Recent open heavy flavor physics studies for the Electron-Ion Collider and application opportunities with AI/ML

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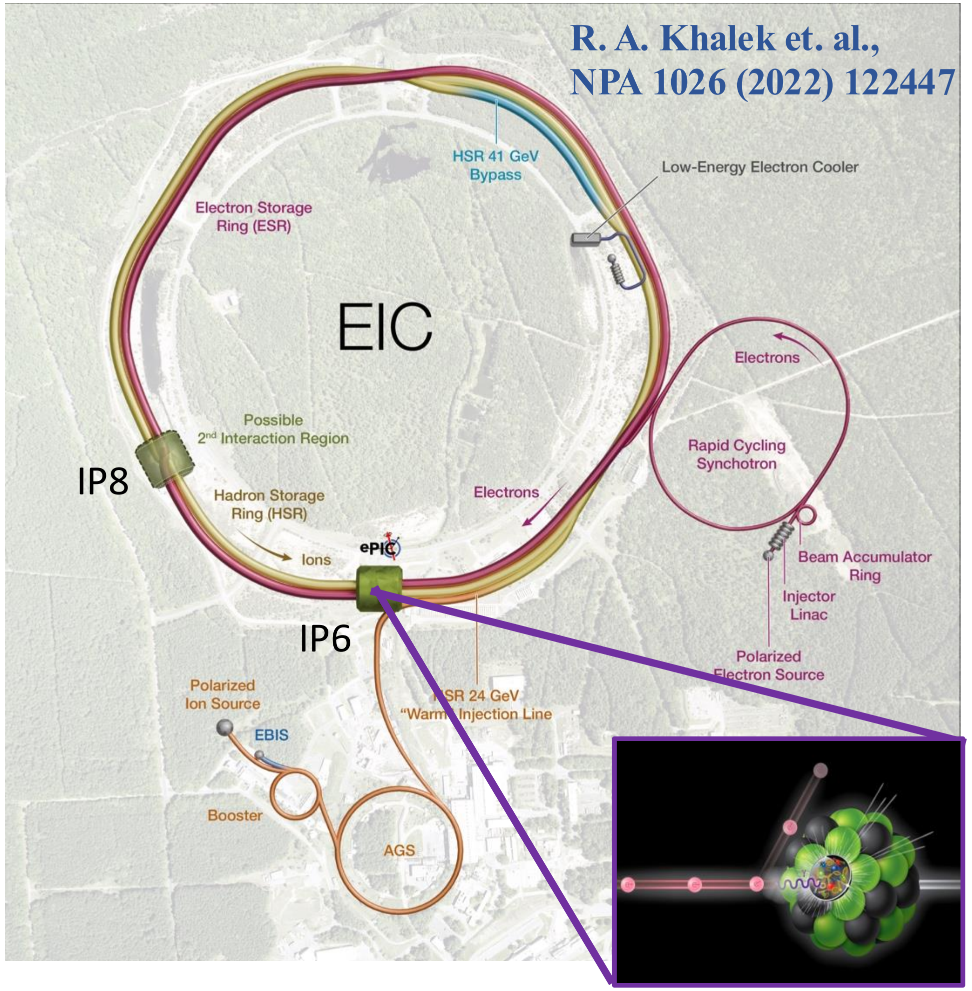
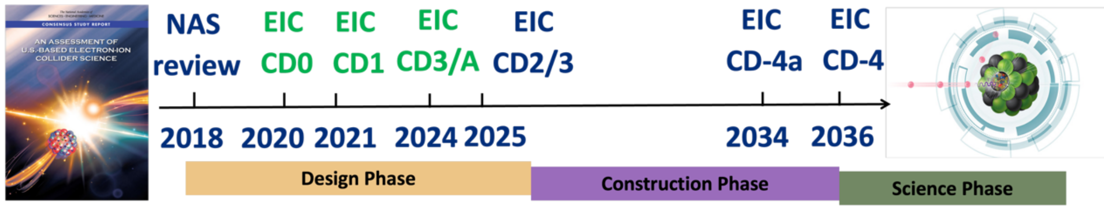
Outline

- Motivation for the EIC open heavy flavor physics.
- Selected open heavy flavor simulation studies for the EIC to explore the parton energy loss mechanism and the hadronization process:
  - Heavy flavor jet and di-jet production in e+p and e+Au collisions.
  - Heavy flavor jet Energy-Energy Correlator (EEC) studies in e+p collisions.
  - Heavy flavor hadron inside jet nuclear modification factor (R_{eA}) projection.
- Application opportunities with AI/ML.
- 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 to solve several fundamental questions in the nuclear physics field.
- The EIC will be built at BNL, and its operation is expected to start in early 2030s.
- The EIC will support up to two Interaction Points (IP6 and IP8).
- The future EIC will operate:
  - (Polarized) p and nucleus (A=2-238) beams at 41, 100-275 GeV.
  - (Polarized) e beam at 5-18 GeV.
  - Instantaneous luminosity L_{int} ~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$. A factor of ~100-1000 higher than HERA.
  - Bunch crossing rate: 10.2 ns.
  - Beam crossing angle at IP6: 25 mrad.

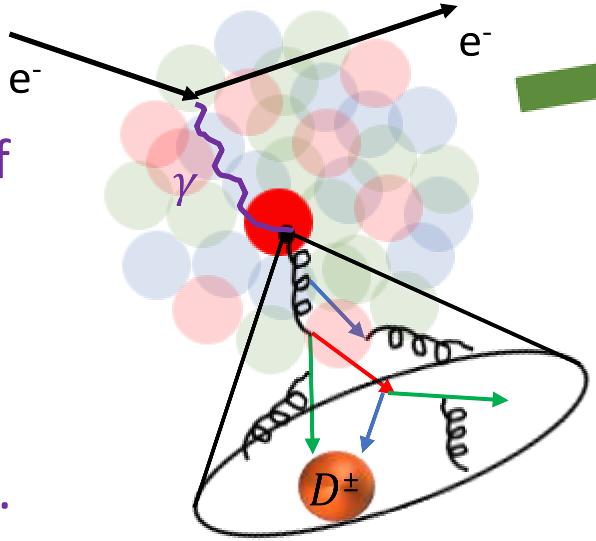




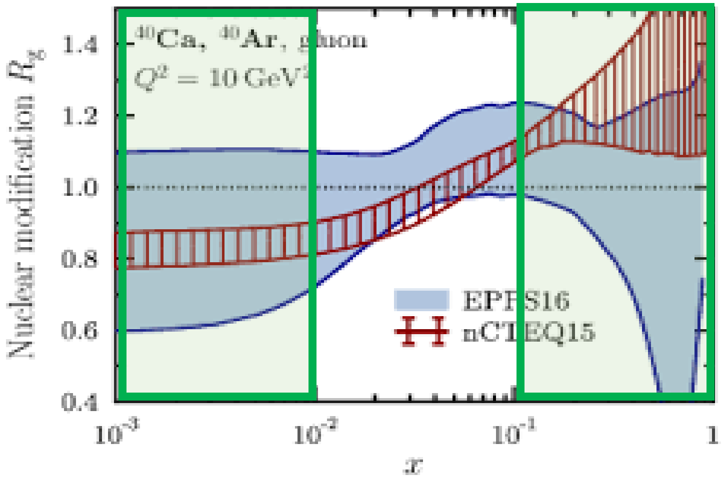
Heavy flavor measurements can enrich the EIC physics program

- 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.

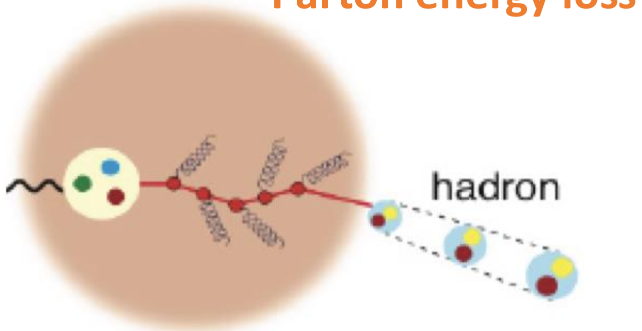
$e^- + \text{Au} \rightarrow e^- + jet(D^{\pm}) + X$



nPDF modification

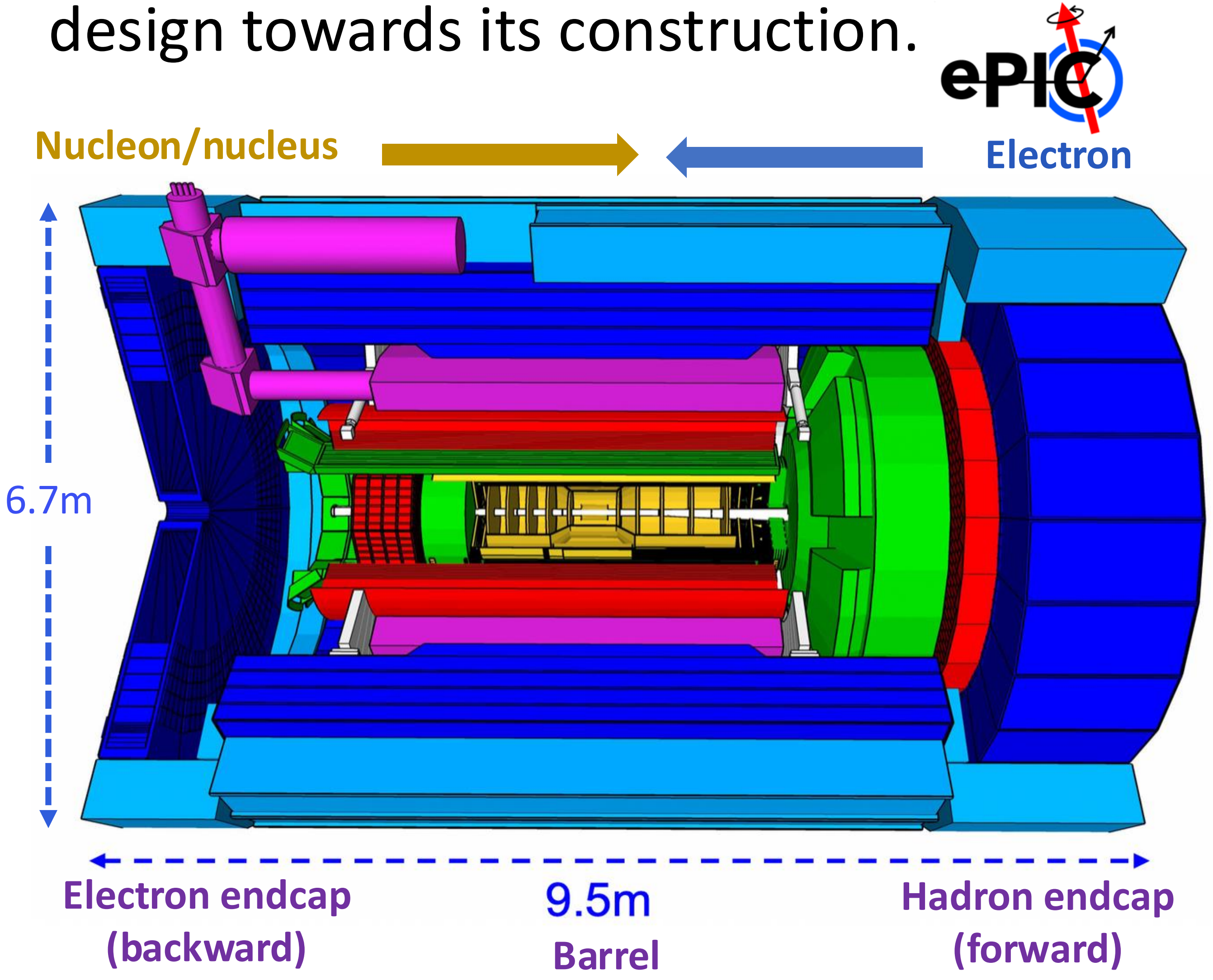


Parton energy loss



Current EIC project detector design by the ePIC collaboration

- The ePIC collaboration is leading the EIC project detector (at IP6) technical design towards its construction.

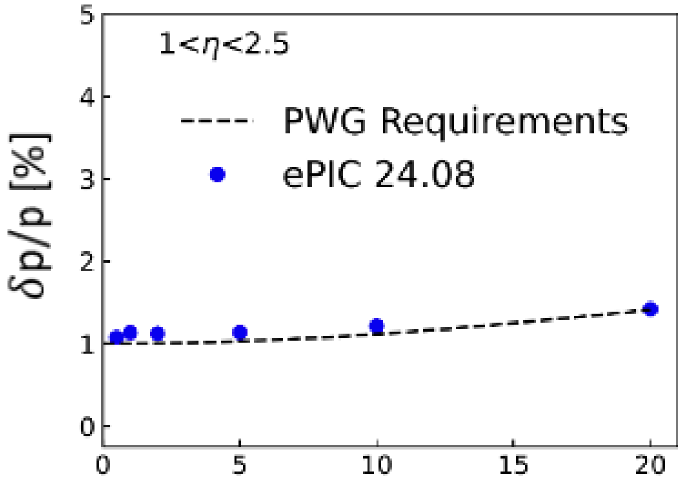


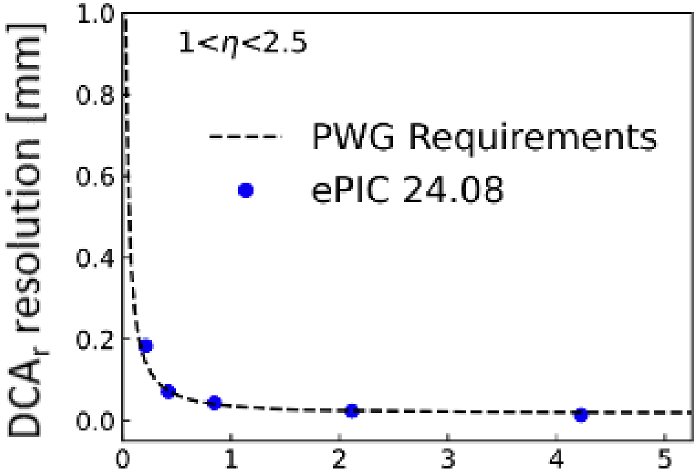
- The ePIC central detector (9.5m X 6.7m) consists of optimized vertex, tracking, PID, EMCal and HCAL subsystems, which enables high precision hadron and jet measurements within the pseudorapidity coverage of $-3.5<\eta<3.5$.
- The ePIC detector also includes the far-forward and far-backward subsystems to detect nuclear breakup, measure the exclusive process and monitor luminosity.

Current EIC project detector performance by the ePIC collaboration

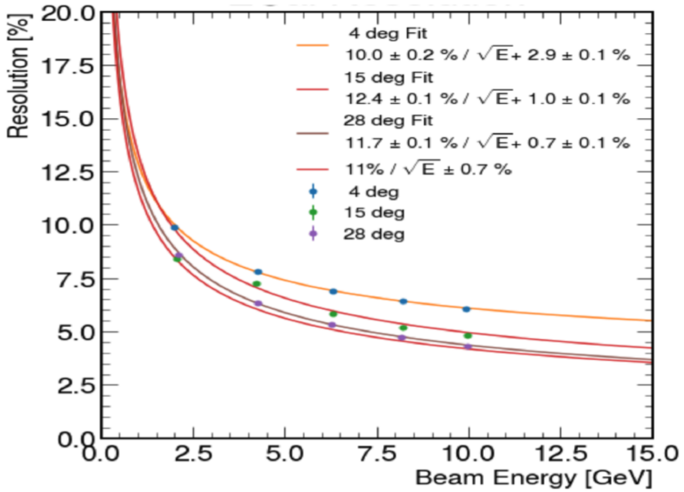
- The ePIC detector design is under optimization and its performance has been extensively evaluated in simulation.

ePIC tracking

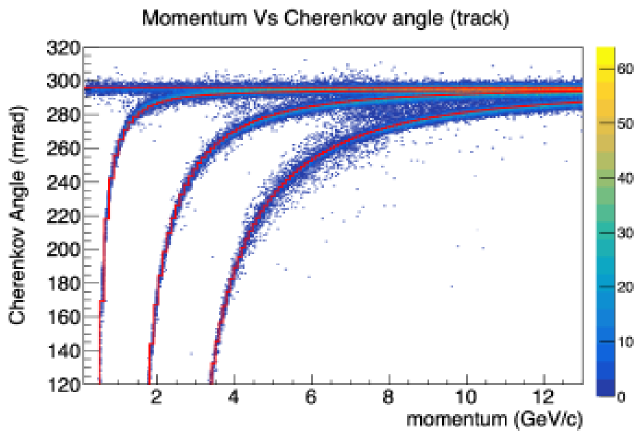




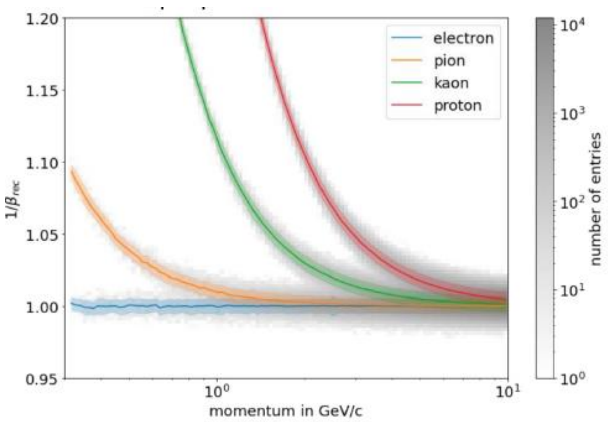
ePIC BEMC



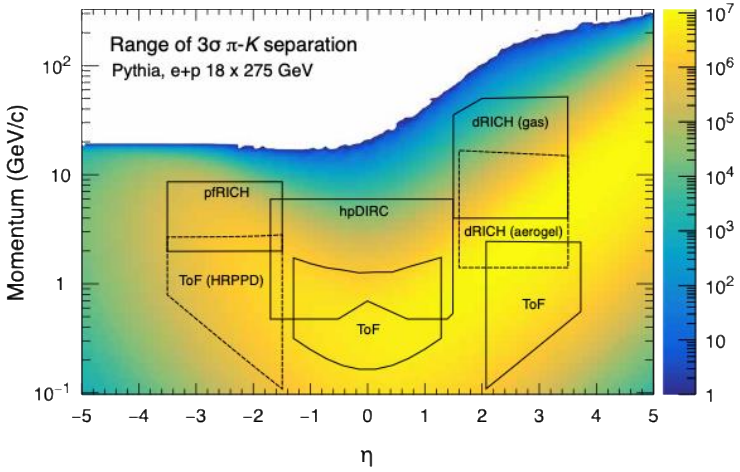
ePIC pfRICH



ePIC hadron-endcap ToF

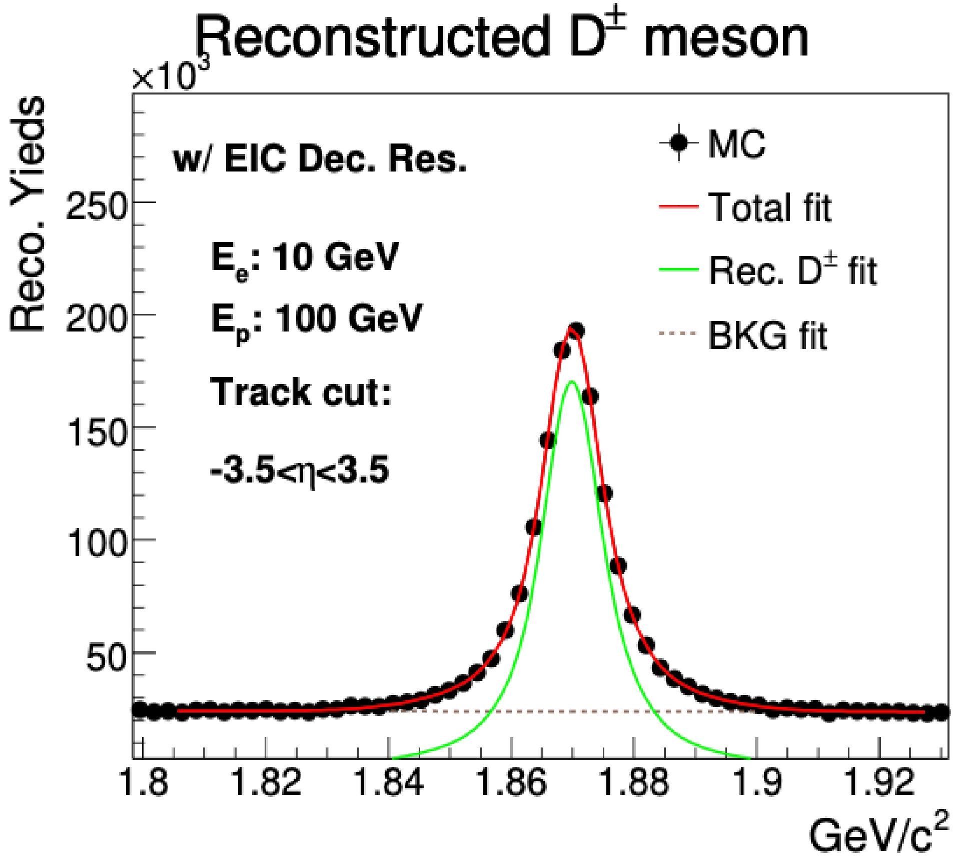


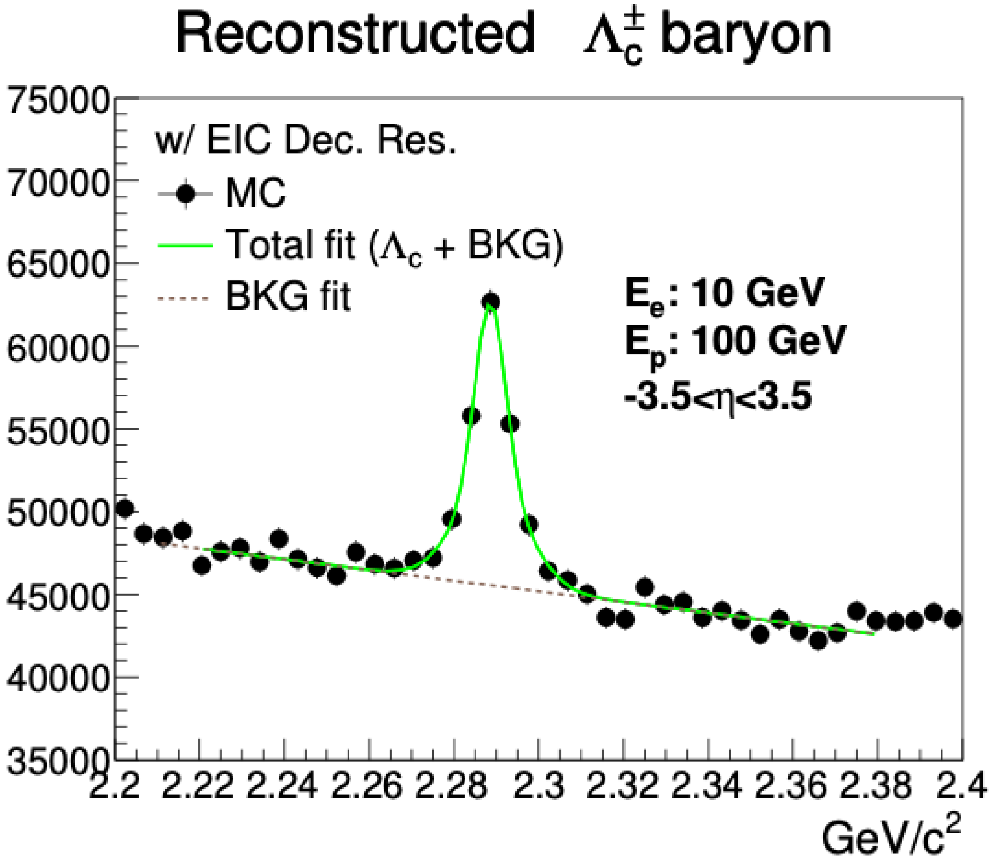
ePIC PID



Reconstruction of open heavy flavor products in e+p simulation

- A variety of heavy flavor hadrons and jets have been successfully reconstructed in a 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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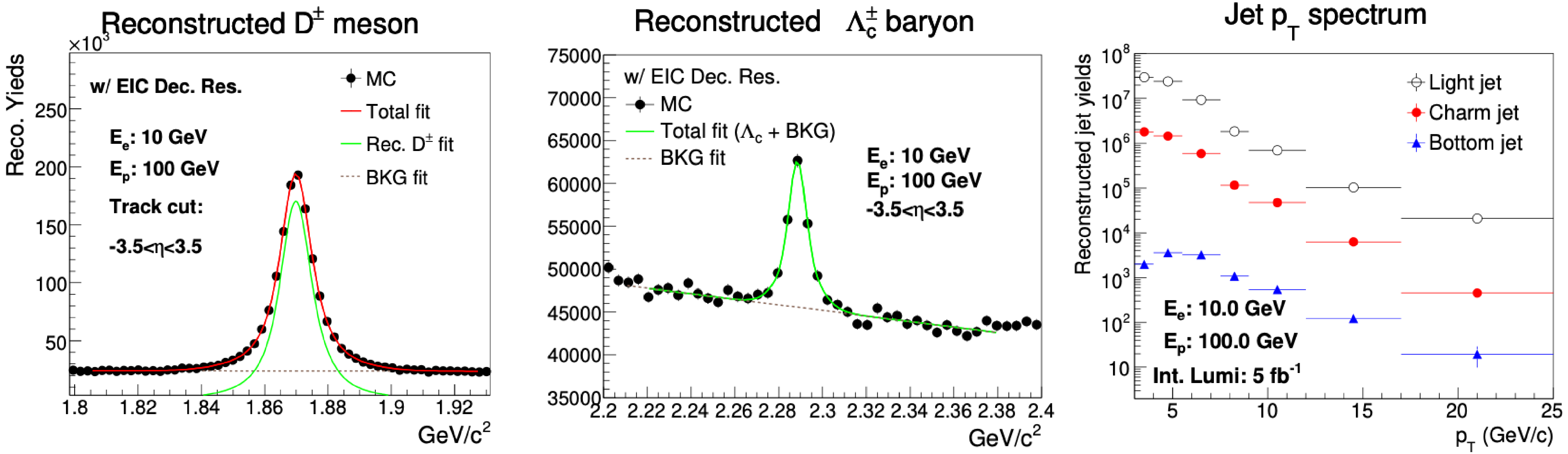
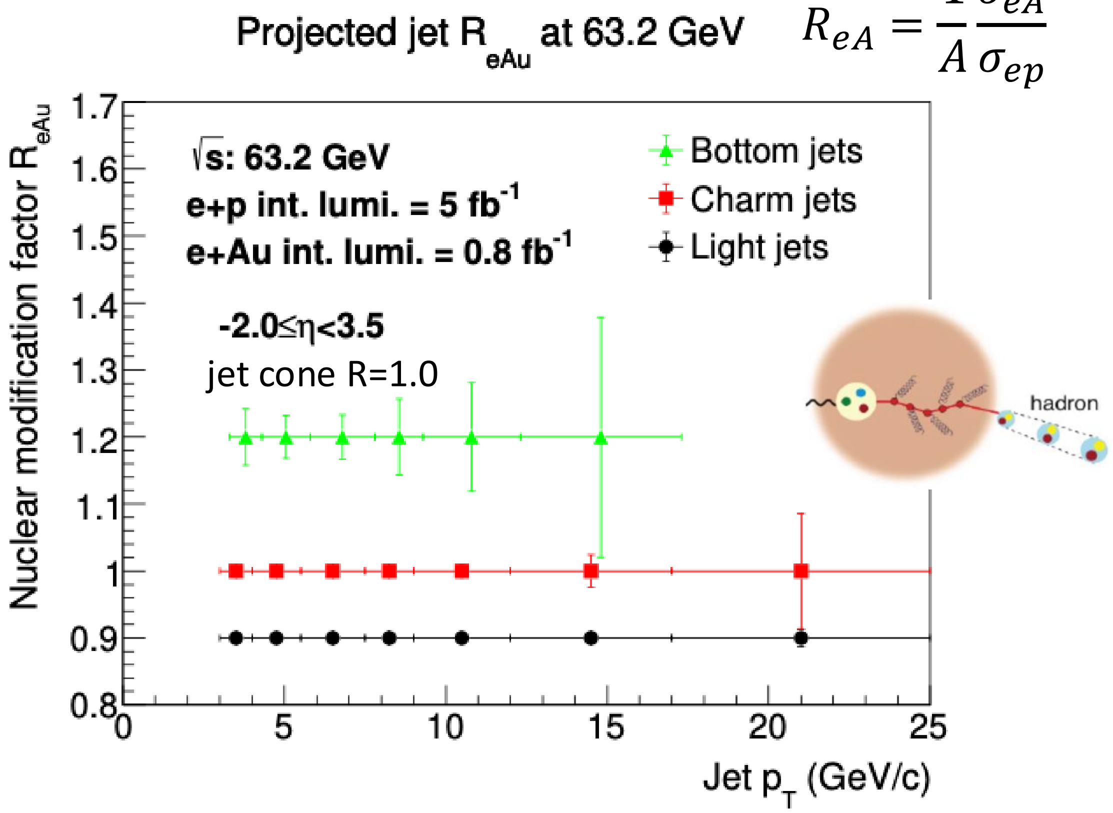
- Heavy flavor hadrons are reconstructed through hadronic decay channels.
- Heavy flavor jets are reconstructed with the anti-k_T algorithm, jet cone R=1.0 and jet flavor is tagged according to the displaced vertex found inside the jet.



Heavy flavor jet production to explore the parton energy loss mechanism

- The future EIC heavy flavor jet nuclear modification factor (R_{eA}) measurements will explore the flavor dependent parton energy loss mechanism with good precision.

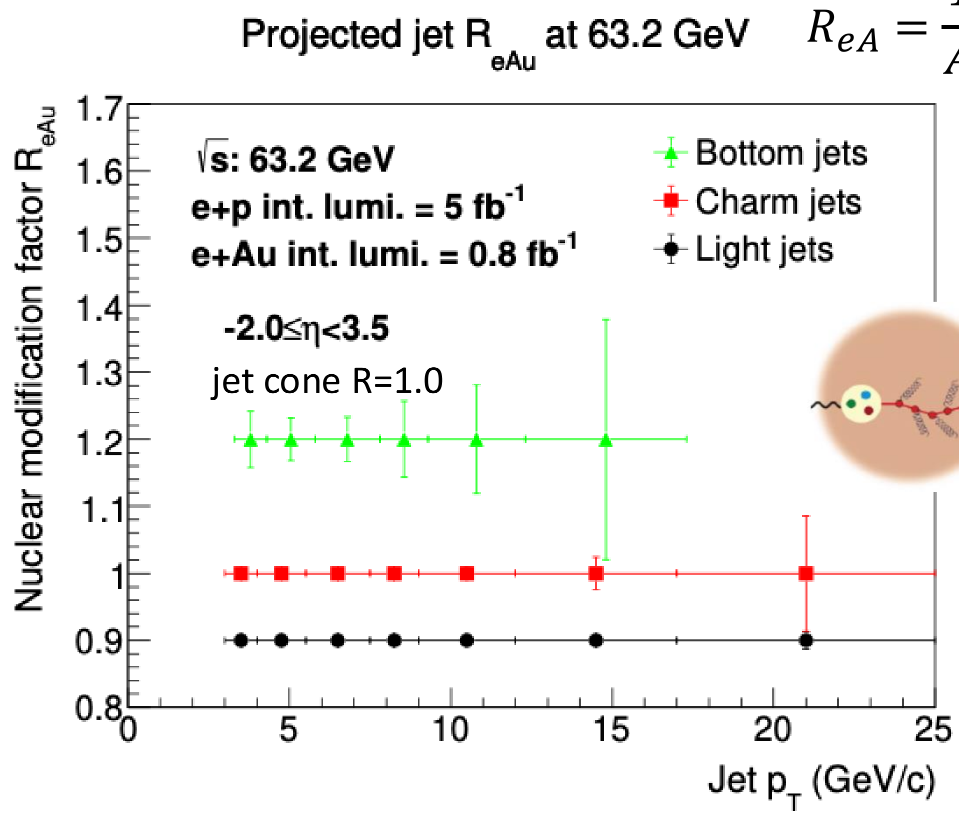
$$R_{eA} = \frac{1}{A}\frac{\sigma_{eA}}{\sigma_{ep}}$$

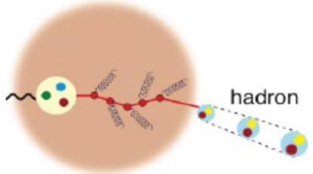


Heavy flavor jet production to constrain the parton energy loss mechanism

- The future EIC heavy flavor jet nuclear modification factor (R_{eA}) measurements will explore the flavor dependent parton energy loss mechanism with good precision.
- Charm di-jet p_T asymmetry (A_j) to be measured at EIC can help extracting the gluon (or heavy quark) transport coefficient properties in cold nuclear medium.

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





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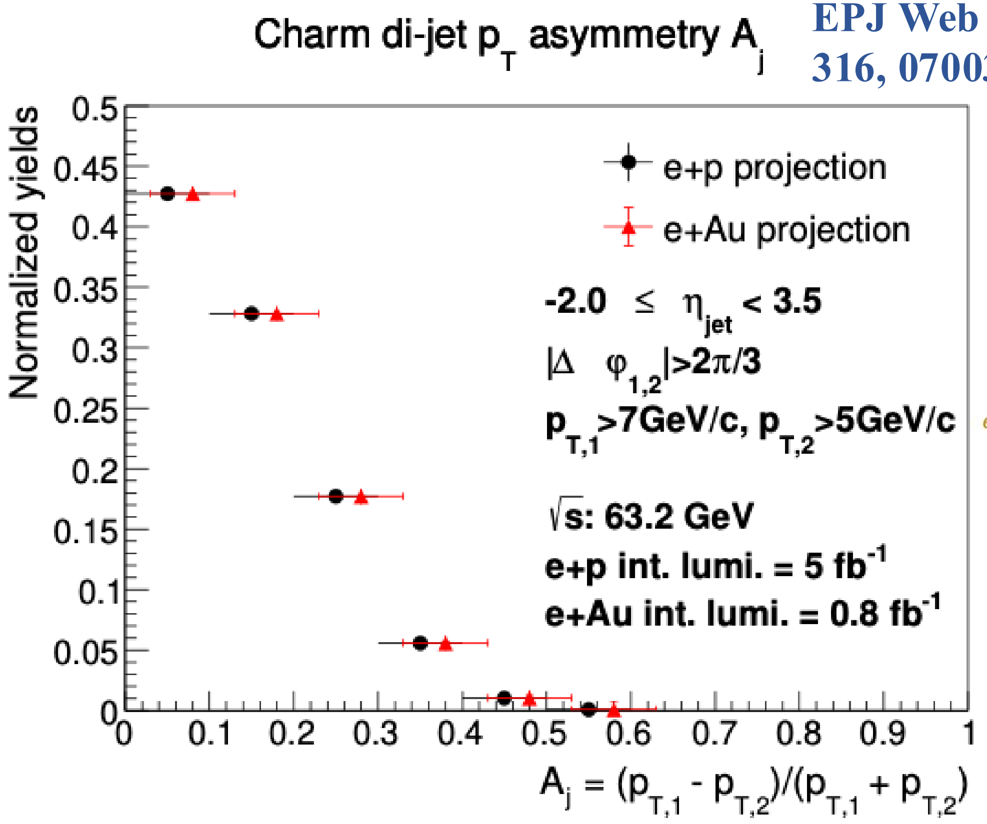
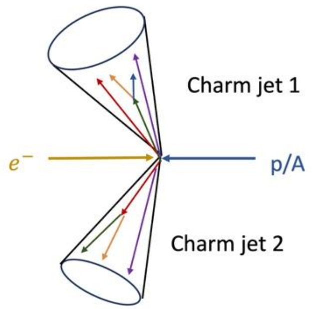
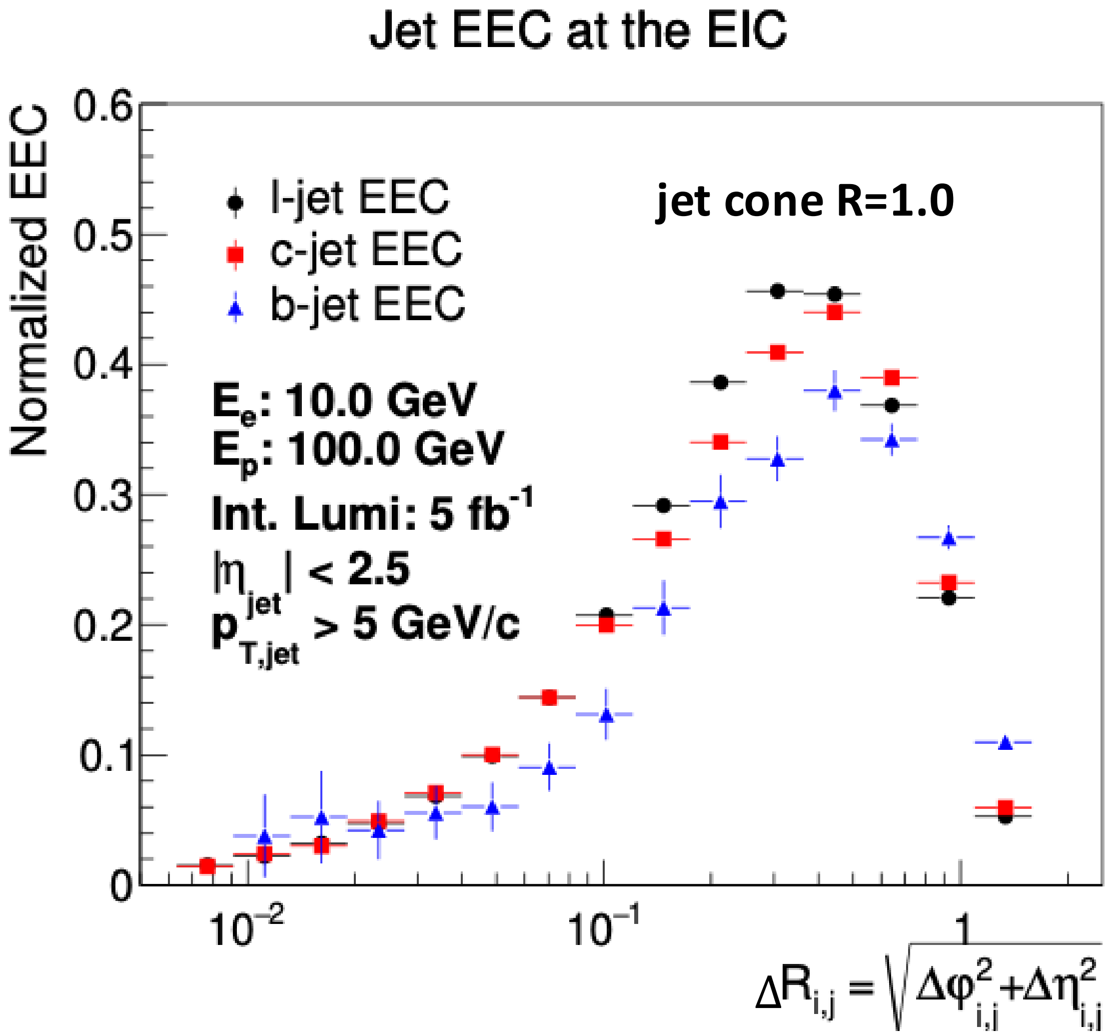




Jet Energy-Energy Correlator at the EIC (I)

- In 63.2 GeV e+p simulation, for reconstructed jets with different flavors (p_T > 5 GeV/c), the normalized energy-energy correlator ($\frac{1}{N_{jet}}\frac{dEEC_{ij}}{\sum EEC_{ij}dR_{ij}}$) of charged particles inside jets versus the ΔR_{ij}, where $EEC_{ij} = \frac{p_{T,i}p_{T,j}}{(p_{T,jet})^2}$.
- The peak position of the normalized energy-energy correlator distributions moves towards a large average $\Delta R_{i,j}$ as the jet flavor changes from light flavor to heavy flavor (charm and bottom).



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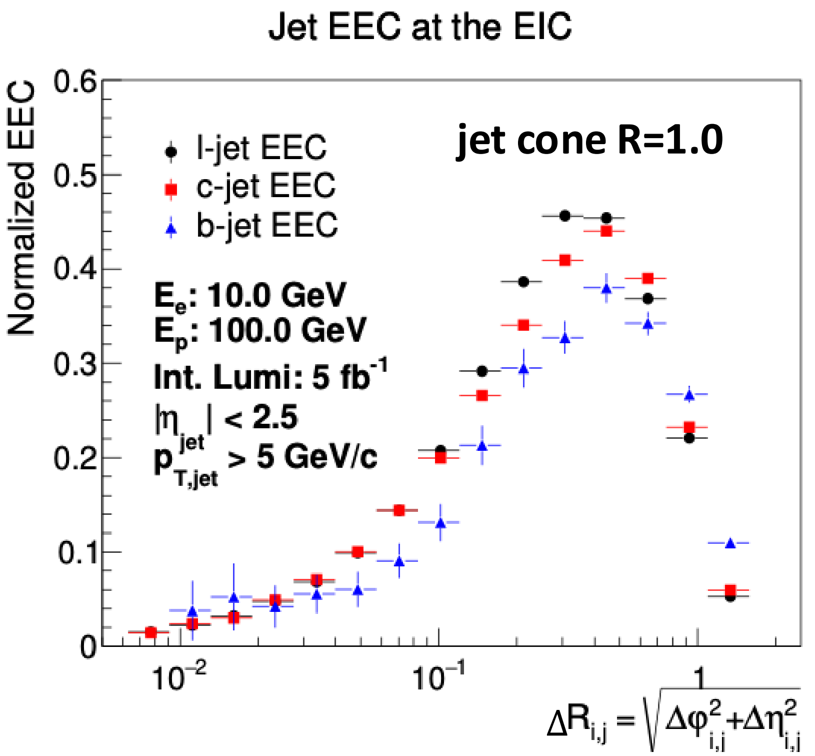
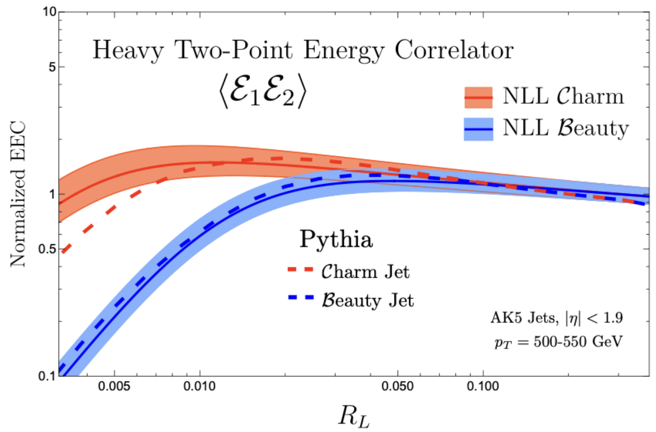
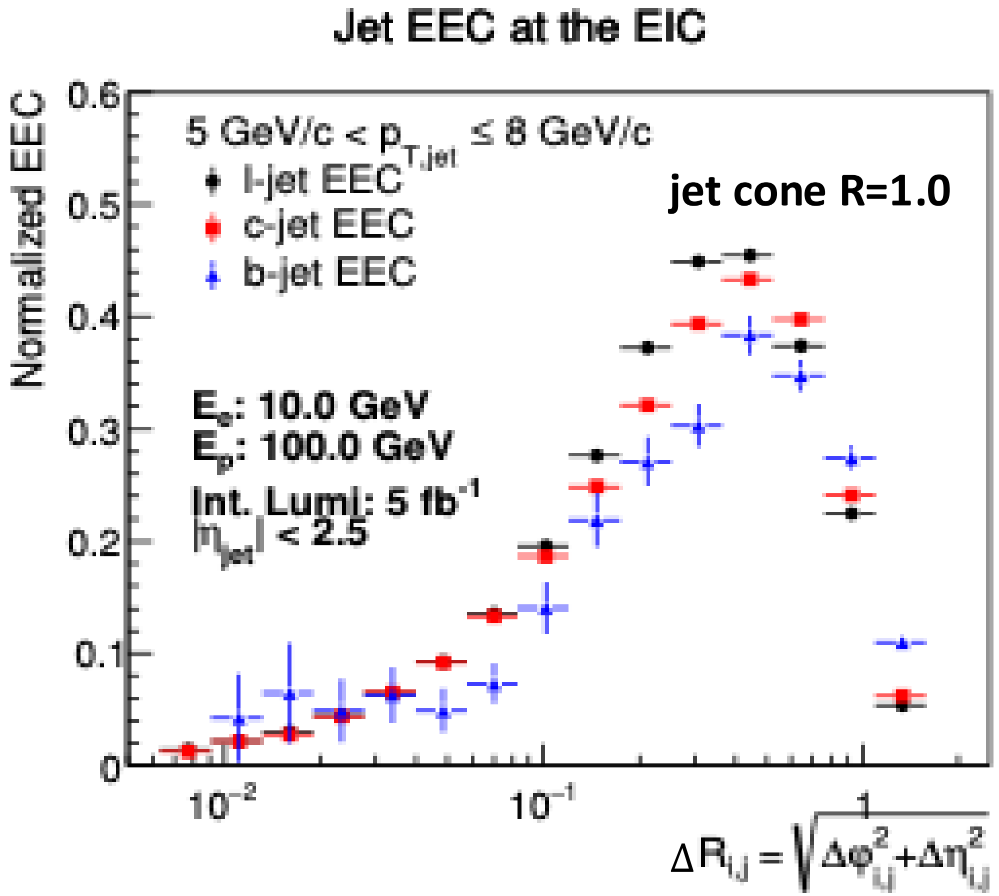
- The peak position of the normalized energy-energy correlator distributions moves towards a large average $\Delta R_{i,j}$ as the jet flavor changes from light flavor to heavy flavor (charm and bottom).
- Similar flavor dependence has been predicted by theorists for high p_T jets in p+p collisions (arXiv: 2210.09311).

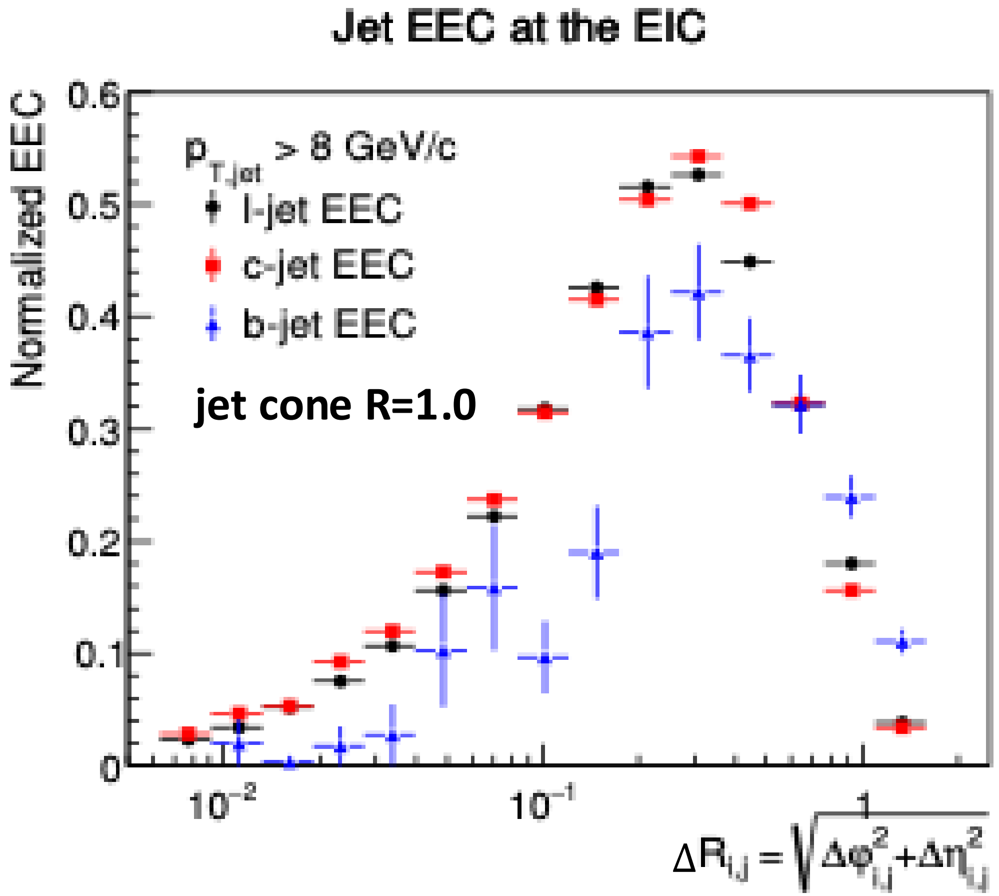




Jet Energy-Energy Correlator at the EIC (II)

- For reconstructed jets with 5 GeV/c < $p_T \leq$ 8 GeV/c (left) and p_T > 8 GeV/c (right) , the normalized energy-energy correlator ($\frac{1}{N_{jet}} \frac{dEEC_{ij}}{\sum EEC_{ij} dR_{ij}}$) of charged particles versus the ΔR_{ij}.

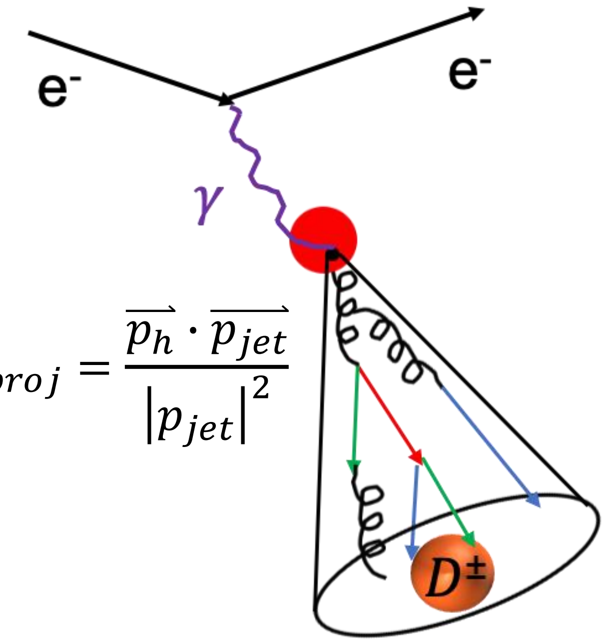




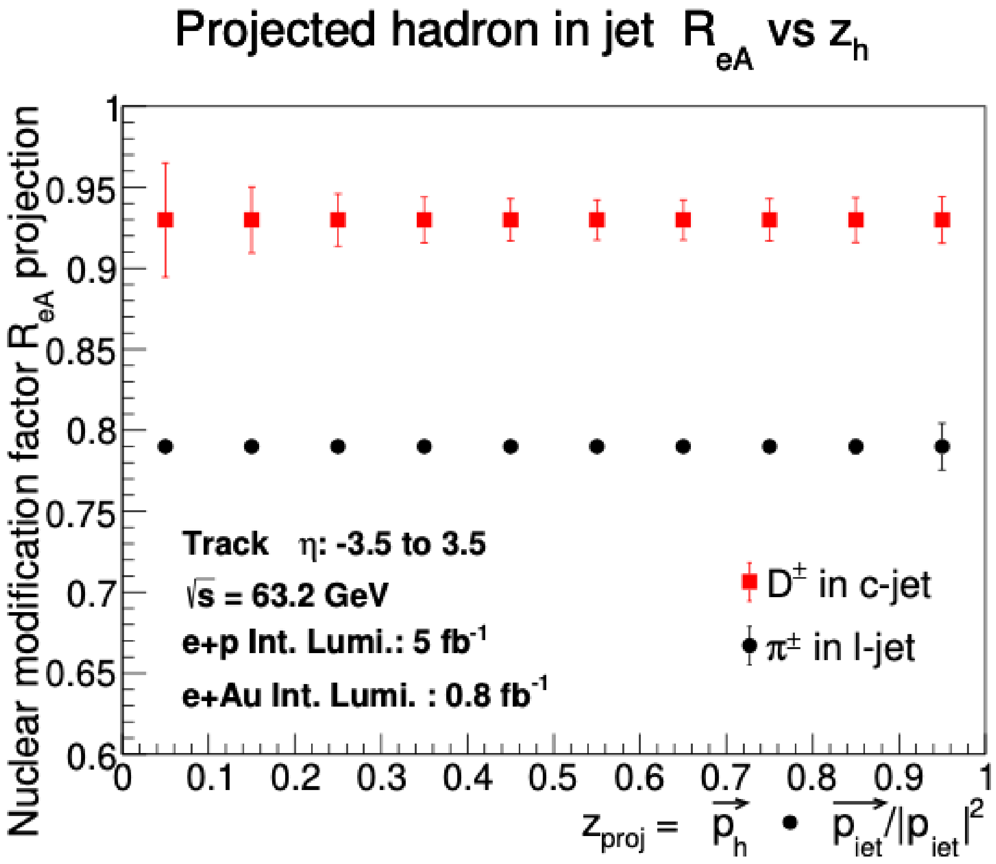
Heavy flavor hadron inside jet nuclear modification factor R_{eAu} projection

- Hadron inside jet productions at the EIC are an ideal probe to directly access the flavor dependent fragmentation functions.

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



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



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

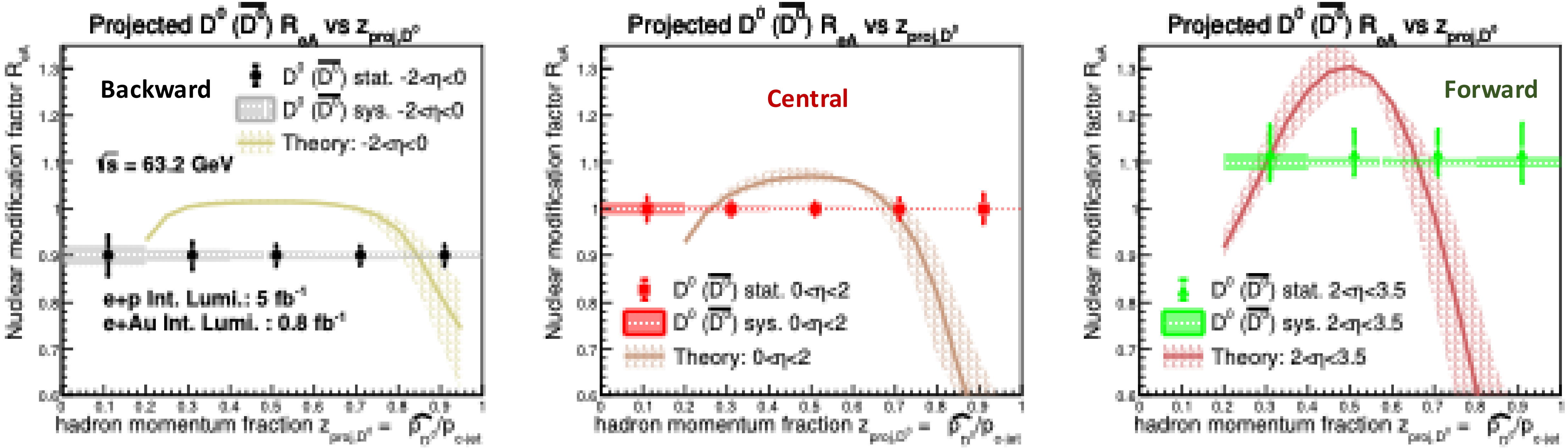
Great precision to be achieved by the EIC measurements in the accessed kinematic phase space.

- Future EIC heavy flavor 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<η<0 (left), 0<η<2 (middle) and 2<η<3.5 (right) regions in 10+100 GeV e+Au collisions with early EIC operation.

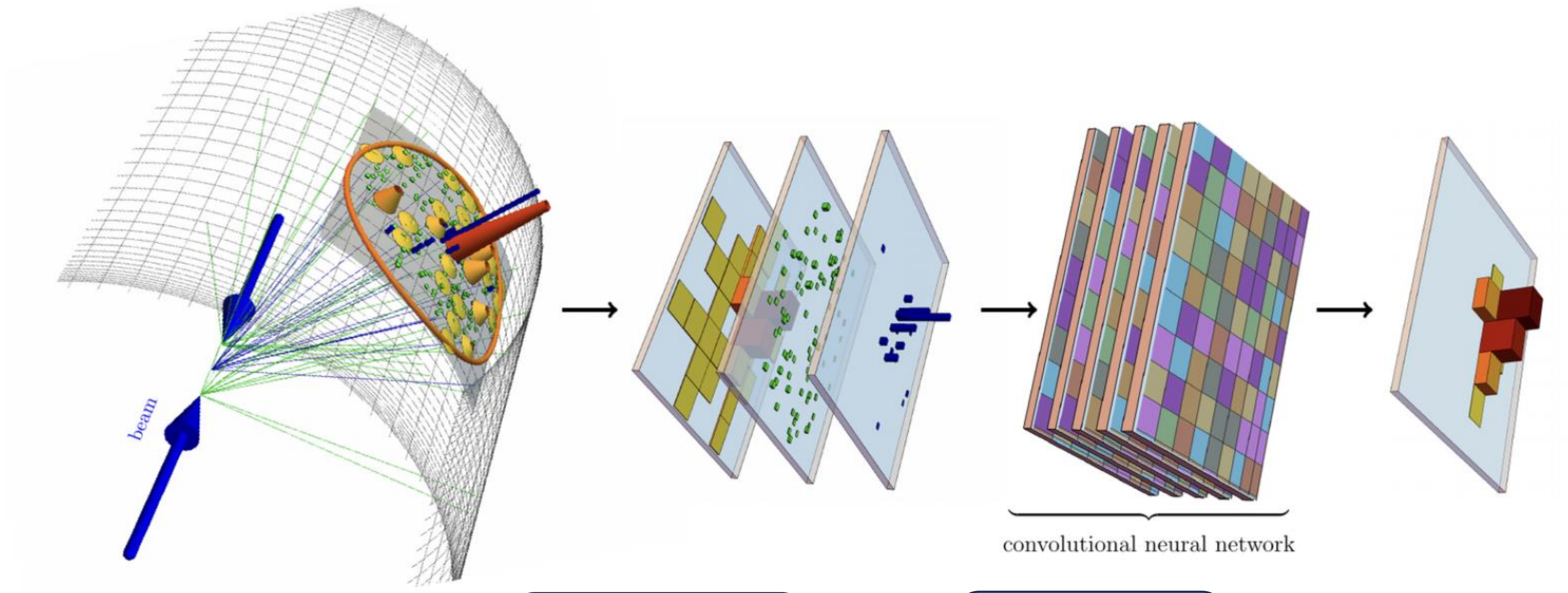
Theoretical calculations: Phys. Lett. B 816 (2021) 136261. EPJ Web of Conferences 316, 07003 (2025)



- 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.

Ideas about implementing AI/ML in HF physics at the EIC

Existing example in pileup event removal via ML at LHC. JHEP 12 (2017) 051



Collision sample → Decomposed detector output → ML application → Physics output

Ideas about implementing AI/ML in HF physics at the EIC

- Available Machine Learning Models for the heavy flavor physics studies:
  - Boost Decision Tree (BDT)
  - Neural Network (NN)
    - Deep Neural Network
    - Attention Neural Network
    - Recurrent Neural Network, e.g., Long Short-Term Memory (LSTM)
    - …
  - …

Ideas about implementing AI/ML in HF physics at the EIC

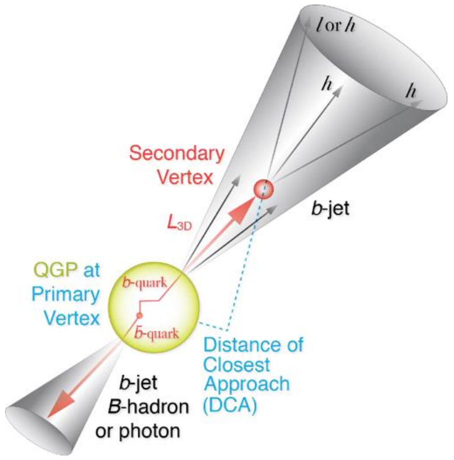
- Implementation at the detector level
  - To enhance the track reconstruction and vertex finding especially for the forward and backward particles.
  - PID performance.
  - Integration of various detector subsystems.
  - …

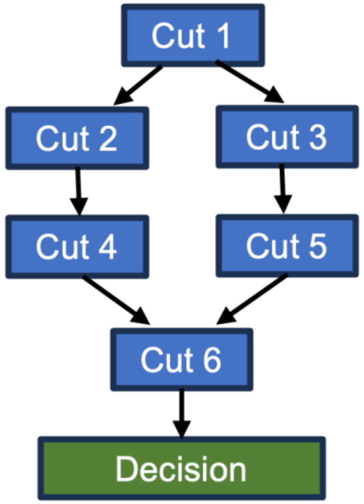
- Implementation at the physics analysis level
  - Enhance the signal finding and the background rejection power.
  - Expand to more fundamental kinematic variables
  - Improve the synergy of various physics parameters such as simultaneously analyze the track kinematic variables and calorimeter kinematic variables.
  - …

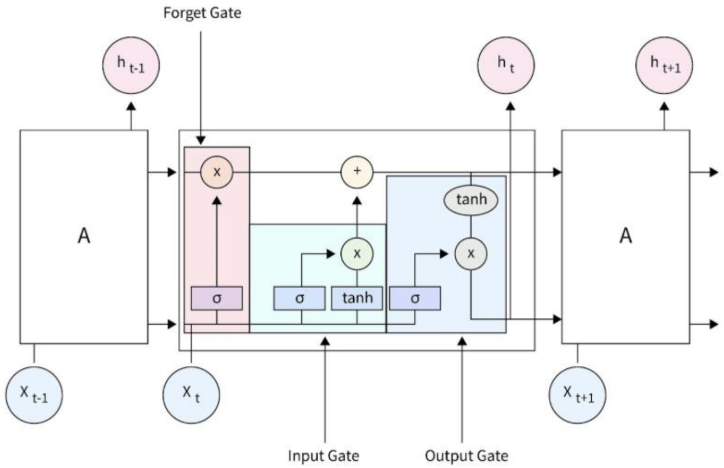
- To achieve improved heavy flavor hadron and jet signatures and corresponding physics performance

One example of recent jet flavor tagging application in p+p simulation

- Neural Network based ML models in comparison with the traditional cut method in the heavy flavor jet tagging in 200 GeV p+p simulation.







Long Short Term Memory (LSTM), Neural Computation 9(8):1735-1780, 1997

Does a jet originate from a heavy quark?

Zhiwan Xu (LANL, ANL)

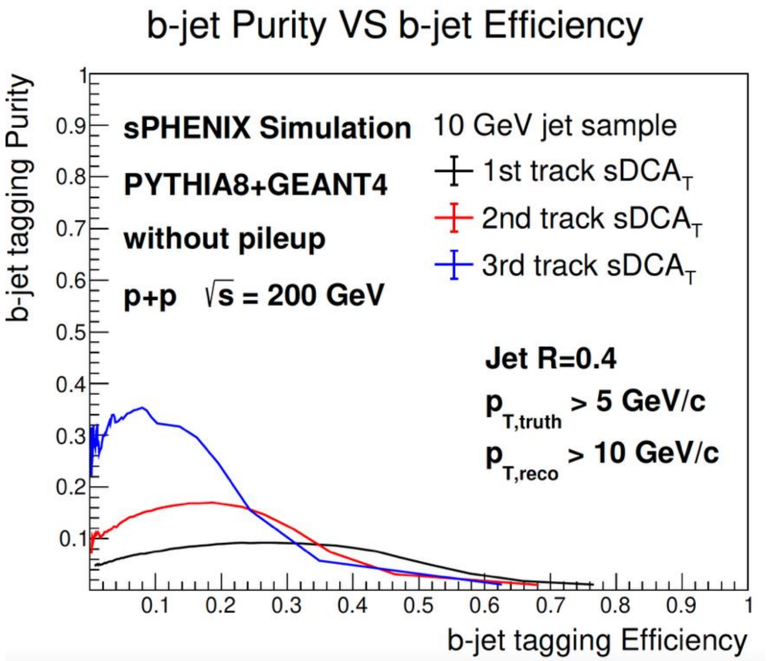
Jakub Kvapil (LANL)

In collaboration with Zhiwan Xu (LANL, ANL) and Jakub Kvapil (LANL)

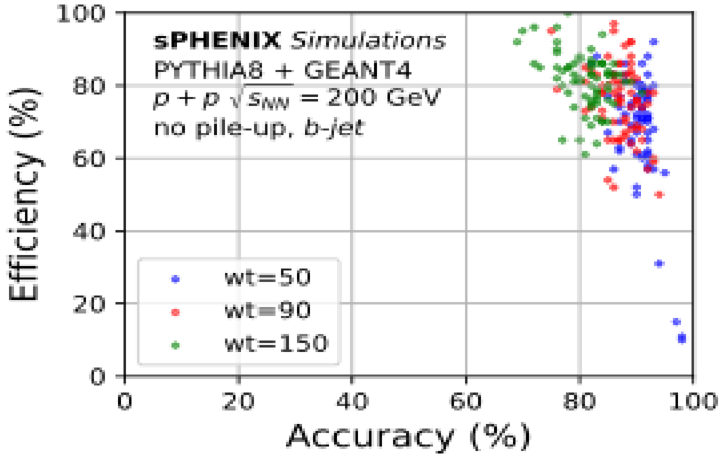
One example of recent jet flavor tagging in p+p simulation

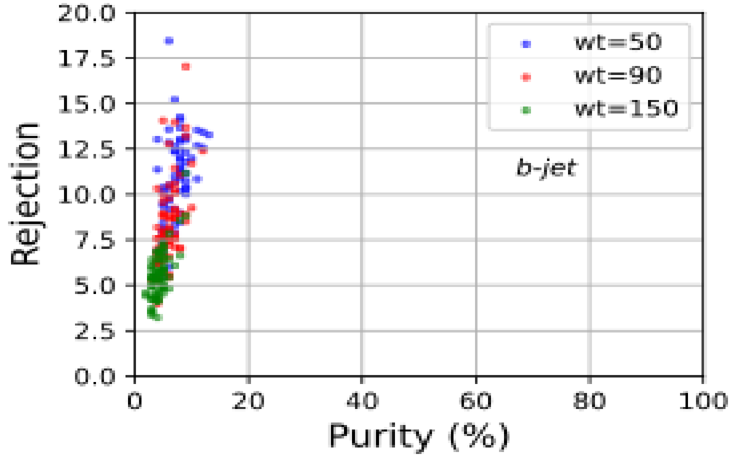
- Neural Network based Long-Short-Term-Memory (LSTM) ML model outperforms the traditional cut method in the heavy flavor jet tagging in 200 GeV p+p simulation.

Traditional cut method



LSTM ML method

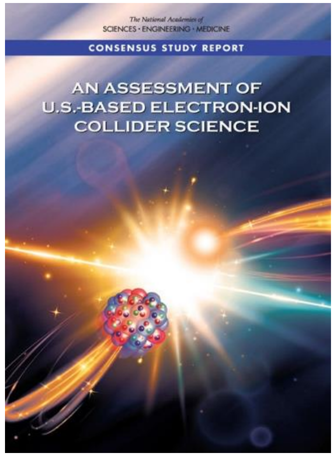




- Attention Neural Network ML model has similar performance as the LSTM model in the heavy flavor jet tagging in 200 GeV p+p simulation.
- Tested the jet tagging performance with both CPUs (~6 hour per sample) and GPUs (~1 min per sample) for the same training and testing.
- Will validate the jet tagging performance for different jet pT kinematic coverage and plan to extend to similar studies for the EIC.

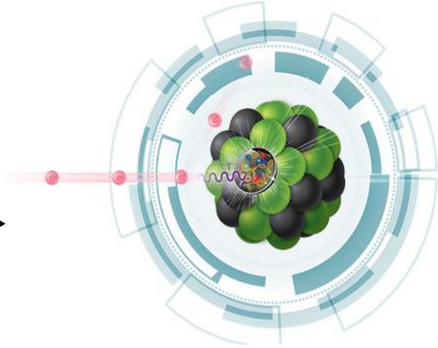
Summary and Outlook

- Great precision will be achieved by future EIC heavy flavor hadron and jet measurements in e+p and e+A collisions within complimentary kinematic regions from existing measurements.
- The future EIC will provide unique opportunities to study both initial- and final-state effects for heavy flavor production such as parton energy loss and hadronization process within a wide kinematic region.
- As we are moving towards the EIC construction in ~2026, we look forward to work with more collaborators for the EIC detector/experiment realization.



NAS review	EIC CD0	EIC CD1	EIC CD3/A	EIC CD2/3	EIC CD-4a	EIC CD-4
2018	2020	2021	2024	2025	2034	2036

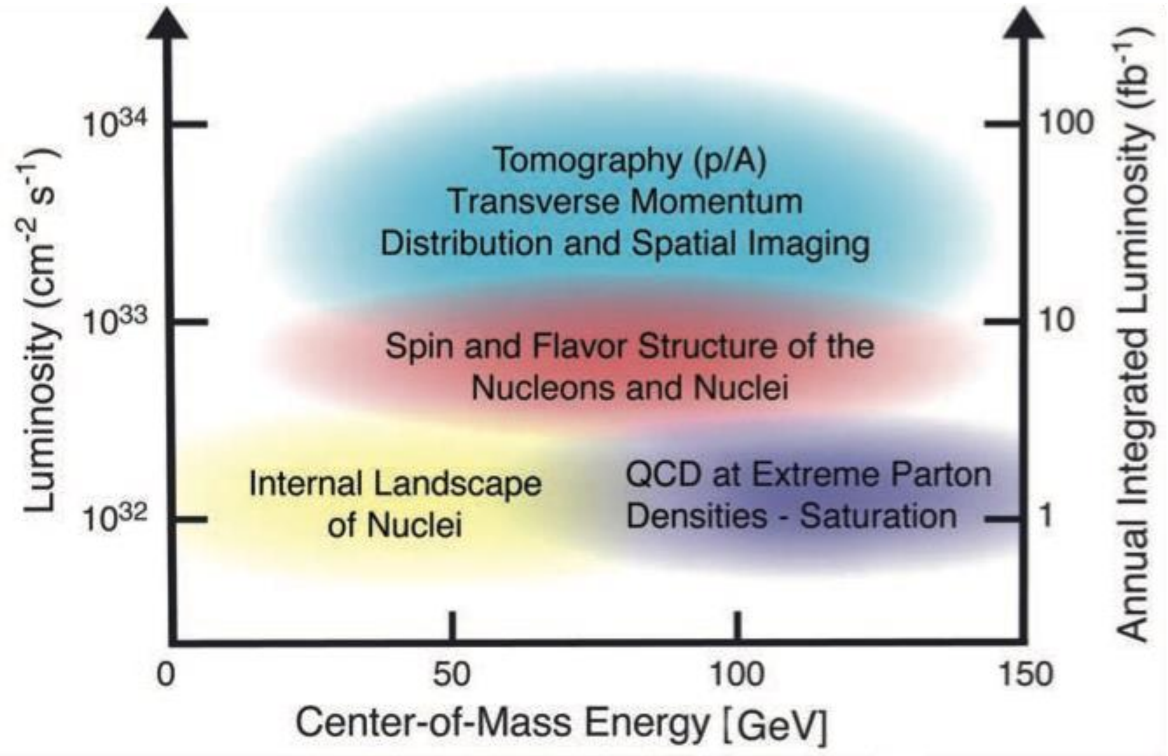
Design Phase | Construction Phase | Science Phase



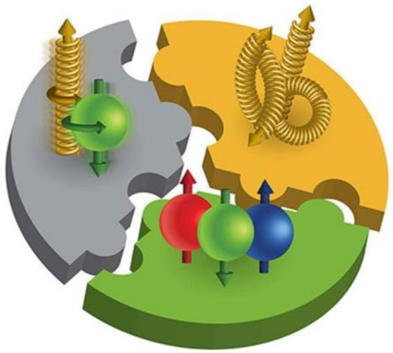
Backup

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

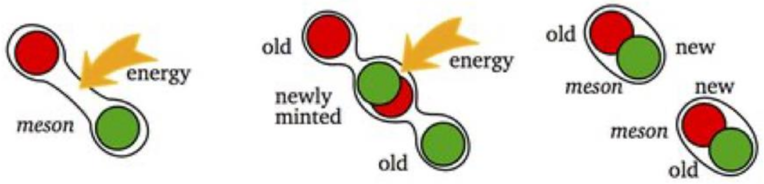
- With a series of e+p and e+A (A=2 to 238) collisions at different center of mass energies (20-141 GeV) and instantaneous luminosities (10^{33-34} $cm^{-2}sec^{-1}$), the future EIC will
  - precisely study the nucleon/nuclei 3D structure.
  - help address the proton spin puzzle.
  - probe the nucleon/nuclei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

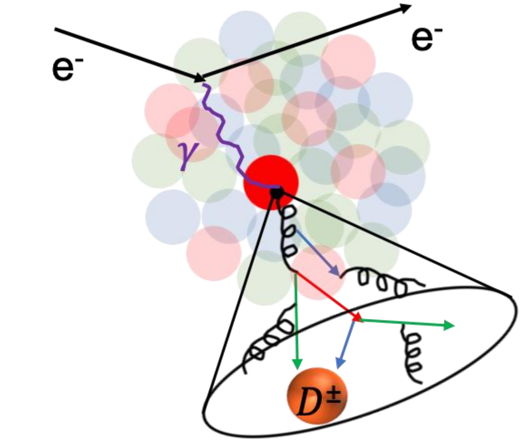


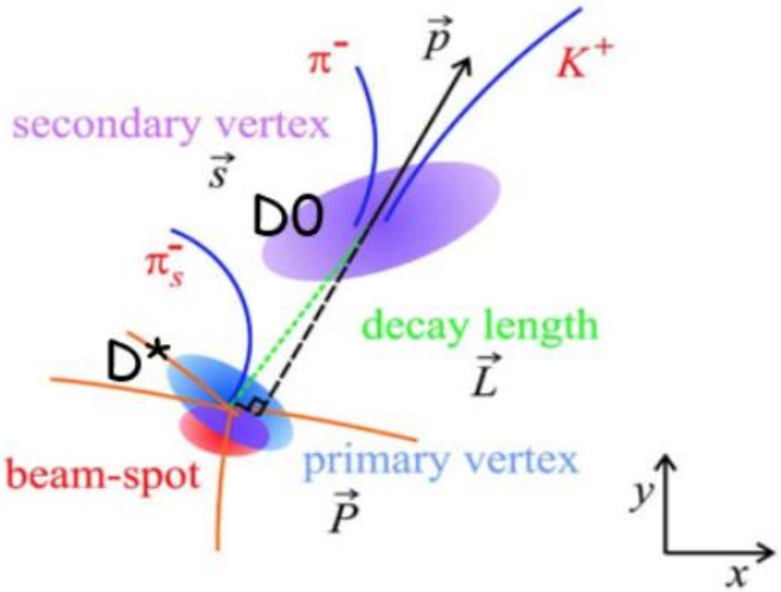
Quark confinement



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.



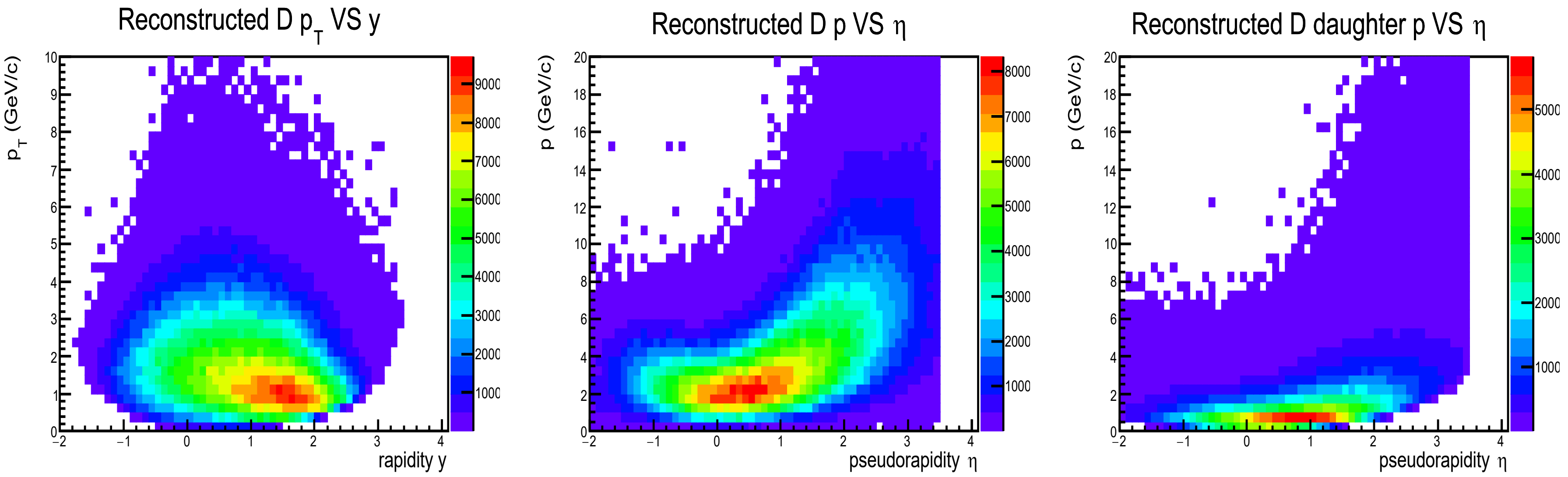


Particle	Mass (GeV/c²)	Average decay length
$D^{\pm}$	1.869	312 micron
D^0	1.864	123 micron
$B^{\pm}$	5.279	491 micron
B^0	5.280	456 micron

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