Heavy-Flavor Studies with the ePIC Experiment at the Electron–Ion Collider

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INFN Bari, Italy

33rd International Workshop on Deep Inelastic Scattering and Related Subjects, Bologna, Italy

Supported by The FAIR Spoke 6 Project, funded by the NextGenerationEU program in Italy

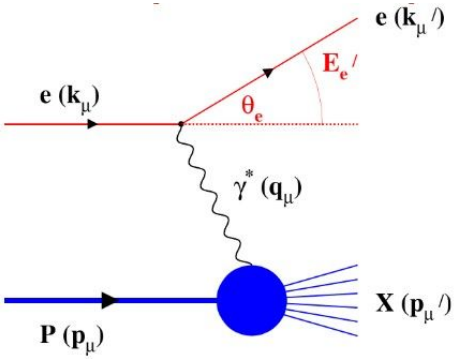
Electron-Ion Collider (EIC)

Why Electron-Ion Collider?

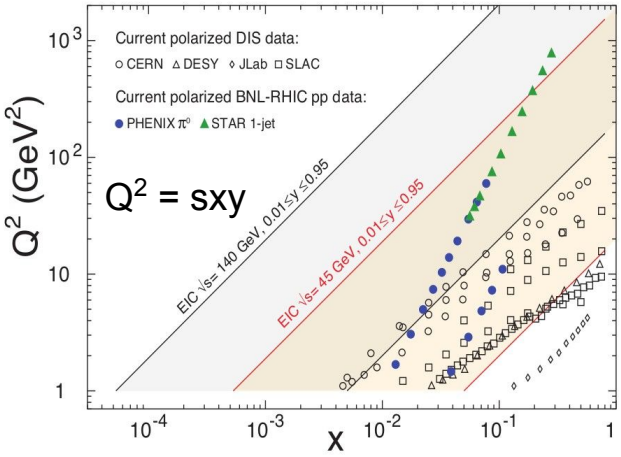
- ➔ **Electron:** Electroweak interaction through Deep Inelastic Scattering (DIS)
- ➔ **Ion:** Polarized protons and light ions to study spin/structure physics
- ➔ **Collider:** Variable center-of-mass energies ($\sqrt{s}$) to achieve wide x_B and Q^2 range to probe extreme gluon density regime

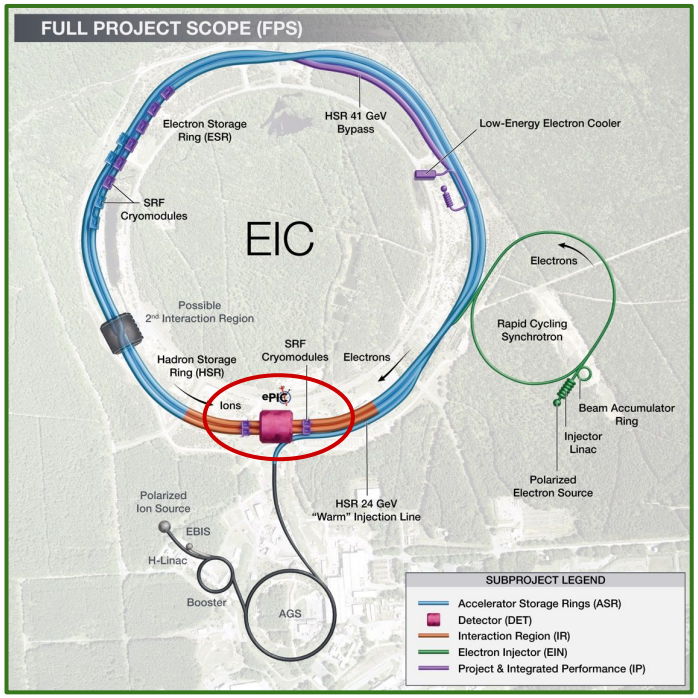
Nucl. Phys. A 1026 (2022) 122447 (**EIC Yellow Report**)

DIS Process



Wide x and Q^2 range





ePIC: electron-Proton/Ion Collider

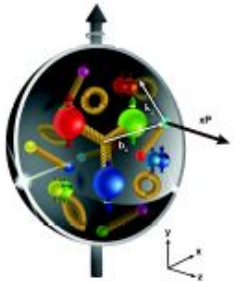
EIC machine @BNL
using RHIC tunnel and RHIC p/A complex

Physics Programs with the ePIC!

Nucl. Phys. A 1026 (2022) 122447

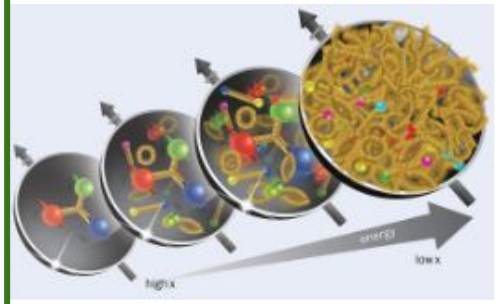
Origin of the proton's spin from fundamental constituents

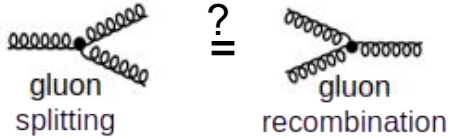
Origin of the proton's mass from fundamental constituents



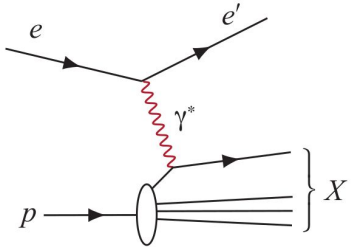
3D imaging of the proton in spatial and momentum space

Hadronization and it's modification in the nuclear medium



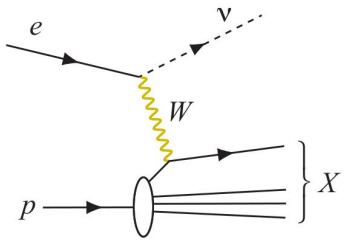


Gluon saturation



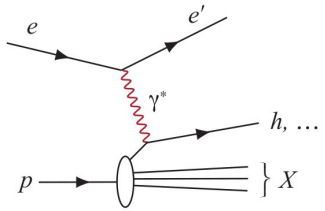
Neutral Current DIS

$\mathcal{L}_{int}$ ~ 1 fb^{-1}



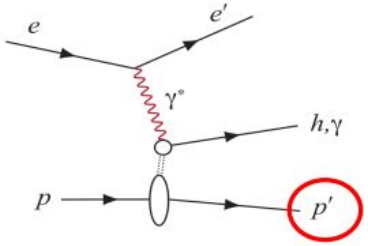
Charged Current DIS

$\mathcal{L}_{int}$ ~ 1 fb^{-1}



Semi-inclusive DIS

$\mathcal{L}_{int}$ ~ 10 fb^{-1}

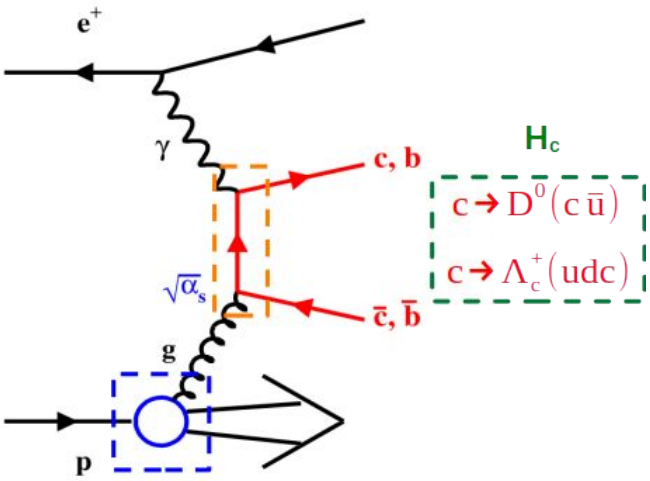


Exclusive process

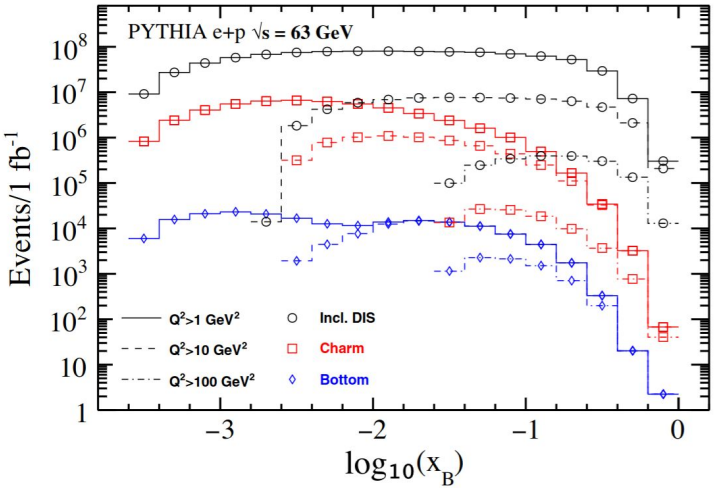
$\mathcal{L}_{int}$ ~ 100 fb^{-1}

Heavy-Flavor (HF) Production

https://doi.org/10.1016/j.ppnp.2015.06.002



PRD104,054002(2021)



Heavy flavor production over a wide x_B region

Charm production → Probes gluon distributions

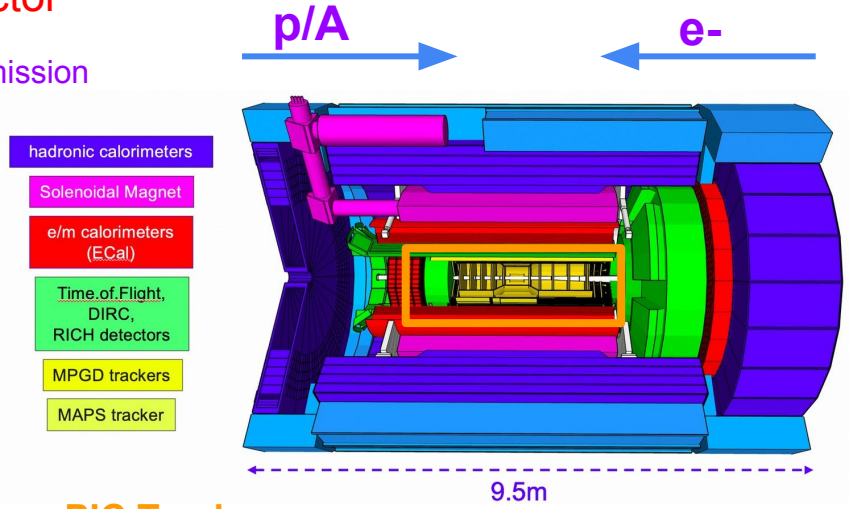
- Main production processes:
  - Photon-Gluon Fusion (PGF) $(\gamma^* + g \rightarrow q + \bar{q})$
  - Leading order DIS $(\gamma^* + q \rightarrow q)$
  - QCD compton scattering $(\gamma^* + q \rightarrow q + g)$

- Hadronization in e+p and e+A collisions
  - R_{eA} vs p_T, x_B, and z
  - Hadronization in cold nuclear matter (CNM)

ePIC Detector

Nucl. Phys. A 1026 (2022) 122447

- ePIC detector exploiting modern technologies to fulfill scientific mission
- 65 nm MAPS technology: **Precise tracking and vertexing**
- AC-LGAD sensors for time-of-flight: **Particle identification**
- MPGD tracker with fast timing: **Tracking with timing**
- DIRC/pfRICH and dRICH: **Particle identification**
- Solenoid magnetic field of 1.7 T
- Wide acceptance (|η| < 3.5)
- Excellent tracking, calorimetry, and particle identification
- Excellent pointing resolution design

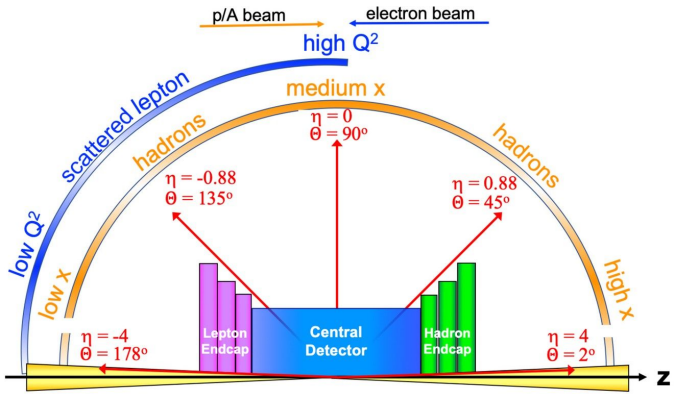


ePIC Tracker

|η|	$\sigma(DCA_{xy})$ μm
0.0–1.0	$20/p_T \oplus 5$
1.0–2.5	$30/p_T \oplus 20$
2.5–3.5	$30/p_T \oplus 40$

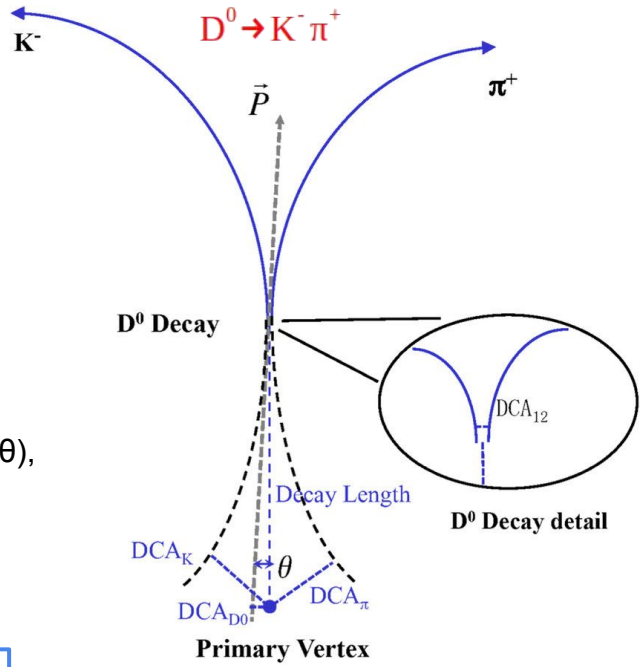
See ePIC dedicated plenary talk by J. Lajoie tomorrow:

EIC: physics, status and perspectives



Reconstruction of D^0 meson

Phys. Rev. C 102, 014905 (2020)



- **Primary Vertex (PV) Reconstruction:**
  - IterativeVertexFinder (IVF) algorithm using ACTS software
  - Allows access to DCA of daughter tracks with respect to Primary Vertex
- **Secondary Vertex (SV) Reconstruction:**
  - Reconstruction of decay vertex position of D^0 ($K^-\pi^+$)
  - Helix swimming, χ^2 minimization algorithms
  - Access to key topological variables e.g., decay length, pointing angle (cosθ), DCA_{D0} , DCA_{12} etc.

Topological Variables

$$\vec{dl} = \vec{SV} - \vec{PV}$$

$$\cos\theta = \frac{\vec{dl} \cdot \vec{p_{D0}}}{|\vec{dl}||\vec{p_{D0}}|}$$

$$DCA_{D0} = |\vec{dl}| \sin\theta$$

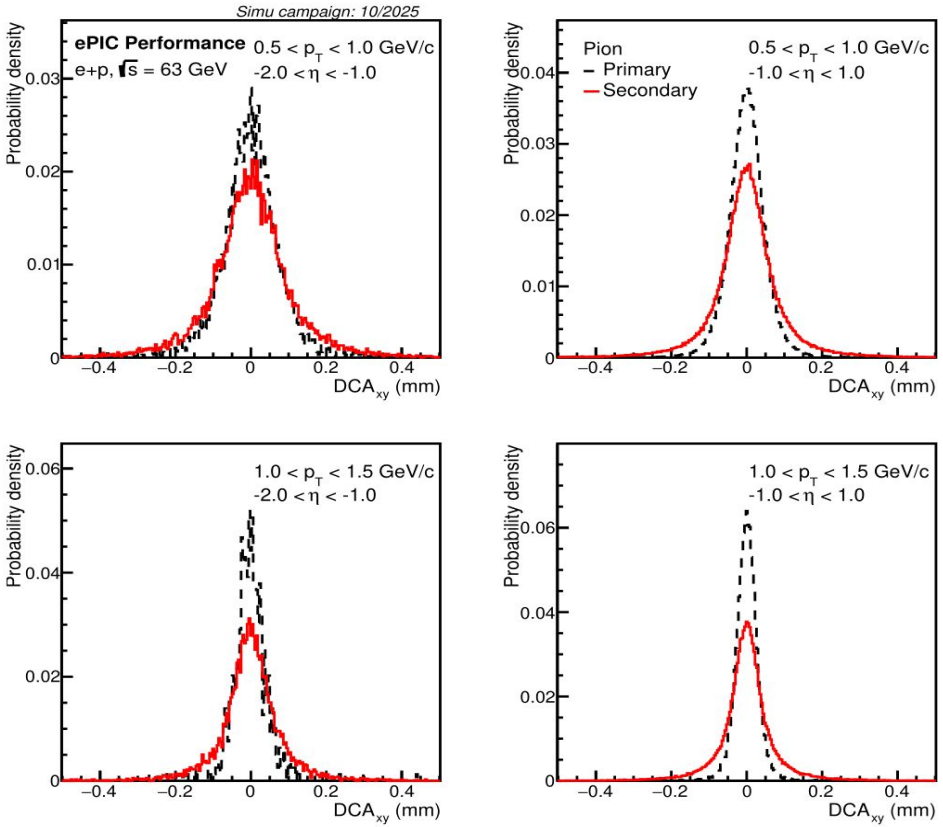
Invariant mass

$$m_{D^0} = \sqrt{(E_{K^-} + E_{\pi^+})^2 - (\vec{p_{K^-}} + \vec{p_{\pi^+}})^2}$$

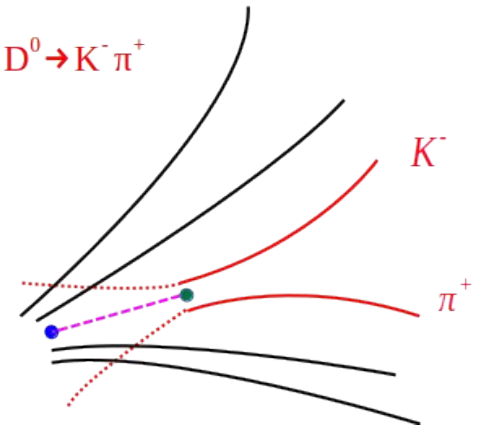
Reconstruction of D^0 mesons relies on their displaced decay topology

Transverse DCA Distribution

DCA_{xy} distribution relative to MC collision vertex for reconstructed **Primary** and **Secondary** (from D^0 decay) pions



Simulation sample: e+p, $Q^2 > 1\ GeV^2$

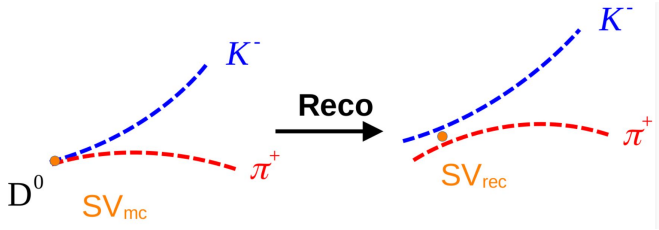


MC collision vertex MC decay vertex (D^0)

Broader DCA_{xy} for secondary pions from D^0 meson due to their displaced decay topology ($c\tau$ = 123 μm)

Secondary Vertexing

Simulation sample: e+p, $Q^2 > 1\ GeV^2$

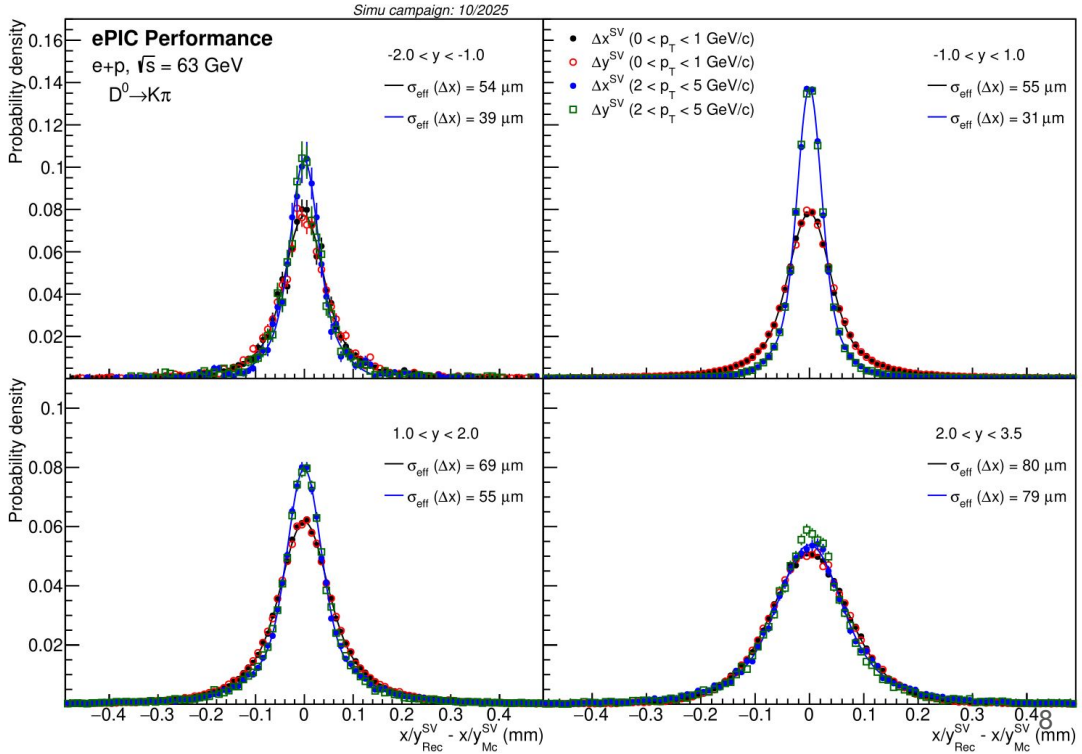


Two Gaussian (A_{core}, σ_{core}, A_{tail}, σ_{tail})

$$\sigma_{eff} = \sqrt{\frac{A_{core}}{(A_{core}+A_{tail})}\sigma_{core}^2 + \frac{A_{tail}}{(A_{core}+A_{tail})}\sigma_{tail}^2}$$

- Resolution improves with p_T
- Best resolution is achieved at mid-rapidity and high transverse momentum, where DCA resolution is optimal

Secondary vertex using χ^2 minimization
Vertex reconstruction using two tracks (daughters)



Invariant Mass Reconstruction of D^0 meson

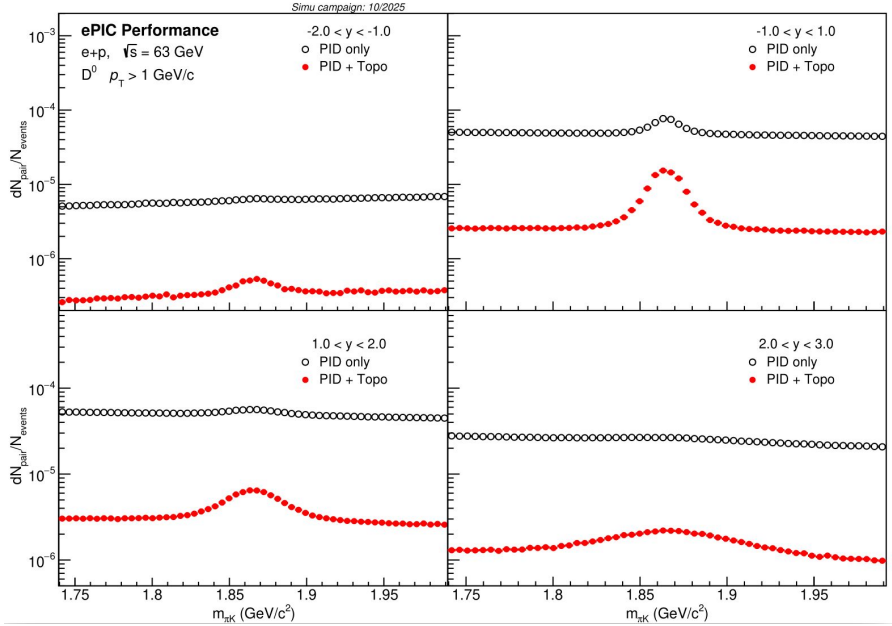
- D^0 meson reconstruction (e+p and e+Au collisions, $Q^2 > 1$ GeV^2)
  - Using only Particle Identification (**PID**)
  - PID + Topolgical selection based on machine learning (ML) (**PID + Topo**)
  - Significant suppression of combinatorial background using ML

ML Framework

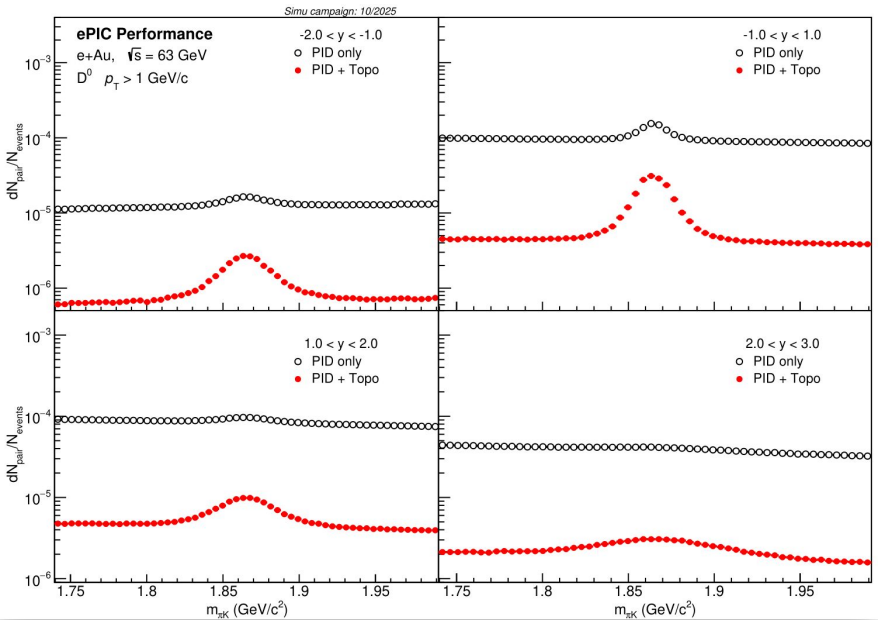
BDT Binary classifier

BDT threshold > 0.75 based on significance optimization

e+p collisions, $Q^2 > 1$ GeV^2



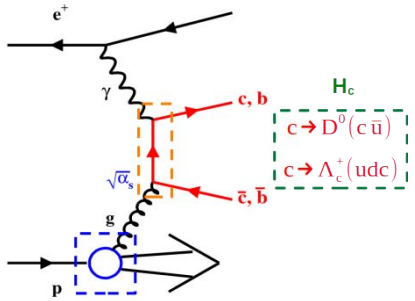
e+Au collisions, $Q^2 > 1$ GeV^2



Hadronization and Parton Propagation in Nuclear Matter

QCD factorization approach (PGF) in e+p collisions

$$d\sigma^{PGF}_{\gamma p \to H_c X} = F_{g/p} \otimes d\sigma_{\gamma g \to c\bar{c}} \otimes D_{c \to H_c}$$



$F_{g/p}$ (x, μ^2): Parton Distribution Function (PDF)

dσ: Hard parton scattering cross section for PGF

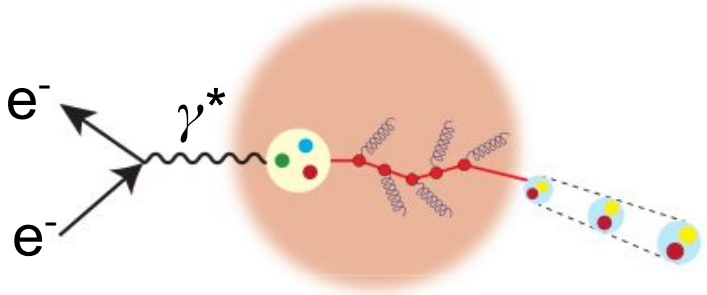
$D_{c->Hc}$ (z, μ^2): Fragmentation function (Hadronization)

z: Fragmentation variable

- e+A Collisions
  - Heavy-flavor hadrochemistry (ratios of different hadrons)
  - R_{eA} vs p_T: Collisional and radiative energy loss
  - R_{eA} vs z: Modified fragmentation in nuclear matter
  - R_{eA} vs x_B: nuclear parton distribution function (nPDF)

Comparison between e+p and e+A collisions

Parton energy loss
(Collisional+Radiative)

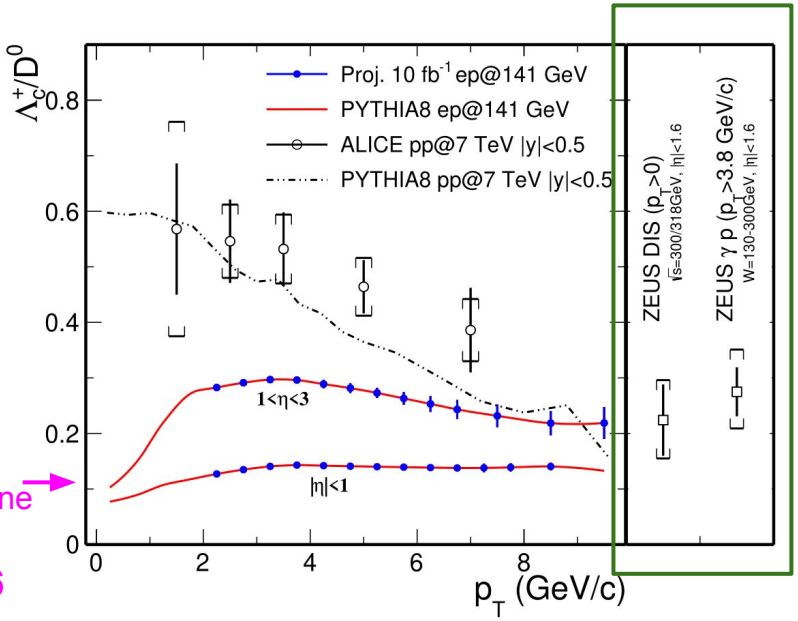


Charm-quark Hadronization

- Hadronization in e+p collisions
  - Λ_c^+/D^0 ratio has been measured in e^+e^- , ep, and pp collisions
  - Violation of universality of fragmentation function ($D_{c->Hc}$ (z, μ^2))?
  - Study from ZEUS in an integrated p_T bin (large errors)
  - Thanks to high-luminosity and wide acceptance of the ePIC:

    p_T and pseudorapidity (η) differential study
- Hadronisation in e+A collisions
  - Variety of colliding nuclei (d, Cu, Ag, Au, etc.)
  - Impact of cold nuclear matter on hadronization

arXiv:2102.08337 [nucl-ex]



e^+e^- fragmentation baseline

$0.113 \pm 0.013 \pm 0.006$

LEP average, EPJC 75, 19 (2015)

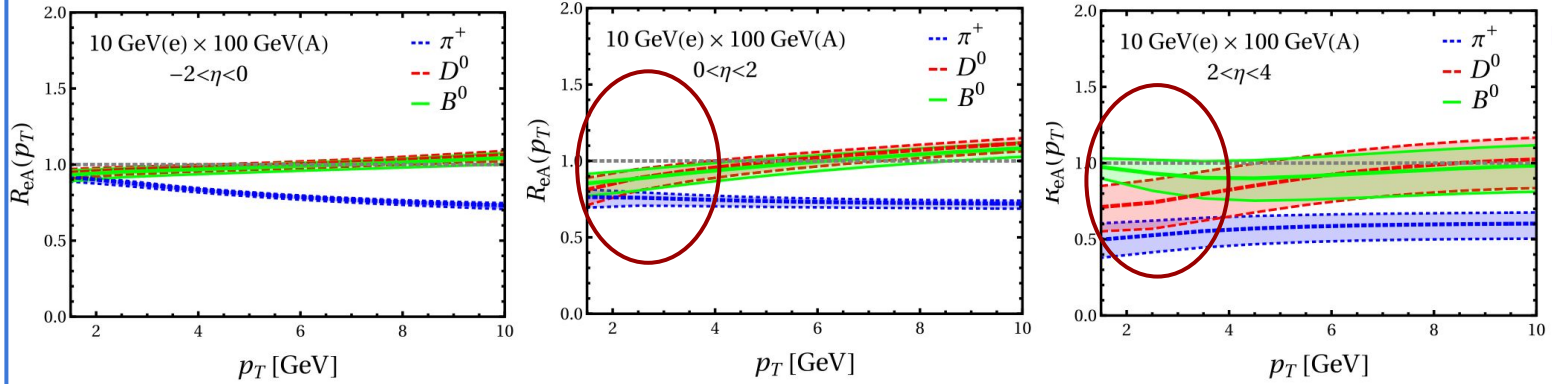
Further look at the performance with full simulations including machine backgrounds

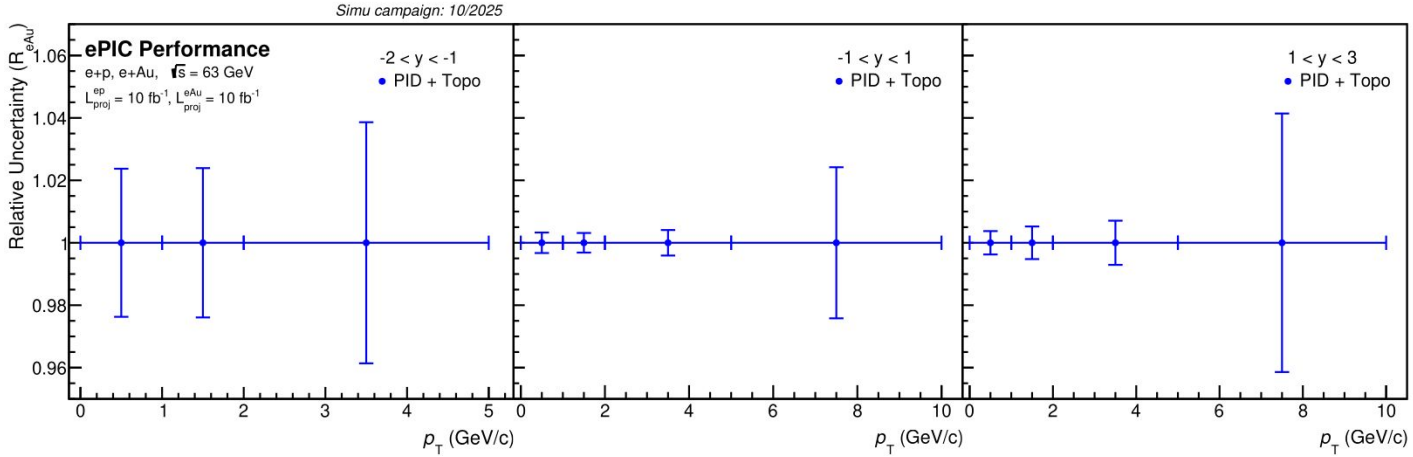
Propagation of Parton through Nuclear Matter

Physics Letters B 816 (2021) 136261

$$R_{eA}(p_T, z, \nu) = \frac{N^{D0}(p_T, z, \nu)_{eAu}}{N^{D0}(p_T, z, \nu)_{ep}} \times \frac{N^{inc}(\nu)_{ep}}{N^{inc}(\nu)_{eAu}}$$

Minimize initial state effect





Excellent statistical precision to study cold nuclear matter effects!

Propagation of Parton through Nuclear Matter

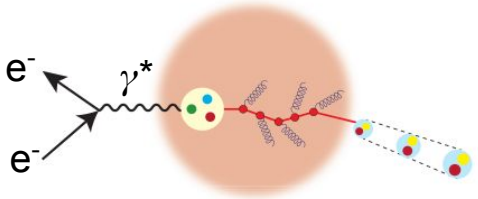
Physics Letters B 816 (2021) 136261

$$R_{eA}(p_T, z, \nu) = \frac{N^{D0}(p_T, z, \nu)_{eAu}}{N^{D0}(p_T, z, \nu)_{ep}} \times \frac{N^{inc}(\nu)_{ep}}{N^{inc}(\nu)_{eAu}}$$

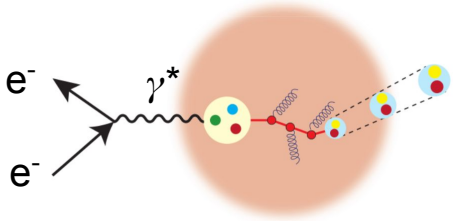
ν: Virtual photon energy

z: fragmentation variable

Large ν

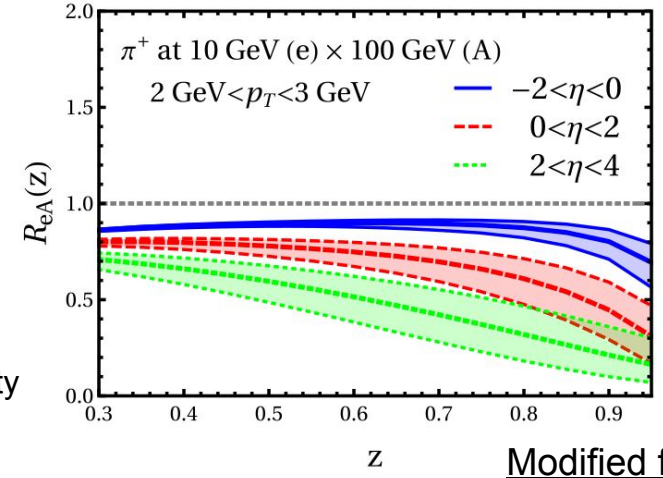


Small ν

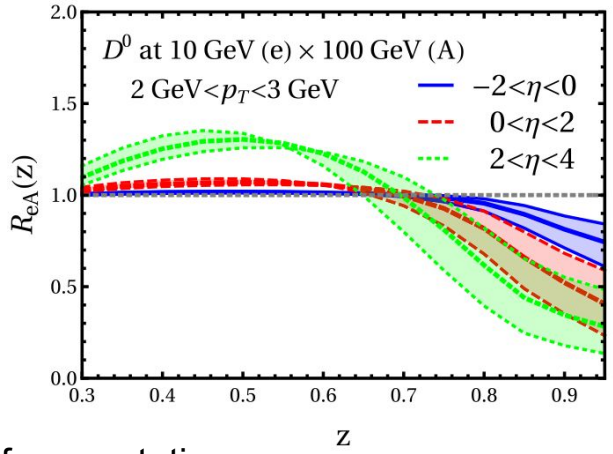


Minimize initial state effect

Light flavor



Heavy flavor



Modified fragmentation

Light hadron (π^+):

- Suppression at all z and rapidities

Heavy hadron (D^0):

- Enhancement at low–moderate z

  while suppression at large z

- Effect more visible at forward rapidity

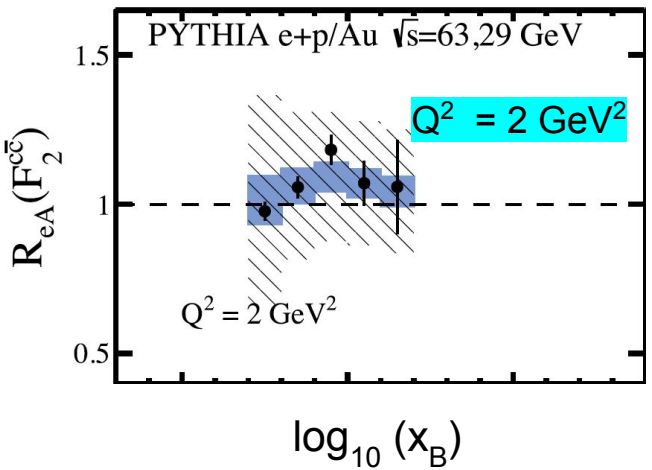
Nuclear Parton Distribution Function (nPDF)

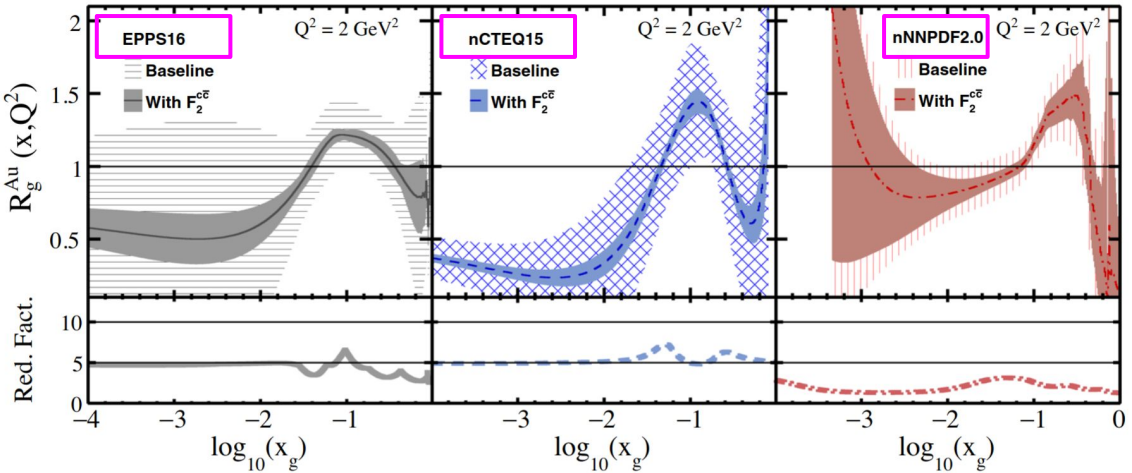
PGF: Impact on constraining gluon distributions

Reduced charm cross section

$$\sigma_r^{c\bar{c}}(x_B, Q^2) = F_2^{c\bar{c}}(x_B, Q^2) - \frac{y^2}{Y^+} F_L^{c\bar{c}}(x_B, Q^2)$$

M. Kelsey, et. al., PRD 104 (2021) 054002



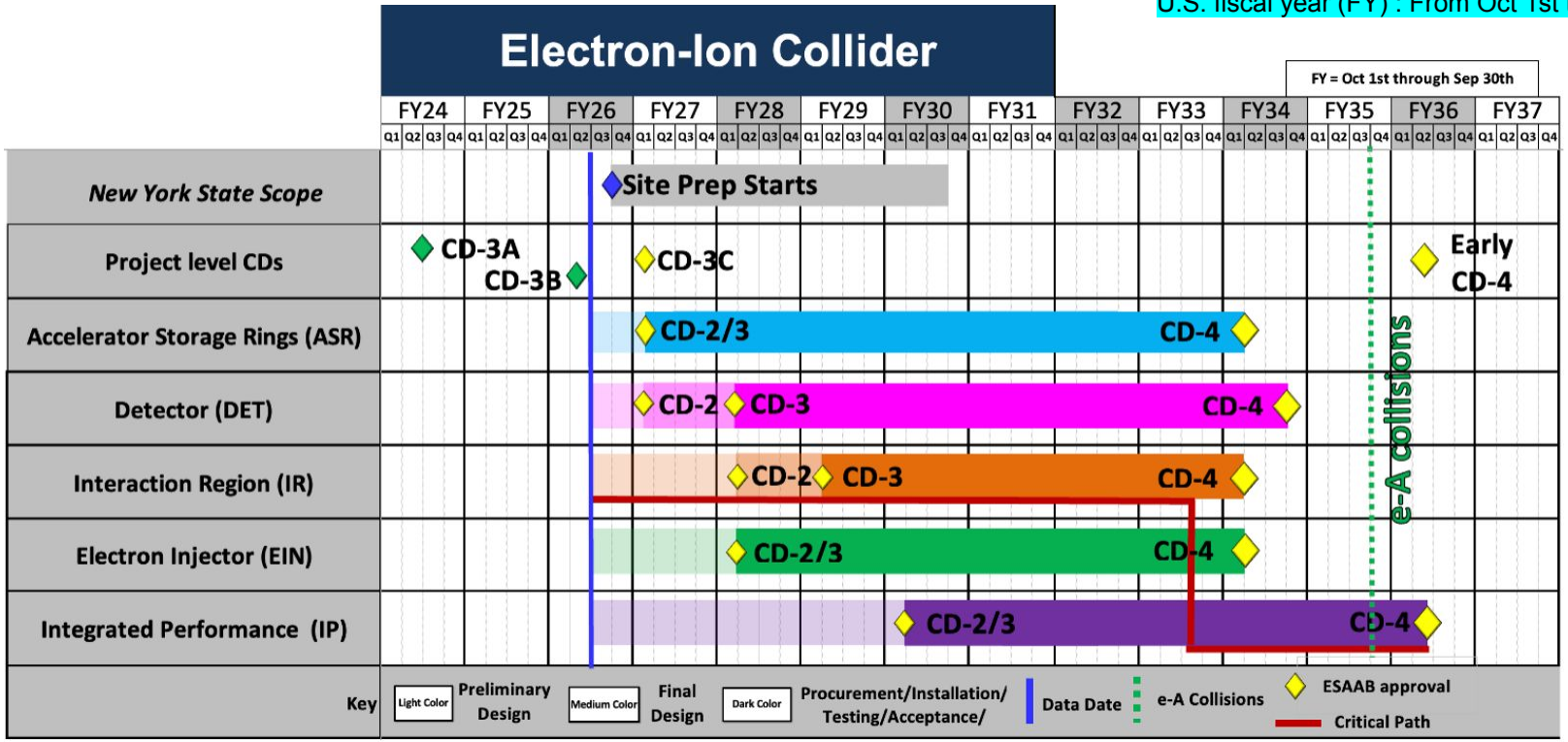


- Significant reduction in the uncertainties on nPDF using charm from low to high X_B
- Further use the full simulation with machine backgrounds to study the constraining power!

Status and Timeline of the EIC Project

- RHIC operation ended on 6 February 2026, transition to the EIC era
- Site preparation begins in U.S. fiscal year (FY) 26 Q4 or early 2027
- **Critical Decision (CD-2/3 and CD-4)**: approval phases for major subsystems, such as **ASR**, **DET,** and **IR**
- **First eA collisions targeted around FY35**

U.S. fiscal year (FY) : From Oct 1st to 30 Sep



Summary and Future Perspective

- EIC will be the first polarized e+A collider with high-luminosity
- Advanced detector technologies and modern analysis techniques to achieve excellent performance
- Future perspective
  - Heavy-flavor hadron reconstruction performance
  - Study of Λ_c^+/D^0 ratio using full simulation
  - Look at performance with machine background
  - Study nuclear modification as a function of z and x_B using full simulation
  - Inclusive and HF-tagged jets in e+p and e+Au collisions

The EIC: a most powerful machine to study nuclear structure!

Thank you for your attention!