Exploration of hadronization through heavy flavor studies at the future Electron-Ion Collider

Xuan Li (xuanli@lanl.gov)

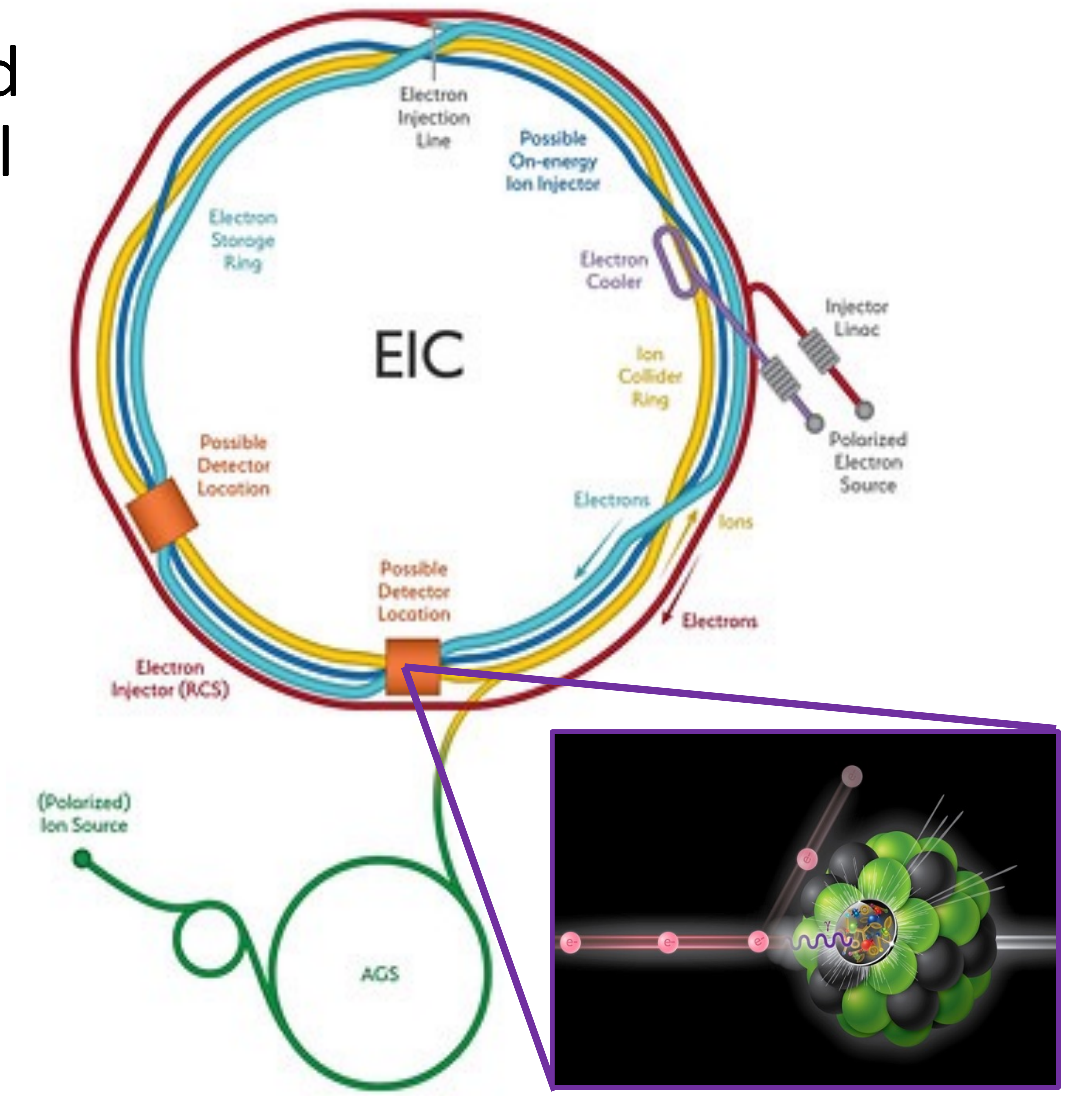
Physics division, Los Alamos National Laboratory

Outline

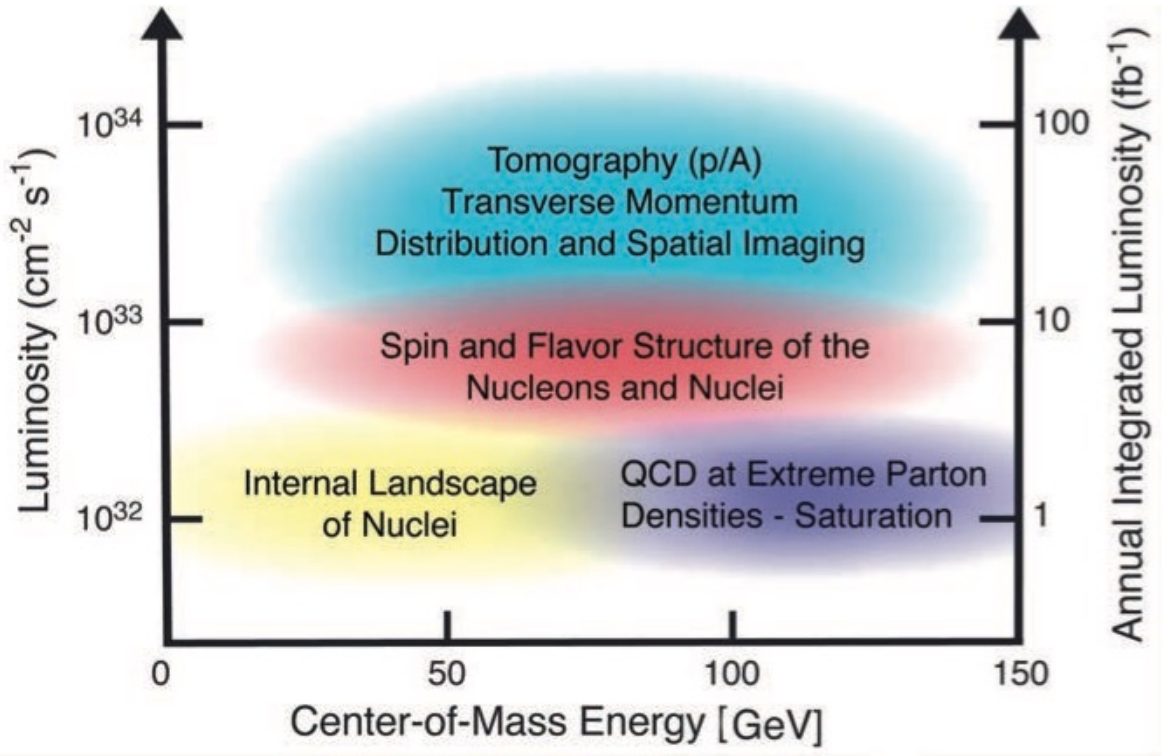
- Motivation
- Heavy flavor probes at the Electron-Ion Collider (EIC).
- Physics projection in exploring the heavy quark hadronization.
- Summary and Outlook.

Introduction to the future Electron-Ion Collider (EIC)

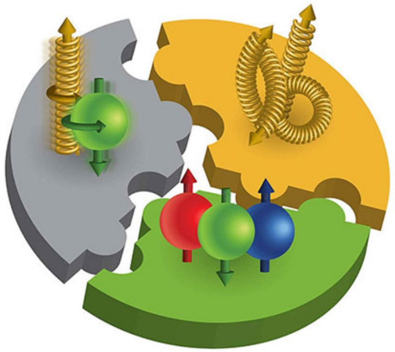
- The future Electron-Ion Collider (EIC) will utilize high-luminosity high-energy e+p and e+A collisions to solve several fundamental questions in the nuclear physics field.
- The EIC project has received CD1 approval from the US DOE in 2021 and will be built at BNL.
- The future EIC will operate:
  - (Polarized) p and nucleus (A=2 to 207) 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.



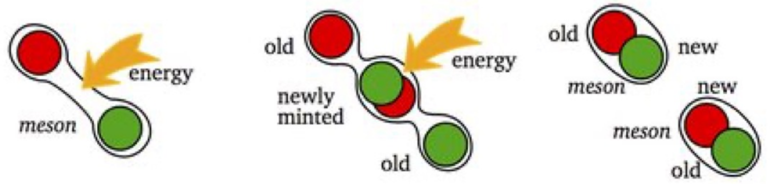
- With a series of e+p and e+A collisions at different center of mass energies and luminosities, the future EIC will
  - precisely study the nucleon/nuclei 3D structure.
  - help address the proton spin puzzle.
  - probe the nucleon/nuclei parton density extreme – gluon saturation.
  - explore how quarks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



Proton spin crisis



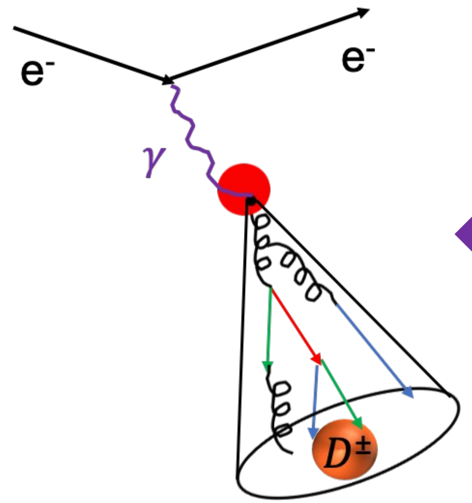
Quark confinement



Heavy flavor measurements can enrich the EIC physics program

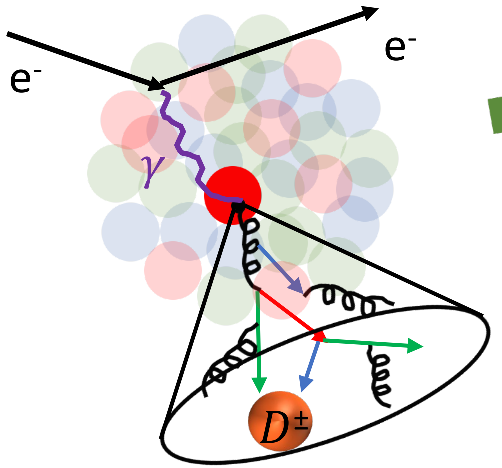
- Heavy flavor hadron and jet measurements at the future EIC can help study its science focuses and play a significant role in exploring
  - Nuclear modification on the initial nuclear Parton Distribution Functions (nPDFs) especially in the high and low Bjorken-x (x_{BJ}) region.
  - Final state parton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

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

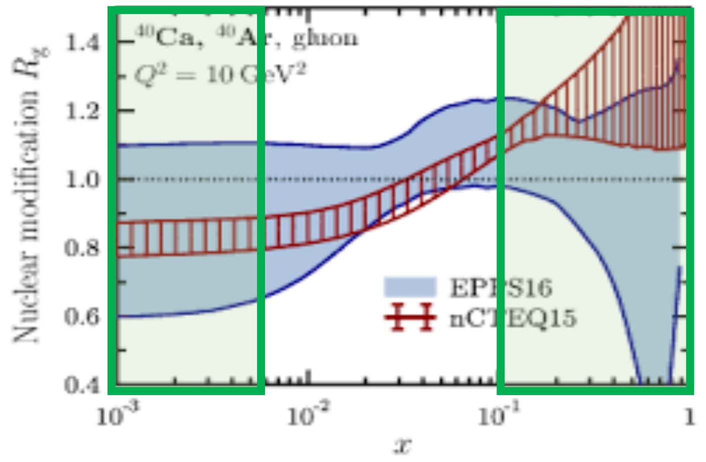


Compare

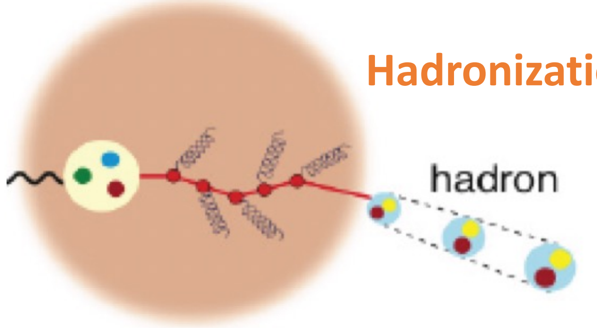
$e^- + \mathrm{Au} \rightarrow e^- + jet(D^\pm) + X$



nPDF modification

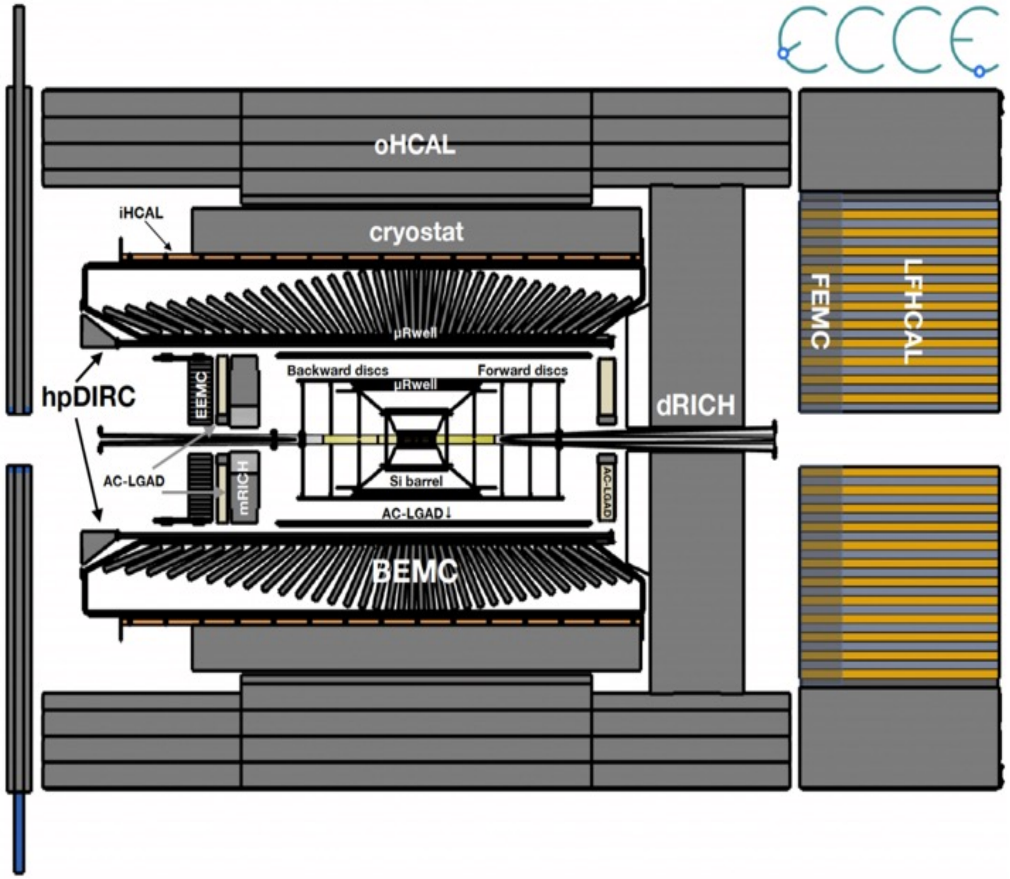


Hadronization

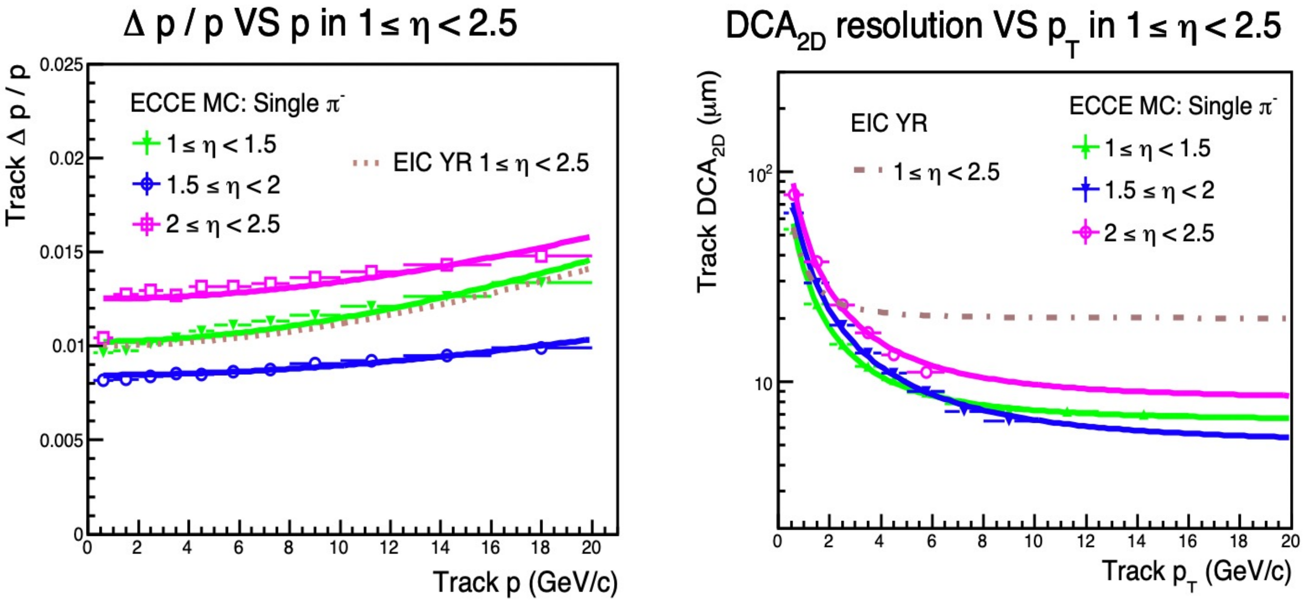


Reference design of the EIC project detector

- The EIC project detector reference design consists of Tracking, Particle ID, EM Calorimeter and Hadronic Calorimeter subsystems. It utilizes the existing Babar magnet (1.4T).



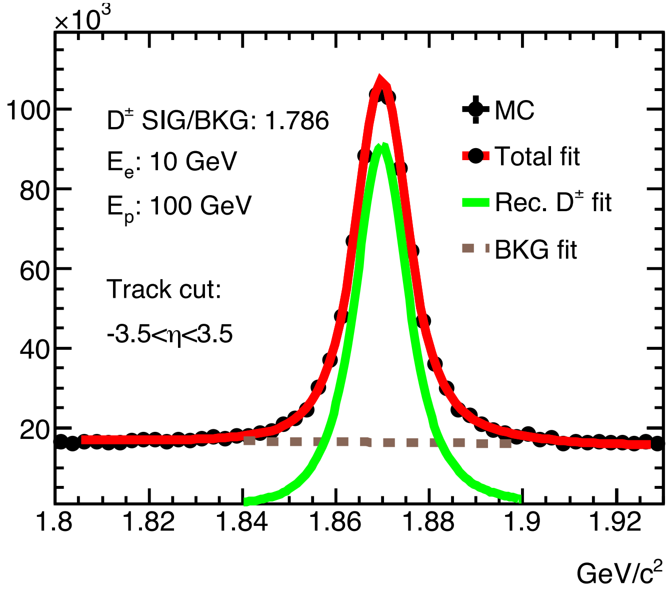
Tracking performance of the EIC detector reference design

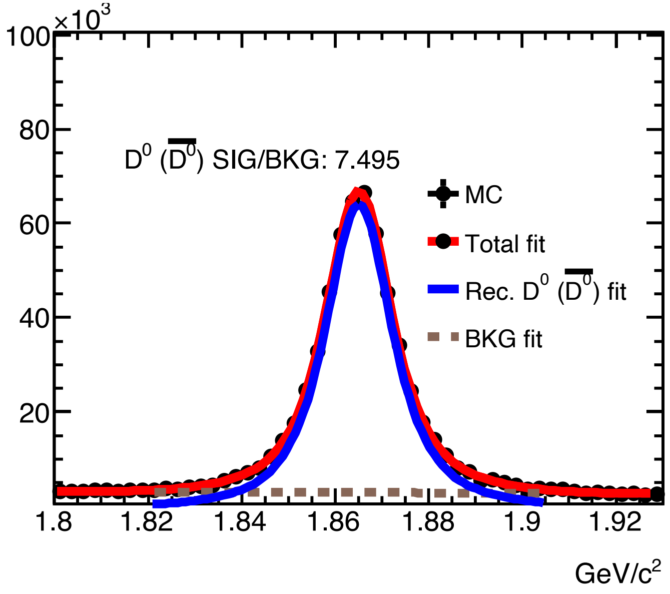


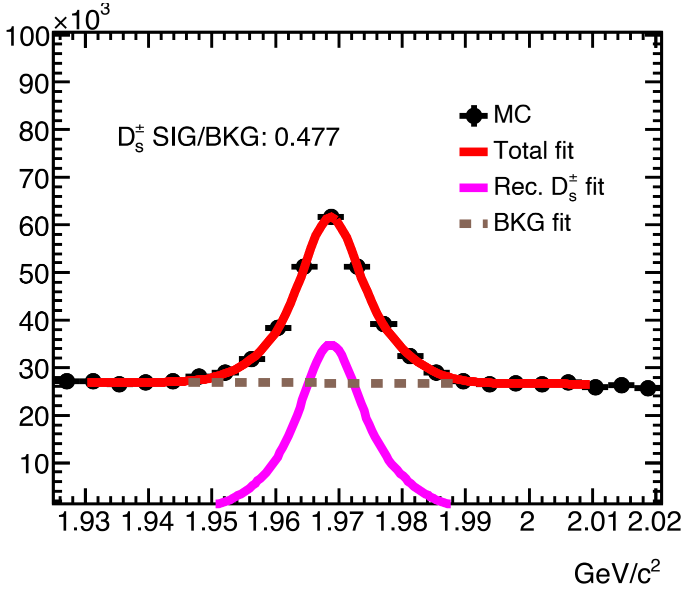
- Move towards the technical design for the EIC project detector by the EPIC collaboration.

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

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



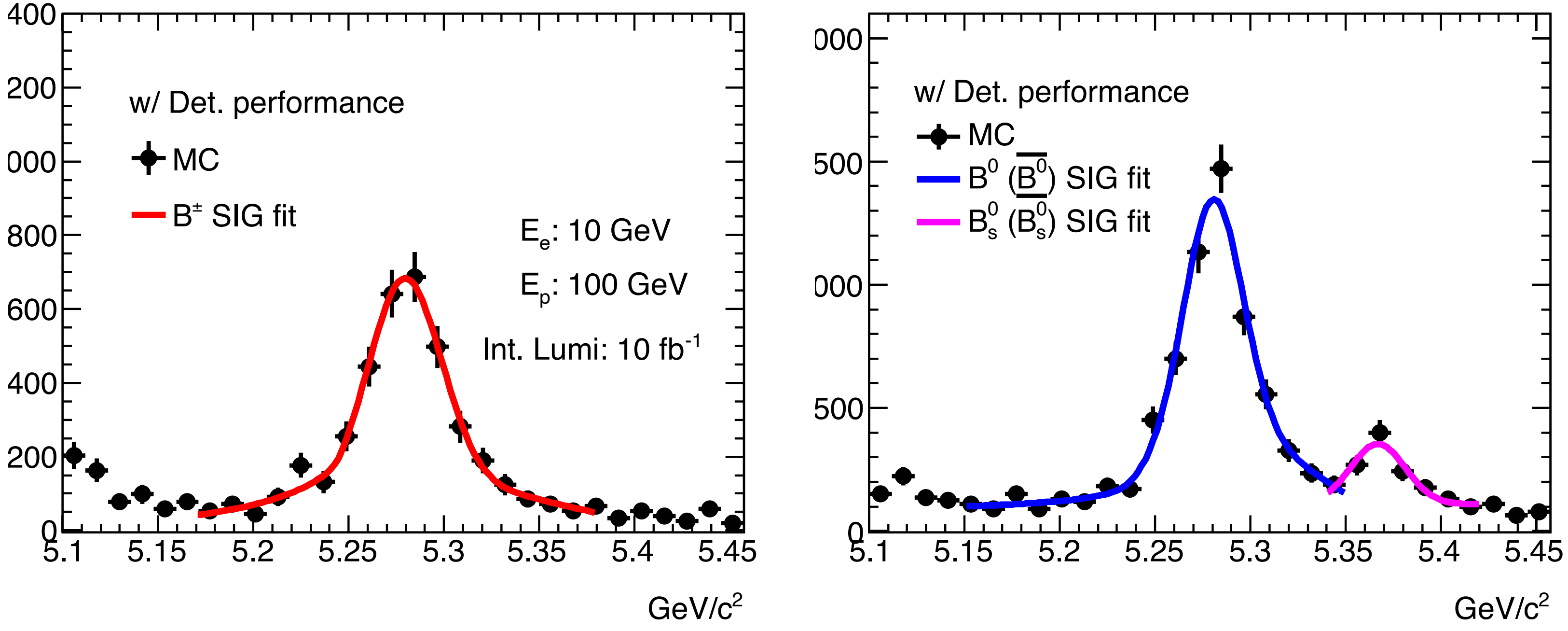




DCA_{2D} matching and angular cuts to suppress the background

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

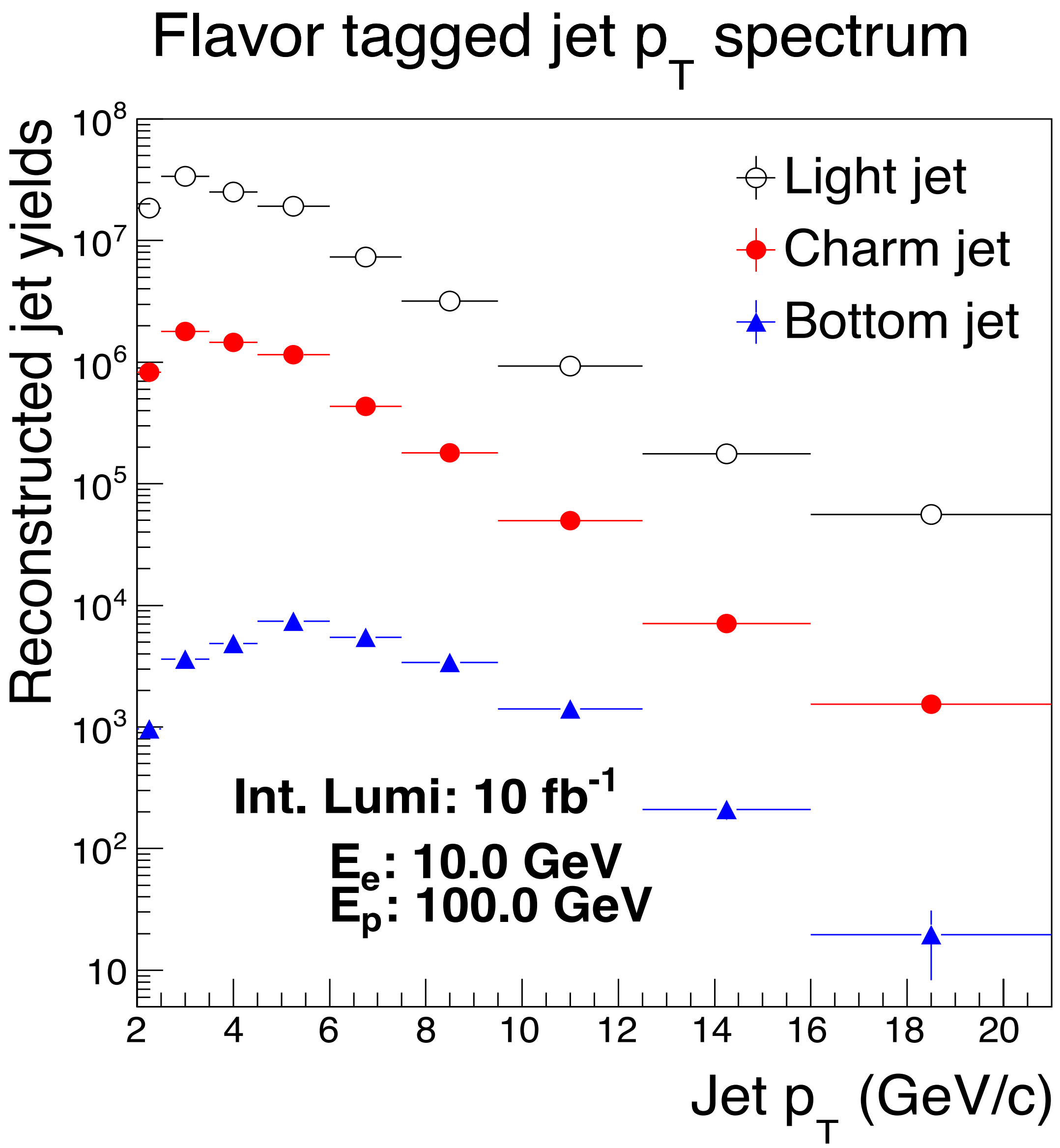
- The full analysis framework which includes the EIC beam angle in event generation (PYTHIA), EIC detector response in GEANT4 simulation, beam remnant & QCD background, and hadron reconstruction algorithm have been setup.
- Mass distributions of reconstructed bottom hadrons using the EIC detector reference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



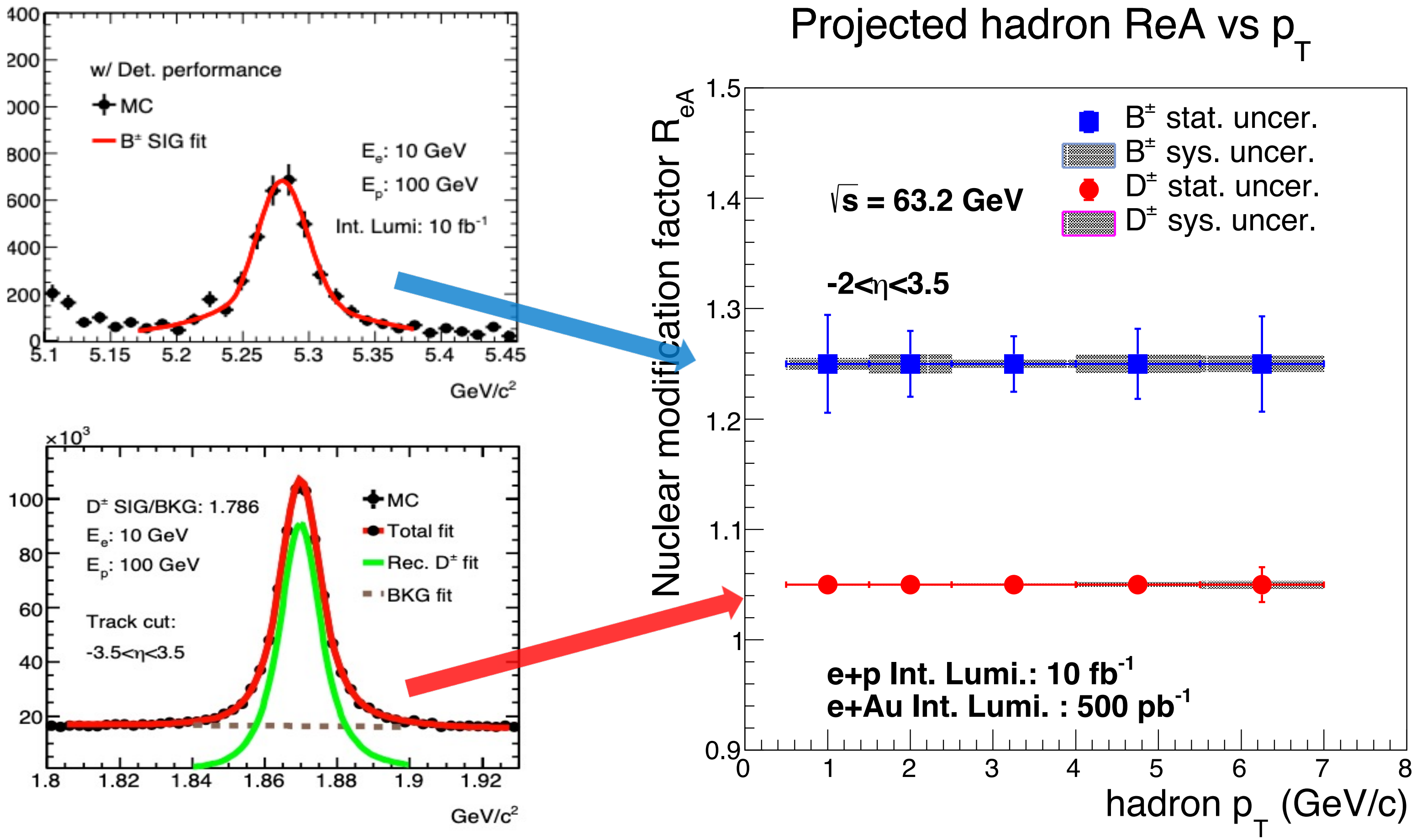
DCA$_{2D}$ matching and angular cuts to suppress the background

Reconstructed heavy flavor jets in e+p simulation

- Heavy flavor jets can be treated as surrogates of the produced heavy quarks.
- P_T spectrum of reconstructed light and heavy flavor jets with the EIC reference detector response in simulation in 10 GeV electron and 100 GeV proton collisions with 10 fb^{-1} integrated luminosity.
- Jet reconstruction: Anti-k_T algorithm with the jet cone radius at 1.0.
- Tagging charm-jets (bottom-jets) with the associated heavy flavor decay 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 detector geometries and corresponding performances.
- Different selection cuts.
- Jet cone radius selection.

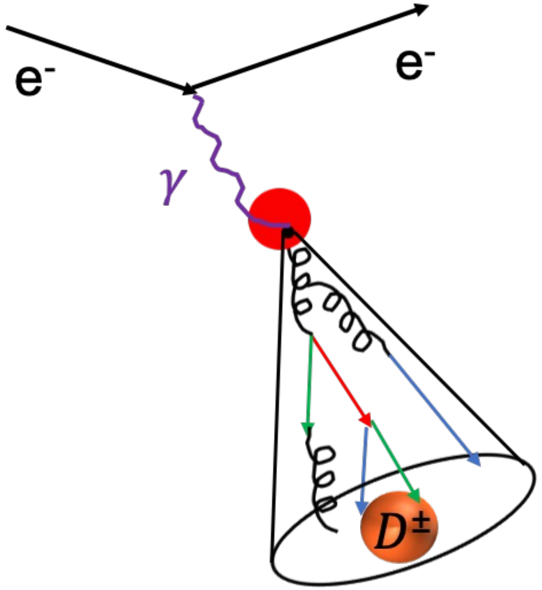
- Good precision can be provided by future EIC reconstructed heavy flavor hadron measurements within the low p_T region to explore the hadronization process in nuclear medium.

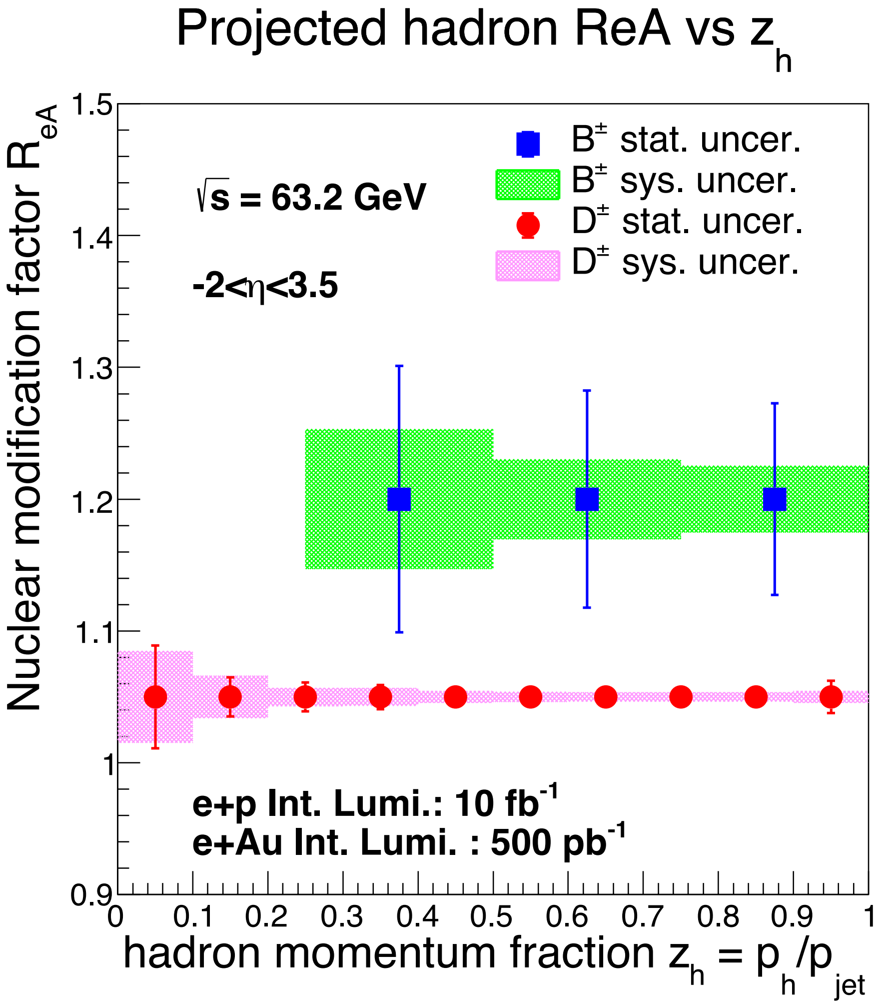
Flavor dependent nuclear modification factor projections (II)

Nuclear modification factor:

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

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





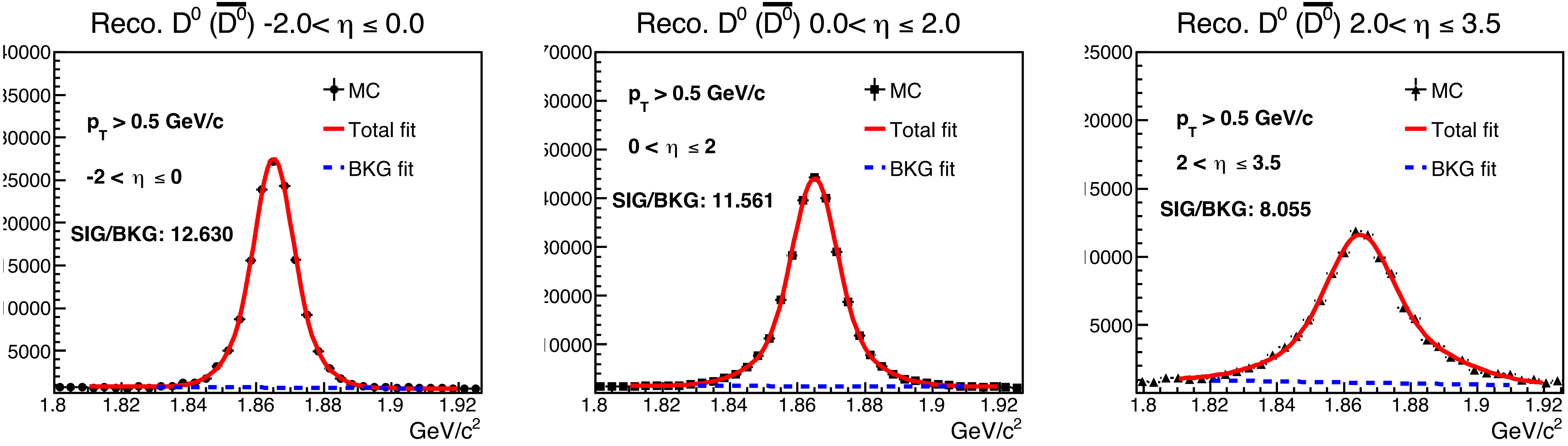
Systematic uncertainty:

- Different detector geometries and corresponding performances.
- Different selection cuts.
- 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 ($\overline{D^0}$) meson reconstruction

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



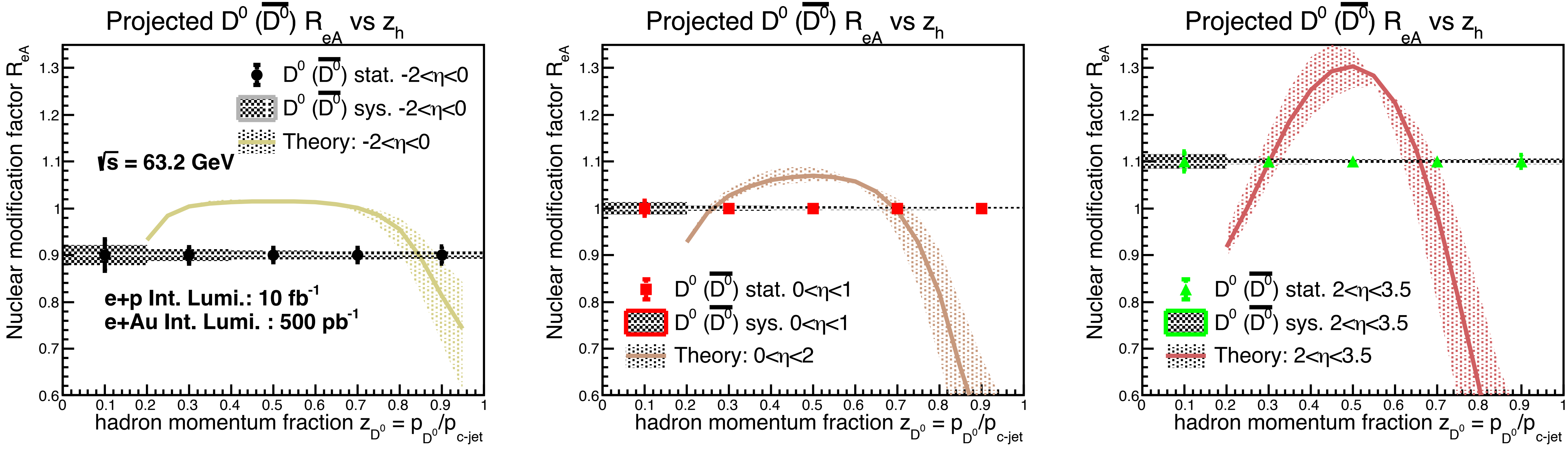
- Compared to heavy ion measurements, better signal over background ratios can be achieved by reconstructed D^0 ($\overline{D^0}$) mesons at the future EIC over a wide pseudorapidity region.

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.

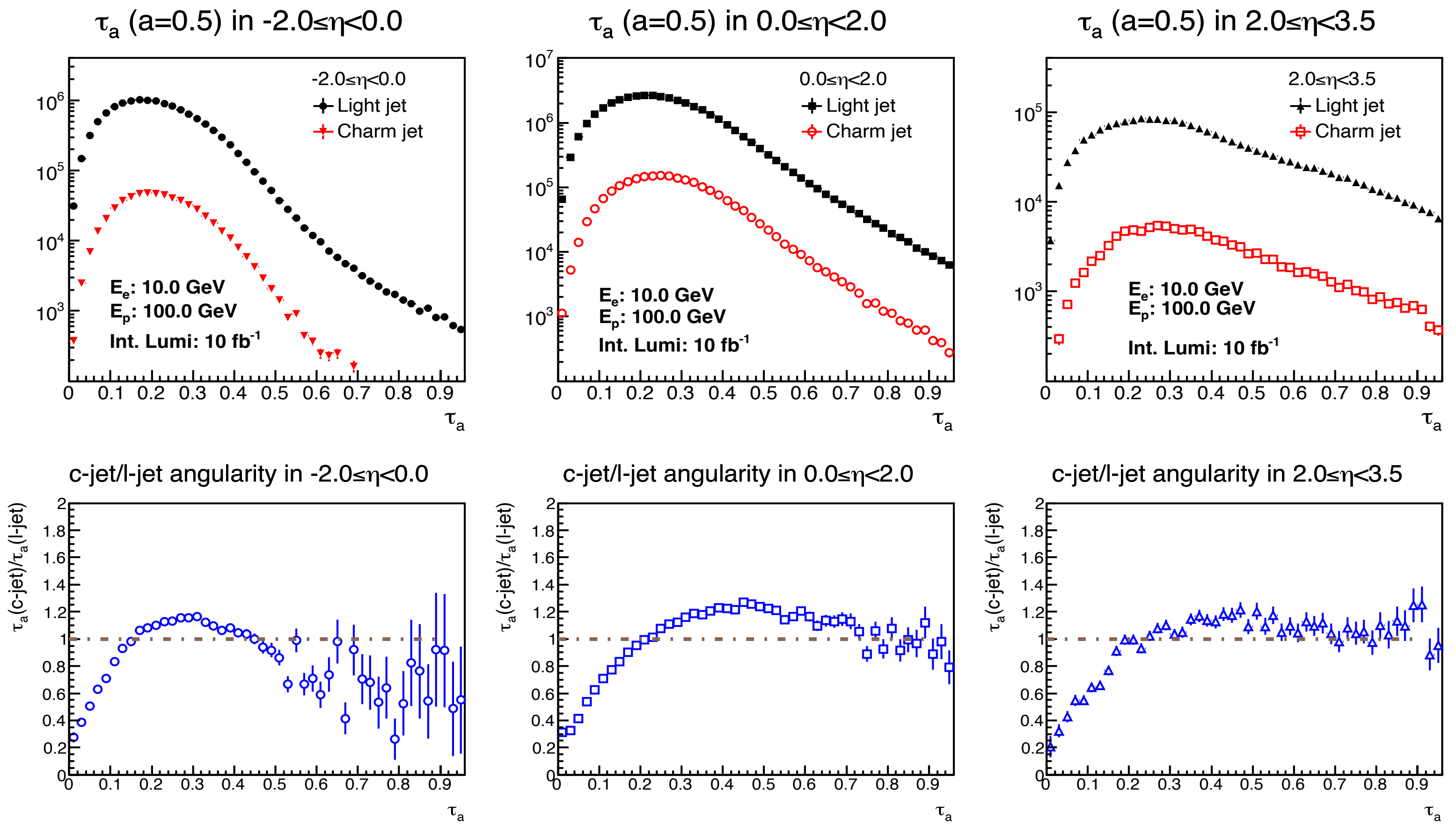


- Good discriminating power in separating different model calculations on the heavy flavor production in a nuclear medium can be provided by future EIC heavy flavor measurements over a wide pseudorapidity region.

A different approach to study the hadronization: jet substructure

- Jet substructure observables are good probes to study the hadron/jet dynamic dependent hadronization process.

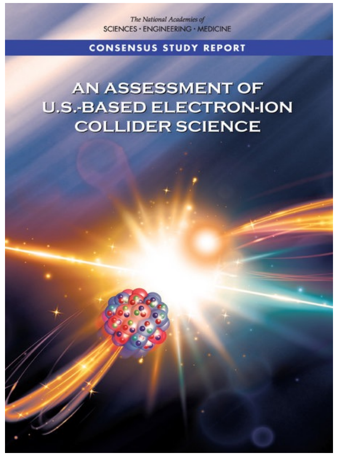
E.g., jet angularity: $\tau_a \equiv \tau_a^{pp} \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta \mathcal{R}_{iJ}\right)^{2-a}$ JHEP 1804 (2018) 110



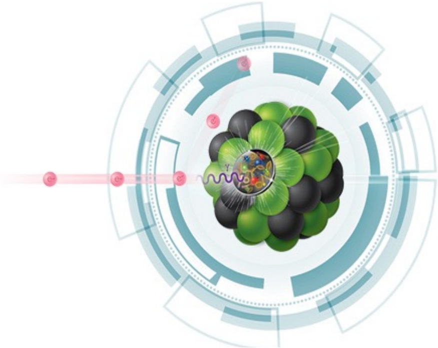
- The charm/light jet angularity shape difference depends on the pseudorapdy.
- Shed light onto how quarks/gluons fragment into final hadrons with different masses.
- Impacts by nuclear medium effects will be studied in e+A collisions.

Summary and Outlook

- Great progresses have been achieved for the EIC detector and physics developments.
- The proposed EIC heavy flavor hadron and jet measurements will significantly improve the knowledge about the fragmentation process in vacuum and nuclear medium in the little constrained kinematic region.
- As we are moving towards the EIC CD2/3A approval, we look forward to work with more collaborators for the EIC detector/experiment realization.



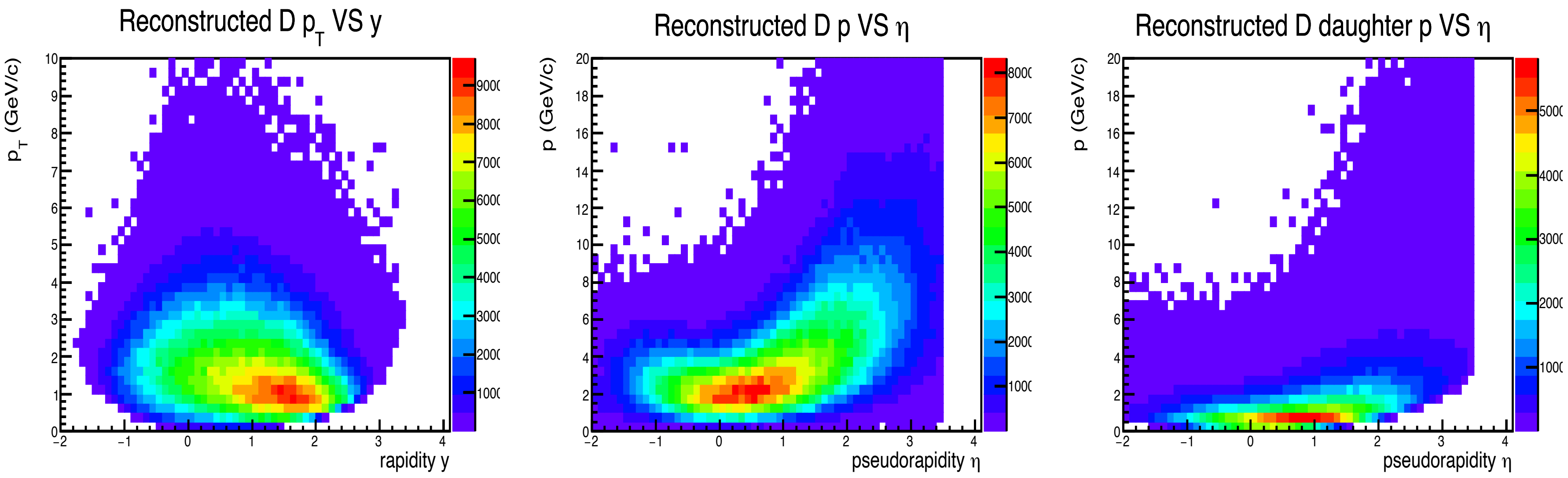
NAS review	EIC CD0	EIC CD1	EIC CD2/3A	EIC CD3	EIC CD-4a	EIC CD-4
2018	2020	2021	2024	2025	2032	2034



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.

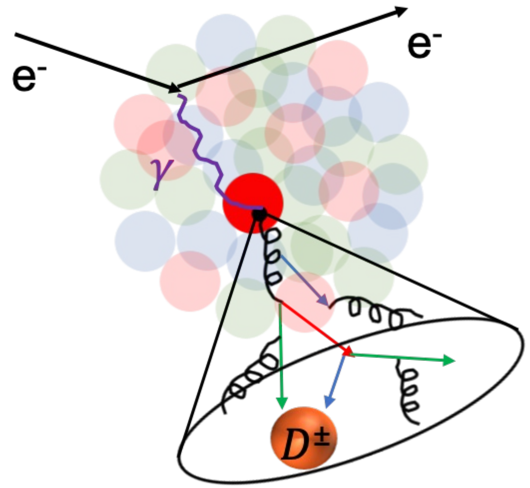


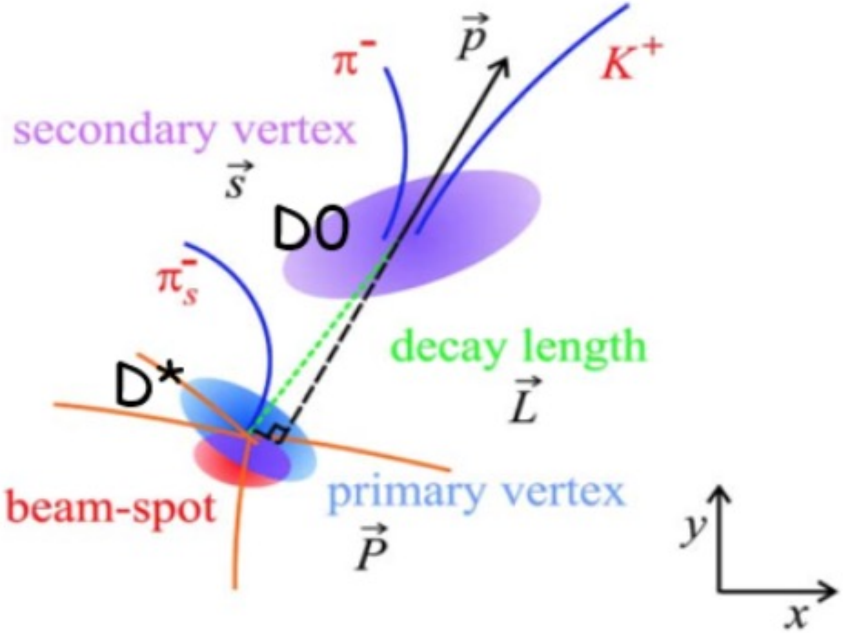
- Fast timing (1-10ns readout) capability allows the separation of different collisions and suppress the beam backgrounds.

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/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

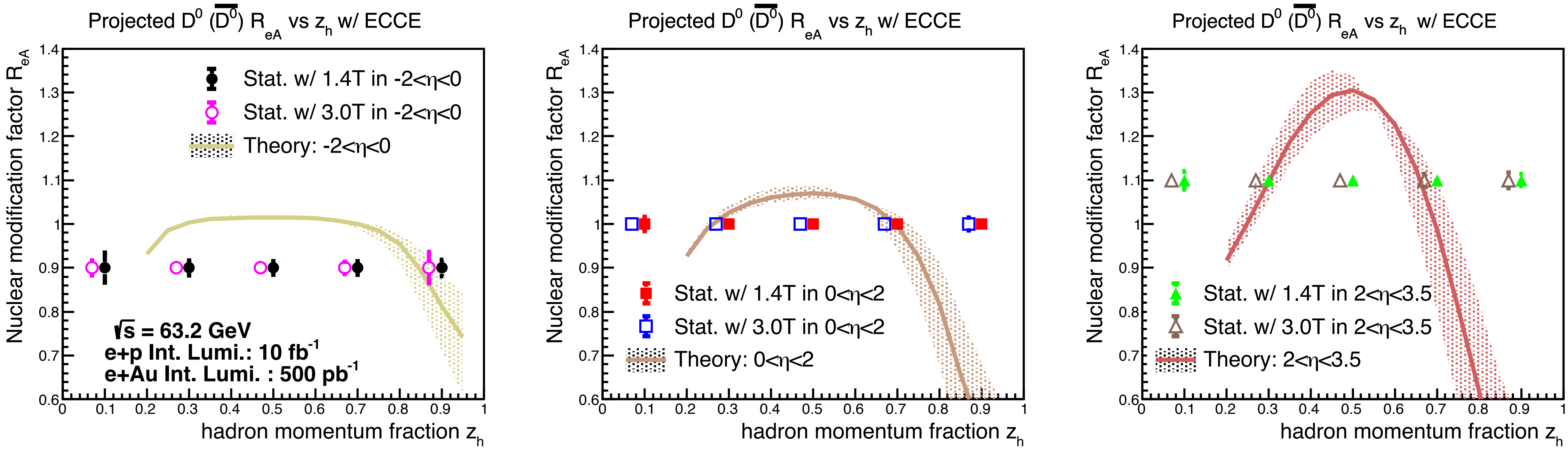
- Heavy flavor physics-driven detector performance requirements:
  - Fine spatial resolution (<100 μm) for displaced vertex reconstruction.
  - Fast timing resolution to suppress backgrounds from neighboring e+p/A collisions.
  - Low material budgets to maintain fine hit resolution.

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.