

Recent open heavy flavor physics studies for the future EIC

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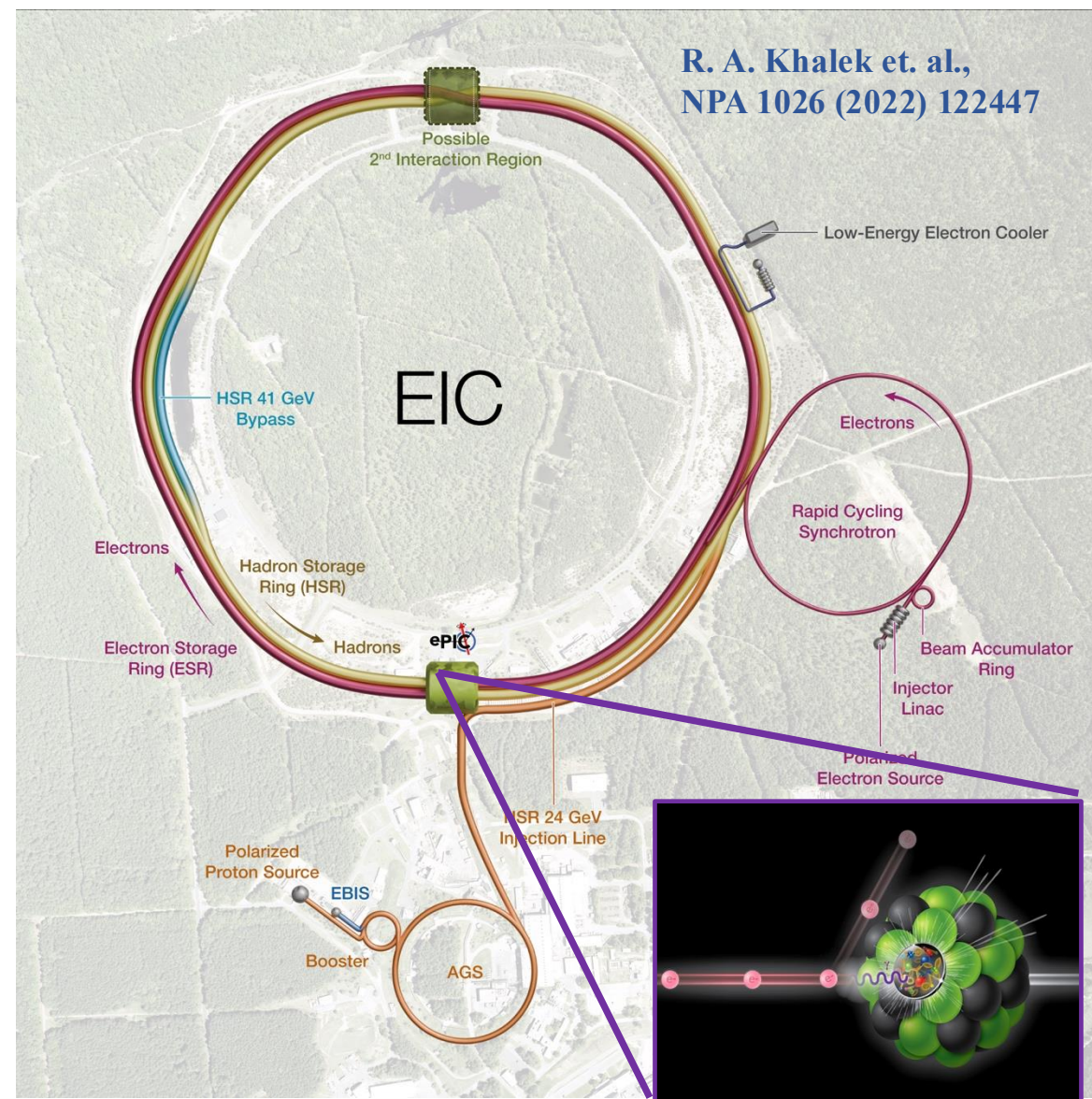
The 17th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

Outline

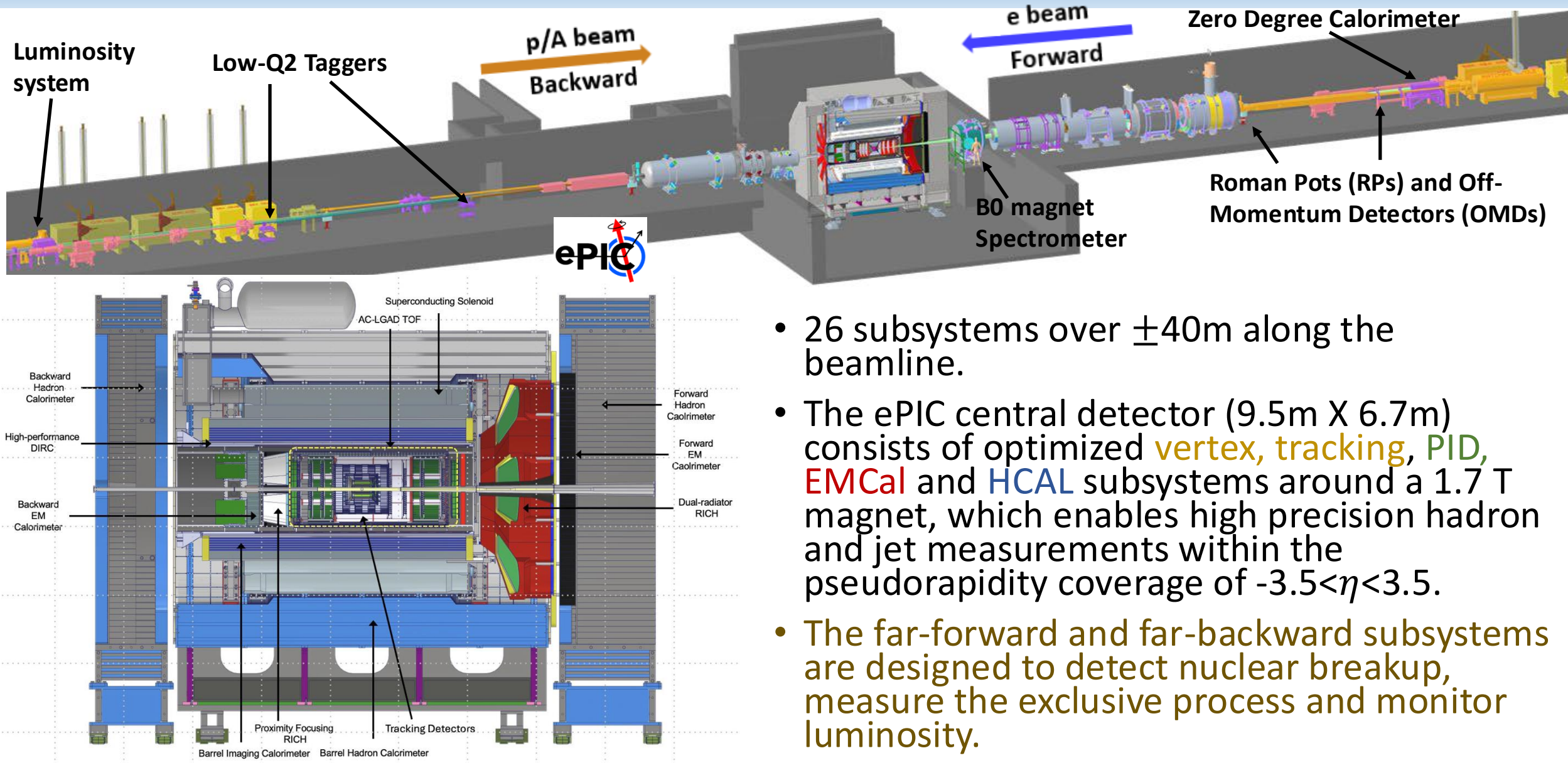
- Introduction of the Electron-Ion Collider (EIC).
- Selected open heavy flavor simulation studies for the EIC:
 - Heavy flavor jet Energy-Energy Correlator (EEC) studies in e+p collisions.
 - Heavy flavor hadron inside jet nuclear modification factor (R_{eA}) projection.
 - Heavy flavor hadron over meson ratio studies in e+p collisions.
- 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 over a broad kinematic region.
- The EIC will be built at BNL, and its operation is expected to start in mid-2030s.
- The EIC will support up to two Interaction Points (ePIC@IP6 and a future 2nd detector).
- The future EIC will operate:
 - (Polarized) p and nucleus (A=2-238) beams at 41, 100-275 GeV.
 - (Polarized) e beam at 5, 10 GeV, with 18 GeV upgradable.
 - Instantaneous luminosity $L_{\text{int}} \sim 10^{33-34} \text{ cm}^{-2} \text{ sec}^{-1}$. A factor of $\sim 10^{2-3}$ higher than HERA.
 - Bunch crossing rate: 10.2 ns.
 - Beam crossing angle at IP6: 25 mrad.



The ePIC detector layout



- 26 subsystems over $\pm 40\text{m}$ along the beamline.
- The ePIC central detector (9.5m X 6.7m) consists of optimized **vertex**, **tracking**, **PID**, **EMCal** and **HCAL** subsystems around a 1.7 T magnet, which enables high precision hadron and jet measurements within the pseudorapidity coverage of $-3.5 < \eta < 3.5$.
- The far-forward and far-backward subsystems are designed to detect nuclear breakup, measure the exclusive process and monitor luminosity.

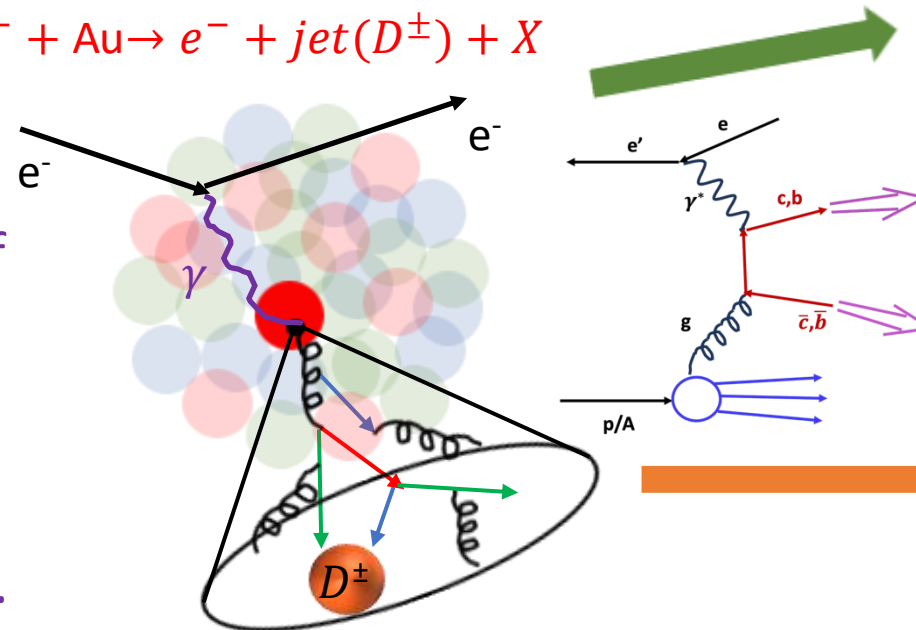
Heavy flavor measurements can enrich the EIC physics program

- Heavy flavor hadron and jet measurements are an important part of the EIC science portfolio and play a significant role in exploring
 - Modification of the 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.

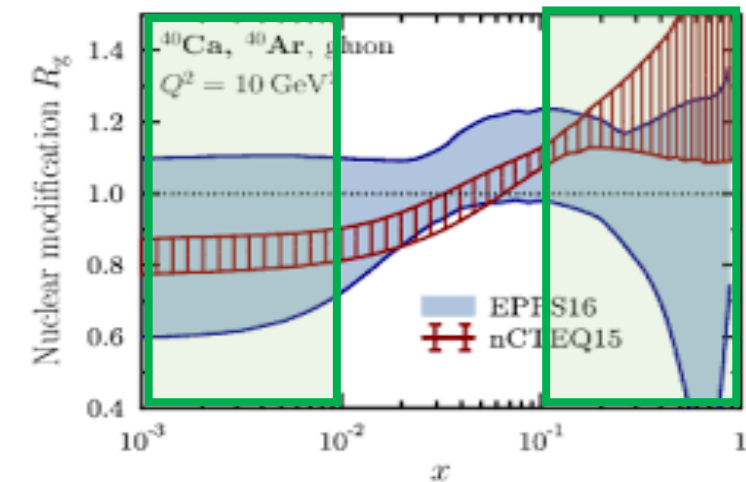
- Uniqueness of the EIC measurements:

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

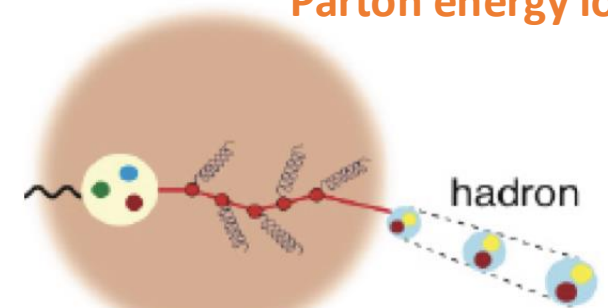
$$e^- + \text{Au} \rightarrow e^- + \text{jet}(D^\pm) + X$$



nPDF modification

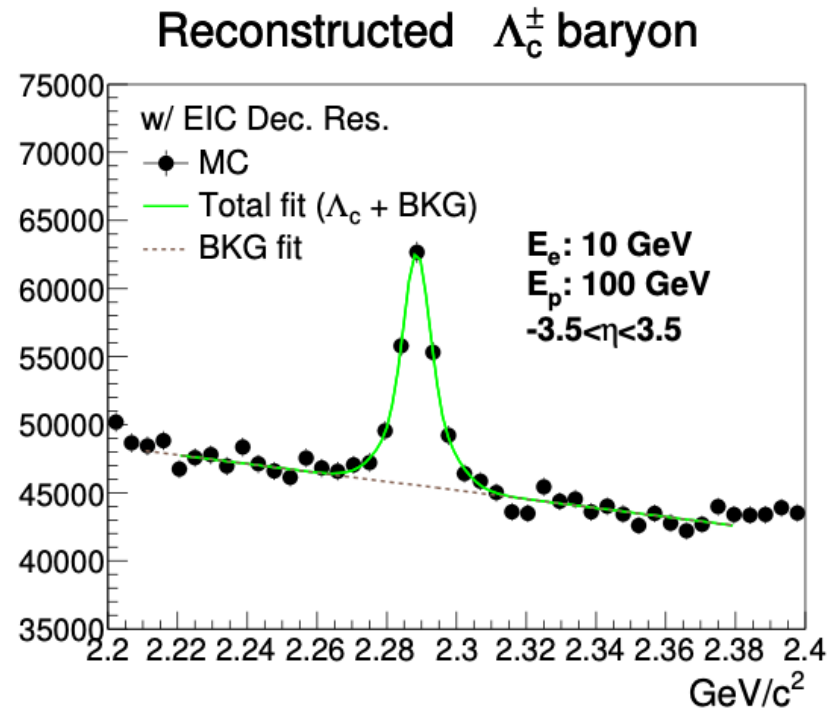
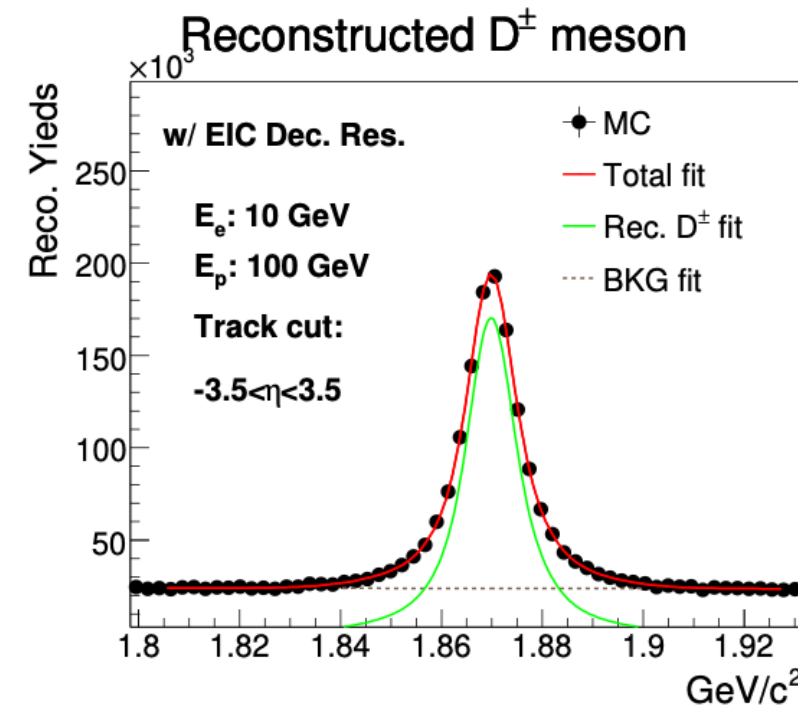


Parton energy loss



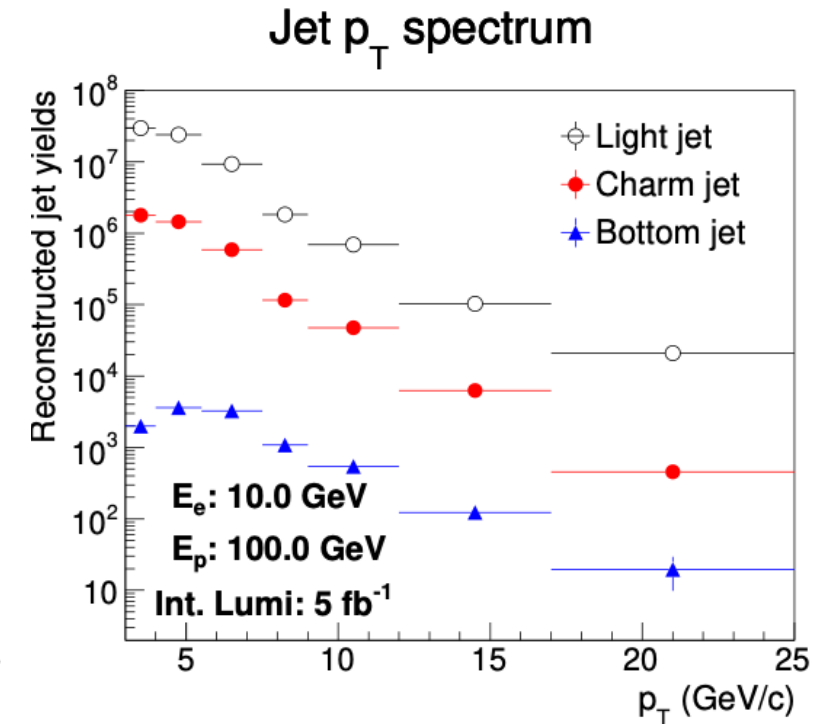
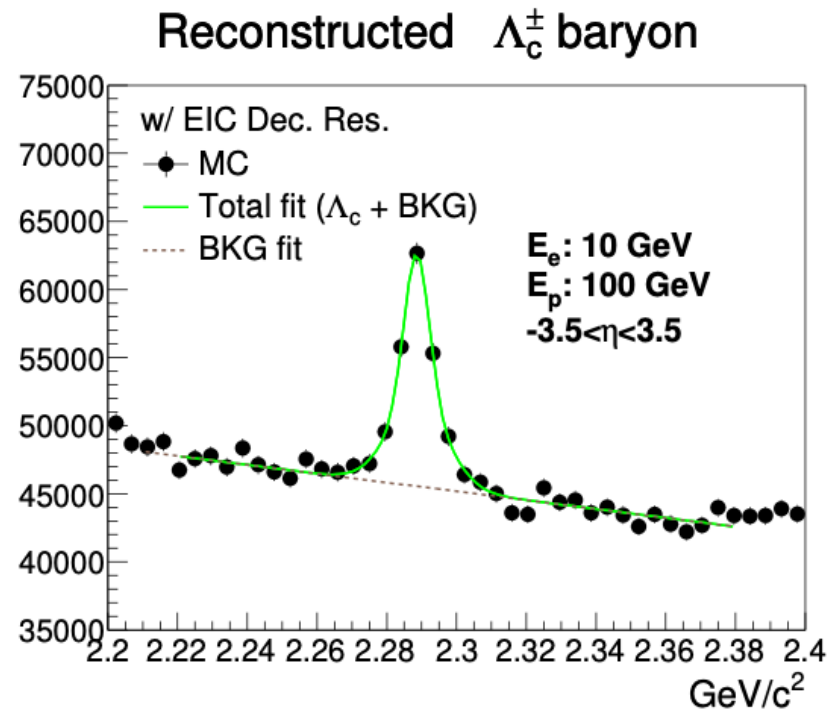
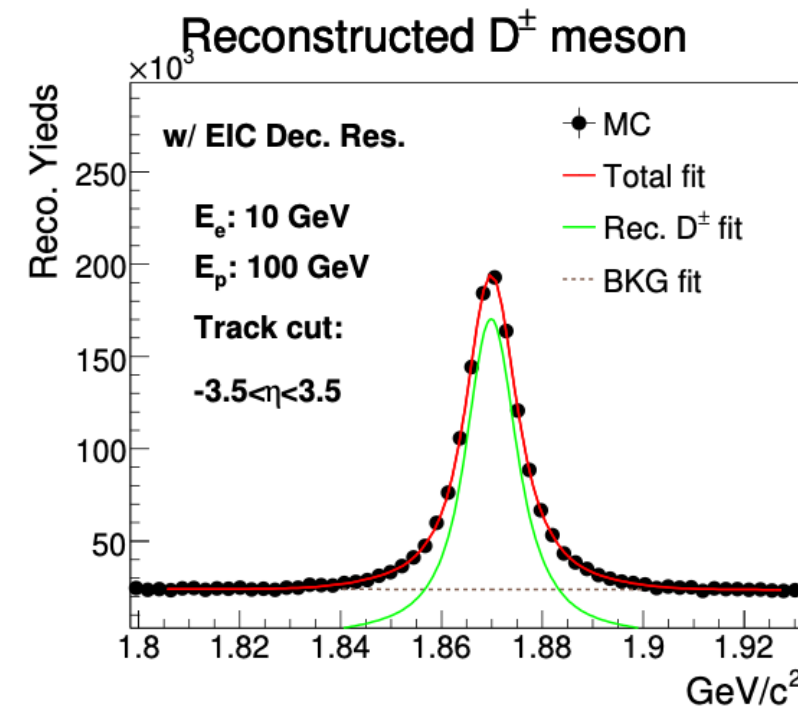
Reconstruction of open heavy flavor products in e+p simulation

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



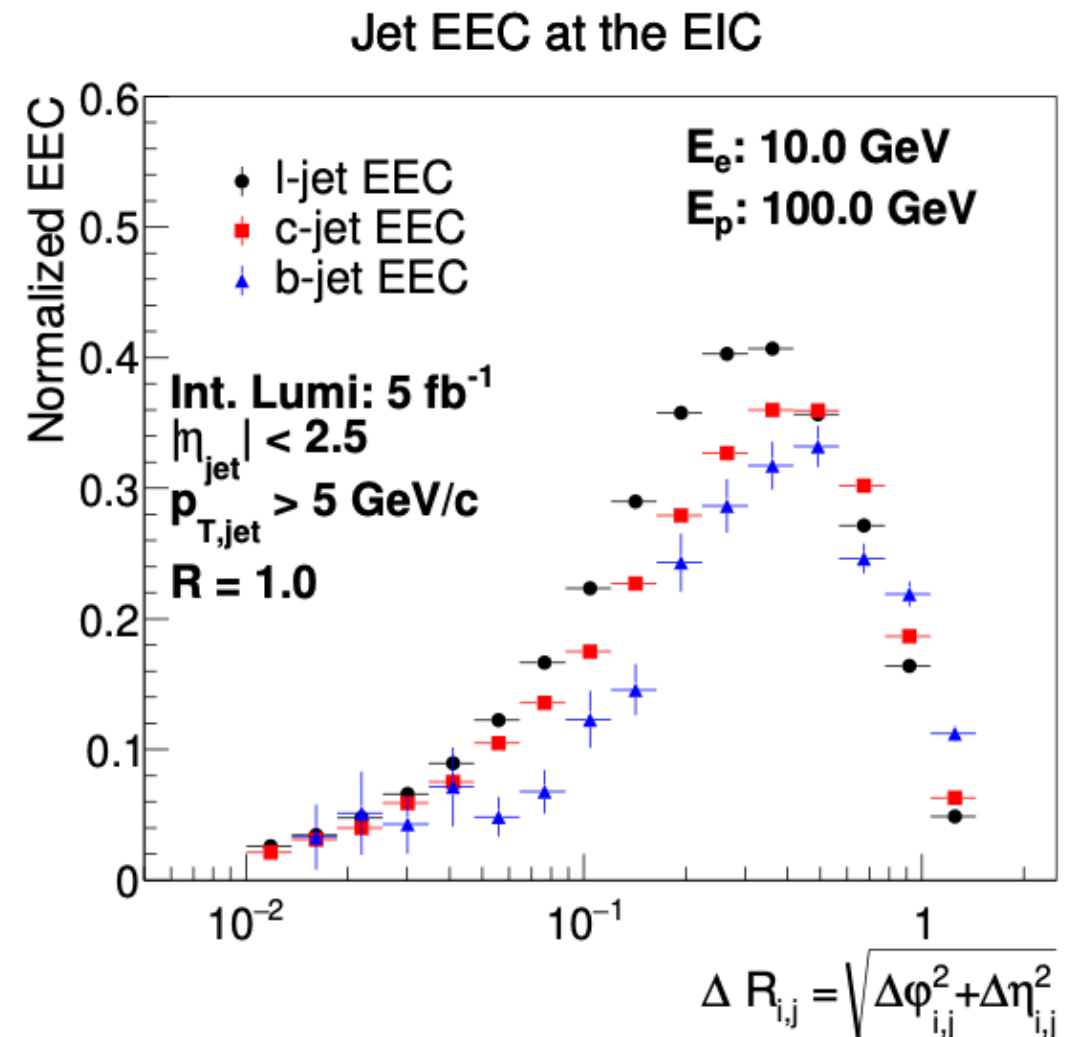
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- **Heavy flavor hadrons are reconstructed through hadronic decay channels.**
- **Heavy flavor jets are reconstructed with the anti- k_T algorithm, jet cone $R=1.0$ and jet flavor is tagged according to the displaced vertex found inside the jet.**



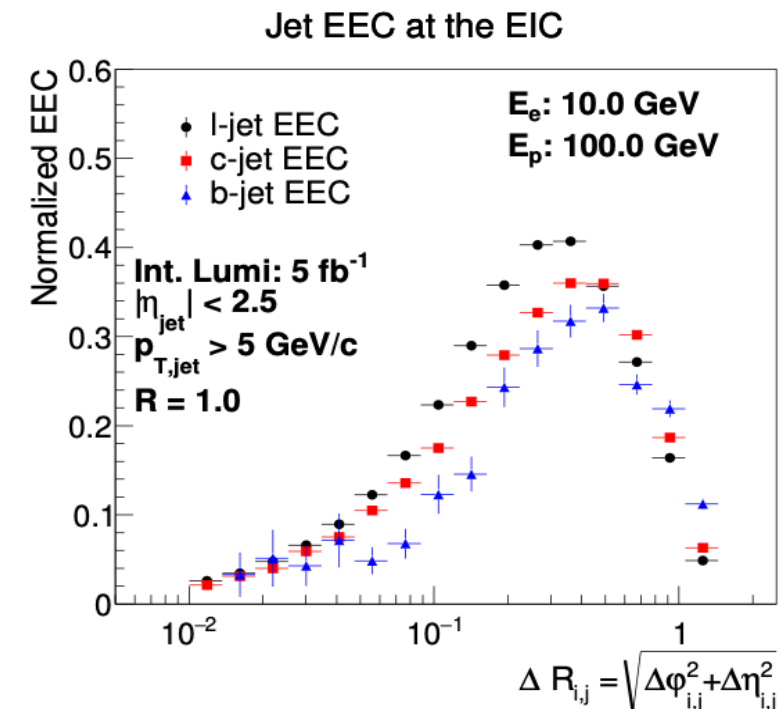
Jet Energy-Energy Correlator (EEC) studies at the EIC

- Jet substructure observables (e.g., the jet energy-energy correlator) provide powerful probes of parton to hadron evolution and parton energy loss mechanism.
- In 63.2 GeV e+p simulation, the normalized jet energy-energy correlator ($\frac{1}{N_{jet}} \frac{dEEC_{ij}}{\sum EEC_{ij} dR_{ij}}$) of charged hadrons inside jets versus the ΔR_{ij} , where $EEC_{ij} = \frac{p_{T,i} p_{T,j}}{(p_{T,jet})^2}$ for light jets (l-jet), **charm jets (c-jet)**, and **bottom jets (b-jet)**.

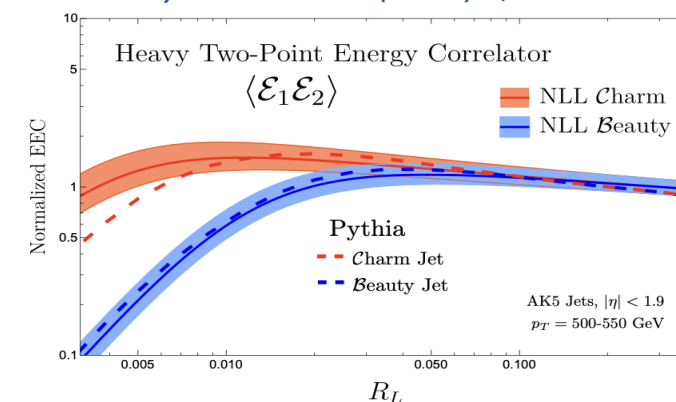


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- Similar flavor dependence has been predicted by theorists for high p_T jets in p+p collisions (bottom panel).



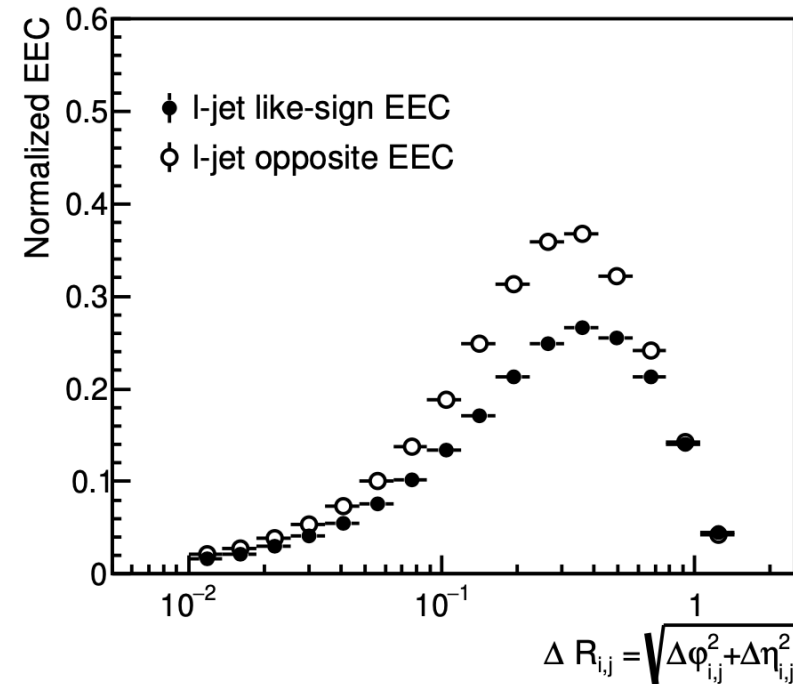
Phys. Rev. D 114 (2026) 3, L031501



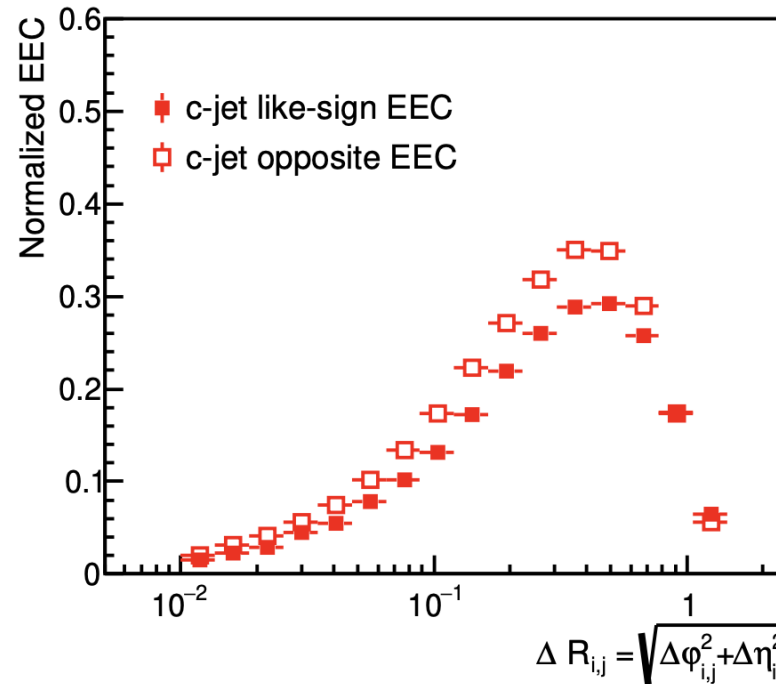
Like- and opposite-sign Jet EEC for jets with different flavors

- Jet EEC are studied separately for like-sign and opposite-sign hadron pairs.
- A consistent enhancement of opposite-sign over like-sign hadron-pair correlation across light-, **charm-**, and **bottom-flavor** jets.

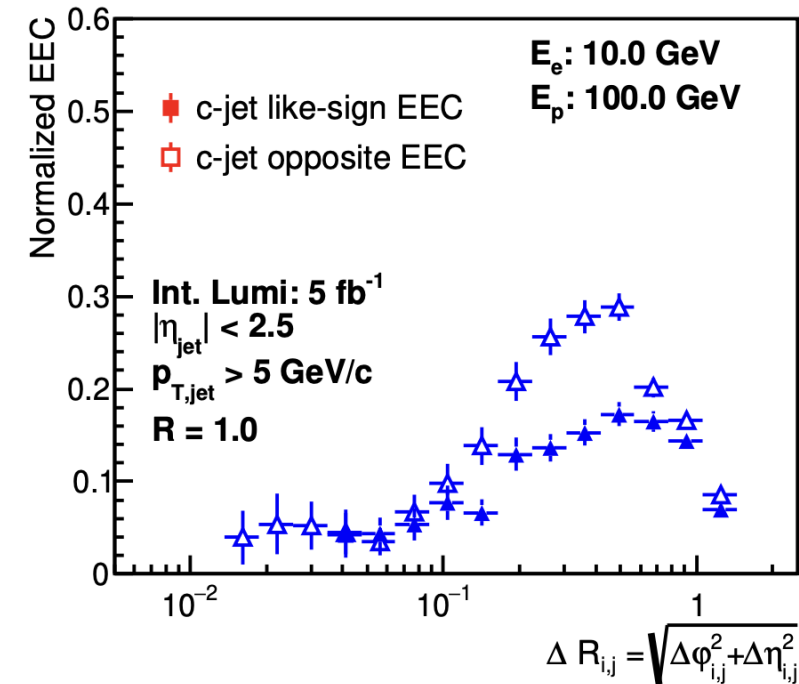
Jet EEC (Like/Opposite) at the EIC



Jet EEC (Like/Opposite) at the EIC

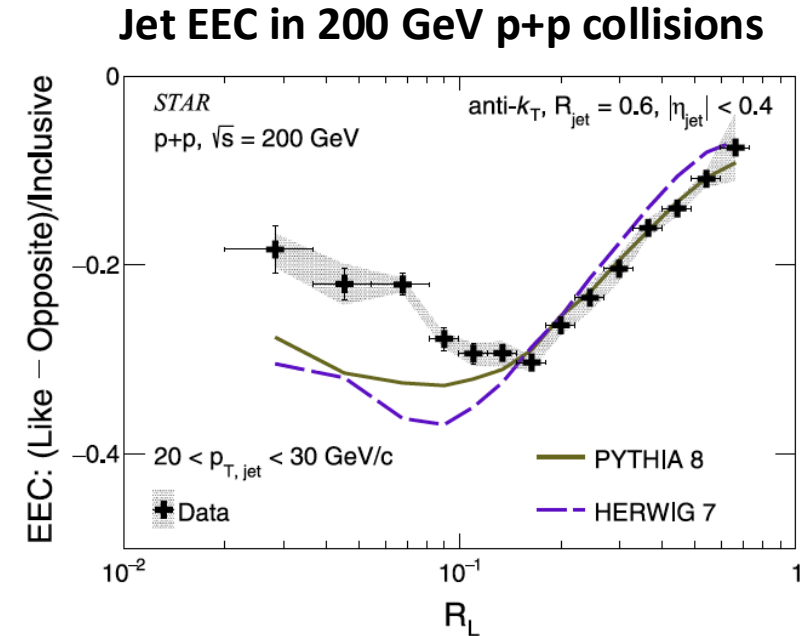
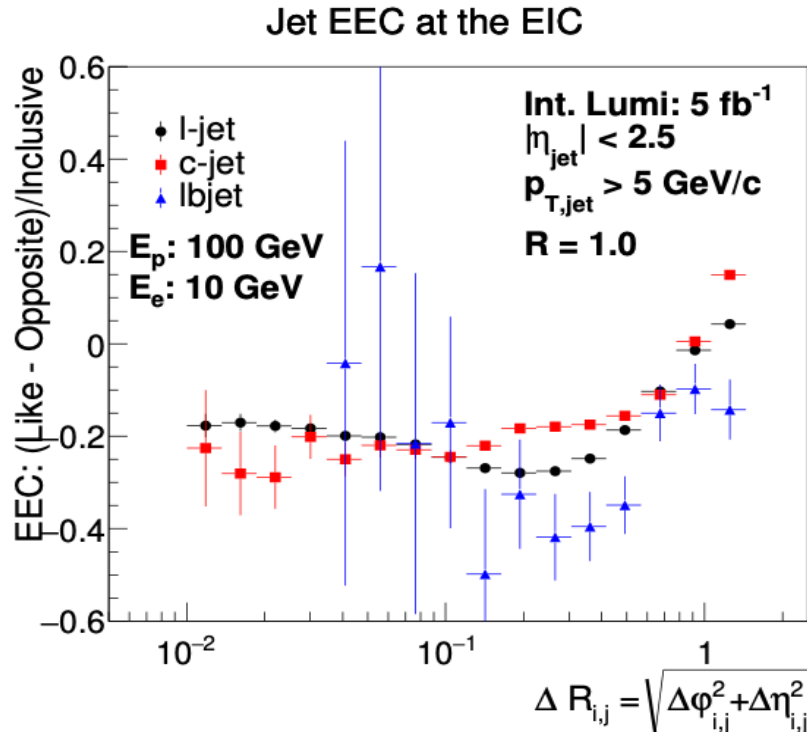


Jet EEC (Like/Opposite) at the EIC



Like- and opposite-sign Jet EEC for jets with different flavors

- The normalized difference between like-sign and opposite-sign jet EECs provides a charge-sensitive observable for investigating potential flavor dependence in parton to hadron evolution.



Phys. Rev. Lett 135, 111901 (2025)

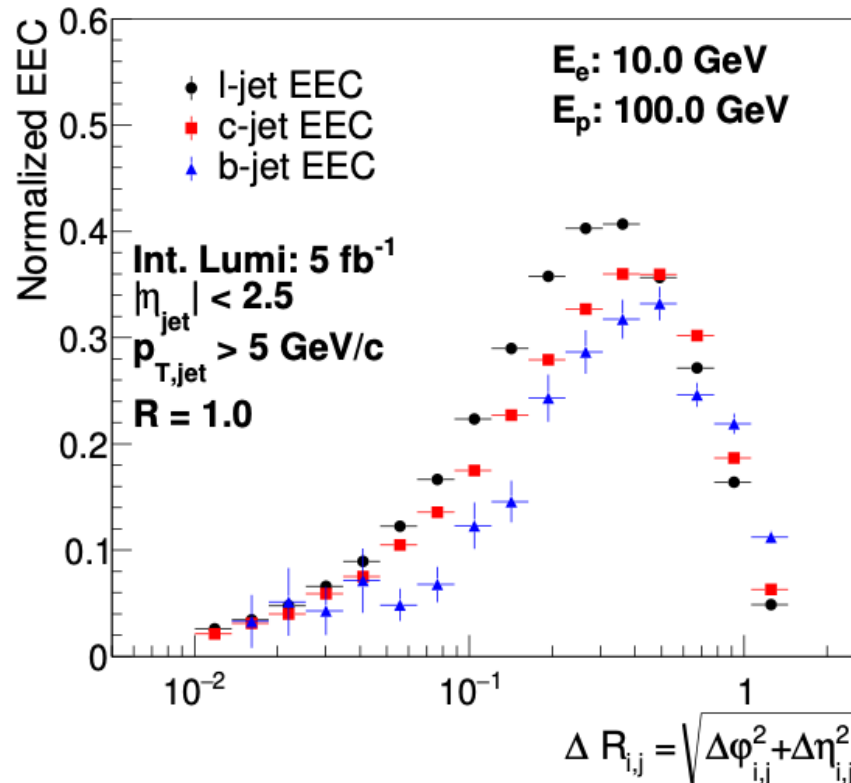
- Slight differences in the turning-point positions are observed among jets of different flavors. EIC will provide new opportunities to explore the non-perturbative hadronization dynamics in the small $\Delta R_{i,j}$ (R_L) region.

Collision energy dependent Jet EEC (I)

- Sequential suppression of the normalized EEC yields for jet with different flavors.
- No significant collision energy dependence ($\sqrt{s} = 63.2 \text{ GeV} \rightarrow 141 \text{ GeV}$) has been observed.

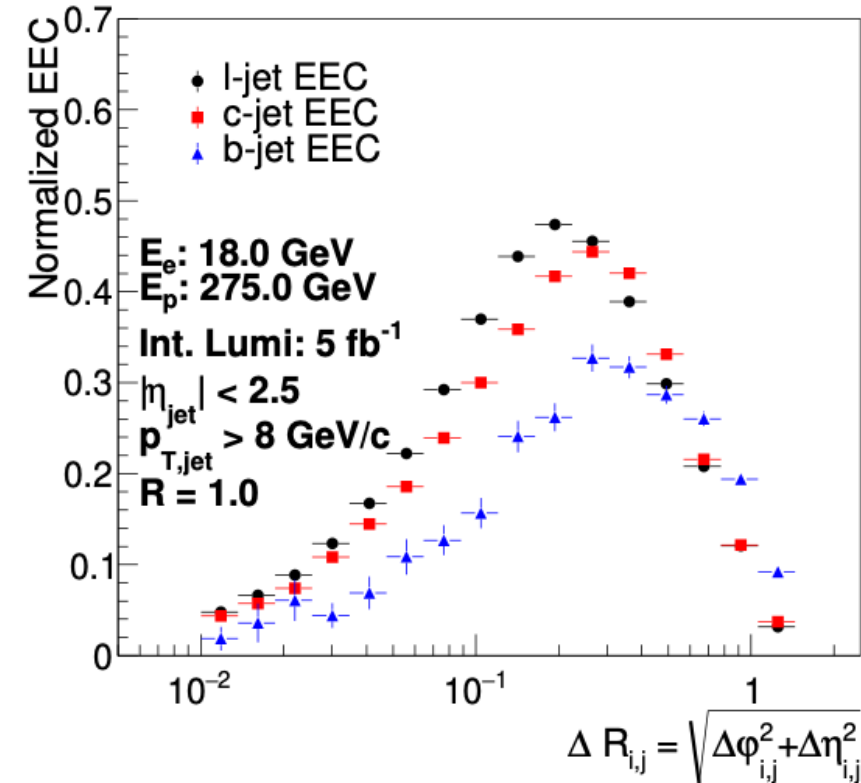
63.2 GeV e+p simulation

Jet EEC at the EIC



141 GeV e+p simulation

Jet EEC at the EIC

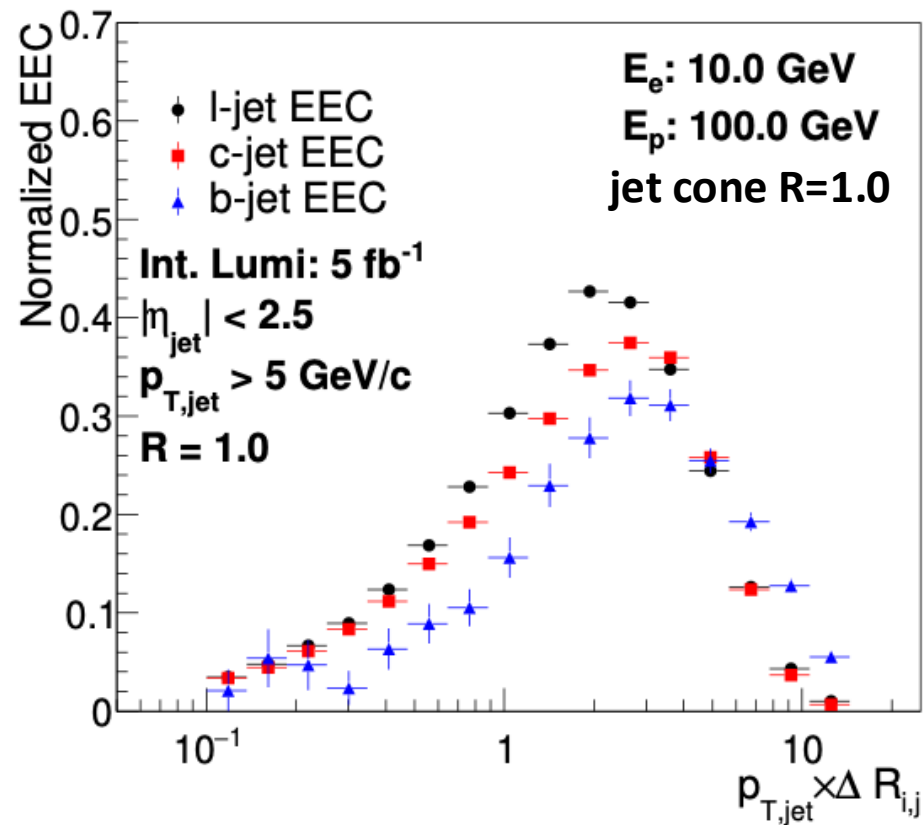


Collision energy dependent Jet EEC (II)

- Similar flavor dependence is observed in the normalized $p_T \times \text{EEC}$ distributions.
- No significant collision energy dependence.

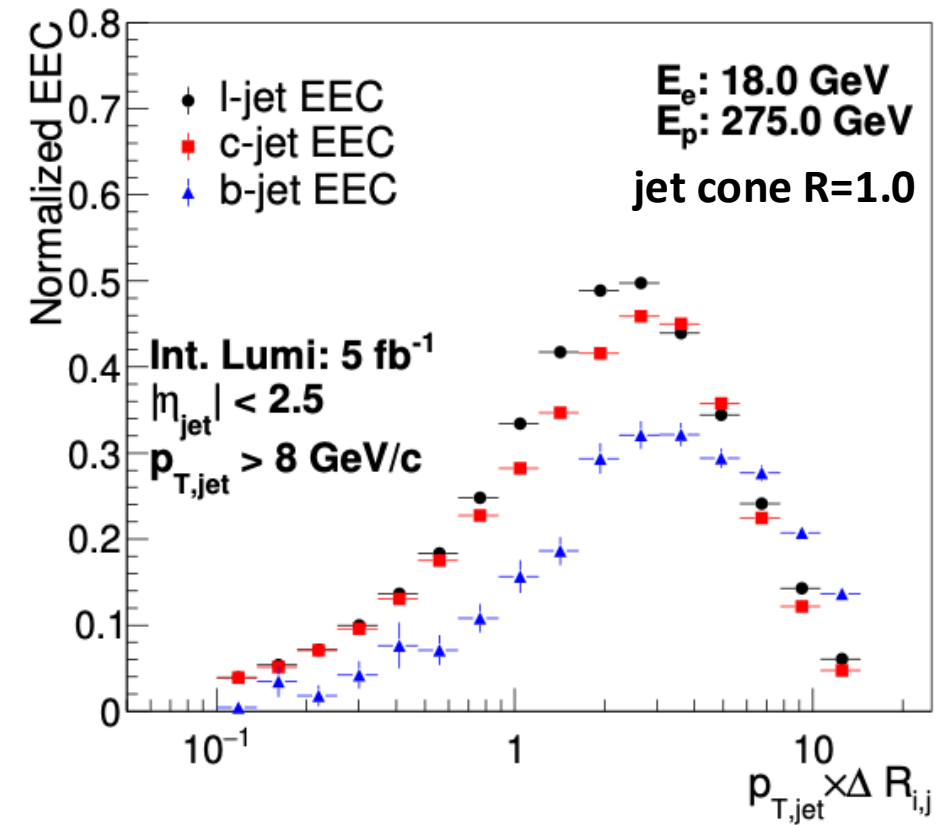
63.2 GeV e+p simulation

Jet EEC at the EIC



141 GeV e+p simulation

Jet EEC at the EIC

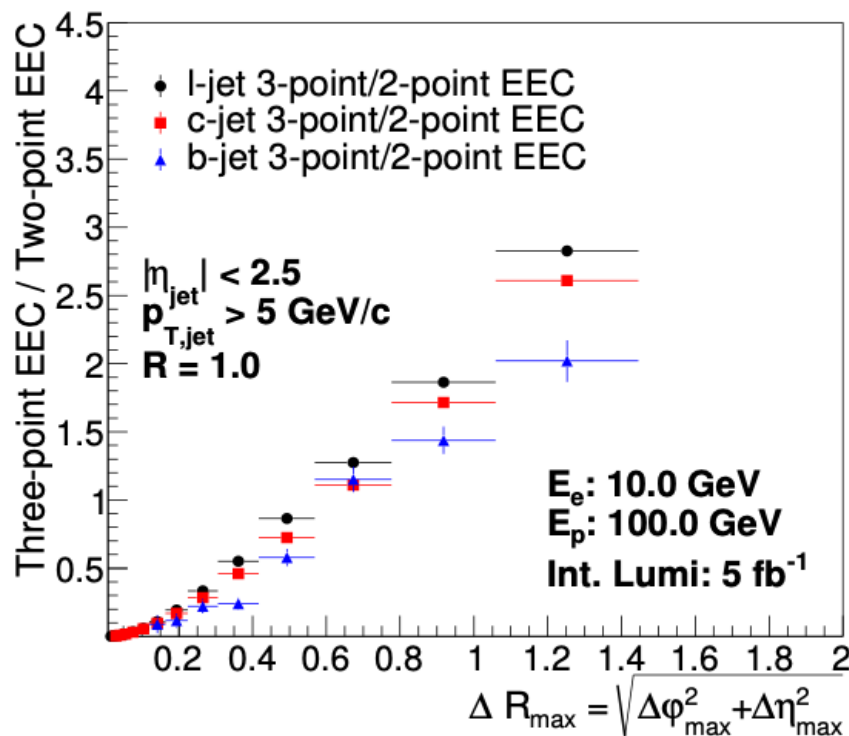


Collision energy dependent Jet EEC (III)

- Three-point jet EEC (E3C): $\frac{1}{N_{jet}} \frac{dEEC_{ijk}}{\sum EEC_{ijk} dR_{ijk,max}}$, where $EEC_{ijk} = \frac{p_{T,i} p_{T,j} p_{T,k}}{(p_{T,jet})^3}$.
- The three-point to two-point jet EEC ratios in 63.2 GeV and 141 GeV e+p collisions are consistent with the flavor dependent parton energy loss patterns.

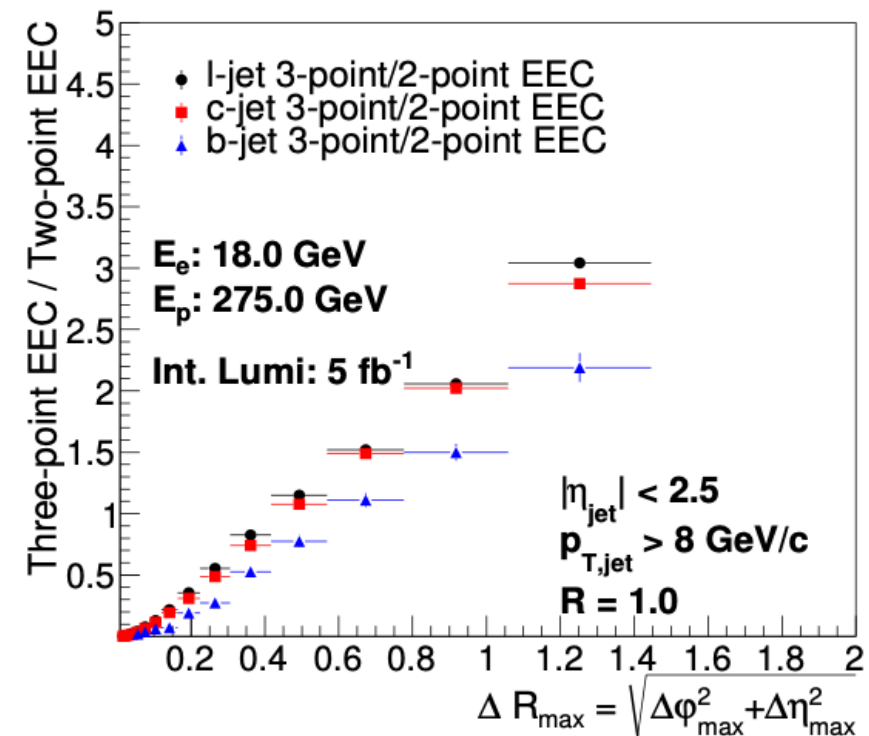
63.2 GeV e+p simulation

EIC jet Three-point/Two-point EEC in e+p



141 GeV e+p simulation

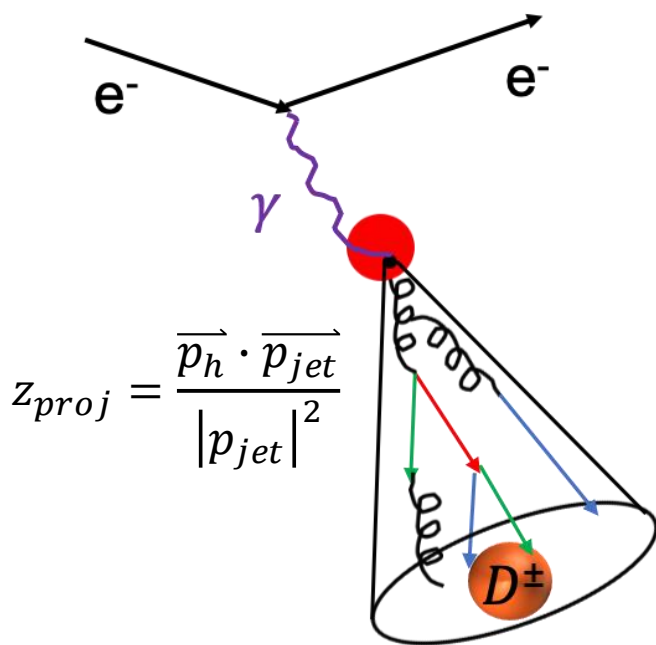
EIC jet Three-point/Two-point EEC in e+p



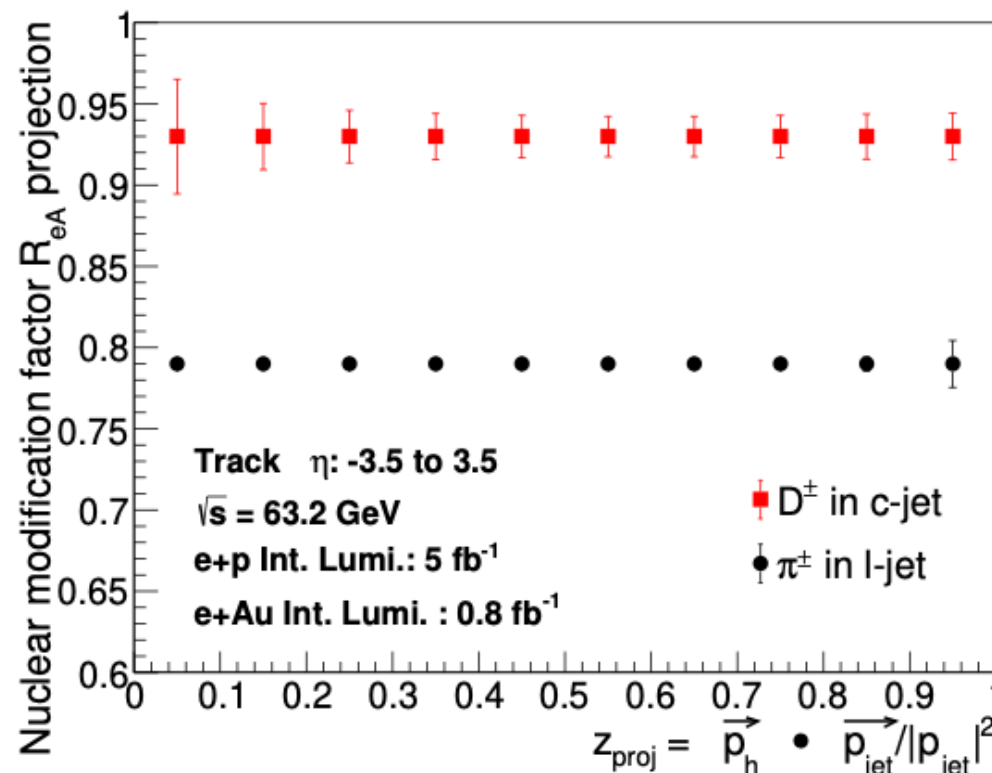
Heavy flavor hadron inside jet nuclear modification factor R_{eAu} projection

- Heavy flavor hadron inside jet productions at the EIC is a unique probe to directly access the flavor dependent fragmentation functions.

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



Projected hadron in jet R_{eA} vs z_h



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

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

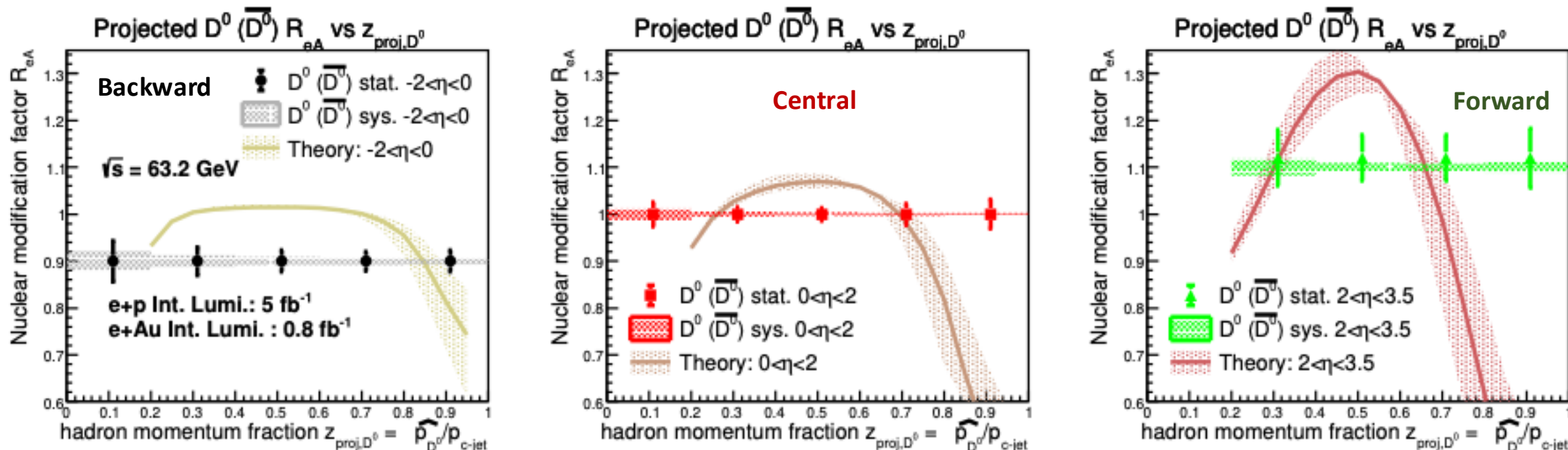
- Future EIC heavy flavor hadron inside jet measurements will provide great constraints in extracting fragmentation functions under different medium conditions.

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 ($Q^2 > 5 \text{ GeV}^2$) with a fraction of projected EIC integrated luminosities.

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

Experimental projection: Web of Conferences 316, 07003 (2025)

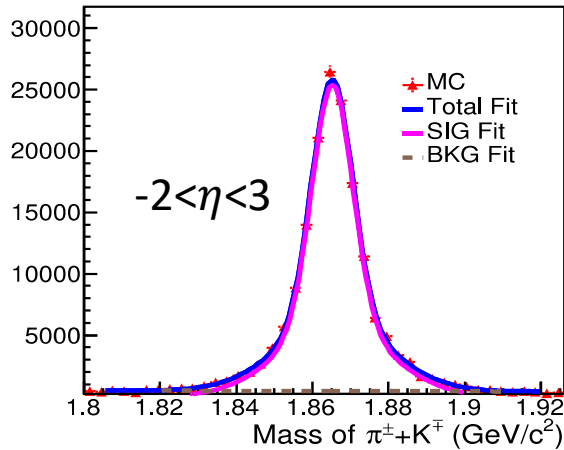


- Good discriminating power in separating different model calculations on the heavy flavor production under different nuclear medium conditions can be provided by future EIC heavy flavor measurements over a wide pseudorapidity region.

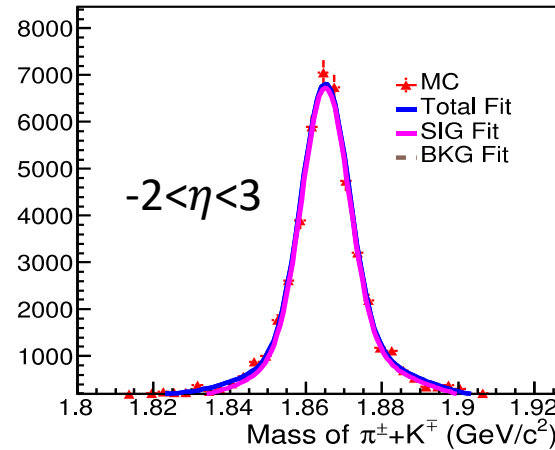
Charm baryon/meson ratios to access the hadronization process (I)

- 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.

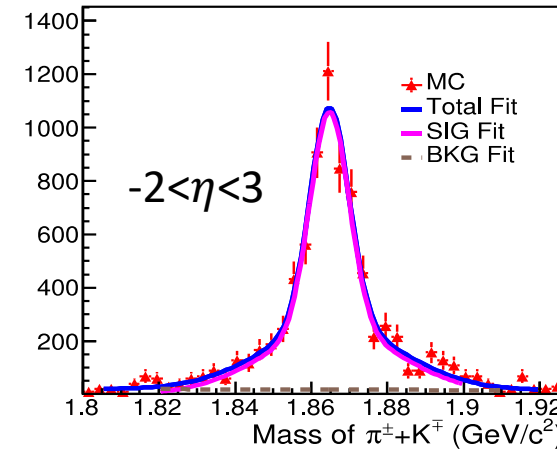
2.5 GeV/c < p_T < 4.0 GeV/c



4.0 GeV/c < p_T < 6.0 GeV/c



6.0 GeV/c < p_T < 10.0 GeV/c

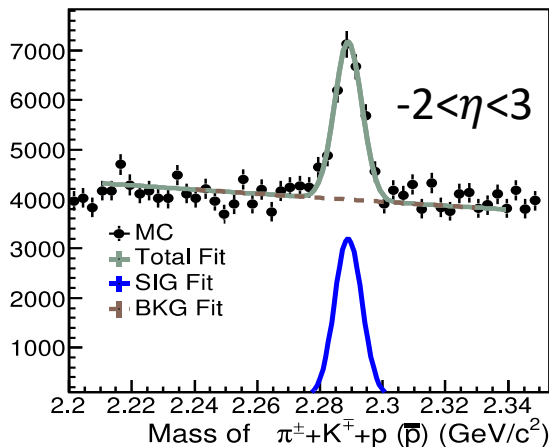


Inclusive charm
hadron reconstruction

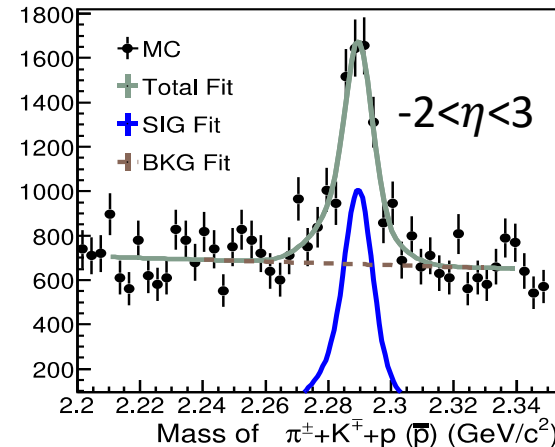


Standalone MC

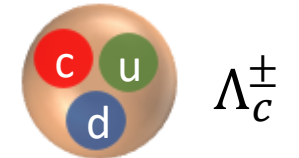
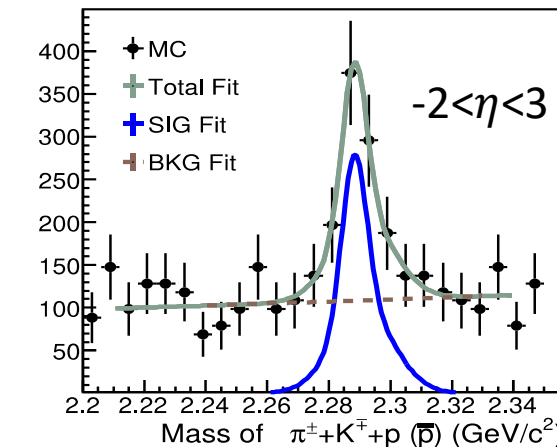
2.5 GeV/c < p_T < 4.0 GeV/c



4.0 GeV/c < p_T < 6.0 GeV/c



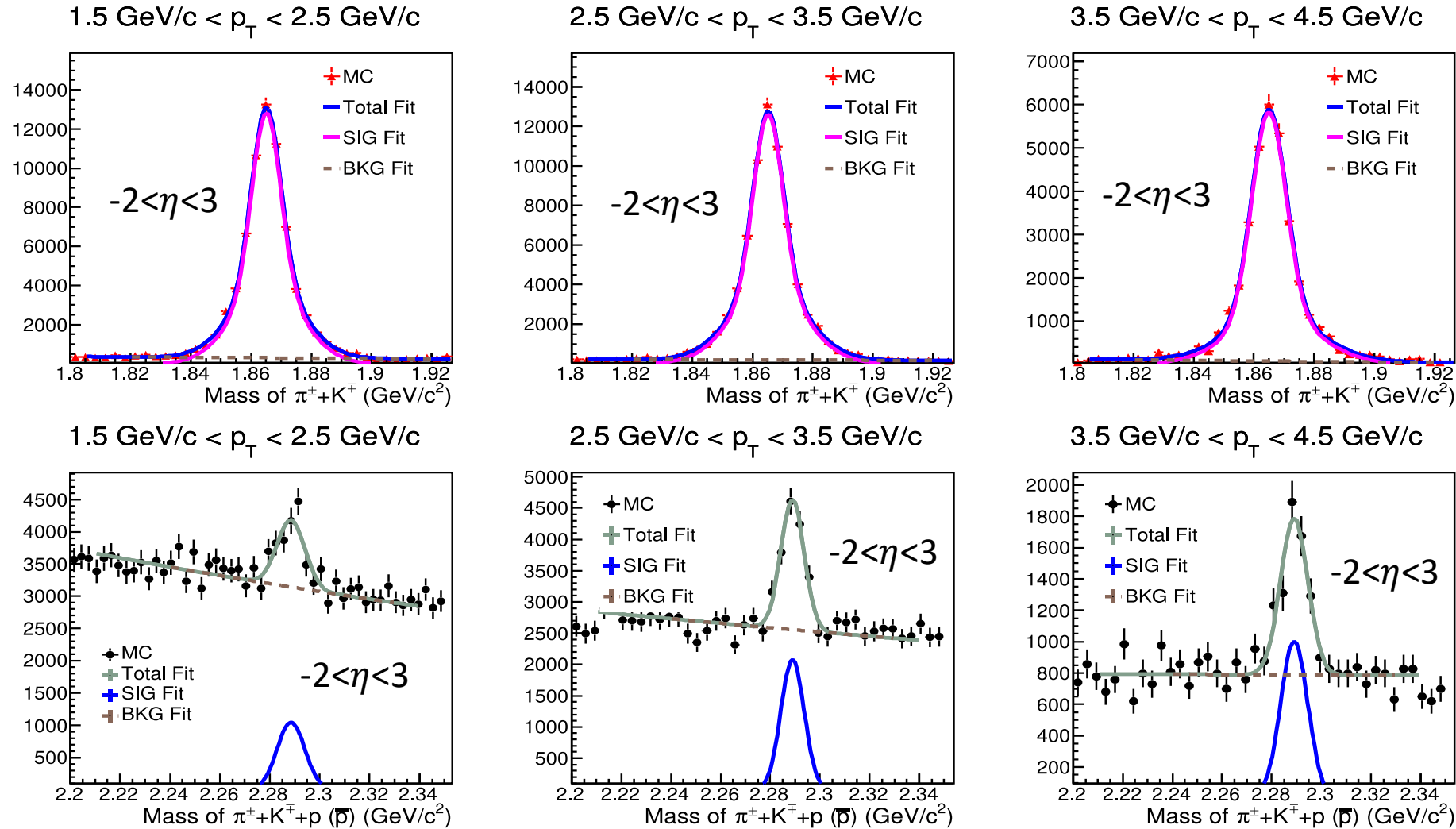
6.0 GeV/c < p_T < 10.0 GeV/c



Standalone MC

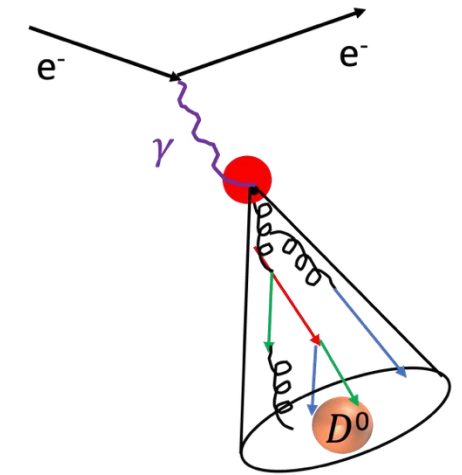
Charm baryon/meson ratios to access the hadronization process (II)

- 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.



Standalone MC

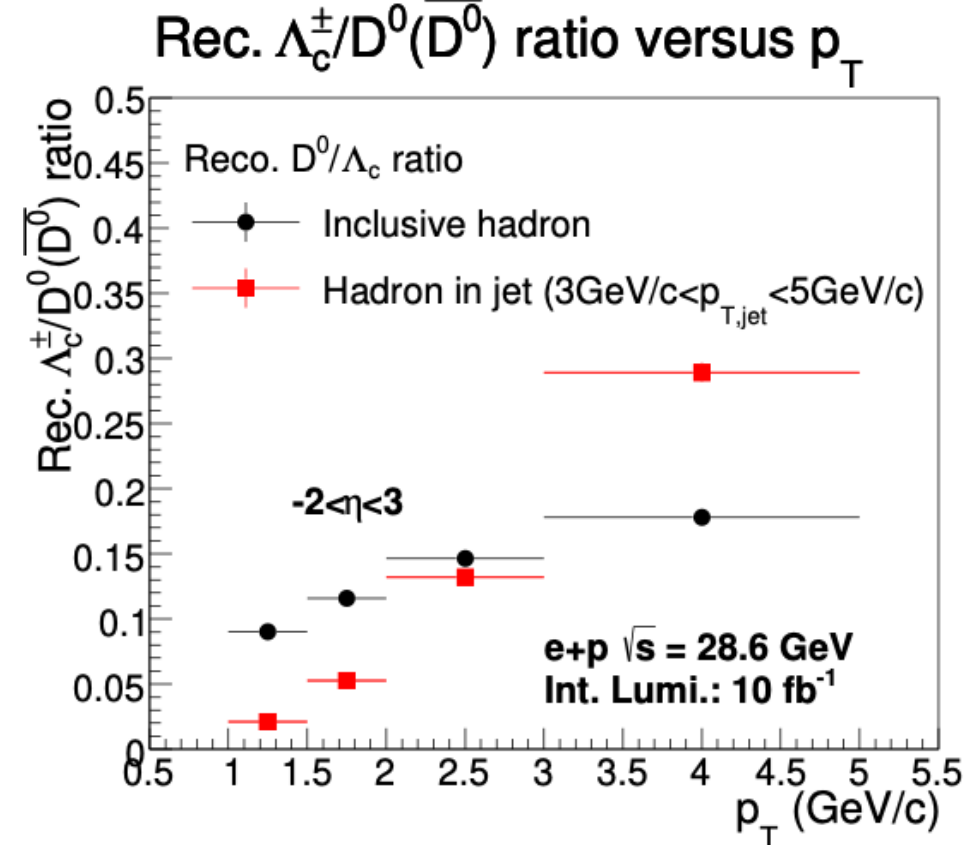
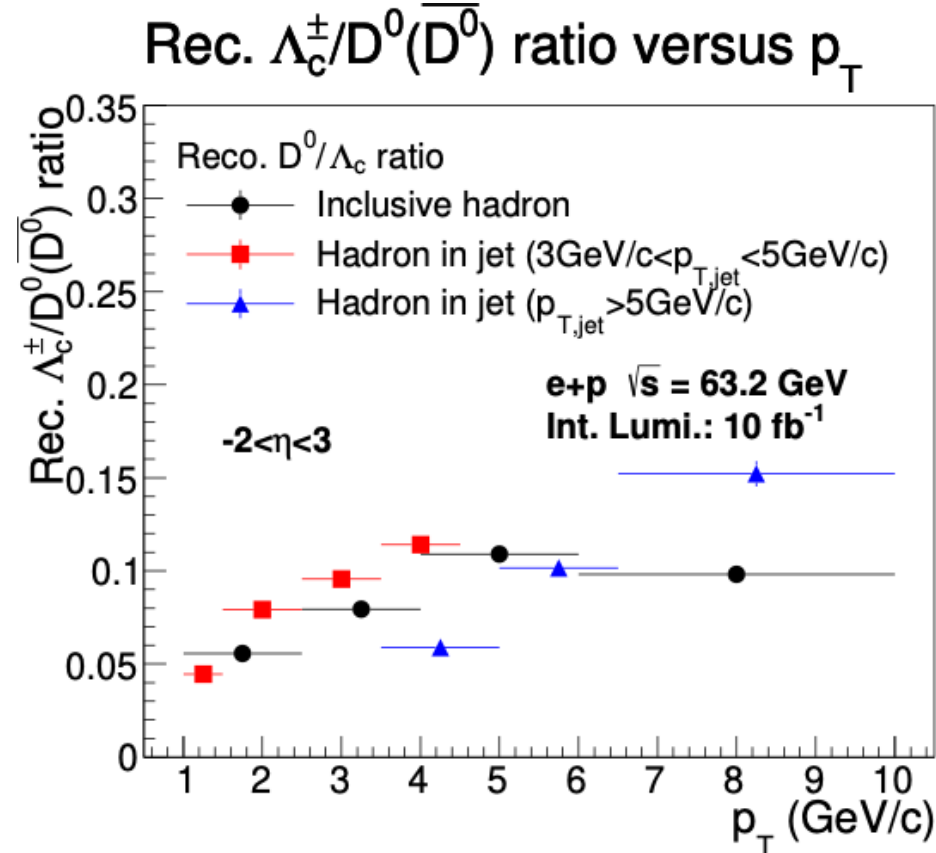
Reconstruction of charm hadrons inside jets with p_T 3-5 GeV/c



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

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

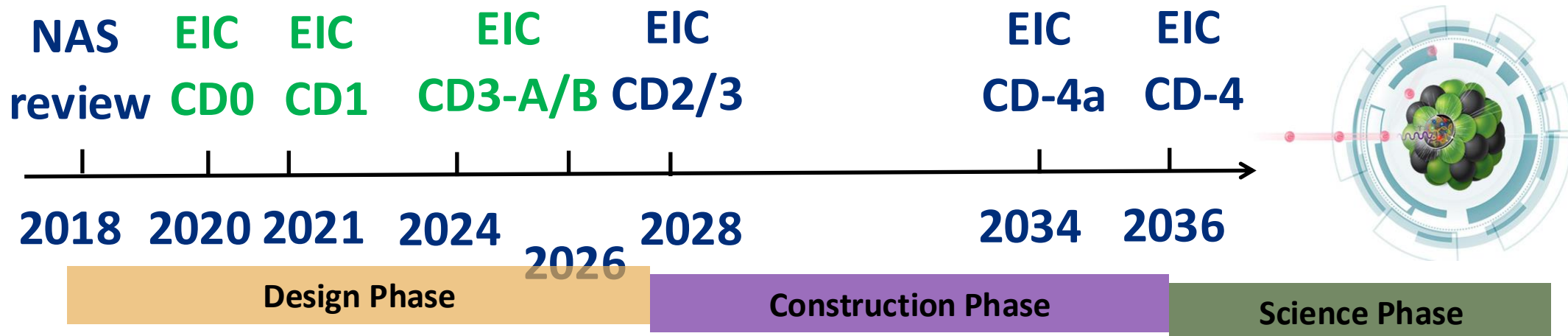
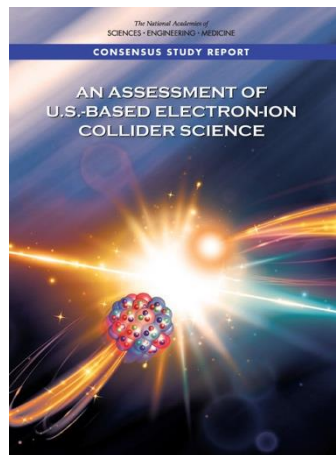
- Different phase spaces of the fragmentation functions can be selected by varying the associated jet p_T for D^0 in jets and Λ_c in jets.



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

Summary and Outlook

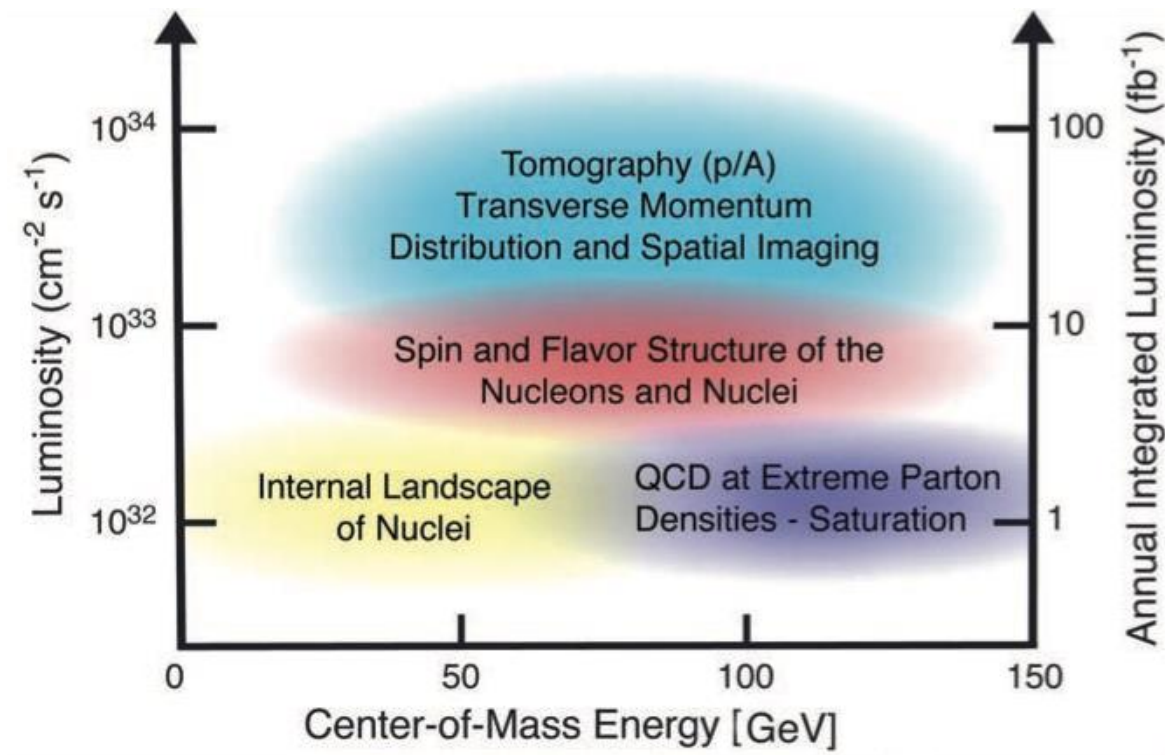
- The EIC will enable precision heavy flavor hadron and jet measurements in e+p and e+A collisions, extending into kinematics regions complementary to existing measurements.
- Its broad kinematic reach will provide unique insights into initial- and final-state effects, including parton energy loss and hadronization dynamics.
- New collaborators are welcome to join us!



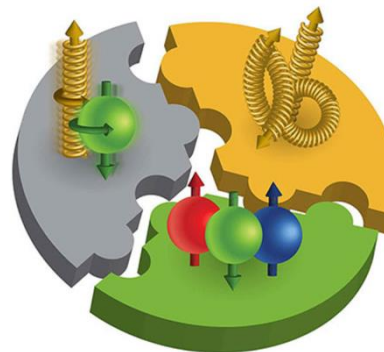
Backup

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

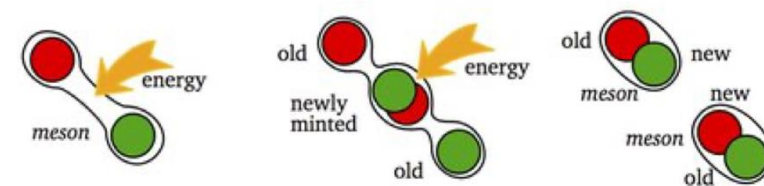
- With a series of e+p and e+A (A=2 to 238) collisions at different center of mass energies (20-141 GeV) and instantaneous luminosities (10^{33-34} $\text{cm}^{-2}\text{sec}^{-1}$), the future EIC will
 - precisely study the nucleon/nuclei 3D structure.
 - help address the proton spin puzzle.
 - probe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

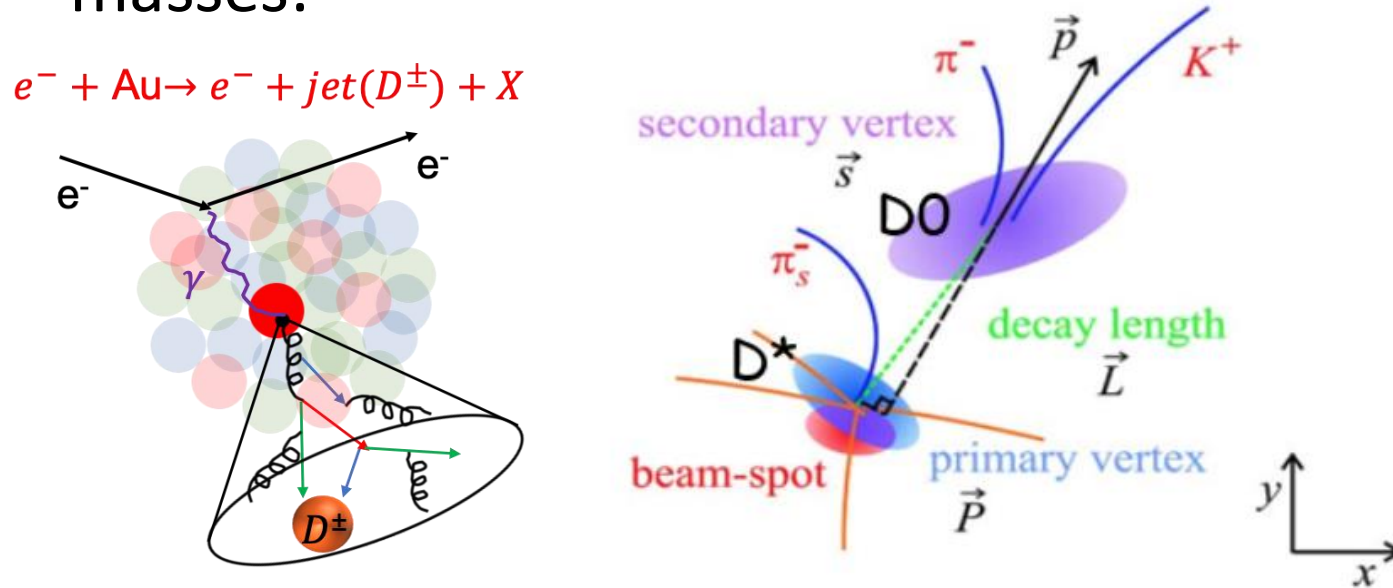


Quark confinement



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.

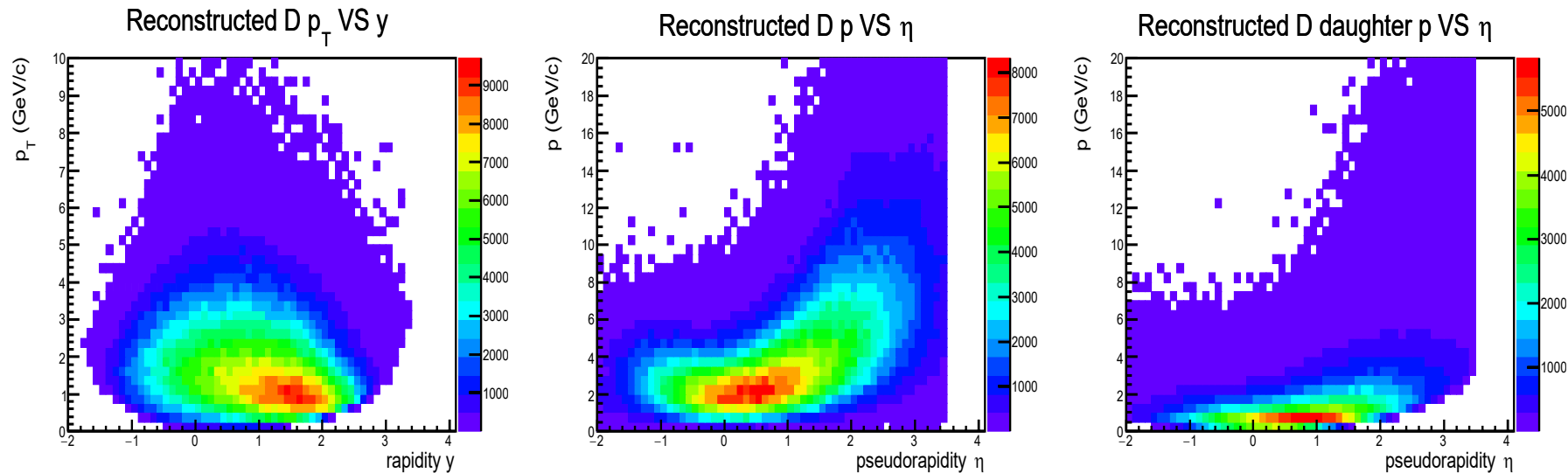


Particle	Mass (GeV/c ²)	Average decay length
$D^\pm$	1.869	312 micron
D^0	1.864	123 micron
$B^\pm$	5.279	491 micron
B^0	5.280	456 micron

- Heavy flavor physics-driven detector performance requirements:
 - Fine spatial resolution 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 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**.

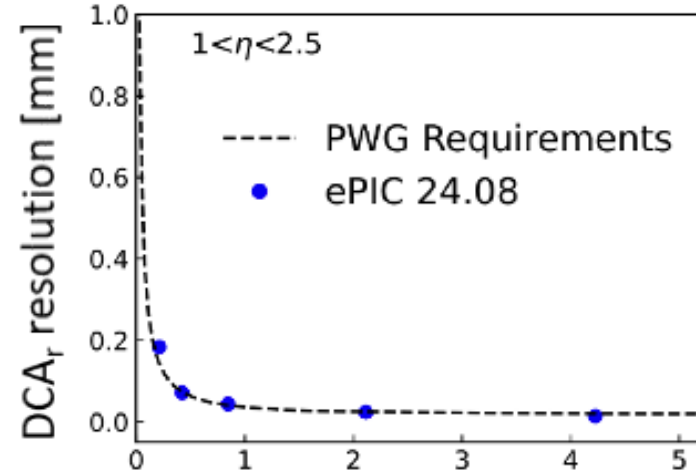
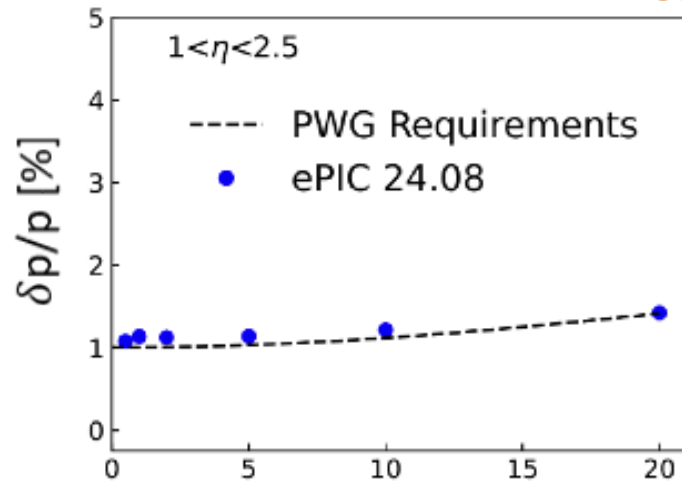


- **Fast timing (1-10ns readout)** capability allows the separation of different collisions and suppress the beam backgrounds.

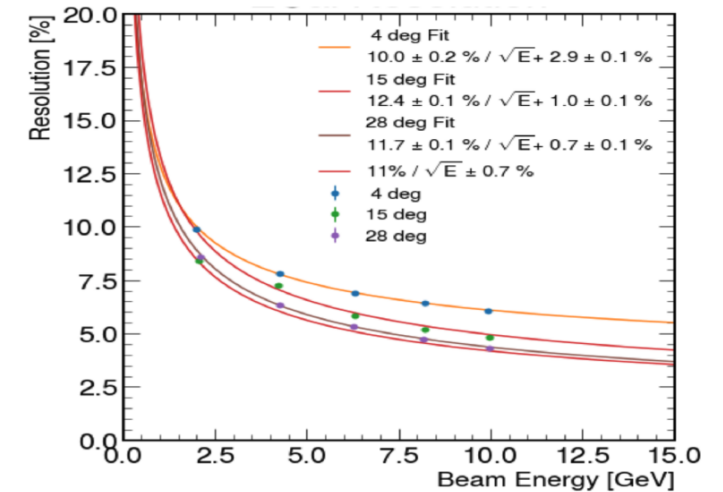
Current EIC project detector performance by the ePIC collaboration

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

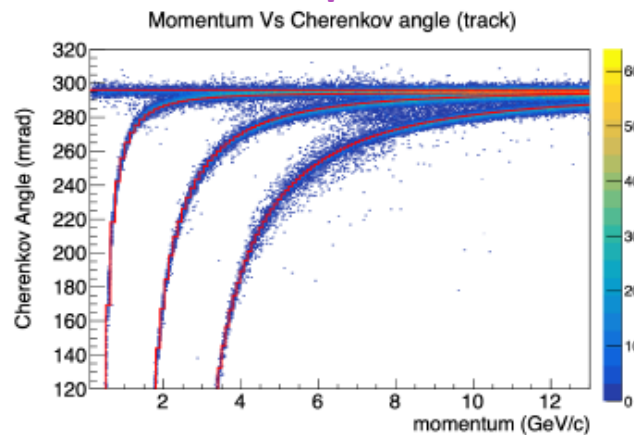
ePIC tracking



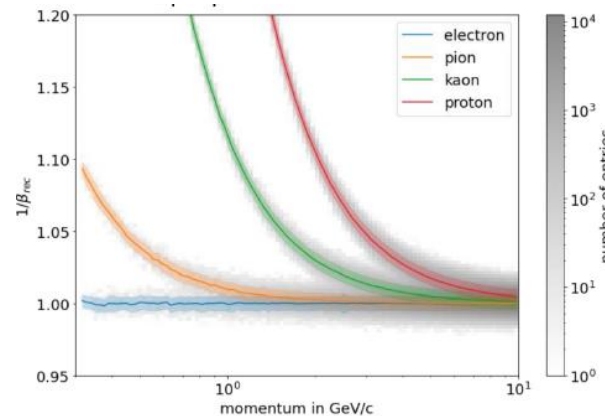
ePIC BEMC



ePIC pFRICH



ePIC hadron-endcap ToF



ePIC PID

