Recent open heavy flavor studies for the Electron-Ion Collider

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INT-24-2B workshop

Heavy Ion Physics in the EIC Era

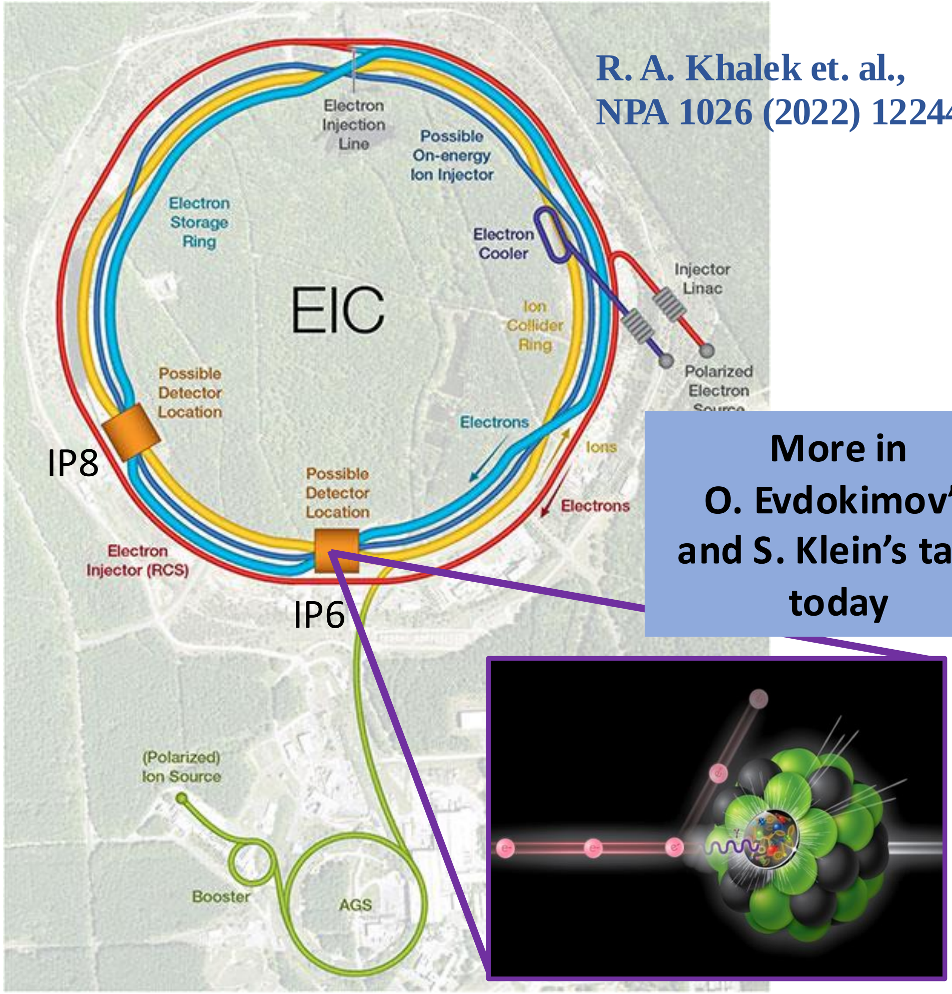
Seattle, WA   August 19-23, 2024

Outline

- Motivation
- Heavy flavor hadron and jet reconstruction in simulation for the Electron-Ion Collider (EIC).
- Selected heavy flavor hadron and jet studies to explore the parton energy loss and hadronization processes at the EIC.
- Summary and Outlook.

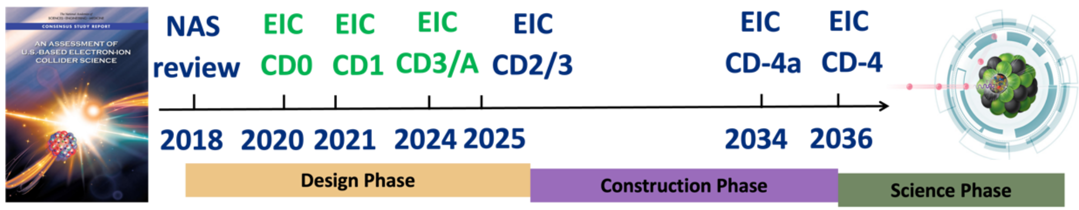
Introduction to the future Electron-Ion Collider (EIC)

- 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 EIC project is scheduled to start construction at BNL in 2025 and its operation is expected in 2030s.
- The EIC will support up to two Interaction Points (IP6, IP8).
- The future EIC will operate:
  - (Polarized) p and nucleus (A=2-238) beams at 41, 100-275 GeV.
  - (Polarized) e beam at 5-18 GeV.
  - Instantaneous luminosity $L_{int} \sim 10^{33\text{-}34}\ cm^{-2}sec^{-1}$. A factor of ~1000 higher than HERA.
  - Bunch crossing rate: 10.2 ns.
  - Beam crossing angle at IP6: 25 mrad.



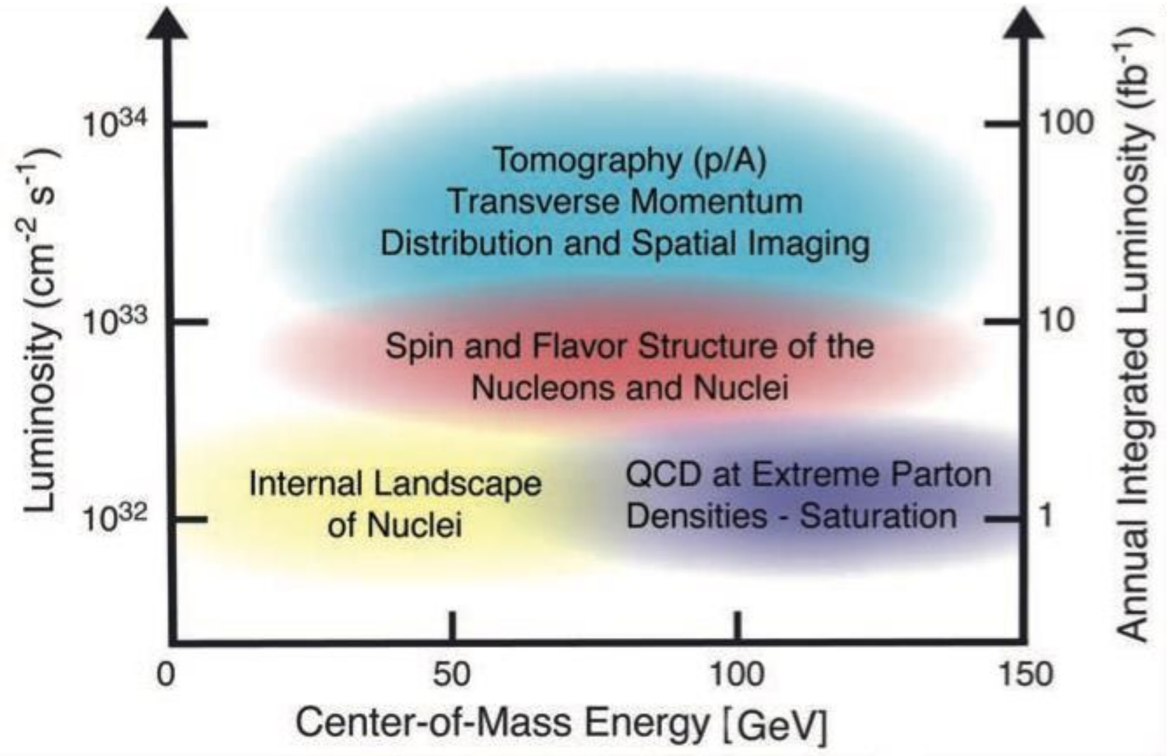
R. A. Khalek et. al., NPA 1026 (2022) 122447

More in O. Evdokimov's and S. Klein's talks today

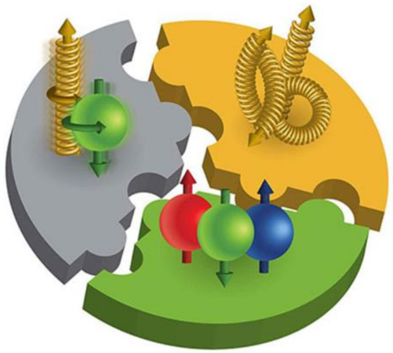


The science objectives of the Electron-Ion Collider (EIC)

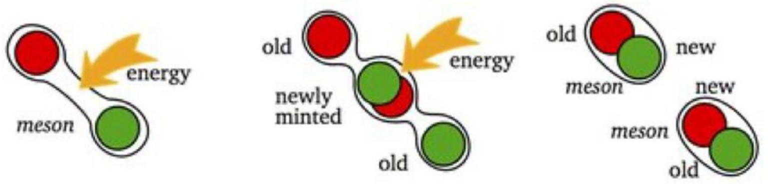
- With a series of e+p and e+A (A=2 to 238) collisions at different center of mass energies (20-141 GeV) and instantaneous luminosities (10^{33-34} $cm^{-2}sec^{-1}$), the future EIC will
  - precisely study the nucleon/nuclei 3D structure.
  - help address the proton spin puzzle.
  - probe the nucleon/nuclei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



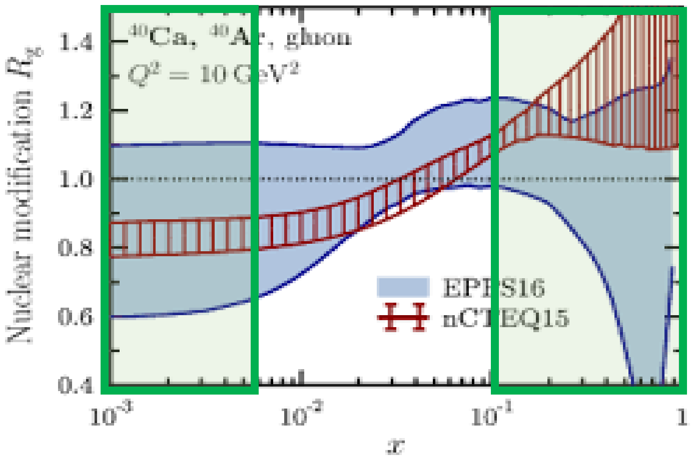
Quark confinement



Heavy flavor measurements can enrich the EIC physics program

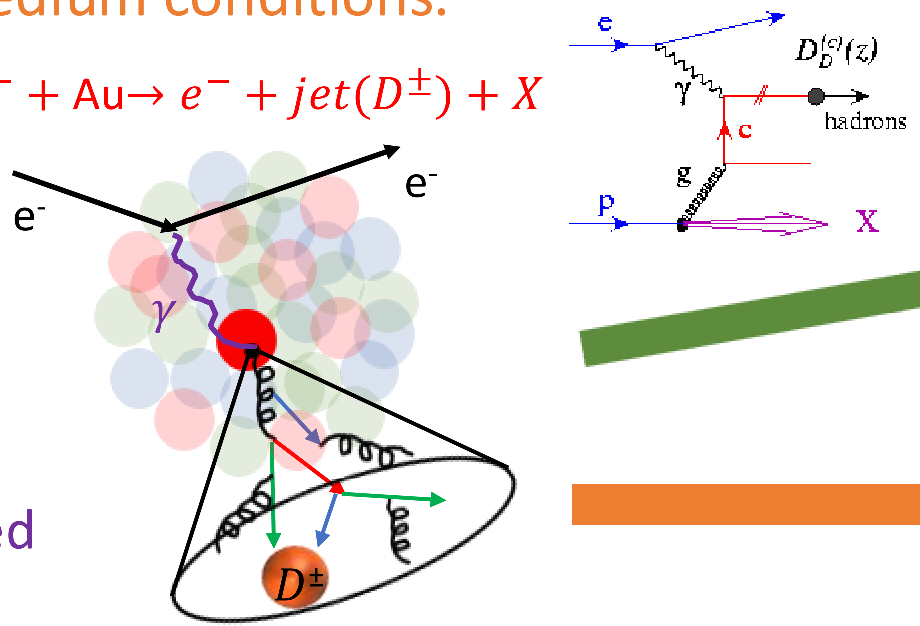
- Heavy flavor hadron and jet measurements are an important part of the EIC science portfolio and play a significant role in exploring
  - Modification on the initial nuclear Parton Distribution Functions (nPDFs) especially in the high and low Bjorken-x (x_{BJ}) region.
  - Final state parton propagation and hadronization processes under different nuclear medium conditions.

nPDF modification

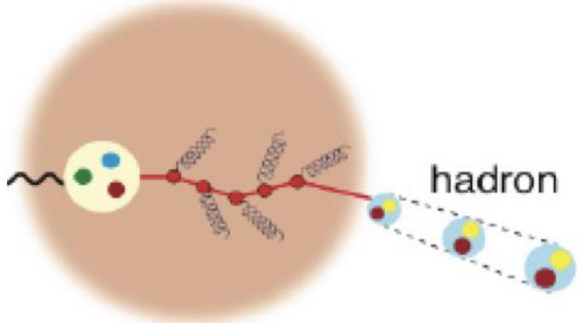


- Uniqueness of the EIC measurements:
  - Precise determination of initial-state parton kinematics.
  - Different cold nuclear medium conditions created in e+A collisions.

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

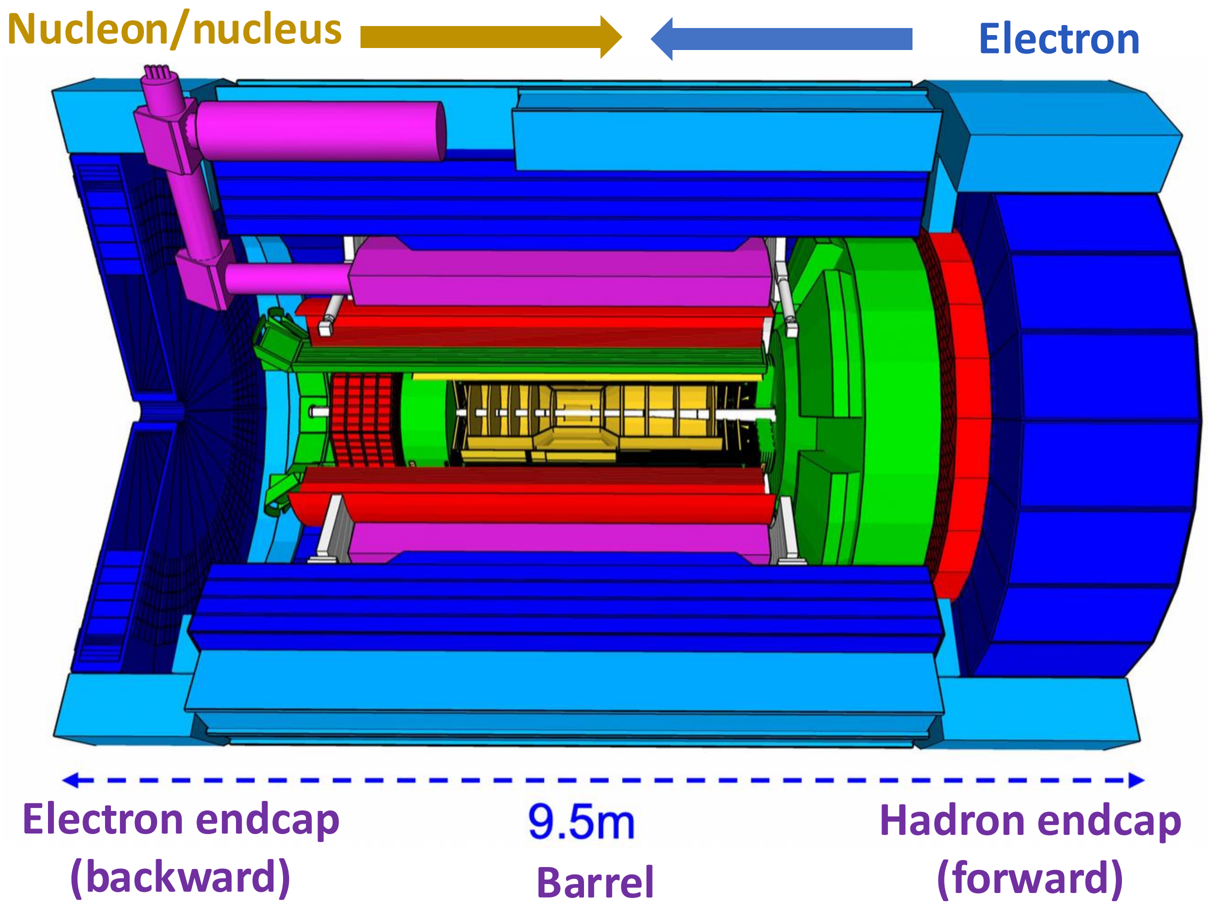


Parton energy loss



Current EIC project detector design by the ePIC collaboration

- The ePIC collaboration is leading the EIC project detector (at IP6) technical design towards construction scheduled in late 2025.
- The 2nd EIC detector (at IP8) is to be developed.

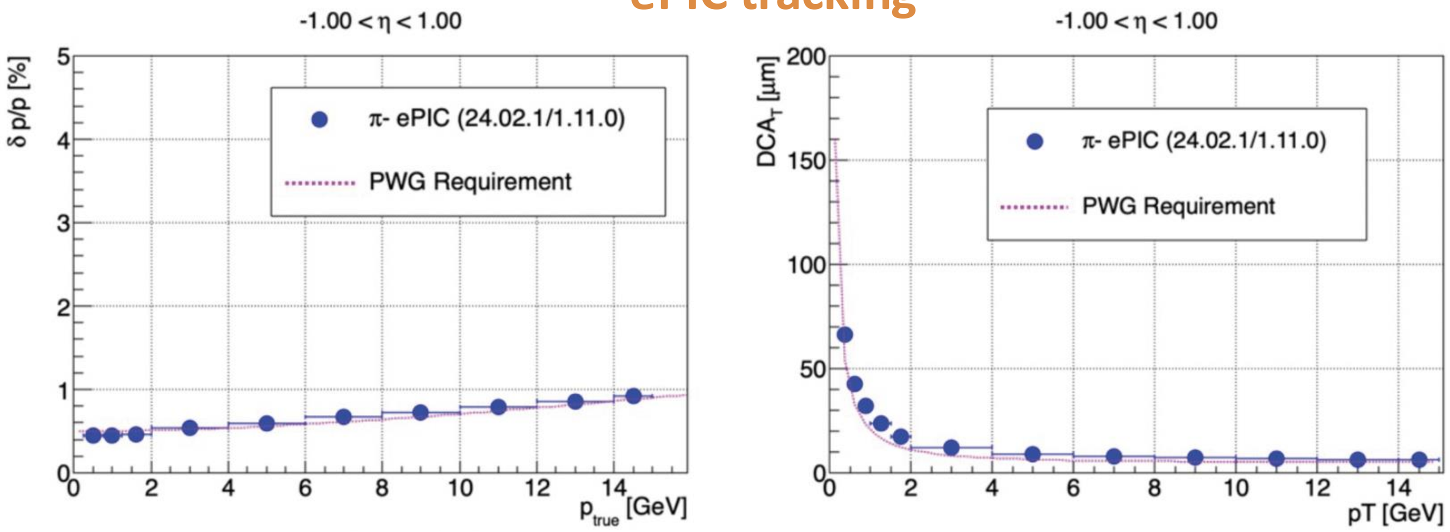


- The ePIC central detector (9.5m X 3.3m) consists of optimized vertex, tracking, PID, EMCal and HCAL subsystems, which enables high precision hadron and jet measurements within the pseudorapidity coverage of $-3.5<\eta<3.5$.
- The ePIC detector also includes the far-forward and far-backward subsystems to detect nuclear breakup, measure the exclusive process and monitor luminosity.

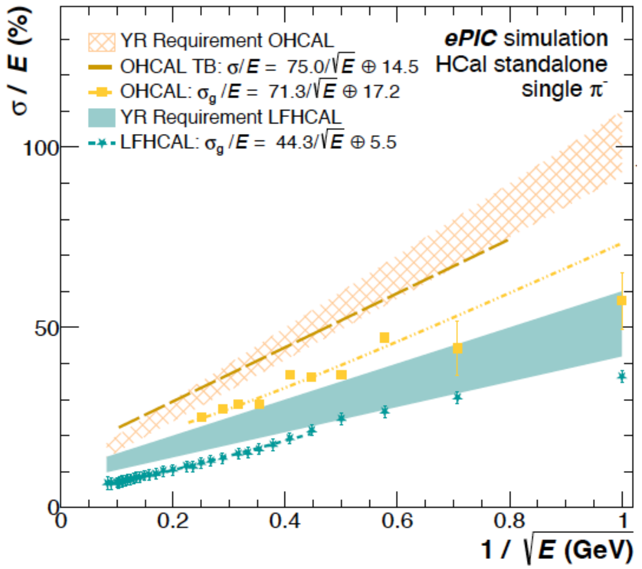
Current EIC project detector performance by the ePIC collaboration

- The ePIC detector design is under optimization and its performance has been extensively evaluated in simulation.

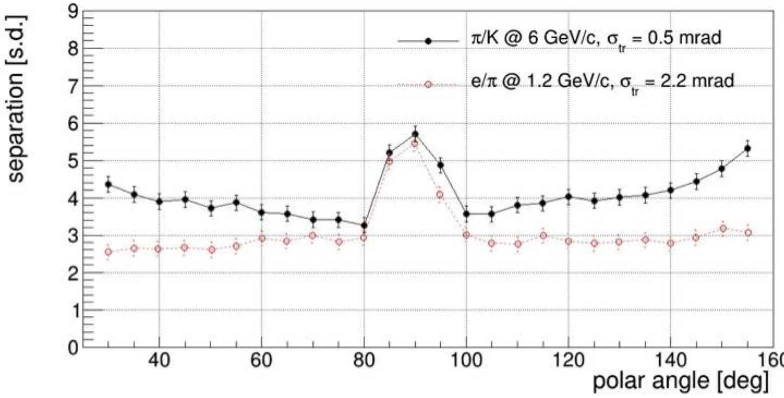
ePIC tracking



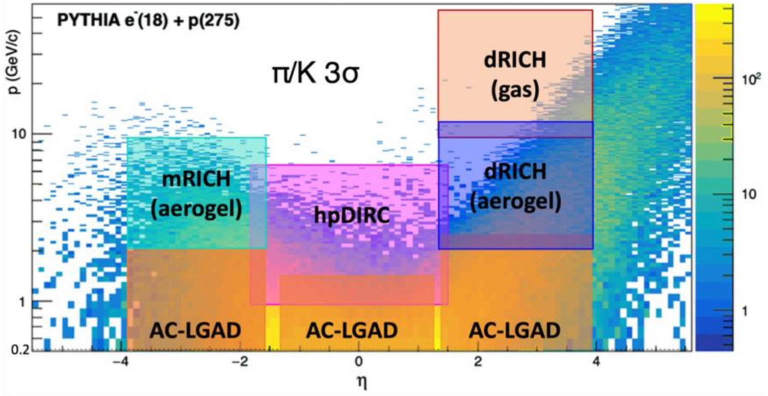
ePIC HCal



ePIC DIRC



ePIC PID



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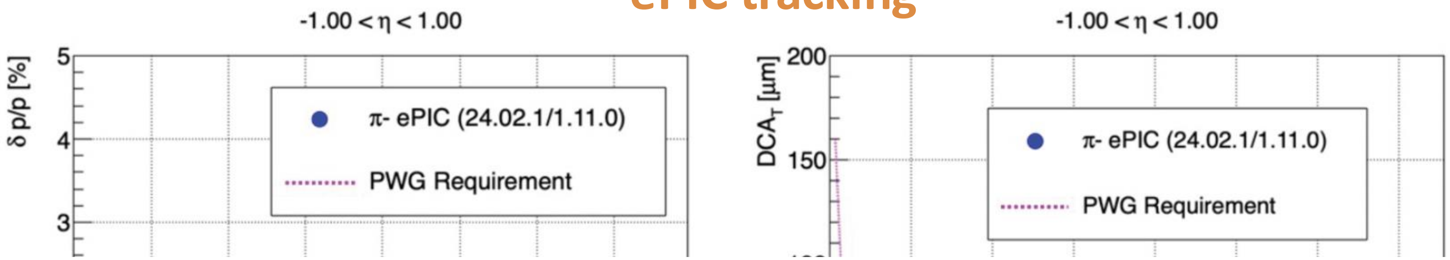
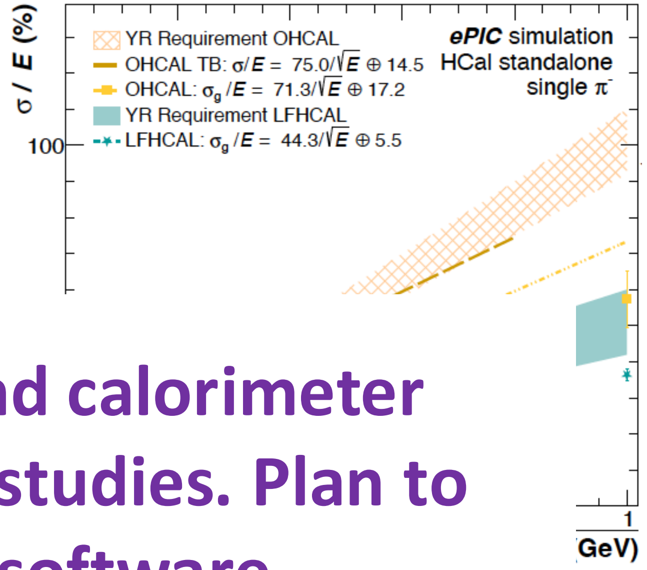
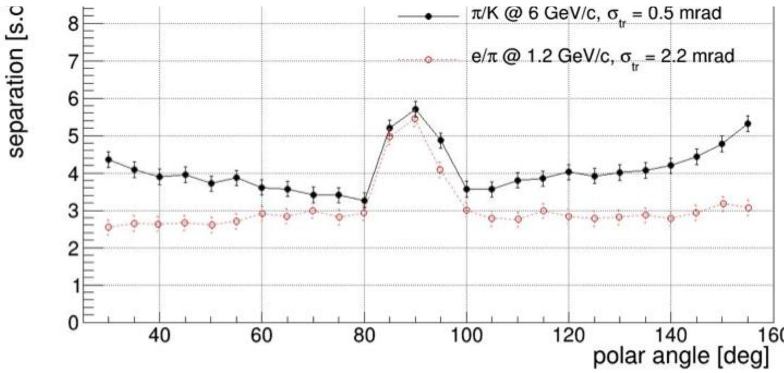
ePIC tracking

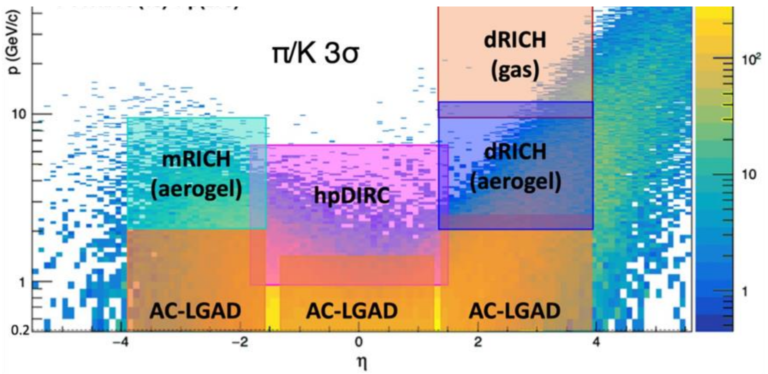


ePIC HCal



Use the parameterized ePIC tracking, PID and calorimeter performance for heavy flavor hadron and jet studies. Plan to integrate these studies within the ePIC software.

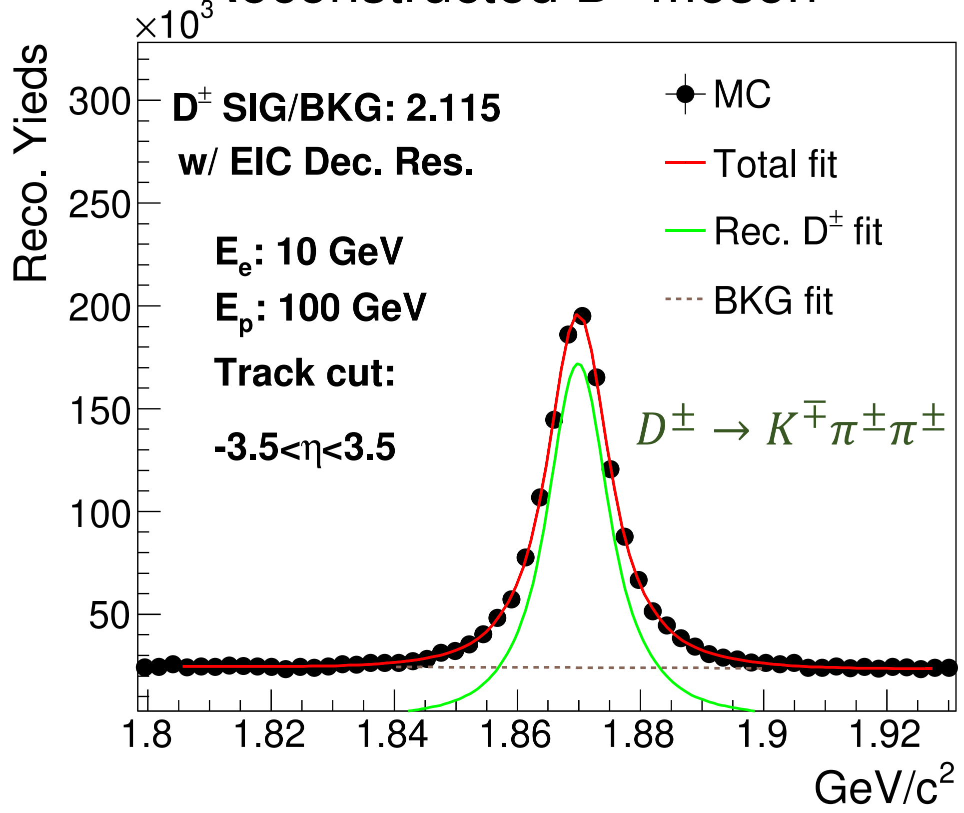




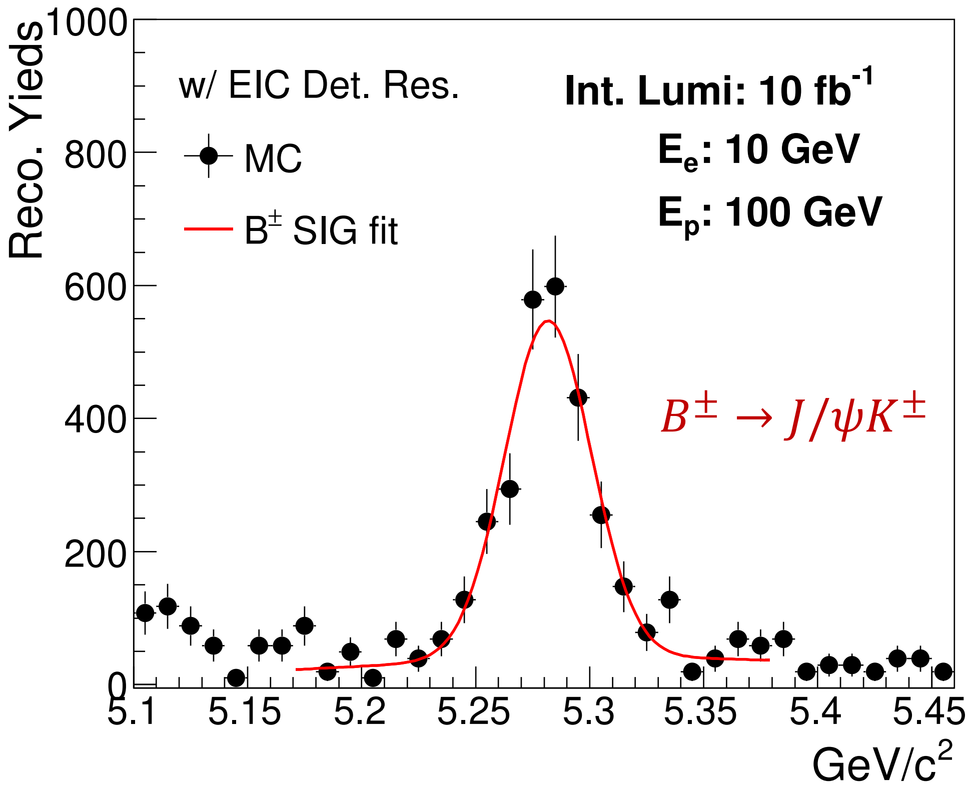
Reconstruction of open heavy flavor products in e+p simulation

- A variety of heavy flavor hadrons and jets have been successfully reconstructed in standalone simulation, which includes the event generation (PYTHIA8), parameterized ePIC detector performance evaluated in GEANT4 simulation.
- Heavy flavor hadrons are reconstructed through hadronic decay channels.

Reconstructed $D^{\pm}$ meson



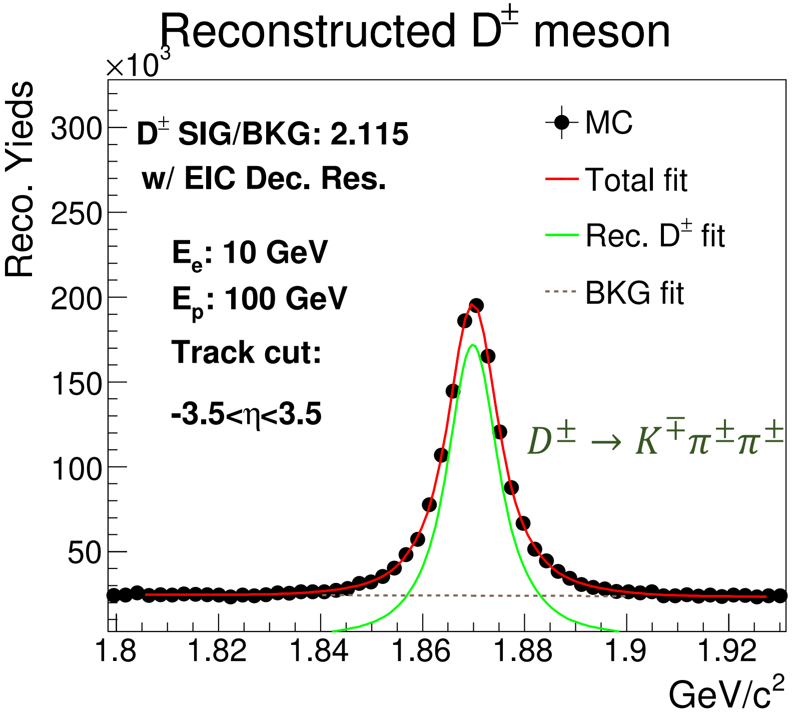
Reconstructed $B^{\pm}$ meson

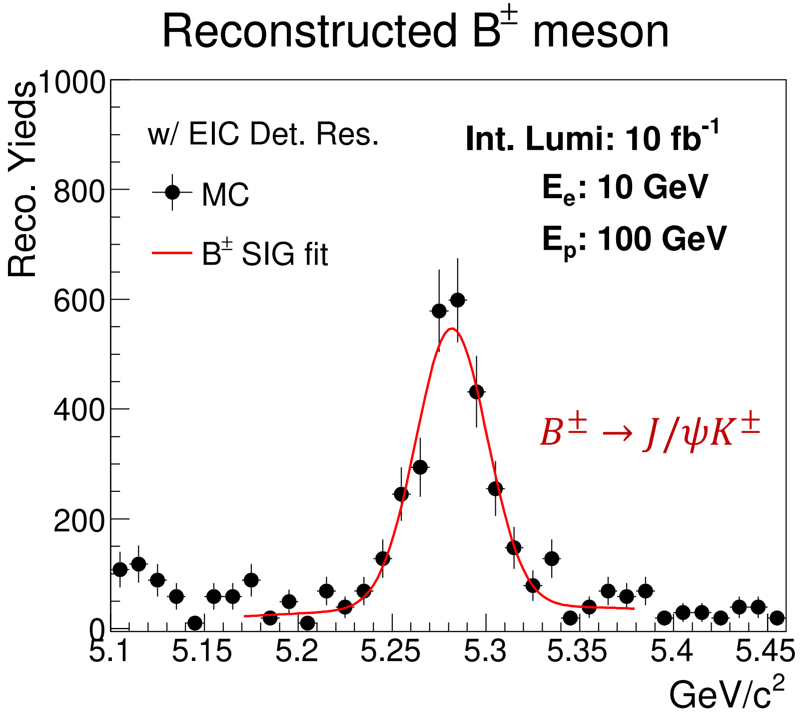


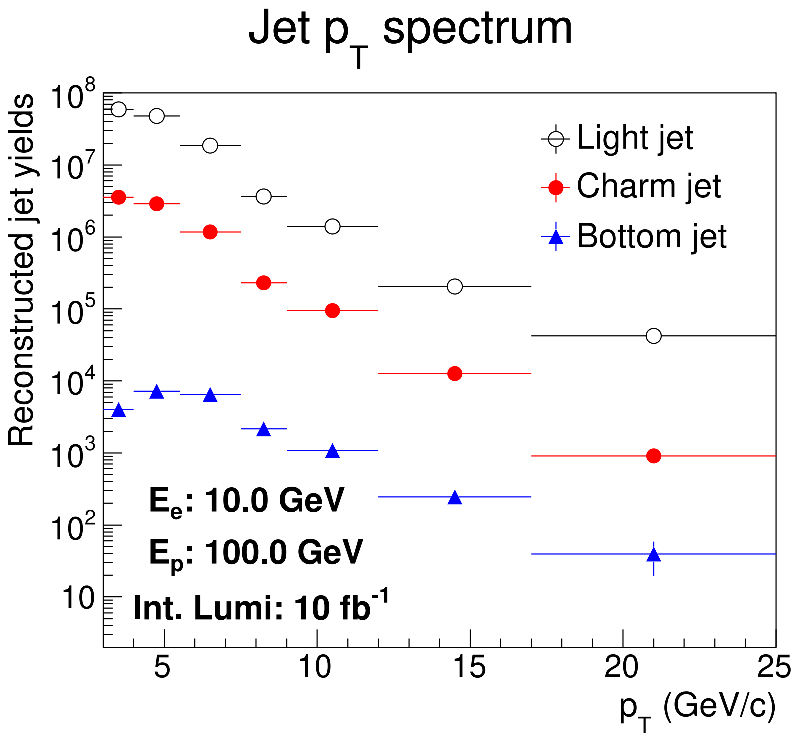
arXiv: 2311.10875

Reconstruction of open heavy flavor products in e+p simulation

- A variety of heavy flavor hadrons and jets have been successfully reconstructed in standalone simulation, which includes the event generation (PYTHIA8), parameterized ePIC detector performance evaluated in GEANT4 simulation.
- Heavy flavor hadrons are reconstructed through hadronic decay channels.
- Heavy flavor jets are reconstructed with the anti-k_T algorithm, jet cone R=1.0 and jet flavor is tagged according to the displaced vertex found inside the jet. ***arXiv: 2311.10875***





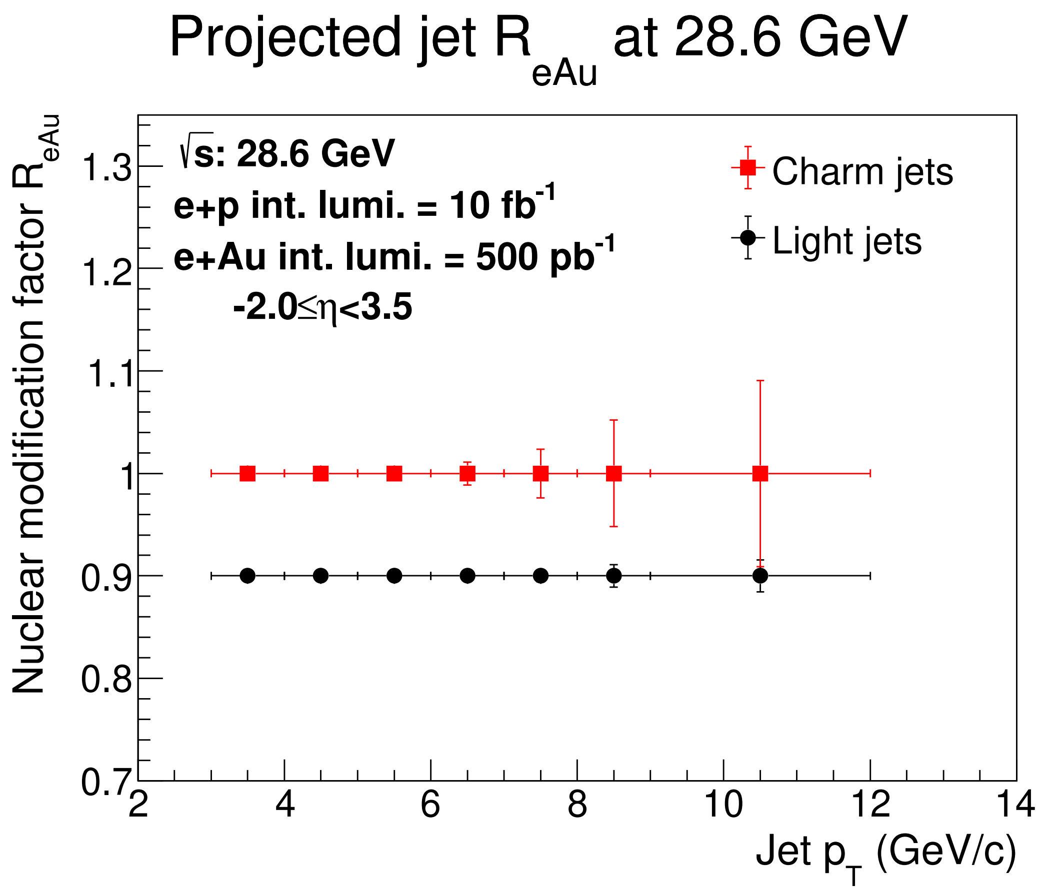


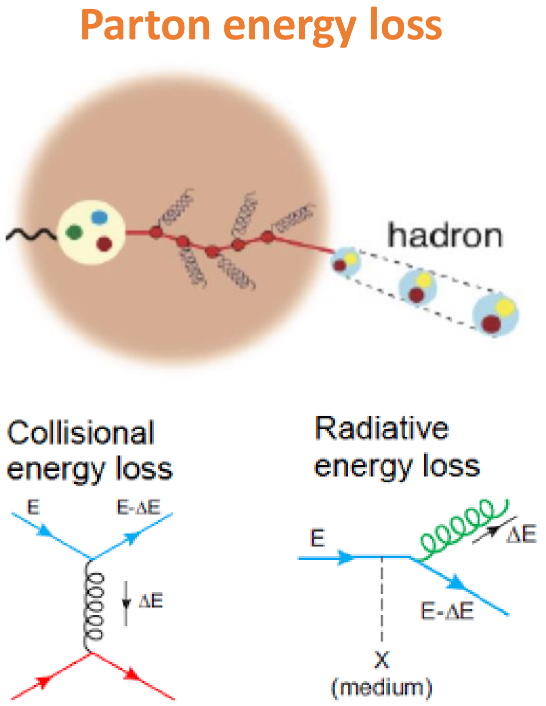
Heavy flavor jet studies at the EIC

Heavy flavor jet R_{eA} to explore parton energy loss mechanism

- Projected nuclear modification factor R_{eA} of jets with different flavors in e+p and e+Au collisions at 28.6 GeV (right).

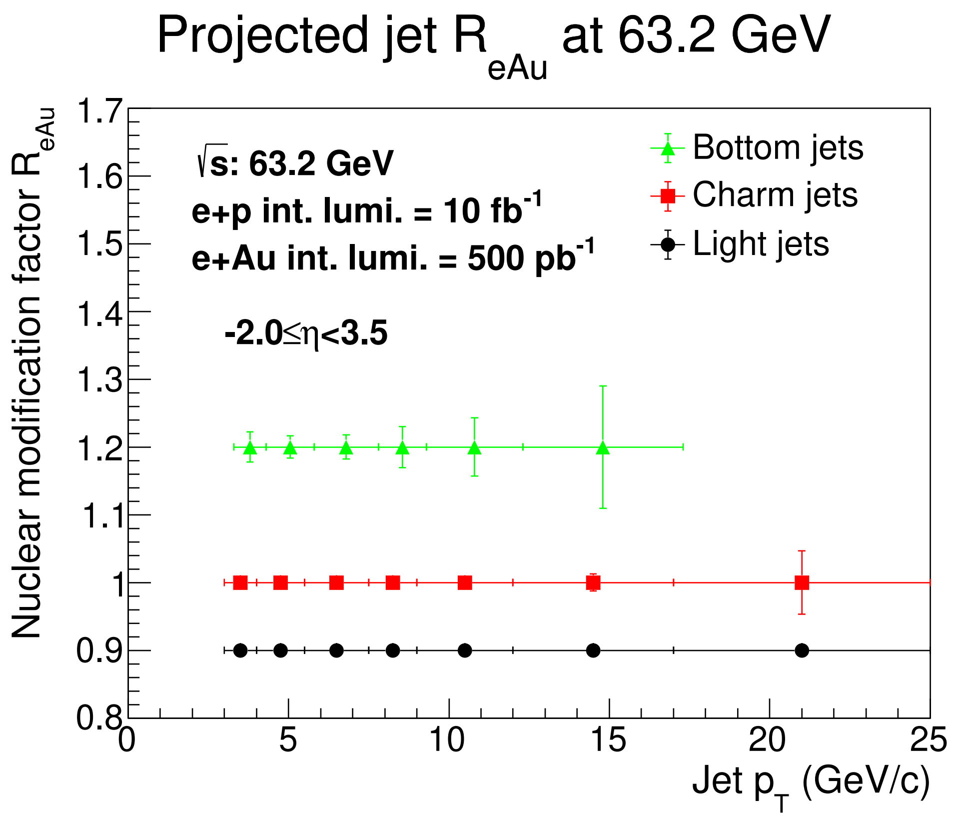
$$R_{eA} = \frac{1}{A}\frac{\sigma_{eA}}{\sigma_{ep}}$$

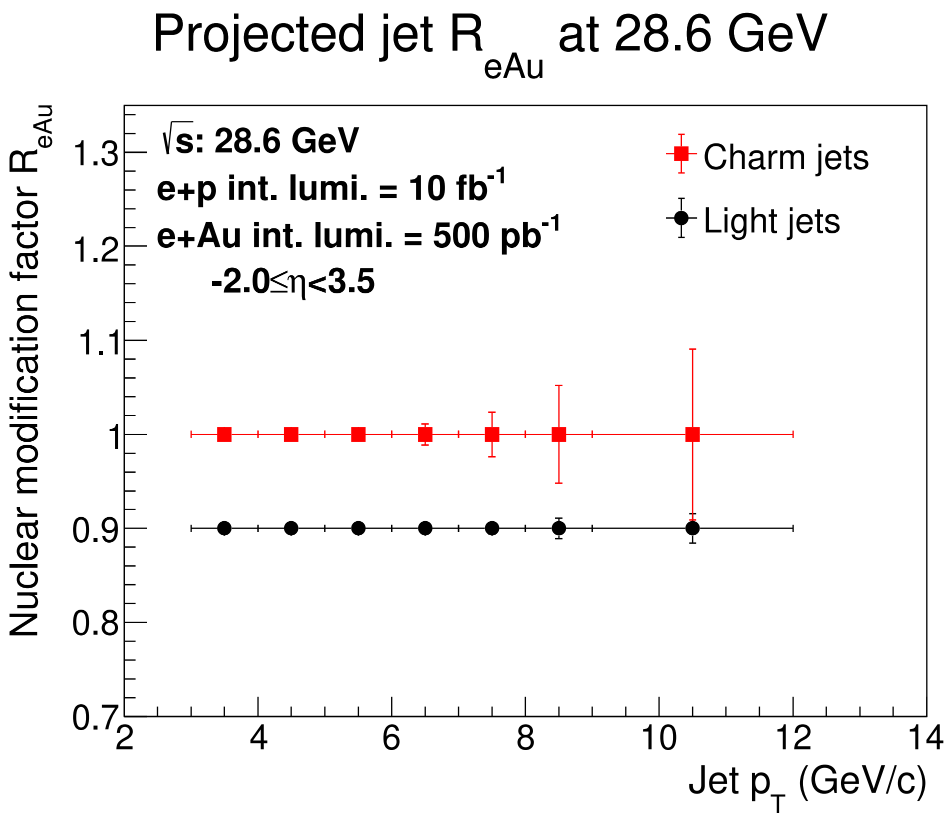




Heavy flavor jet R_{eA} to explore parton energy loss mechanism

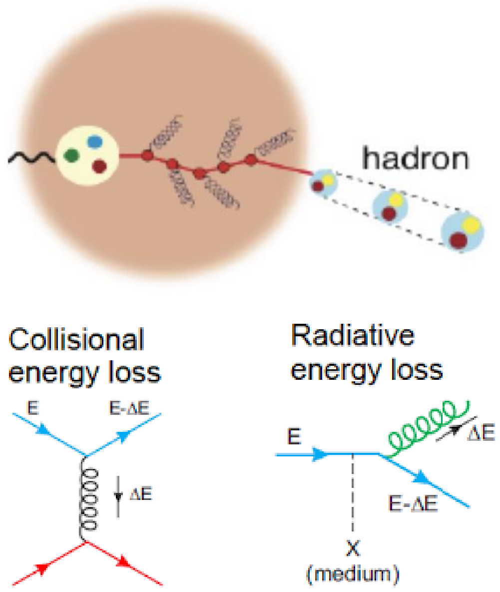
- Projected nuclear modification factor R_{eA} of jets with different flavors in e+p and e+Au collisions at 28.6 GeV (right) and 63.2 GeV (left).





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

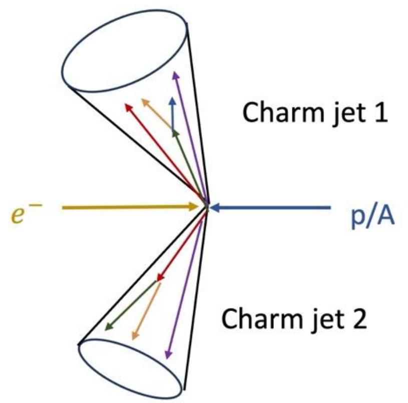
Parton energy loss

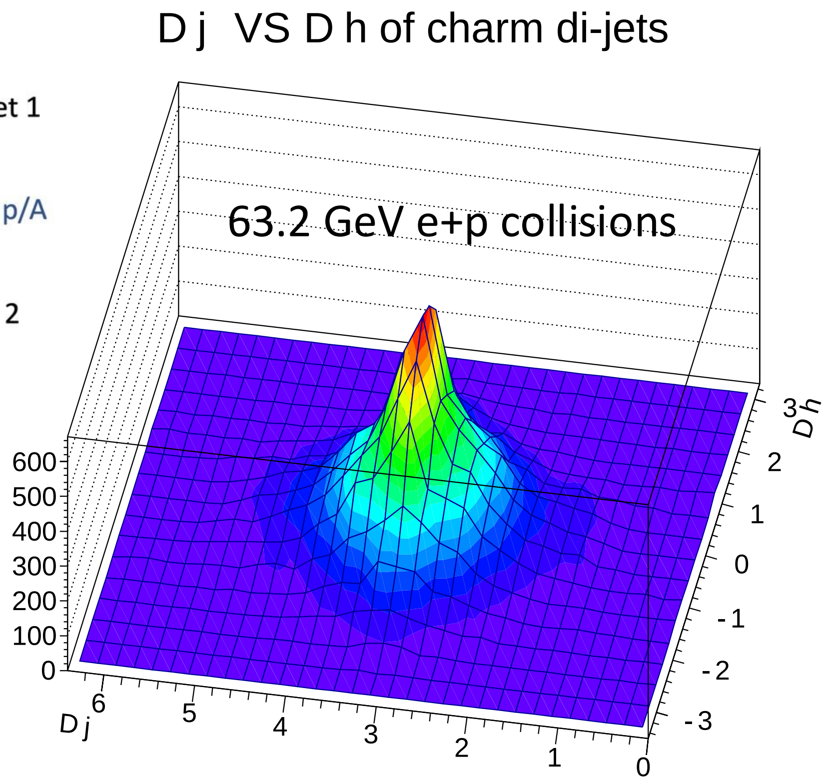


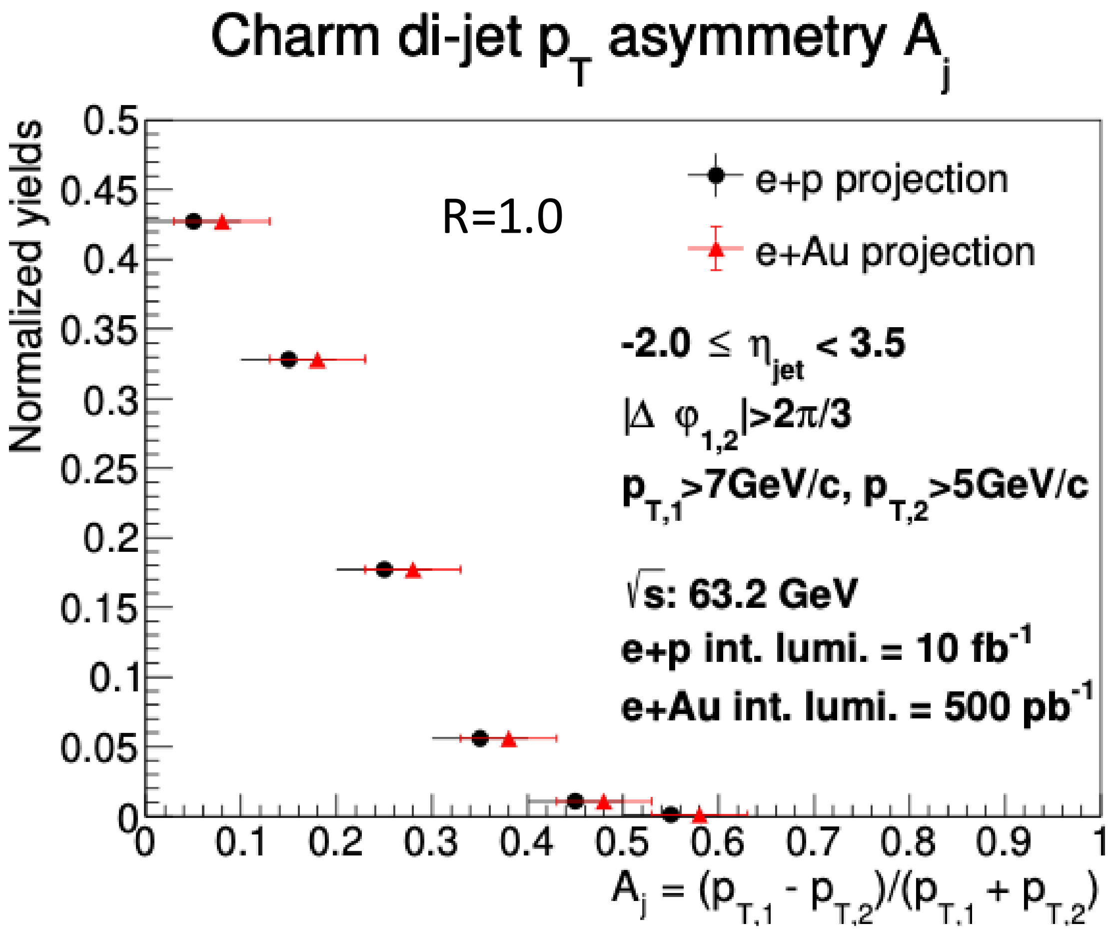
- Great precision to explore the flavor dependent parton energy loss mechanism especially in the low p_T region.

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.





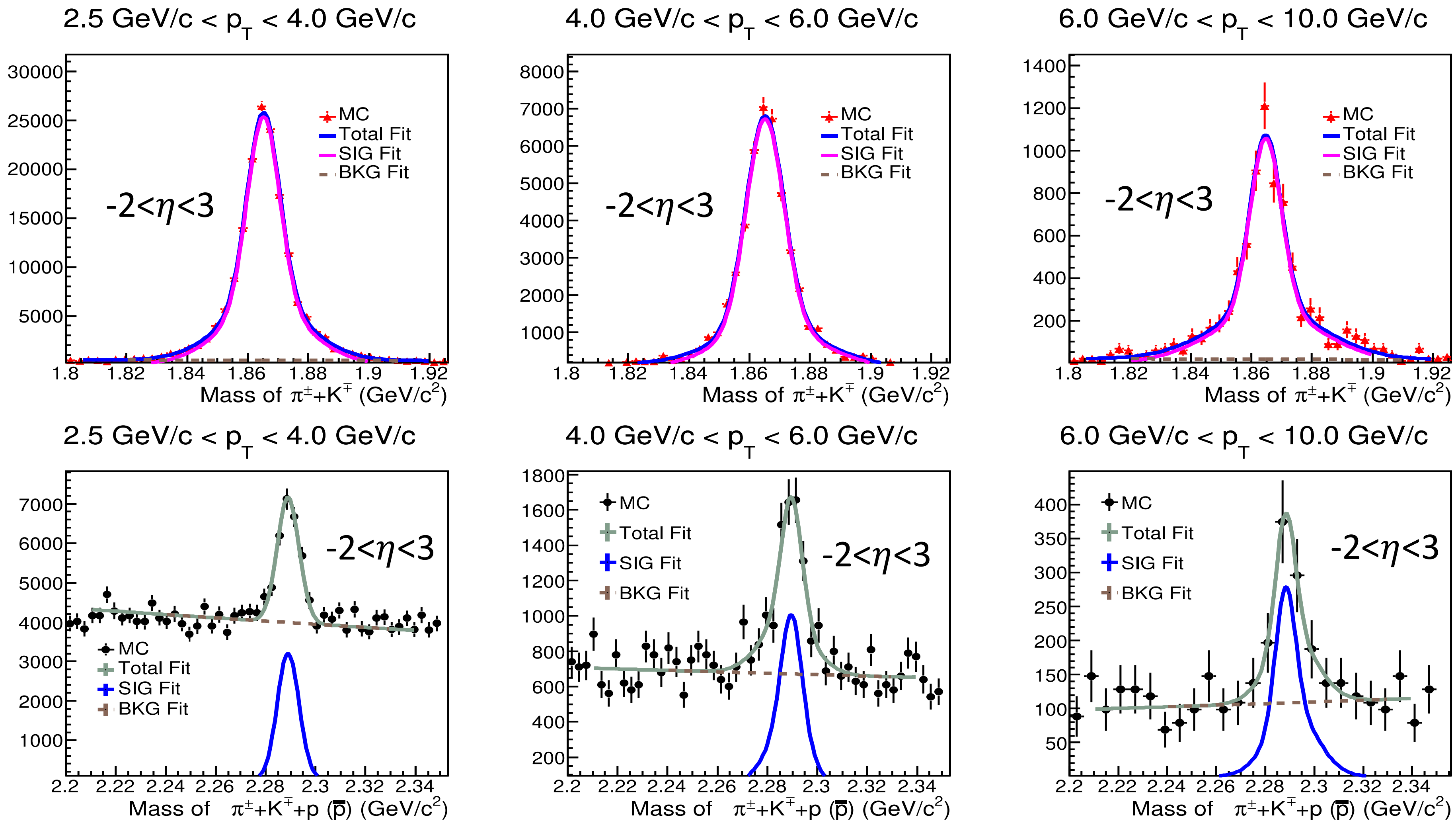


- More differential studies (pseudorapidity separated distributions) are underway.

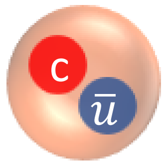
Charm baryon/meson ratio studies at the EIC

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

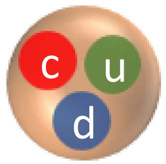
- Clear signals can be found in the p_T separated invariant mass spectrums of reconstructed D^0 and Λ_c in 10 GeV+100 GeV e+p collisions.



Inclusive charm hadron reconstruction



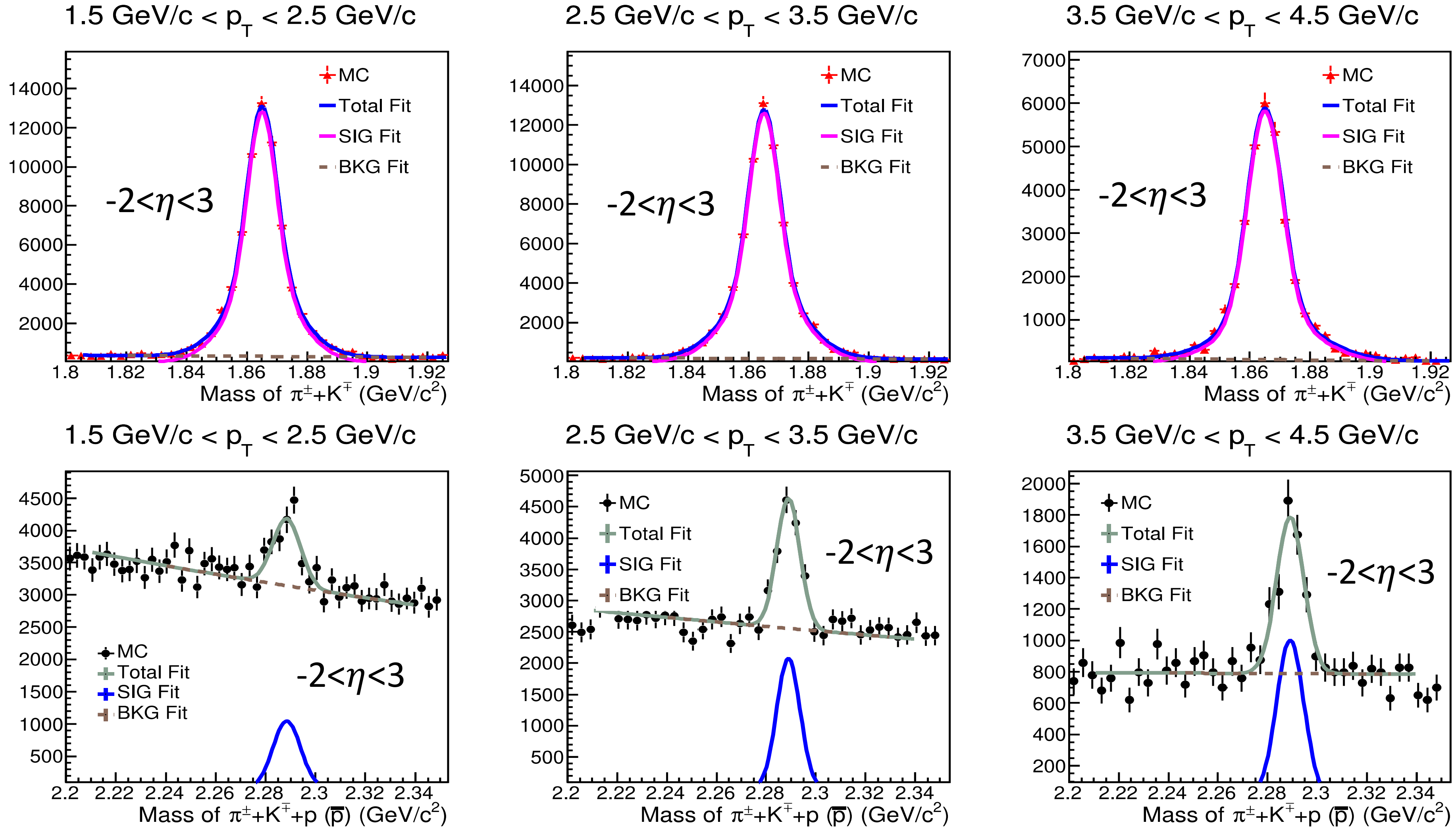
$D^0(\overline{D^0})$



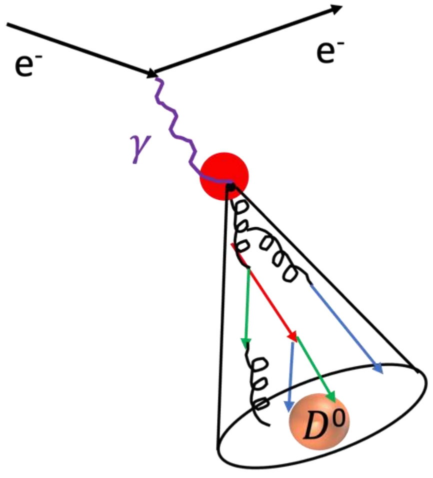
$\Lambda_c^{\pm}$

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.



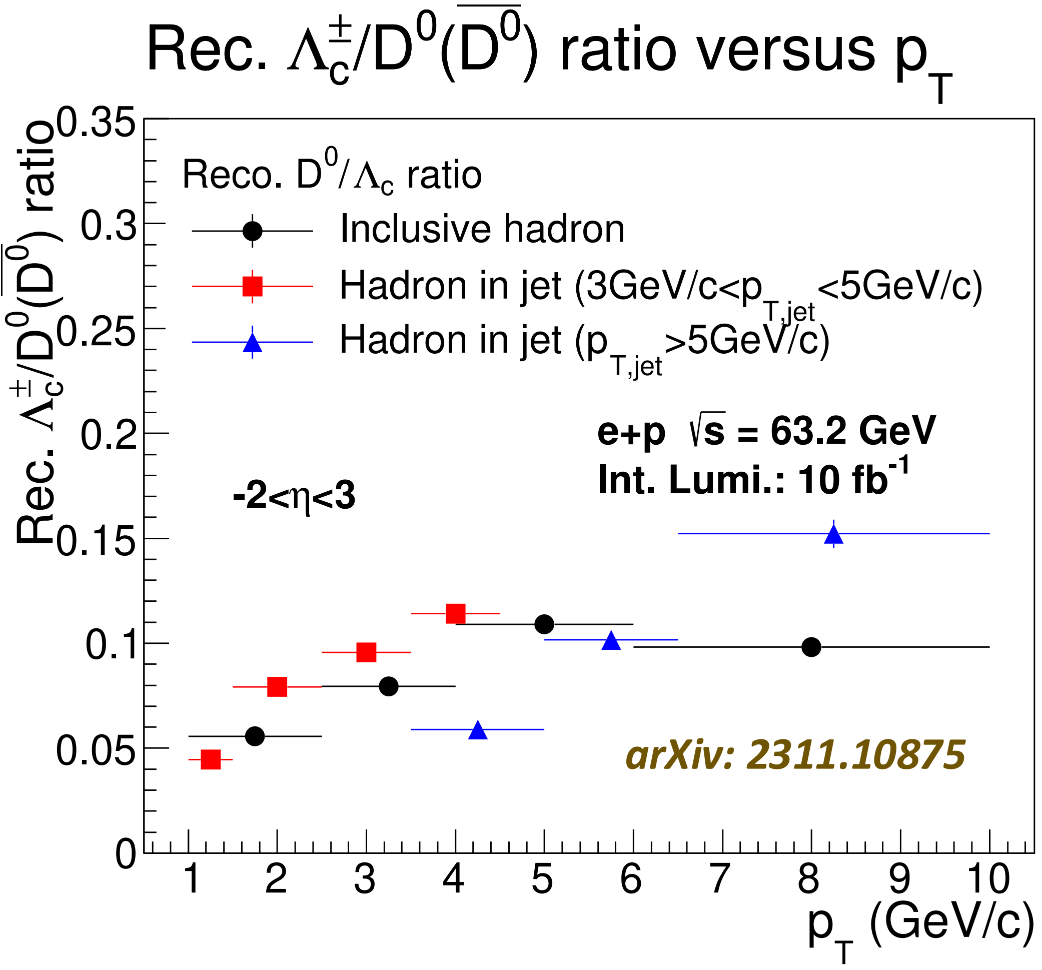
Reconstruction of charm hadrons inside jets with p_T 3-5 GeV/c



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

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

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



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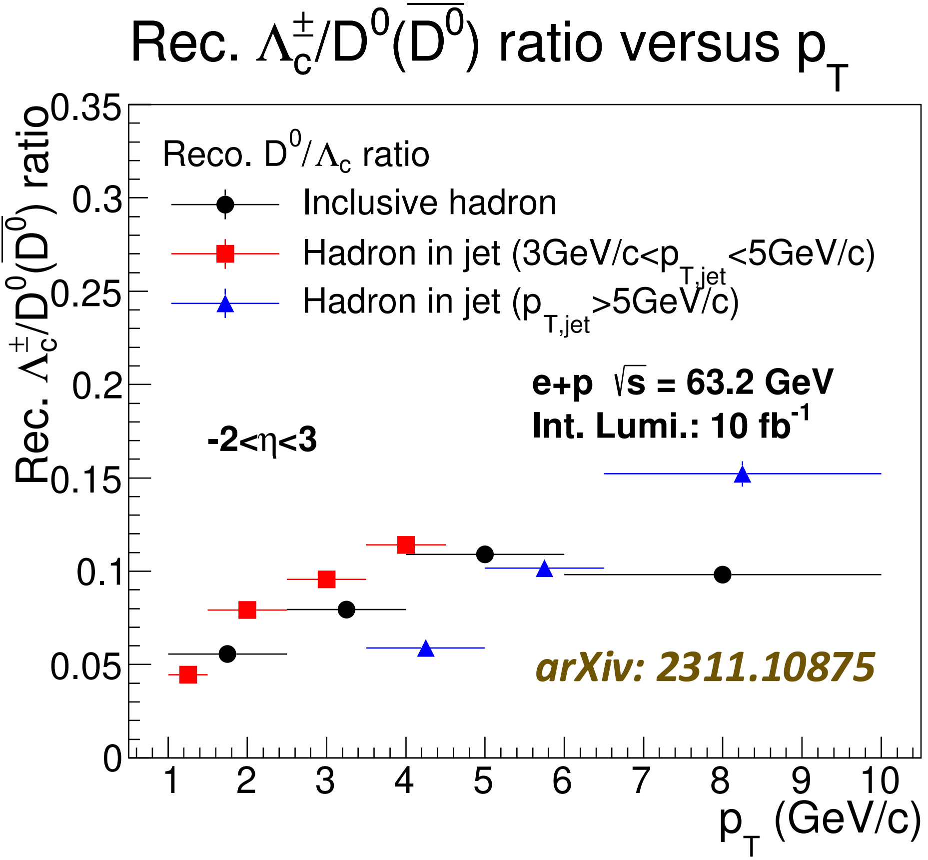
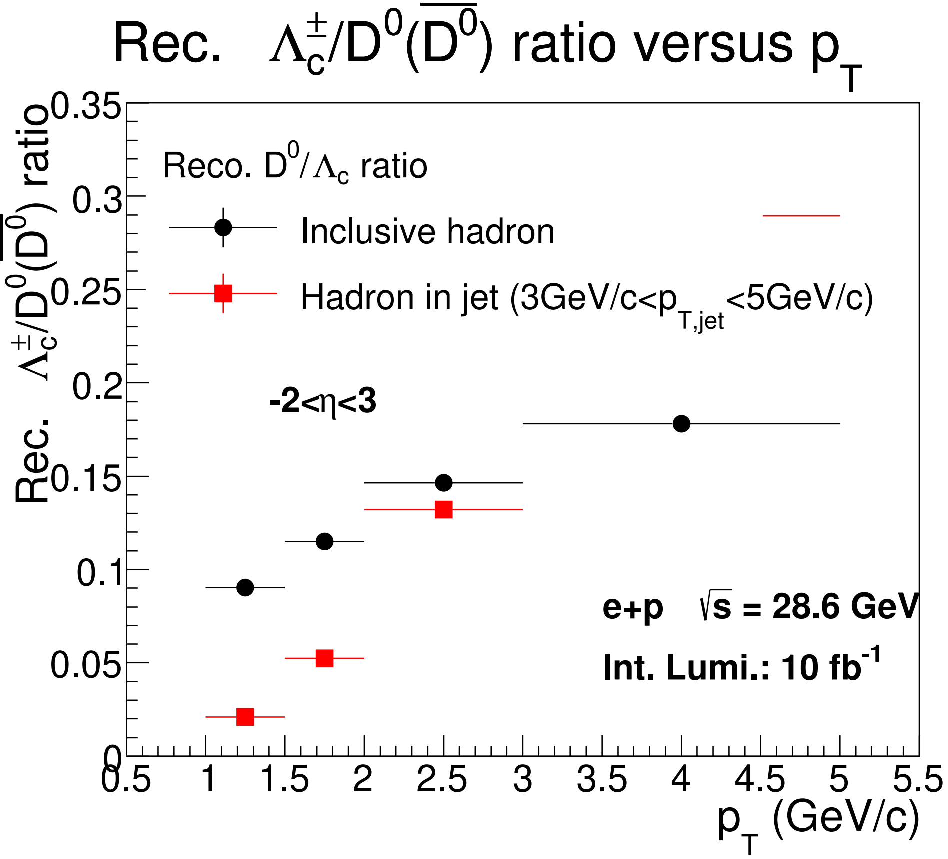




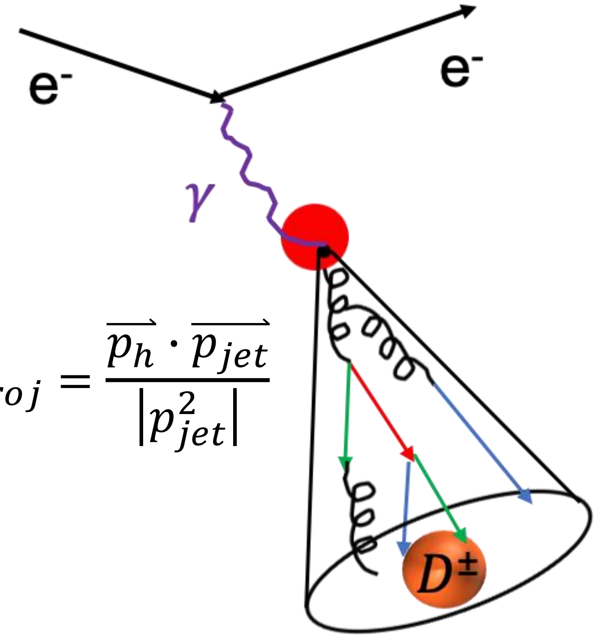
- Unique approach to explore the charm fragmentation function with different scaling factors and different medium conditions from heavy ion measurements.

Heavy flavor hadron inside jet studies at the EIC

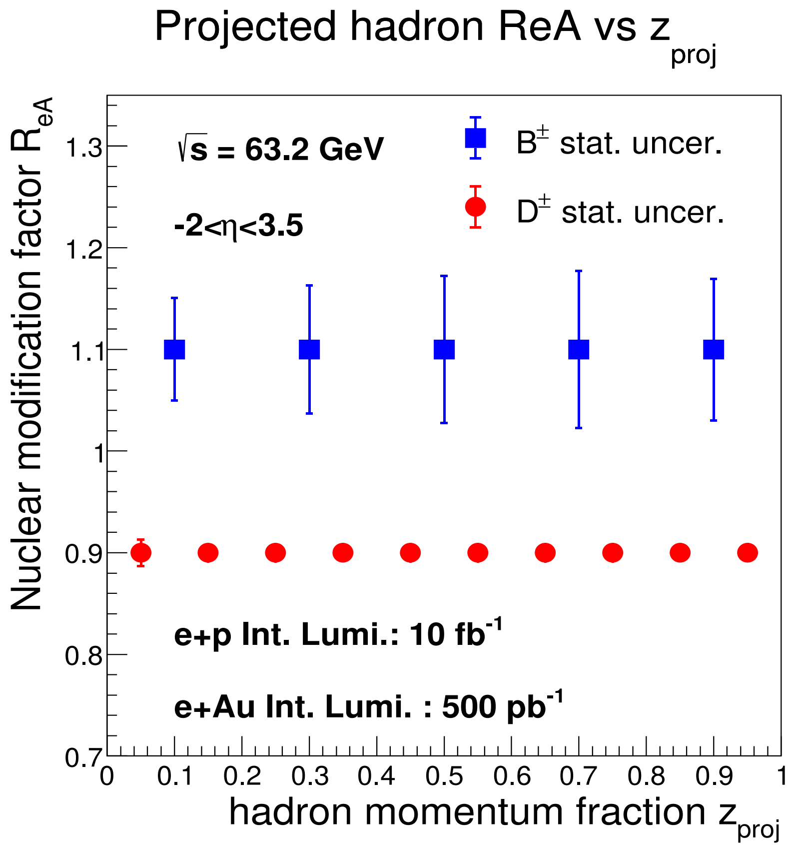
Heavy flavor hadron inside jet nuclear modification factor R_{eAu} projection

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

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



$$z_{proj} = \frac{\overrightarrow{p_h} \cdot \overrightarrow{p_{jet}}}{|p_{jet}^2|}$$



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

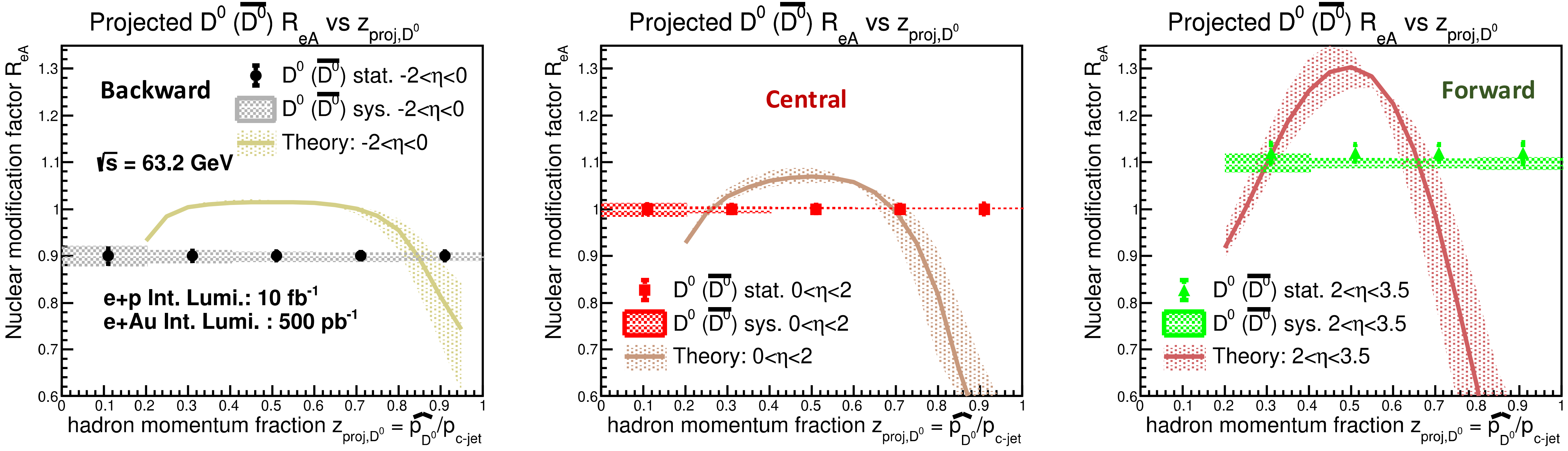
Great precision to be achieved by the EIC measurements in the accessed kinematic phase space.

- Future EIC heavy flavor inside jet measurements will provide great constraints in extracting charm/bottom fragmentation function under different medium conditions.

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. *arXiv: 2311.10875*



- 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.

Jet substructure studies at the EIC

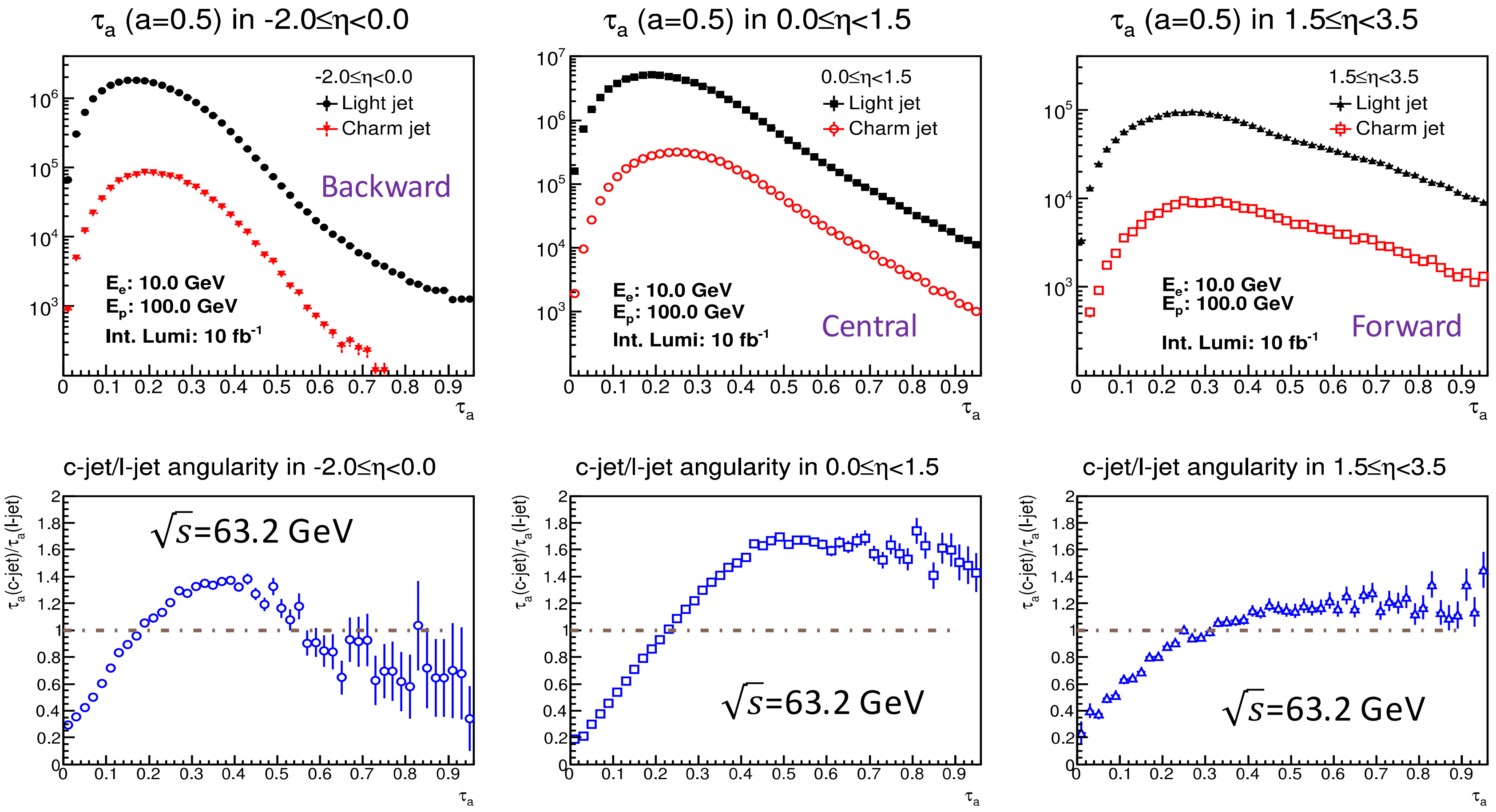
Heavy flavor jet substructure (I)

- Jet substructure observables are good probes to study the parton showering/splitting and 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

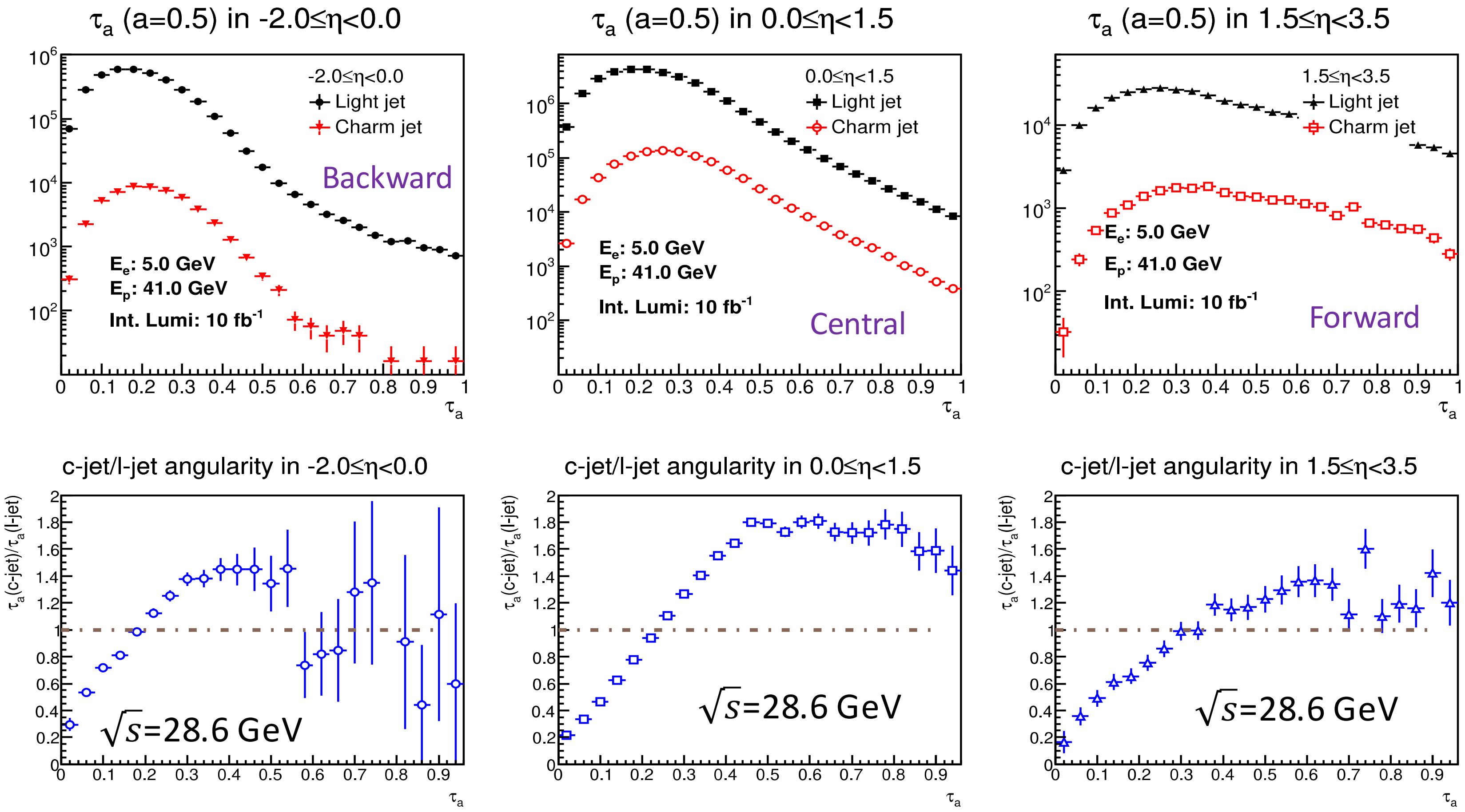


- The charm/light jet angularity shape difference depends on the pseudorapdy.

Heavy flavor jet substructure (II)

- Jet substructure observables are good probes to study the parton showering/splitting and 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

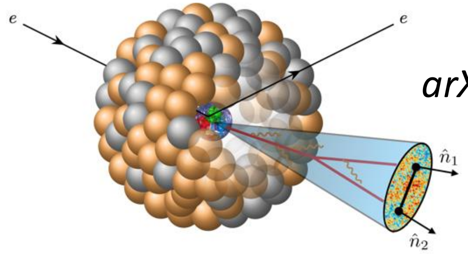


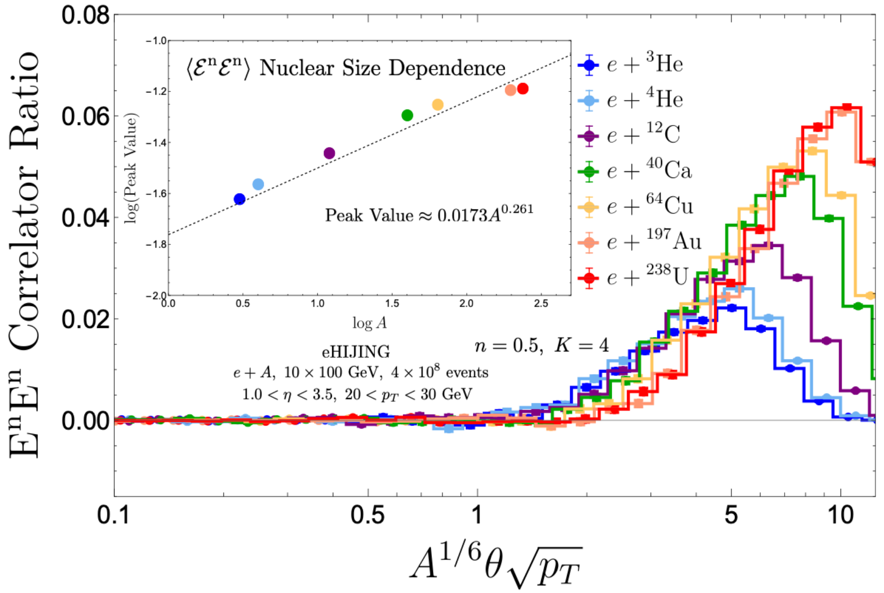
- The charm/light jet angularity shape difference depends on the pseudorapdy and less relies on $\sqrt{s}$.
- Shed light onto the process of parton splitting into final hadrons with different masses.
- Impacts by nuclear medium effects will be studied in e+A collisions.

Other interesting topics

Energy-Energy Correlator in inclusive jets in different e+A collisions

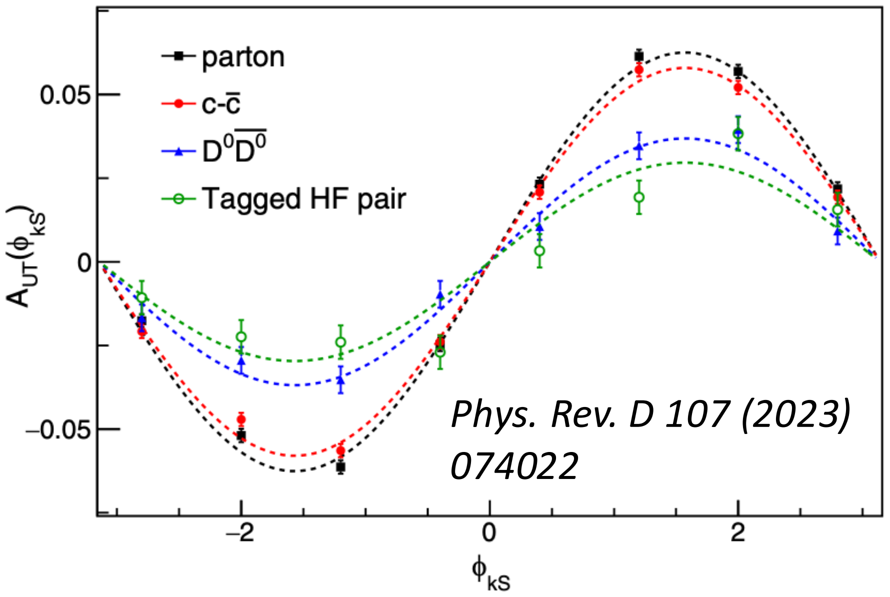
arXiv: 2303.08143





- Energy-energy correlator in heavy flavor jets at the EIC?

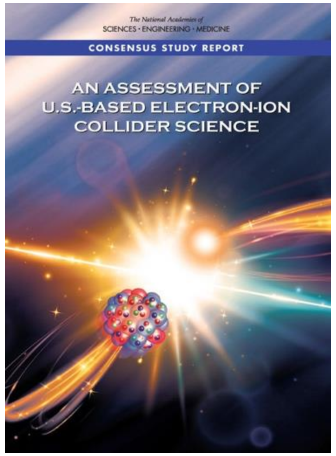
Projected transverse asymmetry A_{UT} for different charm correlation in 18+100 GeV e+p collisions



- Differential charm/bottom di-jet correlation studies to constrain the initial state effects?
- Additional heavy flavor observables to constrain the medium effects?

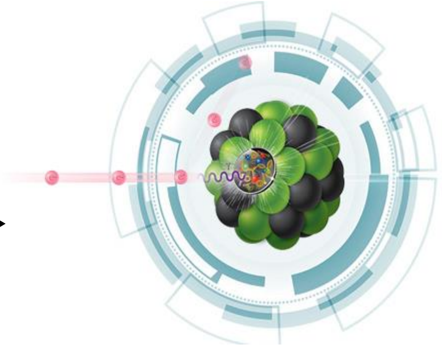
Summary and Outlook

- Great precision will be achieved by the EIC heavy flavor hadron and jet measurements in e+p and e+A collisions within complimentary kinematic regions from existing measurements.
- The future EIC will provide unique opportunities to study both initial and final state effects for heavy flavor production such as parton energy loss and hadronization process within a wide kinematic coverage.
- As we are moving towards the EIC construction in 2025, we look forward to work with more collaborators for the EIC detector/experiment realization.



NAS review	EIC CD0	EIC CD1	EIC CD3/A	EIC CD2/3	EIC CD-4a	EIC CD-4
2018	2020	2021	2024	2025	2034	2036

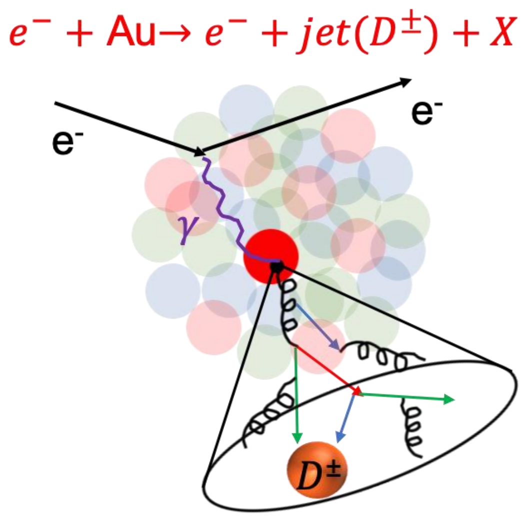
Design Phase (2018–2025) | Construction Phase (2025–2036) | Science Phase (2036–)

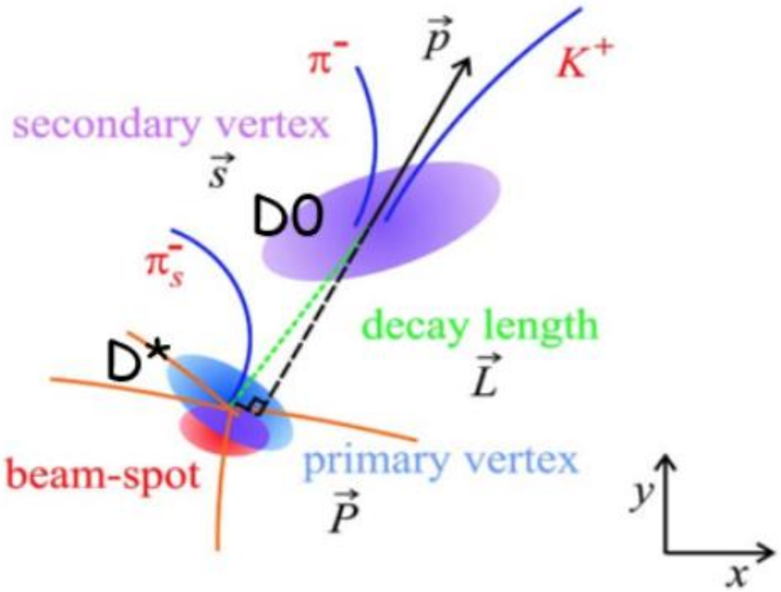


Backup

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.



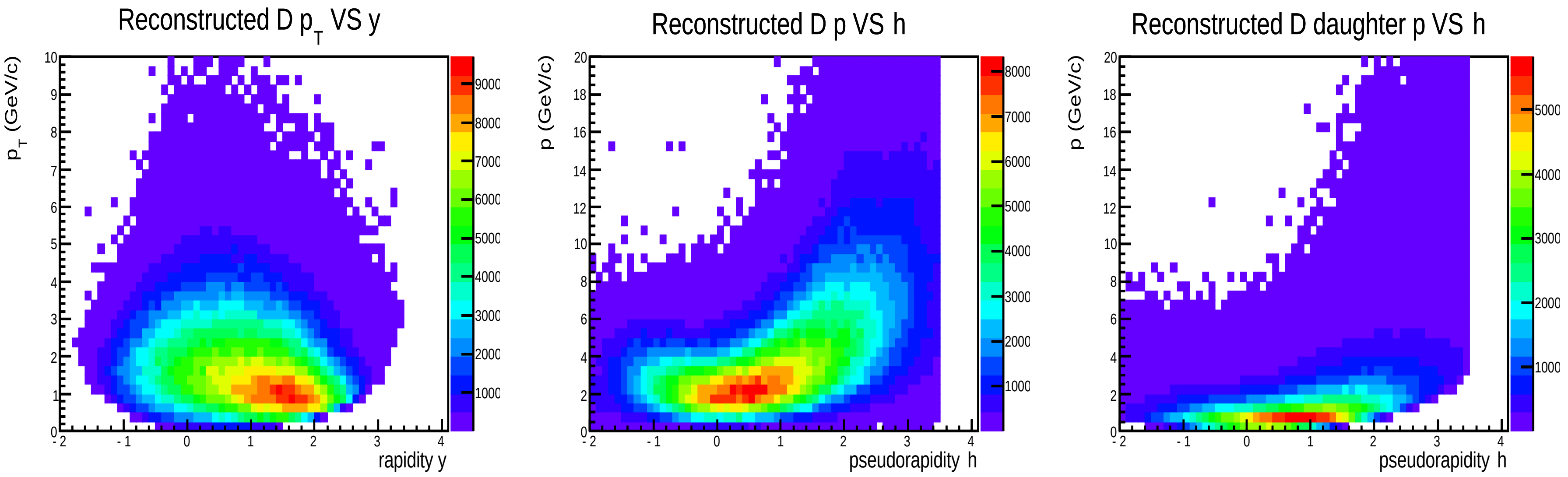


Particle	Mass (GeV/c²)	Average decay length
$D^{\pm}$	1.869	312 micron
D^0	1.864	123 micron
$B^{\pm}$	5.279	491 micron
B^0	5.280	456 micron

- Heavy flavor physics-driven detector performance requirements:
  - Fine spatial resolution for displaced vertex reconstruction.
  - Fast timing resolution to suppress backgrounds from neighboring collisions.
  - Low material budgets to maintain fine hit resolution for track reconstruction.

EIC heavy flavor measurements require high granularity vertex/tracking Dec.

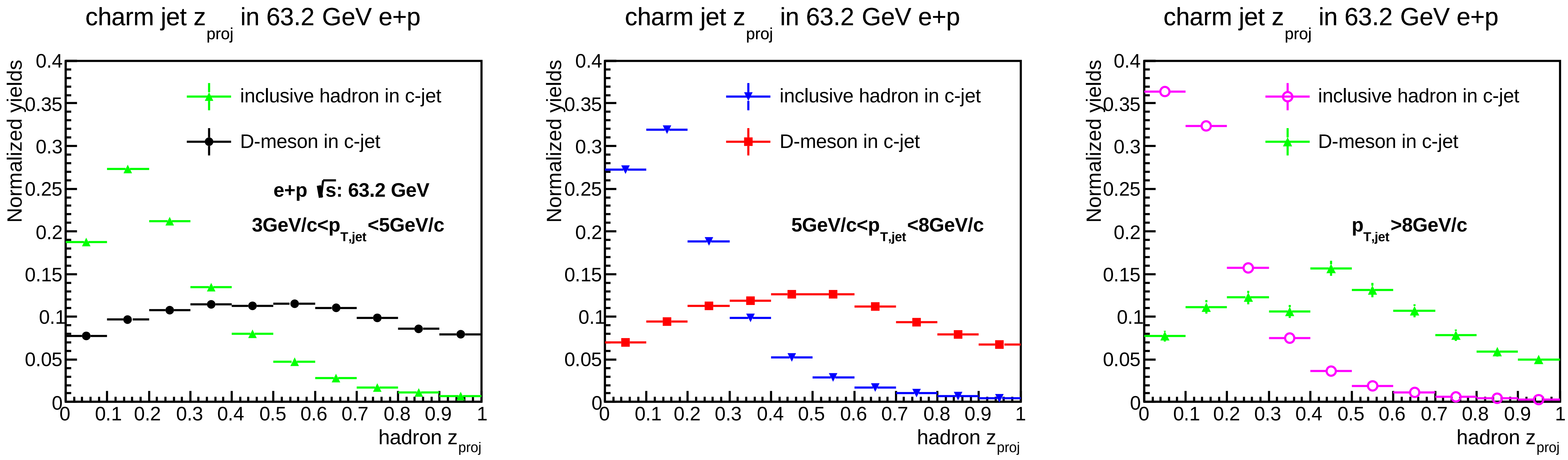
- To meet the heavy flavor physics measurements, a high granularity vertex/tracking detector with low material budgets and fine spatial resolution is needed.
- Particles produced in the asymmetric electron+proton and electron+nucleus collisions have a higher production rate in the forward pseudorapidity.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

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.