Update on Tracking Studies using JANA2 Framework

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Thanks to Dimitry Romanov (Jefferson Lab) and Shujie for the discussion

Outline

- **EPIC Geometry**
  - epic_brycecanyon
  - EPIC Barrel Configuration (used in fast simulation)
- **Basic Performances**
  - Hit Points
  - Estimation of Minimum p_T
  - Acceptance: Eta vs momentum maps (sim/rec)
- **Tracking Performances**
  - Efficiency/Acceptance (Truth seeding)
  - Momentum Resolution
  - Pointing Resolution
- **Summary and Future Plan**

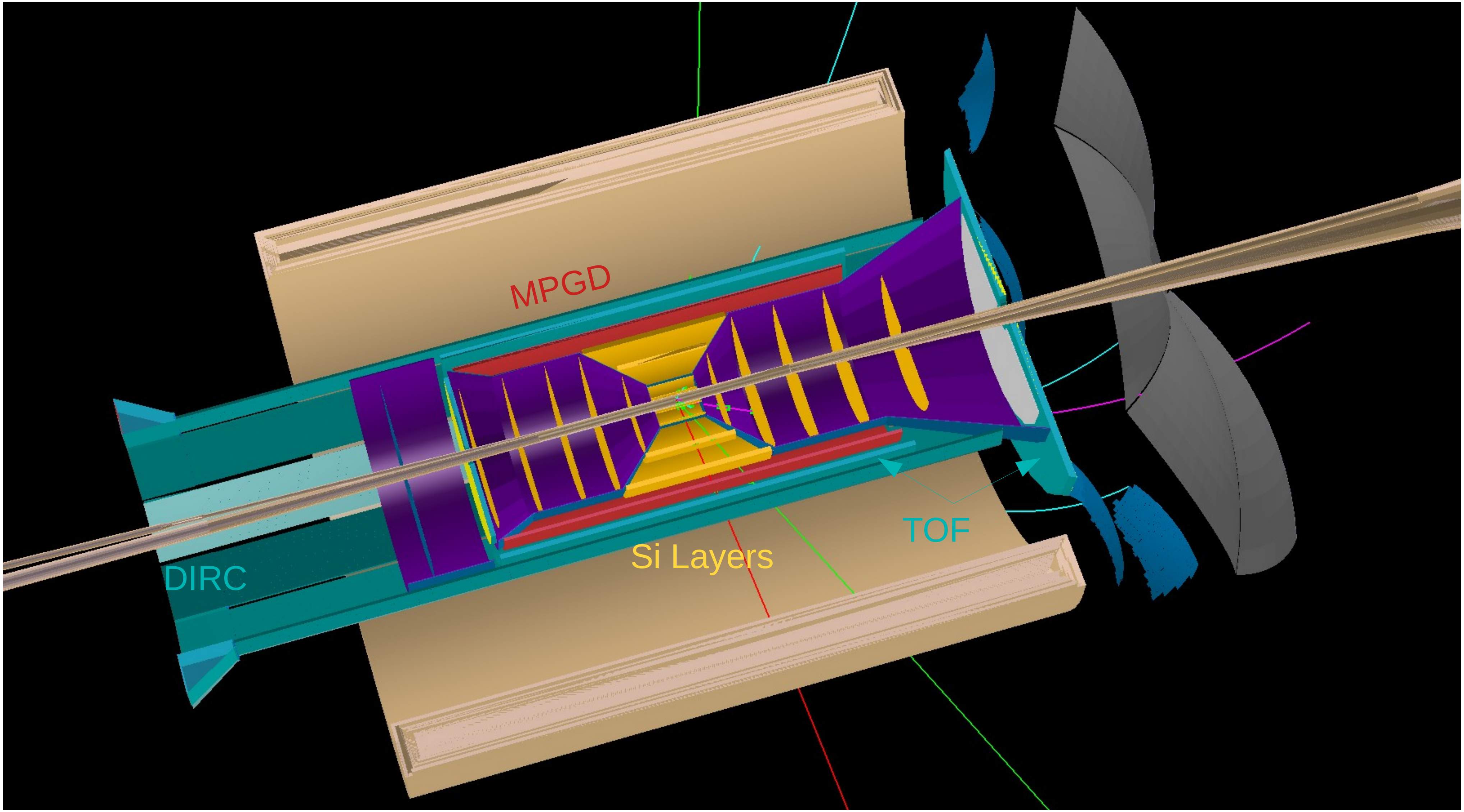
Juggler and JANA2

Both DD4HEP

Physics requirements taken from link below

https://docs.google.com/spreadsheets/d/1ynU7Cu7NlwRvMtbtFdlp_B5xXkw8yBAtWJbenMf-P3U/edit#gid=368031287

EPIC Geometry (epic_brycecanyon)



EPIC Geometry (epic_brycecanyon)

```
  The interaction point subsystems are included before the central detector subsystems.
  This is becuase the IP subsystems, for example the beampipe, will define paramters
  which are subsquently used in the central detector construction -- e.g. the vertex tracker
  uses the beampipe OD to help define its placement.

  The IP subsystems include the Far forward and backward regions. The list of subsystem includes:
   - Interaction region beampipe
   - B0 tracker
   - Off-momentum tracker
   - Far forward roman pots
   - Zero Degree Calorimeter
   - Beam line magnets.
   - and more...
</documentation>


<documentation level="5">
  ## Main magnet
</documentation>
<include ref="${DETECTOR_PATH}/compact/solenoid.xml"/>

<documentation level="10">
  ## Central tracking detectors
</documentation>
<include ref="${DETECTOR_PATH}/compact/tracking/definitions.xml"/>

<include ref="${DETECTOR_PATH}/compact/tracking/vertex_barrel.xml"/>
<include ref="${DETECTOR_PATH}/compact/tracking/silicon_barrel.xml"/>
<include ref="${DETECTOR_PATH}/compact/tracking/mpgd_barrel.xml"/>
<include ref="${DETECTOR_PATH}/compact/tracking/silicon_disks.xml"/>
<include ref="${DETECTOR_PATH}/compact/tracking/support_service_assembly.xml"/>
<include ref="${DETECTOR_PATH}/compact/tracking/tof_barrel.xml"/>
<include ref="${DETECTOR_PATH}/compact/tracking/tof_endcap.xml"/>

<documentation level="10">
  ## PID detectors
</documentation>
<include ref="${DETECTOR_PATH}/compact/pid/dirc.xml"/>
<include ref="${DETECTOR_PATH}/compact/pid/pfrich.xml"/>
<include ref="${DETECTOR_PATH}/compact/pid/drich.xml"/>

<documentation level="11">
  ## Central beam pipe
</documentation>
<include ref="${BEAMLINE_PATH}/ip6/central_beampipe.xml"/>
</lccdd>
```

epic_brycecanyon.xml with calorimeters and far forward detectors removed

shyam@shyam:~/eic/epic$ git tag -l

22.10.0

22.10_rc1

22.11.0

shyam@shyam:~/eic/epic$ git checkout 22.10.0

shyam@shyam:~/eic/epic$ git pull origin main

EPIC Configuration used in Fast Simulation

Barrel Track Model (Cylindrical layers)

```
Detector EPIC: "Detector"
  Name              r [cm]          X0      phi & z res [um] layerEff
0. vertex           0.00          0.0000      -     -          -
1. bpipe            3.18          0.0036      -     -          -
2. VTX1             3.60          0.0005      3      3      0.95
3. VTX2             4.80          0.0005      3      3      0.95
4. VTX3             12.00         0.0005      3      3      0.95
5. BARRSUPPORT      13.50         0.0004      -     -          -
6. BARR1            27.00         0.0025      3      3      0.95
7. BARR2            42.00         0.0055      3      3      0.95
8. MM1     55.00            0.0050     150   150      0.95
9. TOF     64.60            0.0100      30   3000     0.95
```

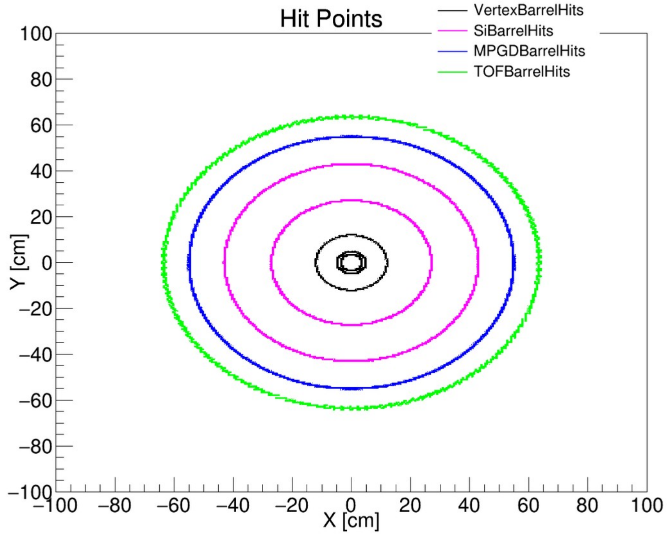
https://wiki.bnl.gov/EPIC/index.php?title=Tracking#Tasks_list

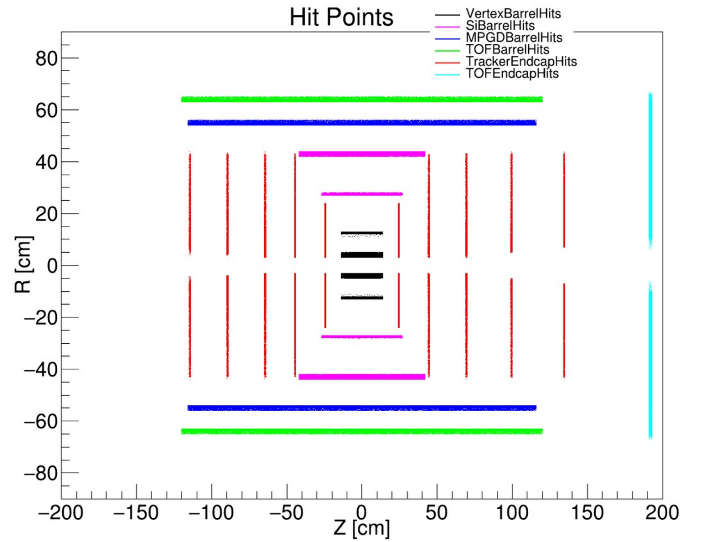
Hits Points

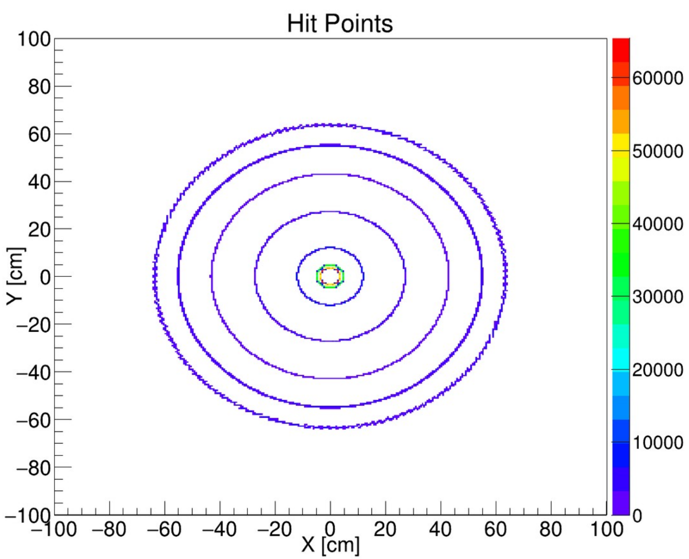
X-Y Points

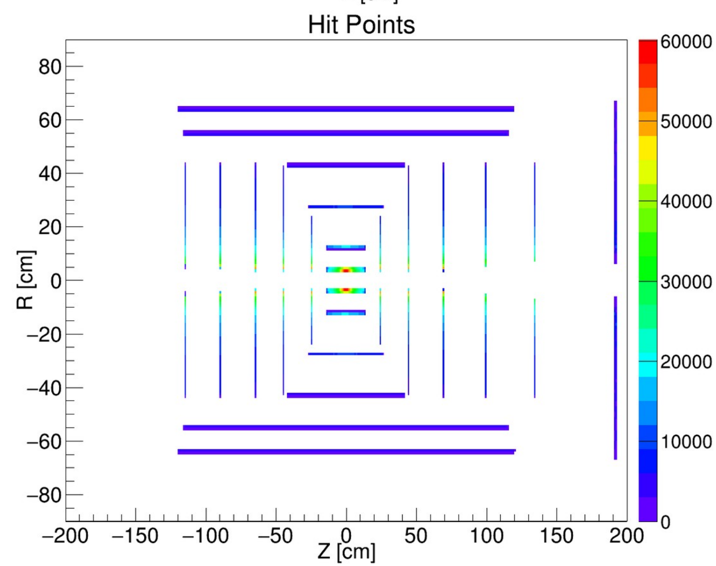
3M pi+ [0.1-30. GeV/c]

R-Z Points

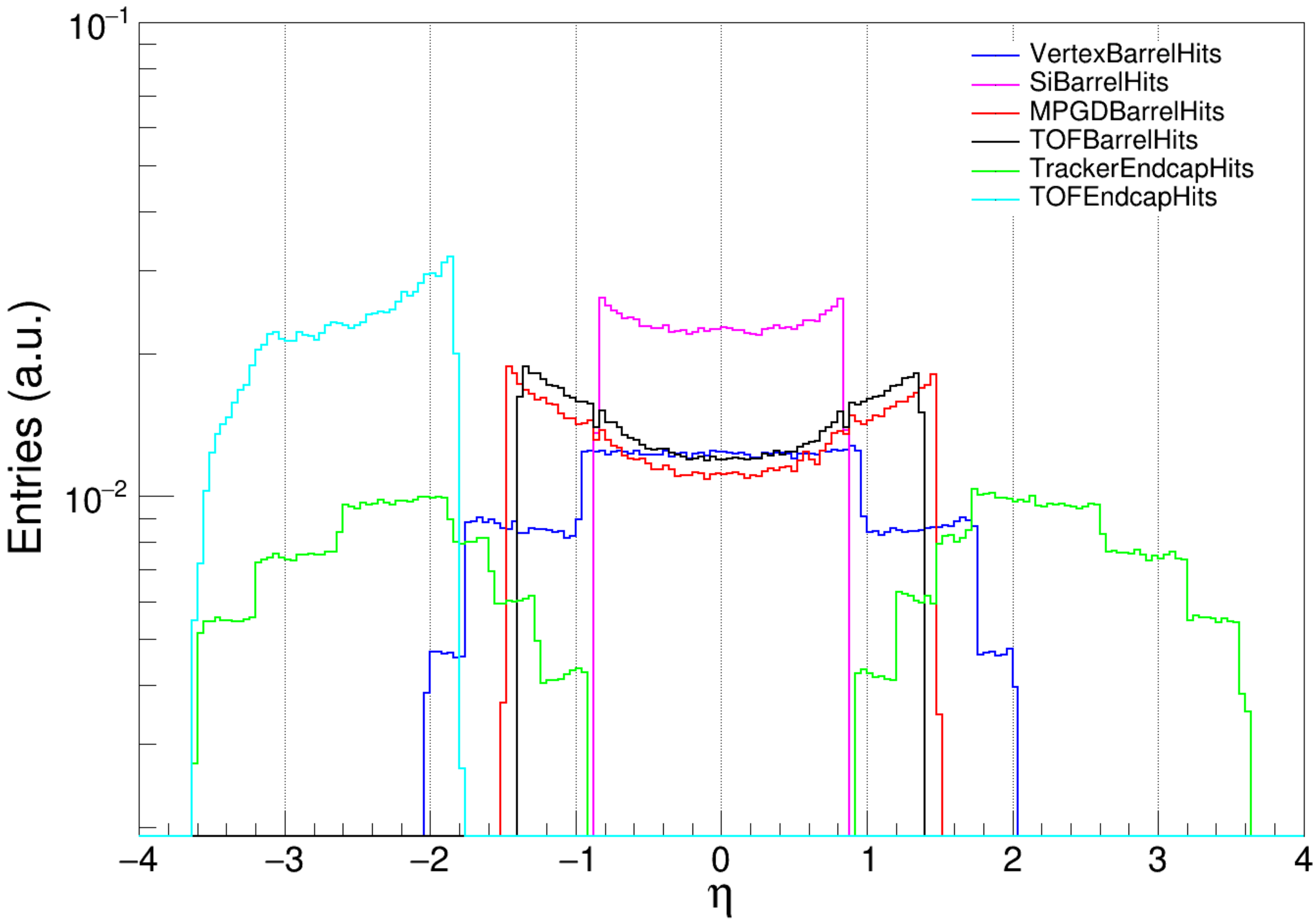








Acceptance η (True Hits)



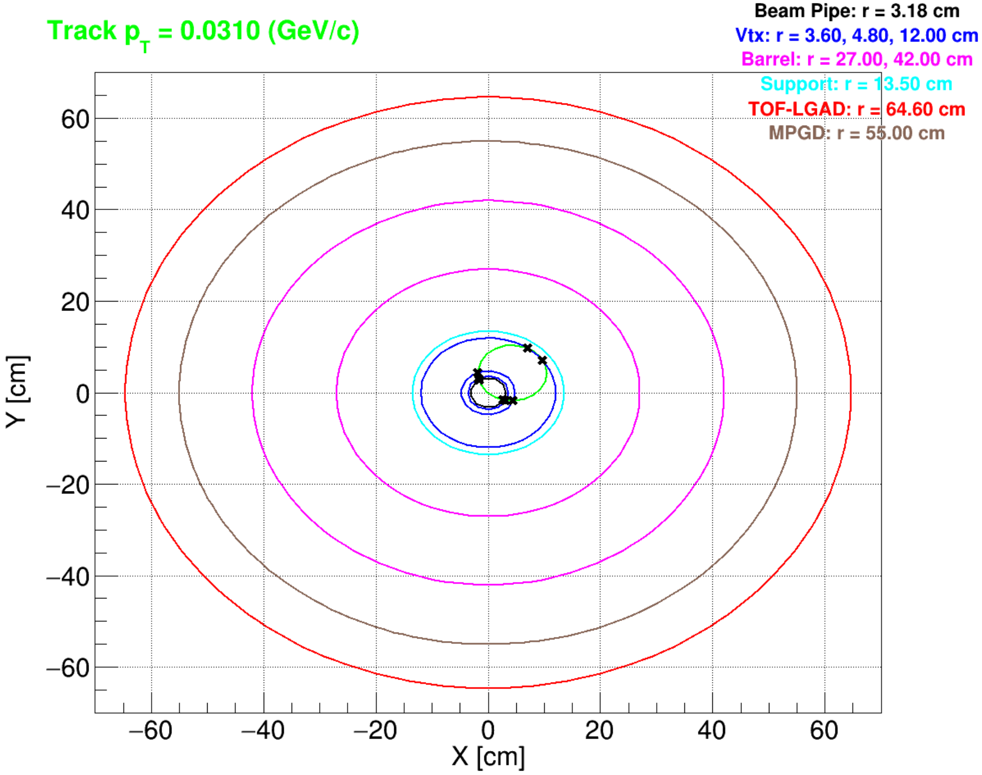
Estimation of Minimum p_T

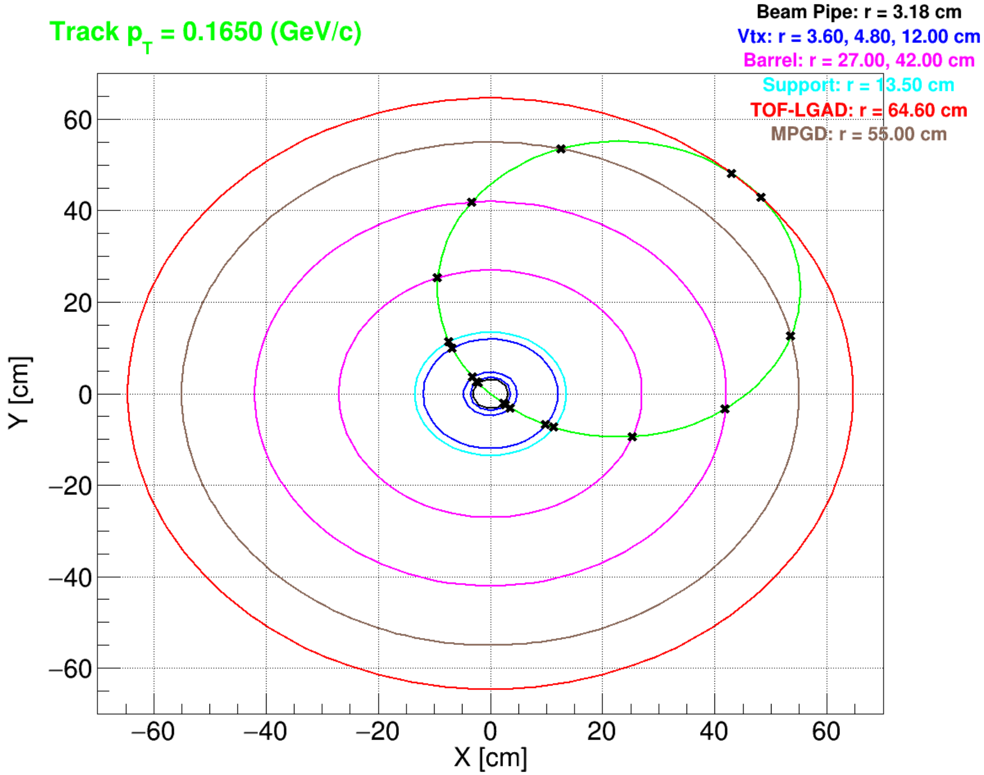
Third layer

p_T = 0.3 B [T] R[m] = (0.3*1.7*0.12)/2 = 0.0306 GeV/c

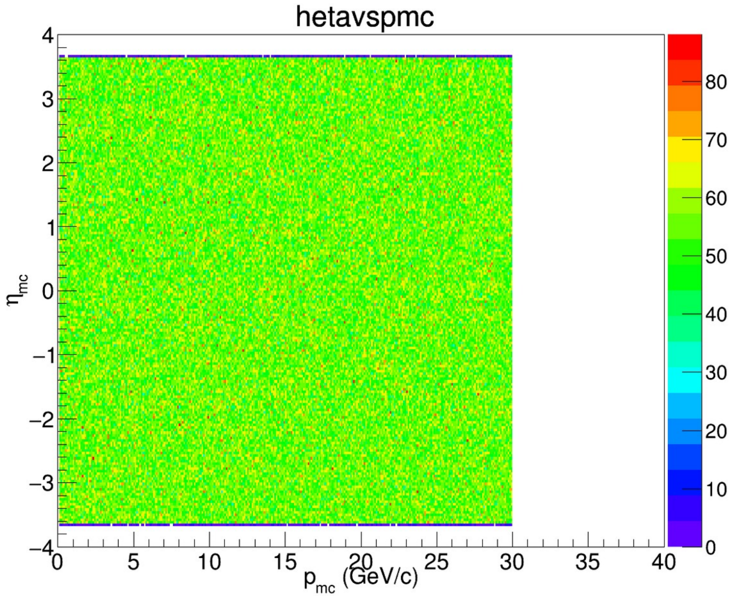
Last layer

p_T = (0.3*1.7*0.646)/2 = 0.16473 GeV/c





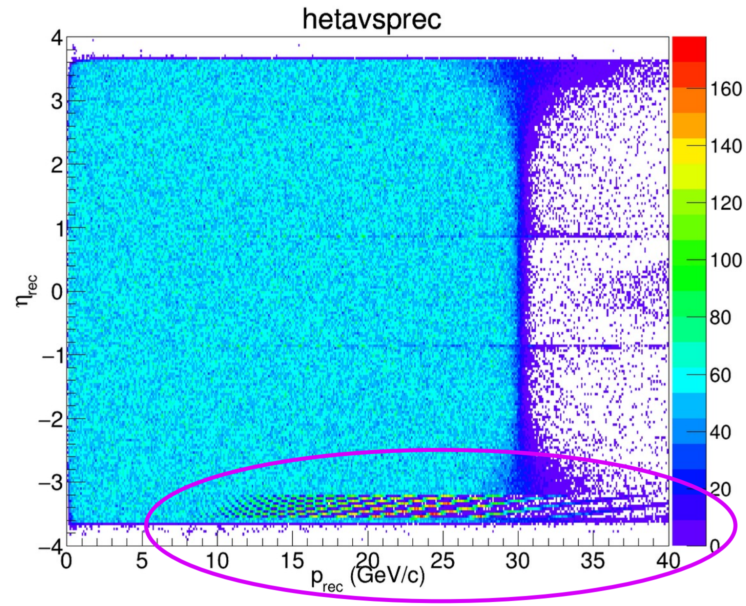
Acceptance: Eta vs momentum maps (sim/rec)

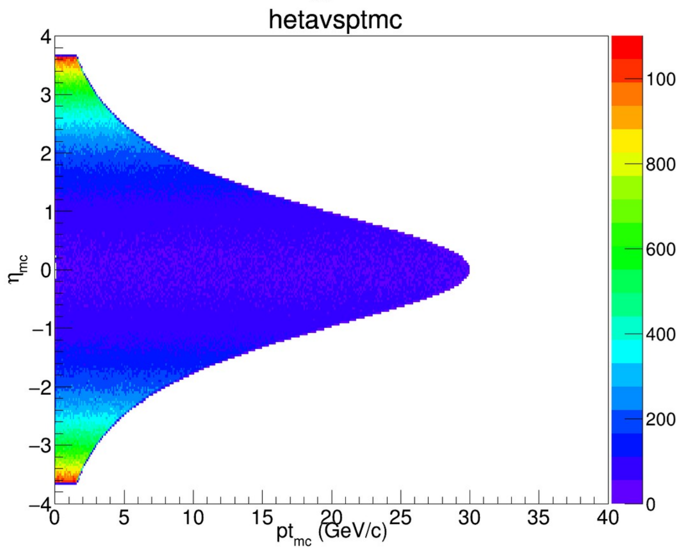


epic_brycecanyon.xml

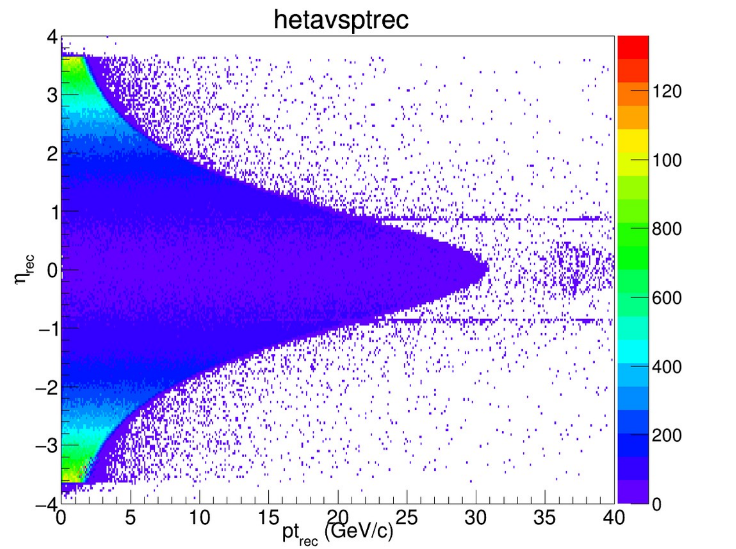
3M pi+ [0.1-30. GeV/c]

Structures in Reco Momentum Related to ETOF



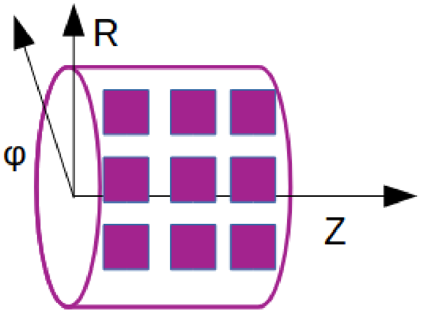


Error Conversion from Global to Local Coordinates!!



Track Parameters (Global to Local)

$\sigma_{\varphi} = \sigma_{z}$ = pixel size/$\sqrt{(12)}$



Cylinder

Global coordinates: (x,y,z,p_x,p_y,p_z)

Track parameters on a surface (l_1,l_2 are local)

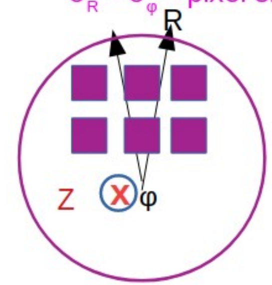
$$(l_1, l_2, \phi, \theta, q/p)$$

https://github.com/NicholasLukow/ATHENA_Tracking_GEM/blob/master/Fun4All_G4_Baseline2.C

For ACTS see backup

First two local parameters describes the pixel dimensions

$\sigma_{R} = \sigma_{\varphi}$ = pixel size/$\sqrt{(12)}$



Disks

Track Parameters in Cylindrical surface:

$$(R\phi, z, \phi, \theta, q/p)$$

If we want to fit hit points: Explicitly mention whether it's on cylinder or disk
<u>Global (x,y,z) to Local (disk or cylinder) conversion</u>

Track Parameters on Disk surface:

$$(R, R\phi, \phi, \theta, q/p)$$

Cylinder (Fun4All)

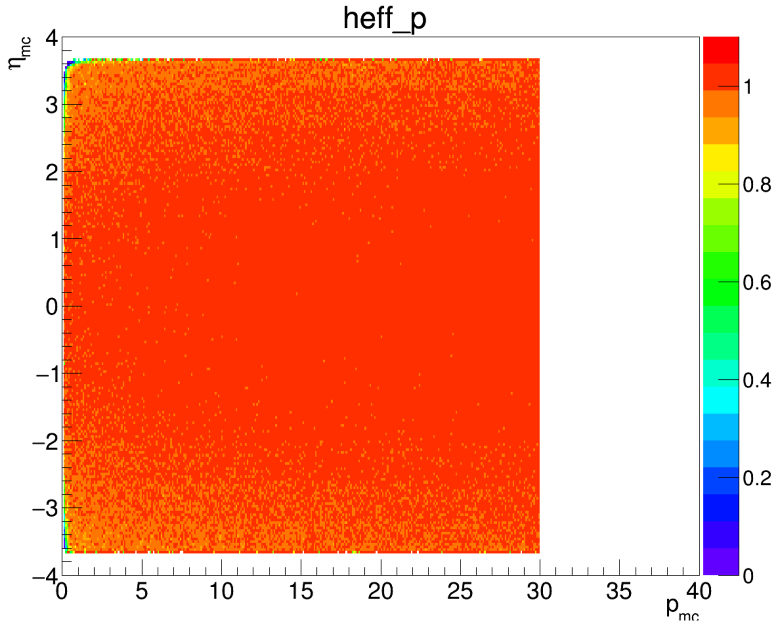
Class PHG4TrackFastSim

Disks (Fun4All)

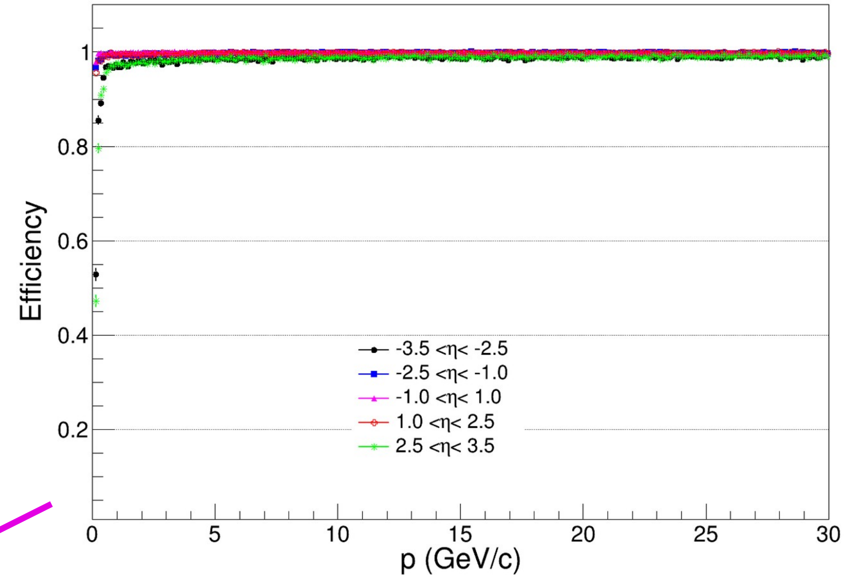
```
PHG4TrackFastSim *kalman = new PHG4TrackFastSim("PHG4TrackFastSim");
// add Vertexing Layers
kalman->add_phg4hits(
                "G4HIT_SVTX",                   // const std::string& phg4hitsNames,
                PHG4TrackFastSim::Cylinder,
                999.,                           // radial-resolution [cm]
                pix_size_vtx/10000./sqrt(12.),  // azimuthal-resolution [cm]
                pix_size_vtx/10000./sqrt(12.),  // z-resolution [cm]
                1,                              // efficiency,
                0                               // noise hits
```

```
//  add Disk Layers
kalman->add_phg4hits(
                "G4HIT_FBST",                        // const std::string& phg4hitsNames,
                PHG4TrackFastSim::Vertical_Plane,
                pix_size_dis/10000./sqrt(12.),       // radial-resolution [cm]
                pix_size_dis/10000./sqrt(12.),       // azimuthal-resolution [cm]
                999.,                                // z-resolution [cm]
                1,                                   // efficiency,
                0                                    // noise hits
                );
```

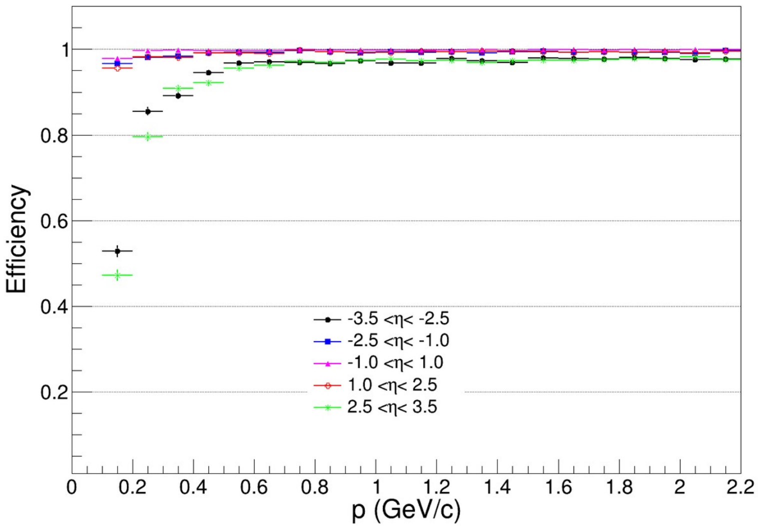
Efficiency/Acceptance (Truth seeding)



3M pi+
[0.1-30. GeV/c]

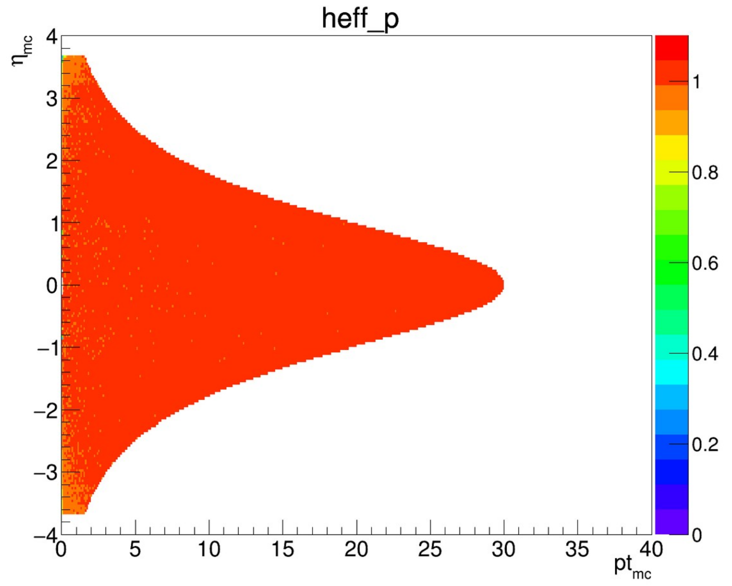


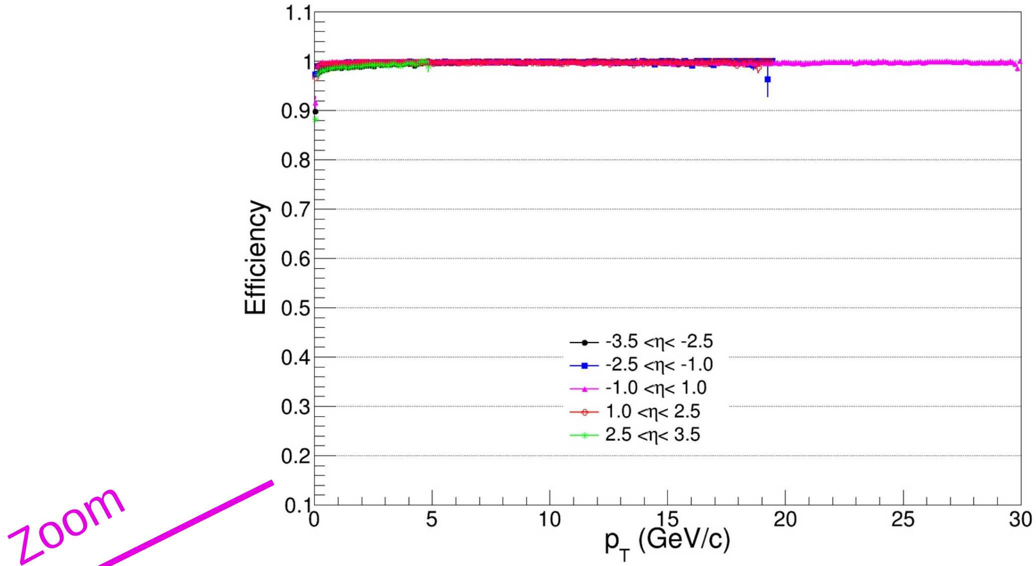
Zoom

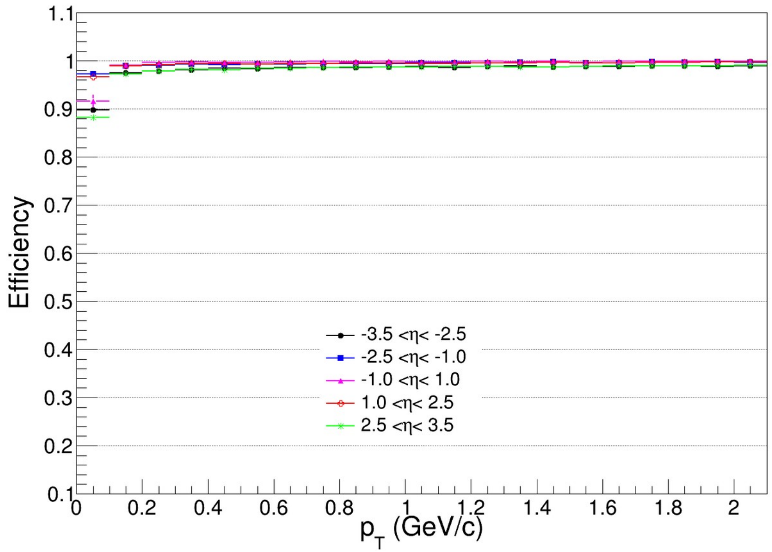


- Acceptance vs momentum
- Acceptance is looking good
- Still to be checked the number of hits and Chi2 as suggested

Efficiency/Acceptance (Truth seeding)



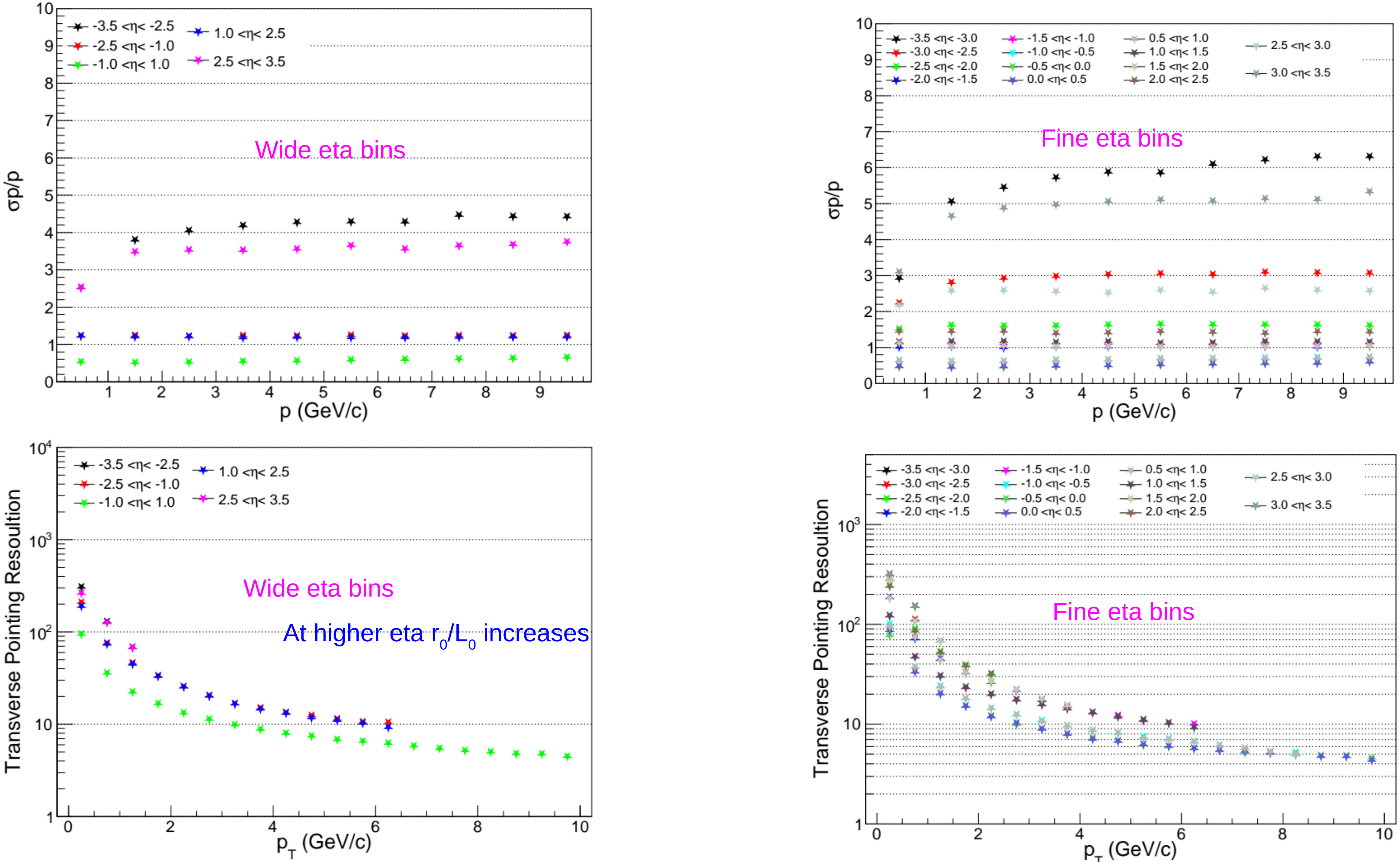




- Acceptance vs transverse momentum
- Acceptance is looking good
- Still to be checked the number of hits and Chi2 as suggested

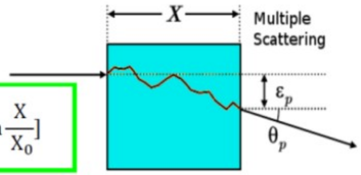
Tracking Performances

epic_brycecanyon.xml



Multiple Scattering

Multiple Scattering (M.S.)

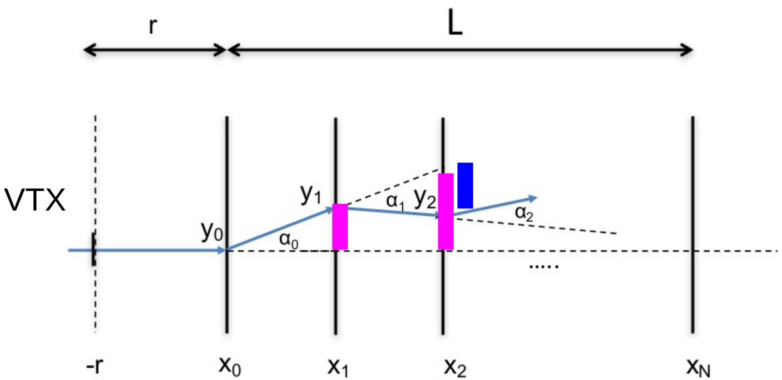


$$\theta_p = 13.6\frac{\text{MeV}z}{\beta cp}\sqrt{\frac{X}{X_0}}\left[1 + 0.038\ln\frac{X}{X_0}\right]$$

$$\epsilon_p \approx \frac{1}{\sqrt{3}}\theta_p X$$

Ref: "Particle Detectors", C. Grupen and B. A. Shwartz

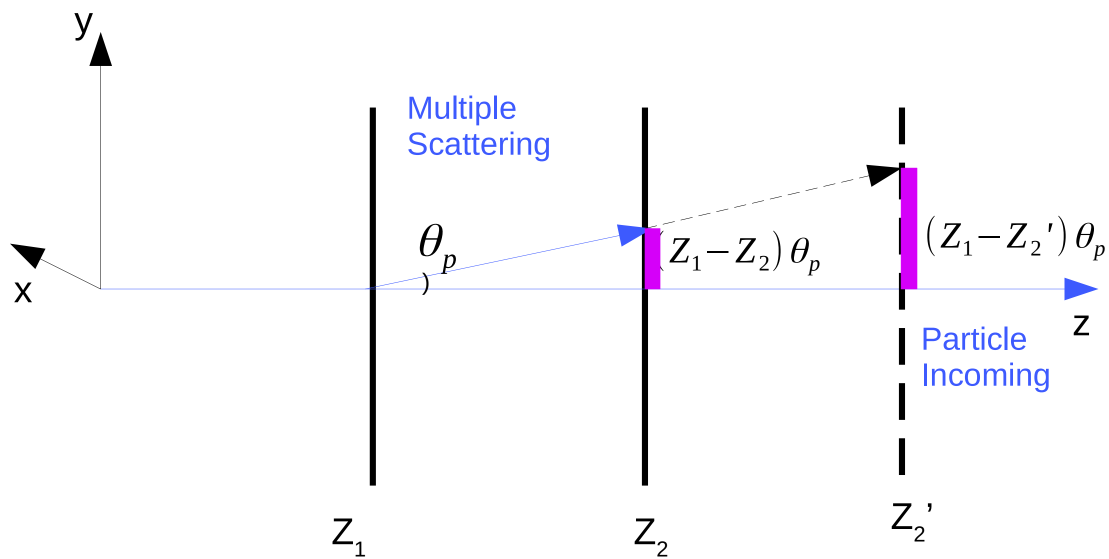
At low p: m.s. dominated by $\propto \frac{1}{p}$



$$\begin{aligned}
y_0 &= f(x_0) + u_0 \\
y_1 &= f(x_1) + u_1 + \boxed{\alpha_0(x_1 - x_0)} \\
y_2 &= f(x_2) + u_2 + \boxed{\alpha_0(x_2 - x_0)} + \boxed{\alpha_1(x_2 - x_1)} \\
&\vdots \\
y_n &= f(x_n) + u_n + \sum_{m=0}^{n-1}\alpha_m(x_n - x_m) \qquad n = 0, 1, \ldots, N
\end{aligned}$$

Negative eta DiskZ: [25,45,70,100,135]
Positive eta DiskZ: [-25,-45,-65,-90,-115]

arXiv:1805.12014



DCA$_{xy}$ Resolution

arXiv:1805.12014

r_0 : distance of near hit

L_0: distance between near and farthest hit from the beamline

DCA$_{xy}$ increases at larger η because r_0/L_0 increases

DCA$_{xy}$ resolution:

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

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

(r_0/L_0) is very important for DCA$_{xy}$ resolutions

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

Barrel

r0 = 3.6; L0 = 64.0-3.6; N = 7;

$\sigma_{r\phi}=10\,\mu m/\sqrt{12}$

Expected DCAxy Resol Barrel (SR): 3.14743 μm

Forward/Backward

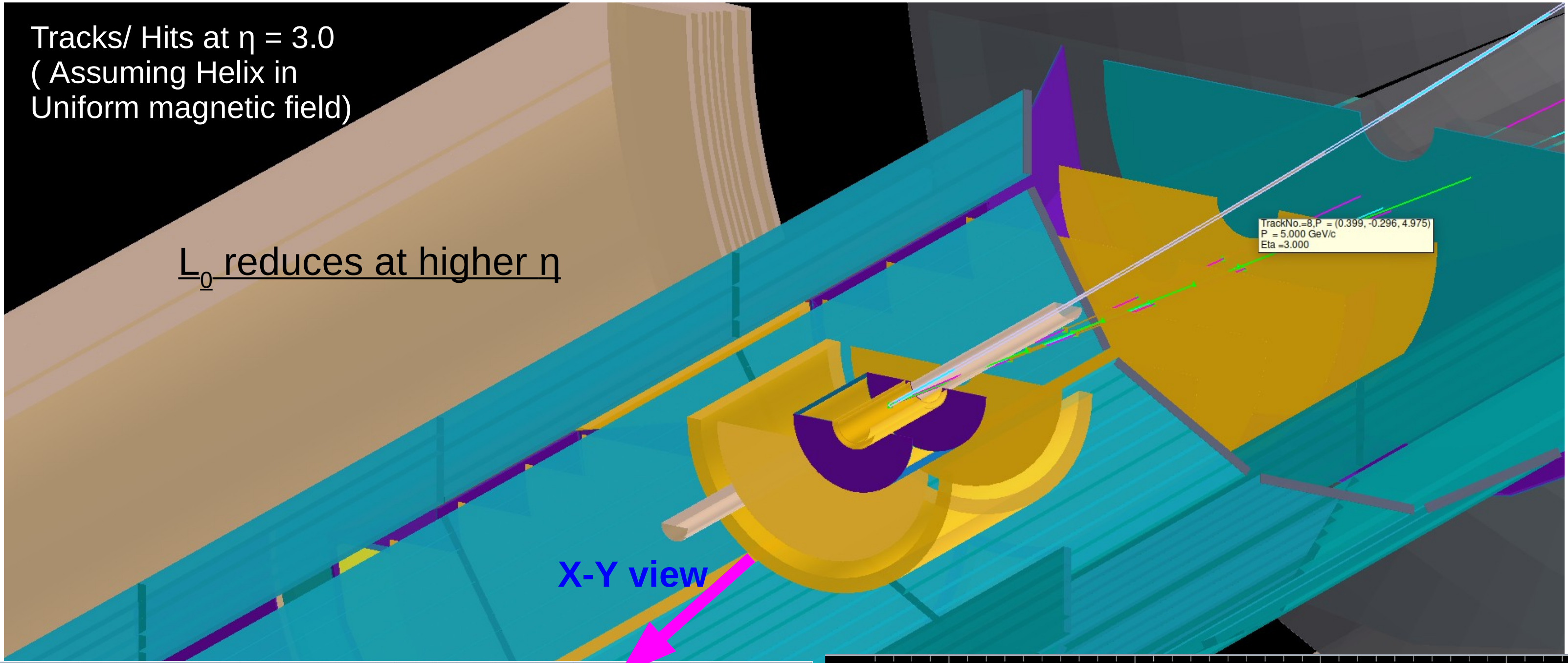
Double_t rmin[5] = {3.67617,3.67617,4.07617,5.37617,7.07617};
Double_t rmax[5] = {24.00010,42.500107,43.12010,43.12010,43.12010};
Double_t z[] ={25., 45., 70., 100., 135.};
Double_t L_0 = 43.12010-3.67617;   N = 4; // number of points

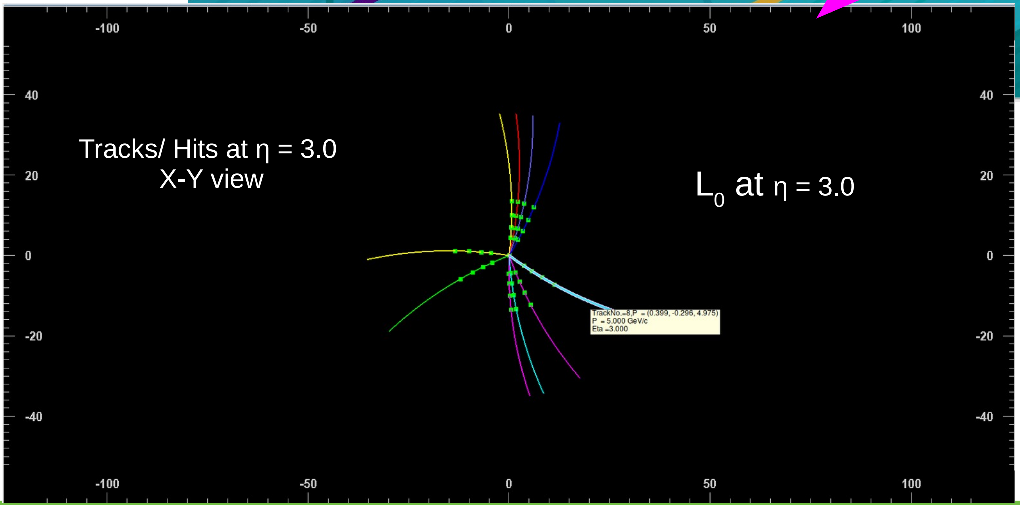
$\sigma_{r\phi}=10\,\mu m/\sqrt{12}$

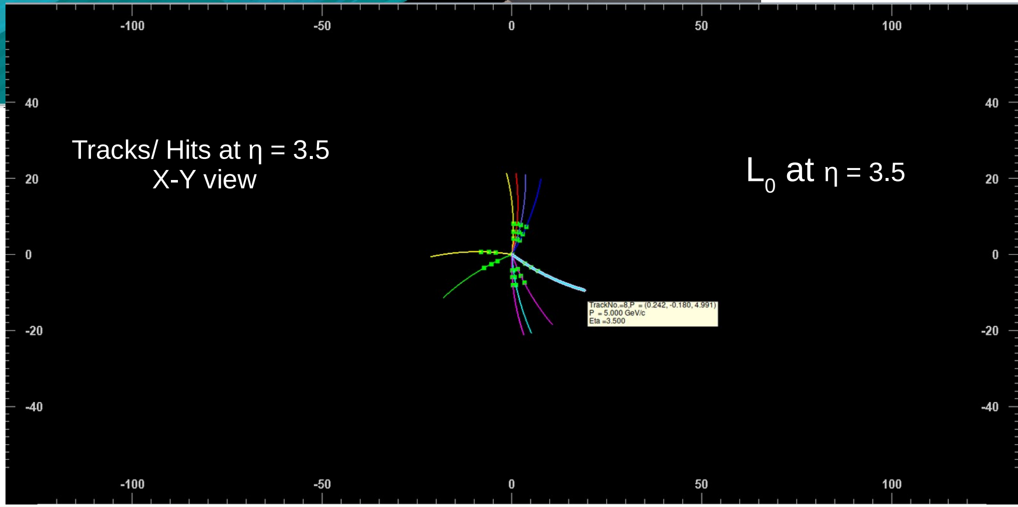
Expected DCAxy Resol Forward (SR): 4.10559 μm

if (L_0 = 20cm then Expected DCAxy = 5.543 μm)

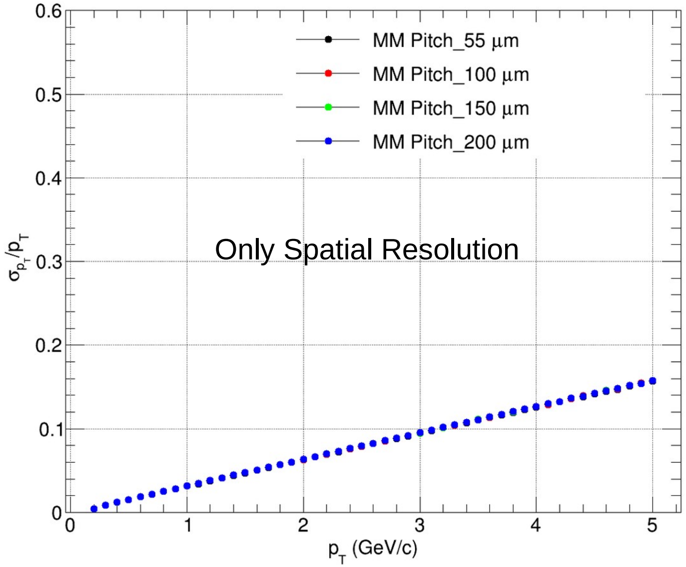
DCA$_{xy}$ Resolution (Forward/Backward)



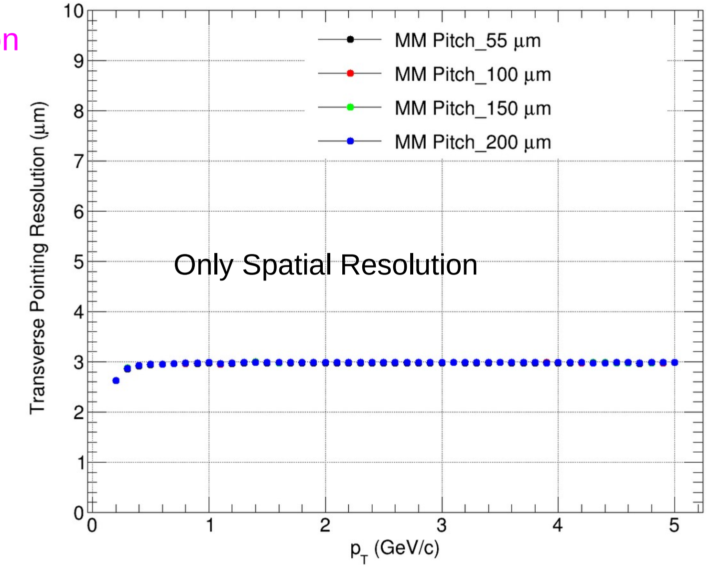




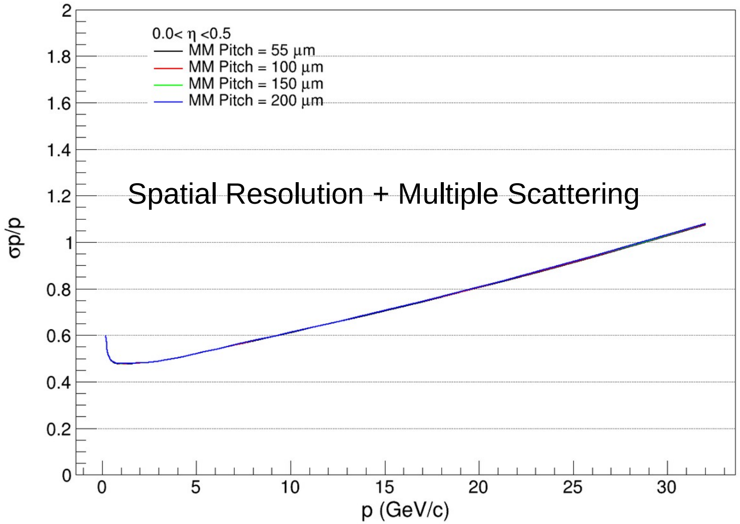
Changing Pitch (Resolution) of MPGD Layer (Fast Simulation)



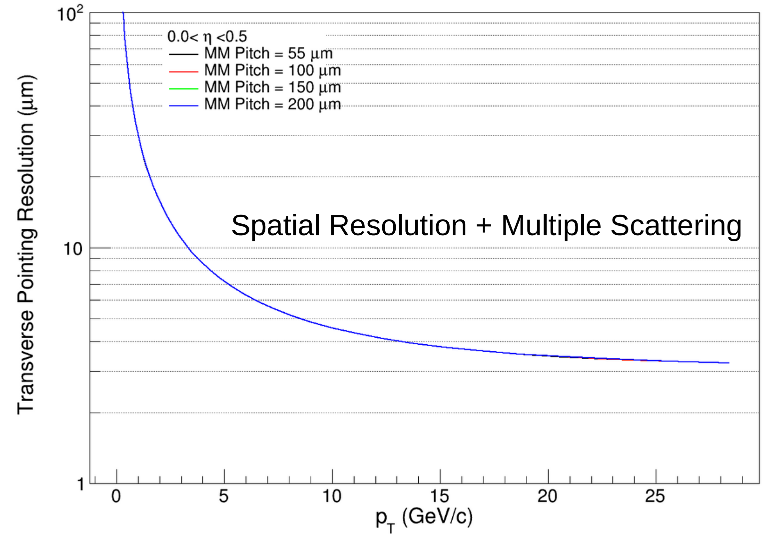
Pitch stands for Resolution



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



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

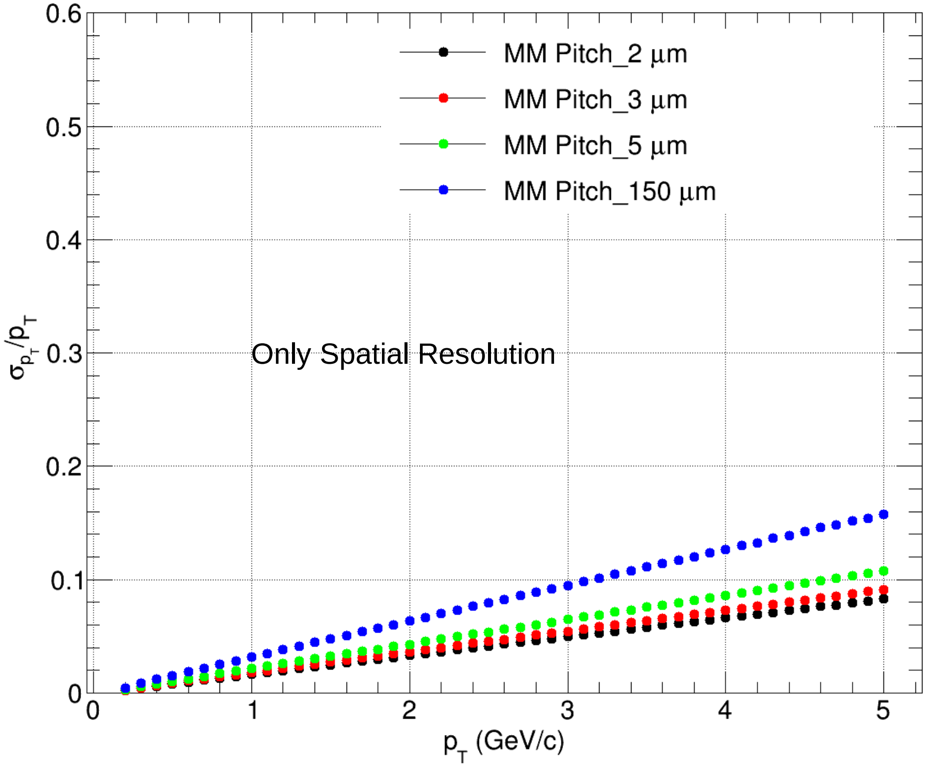


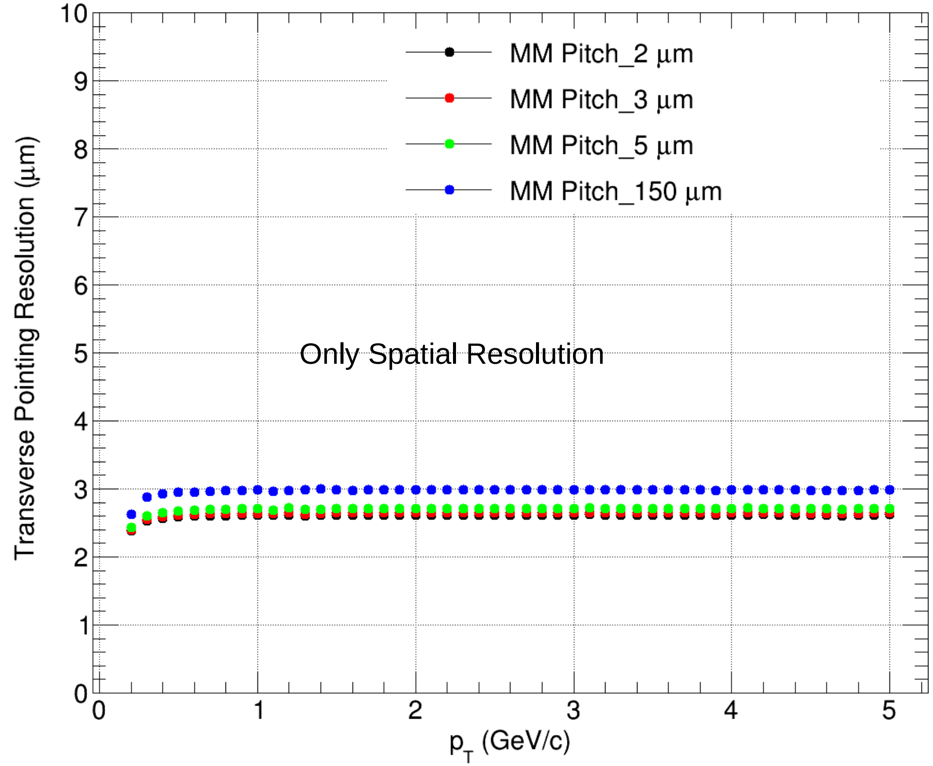
Changing Pitch (Resolution) of MPGD Layer (Fast Simulation)

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

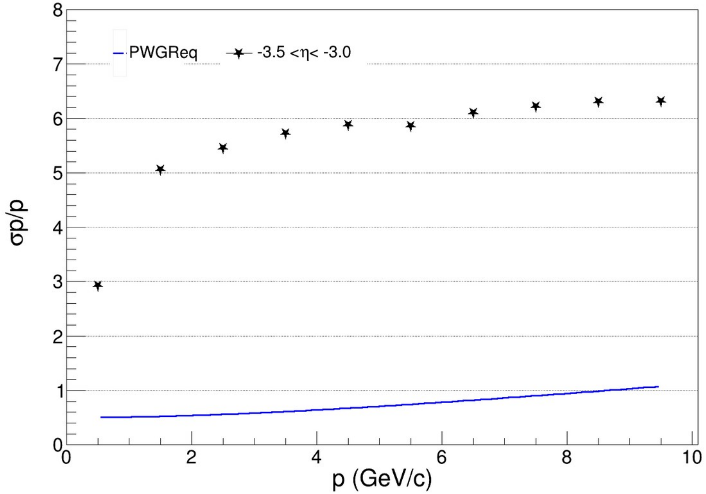
Pitch stands for Resolution

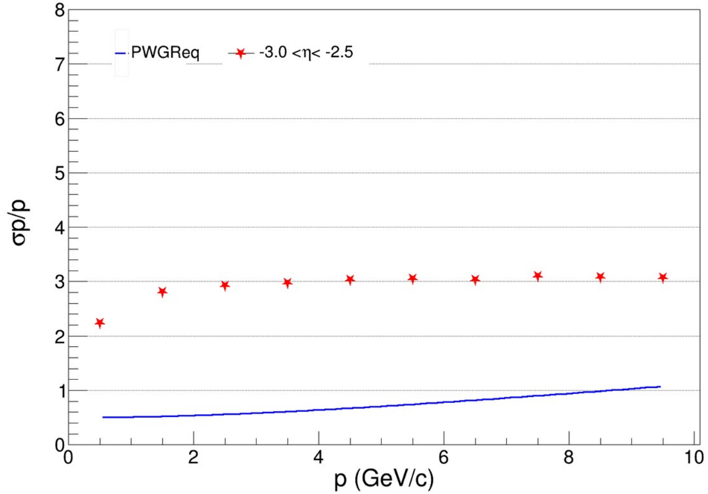
Multiple scattering has dominant contribuition at low momentum

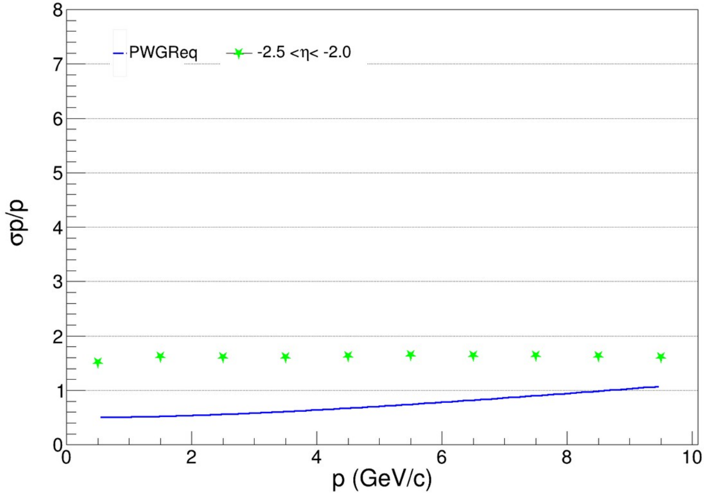


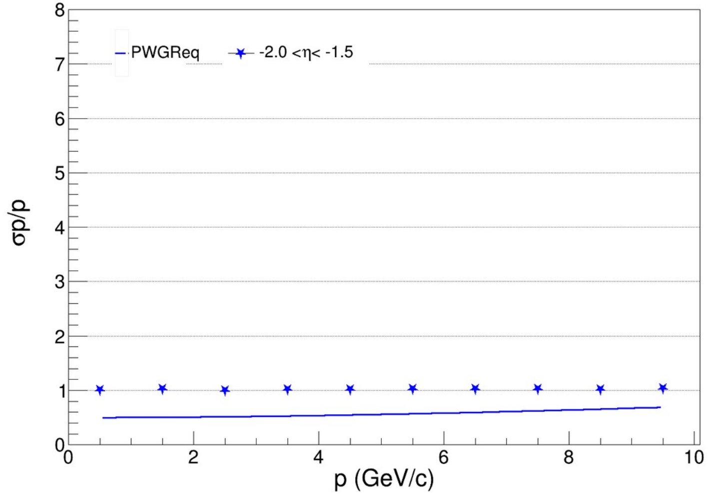


Blue line for Physics Requirements, Markers for DD4HEP Simulation



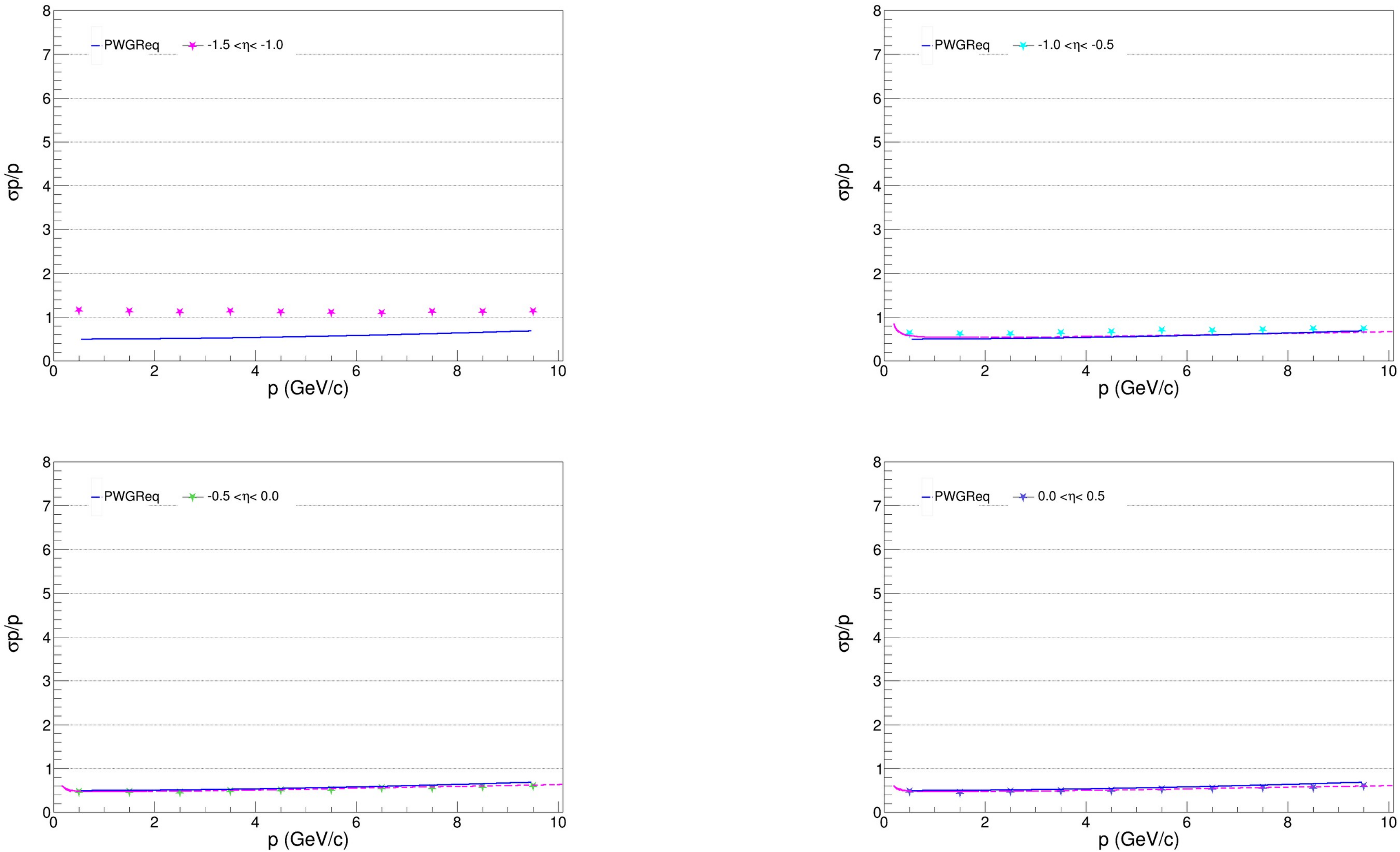






Tracking Performances

Blue line for Physics Requirements, Markers for DD4HEP Simulation, Magenta dotted line for Fast Sim (Kalman filter)



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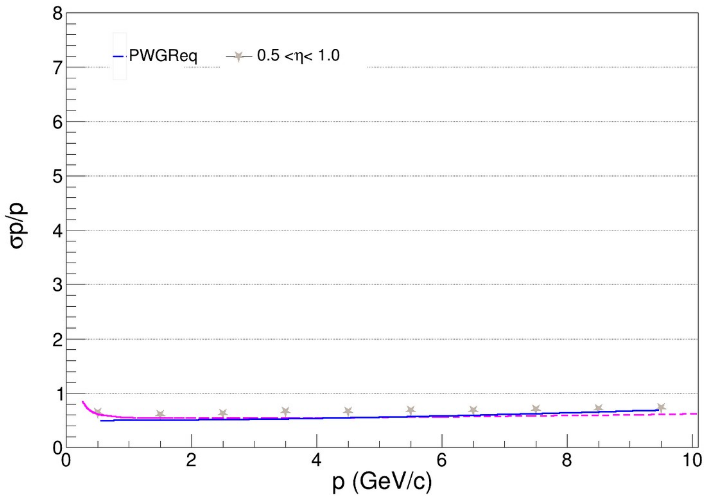
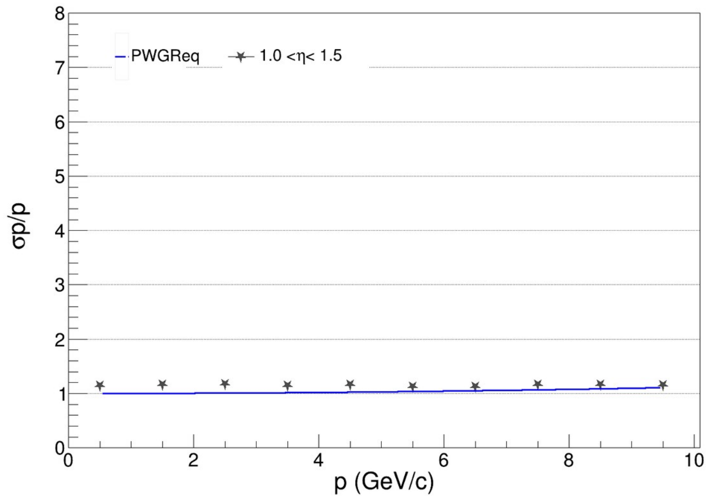
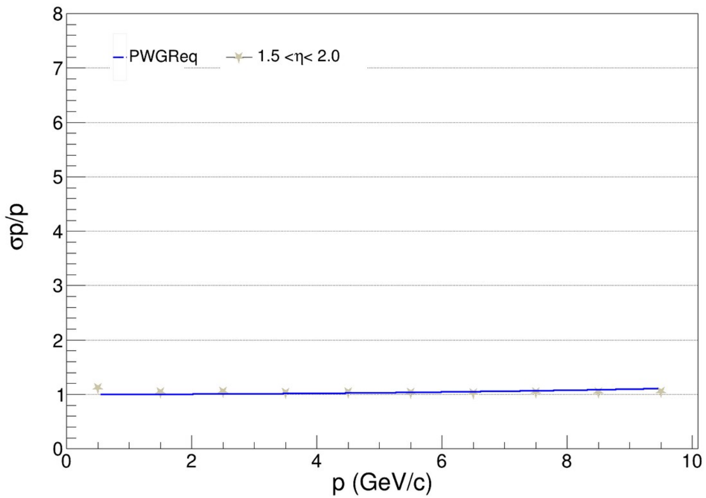
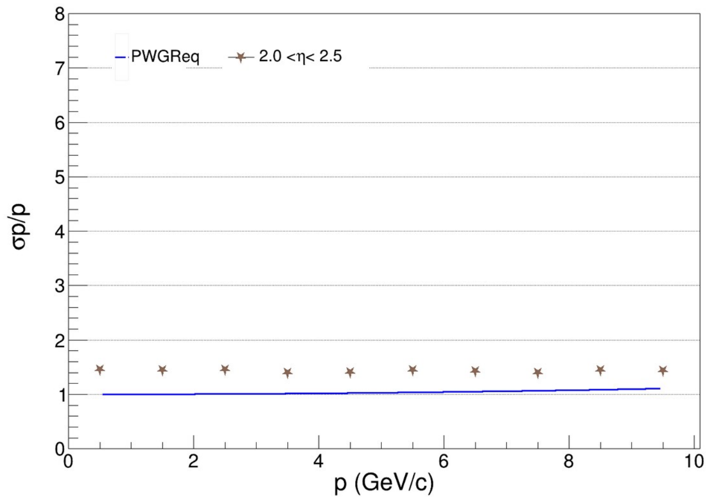


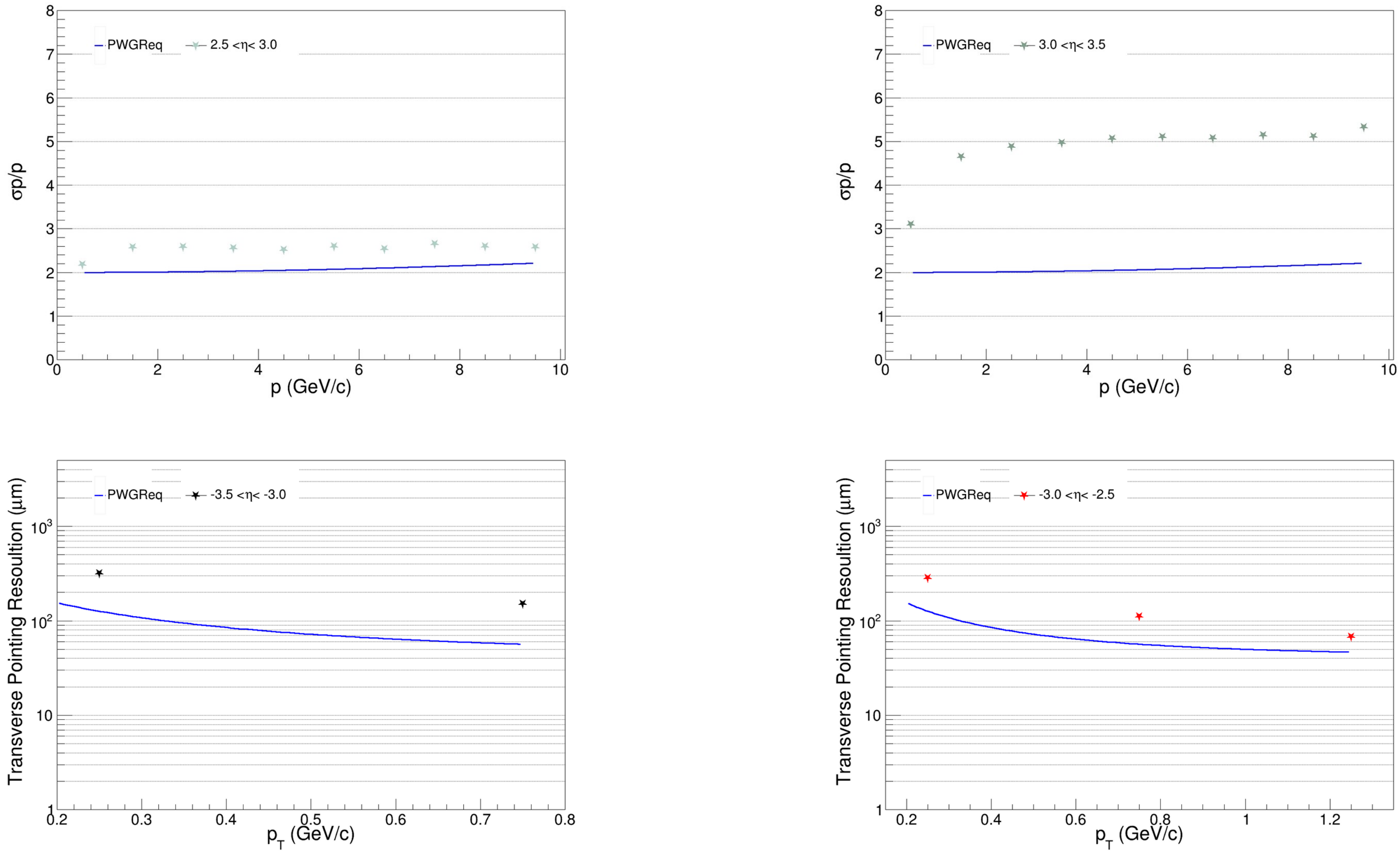






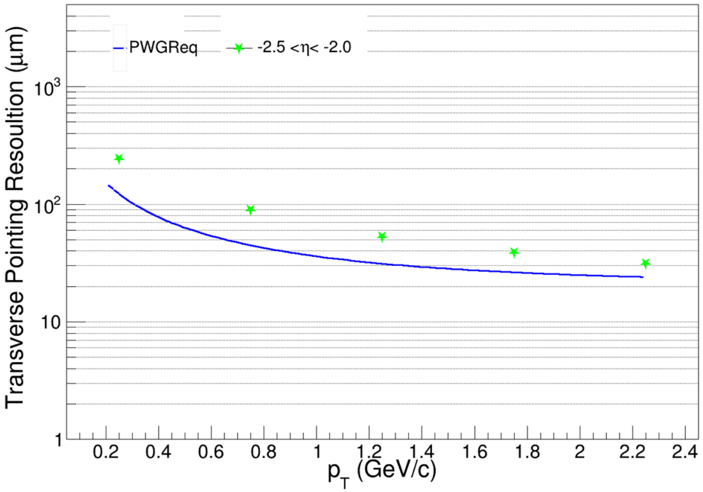
Tracking Performances

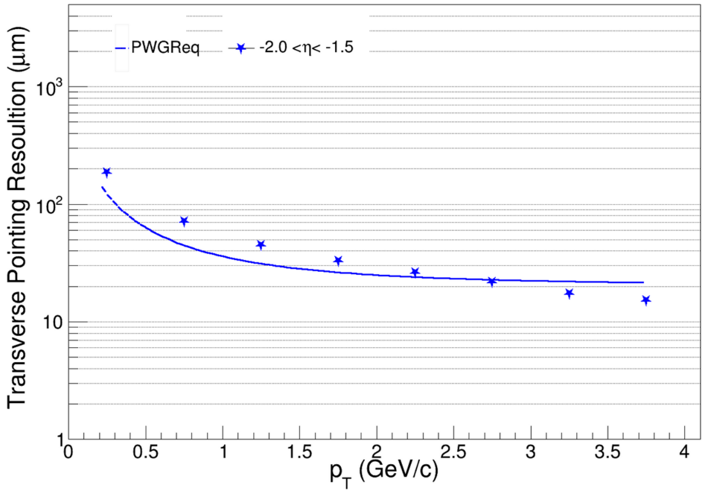
Blue line for Physics Requirements, Markers for DD4HEP Simulation

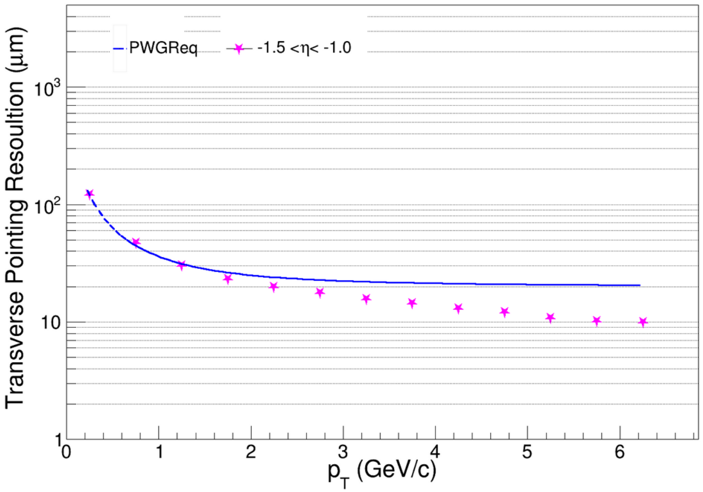


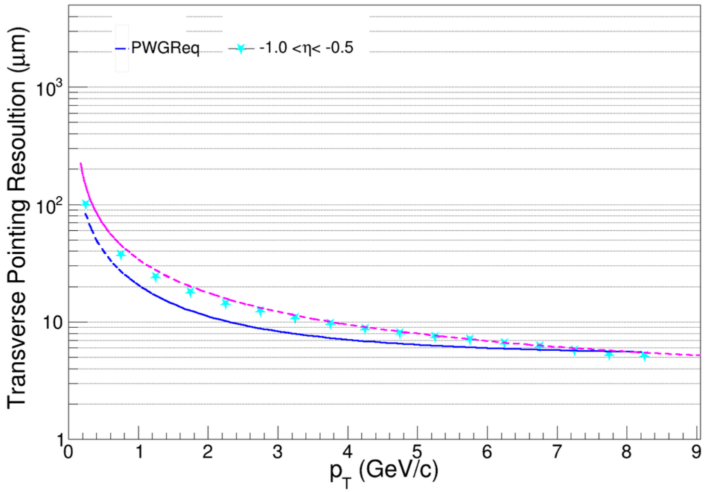
Tracking Performances

Blue line for Physics Requirements, Markers for DD4HEP Simulation, Magenta dotted line for Fast Sim (Kalman filter)



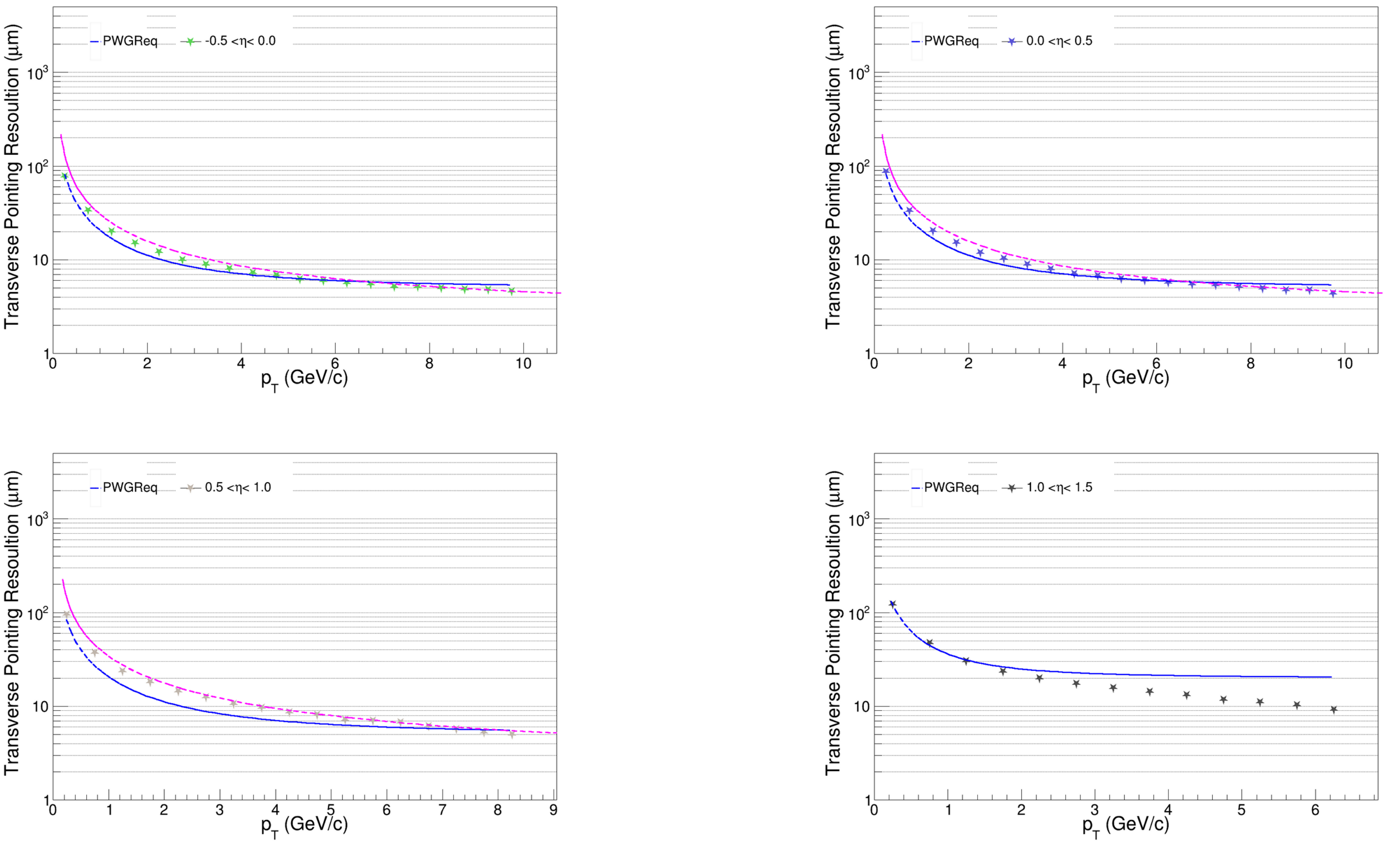






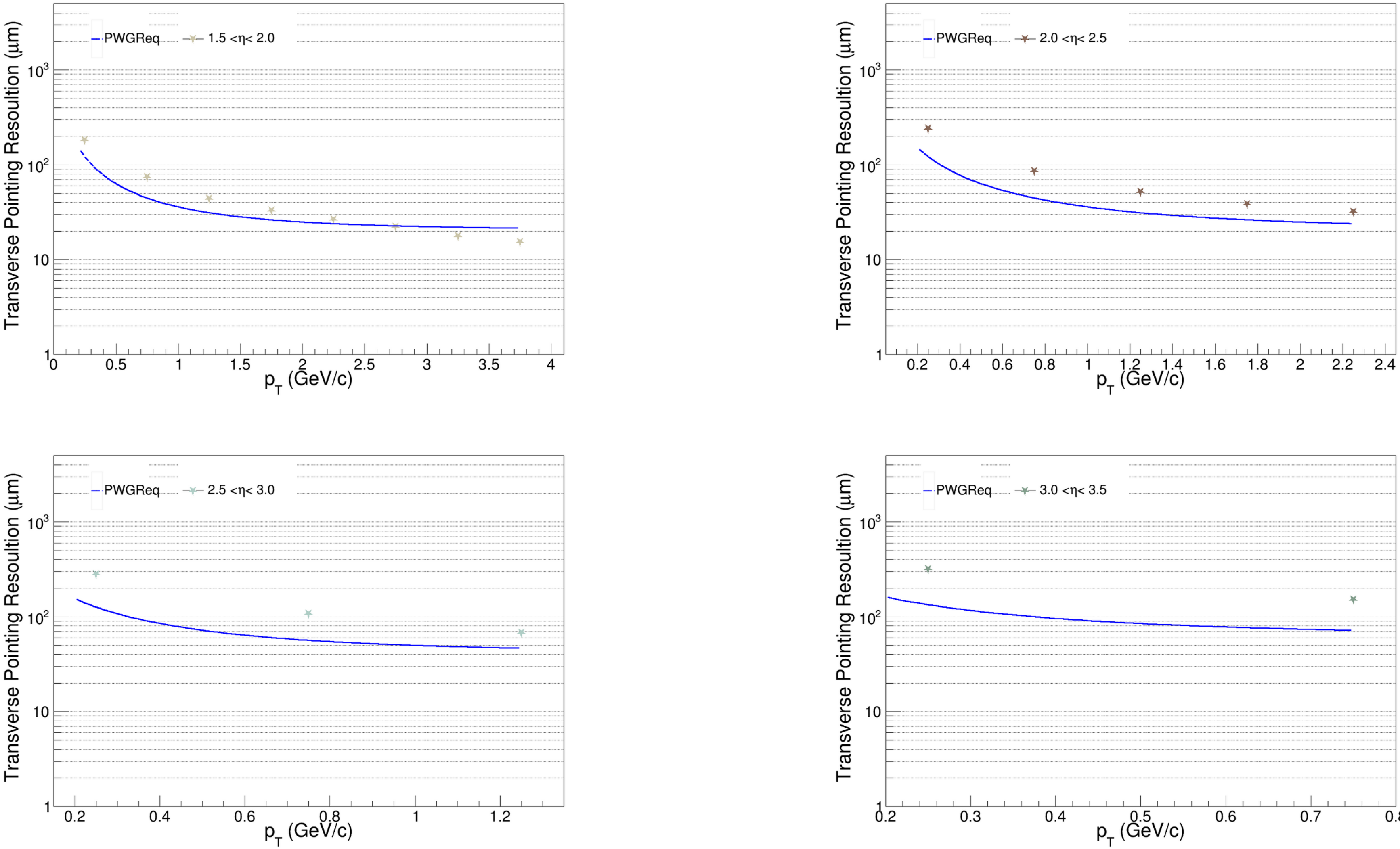
Tracking Performances

Blue line for Physics Requirements, Markers for DD4HEP Simulation, Magenta dotted line for Fast Sim (Kalman filter)



Tracking Performances

Blue line for Physics Requirements, Markers for DD4HEP Simulation



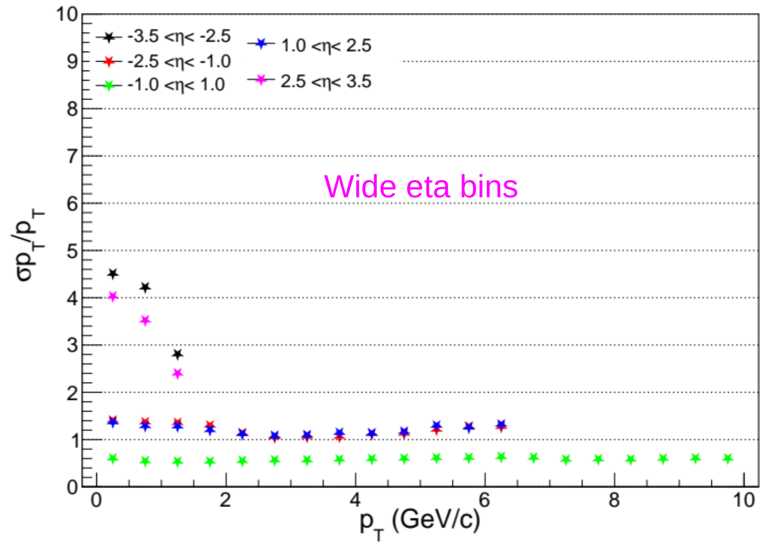
Summary and Future Plan

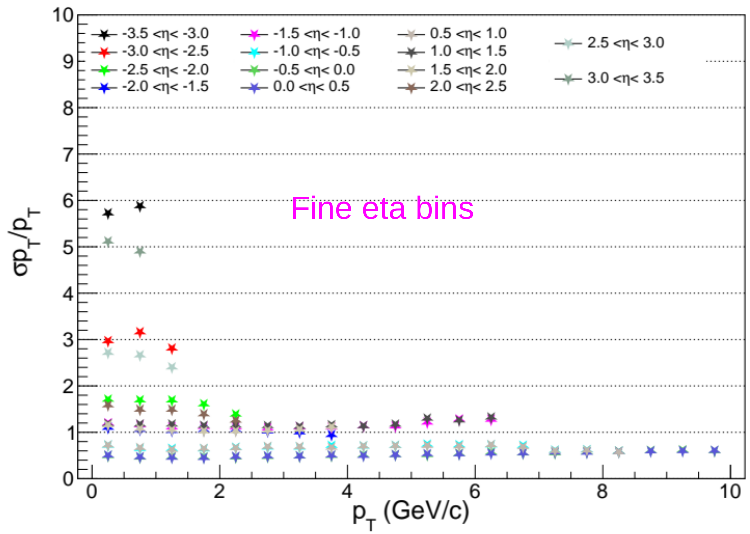
- Check the acceptance with truth seeding.
- Check at the first look of tracking performance and validation of fast simulation tool.
- Next
  - Number of hits per track, Chi2/ndf
  - Started looking at the realistic seeding
  - Comparison with Juggler result is welcomed (by Wenqing)

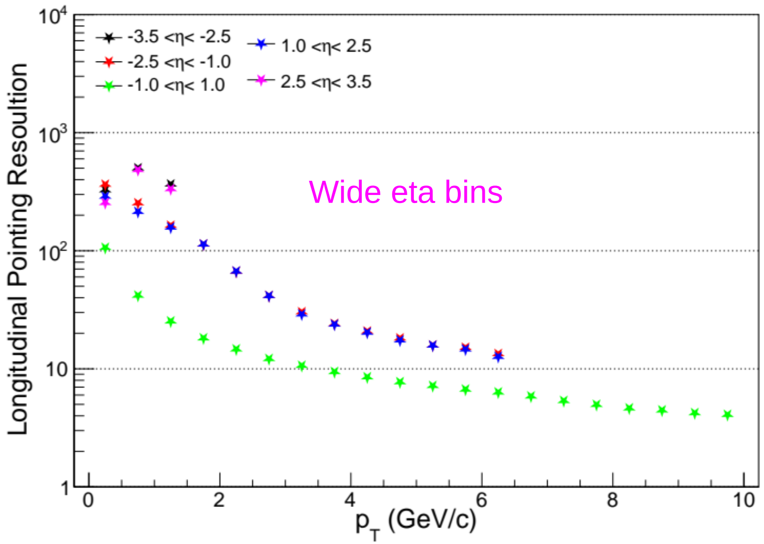
Thank You !!!

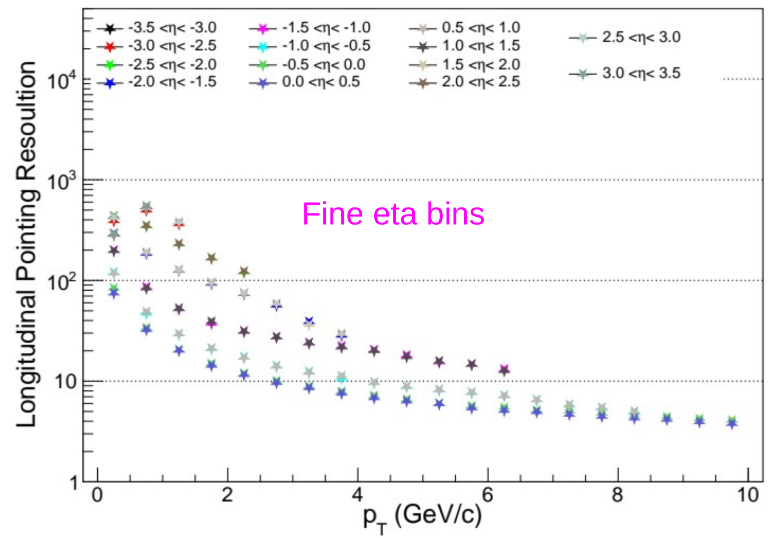
Tracking Performances

epic_brycecanyon.xml









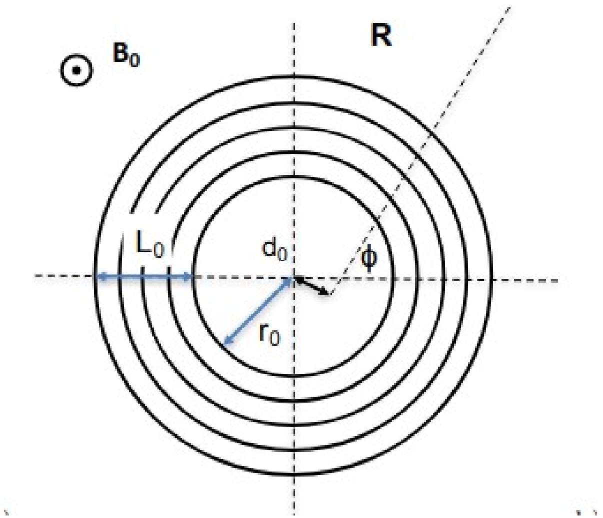
Momentum Resolution

Zbynek Drasal, Werner Riegler

arXiv:1805.12014

Tracking Performances: Momentum and DCA resolutions

Momentum Resolution:affects width of invariant mass peak



p_T resolution:

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

$$\approx \boxed{\frac{12\,\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}}\sqrt{\frac{5}{N+5}}$$

Linear term

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

Constant term (at β<1 increase)

Based on Gluckstern Approach (equal distance between planes and equal spatial resolutions)

SR (Spatial Resolution): Uncertainty associated with finite size of pixels

MS (Multiple Scattering): Uncertainty associated with thickness of Material

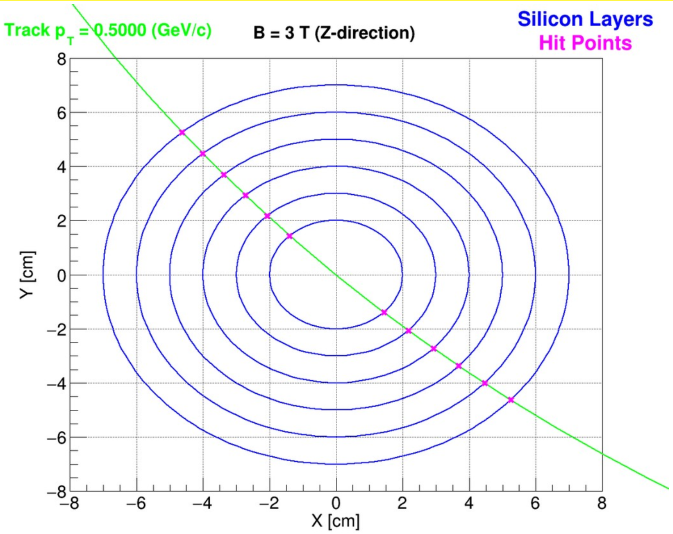
$$\frac{\sigma_{pT}}{p_T} = \sqrt{\left(\frac{\sigma_{pT_{SR}}}{p_T}\right)^2 + \left(\frac{\sigma_{pT_{MS}}}{p_T}\right)^2}$$

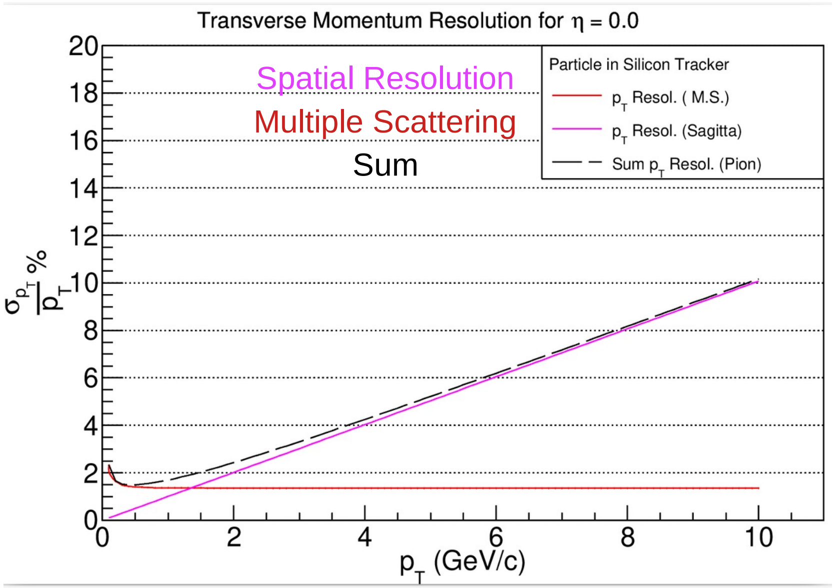
Simple Example

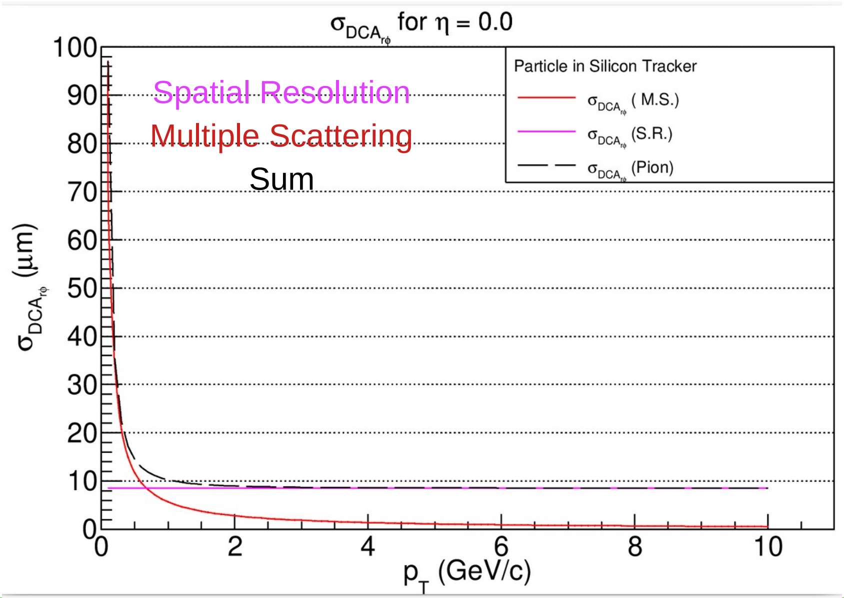
Consider an example of silicon layers of 50 μm thickness

r_0 = 2 cm L_0 = 7-2 = 5 cm;

$$\sigma_{r\phi} = 10\,\mu m/\sqrt{12}$$







Understanding of Multiple Scattering

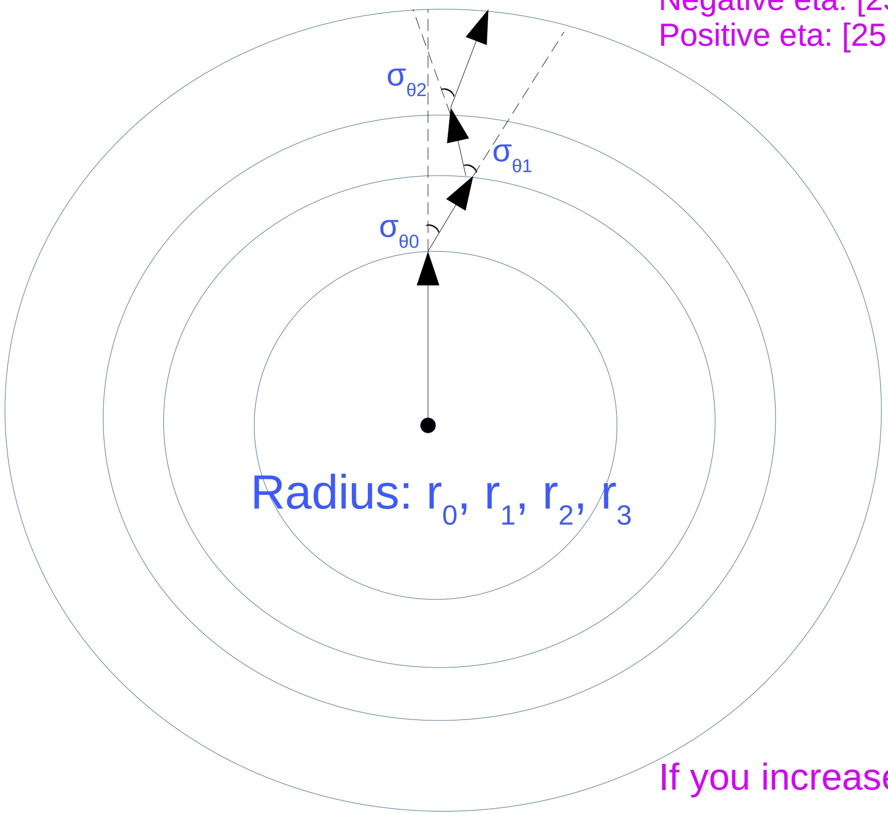
Theta MS σ_θ (Rad): 0.000226371 Theta MS σ_θ (deg): 0.0129701 (50 µm thick Silicon)

ϵ_p will be very small (ignore)

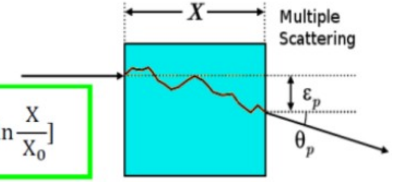
Layer1 smearing: $\sigma_1 = [(r_1 - r_0) * \sigma_{\theta 0}]$

Layer2 smearing: $[(r_2 - r_1) * \sigma_{\theta 1}] + [(r_2 - r_0) * \sigma_{\theta 0}]$

Layer3 smearing: $[(r_3 - r_2) * \sigma_{\theta 2}] + [(r_3 - r_1) * \sigma_{\theta 1}] + [(r_3 - r_0) * \sigma_{\theta 0}]$



Multiple Scattering (M.S.)



$$\sigma_\theta = 13.6 \frac{\mathrm{MeV} z}{\beta c p} \sqrt{\frac{X}{X_0}} \left[1 + 0.038 \ln \frac{X}{X_0}\right]$$

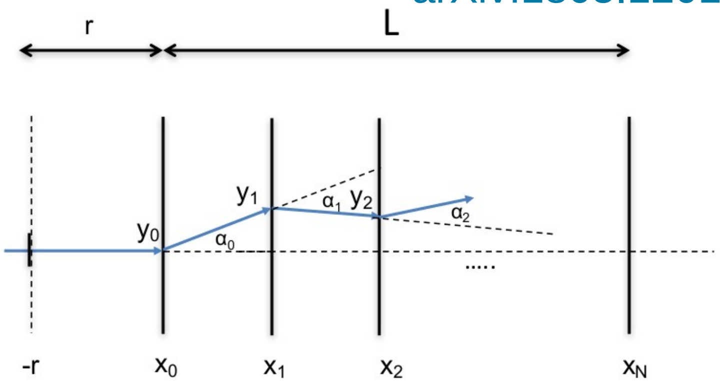
$$\epsilon_p \approx \frac{1}{\sqrt{3}} \theta_p X$$

Ref: "Particle Detectors", C. Grupen and B. A. Shwartz

At low p: m.s. dominated by $\propto \frac{1}{p}$

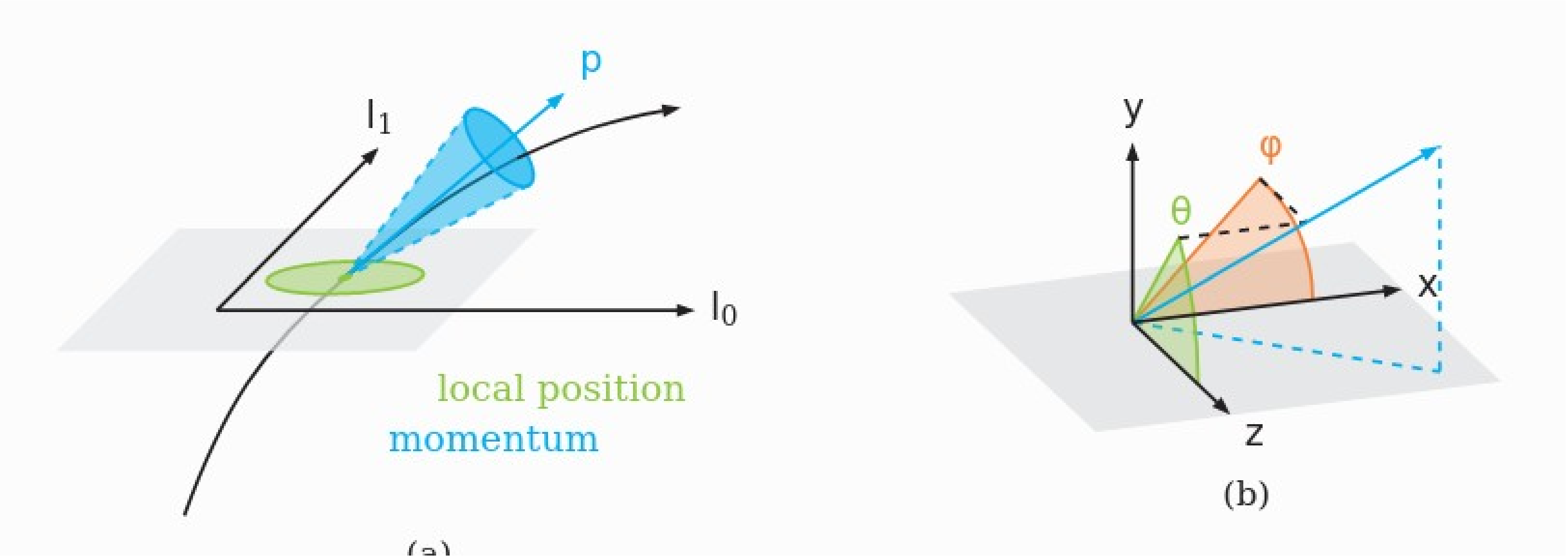
Negative eta: [25,45,70,100,135] (Large MS)
Positive eta: [25,45,65,90,115] (Small MS)

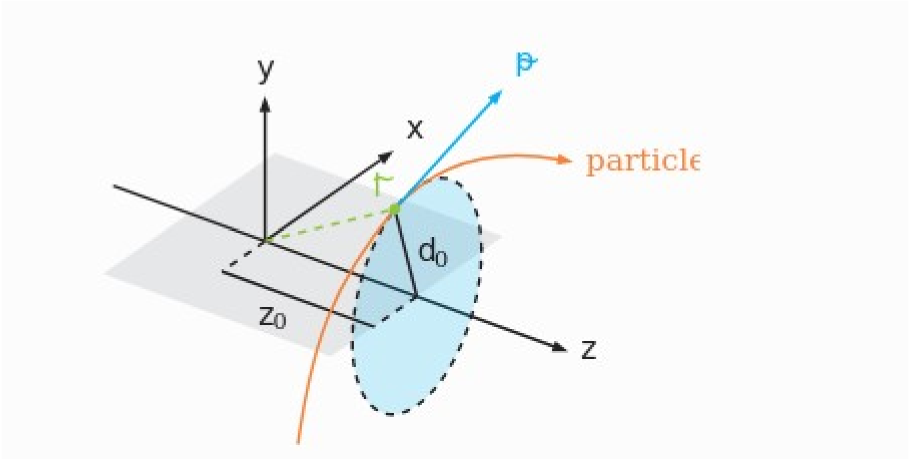
arXiv:1805.12014



$$
\begin{aligned}
y_0 &= f(x_0) + u_0 \\
y_1 &= f(x_1) + u_1 + \alpha_0(x_1 - x_0) \\
y_2 &= f(x_2) + u_2 + \alpha_0(x_2 - x_0) + \alpha_1(x_2 - x_1) \\
&\vdots \\
y_n &= f(x_n) + u_n + \sum_{m=0}^{n-1} \alpha_m(x_n - x_m) \qquad n = 0, 1, \ldots, N
\end{aligned}
$$

If you increase spacing smearing effect increases so multiple scattering !!!





Perigee Representation

Acts Common Tracking Software

Track finding and Track fitting

Event Data Model (EDM)

How to describe track parameter, measurement, track state and track...

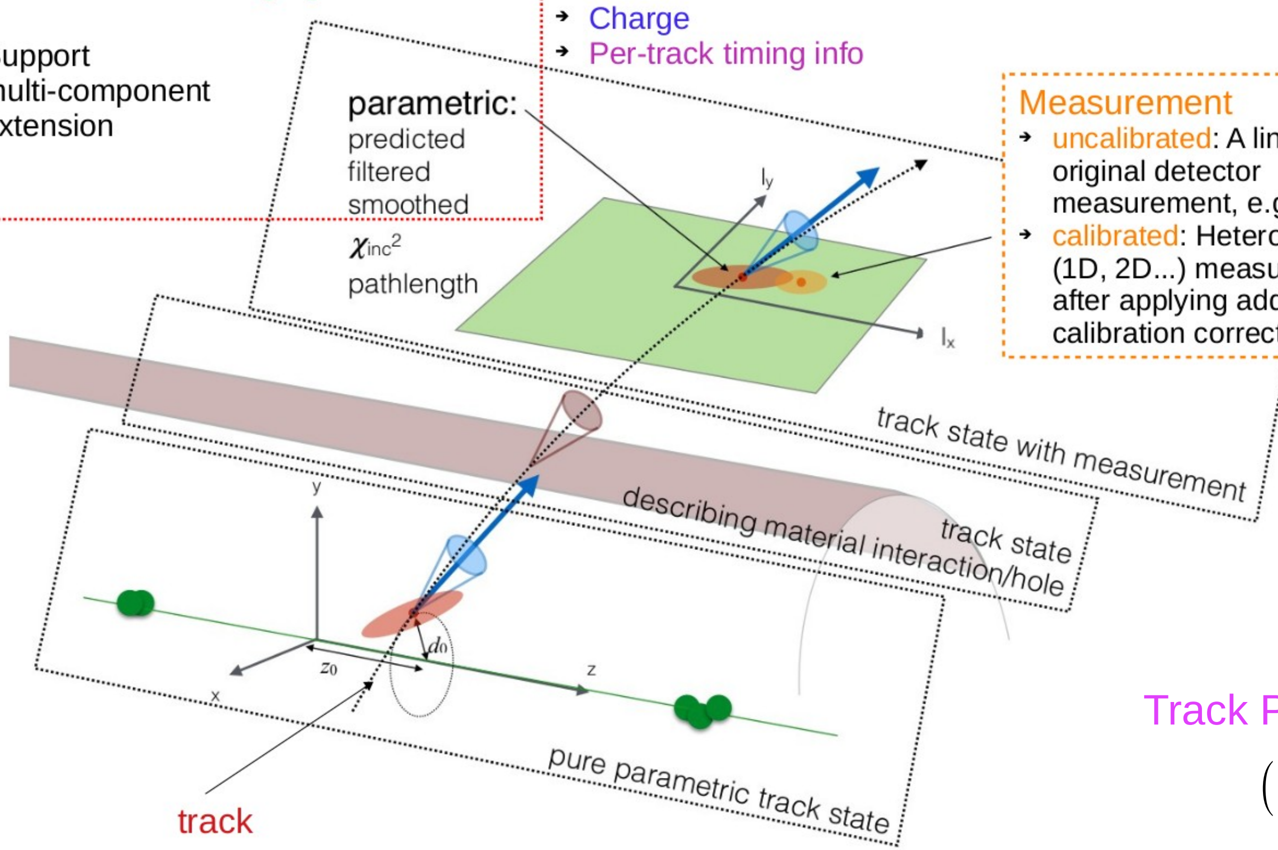
Track parameter: (l_1, l_2, ϕ, θ, q/p, t)

- Local position on surface
- Momentum
- Charge
- Per-track timing info

Support multi-component extension

Measurement

- uncalibrated: A link to original detector measurement, e.g. cluster
- calibrated: Heterogenous (1D, 2D...) measurement after applying additional calibration corrections



Track Parameters (Local):

$$\left(d_0, z_0, \phi, \theta, q/p\right)$$

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Page 9

ACTS Seeding and Tracking

General equation of a circle

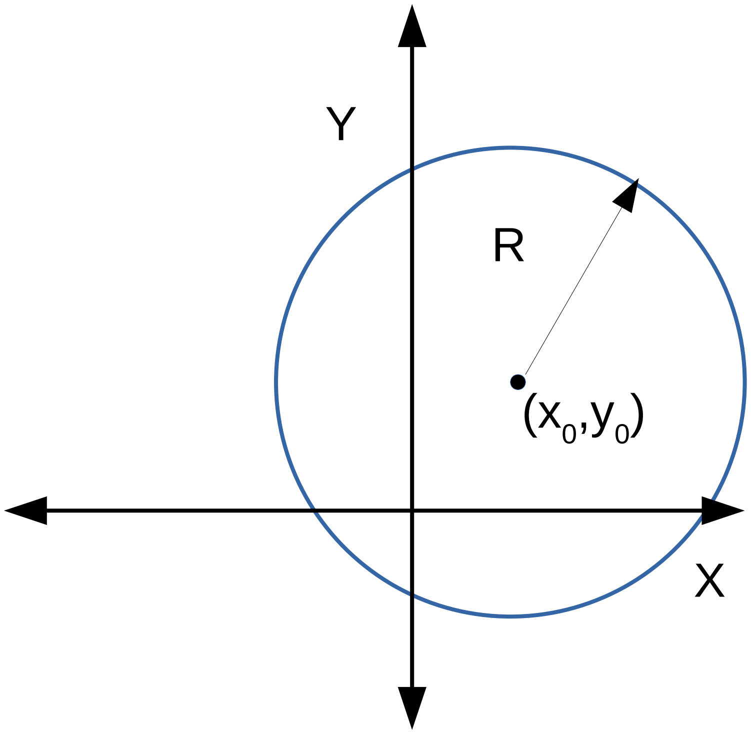
$$(x-x_0)^2+(y-y_0)^2=R^2$$

If circle passed through the vertex (0,0): $x_0^2+y_0^2=R^2$

$$x^2+x_0^2-2xx_0+y^2+y_0^2-2yy_0=R^2$$

using

$$u=\frac{x}{x^2+y^2} \qquad v=\frac{y}{x^2+y^2} \qquad x_0^2+y_0^2=R^2$$



$$x^2+y^2-2xx_0-2yy_0=0$$

$$1-2\frac{xx_0}{x^2+y^2}-2\frac{yy_0}{x^2+y^2}=0$$

$$\boxed{2ux_0+2vy_0=1}$$

Line in u-v space

Find three hits belong to straight line in u-v space and use them as the seeding, later use combinatorial track finding and fitting using Kalman filter https://iopscience.iop.org/article/10.1088/1742-6596/898/4/042011/pdf

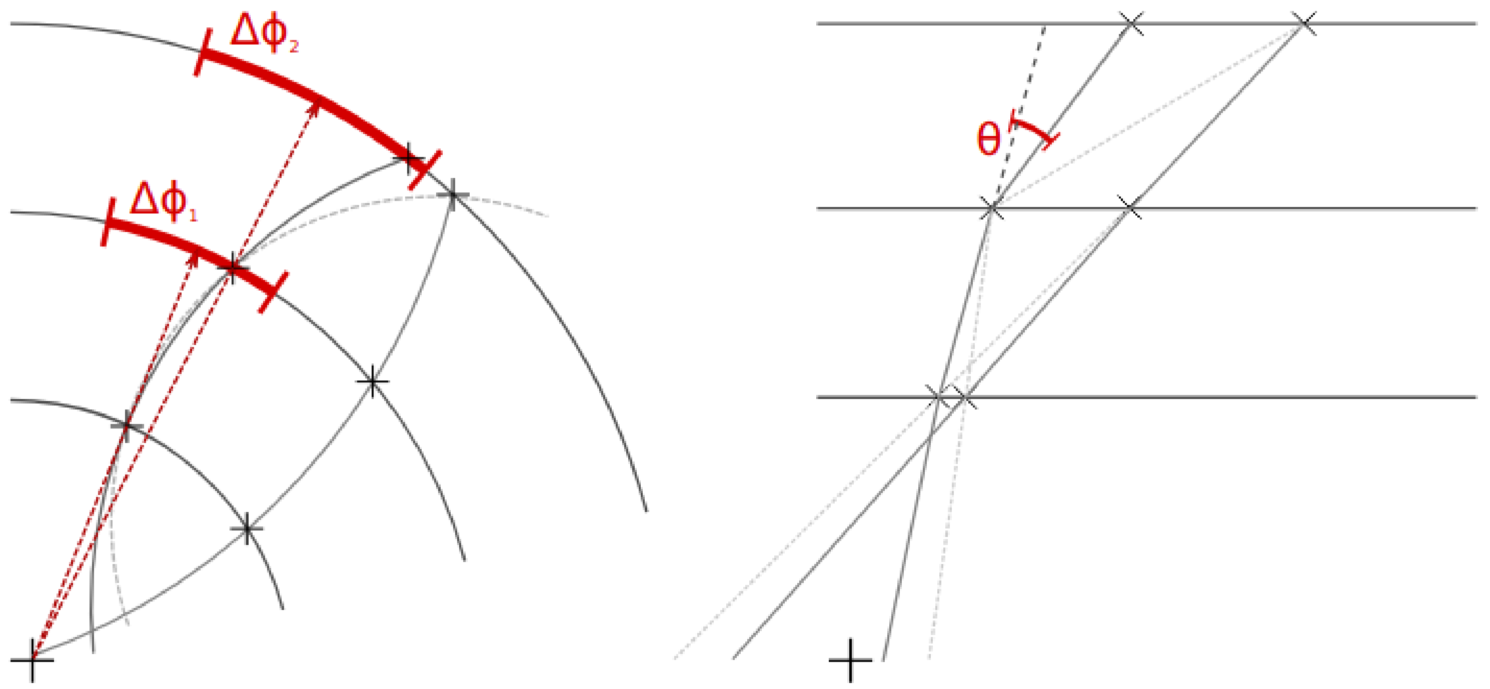


Figure 2. Illustration of the combinatorial seed finder for three-hit seeds in a barrel-like detector. Left: projection of the helix trajectory into the xy-plane transverse to the magnetic field direction. The two search windows $\Delta\phi_{\{1,2\}}$ on the second and third layer are defined with respect to the space point in the preceding layer. Right: hit combinations in the rz-plane along the magnetic field direction. The $\Delta\theta$ cut is defined as the difference in polar angle between the two hit doublets. Solid lines indicate true seeds, dashed lines indicate combinatorial background.