# Angular Resolutions at the DIRC Update

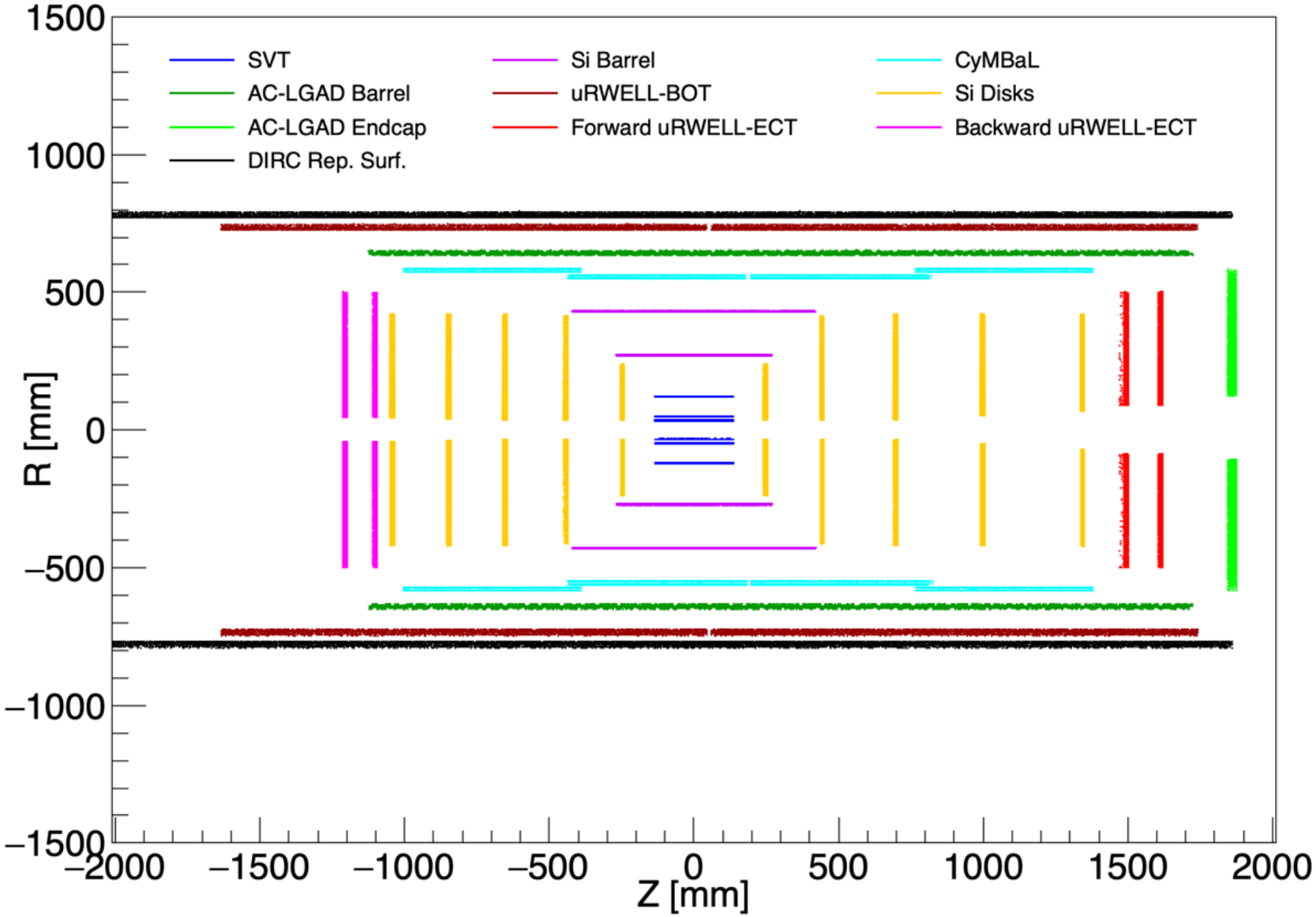
Matt Posik
Temple University

# Simulation Details

- ePIC: 25.04.1
- EICrecon: v1.24.0
- $\pi^-$ single particle
- Fixed momenta values
- $\Delta\theta = 2^o,\ \Delta\phi = 360^o$
- DIRC Reference Surface

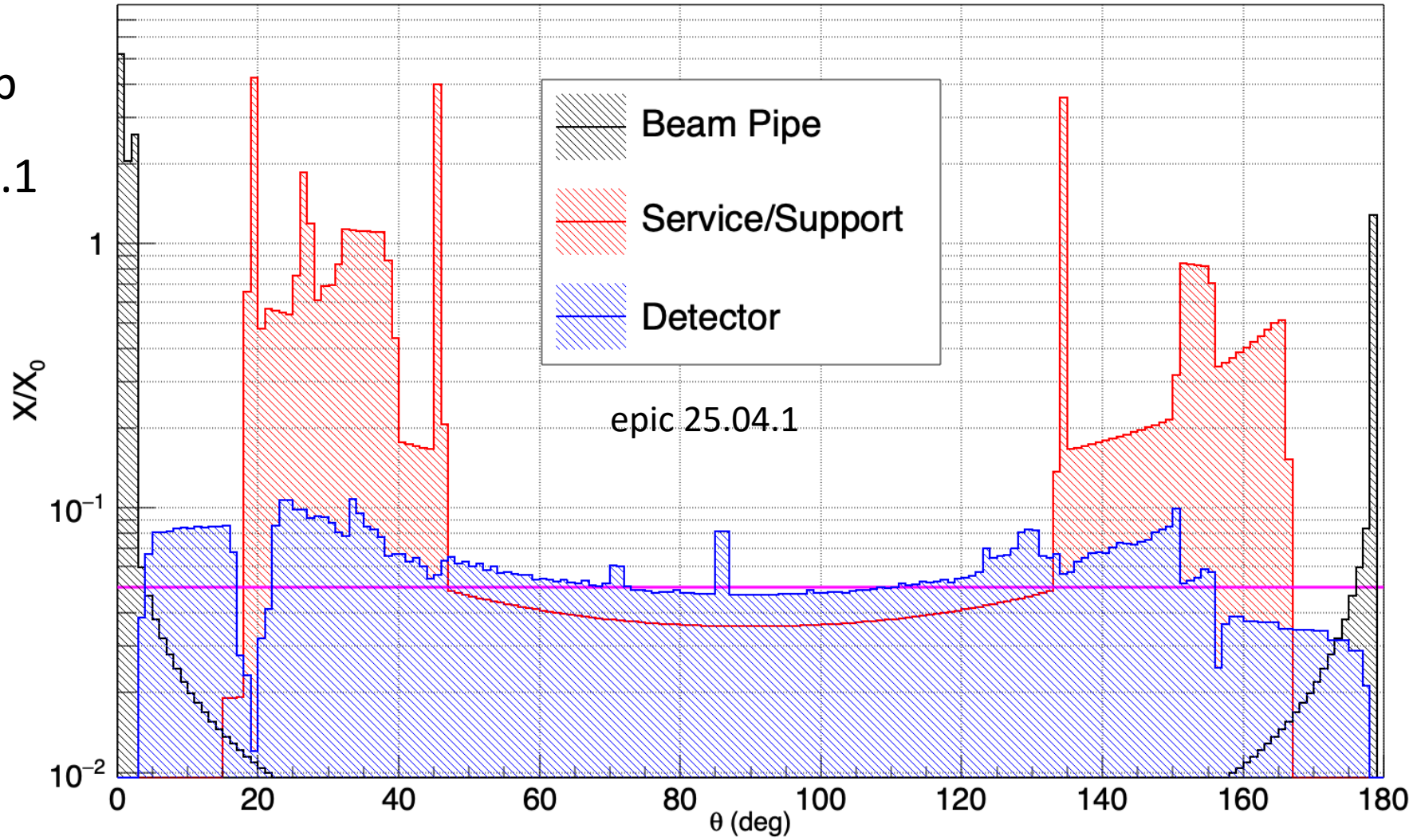
  R = 770.5 mm

➢ All resolutions presented are with respect to R = 770.5mm surface



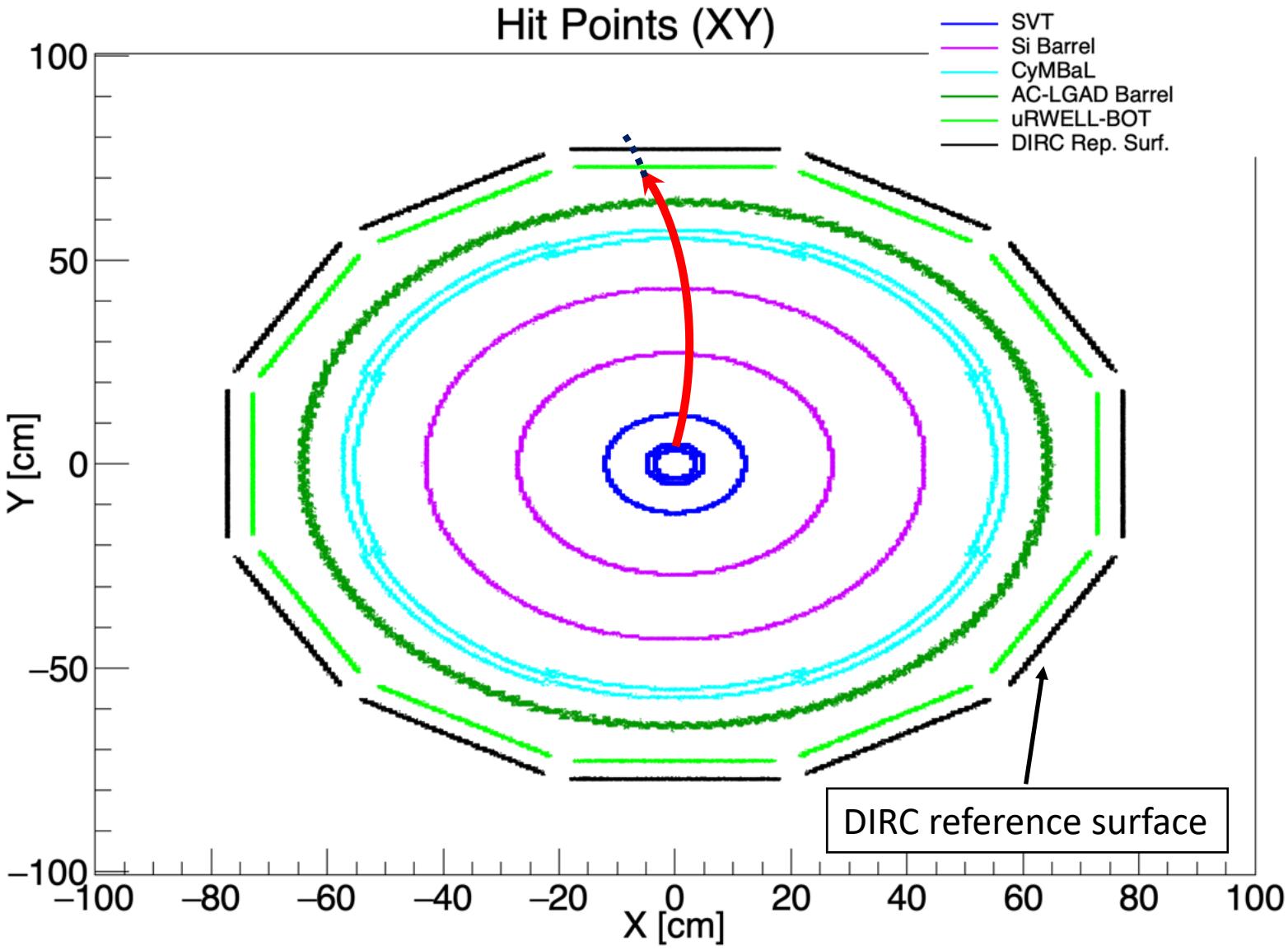
# Material: DD4HEP

- Use default material map included with epic 25.04.1



# Accessing Angular Resolutions

- Momentum vector information accessed via track propagation to desired target surface (e.g. DIRC)
  - Reference surface provides true momentum vector via SimHit
  - ACTS target surface provides reconstructed momentum vector via trajectory propagation



# Extracting Angular Resolutions: Residual Approach

- Loop over trajectories and propagate them to the ACTS surface

## Trajectory loop snippet

```
// Iterate over trajectories
m_log->debug("Propagating through {} trajectories", trajectories.size());
for (size_t traj_index = 0; traj_index < trajectories.size(); traj_index++) {
    auto &trajectory = trajectories[traj_index];
    m_log->trace(" -- trajectory {} --", traj_index);

    std::unique_ptr<edm4eic::TrackPoint> proj_DIRC_point;
    try {
        // >>> try to propagate to surface <<<
        proj_DIRC_point = m_propagation_algo.propagate(edm4eic::Track{}, trajectory, m_dirc_surf);
    }
```

Propagate trajectories to ACTS surface

## Propagated track point information

```
auto DIRC_proj_pos   = proj_DIRC_point->position;
auto DIRC_proj_len   = proj_DIRC_point->pathlength;
auto DIRC_proj_mom   = proj_DIRC_point->momentum;
auto DIRC_proj_theta = proj_DIRC_point->theta;
auto DIRC_proj_phi   = proj_DIRC_point->phi;
```

# Extracting Angular Resolutions: Residual Approach

- Angles determined from reference and propagated trajectory hit point via TVector
  - **Momentum Vector** (on DIRC surface)

$$\vec{p} = (px, py, pz)$$

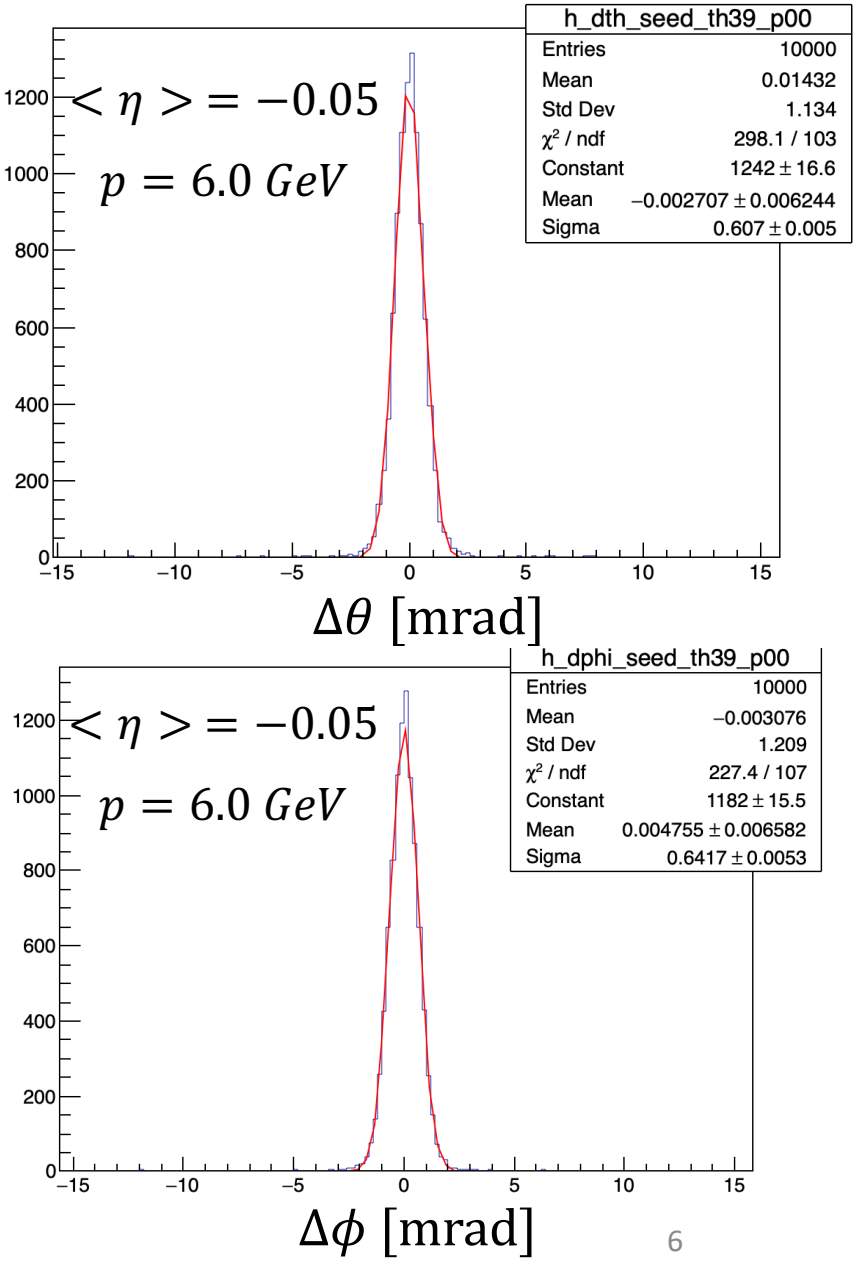
  - **Momentum Vector Direction** (on DIRC surface)

$$\theta_{ref}^{DIRC} = \vec{p}_{ref}^{DIRC}.\text{Theta}() \qquad \theta_{prop}^{DIRC} = \vec{p}_{prop}^{DIRC}.\text{Theta}()$$

$$\phi_{ref}^{DIRC} = \vec{p}_{ref}^{DIRC}.\text{Phi}() \qquad \phi_{prop}^{DIRC} = \vec{p}_{prop}^{DIRC}.\text{Phi}()$$

$$\Delta\theta^{DIRC} = \theta_{prop}^{DIRC} - \theta_{ref}^{DIRC}$$

$$\Delta\phi^{DIRC} = \phi_{prop}^{DIRC} - \phi_{ref}^{DIRC}$$




- Take difference of truth hit and propagated track point
  - Resolution is given by Gaussian sigma

# Extracting Angular Resolutions: Covariance Matrix Approach

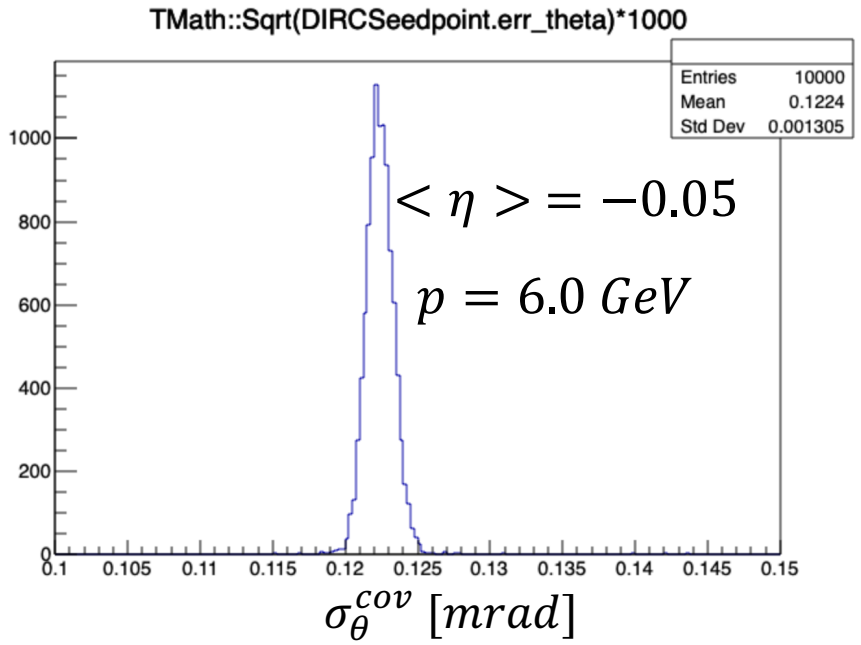
- Using the tracking covariance matrix is an alternative approach to using the residual approach
- Angular resolutions extracted from edm4eic::TrackPoint::directionError
- Resolution is $< \sqrt{(\sigma^{cov})^2} >$

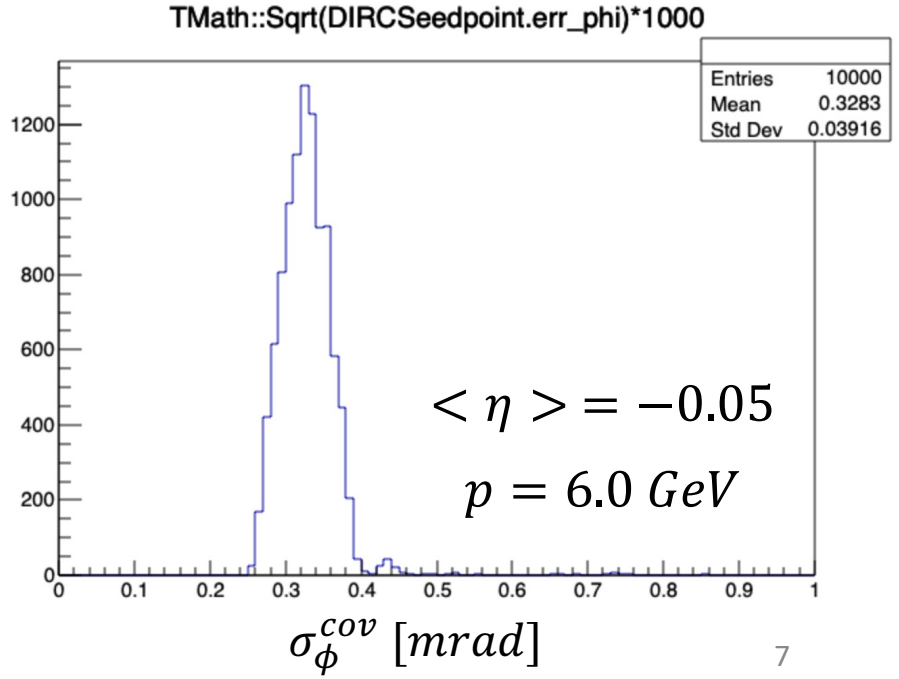
TrackPropagation.cc

```
// Direction
const float theta(parameter[Acts::eBoundTheta]);
const float phi(parameter[Acts::eBoundPhi]);
const decltype(edm4eic::TrackPoint::directionError) directionError{
        static_cast<float>(covariance(Acts::eBoundTheta, Acts::eBoundTheta)),
        static_cast<float>(covariance(Acts::eBoundPhi, Acts::eBoundPhi)),
        static_cast<float>(covariance(Acts::eBoundTheta, Acts::eBoundPhi))
};
```

Propagated track point information

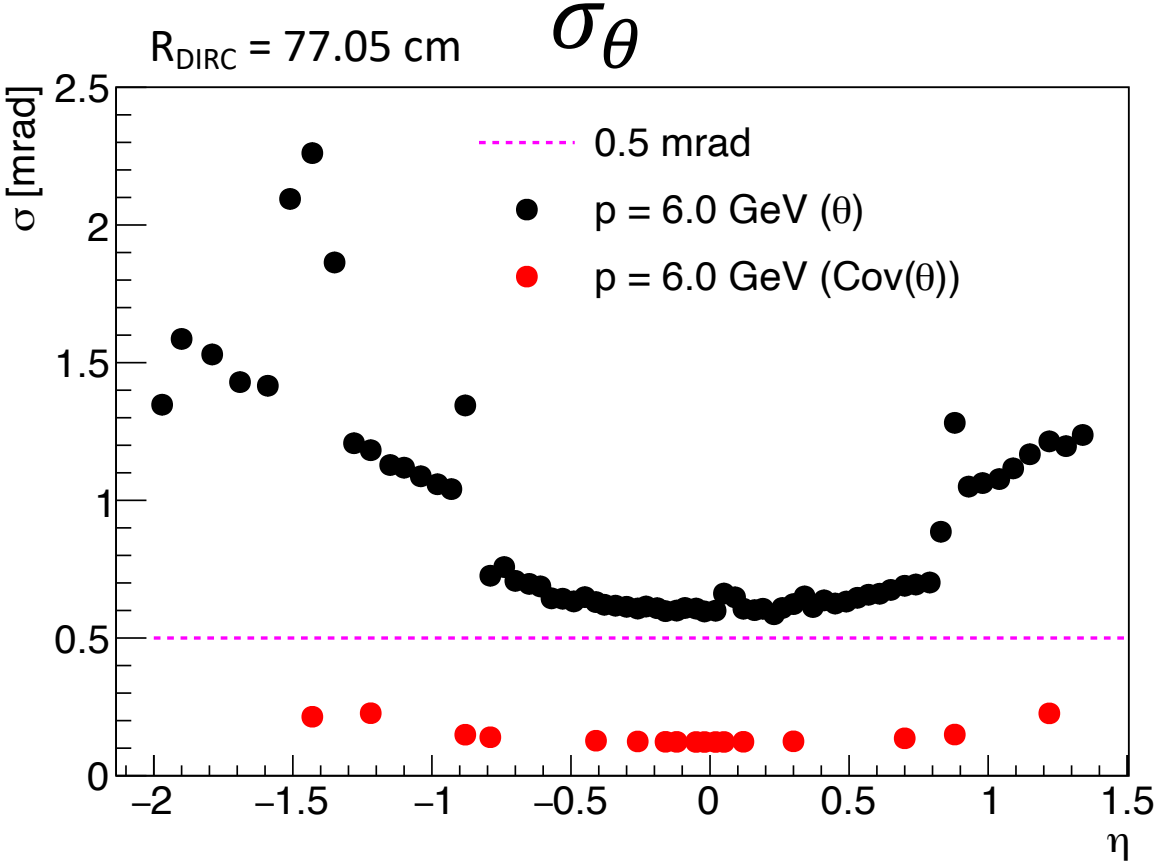
```
auto DIRC_proj_phi   = proj_DIRC_point->phi;
auto DIRC_proj_theta_theta_error = proj_DIRC_point->directionError.xx;
auto DIRC_proj_phi_phi_error     = proj_DIRC_point->directionError.yy;
auto DIRC_proj_theta_phi_error   = proj_DIRC_point->directionError.xy;
TVector3 proj_pos_vector(DIRC_proj_pos.x, DIRC_proj_pos.y, DIRC_proj_pos.z);
TVector3 proj_mom_vector(DIRC_proj_mom.x, DIRC_proj_mom.y, DIRC_proj_mom.z);
```

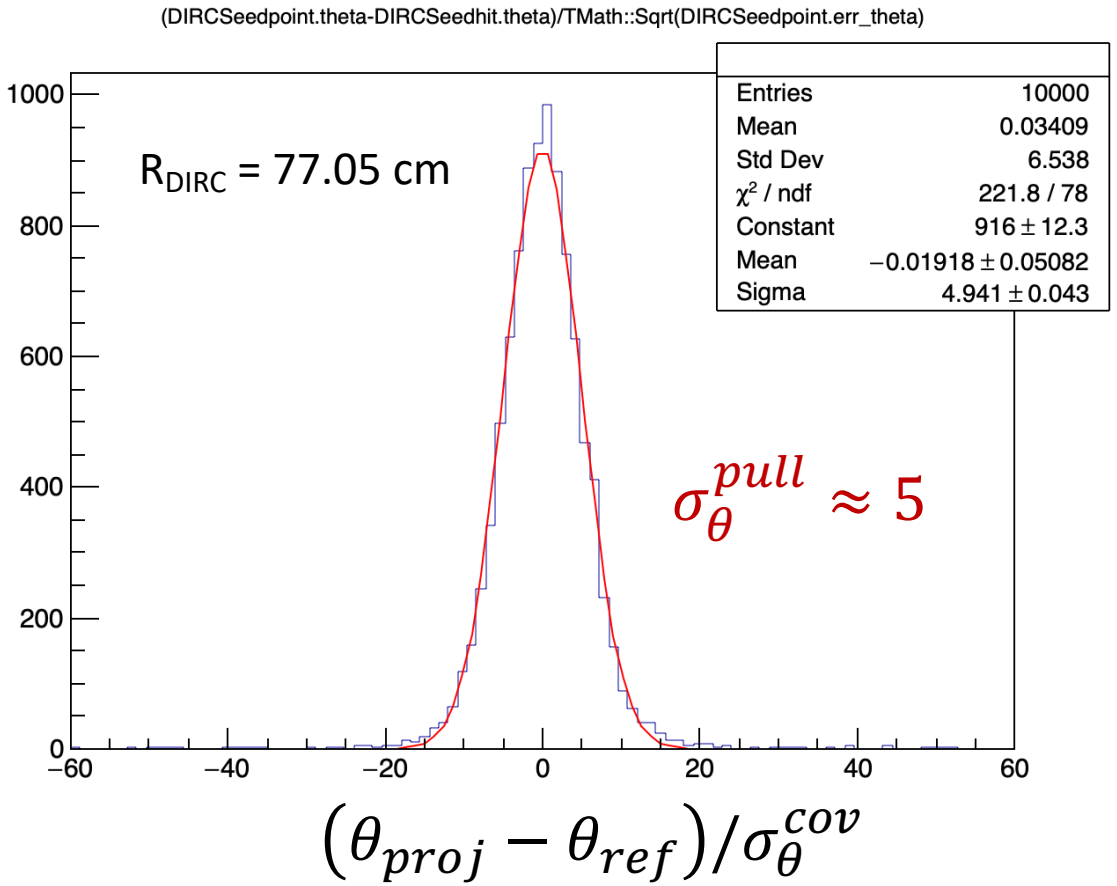


# Angular Resolution Results: Previous Propagation

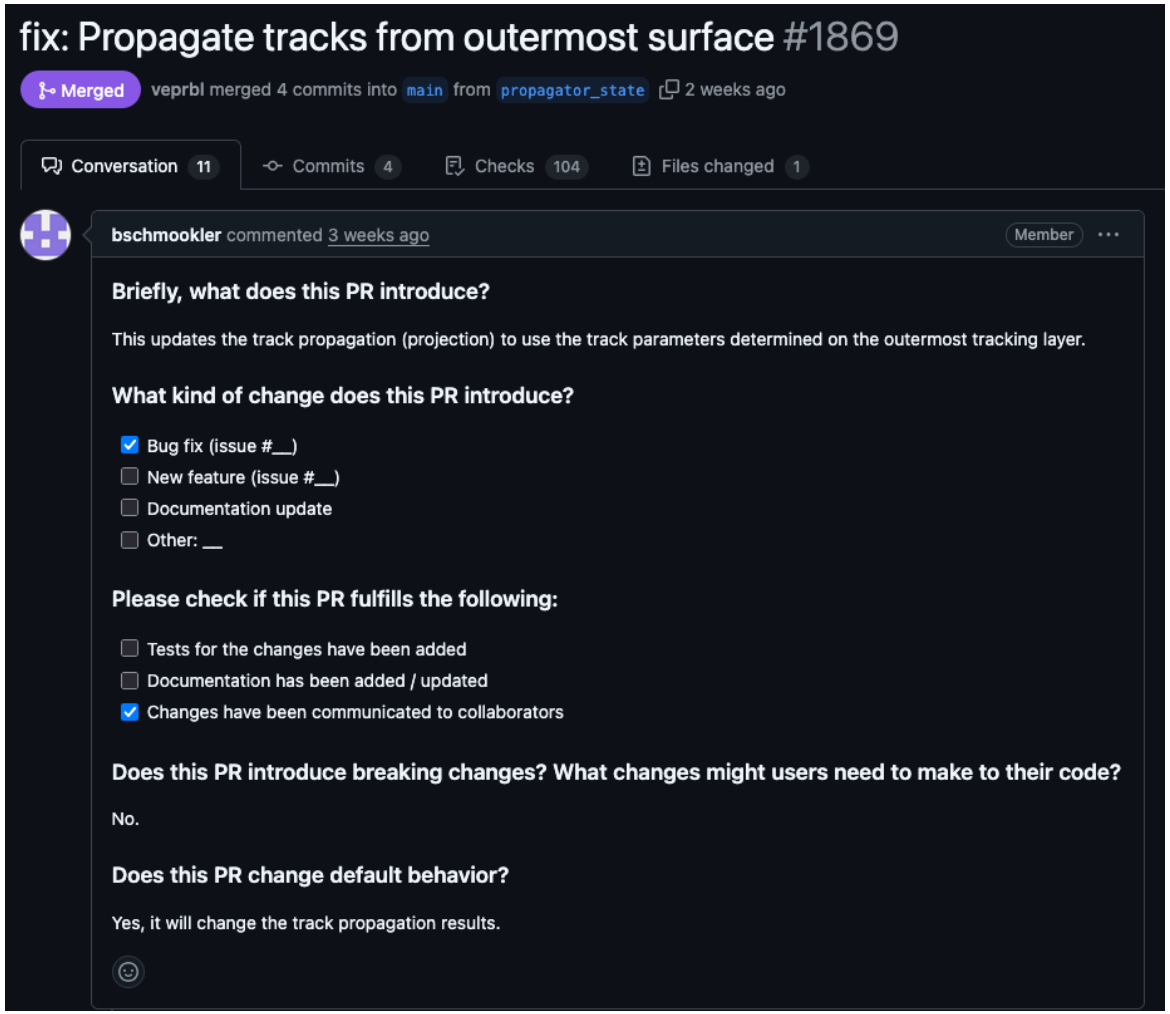
- $\pi^-$ single particle



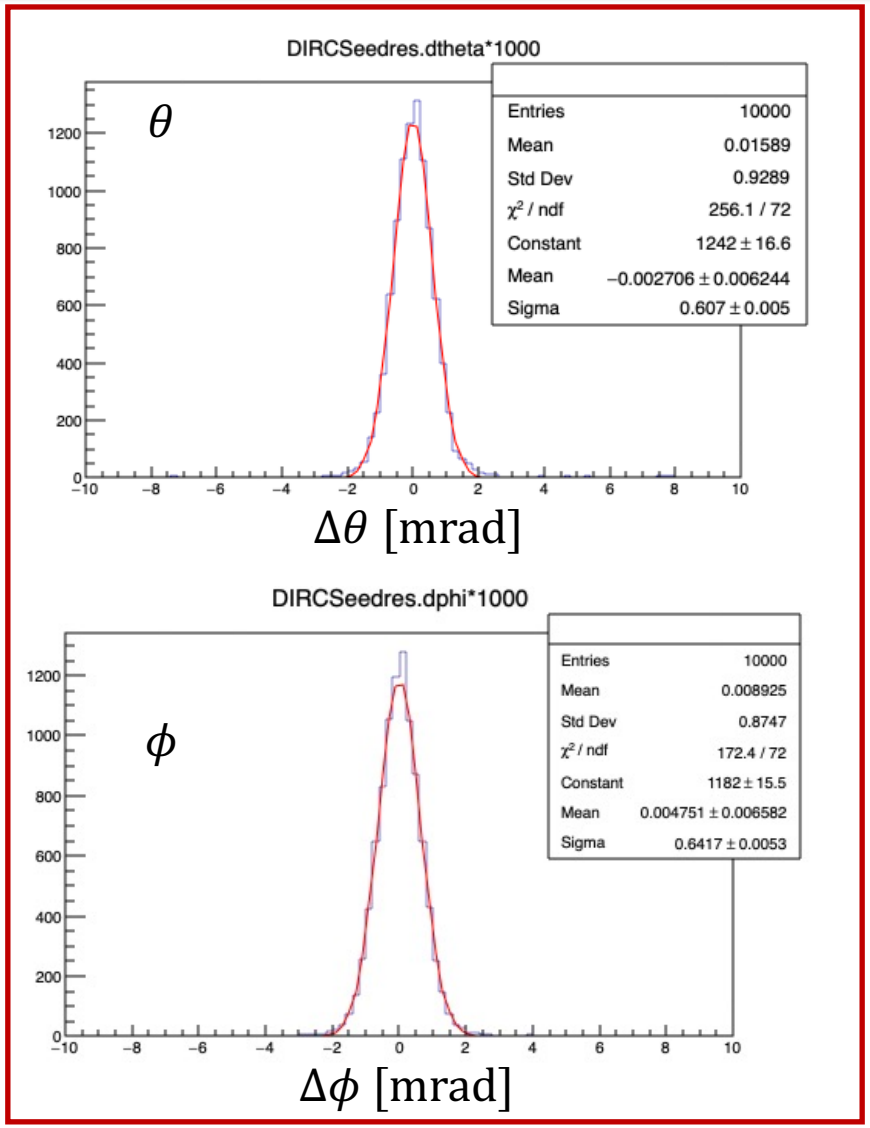
# Propagation Fix

- EICrecon PR #1869
  - Bug identified and fixed during ACTS4NP workshop
  - Fix has been merged into main software

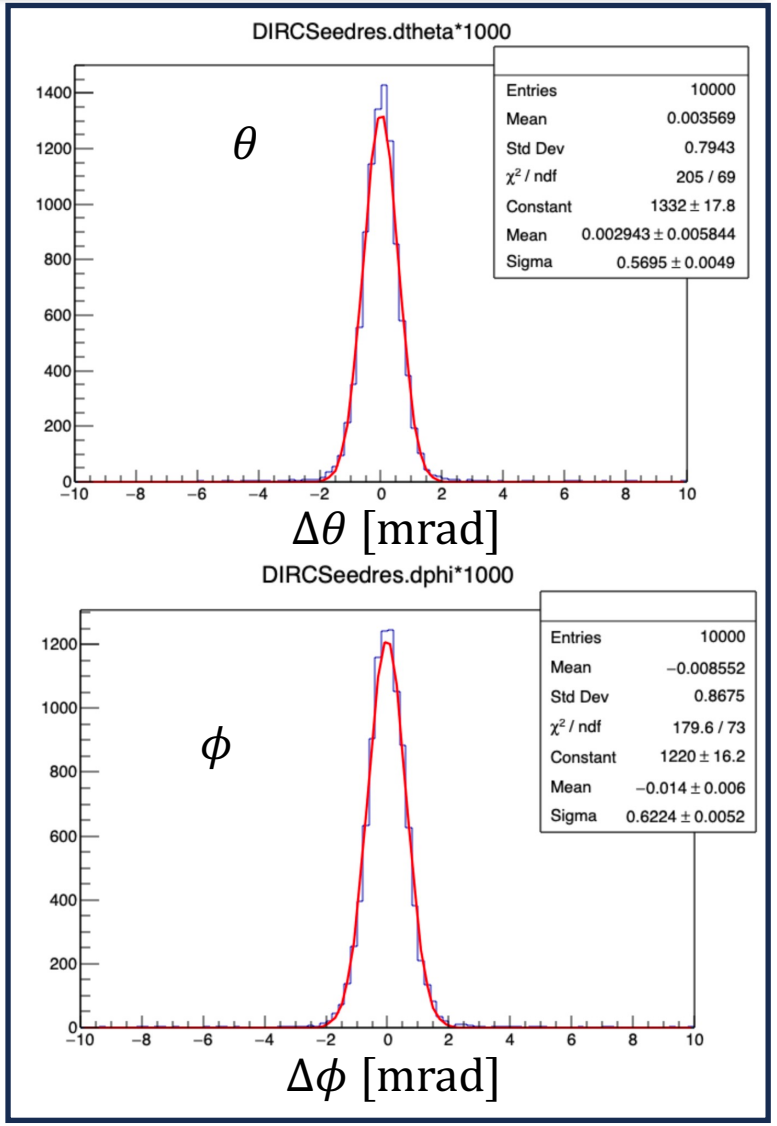


# Propagation Comparisons: Eta = -0.05, P = 6 GeV

- Improvement seen in $\theta$ and $\phi$ residuals after propagation fix



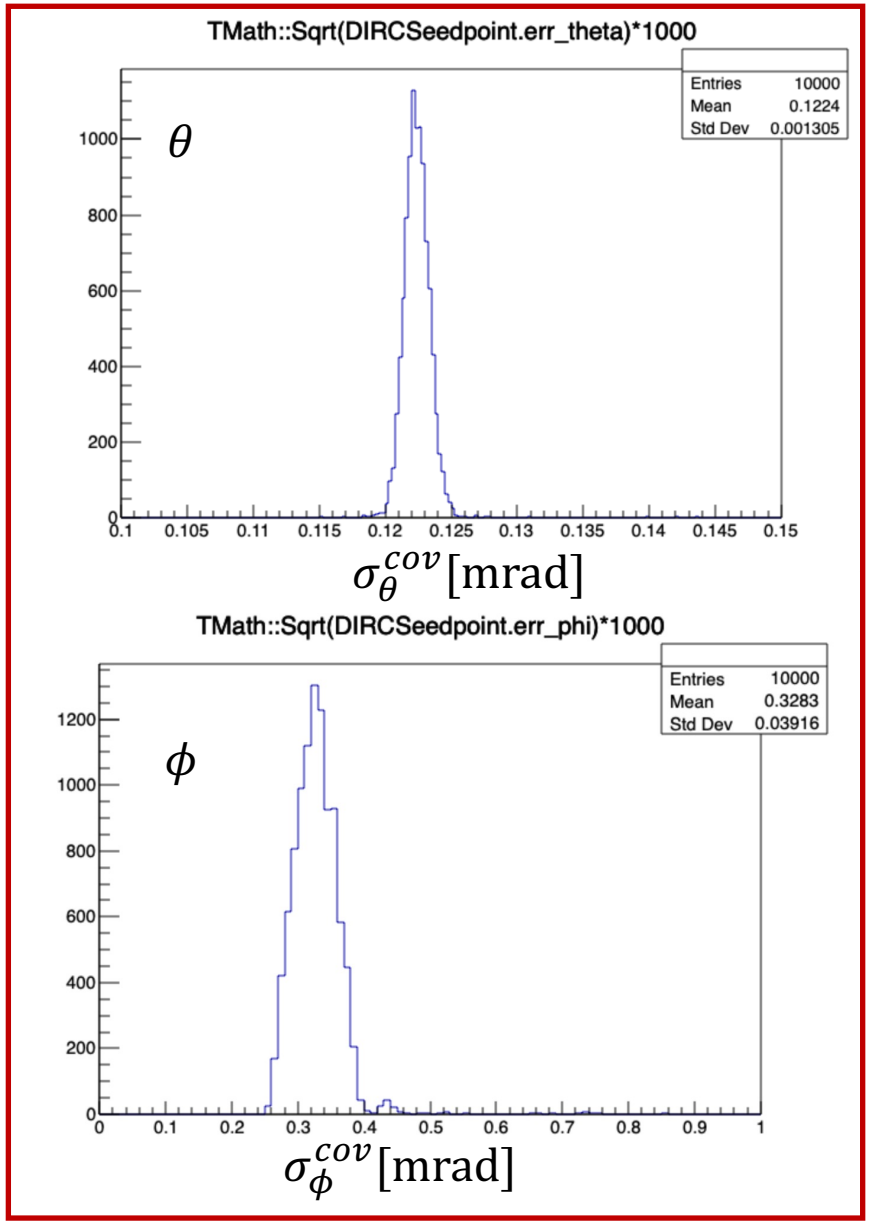

Before Fix



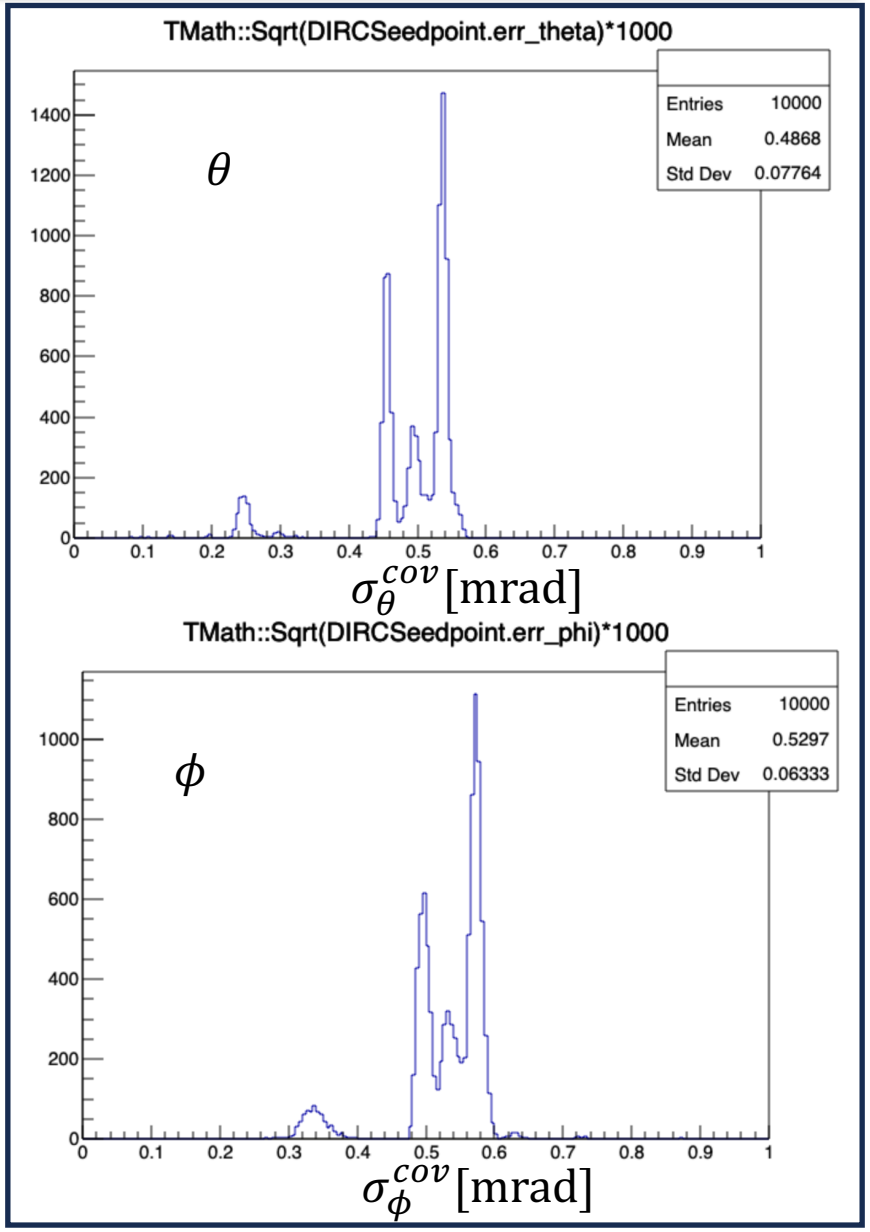

With fix

# Propagation Comparisons: Eta = -0.05, P = 6 GeV

- Mean errors from covariance matrix increase and are in better agreement with residual method results
- Some structure is now seen in the covariance error distributions



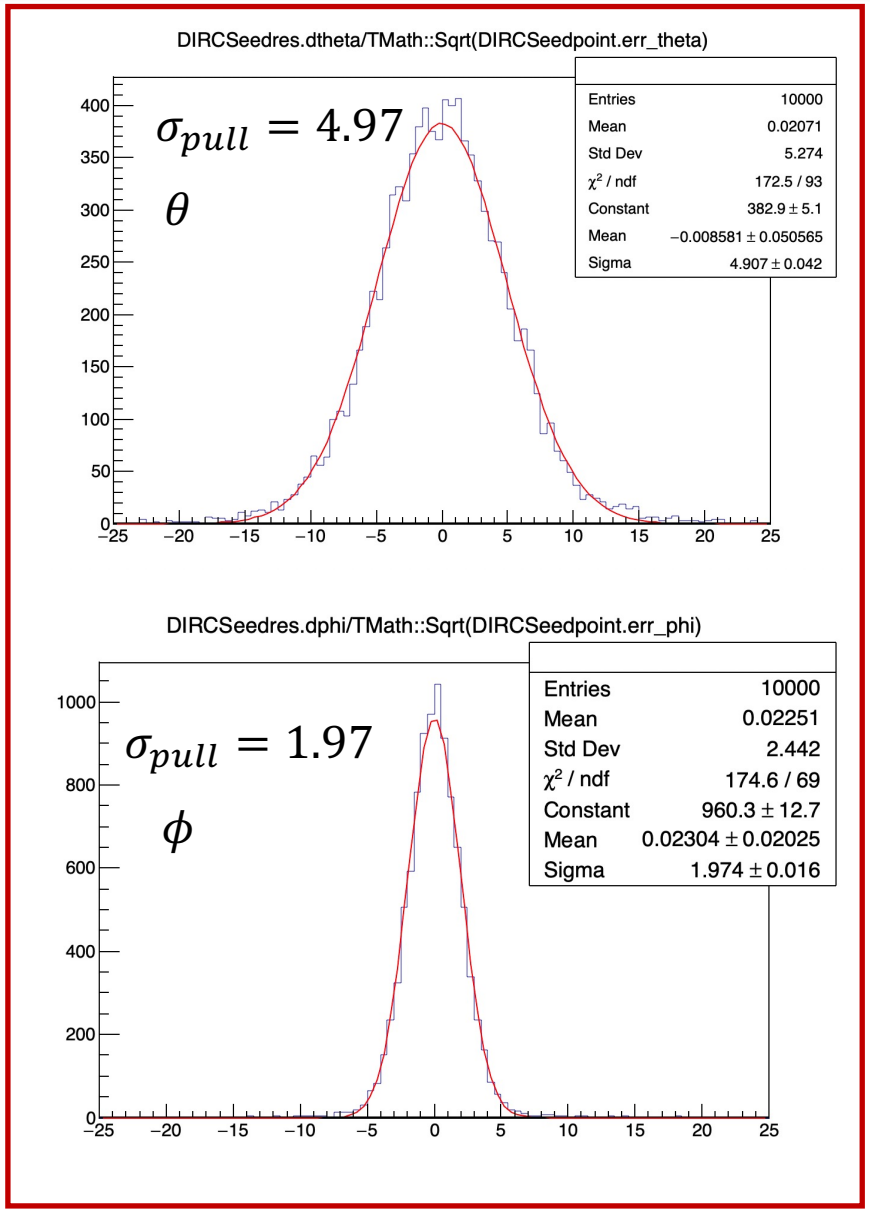

Bug



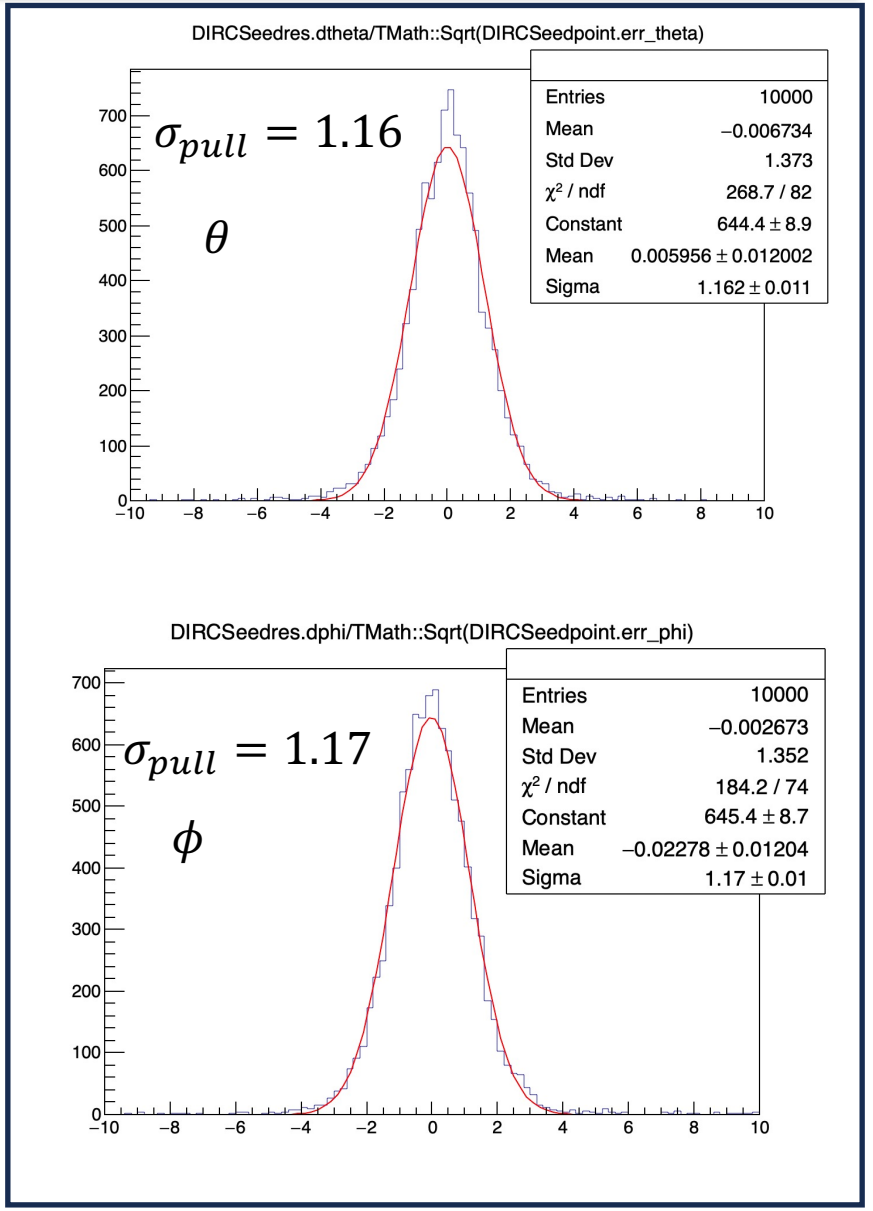

With fix

# Propagation Comparisons: Eta = -0.05, P = 6 GeV

- Pull distribution spread much closer to 1 after propagation fix → better consistency between residuals and covariant matrix errors



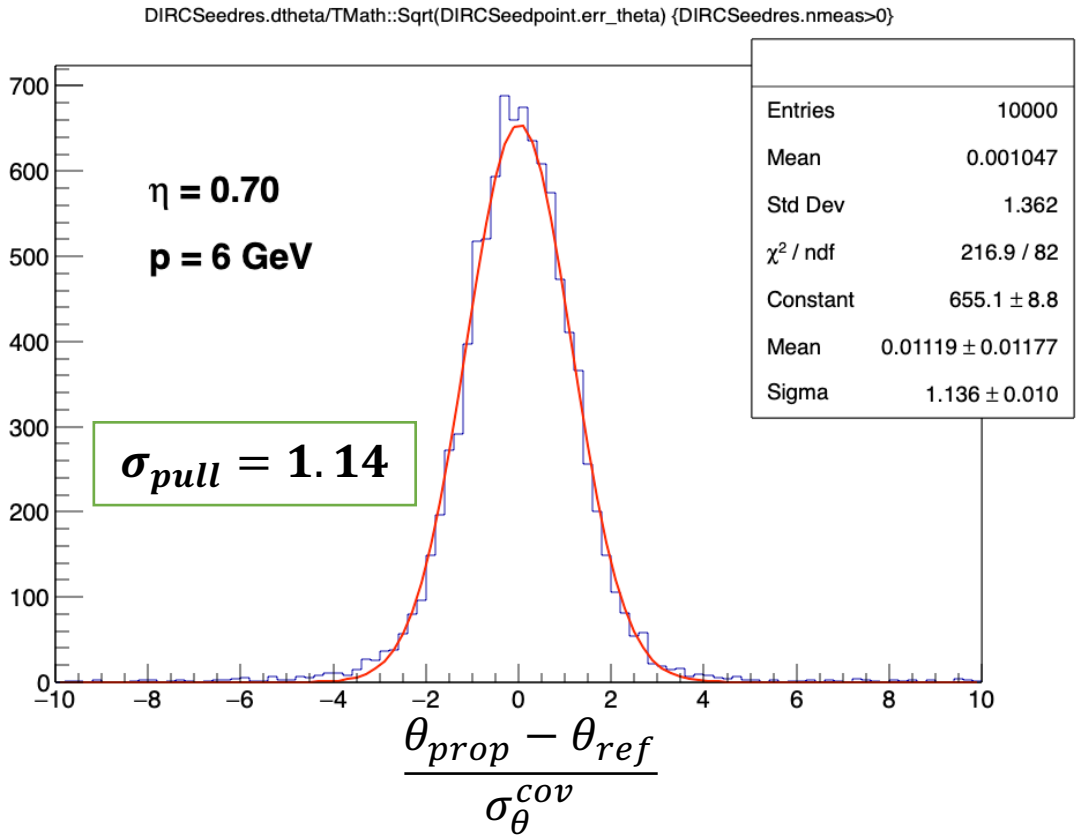

Bug

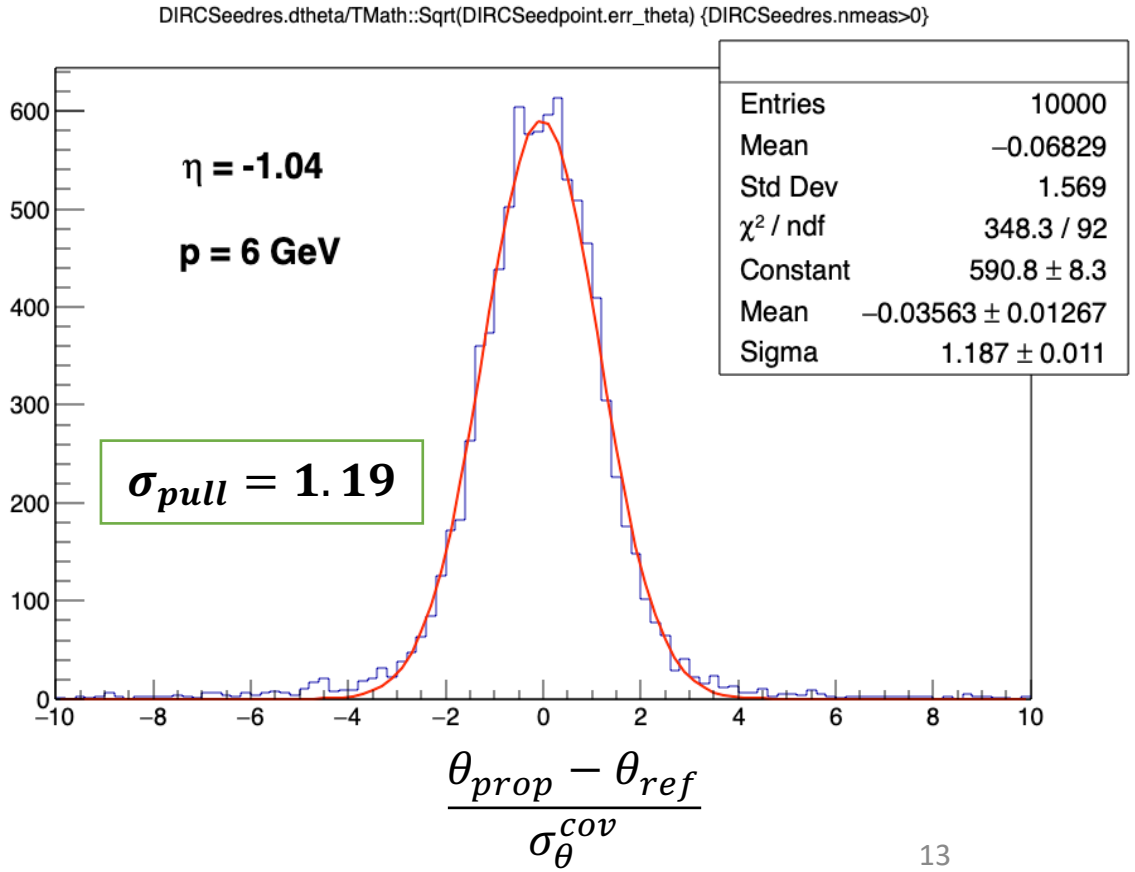



With fix

# Pull Distributions: Theta

- Residual method statistically consistent with covariance matrix
  - $pull = \frac{\theta_{prop} - \theta_{ref}}{\sigma_{\theta}^{cov}}$ , $\sigma_{pull} \sim 1$
  - $\sigma_{\theta,\phi}^{cov}$ not considered in this study



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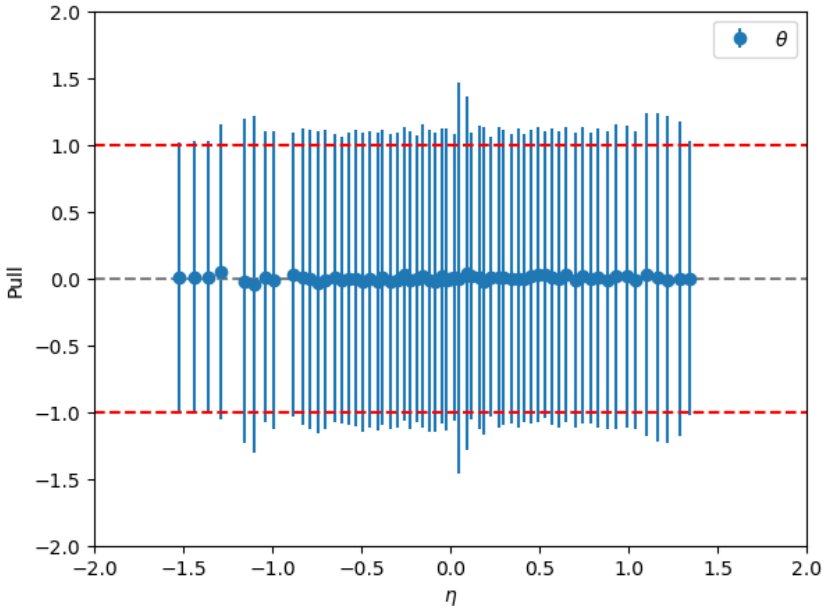
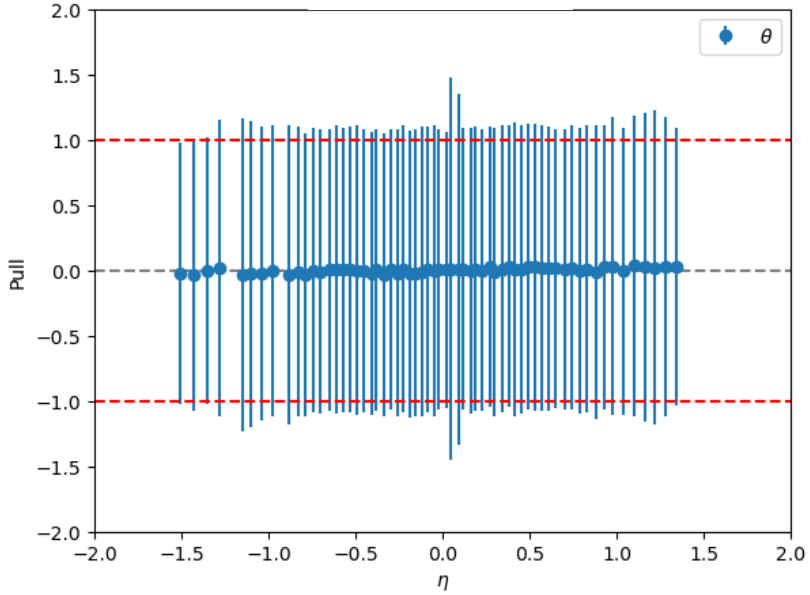
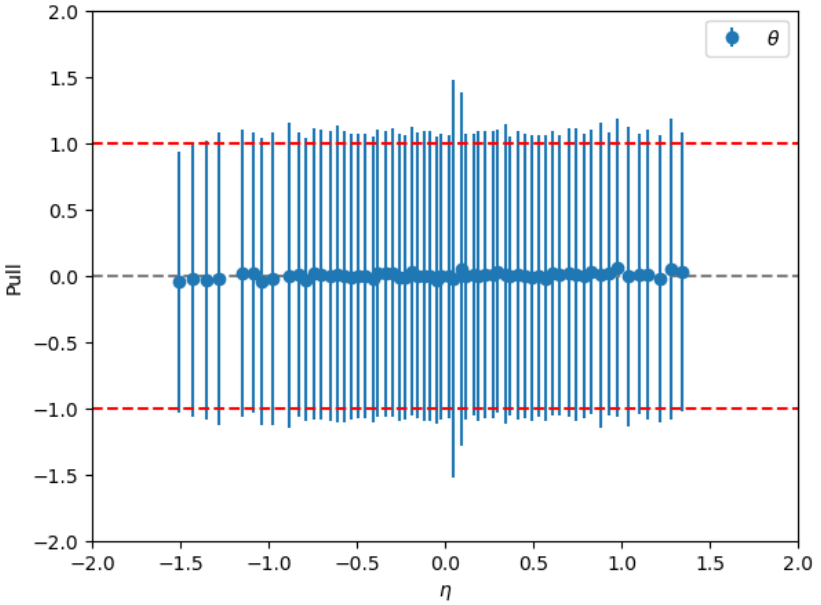
$p = 2\ GeV$




$p = 6\ GeV$

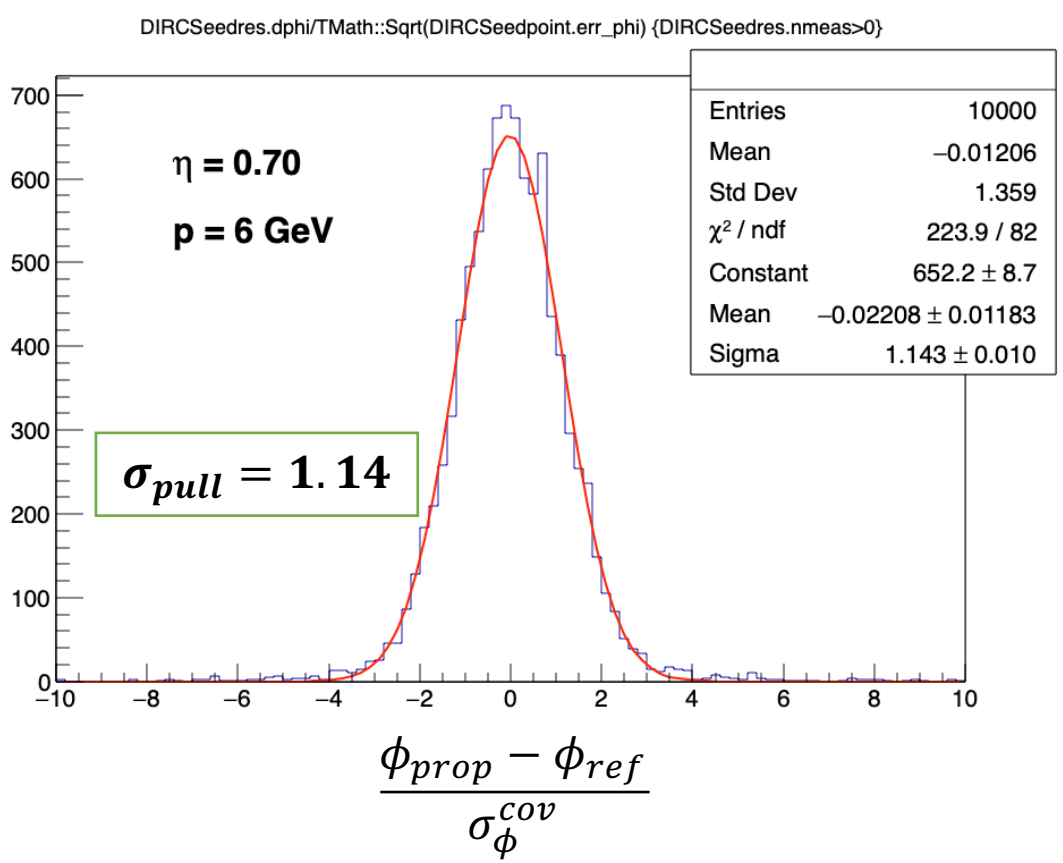


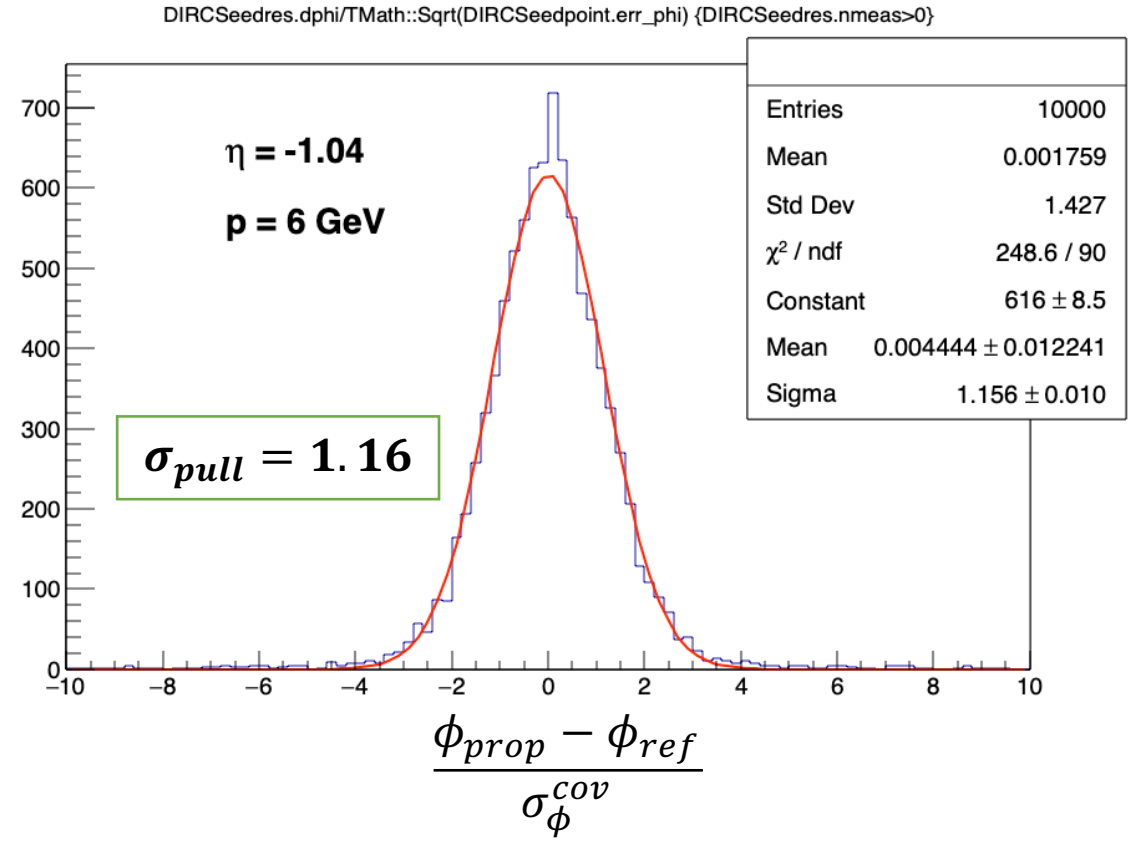

$p = 10\ GeV$



# Pull Distributions: Phi

- Residual method statistically consistent with covariance matrix
  - $pull \quad = \frac{\phi_{prop} - \phi_{ref}}{\sigma_{\phi}^{cov}}, \sigma_{pull} \sim 1$
  - $\sigma_{\theta,\phi}^{cov}$ not considered in this study



# Pull Distributions: Phi

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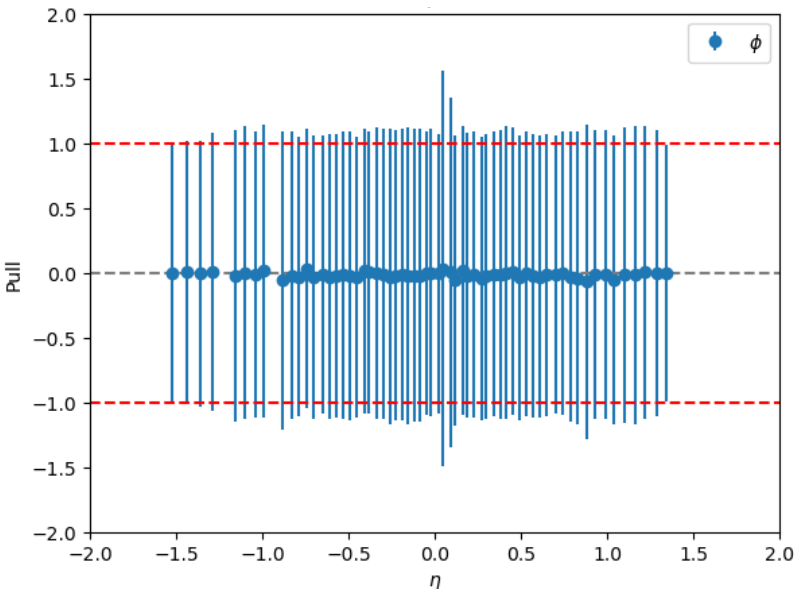
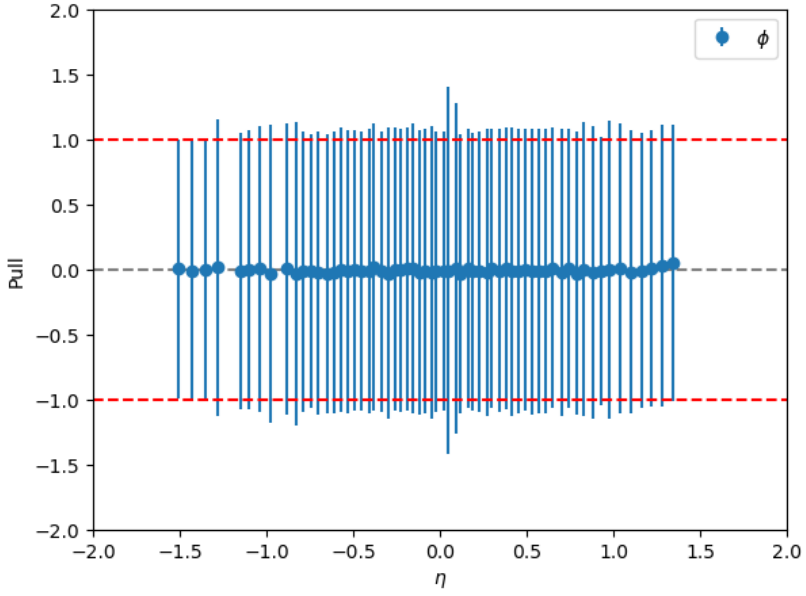
  - $pull \quad = \frac{\phi_{prop} - \phi_{ref}}{\sigma_{\phi}^{cov}}, \sigma_{pull} \sim 1$
  - $\sigma_{\theta,\phi}^{cov}$ not considered in this study

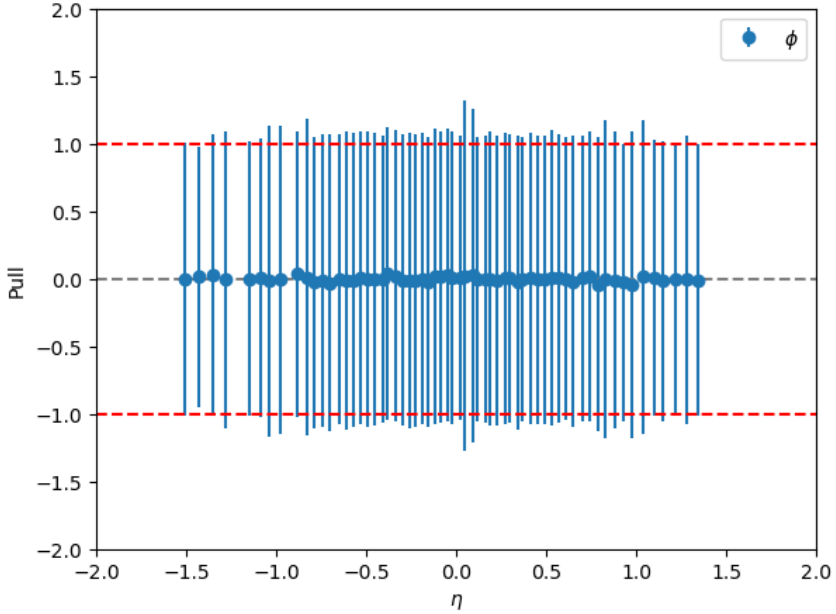
$p = 2\ GeV$




$p = 6\ GeV$



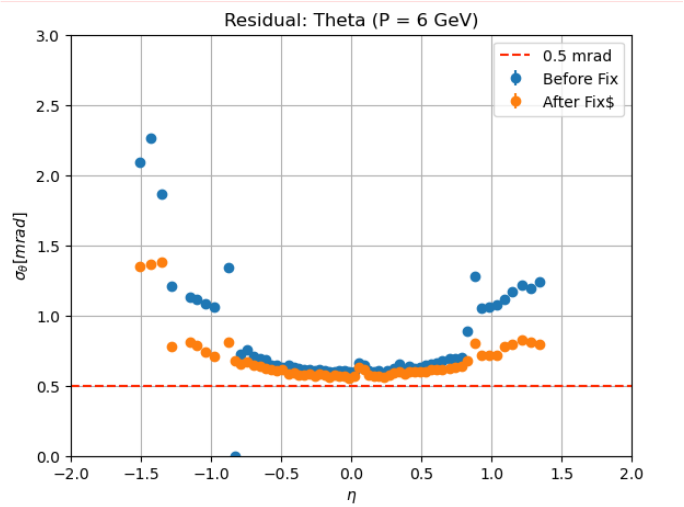

$p = 10\ GeV$

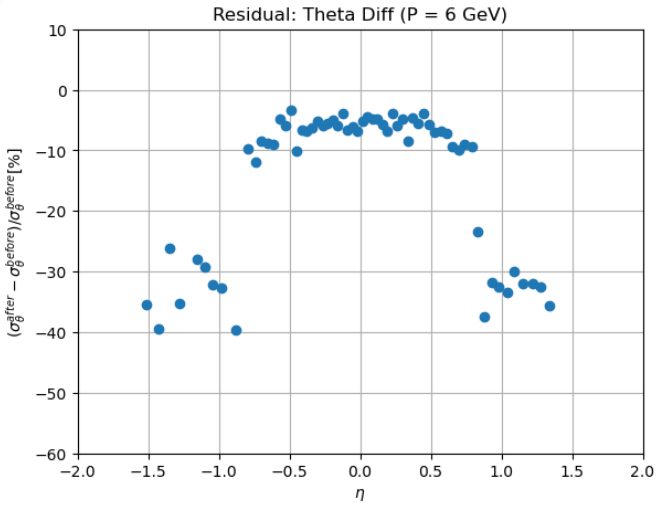


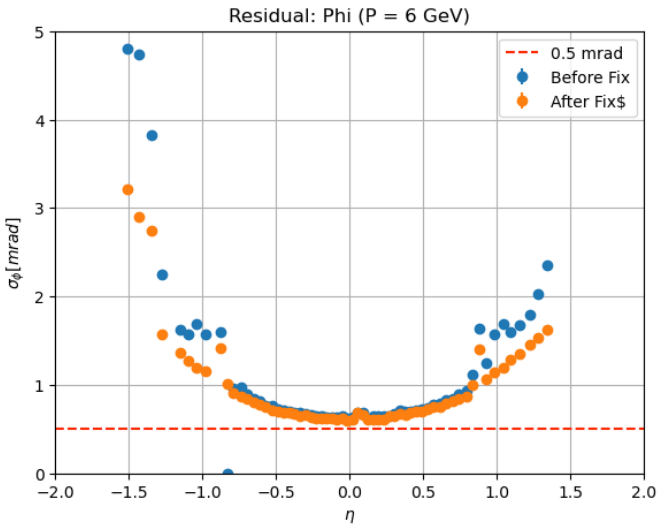
# Before and After Residual Comparisons

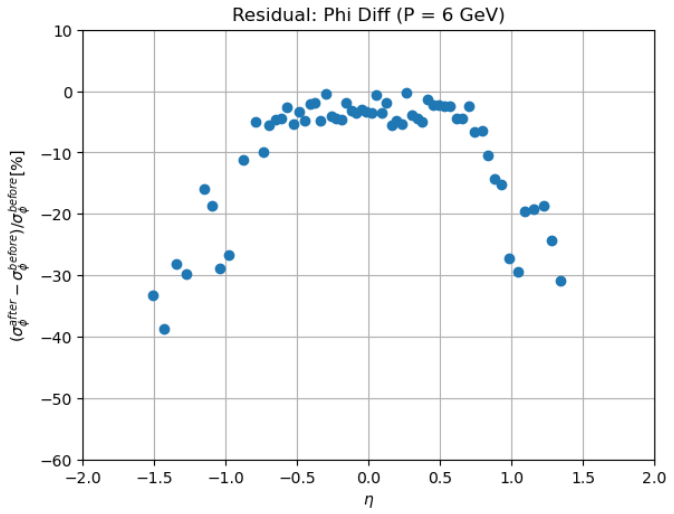
- Overall resolutions improve with corrected propagation algo.
- Relative difference, $\frac{100 \cdot (\sigma_{after} - \sigma_{before})}{\sigma_{before}}$

  shows small improvement around central $\eta$ and more significant improvement at larger $|\eta|$



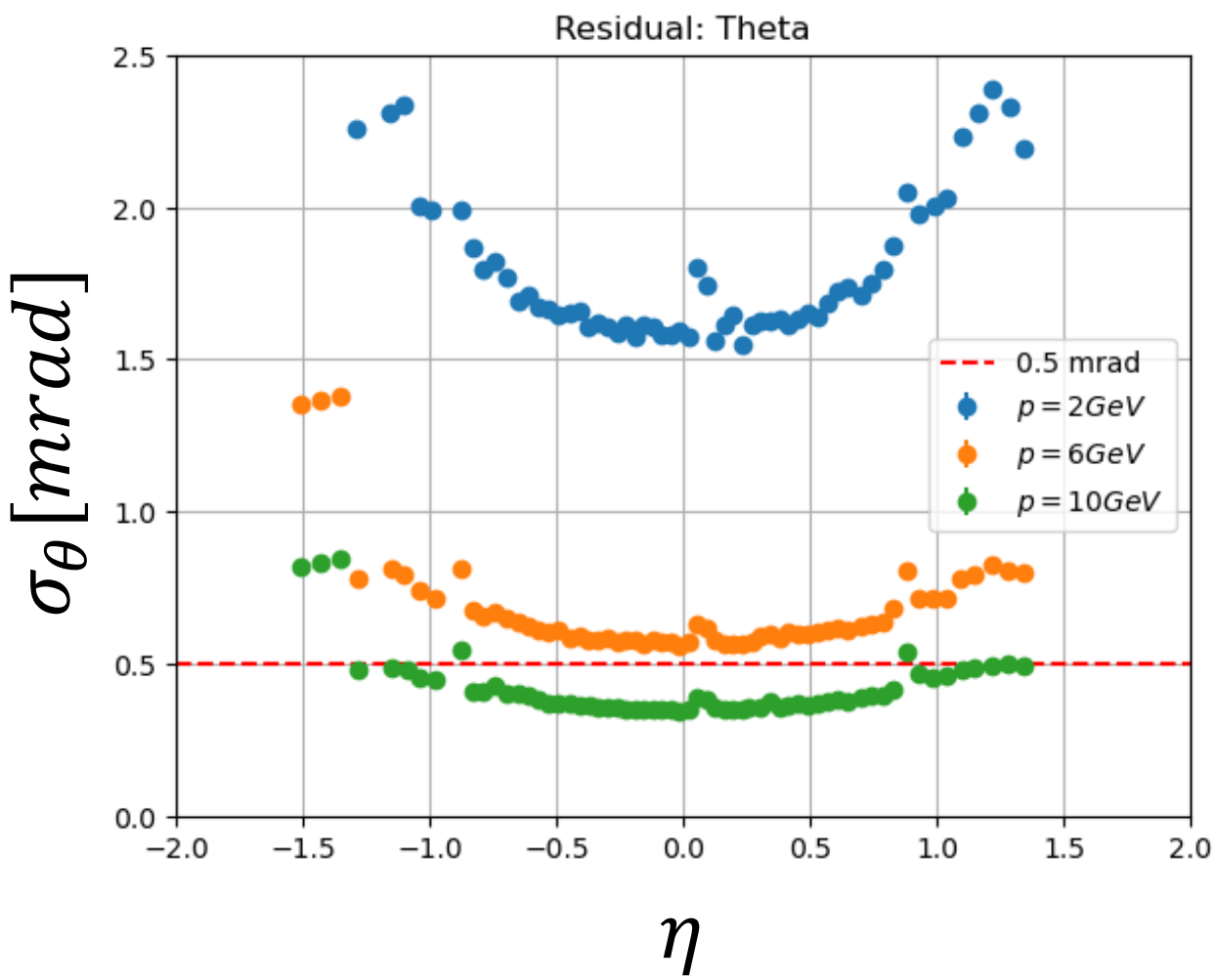



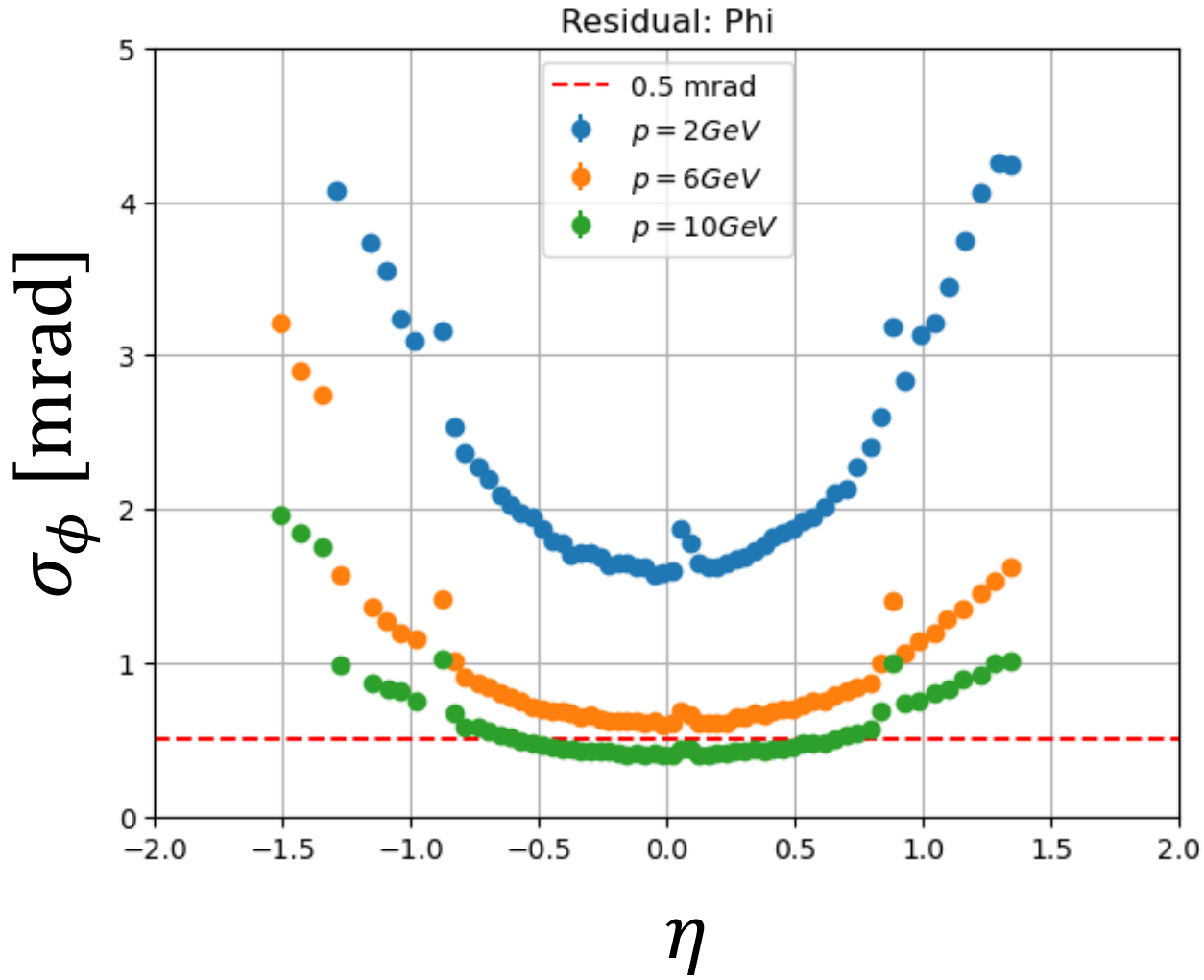



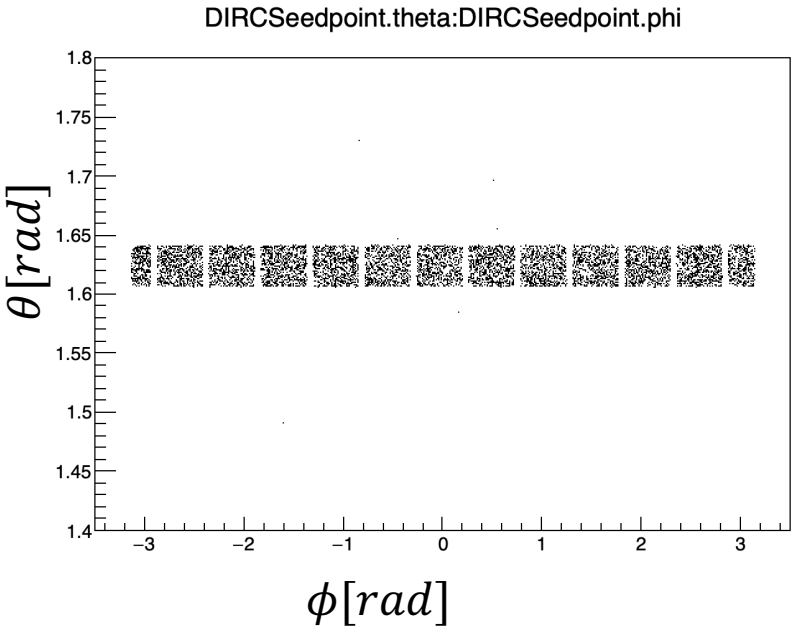
# Resolutions: Residual Method

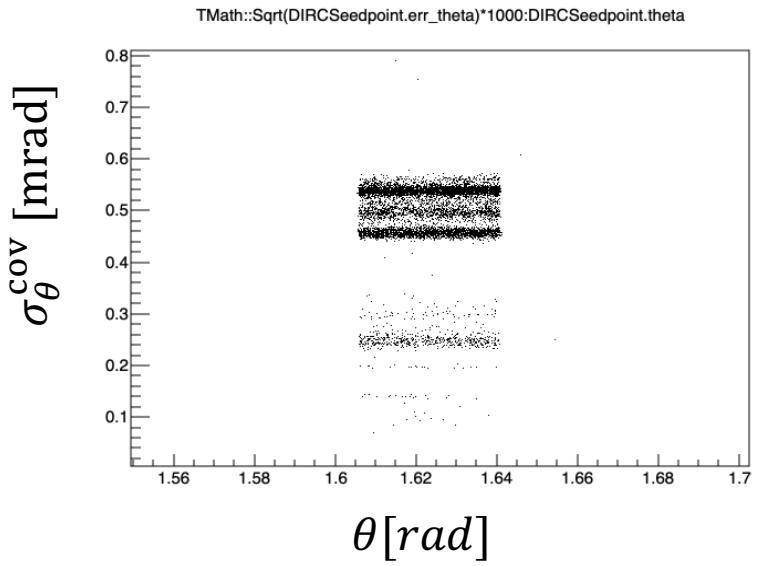
- After fix (3 momenta settings)

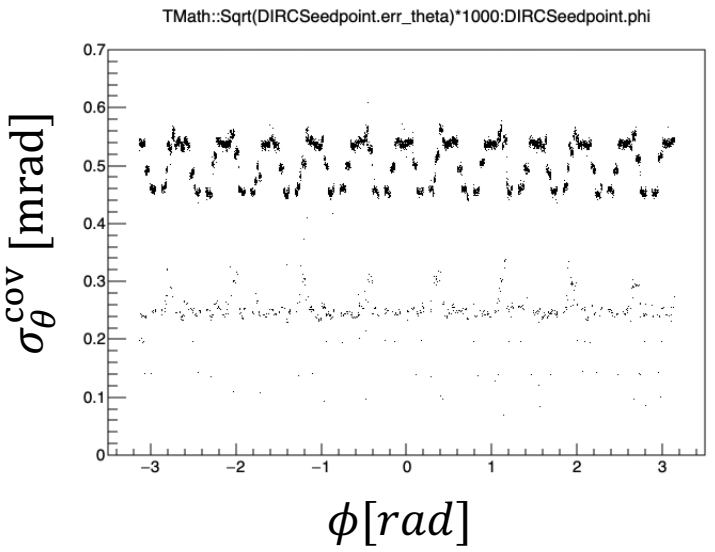


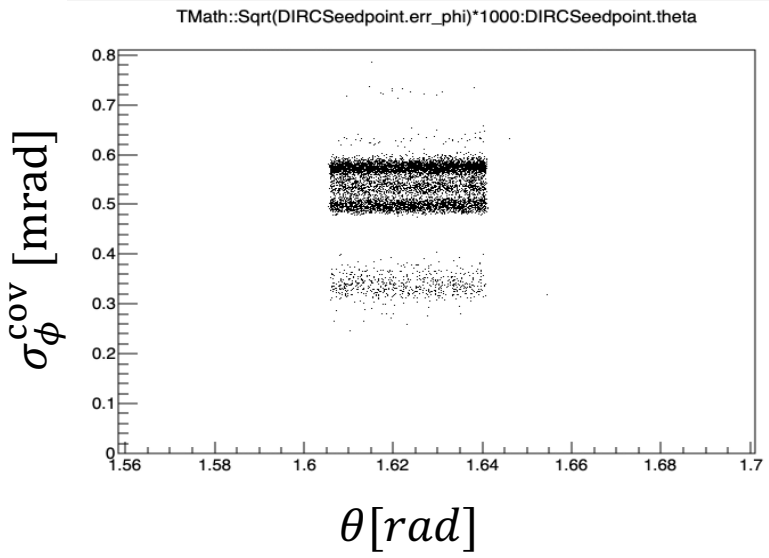



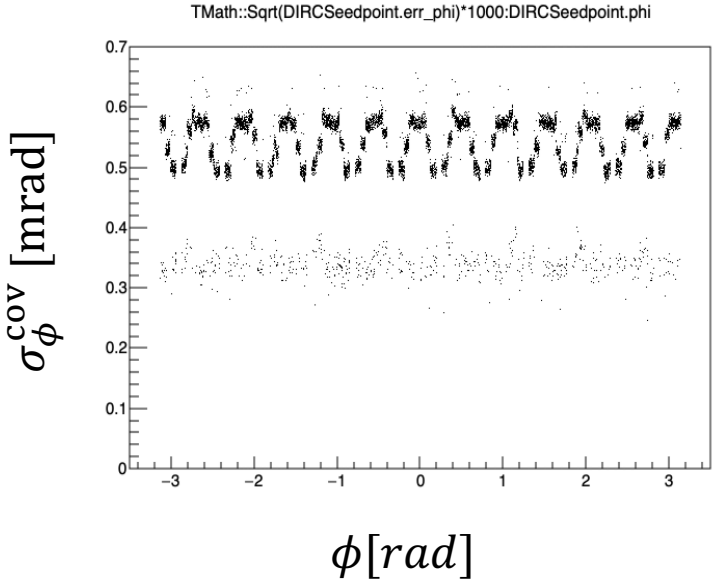
# Covariance Matrix Error Distributions: $\eta = -0.05, p = 6\ GeV$



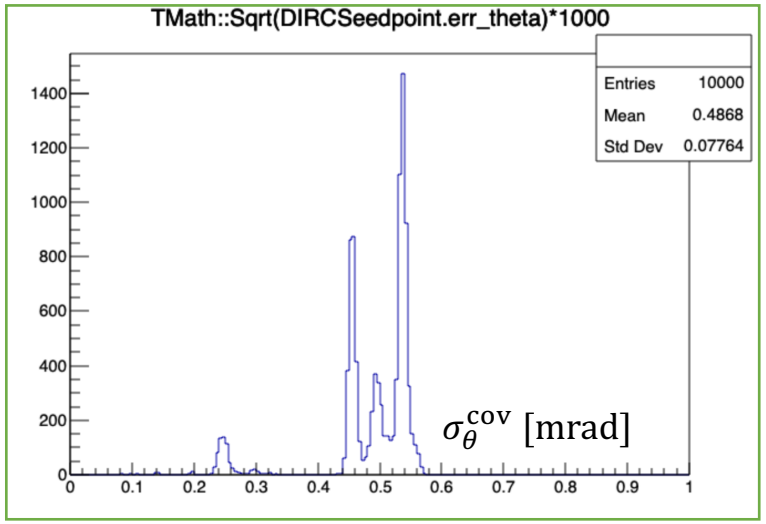



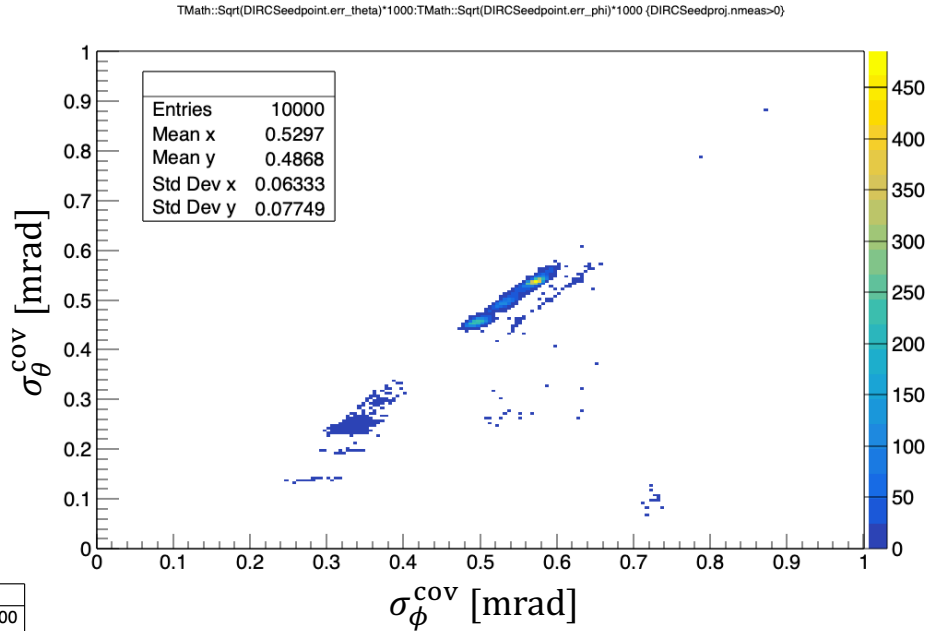



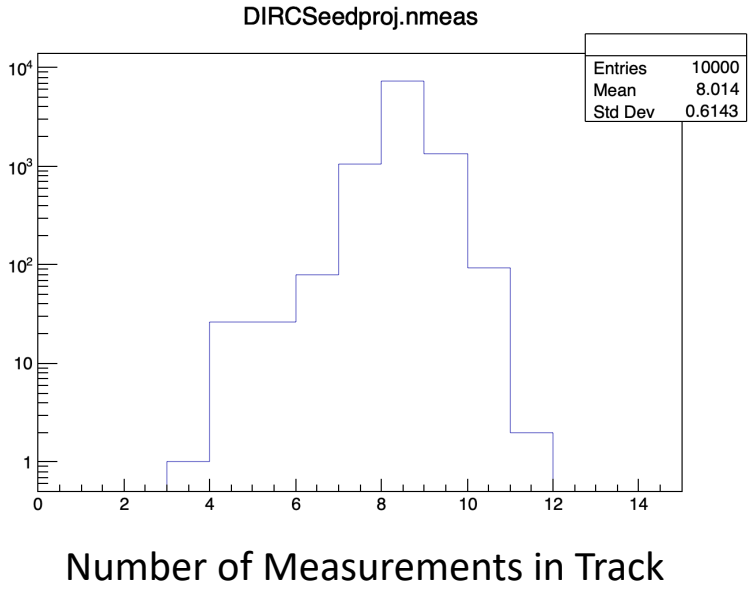

- Segmentations in acceptance due to DIRC/BOT segmentations
- Three peak structure seen in cov. Error distributions
- Oscillations of resolution seen in $\phi$ due to DIRC/BOT segmentation

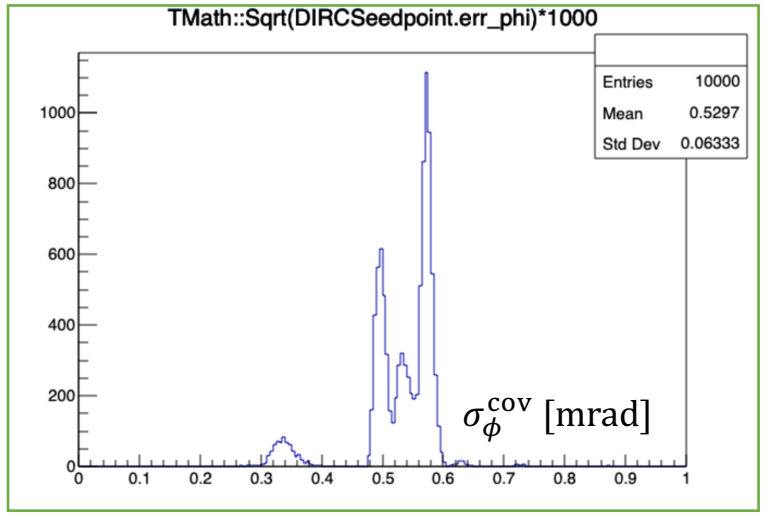
# Covariance Matrix Error Distributions: $\eta = -0.05, p = 6\ GeV$

- Quick look at covariance error dependency on the number of measurements in the track



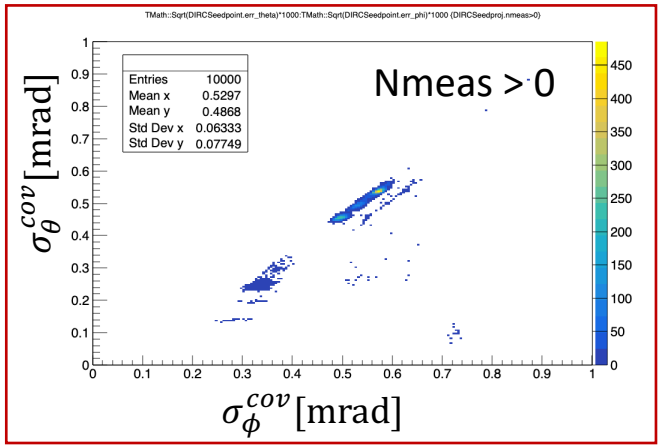



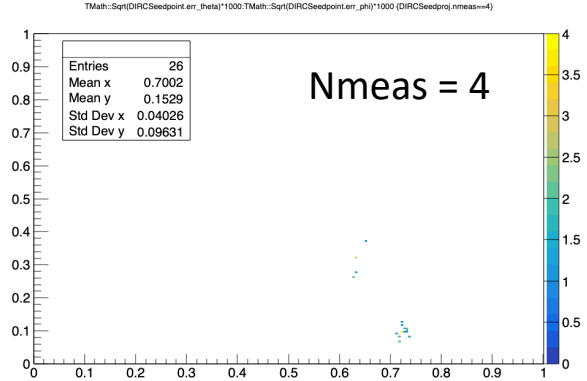



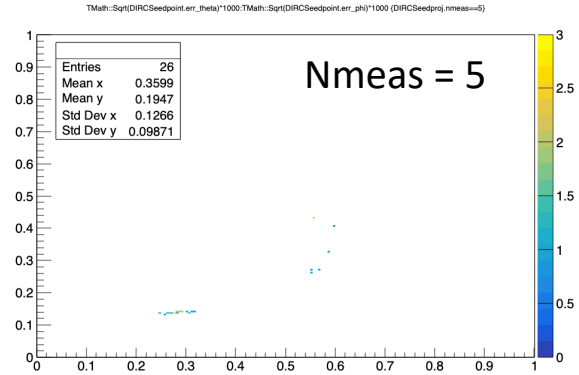



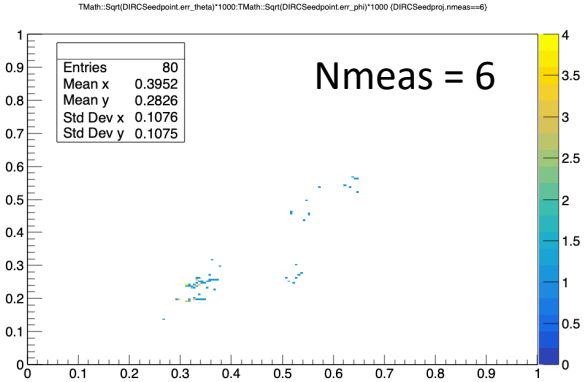
# Covariance Matrix Error Distributions: $\eta = -0.05, p = 6\ GeV$

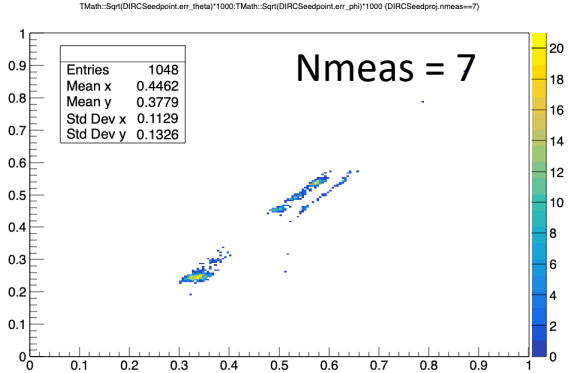
- Quick look at covariance error dependency on the number of measurements in the track
- Clear dependance on number of measurements
- Similar behavior seen for other $\eta$ and momentum

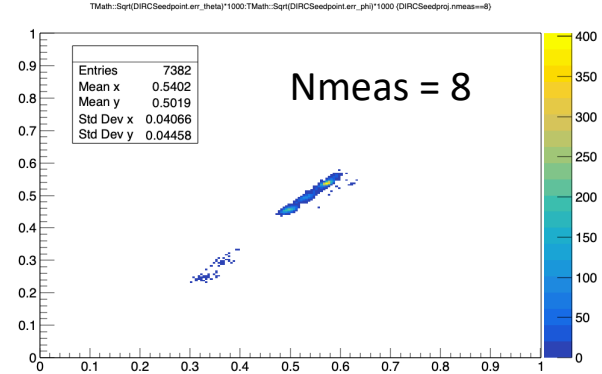


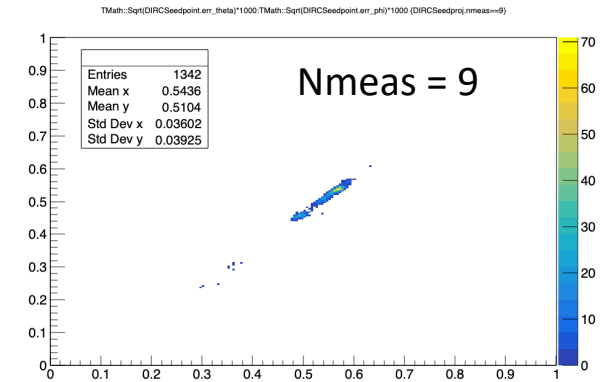



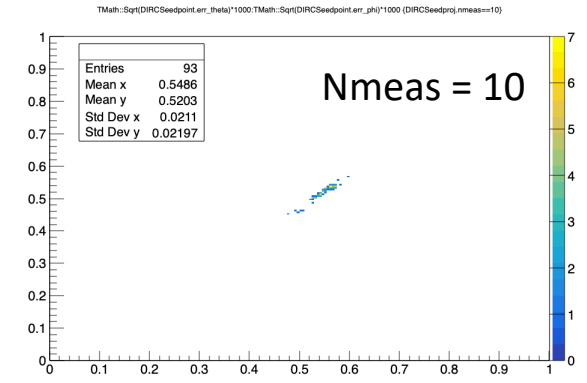



# Angular Tracking Divergence

- Follow up on some comments received in various meetings/discussions
  - Angular tracking divergence between true and reconstructed momentum vectors
    - Access via dot product between momentum vectors

- **Momentum Vector** (at DIRC surface)

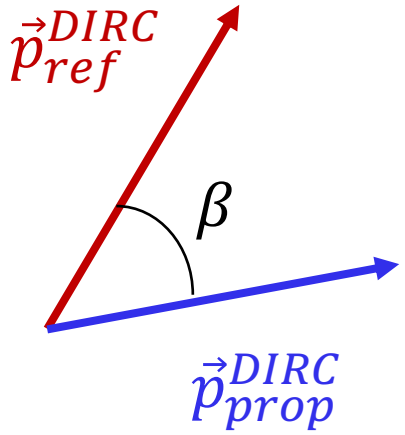
$$\vec{p}^{DIRC}_{ref,prop} = (p_x^{DIRC}, p_y^{DIRC}, p_z^{DIRC})$$

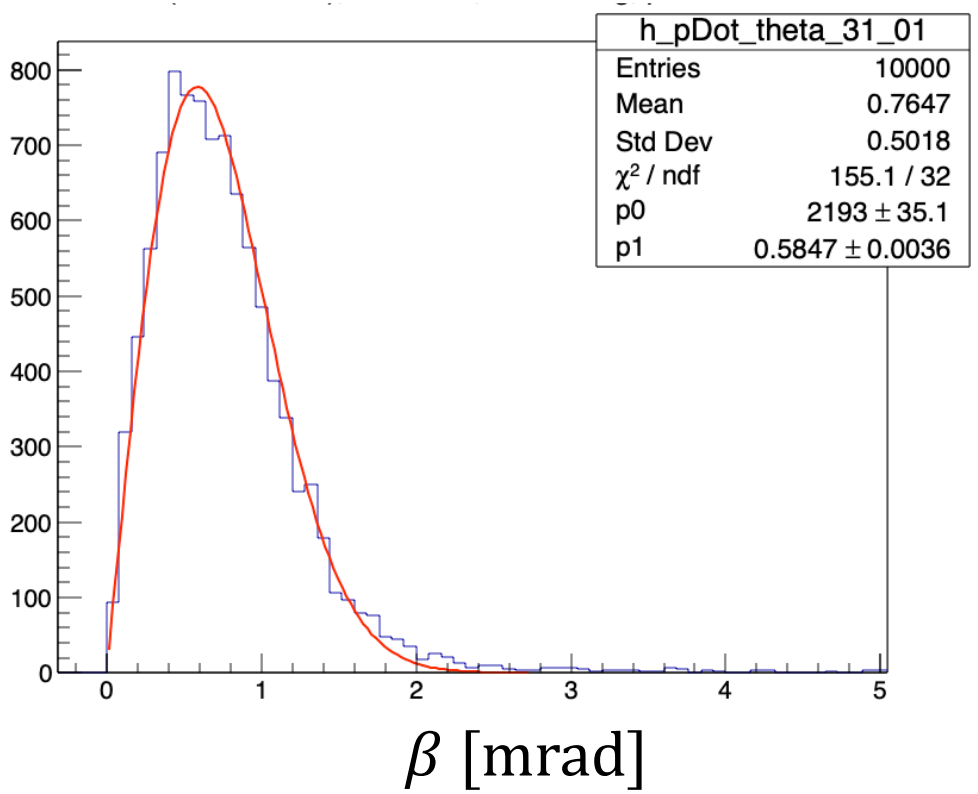
- **Momentum Vector** (at DIRC surface)

$$\beta = ACos\left(\frac{\left(\vec{p}^{DIRC}_{prop} \cdot \vec{p}^{DIRC}_{ref}\right)}{\left|\vec{p}^{DIRC}_{prop}\right|\left|\vec{p}^{DIRC}_{ref}\right|}\right)$$

- **Fit Function:**

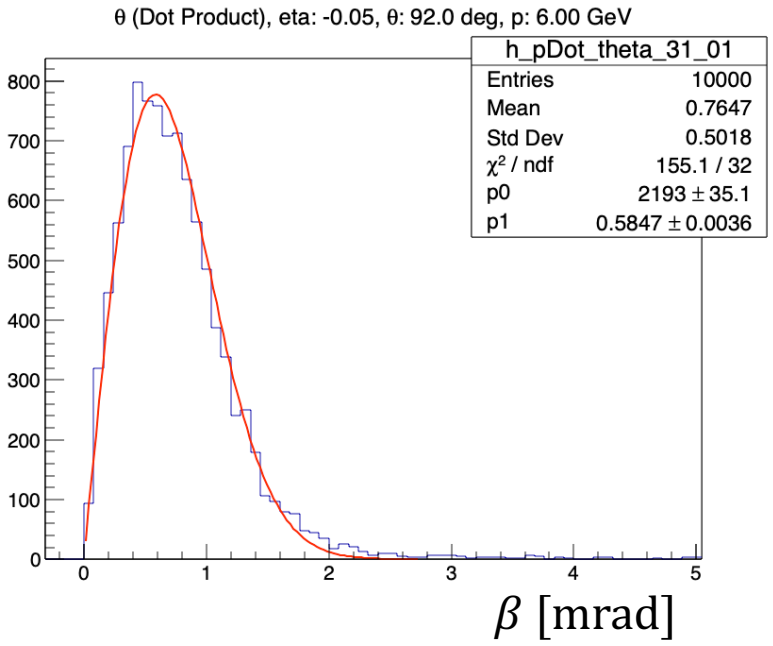
$$f(\beta) = A\beta \exp^{-\left(\frac{\beta^2}{2\sigma_\beta^2}\right)}$$

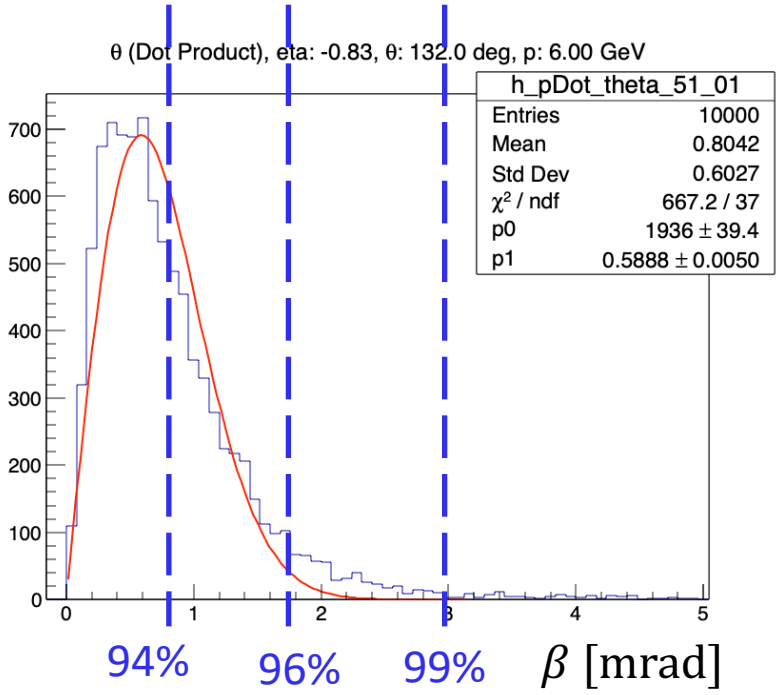


# Resolution via Momentum Dot Product

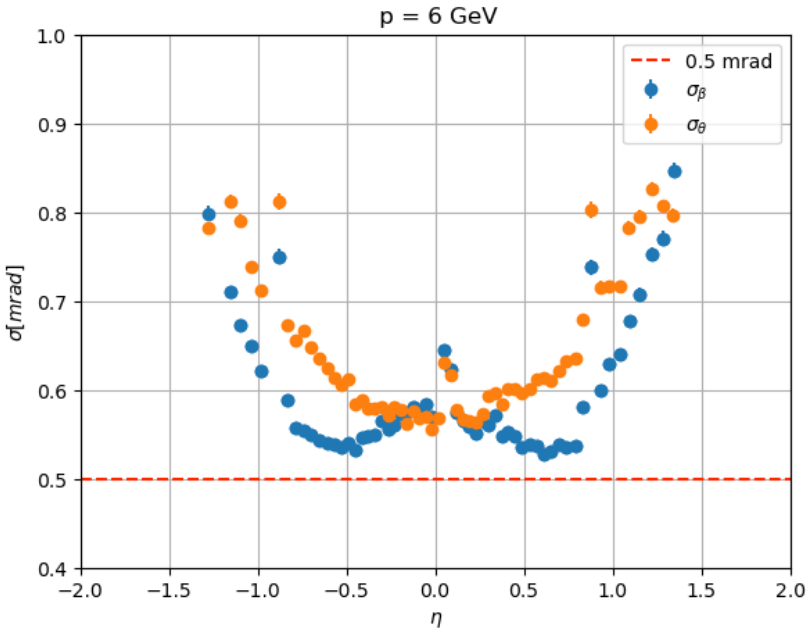
- Near $\eta \approx 0$, fits describe distribution pretty well
- Fit description of distribution worsens with increasing $|\eta|$
- Alternative: Truncate histogram based on yield and use histogram Standard Deviation value as resolution



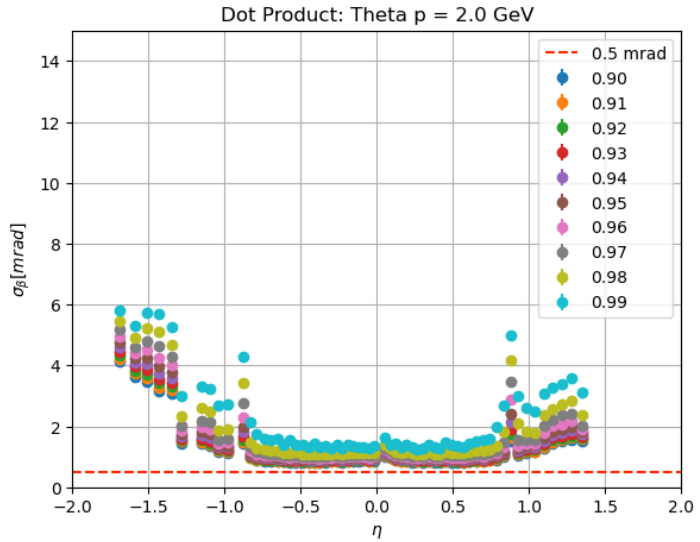



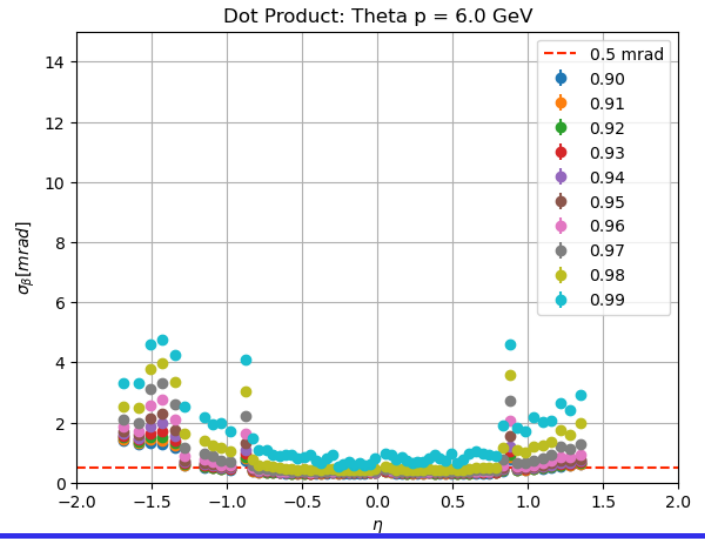

$\sigma_\theta$ (Residual Method)

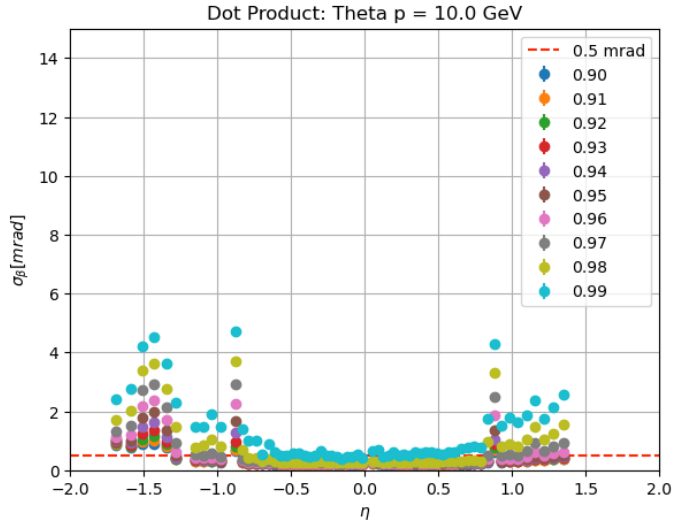
$\sigma_\beta$ (Dot Product Method)

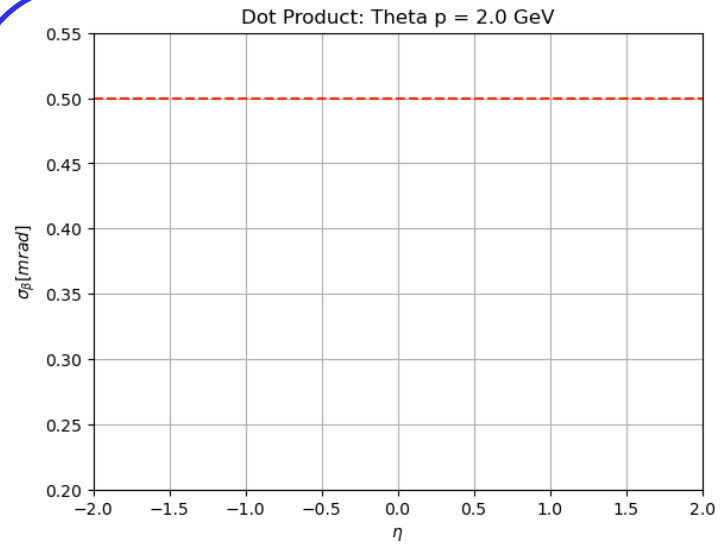


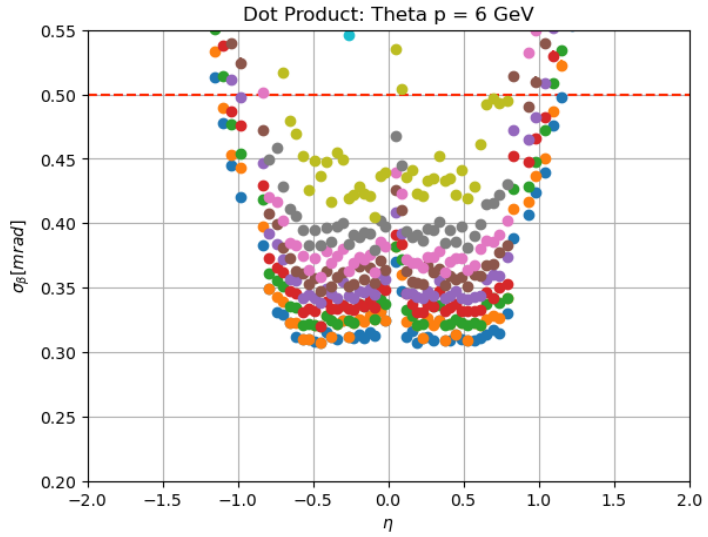
# Resolution via Momentum Dot Product: Truncation

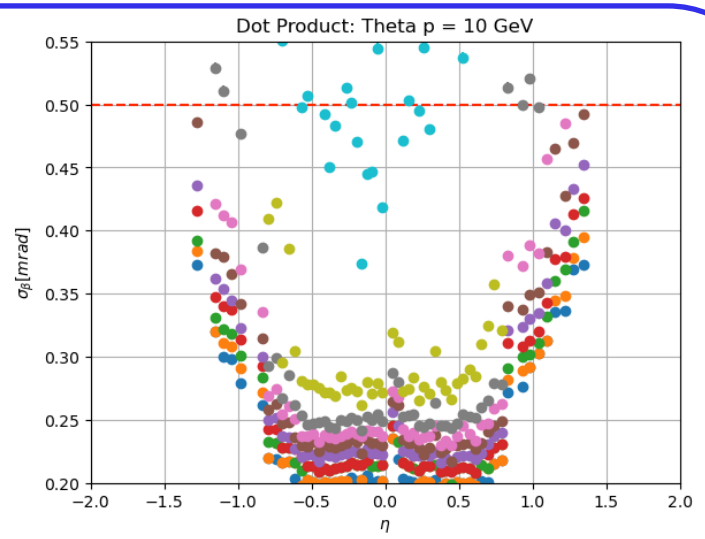


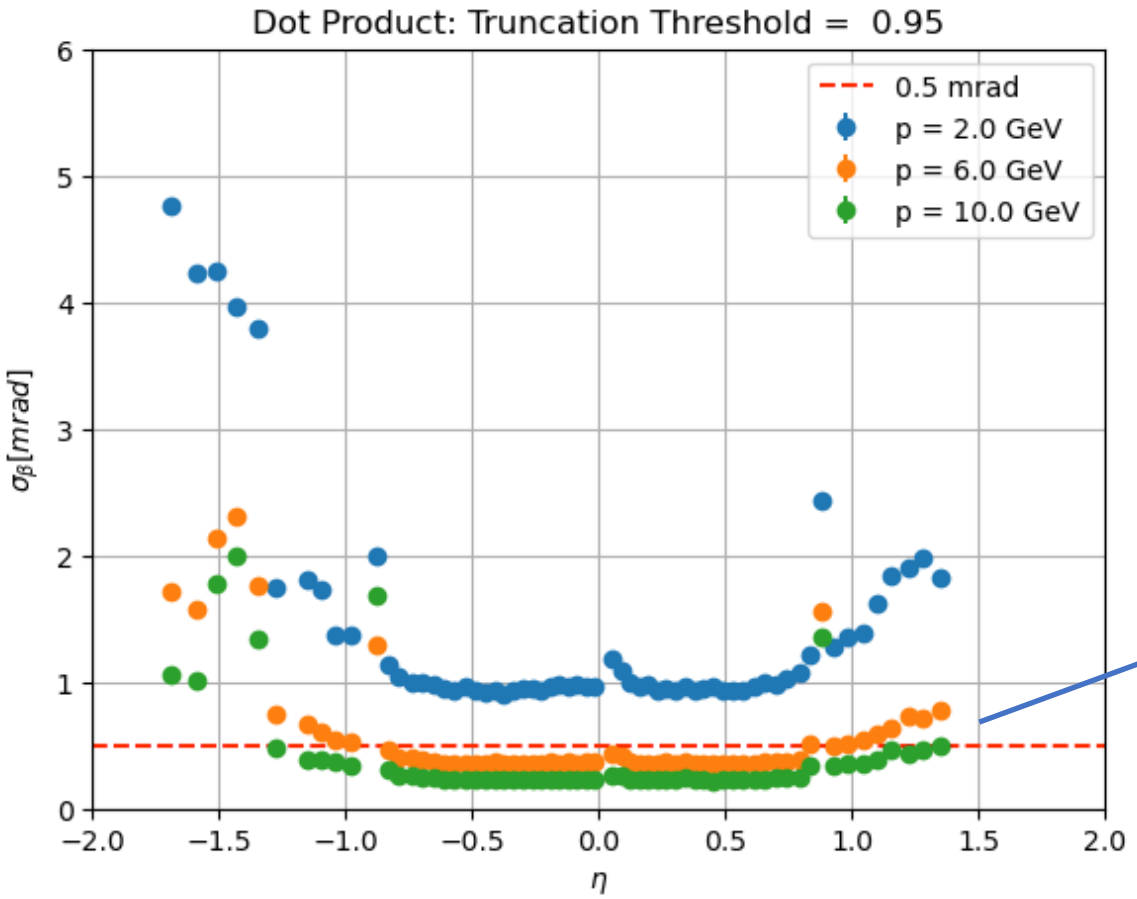



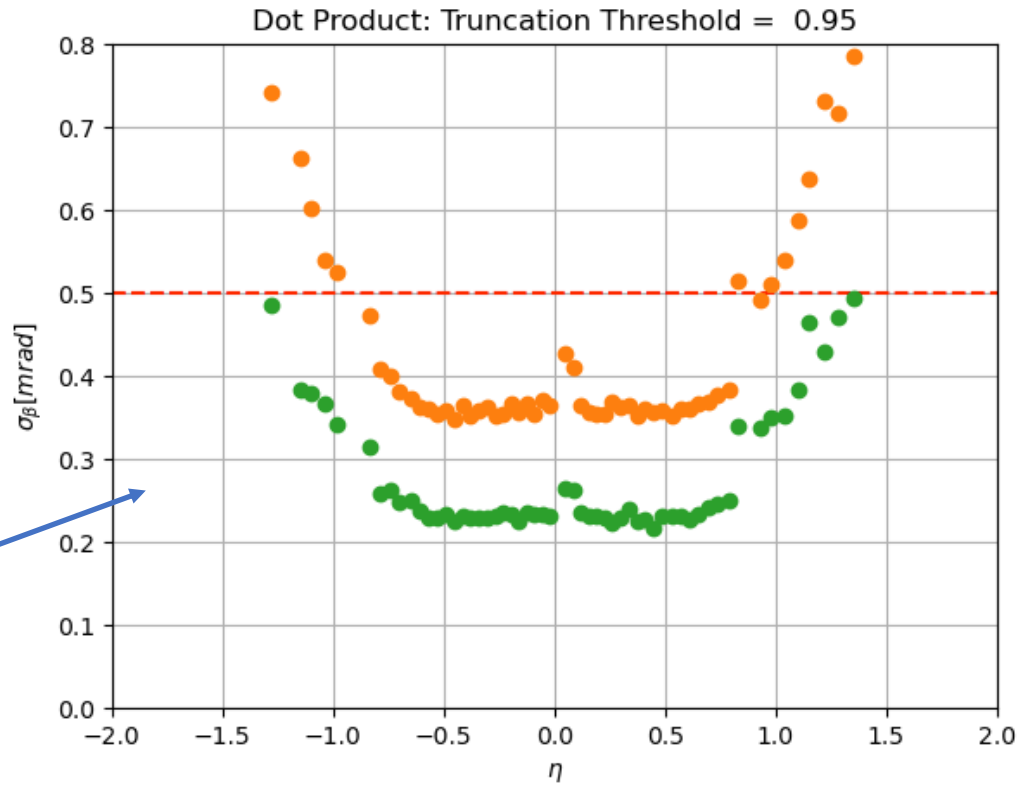




Zoomed in vertical scale

# Resolution via Momentum Dot Product: Truncation

- Results for truncation threshold at 95% of histogram yield



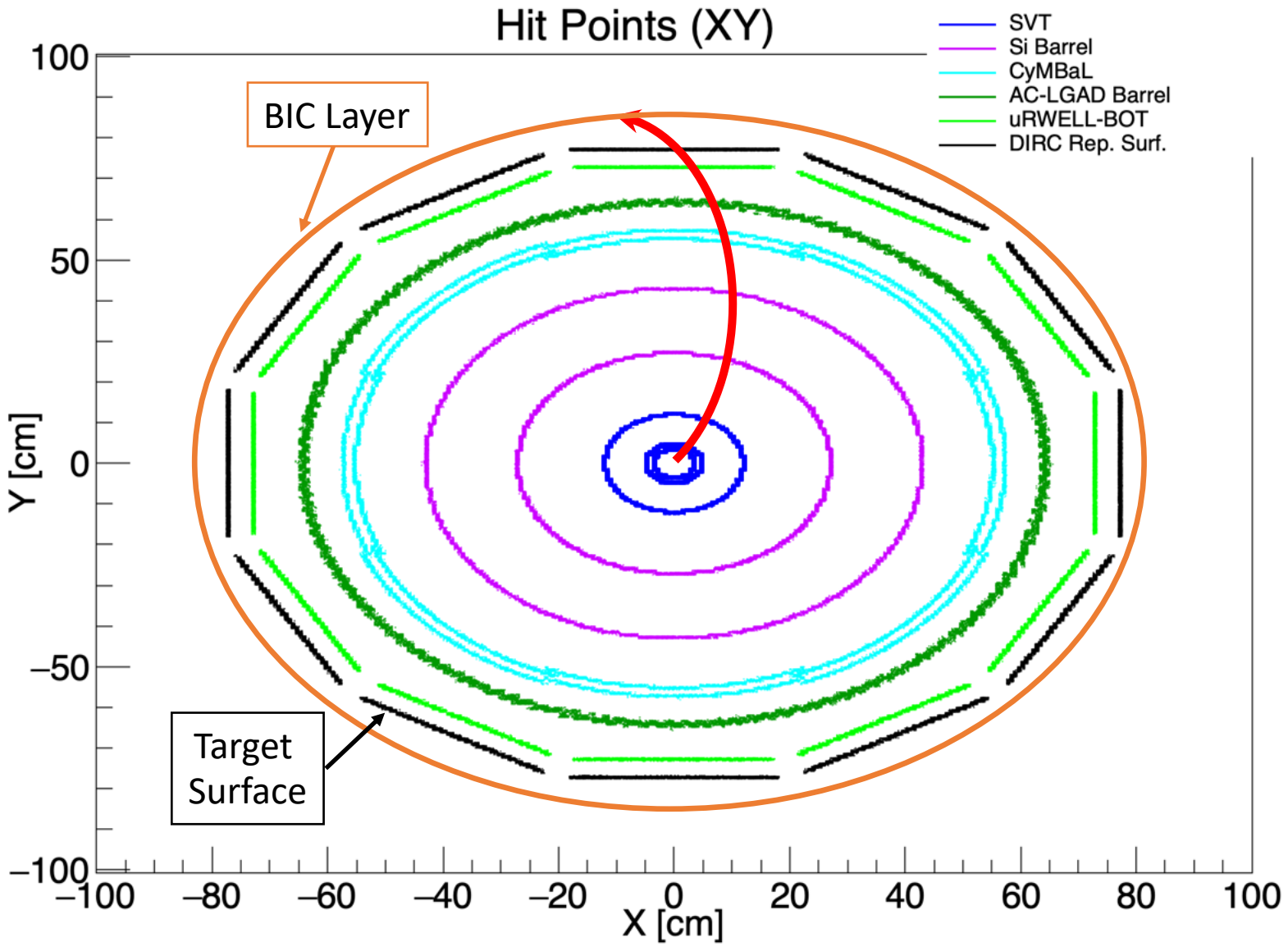
# Summary

- The Covariance matrix and Residual methods now give more consistent results
  - Spread of pull distributions $\sigma \approx 1$
- Followed up on some suggestions regarding the track angular divergence (Dot Product approach)
- Open points:
  1. Better understanding of covariance error structure
  2. BIC impact on tracking needs to be assessed
     - Technical issue → see next slide

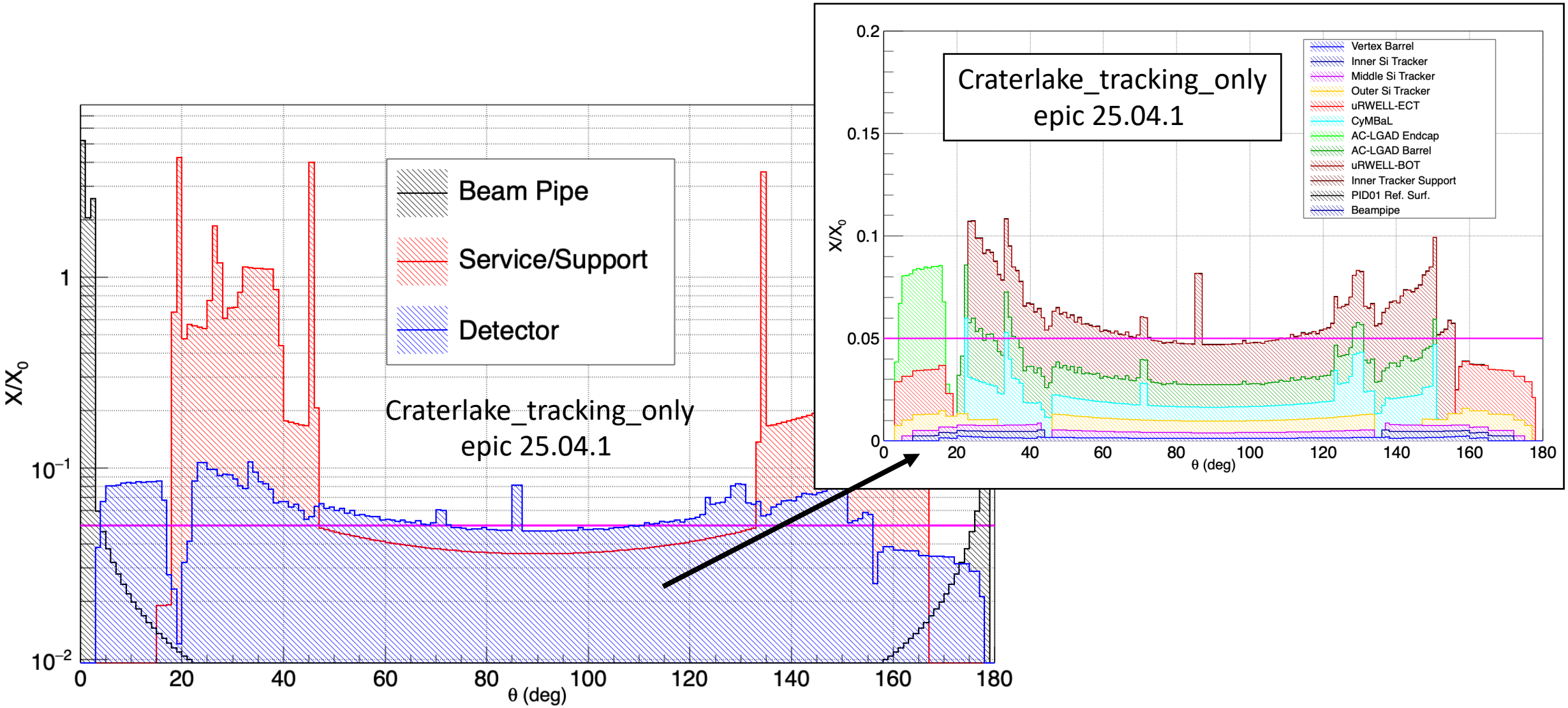
# Technical Propagation Issue

- Propagation begins at the track tip (e.g. outer most layer) and propagates outward
- With BIC as last “tracking” layer, propagation needs to operate inward back to DIRC surface to obtain final resolution

➢ Is there a way to do this in our current software?



# Material: DD4HEP



# Resolutions: Residual Method

- After propagation fix (3 momenta settings)