

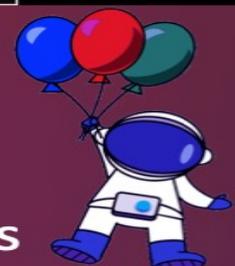
Exploration of hadronization through heavy flavor production at the future Electron-Ion Collider

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Quark Matter 2023



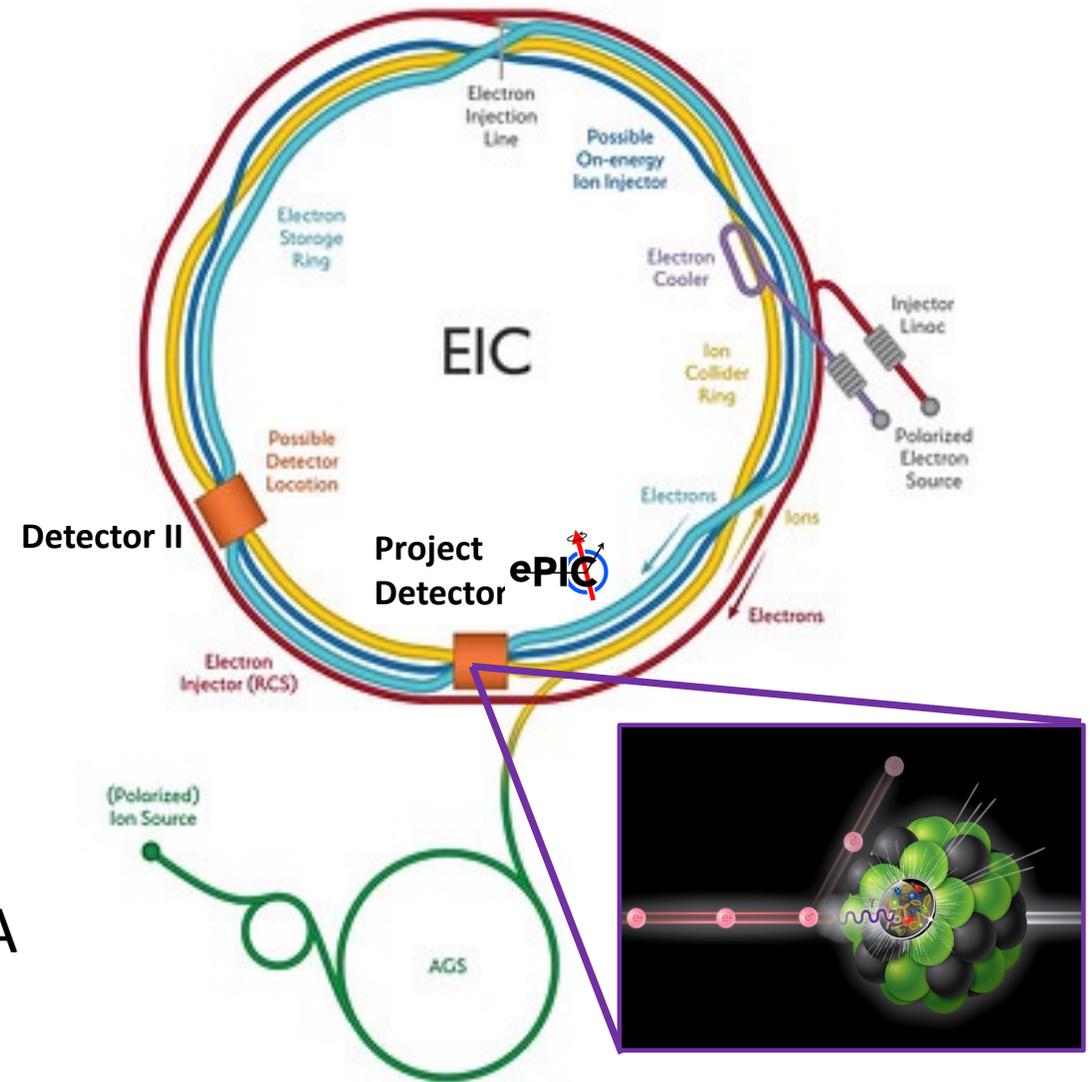
The 30th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions

Outline

- Introduction and motivation
- Heavy flavor hadron and jet reconstruction in simulation for the Electron-Ion Collider (EIC).
- Heavy flavor hadron, jet and correlation physics studies to explore the hadronization process at the EIC.
- Summary and Outlook.

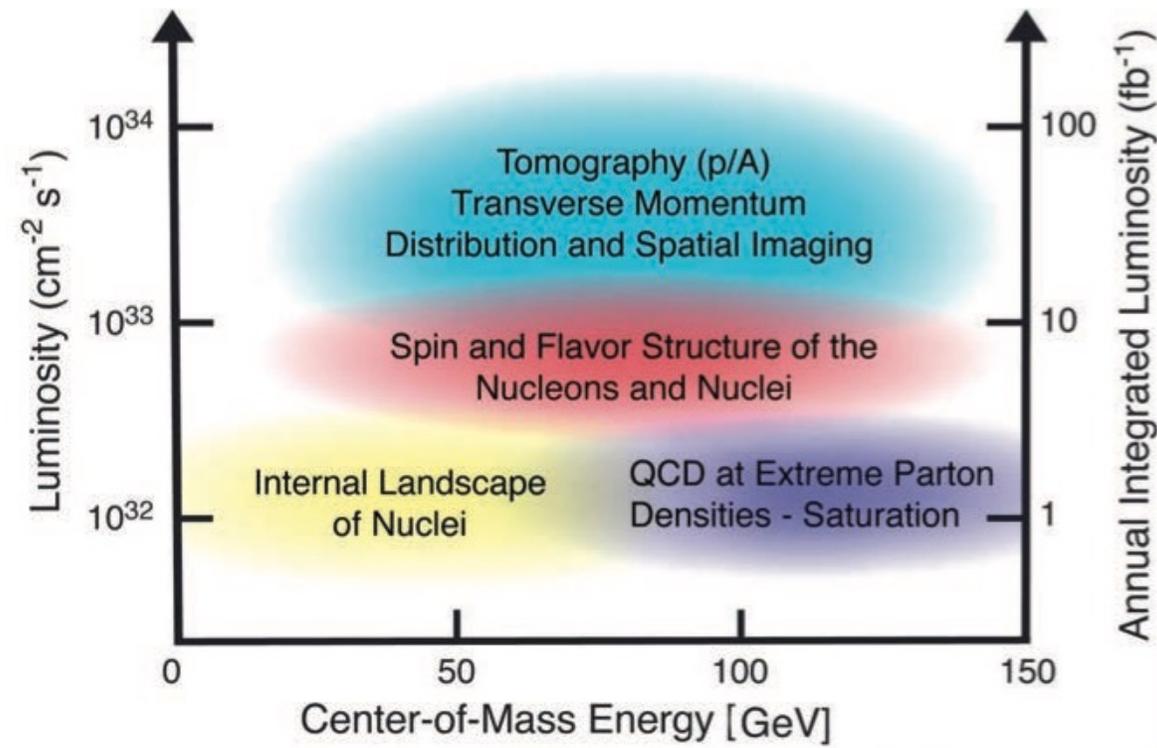
Introduction to the future Electron-Ion Collider (EIC)

- 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.
- This project has received CD1 approval from the US DOE in 2021 and will be built at BNL.
- The future EIC will operate:
 - (Polarized) p beam at 41-275 GeV and nucleus (A=2 to 238) beam at Z/A E_p.
 - (Polarized) e beam at 2.5-18 GeV.
 - Instant luminosity $L_{\text{int}} \sim 10^{33-34} \text{ cm}^{-2}\text{sec}^{-1}$. A factor of ~ 1000 higher than HERA.
 - Bunch crossing rate: $\sim 10 \text{ ns}$.

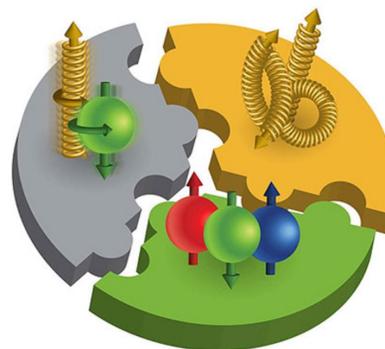


The science objectives of the Electron-Ion Collider (EIC)

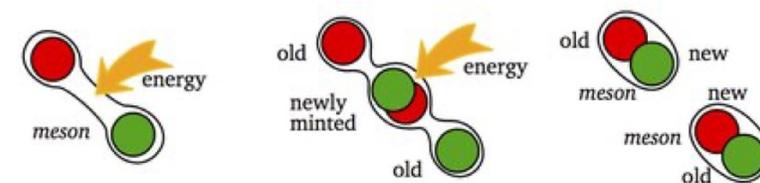
- With a series of e+p and e+A (A=2 to 238) collisions at different center of mass energies (20-141 GeV) and luminosities ($10^{33-34} \text{ cm}^{-2}\text{sec}^{-1}$), the future EIC will
 - precisely study the nucleon/nuclei 3D structure.
 - help address the proton spin puzzle.
 - probe the nucleon/nuclei 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



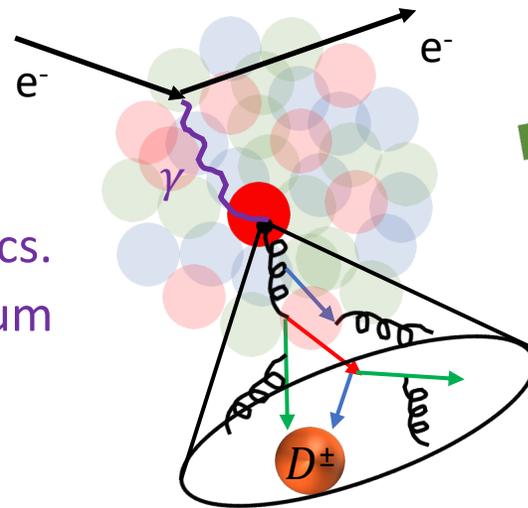
Heavy flavor measurements can enrich the EIC physics program

- Heavy flavor hadron and jet measurements are an important part of the EIC science portfolio 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 and hadronization processes under different nuclear medium conditions.

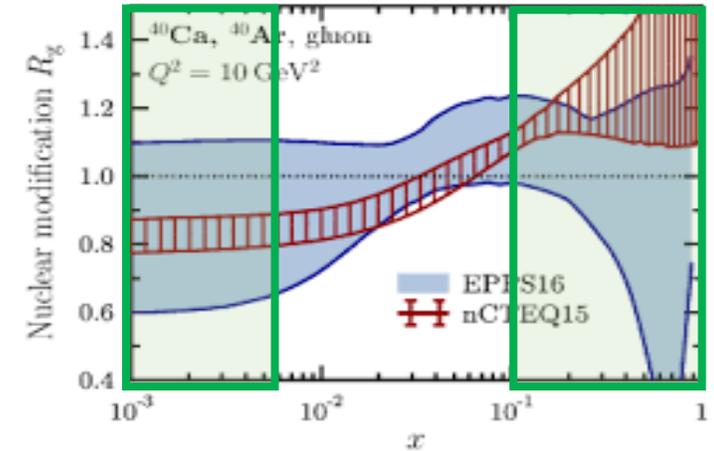
- **Uniqueness of the EIC measurements:**

- Precise determination of initial-state parton kinematics.
- Different cold nuclear medium conditions created in e+A collisions.

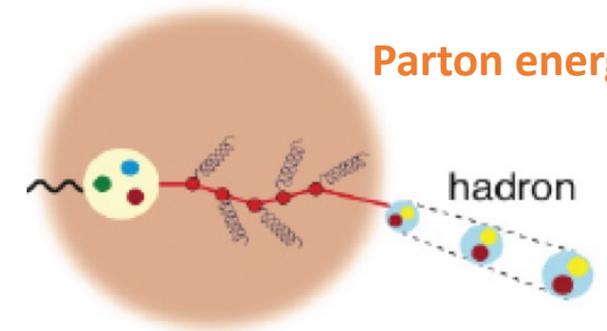
$$e^- + Au \rightarrow e^- + jet(D^\pm) + X$$



nPDF modification

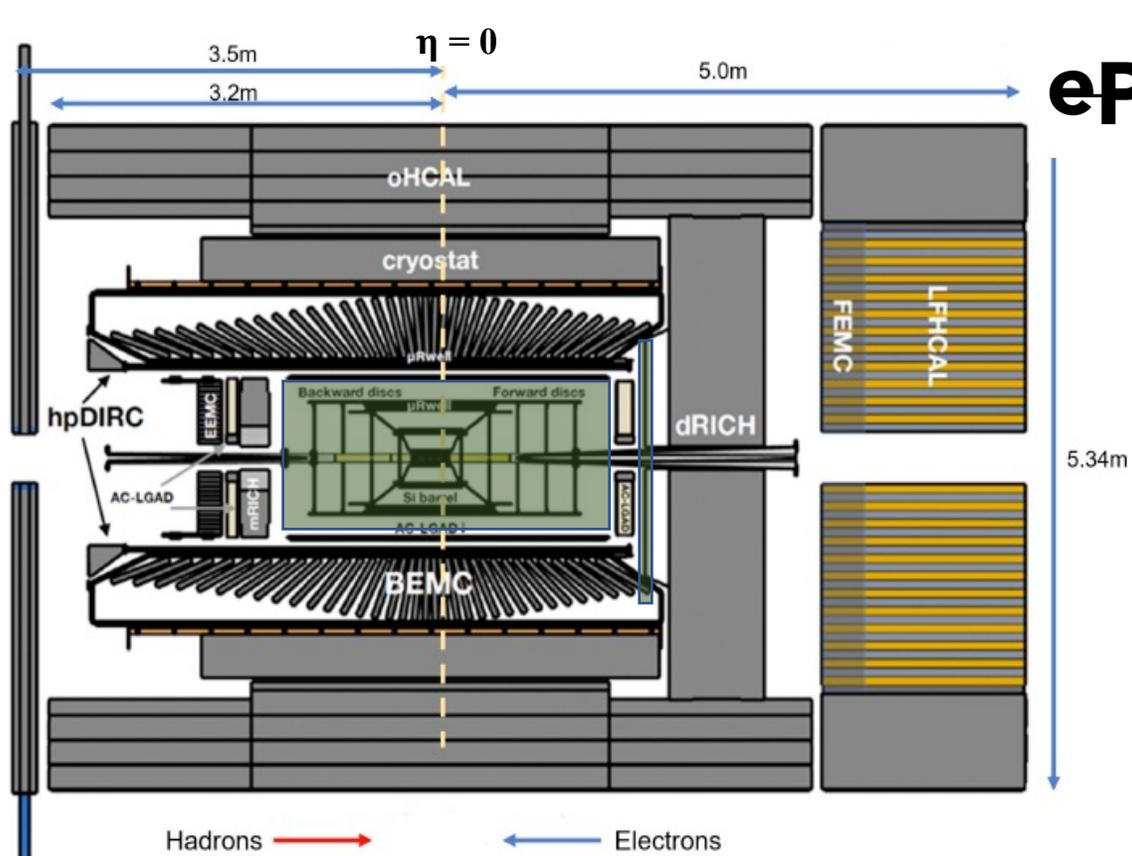


Parton energy loss

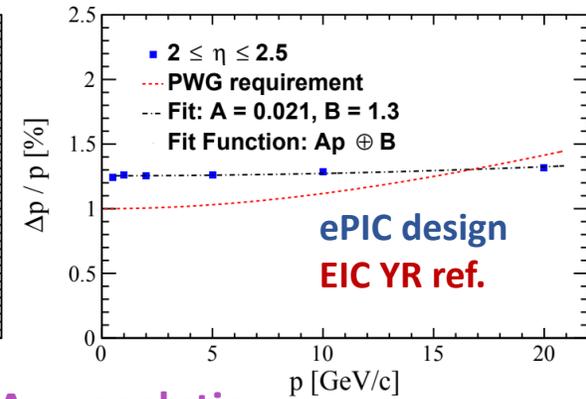
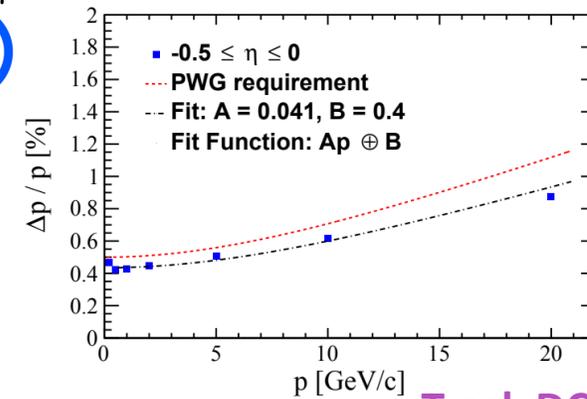


ePIC detector design and key performance for HF reconstruction

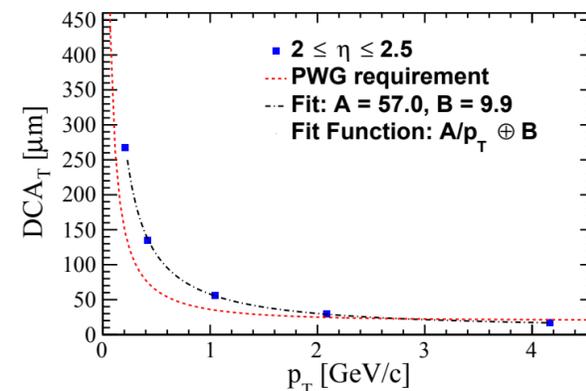
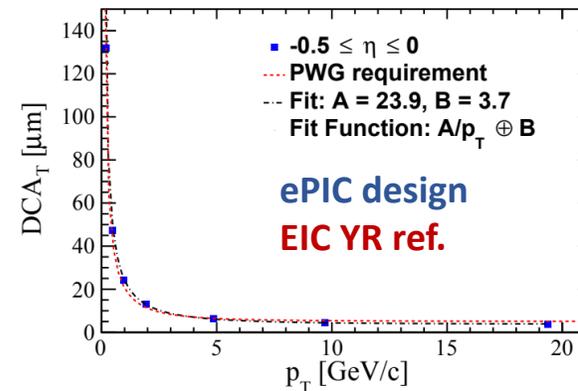
- The current EIC project detector design (ePIC), which consists of MAPS, MPGD and AC-LGAD tracking detectors, can achieve good momentum and transverse DCA_{2D} resolutions. The ePIC detector will utilize stream readout and can provide precise particle identification and energy determination for heavy flavor reconstruction.



Track momentum resolution

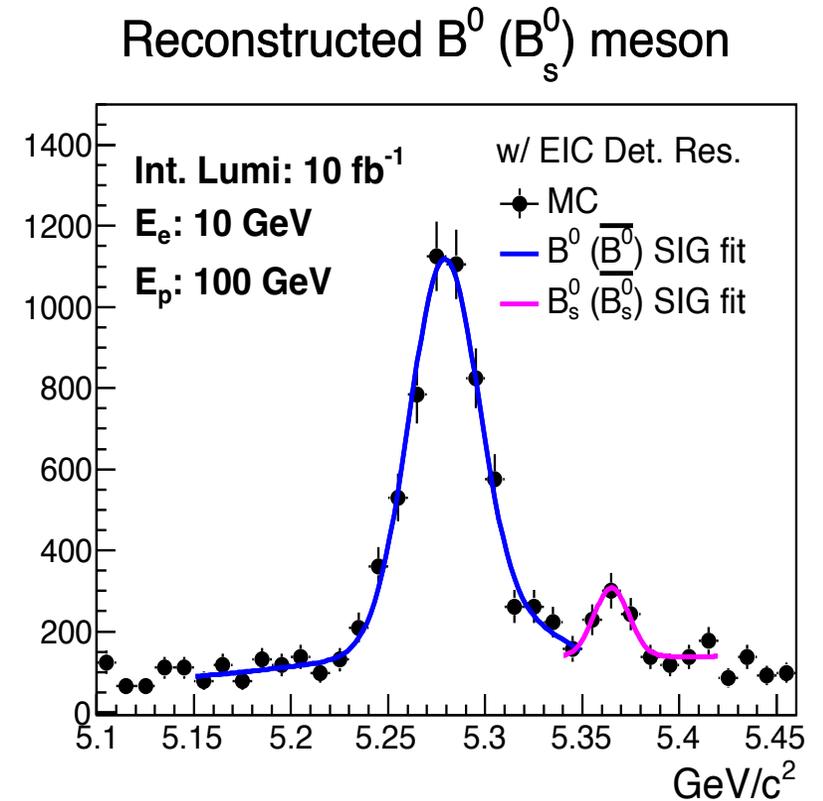
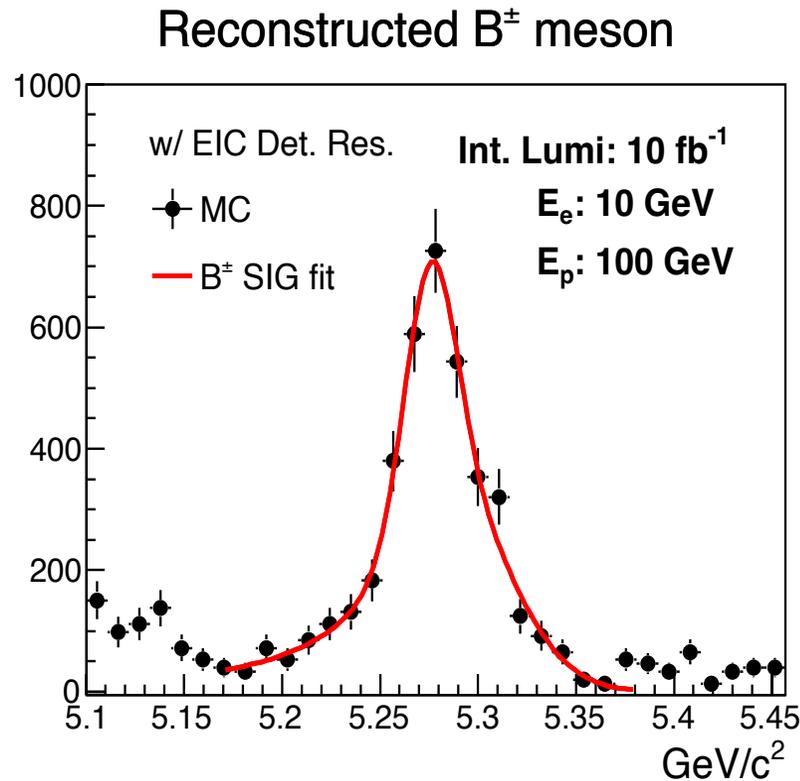
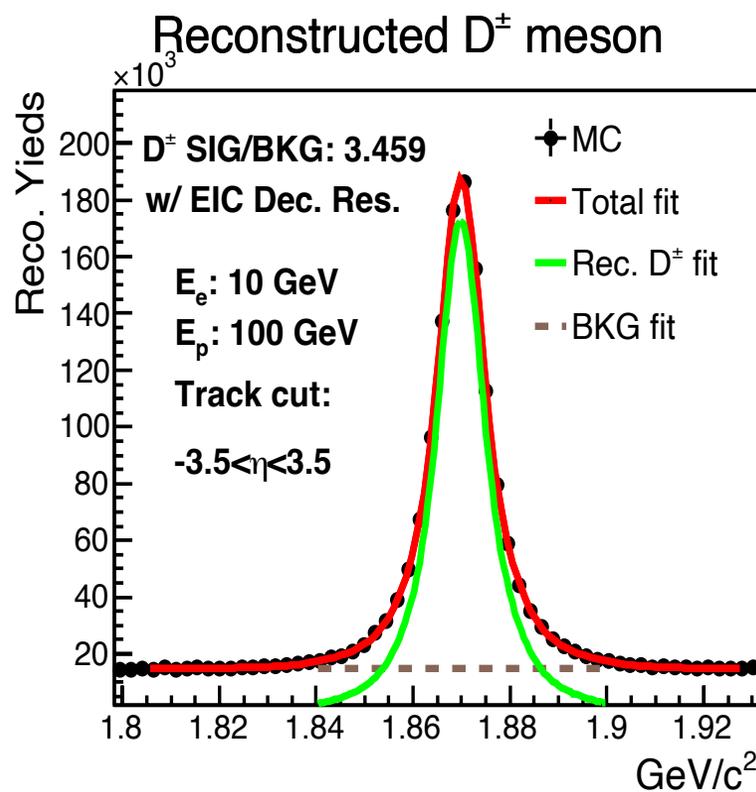


Track DCA_{2D} resolution



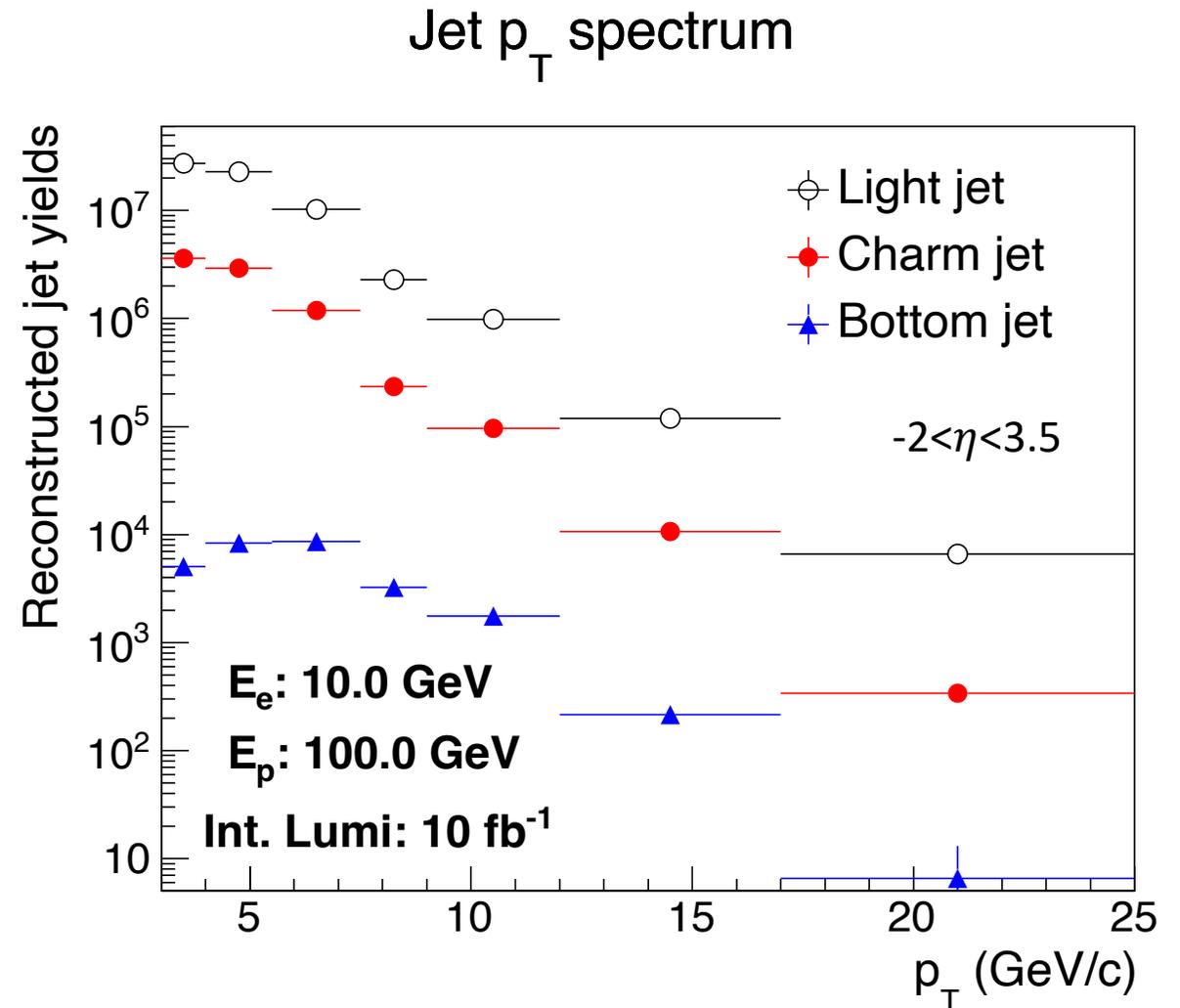
Reconstruction of open heavy flavor hadron in e+p simulation

- A variety of heavy flavor hadrons have been successfully reconstructed in simulation, which includes the event generation (PYTHIA), EIC ePIC detector performance evaluated in GEANT4 simulation, beam remnant & QCD background, and developed heavy flavor reconstruction algorithm.



Reconstructed heavy flavor jets in e+p simulation

- Jets are reconstructed with the anti- k_T algorithm and cone radius R is 1.0.
- Reconstructed jet yields with different flavors in simulation using the EIC detector performance in 10 GeV electron and 100 GeV proton collisions with 10 fb^{-1} integrated luminosity.
- **Charm-jets (bottom-jets)**, which are surrogates of the created heavy quarks, are tagged with the associated displaced vertex.
- Reconstructed jet yields are not corrected with the corresponding efficiency and purity yet.

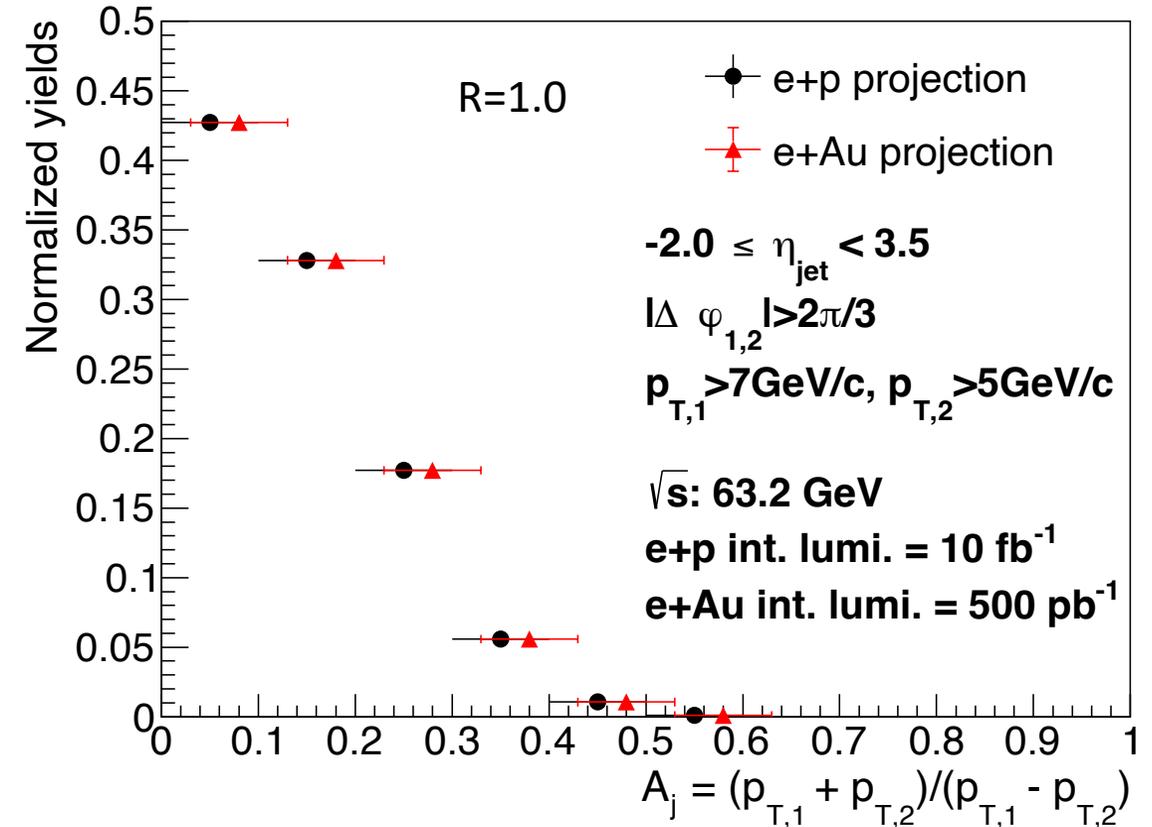
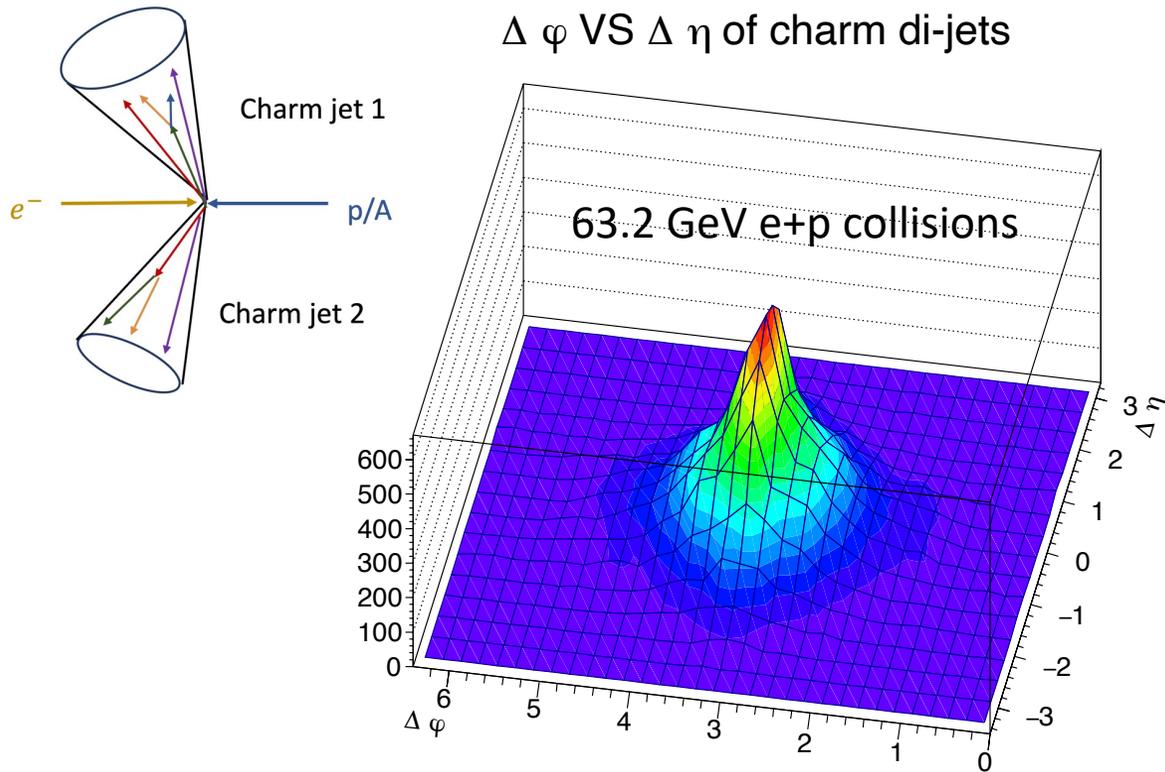


Most jets with $p_T < 15 \text{ GeV/c}$

Heavy flavor di-jet production at the EIC to study parton propagation

- Back-to-back heavy flavor di-jet measurements in e+p and e+A collisions can help constrain the gluon (or heavy quark) transport coefficient properties in cold nuclear medium.

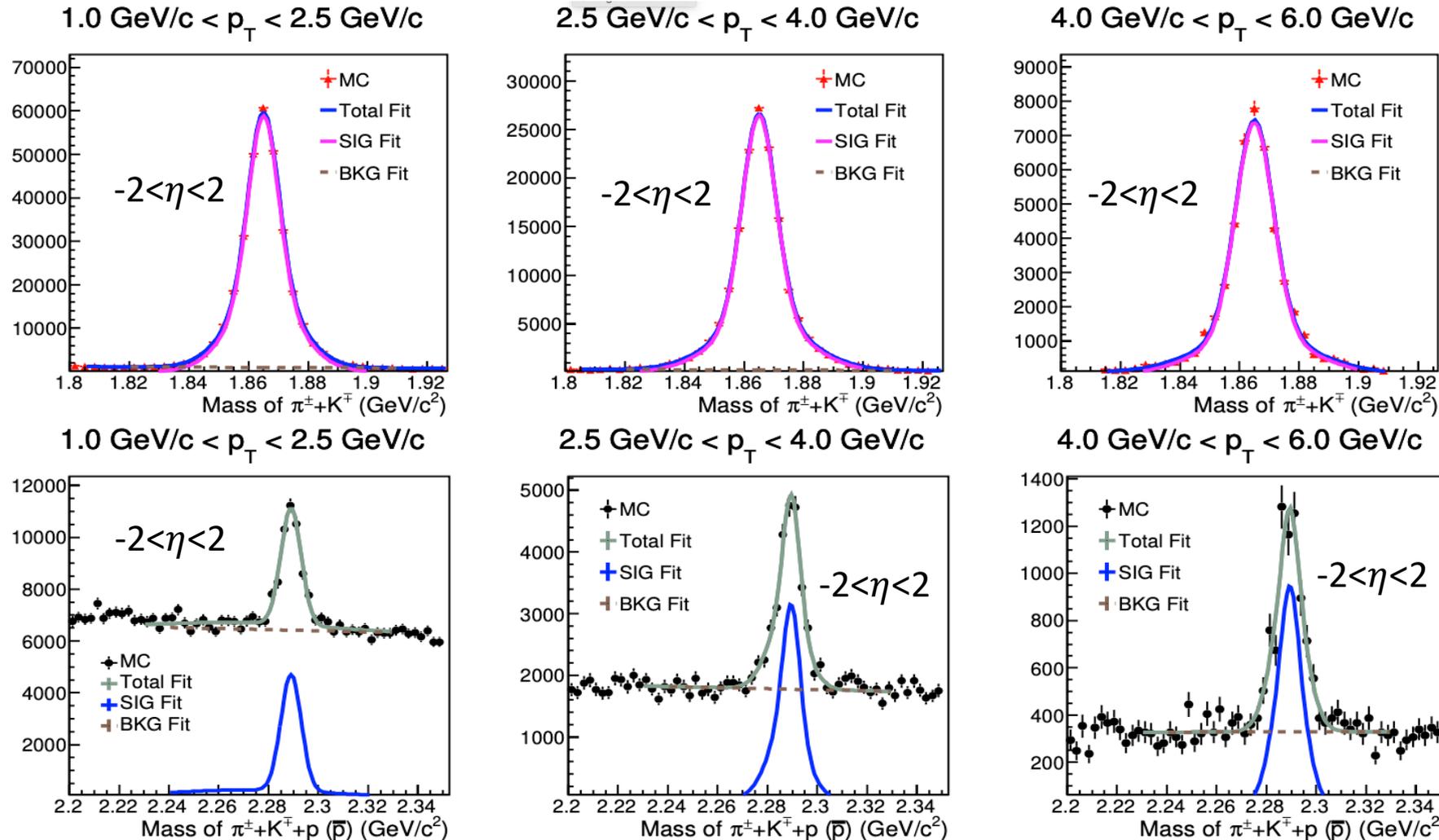
Charm di-jet p_T asymmetry A_j



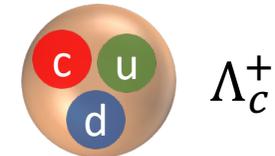
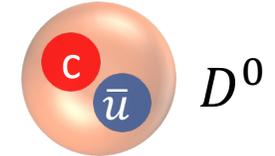
- More differential studies (pseudorapidity separated distributions) are underway.

Charm meson/baryon ratios to access the hadronization process (I)

- Clear signals can be found in the p_T separated invariant mass spectrums of reconstructed D^0 and Λ_c in 10 GeV+100 GeV e+p collisions.

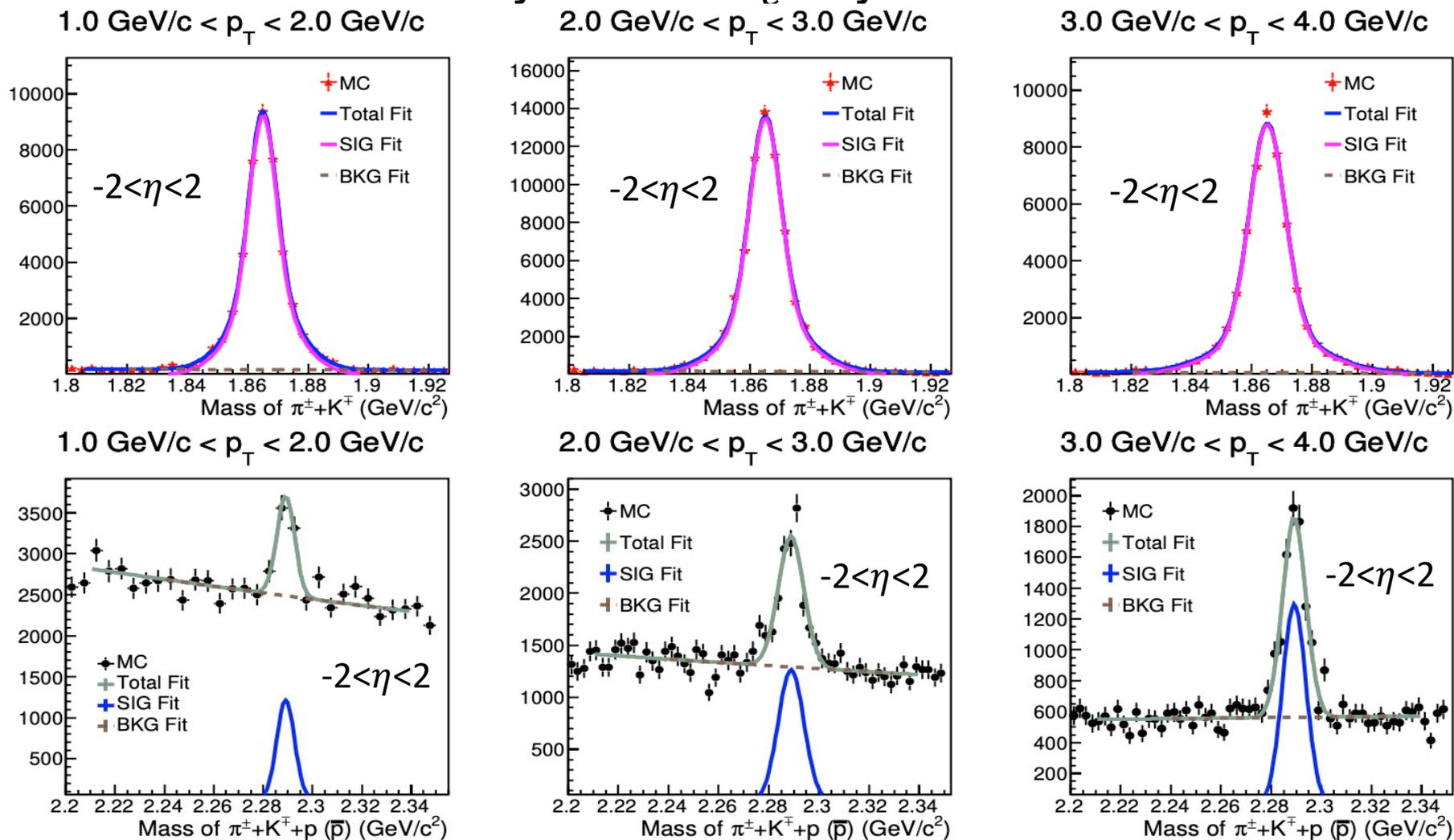


Inclusive charm hadron reconstruction

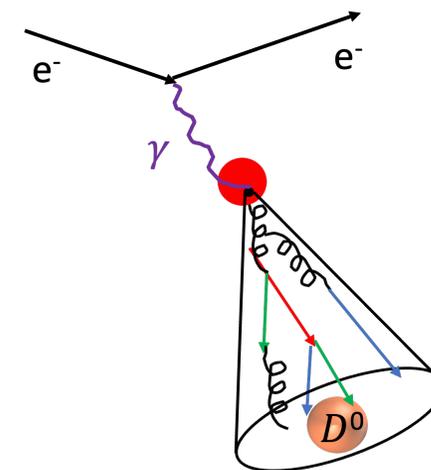


Charm meson/baryon ratios to access the hadronization process (II)

- Clear signals can be found in the p_T separated invariant mass spectrums of reconstructed D^0 in jets and Λ_c in jets in 10 GeV+100 GeV e+p collisions.



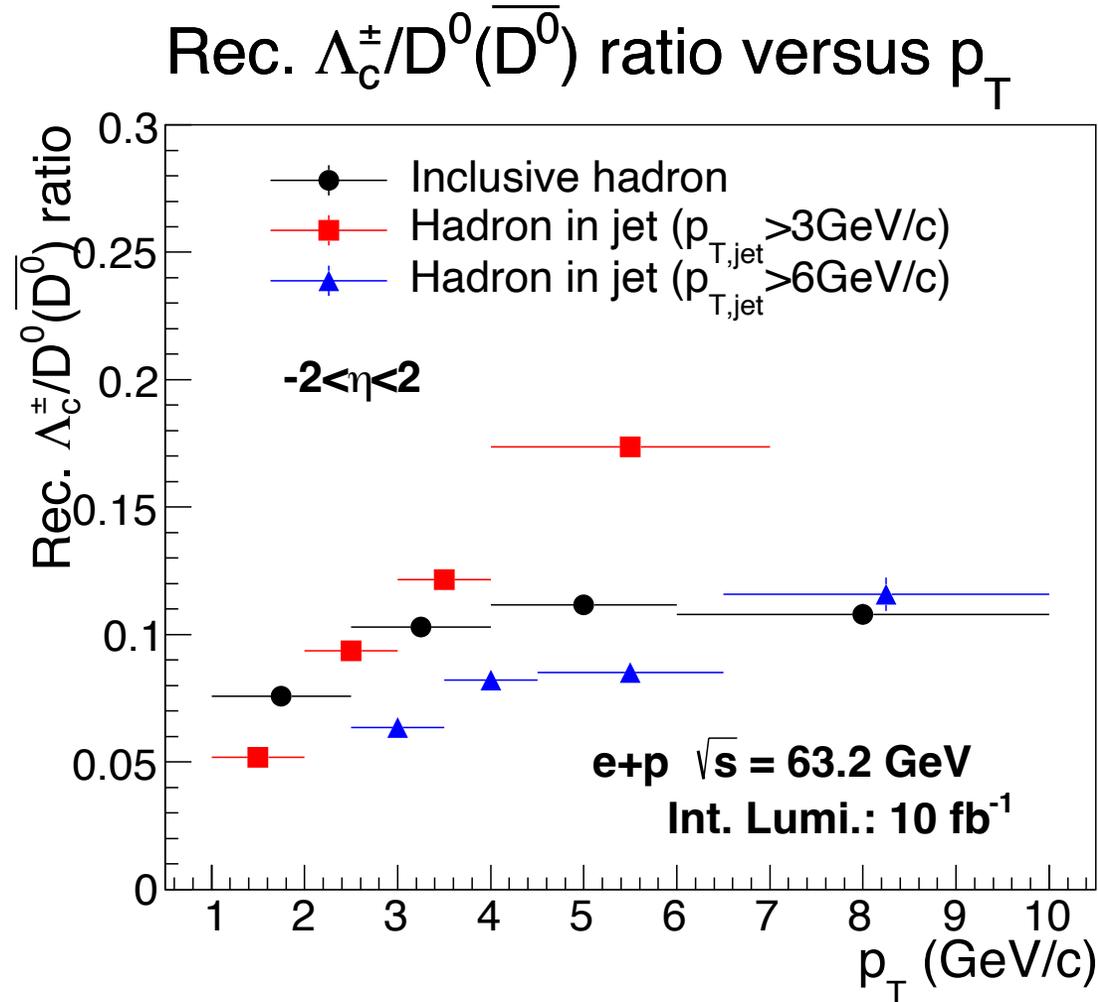
Reconstruction of charm hadrons inside jets with $p_T > 3 \text{ GeV}/c$



$$e^- + p \rightarrow e^- + jet(D^0) + X$$

Charm meson/baryon ratios to access the hadronization process (II)

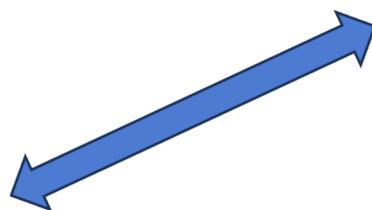
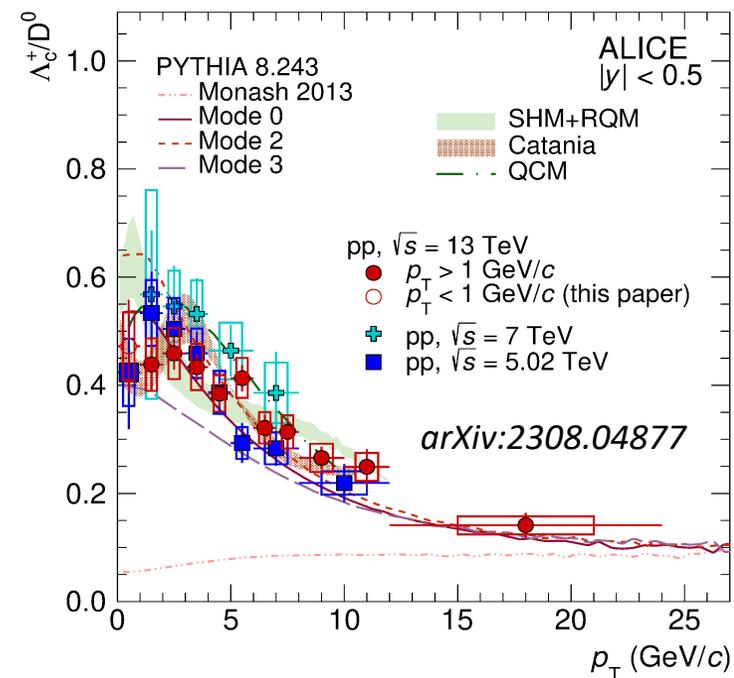
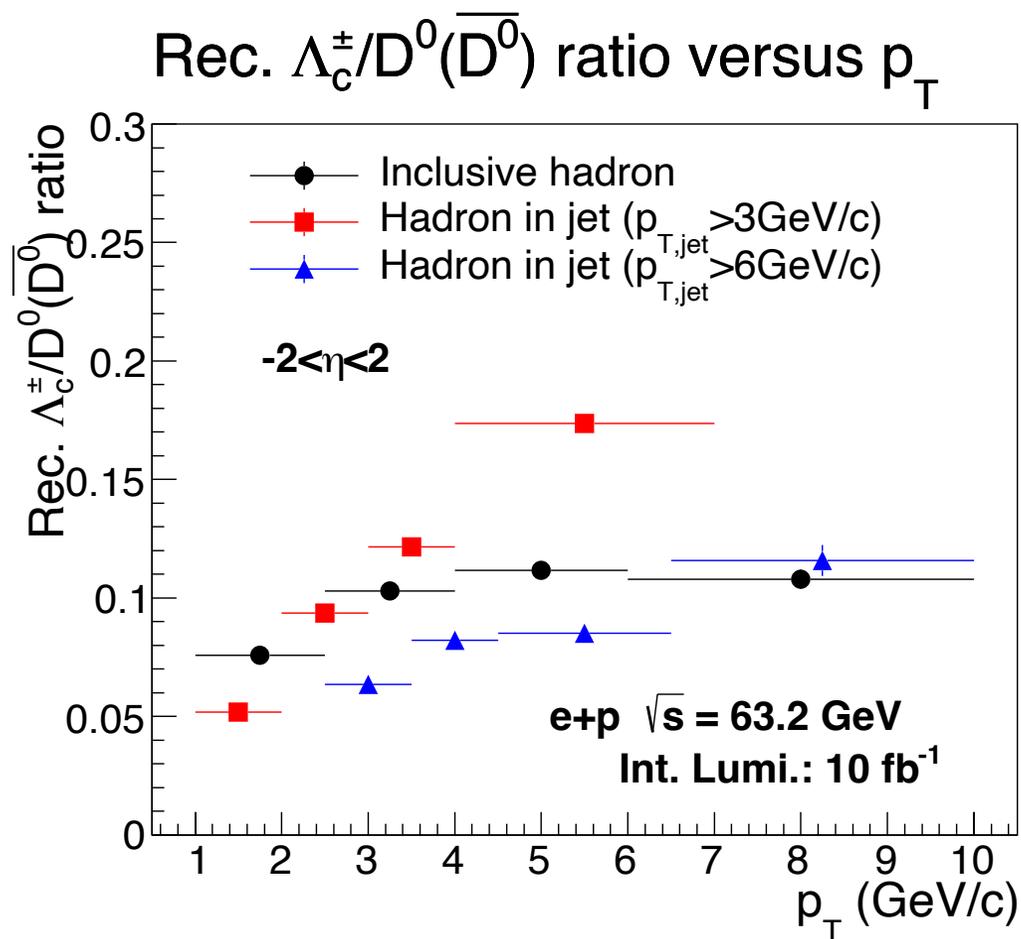
- Different phase spaces of the fragmentation can be selected by varying the associated jet p_T for D^0 in jets and Λ_c in jets.



- Reflects the PYTHIA string fragmentation function of charm meson/baryon production in e+p collisions.
- Will work on the studies in e+Au collisions to validate any potential nuclear medium modification on the hadronization process.

Charm meson/baryon ratios to access the hadronization process (II)

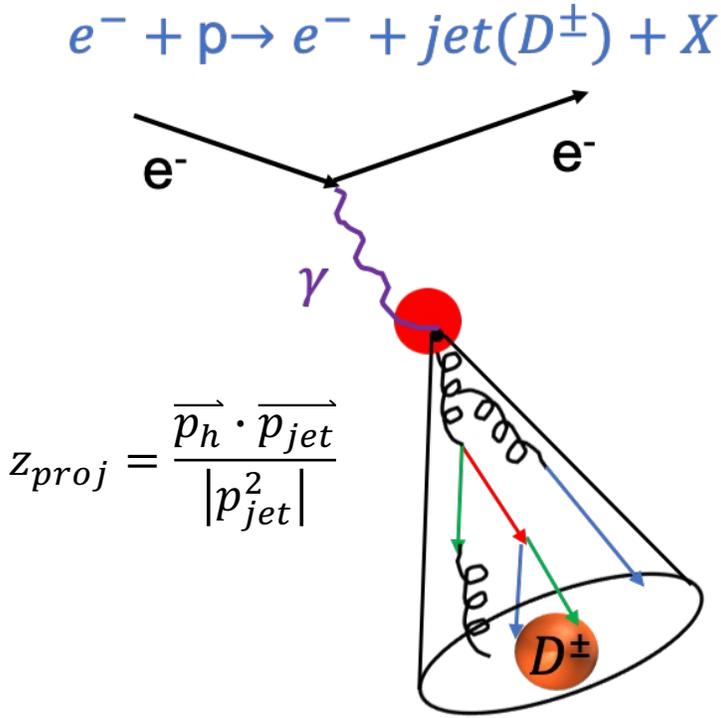
- Different phase spaces of the fragmentation can be selected by varying the associated jet p_T for D^0 in jets and Λ_c in jets.



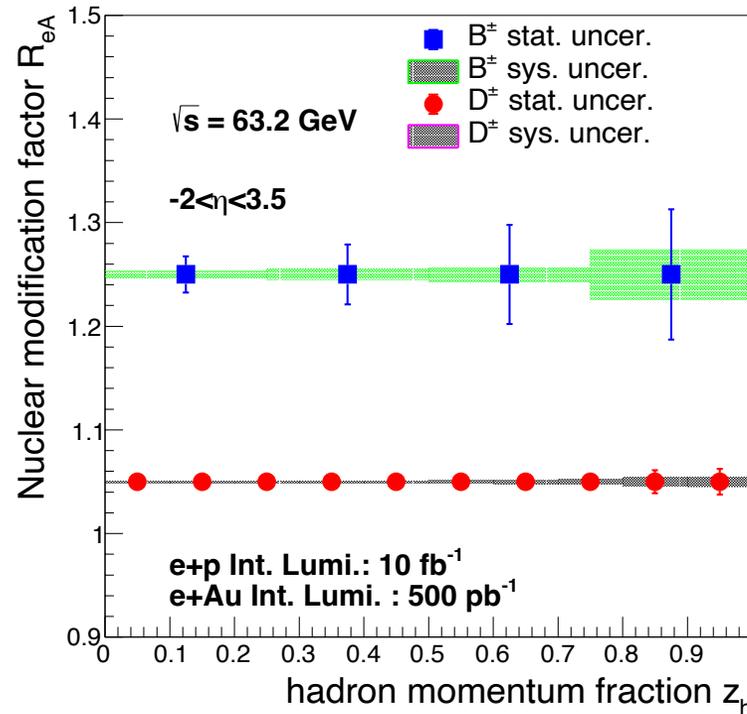
- Future EIC measurements in e+p and e+A collisions will provide a unique approach to check the universality of charm fragmentation function.

Hadron inside jet nuclear modification factor R_{eAu} projection

- Hadron inside jet studies at the EIC can provide good sensitivity to directly extract the flavor dependent fragmentation functions.



Projected hadron R_{eA} vs z_h



$$R_{eA} = \frac{1}{A} \frac{\sigma_{eA}}{\sigma_{ep}}$$

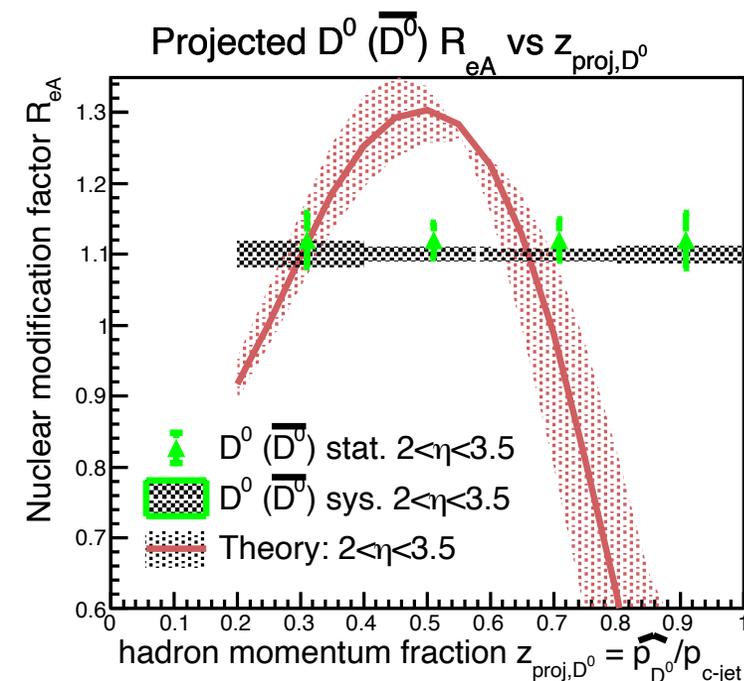
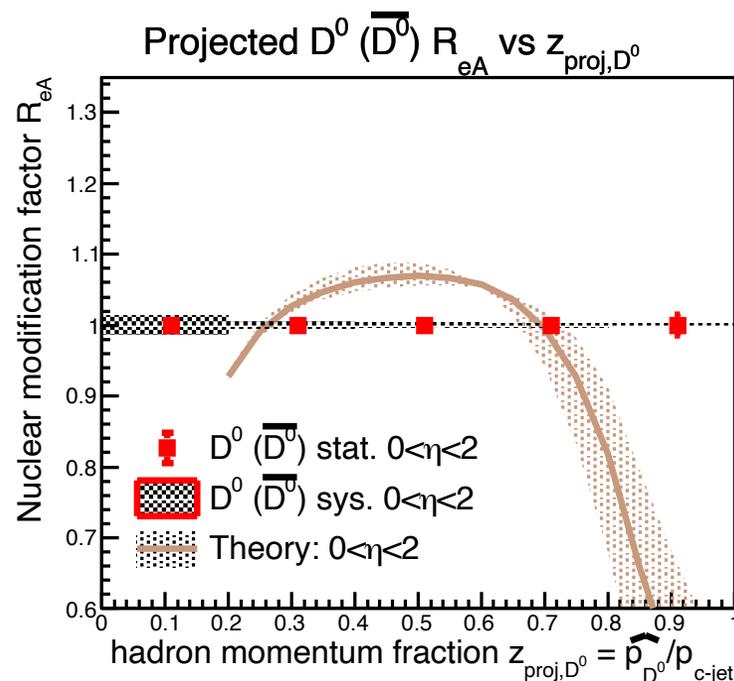
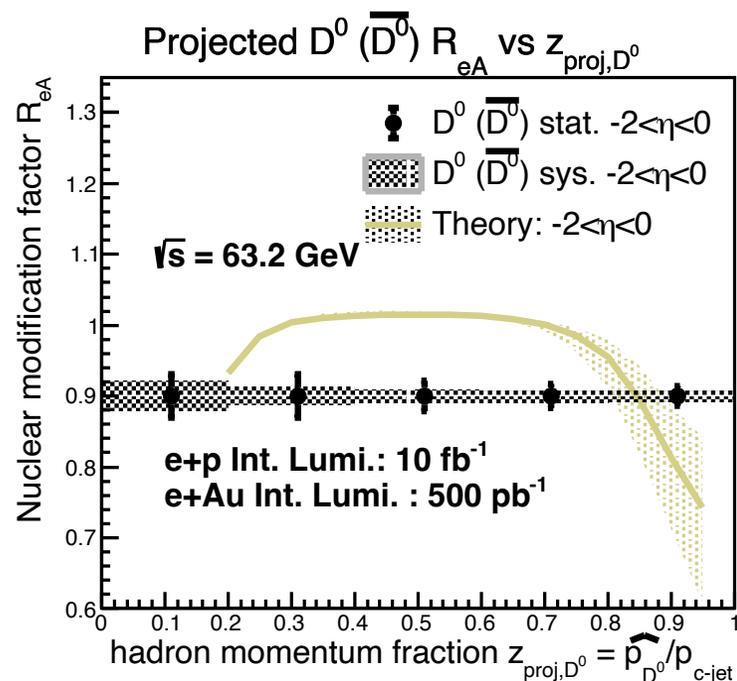
Best precision to be achieved by the EIC measurements in the accessed kinematic phase space.

- Projected R_{eAu} statistical uncertainties of D^\pm inside charm jets (red) and B^\pm inside bottom jets (green) in 10 GeV electron and 100 GeV gold collisions.

Pseudorapidity dependent D^0 ($\overline{D^0}$) inside charm jet R_{eAu} projection

- Projected accuracy of D^0 ($\overline{D^0}$) inside charm jet R_{eAu} within $-2 < \eta < 0$ (left), $0 < \eta < 2$ (middle) and $2 < \eta < 3.5$ (right) regions in 10+100 GeV e+Au collisions with around one-year EIC operation.

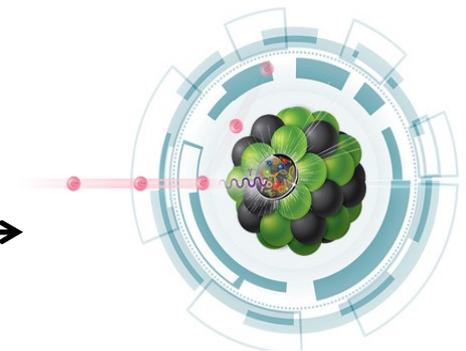
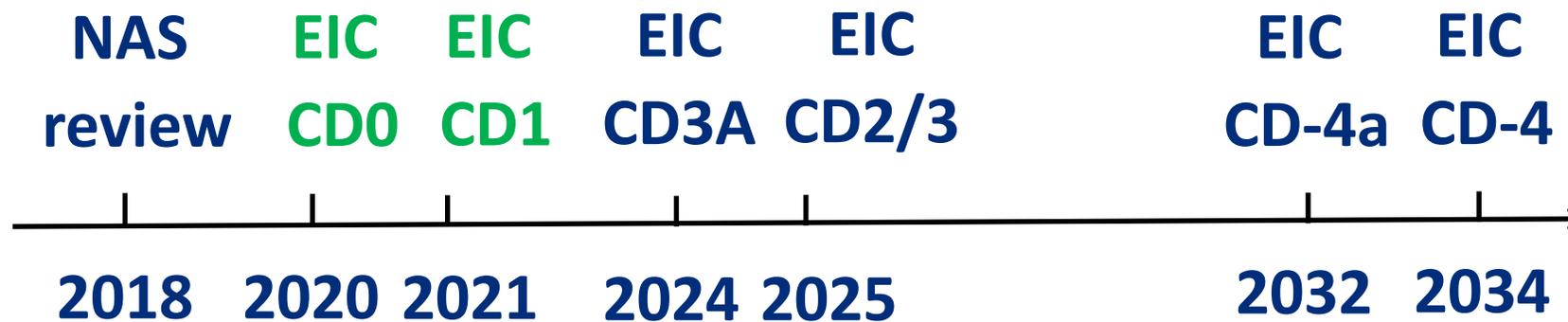
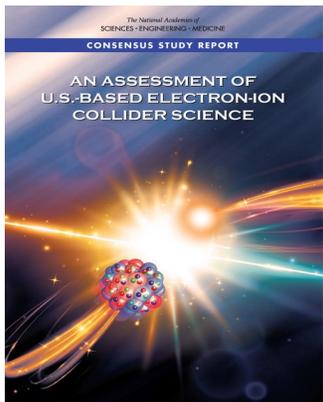
Theoretical calculations: Phys. Lett. B 816 (2021) 136261.



- 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.

Summary and Outlook

- The future EIC will provide unique opportunities to study the heavy quark hadronization process within a wide kinematic coverage.
- Great precision will be achieved by the EIC heavy flavor hadron and jet measurements in e+p and e+A collisions. Heavy flavor hadron inside jet measurements will play an important role in studying the flavor dependent hadronization under different nuclear medium conditions.
- As we are moving towards the EIC construction in 2025, we look forward to work with more collaborators for the EIC detector/experiment realization.



Workshop Announcement

- We will organize the “2nd workshop on advancing the understanding of non-perturbative QCD using energy flow” CFNS workshop at Stony Brook University from November 6-9, 2023. **Please join us in person or online!**
- Indico page: <https://indico.cfnsbu.physics.sunysb.edu/event/110/>

2nd workshop on advancing the understanding of non-perturbative QCD using energy flow

Nov 6 – 9, 2023
Stony Brook University/Online
America/New_York timezone

- Overview
- Registration
- Participant List
- Remote participation via ZOOM

Contact

✉ cfns_contact@stonybro...

This event may be attended in person, or virtually using Zoom (require explicit host permission after connecting, usually approved quickly).

This event is part of the CFNS workshop/ad-hoc meeting series. See the [CFNS conferences](#) page for other events.

Perturbative quantum chromodynamics (pQCD) provides a systematically improvable approach to study the dynamics of the strong interaction. It successfully describes data from high energy experiments across a wide range of energy scales and in various collision systems. However, much of the theoretical uncertainty in realistic calculations comes from the inaccurate model description of non-perturbative (np) effects in the low energy regime. These np effects present themselves in lepton-lepton, lepton-hadron and hadron-hadron collisions, with substantial overlap in their phase space along with a distinct set of contributions for each system. Manifestation of the np effects exists in the initial state of the parton/nucleon distributions and also persists in the final state via target fragmentation and hadronization. The goal of this workshop is to aggregate current knowledge related to np effects across systems in order to brainstorm novel measurements at the EIC to investigate the fundamental transition from p-np QCD, utilizing collinear energy flows of jets, heavy flavor (HF) hadrons and target fragments. This workshop proposes an initiative that brings together theorists and experimentalists towards envisioning a collective framework, conceptually and via observables, that are aimed at understanding npQCD.

In this 4-day workshop, we will focus on **Jet substructure, Heavy-Flavor, Initial State & Spin Physics and EIC Prospects**. On each day we have experimental talks on various collision systems, summary talks contrasting different systems, and theory talks on np effects and p-np transition.

Organizers:

Bill Li

Charles-Joseph Naim

Liliana Apolinario

Raghav Kunnawalkam Elayavalli

Xiaoxuan Chu

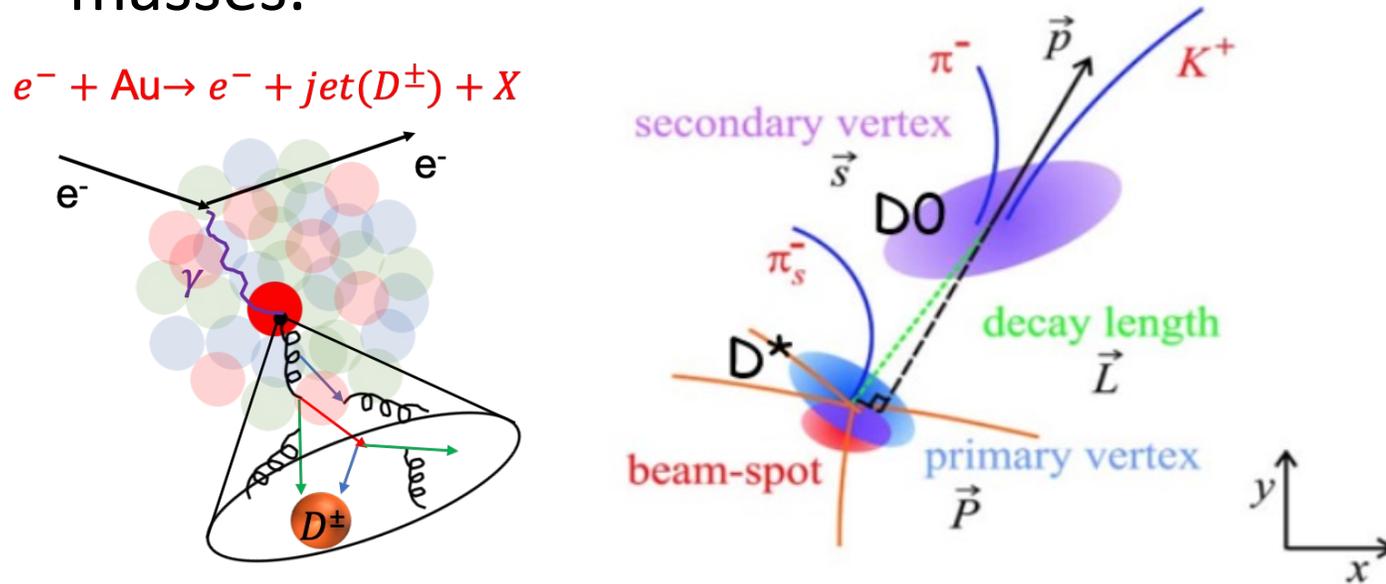
Xuan Li

Yang-Ting Chien

Backup

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.

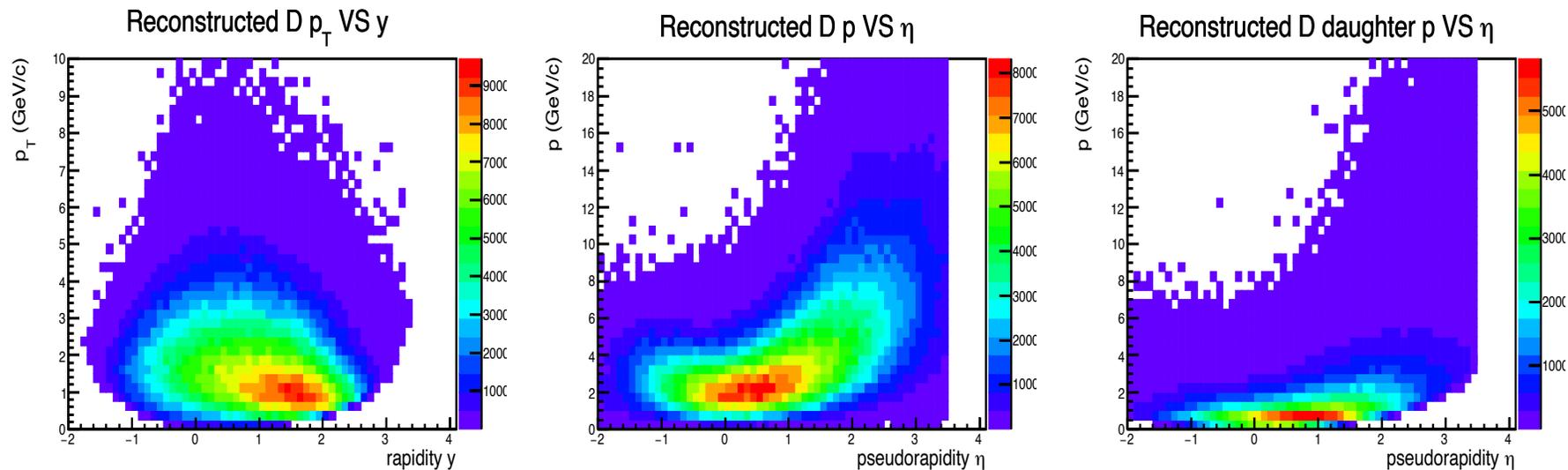


Particle	Mass (GeV/c ²)	Average decay length
D^\pm	1.869	312 micron
D^0	1.864	123 micron
B^\pm	5.279	491 micron
B^0	5.280	456 micron

- Heavy flavor physics-driven detector performance requirements:
 - Fine spatial resolution ($<80 \mu\text{m}$) for displaced vertex reconstruction.
 - Fast timing resolution ($<2 \mu\text{s}$) to suppress backgrounds from neighboring collisions.
 - Low material budgets to maintain fine hit resolution for track reconstruction.

EIC detector requirements for a silicon vertex/tracking detector

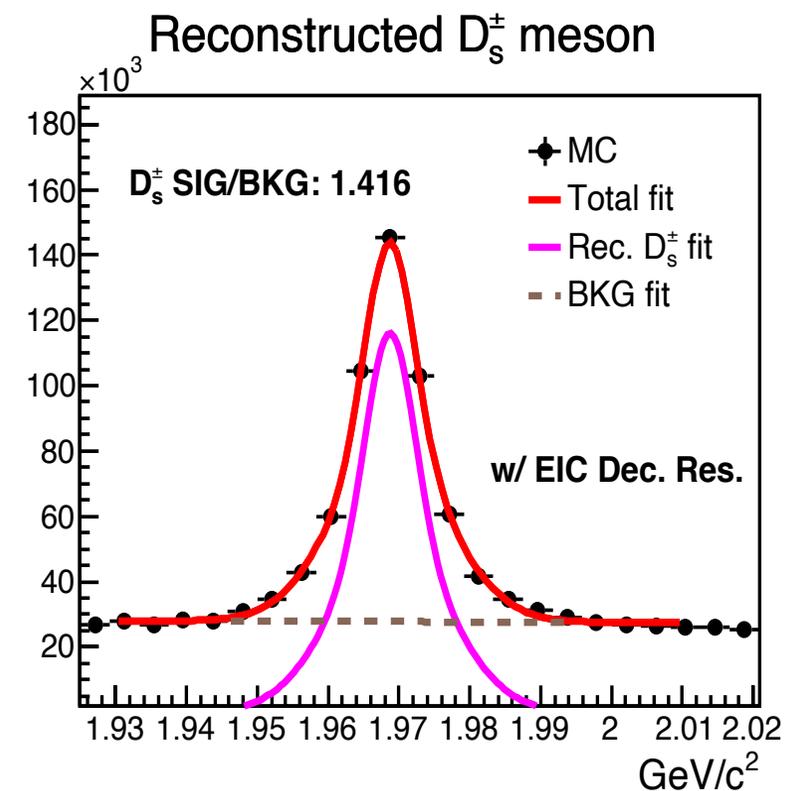
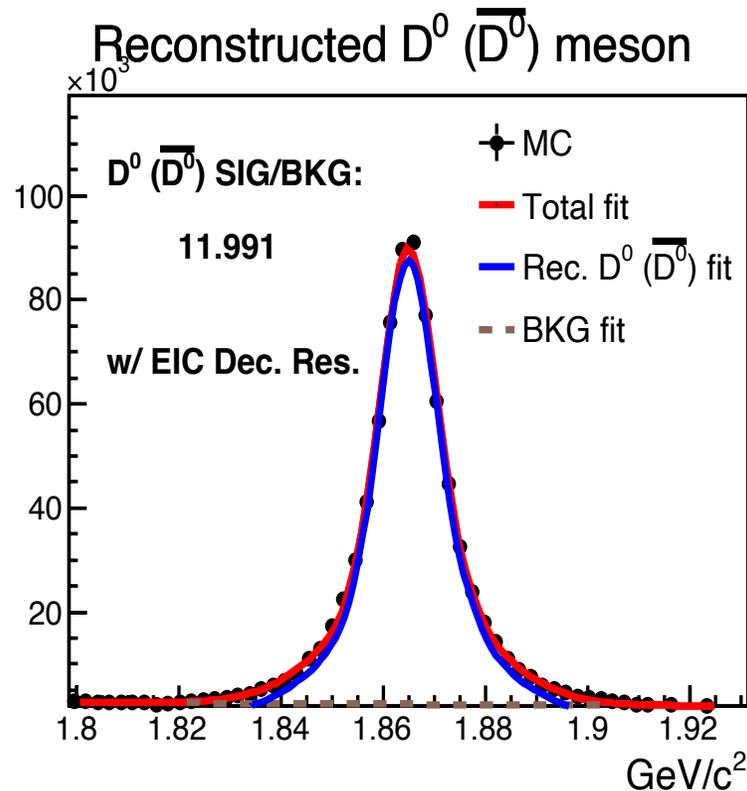
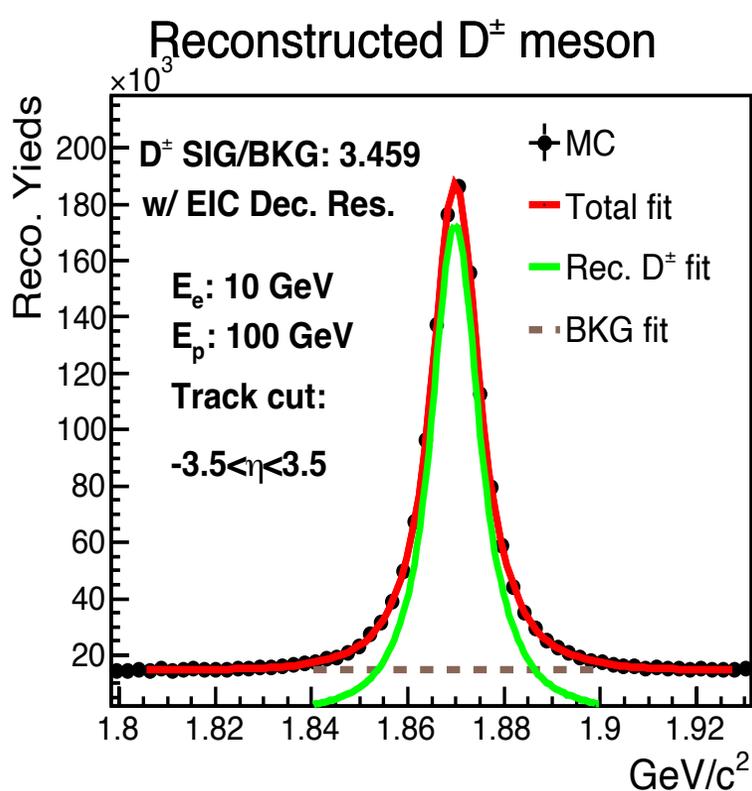
- To meet the heavy flavor physics measurements, a silicon vertex/tracking detector with **low material budgets** and **fine spatial resolution** is needed.
- Particles produced in the asymmetric electron+proton and electron+nucleus collisions have a higher production rate in the forward pseudorapidity.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

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

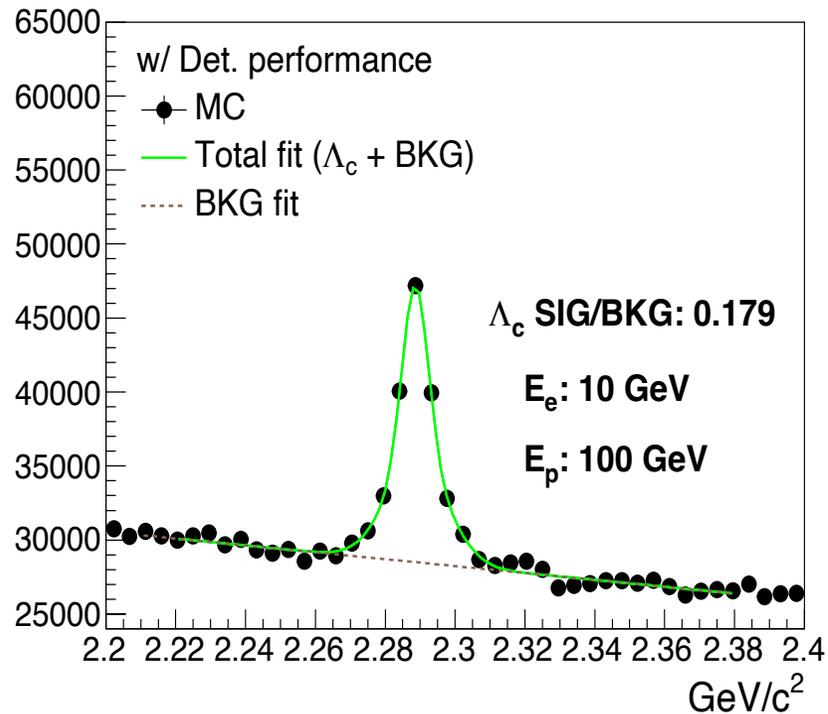
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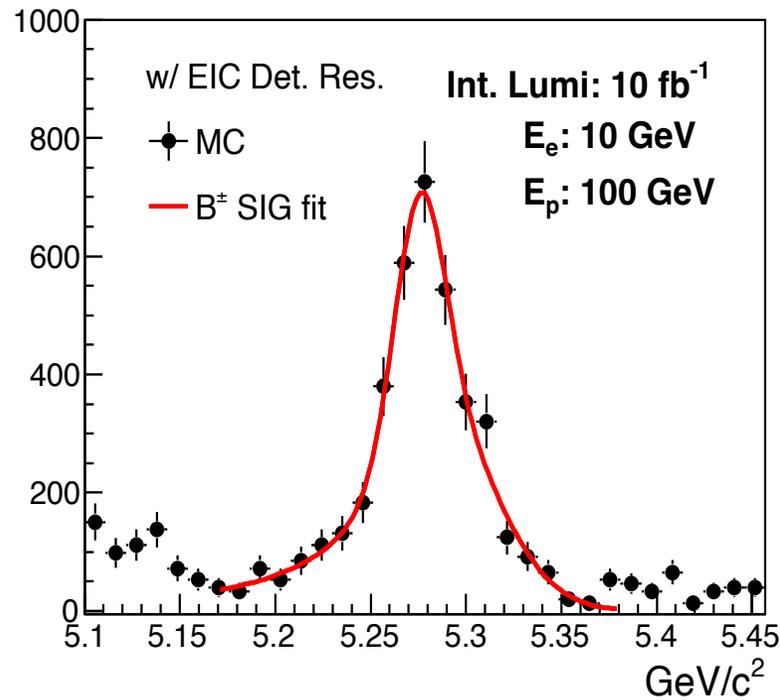
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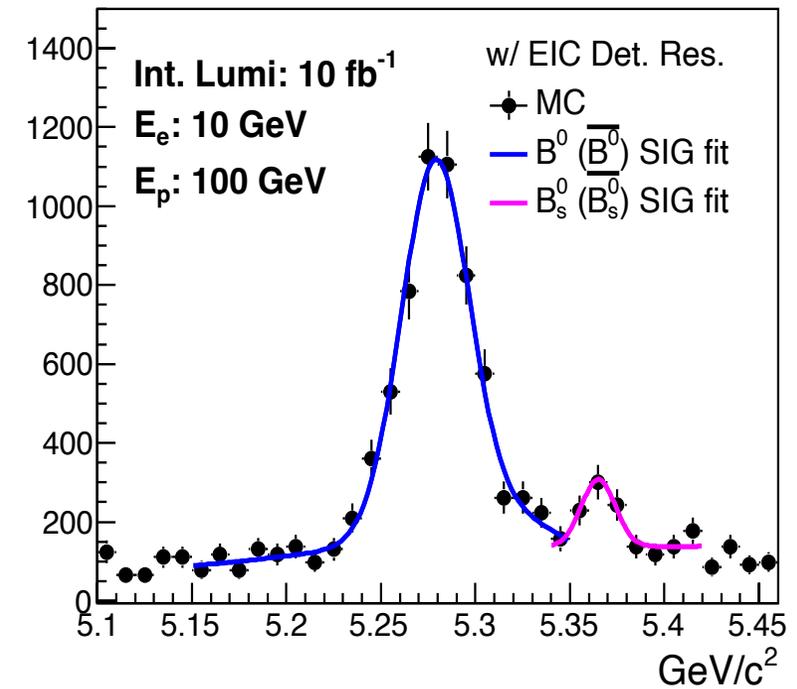
Cluster mass of $\pi^\pm + K^\mp + p (\bar{p})$



Reconstructed B^\pm meson



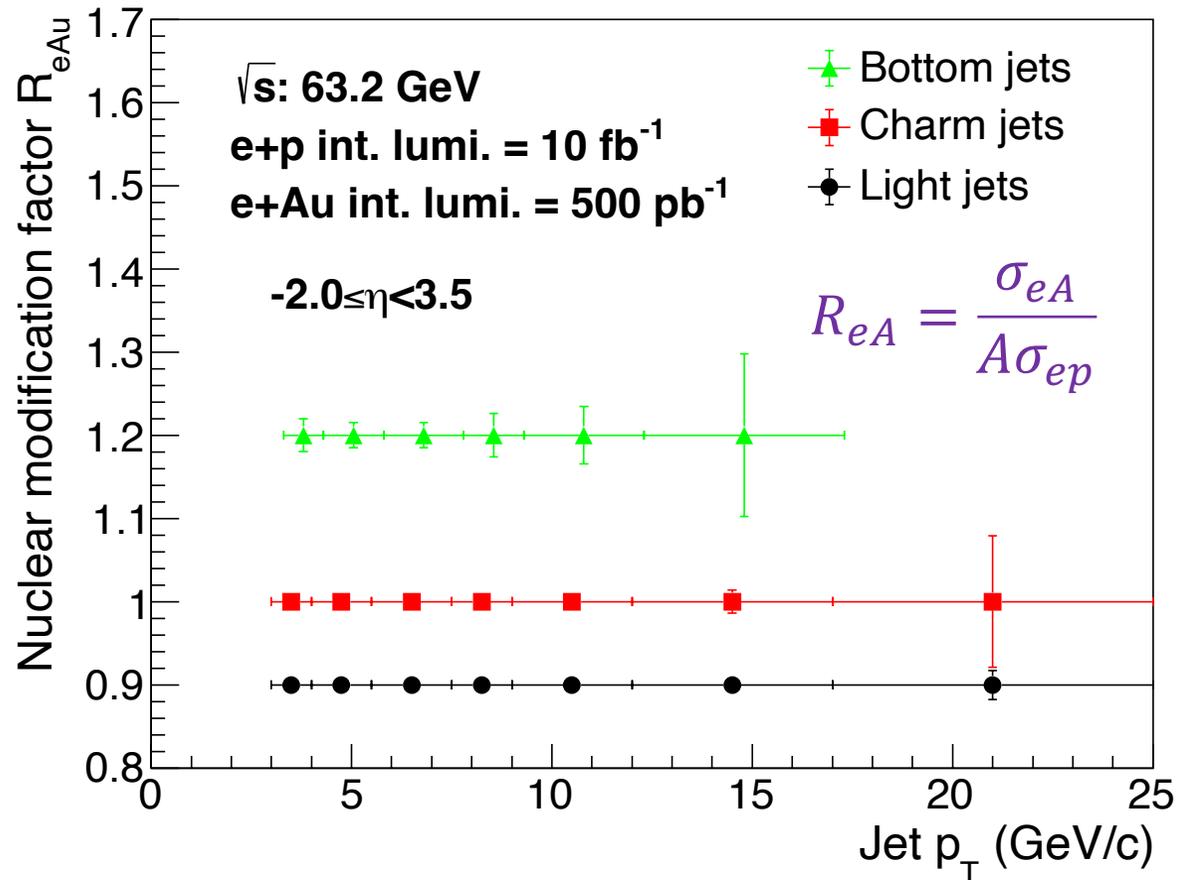
Reconstructed $B^0 (B_s^0)$ meson



Jet nuclear modification factor R_{eAu} projection

- Projected statistical uncertainties of R_{eAu} of light flavor jets (black), charm jets (red) and bottom jets (green) in 10 GeV electron and 100 GeV gold collisions.

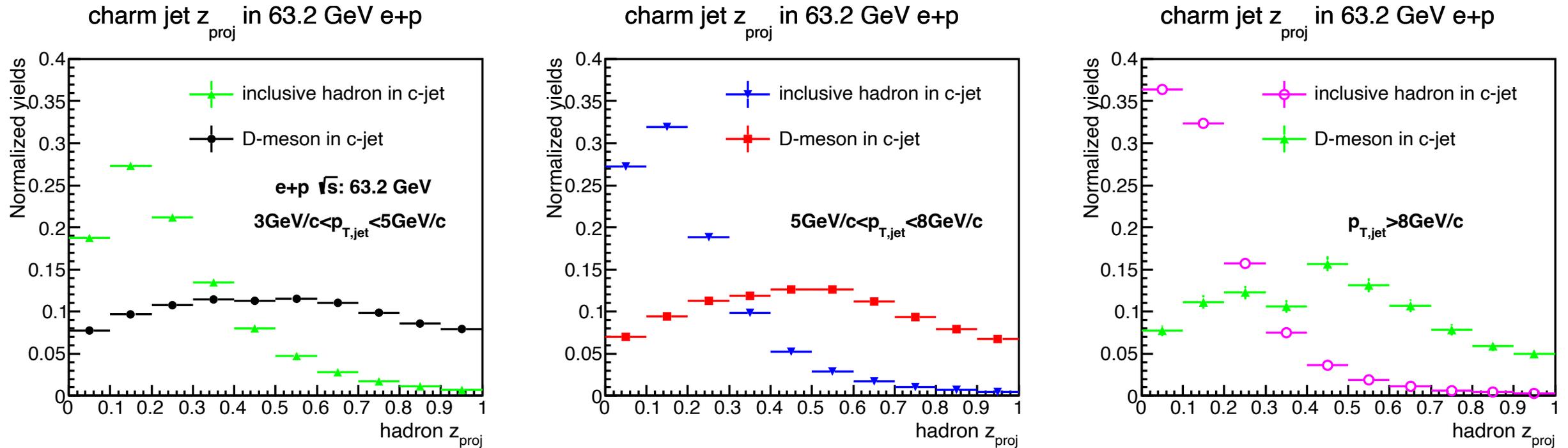
Projected jet R_{eAu} at 63.2 GeV



- EIC will provide unique opportunities to probe low p_T ($p_T < 15$ GeV/c) heavy flavor jets in cold nuclear medium with good precision to study the flavor dependent parton energy loss mechanism.
- Comparison between the EIC measurements and results achieved in heavy ion collisions can help extracting values of parton transport coefficient in different nuclear media.

Kinematic dependent charm jet substructure in e+p collisions

- Hadron inside charm jet z_{proj} distributions with jet p_T in 3-5 GeV/c (left), 5-8 GeV/c (middle), > 8 GeV/c (right) in 10+100 GeV e+p simulation.



- The hadron inside charm jet z_{proj} distributions depend on the hadron flavor and jet p_T . Further studies in different e+A collisions will help explore the flavor dependent hadronization process under different medium conditions.