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

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

Los Alamos NATIONAL LABORATORY

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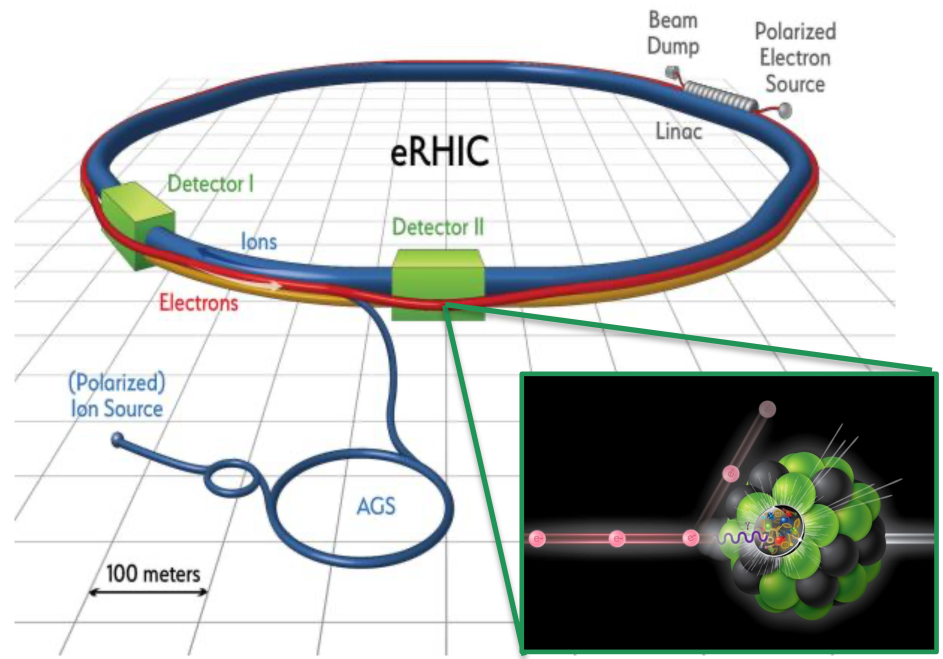
Outline

- Why and how to measure heavy flavor at the future Electron-Ion Collider (EIC)?
- Detector design and developments to realize the EIC heavy flavor measurements.
- Open heavy flavor hadron/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/^{3}He beams at 40-275 GeV.
  - (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: 1-10 ns.
- e-A collisions at the EIC:
  - Multiple nuclear species (A=2-208) and variable center of mass energies.
  - Instant luminosity L_{int} ~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$.
  - Bunch crossing rate: 1-10 ns.



Heavy quarks play a special role within the EIC science portfolio

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

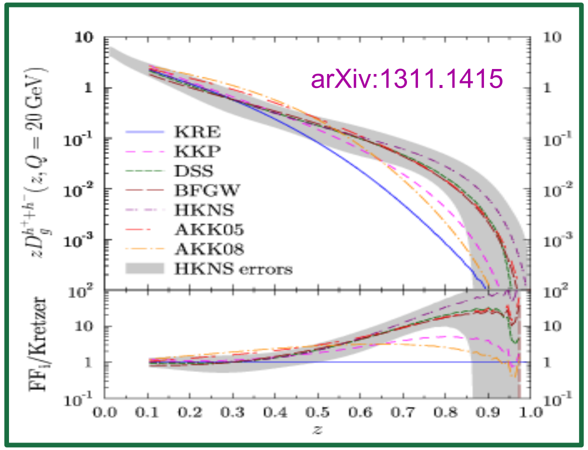
$$d\sigma_{\text{jet [hadron]}} = f(x_B) \times H\ [\times D(z_h)\ ]$$

Distribution of quarks and gluons in nucleons/nuclei

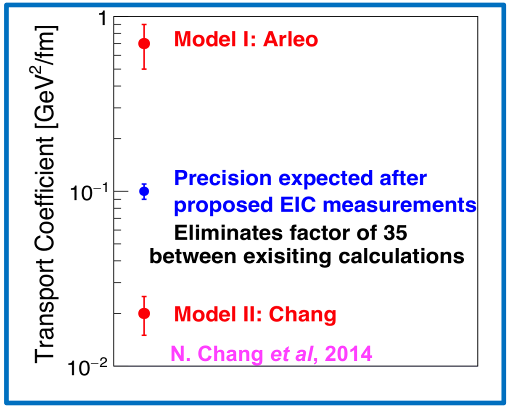
Accurately computable perturbative part

Fragmentation function

gluon FF



Nuclear transport coefficient

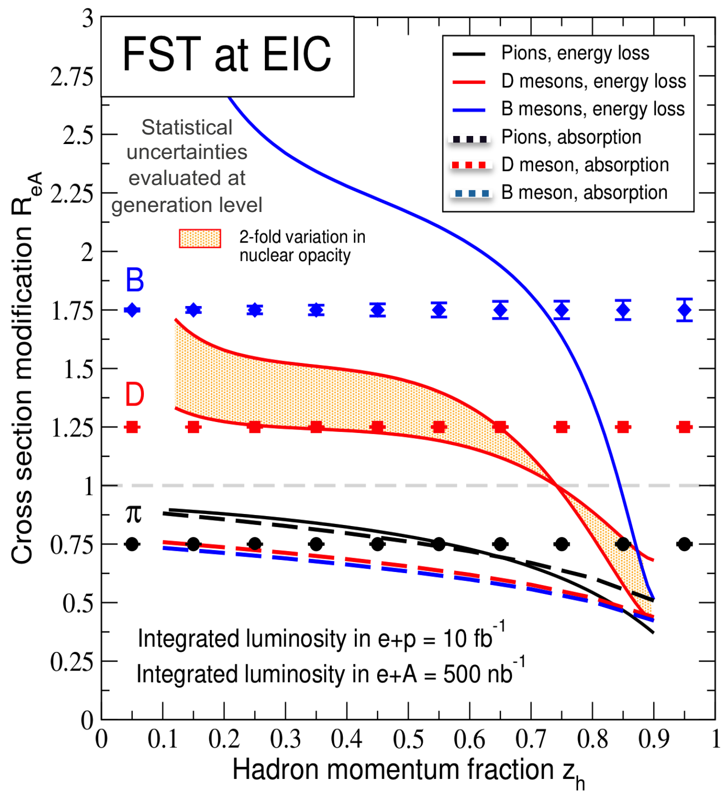


- Heavy quark nuclear transport properties are predicted to be distinctly different from light quarks, giving unique discriminating power between different models.

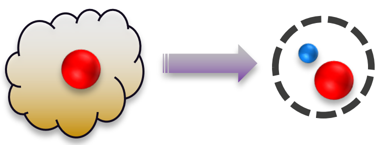
Heavy flavor physics observables at the EIC to probe hadronization in medium

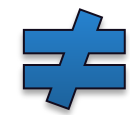
- Calculations done in the energy loss approach:
  - **Tremendous discriminating power** between models of energy loss and hadronization in matter.
  - Can **constrain nuclear opacities & transport properties to 20%.**
- Strong discriminating power provided by heavy flavor measurements to separate different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

EPJ Web of Conferences 235, 04002 (2020)

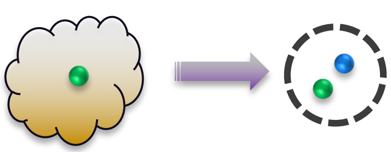


Heavy quark fragmentation modification in e+A collisions



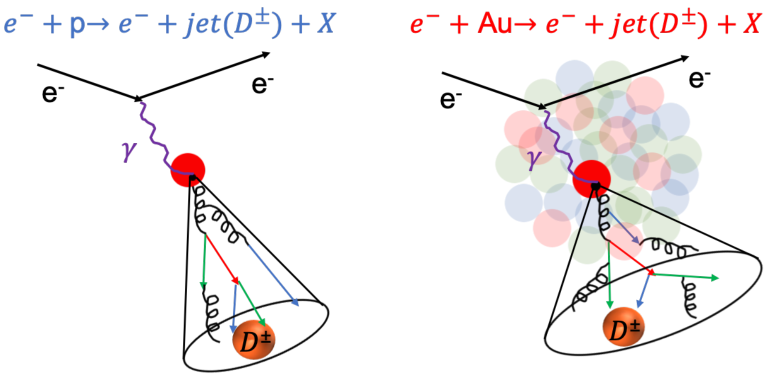


Light quark fragmentation modification in e+A collisions



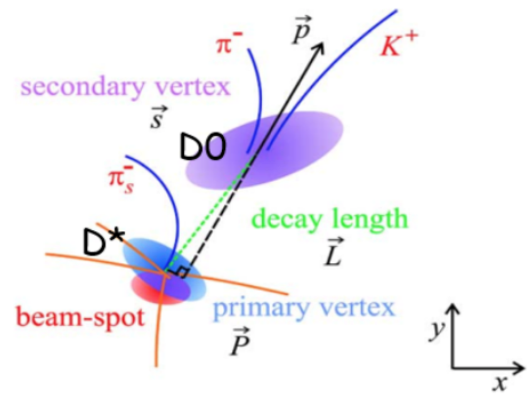
How to measure heavy quarks in experiments?

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



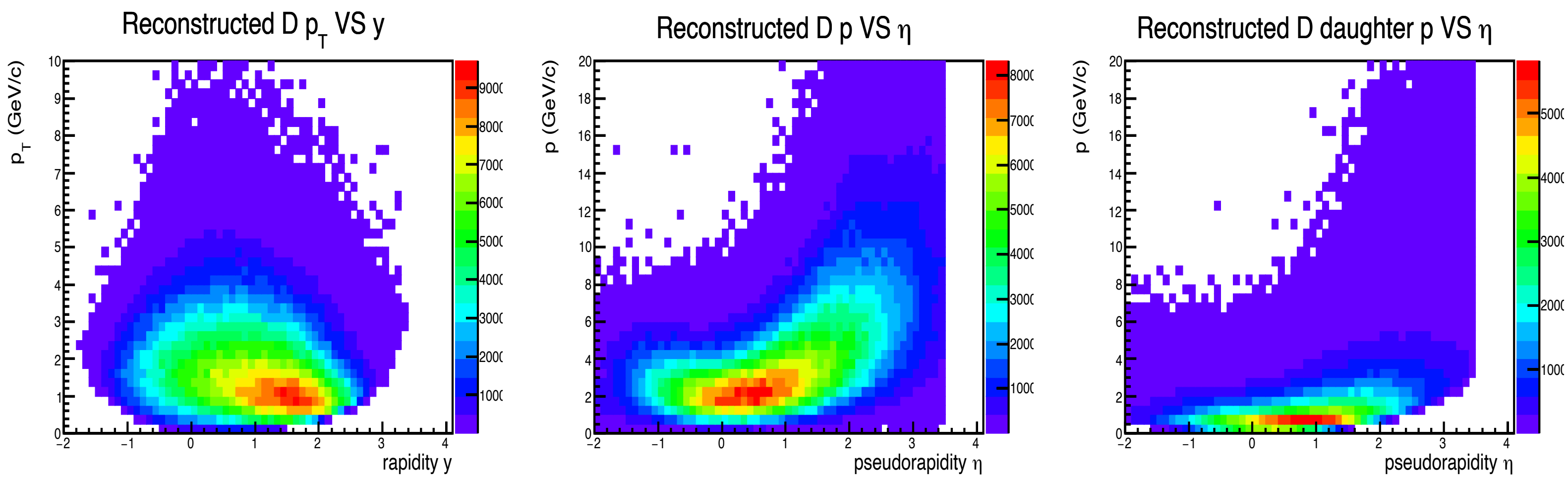
Particle	Mass (GeV/c²)	Average decay length
$D^\pm$	1.869	312 micron
D^0	1.864	123 micron
$B^\pm$	5.279	491 micron
B^0	5.280	456 micron

- 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.



A forward silicon vertex/tracking detector is required at the EIC

- 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.



- To meet the heavy flavor physics measurements, a silicon vertex/tracking detector with low material budgets and fine spatial resolution is needed.

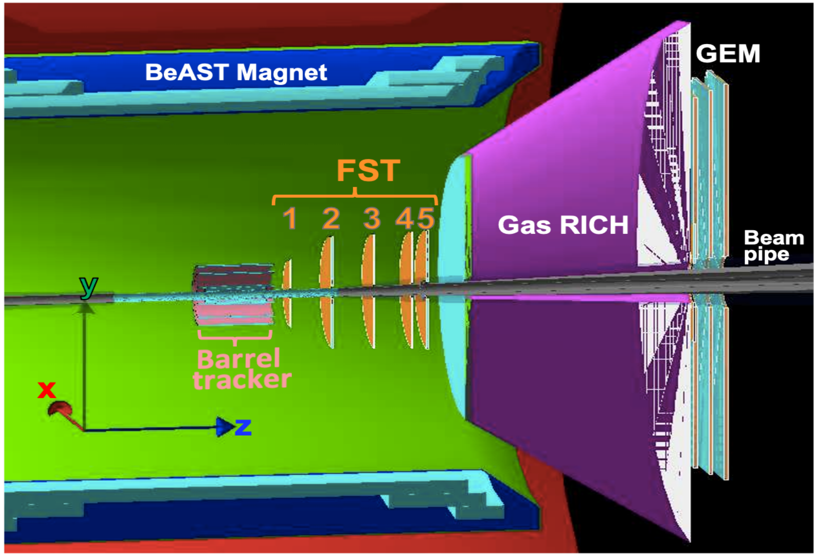
Conceptual design of the proposed Forward Silicon Tracking detector for the EIC

- GEANT4 simulation within the Fun4All framework:
  - The proposed Forward Silicon Tracking detector (FST) with 1.0 < η < 3.5 :

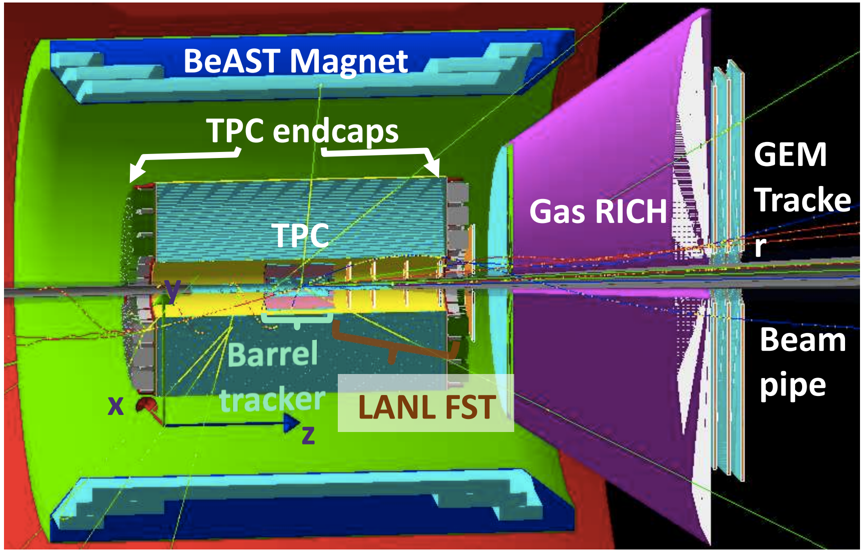
3 planes of Monolithic Active Pixel Sensor (MAPS) silicon detector and 2 forward planes of HV-MAPS silicon detector.

See more details in arXiv:2009.02888

LANL FST integrated inside the EIC



Different geometries have been explored

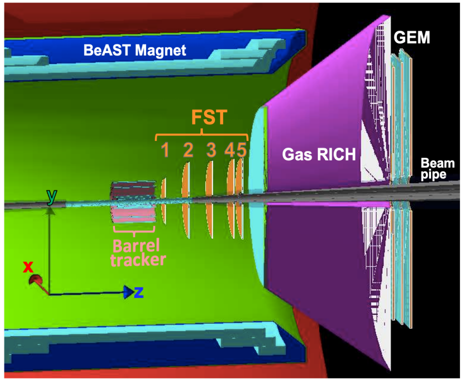


Reconstructed heavy flavor hadron with the proposed FST in simulation

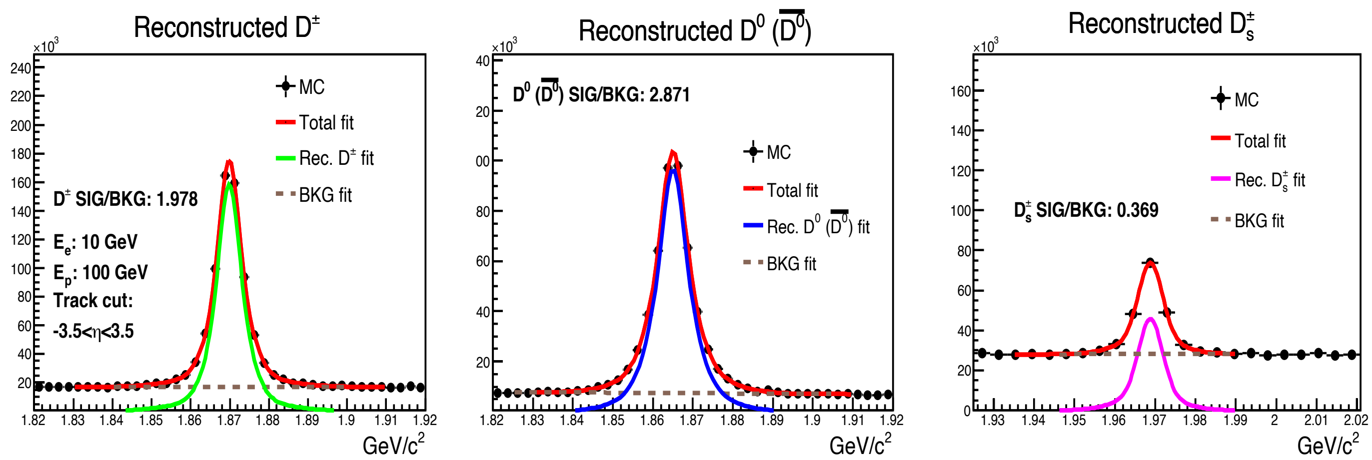
- The full analysis framework which includes the event generation (PYTHIA), detector response in GEANT4 simulation, beam remnant & QCD background, and hadron reconstruction algorithm have been setup.
- Mass distributions of reconstructed D-meson family in 10 GeV electron and 100 GeV proton collisions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

Different detector geometries and magnet options have been studied. More details in **arXiv:2009.02888.**

Detector geometry

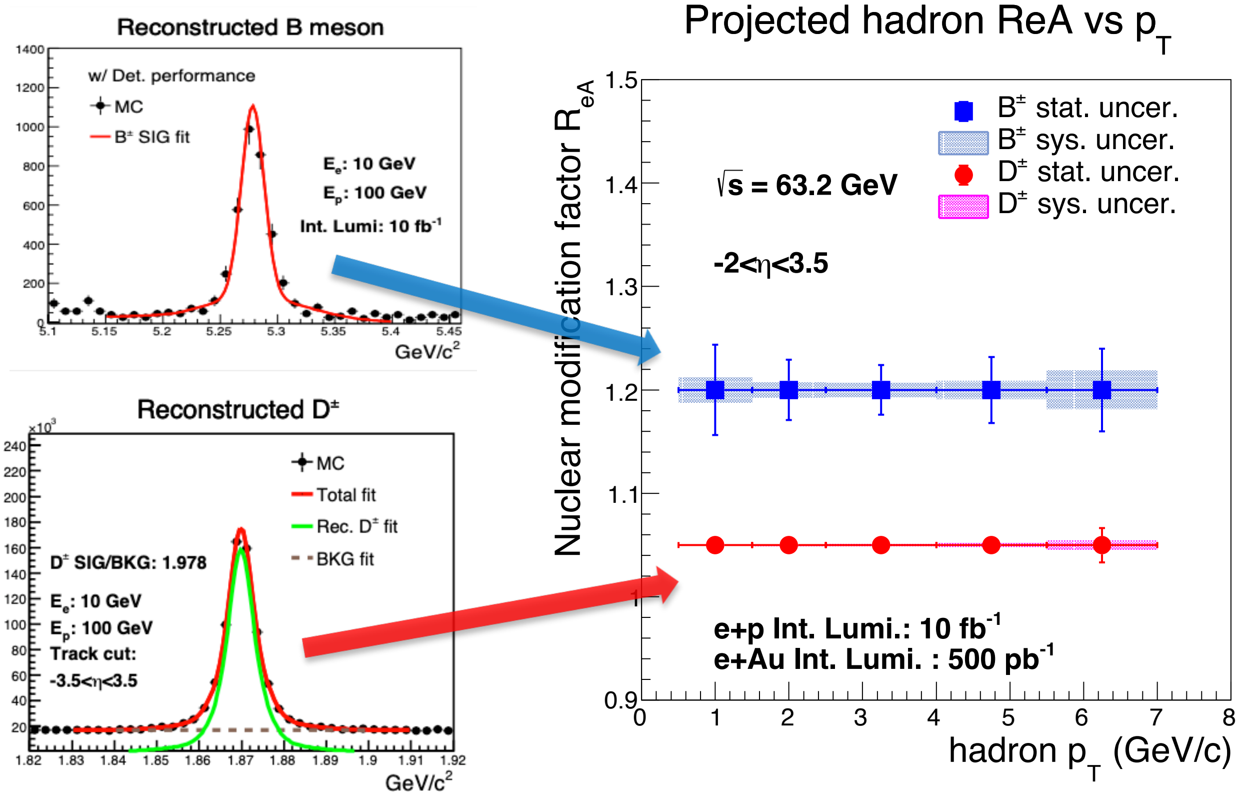


Reconstructed D-meson mass spectrum



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.



Nuclear modification factor:

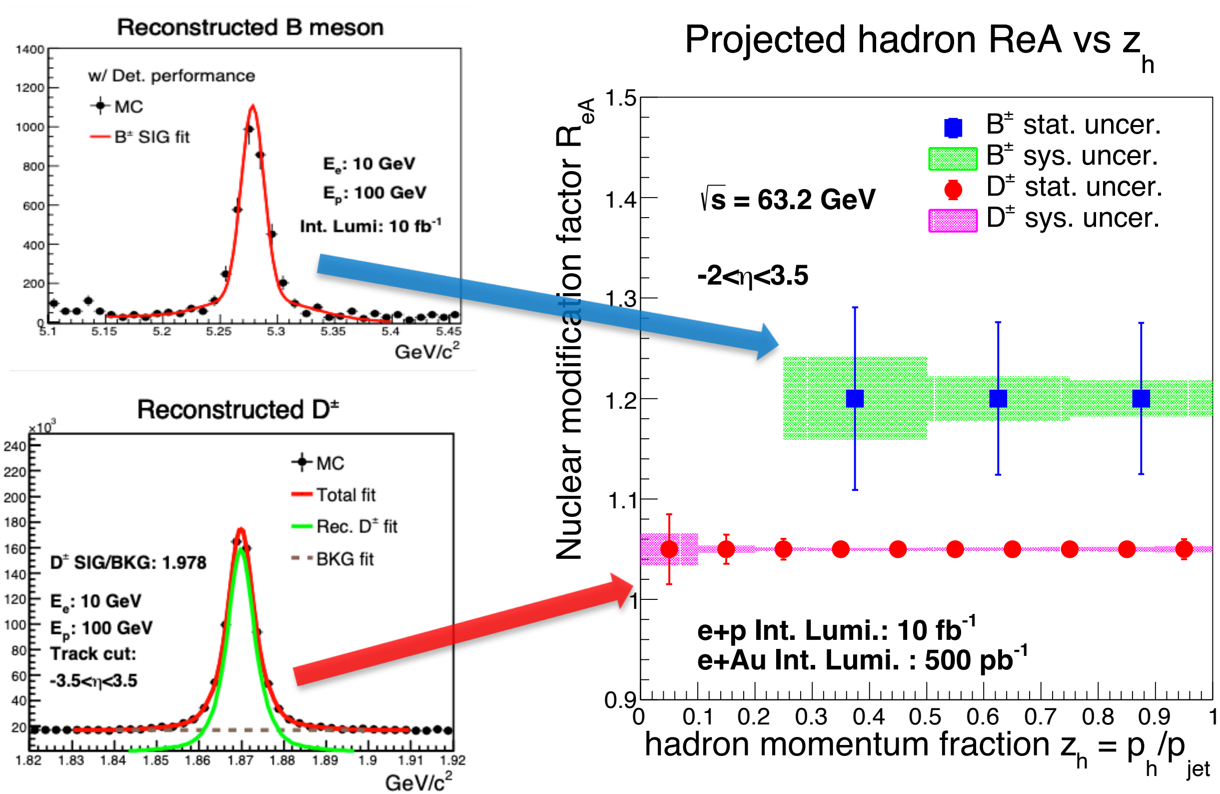
$$R_{eA} = \frac{\sigma_{eA}}{A\sigma_{ep}}$$

Systematic uncertainty sources:

- Different detector designs and performances.
- Different magnet options: Beast VS Babar.

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.

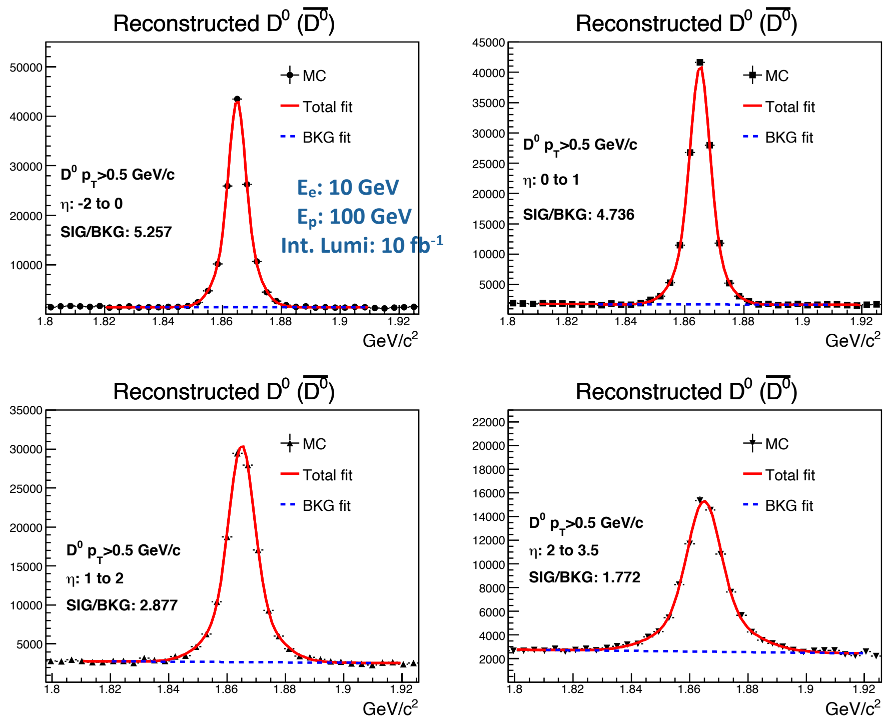


- Good statistical uncertainties can be achieved by reconstructed heavy flavor hadrons.
- Can provide good discriminator power to separate different model predictions.

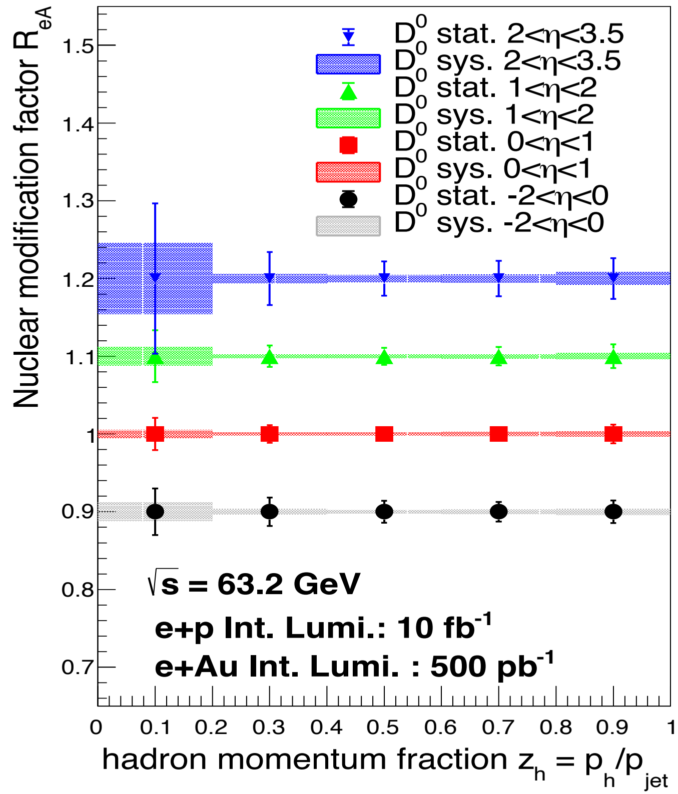
Separate the kinematics: pseudorapidity dependence

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

η dependent reconstructed D^0 mass distribution



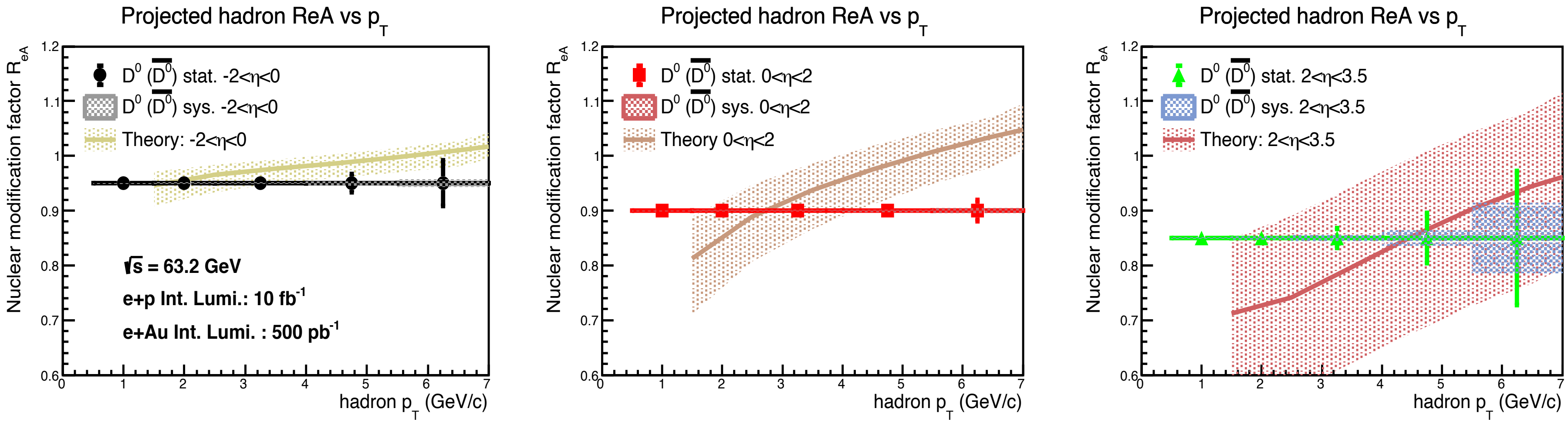
Projected hadron ReA vs z_h



Comparison with the theoretical predication

- 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.

p_T dependent R_{eA} for D^0 meson in different pseudorapidity regions

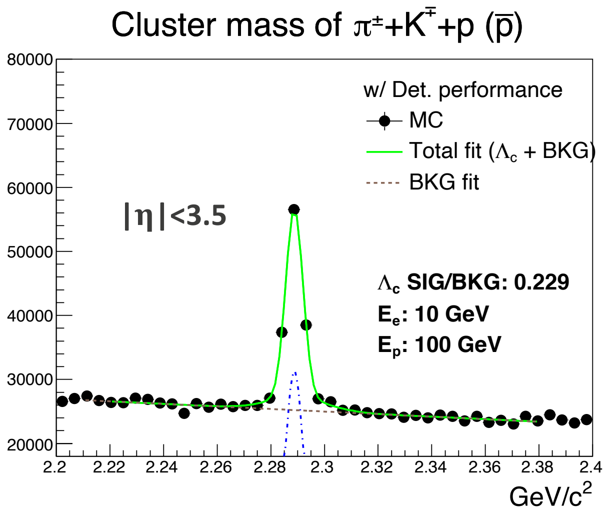


Theoretical calculations from the HF tomography in EIC, arXiv: 2007.10994

Heavy flavor hadron and jet studies

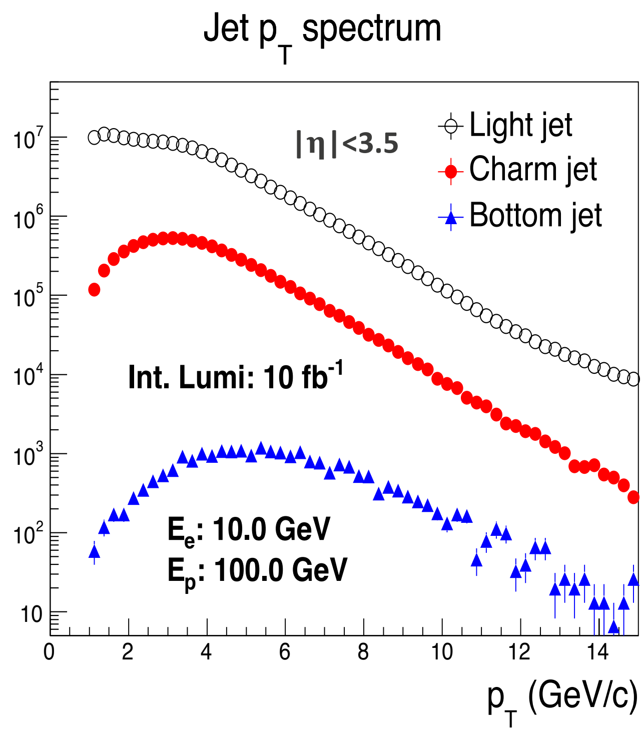
- More reconstructed heavy flavor products have been explored in the full simulation including vertex, tracking and PID performance.

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



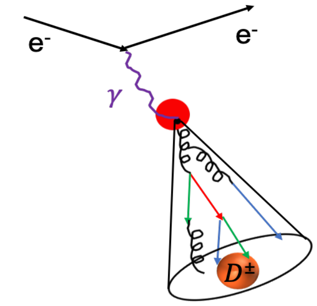
- Jet reconstruction using the anti-k_T algorithm with cone radius at 1.0.
- Tag charm-jets (bottom-jets) with associated displaced vertex.
- Jet yields are not corrected by the reconstruction efficiency yet.

Jet substructure for different flavor jets

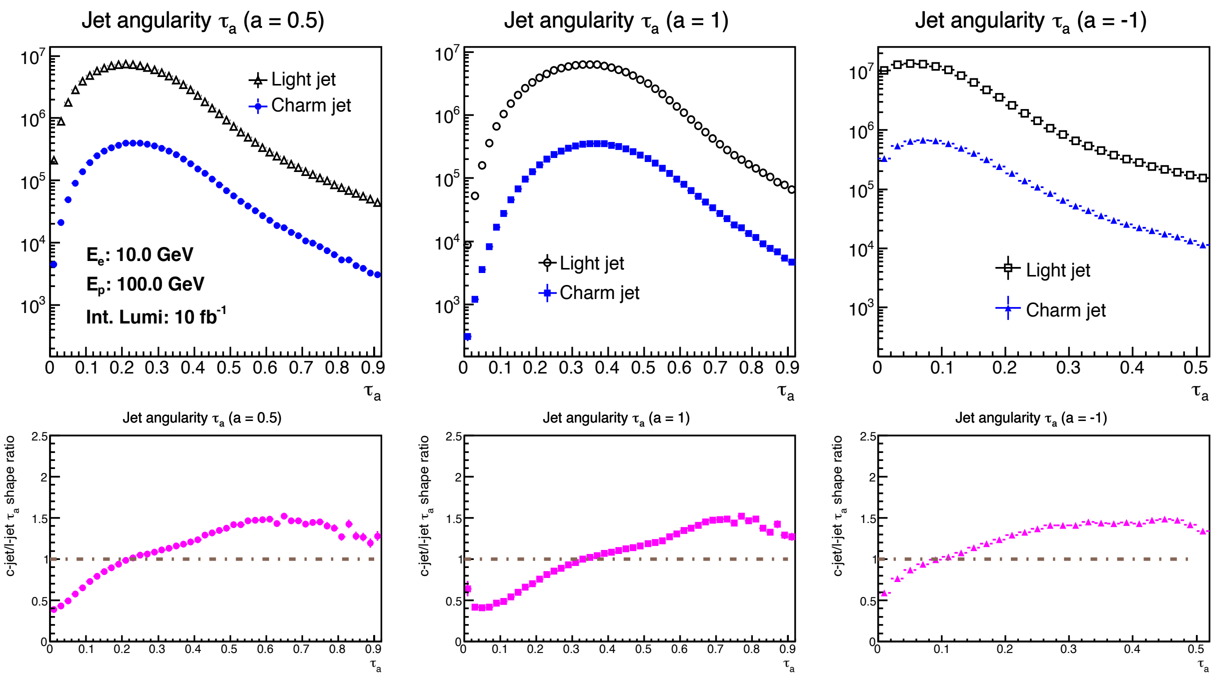
- A new probe to explore the hadronization origin and process: jet angularity.

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

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



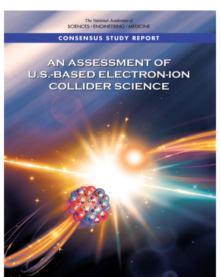
Initial studies in arXiv: 2007.14417

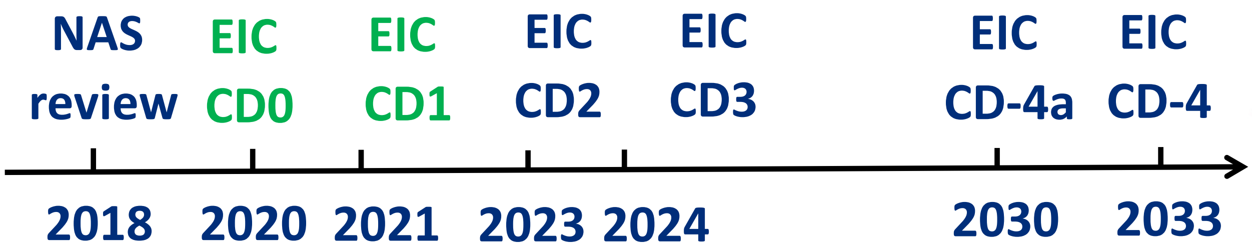


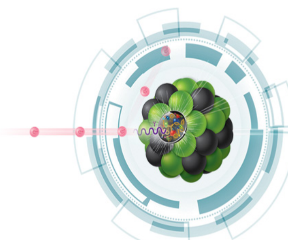
- Shed light into how quarks/gluons recombine into final hadrons with different masses.
- Impacts by nuclear medium effects will be studied in e+A collisions.

Summary and Outlook

- Good 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.



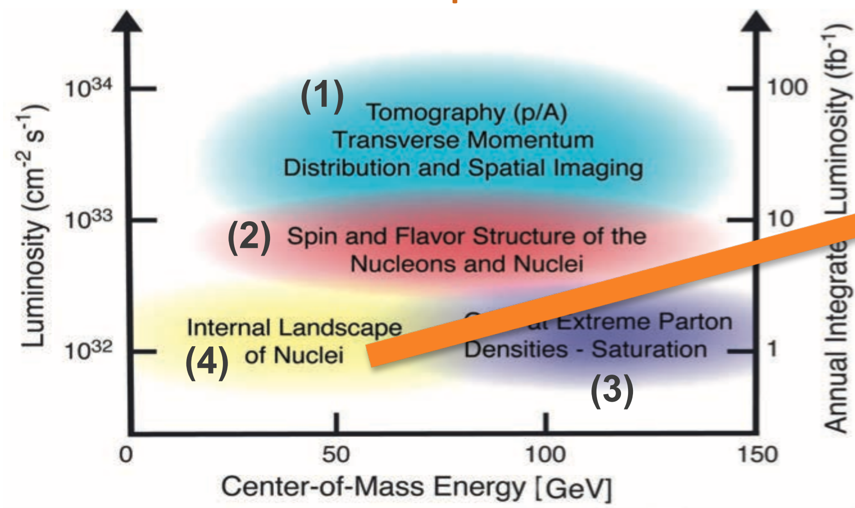




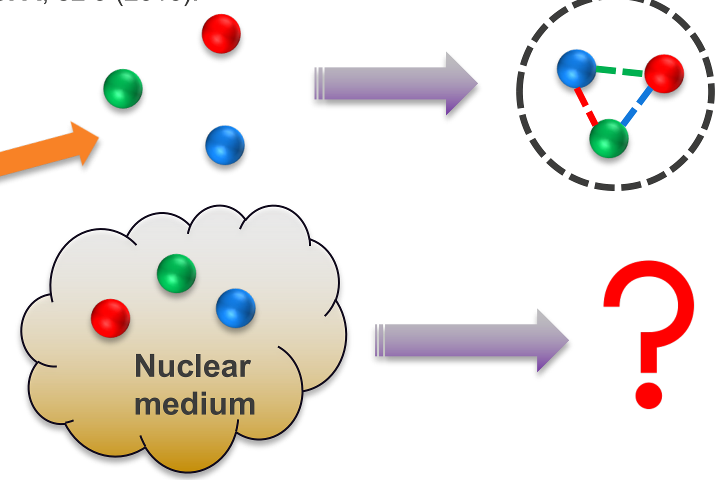
Backup

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.



A. Accardi et al, **Eur. Phy. J. A**, 52 9 (2016).



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.

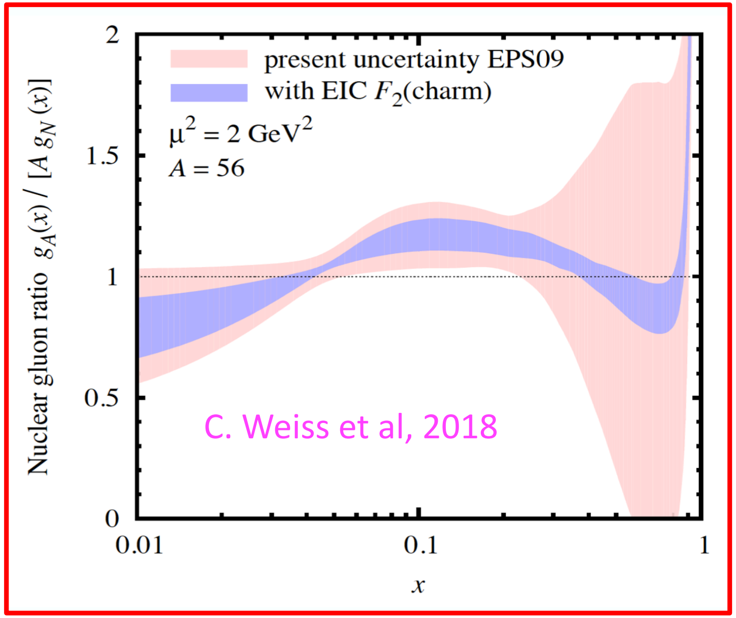
$$d\sigma_{jet} = f(x_B) \times H$$

Distribution of quarks and gluons in nucleons/nuclei

Accurately computable perturbative part

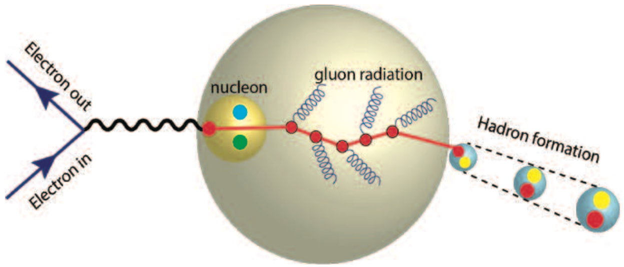
- The measured heavy flavor jet cross section contains information about the initial nucleon/nuclear parton (quark or gluon) distributions.

gluon nPDF ratio



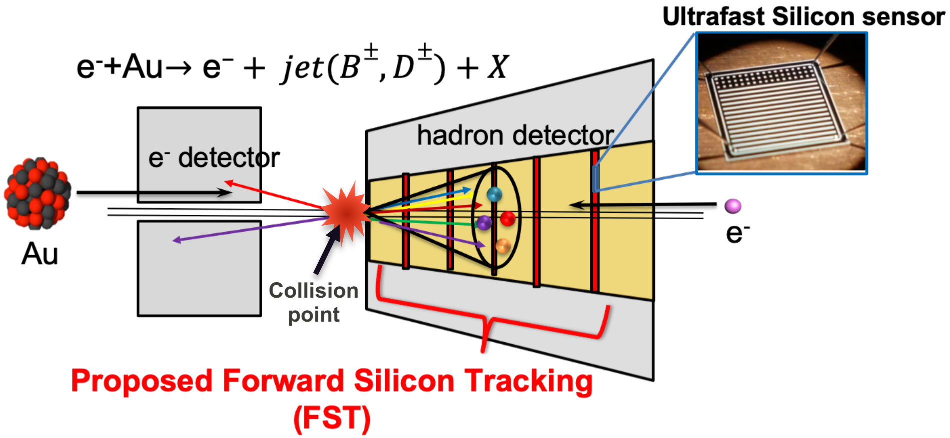
New EIC heavy flavor and jet program at LANL

- 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.



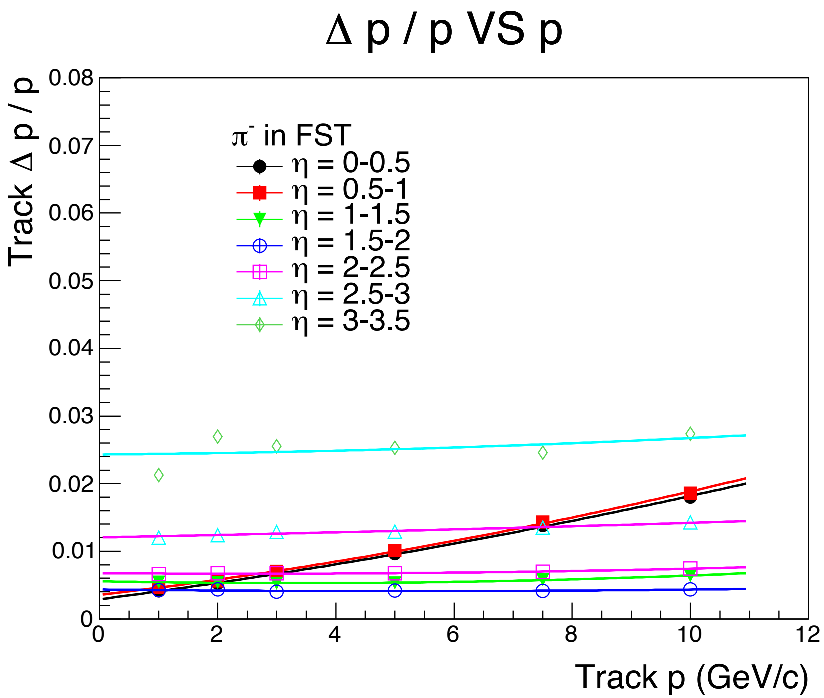
- Through this EIC project at LANL, we will explore hadronization processes and their medium modifications using heavy flavor and jet probes at the EIC.

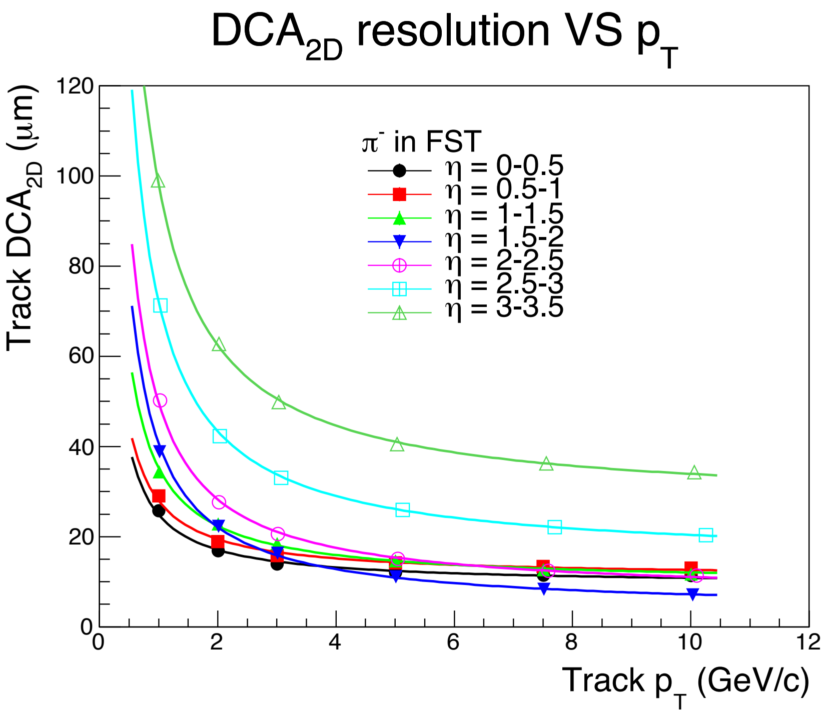
- We will carry out detector R&D for several advanced silicon sensor candidates and complete the conceptual design for a forward silicon tracking detector to realize the EIC heavy flavor and jet physics measurements.



LANL FST performance

- With Beast magnet



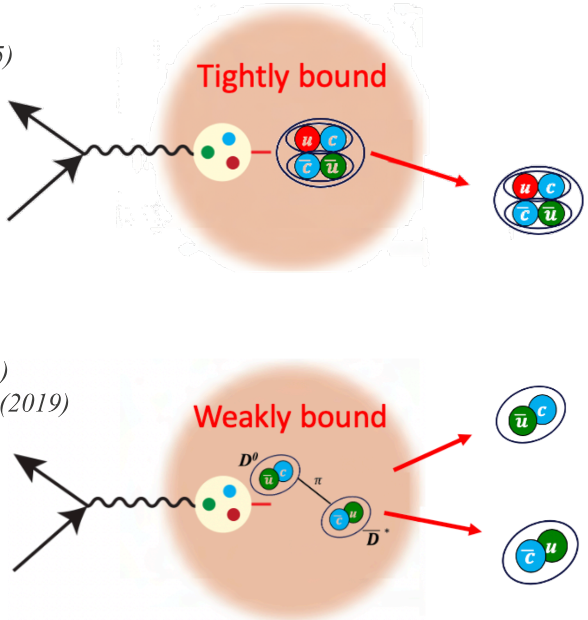


Exotic heavy flavor states at the EIC

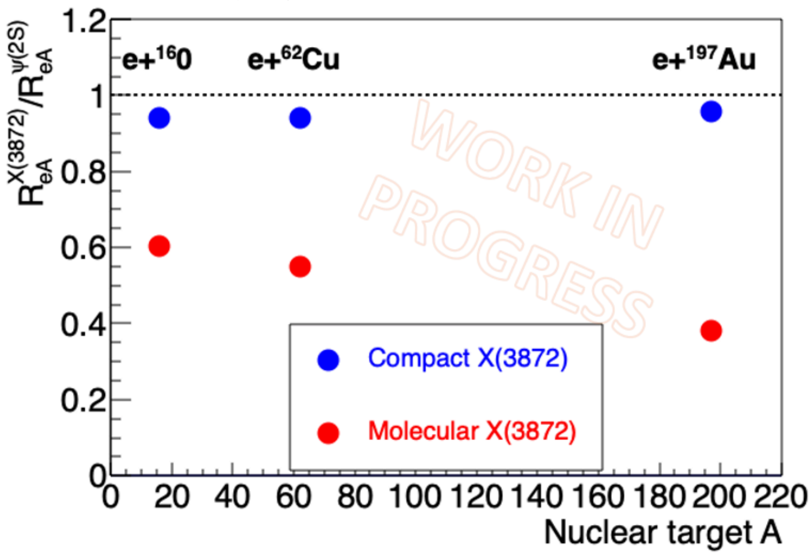
- New physics observables are under study.
  - Structure and formation process of new exotic hadrons, e.g. X(3872) can be explored by measuring their suppression in e+A collisions.

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 $\sqrt{s}$ = 63.2GeV



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