Tracking Performance Using Fast Simulation Studies and Their Improvements

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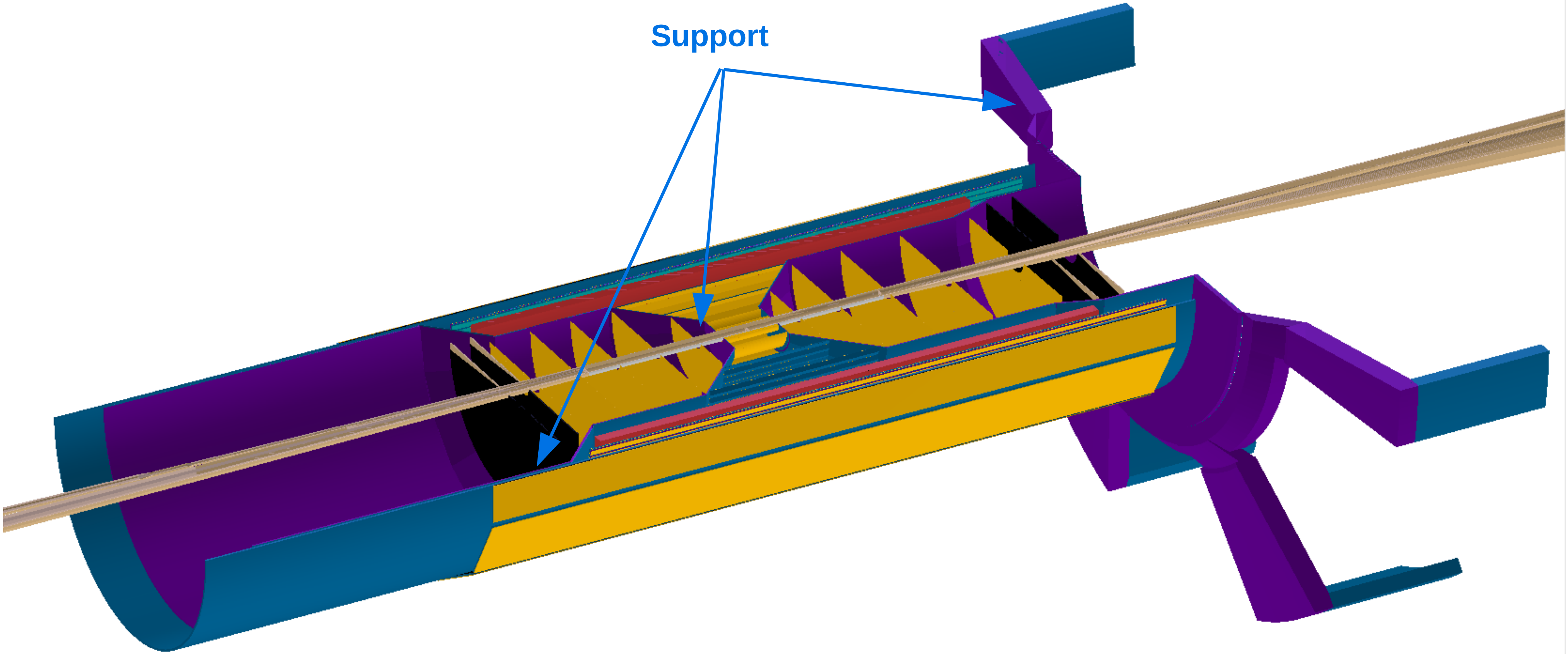
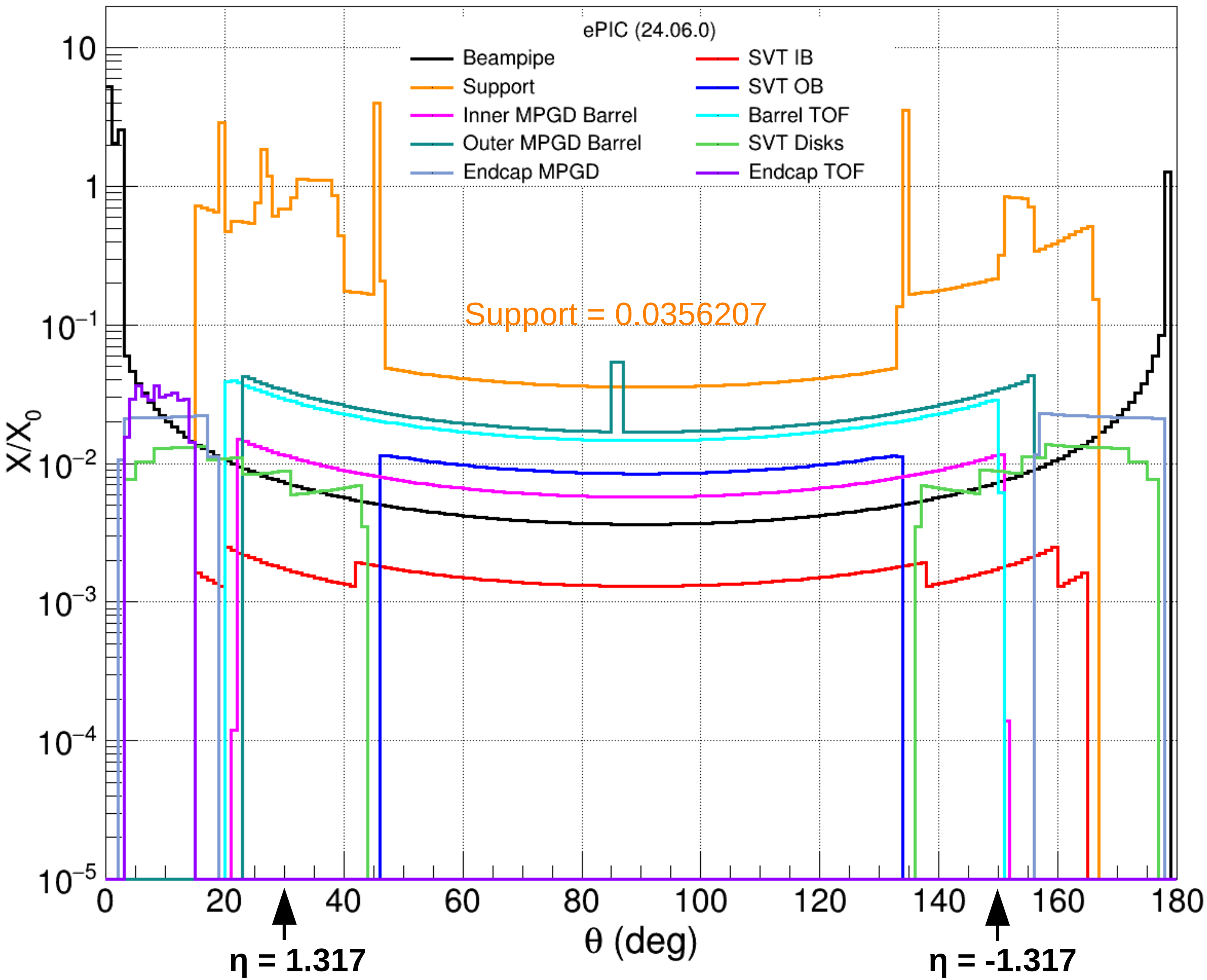
ePIC Tracker (24.06.0)

epic_craterlake_tracking_only.xml



There is an extra support layer before outerMPGD: Additional scattering will affect theta/phi resolutions

Material Budget (ePIC 24.06.0)

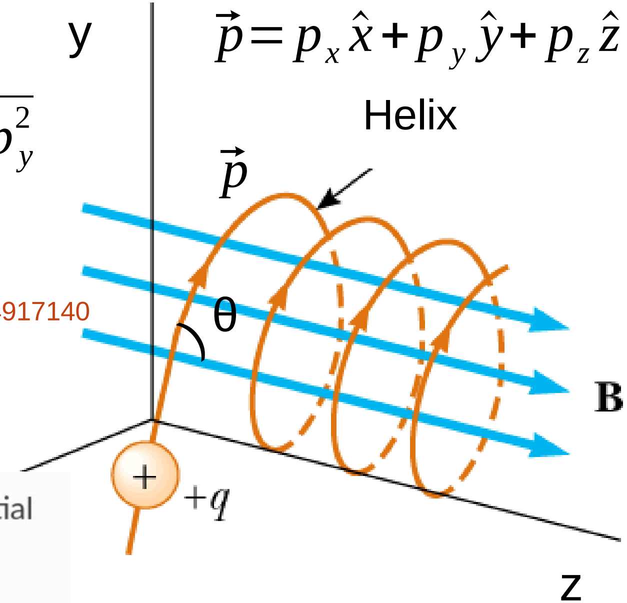


Charged Particle in Magetic Field (Lorentz Force)

$$\vec{F} = q(\vec{v} \times \vec{B})$$

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$\vec{p} = p_x \hat{x} + p_y \hat{y} + p_z \hat{z}$$



If B is uniform the trajectory is helix (easier) apart from the deviations from the multiple scattering at each detector plane

https://doi.org/10.1063/1.4917140

RK propagator also used in Genfit (fun4All)

The Runge-Kutta-Nyström method from above can be adapted to handle second order differential equations, as is needed for the equations of motion in question, **B-field map**

Ref: ACTS

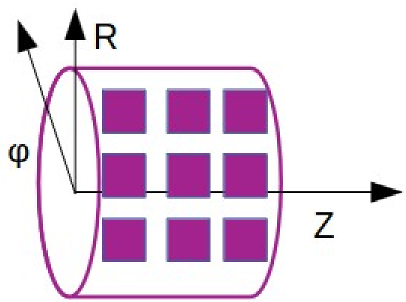
$$\frac{d^2\vec{r}}{ds^2} = \frac{q}{p}\left(\frac{d\vec{r}}{ds} \times \vec{B}(\vec{r})\right) = f(s, \vec{r}, \vec{T}), \qquad \vec{T} \equiv \frac{d\vec{r}}{ds},$$

If B depends on **r (B map required)** the trajectory is predicted analytically solving RK method (RK track propagator)

Full Simulation: RK method

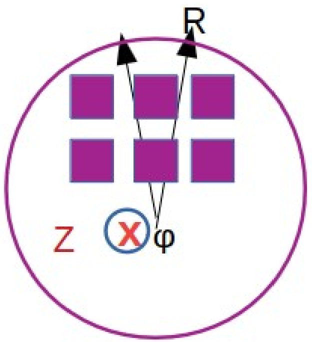
Fast Simulation: Helix method (can also be done with RK method)

Barrel Track Model



Cylinder

Forward/Backward Track Model



Disks

Fast Simulation (Kalman and Global fit)

Fast Simulation (Kalman)

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

Parameter Covariance

	l_0	l_1	ϕ	θ	$1/p$
l_0	σ^2_{l0}	σ_{l0l1}	$\sigma_{l0\phi}$	$\sigma_{l0\theta}$	$\sigma_{l0.1/p}$
l_1	σ_{l1l0}	σ^2_{l1}	$\sigma_{l1\phi}$	$\sigma_{l1\theta}$	$\sigma_{l1.1/p}$
ϕ	$\sigma_{\phi l0}$	$\sigma_{\phi l1}$	σ^2_{ϕ}	$\sigma_{\phi\theta}$	$\sigma_{\phi.1/p}$
θ	$\sigma_{\theta l0}$	$\sigma_{\theta l1}$	$\sigma_{\theta\phi}$	σ^2_{θ}	$\sigma_{\theta.1/p}$
$1/p$	$\sigma_{1/p.l0}$	$\sigma_{1/p.l1}$	$\sigma_{1/p.\phi}$	$\sigma_{1/p.\theta}$	$\sigma^2_{1/p}$

Symmetric matrix = 5(5+1)/2 = 15 independent entries

Two Independent Algorithms (Barrel Track Model)

Extrapolate to the Vertex

$\sigma_{l0} \rightarrow \sigma(DCA_{xy}) \qquad \sigma_{l1} \rightarrow \sigma(DCA_z)$

$\sigma_\theta \qquad \sigma_\phi \qquad \frac{\sigma_{1/p}}{(1/p)} = \frac{1/p^2 * \sigma_p}{(1/p)} = \frac{\sigma_p}{p}$

https://indico.bnl.gov/event/17750/contributions/71187/attachments/44843/75637/EPIC_Tracking_Meeting_Shyam1Dec2022.pdf

Three Options (Kalman):

1. **Outward-->Inward fitting**
2. **Inward--> Outward fitting**
3. Combined estimate (Weighted average)

Fast Simulation (Global fit)-generates intermediate distributions (DCA_{xy}, Δp_T, $\Delta\phi$, $\Delta\theta$, chi2)

Assuming uniform magnetic field (helix), ignoring energy loss, assuming Gaussian multiple scattering

Provide the optimal **parameters (global)** for the track based on simultaneous chi2 minimization considering all hit points

Global fit developed by Shyam

Fast Simulations (ePIC Geometry)

ePIC:24.06.0 layout

Double_t radius[] = {3.18,3.6,4.8,12.0,27.0,42.0,55.0,64.0,67.5,72.5};

Double_t x_x0[] = {0.00364154,0.0005,0.0005,0.0005,0.0025,0.0055,0.00573451,0.0146278,0.0356207,0.0168985};

SiLayerResolution = 20 µm

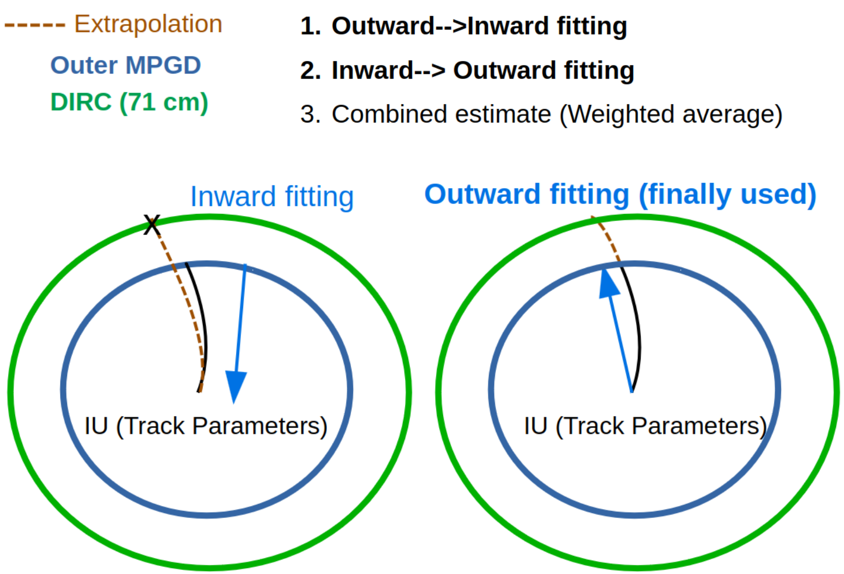
MMLayerResolution = 150 µm

LGADResolution = 30 µm

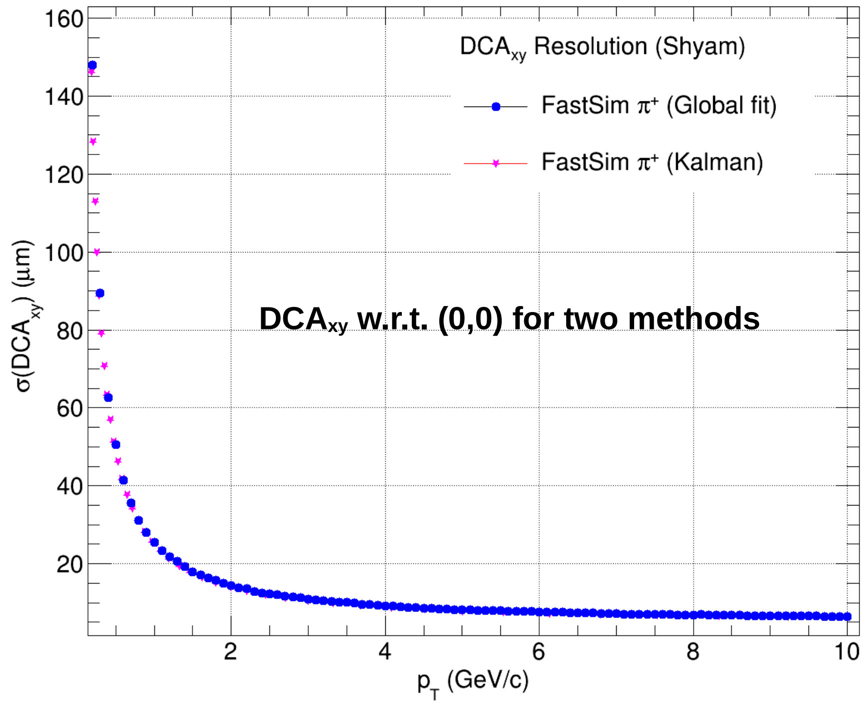
Innermost update (IU)

Three Options (Kalman):

1. **Outward-->Inward fitting**
2. **Inward--> Outward fitting**
3. Combined estimate (Weighted average)



First step is validation (Global fit and Kalman)



Kalman uses two steps for theta/phi resolutions to avoid extrapolation to large distance

I can also apply to the real data using the algorithm

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

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

In the lower momentum region use TOF information while for high-momentum chrerenkov method to improve the tracking performances

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

DIRC layer

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

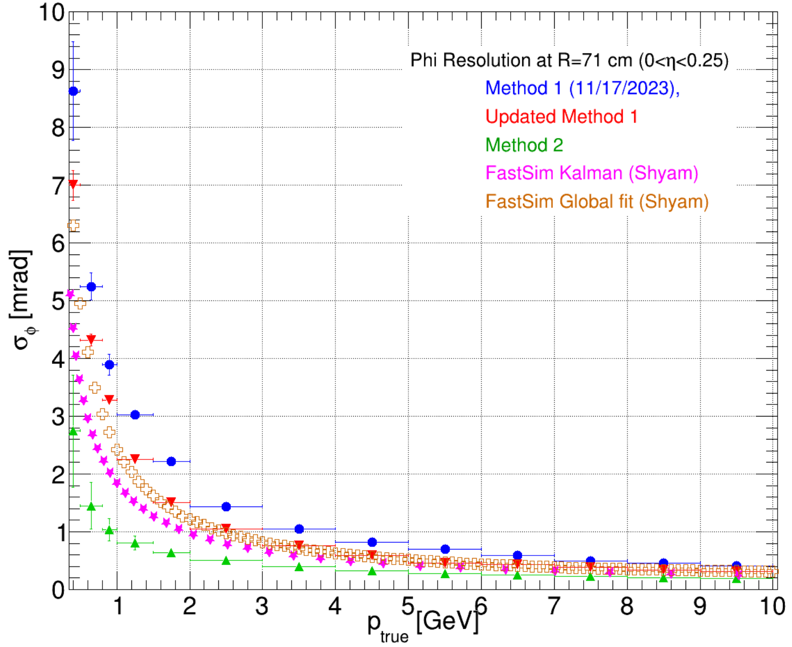
- **Track extrapolation uncertainty at DIRC layer: Estimation of Theta/Phi resolutions at DIRC (at 71 cm)**
- Chromatic uncertainty due to emission of photons of different energy (refractive index n = n(E))
- Measurement uncertainty in the position reconstruction of photons due to pixel size

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)

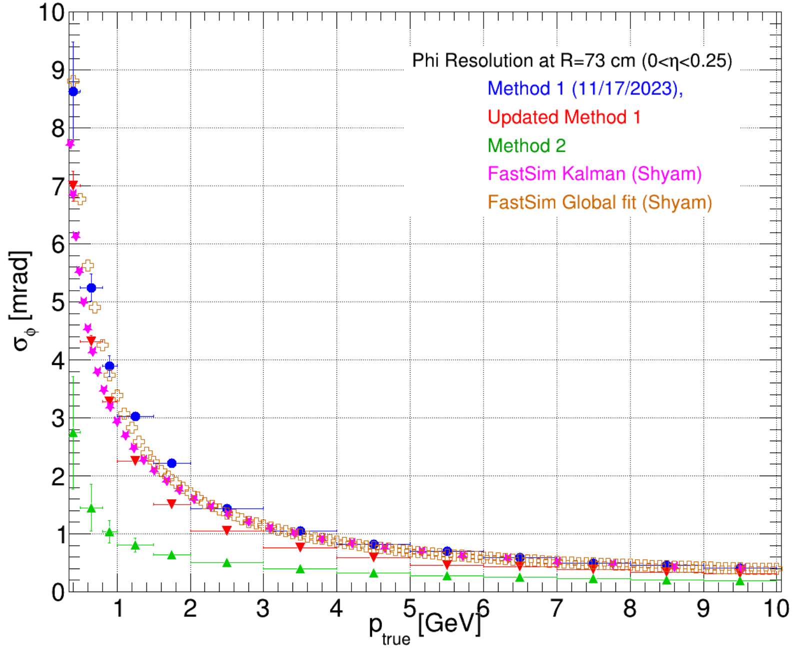
ePIC:old layout without barrel support

Outer MPGD: 68.7 cm



ePIC:24.06.0 layout with barrel support

Outer MPGD: 73 cm



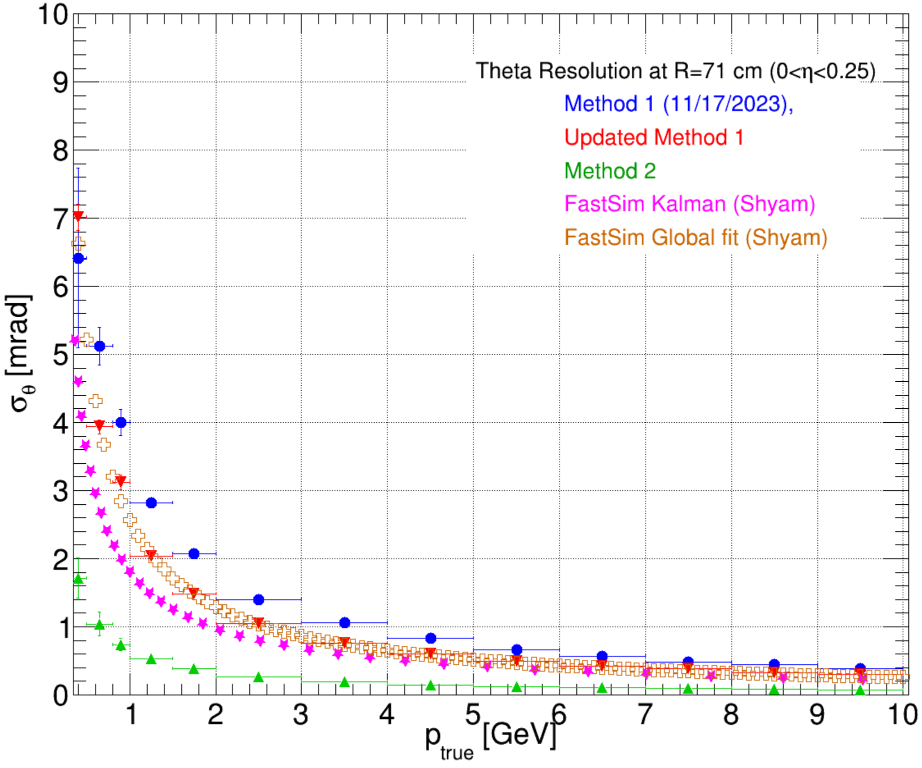
Theta Resolutions

Kalman uses two steps: Outward-->Inward and Inward-->Outward

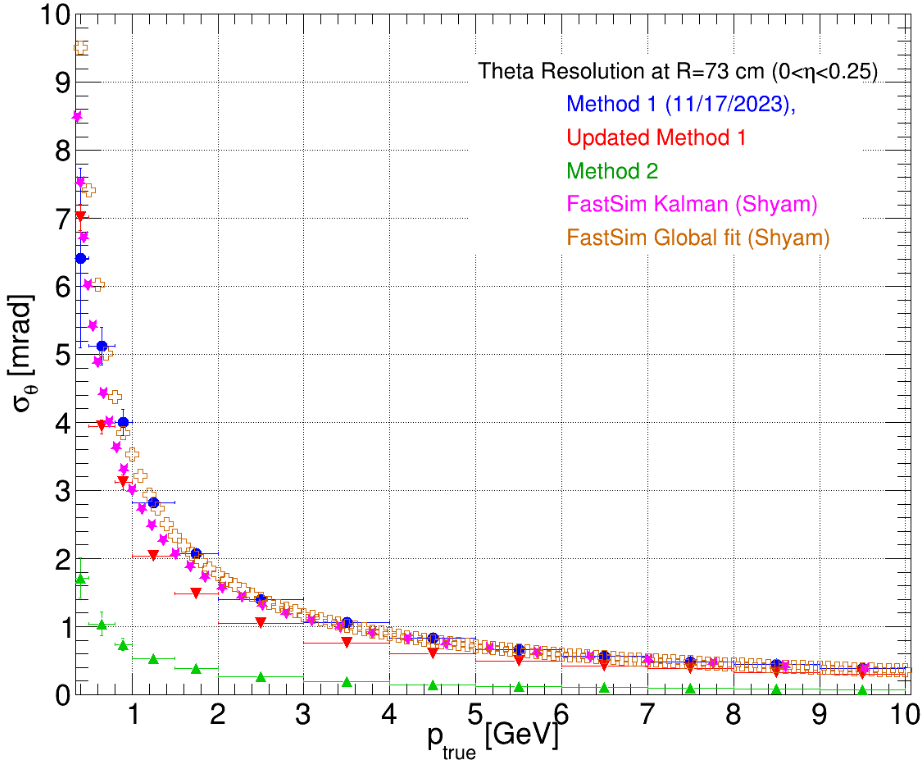
ePIC:old layout without barrel support

ePIC:24.06.0 layout with barrel support

Outer MPGD: 68.7 cm



Outer MPGD: 73 cm



As expected Theta resolutions is increased because of support layer

Spatial Resolution and Multiple Scattering (Fast Simulation)

$$\Delta\phi|_{res.} = \frac{\sqrt{12}\sigma_{r\phi}}{L_0\sqrt{(N-1)(N+1)(N+2)(N+3)}}\sqrt{(16N^3+2N^2-3N)+\frac{60N^3 r_0}{L_0}+\frac{60N^3 r_0^2}{L_0^2}}$$

$$\approx \frac{\sigma_{r\phi}}{L_0}\frac{8\sqrt{3}}{\sqrt{N+5}}\sqrt{1+\frac{15}{4}\frac{r_0}{L_0}+\frac{15}{4}\frac{r_0^2}{L_0^2}}$$

$$\Delta\phi|_{m.s.} = \frac{1}{\beta p_T} f\left(\frac{d}{X_0\sin\theta}\right)\sqrt{\frac{N-3/4}{N-1}+\frac{N}{N-1}\left(\frac{r_0}{L_0}\right)+\frac{N^2}{N-1}\left(\frac{r_0}{L_0}\right)^2}$$

$$\approx \frac{0.0136\,\mathrm{GeV/c}}{\beta p_T}\sqrt{\frac{d}{X_0\sin\theta}}\sqrt{1+\left(\frac{r_0}{L_0}\right)+\left(\frac{r_0}{L_0}\right)^2}$$

$$\Delta\theta|_{res.} = \frac{\sigma_z\sin^2\theta}{L_0}\sqrt{\frac{12N}{(N+1)(N+2)}}$$

$$\approx \frac{2\,\sigma_z\sin^2\theta}{L_0}\sqrt{\frac{3}{N+3}}$$

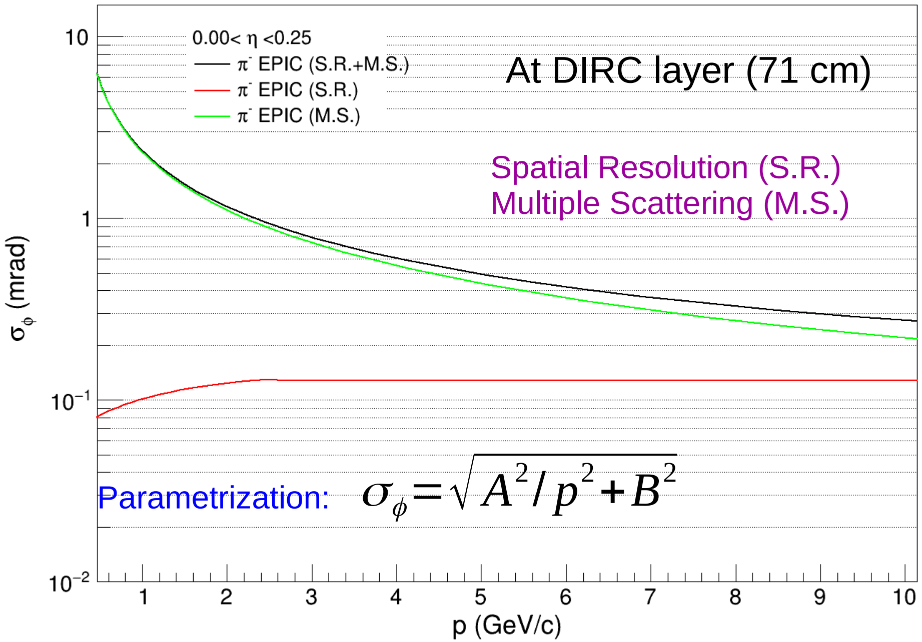
$$\Delta\theta|_{m.s.} = \frac{\sin\theta}{\beta\, p_T} f\left(\frac{d}{X_0\,\sin\theta}\right)$$

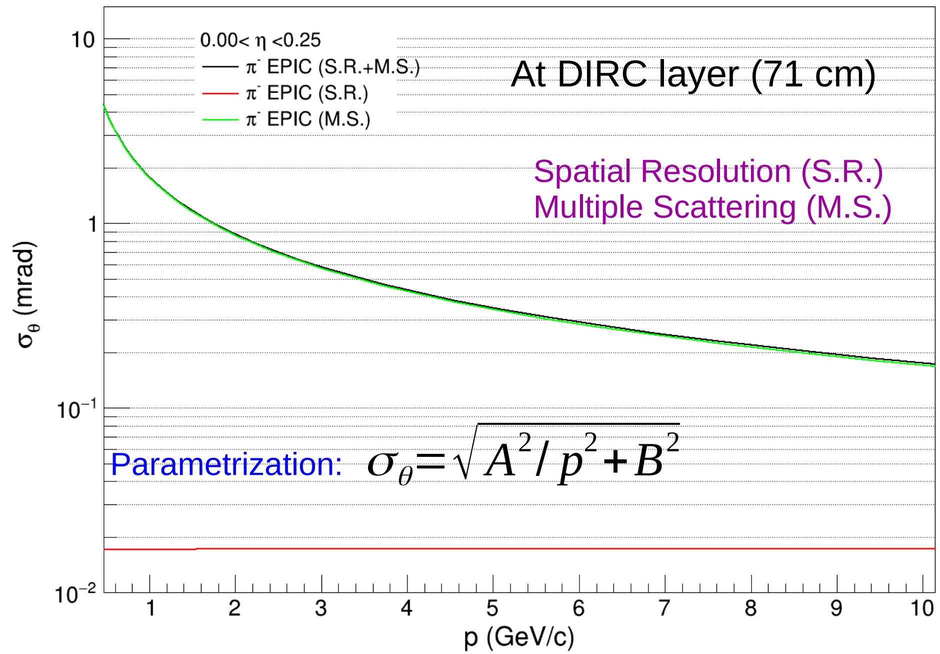
$$\approx \frac{0.0136\,\mathrm{GeV/c}\,\sin\theta}{\beta\, p_T}\sqrt{\frac{d}{X_0\,\sin\theta}}$$

Fomula for Theta/Phi resolution w.r.t. vertex

arXiv:1805.12014 [physics.ins-det]

Case of Outward-->Inward fitting and then extrapolation to 71.0 cm considering M.S.



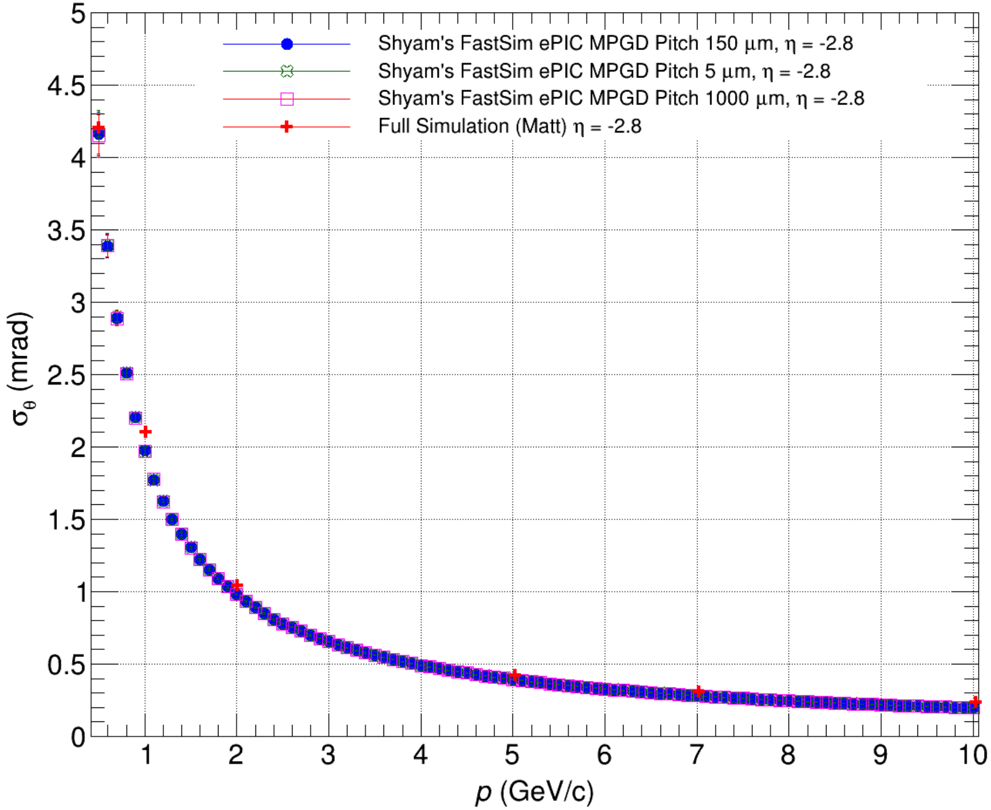


Theta/Phi Resolutions with different MPGD Resolutions

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

Z position = {25.,45.,65.,85.0,105.0,110.0,120.0};

Double_t x_x0Si = 0.0024   Double_t x_x0MM = 0.02



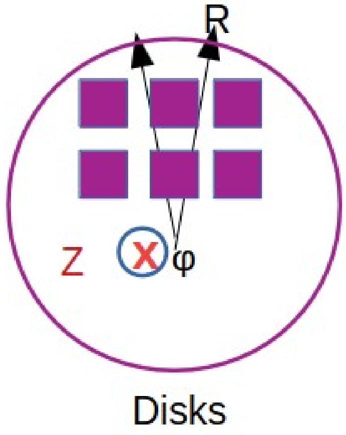
pfRich: Proximity Focusing RICH

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

Minor difference because global fit is based on uniform magnetic field

Further understanding to the major contributor to the uncertainity

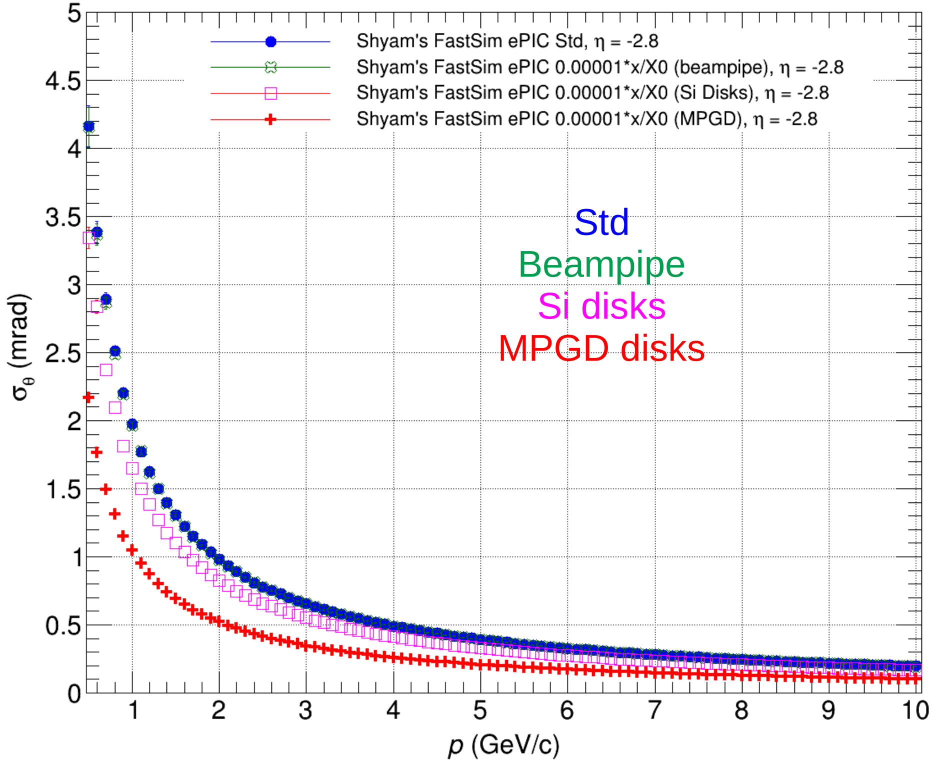
PfRICH Z = -123.5

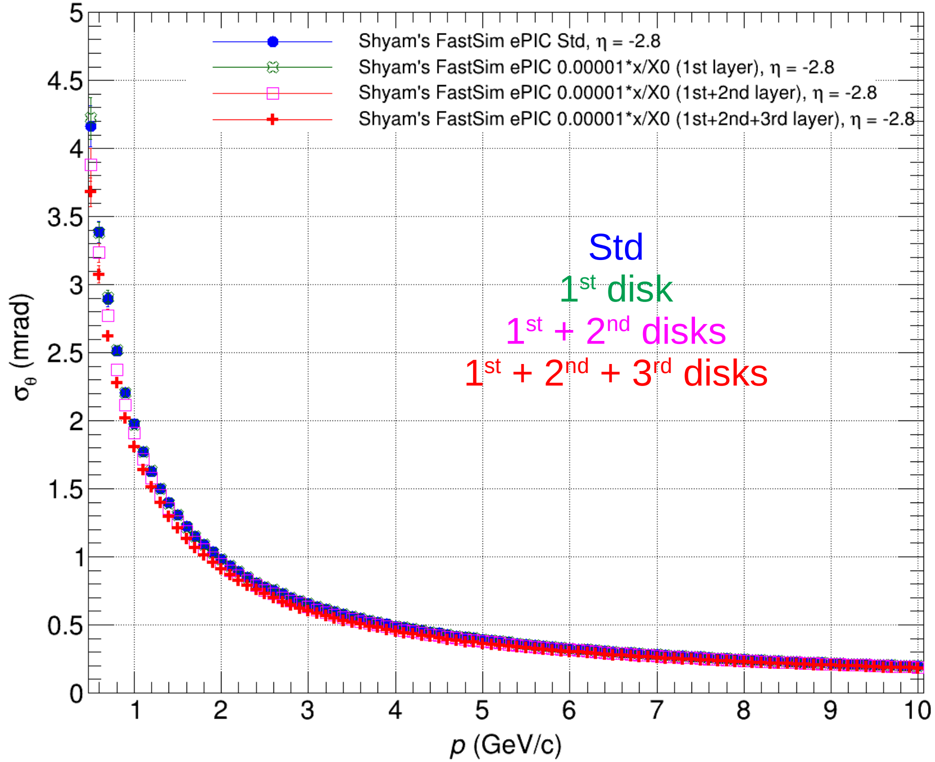


Working on improvement of theta/phi resolutions

Material Budget

Different Cases: Reduction of Material budget (switching off multiple scattering) by a factor of 10000

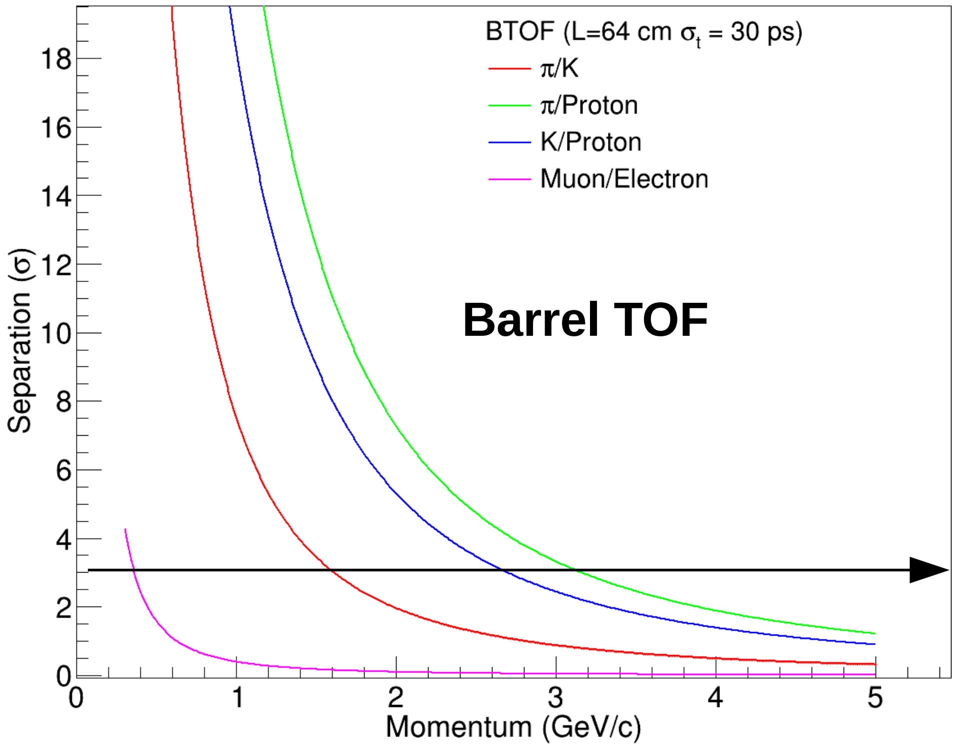


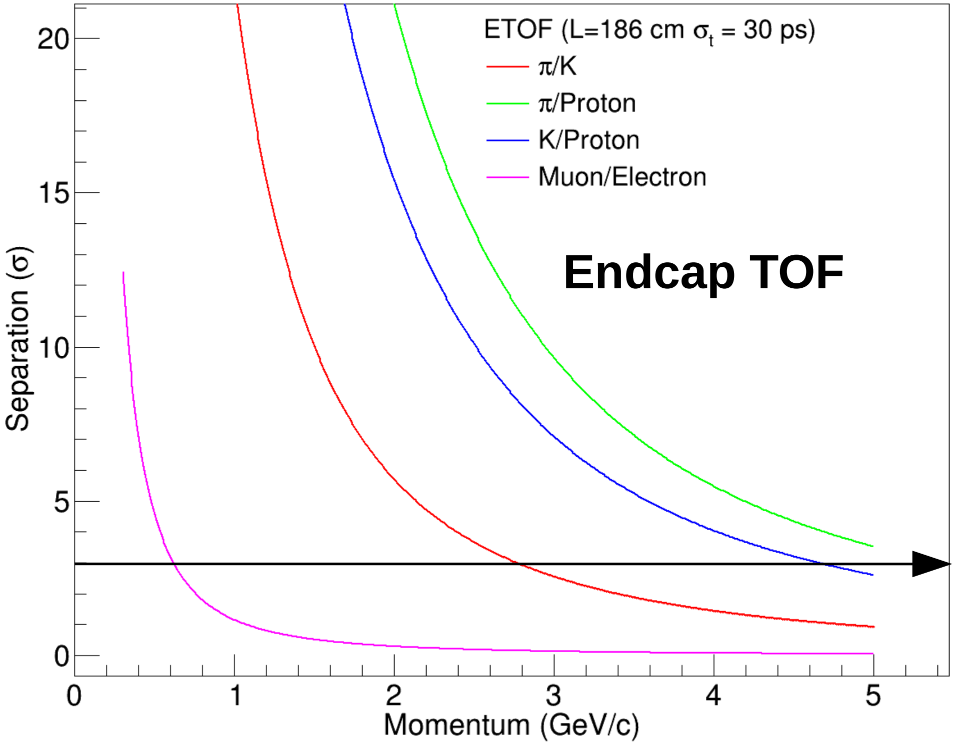


Particle Identification

Separation (Particles A & B): $$n=\frac{(TOF)_A-(TOF)_B}{\sigma_t} = \frac{L}{p\,c\,\sigma_t}(E_A-E_B)$$

Very good particle separation (expected) at low momentum: use PID information to improve performances





Improvement of Performances (Preliminary Ideas)

- **Method:** Using mean dE/dx information see paper.

Look article for dE/dx vs p: arXiv:hep-ex/0104006

- **Option 1: TOF will provide a good separation at low momentum (similar idea for other methods of particle identification)**
  - Identify a particle using beta vs momentm band (TOF = L/β)
  - We assume length and beta measured precisely which depends on precise measurement of time-of-flight
  - Assign ideal mass to each identified particle and recalculate the momenta

$$p_{recal} = m_0(ideal)\,\beta\ (measurement)\,\gamma c$$

- **Option 2: TOF will provide a good separation at low momentum**
  - Identify a particle using beta vs momentm band (TOF = L/β)
  - Project beta distribution (Gaussian) at a given momentum then use mean value
  - Assign ideal mass to each identified particle and recalculate the momenta
- **Option 3: TOF will provide a good separation at low momentum**
  - Identify a particle using beta vs momentm band (TOF = L/β)
  - We assume beta measured precisely which depends on precise measurement of time-of-flight
  - Assign ideal mass to each identified particle and recalculate the momenta use this moment and beta to refit the track with Kalman.

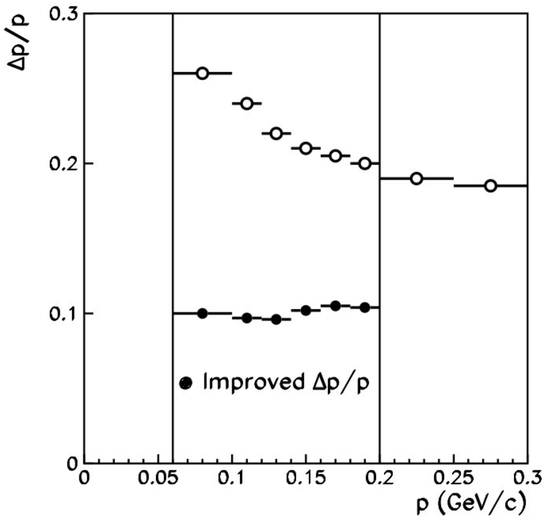


Figure 4: Momentum resolution improvement in the momentum range 50 – 200MeV/c in STAR-SVT. Open circles denote the resolution obtained by a helix fit and filled circles the resolution when the momentum is extracted from the dE/dx information.

At the moment, we fit the track with pion hypothesis

Summary

- Extracted the tracking performances with the latest geometry ePIC (24.06.0)
- Studies several configurations to understand the sources of errors
- Ideas to improve the tracking performances but need further test and improvements

Thank You !!