TOF Simulation Meeting

2024/11/19 (Tue)

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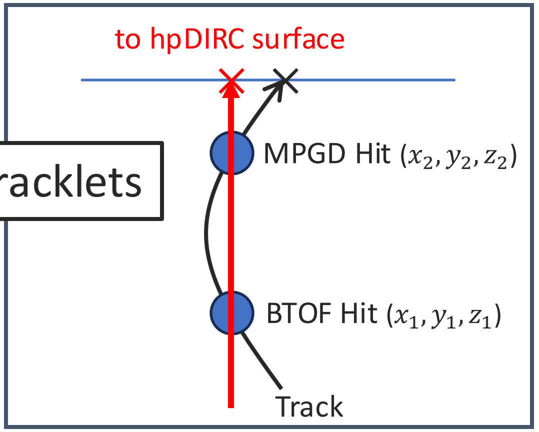
- Modification of the angular resolution formula using tracklets (outer MPGD + BTOF)
- Calculation of angular resolution with BTOF material
- Calculation of angular resolution using fast track (inner MPGD + outer MPGD + BTOF)

Modified calculation of angular resolution using **tracklets (2points)**

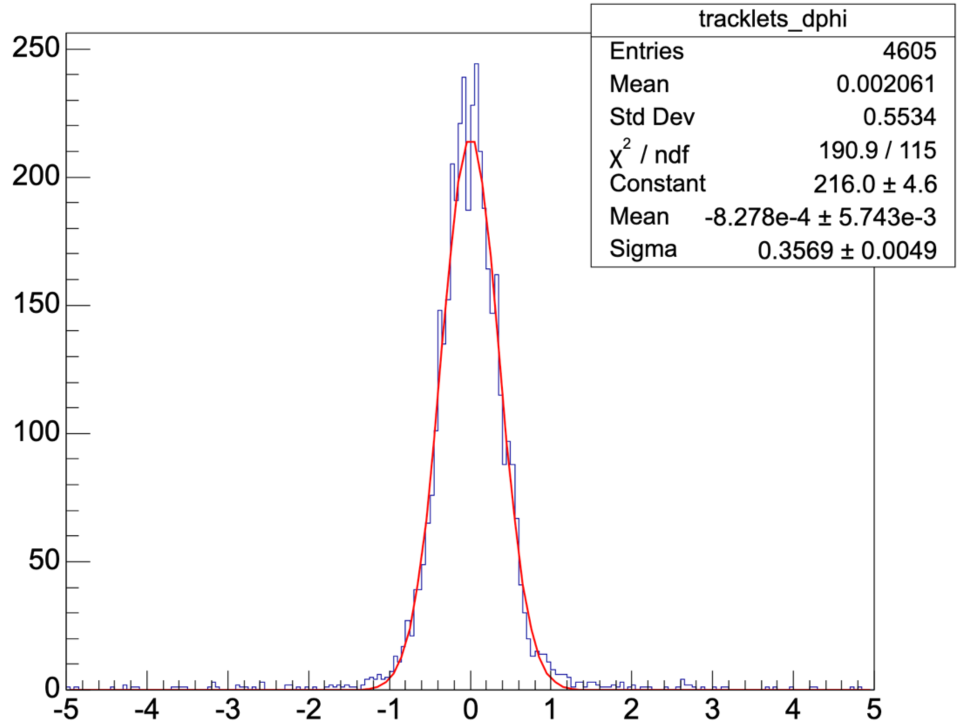
■Tracklets of outer MPGD + BTOF

- $\Delta\theta = \theta(track) - \theta(MC), \qquad \Delta\phi = \phi(track) - \phi(MC)$
- $\theta = arctan2(r_2 - r_1, z_2 - z_1) = arctan2\left(\sqrt{x_2^2 + y_2^2} - \sqrt{x_1^2 + y_1^2}, z_2 - z_1\right)$
- $\phi = arctan2((y_2 - y_1), (x_2 - x_1))$

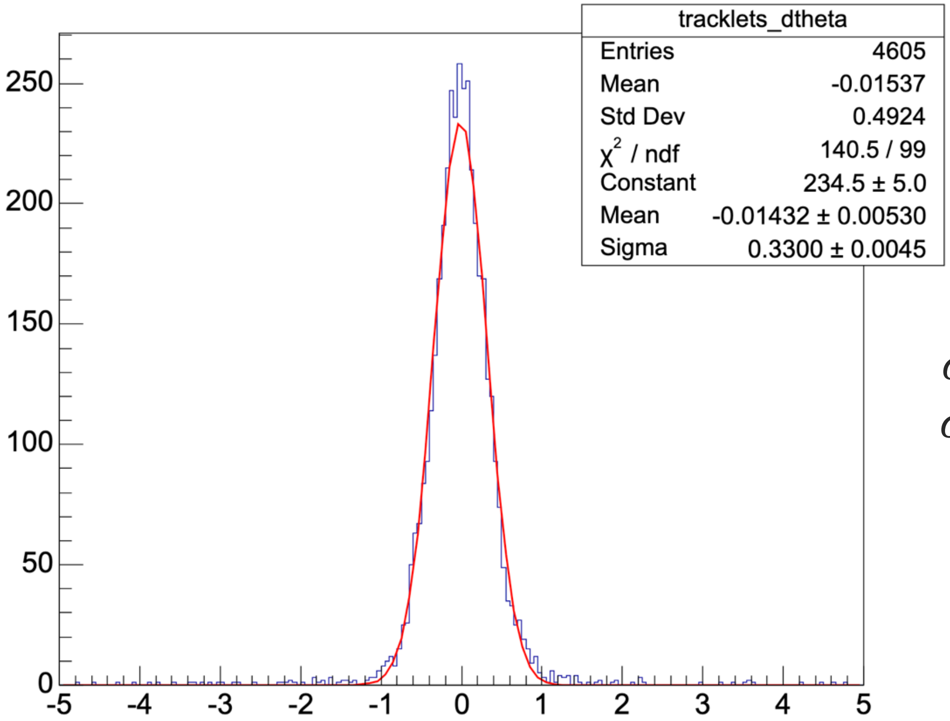
Tracklets



$\Delta\phi$ $[mrad]$ (6GeV, 92 < θ < 94)



Δθ $[mrad]$ (6GeV, 92 < θ < 94)

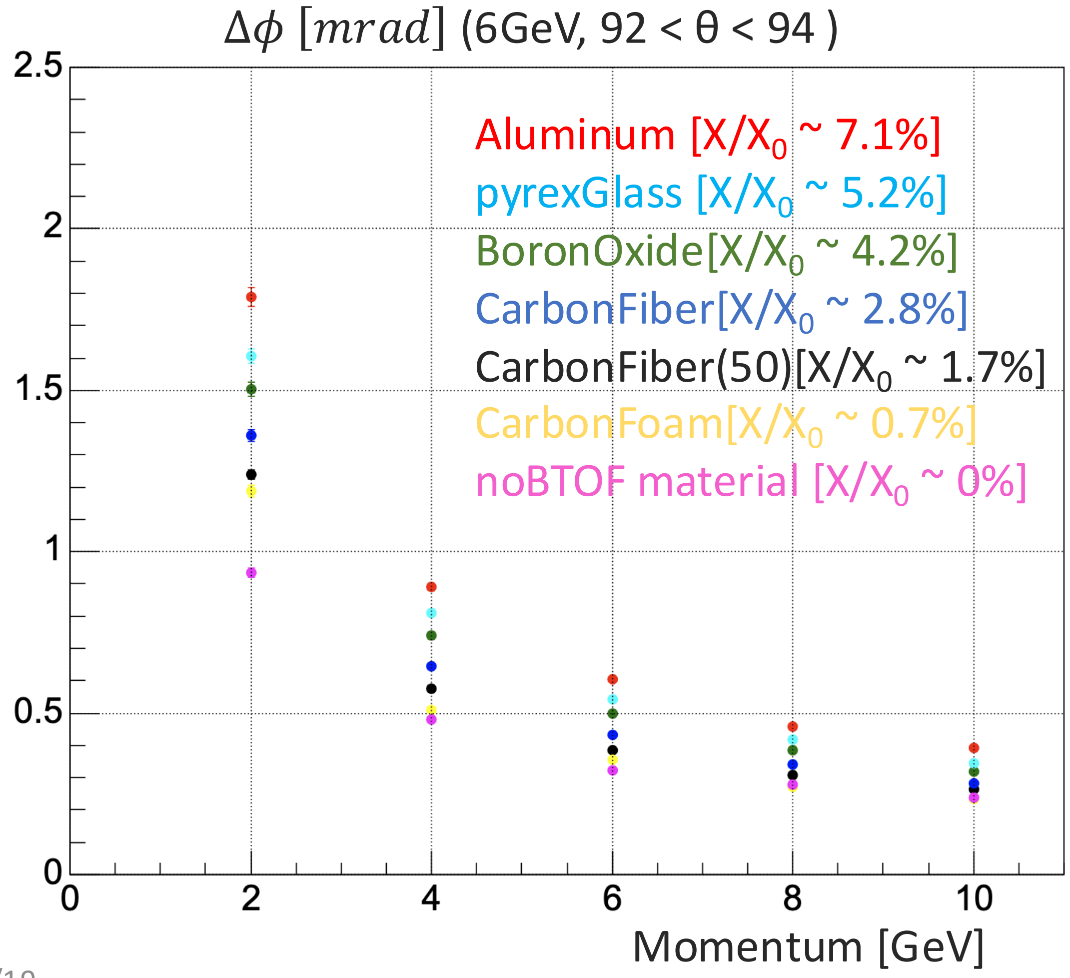


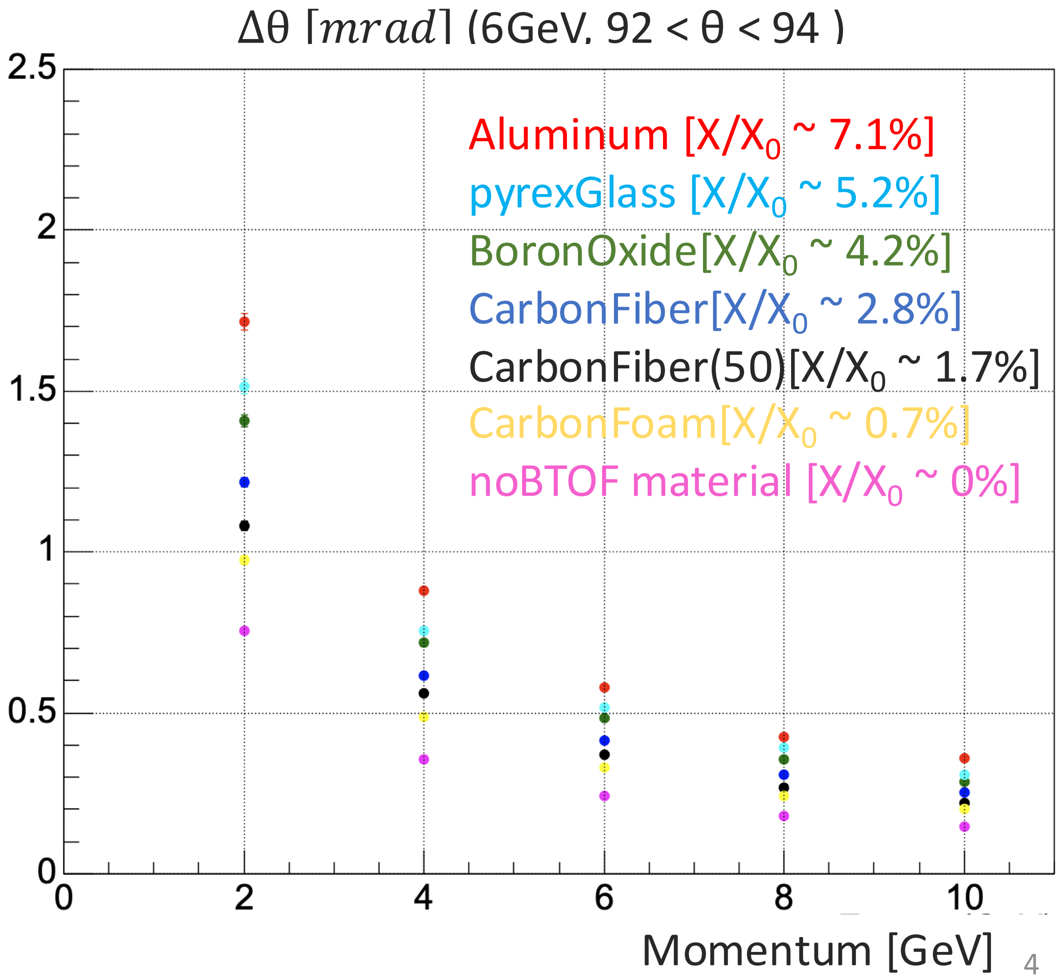
$\sigma_\theta = 0.330 \pm 0.005\ [mrad]$

$\sigma_\phi = 0.357 \pm 0.005\ [mrad]$

Modified calculation of angular resolution using **tracklets (2points)**

■Graph of the angular resolution for each BTOF material, particle momentum



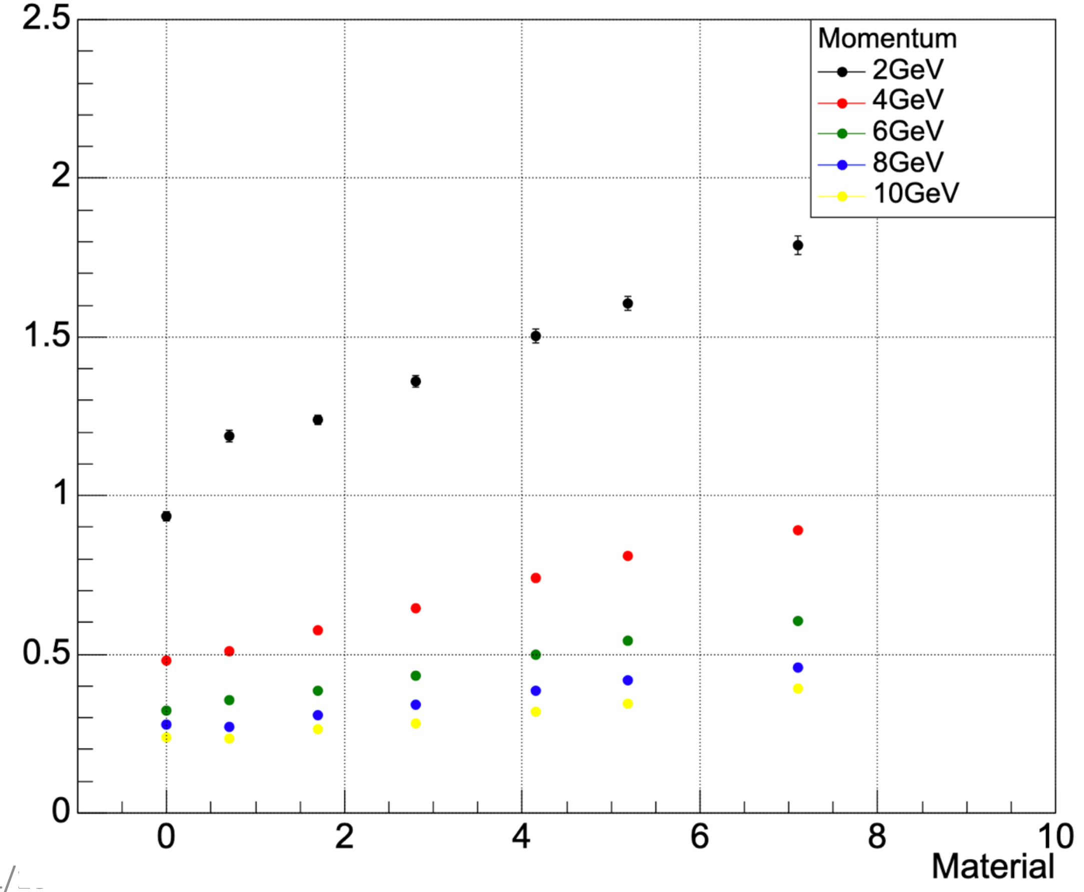


Modified calculation of angular resolution using **tracklets (2points)**

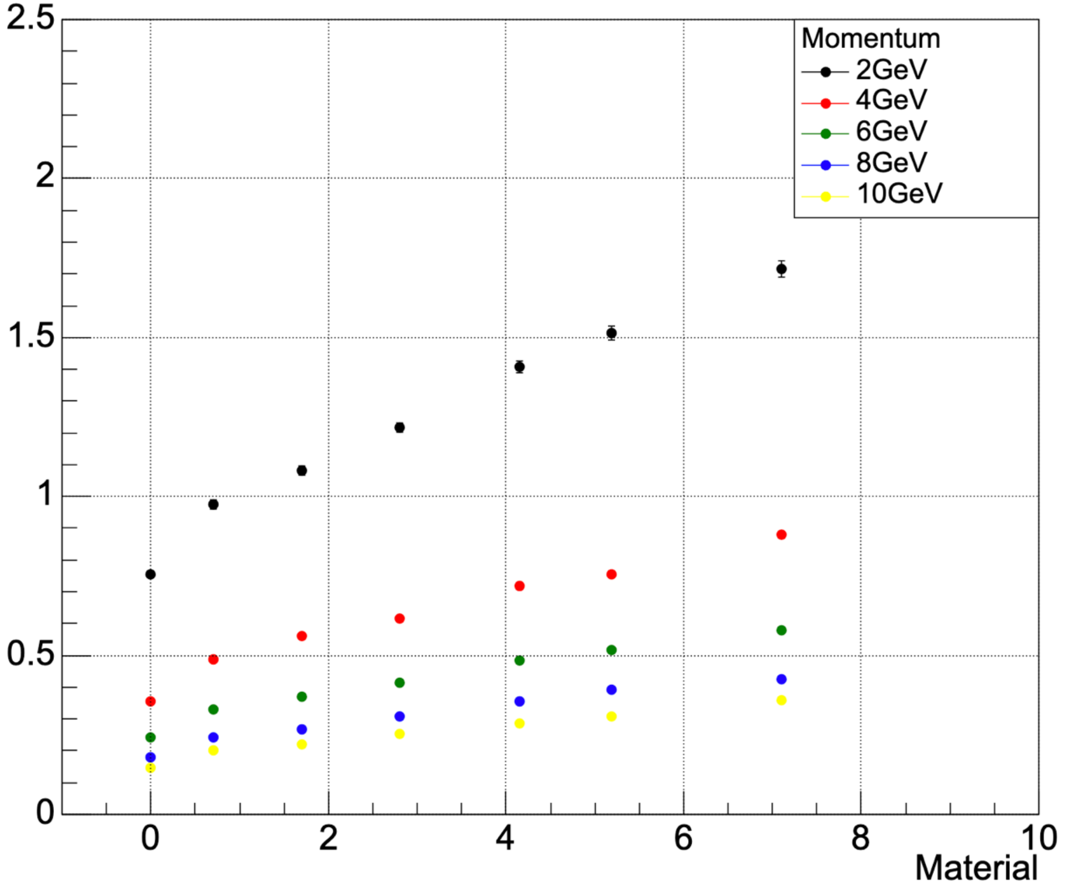
■Graph of the angular resolution for each BTOF material, particle momentum

- The graph for 6 GeV shows that the line around the 4~5% material budget satisfies the 0.5 [mrad] requirement.

$\Delta\phi\ [mrad]$ (6GeV, 92 < θ < 94)

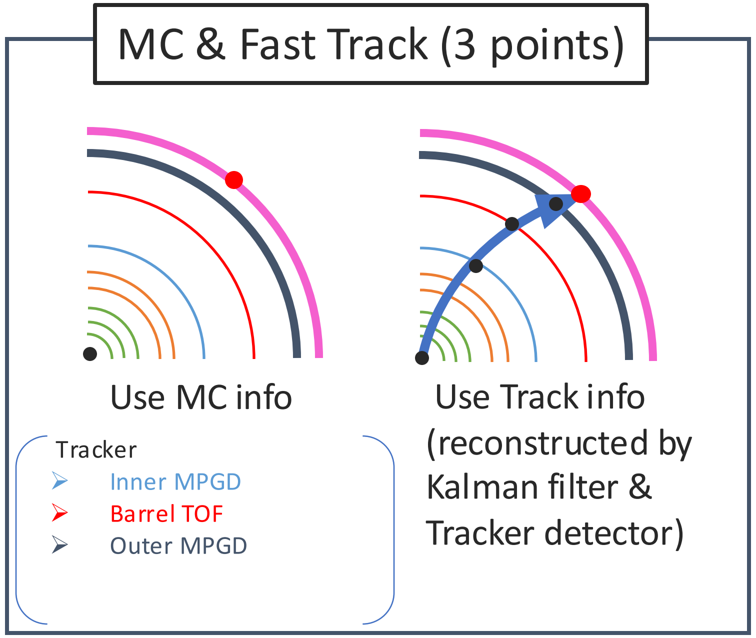


$\Delta\theta\ [mrad]$ (6GeV, 92 < θ < 94)



Calculation of angular resolution using **fast track (3 points)**

- Angular resolution calculated from particle momentum in MC and fast track (inner MPGD + outer MPGD + BTOF)

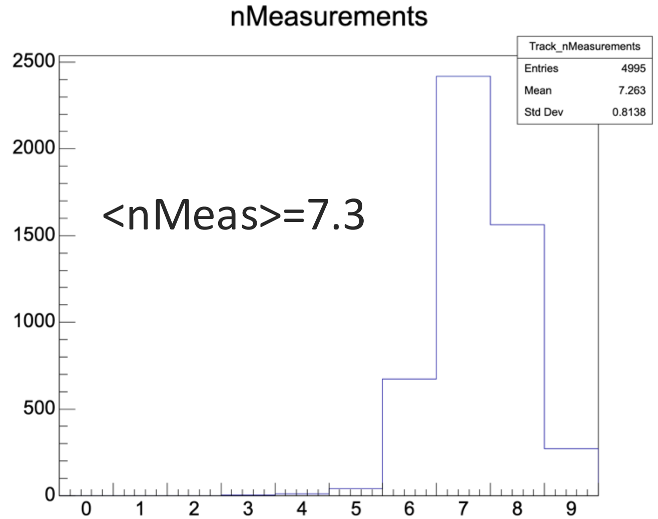


EICrecon/src/global/tracking/tracking.cc

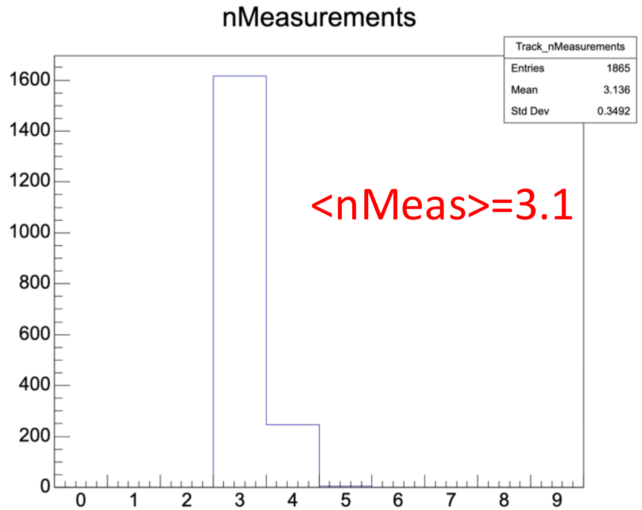
Remove Si hit collections

```
    // Possible collections from arches, brycecanyon and craterlake configurations
    std::vector<std::tuple<std::string, std::string, std::string, std::string>> possible_collections = {
        // {"SiBarrelHits", "SiBarrelRawHits", "SiBarrelRawHitAssociations", "SiBarrelTrackerRecHits"},
        // {"VertexBarrelHits", "SiBarrelVertexRawHits", "SiBarrelVertexRawHitAssociations", "SiBarrelVertexRecHits"},
        // {"TrackerEndcapHits", "SiEndcapTrackerRawHits", "SiEndcapTrackerRawHitAssociations", "SiEndcapTrackerRecHits"},
        {"TOFBarrelHits", "TOFBarrelRawHits", "TOFBarrelRawHitAssociations", "TOFBarrelRecHit"},
        {"TOFEndcapHits", "TOFEndcapRawHits", "TOFEndcapRawHitAssociations", "TOFEndcapRecHits"},
        {"MPGDBarrelHits", "MPGDBarrelRawHits", "MPGDBarrelRawHitAssociations", "MPGDBarrelRecHits"},
        {"OuterMPGDBarrelHits", "OuterMPGDBarrelRawHits", "OuterMPGDBarrelRawHitAssociations", "OuterMPGDBarrelRecHits"},
        {"BackwardMPGDEndcapHits", "BackwardMPGDEndcapRawHits", "BackwardMPGDEndcapRawHitAssociations", "BackwardMPGDEndcapRecHits"},
        {"ForwardMPGDEndcapHits", "ForwardMPGDEndcapRawHits", "ForwardMPGDEndcapRawHitAssociations", "ForwardMPGDEndcapRecHits"},
        {"B0TrackerHits", "B0TrackerRawHits", "B0TrackerRawHitAssociations", "B0TrackerRecHits"}
    };
```

Full Track Reconstruction



Fast Tracklet Reconstruction

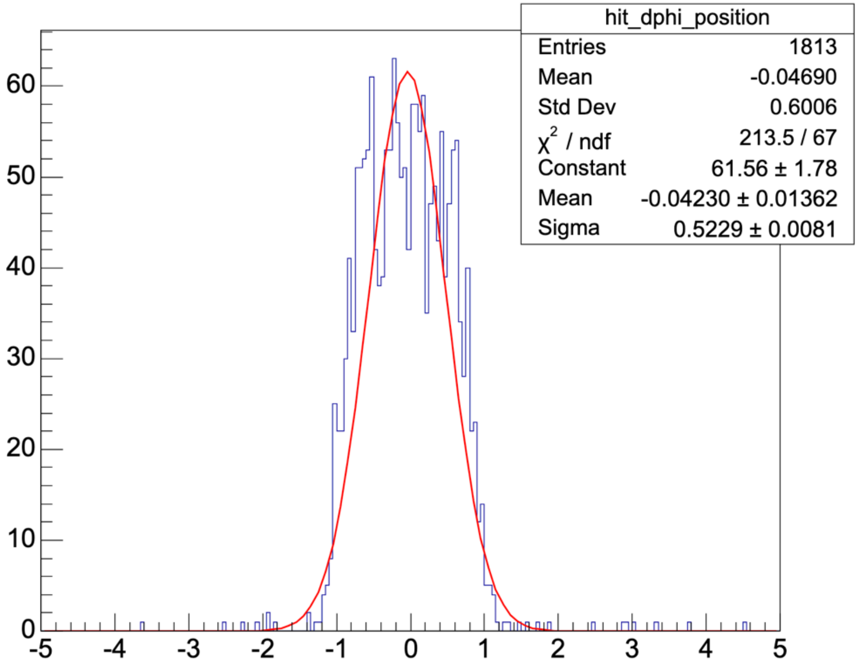


Calculation of angular resolution using **fast track (3 points)**

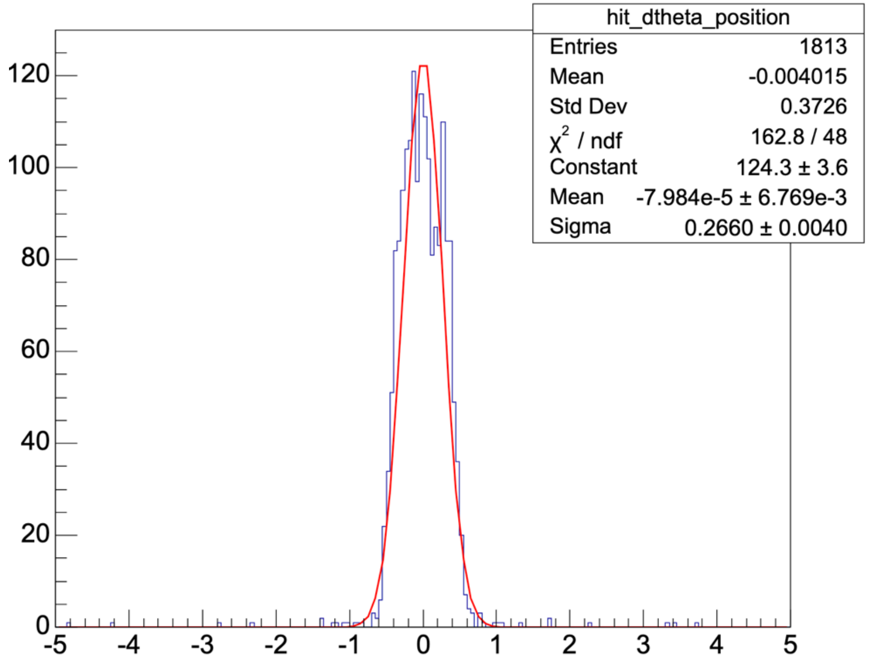
■ Angular resolution calculated from particle momentum in MC and fast track (inner MPGD + outer MPGD + BTOF)

- $\Delta\theta = \theta(track) - \theta(MC)$, $\Delta\phi = \phi(track) - \phi(MC)$
- $\theta = arctan2\left(\sqrt{x^2 + y^2}, z\right)$, $\phi = arctan2(x, y)$

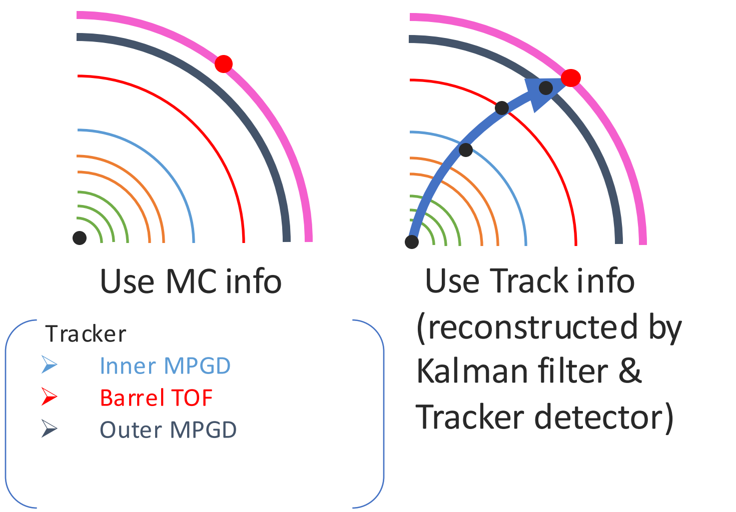
$\Delta\phi\ [mrad]$ (6GeV, 92 < θ < 94)



$\Delta\theta\ [mrad]$ (6GeV, 92 < θ < 94)



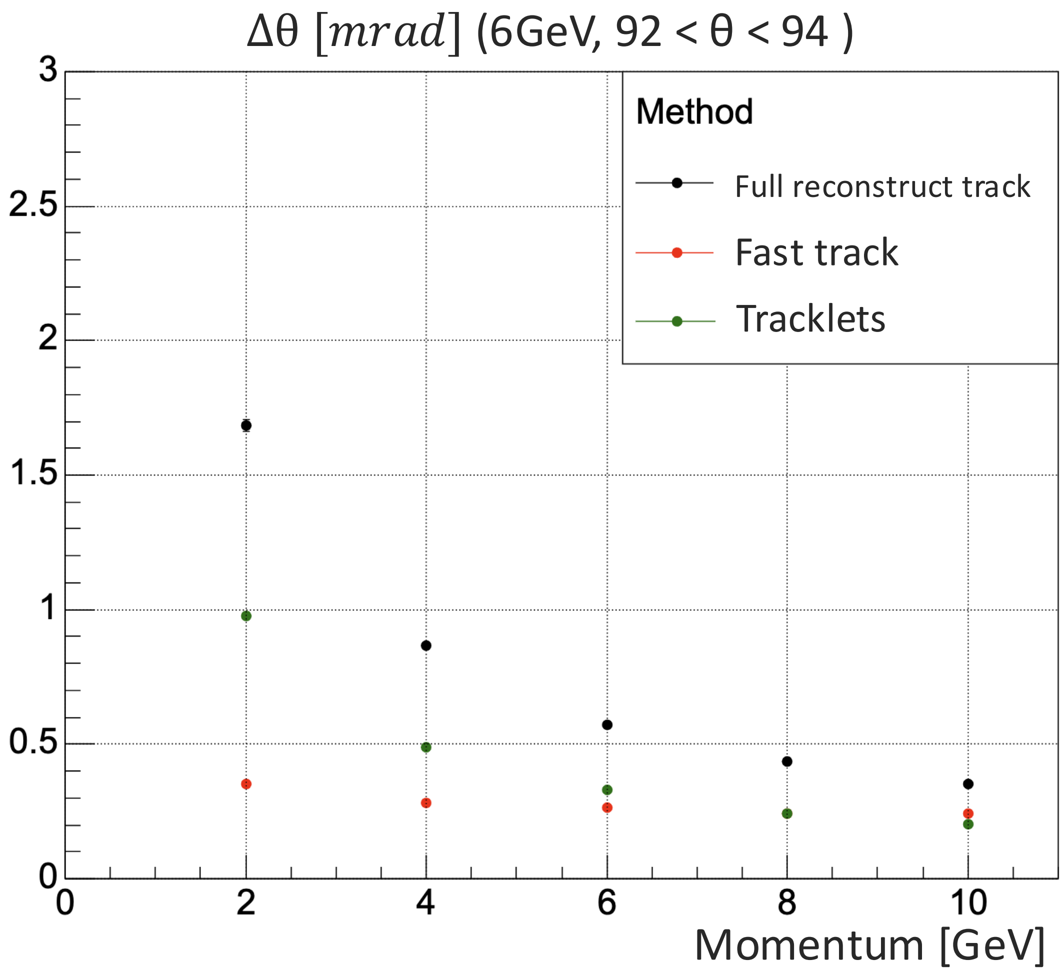
MC & Fast Track (3 points)

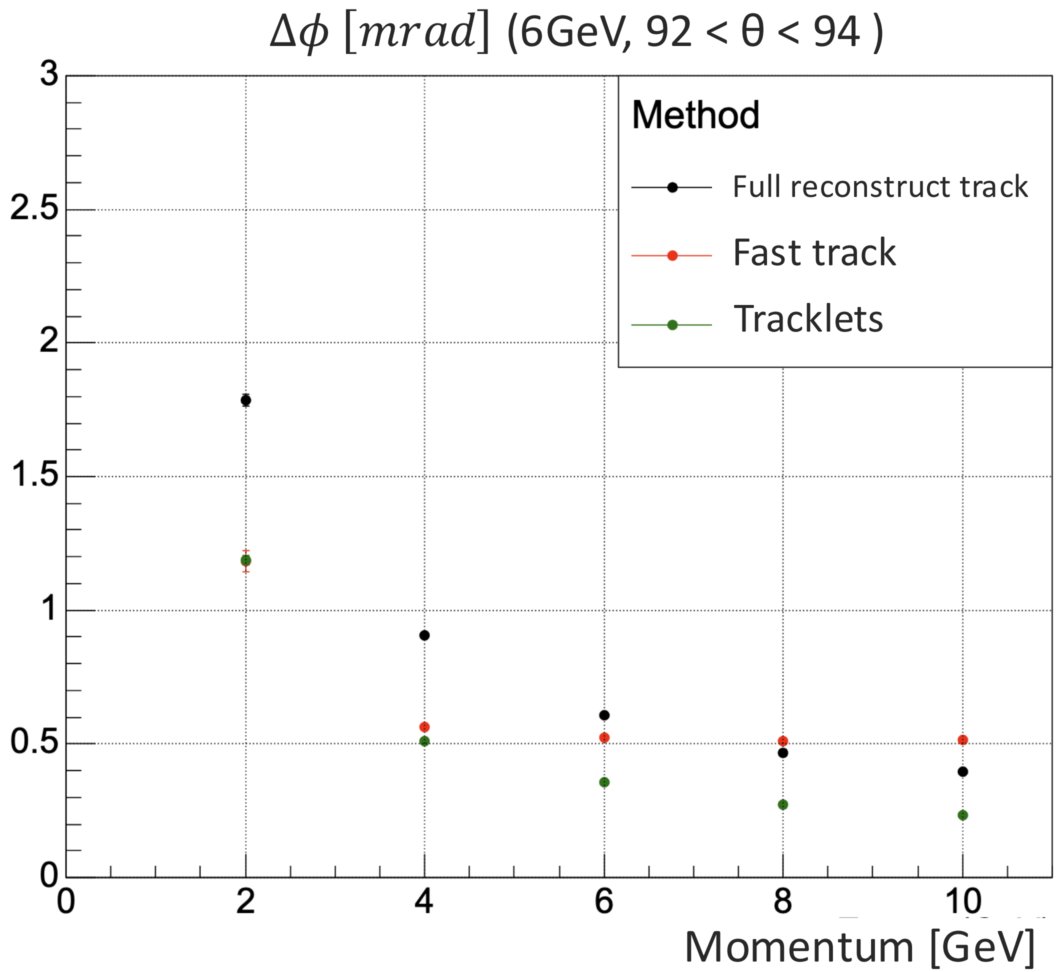


$$\sigma_\theta = 0.266 \pm 0.004\ [mrad]$$
$$\sigma_\phi = 0.523 \pm 0.008\ [mrad]$$

Comparison of methods for calculating angular resolution

■For $\Delta\phi$, flat graphs above 4 GeV

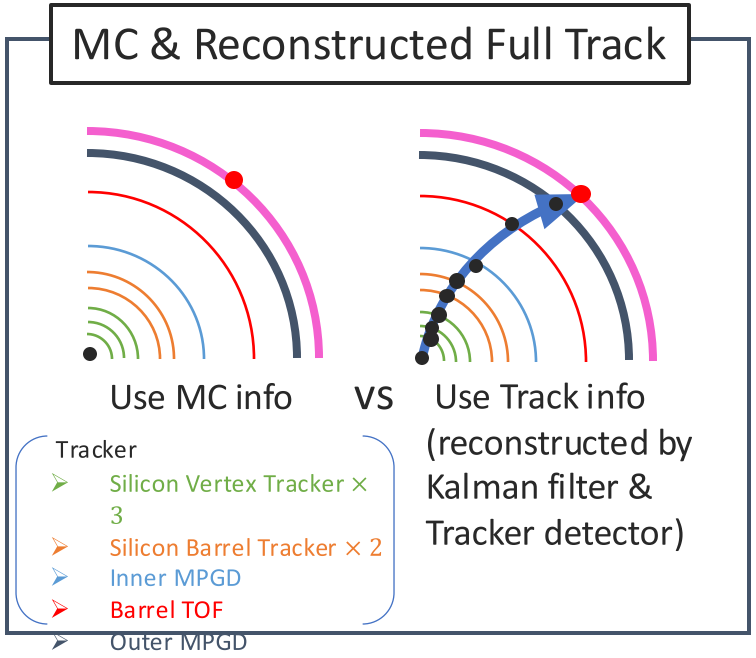




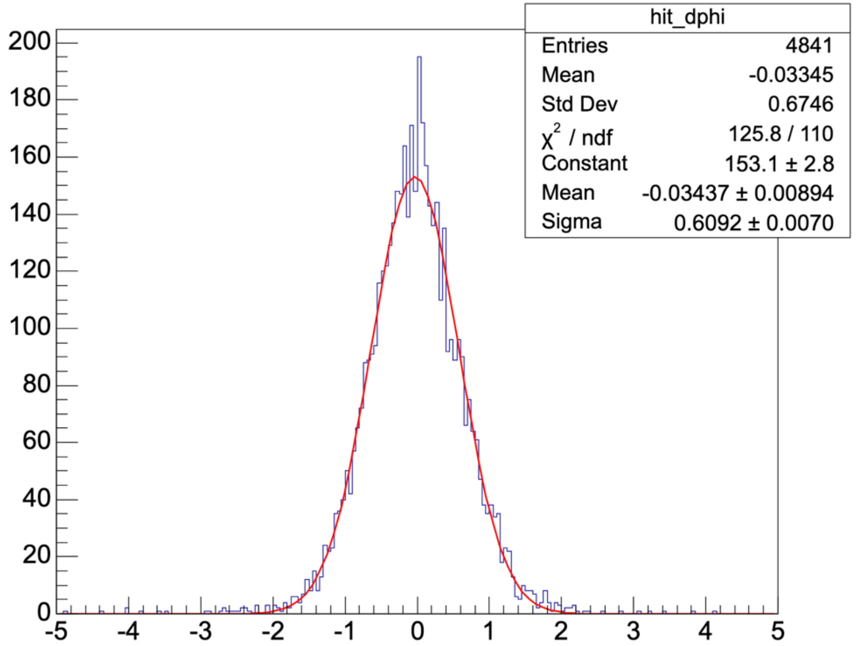
Back up

Calculation of angular resolution using **reconstructed full track**

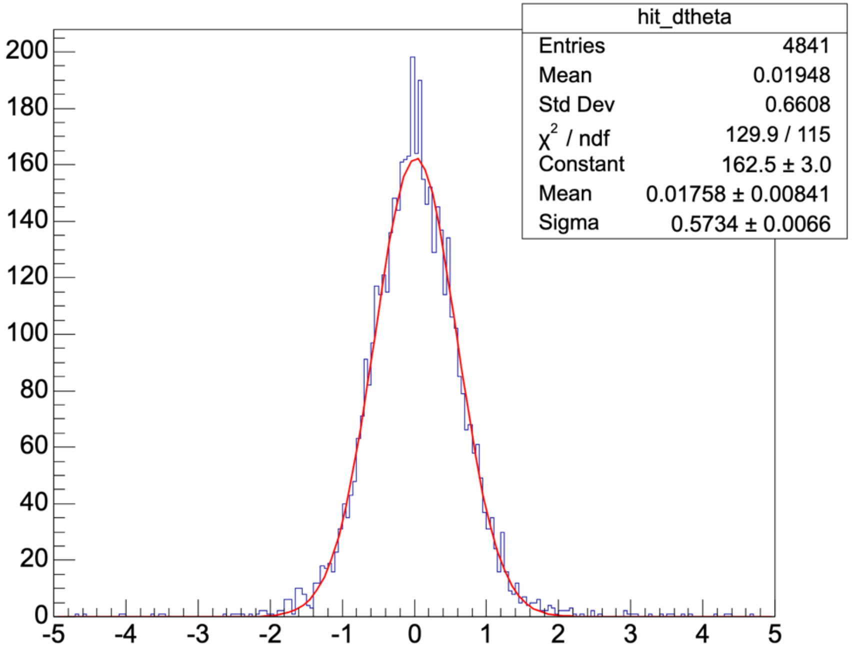
- Angular resolution calculated from particle momentum in MC and reconstructed track
  - $\Delta\theta = \theta(track) - \theta(MC)$, $\Delta\phi = \phi(track) - \phi(MC)$
  - $\theta = arctan2\left(\sqrt{{p_x}^2 + {p_y}^2}, p_z\right)$, $\phi = arctan2(p_y, p_x)$
  - Angular resolution is given by Gaussian sigma



$\Delta\phi\ [mrad]$ (6GeV, 92 < θ < 94)



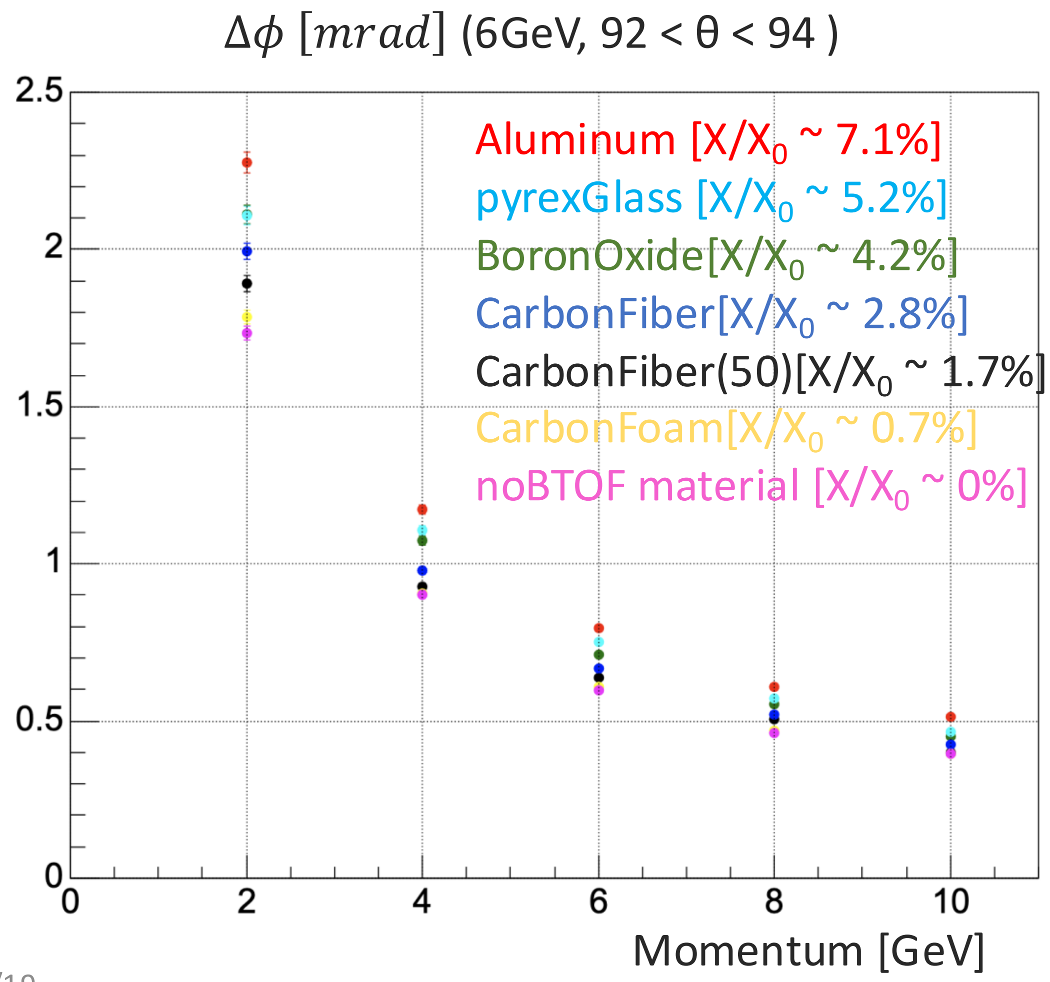
Δθ $[mrad]$ (6GeV, 92 < θ < 94)

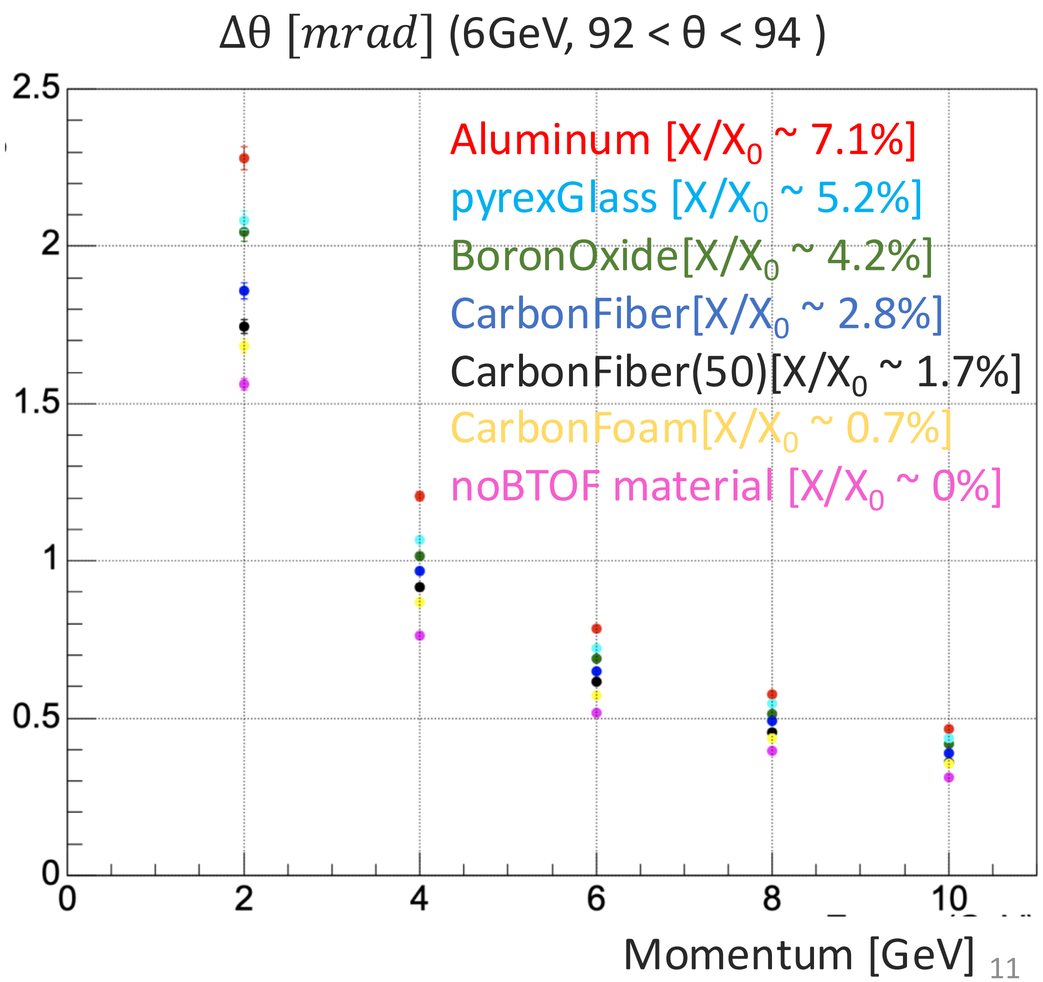


$$\sigma_\theta = 0.573 \pm 0.007\ [mrad]$$
$$\sigma_\phi = 0.609 \pm 0.007\ [mrad]$$

Calculation of angular resolution using **reconstructed full track**

■Graph of the angular resolution for each BTOF material, particle momentum

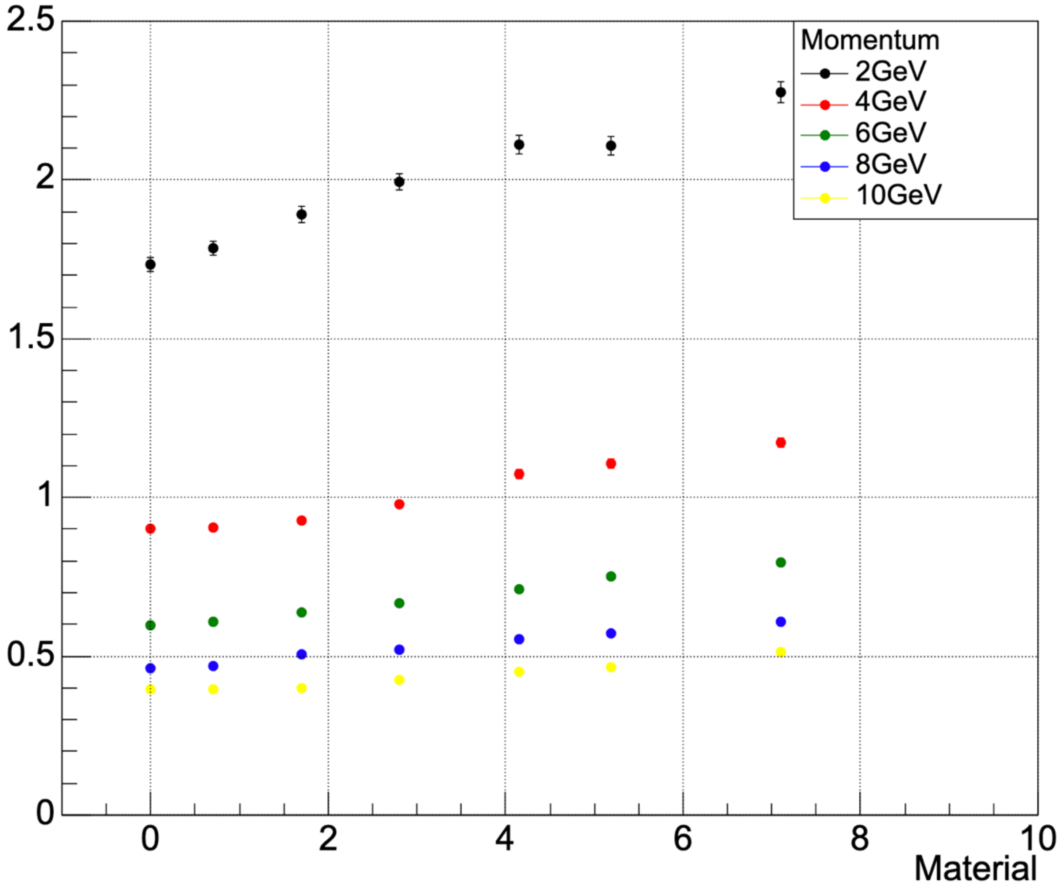




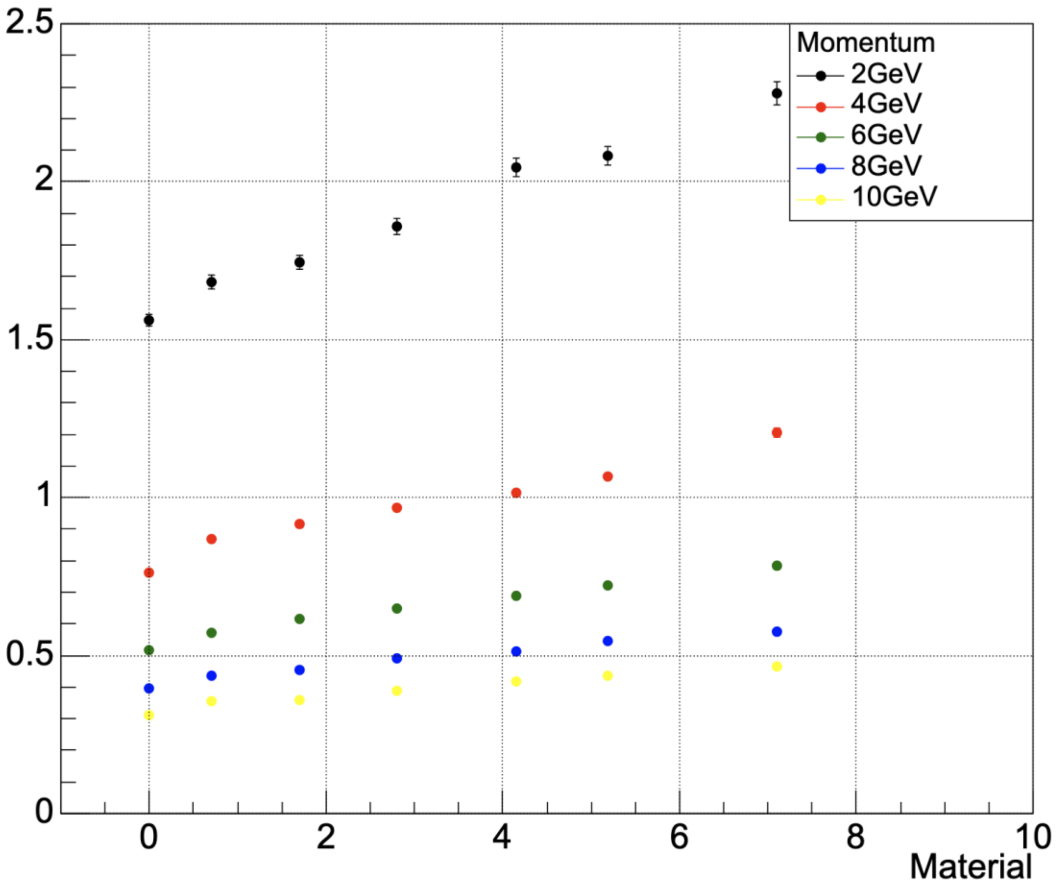
Calculation of angular resolution using **reconstructed full track**

■Graph of the angular resolution for each BTOF material, particle momentum

$\Delta\phi\ [mrad]$ (6GeV, 92 < θ < 94)

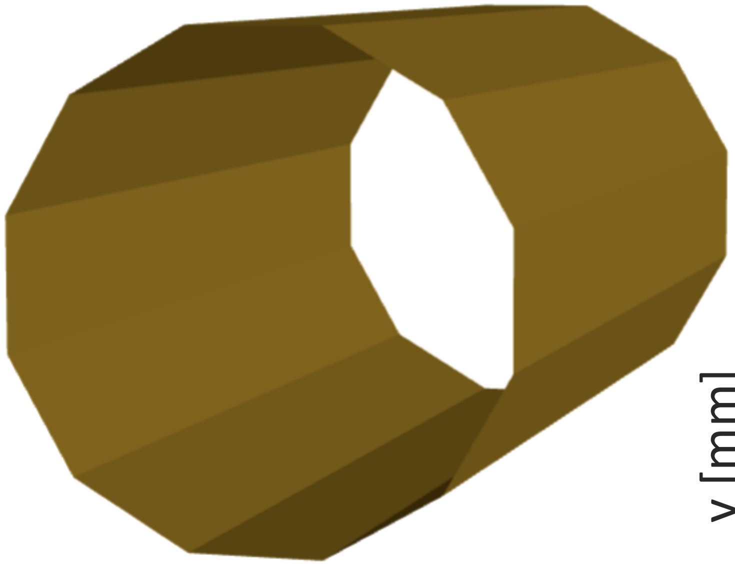


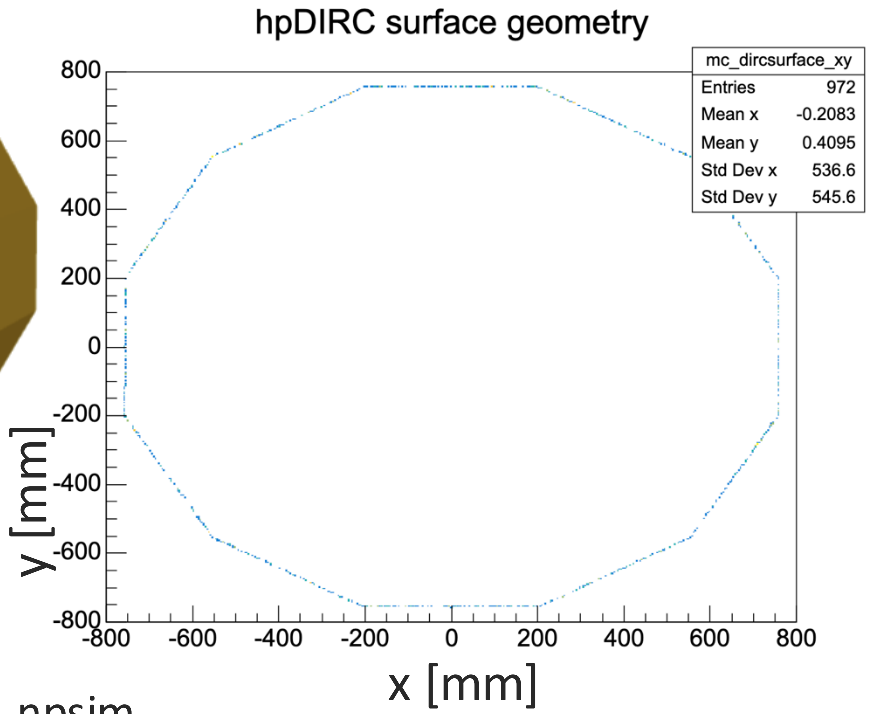
$\Delta\theta\ [mrad]$ (6GeV, 92 < θ < 94)



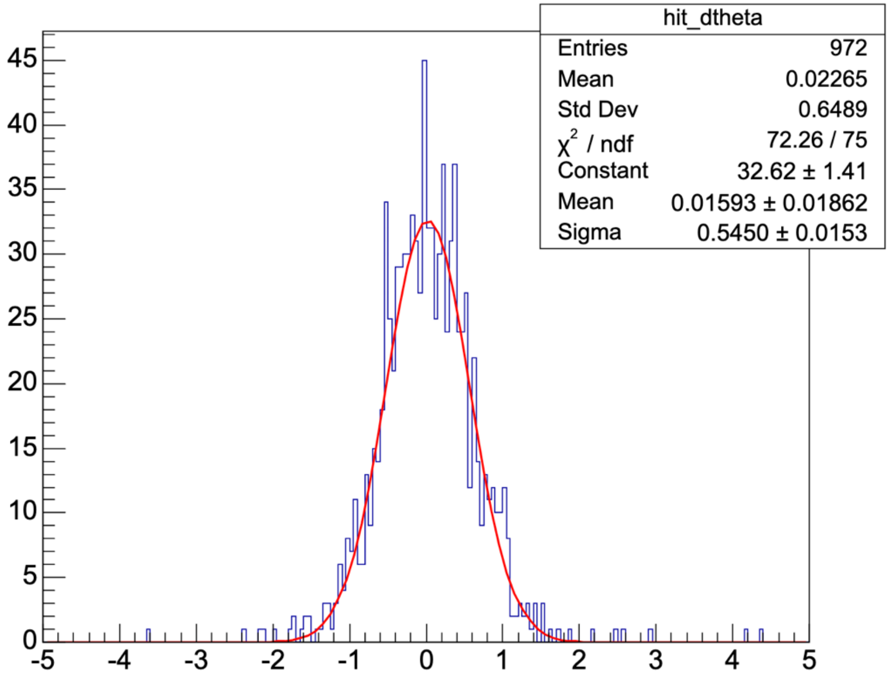
Define the exact location for this calculation of resolution

- More precise hpDIRC surface configuration (https://github.com/sourav-tarafdar/epic/blob/main/compact/tracking/dirc_ref.xml)





$\Delta\theta\ [mrad]$



Single particle : π^- , 1000events, npsim
Momentum : 6 [GeV/c]
Direction : $0^\circ \leq \phi \leq 360^\circ$,
$92^\circ \leq \theta \leq 94^\circ \rightarrow \langle\eta\rangle = -0.05$

$\boxed{\sigma = 0.5450 \pm 0.0153\ [mrad]}$

Use tracklets of MPGD + BTOF

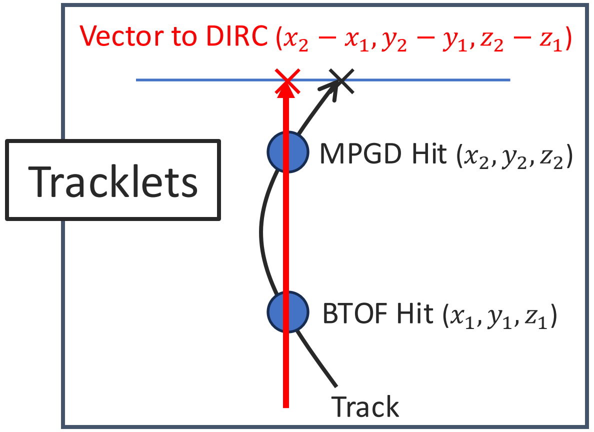
➢ $\theta, \phi(MC)$: Calculated from MC information for each detector hit

edm4hep::SimTrackerHit → "TOFBarrelHits", "OuterMPGDBarrelHits" get position <u>(x, y, z)</u>

(x_1, y_1, z_1) (x_2, y_2, z_2)

- Calculated the angle of incidence of the particle into the hpDIRC from the truth hit position to the detector

- $\theta = arctan2\left(\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}, (z_2 - z_1)\right)$
- $\phi = arctan2((y_2 - y_1), (x_2 - x_1))$




```
edm4hep::SimTrackerHit:
  Description: "Simulated tracker hit"
  Author: "EDM4hep authors"
  Members:
    - uint64_t cellID      // ID of the sensor that created this hit
    - float eDep [GeV]               // energy deposited in the hit
    - float time [ns]                // proper time of the hit in the lab frame
    - float pathLength               // path length of the particle in the sensitive material that resulted in this hit
    - int32_t   quality                  // quality bit flag
    - edm4hep::Vector3d position [mm] // the hit position
    - edm4hep::Vector3f momentum [GeV] // the 3-momentum of the particle at the hits position
  OneToOneRelations:
    - edm4hep::MCParticle particle // MCParticle that caused the hit
```

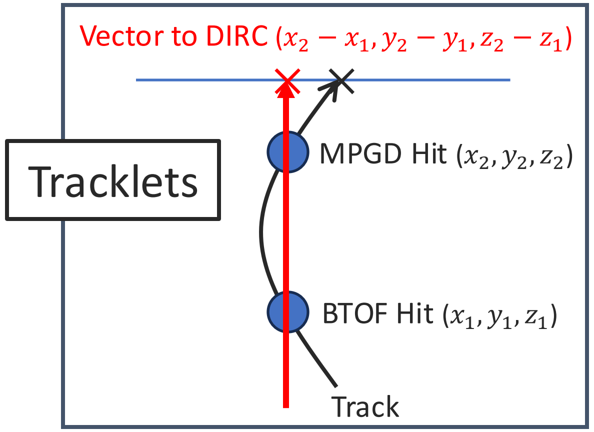
Use tracklets of MPGD + BTOF

➢ $\theta, \phi(track)$: Calculated from Track information for each detector hit

edm4eic::TrackPoint → Using the position of the particles along the reconstructed track on each detector

- Track reconstruction : use Kalman filter & tracker detectors (vtx×3 + silicon×2 + MPGDs + BTOF)
- Along the reconstructed track and equal to r of the MC hit

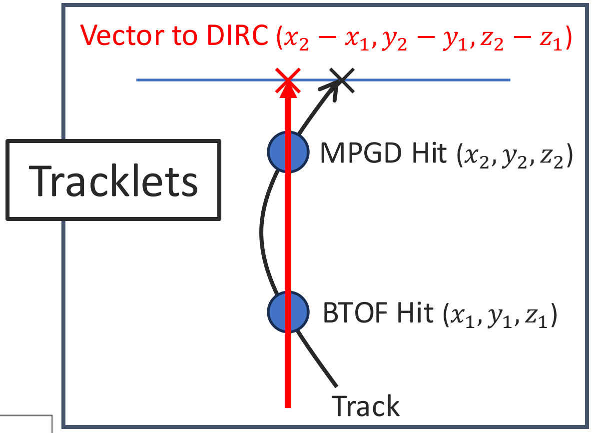
- $\theta = arctan2\left(\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}, (z_2 - z_1)\right)$
- $\phi = arctan2((y_2 - y_1), (x_2 - x_1))$



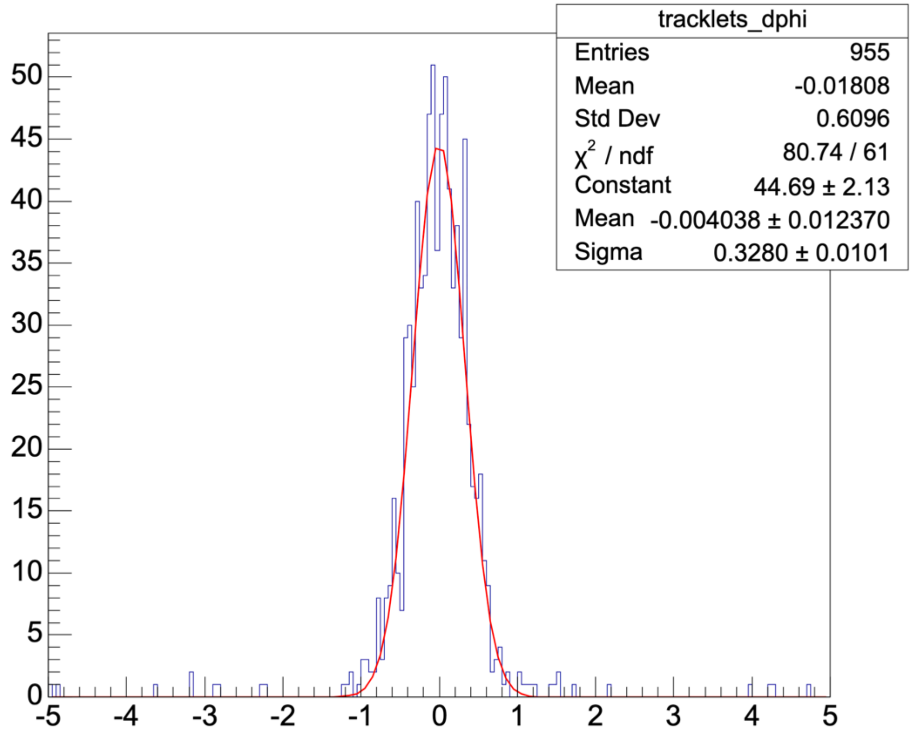
The resolution was calculated by comparing the position on the detector with the value from the MC or the value from the track.

Use tracklets of MPGD + BTOF

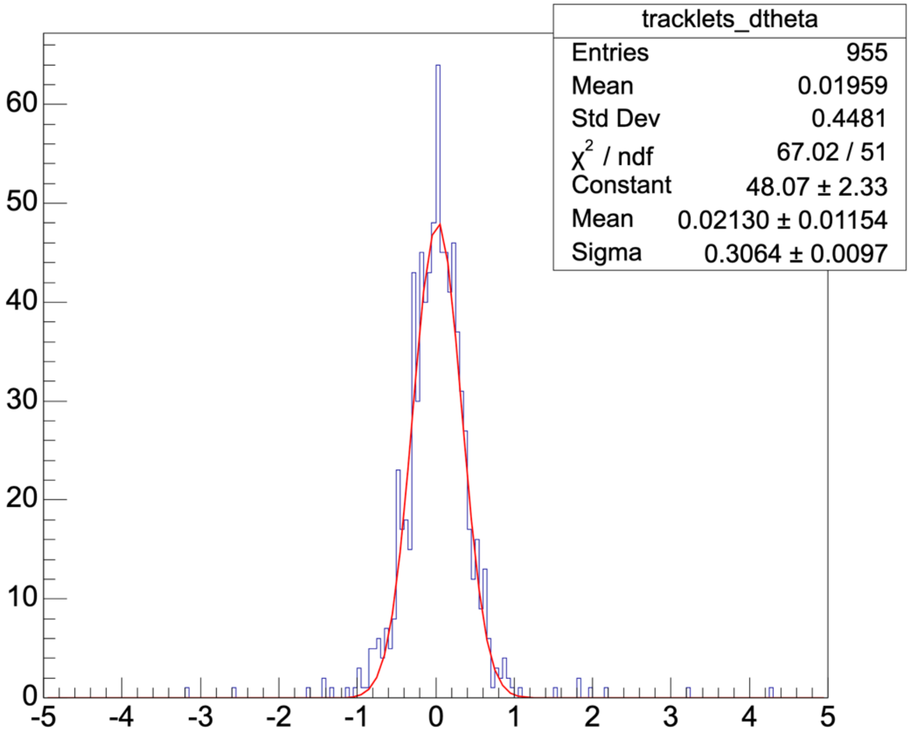
- Tracklets of outer MPGD + BTOF
  - $\Delta\theta = \theta(track) - \theta(MC)$, $\Delta\phi = \phi(track) - \phi(MC)$
  - $\theta = arctan2\left(\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}, (z_2 - z_1)\right)$
  - $\phi = arctan2((y_2 - y_1), (x_2 - x_1))$



$\Delta\phi$ $[mrad]$



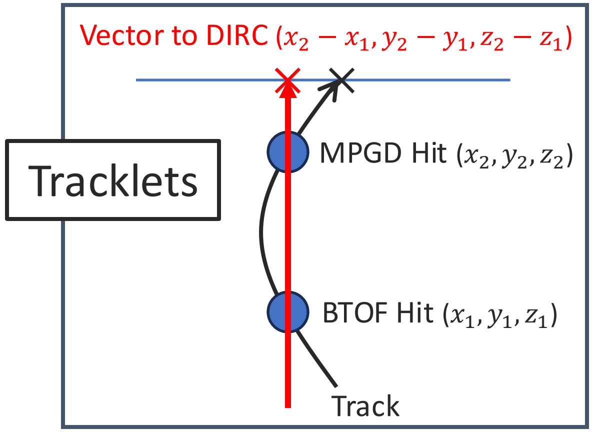
$\Delta\theta$ $[mrad]$



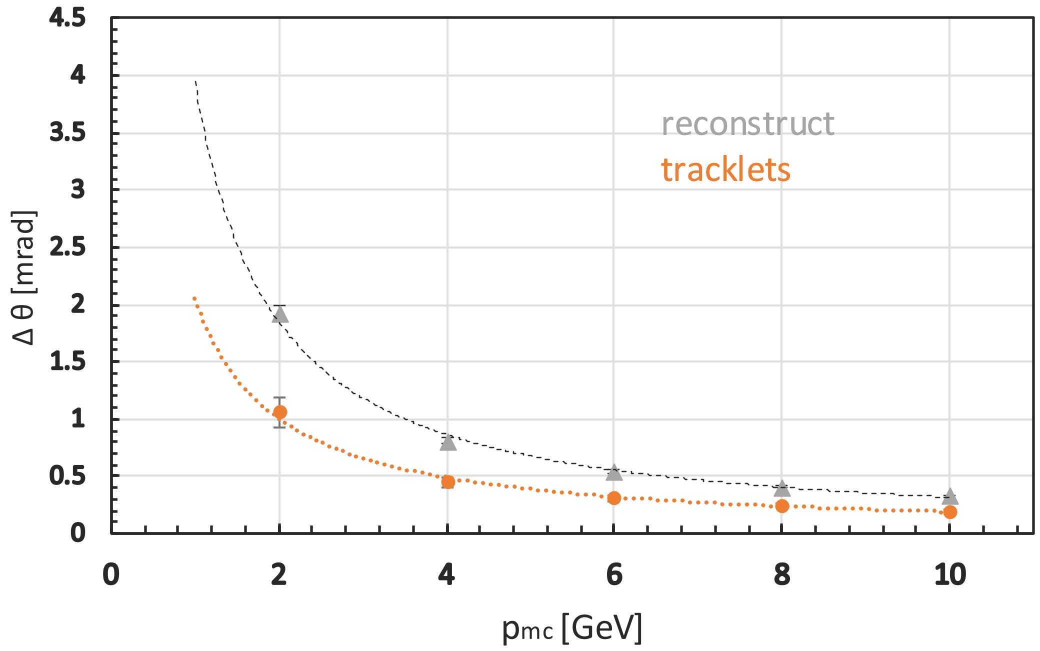
$\sigma = 0.3064 \pm 0.0097$ $[mrad]$

Use tracklets of MPGD + BTOF

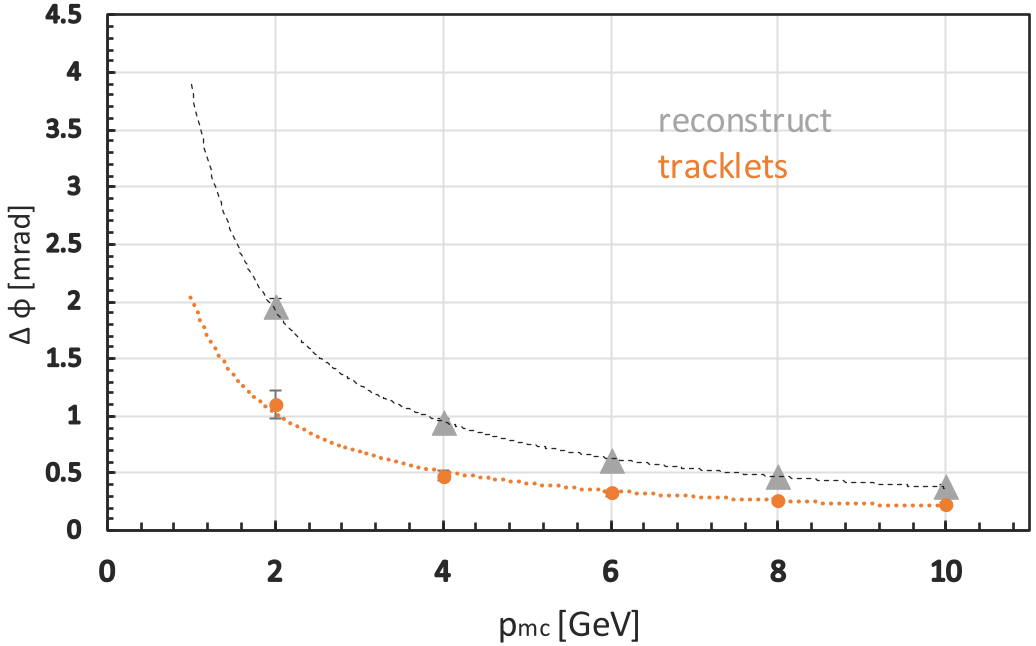
- Tracklets of outer MPGD + BTOF
  - $\Delta\theta = \theta(track) - \theta(MC), \qquad \Delta\phi = \phi(track) - \phi(MC)$
  - $\theta = arctan2\left(\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}, (z_2 - z_1)\right)$
  - $\phi = arctan2((y_2 - y_1), (x_2 - x_1))$



Δθ [mrad] 92 < θ < 94, <η> = -0.05



Δϕ [mrad] 92 < θ < 94, <η> = -0.05



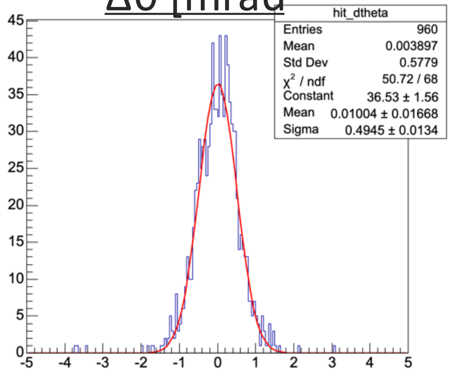
Resolution with and without BTOF material at all

■without BTOF material → Change all BTOF material to “vacuum”

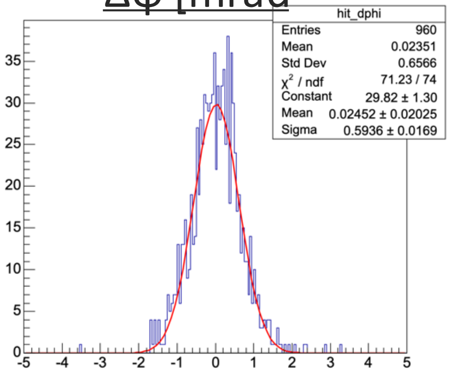
```
<module_component name="sensor" material="Vacuum" sensitive="true" width="BarrelTOF_Sensor_width" length="BarrelTOF_length1" thickness="BarrelTOF_Sensor_thickness" vis="TOFSensorVis" >
  <position x="BarrelTOF_Sensor_position" y="0" z="0" />
</module_component>
<module_component name="hybridtop" material="Vacuum" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_Hybrid_thickness" vis="TOFHybridVis" >
  <position x="BarrelTOF_Service_position" y="0" z="0" />
</module_component>
<module_component name="cfskintop" material="Vacuum" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFSkin_thickness" vis="TOFCSkinVis" >
  <position x="BarrelTOF_Service_position" y="0" z="0" />
</module_component>
<module_component name="coolingtube" material="Vacuum" sensitive="false" width="BarrelTOF_CoolingTube_width" length="BarrelTOF_length1" thickness="BarrelTOF_CoolingTube_thickness" vis="TOFCoolingTubeVis" >
  <position x="BarrelTOF_CoolingTube_position" y="0" z="0" />
</module_component>
<module_component name="coolant" material="Vacuum" sensitive="false" width="BarrelTOF_Coolant_width" length="BarrelTOF_length1" thickness="BarrelTOF_Coolant_thickness" vis="TOFCoolantVis" >
  <position x="BarrelTOF_Coolant_position" y="0" z="0" />
</module_component>
<module_component name="cfoam" material="Vacuum" sensitive="false" width="BarrelTOF_CFoam_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFoam_thickness" vis="TOFCFoamVis" >
  <position x="BarrelTOF_CFoam_position" y="0" z="0" />
</module_component>
<module_component name="choneycomb" material="Vacuum" sensitive="false" width="BarrelTOF_CHoneycomb_width" length="BarrelTOF_length1" thickness="BarrelTOF_CHoneycomb_thickness" vis="TOFCHoneycombVis" >
  <position x="BarrelTOF_CHoneycomb_position" y="0" z="-1*BarrelTOF_CFoam_thickness" />
</module_component>
<module_component name="cfskinbottom" material="Vacuum" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFSkin_thickness" vis="TOFCSkinVis" >
  <position x="BarrelTOF_Service_position" y="0" z="0" />
</module_component>
<module_component name="hybridbottom" material="Vacuum" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_Hybrid_thickness" vis="TOFHybridVis" >
  <position x="BarrelTOF_Service_position" y="0" z="0" />
</module_component>
```

92 < θ < 94 , p = 6 GeV

Δθ [mrad



Δϕ [mrad



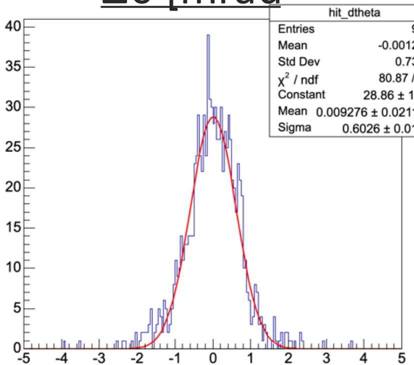
Resolution with carbon fiber BTOF

- Change CarbonFoam(0.09 g/cm^3 : 0.7%[X_0/X]) to CarbonFiber(1.5 g/cm^3 : 2.8 %[X/X_0])

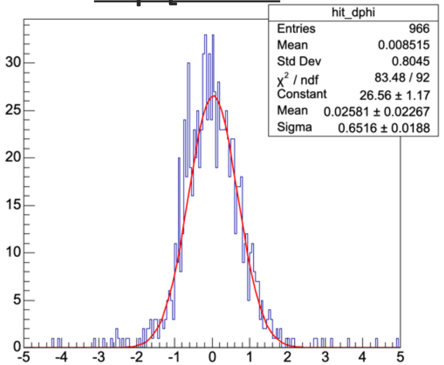
```xml
<comment>
  Tracker Barrel Modules
</comment>
<module name="BarrelTOF_Module1" vis="TOFBarrelModuleVis">
  <module_component name="sensor" material="Silicon" sensitive="true" width="BarrelTOF_Sensor_width" length="BarrelTOF_length1" thickness="BarrelTOF_Sensor_thickness" vis="TOFSensorVis" >
    <position x="BarrelTOF_Sensor_position" y="0" z="0" />
  </module_component>
  <module_component name="hybridtop" material="Kapton" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_Hybrid_thickness" vis="TOFHybridVis" >
    <position x="BarrelTOF_Service_position" y="0" z="0" />
  </module_component>
  <module_component name="cfskintop" material="CFRPMix2" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFSkin_thickness" vis="TOFCSkinVis" >
    <position x="BarrelTOF_Service_position" y="0" z="0" />
  </module_component>
  <module_component name="coolingtube" material="Aluminum" sensitive="false" width="BarrelTOF_CoolingTube_width" length="BarrelTOF_length1" thickness="BarrelTOF_CoolingTube_thickness" vis="TOFCoolingTubeVis"
    <position x="BarrelTOF_CoolingTube_position" y="0" z="0" />
  </module_component>
  <module_component name="coolant" material="NOVEC7200" sensitive="false" width="BarrelTOF_Coolant_width" length="BarrelTOF_length1" thickness="BarrelTOF_Coolant_thickness" vis="TOFCoolantVis" >
    <position x="BarrelTOF_Coolant_position" y="0" z="0" />
  </module_component>
  <module_component name="cfoam" material="CarbonFiber" sensitive="false" width="BarrelTOF_CFoam_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFoam_thickness" vis="TOFCFoamVis" >
  <!-- <module_component name="cfoam" material="CarbonFoam" sensitive="false" width="BarrelTOF_CFoam_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFoam_thickness" vis="TOFCFoamVis" > -->
    <position x="BarrelTOF_CFoam_position" y="0" z="0" />
  </module_component>
  <module_component name="choneycomb" material="CFRPMix" sensitive="false" width="BarrelTOF_CHoneycomb_width" length="BarrelTOF_length1" thickness="BarrelTOF_CHoneycomb_thickness" vis="TOFCHoneycombVis" >
    <position x="BarrelTOF_CHoneycomb_position" y="0" z="-1*BarrelTOF_CFoam_thickness" />
  </module_component>
  <module_component name="cfskinbottom" material="CFRPMix2" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFSkin_thickness" vis="TOFCSkinVis" >
    <position x="BarrelTOF_Service_position" y="0" z="0" />
  </module_component>
  <module_component name="hybridbottom" material="Kapton" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_Hybrid_thickness" vis="TOFHybridVis" >
    <position x="BarrelTOF_Service_position" y="0" z="0" />
  </module_component>
```

92 < θ < 94 , p = 6 GeV

Δθ [mrad



Δϕ [mrad



+1-2% material to BTOF and study its impact

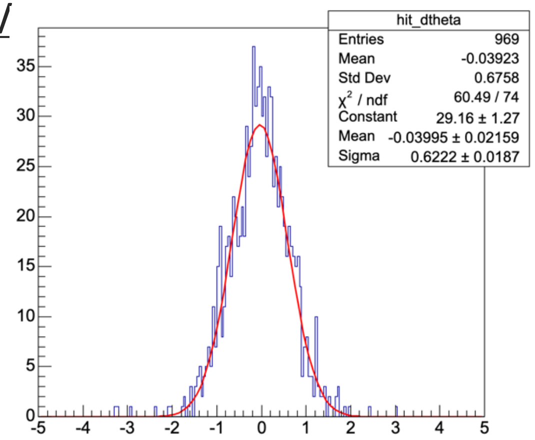
- Change CarbonFoam(0.09 g/cm^3 : 0.7%[X_0/X]) to CarbonFiber50D(0.75 g/cm^3 : 1.7 %[X_0/X])

```xml
<module_component name="sensor" material="Silicon" sensitive="true" width="BarrelTOF_Sensor_width" length="BarrelTOF_length1" thickness="BarrelTOF_Sensor_thickness" vis="TOFSensorVis" >
  <position x="BarrelTOF_Sensor_position" y="0" z="0" />
</module_component>
<module_component name="hybridtop" material="Kapton" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_Hybrid_thickness" vis="TOFHybridVis" >
  <position x="BarrelTOF_Service_position" y="0" z="0" />
</module_component>
<module_component name="cfskintop" material="CFRPMix2" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFSkin_thickness" vis="TOFCSkinVis" >
  <position x="BarrelTOF_Service_position" y="0" z="0" />
</module_component>
<module_component name="coolingtube" material="Aluminum" sensitive="false" width="BarrelTOF_CoolingTube_width" length="BarrelTOF_length1" thickness="BarrelTOF_CoolingTube_thickness" vis="TOFCoolingTubeVis" >
  <position x="BarrelTOF_CoolingTube_position" y="0" z="0" />
</module_component>
<module_component name="coolant" material="NOVEC7200" sensitive="false" width="BarrelTOF_Coolant_width" length="BarrelTOF_length1" thickness="BarrelTOF_Coolant_thickness" vis="TOFCoolantVis" >
  <position x="BarrelTOF_Coolant_position" y="0" z="0" />
</module_component>
<module_component name="cfoam" material="CarbonFiber_50D" sensitive="false" width="BarrelTOF_CFoam_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFoam_thickness" vis="TOFCFoamVis" >
<!-- <module_component name="cfoam" material="CarbonFoam" sensitive="false" width="BarrelTOF_CFoam_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFoam_thickness" vis="TOFCFoamVis" > -->
  <position x="BarrelTOF_CFoam_position" y="0" z="0" />
</module_component>
<module_component name="choneycomb" material="CFRPMix" sensitive="false" width="BarrelTOF_CHoneycomb_width" length="BarrelTOF_length1" thickness="BarrelTOF_CHoneycomb_thickness" vis="TOFCHoneycombVis" >
  <position x="BarrelTOF_CHoneycomb_position" y="0" z="-1*BarrelTOF_CFoam_thickness" />
</module_component>
<module_component name="cfskinbottom" material="CFRPMix2" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFSkin_thickness" vis="TOFCSkinVis" >
  <position x="BarrelTOF_Service_position" y="0" z="0" />
</module_component>
<module_component name="hybridbottom" material="Kapton" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_Hybrid_thickness" vis="TOFHybridVis" >
  <position x="BarrelTOF_Service_position" y="0" z="0" />
</module_component>
```

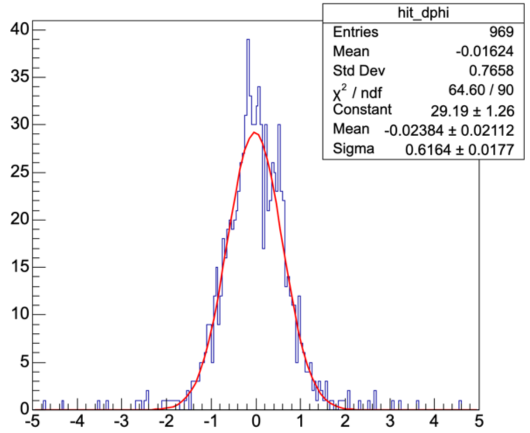
```xml
<material name="CarbonFiber">
  <D type="density" value="1.5" unit="g/cm3"/>
  <fraction n="0.65" ref="C"/>
  <fraction n="0.35" ref="Epoxy"/>
</material>
<material name="CarbonFiber_50D">
  <D type="density" value="0.75" unit="g/cm3"/>
  <fraction n="0.65" ref="C"/>
  <fraction n="0.35" ref="Epoxy"/>
</material>
```

92 < θ < 94 , p = 6 GeV

Δθ [mrad

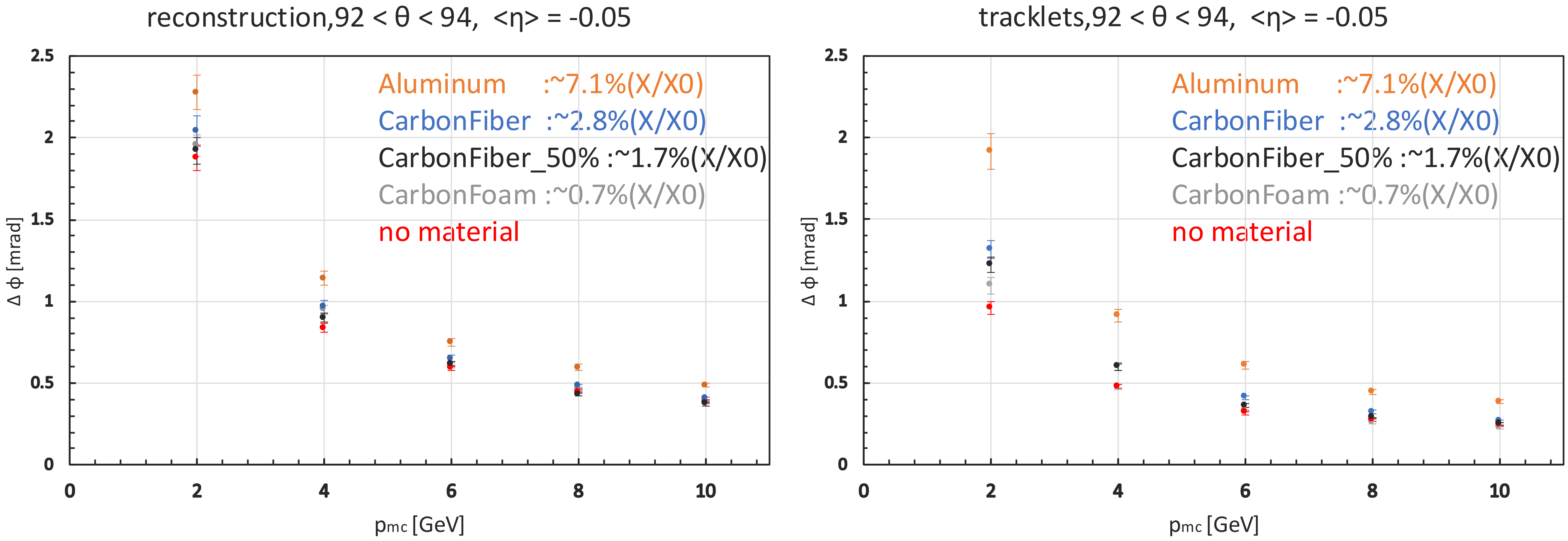


Δϕ [mrad



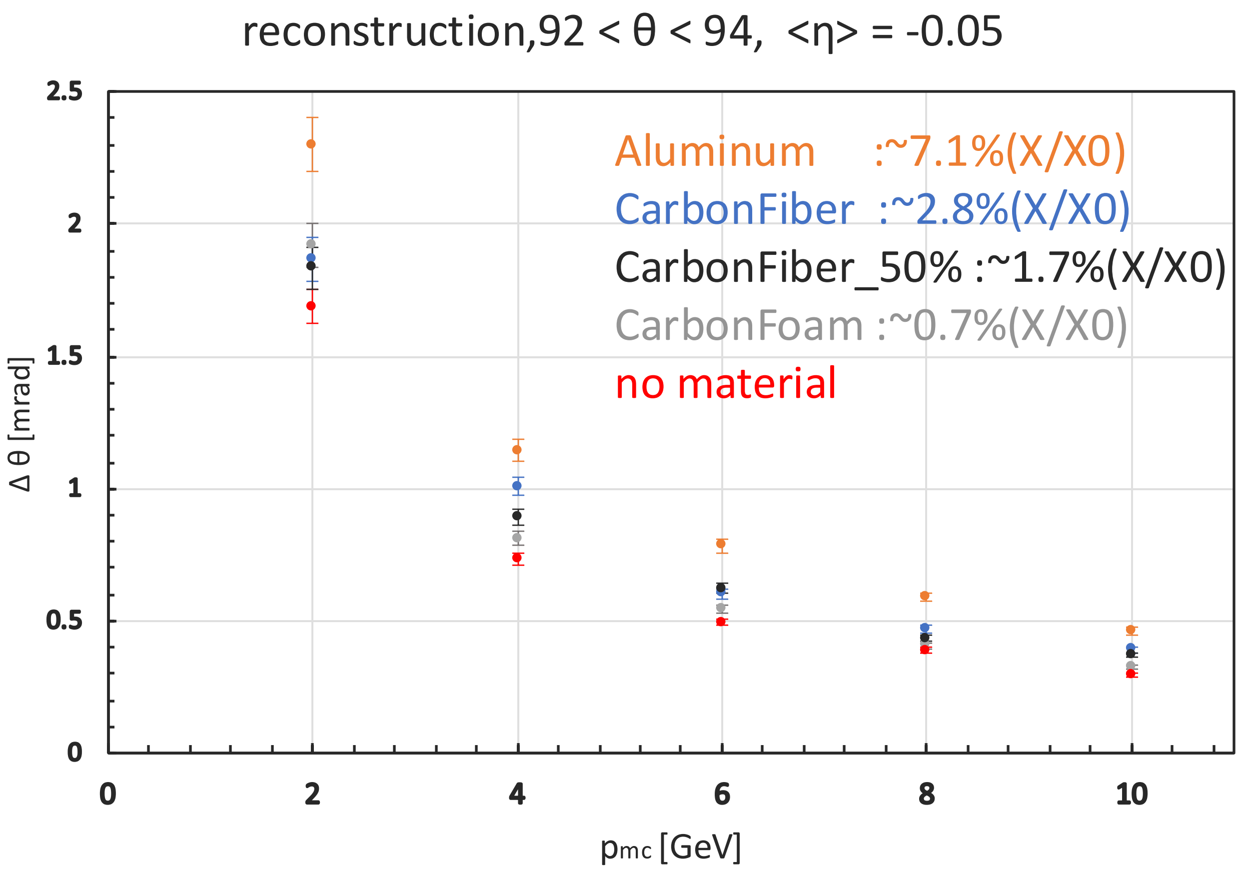
Results for some changes in particle momentum and BTOF material

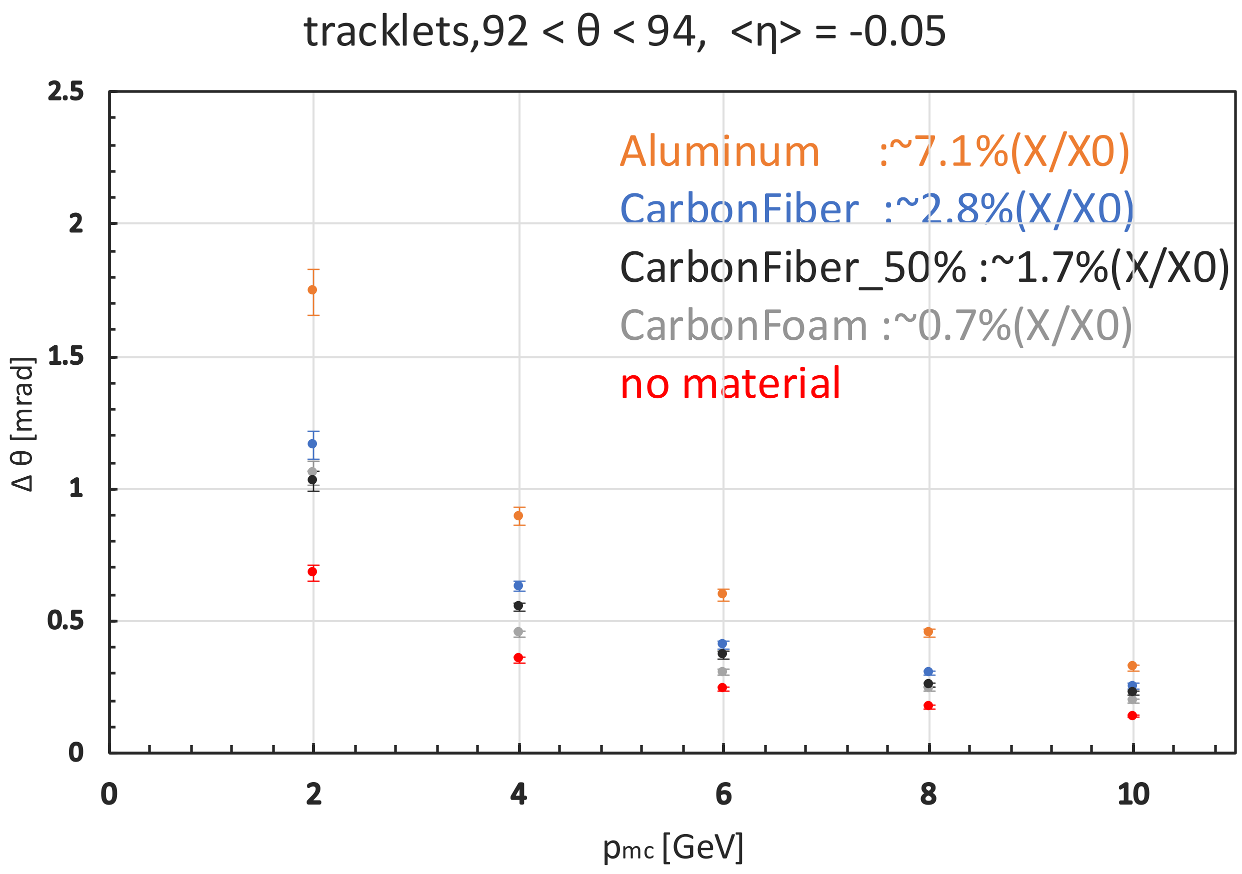
■Δϕ : Reconstruction & Tracklets



Results for some changes in particle momentum and BTOF material

■Δθ : Reconstruction & Tracklets





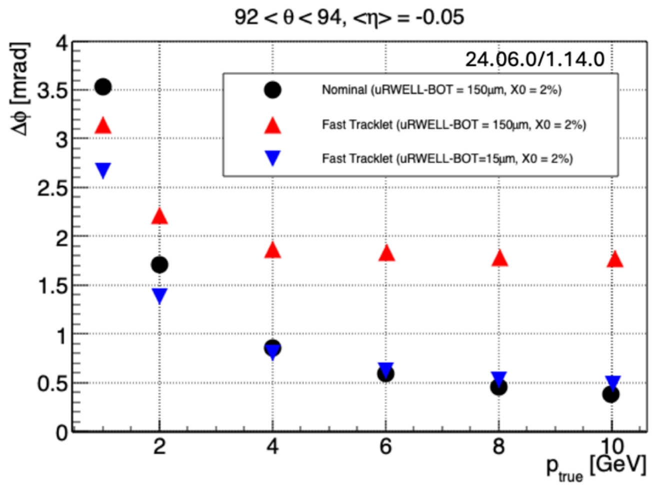
Remaining tasks (Plan)

1. Use tracklets of MPGDs + BTOF (3 points)

   Track reconstruction with only 3 detectors with better time resolution compared to vtx tracker & silicon tracker

   Need to confirm the results as they show a different trend from Matthew's results who performed a similar simulation.

   https://indico.bnl.gov/event/24221/contributions/94046/attachments/55823/95470/07_15_2024_DIRCAngleRes.pdf

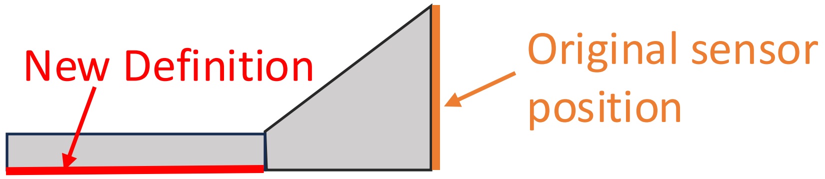


2. Use Kalman filter inside-out

   Just consider it after all other tasks are completed.

Simulation

1. Define the surface of hpDIRC using Geant4 (hpDIRC surface)
   - Because no particles are detected on the surface of the hpDIRC
   - <u>To obtain MC information of particles at hpDIRC surface</u>



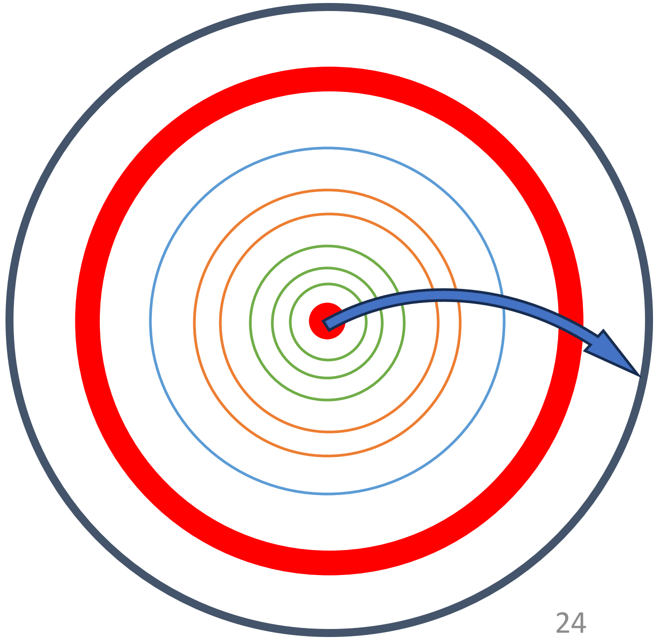
2. Calculate angle of incident particles from hit information (momentum) to detector
   - MC info(mc.theta)： Use MC information of the detector defined in 1.
   - Track info(track.theta)： Get values from propagation of reconstructed tracks from tracker

Tracker Detectors (Barrel)

- Silicon Vertex Tracker × 3
- Silicon Barrel Tracker × 2
- Inner MPGD (Micro Pattern Gas Detector)
- Barrel TOF
- Outer MPGD

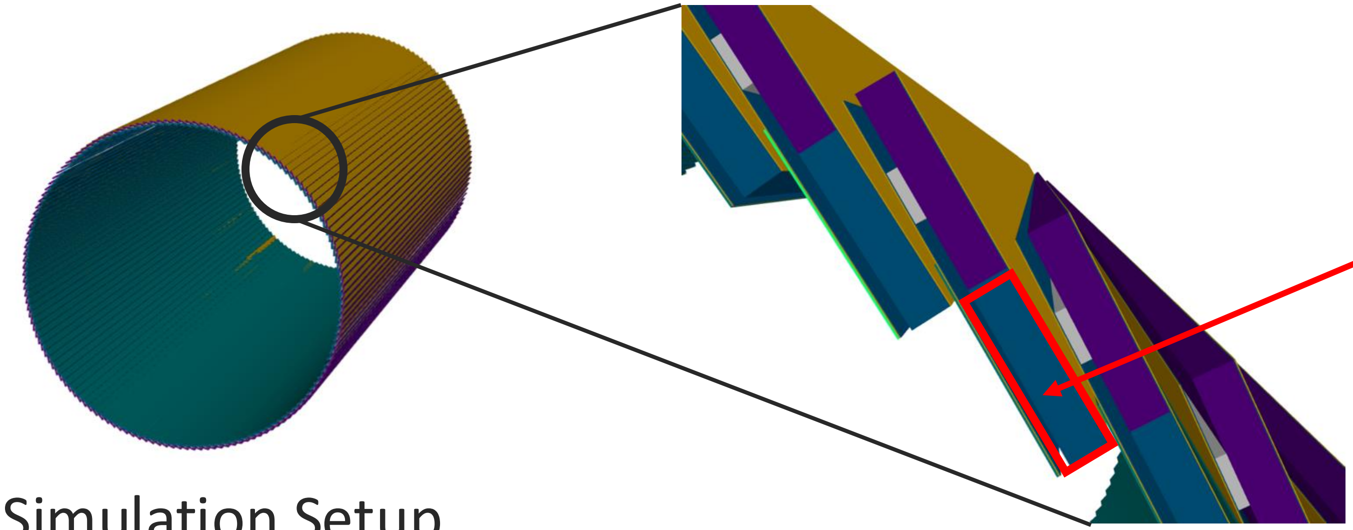
Kalman filter to reconstruct tracks

Using track parameter information on hpDIRC surface (r = 75.5 cm)



Simulation

3. Change the BTOF material and perform the same simulation



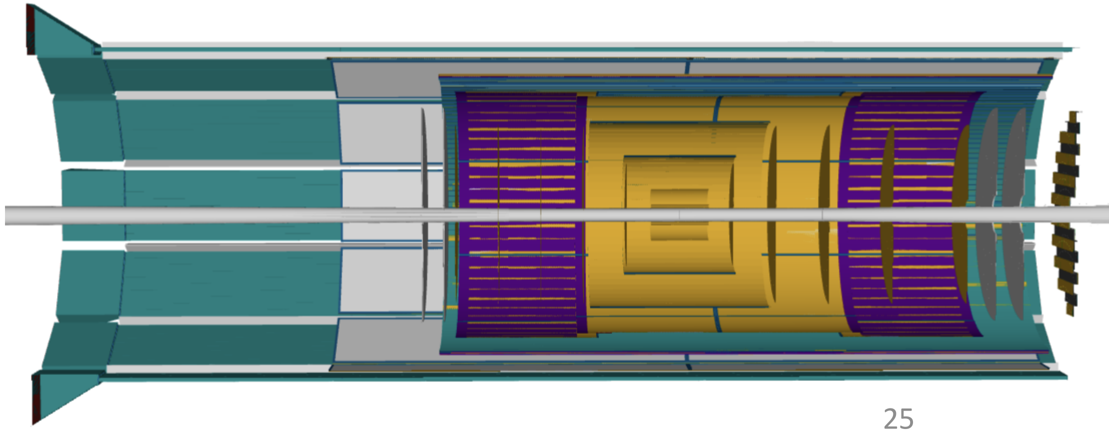
<u>Carbon foam</u> : 0.09 g/cm^3, 5.8mm
~ 0.7 % (X/X0)

↓Change material

<u>Aluminum</u> : 2.65 g/cm^3
~ 7.1 % (X/X0)

■Simulation Setup

- EICrecon : Particle collision reconstruction using phythia8, Geant4, and track reconstruction algorithms using ePIC detector structures are available.
- Single particle : π^-
- Momentum : 1, 2, 4, 6, 8, 10 [GeV/c]
- Direction : $0^\circ \leq \phi \leq 360^\circ$, $92^\circ \leq \theta \leq 94^\circ \rightarrow \langle\eta\rangle = -0.05$

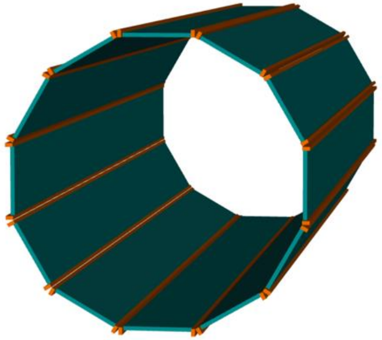


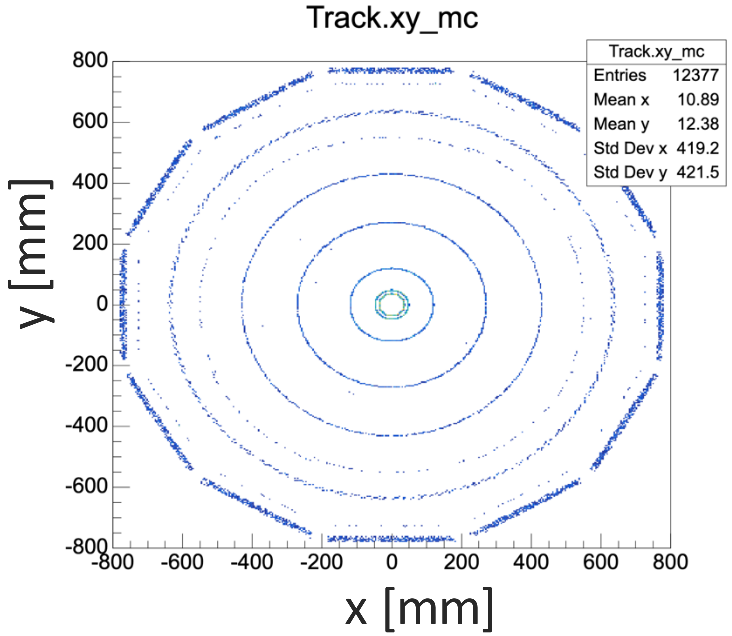
Results - Hit position on hpDIRC surface

■Generates 1000event single particles (6 GeV/c, $0^{\circ} \leq \phi \leq 360^{\circ}, 92^{\circ} \leq \theta \leq 94^{\circ}$)

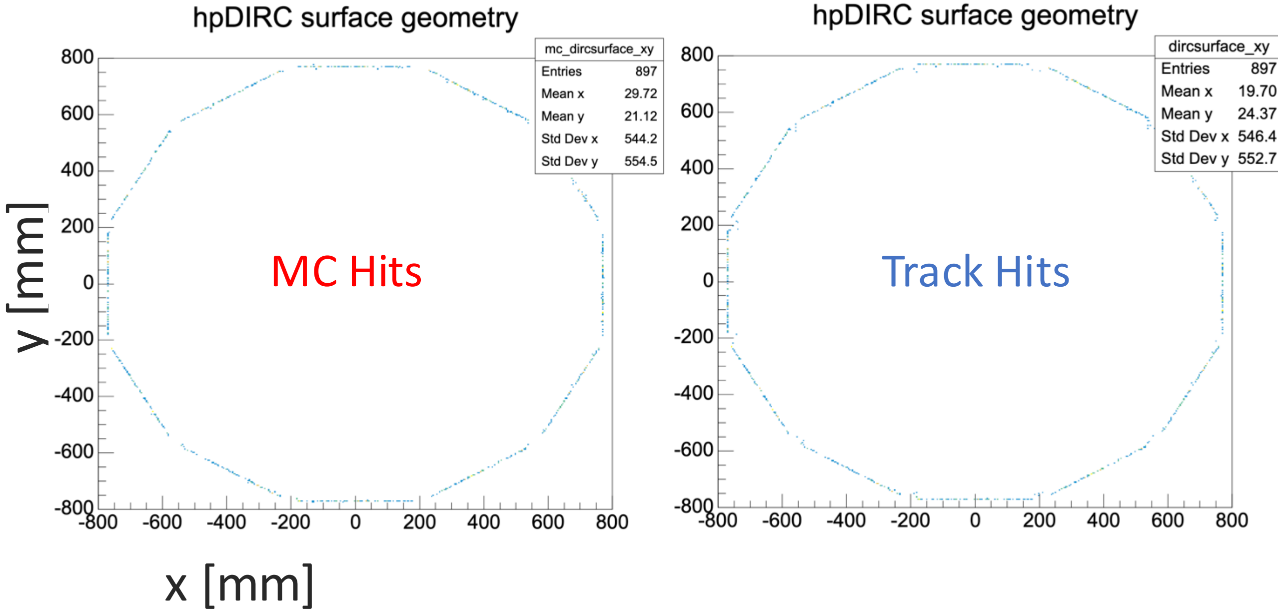
- Get particle information on hpDIRC surface defined by Geant4 (MC info)

➢ Can get as well as MC information for epic's tracker detector
➢ The outermost layer is the <u>hpDIRC surface</u> defined by myself





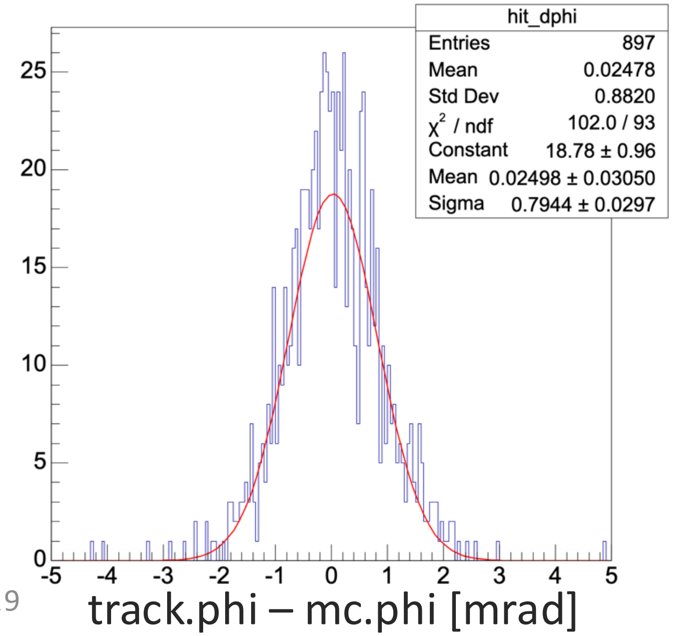
➢ MC information and particle information obtained by propagating tracks on hpDIRC surface



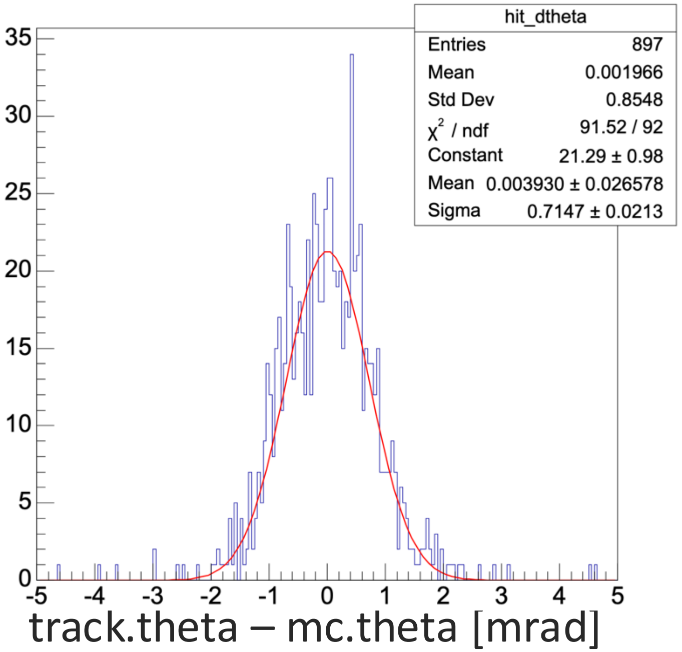
Results - Angular distribution on hpDIRC surface

- Angular resolution calculated from particle momentum in MC and track information
  - $\Delta\theta = \theta(track) - \theta(MC), \qquad \Delta\phi = \phi(track) - \phi(MC)$
  - $\theta = arctan2\left(\sqrt{{p_x}^2 + {p_y}^2}, p_z\right), \qquad \phi = arctan2(p_y, p_x)$
  - Angular resolution is given by Gaussian sigma
  - The higher the momentum,
    the better the angular resolution.

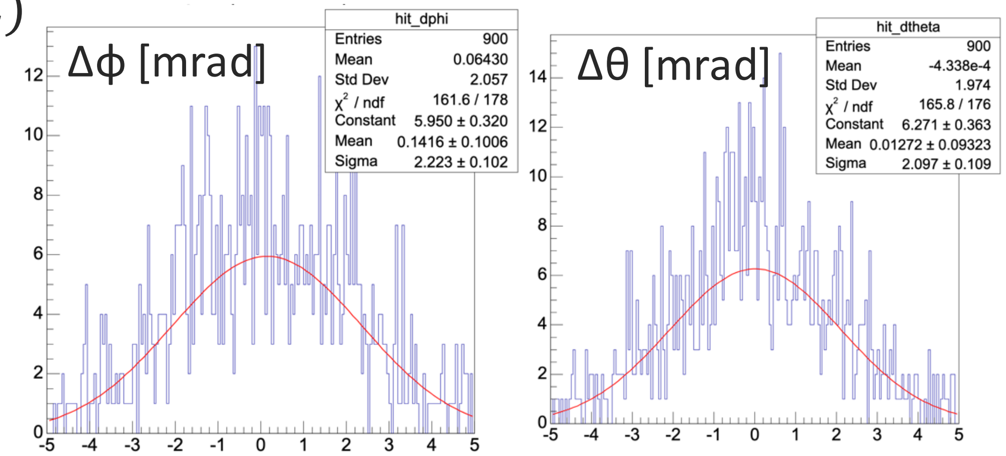
Δϕ [mrad] , 92 < θ < 94 , p = 6 GeV



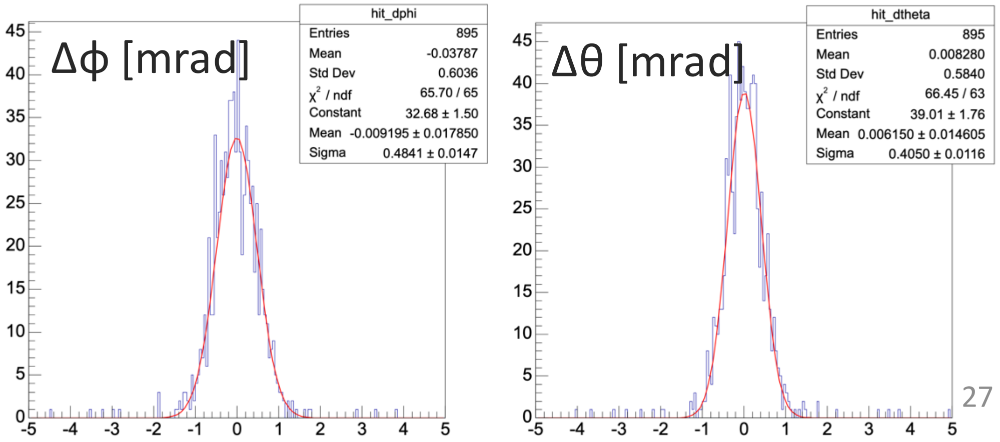
Δθ [mrad] , 92 < θ < 94 , p = 6 GeV



92 < θ < 94 , p = 2 GeV



92 < θ < 94 , p = 10 GeV



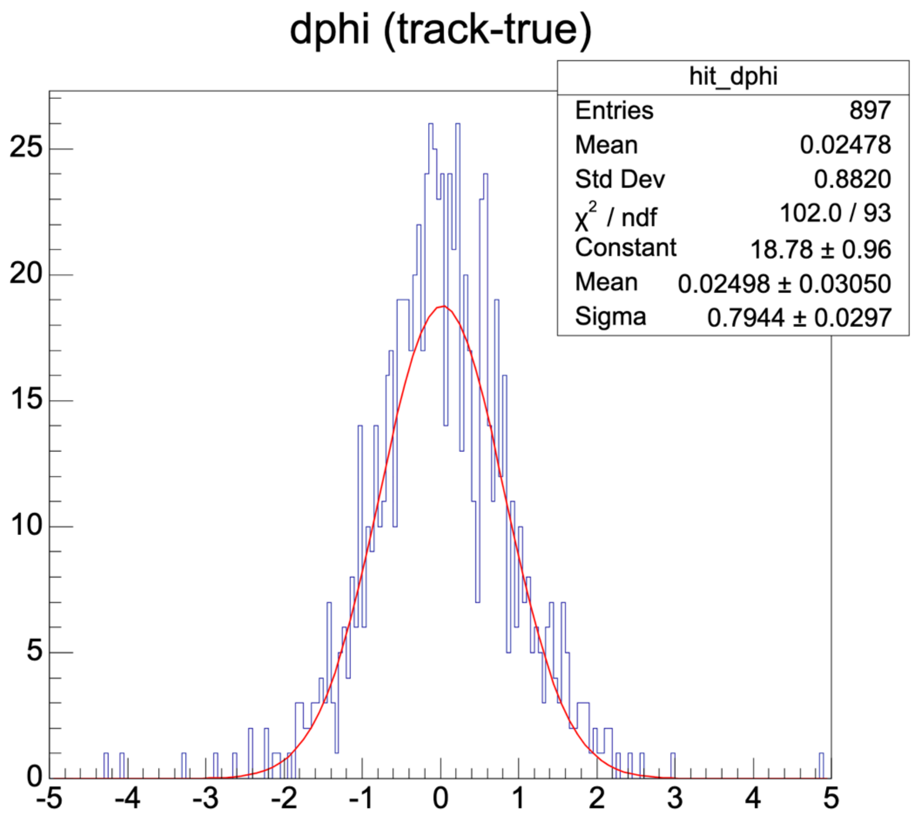
Angular distribution on hpDIRC surface

- Single particle : π^- (1000 events)
- Momentum : 1,2,4,6.8,10 [GeV/c]
- Direction : $0^\circ \leq \phi \leq 360^\circ$, $92^\circ \leq \theta \leq 94^\circ \rightarrow \langle\eta\rangle = -0.05$

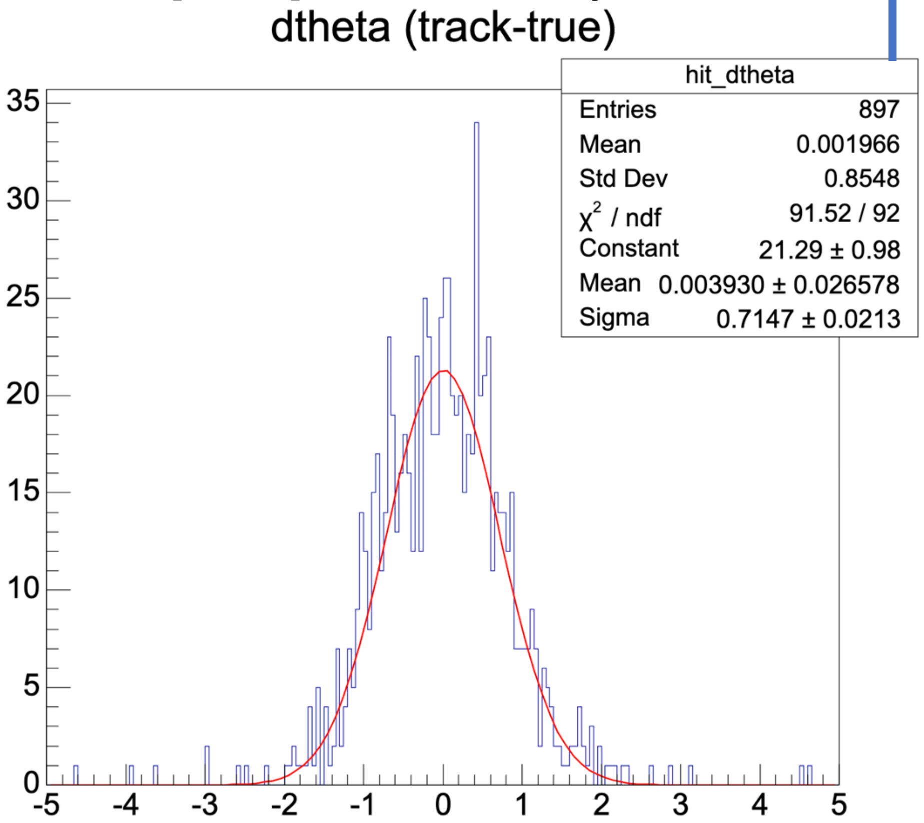
$\sigma = 0.7147 \pm 0.0213\ [mrad]$

Even if we use the carbon form (default setting), we cannot fulfill the request from hpDIRC
(delta_angle=0.5mrad@6GeV)

Δϕ [mrad] , 92 < θ < 94 , p = 6 GeV



Δθ [mrad] , 92 < θ < 94 , p = 6 GeV



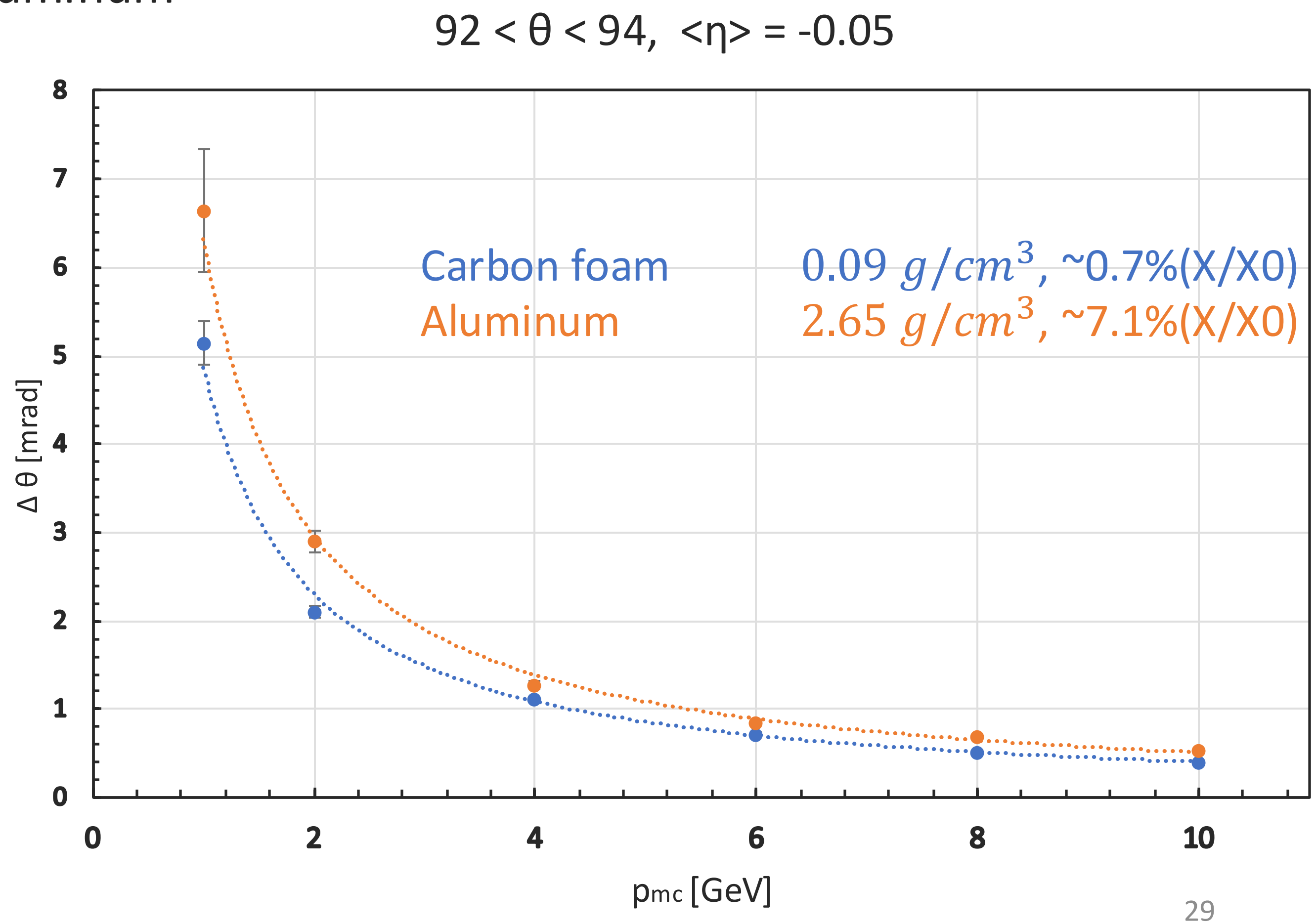
Results - Angular resolution on hpDIRC surface

■Results for some changes in particle momentum and BTOF material.

- Part of BTOF Carbon foam changed to Aluminum
- The value of Δθ increases

But…

- Current structure (Carbon foam) does not satisfy hpDIRC requirements.
- Please tell me your opinion on this simulation



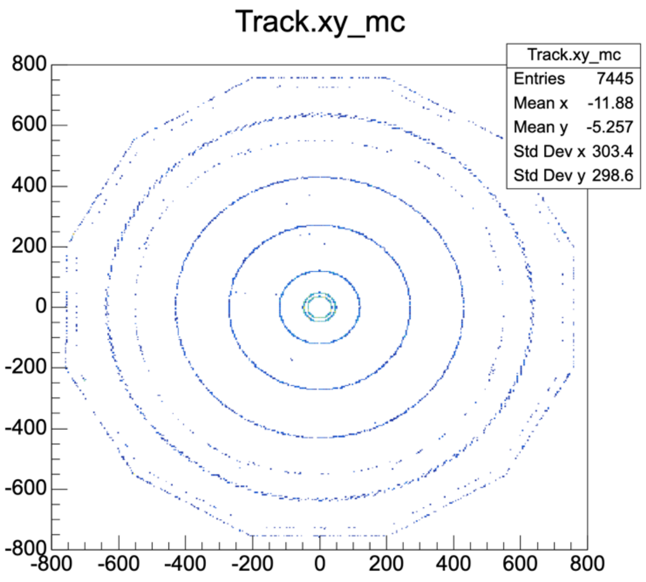
Data generation

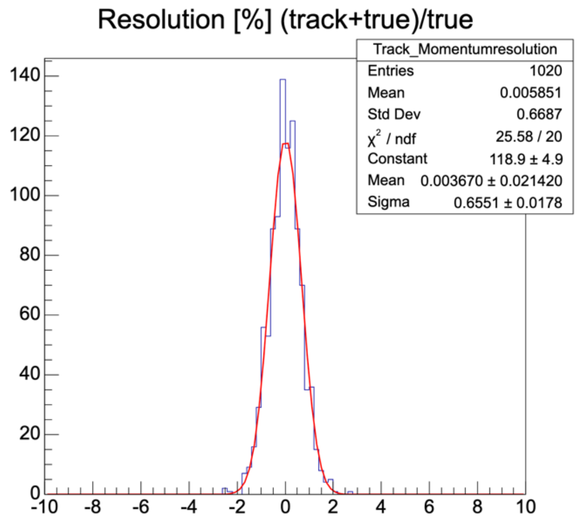
■Data Generation Settings

- EICrecon : Particle collision reconstruction using phythia8, Geant4, and track reconstruction algorithms using ePIC detector structures are available.
- Single particle : π^{-}(1000 events)
- Momentum : 6 [GeV/c]
- Direction : $0^{\circ} \leq \phi \leq 360^{\circ}$,
  $92^{\circ} \leq \theta \leq 94^{\circ} \rightarrow \langle \eta \rangle = -0.05$

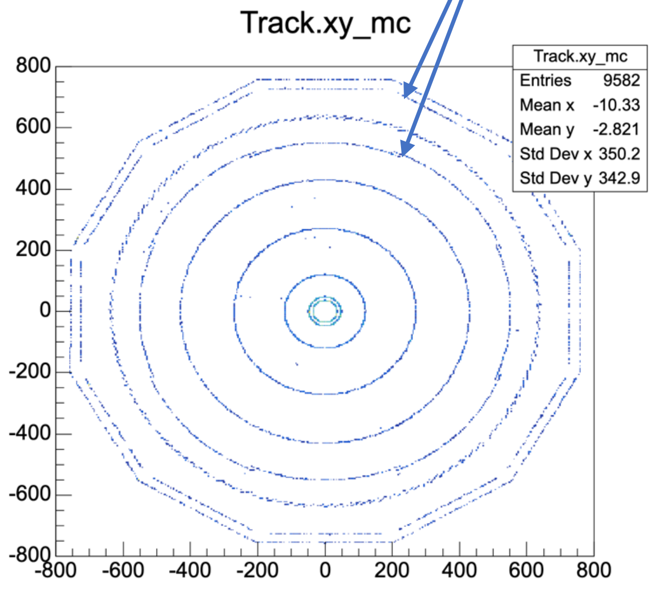
Inner & outer MPGD hits a lot
→ Is there some effect on the track reconstruction?

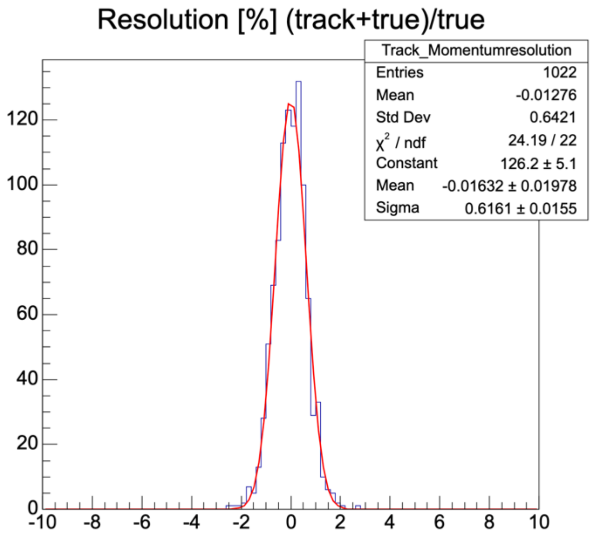
➢ **ddsim**





➢ **npsim** (Simulation with Cherenkov detector)





Data generation (new ver.)

■Data Generation Settings

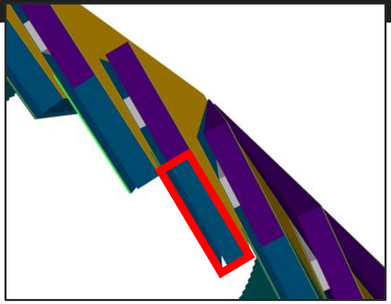
- EICrecon : Particle collision reconstruction using phythia8, Geant4, and track reconstruction algorithms using ePIC detector structures are available.
- npsim
- Single particle : π^{-}(1000 events)
- Momentum : 1, 2, 4, 6, 8, 10 [GeV/c]
- Direction : $0^{\circ} \leq \phi \leq 360^{\circ}$,
  $92^{\circ} \leq \theta \leq 94^{\circ} \rightarrow \langle\eta\rangle = -0.05$

```
npsim --compactFile=$DETECTOR_PATH/epic.xml
      -N=1000
      --random.seed 1
      --enableGun
      --gun.particle "pi-"
      --gun.momentumMin "10*GeV" --gun.momentumMax "10*GeV"
      --gun.thetaMin 92.0*deg --gun.thetaMax 94.0*deg
      --gun.distribution uniform
      --outputFile epic_fakedirc_pi_10GeV_1000event_ddsim.edm4hep.root
```

Detector settings

■BTOF material (epic/compact/tracking/tof_barrel.xml)

```xml
<module name="BarrelTOF_Module1" vis="TOFBarrelModuleVis">
  <module_component name="sensor" material="Silicon" sensitive="true" width="BarrelTOF_Sensor_width" length="BarrelTOF_length1" thickness="BarrelTOF_Sensor_thickness" vis="TOFSensorVis" >
    <position x="BarrelTOF_Sensor_position" y="0" z="0" />
  </module_component>
  <module_component name="hybridtop" material="Kapton" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_Hybrid_thickness" vis="TOFHybridVis" >
    <position x="BarrelTOF_Service_position" y="0" z="0" />
  </module_component>
  <module_component name="cfskintop" material="CFRPMix2" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFSkin_thickness" vis="TOFCSkinVis" >
    <position x="BarrelTOF_Service_position" y="0" z="0" />
  </module_component>
  <module_component name="coolingtube" material="Aluminum" sensitive="false" width="BarrelTOF_CoolingTube_width" length="BarrelTOF_length1" thickness="BarrelTOF_CoolingTube_thickness" vis="TOFCoolingTubeVis" >
    <position x="BarrelTOF_CoolingTube_position" y="0" z="0" />
  </module_component>
  <module_component name="coolant" material="NOVEC7200" sensitive="false" width="BarrelTOF_Coolant_width" length="BarrelTOF_length1" thickness="BarrelTOF_Coolant_thickness" vis="TOFCoolantVis" >
    <position x="BarrelTOF_Coolant_position" y="0" z="0" />
  </module_component>
  <module_component name="cfoam" material="Aluminum5083" sensitive="false" width="BarrelTOF_CFoam_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFoam_thickness" vis="TOFCFoamVis" >
  <!-- <module_component name="cfoam" material="CarbonFoam" sensitive="false" width="BarrelTOF_CFoam_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFoam_thickness" vis="TOFCFoamVis" > -->
    <position x="BarrelTOF_CFoam_position" y="0" z="0" />
  </module_component>
  <module_component name="choneycomb" material="CFRPMix" sensitive="false" width="BarrelTOF_CHoneycomb_width" length="BarrelTOF_length1" thickness="BarrelTOF_CHoneycomb_thickness" vis="TOFCHoneycombVis" >
    <position x="BarrelTOF_CHoneycomb_position" y="0" z="-1*BarrelTOF_CFoam_thickness" />
  </module_component>
  <module_component name="cfskinbottom" material="CFRPMix2" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_CFSkin_thickness" vis="TOFCSkinVis" >
    <position x="BarrelTOF_Service_position" y="0" z="0" />
  </module_component>
  <module_component name="hybridbottom" material="Kapton" sensitive="false" width="BarrelTOF_Module_width" length="BarrelTOF_length1" thickness="BarrelTOF_Hybrid_thickness" vis="TOFHybridVis" >
    <position x="BarrelTOF_Service_position" y="0" z="0" />
  </module_component>
```



Changed material

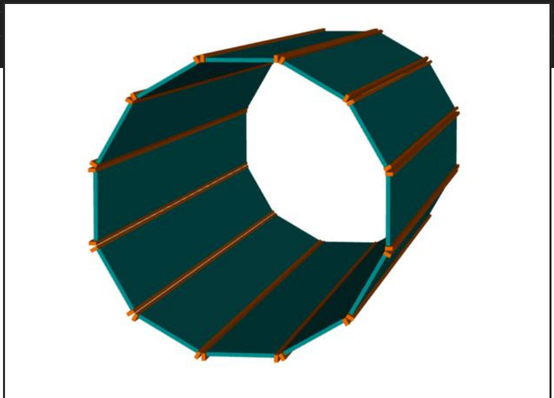
Default material

Detector settings (old ver.)

■hpDIRC surface (Referring to https://github.com/eic/athena/compact/fake_dirc.xml)

```xml
<lccdd>

  <define>
    <constant name="DIRCModule_count"          value="12" />
    <constant name="DIRCBar_thickness"         value="17*mm" />
    <constant name="DIRCBar_length"            value="DIRC_length-8*cm" />
    <constant name="DIRCSkinFront_thickness"   value="2.5*mm" />
    <constant name="DIRCSkinBack_thickness"    value="2.5*mm" />
    <constant name="DIRCFrame_width"           value="20*mm"/>
    <constant name="DIRCFrame_length"          value="DIRC_length"/>
    <constant name="DIRCFrame_thickness"       value="40*mm"/>
    <constant name="DIRCModule_rmax"           value="DIRC_rmin + DIRCBar_thickness + DIRCSkinFront_thickness + DIRCSkinBack_thickness"/>
    <constant name="DIRCModule_thickness"      value="DIRCModule_rmax - DIRC_rmin" />
    <constant name="DIRCFrame_rmax"            value="DIRC_rmin + DIRCFrame_thickness" />
    <constant name="DIRCModule_halfangle"      value="180*degree/DIRCModule_count" />
    <constant name="DIRCModule_width"          value="2*DIRC_rmin * tan(DIRCModule_halfangle)"/>
    <constant name="DIRCModule_rmin"           value="DIRC_rmin + 1*cm"/>
  </define>

  <detectors>
    <detector id="BarrelDIRC_ID" name="FakeDIRC" type="epic_FakeDIRC" readout="DIRCBarHits" vis="DIRCVis">
      <dimensions rmin="DIRC_rmin" rmax="DIRC_rmax" length="DIRC_length" />
      <position x="0" y="0" z="DIRC_offset" />
      <comment> Fake DIRC modules </comment>
      <module name="DIRCModule" vis="DIRCModuleVis">
        <module_component name="FrontSkin"
               material="CarbonFiber"
               sensitive="false"
               width="DIRCModule_width"
               thickness="DIRCSkinFront_thickness"
               vis="DIRCSupportVis"
               length="DIRCBar_length" />
        <module_component name="QuartzBar"
               material="Quartz"
               sensitive="true"
               width="DIRCModule_width"
               thickness="DIRCBar_thickness"
               vis="DIRCBarVis"
               length="DIRCBar_length" />
        <module_component name="BackSkin"
               material="CarbonFiber"
               sensitive="false"
               width="DIRCModule_width"
               thickness="DIRCSkinBack_thickness"
               vis="DIRCSupportVis"
               length="DIRCBar_length" />
        <frame material="StainlessSteel"
               width="DIRCFrame_width"
               length="DIRCFrame_length"
               vis="DIRCFrameVis"
               thickness="DIRCFrame_thickness" />
      </module>
```

```xml
      </module>
      <comment> Fake DIRC layers </comment>
      <layer module="DIRCModule" id="1" vis="DIRCLayerVis">
        <barrel_envelope
          inner_r="DIRC_rmin"
          outer_r="DIRC_rmax"
          z_length="DIRC_length" />
        <rphi_layout
          phi_tilt="0"
          nphi="DIRCModule_count"
          phi0="0"
          rc="0.5*(DIRCModule_rmin+DIRCModule_rmax)"
          dr="0" />
        <z_layout
          dr="0.0*mm"
          z0="0.0*mm"
          nz="1" />
      </layer>
    </detector>
  </detectors>

  <readouts>
    <readout name="DIRCBarHits">
      <segmentation type="CartesianGridXY" grid_size_x="3.0*mm" grid_size_y="3.0*mm" />
      <id>system:8,layer:4,module:8,section:4,x:32:-16,y:-16</id>
    </readout>
  </readouts>

</lccdd>
```



About Analysis Code

■Track information (Referring to https://github.com/eic/EICrecon/src/algorithms/tracking/TrackPropagation.cc)

```cpp
    const auto &dirc = *static_cast<const edm4hep::SimTrackerHitCollection*>(event->GetCollectionBase("DIRCBarHits"));
    for(auto hit: dirc) {
        auto& mcinfo = hit.getMCParticle();
        auto& mcpos = hit.getPosition();
        auto& mcmom = hit.getMomentum();

        if (mcinfo.getGeneratorStatus() != 1) continue;
        if (i != 0 ) continue;

        auto mcr = sqrt(mcpos.x*mcpos.x + mcpos.y*mcpos.y + mcpos.z*mcpos.z);
        auto mcrt = sqrt(mcpos.x*mcpos.x + mc
                                              <error-type> &mcmom
        auto mcp = sqrt(mcmom.x * mcmom.x + m                    om.z * mcmom.z);
        auto mcpt = sqrt(mcmom.x * mcmom.x + mcmom.y * mcmom.y);
        auto mceta = -log(tan(atan2(sqrt(mcmom.x*mcmom.x+mcmom.y*mcmom.y),mcmom.z)/2.));
        auto mctheta = atan2(sqrt(mcmom.x*mcmom.x + mcmom.y*mcmom.y),mcmom.z);
        auto mcphi = atan2(mcmom.y, mcmom.x);
        // auto mceta = -log(tan(atan2(sqrt(mcpos.x*mcpos.x+mcpos.y*mcpos.y),mcpos.z)/2.));
        // auto mctheta = atan2(sqrt(mcpos.x*mcpos.x + mcpos.y*mcpos.y),mcpos.z);
        // auto mcphi = atan2(mcpos.y, mcpos.x);

        std::unique_ptr<edm4eic::TrackPoint> hpdirc_point;
        const auto hpdircR = mcrt;
        const auto hpdircMinZ = -2526.0;
        const auto hpdircMaxZ = 1850.0;
        auto hpdircBounds = std::make_shared<Acts::CylinderBounds>(hpdircR, (hpdircMaxZ-hpdircMinZ)/2);
        auto hpdirc_t = Acts::Translation3(Acts::Vector3(0, 0, (hpdircMaxZ+hpdircMinZ)/2));
        auto hpdirc_trf = Acts::Transform3(hpdirc_t);
        hpdirc_surface = Acts::Surface::makeShared<Acts::CylinderSurface>(hpdirc_trf, hpdircBounds);
        try {hpdirc_point =  m_propagation_algo.propagate(edm4eic::Track{}, trajectory, hpdirc_surface);}
        catch(std::exception &e) {throw JException(e.what());}
        if(!hpdirc_point) {
        fprintf (outputfileTrack,"could not propagate!\n");
        continue;
        }
            auto pos = hpdirc_point->position;
            auto mom = hpdirc_point->momentum;
            auto length = hpdirc_point->pathlength;
            auto theta = hpdirc_point->theta;
            auto phi = hpdirc_point->phi;
            auto eta = -log(tan(atan2(sqrt(mom.x*mom.x + mom.y*mom.y),mom.z)/2.));
            auto r = sqrt(pos.x*pos.x + pos.y*pos.y + pos.z*pos.z);
            auto rt = sqrt(pos.x*pos.x + pos.y*pos.y);
            Track_xy -> Fill(pos.x, pos.y);
            Hitpoints_dircsurface_xy -> Fill(pos.x, pos.y);
            Hitpoints_dircsurface_z -> Fill(pos.z);
            if(pos.x > 0)Track_rz -> Fill(pos.z, rt);
                    else Track_rz -> Fill(pos.z, -rt);
            hit_propagate_eta -> Fill(eta);
            hit_propagate_phi -> Fill(phi);
            hit_propagate_theta -> Fill(theta);
            fprintf (outputfileTrack,"Reconstructed DIRC hit  x:%f, y:%f, z:%f, r:%f, rt:%f, theta:%f, phi:%f\n", pos.x, pos.y, pos.z, length, rt, theta, phi);
            fprintf (outputfileTrack, "MC DIRCsurface x:%f, y:%f, z:%f, r:%f, rt:%f, theta:%f, phi:%f, p:%f\n", mcpos.x, mcpos.y, mcpos.z, mcr, mcrt, mctheta, mcphi, mcp);
```

```cpp
            auto reso_eta = (eta - mceta)/mceta * 100;
            auto reso_phi = (phi - mcphi)/mcphi * 100;
            auto reso_theta = (theta - mctheta)/mctheta * 100;
            auto deta = (eta - mceta)* 1000;
            auto dphi = (phi - mcphi)* 1000;
            auto dtheta = (theta - mctheta)* 1000;

            hit_true_eta -> Fill(mceta);
            hit_true_phi -> Fill(mcphi);
            hit_true_theta -> Fill(mctheta);
            hit_resolution_eta -> Fill(reso_eta);
            hit_resolution_phi -> Fill(reso_phi);
            hit_resolution_theta -> Fill(reso_theta);
            hit_deta -> Fill(deta);
            hit_dphi -> Fill(dphi);
            hit_dtheta -> Fill(dtheta);

            Hitpoints_dircsurface_mc_xy -> Fill(mcpos.x, mcpos.y);
            Hitpoints_dircsurface_mc_z -> Fill(mcpos.z);

            fprintf (outputfileMC, "DIRCsurface  r:%f, rt:%f, p:%f, eta:%f, phi:%f, theta:%f\n", mcr, mcrt, mcp, mceta, mcphi, mctheta);
            i++;
        }
```

Get the parameters of the reconstructed track at any r.

(Trajectory
→ CentralCKFActsTrajectories)

About Analysis Code

■MC information (edm4hep::SimTrackerHit)

```cpp
std::vector<std::string> sim_data_names = {
    "VertexBarrelHits",         // Vertex
    "SiBarrelHits",             // Barrel Tracker
    "MPGDBarrelHits",           // MPGD
    "TOFBarrelHits",             // Barrel TOF
    "OuterMPGDBarrelHits",      // MPGD DIRC
    "TrackerEndcapHits",        // End Cap tracker
    "TOFEndcapHits",            // End Cap TOF
    "DIRCBarHits",
};
for(int i = 0; i < sim_data_names.size(); i++ ) {
    auto data_name = sim_data_names[i];
    const auto &hits = *static_cast<const edm4hep::SimTrackerHitCollection*>(event->GetCollectionBase(data_name));
    const char* Data_name = data_name.c_str();  //fprintfに出力する際に文字化けを防ぐための措置
    for(auto hit: hits) {
        auto& mcinfo = hit.getMCParticle();
        auto& pos = hit.getPosition();
        auto& mom = hit.getMomentum();
        auto r = sqrt(pos.x*pos.x + pos.y*pos.y + pos.z*pos.z);
        auto rt = sqrt(pos.x*pos.x + pos.y*pos.y);
        auto p = sqrt(mom.x * mom.x + mom.y * mom.y + mom.z * mom.z);
        auto pt = sqrt(mom.x * mom.x + mom.y * mom.y);
        auto eta = -log(tan(atan2(sqrt(mom.x*mom.x+mom.y*mom.y),mom.z)/2.));
        auto phi = atan2(mom.y, mom.x);
        auto theta = atan2(sqrt(mom.x*mom.x + mom.y*mom.y),mom.z);


        if (mcinfo.getGeneratorStatus() != 1) continue;
        auto pdg = mcinfo.getPDG();
        auto& mcmom = mcinfo.getMomentum();
        auto status = mcinfo.getGeneratorStatus();
        auto mcp = sqrt(mcmom.x * mcmom.x + mcmom.y * mcmom.y + mcmom.z * mcmom.z);
        auto mceta = -log(tan(atan2(sqrt(mcmom.x*mcmom.x+mcmom.y*mcmom.y),mcmom.z)/2.));
        Track_xy_mc -> Fill(pos.x, pos.y);
        if(pos.x > 0)Track_rz_mc -> Fill(pos.z, rt);
            else Track_rz_mc -> Fill(pos.z, -rt);
        fprintf (outputfileMC, "%s  r:%f, rt:%f, p:%f, eta:%f, phi:%f, theta:%f, cp:%f, mceta:%f, pdg:%d\n",Data_name, r, rt, p, eta, phi, theta, mcp, mceta, pdg);
    }
}
```