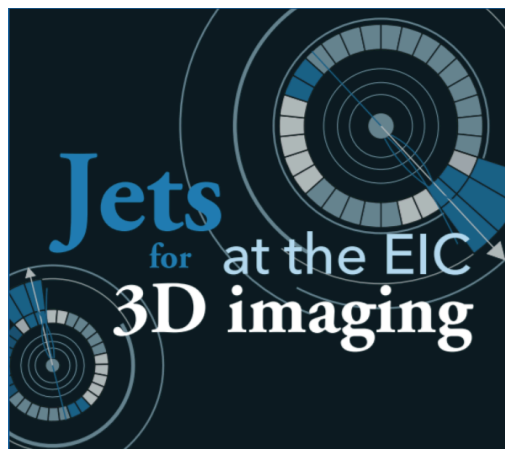


Heavy Flavor and jet studies for the future Electron-Ion Collider

LA-UR-20-29562

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Los Alamos National Laboratory



*Jets for 3D imaging
online workshop
Nov. 23 to 25, 2020*



Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

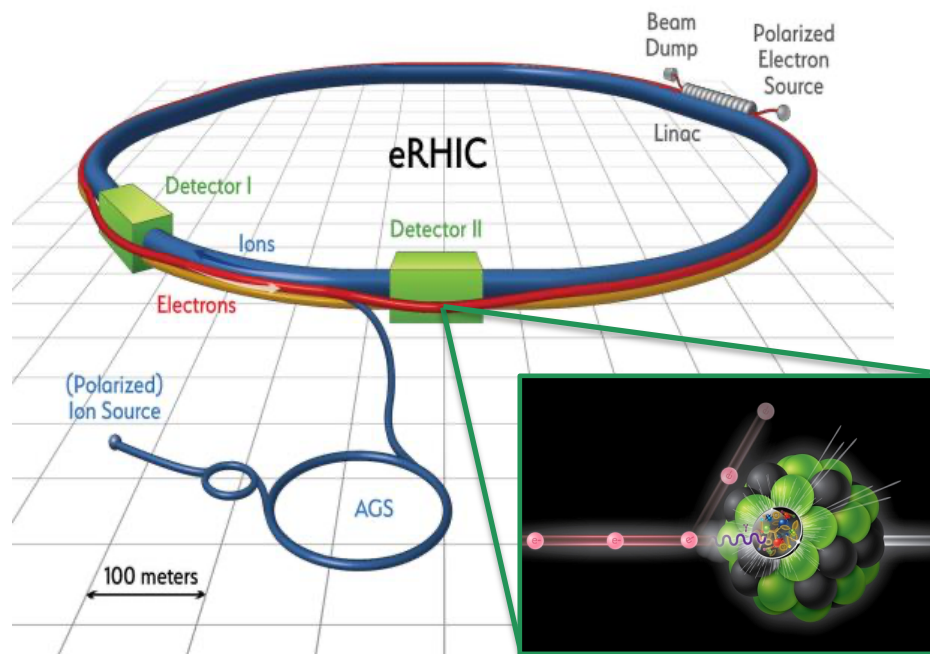
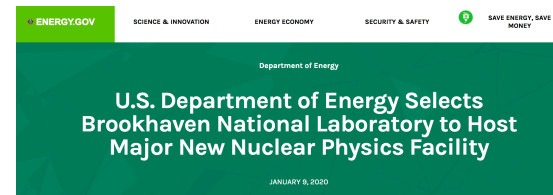
LA-UR-20-29562

Outline

- Why to measure heavy flavor and jets at the EIC?
- How to measure heavy flavor at the EIC?
- Initial forward silicon tracker detector design and tracking performance.
- Open heavy flavor and jet studies in simulation.
- Summary and outlook.

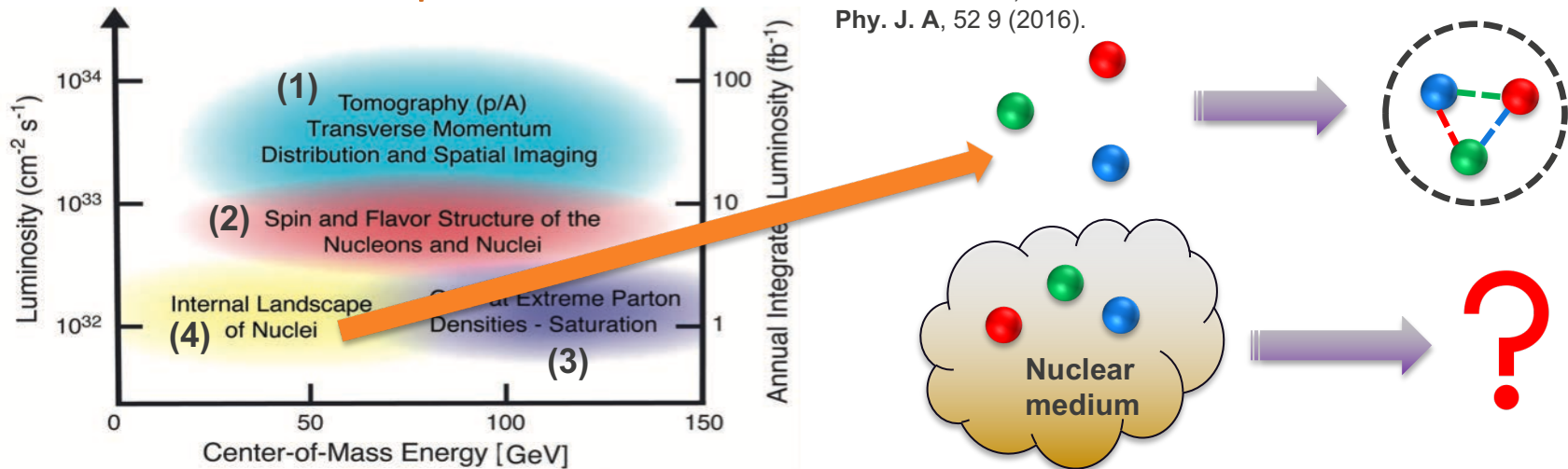
The Electron-Ion Collider will bring new opportunities in high-energy nuclear physics

- The proposed Electron-Ion Collider (EIC) CD0 has been announced and the site is selected to be BNL.
- e-p collisions at the EIC:
 - (Polarized) p, d/³He beams at 41-275 GeV.
 - (Polarized) e beam at 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: 1-10 ns.
- e-A collisions at the EIC:
 - Multiple nuclear species ($A=2-208$) and variable center of mass energies.
 - Instant luminosity $L_{\text{int}} \sim 10^{33-34} \text{ cm}^{-2}\text{sec}^{-1}$.
 - Bunch crossing rate: 1-10 ns.



Fundamental questions to be explored by the EIC

- The proposed EIC will (1) precisely study the nucleon/nuclei 3D structure, (2) help address the proton spin puzzle and (3) explore the nucleon/nuclei parton density extreme – gluon saturation.
- It will provide a clean environment to (4) explore how quarks and gluons form visible matter inside the vacuum/medium, which is referred to as the hadronization process.



Heavy quarks play a special role within the EIC science portfolio (I)

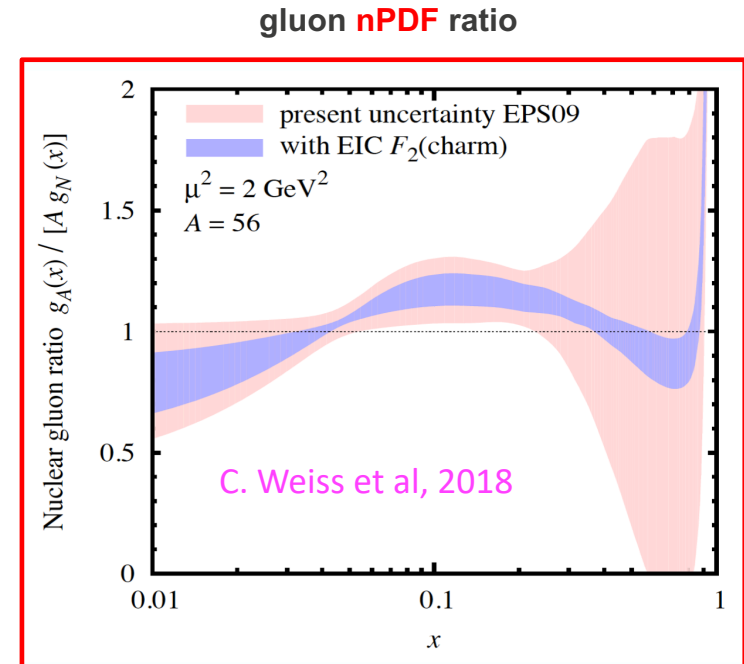
- Heavy quarks **c** (charm $M_c=1.3$ GeV), **b** (bottom $M_b=4.5$ GeV) are heavier than the proton. They are created in the initial collision and can probe the parton (quark or gluon) evolution processes inside the vacuum and the medium.

$$d\sigma_{\text{jet}} = f(x_B) \times H$$

Distribution of quarks and gluons in nucleons/nuclei

Accurately computable perturbative part

- The measured heavy flavor jet cross section contains information about the **initial nucleon/nuclear parton (quark or gluon) distributions**.



Heavy quarks play a special role within the EIC science portfolio (II)

- The measured heavy flavor jet/hadron cross section contains the information about both the **initial nucleon/nuclear parton distributions** and the **final state hadronization and fragmentation processes**.

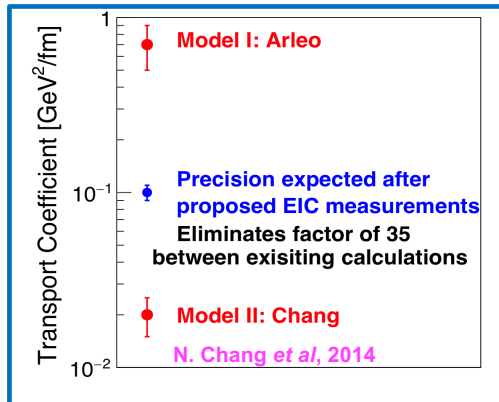
$$d\sigma_{\text{jet [hadron]}} = f(x_B) \times H [\times D(z_h)]$$

Distribution of quarks and gluons in nucleons/nuclei

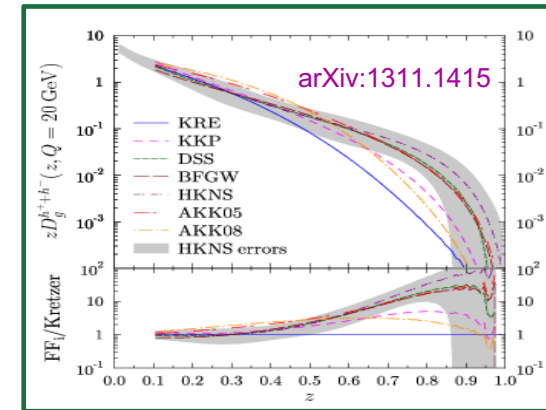
Accurately computable perturbative part

Hadronization function

Nuclear transport coefficient



gluon **FF**

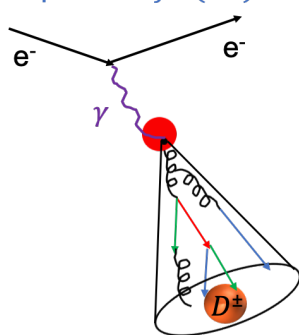


- Heavy quark nuclear transport properties are predicted to be distinctly different from light quarks, giving unique discriminating power between different models.

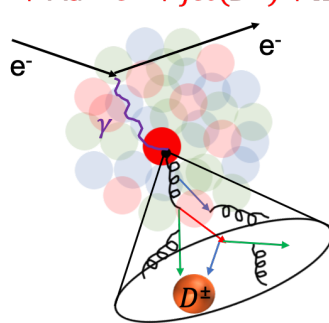
How to measure heavy quarks in experiments?

- At the EIC, hadrons or jets which contain heavy quarks can be identified by detectors using their unique lifetime and masses.

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



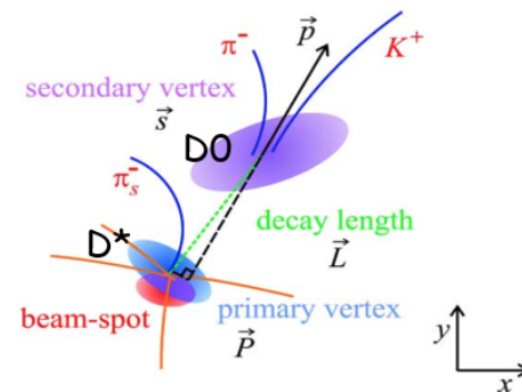
$$e^- + Au \rightarrow e^- + jet(D^\pm) + X$$



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

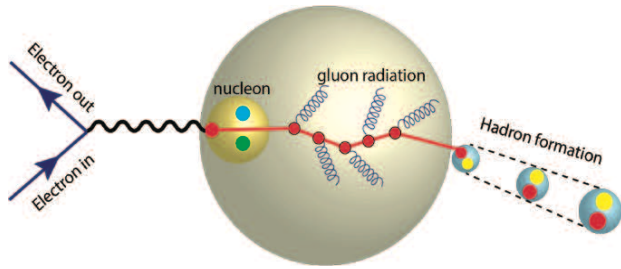
- Physics-driven detector performance requirements:

- Fine spatial resolution (<100 μm) for displaced vertex reconstruction.
- Fast timing resolution to suppress backgrounds from neighboring collisions.
- Low material budgets to maintain fine hit resolution.



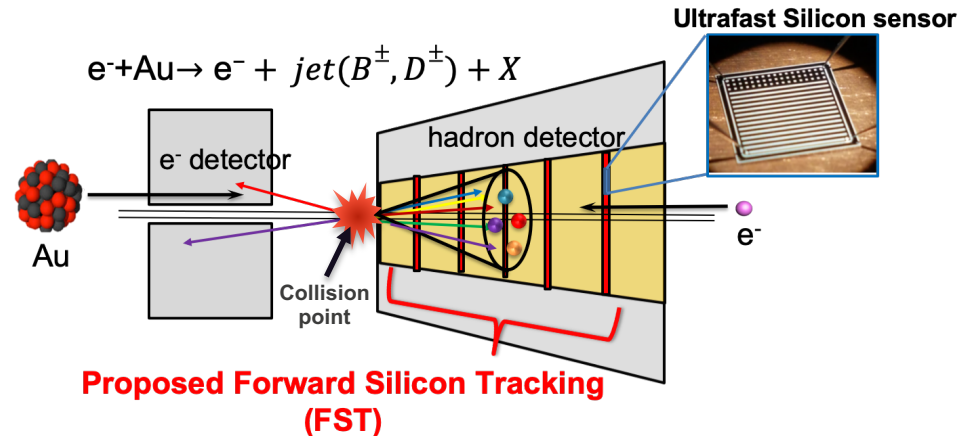
New EIC heavy flavor and jet program at LANL

- An EIC DR (20200022DR), Oct. 2019 to Sep. 2022, is funded by the LANL LDRD office with PI: Ivan Vitev, Co-PI: Xuan Li and 15+ staff/postdocs.



- Through this EIC project at LANL, we will explore hadronization processes and their medium modifications using heavy flavor and jet probes at the EIC.

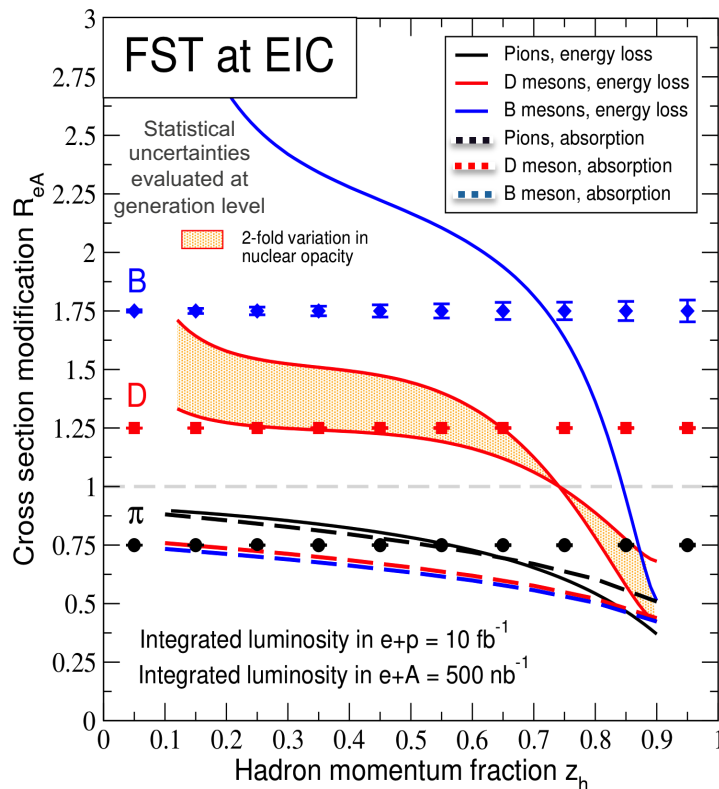
- We will carry out detector R&D for several advanced silicon sensor candidates and complete the conceptual design for a **forward silicon tracking detector** to realize the EIC heavy flavor and jet physics measurements.



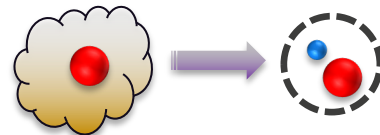
Heavy flavor physics observables at the EIC to probe hadronization

- Calculations done in the energy loss approach:
 - **Tremendous discriminating power** between models of energy loss and hadronization in matter.
 - Can **constrain nuclear opacities & transport properties to 20%**.
- Strong discriminating power provided by heavy flavor measurements to separate different nuclear effects.

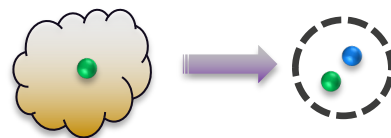
EPJ Web of Conferences 235, 04002 (2020)



Heavy quark
fragmentation
modification in
e+A collisions



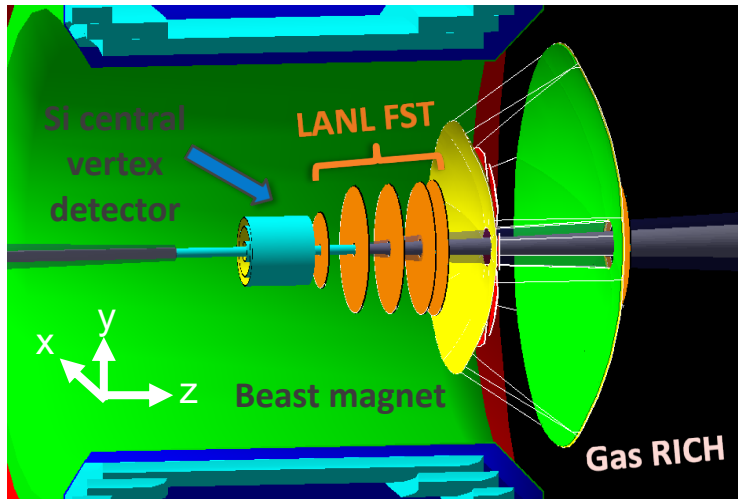
Light quark
fragmentation
modification in
e+A collisions



Conceptual design of the proposed Forward Silicon Tracking detector for the EIC

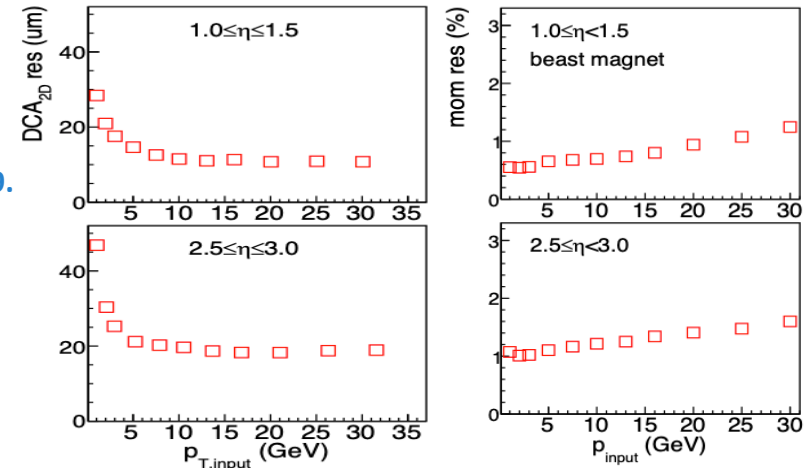
- GEANT4 simulation within the Fun4All framework:
 - Assumed mid-rapidity silicon vertex detector with 5 barrel layers based on the Monolithic Active Pixel Sensor (MAPS) type technology.
 - Forward-rapidity silicon tracking detector (FST) with $1.0 < \eta < 3.5$: 3 planes of MAPS silicon detector and 2 forward planes of HV-MAPS silicon detector.

LANL FST integrated inside the EIC



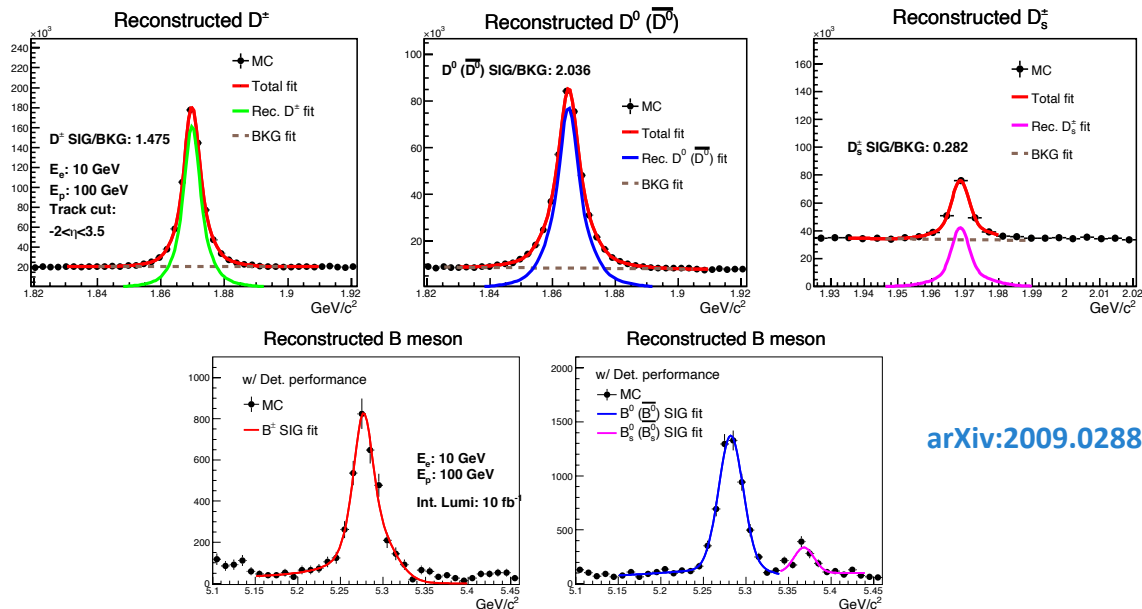
LANL FST tracking performance meets the open heavy flavor reconstruction requirements

arXiv:2009.02888



Reconstructed heavy flavor hadron with the proposed FST in simulation

- The full analysis framework which includes the **event generation** (PYTHIA), **detector response in GEANT4 simulation**, **beam remnant & QCD background**, and hadron reconstruction algorithm have been setup.
- Mass distributions of reconstructed **D-meson** and **B-meson** family in 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 fb^{-1} .

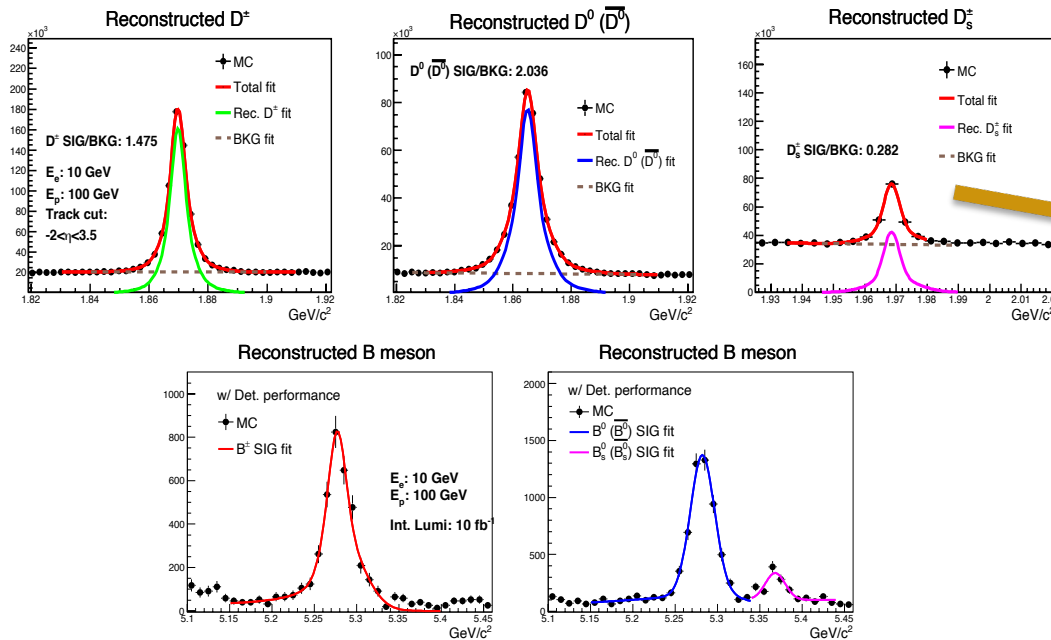


arXiv:2009.02888

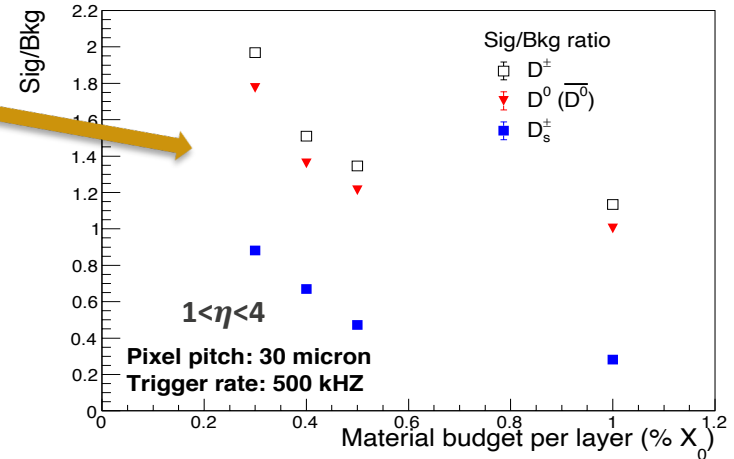
- Central, backward and forward tracking performance.
- Primary vertex resolution: 20-35 (μm) depends on the track multiplicity.
- 95% $K/\pi/p$ separation over all the acceptance.
- Charged track clusters with a decay length (DCA) cut.

Reconstructed heavy flavor hadron with the proposed FST in simulation

- Heavy flavor physics studies can provide guidance on the EIC detector technology selection and conceptual design.
- Mass distributions of fully reconstructed D-meson and B-meson.
- Provide detector requirements based on physics needs.

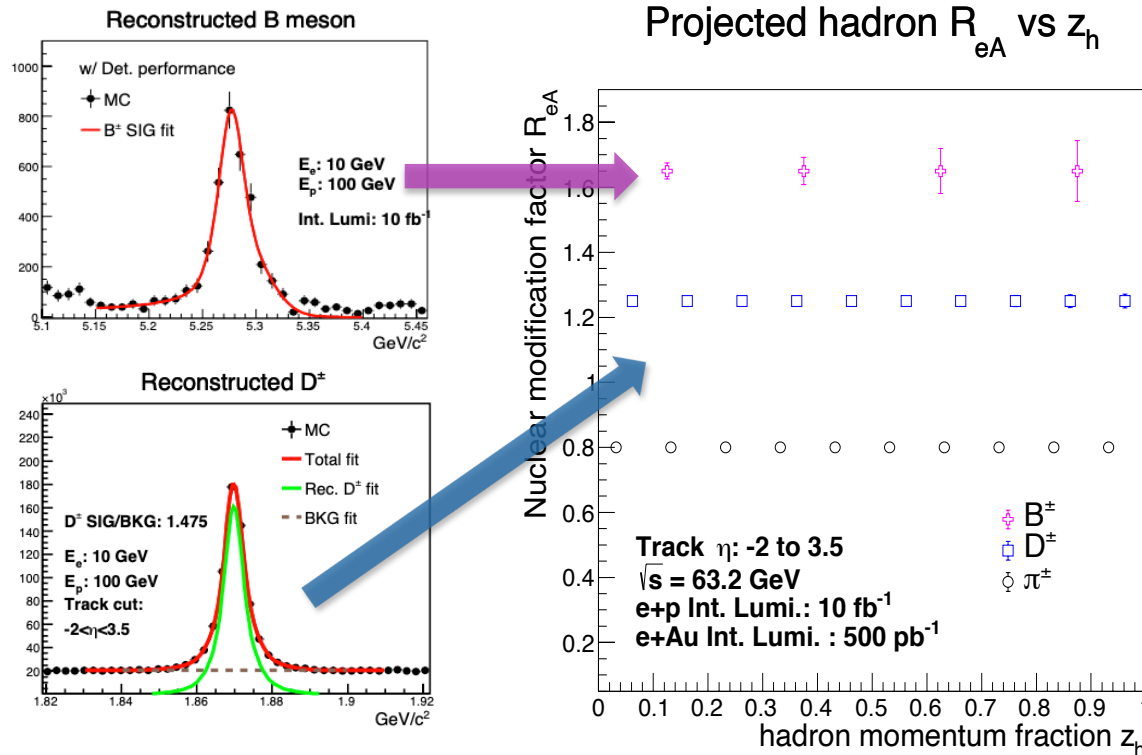


Signal/Background VS Material budget per layer



Flavor dependent nuclear modification factor projections for reconstructed hadrons

- Inclusive flavor dependent hadron nuclear modification factor R_{eA} projection in 10+100 GeV e+Au collisions.

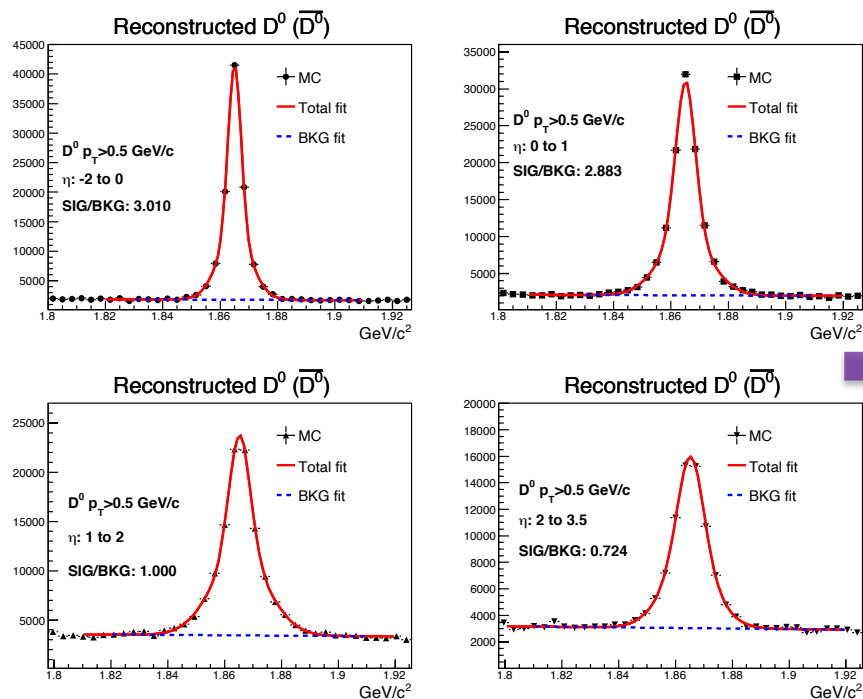


- Good statistical uncertainties can be achieved by reconstructed heavy flavor hadrons.
- Can provide sufficient discriminator power to separate different model predictions.

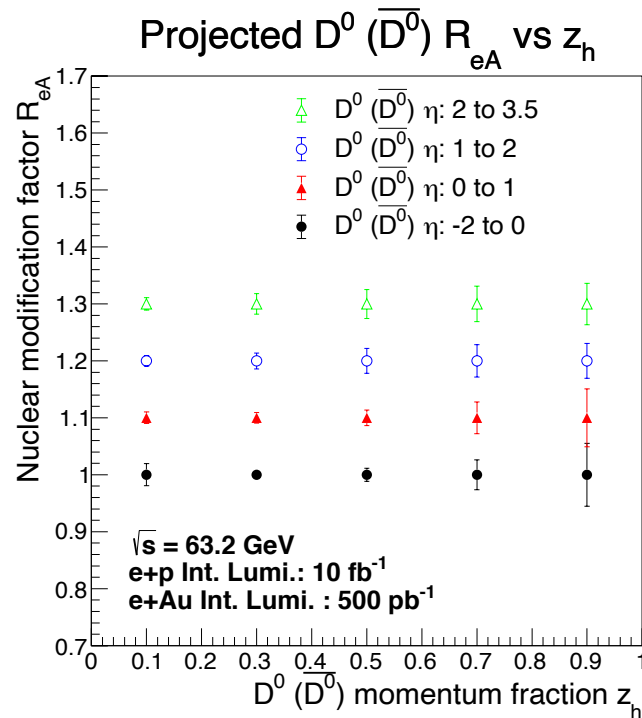
Separate the kinematics: pseudorapidity dependence

- Heavy flavor produced in different pseudorapidity regions experience different initial and final state effects.

η dependent reconstructed D^0 mass distribution



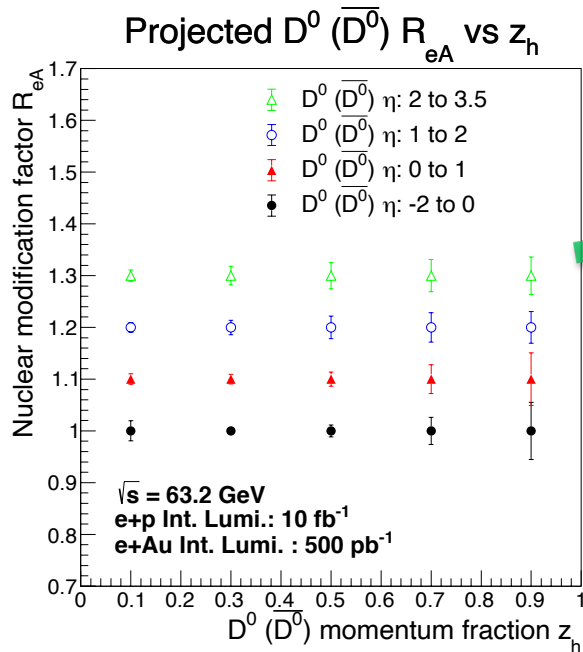
η dependent reconstructed D^0 R_{eA} projection



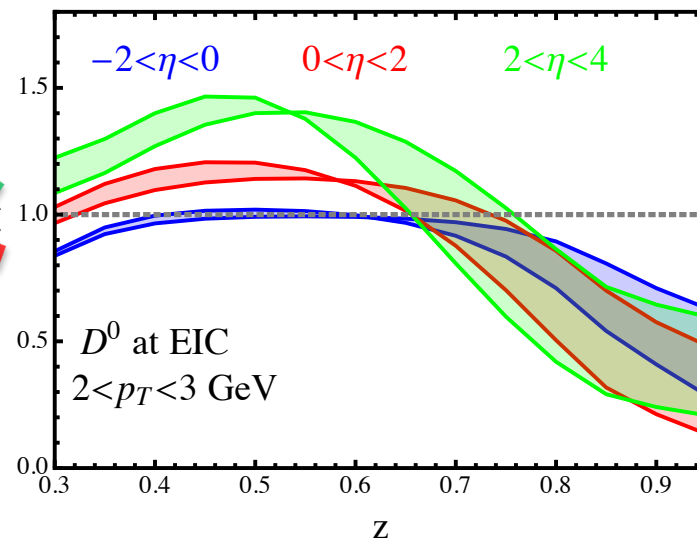
Separate the kinematics: pseudorapidity dependence

- Heavy flavor measurements especially in the forward regions at the EIC has enhanced sensitivity to the hadronization process in medium and the nuclear transport properties.

η dependent reconstructed D^0 R_{eA} projection



NLO calculations

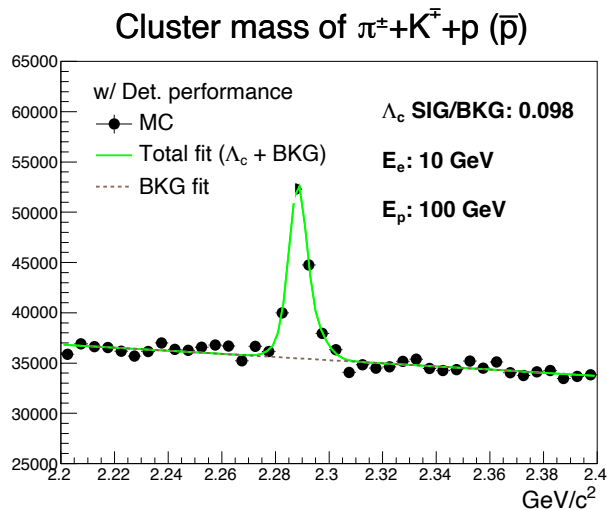


HF tomography in EIC, arXiv: 2007.10994

Heavy flavor hadron and jet studies

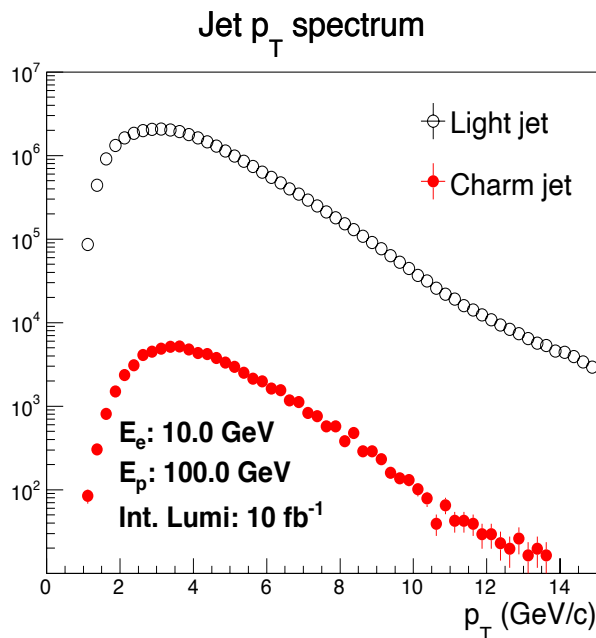
- More reconstructed heavy flavor products have been explored in the full simulation including vertex, tracking and PID performance.

Charm baryon reconstruction



A different approach to the hadronization process such as Λ_c/D ratio to check the impacts from recombination in vacuum/medium.

Flavor tagged jet yields



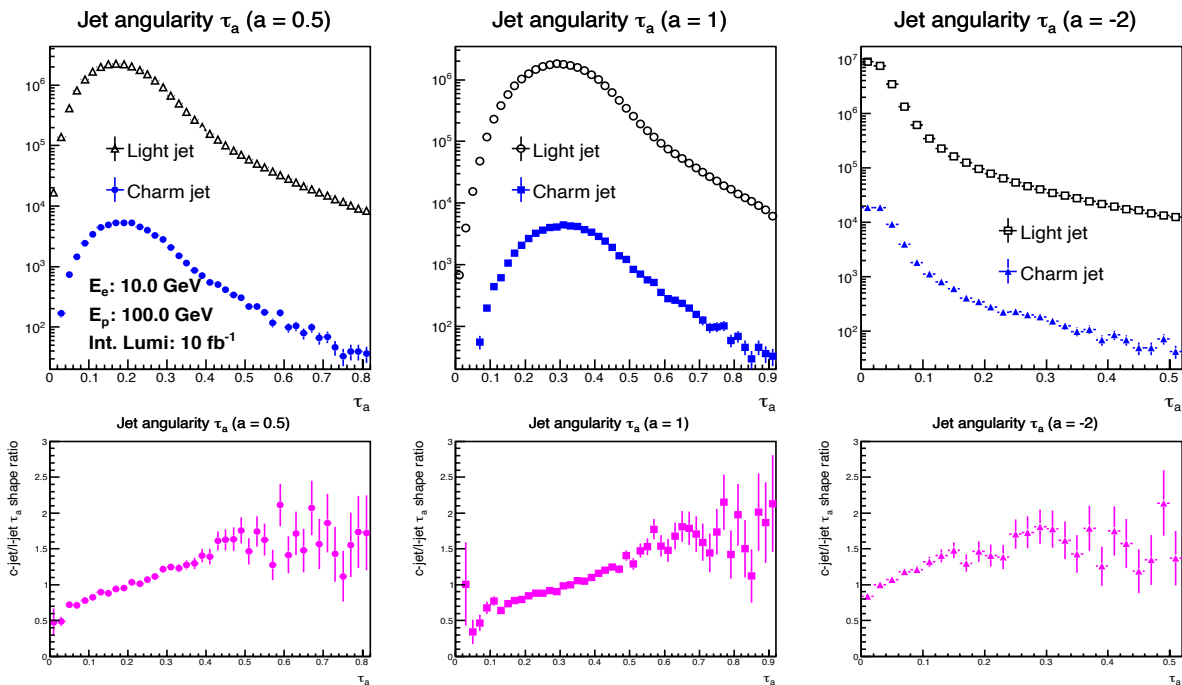
- Jet reconstruction using the anti- k_T algorithm with cone radius 0.8.
- Tag **charm-jets** with at least one charm hadron inside the jet cone.
- If no heavy flavor hadrons are found inside the jet cone, tag this jet as a light flavor jet.
- Jet yields are not corrected by the reconstruction efficiency yet.

Jet substructure for different flavor jets

- A new probe to explore the hadronization origin and process: jet angularity.

Definition: $\tau_a \equiv \tau_a^{pp} \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i (\Delta \mathcal{R}_{iJ})^{2-a}$ **JHEP 1804 (2018) 110**

Initial studies in arXiv: 2007.14417

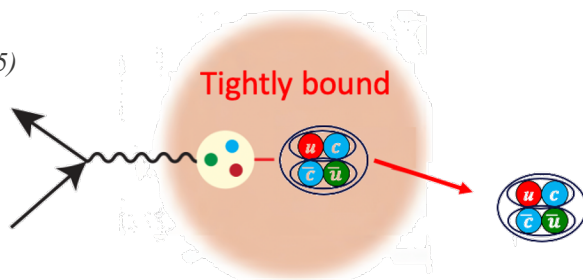


- Jet origin from a quark/gluon can be distinguished from this study.
- Shed light into how quark/gluon recombined into final hadrons with different masses.
- Impacts by nuclear medium effects will be studied in e+A collisions.

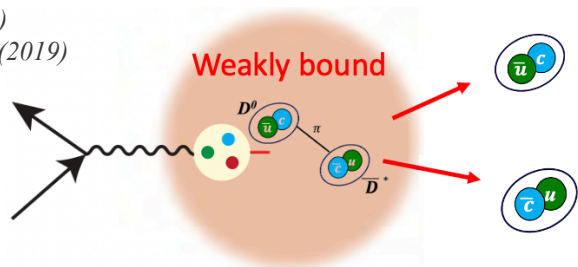
Exotic heavy flavor states at the EIC

- New physics observables are under study.
 - Structure and formation process of new exotic hadrons, e.g. X(3872) can be explored by measuring their suppression in e+A collisions.

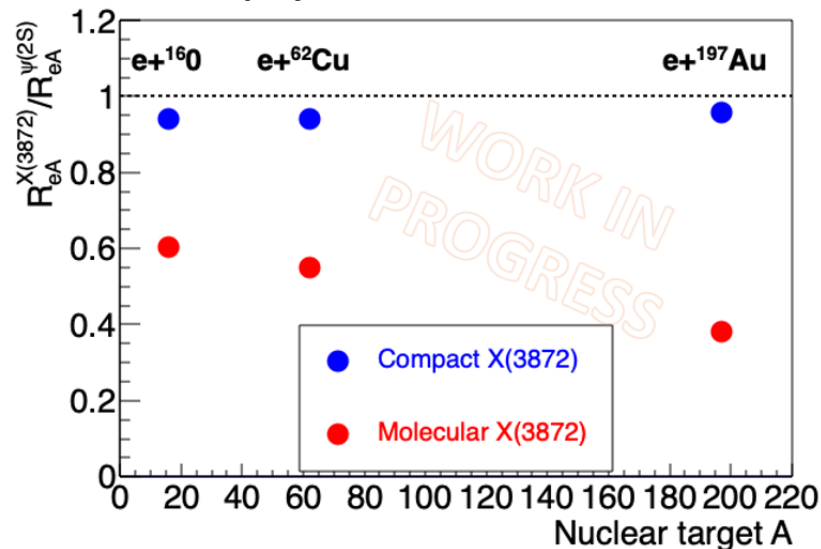
PRD 71, 014028 (2005)
PLB 662 424 (2008)



PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)



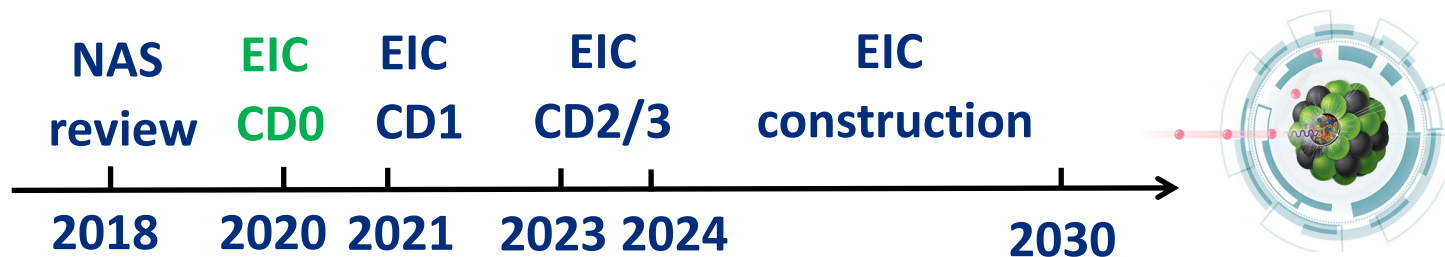
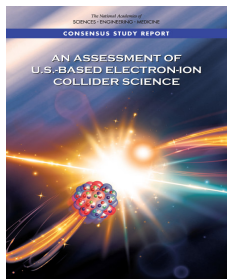
Relative modification of X(3872)/ $\psi(2S)$
projection at $\sqrt{s} = 63.2\text{GeV}$



Arleo et al., PRC, 61 054906 (2000)

Summary and Outlook

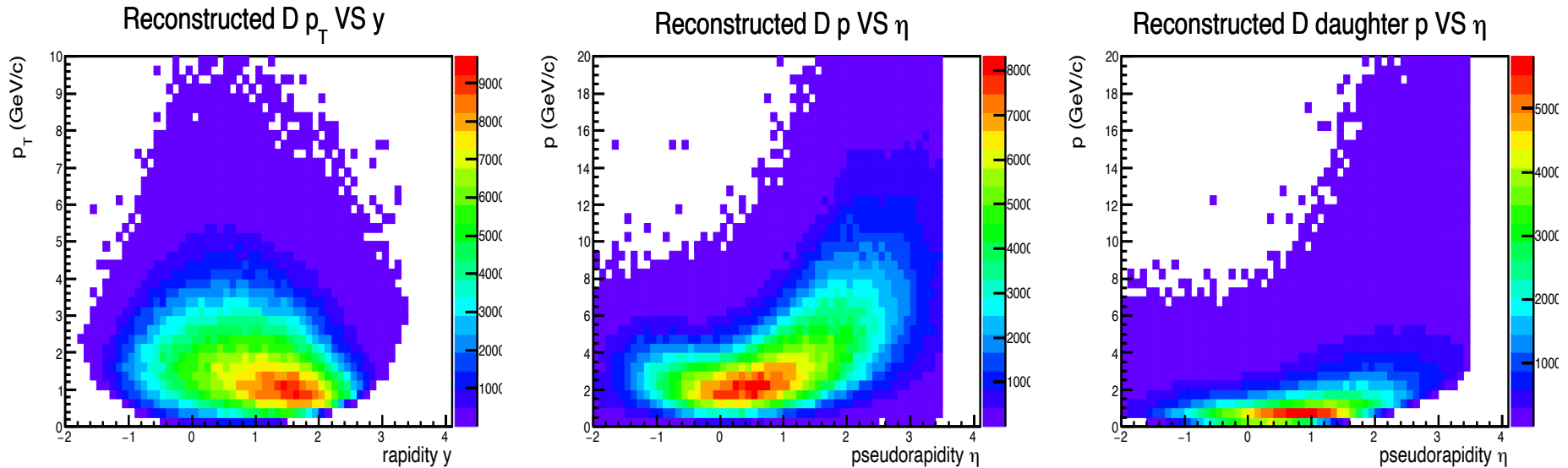
- Nice progresses and results have been achieved in the EIC heavy flavor and jet studies with detector performances evaluated in full simulation.
- The new heavy flavor and jet program for the EIC will explore the flavor dependent parton energy loss in medium and the hadronization processes in the poorly constrained kinematic region.
- We look forward to work with more collaborators and contribute to the EIC realization.



Backup

D-meson kinematics

- In 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 fb^{-1}



Reconstructed D^0 mass distributions in different p_T bins

- In 10+100 GeV e+p collisions with integrated luminosity at 10 fb^{-1} .

