Benchmarking Tracking Performance and Charm Hadron Reconstruction in the ePIC Experiment

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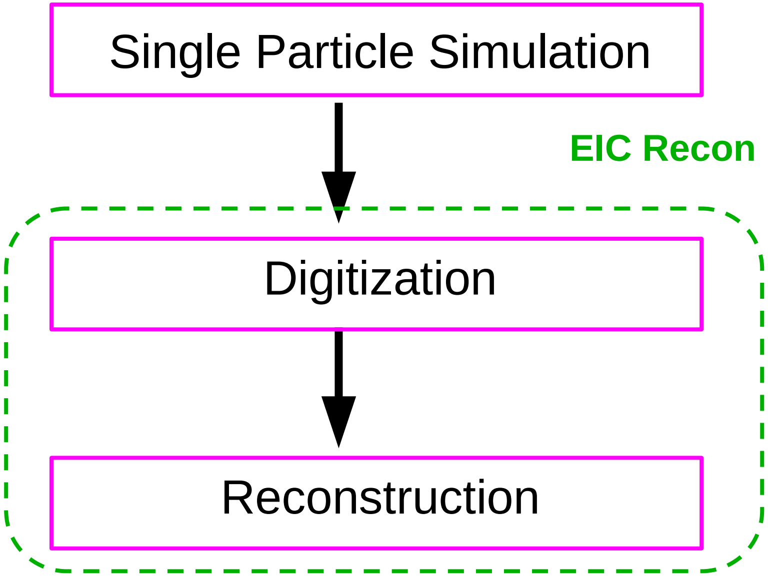
Previous studies (Average number of hits)

https://indico.bnl.gov/event/23130/contributions/90774/attachments/54104/92571/Tracking_Performances_Shyam_25April24.pdf

Simulation and Reconstruction in ePIC experiment

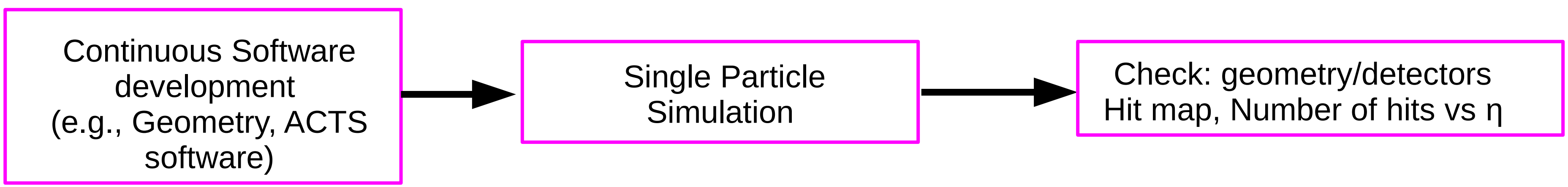


DD4HEP and GEANT4 (Particle Gun): Single particle generation and their propagation using G4ParticleGun in GEANT4

Digitization (detector response): For silicon detectors hits are smeared (Gaussian) according to spatial resolutions after applying an energy threshold

Tracking in EIC Recon using ACTS (A Common Tracking Software): Digitized hits are used for the track reconstruction in ACTS framework

Why single particle tracking benchmarks?



Simulation and Reconstruction in ePIC experiment

Continuous Software development (e.g., Geometry, ACTS software) → Single Particle Reconstruction → Check: Momentum, DCA resolutions, and pull distributions of track parameters

Two main options:

- Test mode: run 10k events
- Full simulation campaigns

GNU: Makefile (compile)   Python: Snakemake

Snakefile setting: Snakefile

Concept is similar: target-rule (command)

```
rule tracking_performance_campaigns:
    input:
        expand(
            "results/tracking_performances/{CAMPAIGN}",
            CAMPAIGN=[
                "24.10.1",
                "25.04.1",
            ],
        )
```

"24.10.1" → Produced with **float** so breaks as expected

"25.04.1" → Produced with **double** so working fine after change

Tracking performances was not working fine: **Fixed**

```
benchmarks/tracking_performances/Tracking_Performances.C
@@ -77,9 +77,9 @@ void Tracking_Performances(TString filename="tracking_output",TString particle="
    TTreeReaderArray<Double_t> vx_mc(myReader, "MCParticles.vertex.x");
    TTreeReaderArray<Double_t> vy_mc(myReader, "MCParticles.vertex.y");
    TTreeReaderArray<Double_t> vz_mc(myReader, "MCParticles.vertex.z");
-   TTreeReaderArray<Float_t> px_mc(myReader, "MCParticles.momentum.x");
-   TTreeReaderArray<Float_t> py_mc(myReader, "MCParticles.momentum.y");
-   TTreeReaderArray<Float_t> pz_mc(myReader, "MCParticles.momentum.z");
    TTreeReaderArray<Int_t> status(myReader, "MCParticles.generatorStatus");
    TTreeReaderArray<Int_t> pdg(myReader, "MCParticles.PDG");
    TTreeReaderArray<Int_t> match_flag(myReader,
  Form("CentralCKF%sTrackParameters.type",tag.Data()));
```

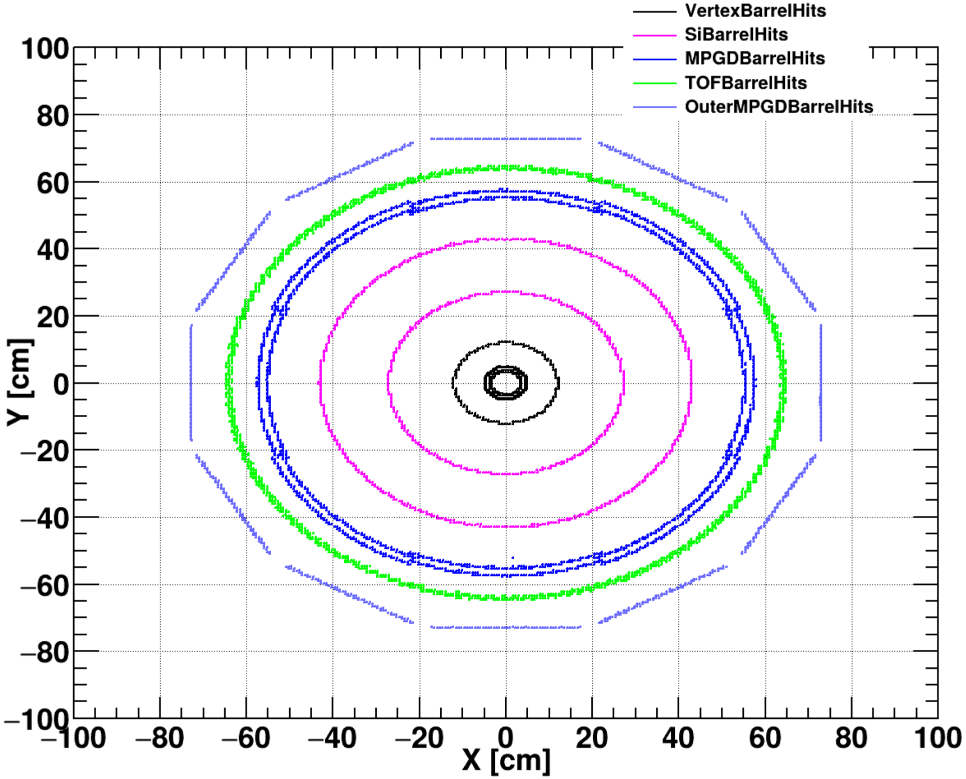
```
    TTreeReaderArray<Double_t> vx_mc(myReader, "MCParticles.vertex.x");
    TTreeReaderArray<Double_t> vy_mc(myReader, "MCParticles.vertex.y");
    TTreeReaderArray<Double_t> vz_mc(myReader, "MCParticles.vertex.z");
+   TTreeReaderArray<Double_t> px_mc(myReader, "MCParticles.momentum.x");
+   TTreeReaderArray<Double_t> py_mc(myReader, "MCParticles.momentum.y");
+   TTreeReaderArray<Double_t> pz_mc(myReader, "MCParticles.momentum.z");
    TTreeReaderArray<Int_t> status(myReader, "MCParticles.generatorStatus");
    TTreeReaderArray<Int_t> pdg(myReader, "MCParticles.PDG");
    TTreeReaderArray<Int_t> match_flag(myReader,
  Form("CentralCKF%sTrackParameters.type",tag.Data()));
```

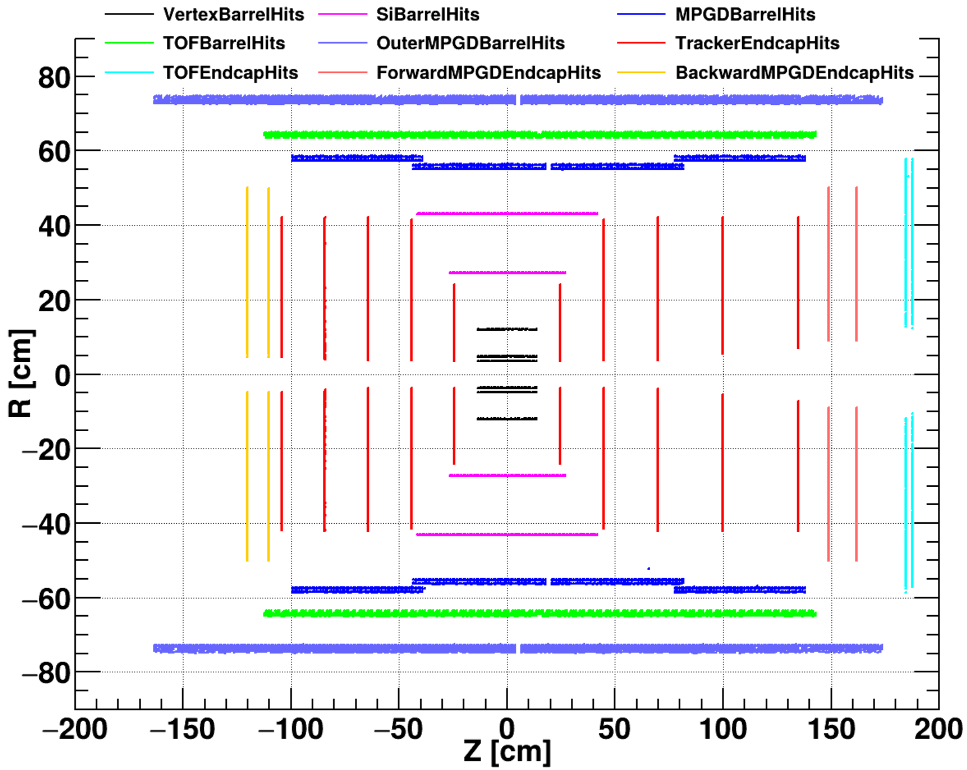
Change type from **float to double**

Hit Maps (Simulation Level)

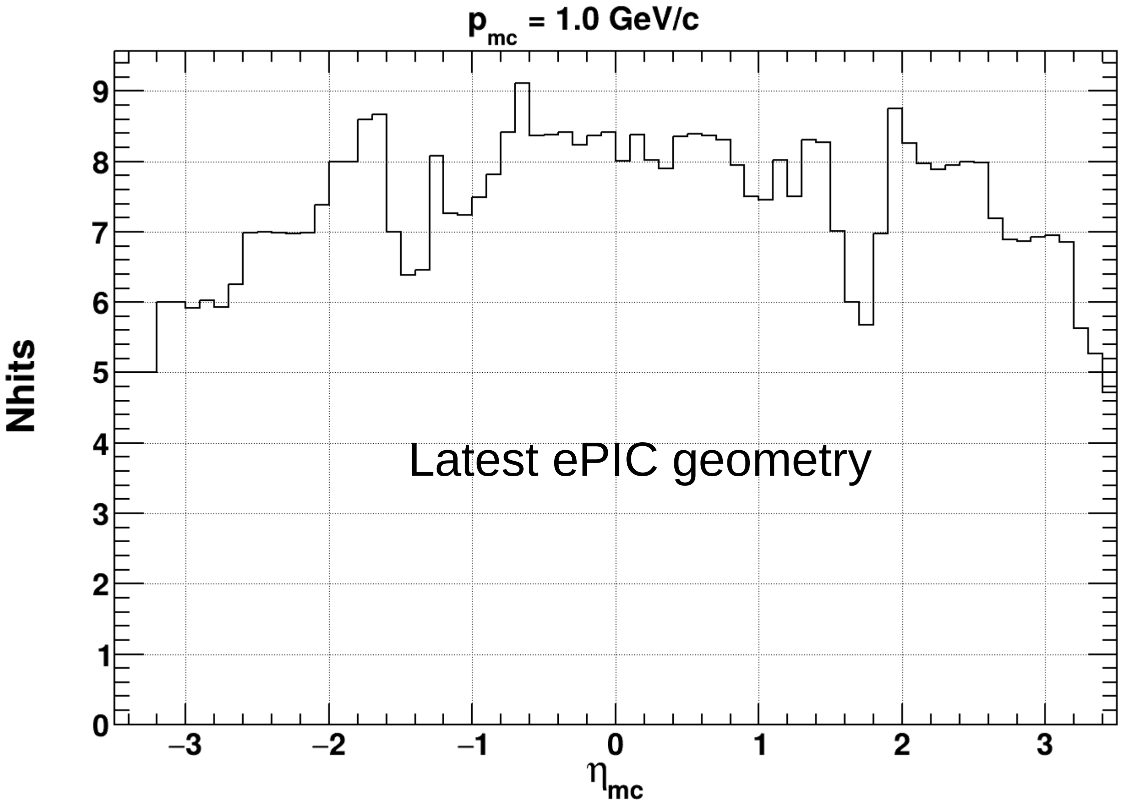
10k Events (pi-)

MOMENTUM=[0.5, 1.0, 2.0, 5.0, 10.0, 15.0]





Average Number of Hits vs η



Nhits >= 4
ndf (trackfit) >=3

Nhits = 3 will lead to biased results due to the low number of degrees of freedom (ndf = 1)

Similar plots for other momentum ranges are produced

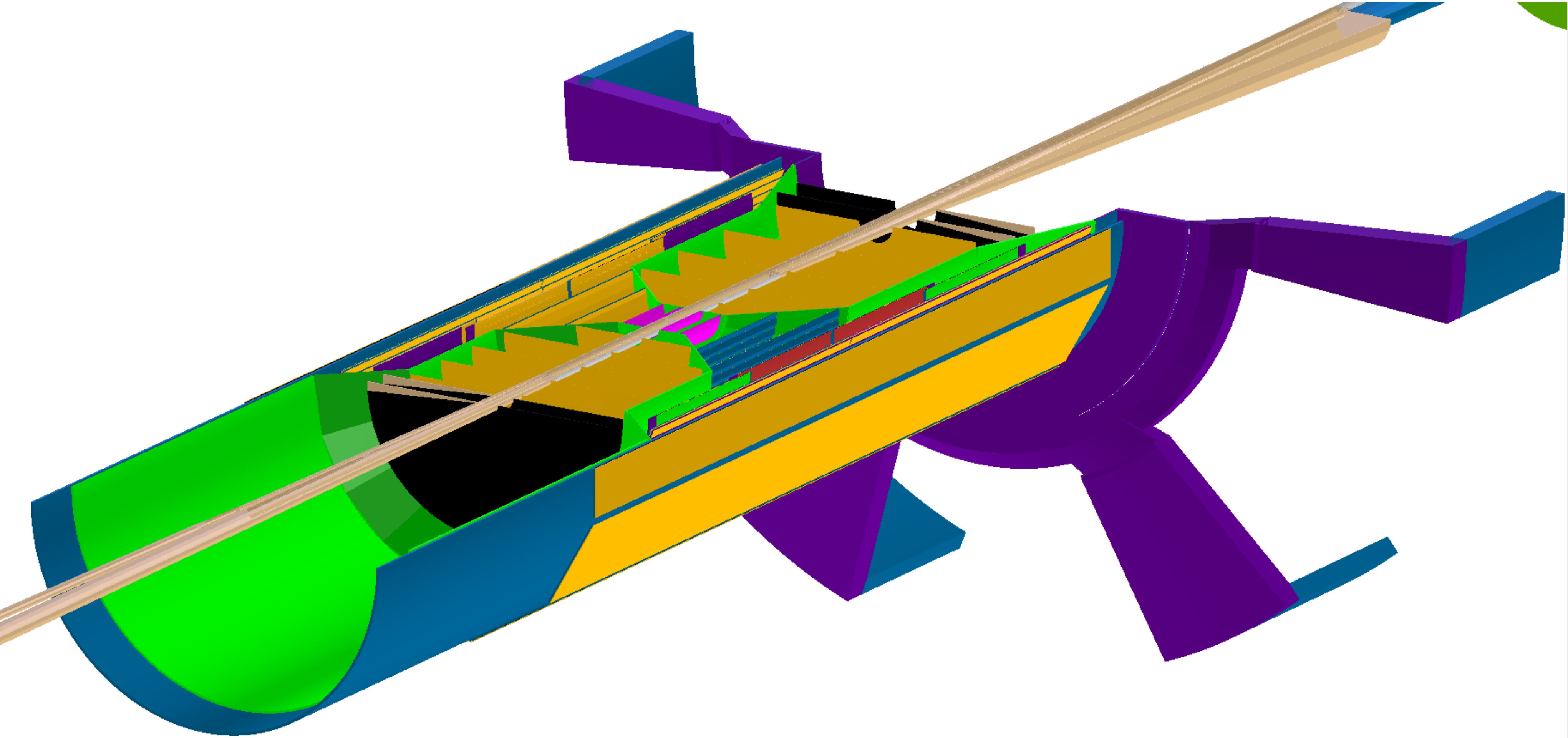
Tracking Performances Results

https://github.com/eic/detector_benchmarks/pull/113

The ePIC Tracker

shyam@shyam:~/eic/epic$ git describe --tags --abbrev=0
24.12.0
shyam@shyam:~/eic/EICrecon$ git describe --tags --abbrev=0
v1.20.0

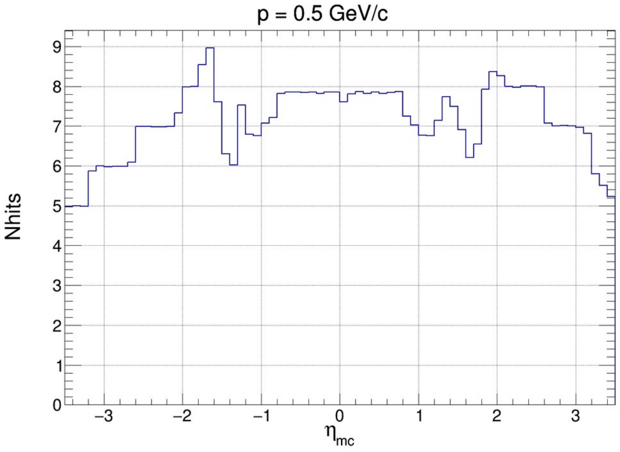
Geometry Parameters

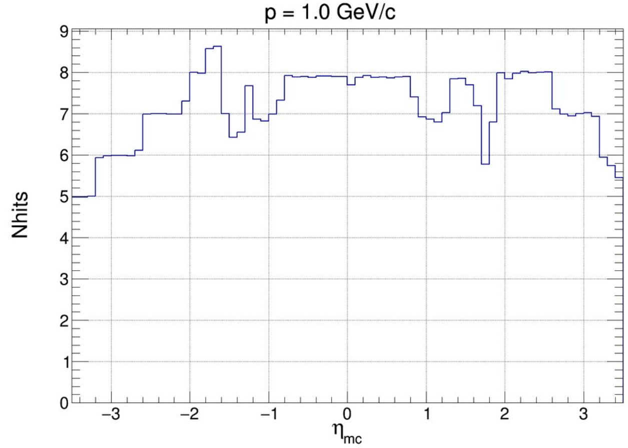


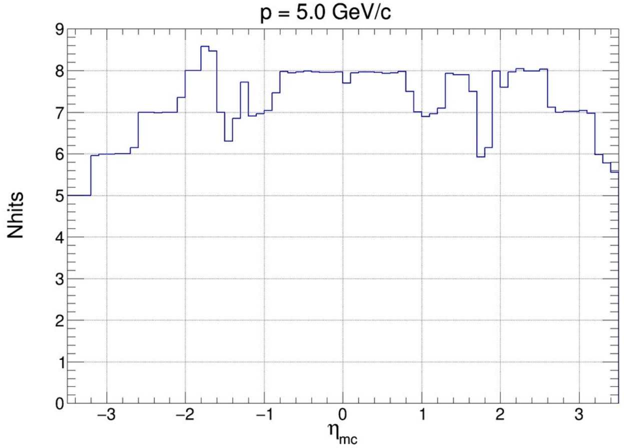
Nhits vs Eta

ePIC: 24.04.0

Nhits>=5 as reported



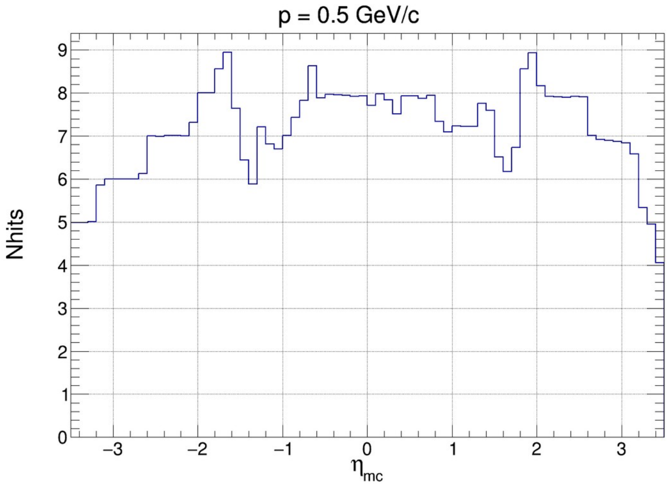


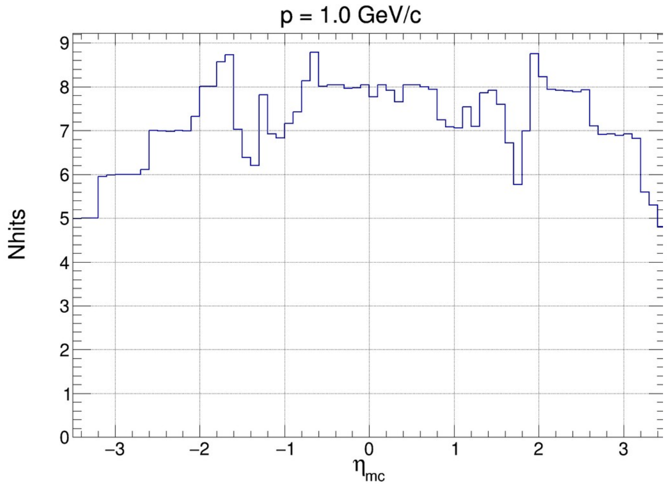


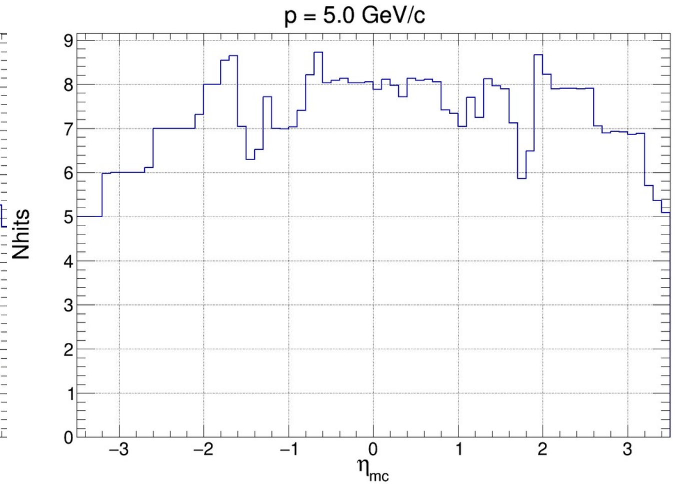
ePIC: 24.12.0

Nhits>=4

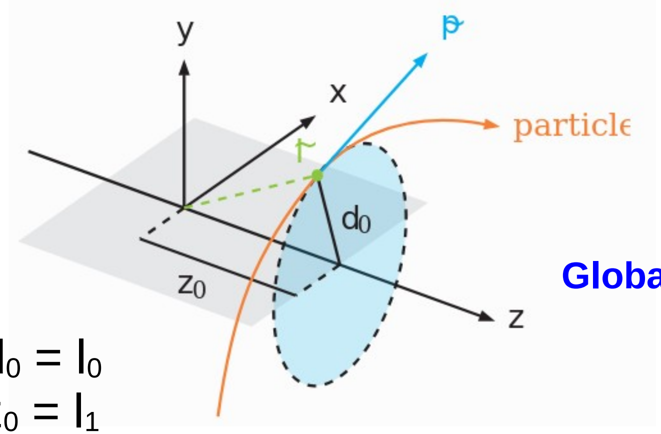
Forward beampipe radius is increased







Track Parameters $(l_0, l_1, \phi, \theta, q/p, time)$ If tracking algorithm is working fine Pull must be consistent with unity



$d_0 = l_0$
$z_0 = l_1$

At Point of closest approach

$$(l_0, l_1, \phi, \theta, q/p)$$

Global (Lab frame)

$$(x, y, z, p_x, p_y, p_z, q)$$

$$x = -l_0 \sin\phi, \quad y = l_0 \cos\phi, \quad z = l_1$$

$$p_x = p\cos\phi \sin\theta, \quad p_y = p\sin\phi\sin\theta, \quad p_z = p\cos\theta$$

$$charge = sign(q/p)$$

Plan to add it to the benchmarks

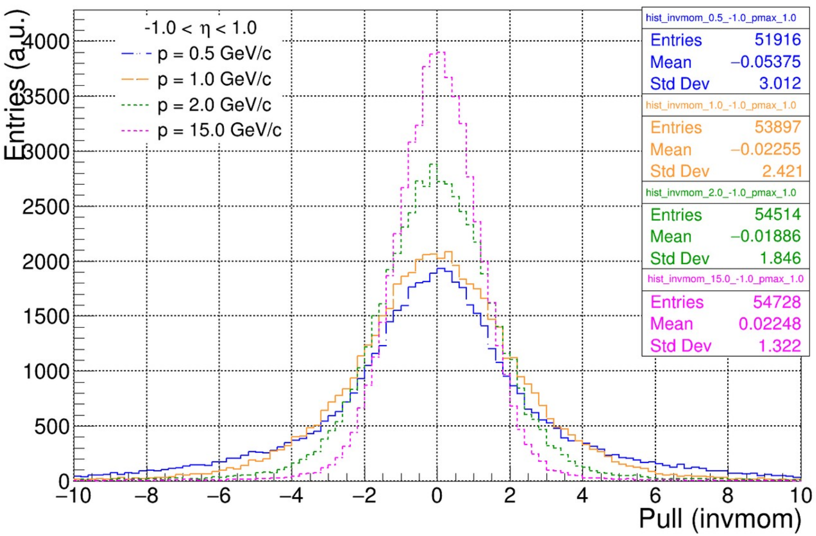
$$\text{Pull } l_0 = \frac{(l_{0\,rec} - l_{0\,gen})}{\sigma_{l0}} \qquad \text{Pull } \phi = \frac{(\phi_{rec} - \phi_{gen})}{\sigma_\phi} \qquad \text{Pull } q/p = \frac{(q/p_{rec} - q/p_{gen})}{\sigma_{q/p}}$$

$$\text{Pull } l_1 = \frac{(l_{1\,rec} - l_{1\,gen})}{\sigma_{l1}} \qquad \text{Pull } \theta = \frac{(\theta_{rec} - \theta_{gen})}{\sigma_\theta} \qquad \text{Pull } p = \frac{(p_{rec} - p_{gen})}{\sigma_p}$$

Simulation of 200K pi- for momentum 0.5, 1.0, 2,0, 15.0 GeV/c

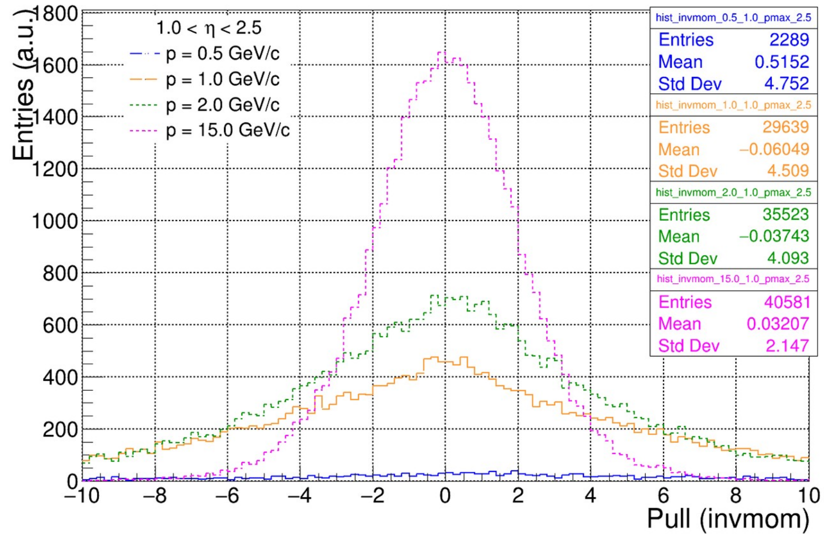
ePIC: 24.12.0
EICRecon: v1.20.0

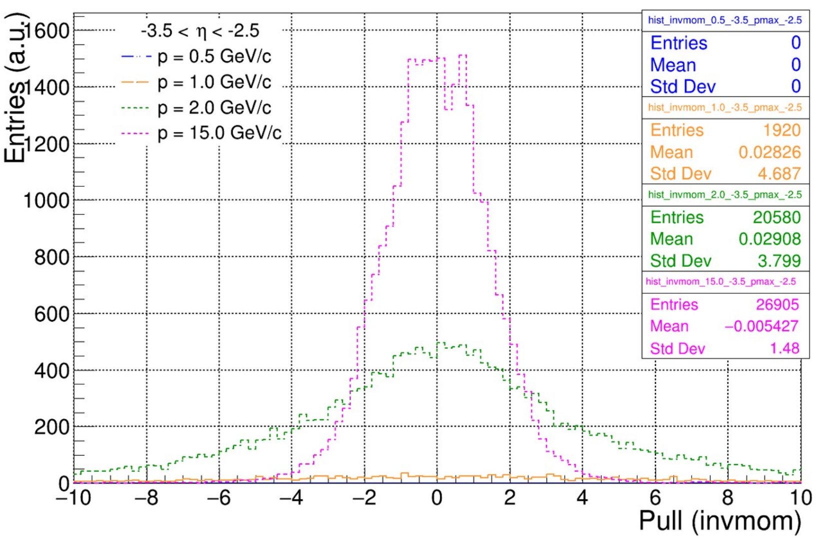
Pull distributions (Inverse Momentum)



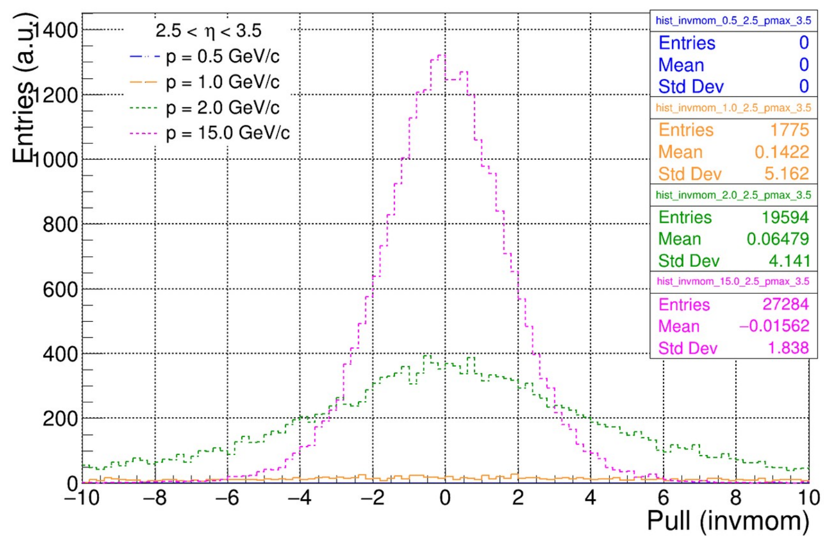
ePIC: 24.12.0

EICRecon: v1.20.0

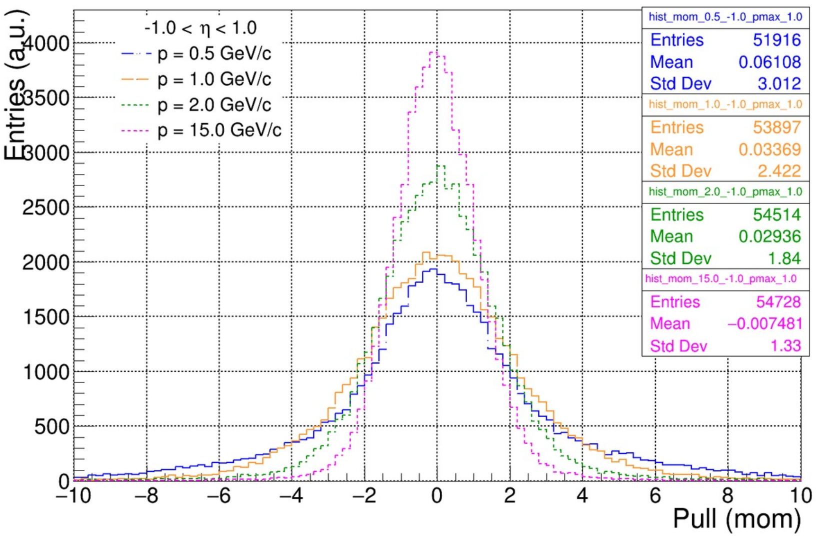


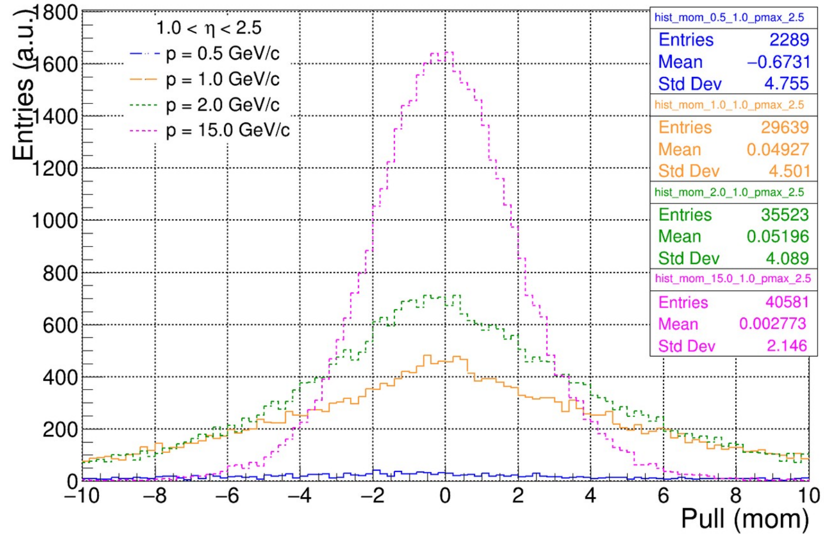


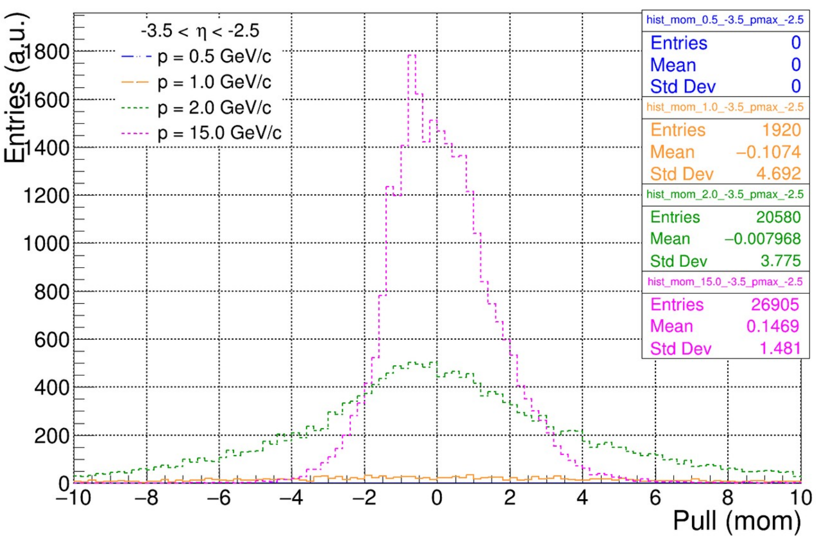
Inverse Momentum = 1/p

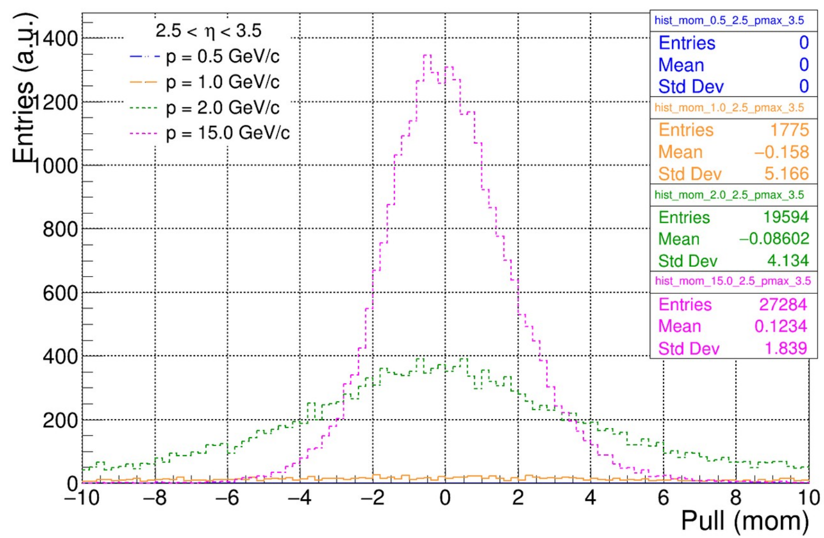


Pull distributions (Momentum)

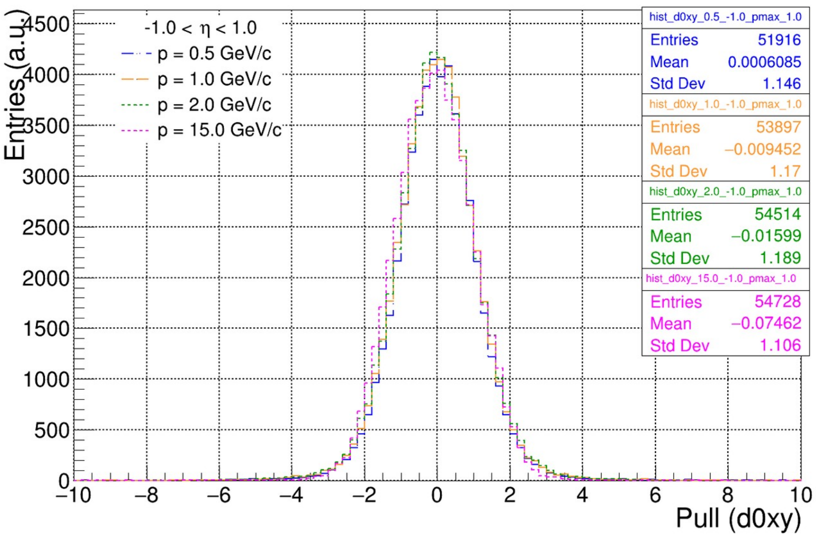


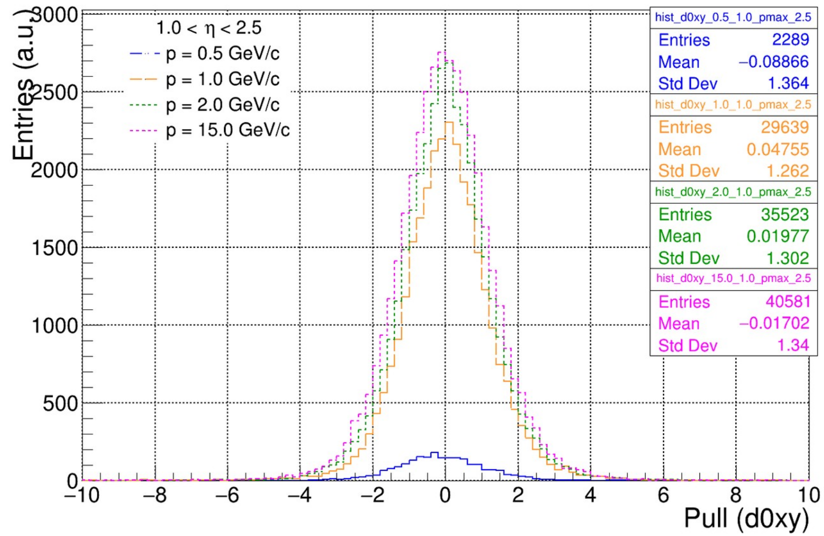


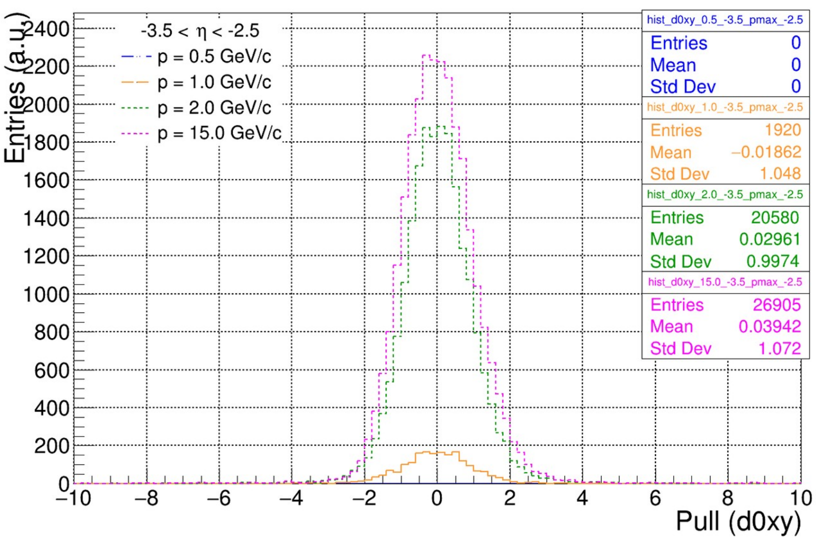


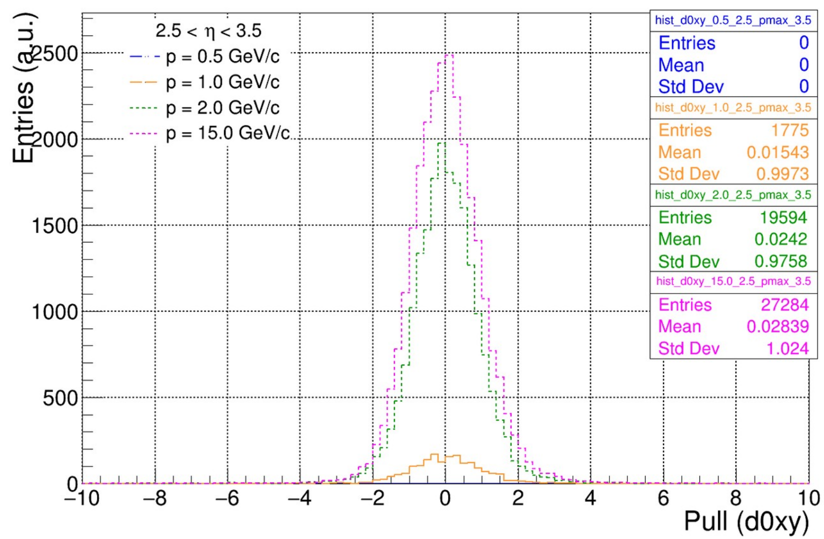


Pull distributions (l_0 or d_{0xy})

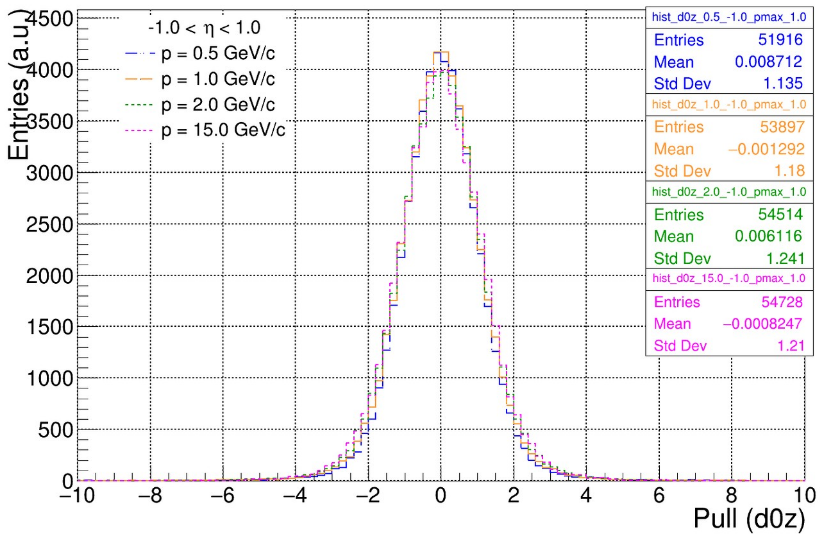


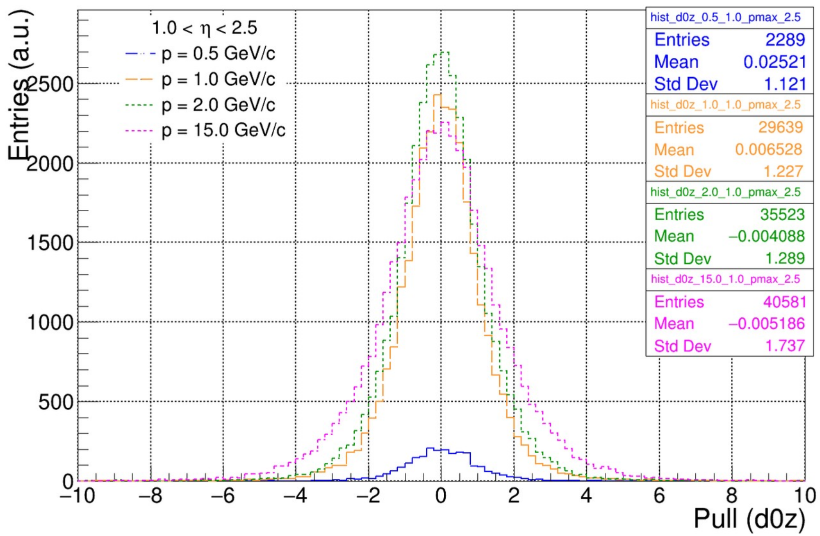


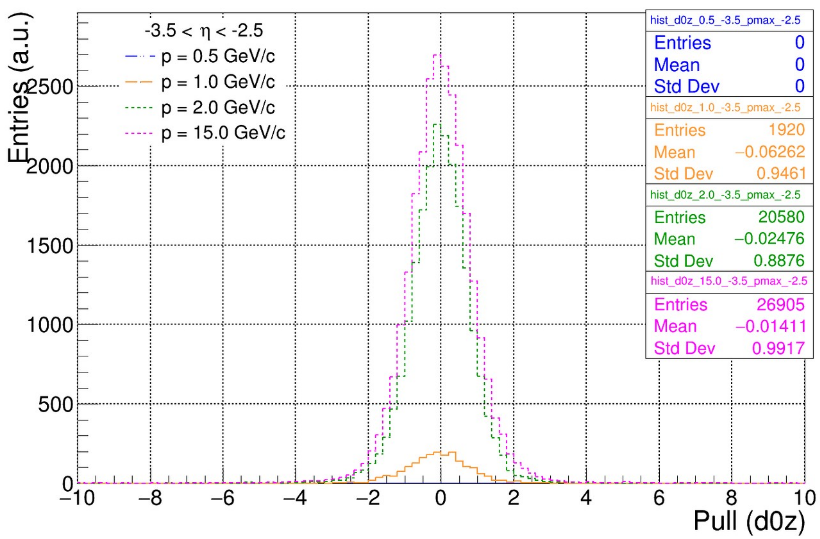


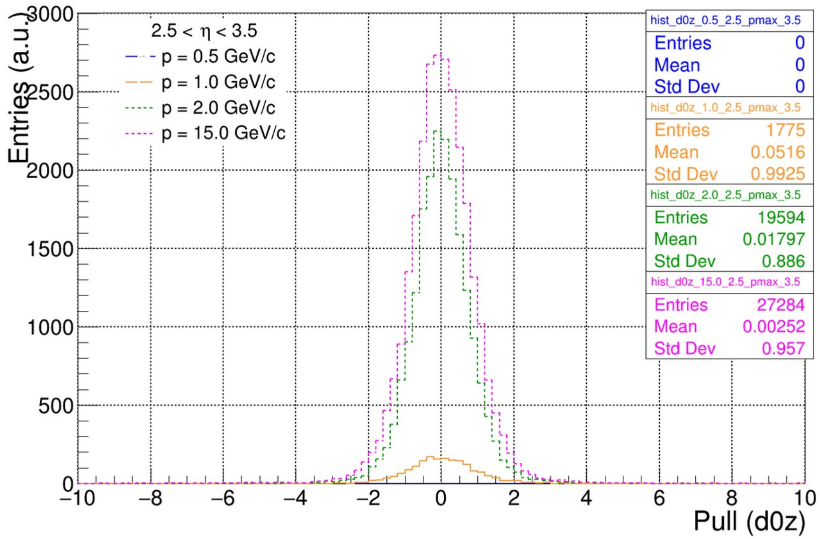


Pull distributions (l_1 or d_{0z})

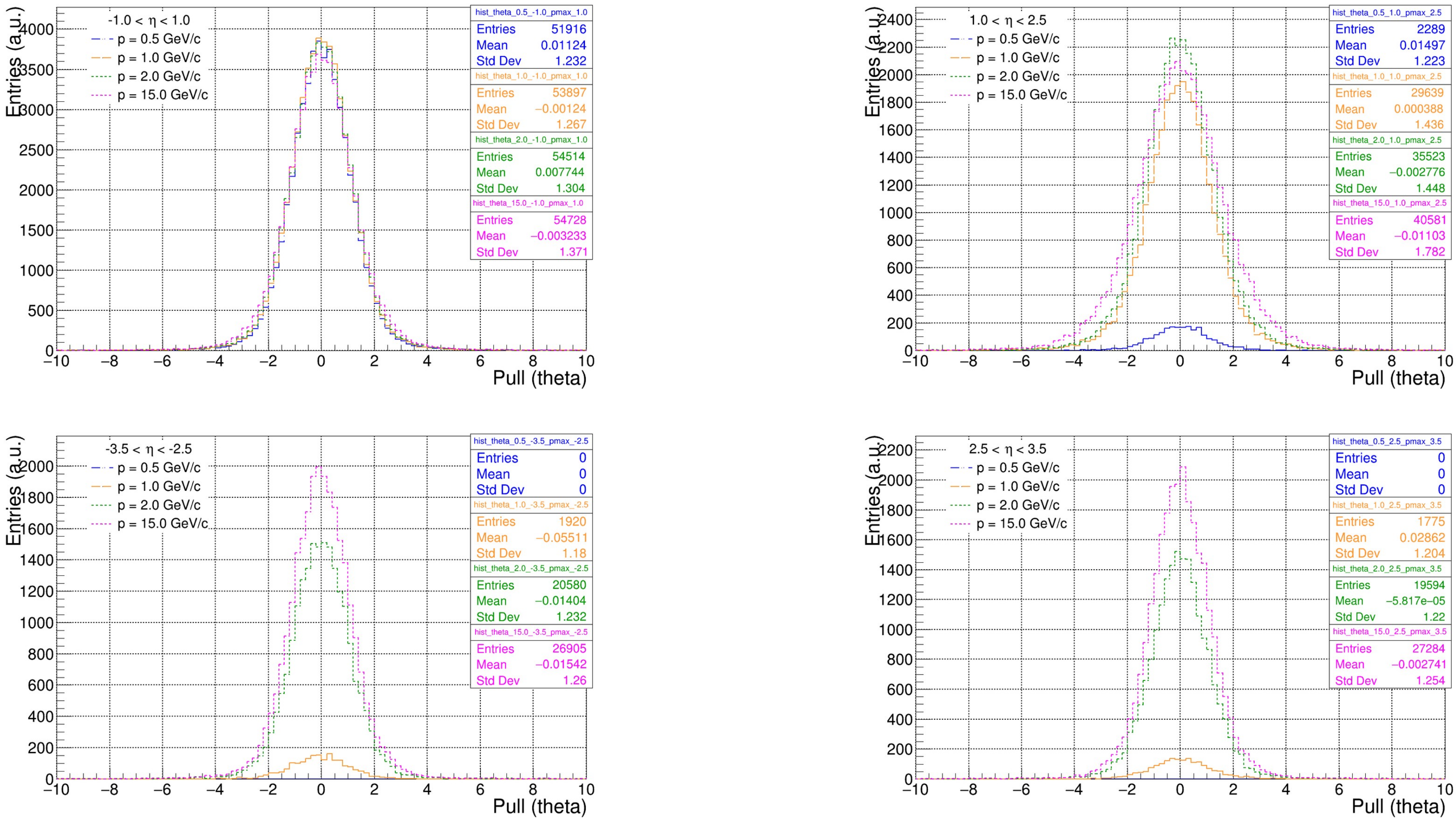




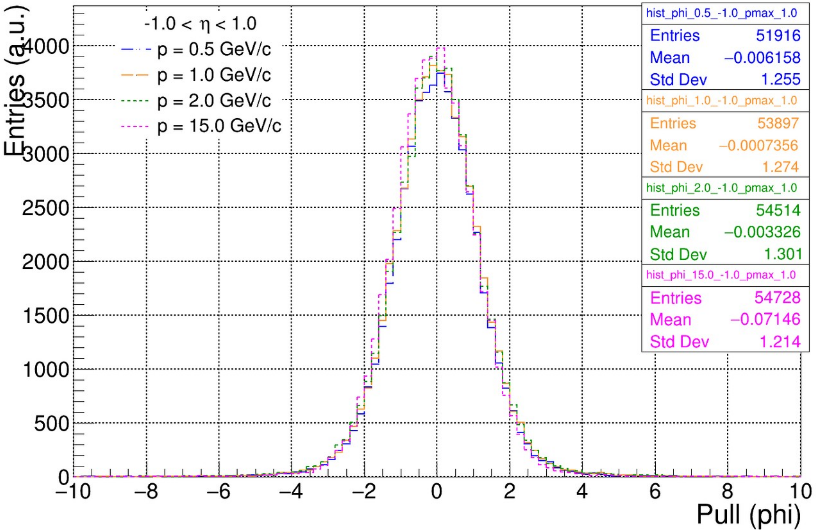


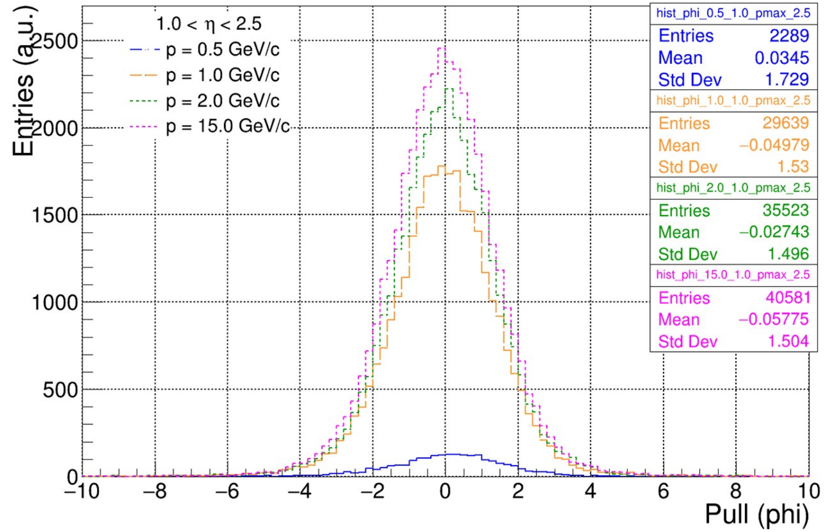


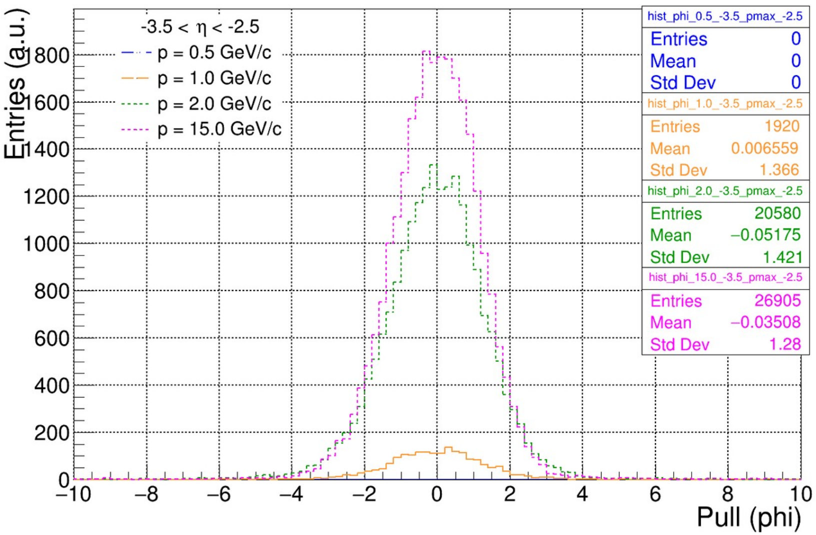
Pull distributions (Theta)

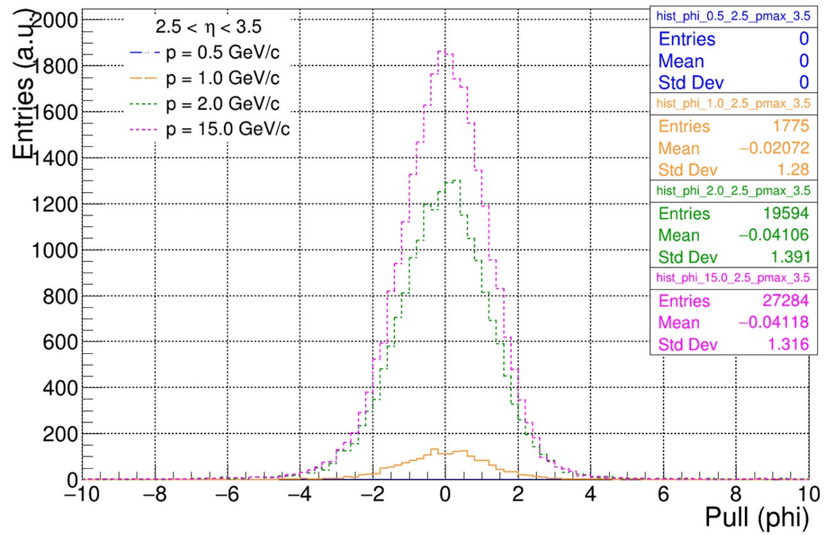


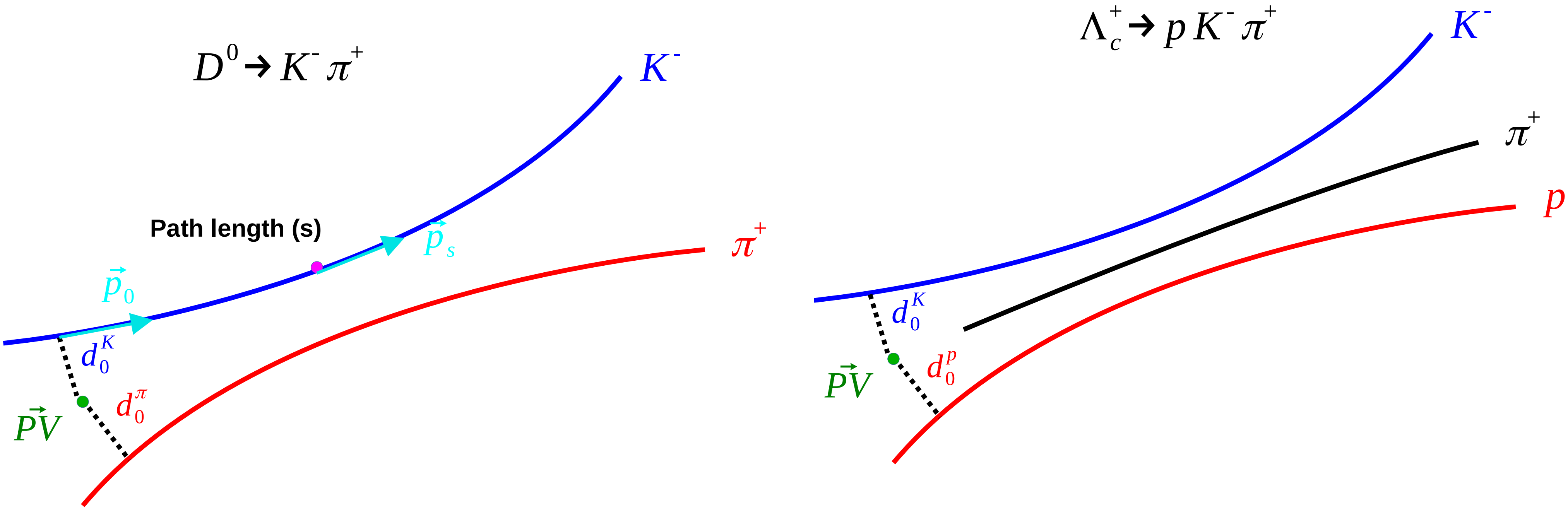
Pull distributions (Phi)



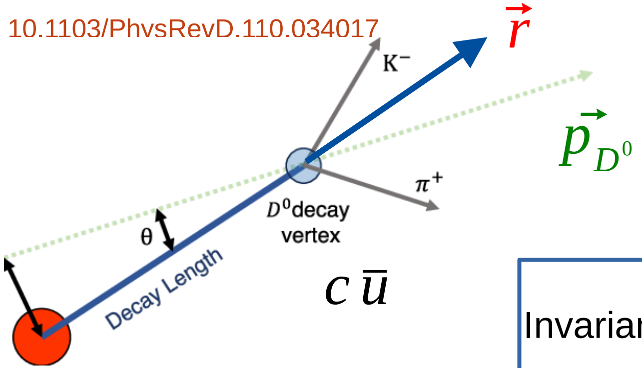






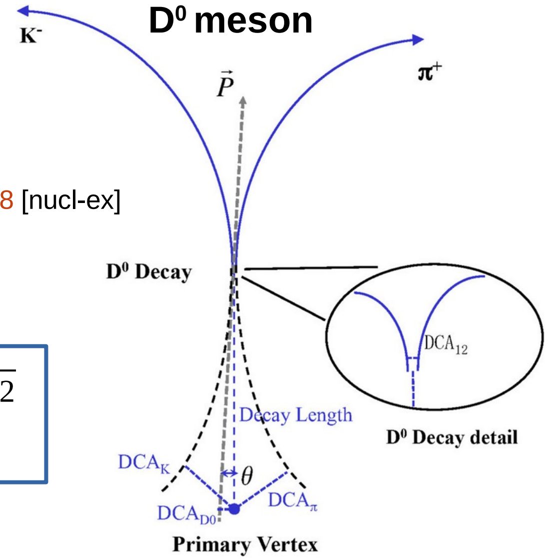


Slides from Jets and Heavy-flavor meeting



cτ = 123 µm

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



Topological Variables:

- DCA_{K^-} and DCA_{π^+} with respect to the reconstructed primary vertex (d0_k, d0_pi)
- Decay length of D^0 meson (decaylength)
- Cosθ (angle between **dl** and $\mathbf{p}_{D0}$)
- DCA_{12} distance between the daughter tracks of D^0
- DCA_{D0} impact parameter of reconstructed D^0 meson
- m_{D0} invariant mass of kaon and pion pairs
- pt_D0 reconstructed pt of the D^0 meson
- eta_D0 reconstructed η of the D^0 meson
- Multiplicity (mult)

Decay length (dl), Primary Vertex (PV), Secondary Vertex (SV)

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

$$\cos\theta = \frac{\vec{dl}\,.\,\vec{p}}{|\vec{dl}||\vec{p}|}$$

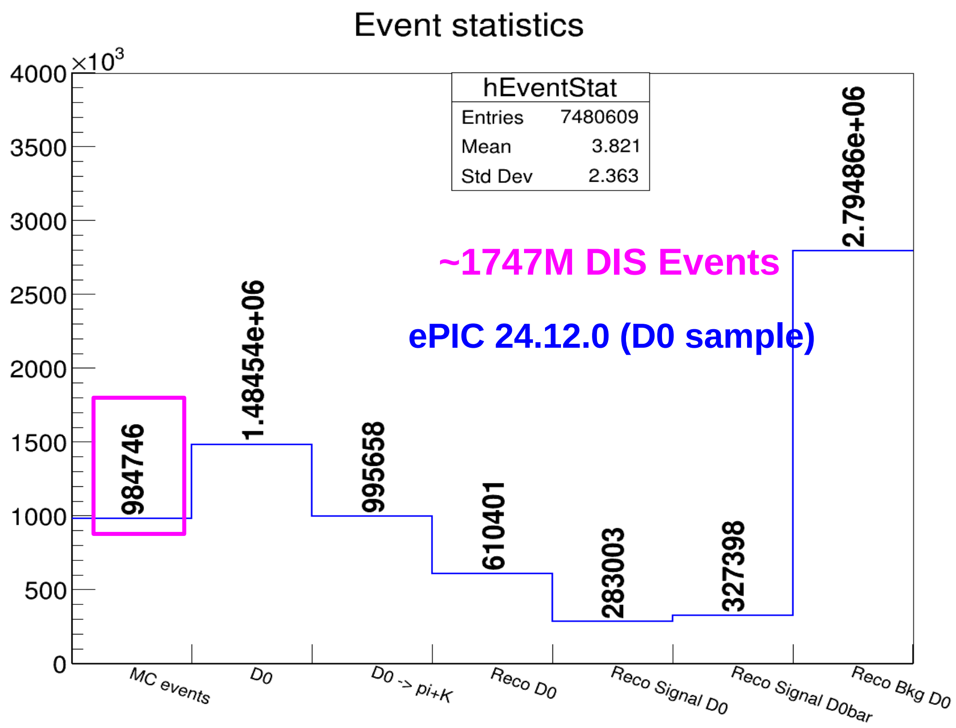
$$DCA_{D0} = dl \sin\theta$$

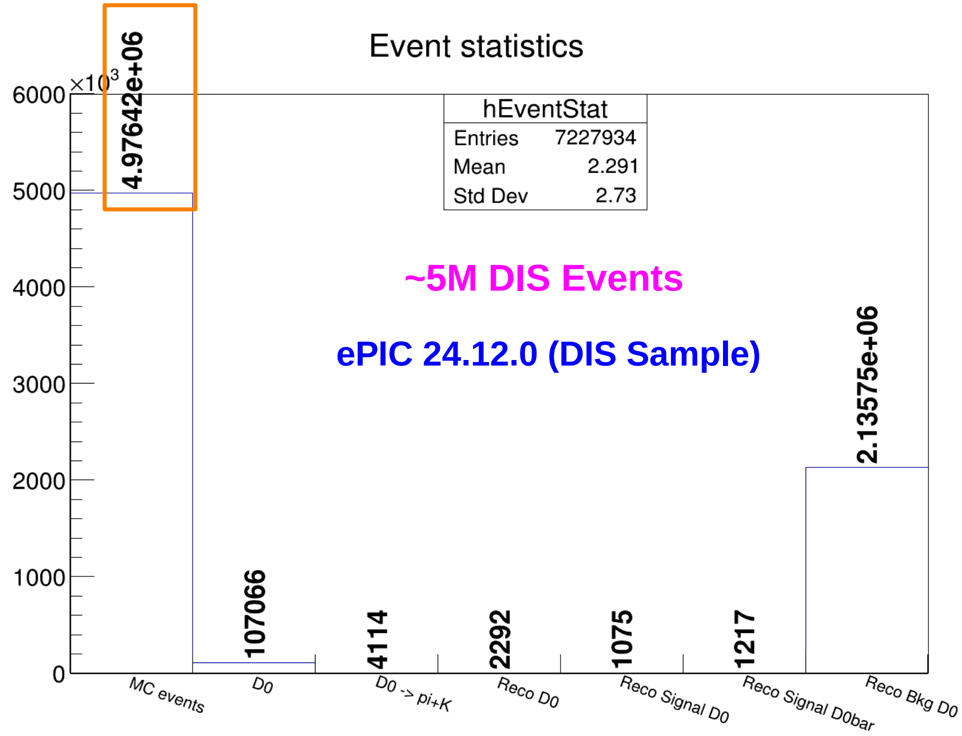
Data Sample for ML ($Q^2 > 1$ GeV^2)

- BDT requires the features for the signal D^0 meson and background D^0 meson (fake combinations of pion,kaon)
  - D^0 enriched same created filtering **PYTHIA8 ep, NC, 10X100, Q^2 >1 GeV^2 events (~1747M)** such that each event consist one $D^0 \rightarrow$ k-π+ known as Signal taken from 24.12.0/epic_craterlake/SIDIS/D0_ABCONV/pythia8.306-1.1/10x100/q2_1):

    Total files 1879 and Events = 984746

  - Background from 24.12.0/epic_craterlake/DIS/NC/10x100/minQ2=1: **Total files 5180 and Events = 4976419**





Secondary Vertex Reconstruction (D^0)

$$D^0 \rightarrow K^- \pi^+$$

Secondary Vertex

Approach 1 (Analytical)

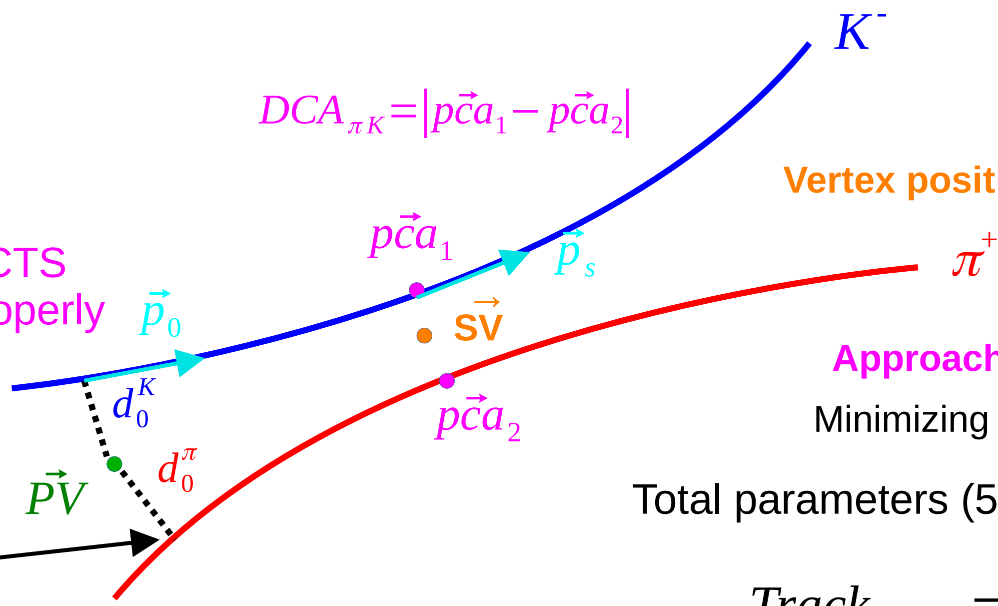
$$\vec{SV} = \frac{\vec{pca}_1 + \vec{pca}_2}{2}$$

$$DCA_{\pi K} = |\vec{pca}_1 - \vec{pca}_2|$$

Vertex position $\vec{SV}$ = (v_x, v_y, v_z)

Secondary vertexing in ACTS considers tracking errors properly

Ignored track errors (at the moment)



$$Track_{DCA} = (\vec{r}_0, \vec{p}_0, q)$$

$$Track_{At(s)} = (\vec{r}_s, \vec{p}_s, q)$$ s: path length

Approach 2 (Shyam)

Minimizing the distance

Total parameters (5) = (v_x, v_y, v_z, s_1, s_2)

$$Track_{At(s1)} = (\vec{r}_{s1}, \vec{p}_{s1}, q_1)$$

$$Track_{At(s2)} = (\vec{r}_{s2}, \vec{p}_{s2}, q_2)$$

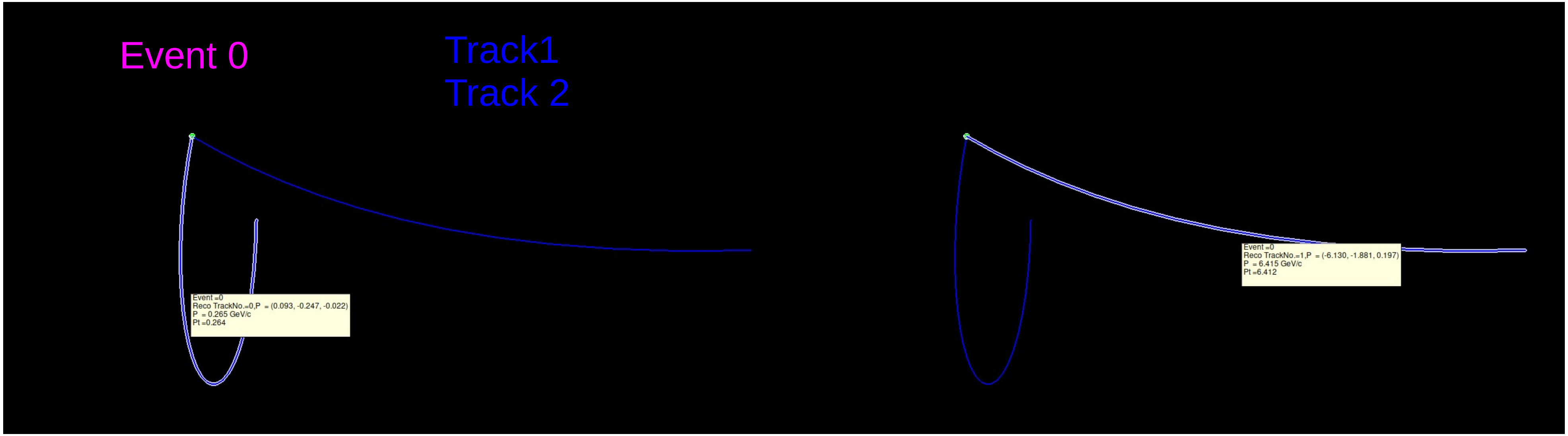
Minimize $d = \sqrt{(\vec{r}_{s1} - \vec{v})^2 + (\vec{r}_{s2} - \vec{v})^2}$

Comparison of four approaches:

- Helix1 (using helix1 to find **pca_1** and **pca_2)**
- Distance minimization (d)
- Helix2 (using helix2 to find **pca_1** and **pca_2)**
- Using average of Helix1 and Helix2

Event display (First two tracks)

Root Based: Event display



- Visualization of two tracks in Event 0 (Either Signal pair or Bkg pair)
- Visualization of **pca** and secondary vertex with different approaches
- Distance minimization returns the unique point

Different approaches:

- Helix1 (using helix1 to find **pca$_1$** and **pca$_2$)**
- Distance minimization (d)
- Helix2 (using helix2 to find **pca$_1$** and **pca$_2$)**

Event display (First two tracks)

Root Based: Event display

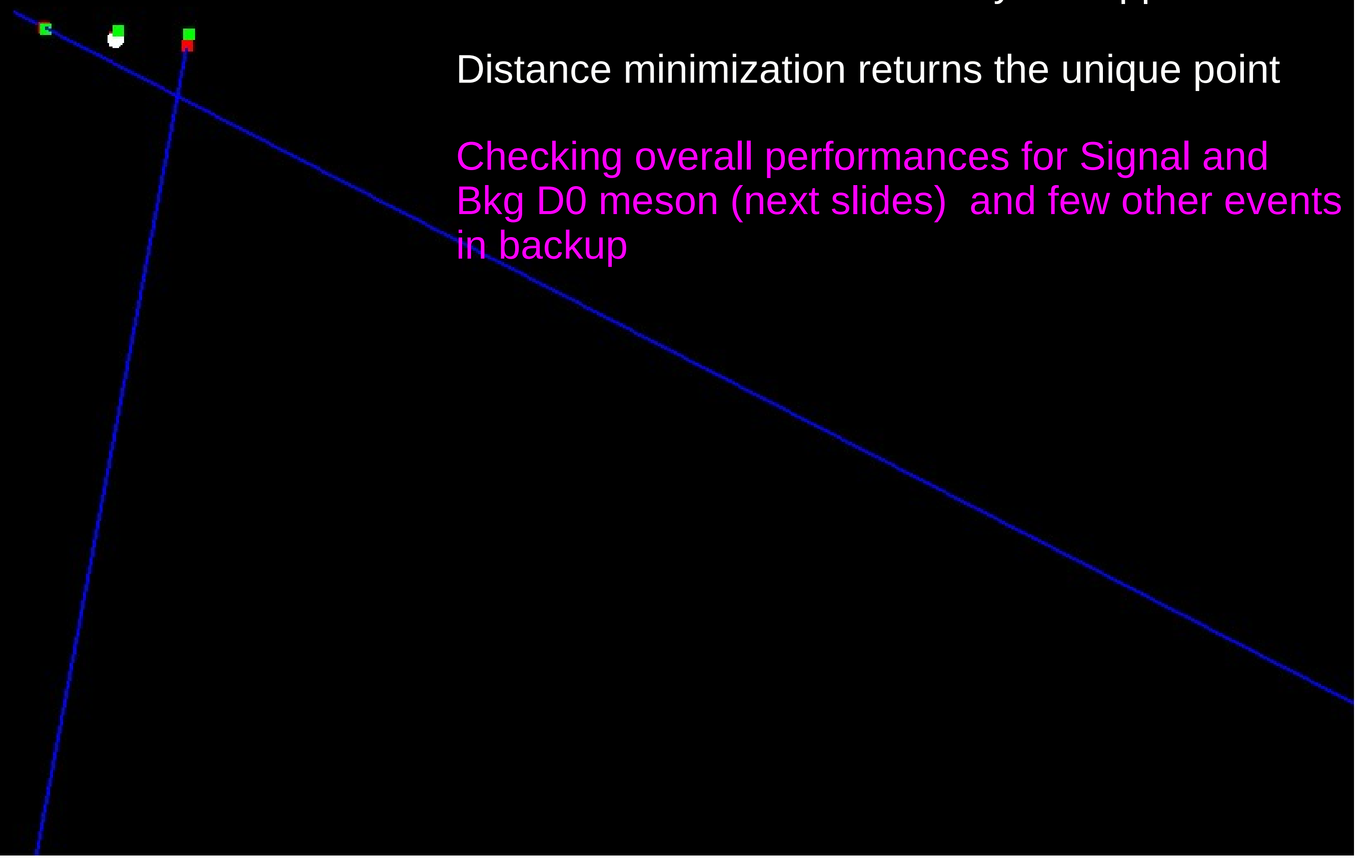
Event 0

Green marker track1 reference

Red marker track2 reference

White marker (distance minimization)

Green track1



All three methods (**track 1 reference**, **track2 reference**, **and distance minimization**) are compatible

Minor difference is due to analytical approach

Distance minimization returns the unique point

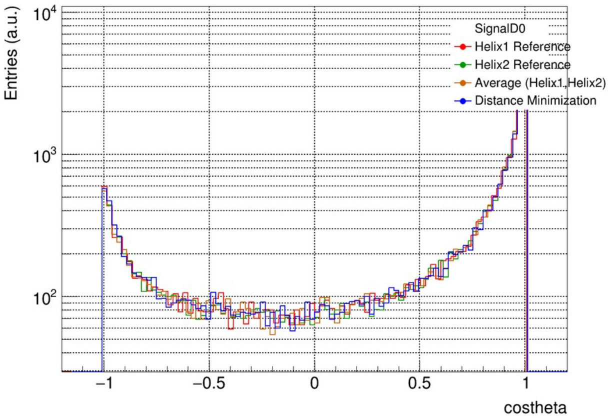
Checking overall performances for Signal and Bkg D0 meson (next slides) and few other events in backup

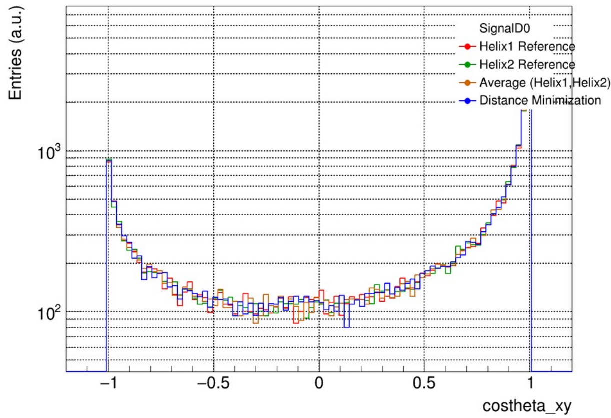
Comparison Distribution for D^0 meson (Q^2>1GeV^2)

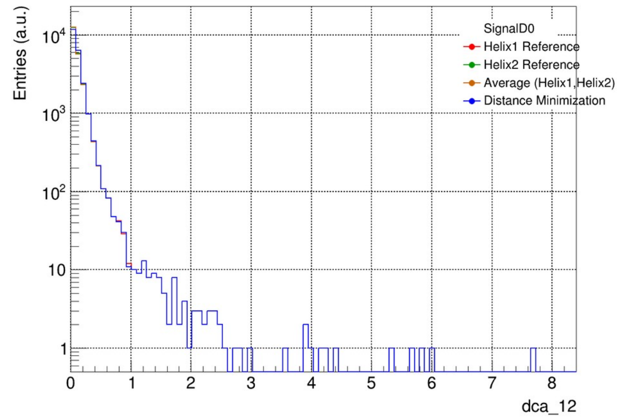
All methods are compatible

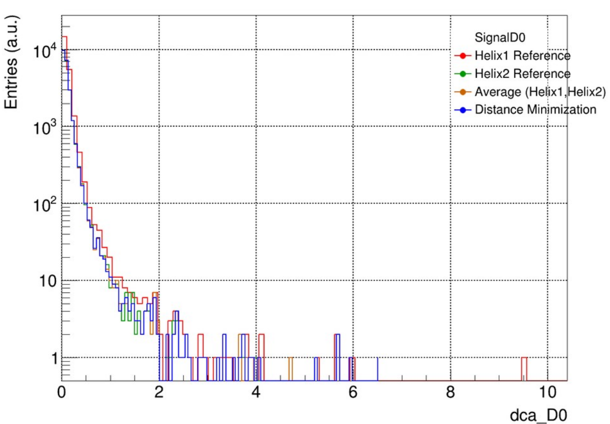
Signal D^0 meson

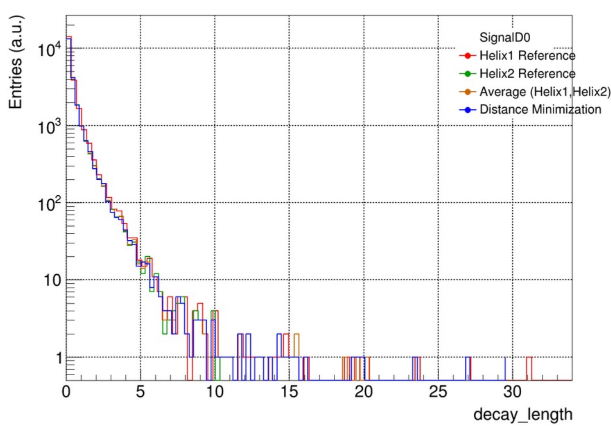
Distance minimization gives unique secondary vertex

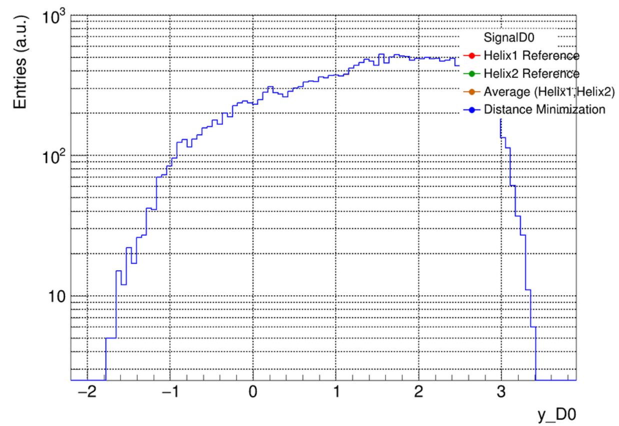








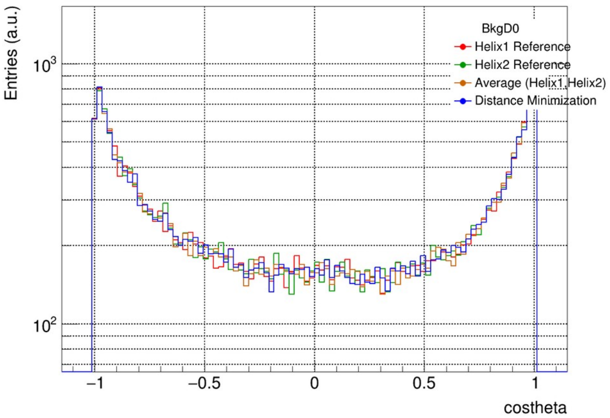


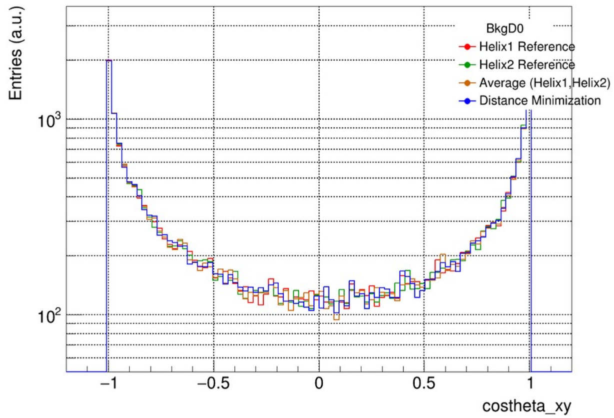


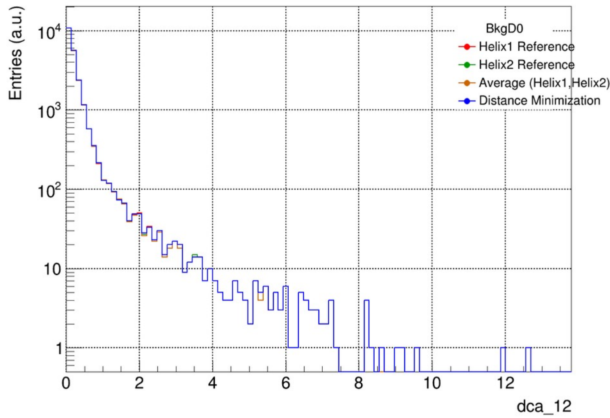
Comparison Distribution for D^0 meson (Q^2>1GeV^2)

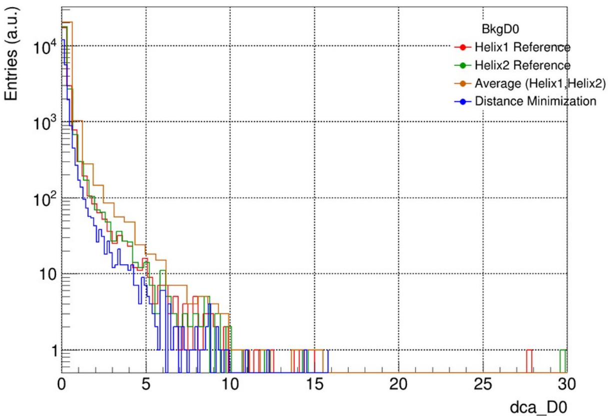
All methods are compatible

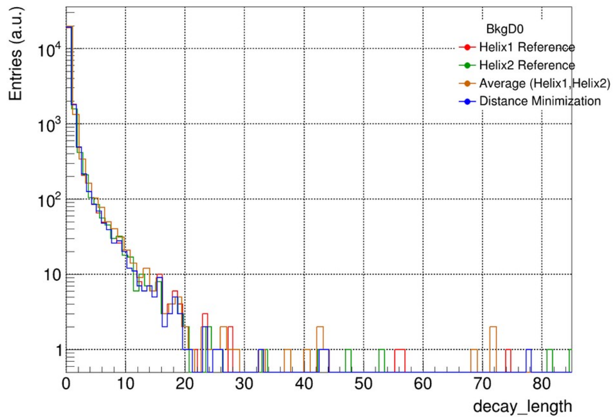
Bkg D^0 meson

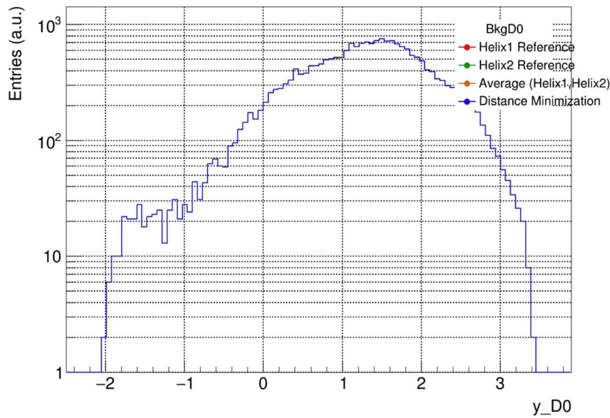












Secondary Vertex Reconstruction (Λ_c^+)

Secondary Vertex

$$\Lambda_c^+ \rightarrow p\, K^- \pi^+$$

$DCA_{k\pi} = |\vec{pca}_1 - \vec{pca}_2|$, $DCA_{kp} = |\vec{pca}_1 - \vec{pca}_3|$, $DCA_{p\pi} = |\vec{pca}_3 - \vec{pca}_2|$

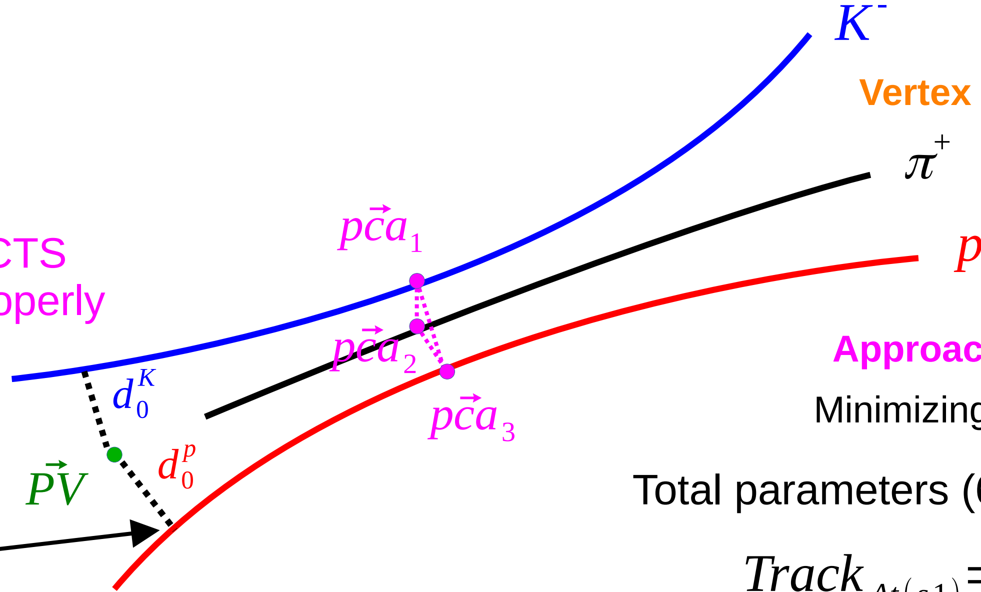
DCA_{12} = min {$DCA_{\pi K}$, DCA_{KP}, $DCA_{\pi P}$} Cut

Approach 1 (Analytical)

$$\vec{SV} = \frac{\vec{pca}_1 + \vec{pca}_2 + \vec{pca}_3}{3}$$

Secondary vertexing in ACTS considers tracking errors properly

Ignored track errors (at the moment)



$$Track_{DCA} = (\vec{r}_0, \vec{p}_0, q)$$

$$Track_{At(s)} = (\vec{r}_s, \vec{p}_s, q)$$ s: path length

Total parameters (6) = (v_x, v_y, v_z, s_1, s_2, s_3)

Vertex position $\vec{SV}$ = (v_x, v_y, v_z)

Approach 2 (Shyam)

Minimizing the distance

Total parameters (6) = (v_x, v_y, v_z, s_1, s_2, s_3)

$$Track_{At(s1)} = (\vec{r}_{s1}, \vec{p}_{s1}, q_1)$$

$$Track_{At(s2)} = (\vec{r}_{s2}, \vec{p}_{s2}, q_2)$$

$$Track_{At(s3)} = (\vec{r}_{s3}, \vec{p}_{s3}, q_3)$$

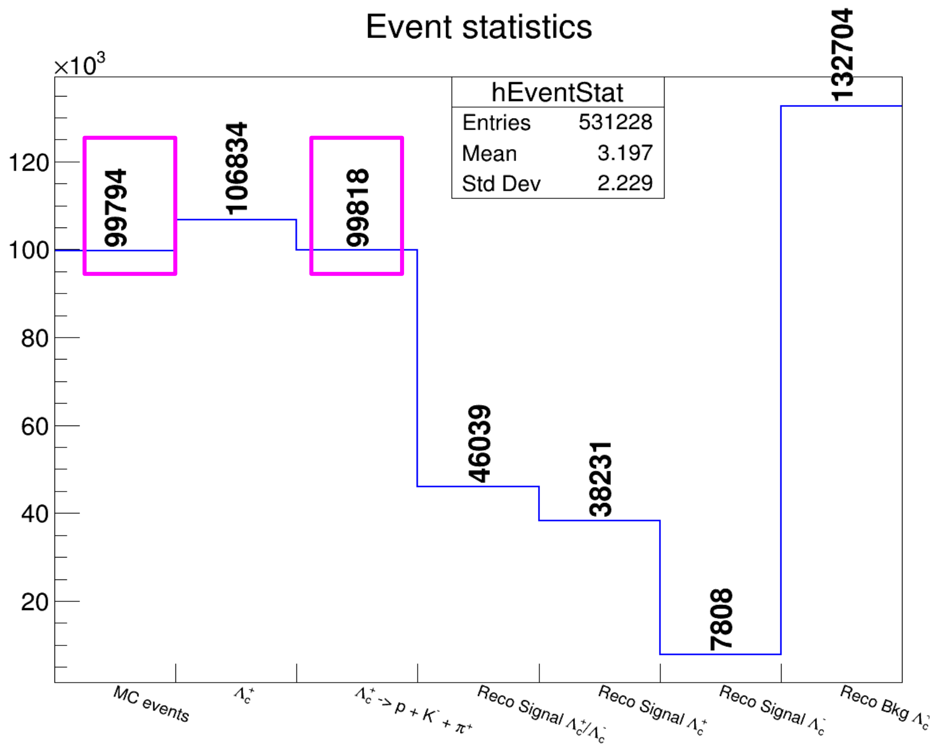
Minimize $$d = \sqrt{(\vec{r}_{s1} - \vec{v})^2 + (\vec{r}_{s2} - \vec{v})^2 + (\vec{r}_{s3} - \vec{v})^2}$$

Λ_c^+ Reconstruction

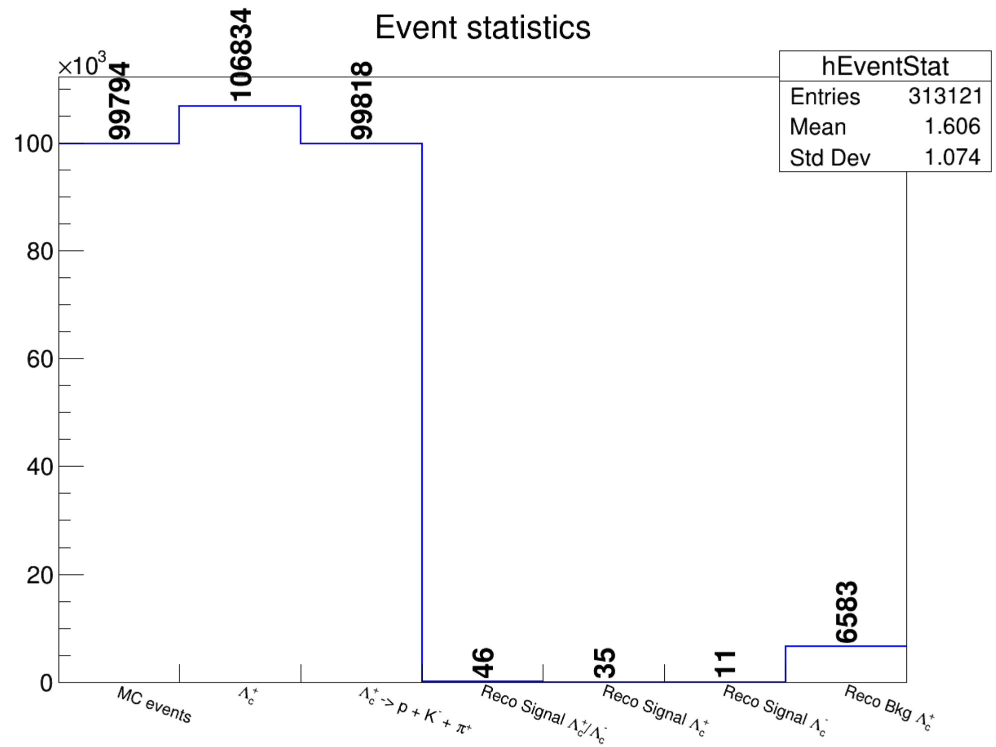
PYTHIA8 ep NC (10x100 Q^2>1) Λ_c^+ sample: by Rongrong

$$\Lambda_c^+ \rightarrow p\, K^-\, \pi^+$$

Truth PID

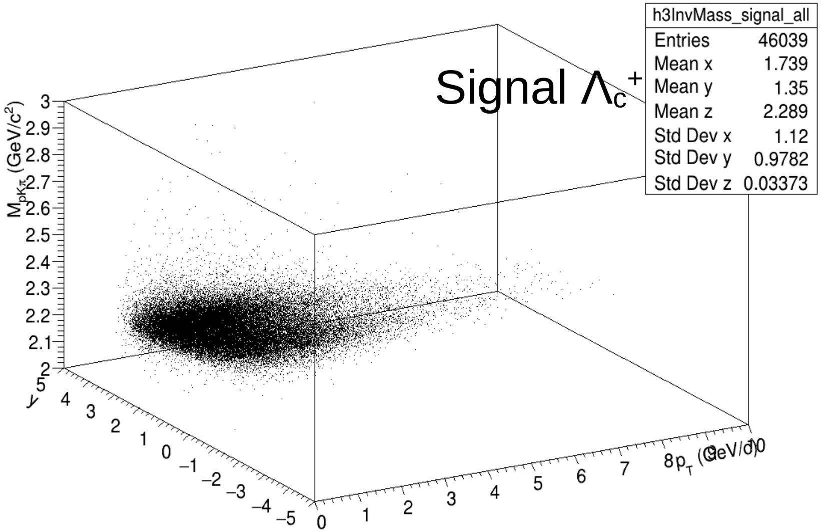


Real PID

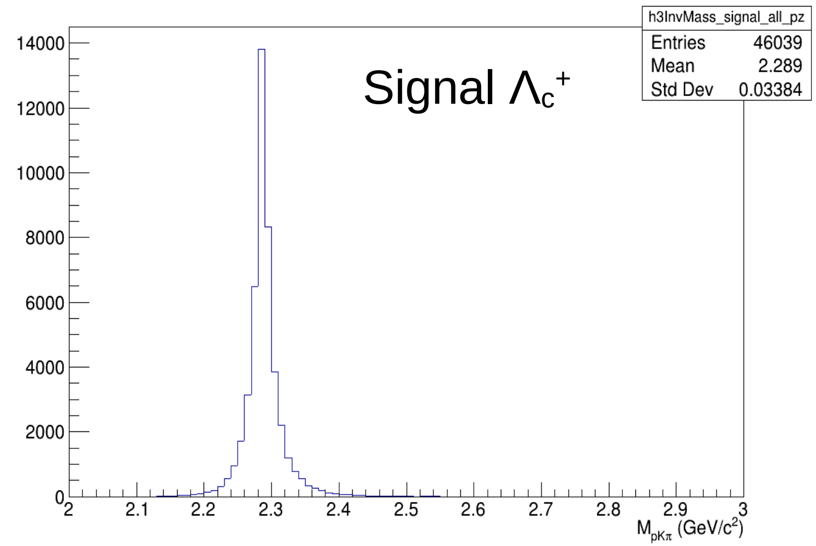


Issue coming from proton PID in Real PID, basically from lookup tables (loosing protons)

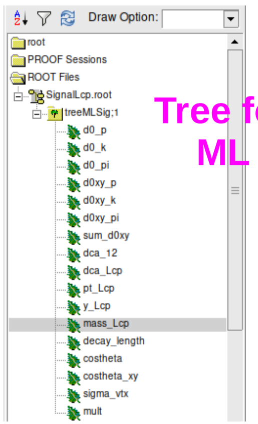
Results



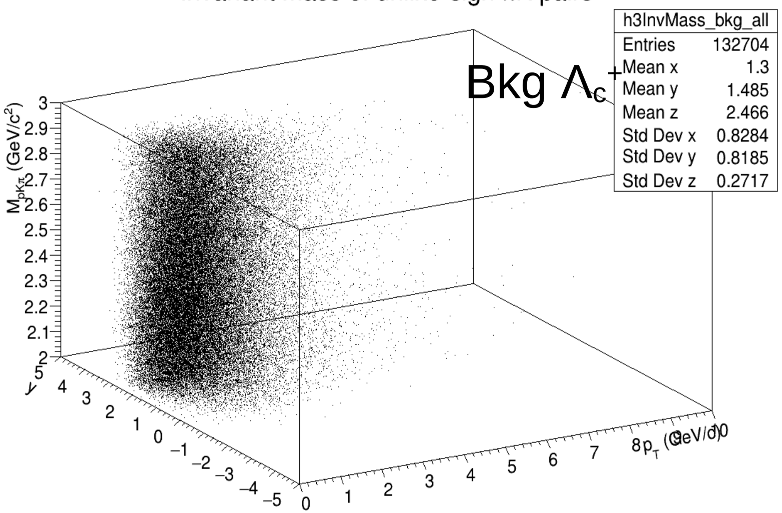
Projection



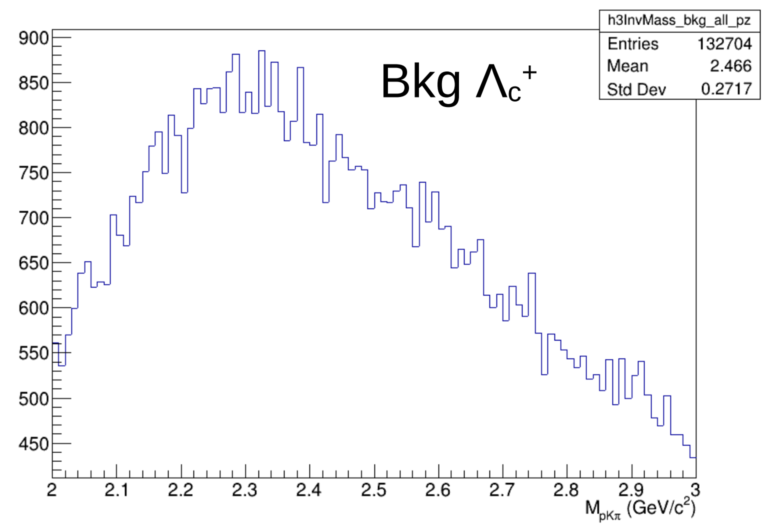
Invariant mass of unlike-sign πK pairs



Tree for ML

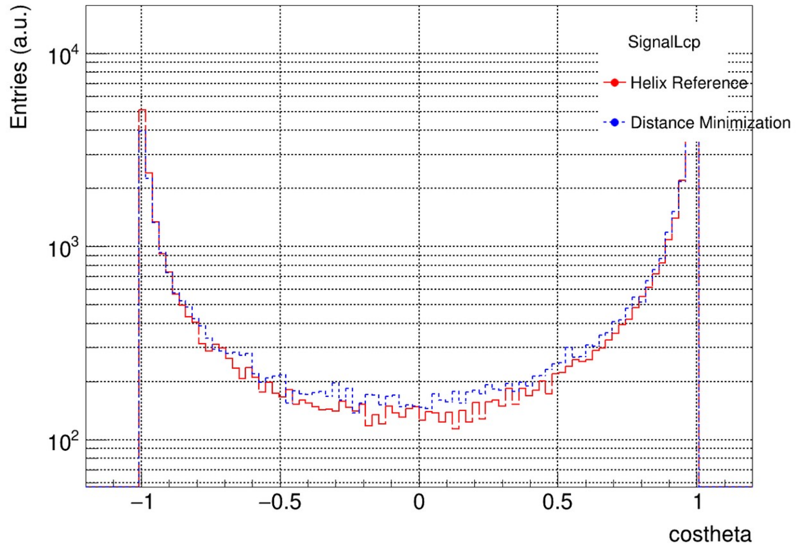


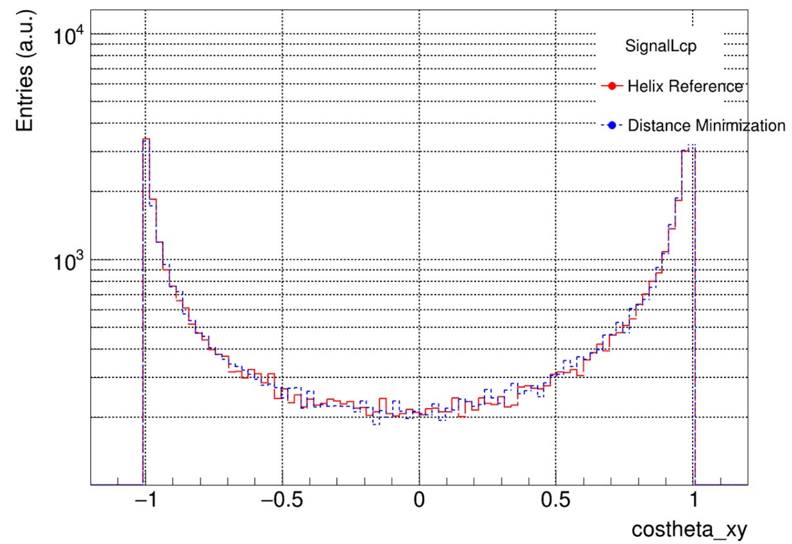
Projection

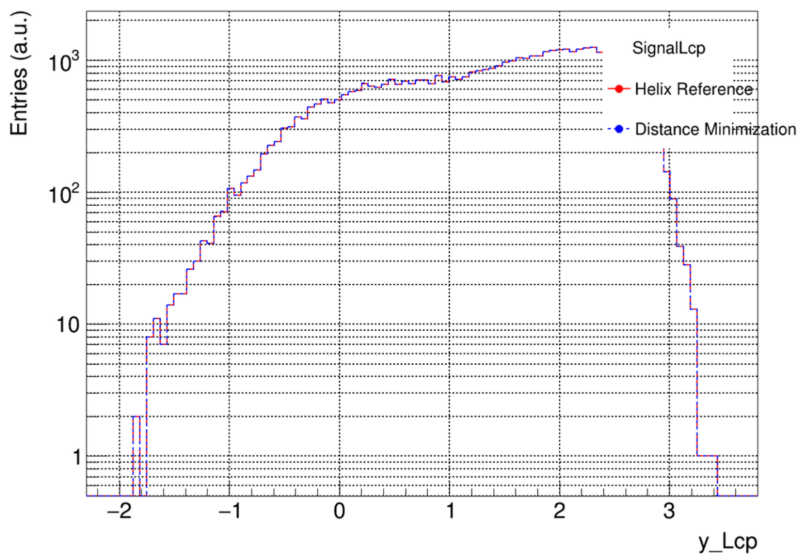


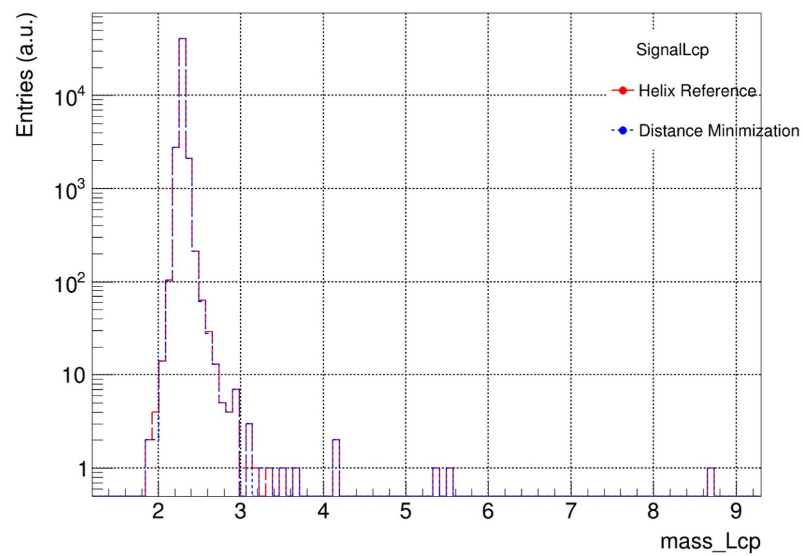
Comparison (Results)

Signal Λ_c^+



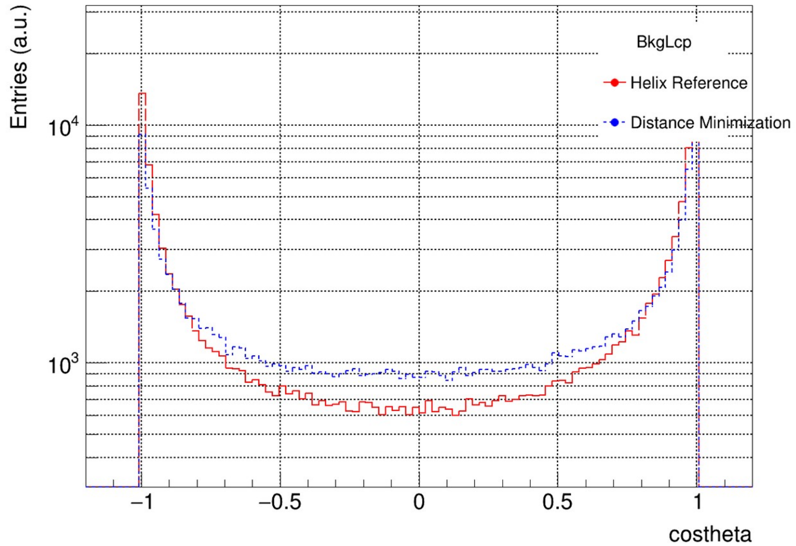


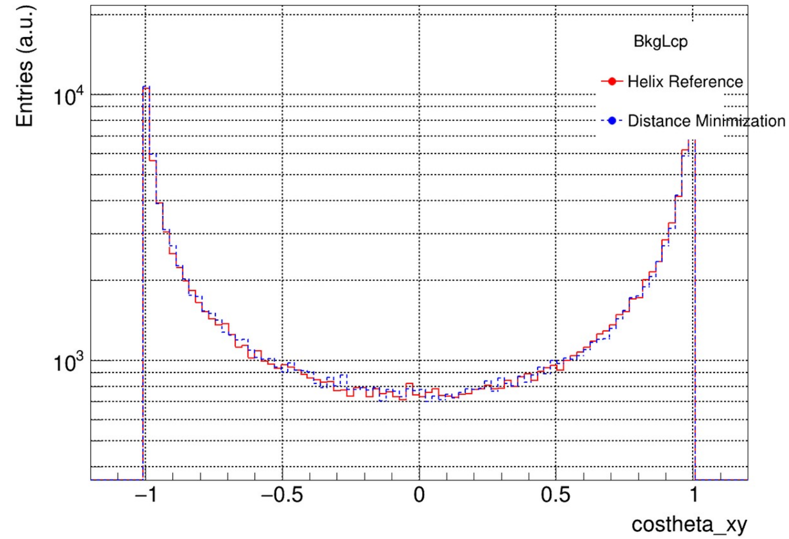


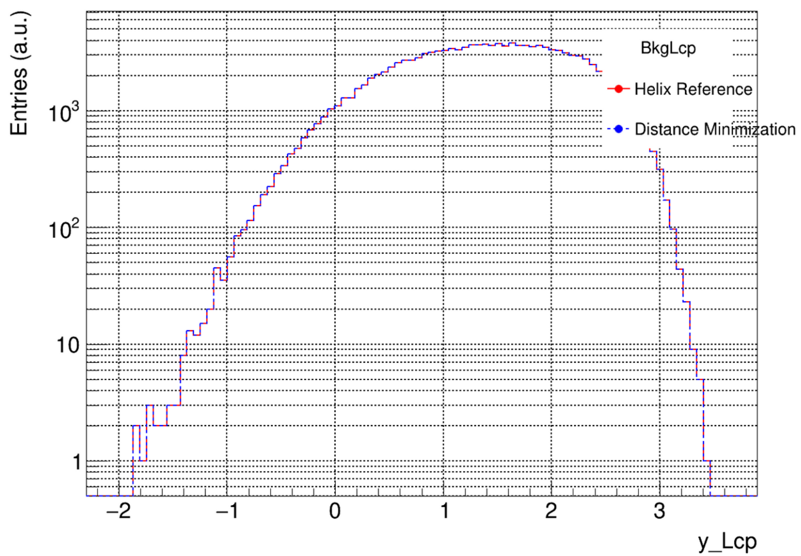


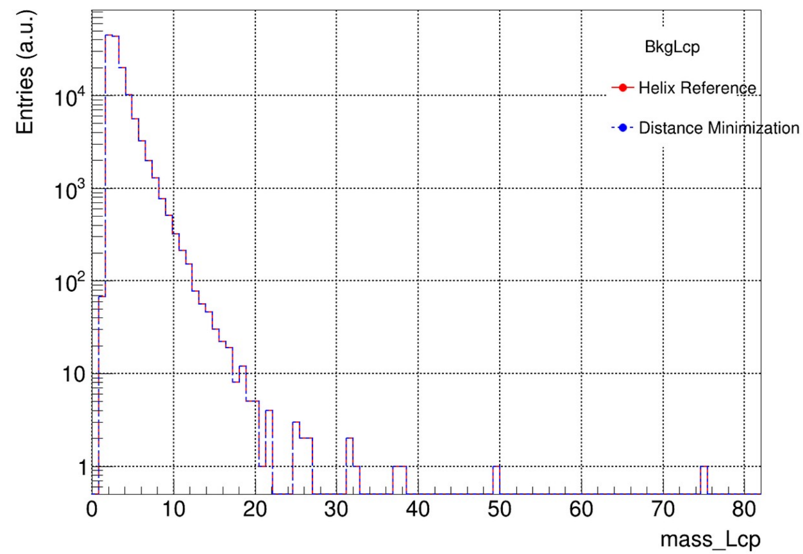
Comparison (Results)

Bkg Λ_c^+



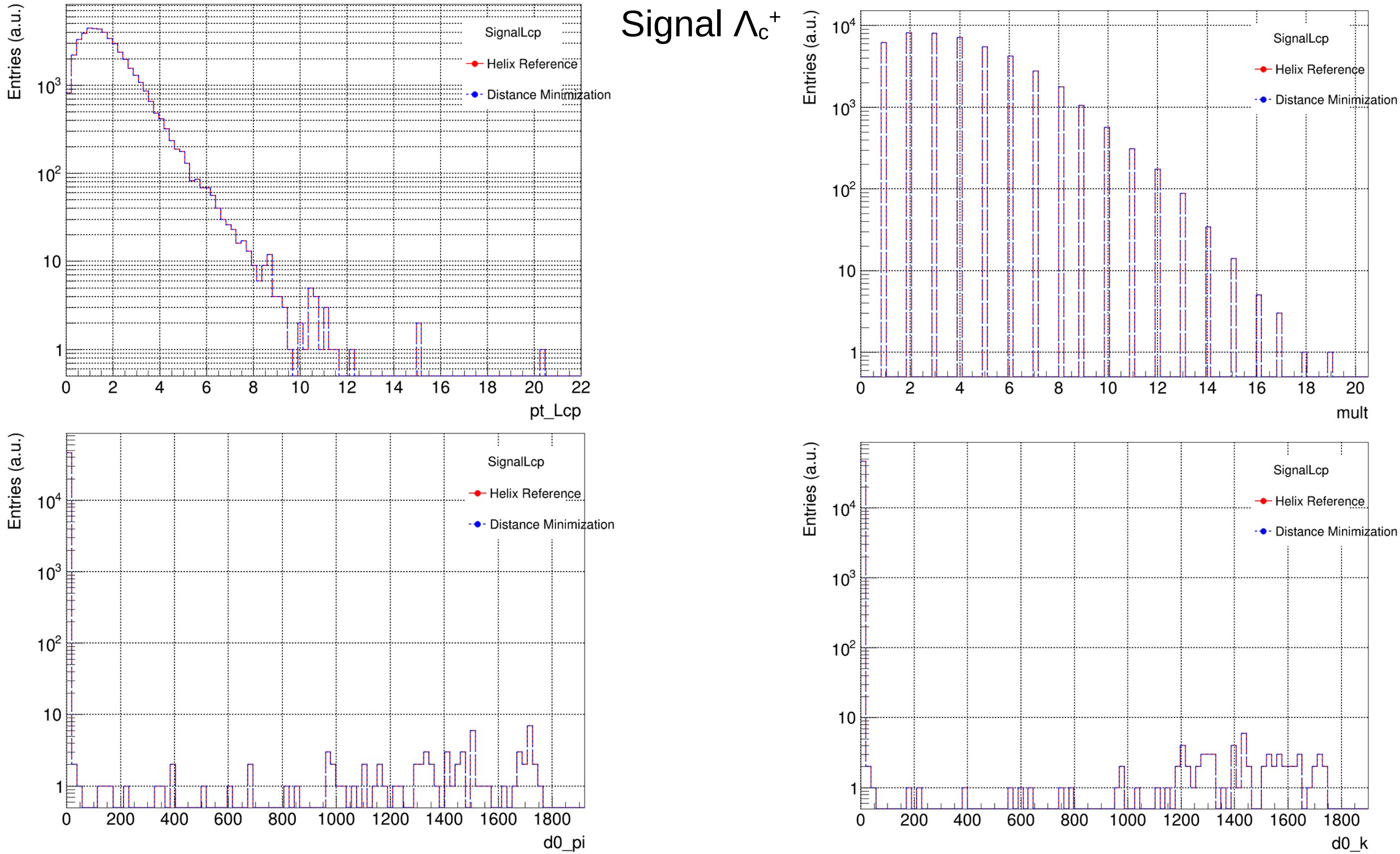






Comparison (Results)

Signal Λ_c^+



Summary and Future Plan

- Tracking Performances are now working fine (Issue was related to data type conversion not the beampipe)
- Included hit maps and average number of hits per tracking to the benchmarks
- I further checked the pull distributions for the track parameters
- Compared with the different methods of extracting the secondary vertex, they are compatible with analytical method which is faster (we will use official code for secondary vertex in ACTS)
- First implementation of Λ_c^+ reconstruction is completed and will commit the code soon
- Future Plan
  - Include hit maps and average number of hits per track for each momentum
  - Need to understand why pull distributions for momentum are not consistent with unity especially for higher η
  - Implement pull distributions to the benchmarks
  - Implementation of machine learning for Λ_c^+ is in progress

Track Parametrization (Local to Global)

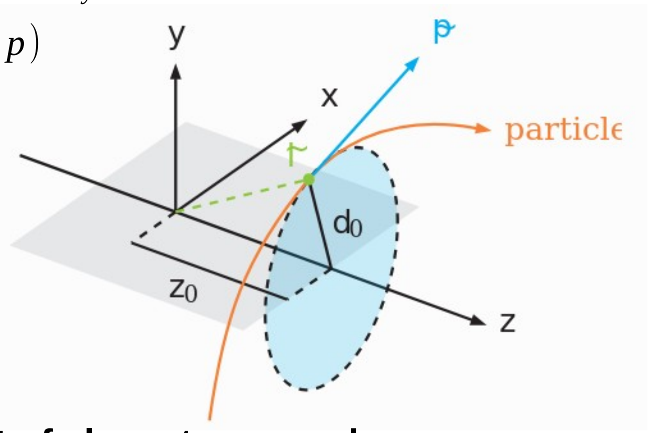
Helical Track model: $(l_0, l_1, \phi, \theta, q/p)$

$x = -l_0 \sin\phi, \quad y = l_0 \cos\phi, \quad z = l_1$

$p_x = p\cos\phi\sin\theta, \quad p_y = p\sin\phi\sin\theta, \quad p_z = p\cos\theta$

$charge = sign(q/p)$

$d_0 = l_0$
$z_0 = l_1$



At Point of closest approach (perigee surface)

$(l_0, l_1, \phi, \theta, q/p)$

↓ **Global (Lab frame)**

$(x, y, z, p_x, p_y, p_z, q)$

```
Vector3 LineSurface::localToGlobal(const GeometryContext& gctx, const Vector2& lposition, const Vector3& direction) const

{

 Vector3 unitZ0 = lineDirection(gctx);

// get the vector perpendicular to the momentum direction and the straw axis

Vector3 radiusAxisGlobal = unitZ0.cross(direction);

Vector3 locZinGlobal = transform(gctx) * Vector3(0., 0., lposition[1]);

// add loc0 * radiusAxis

return Vector3(locZinGlobal + lposition[0] * radiusAxisGlobal.normalized());

}
```

Calculation

UnitZ0: is (0,0,1) vector along the z-axis for cylinder and disks.

direction: (p Cos(phi) Sin(theta), p Sin(phi) Sin(theta), p Cos(theta))

radiusAxisGlobal = UnitZ0 Cross product direction = (-p Sin(phi) Sin(theta), p Cos(phi) Sin(theta), 0)

radiusAxisGlobal.Normalized = (-Sin(phi), Cos(phi), 0)locZinGlobal = (0,0,l1) (is same as global)

Global position = locZinGlobal + lposition[0] * radiusAxisGlobal.normalized() = (0,0,l1) + l0(-Sin(phi), Cos(phi), 0)Global Position = (-l0 Sin(phi), l0 Cos(phi), l1)

Returns the components, which we are using in HF analysis.

$x = -l_0 \sin\phi, \; y = l_0 \cos\phi, \; z = l_1$

Covariance Matrix in ACTS

For each fitted track we get track parameters and covariance matrix

Track Parameters $(l_0, l_1, \phi, \theta, q/p, time)$

$$\begin{array}{c} \\ l_0 \\ l_1 \\ \phi \\ \theta \\ q/p \\ time \end{array} \begin{array}{c} \begin{array}{cccccc} l_0 & l_1 & \phi & \theta & q/p & time \end{array} \\ \begin{bmatrix} \sigma^2(l_0) & \mathrm{cov}(l_0,l_1) & \mathrm{cov}(l_0,\phi) & \mathrm{cov}(l_0,\theta) & \mathrm{cov}(l_0,q/p) & \mathrm{cov}(l_0,t) \\ . & \sigma^2(l_1) & \mathrm{cov}(l_1,\phi) & \mathrm{cov}(l_1,\theta) & \mathrm{cov}(l_1,q/p) & \mathrm{cov}(l_1,t) \\ . & . & \sigma^2(\phi) & \mathrm{cov}(\phi,\theta) & \mathrm{cov}(\phi,q/p) & \mathrm{cov}(\phi,t) \\ . & . & . & \sigma^2(\theta) & \mathrm{cov}(\theta,q/p) & \mathrm{cov}(\theta,t) \\ . & . & . & . & \sigma^2(q/p) & \mathrm{cov}(q/p,t) \\ . & . & . & . & . & \sigma^2(t) \end{bmatrix} \end{array}$$

Symmetric matrix: Independent entries = n(n+1)/2 = 6*7/2 = 21

```
Processing ReadCovarianceArray_new.C...
Event 0, number of tracks: 8
  Track 0 covariance:
    cov[0] = 0.0104456
    cov[1] = 2.366e-06
    cov[2] = 0.0103324
    cov[3] = -0.000289634
    cov[4] = 7.52669e-07
    cov[5] = 8.04972e-06
    cov[6] = -8.12589e-07
    cov[7] = 0.000284166
    cov[8] = 4.50984e-08
    cov[9] = 7.82997e-06
    cov[10] = 0.000153944
    cov[11] = 7.02629e-07
    cov[12] = -4.94218e-06
    cov[13] = 5.14138e-09
    cov[14] = 0.00011838
    cov[15] = -1.41347e-06
    cov[16] = -3.20263e-06
    cov[17] = 3.89044e-08
    cov[18] = -8.82041e-08
    cov[19] = 2.242e-09
    cov[20] = 0.000333566
```

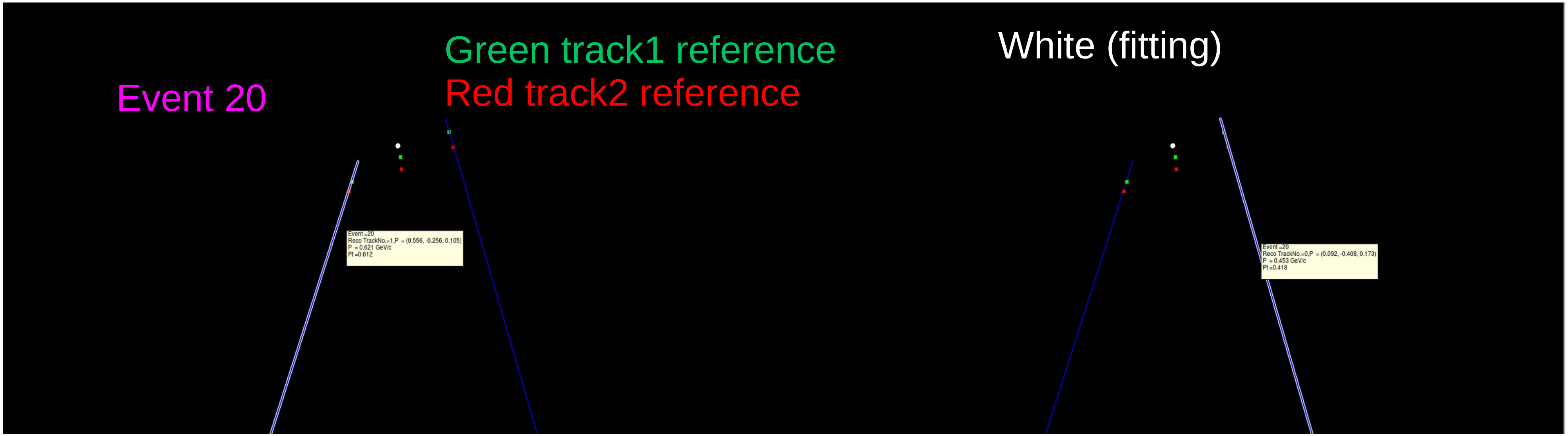
Cov[0] = cov(l0, l0)
Cov[1] = cov(l0, l1)
Cov[2] = cov(l1, l1)
Cov[3] = cov(l0, φ)
cov[4] = cov(l1, φ)
cov[5] = cov(φ, φ)
cov[6] = cov(l0, θ)
cov[7] = cov(l1, θ)
cov[8] = cov(φ, θ)
cov[9] = cov(θ, θ)
cov[10] = cov(l0, q/p)
Cov[11] = cov(l1, q/p)
Cov[12] = cov(φ, q/p)
Cov[13] = cov(θ, q/p)
Cov[14] = cov(q/p, q/p)
Cov[15] = cov(l0, time)
Cov[16] = cov(l1, time)
Cov[17] = cov(φ, time)
Cov[18] = cov(θ, time)
Cov[19] = cov(q/p, time)
Cov[20] = cov(time, time)

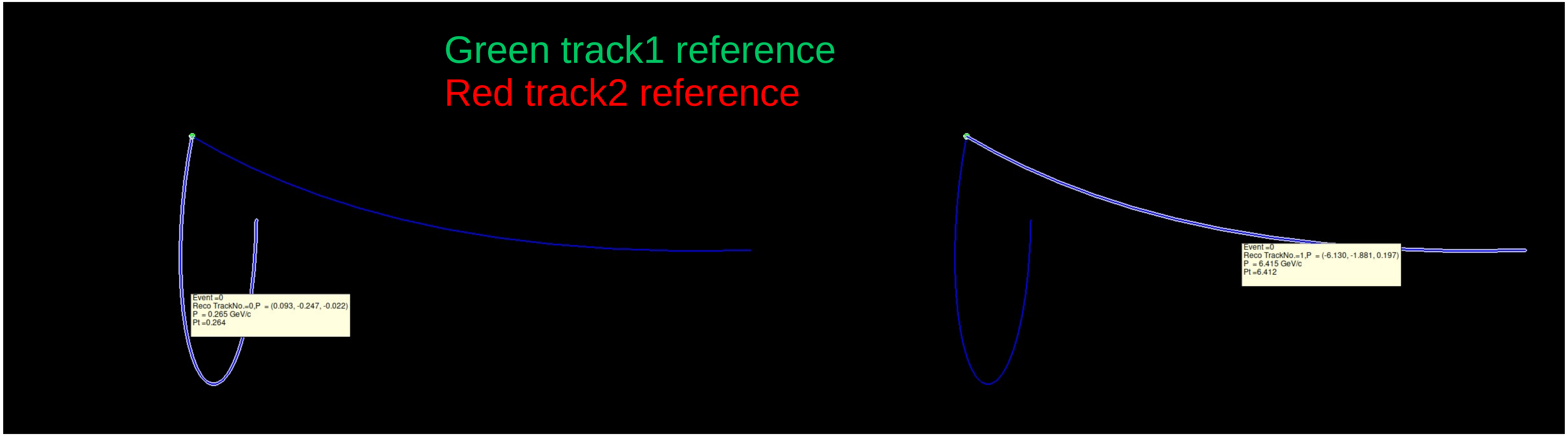
$\sigma_{l0} = \sqrt{(Cov[0])}$ $\sigma_{l1} = \sqrt{(Cov[2])}$

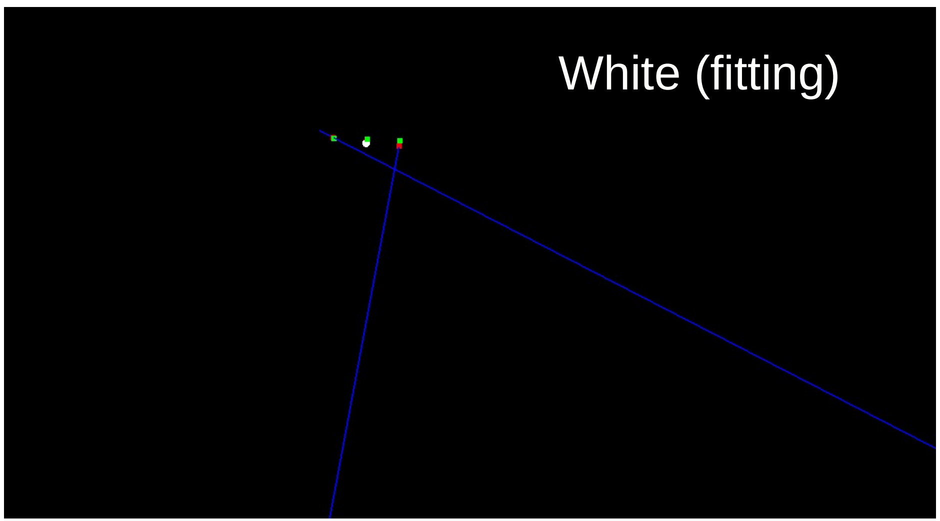
$\sigma_{\phi} = \sqrt{(Cov[5])}$ $\sigma_{\theta} = \sqrt{(Cov[9])}$

$\sigma_q / p = \sqrt{(Cov[14])}$

Event display (First two tracks)







- All three methods (**track 1 reference, track2 reference, and distance minimization**) are compatible
- Minor difference is due to analytical approach
- Distance minimization returns the unique point