Extracting heavy flavor particles with ePIC

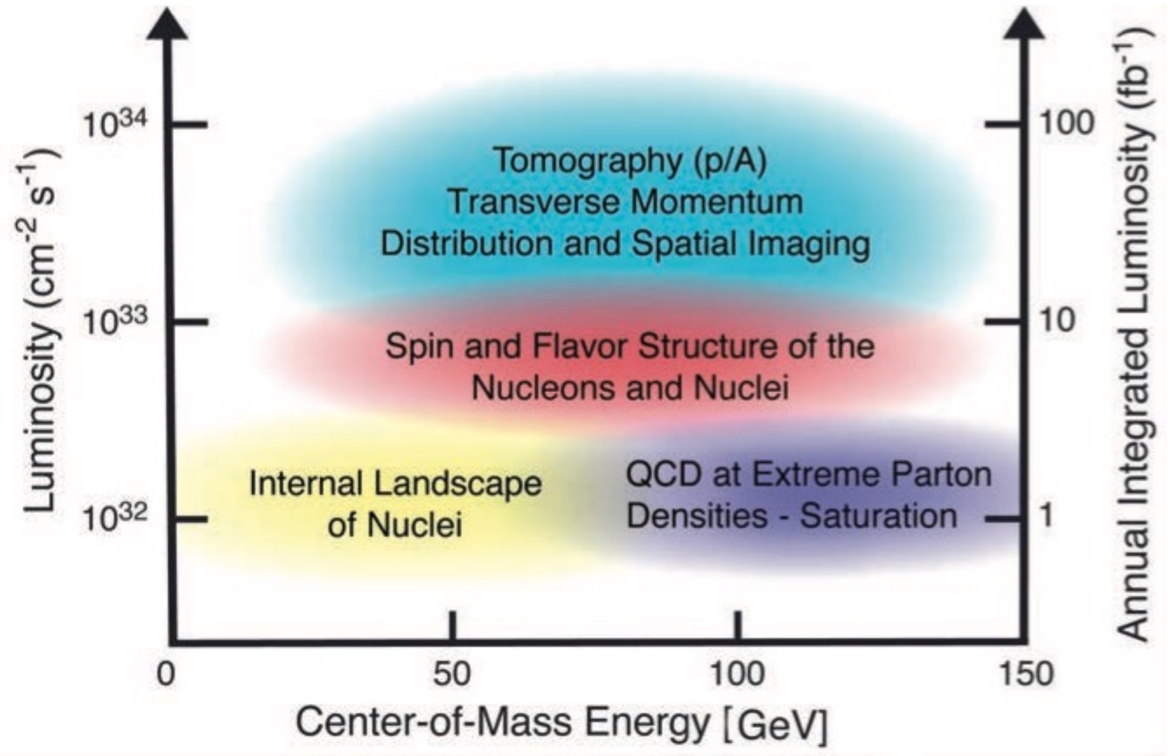
Xuan Li (xuanli@lanl.gov)
Los Alamos National Laboratory

Outline

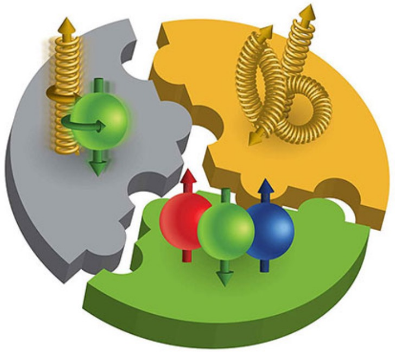
- Motivation to the heavy flavor physis at the Electron-Ion Collider (EIC).
- Introduction to the ePIC detector.
- Heavy flavor hadron and jet reconstruction in simulation and related physics projections.
- Summary and Outlook

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

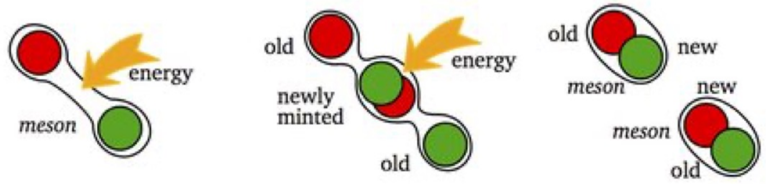
- With a series of e+p and e+A (A=2 to 238) collisions at different center of mass energies (20-141 GeV) and luminosities ($10^{33\text{-}34}$ $cm^{-2}sec^{-1}$), the future EIC will
  - precisely study the nucleon/nuclei 3D structure.
  - help address the proton spin puzzle.
  - probe the nucleon/nuclei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



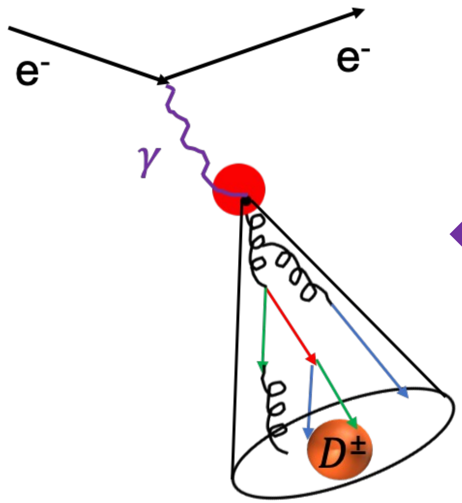
Quark confinement



Heavy flavor measurements can enrich the EIC physics program

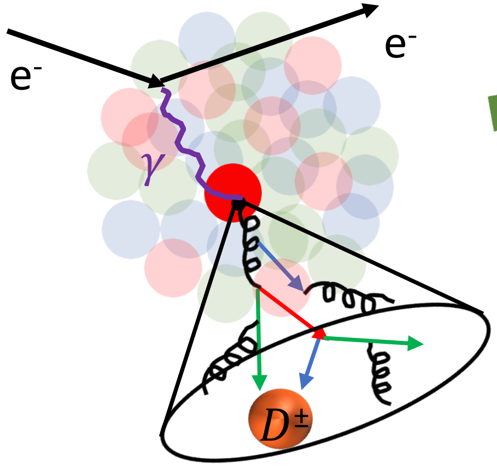
- Heavy flavor hadron and jet measurements are an important part of the EIC science portfolio and play a significant role in exploring
  - Nuclear modification on the initial nuclear Parton Distribution Functions (nPDFs) especially in the high and low Bjorken-x (x_{BJ}) region.
  - Final state parton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

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

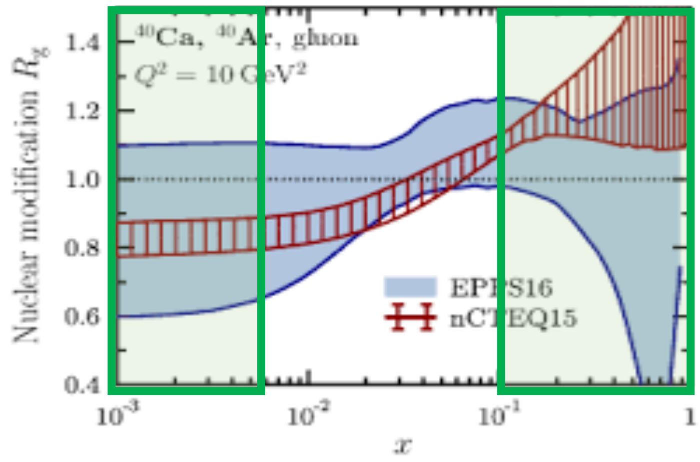


Compare

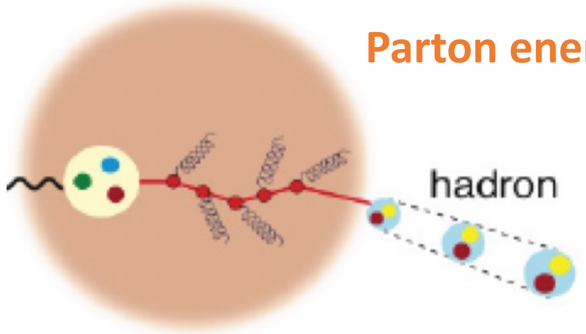
$e^- + \mathrm{Au} \rightarrow e^- + jet(D^{\pm}) + X$



nPDF modification



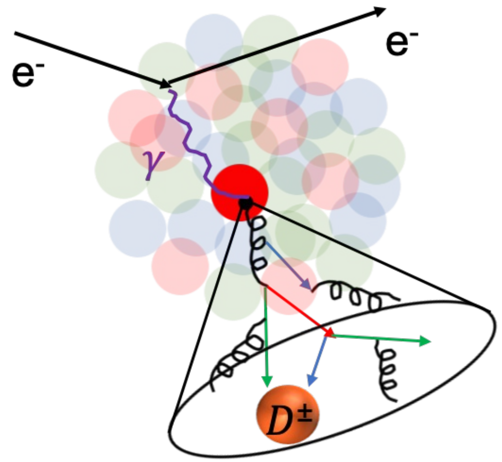
Parton energy loss

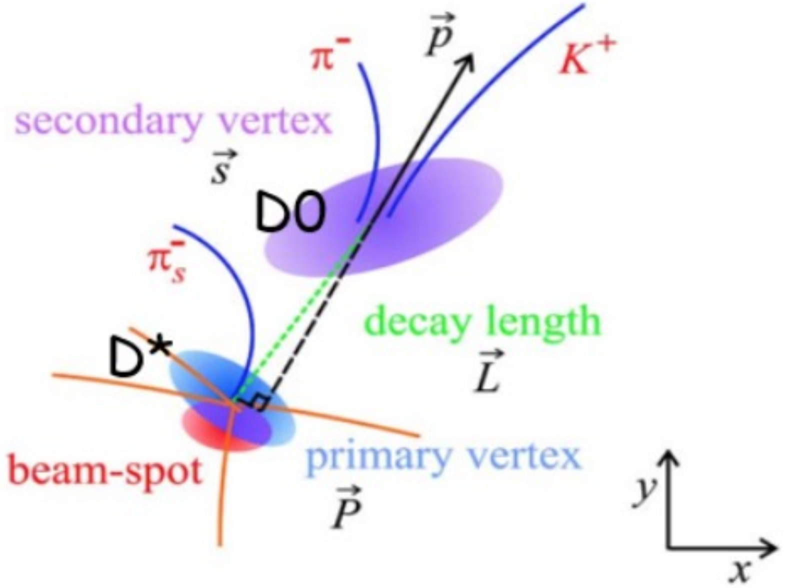


High precision vertex/tracking detector is required to measure HF products

- 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.

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



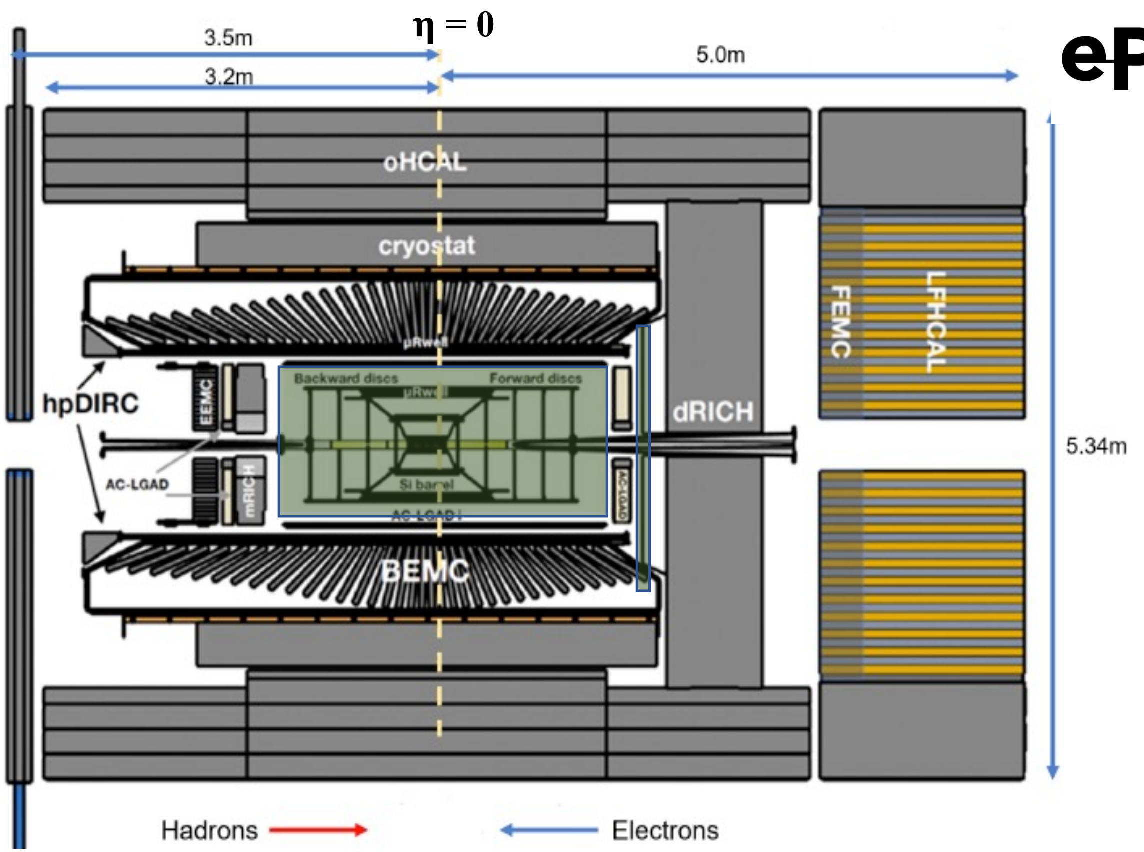


Particle	Mass (GeV/c²)	Average decay length
$D^\pm$	1.869	312 micron
D^0	1.864	123 micron
$B^\pm$	5.279	491 micron
B^0	5.280	456 micron

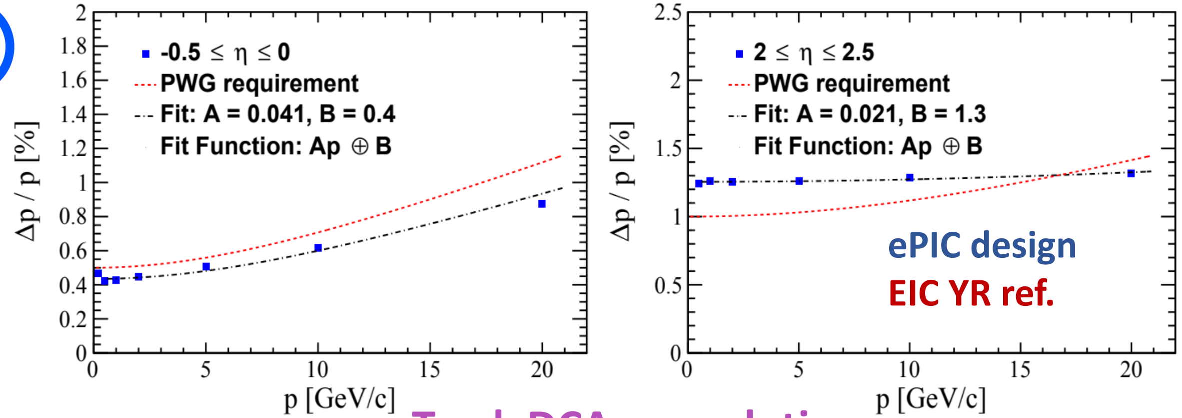
- Heavy flavor physics-driven detector performance requirements:
  - Fine spatial resolution (< 80 μm) for displaced vertex reconstruction.
  - Fast timing resolution (< 2 μs) to suppress backgrounds from neighboring collisions.
  - Low material budgets to maintain fine hit resolution for track reconstruction.

ePIC detector design and key performance for HF reconstruction

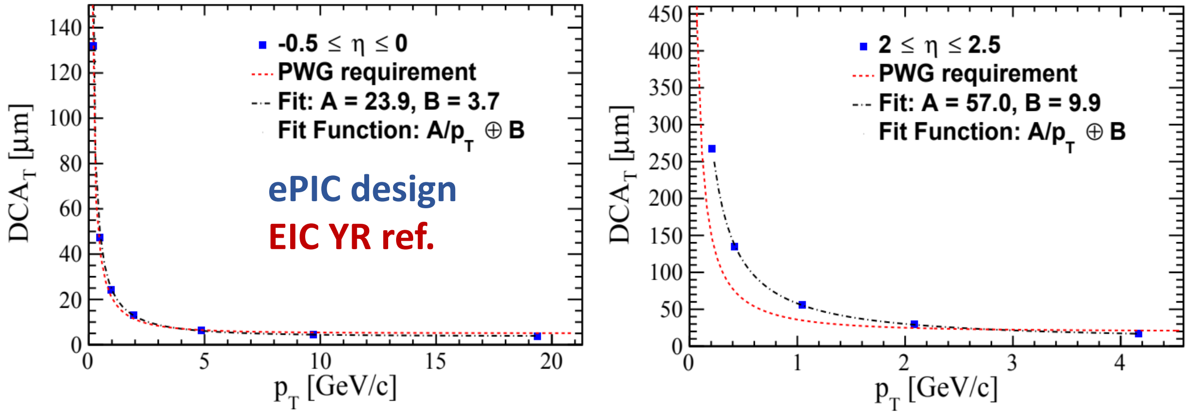
- The current EIC project detector design (ePIC), which consists of MAPS, MPGD and AC-LGAD tracking detectors, can achieve good momentum and transverse DCA (DCA_{2D}) resolutions. The ePIC detector can also provide precise particle identification and energy determination for heavy flavor reconstruction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



Track momentum resolution

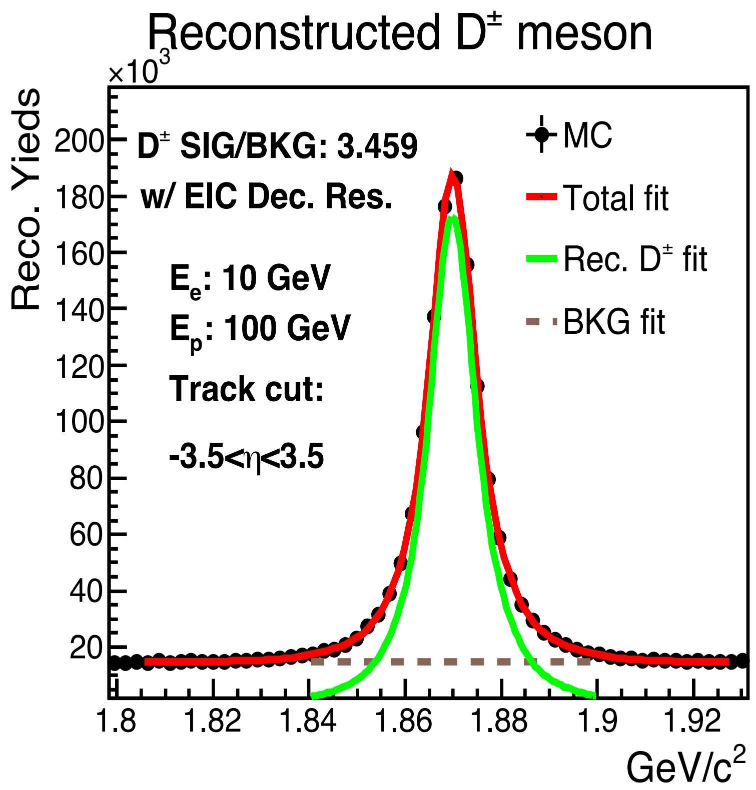


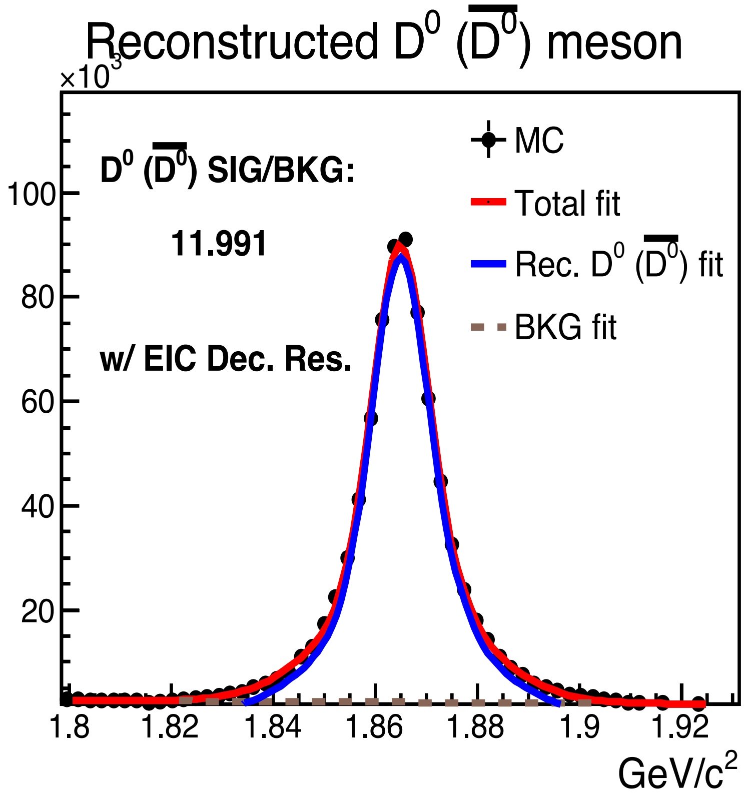
Track DCA_{2D} resolution

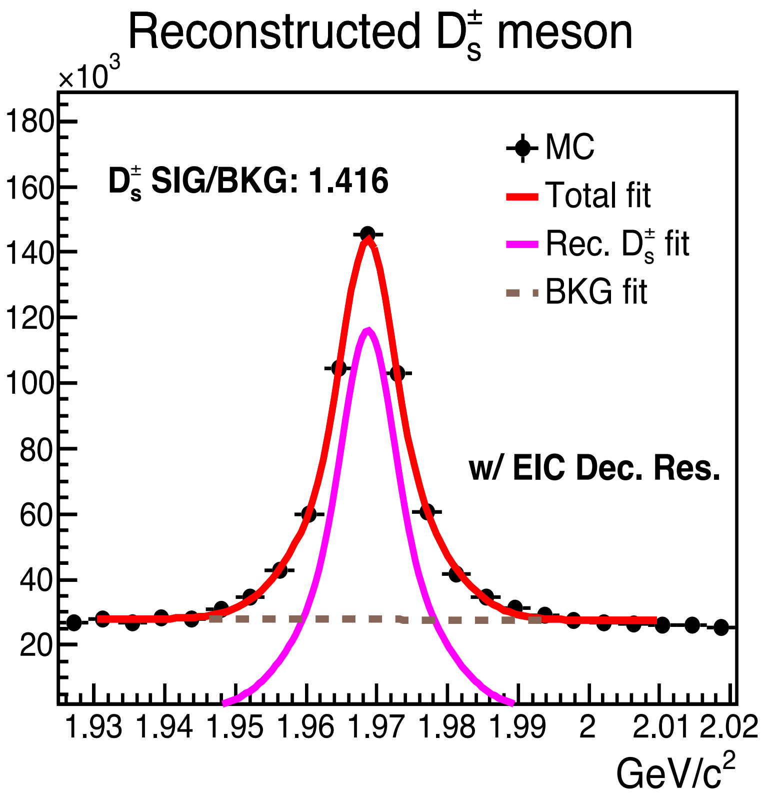


Reconstruction of open heavy flavor hadron in e+p simulation (I)

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

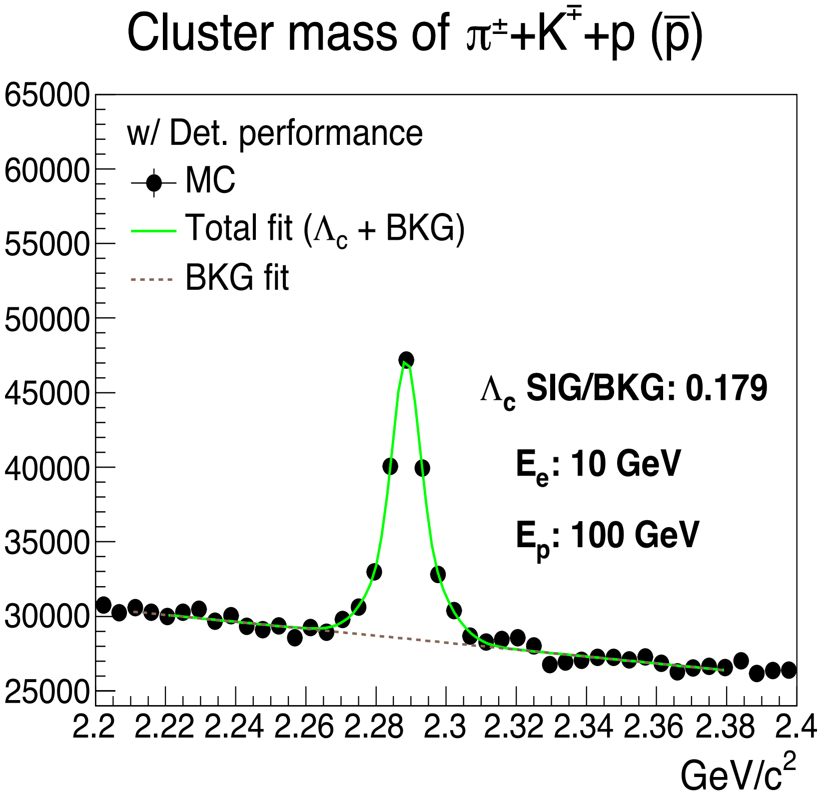


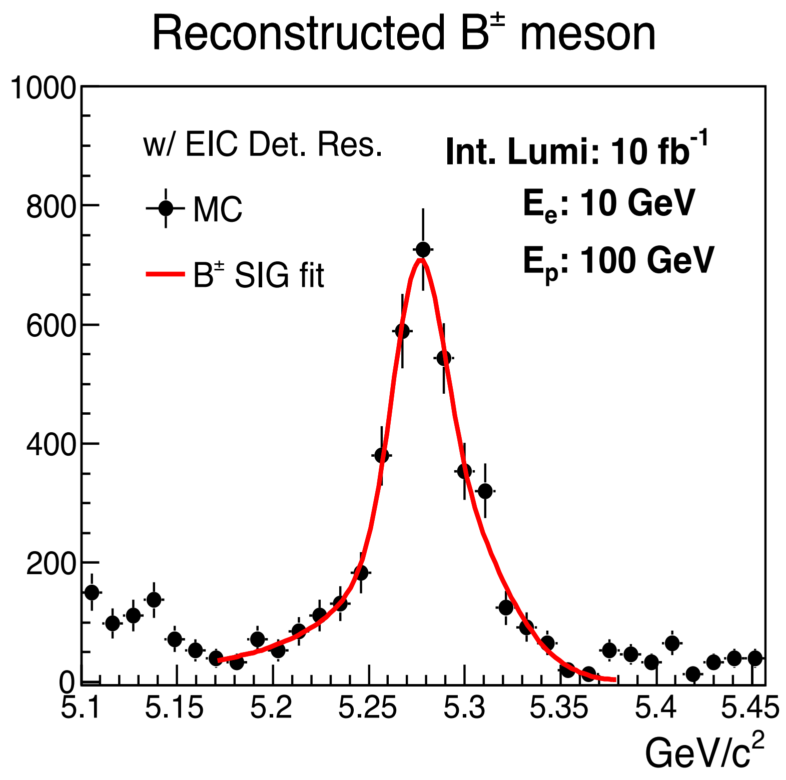


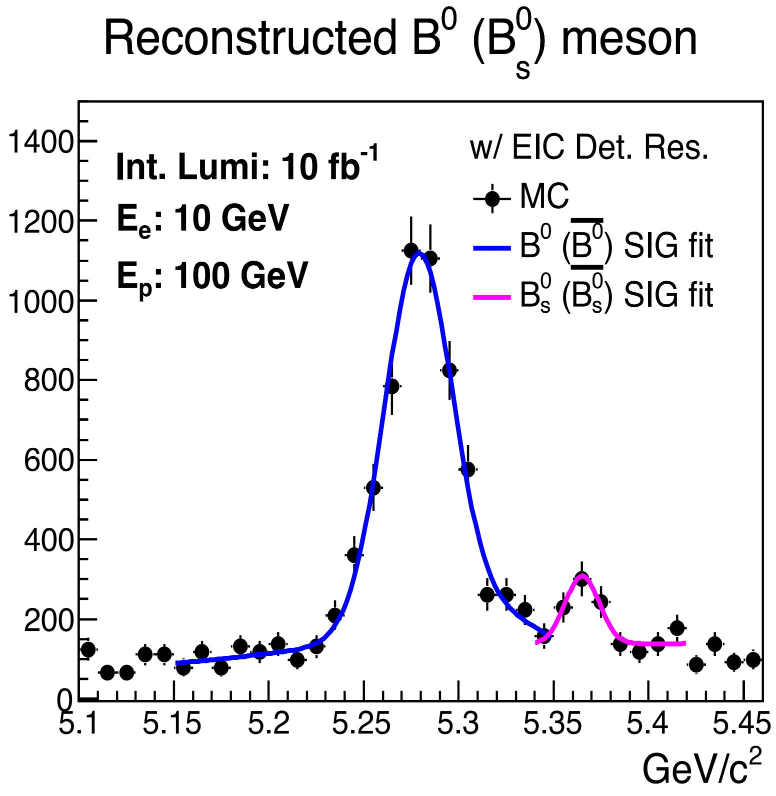


Reconstruction of open heavy flavor hadron in e+p simulation (II)

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

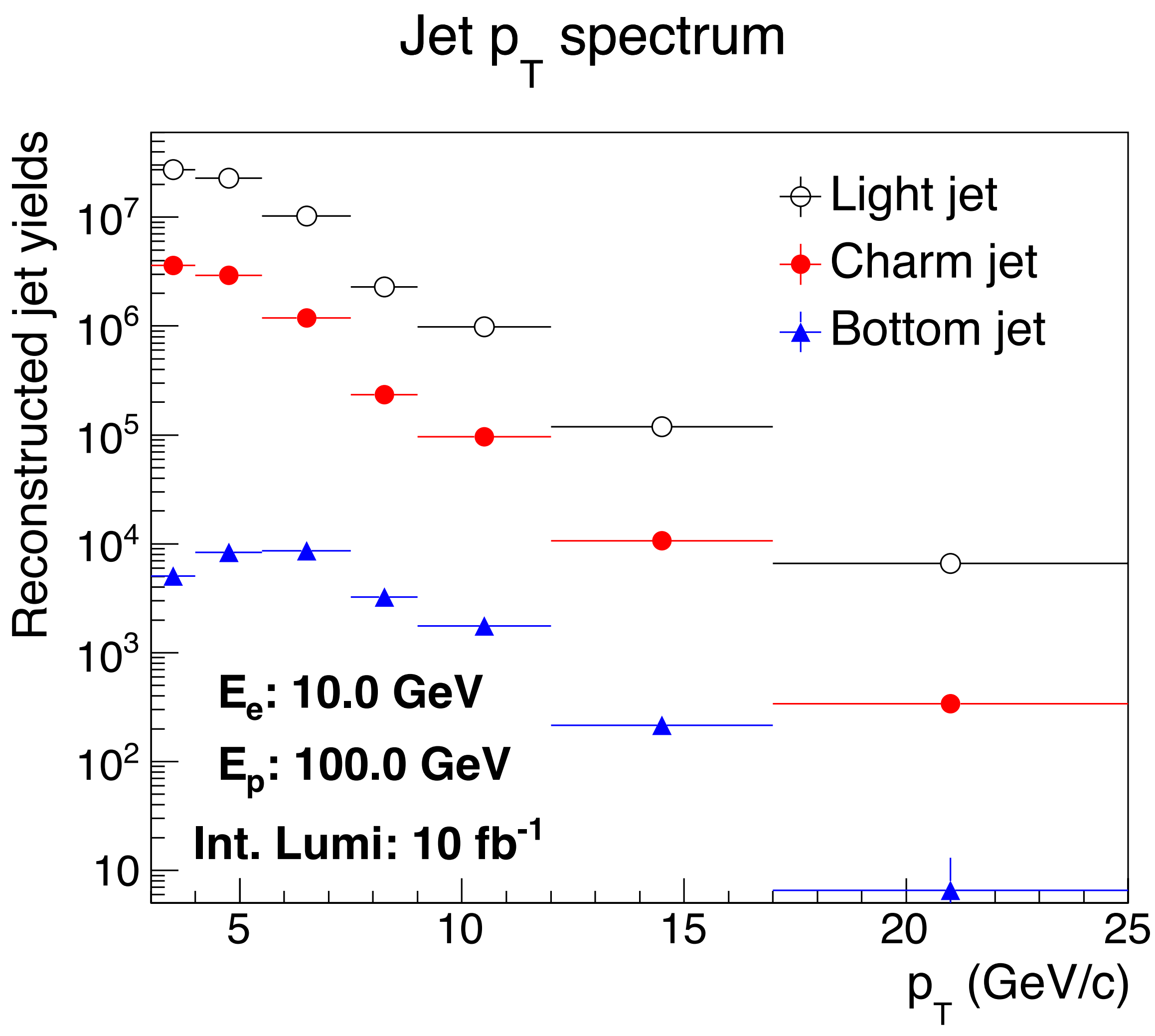






Reconstructed heavy flavor jets in e+p simulation

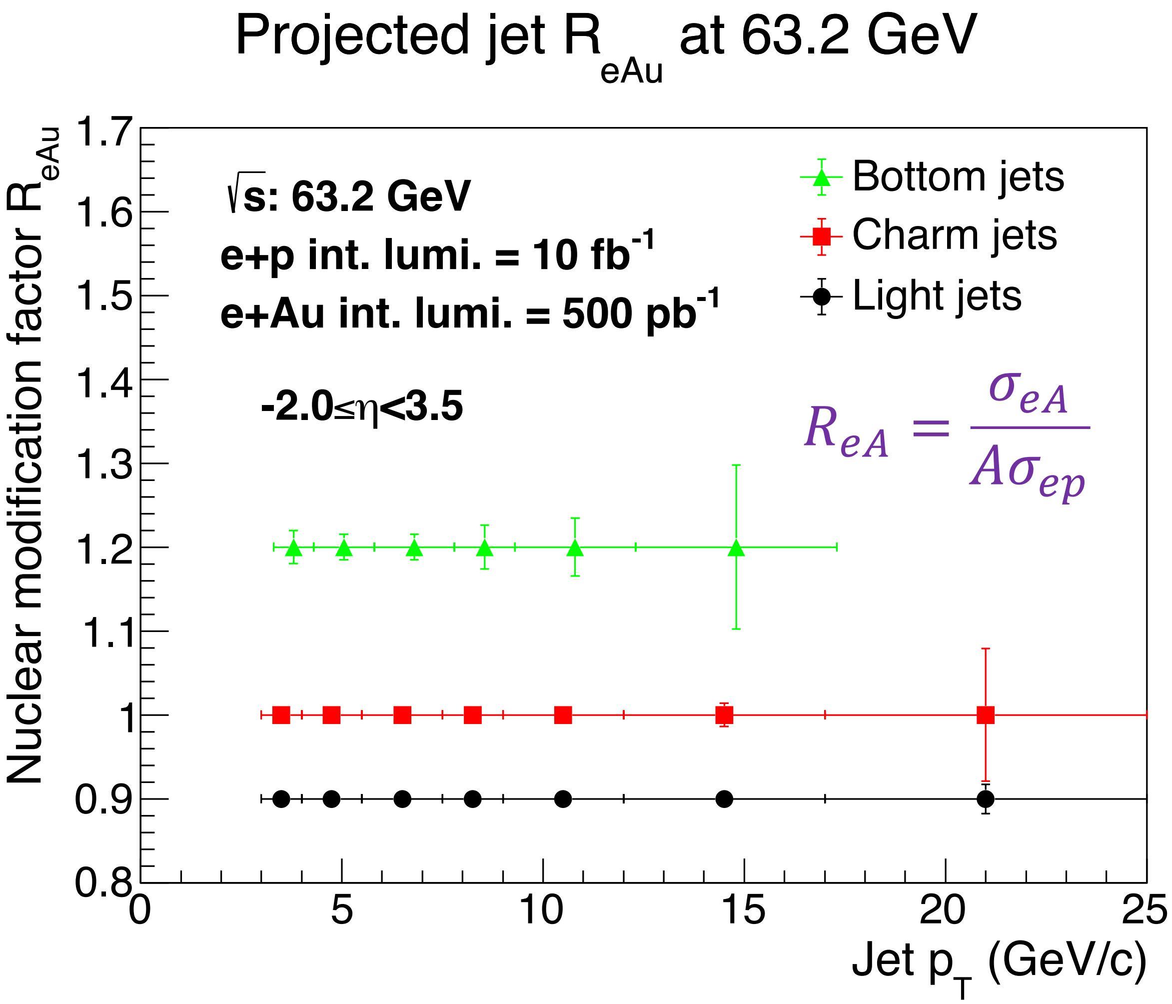
- Heavy flavor jets can be treated as the surrogate of the produced heavy quarks.
- P_T spectrum of reconstructed jets with different flavors in simulation using the ePIC detector performance in 10 GeV electron and 100 GeV proton collisions with 10 fb^{-1} integrated luminosity.
- Jets are reconstructed with the anti-k_T algorithm and cone radius R is 1.0.
- Charm-jets (bottom-jets) 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 GeV/c

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.

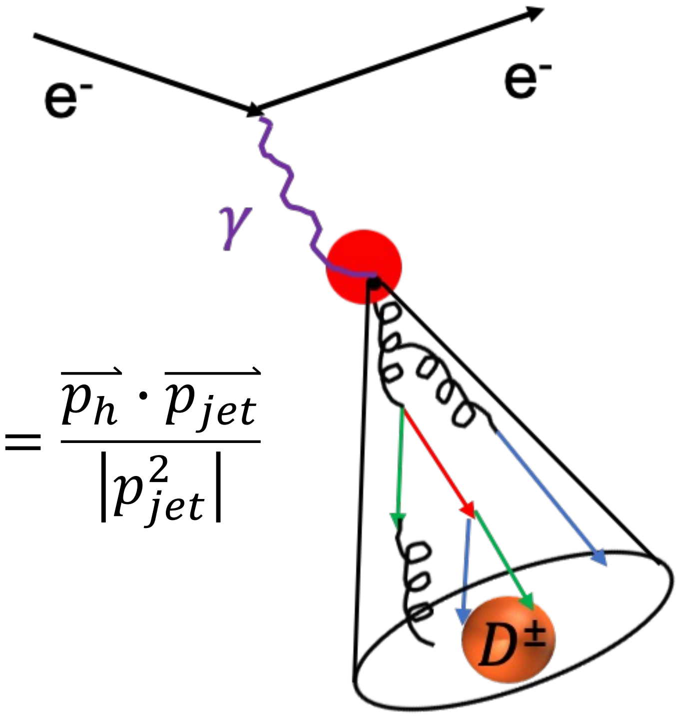


- EIC will provide unique opportunities to probe low p_T (p_T < 15 GeV/c) heavy flavor jets in cold nuclear medium with good precision to study the flavor dependent parton energy loss mechanism.
- Comparison between the EIC measurements and results achieved in heavy ion collisions can help extracting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

Hadron inside jet production to explore the hadronization process

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

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

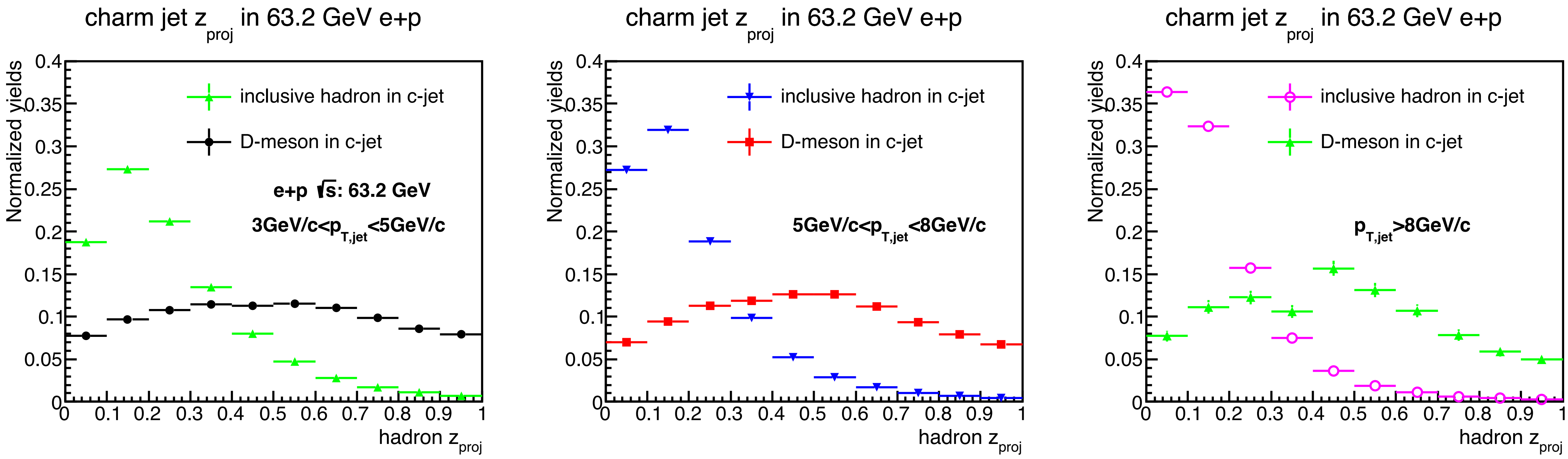


$$z_{proj} = \frac{\overrightarrow{p_h} \cdot \overrightarrow{p_{jet}}}{|p_{jet}^2|}$$

- Jet substructure observables can help extracting the jet kinematic properties and shed light on the interference between the quarks/gluons and the surrounding nuclear medium.
- Will discuss the studies of hadron momentum fraction, z_{proj} for hadrons inside heavy flavor jets in e+p collisions and its nuclear modification factor projection in e+A collisions.

Kinematic dependent charm jet substructure in e+p collisions

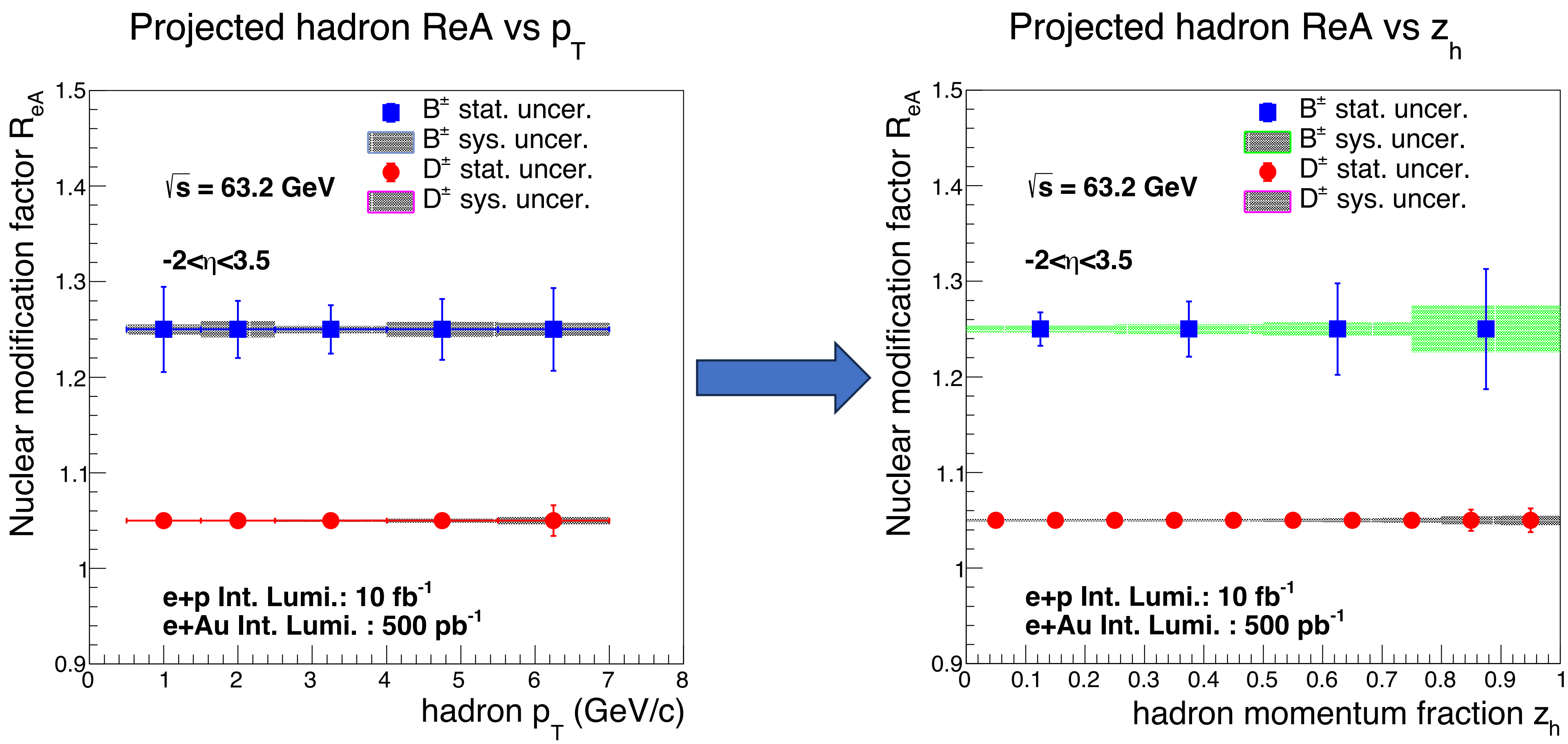
- Hadron inside charm jet z_{proj} distributions with jet p_T in 3-5 GeV/c (left), 5-8 GeV/c (middle), > 8 GeV/c (right) in 10+100 GeV e+p simulation.



- 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.

Heavy flavor hadron nuclear modification factor R_{eAu} projection

- Projected R_{eAu} statistical (systematical) uncertainties of inclusive heavy flavor hadrons (left) and heavy flavor hadron inside jets (right) in 10 GeV electron and 100 GeV gold collisions.



Great precision in constraining the heavy quark hadronization process will be provided by the EIC even with one-year operation!

A different approach to study the hadronization: jet angularity

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

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

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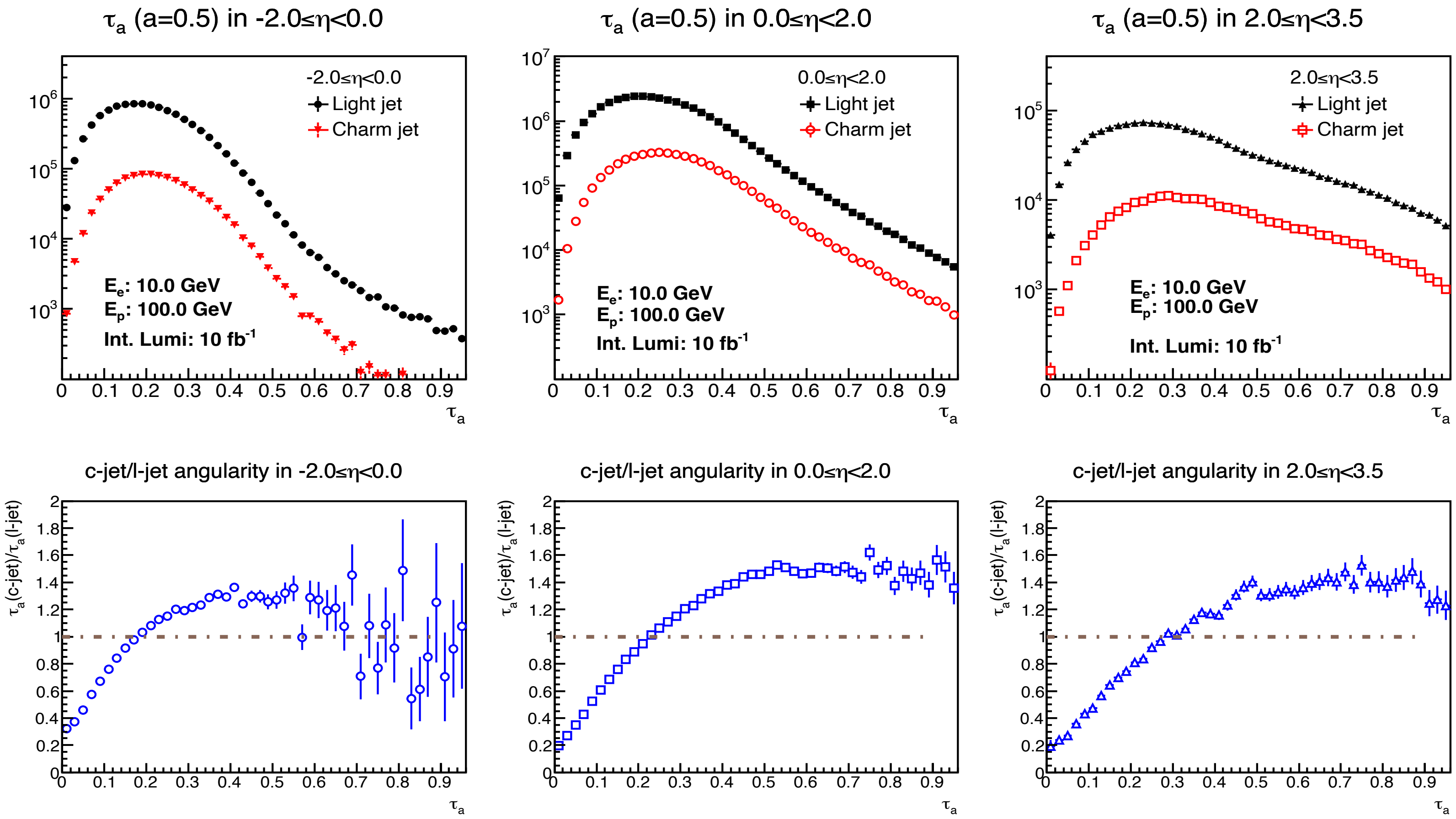
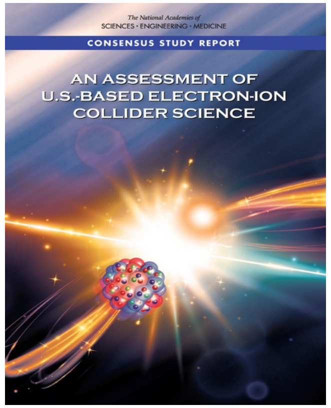


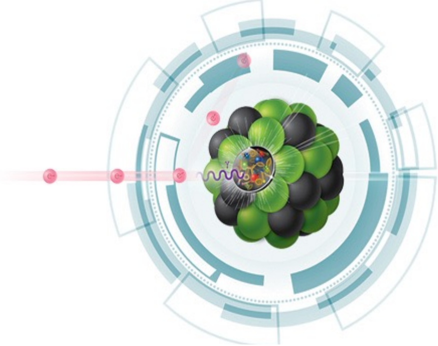
- The charm/light jet angularity shape difference depends on the pseudorapdy.
- Shed light onto how quarks/gluons fragment into final hadrons with different masses.
- Impacts by nuclear medium effects will be studied in e+A collisions.

Summary and Outlook

- High precision heavy flavor hadron and jet measurements in e+p and e+A collisions enabled by the ePIC detector will shed light on the heavy quark production and constrain its initial and final state effects.
- As the ePIC detector design is evolving, the associated physics projection will be updated accordingly but we don’t expect major changes on the physics impacts.
- As we are moving towards the EIC construction in 2025, we look forward to work with more collaborators for the ePIC detector/experiment realization.



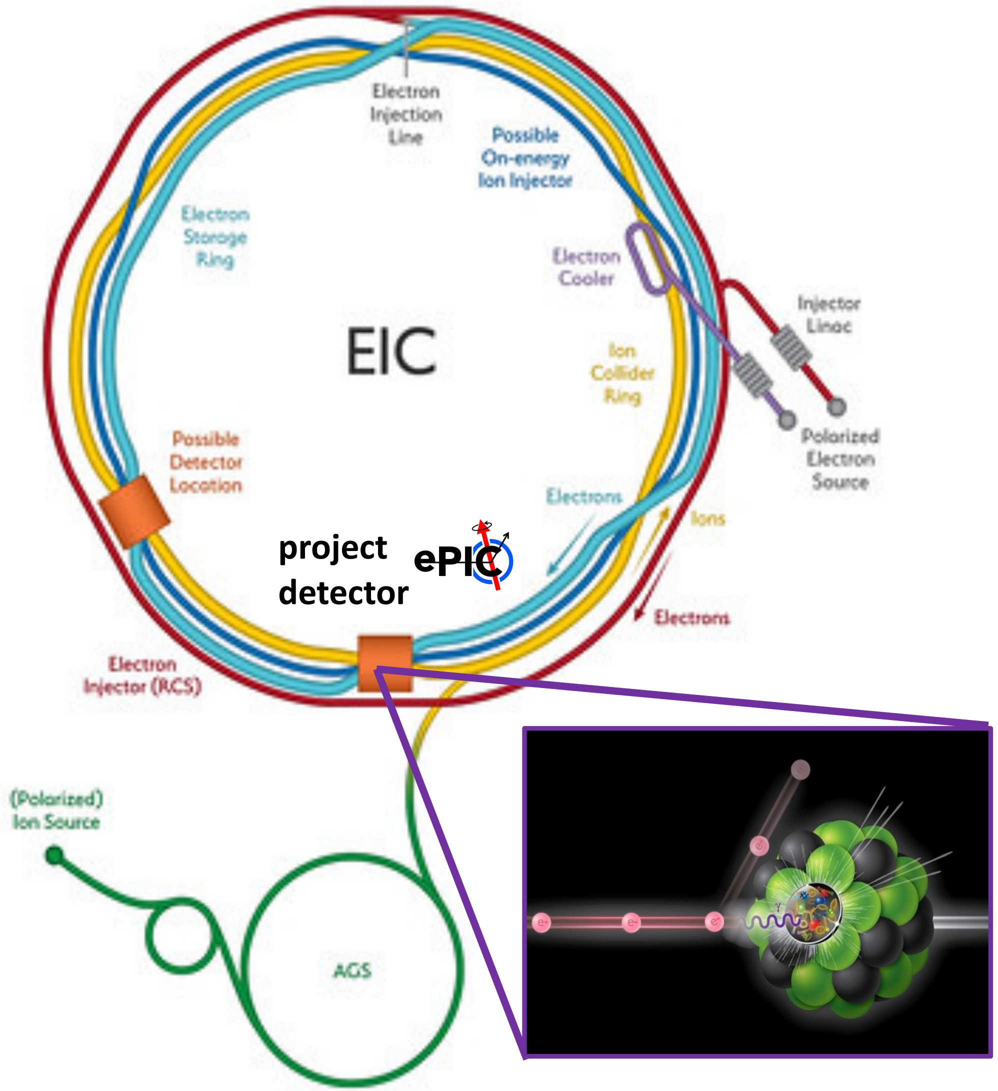
NAS review	EIC CD0	EIC CD1	EIC CD3A	EIC CD2/3	EIC CD-4a	EIC CD-4
2018	2020	2021	2024	2025	2032	2034



Backup

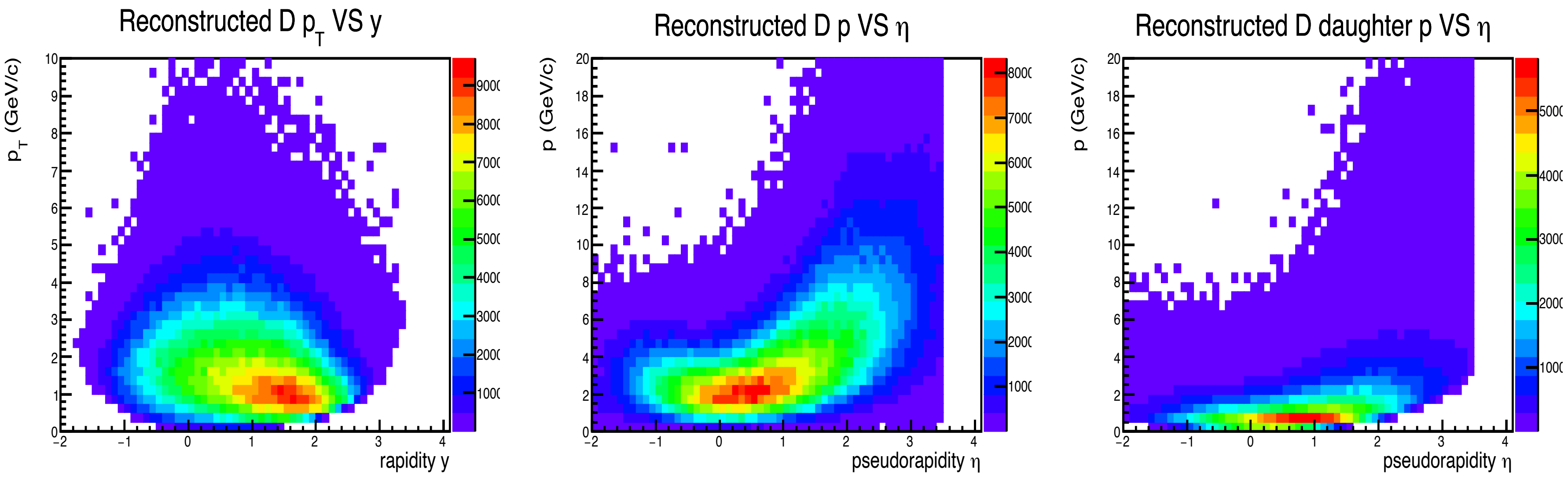
Introduction to the future Electron-Ion Collider (EIC)

- 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 Ep.
  - (Polarized) e beam at 2.5-18 GeV.
  - Instant luminosity L_{int} ~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$. A factor of ~1000 higher than HERA.
  - Bunch crossing rate: ~10 ns.



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.