Los Alamos NATIONAL LABORATORY

Previous Heavy Flavor Benchmark

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Outline

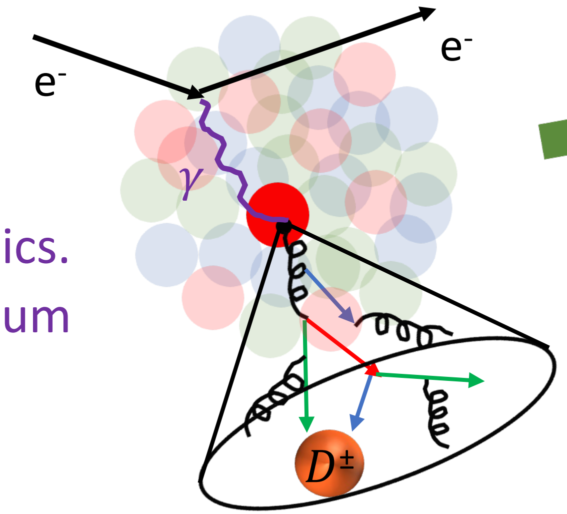
- Motivation
- Heavy flavor highlight from ATHENA and ECCE.
- Heavy flavor hadron and jet studies in standalone simulation with the ePIC detector performance.
- Near-term plan about using the ePIC DD4HEP software.
- Summary and Outlook.

Heavy flavor measurements can enrich the EIC physics program

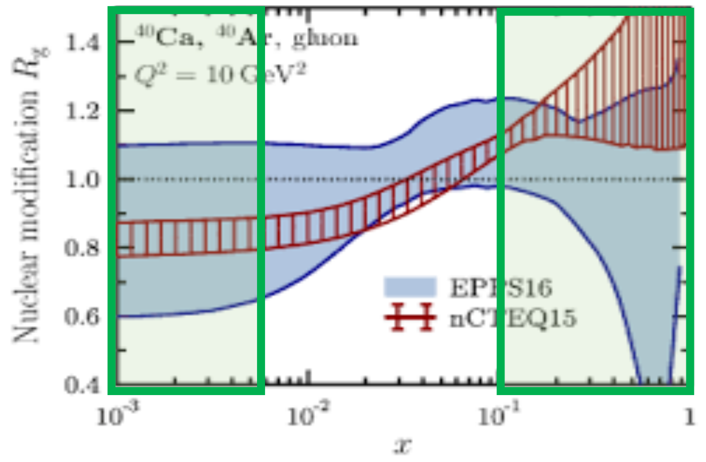
- Heavy flavor hadron and jet measurements are an important part of the EIC science portfolio and play a significant role in exploring
  - Nuclear modification on the initial nuclear Parton Distribution Functions (nPDFs) especially in the high and low Bjorken-x (x_{BJ}) region.
  - Final state parton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

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

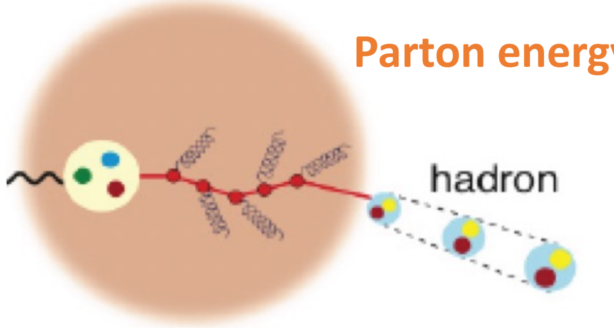
- Uniqueness of the EIC measurements:
  - Precise determination of initial-state parton kinematics.
  - Different cold nuclear medium conditions created in e+A collisions.



nPDF modification



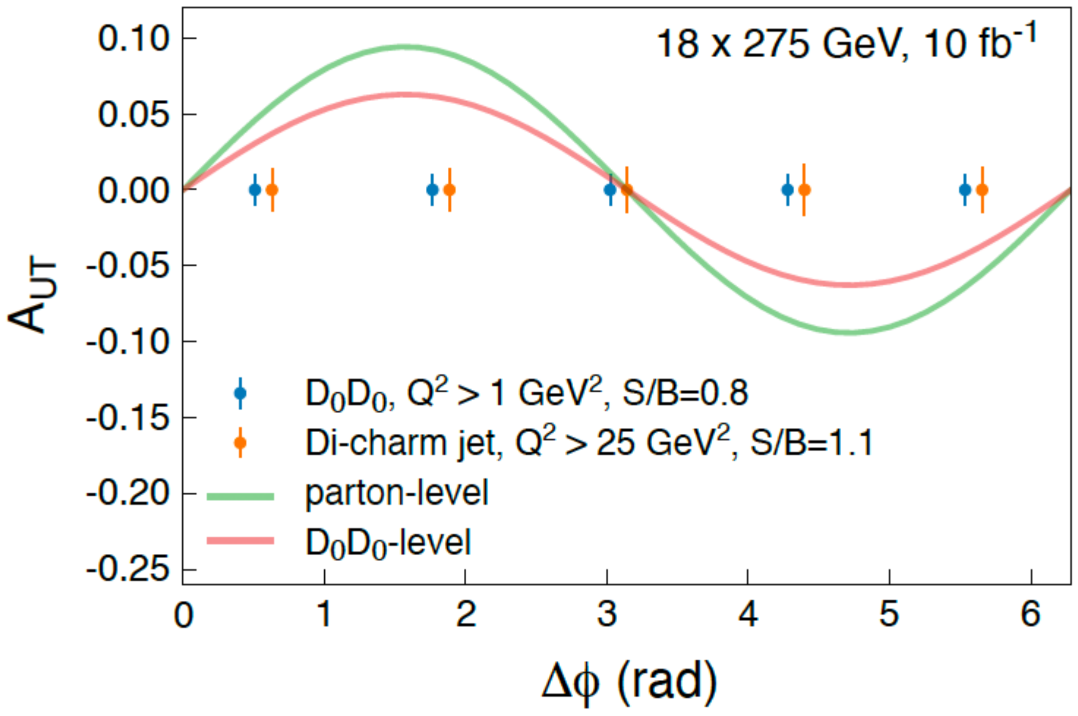
Parton energy loss

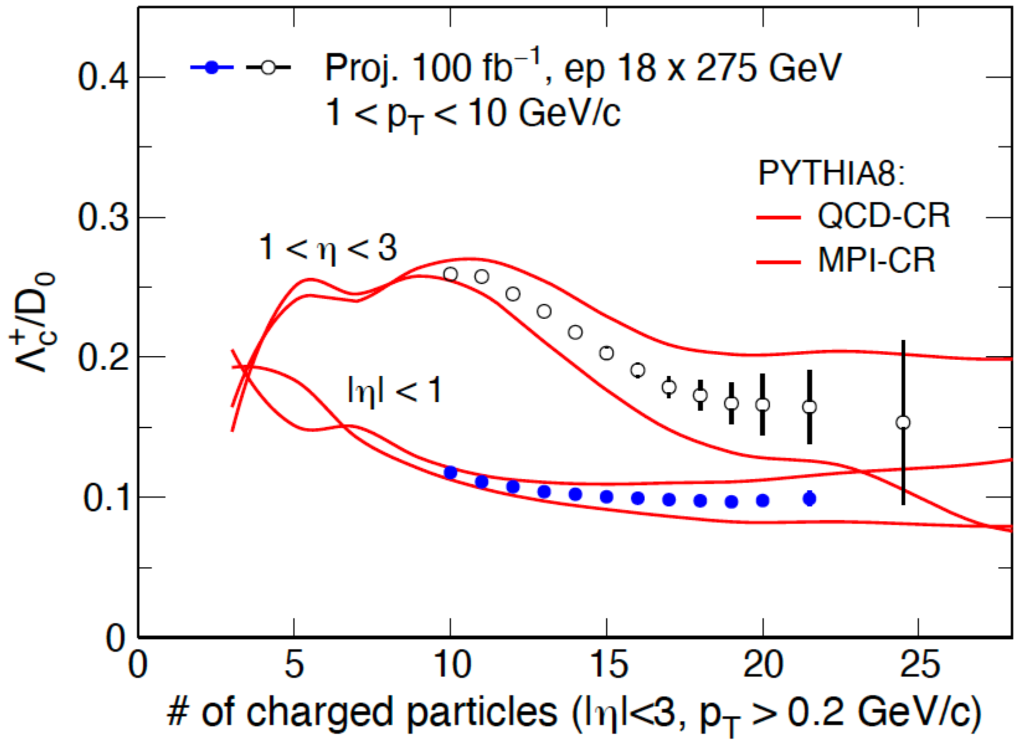


Selected open heavy flavor highlight from ATHENA

- Imaging the proton spin structure via di-D^0 and di-charm-jet A_{UT} measurement in 18+275 GeV polarized e+p collisions.
- Explore the charm hadronization via Λ_c/D^0 measurement.

JINST 17 (2022) P10019

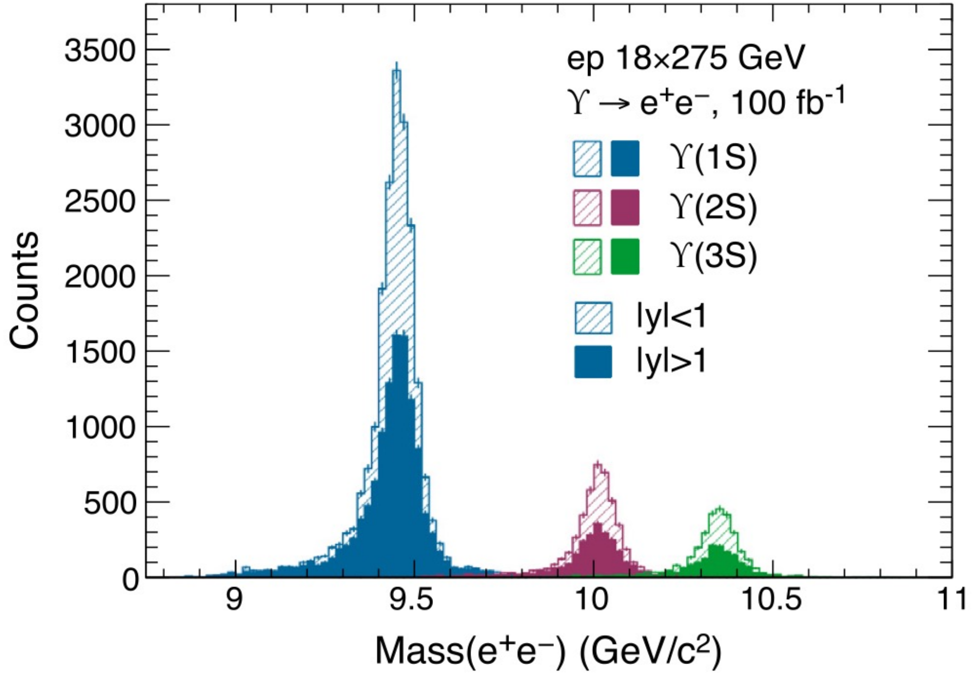




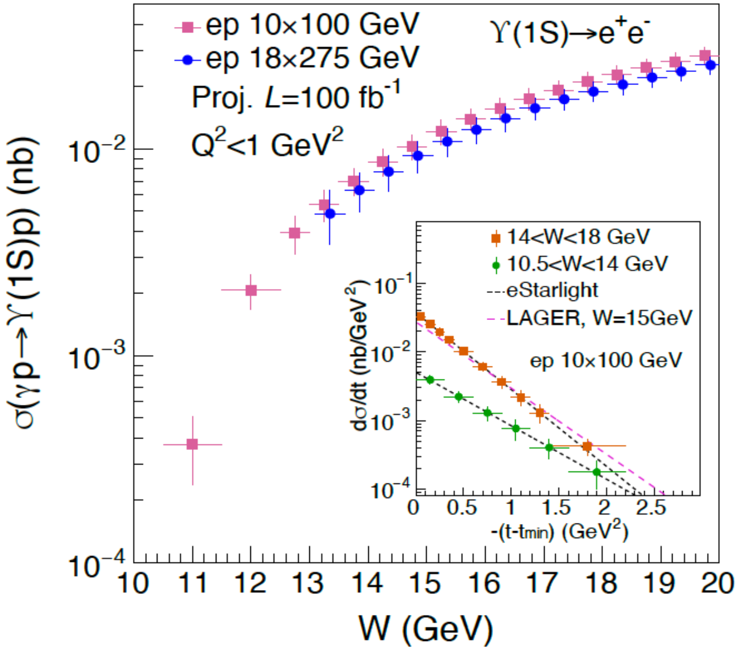
Selected quarkonium highlight from ATHENA

- ATHENA exclusive ϒ reconstruction via di-electron channel in 18+275 GeV e+p simulation.
- Clear ϒ(1s), ϒ(2s) and ϒ(3s) signals in the |y|<1 and |y|>1 rapidity regions.

NIM A 1046 (2023) 167606



Near threshold ϒ production



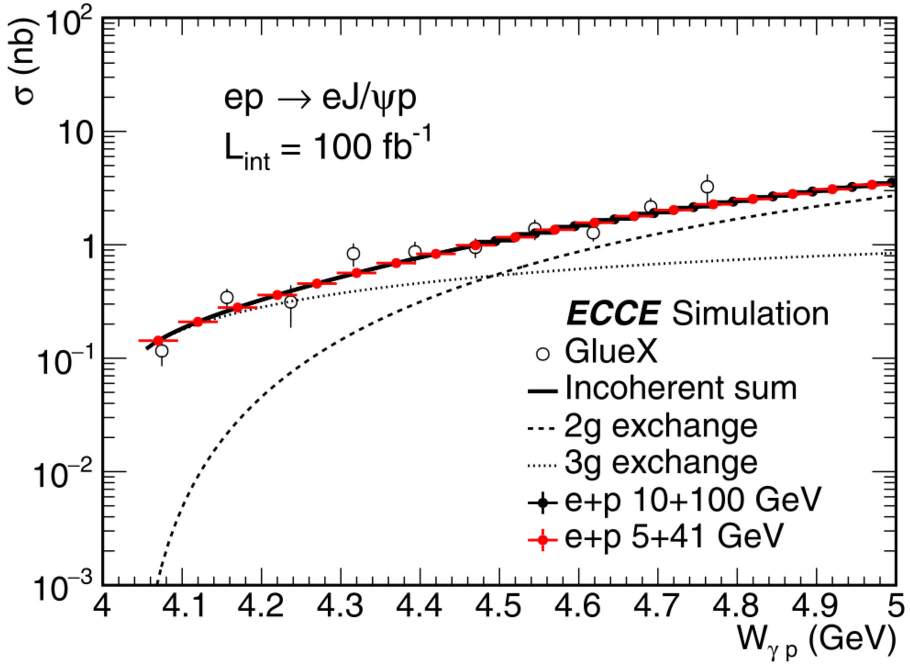
JINST 17 (2022) P10019

- Need high statistics (100 fb^{-1}) and high energy (e.g., 18+275 GeV).
- How about e+A reconstruction?

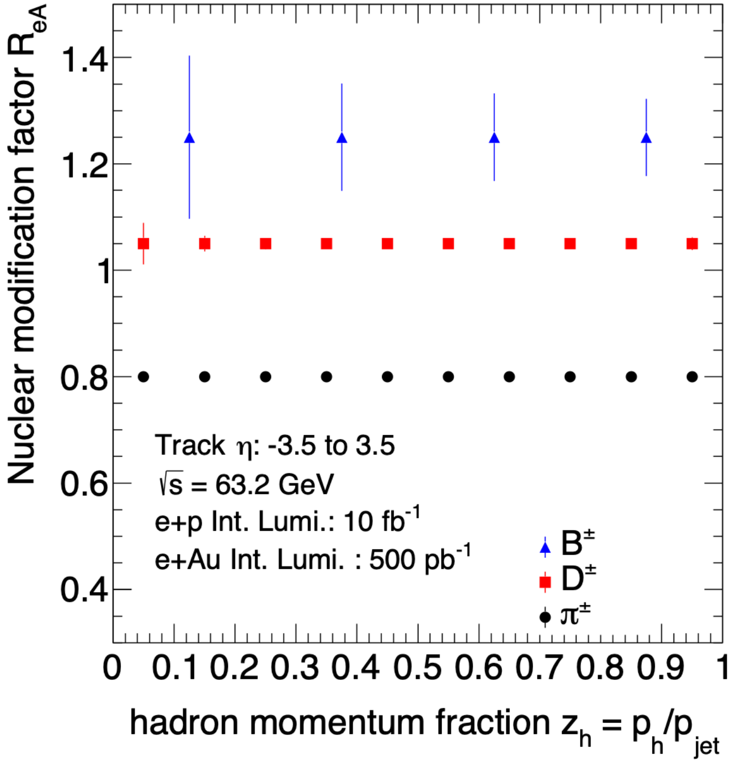
Selected heavy flavor highlight from ECCE

- Great precision of near threshold J/ψ production paves the path to explore the pentaquark charm hadron capability.
- High precision heavy flavor nuclear modification factor (R_{eA}) in 10+100 GeV e+p and e+Au collisions provide unique access to the heavy quark hadronization.

NIM A 1048 (2023) 167956

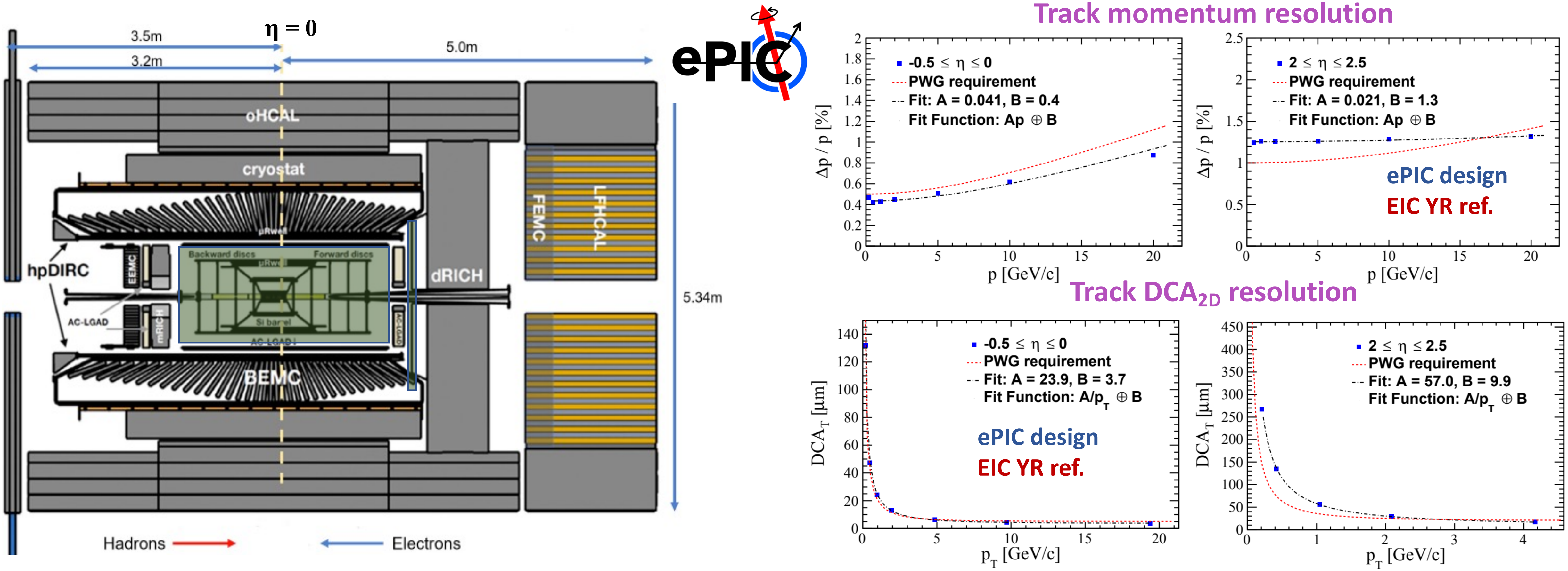


arXiv: 2207.10632



ePIC detector design and key performance for HF reconstruction

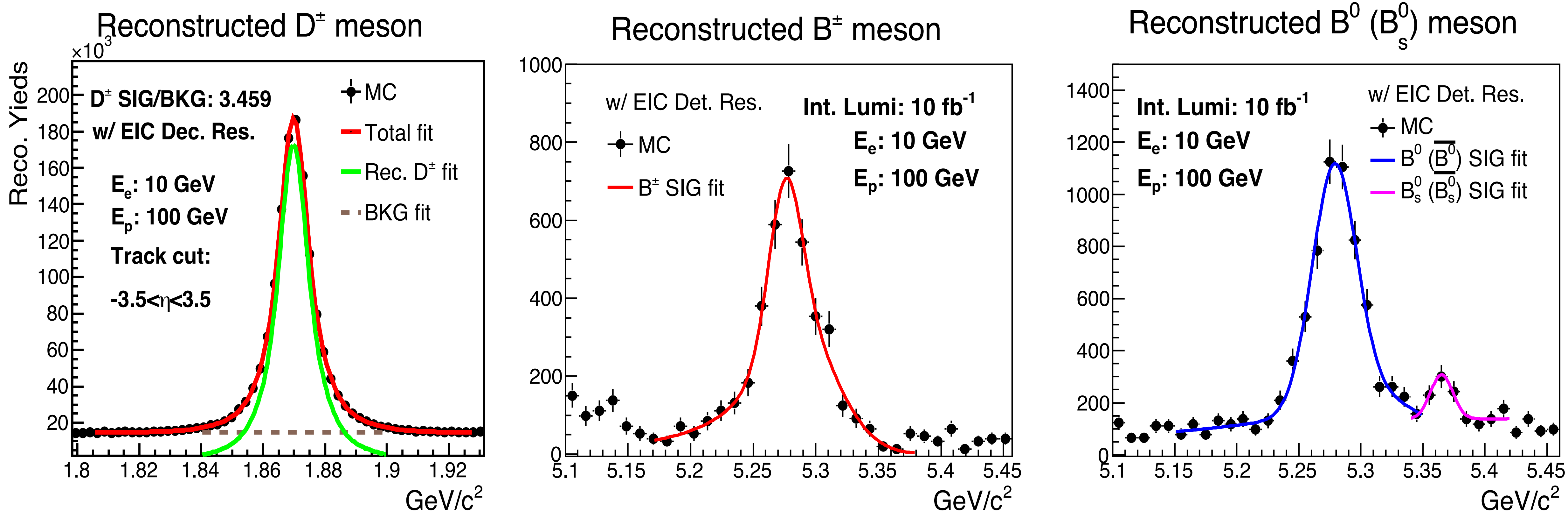
- The current EIC project detector design (ePIC), which consists of MAPS, MPGD and AC-LGAD tracking detectors, can achieve good momentum and transverse DCA_{2D} resolutions. The ePIC detector will utilize stream readout and can provide precise particle identification and energy determination for heavy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



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.

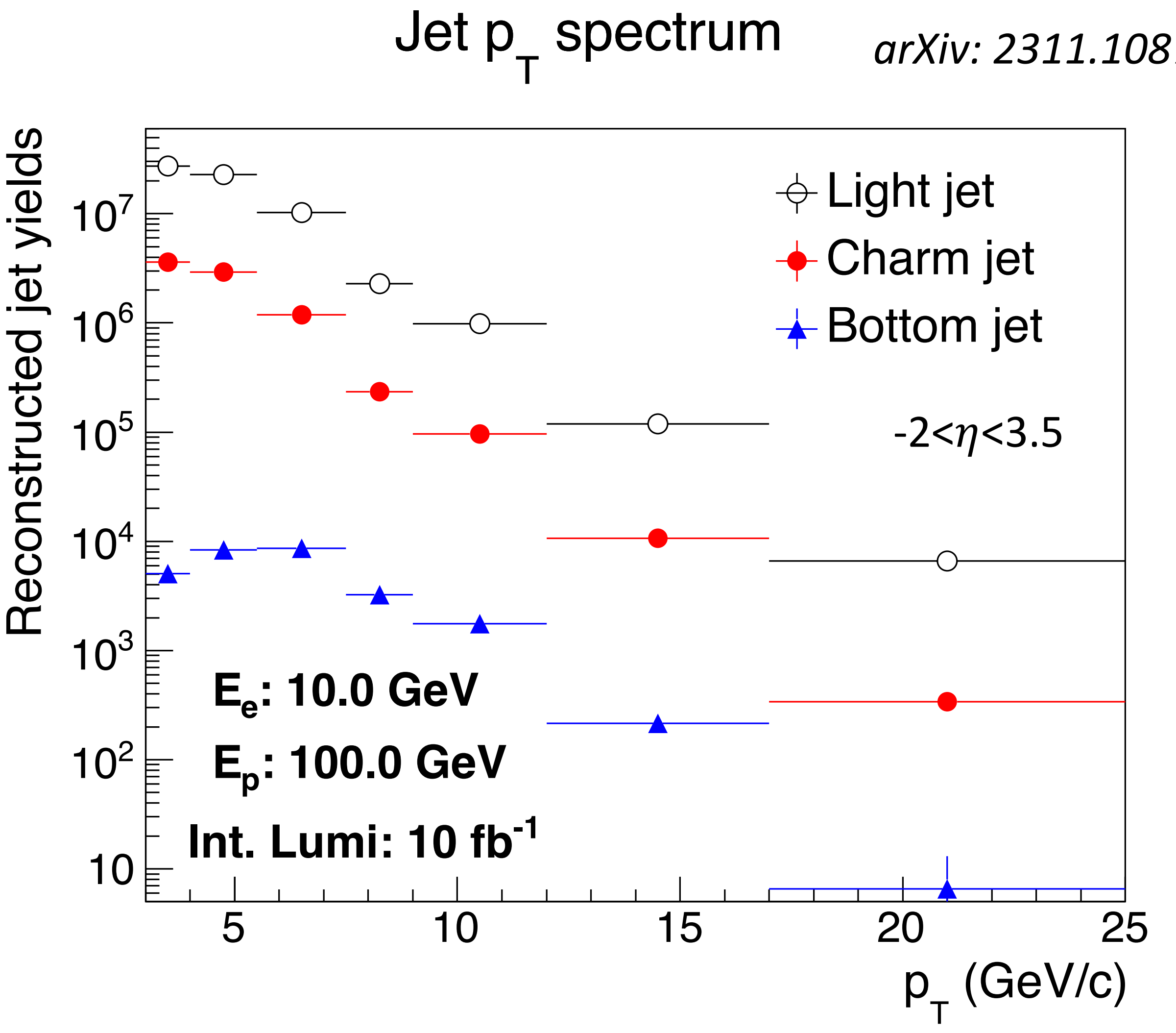
arXiv: 2311.10875



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.

arXiv: 2311.10875

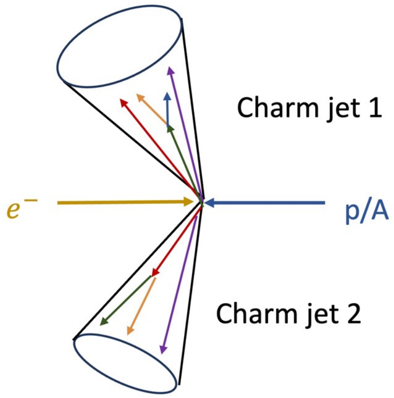


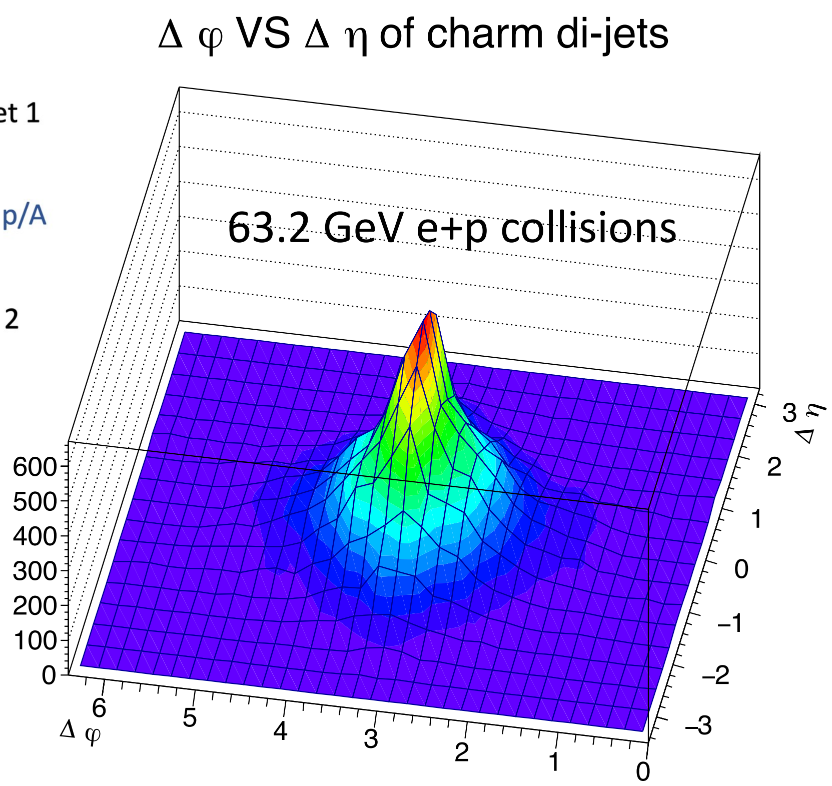
Most jets with p_T < 15 GeV/c

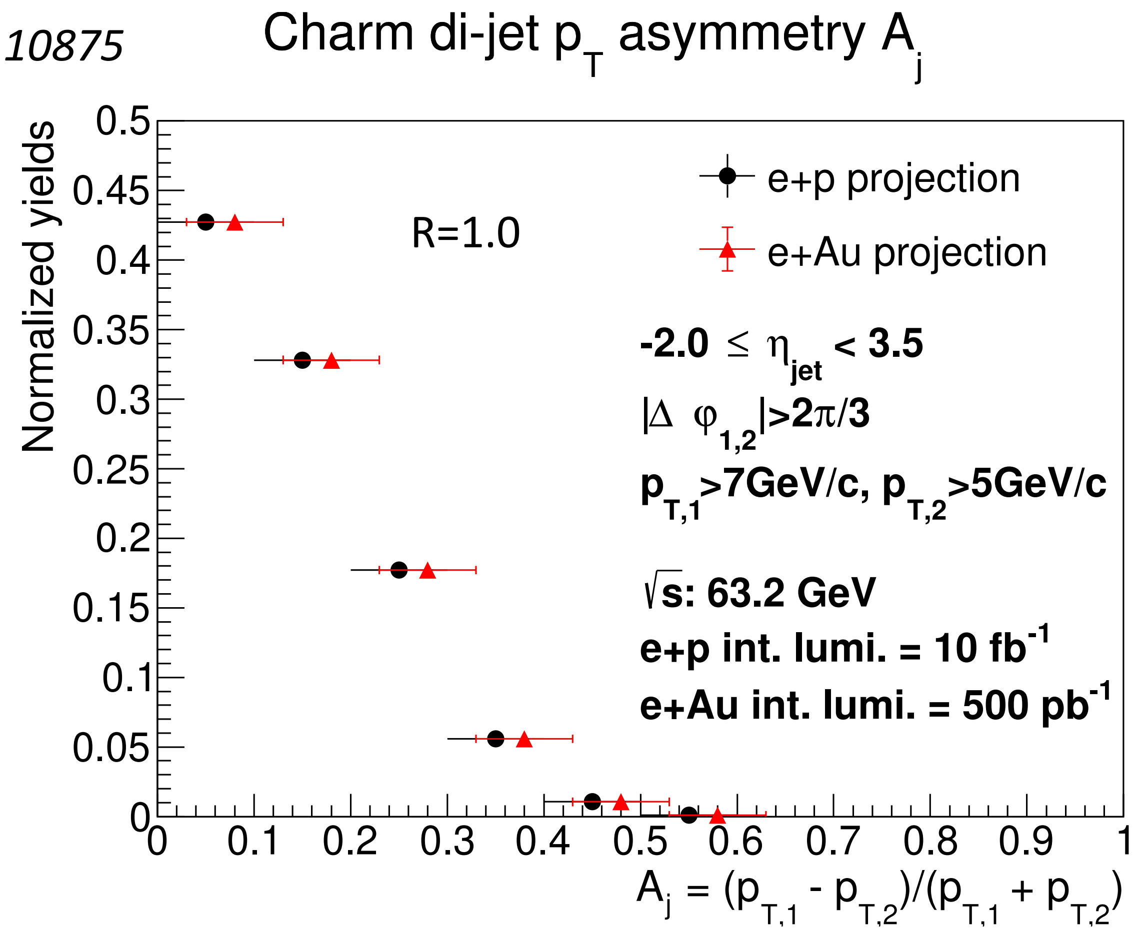
Heavy flavor di-jet production at the EIC to study parton propagation

- 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.

arXiv: 2311.10875



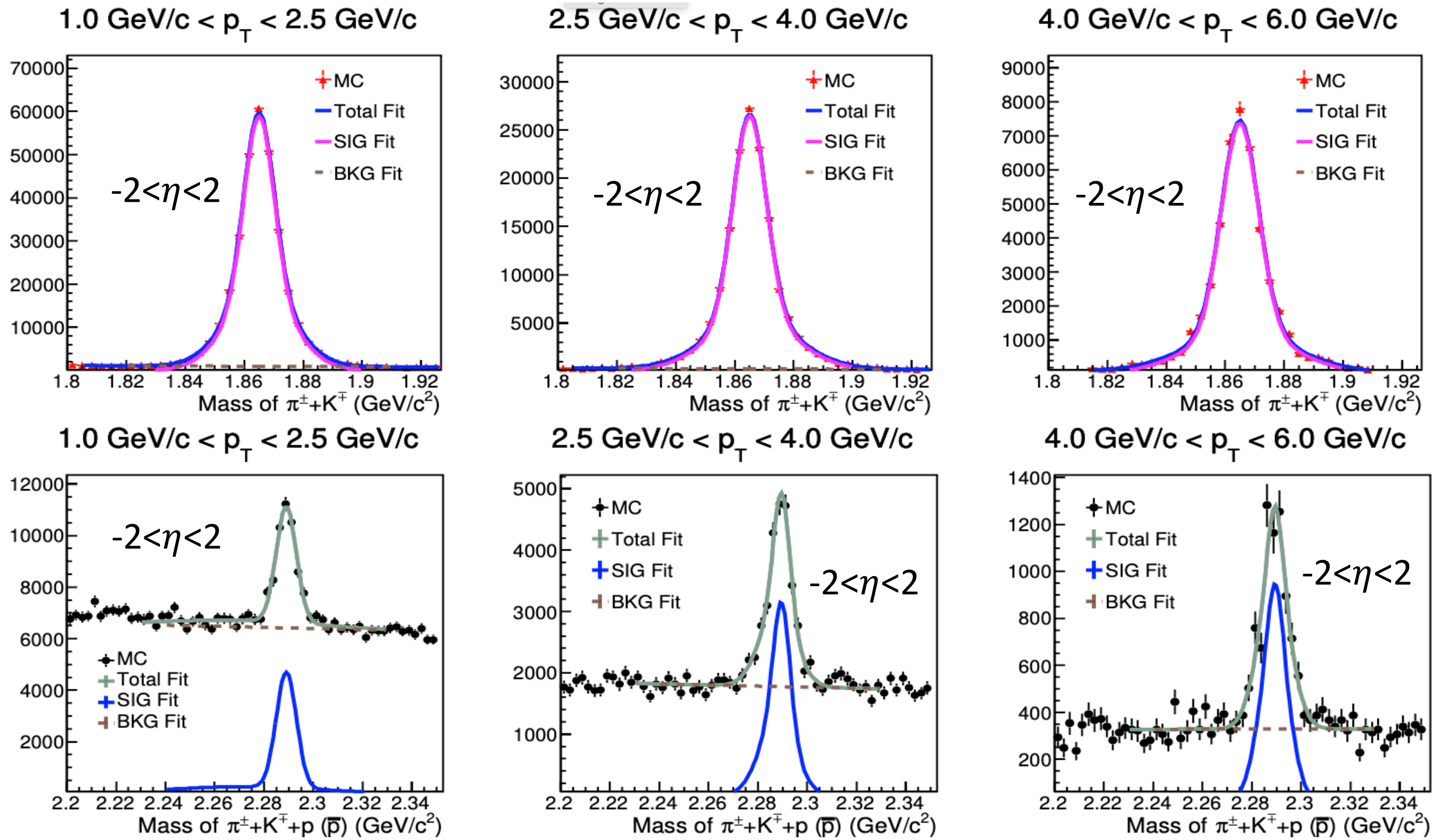




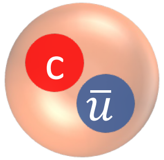
- More differential studies (pseudorapidity separated distributions) are underway.

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

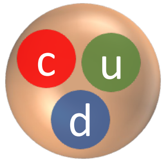
- Clear signals can be found in the p_T separated invariant mass spectrums of reconstructed D^0 and Λ_c in 10 GeV+100 GeV e+p collisions.



Inclusive charm hadron reconstruction



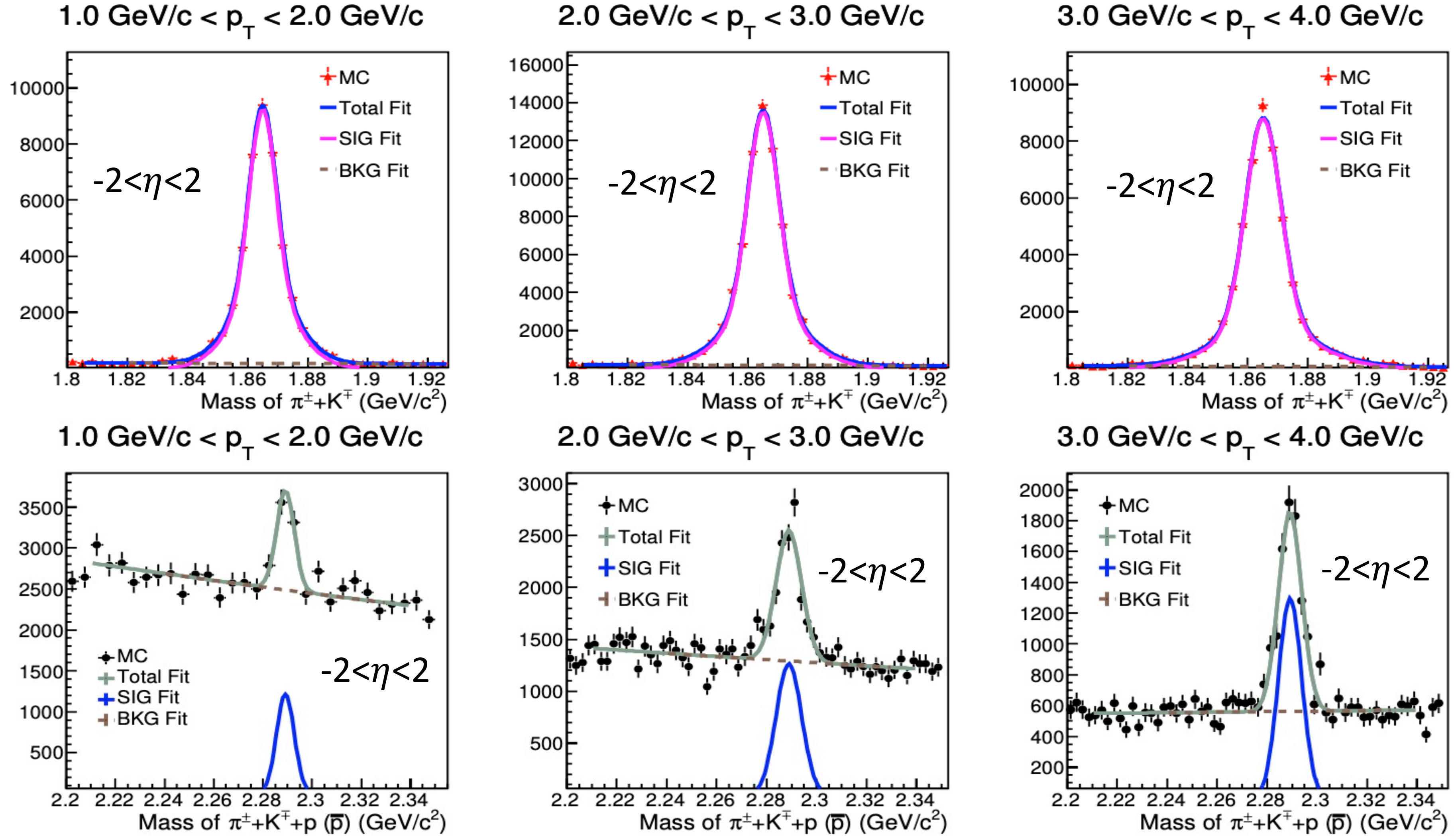
D^0



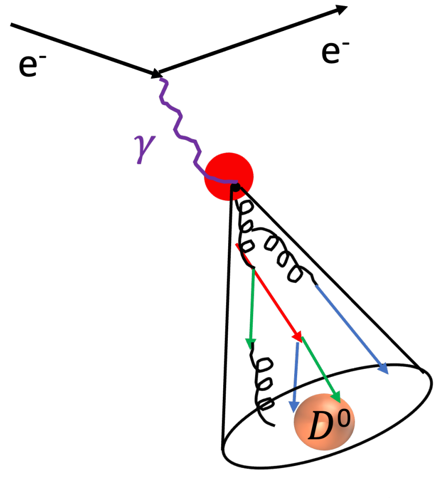
Λ_c^+

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 GeV/c

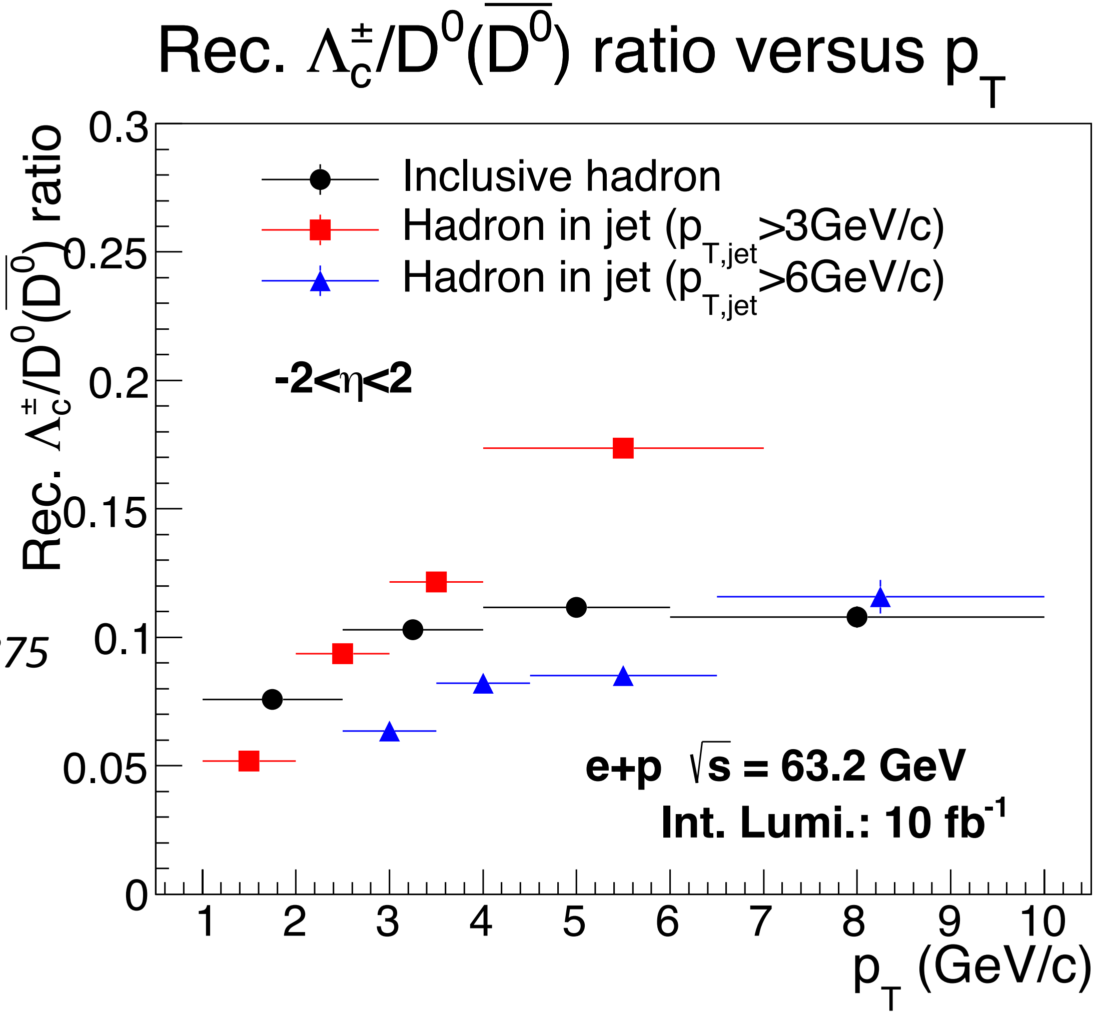


$e^- + p \rightarrow e^- + jet(D^0) + X$

arXiv: 2311.10875

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

- 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.



arXiv: 2311.10875

- 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 (III)

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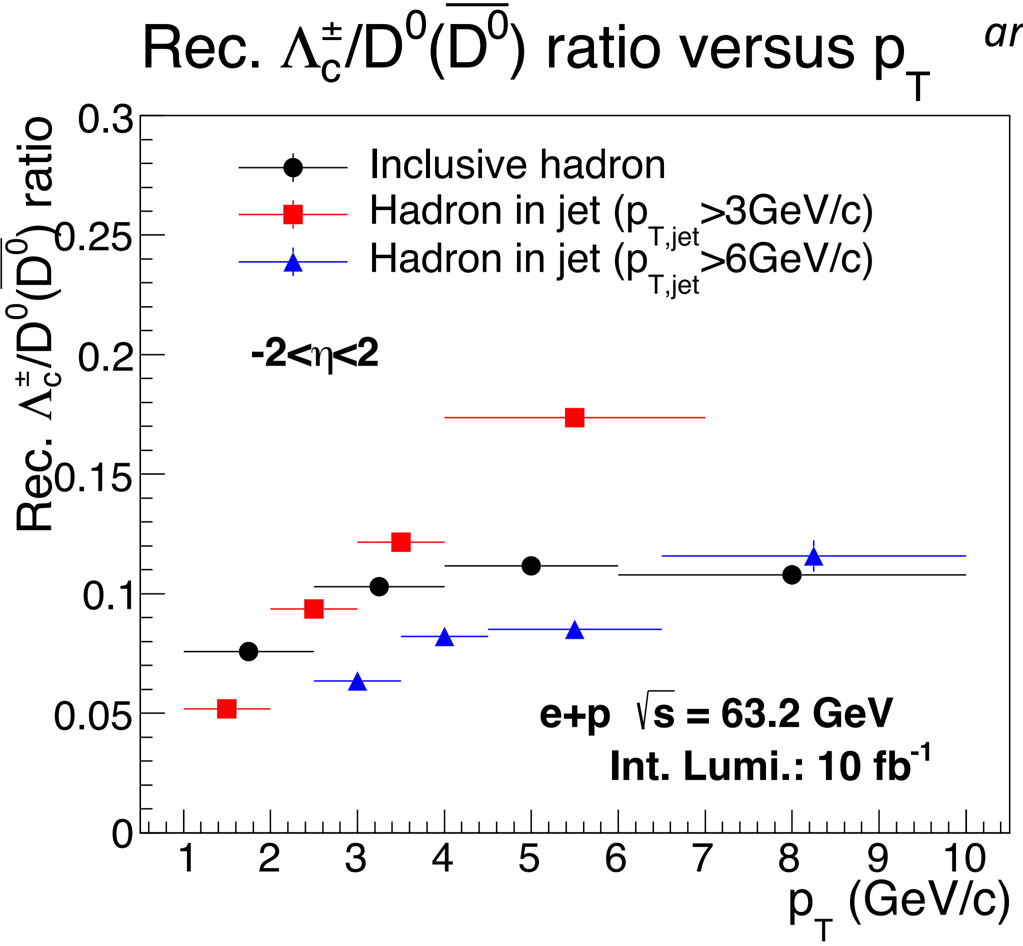
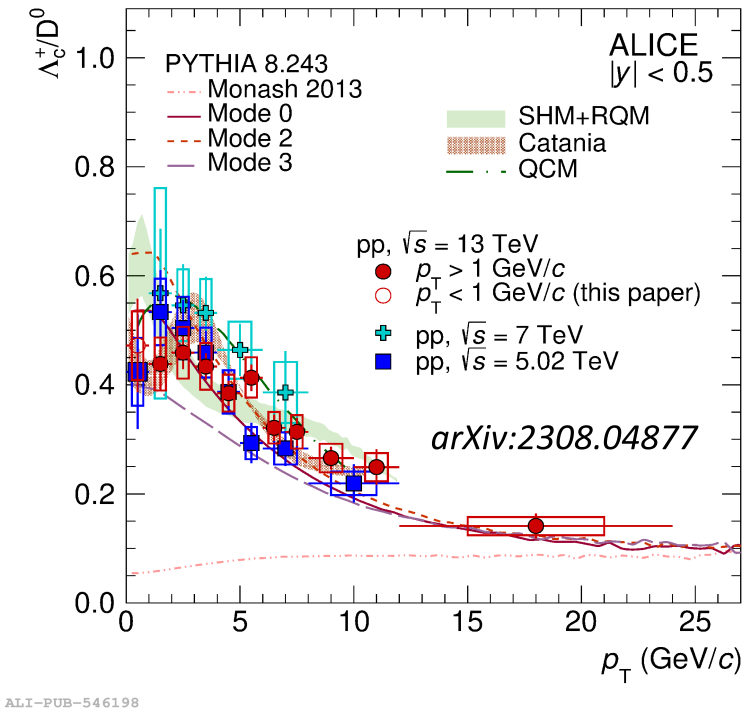


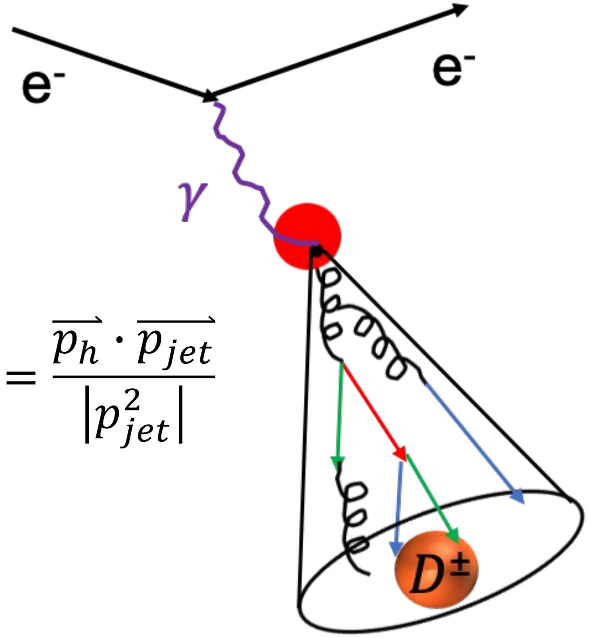


- Future EIC measurements in e+p and e+A collisions will provide a unique approach to check the universality of charm fragmentation function.

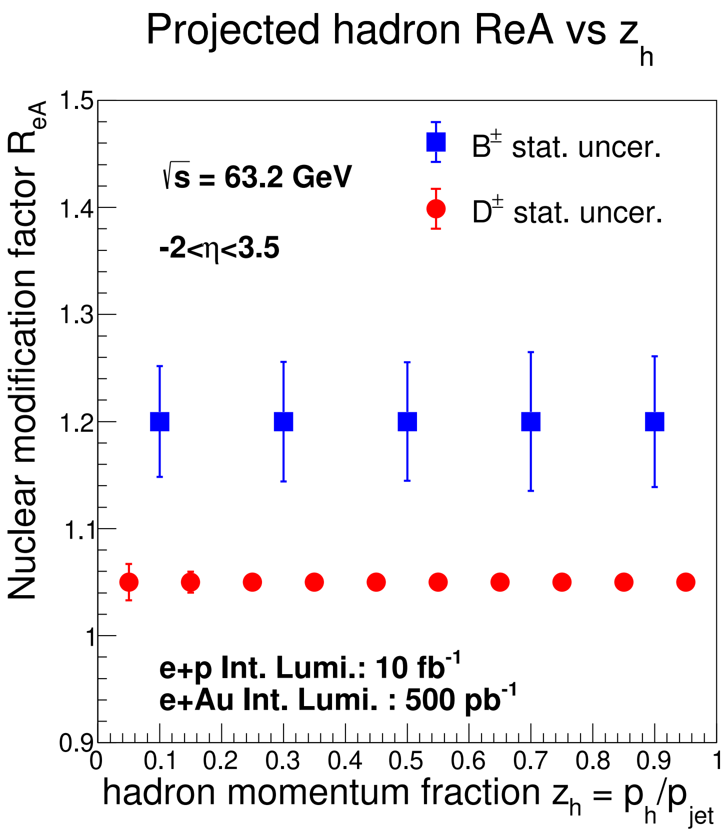
Hadron inside jet nuclear modification factor R_{eAu} projection

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

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



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



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

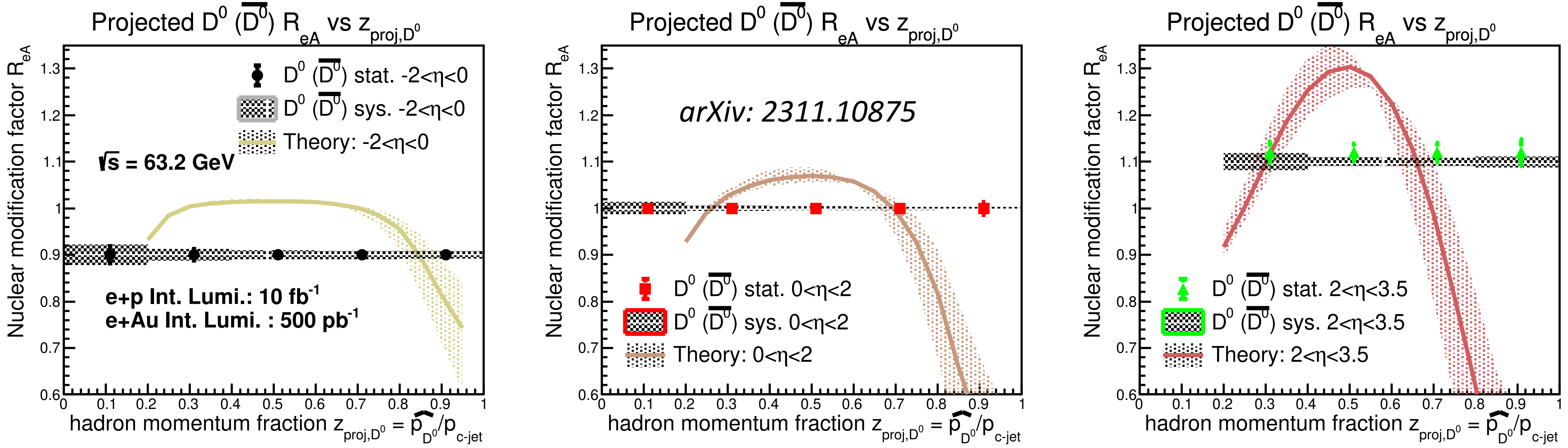
Best precision to be achieved by the EIC measurements in the accessed kinematic phase space.

- 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.

arXiv: 2311.10875

Near-term plan for integration with the ePIC DD4HEP software

- Look forward to work closely with the ePIC tracking and vertex finding taskforce and the ePIC HFJ WG colleagues to develop the heavy flavor reconstruction package within the DD4HEP software.
  - Start with inclusive D^0 and Λ_c reconstruction in e+p collisions (need reconstructed primary vertex and track information, PID performance in place).
  - Will extend these studies with non-prompt D^0 meson and heavy flavor jet tagging depends upon the displaced vertex finding status.
  - Will update the inclusive heavy flavor hadron yields and D^0 inside jet physics projection.
  - Update the associated physics projection.
  - …
- Suggestions and comments are very welcome!

Summary and Outlook

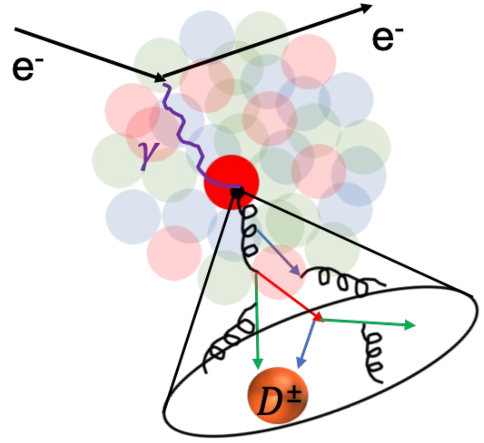
- Heavy flavor hadron and jet studies at the EIC will provide unique opportunities to explore both initial and final state effects with great precision especially in the not well constrained kinematic region.
- New heavy flavor hadron and jet physics observables have been extensively studied using the standalone simulation package and look forward to the integration within the ePIC DD4HEP framework.
- Will work with other colleagues to update the proposed heavy flavor physics performance and projection.

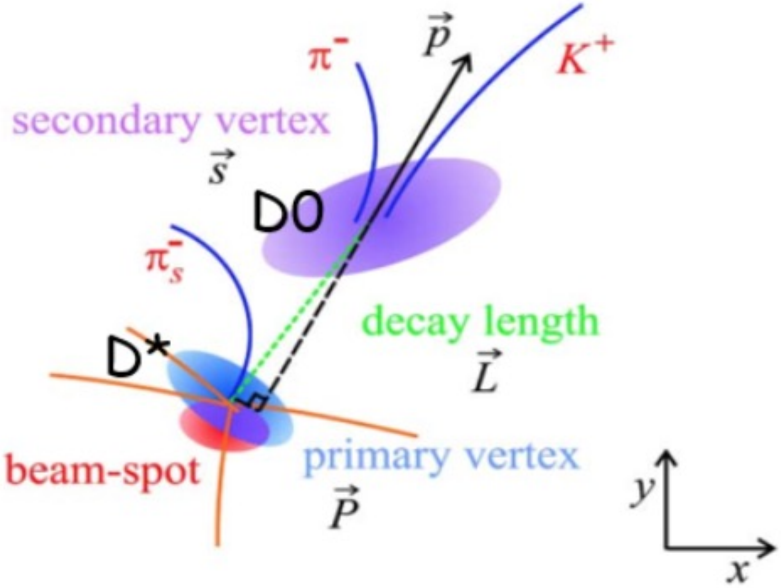
Backup

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.

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



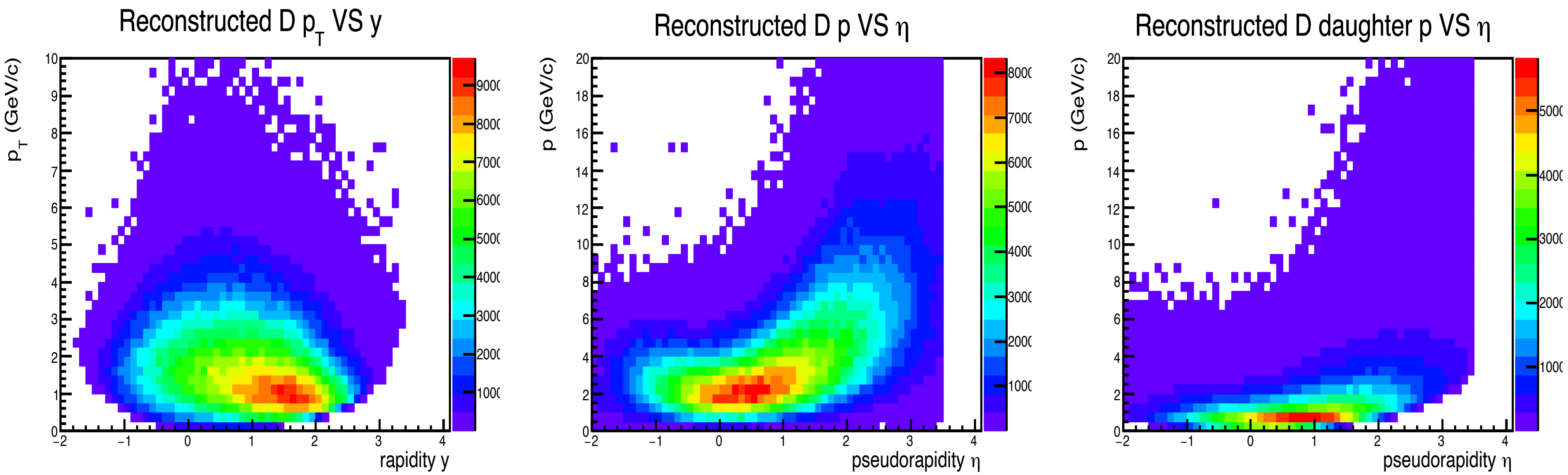


Particle	Mass (GeV/c^2)	Average decay length
$D^{\pm}$	1.869	312 micron
D^0	1.864	123 micron
$B^{\pm}$	5.279	491 micron
B^0	5.280	456 micron

- Heavy flavor physics-driven detector performance requirements:
  - Fine spatial resolution (<80 μm) for displaced vertex reconstruction.
  - Fast timing resolution (<2μs) 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.