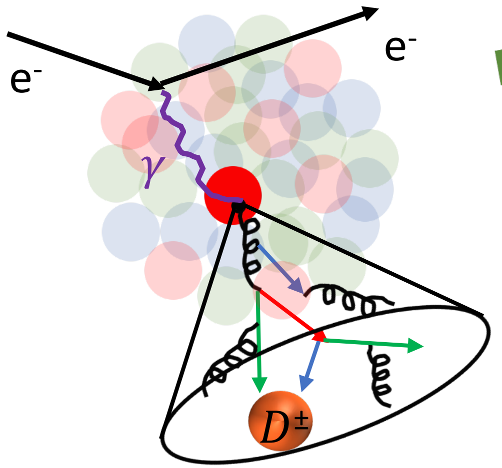
- Heavy flavor hadron and jet measurements at the future EIC can help solve the listed science problems and play a significant role in exploring
  - Medium modifications on the initial nuclear Parton Distribution Functions (nPDFs) especially in the high and low Bjorken-x (x_{BJ}) region.
  - Final state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

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

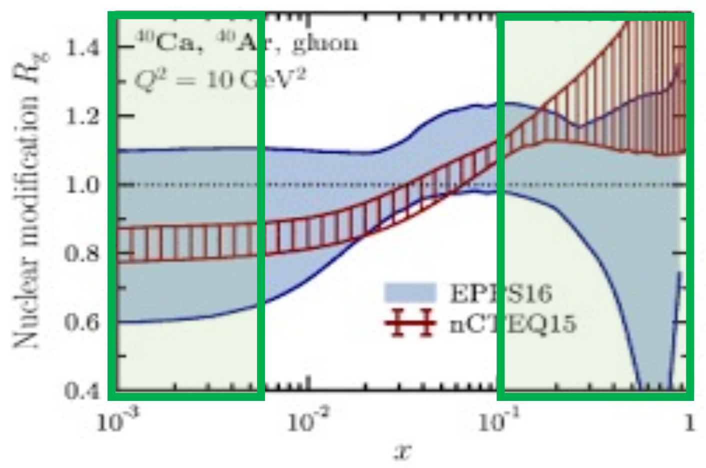


Compare

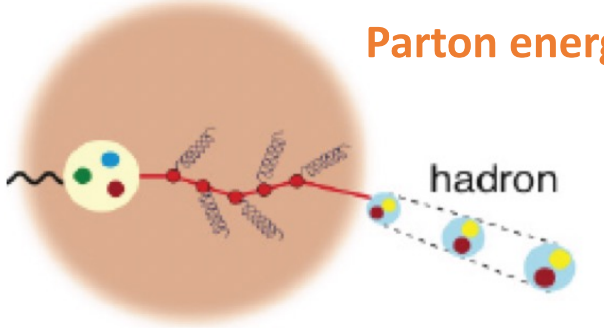
$e^- + \text{Au} \rightarrow e^- + jet(D^{\pm}) + X$



nPDF modification



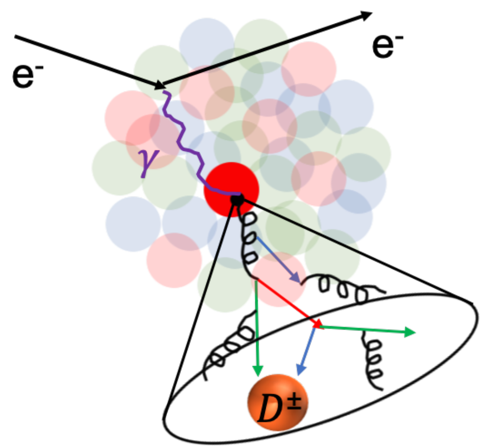
Parton energy loss

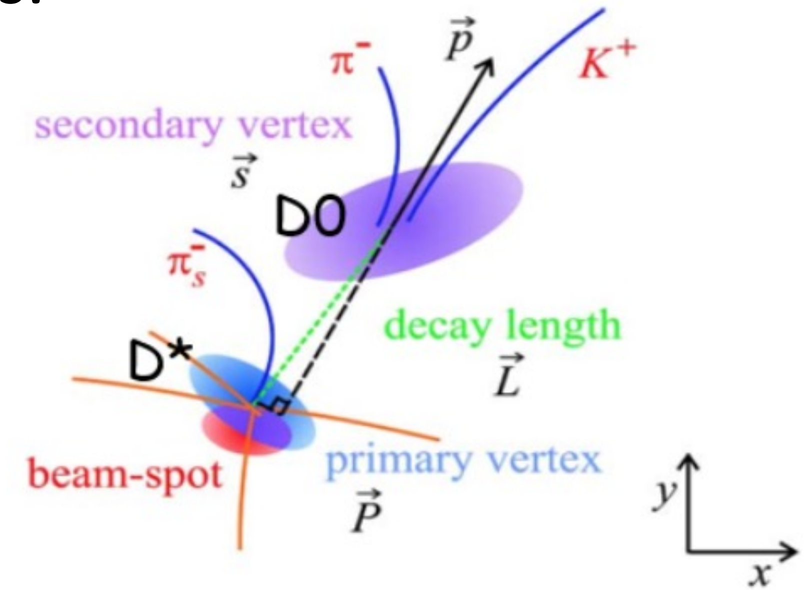


High precision vertex/tracking detector is required to measure HF products

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

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

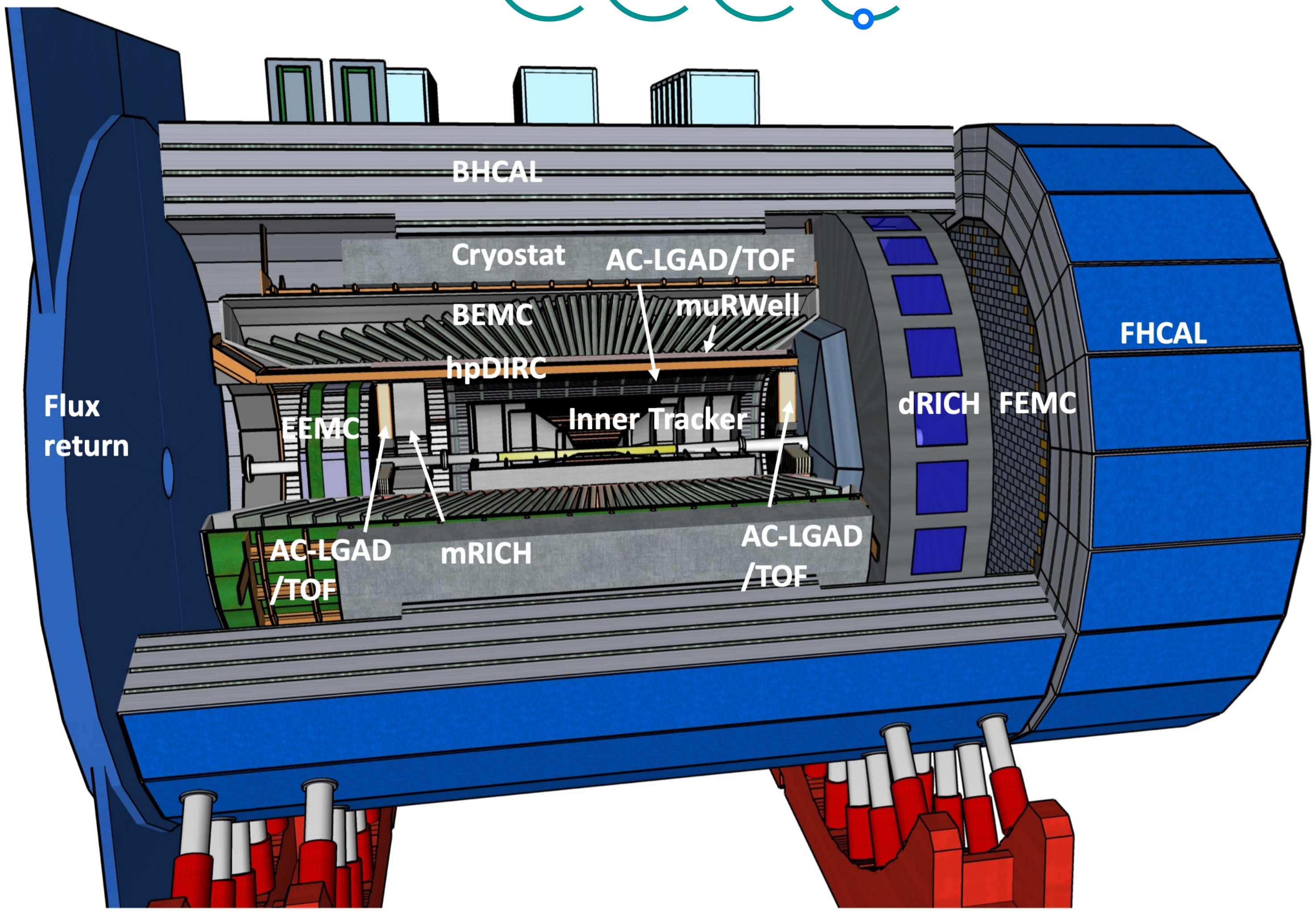




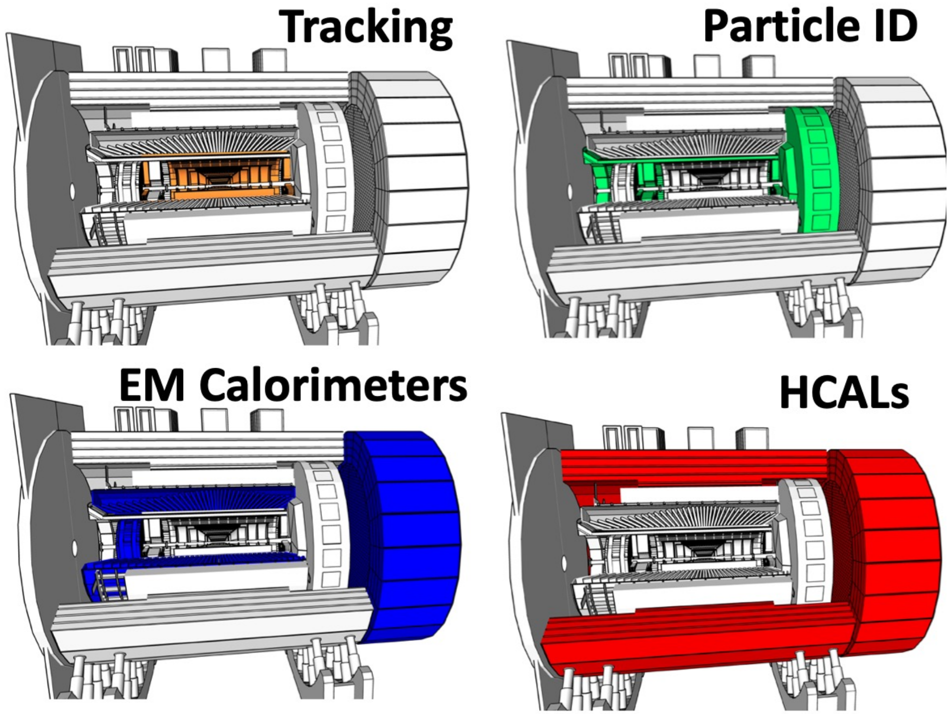
Particle	Mass (GeV/c²)	Average decay length
$D^{\pm}$	1.869	312 micron
D^0	1.864	123 micron
$B^{\pm}$	5.279	491 micron
B^0	5.280	456 micron

- 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.

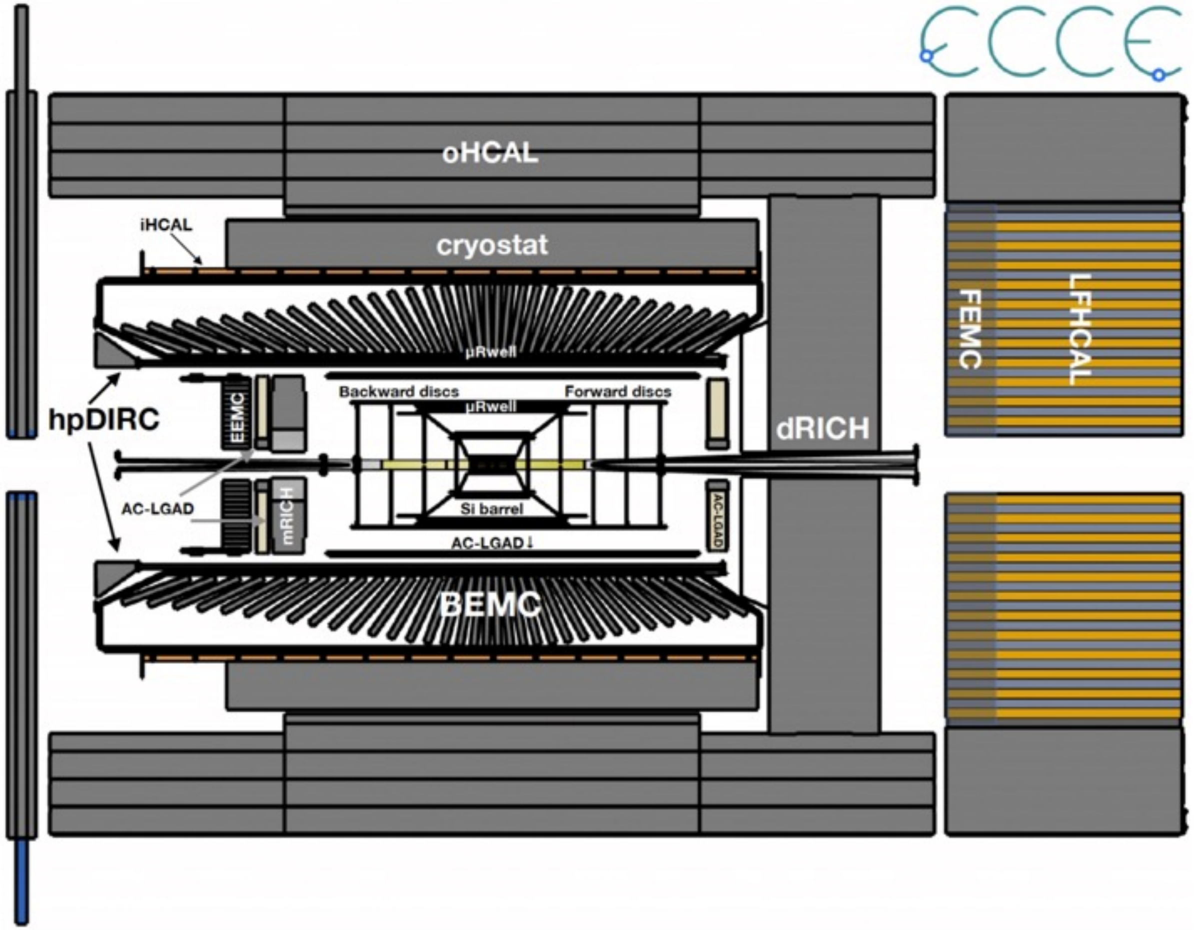
ECCE detector layout



- The proposed ECCE detector consists of Tracking, Particle ID, EM Calorimeters and Hadronic Calorimeter subsystems. It utilizes the existing Babar magnet (1.4T).



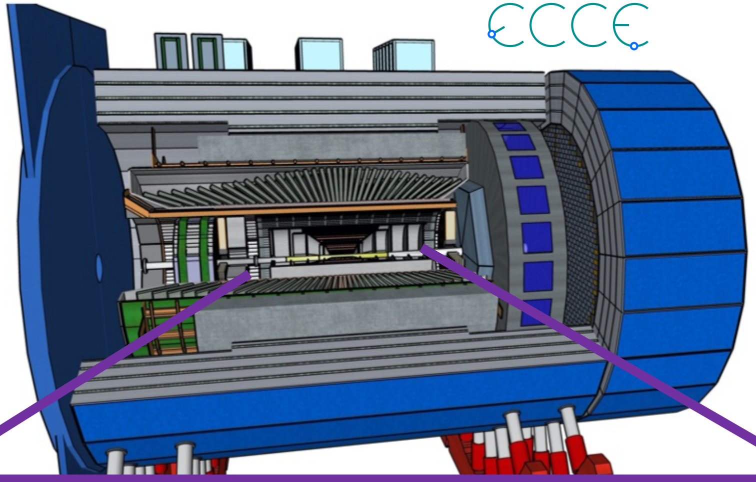
ECCE tracking detector concept

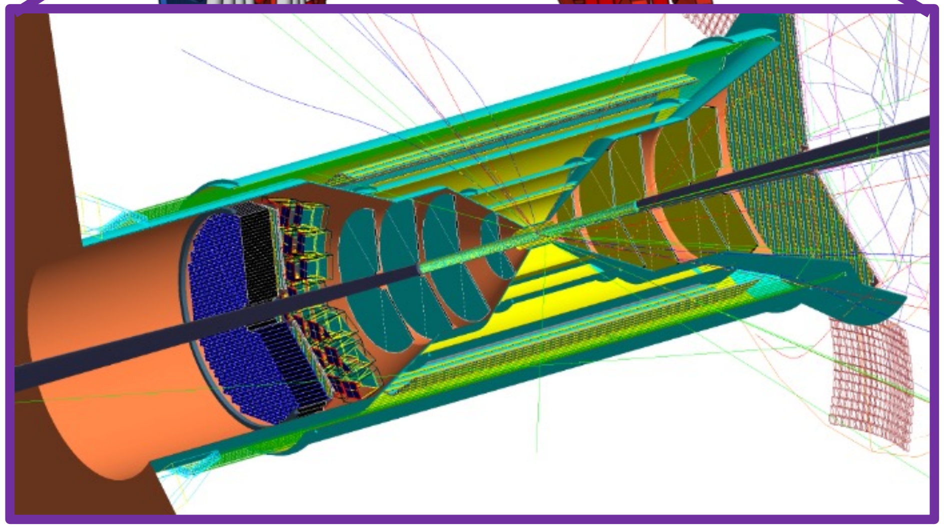


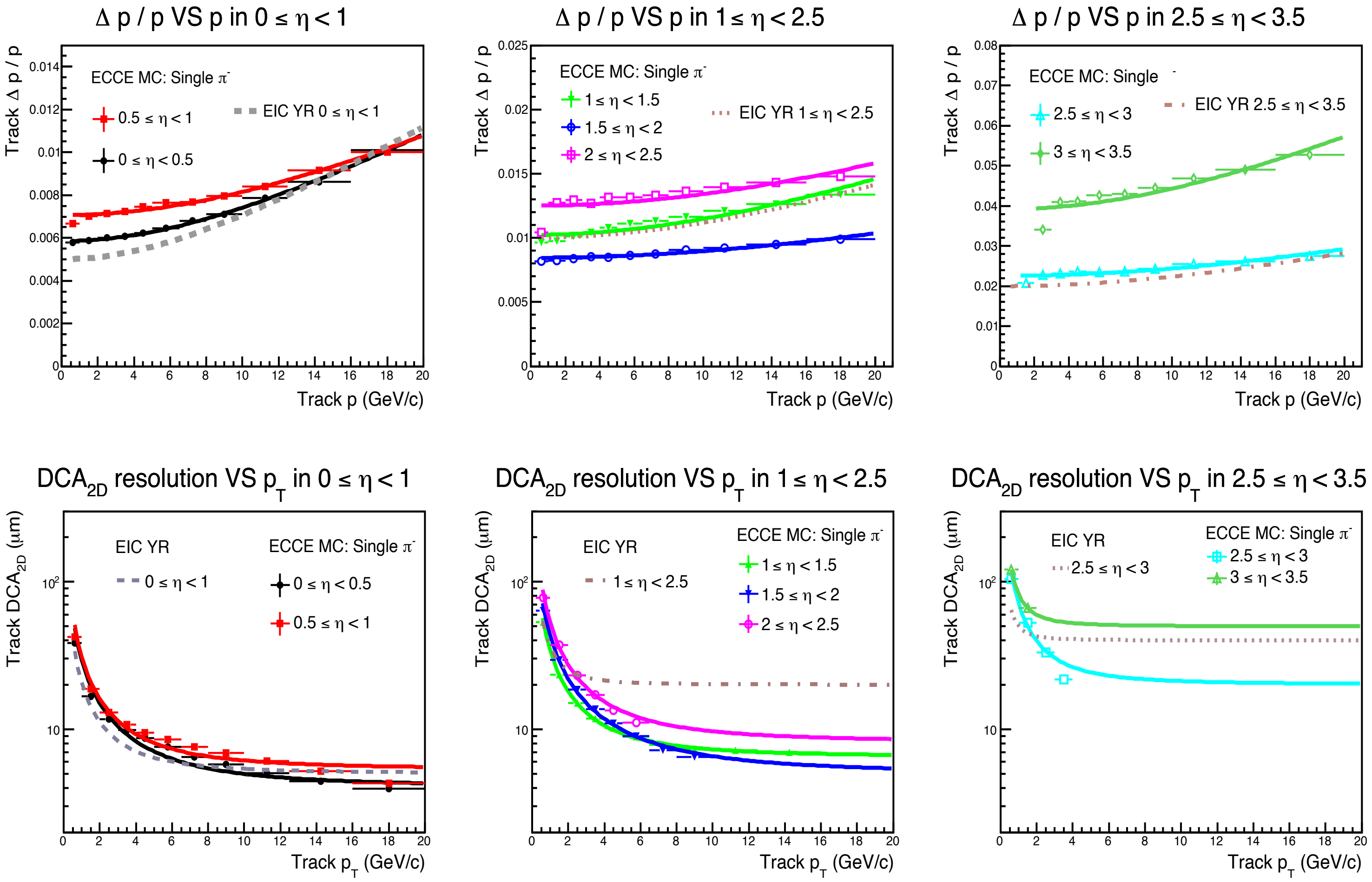
- The ECCE tracking detector consists of
  - Monolithic Active Pixel Sensor (MAPS) based silicon vertex/tracking subdetector with 3-barrel vertex layers, 2-barrel middle layers , 5 forward disks and 4 backward disks. The single layer/disk hit spatial resolution is around 3μm.
  - Micro-Rwell (μRwell) gas tracking subdetector with 3-barrel tracking layers further out from the beam-pipe than the silicon layers. The single layer hit spatial resolution is around 45-50 μm.
  - Moreover, the forward and backward AC-LGAD based ToF can serve as the outer tracker as well.

ECCE tracking detector concept and performance

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

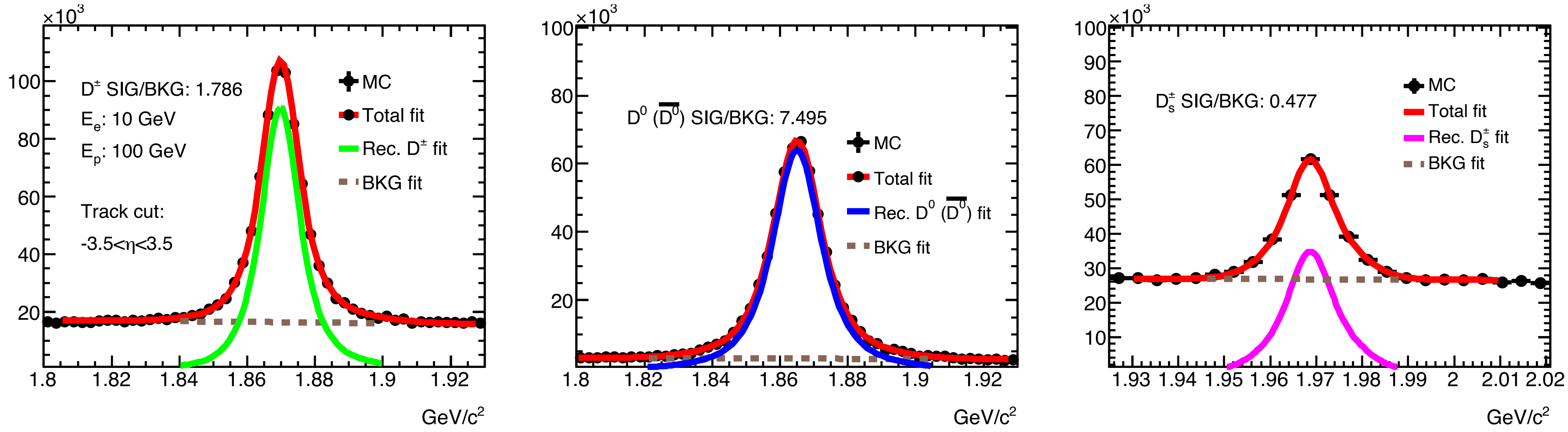






Reconstruction of open heavy flavor hadron in e+p simulation (I)

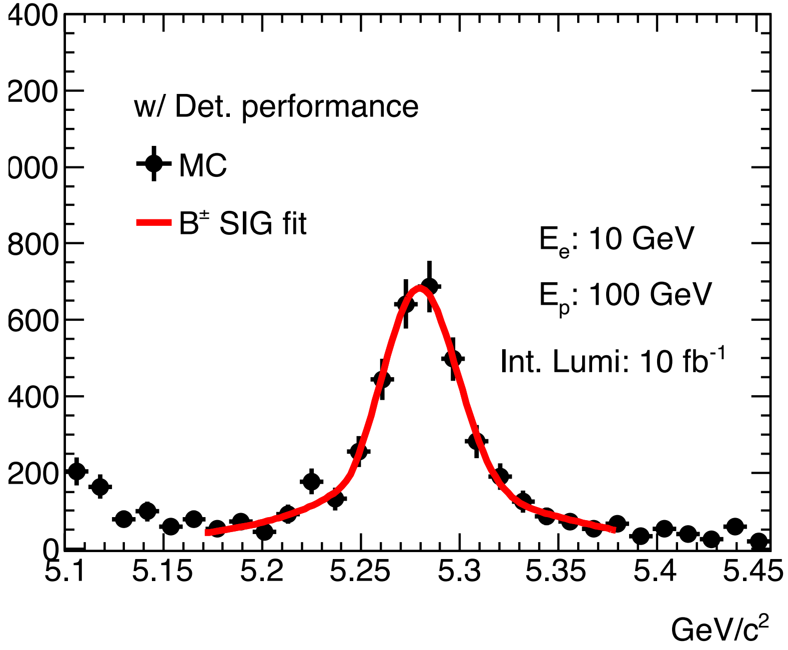
- The full analysis framework which includes the event generation (PYTHIA), ECCE detector response in GEANT4 simulation, beam remnant & QCD background, and hadron reconstruction algorithm have been setup.
- Mass distributions of reconstructed charm hadrons using the ECCE detector performance inside the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

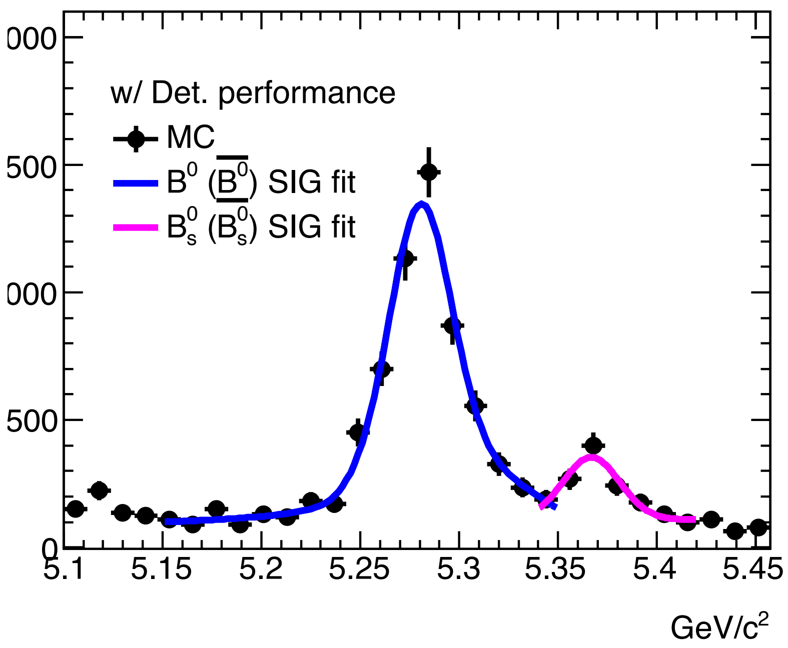


DCA$_{2D}$ matching and angular cuts to suppress the background

Reconstruction of open heavy flavor hadron in e+p simulation (II)

- 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}.

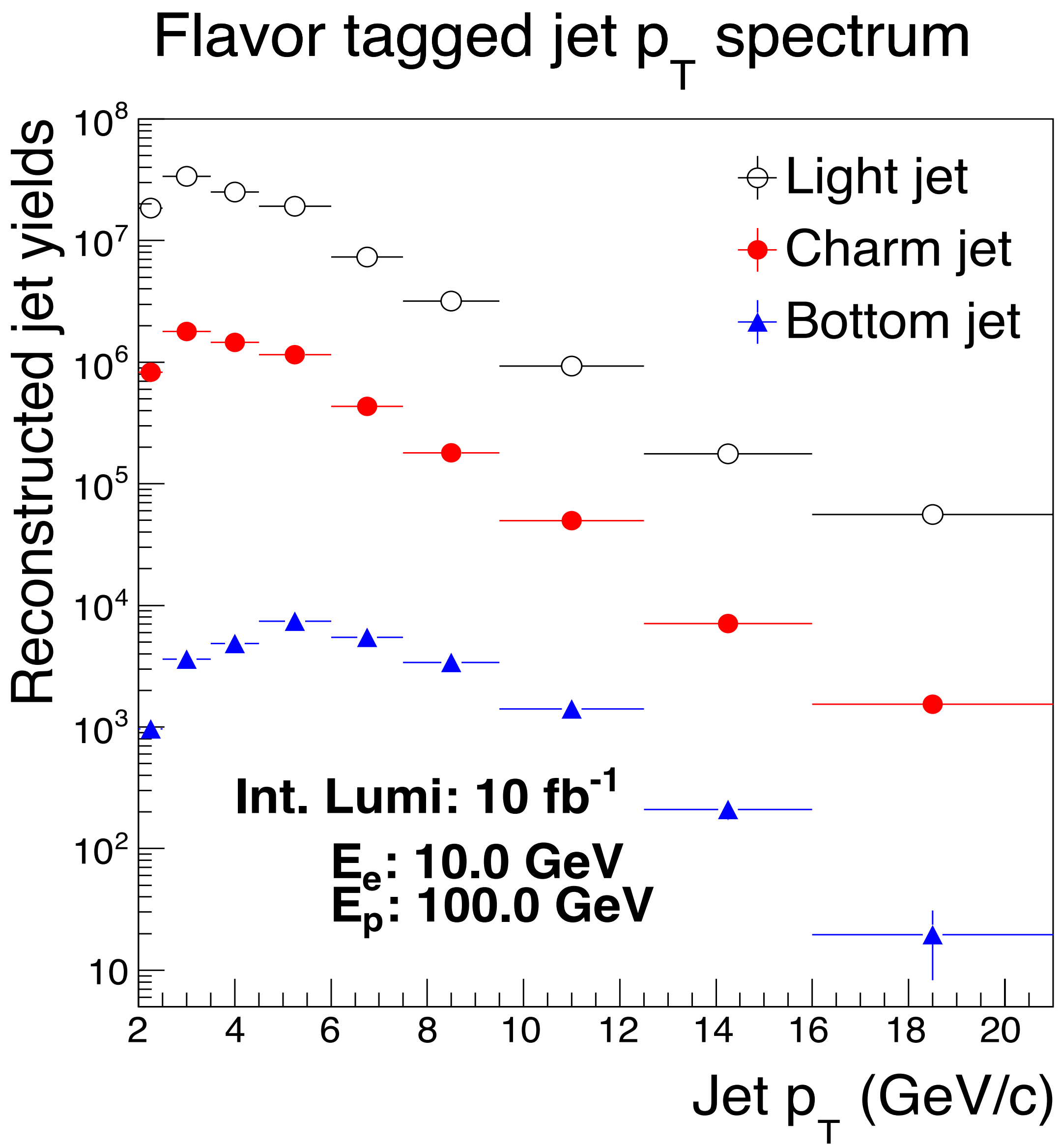




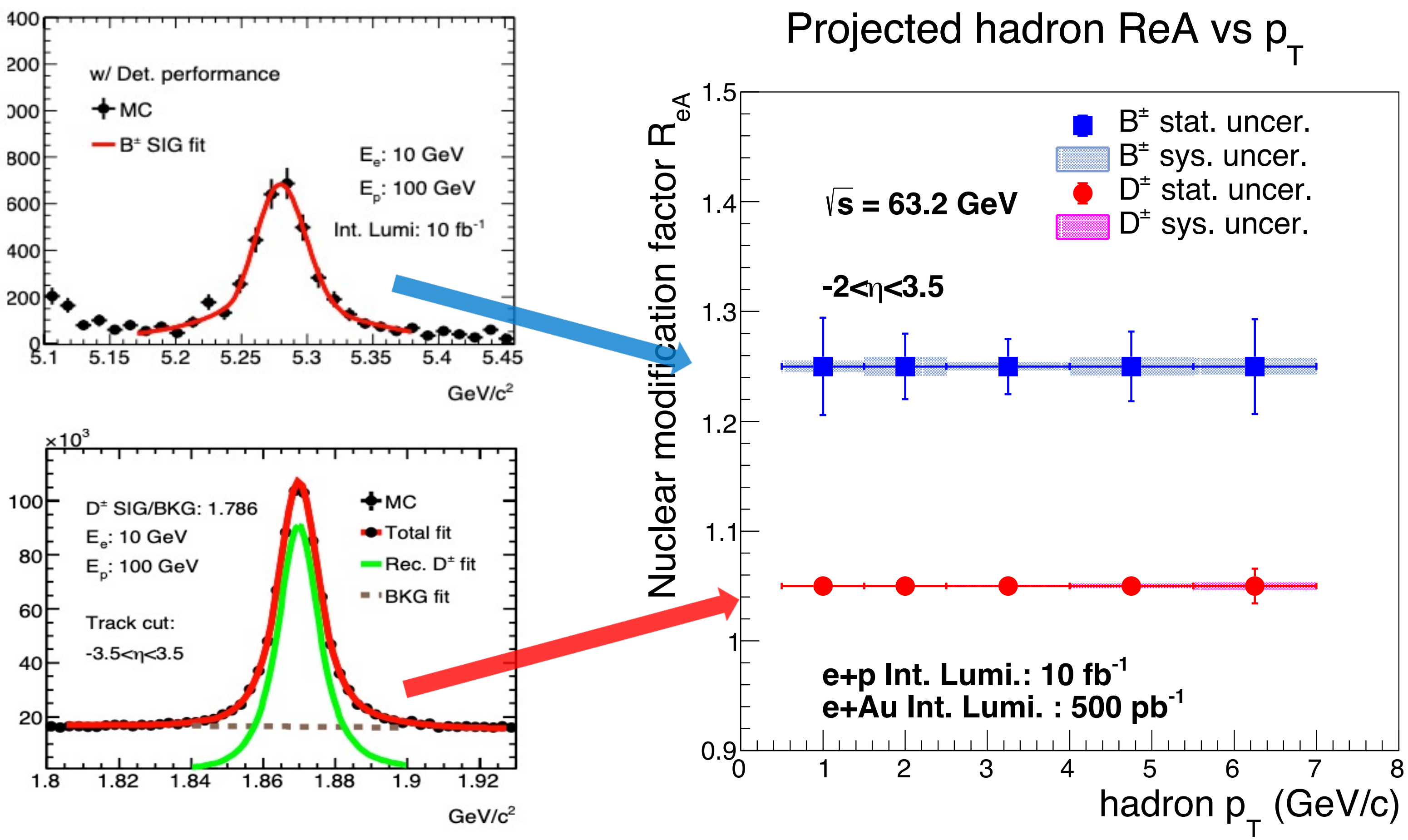
DCA$_{2D}$ matching and angular cuts to suppress the background

Reconstructed heavy flavor jets in e+p simulation

- Heavy flavor jets can be treated as surrogates of the initial heavy quarks.
- P_T spectrum of reconstructed light and heavy flavor 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 (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.

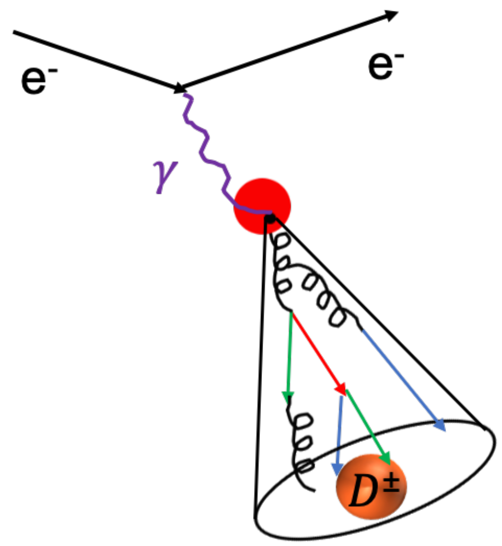
- Good precision can be provided by future EIC reconstructed heavy flavor hadron measurements within the low p_T region to explore the hadronization process in nuclear medium.

Flavor dependent nuclear modification factor projections (II)

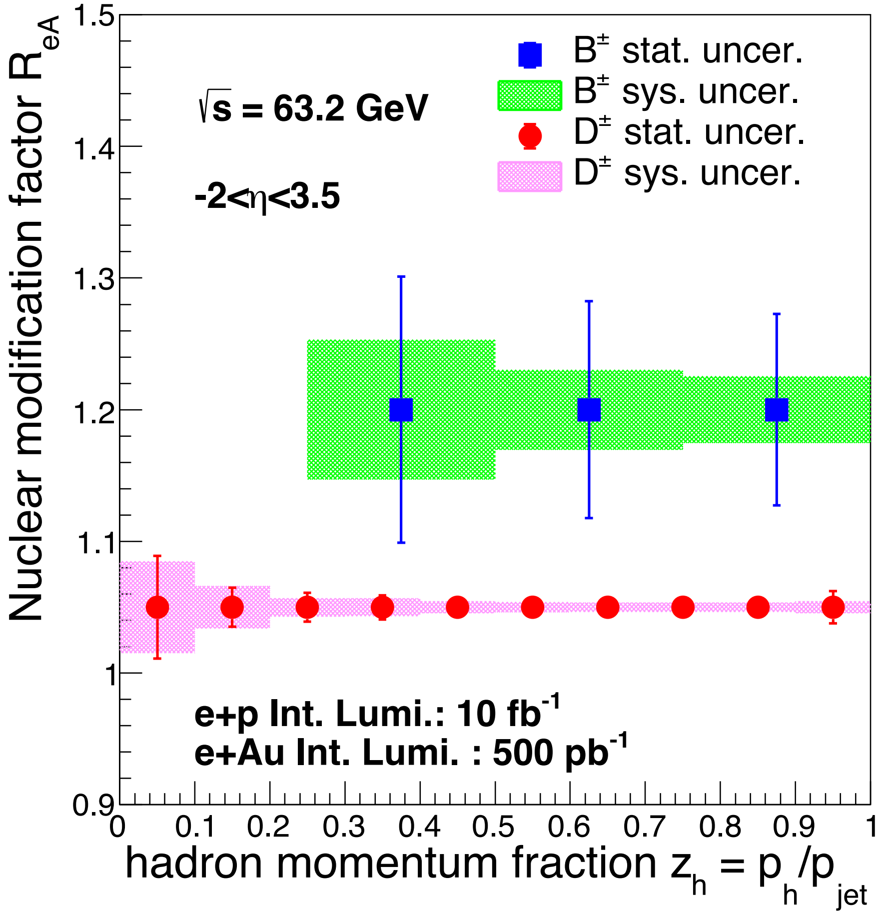
Nuclear modification factor:

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

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



Projected hadron ReA vs z_h



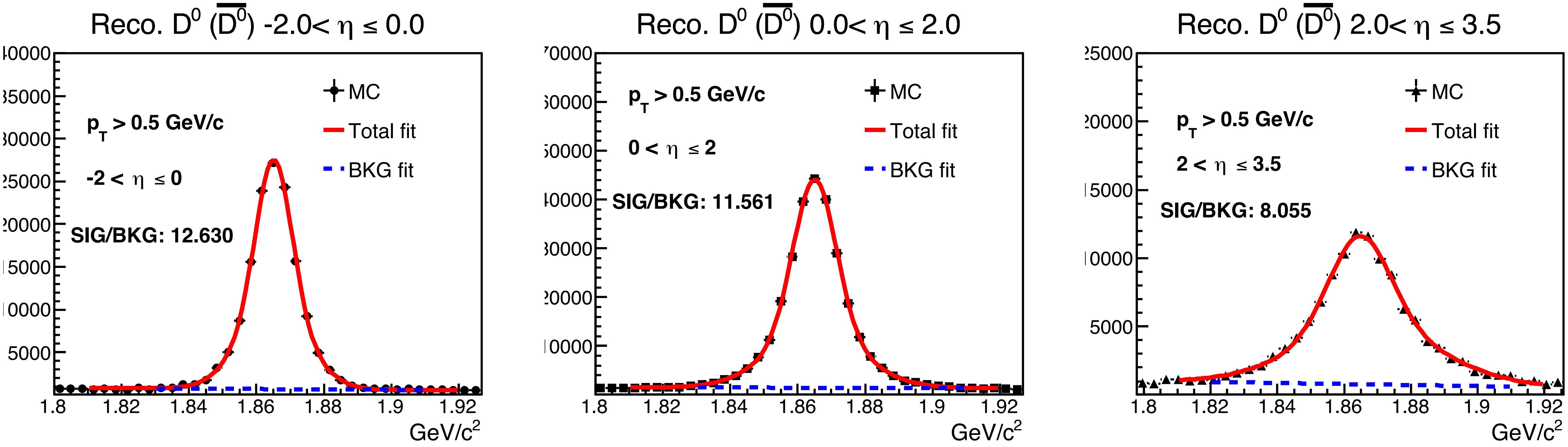
Systematic uncertainty:

- 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 constraints on the fragmentation function in the high z_h region.

Pseudorapidity dependent D^0 meson reconstruction

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



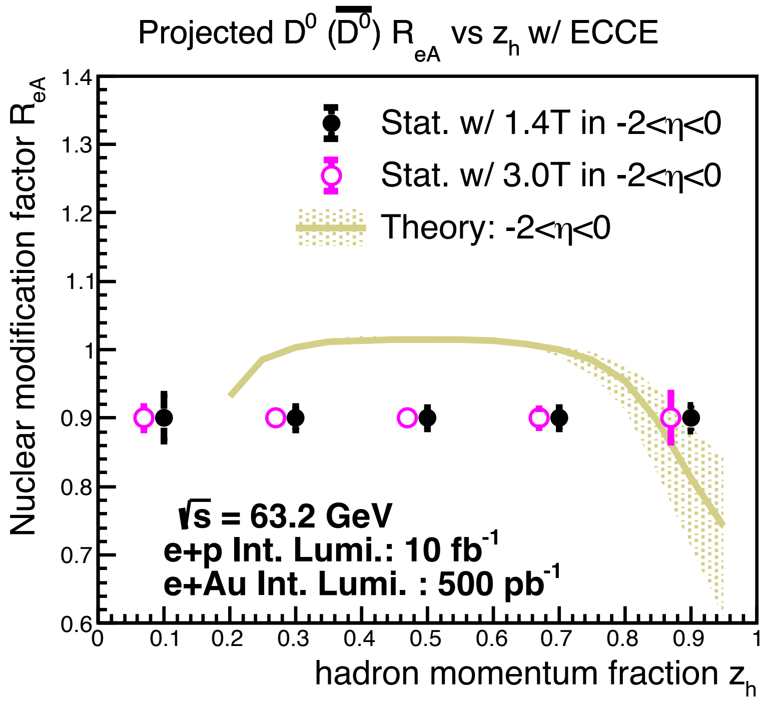
- Compared to heavy ion measurements, better signal over background ratios can be achieved by reconstructed D^0 ($\overline{D^0}$) mesons at the future EIC over a wide pseudorapidity region.

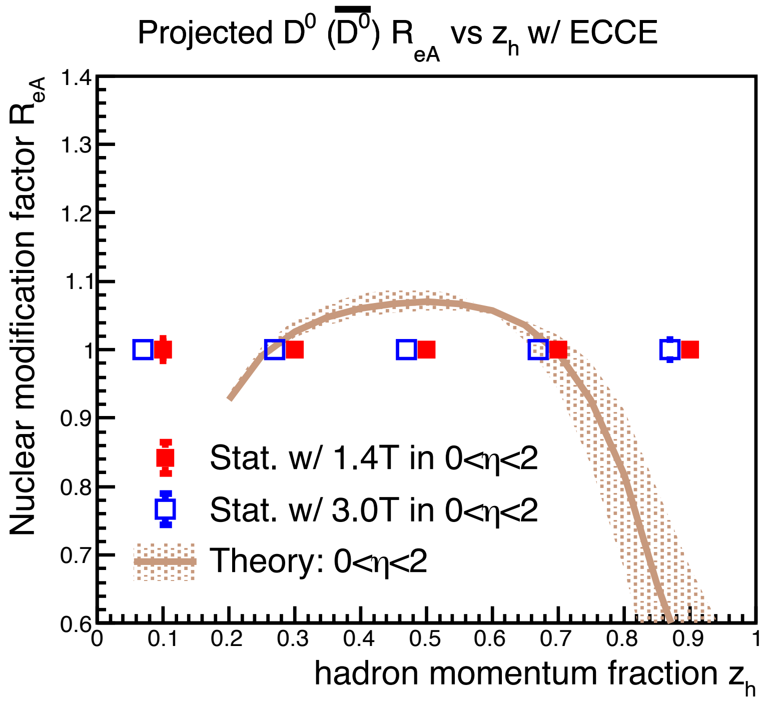
Pseudorapidity dependent HF nuclear modification factor projections (II)

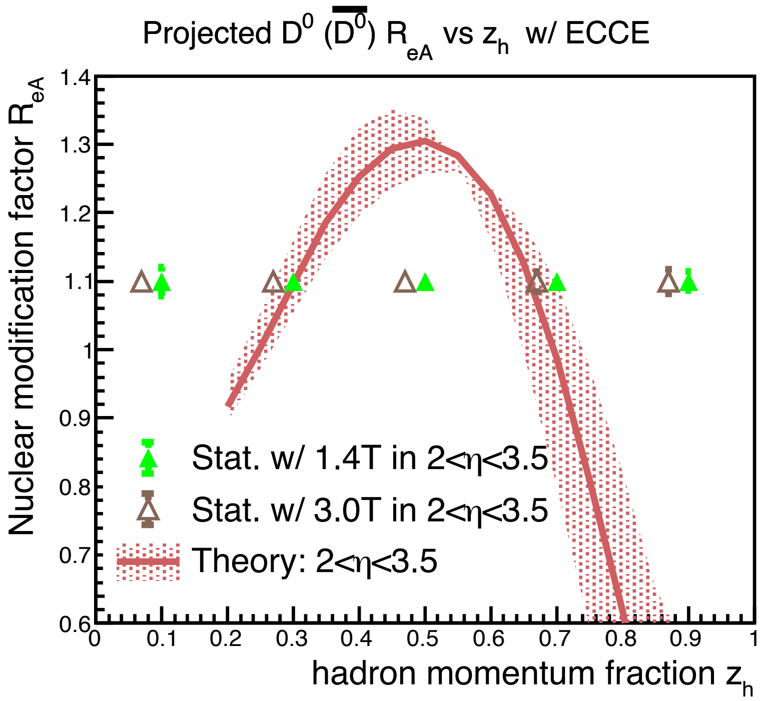
Nuclear modification factor:

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

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







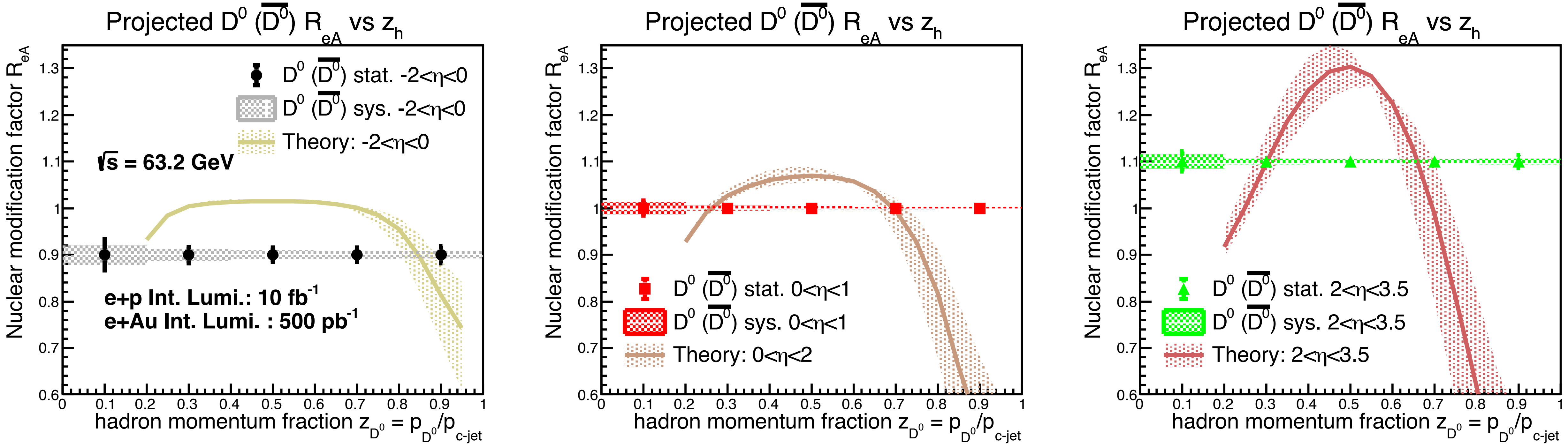
- Good statistical uncertainties can be provided by both the 1.4T and 3.0T magnetic fields to constrain the theoretical predications especially in the high hadron momentum fraction region.

Pseudorapidity dependent HF nuclear modification factor projections (II)

Nuclear modification factor:

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

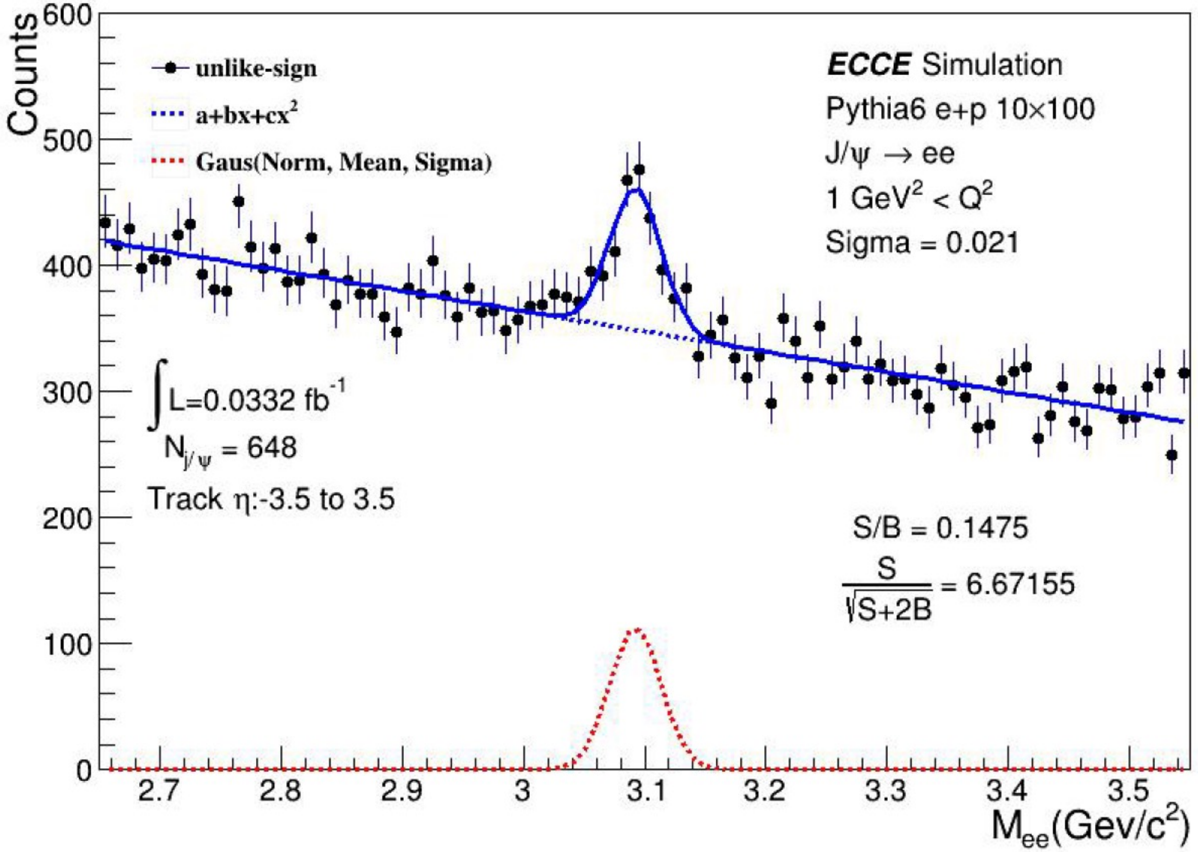
Theoretical calculations with projections normalized by inclusive production: H. T. Li, Z. L. Liu and I, Vitev, Phys. Lett. B 816 (2021) 136261.



- Good 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.

Quarkonia studies at ECCE (inclusive J/ψ reconstruction)

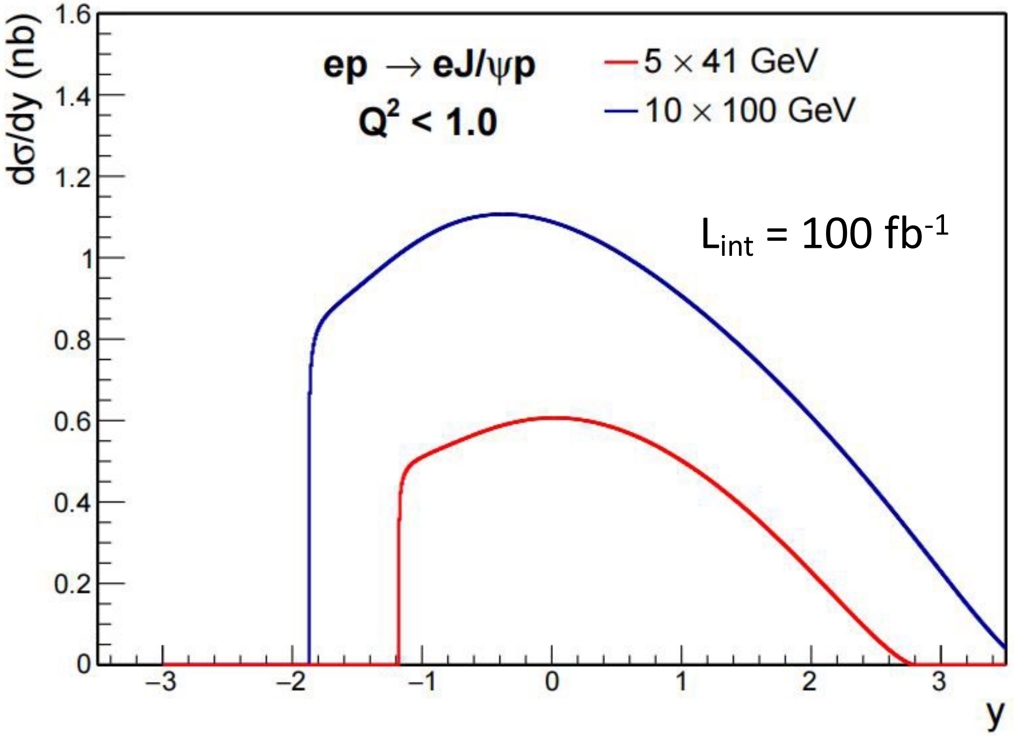
- Clear reconstructed J/$\psi \rightarrow e^+e^-$ signals have been found in the di-electron mass spectrum with the full ECCE detector performance in 10+100 e+p simulation.

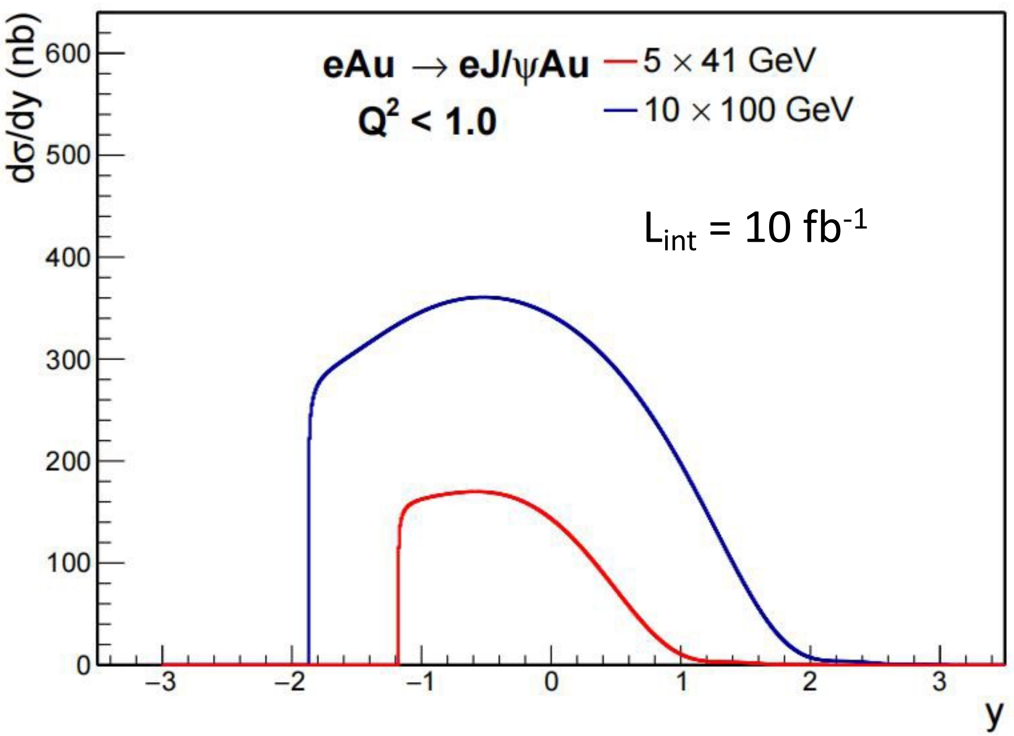


- Full ECCE tracking performance (-3.5<η<3.5).
- Assume 100% eID efficiency.
- With around 1 yr EIC operation (10 fb^{-1}), we expect to reconstructed around 200k J/ψ.
- The muon decay channel (J/$\psi \rightarrow \mu^+\mu^-$) is under study.

Quarkonia studies at ECCE (exclusive J/ψ cross section)

- Rapidity distribution of exclusive photoproduction J/ψ in 5×41 GeV and 10×100 GeV e+p and e+Au collisions with the eSTARLight simulation.

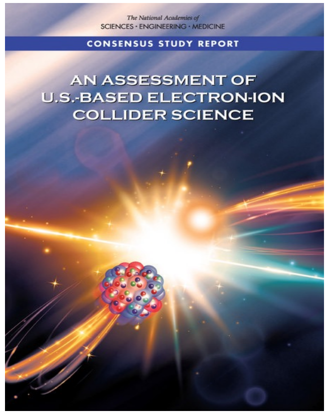




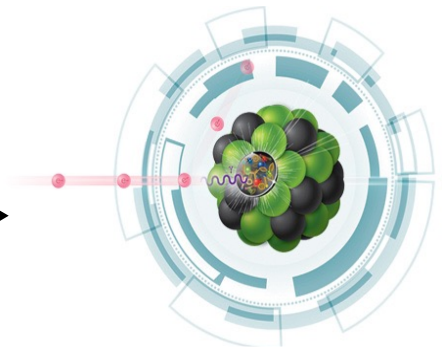
- A broad kinematic coverage can be accessed by the exclusive J/ψ measurements in e+p and e+Au collisions at different center of mass energies.

Summary and Outlook

- Good progresses and results have been achieved in the ECCE heavy flavor hadron/jet studies with detector performances evaluated in full simulation.
- Great precisions will be provided by future EIC heavy flavor measurements in exploring the hadronization process and initial nucleon/nucleus parton distribution functions in vacuum and nuclear medium within the poorly constrained kinematic regions.
- We look forward to work with more collaborators and contribute to the EIC realization.



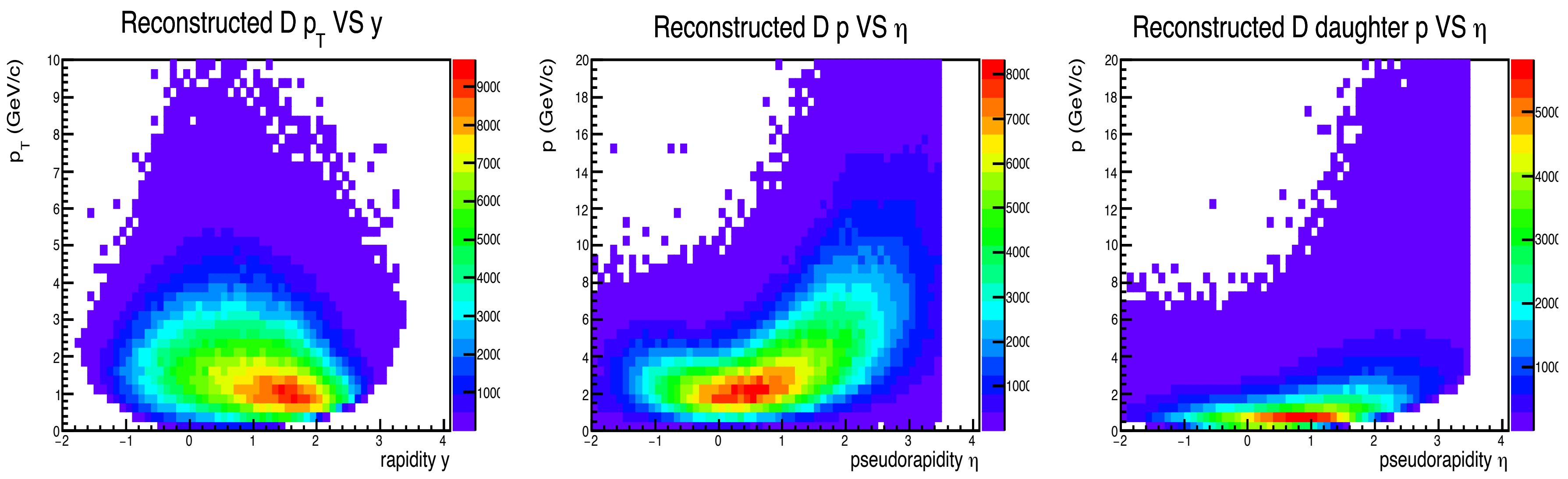
NAS review	EIC CD0	EIC CD1	EIC CD2	EIC CD3	EIC CD-4a	EIC CD-4
2018	2020	2021	2023	2024	2030	2033



Backup

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 (~10ns readout) capability allows the separation of different collisions and suppress the beam backgrounds.