Physics Perspectives with the ePIC Tracker Performances

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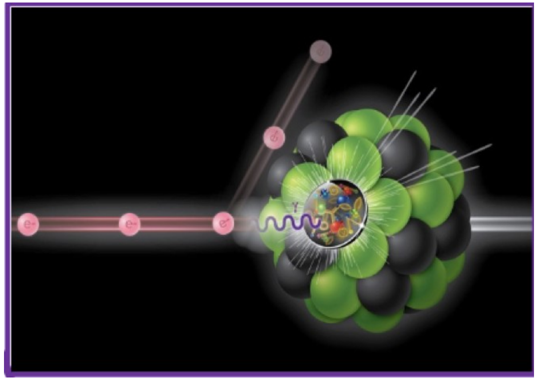
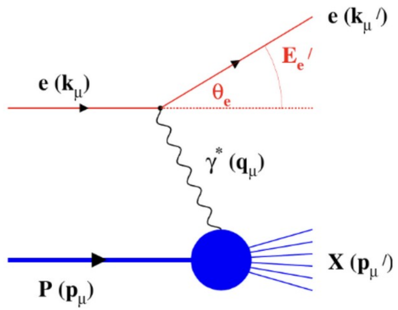
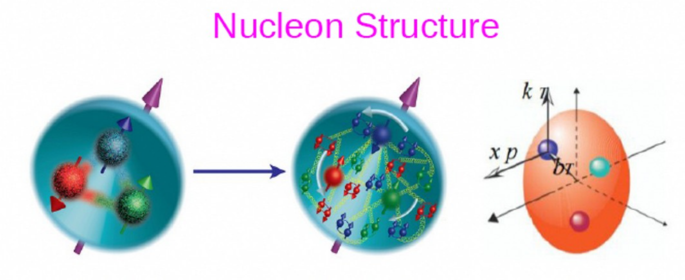
Physics Goals of the ePIC Experiment



Polarized ep and e-A collisions with a variable center-of-mass energies and high luminosities

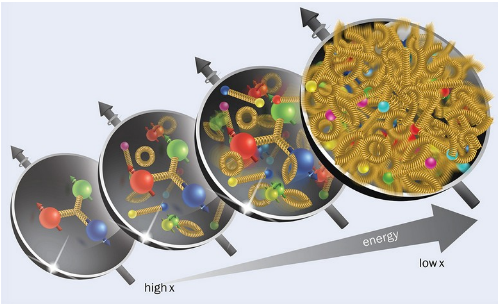




A selection on few topics:

Look into nucleons with high precision → 3D structure

- Investigate parton distributions of nucleons and nuclei
- Spin and flavour structure of nucleons and nuclei

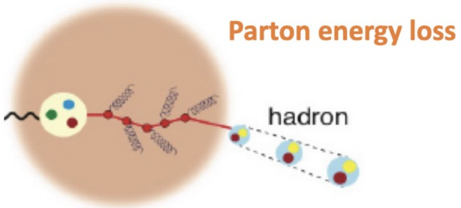


QCD at high parton density - gluon saturation

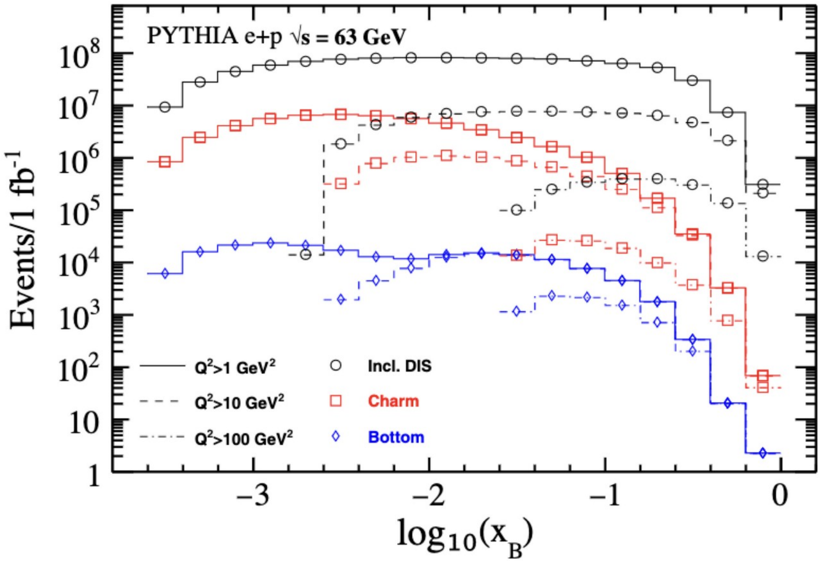
- nPDF in a wide range of Bjorken-x

Explore hadronization inside the vacuum/medium

Explore energy loss in CNM (Cold Nuclear Matter) effects

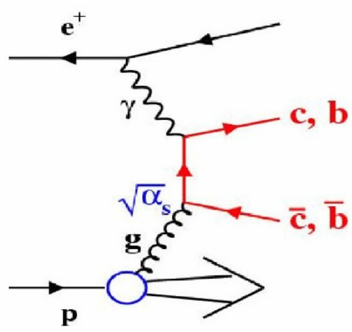


M. Kelsey et al. PRD104,054002(2021)



High c/b production over a wide range x_B

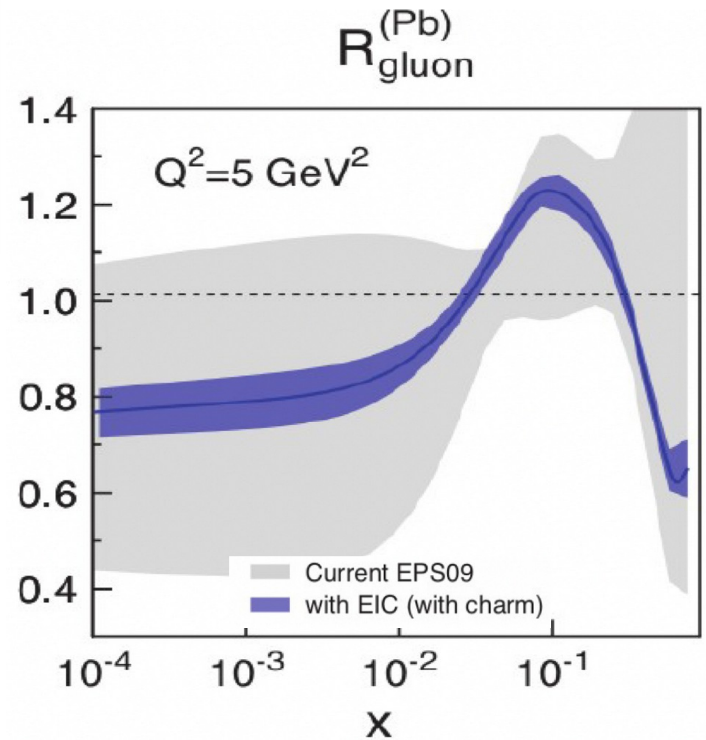
Photon gluon fusion



$$R_i^A(x,Q^2)=\frac{f_i^A(x,Q^2)}{f_i^p(x,Q^2)}$$

f_i^p (x, Q^2): pdf of proton

f_i^A (x, Q^2): pdf of nucleus



Heavy quark production in DIS: help to study gluon dynamics inside nucleon/nucleus

- gluon nPDF, gluon helicity, gluon TMD etc…

significant impact on the reduction of the gluon uncertainty band from high to low-x

Ref: A. Deshpande, Electron Ion Collider: The next QCD frontier Understanding the Glue that Binds Us All, COOL'15, Jefferson Lab, USA, 2015.

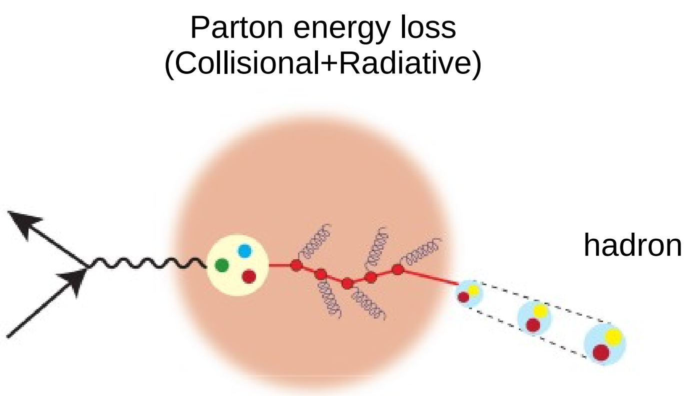
Emmanuel Sauvan, CPPM Marseille. H1 Report, DESY PRC 26/05/05
AIP Conf. Proc. 870, 432–435 (2006)
https://doi-org.ezproxy.cern.ch/10.1063/1.2402670

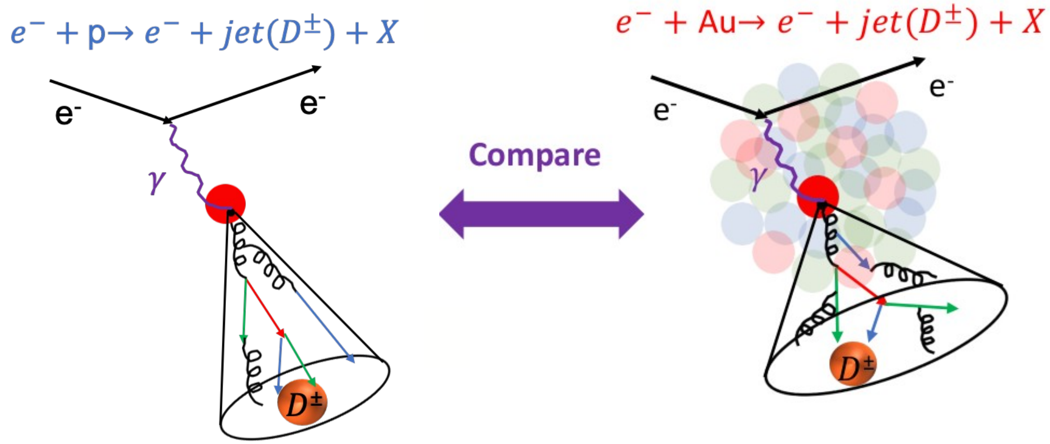
Precise heavy-flavour measurement at ePIC can further constrain nPDFs

Study hadronization scale and transport inside the nuclear medium

- R_{eA}: open charm hadrons (D mesons, Λ_c, etc…)

Comparison between ep and eA collisions





- Heavy-quark: propagation inside the “cold” nuclear matter
- Heavy-flavour hadrochemistry and collectivity:
  - ➔ **hadronization modification in cold-nuclear matter**

Nuclear modification factor: $$R_{eA} = \frac{\sigma_{eA}}{A \times \sigma_{ep}}$$

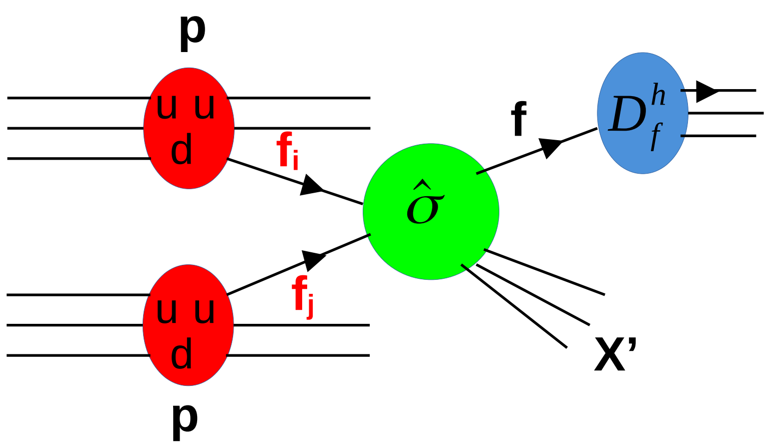
Fragmentation and Heavy-flavour jets

- Production of heavy-quark (charm, beauty) hadron can be calculated using factorization approach:

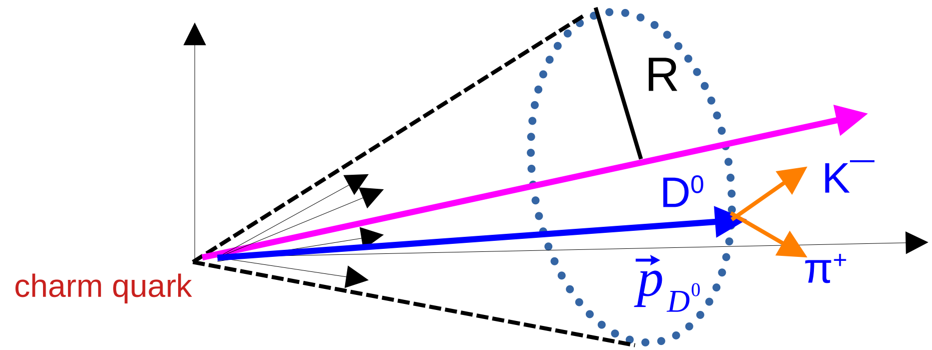
$z = p_{HQ}/p_Q$

$$\frac{d\sigma^{NN\to H_Q X}}{dp_T^{H_Q}}\left(\sqrt{s_{NN}}, M_Q, \mu_F^2, \mu_R^2\right) = \sum_{i,j=q,\bar{q},g} f_i(x_1,\mu_F^2)\otimes f_j(x_2,\mu_F^2)\otimes d\hat{\sigma}^{ij\to Q\bar{Q}}\left(\alpha_s(\mu_R^2),\mu_F^2,M_Q,x_1,x_2,s_{NN}\right)\otimes D_Q^{H_Q}(z,\mu_F^2)$$

Parton distribution functions **Hard Scattering Cross-section** **Fragmentation function**



z = $pD^0/p_{ch,jet}$ = proxy for $pD^0/p_{charm\ quark}$ = fraction of parton momentum carried by a hadron



S. Kumar* on behalf of the ALICE collaboration
https://doi.org/10.22323/1.449.0261

Fragmentation function:

- Probability that heavy-quark (Q) will hadronize in a heavy-flavour hadron (H_Q) with momentum fraction z
- Usually assumed to be **universal** and constrained from e^+e^- and ep collider data and used for other in different collision systems and energies

Jets containing charged particles and prompt D^0 mesons ($p_{ch\ jet}$)

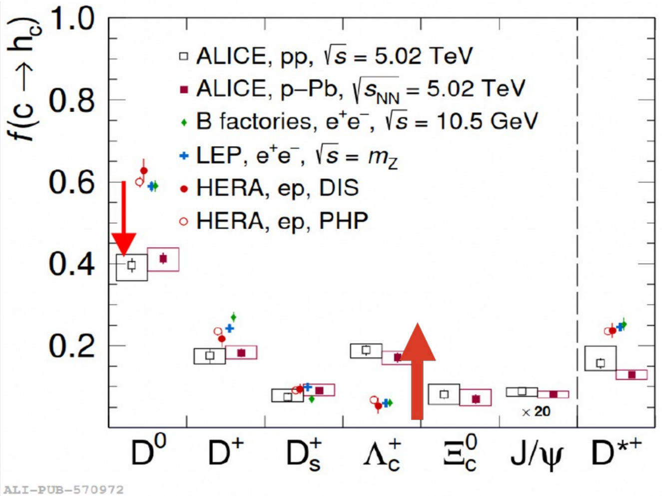
Important to study heavy-flavour jets

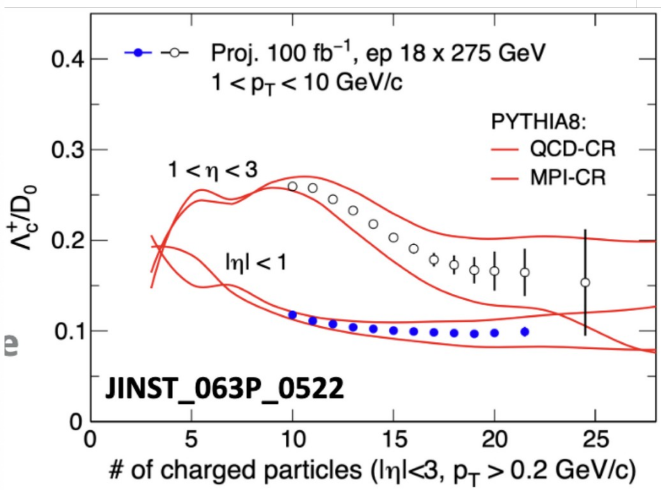
More hints on Hadronization: heavy-flavour baryon over meson ratios

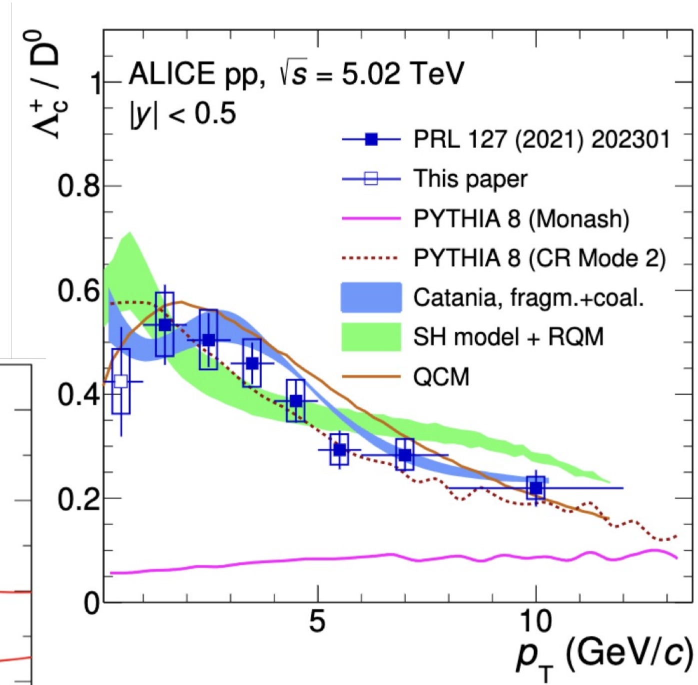
- charm/beauty baryon-to-meson ratios: higher than measurements at ee, ep collisions for p_T < 10 GeV/c
  - ➔ Predictions that include baryon enhancement mechanisms describe data

https://doi.org/10.1103/PhysRevC.107.064901

0.113 ± 0. 013±0.006
(LEP average, EPJC 75, 19 (2015))







PRD 105, L011103 (2022) arXiv:2105.06335 [nucl-ex]

Λ_c/D^0 ratio to study hadron chemistry: impact at low-p_T range and forward rapidity

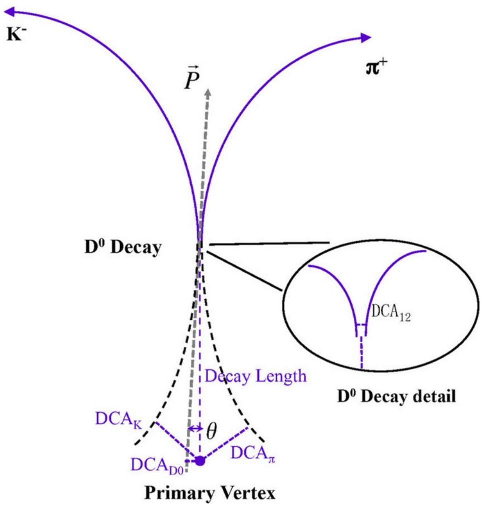
Violation of universality of fragmentation fractions (FF) already in pp collisions

➔ Cannot rely on e^+e^- FF to get charm cross section

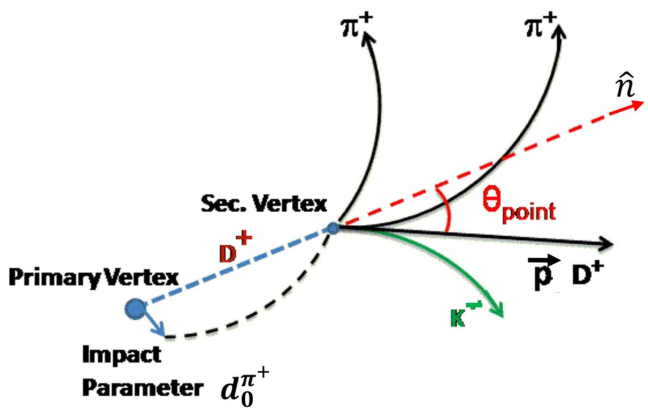
Measure fragmentation fractions at ePIC with different nuclei systems for more understanding!!

Reconstruction of B, D-meson, and Λ_c^+-baryon using **primary and secondary vertexing**

D^0 meson



D^+ meson



Particle	Mass (GeV/c²)	cτ (μm)
$D^\pm$	1.869	312
D^0	1.864	123
$B^\pm$	5.279	491
B^0	5.280	456
Λ_c^+	2.286	60

2-prong decay

3-prong decay

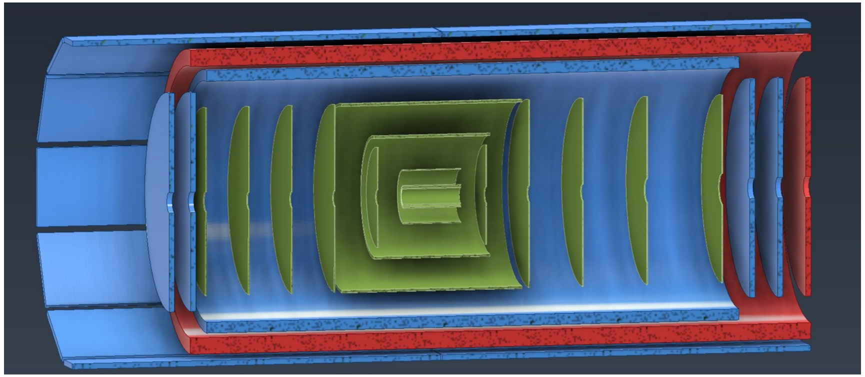
arXiv:1911.12168 [nucl-ex]

Invariant mass: $m_{D^0} = \sqrt{(E_{K^-} + E_{\pi^+})^2 - (\vec{p}_{K^-} + \vec{p}_{\pi^+})^2}$

Main requirements:

- High luminosity + good detector acceptance
- Good pointing and momentum resolution. And vertex separations?

The ePIC tracking system (|η| < 3.5) is a hybrid detector based on both silicon and gaseous technologies



SVT IB, OB and Disks (MAPS)

MPGD Barrels and Disks

AC-LGAD TOF

Barrel Region:

- **Silicon Vertex Tracker (SVT):**
  - SVT Inner Barrel (IB) L_0, L_1, L_2 and Outer Barrel (OB) L_3, L_4
  - Monolithic Active Pixel Sensors (MAPS) based on 65 nm CMOS technology being developed by ALICE
  - High granularity and low material budget are the key features to achieve a good momentum and pointing resolution
- **MPGD (Micro-Pattern Gas Detectors)**
  - Gaseous detectors to cover a large outer tracking volume
  - Provides a good timing performance (Provide ∼ 10 − 30 ns timing resolution) for pattern recognition
- **AC-LGAD Sensors**
  - Excellent time resolution for the particle identification by time-of-fight method
  - Provides an extra hit for pattern recognition and tracking

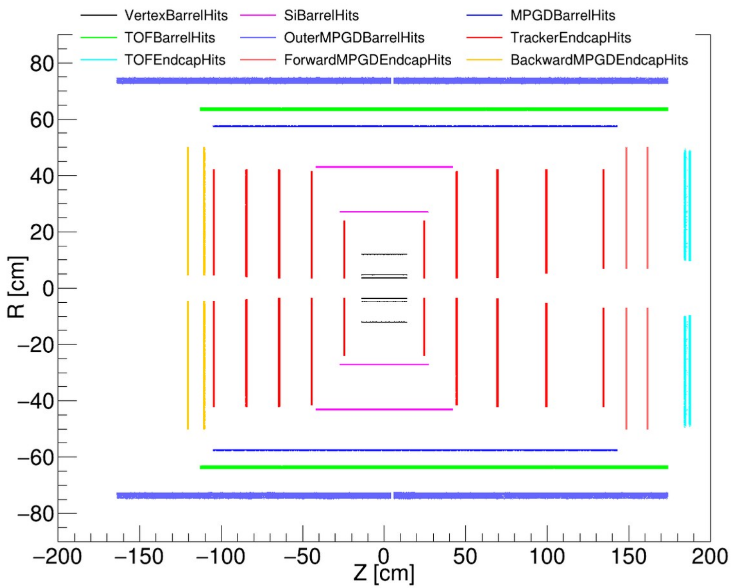
SVT to achieve a precise tracking and vertexing capability

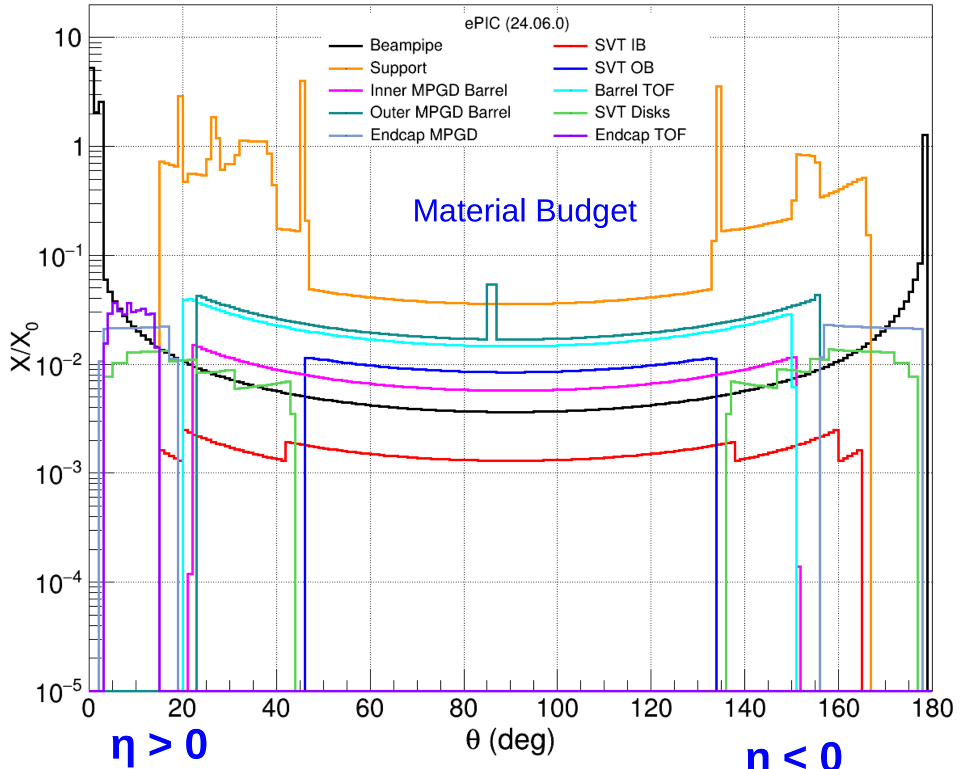
(pitch ~ 20 μm)

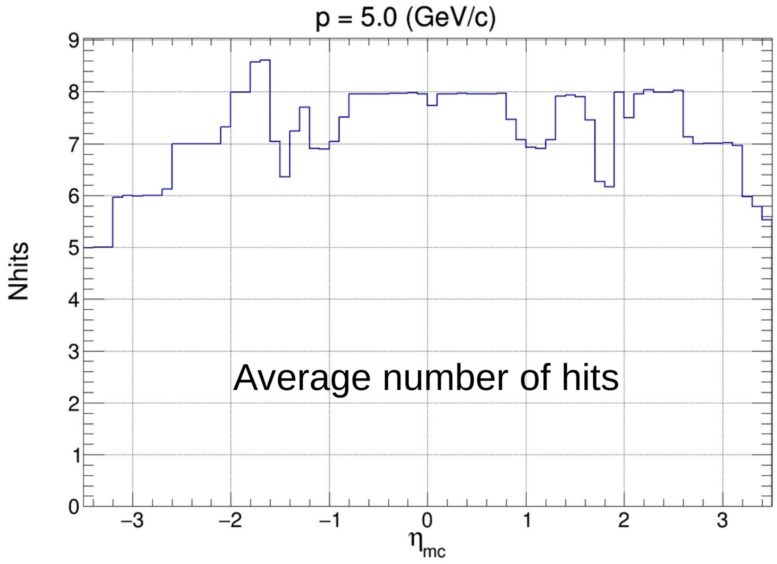
Forward region: Five MAPS silicon disks followed by two MPGD (Micro-Pattern Gas Detectors) layers and a TOF layer

Backward region: Five MAPS silicon disks followed by two MPGD layers

The ePIC Tracker Hit Map and Material Budget







Minimal amount of material in the SVT IB and OB

- support material for services in conical shape

Average number of hits ≥ 5 for |η| < 3.5

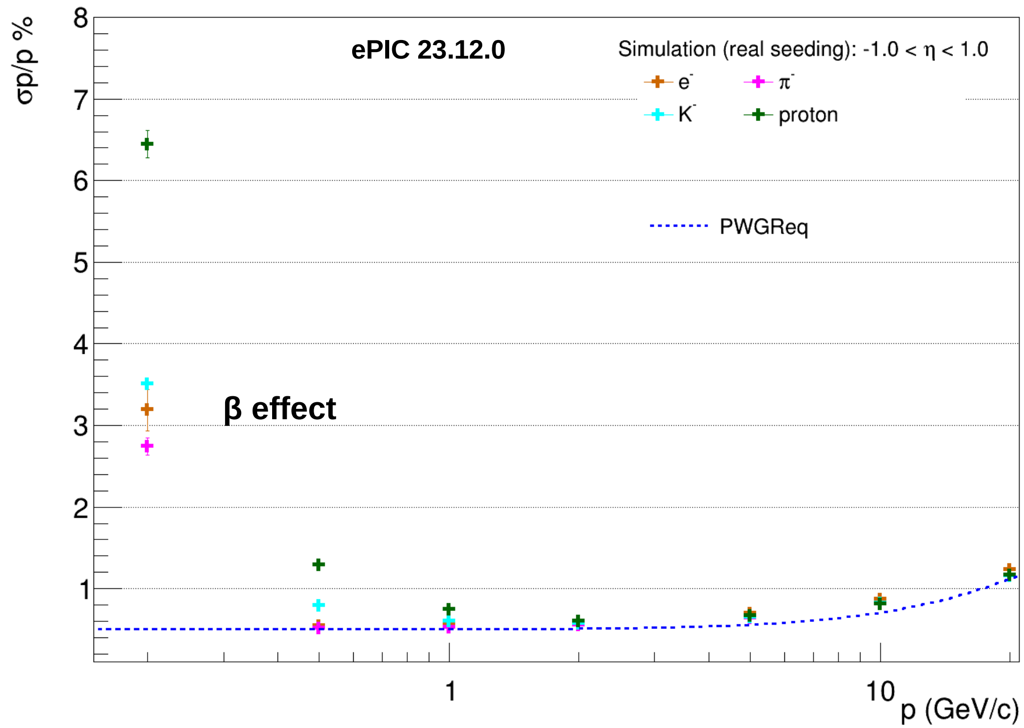
Reconstruction of particle trajectory (in presence of non-uniform magnetic field, material effect, background hits)-**4D tracking**

Tracking: Track finding and fitting using combinatorial Kalman Filter (CKF): **ACTs (A Common Tracking Software)**

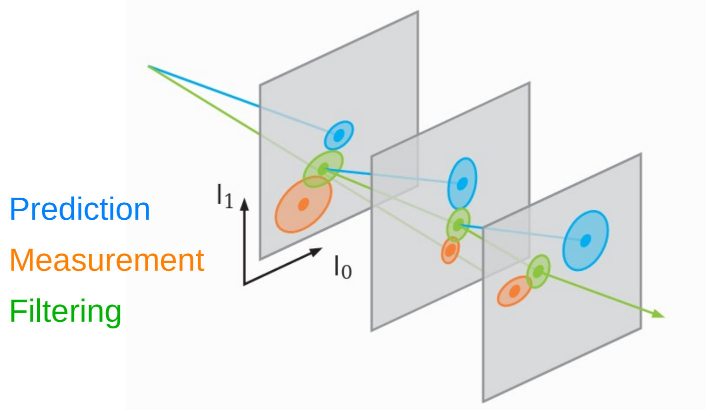
Track Parameters: $(l_0,\ l_1\ ,\ \phi,\ \theta,\ 1/p,\ t)$

- l_0 ,l_1: local parameters describing the sensor surface
- ϕ: Azimuthal angle in global coordinates
- θ: angle w.r.t. z axis in global coordinates
- p: Momentum of the track
- **t: time of hit (important due to background)**

Momentum Resolution



Inward--> Outward fitting
Outward-->Inward fitting



Three Steps (Kalman Filter)

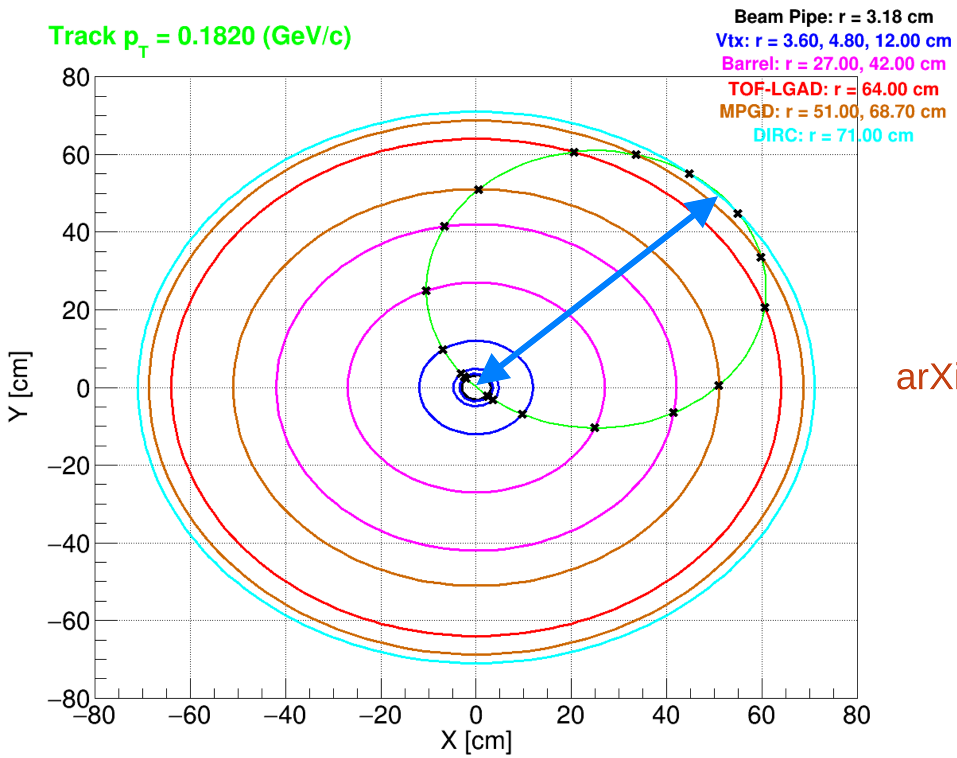
1. Extrapolation
2. Filtering
3. Smoothing

Tracking Performances

$$p_T(GeV/c) = 0.3\,B[T]\,R_{track}[m]$$

$$p_{Tmin} = 0.3 \times 1.7 \times 0.3435 = 0.1752\,GeV/c$$

At η = 0 $\quad R_{track} = \frac{R_{OutMPGD}}{2} = 0.3435\,m$



$$\frac{\Delta p_T}{p_T}\Big|_{res.} = \frac{\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{720 N^3}{(N-1)(N+1)(N+2)(N+3)}} \approx \frac{12\,\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} = \frac{N}{\sqrt{(N+1)(N-1)}}\,\frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0 \sin\theta}}\left(1 + 0.038 \ln \frac{d}{X_0 \sin\theta}\right)$$

Constant term (at β<1 increase)

arXiv:1805.12014

$$\frac{\sigma_{pT}}{p_T} = \sqrt{\left(\frac{\sigma_{pT_{SR}}}{p_T}\right)^2 + \left(\frac{\sigma_{pT_{MS}}}{p_T}\right)^2}$$

$$\Delta d_0|_{res.} \approx \frac{3\sigma_{r\phi}}{\sqrt{N+5}}\sqrt{1 + \frac{8r_0}{L_0} + \frac{28r_0^2}{L_0^2} + \frac{40r_0^3}{L_0^3} + \frac{20r_0^4}{L_0^4}}$$

$$\Delta d_0|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{\beta p_T}\, r_0 \sqrt{\frac{d}{X_0 \sin\theta}}\sqrt{1 + \frac{1}{2}\left(\frac{r_0}{L_0}\right) + \frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$

$$\sigma_{d_0} = \sqrt{\sigma_{d0_{SR}}^2 + \sigma_{d0_{MS}}^2}$$

Tracking Performances (Fast Simulation)

Spatial Resolution (SR): Uncertainty associated with pixel size ($\sigma_{r\varphi}$)

Multiple Scattering (MS): Uncertainty associated with material thickness (x/X_0)

arXiv:1805.12014 [physics.ins-det]

Curvature

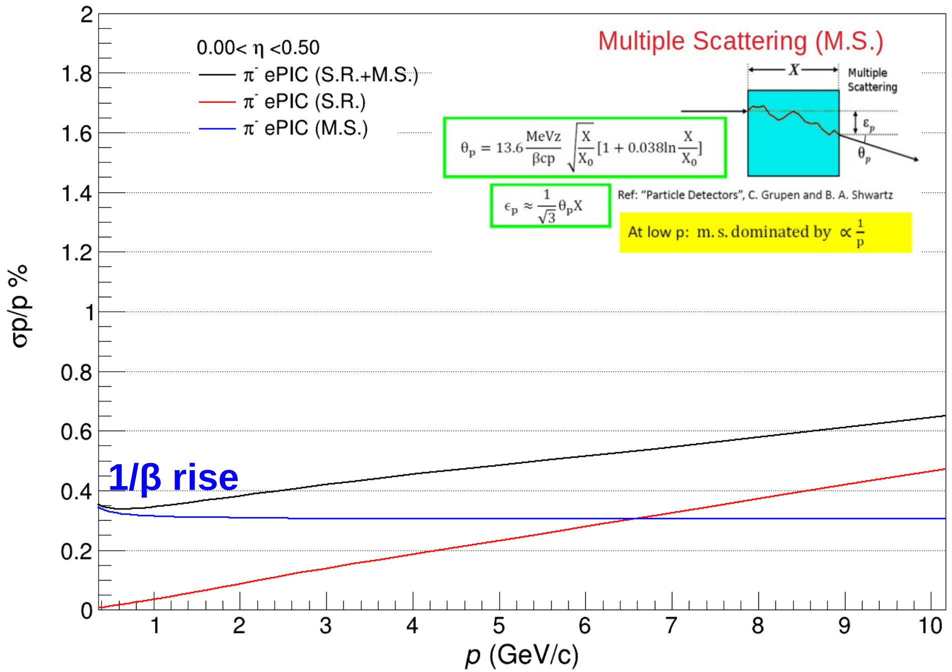
$$\frac{\sigma_{p_T}}{p_T}(SR) \propto \sigma_{r\phi}\, p$$

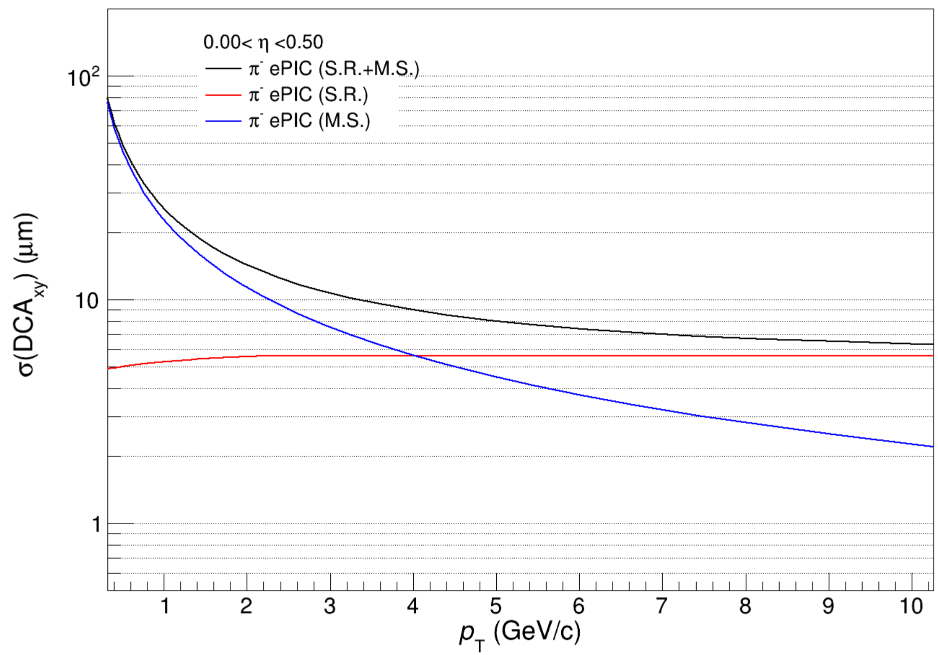
$$\frac{\sigma_{p_T}}{p_T}(MS) \propto \frac{1}{\beta p}\, p = \frac{Const}{\beta}$$

Curvature

Momentum and mass Hypothesis

$$\sigma_{d_0} = \sqrt{\sigma_{d_0 SR}^{\;2} + \sigma_{d_0 MS}^{\;2}}$$



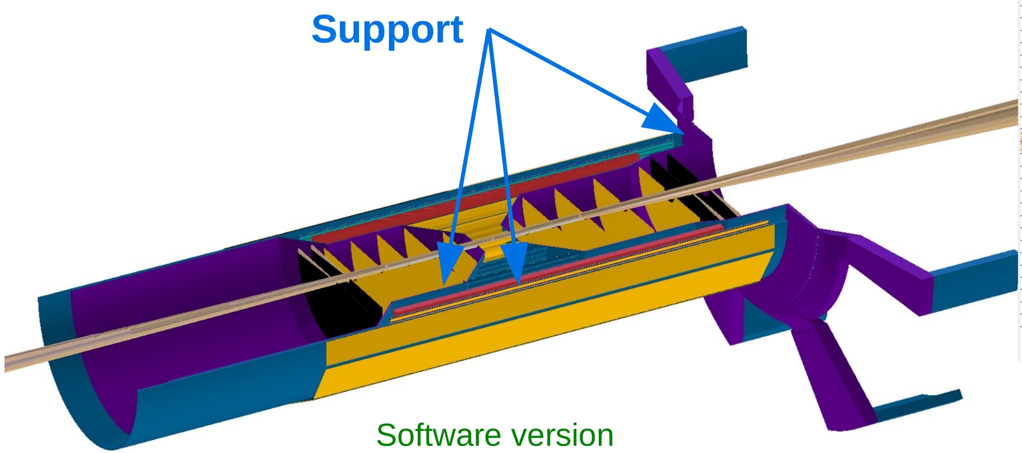


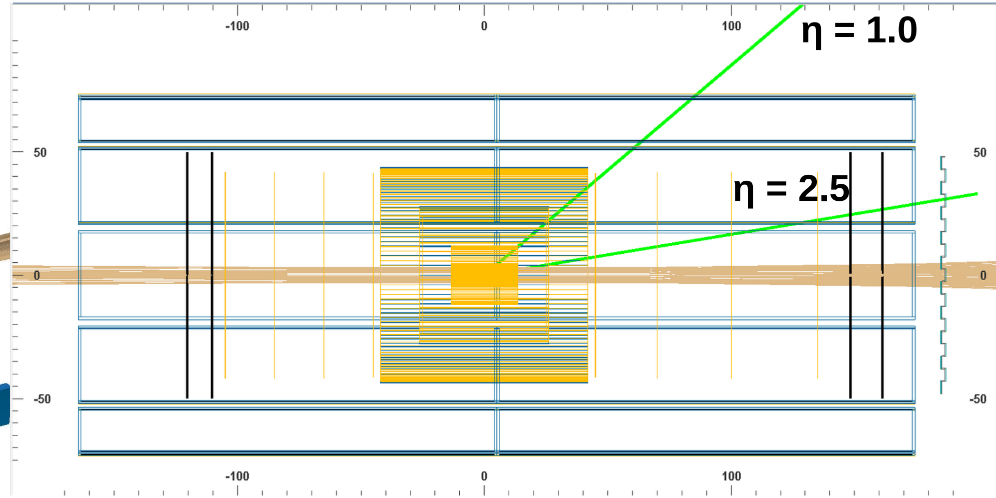
Geometry and Momentum Resolutions (Real Seed)

Different η regions

My Slides

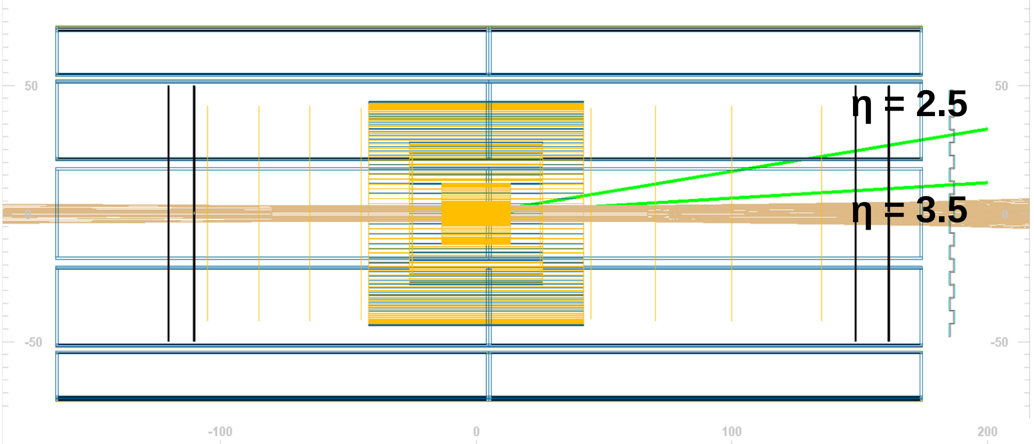
epic_craterlake_tracking_only.xml

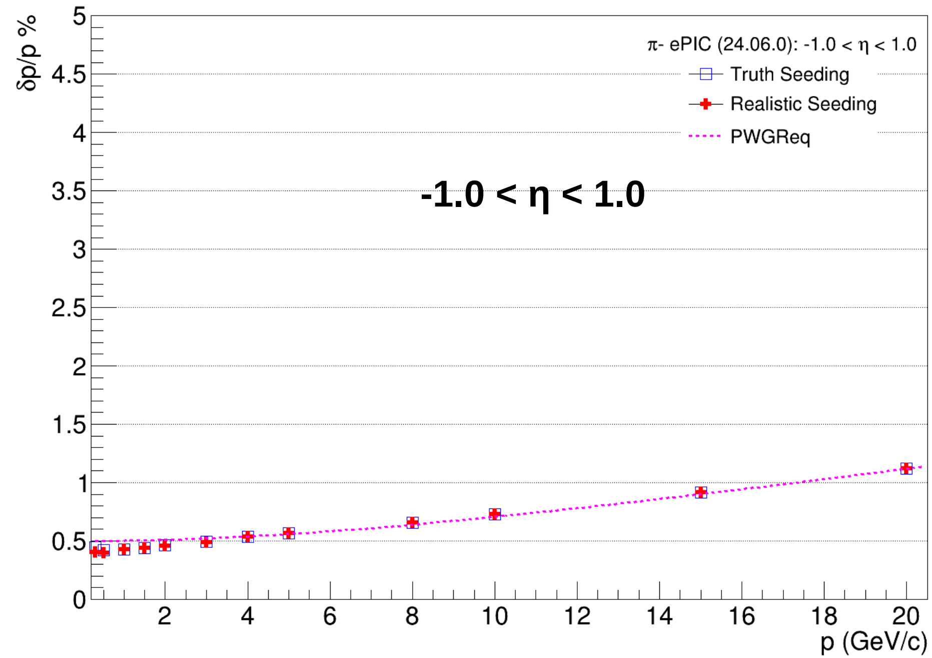




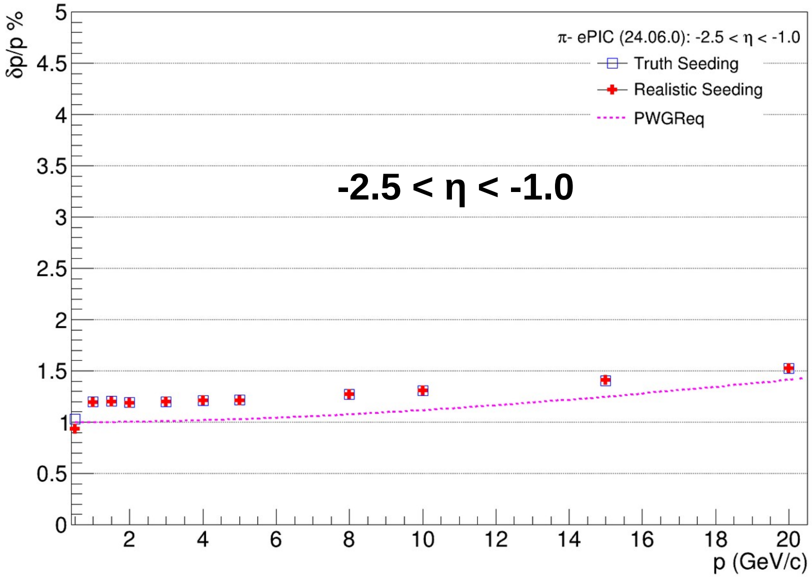
Software version

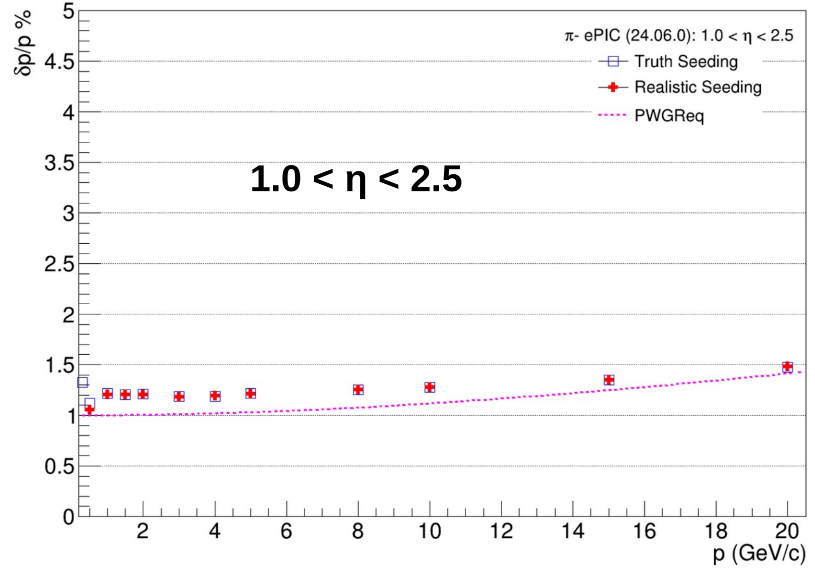
shyam@shyam:~/eic/epic$ git describe --tags --abbrev=0
24.06.0
shyam@shyam:~/eic/EICrecon$ git describe --tags --abbrev=0
v1.14.0

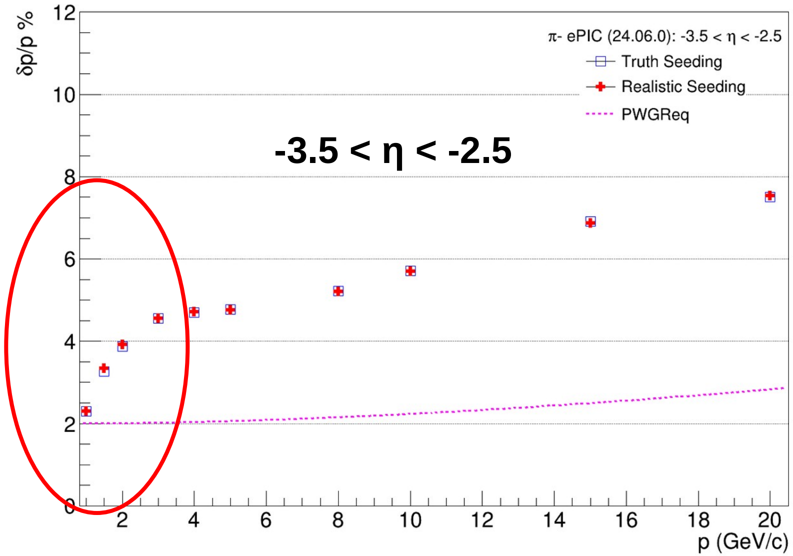




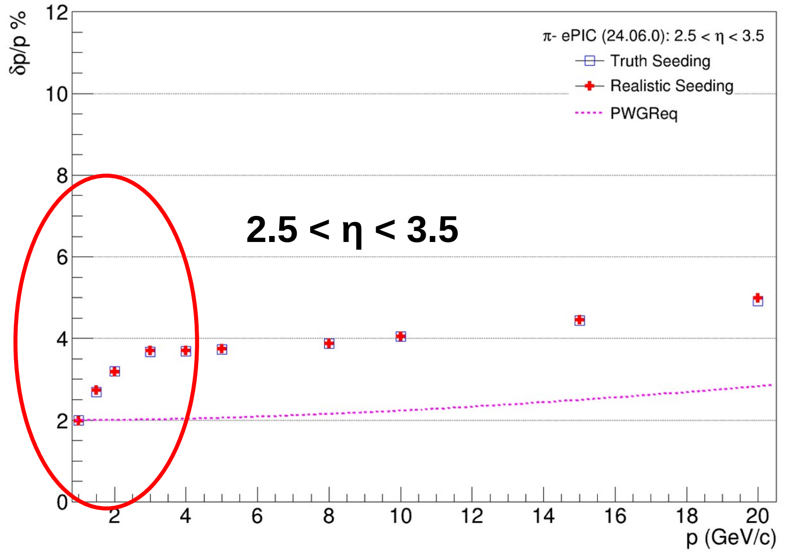
Momentum Resolutions (Truth/Real Seed)







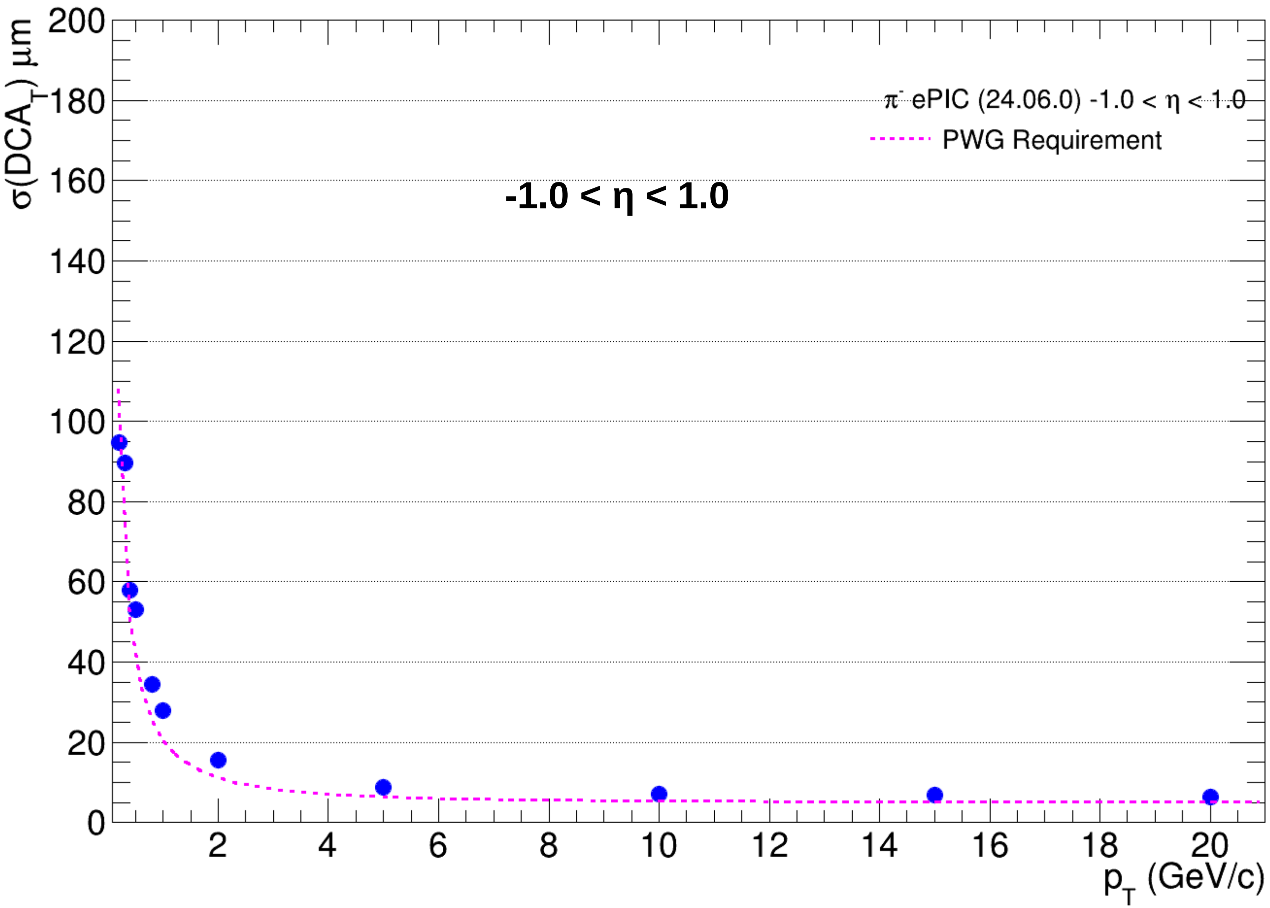
Need to understand



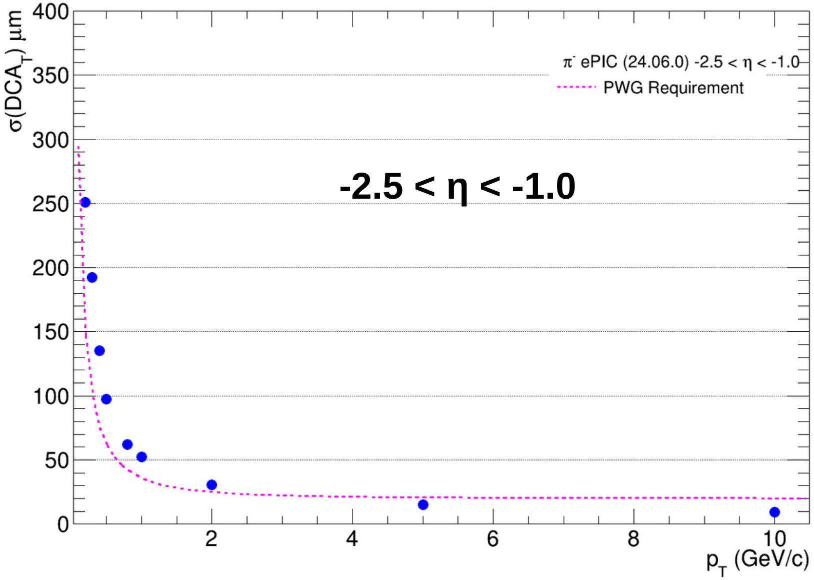
DCA_T Resolutions (Real Seed)

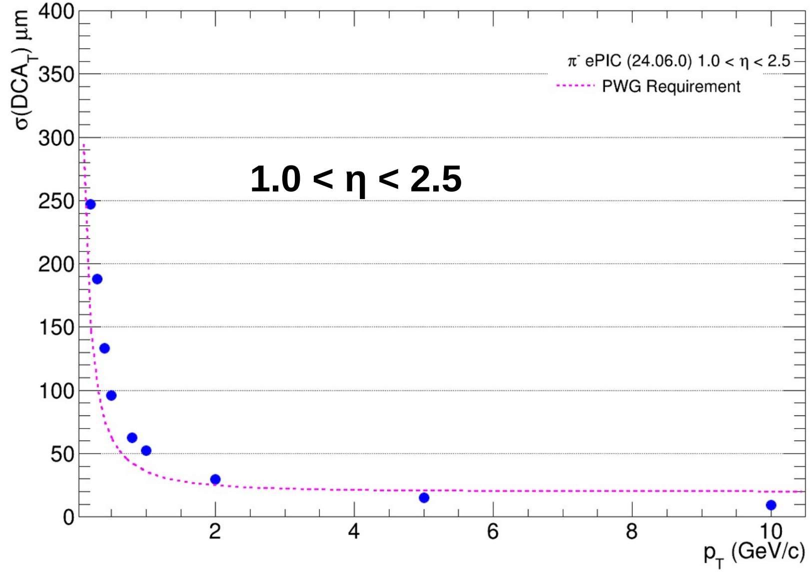
Some of the regions momentum resolutions requirements are not met: information from **particle identification detectors (TOF, dRICH, pfRICH, electromagentic calorimeter)** can help but need to be studied

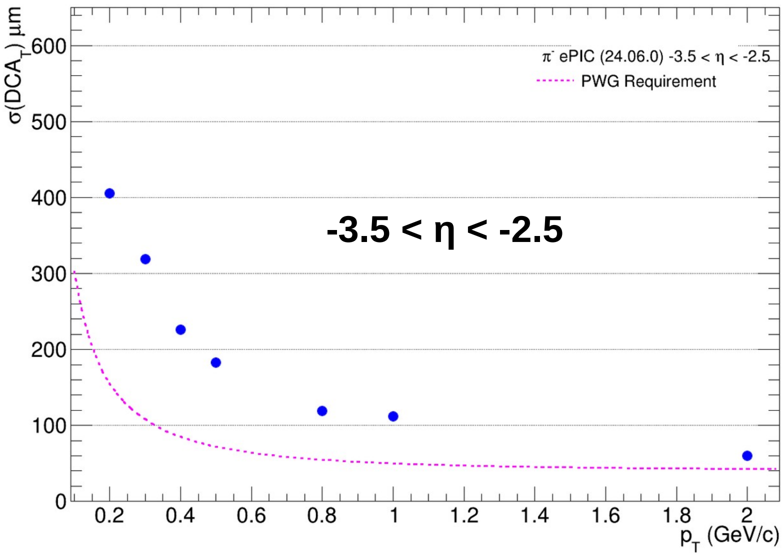
arXiv:hep-ex/0104006

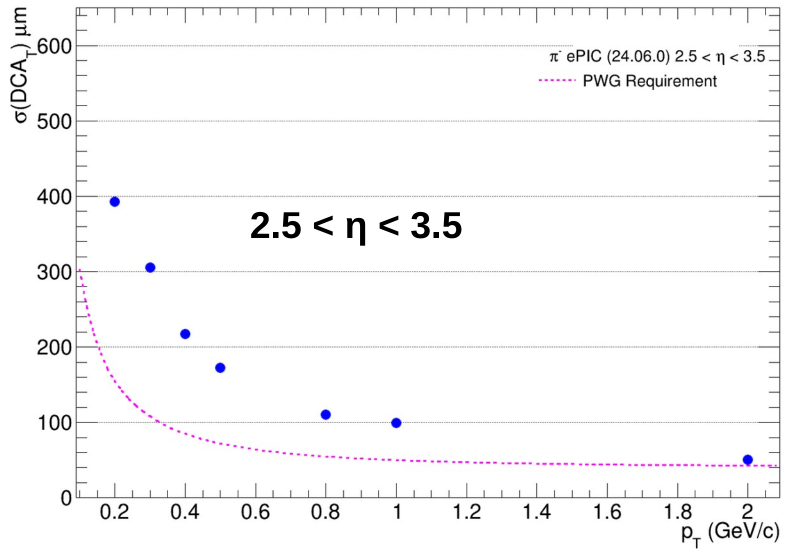


DCA_T Resolutions (Real Seed)









Particle Identification

- Energy loss versus momentum (Bethe-Bloch particle identification)

Separation between particles A and B:

$$n = \frac{\left(\frac{dE}{dx}\right)_A - \left(\frac{dE}{dx}\right)_B}{\sigma\left(\frac{dE}{dx}\right)}$$

arXiv:hep-ex/0104006

- Time-of-Flight (TOF) method

Separation between particles A and B:

$$n = \frac{(TOF)_A - (TOF)_B}{\sigma_t}$$

Excellent time resolution AC-LGAD ~30 ps

Small uncertainity in σ_t important to improve separation

- Cherenkov method

Separation between particles A and B:

$$n = \frac{(\theta)_A - (\theta)_B}{\sigma_\theta}$$

Small uncertainity in σ_θ (several contributiing factors) important to improve separation

TOF provides excellent particle identification in low-momentum range: **utilize TOF-PID information** to improve the uncertainity σ_θ , σ_ϕ in low momentum regime?

In the forward region use TOF (low momentum) and d-RICH (high momentum) for the **improvement of momentum resolution?**

Theta/Phi Resolutions

Important for Cherenkov Particle Identification ($\sigma_\theta, \sigma_\phi$)

DIRC layer

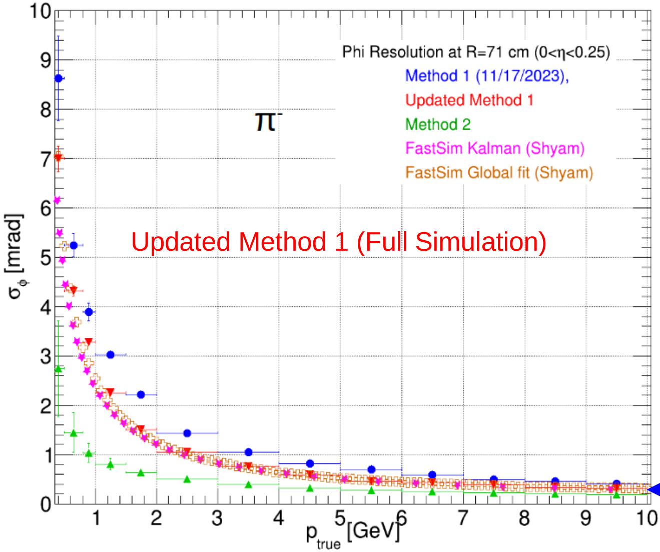
$$\cos\theta = \frac{1}{\beta n}$$

- **Track extrapolation uncertainty at DIRC layer: Estimation of Theta/Phi resolutions at DIRC (at 71 cm)**
- Chromatic uncertainty due to emission of photons of different energy (refractive index n = n(E))
- Measurement uncertainty in the position reconstruction of photons due to pixel size

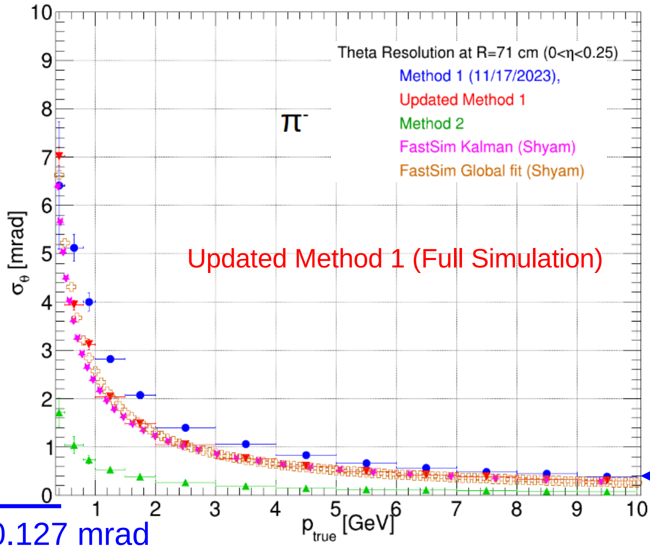
Fast Simulation (Kalman) uses Inward to Outward fitting algorithm considering multiple scattering at the Outer MPGD layer

Global fit also take care of multiple scattering at Outer MPGD layer (parameters are global)

Good compatibilty between Updated Method1 and Fast Simulations

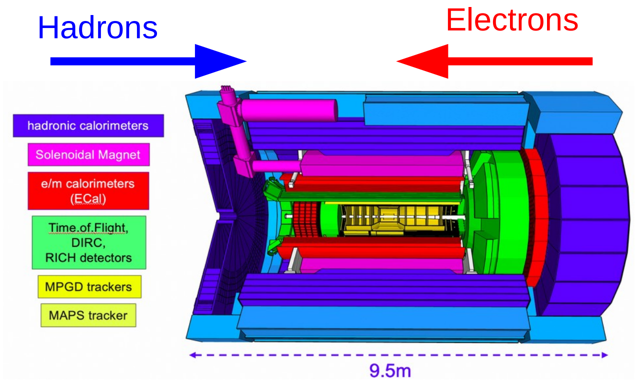


0.127 mrad



0.017 mrad

DIRC: Disk Imaging Ring Cherenkov

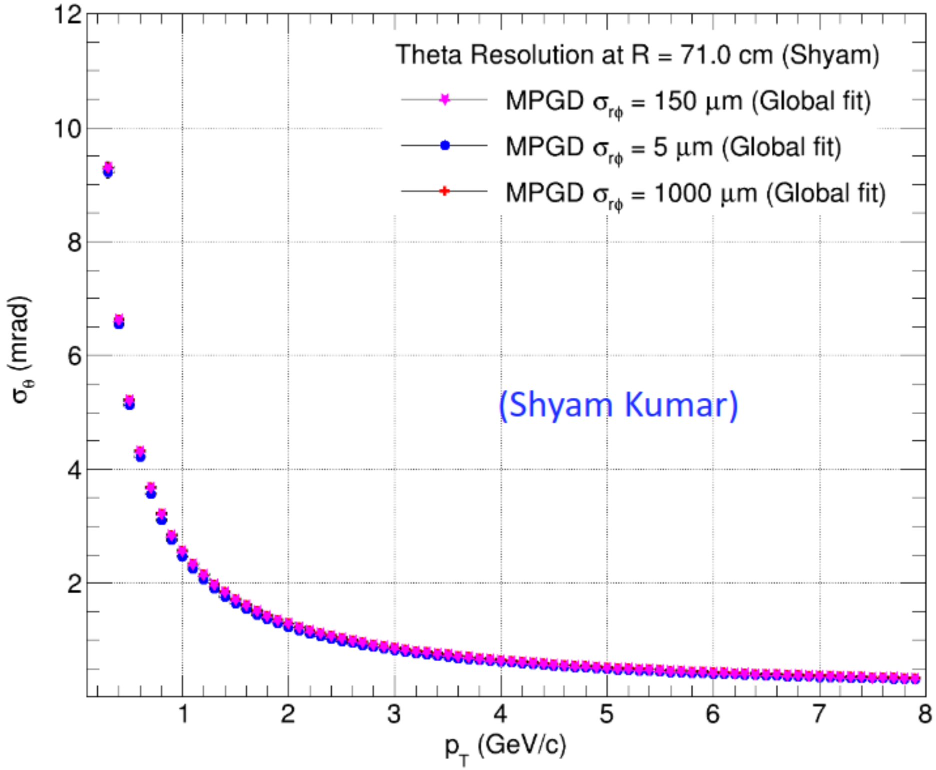


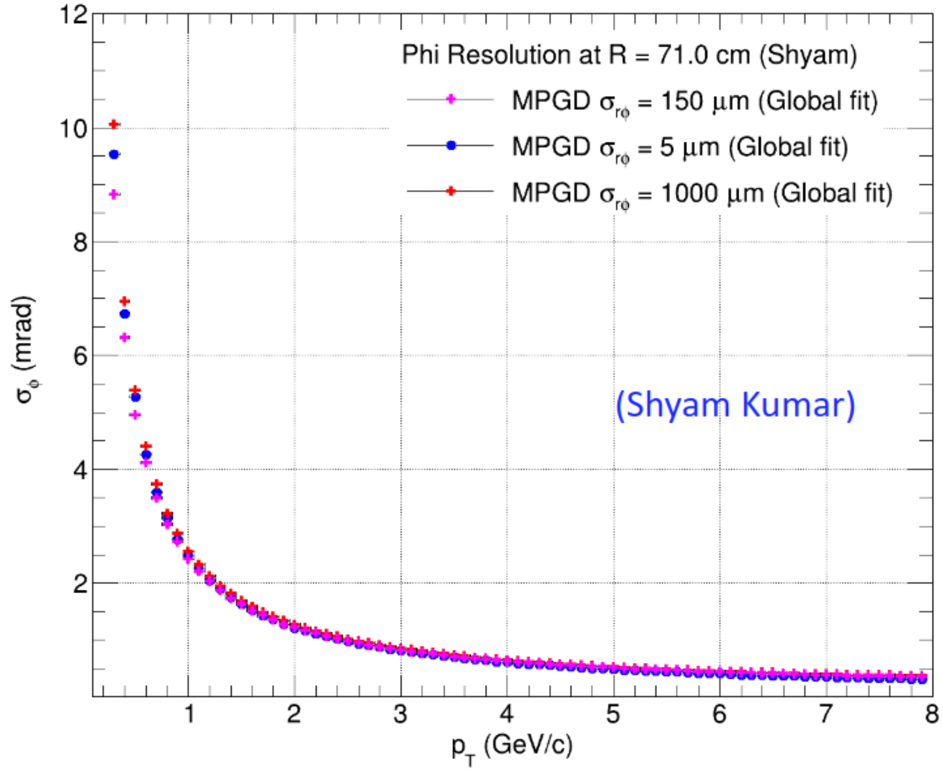
https://indico.bnl.gov/event/20473/contributions/85332/attachments/51915/89153/Fast_Simulation_ePIC_Collaboration_Meeting_Shyam_Kumar.pdf

- Fast simulations show angular resolutions not very sensitive to MPGD resolution
  - Agrees with behavior found in ePIC simulations

Matt's slides DIRC layer

Dominated by Multiple Scattering





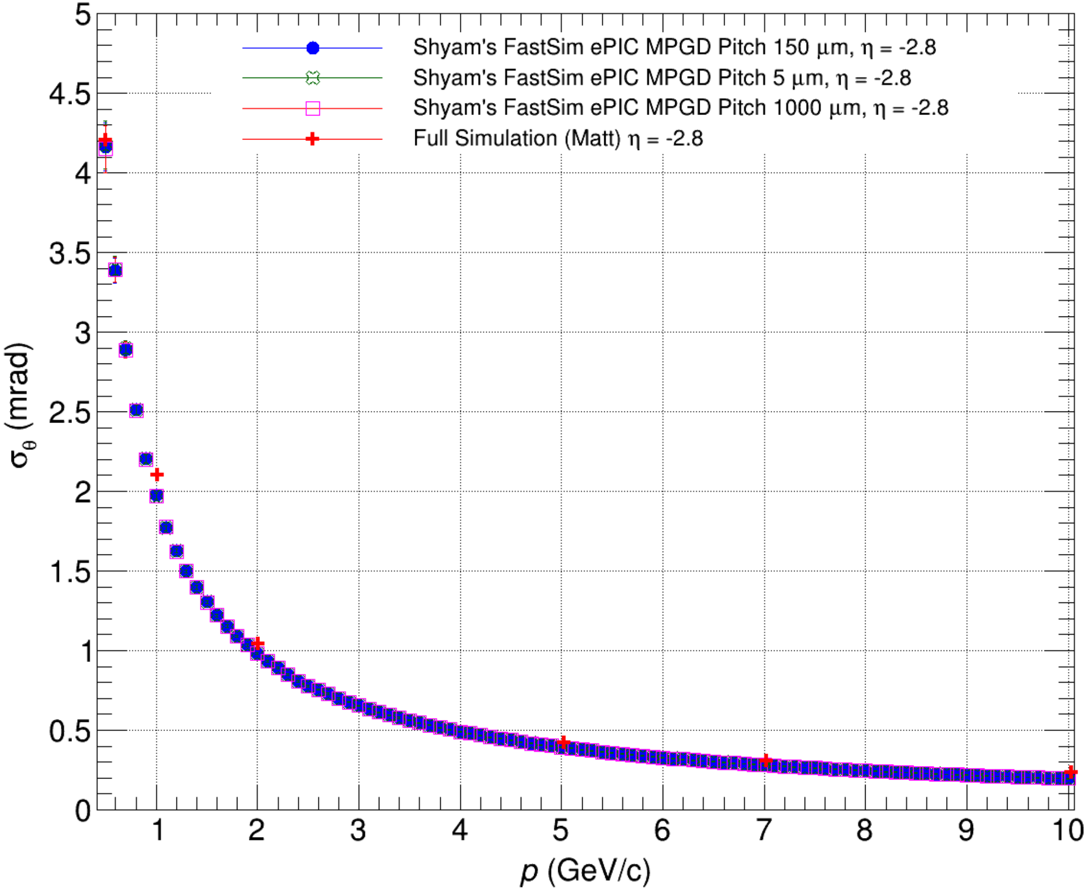
April 22nd, 2024

Working on improvement of theta/phi resolutions

https://indico.bnl.gov/event/23351/contributions/91831/attachments/54626/93469/05-20-2024_AngularResolution_UPDATE.pdf

Theta/Phi Resolutions with different MPGD Resolutions

Recently implemented forward/backward track model to the global fit understand pfRICH performances



pfRich: Proximity Focusing RICH

https://eic.jlab.org/Geometry/Detector/Detector-20240426175116.html

Minor difference because global fit is based on uniform magentic field

Further understanding to the major contributor to the uncertainity

PfRICH Z = -123.5

Working on improvement of theta/phi resolutions

Summary

- ePIC tracker consists of both state-of-the-art silicon and gaseous detector technologies
- ePIC SVT IB and OB will help to achieve required momentum resolution and DCA performance
- MPGD layers will also help in pattern recognition as they provide space point with a good timing information over a large area
- There are some η regions in which performances are not met: particle identification information can help
- The ePIC tracker is optimized in terms of technology and layout to achieve the required physics performance set by the EIC LoI
- **Starting analysis on HF signals and jets (also with ML techniques)** to have a feedback on the physics performances

THANK YOU !!!

Ref: Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report arXiv:2103.05419 [physics.ins-det]

Kinematics and Detector Requirements

DIS Kinematics

Resolution power

$$Q^2 = -q^2 = -(k_\mu - k_\mu')^2$$

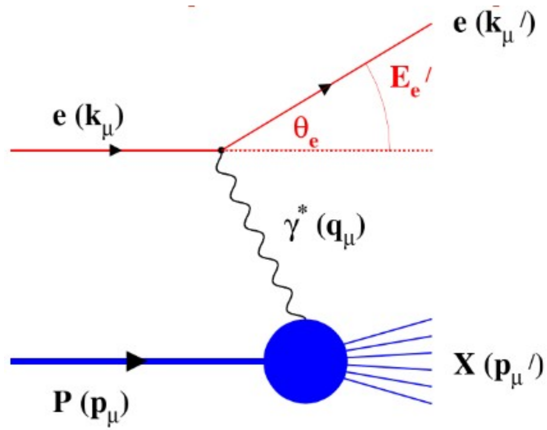
$$Q^2 = 2 E_e E_e' (1 - \cos\theta_e)$$

Inelasticity

$$y = \frac{pq}{pk} = 1 - \frac{E_e'}{E_e} \cos^2\left(\frac{\theta_e}{2}\right)$$

Momentum fraction of struck quark

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$



$$s = 4 E_e E_p$$

$$Q^2 = s\,x\,y$$

Measurement of a scattered electron with high resolution in the Lepton Endcap (-3.5 < η < -1.0)

Determines electron kinematics

Particle energy: ~ 0.02-18 GeV

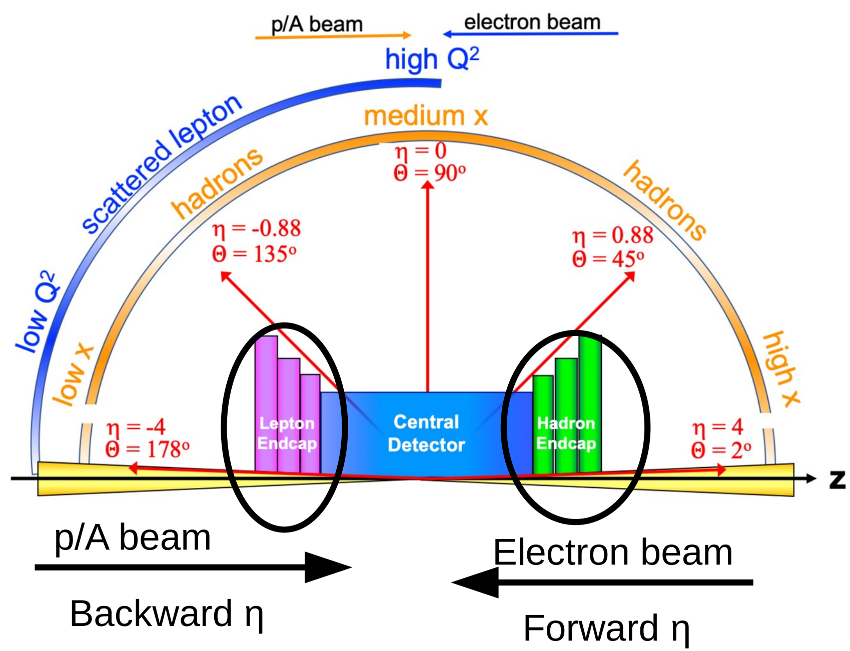
x is the fraction of the proton's momentum carried by the struck quark

y is the fraction of the electron's energy lost in the proton rest frame

Scattered electron: **low Q^2 to high Q^2 region** at mid and backward η

Hadrons: **low x to high x region at all η**

High granularity and low material budget in Central, Far-Forward and Far-Backward play a very crucial role to met the physics requirements



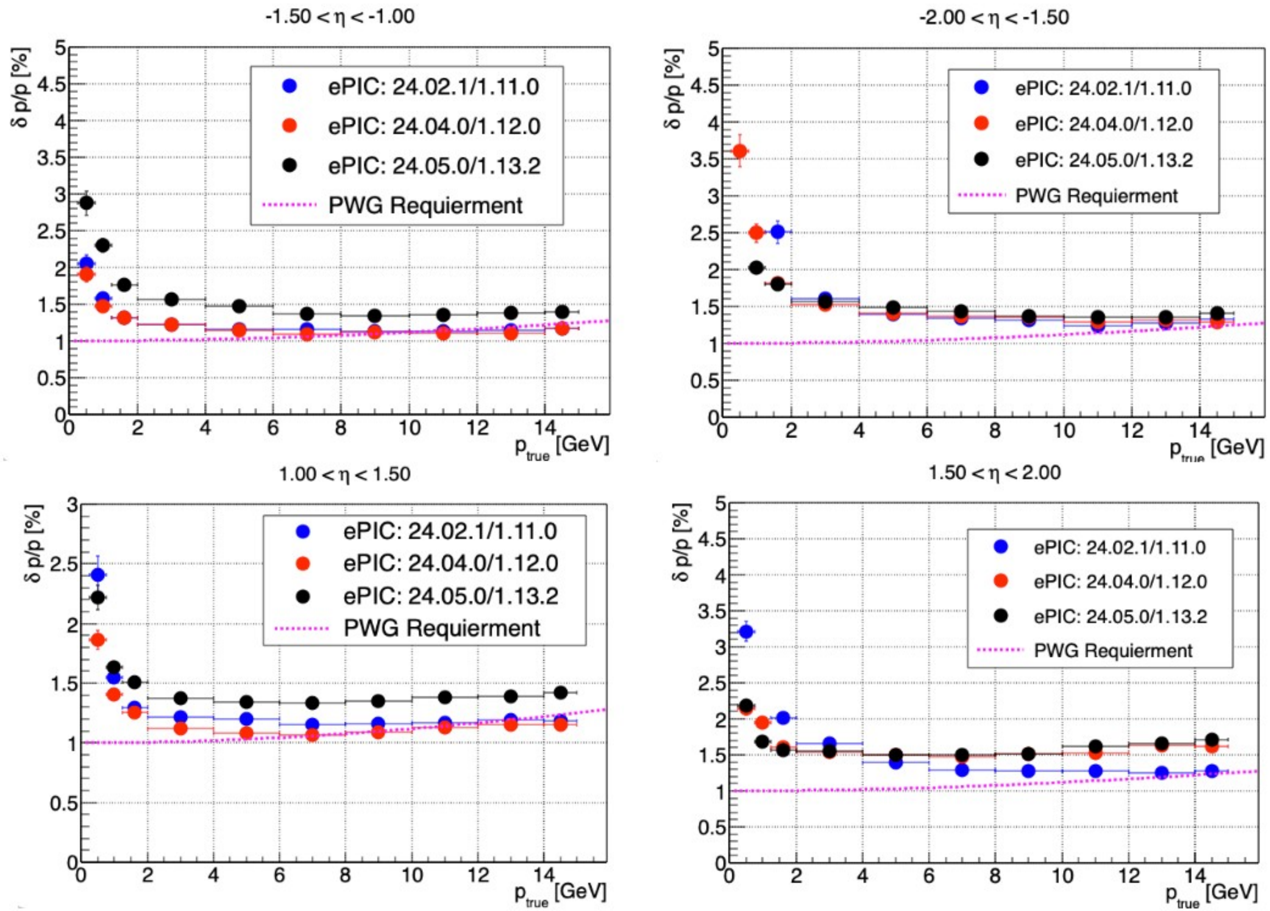
https://indico.bnl.gov/event/23630/contributions/92294/attachments/54845/93843/05-30-2024-TrackingWG_CraterLakeComparisons.pdf

Momentum Resolution: $1.0 < |\eta| < 2.5$

ePIC

- Single particle: π^-

Matt's Slides



ePIC Tracking WG Meeting: May 30th, 2024

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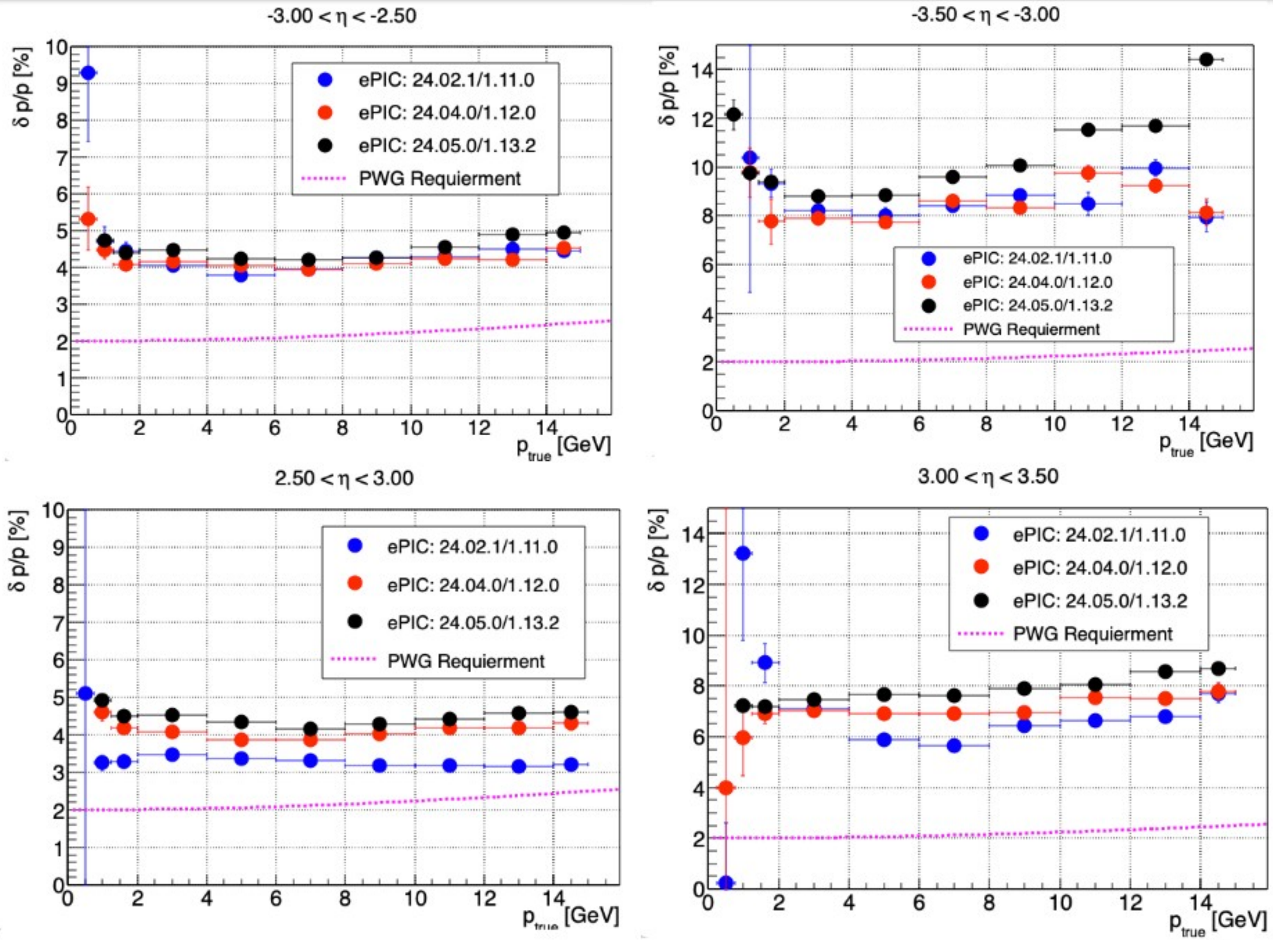
https://indico.bnl.gov/event/23630/contributions/92294/attachments/54845/93843/05-30-2024-TrackingWG_CraterLakeComparisons.pdf

Momentum Resolution: $|\eta| > 2.5$

- Single particle: π^-

Matt's Slides



ePIC Tracking WG Meeting: May 30th, 2024

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