EIC heavy flavor physics introduction and highlight

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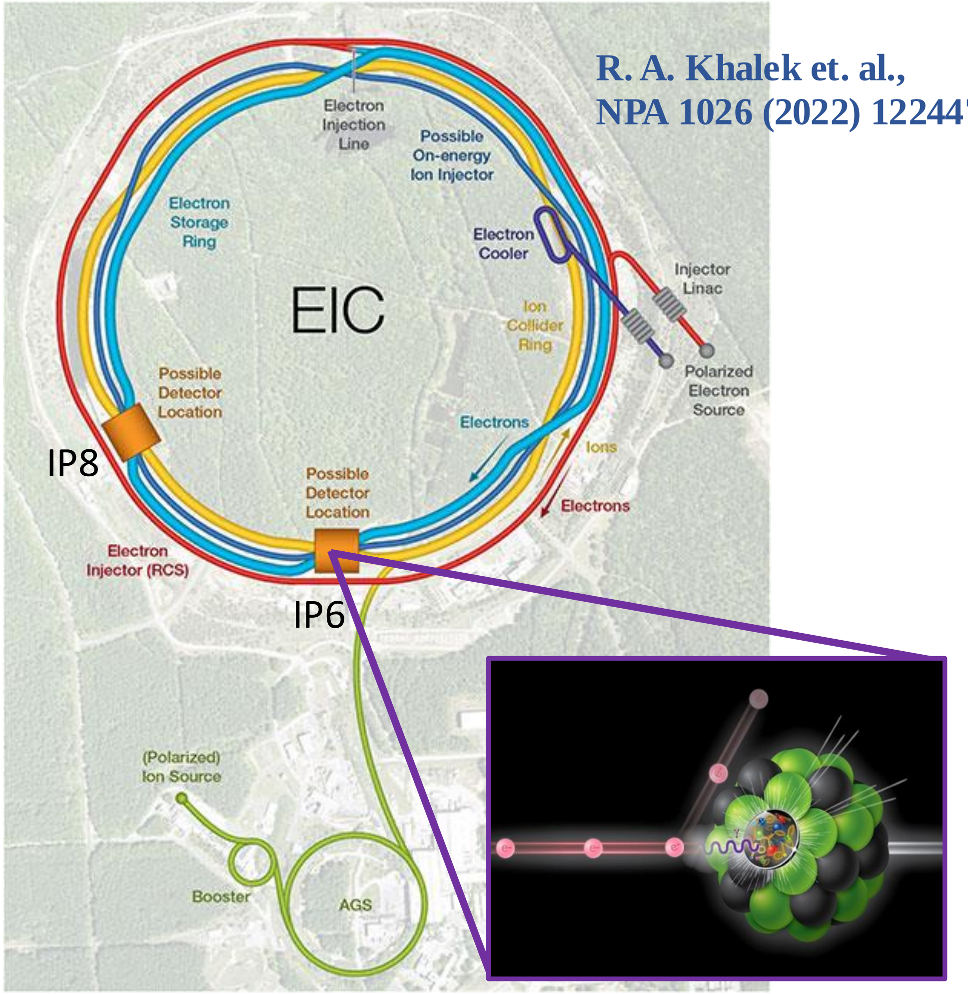
Outline

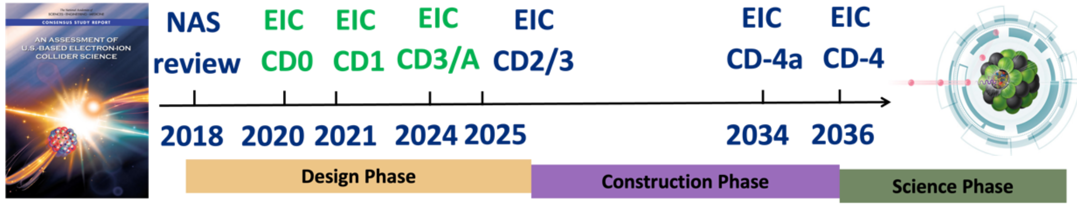
- Introduction to the Electron-Ion Collider (EIC).
- Overview of the ePIC detector.
- Heavy flavor hadron and jet reconstruction in simulation for the Electron-Ion Collider (EIC).
- Selected heavy flavor hadron and jet studies to explore the parton energy loss and hadronization processes at the EIC.
- 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 project is scheduled to start construction at BNL in 2025 and its operation is expected in 2030s.
- The EIC will support up to two Interaction Points (IP6, 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 ~1000 higher than HERA.
  - Bunch crossing period: 10.2 ns. Physics collision rate is ~500kHz.

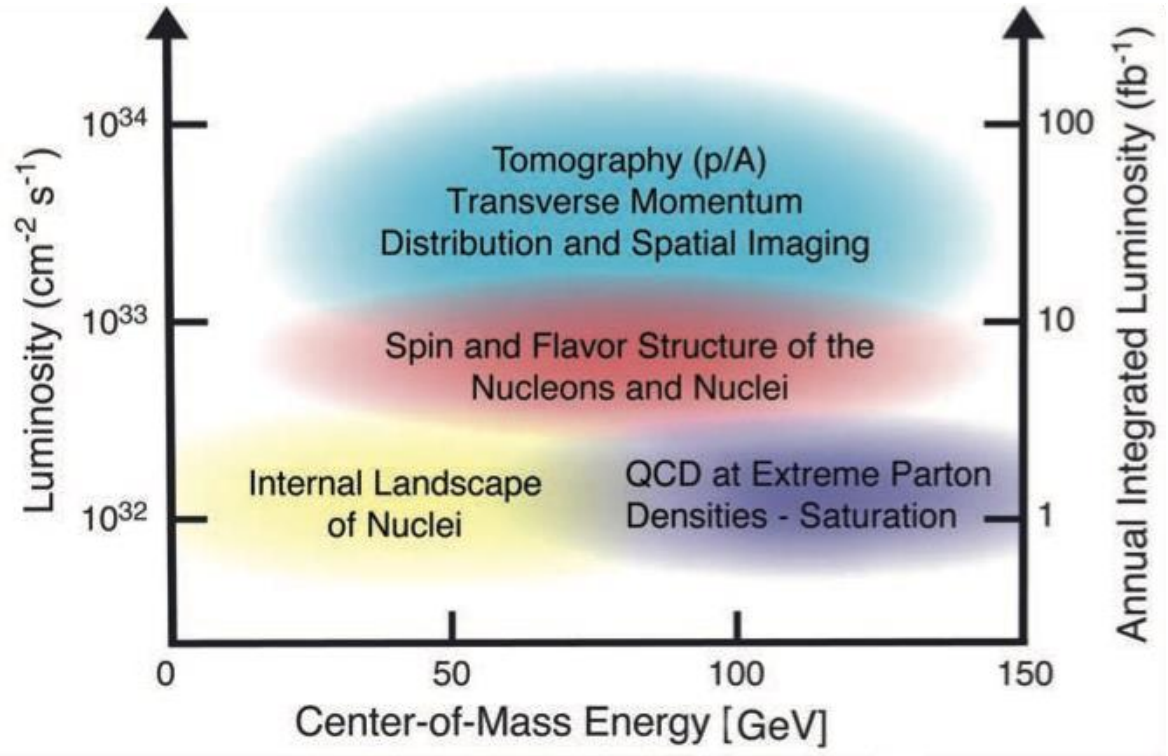


R. A. Khalek et. al., NPA 1026 (2022) 122447

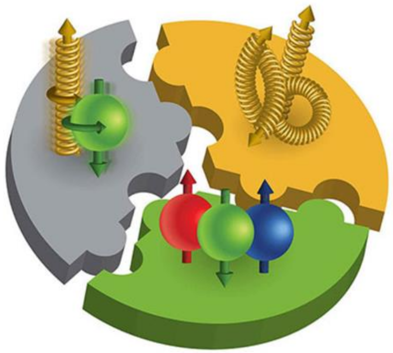


The science objectives of the Electron-Ion Collider (EIC)

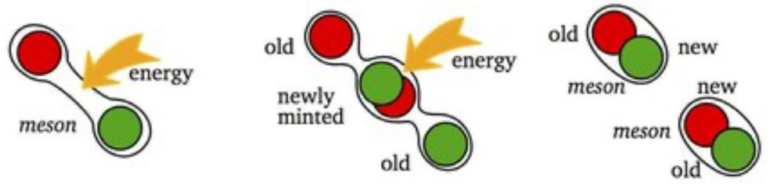
- With a series of e+p and e+A (A=2 to 238) collisions at different center of mass energies (20-141 GeV) and instantaneous luminosities ($10^{33\text{-}34}$ $cm^{-2}sec^{-1}$), the future EIC will
  - precisely study the nucleon/nuclei 3D structure.
  - help address the proton spin puzzle.
  - probe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



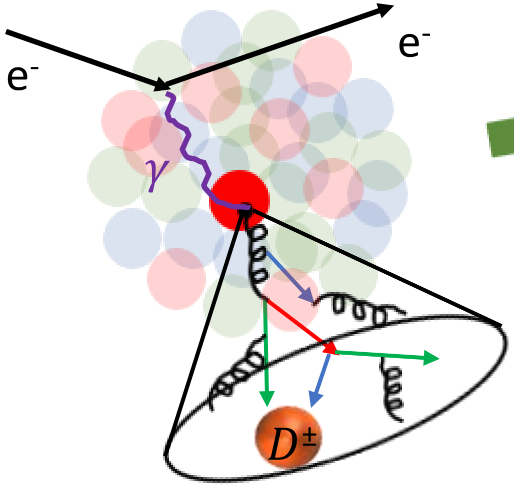
Quark confinement



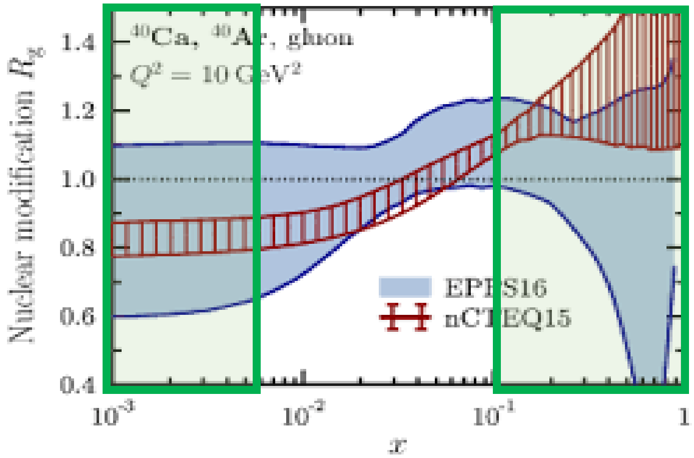
Heavy flavor measurements can enrich the EIC physics program

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

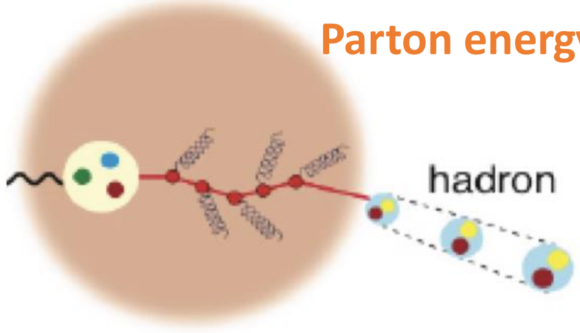
$e^- + \mathrm{Au} \rightarrow e^- + jet(D^\pm) + X$



nPDF modification

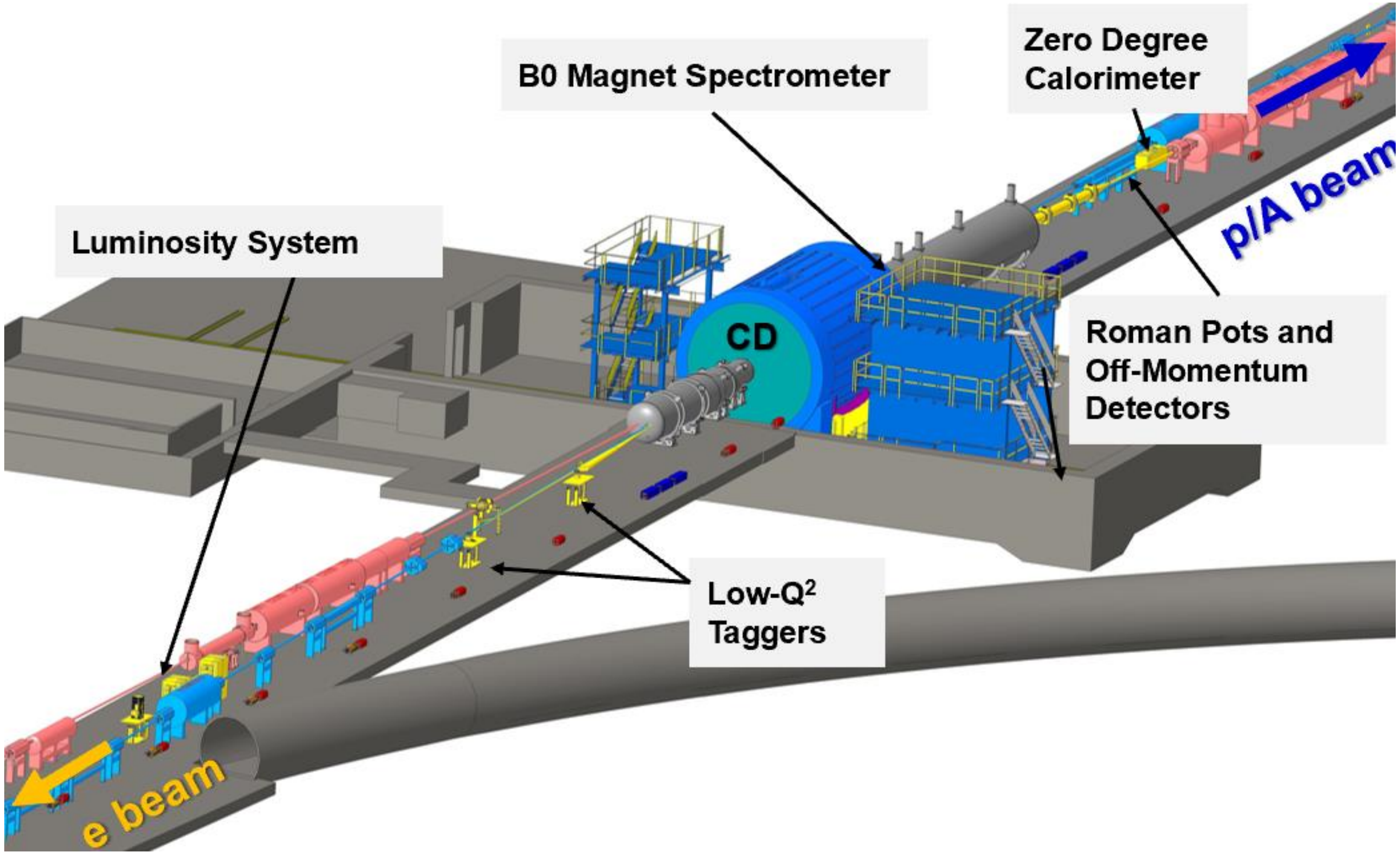


Parton energy loss



Current EIC project detector design by the ePIC collaboration

- The ePIC collaboration is leading the EIC project detector (at IP6) technical design towards the EIC construction scheduled to start in late 2025.



- There is a 25 mrad beam crossing angle at IP6.
- The ePIC detector consists of the far-forward detector, central detector and far-backward detector.

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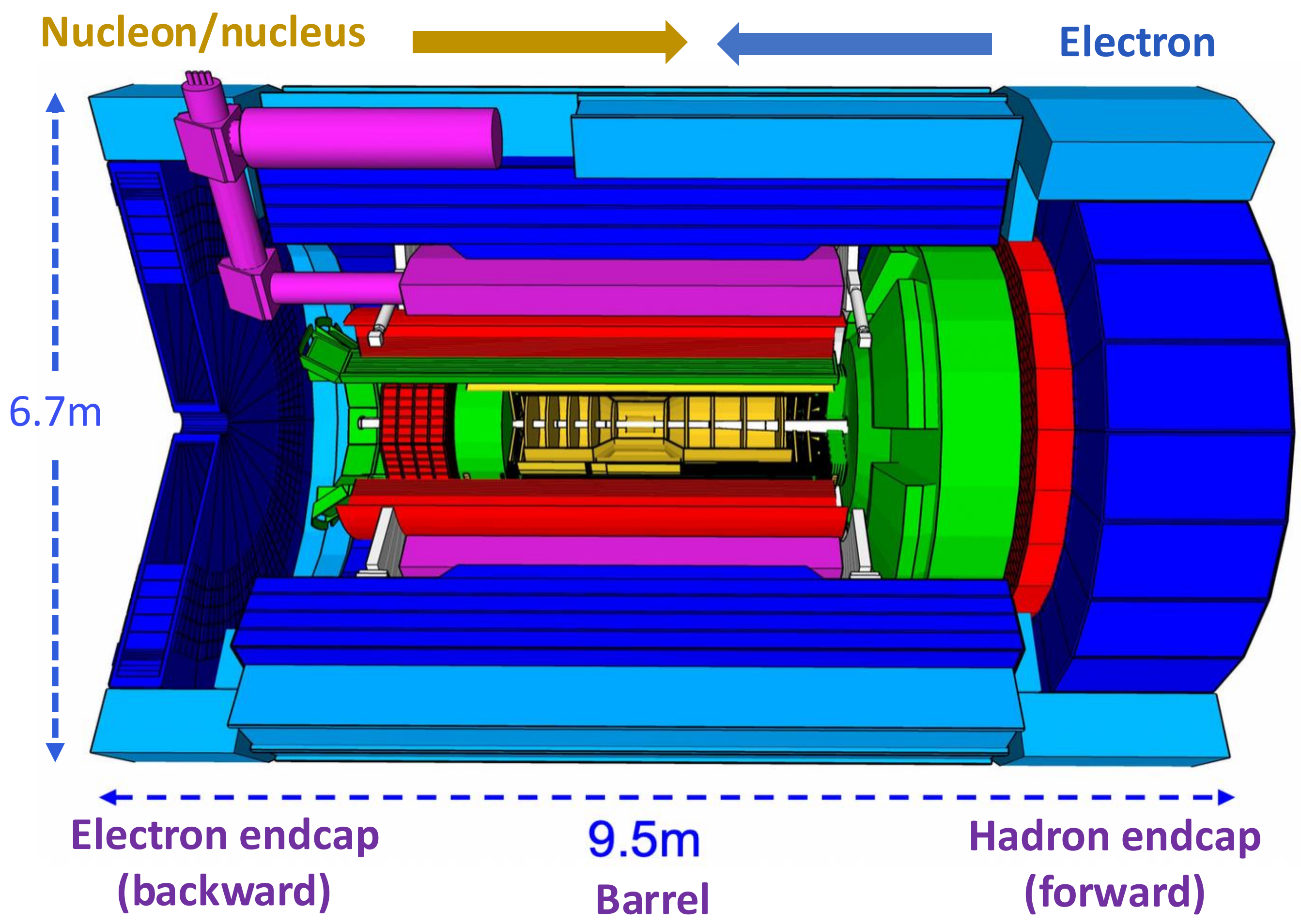
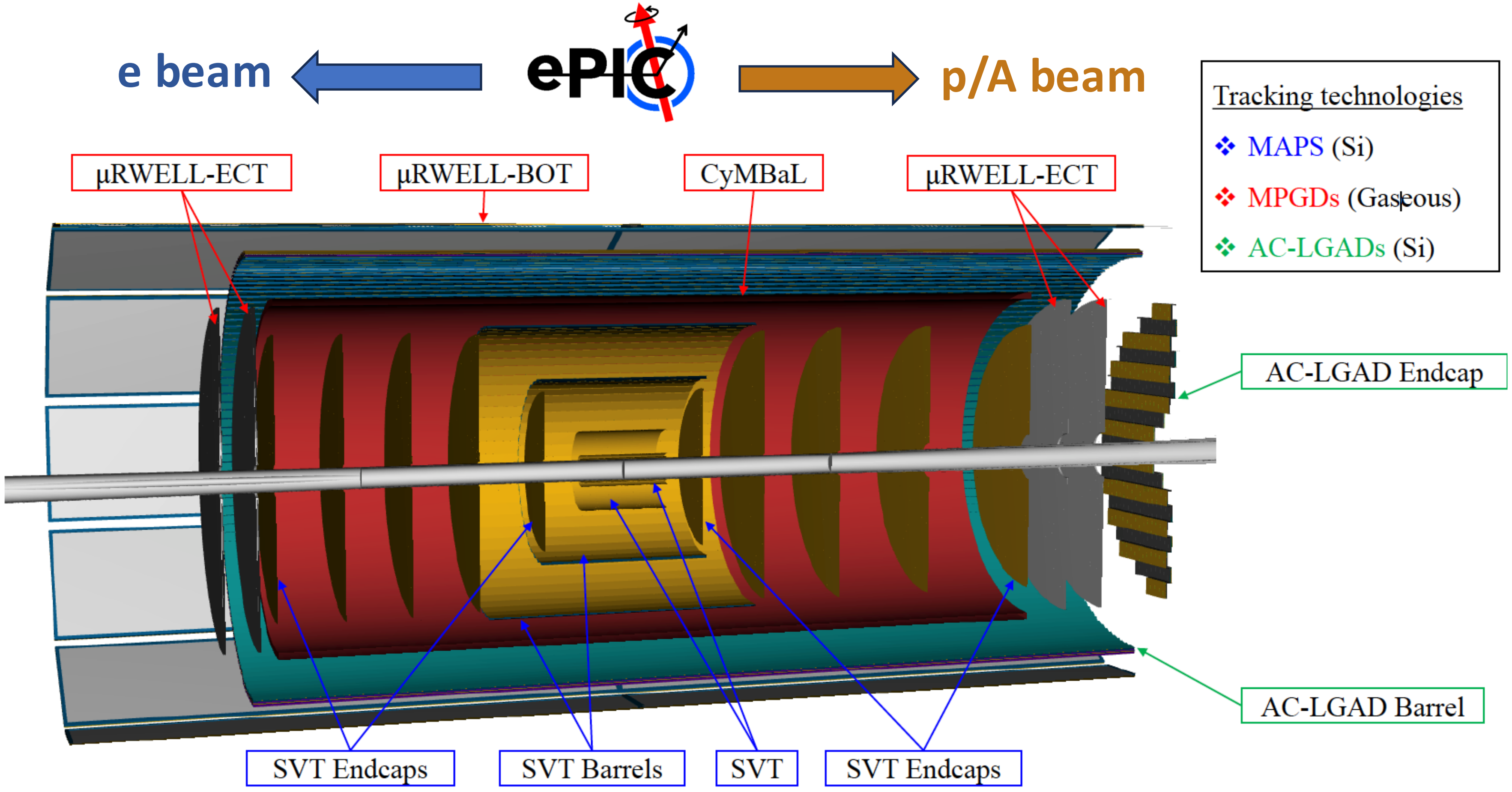


- The ePIC central detector (9.5m X 6.7m) consists of optimized vertex, tracking, PID, EMCal and HCAL subsystems, which enables high precision hadron and jet measurements within the pseudorapidity coverage of $-3.5<\eta<3.5$.

ePIC Tracking Detector

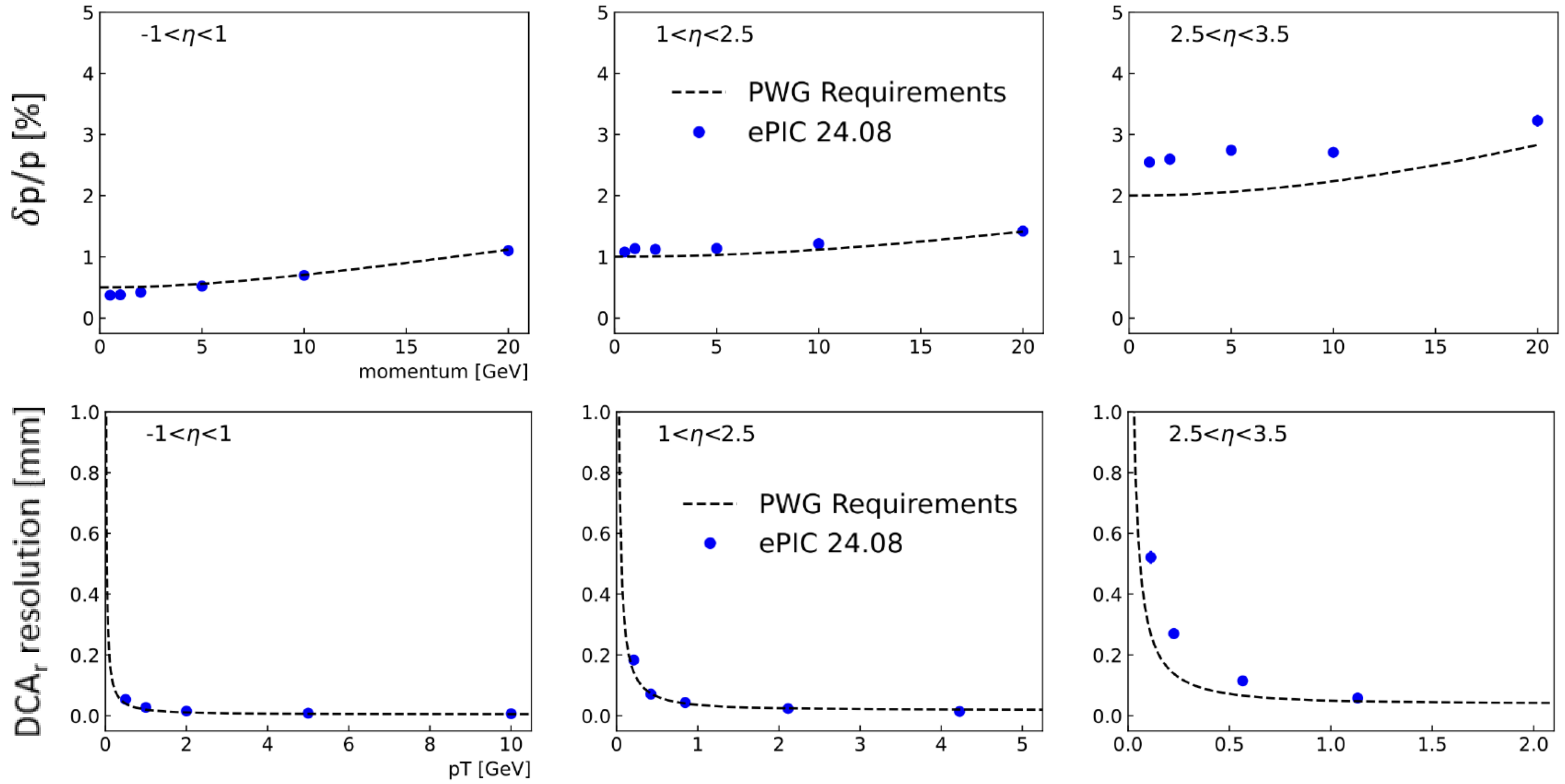
- The ePIC vertex and tracking detector includes the 65nm Monolithic Active Pixel Sensor (MAPS) based Silicon Vertex Tracker (SVT), the Micromegas/μRWELL based tracking layers and the AC-LGAD based outer tracker (TOF).



- The SVT consists of 5 layers in the barrel region, 5 disks in hadron-endcap region and 5 disks in the electron-endcap region.
- There are one Micromegas based barrel layer (CyMBaL), one μRWELL based barrel layer (μRWELL-BOT), two MPGD disks in the hadron-endcap region and two MPGD disks in the electron-endcap region.
- One AC-LGAD barrel layer and one AC-LGAD hadron-endcap disk serves as the outer tracker.

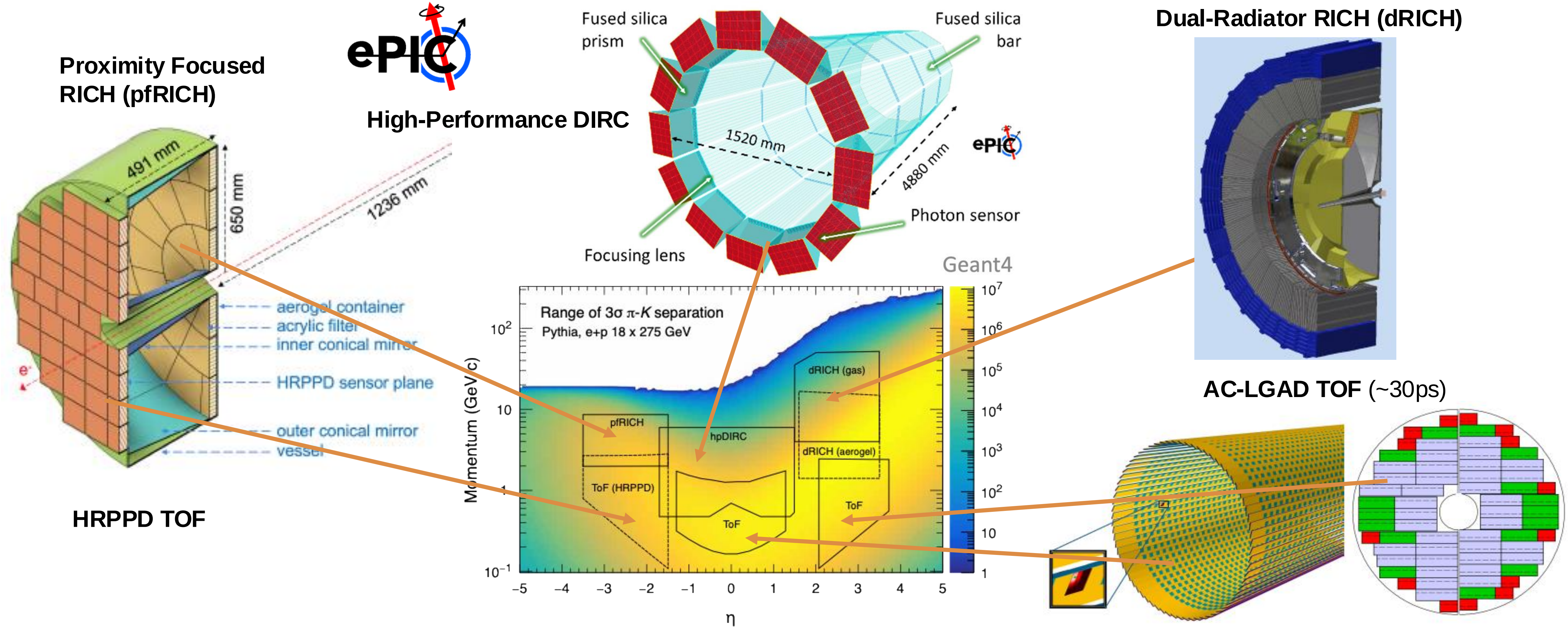
ePIC tracking performance

- In most kinematic regions, the current ePIC tracking performance meets the EIC yellow report requirements.



ePIC PID detector

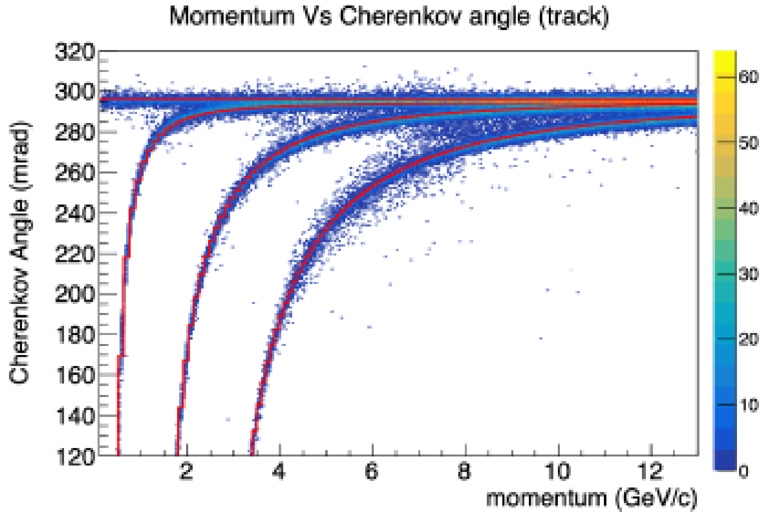
- ePIC PID detector consists of Ring Imaging Cherenkov (RICH), Detection of Internally Reflected Cherenkov (DIRC) and Time of Flight (ToF) subsystems.



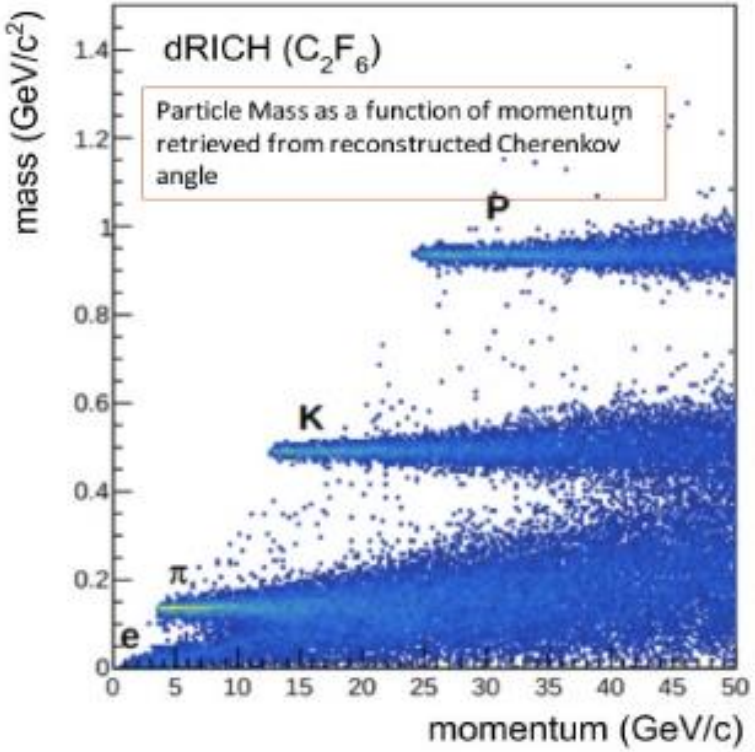
ePIC PID performance

- The ePIC PID detector can provide better than 3σ K/π/p separation
  - in the forward (hadron going) region: up to 50 GeV/c track momentum
  - in the central (barrel) region: up to 6 GeV/c track momentum
  - In the backward (electron going) region: up to 10 GeV/c track momentum

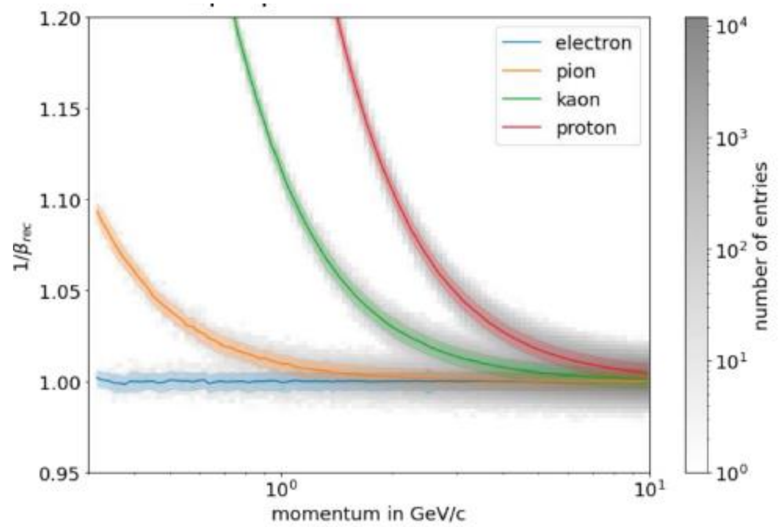
ePIC pfRICH performance



ePIC dRICH performance



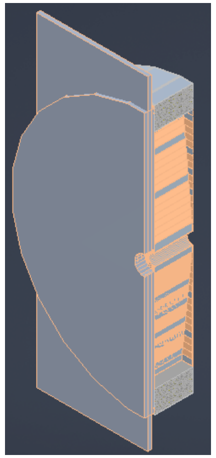
ePIC hadron-endcap ToF performance



ePIC calorimeter detector

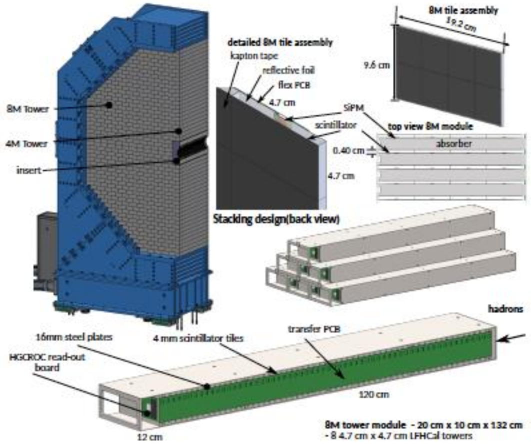
- The ePIC detector includes ElectroMagnetic Calorimeter (EMC) and Hadronic Calorimeter (HCAL) to cover the pseudorapidity region of $|\eta| \leq 3.5$.

EHCAL: *Steel/Sc sandwich tail catcher*



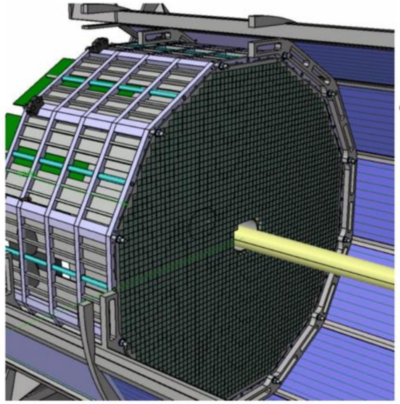
e beam ← ePIC → **p/A beam**

LFHCAL: *Longitudinally separated HCAL with high-h insert*

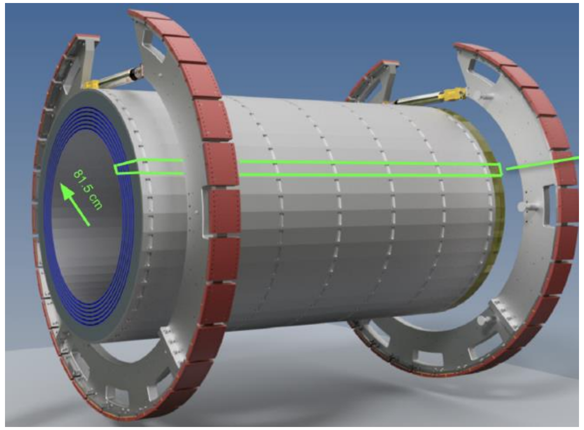


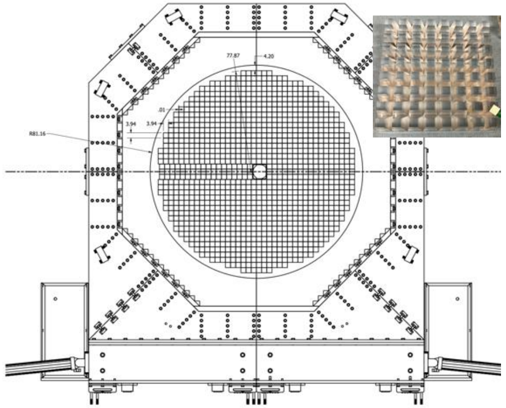
Barrel HCAL:
Steel/Sc sampling calorimeter
(sPHENIX re-use)

EEMC: *homogenous high resolution PbWO4 crystal ECal*



BEMC: *barrel imaging calorimeter (AstroPix chips interleaved with Pb-SciFi layers)*



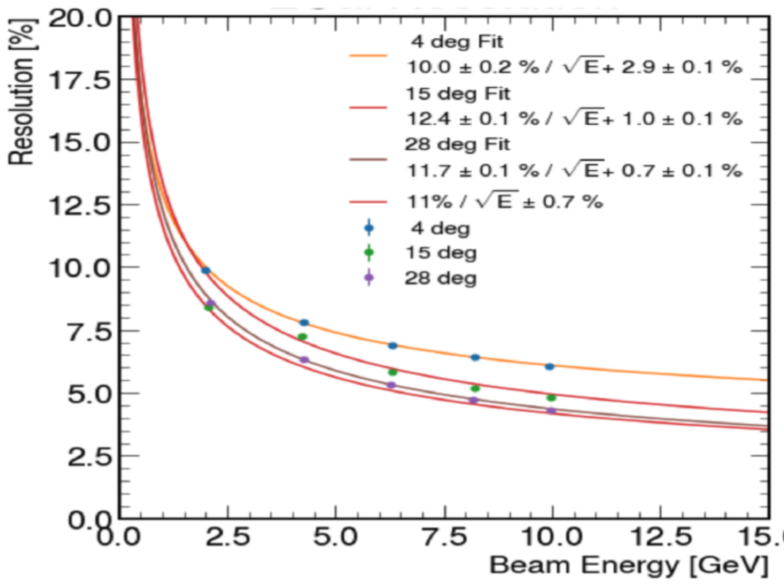


FEMC: *W-Scintillating Fiber calorimeter*

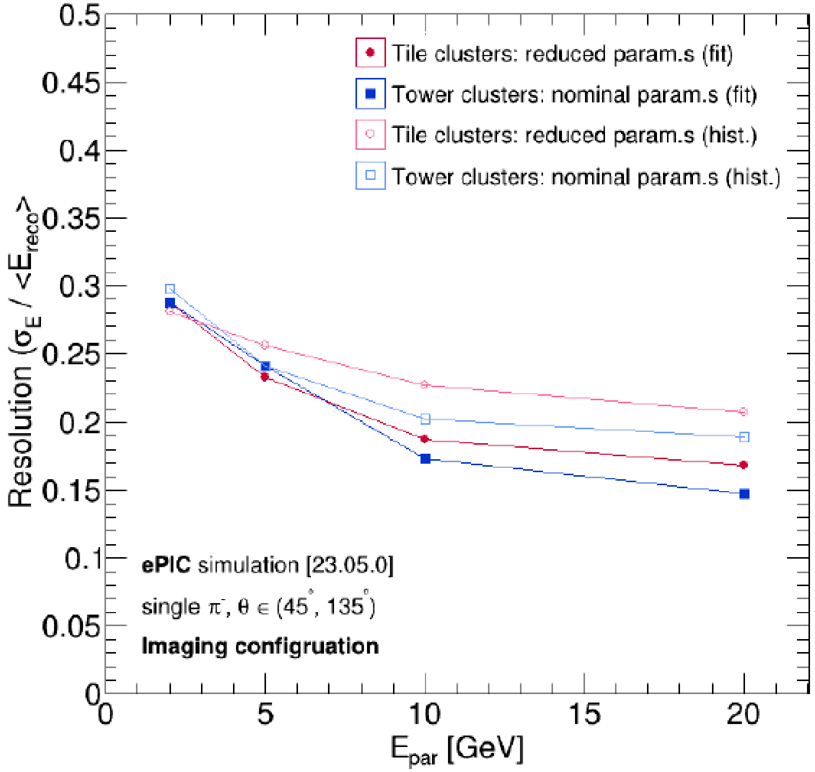
ePIC calorimeter performance

- The ePIC calorimeter performance can meet the EIC yellow report requirement.
- The calorimeters are designed to complement the tracking detector in the particle-flow algorithm.

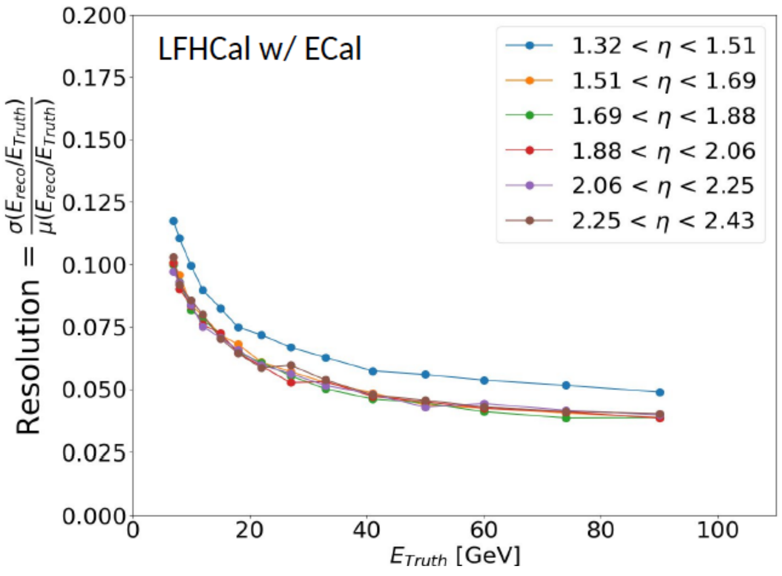
ePIC BEMC energy resolution from beam tests



ePIC BHCAL energy resolution in MC

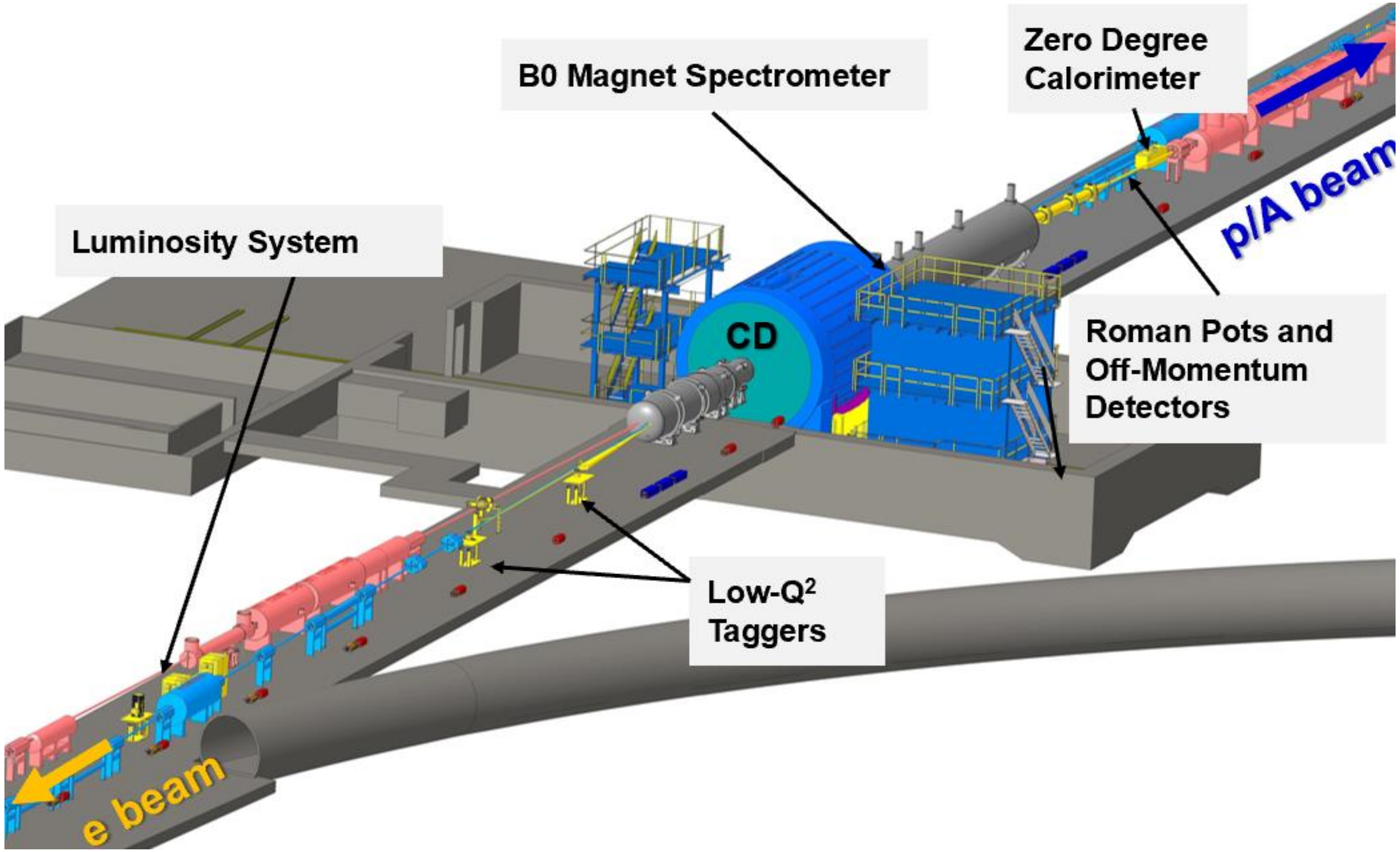


ePIC LFHCal w/ ECal energy resolution in MC



ePIC far-forward and far-backward detector

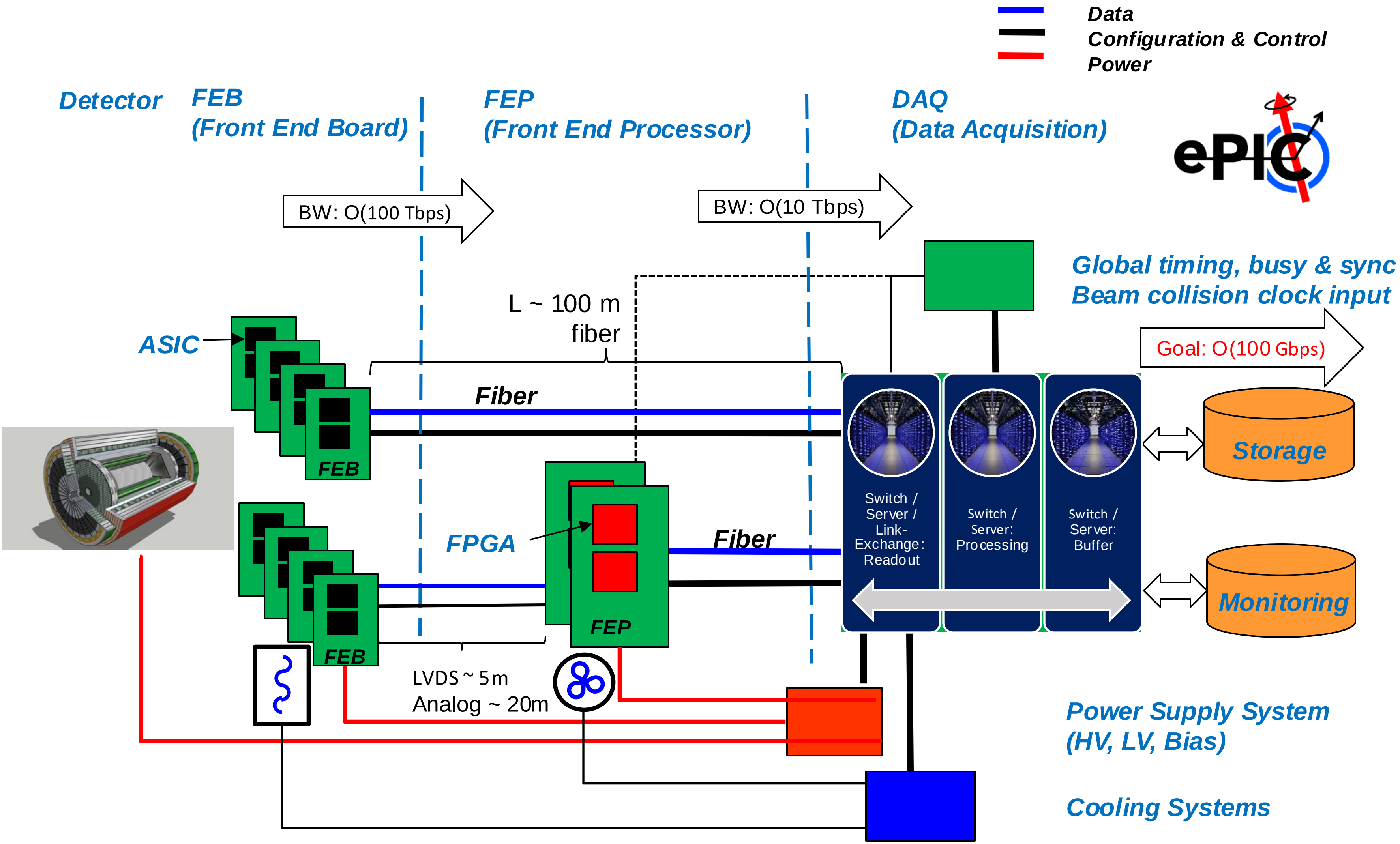
- **B0 Magnet Spectrometer**
  - Forward scattered proton and gamma detection.
  - AC-LGAD 4 planes and $PbWO_4$ EMCAL.
- **Roman Pots and Off-Momentum Detectors**
  - Forward scattered proton and nuclei detection.
  - 2 stations with 2 AC-LGAD tracking layers each.
- **Zero-Degree Calorimeter**
  - Forward scattered neutron and gamma detection.
  - $PbWO_4$ EMCAL and Steel-SiPM-on-Tile HCAL.
- **Luminosity System:**
  - 2 AC-LGAD/FCFD tracking layers and Tungsten-powder +SciFi Calorimeter.



- **Low-Q2 Taggers**
  - Detection of scattered electrons.
  - 2 stations with 4 Si/Timepix4 tracking layers each and Tungsten-powder + SciFi Calorimeter.

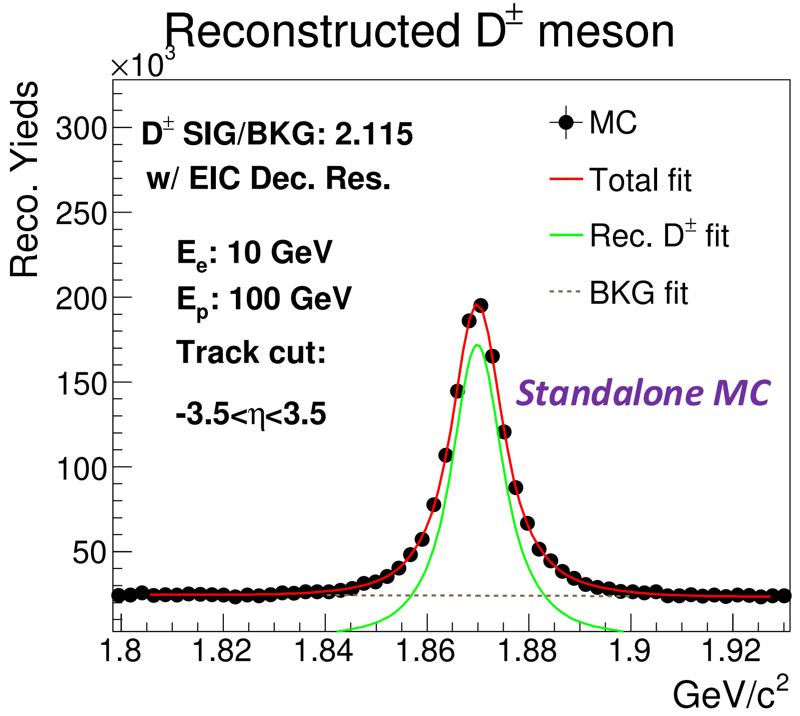
ePIC detector streaming readout

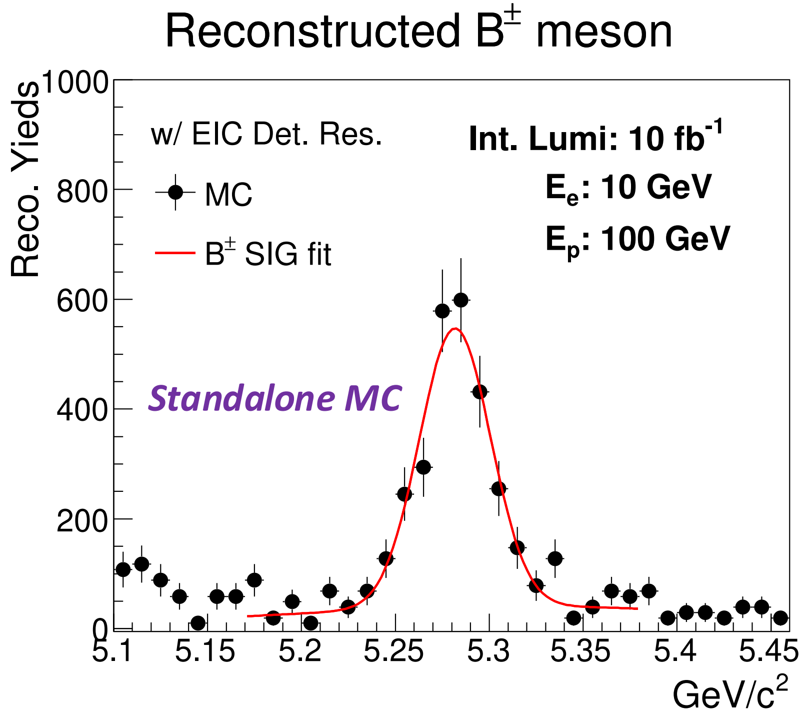
- All collision data are digitized and zero suppressed in FEB.
- Low/zero deadtime.
- Event selection can be based upon full data from all detectors (in real time or later).
- No global latency requirements.
- Data volume is reduced as much as possible at each stage.



Reconstruction of open heavy flavor products in e+p simulation

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





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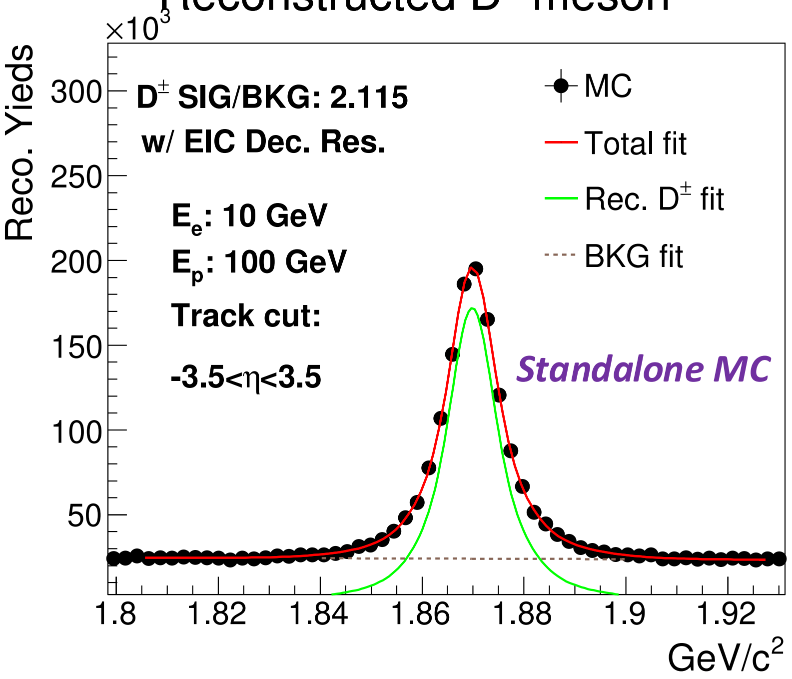
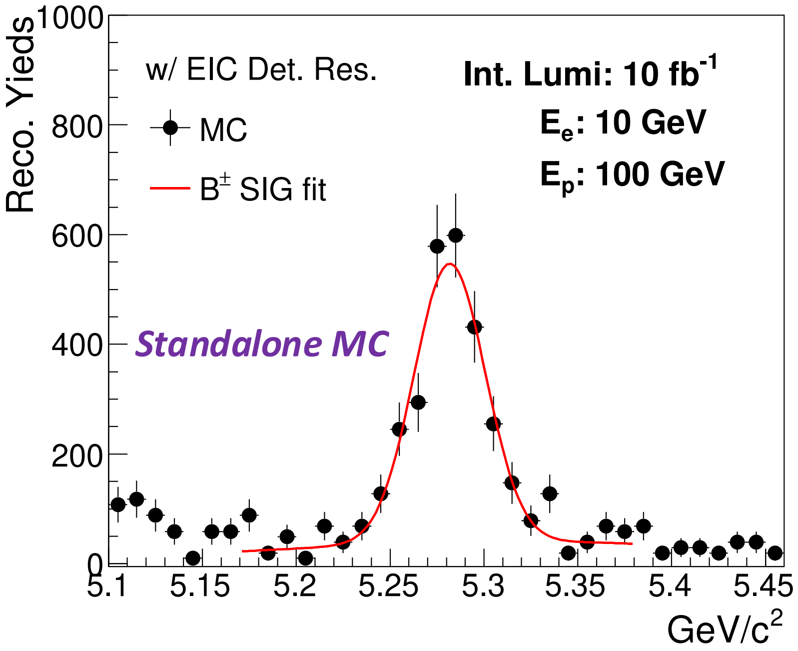
- Heavy flavor hadrons are reconstructed through hadronic decay channels.
- Heavy flavor jets are reconstructed with the anti-k_T algorithm, jet cone R=1.0 and jet flavor is tagged according to the displaced vertex found inside the jet.

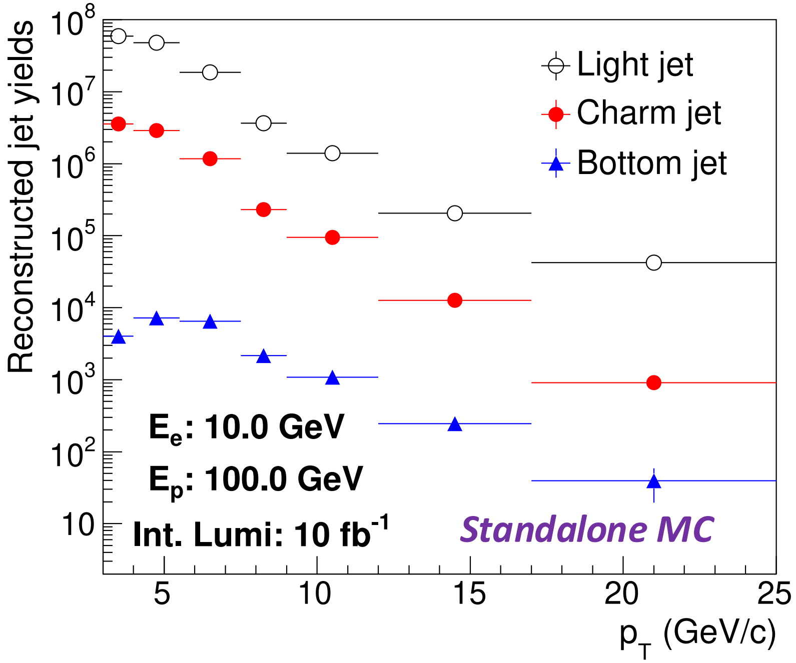
Reconstructed $D^{\pm}$ meson



Reconstructed $B^{\pm}$ meson

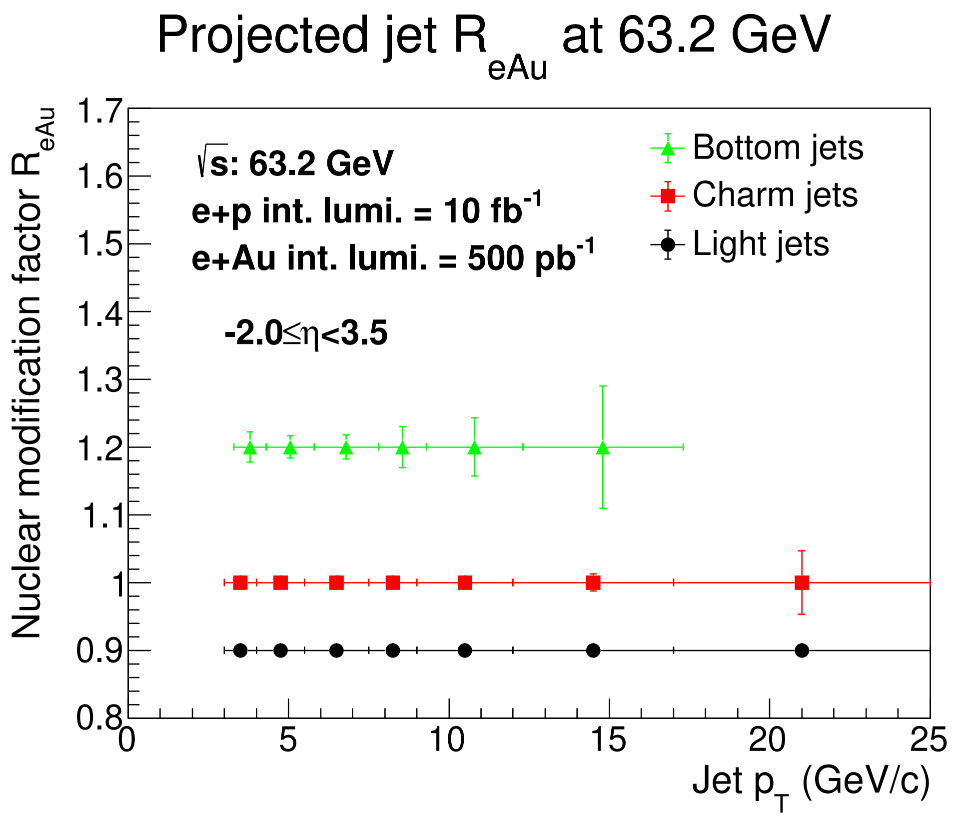


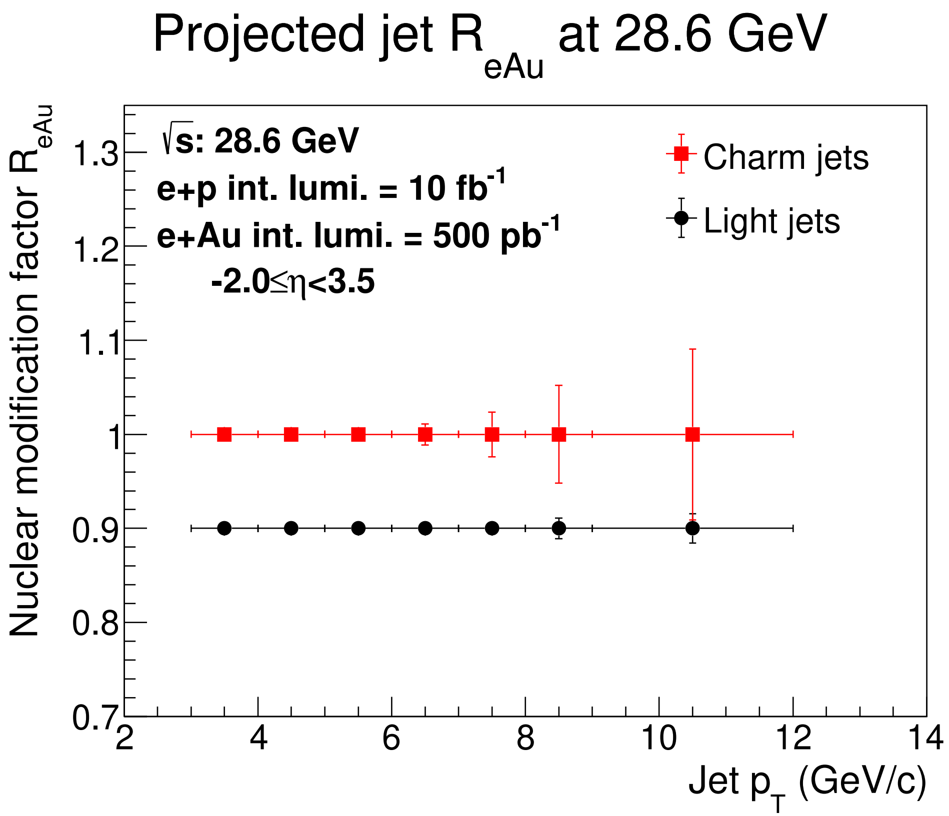
Jet p_T spectrum



Heavy flavor jet R_{eA} to explore parton energy loss mechanism

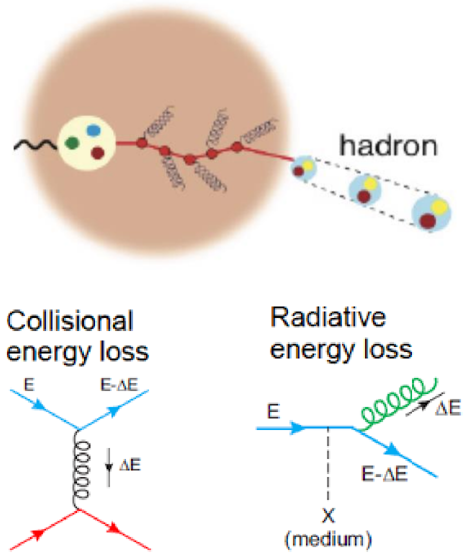
- Projected nuclear modification factor R_{eA} of jets with different flavors in e+p and e+Au collisions at 63.2 GeV (left) and 28.6 GeV (right).





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

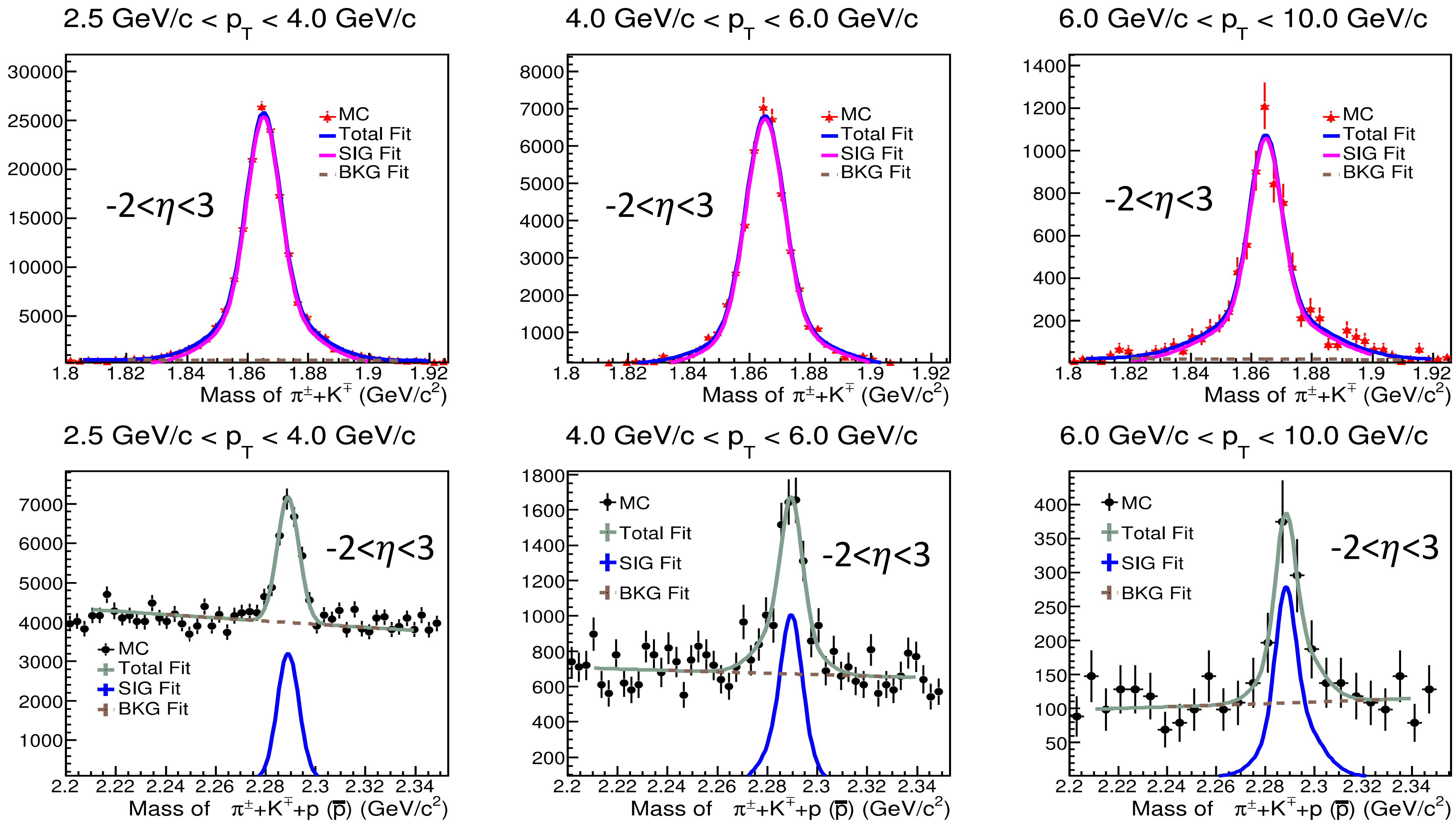
Parton energy loss



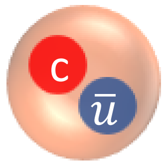
- Great precision to explore the flavor dependent parton energy loss mechanism especially in the low p_T region.

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.

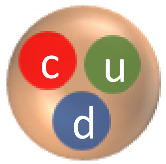


Inclusive charm hadron reconstruction



$D^0(\overline{D^0})$

Standalone MC

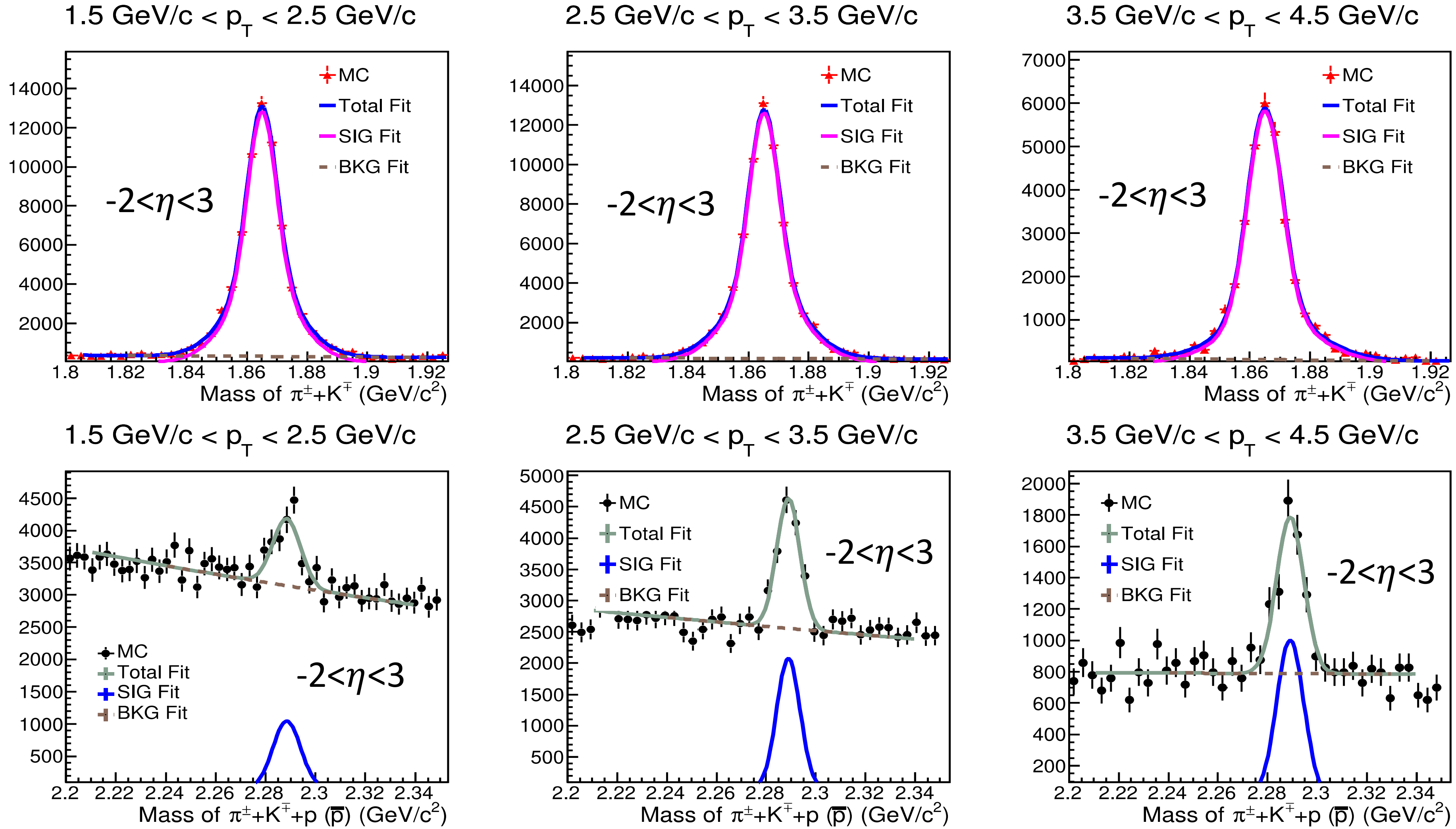


$\Lambda_c^{\pm}$

Standalone MC

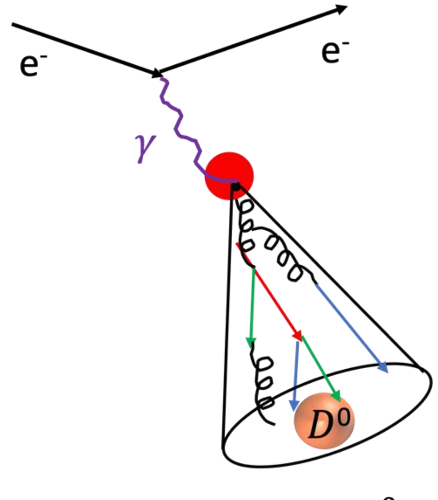
Charm baryon/meson ratios to access the hadronization process (II)

- 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

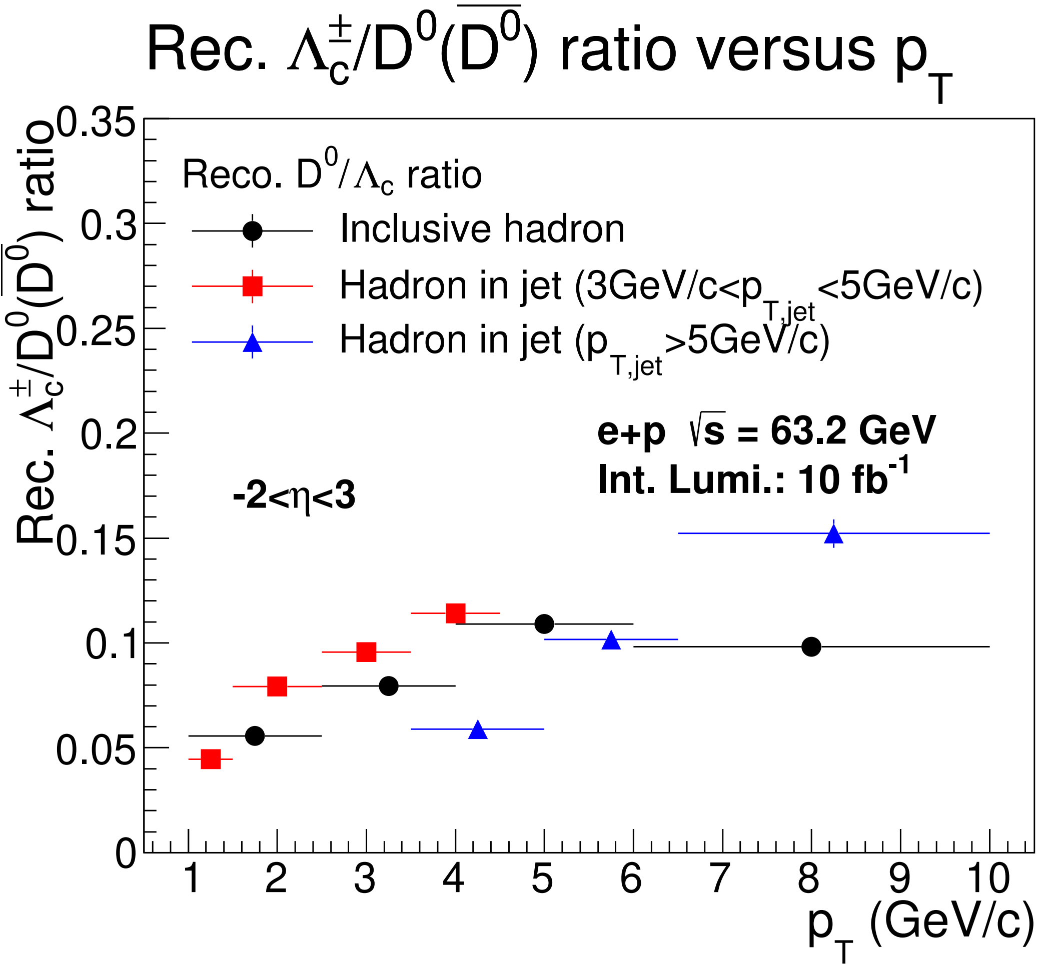
Reconstruction of charm hadrons inside jets with p_T 3-5 GeV/c



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

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.



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

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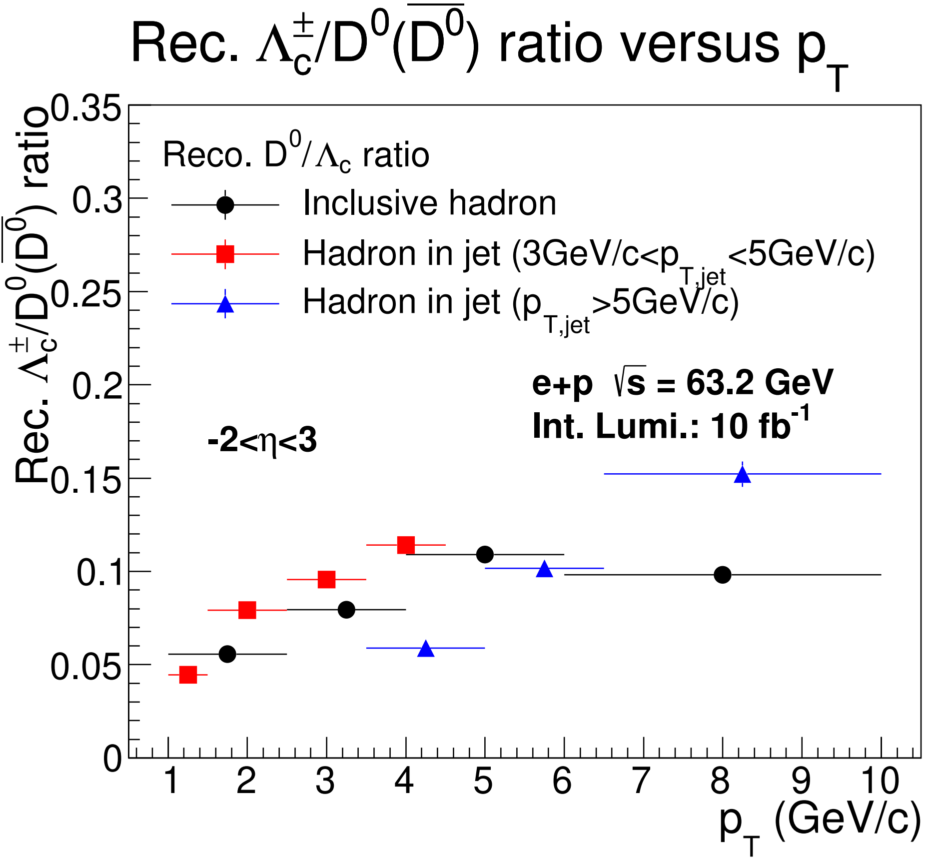
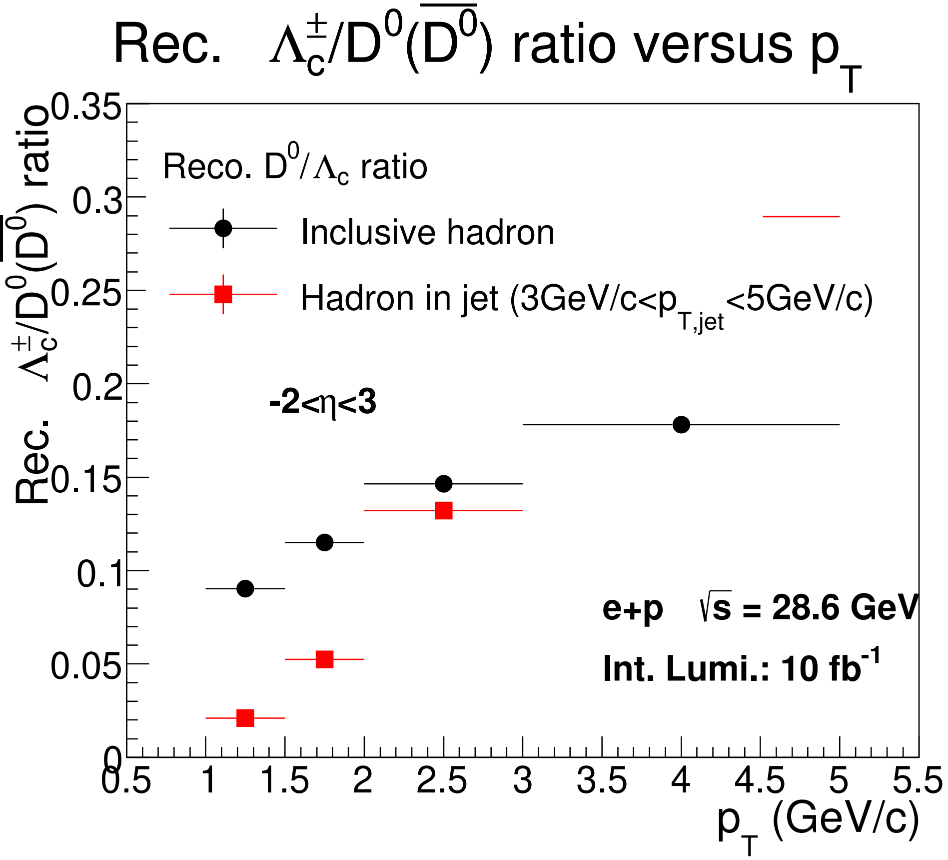


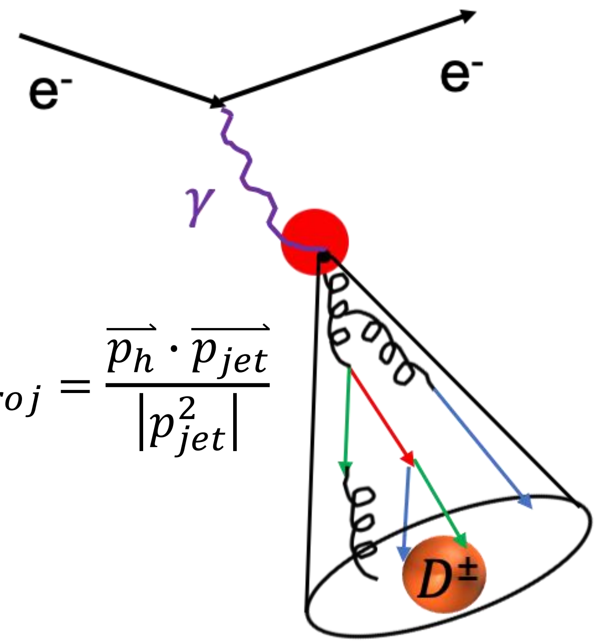


- Unique approach to explore the charm fragmentation function with different scaling factors and different medium conditions from heavy ion measurements.

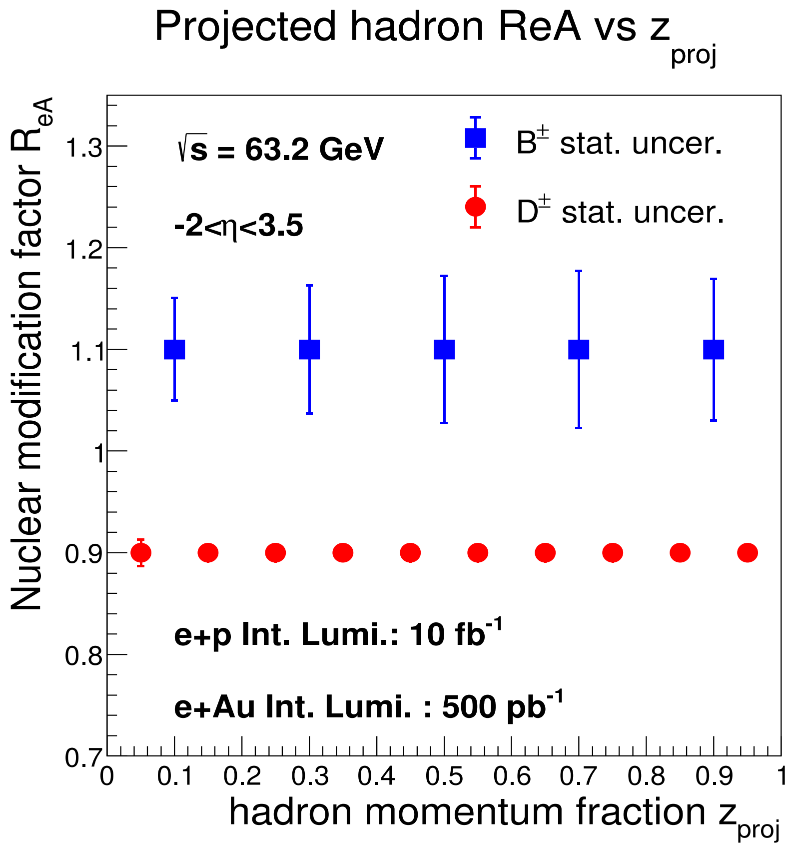
Heavy flavor hadron inside jet nuclear modification factor R_{eAu} projection

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

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



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



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

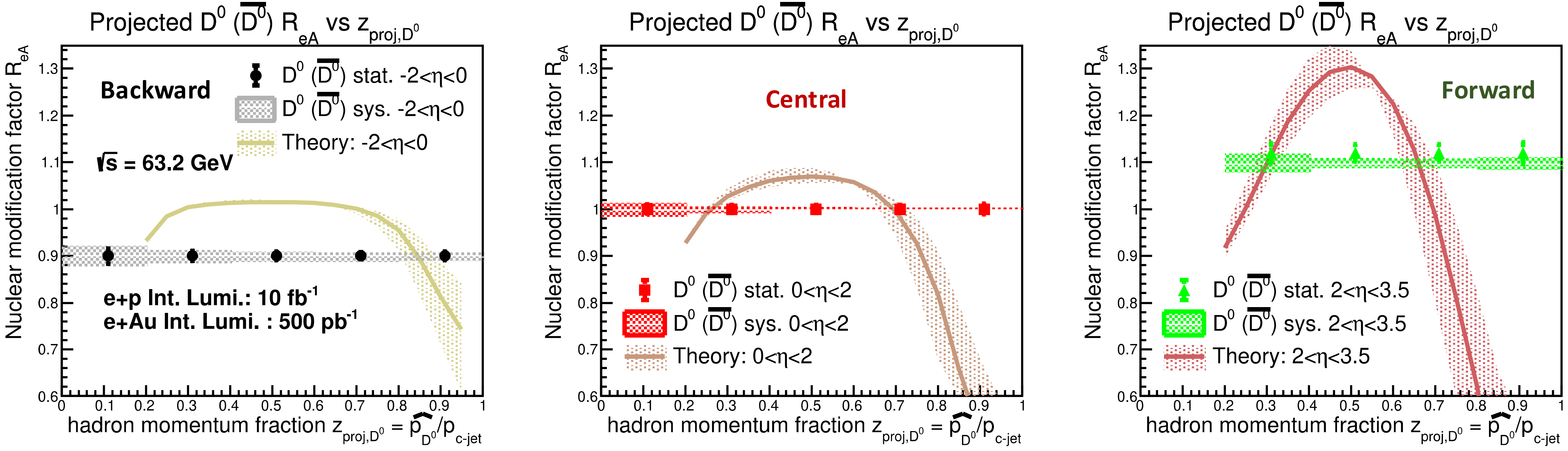
Great precision to be achieved by the EIC measurements in the accessed kinematic phase space.

- Future EIC heavy flavor inside jet measurements will provide great constraints in extracting charm/bottom fragmentation function 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 with around one-year EIC operation.

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



- 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.

Heavy flavor jet substructure (I)

- Jet substructure observables are good probes to study the parton showering/splitting and 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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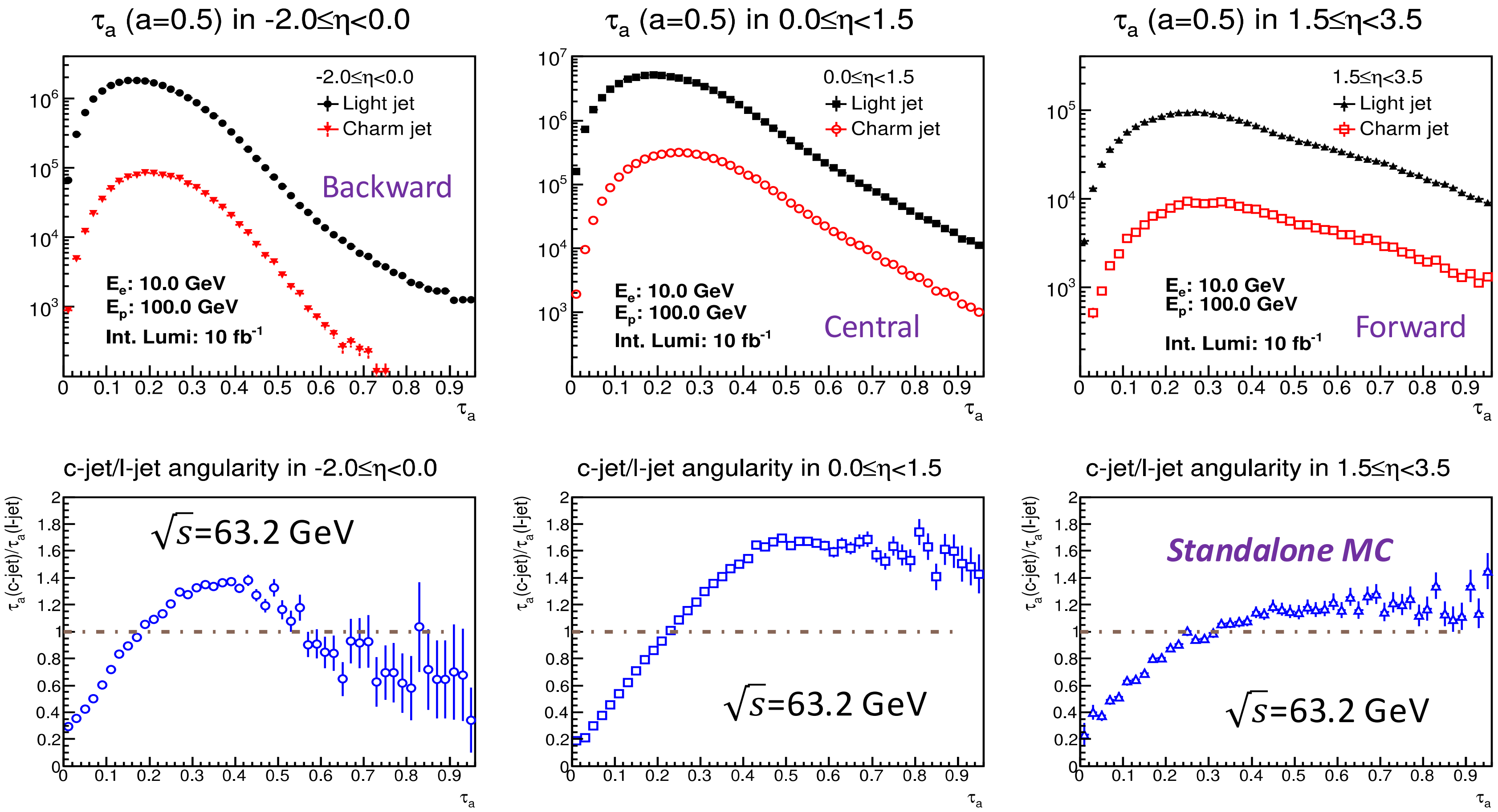

- The charm/light jet angularity shape difference depends on the pseudorapdy.

Heavy flavor jet substructure (II)

- Jet substructure observables are good probes to study the parton showering/splitting and 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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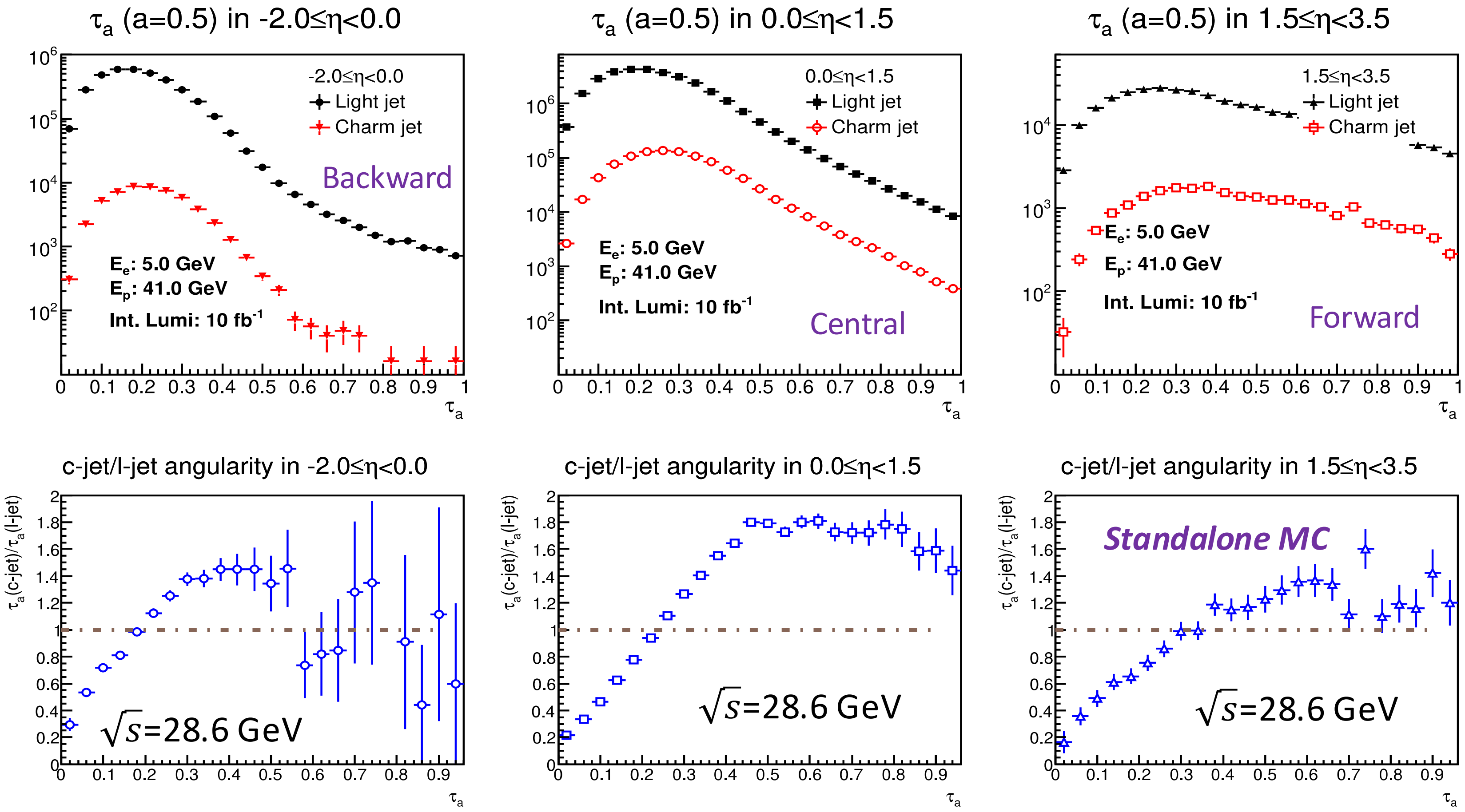
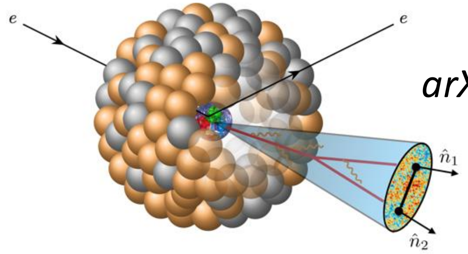


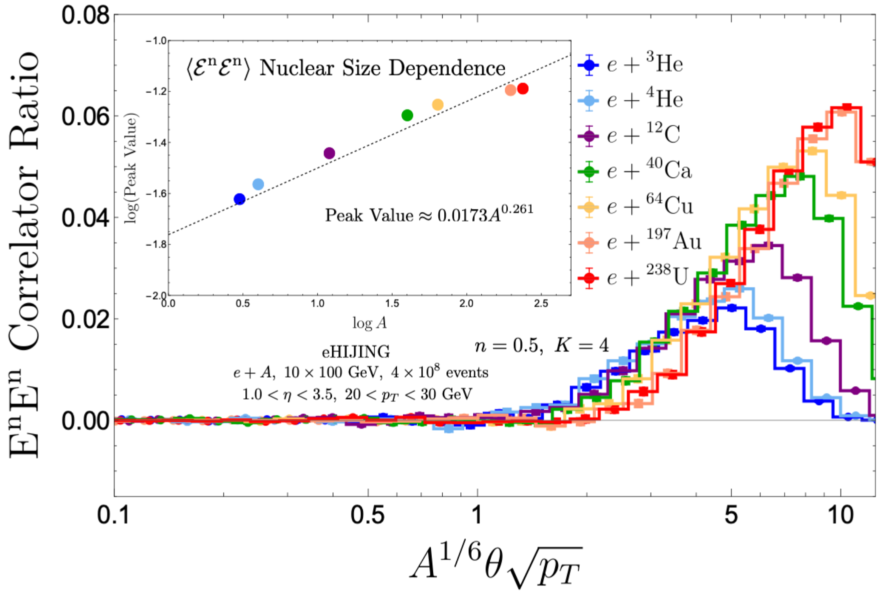
- The charm/light jet angularity shape difference depends on the pseudorapdy and less relies on $\sqrt{s}$.
- Shed light onto the process of parton splitting into final hadrons with different masses.
- Impacts by nuclear medium effects will be studied in e+A collisions.

Other interesting topics

Energy-Energy Correlator in inclusive jets in different e+A collisions

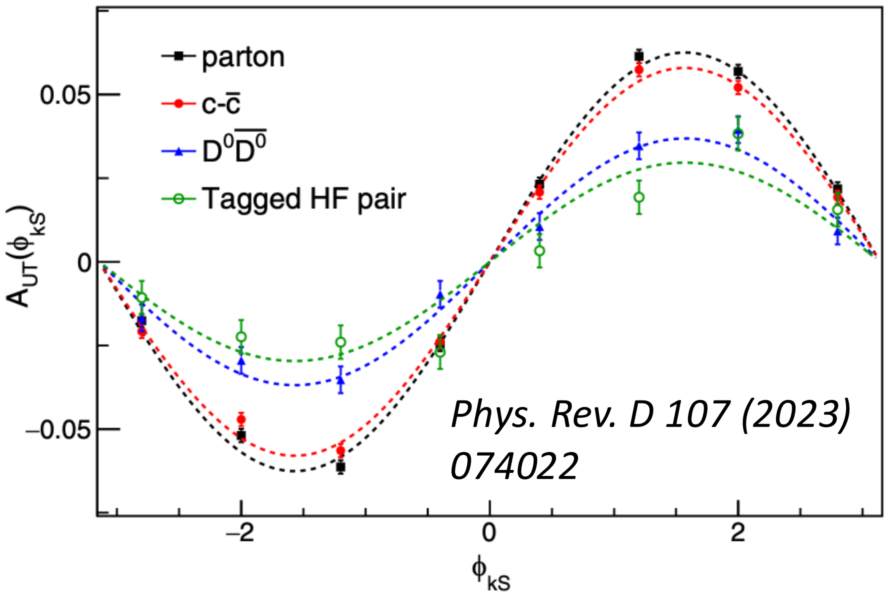


arXiv: 2303.08143



- Energy-energy correlator in heavy flavor jets at the EIC?

Projected transverse asymmetry A_{UT} for different charm correlation in 18+100 GeV e+p collisions



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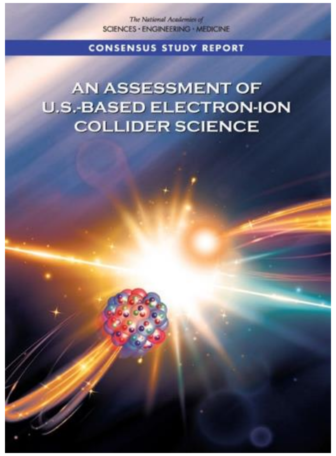
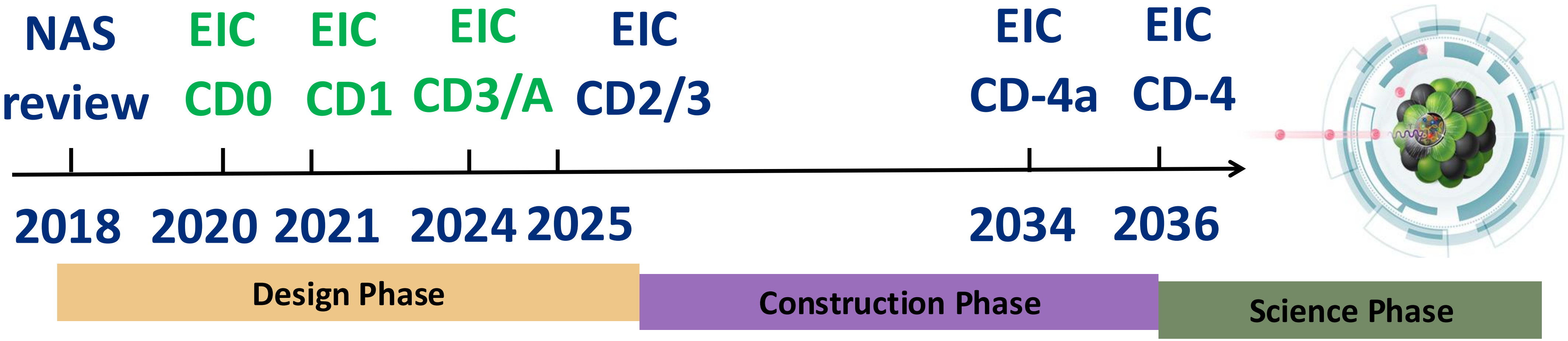
- Differential charm/bottom di-jet correlation studies to constrain the initial state effects?
- Additional heavy flavor observables to constrain the medium effects?

Summary and Outlook

- Great precision will be achieved by the 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 coverage.
- As we are moving towards the EIC construction in 2025, we look forward to work with more collaborators for the EIC detector/experiment realization.



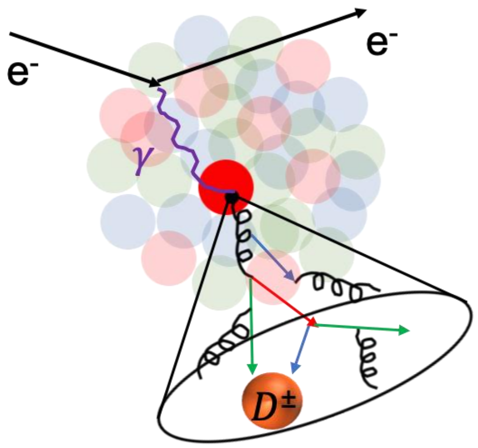


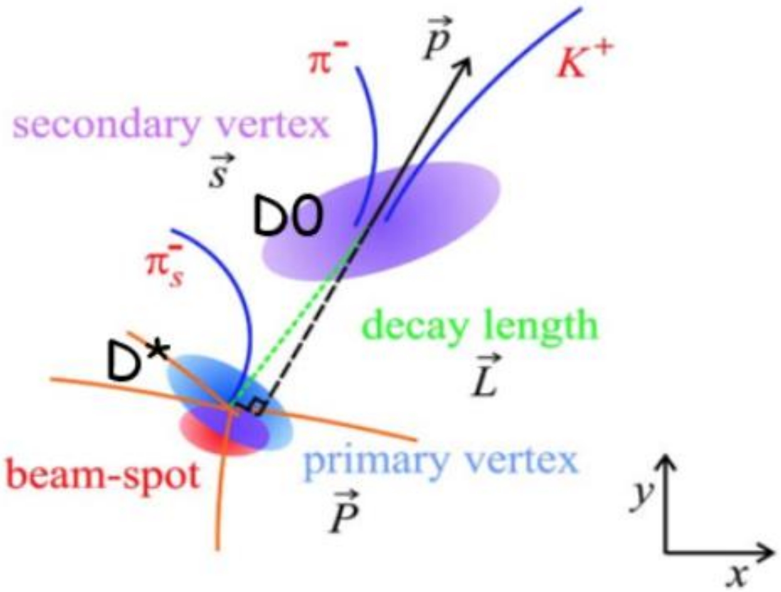
Backup

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.

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



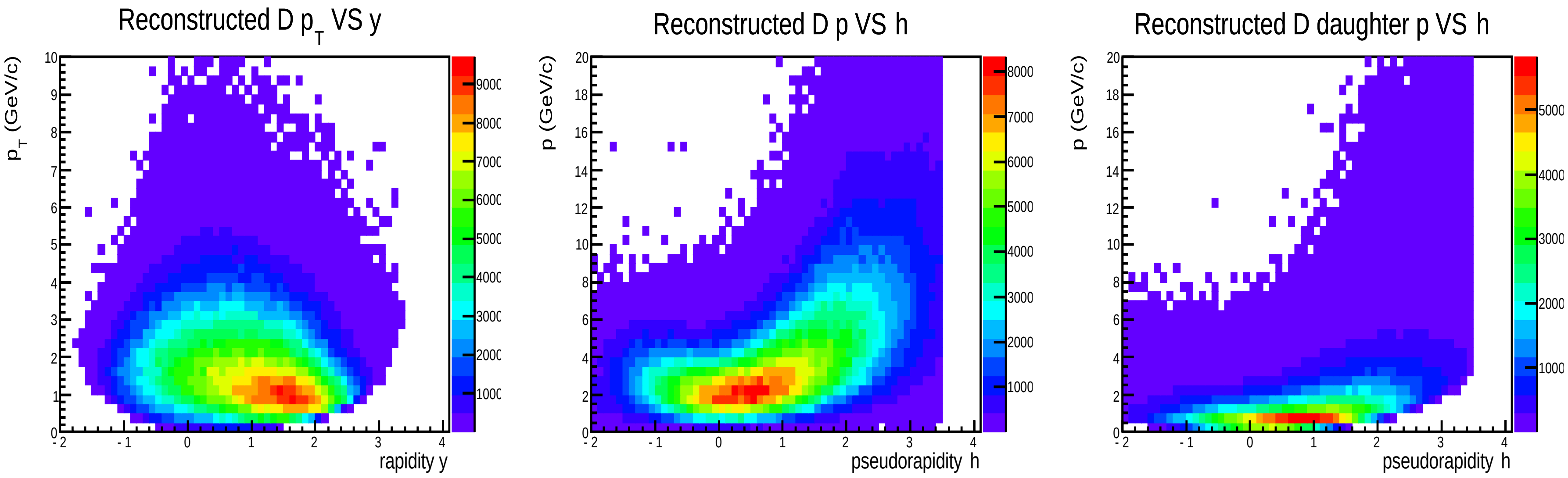


Particle	Mass (GeV/c²)	Average decay length
$D^{\pm}$	1.869	312 micron
D^0	1.864	123 micron
$B^{\pm}$	5.279	491 micron
B^0	5.280	456 micron

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

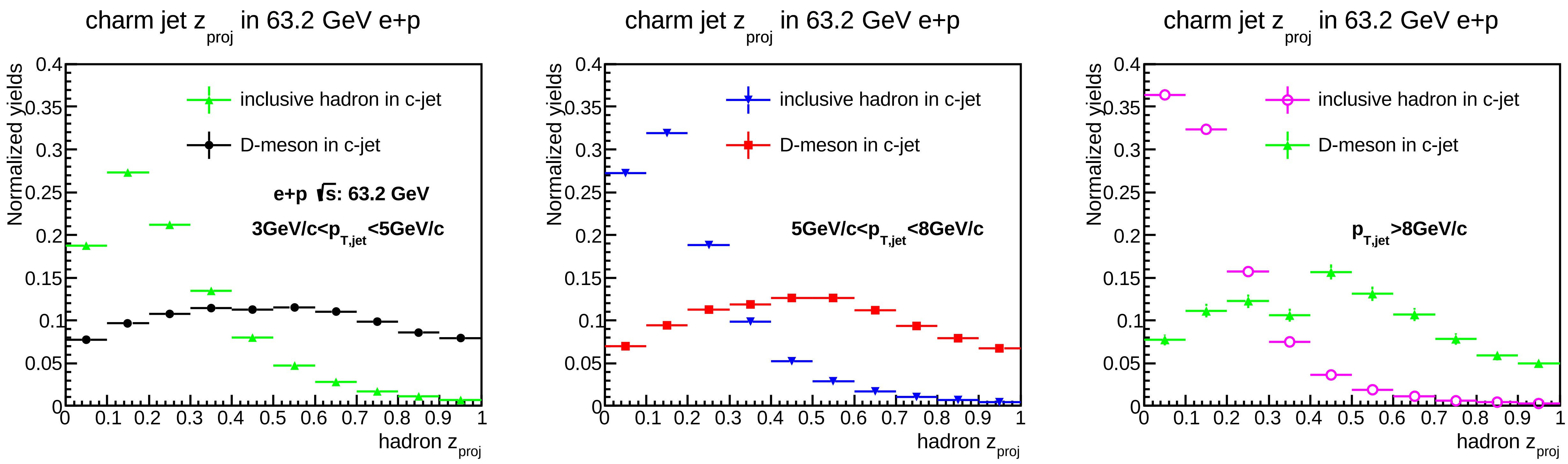
- To meet the heavy flavor physics measurements, a silicon vertex/tracking detector with low material budgets and fine spatial resolution is needed.
- Particles produced in the asymmetric electron+proton and electron+nucleus collisions have a higher production rate in the forward pseudorapidity. The 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.

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.

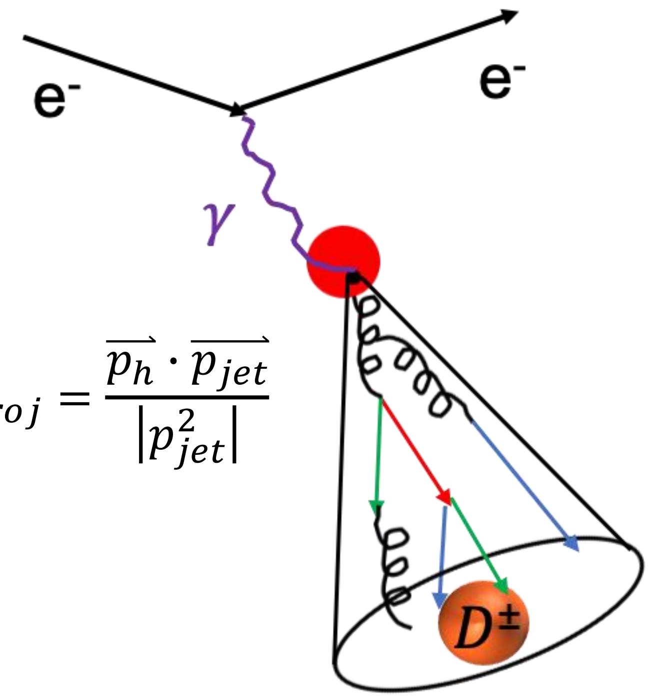


- The hadron inside charm jet z_{proj} distributions depend on the hadron flavor and jet p_T. Further studies in different e+A collisions will help explore the flavor dependent hadronization process under different medium conditions.

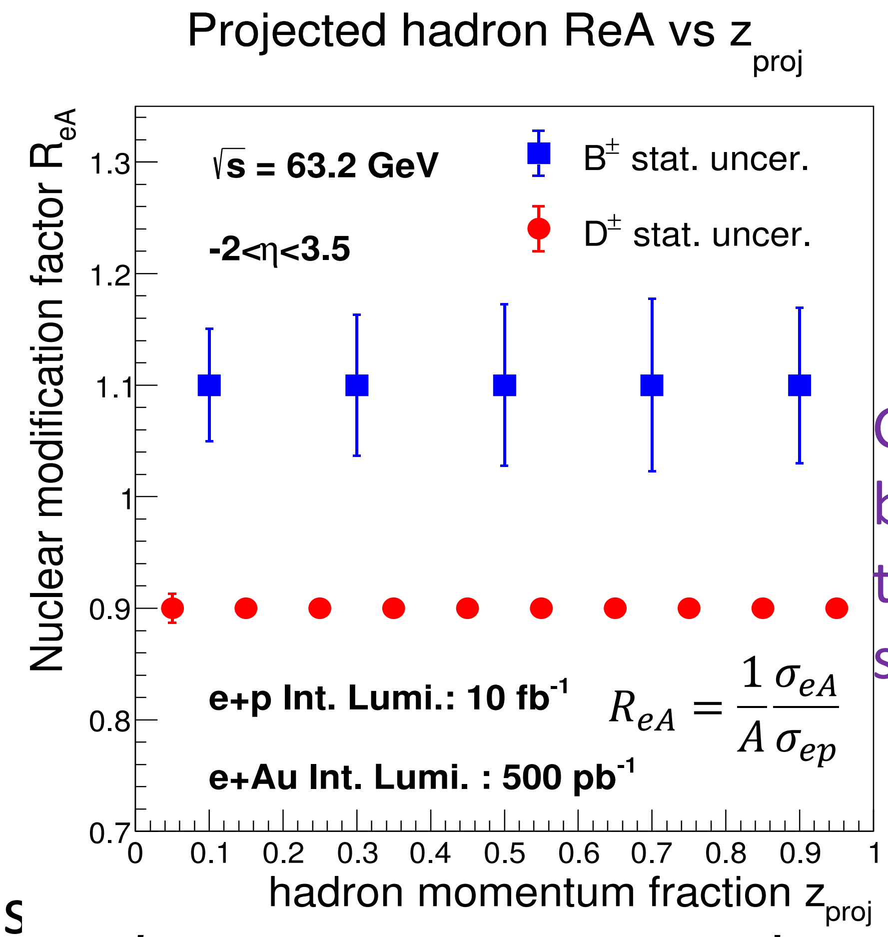
Heavy flavor hadron inside jet nuclear modification factor R_{eAu} projection

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

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



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



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

- Future EIC heavy flavor ins … e great constraints in extracting charm/bottom fragmentation function under different medium conditions.