Transverse Single-Spin Asymmetries (TSSAs) in $\pi^{\pm}$ Production at Mid-rapidity in Transverse Polarized $p + p$ Collisions at $\sqrt{s} = 200$ GeV in PHENIX

Spin PWG meeting

Korea Univ.
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Calculation (Formula)

Geometric Weighting

$$A_N = \frac{1}{\langle |\ cos\phi\ | \rangle} \frac{1}{P} A_N^{raw}$$

$$\sigma_{A_N} = |A_N| \sqrt{\left(\frac{\sigma_{A_N^{raw}}}{A_N^{raw}}\right)^2 + \left(\frac{\sigma_P}{P}\right)^2}$$

Square Root Formula

$$A_N^{raw} = \frac{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}$$

$$\sigma_{A_N^{raw}} = \frac{\sqrt{N_L^{\uparrow} N_R^{\downarrow} N_L^{\downarrow} N_R^{\uparrow}}}{\left(\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} N_R^{\uparrow}}\right)^2} \sqrt{\frac{1}{N_L^{\uparrow}} + \frac{1}{N_L^{\downarrow}} + \frac{1}{N_R^{\uparrow}} + \frac{1}{N_R^{\downarrow}}}$$

Averaging Over Fills (The Weighted Mean Formula)

$$A_{N,average} = \frac{\sum_{i=Fill} {A_{N,i}}/{\sigma^2}_{A_{N,i}}}{\sum_{i=Fill} {1}/{\sigma^2}_{A_{N,i}}}$$

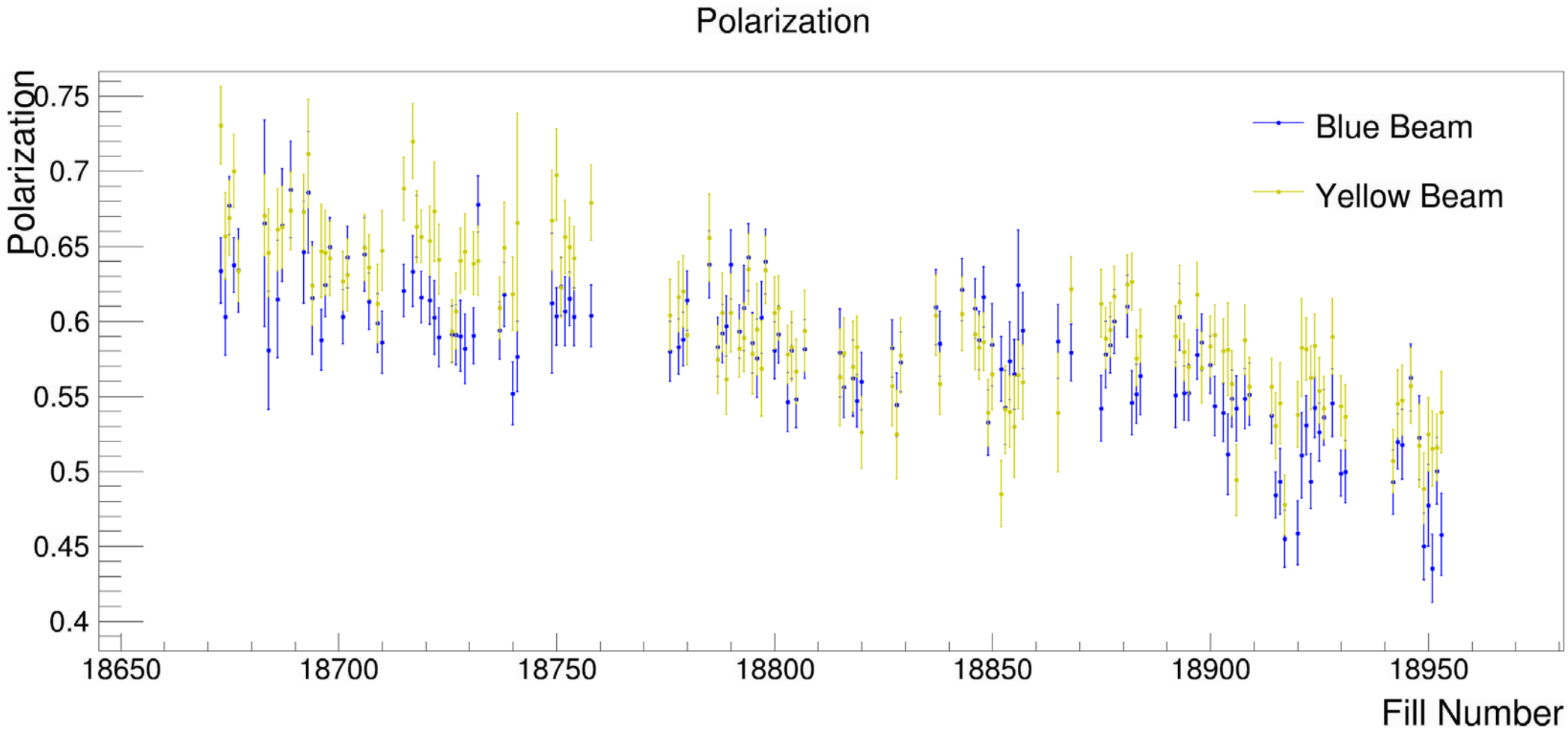
$${\sigma^2}_{A_{N,average}} = \frac{1}{\sum_{i=Fill} {1}/{\sigma^2}_{A_{N,i}}}$$

Relative Luminosity Formula

$$A_N^{raw} = \frac{N_L^{\uparrow} - \mathcal{R} N_L^{\downarrow}}{N_L^{\uparrow} + \mathcal{R} N_L^{\downarrow}}$$

$$\sigma_{A_N^{raw}} = \frac{2\mathcal{R} N_L^{\uparrow} N_L^{\downarrow}}{\left(N_L^{\uparrow} + \mathcal{R} N_L^{\downarrow}\right)^2} \sqrt{\frac{1}{N_L^{\uparrow}} + \frac{1}{N_L^{\downarrow}}}$$

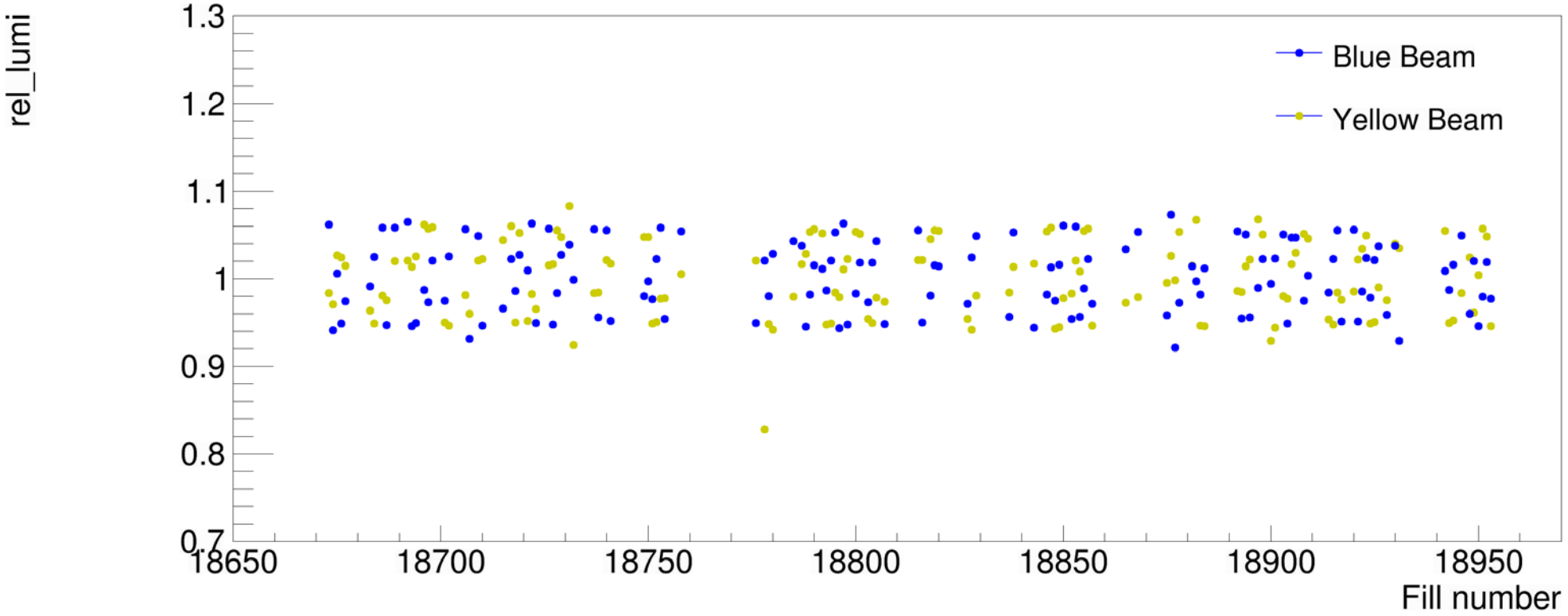
Polarization vs fillnumber



- The proton beam is never 100% polarized and collisions between unpolarized protons dilute the A_N measurement.

- The dilution must be corrected by dividing by the average beam polarization.

Rel_lumi vs fillnumber

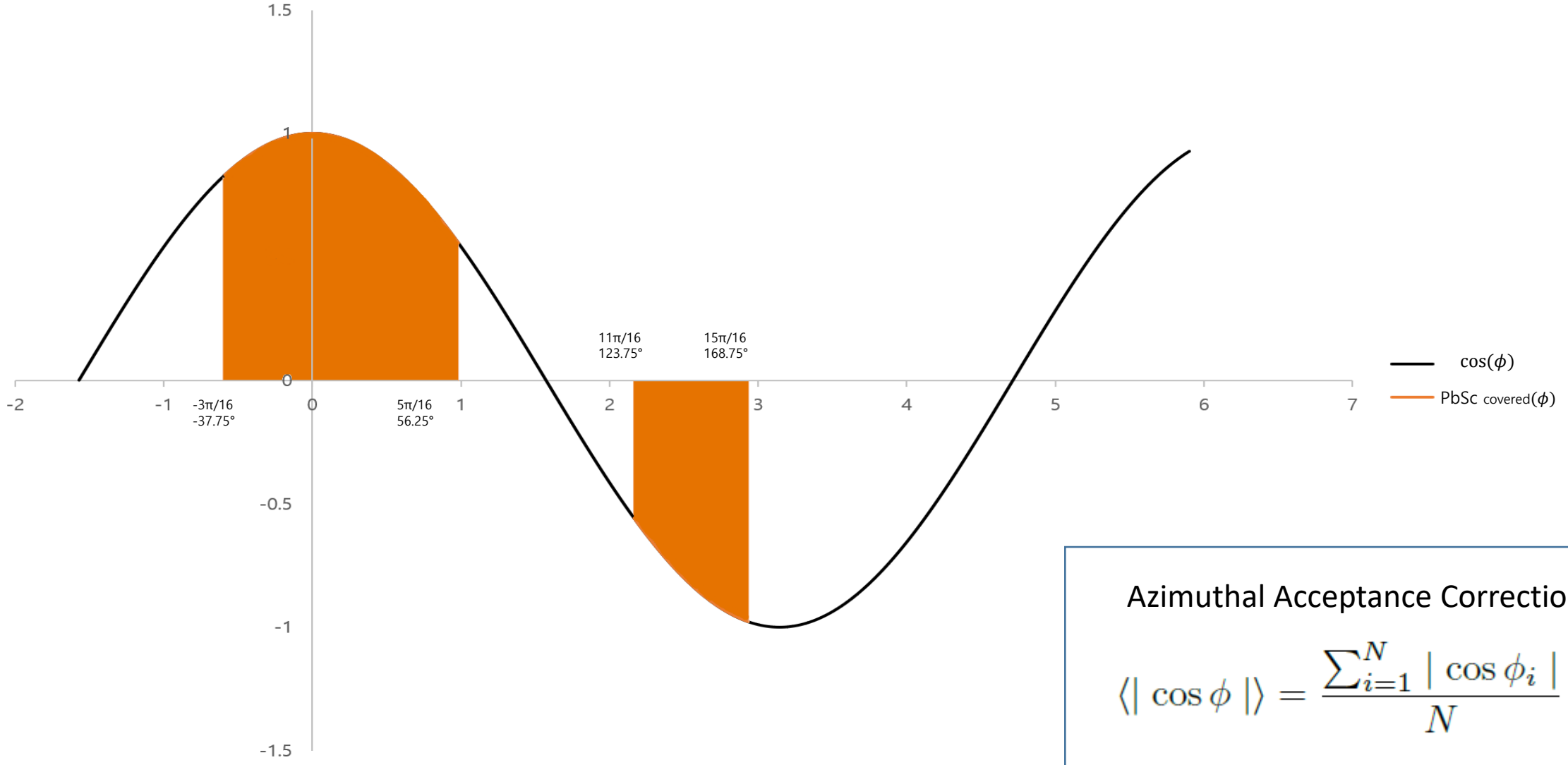


$R = L_{\uparrow}/L_{\downarrow}$

Fill number = 18778
rellumiB = 1.02079
rellumiY = 0.827717

The relative luminosity asymmetry formula uses counts that are only on one side of the detector at a time and then calculates the asymmetry for when the beam was spin up versus spin down.

Acceptance Correction



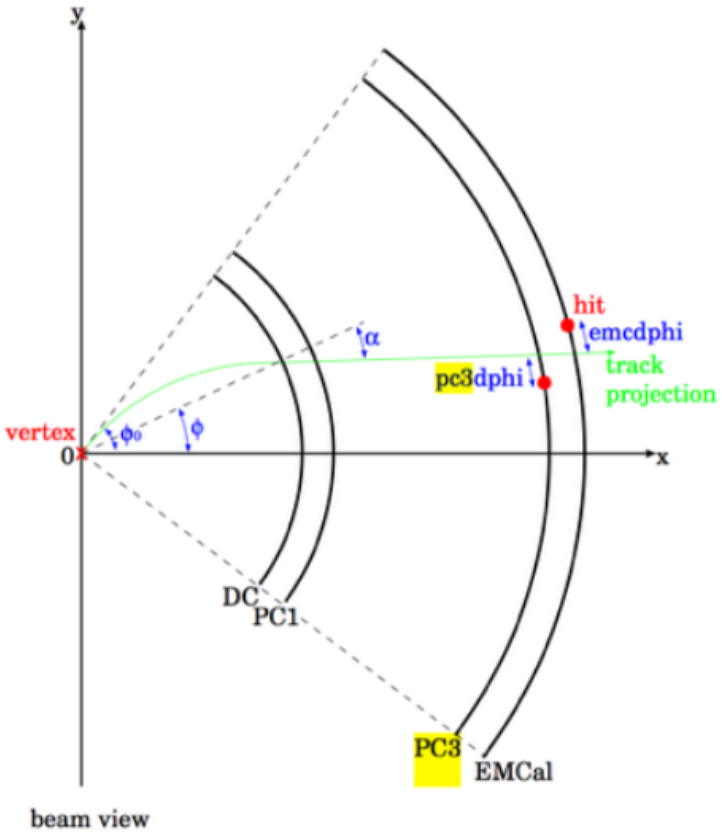
Azimuthal Acceptance Correction

$$\langle | \cos\phi | \rangle = \frac{\sum_{i=1}^{N} | \cos\phi_i |}{N}$$

Acceptance Correction

- emcdphi and pc3dphi : track-to-hit distance in EMCal and PC3 in phi, respectively.

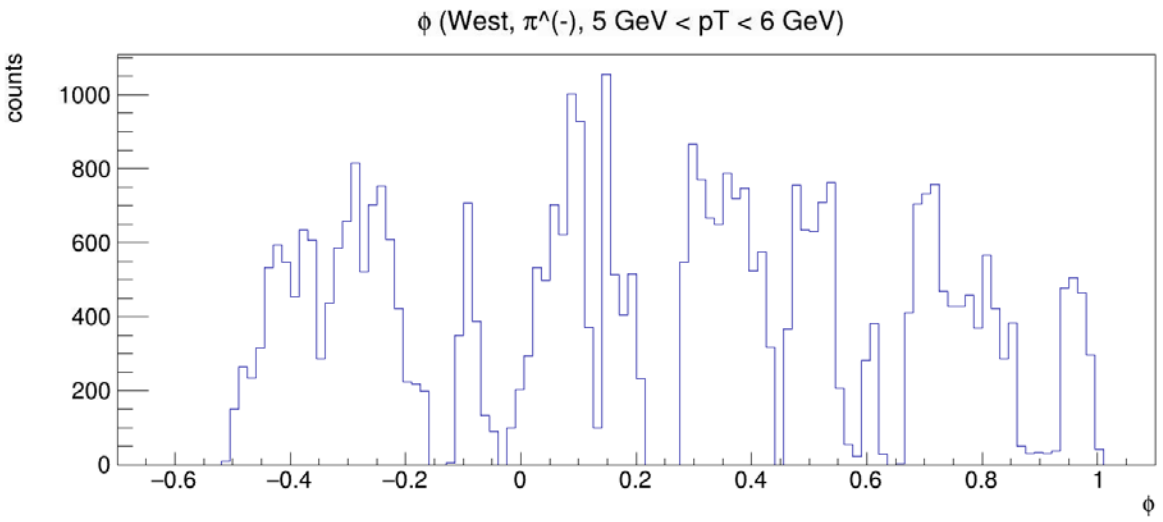
- "Recon. track of decay particle" and "Fake track" tend to have a large emcdphi and pc3dphi.

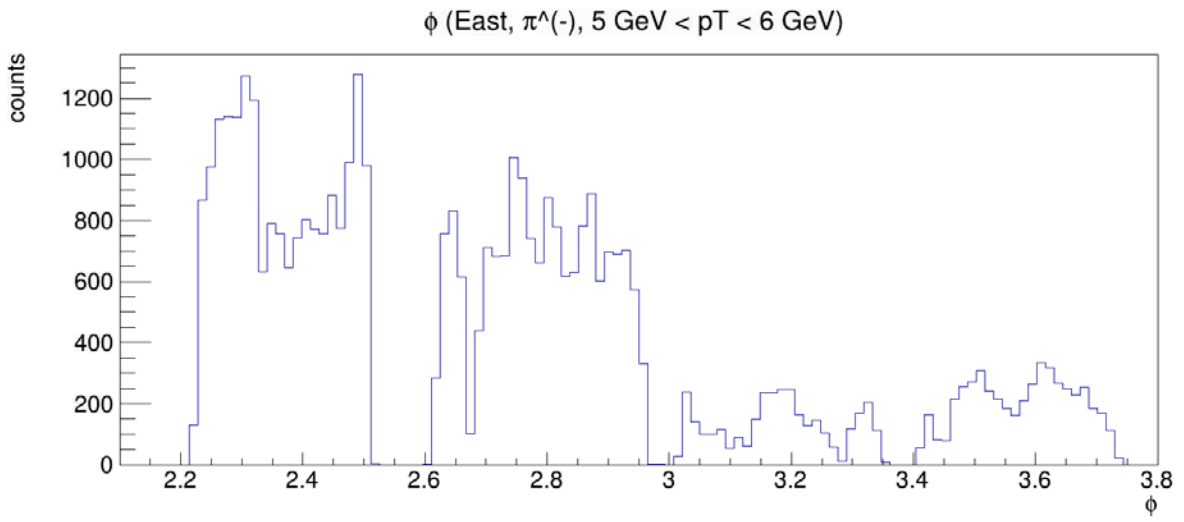


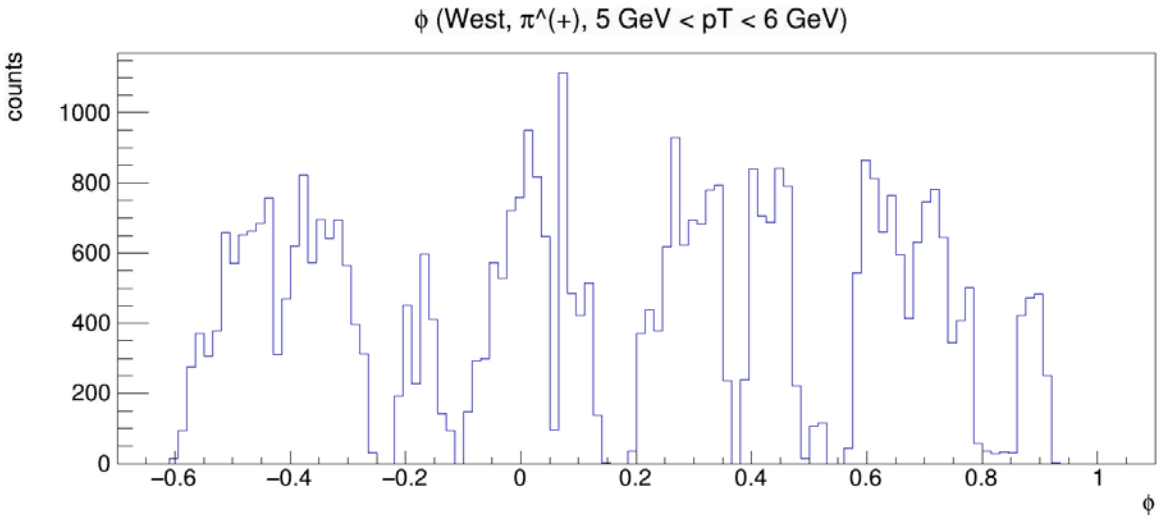
I using "phi0"

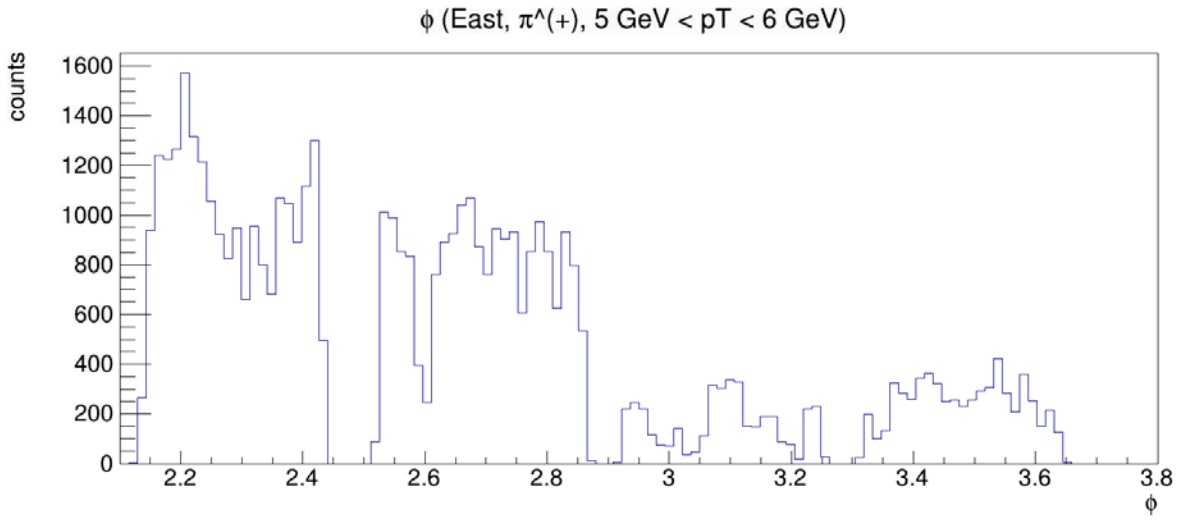
By Using " _trk->get_phi0(); "

Phi distribution 5 GeV < pT < 6 GeV

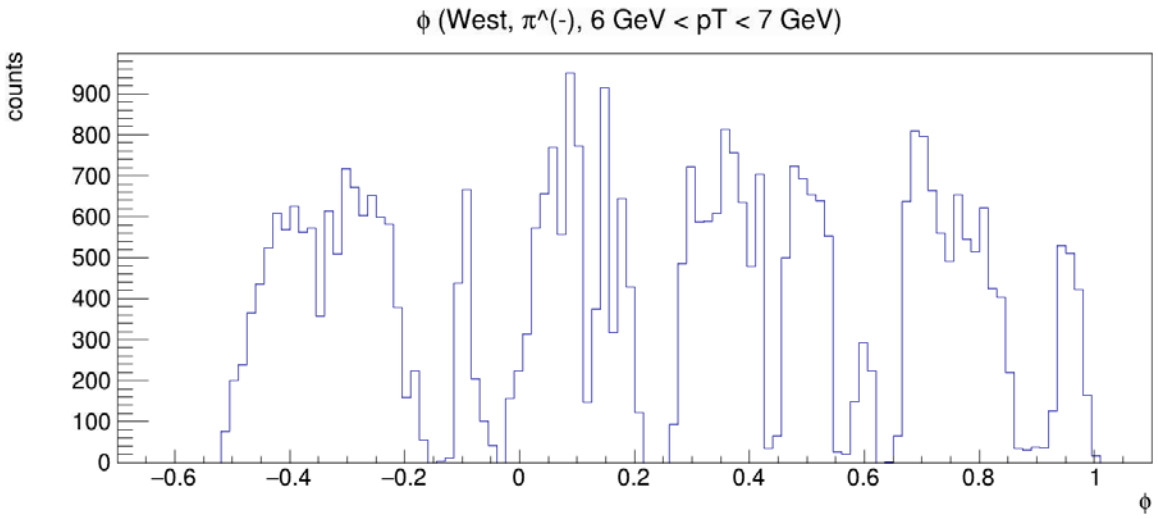


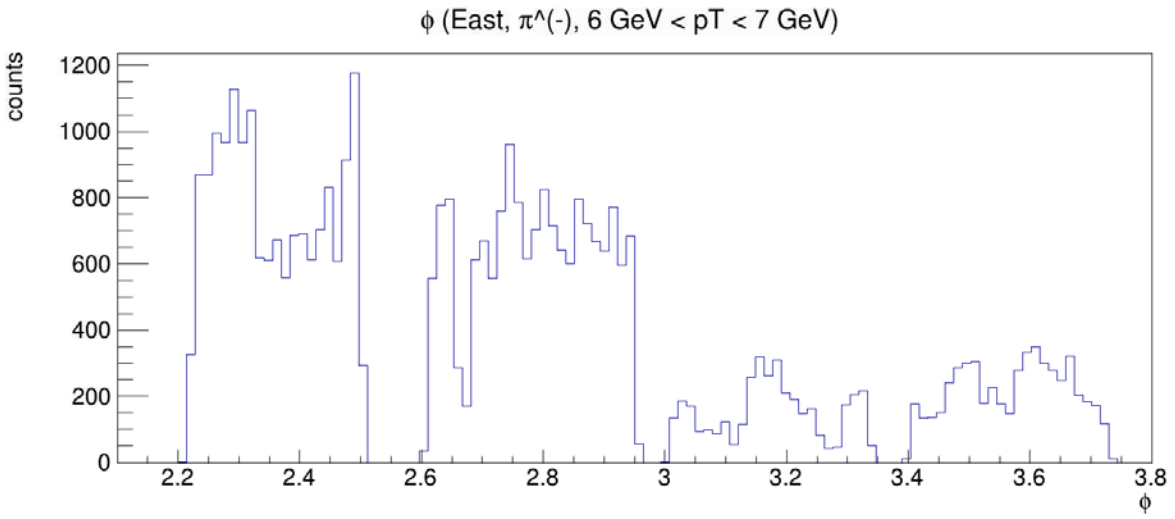


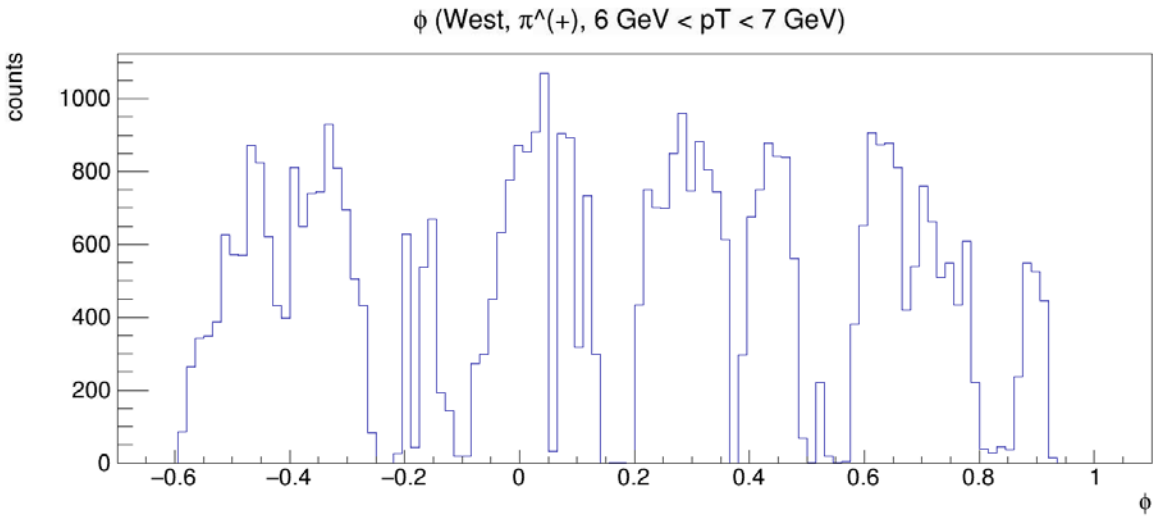


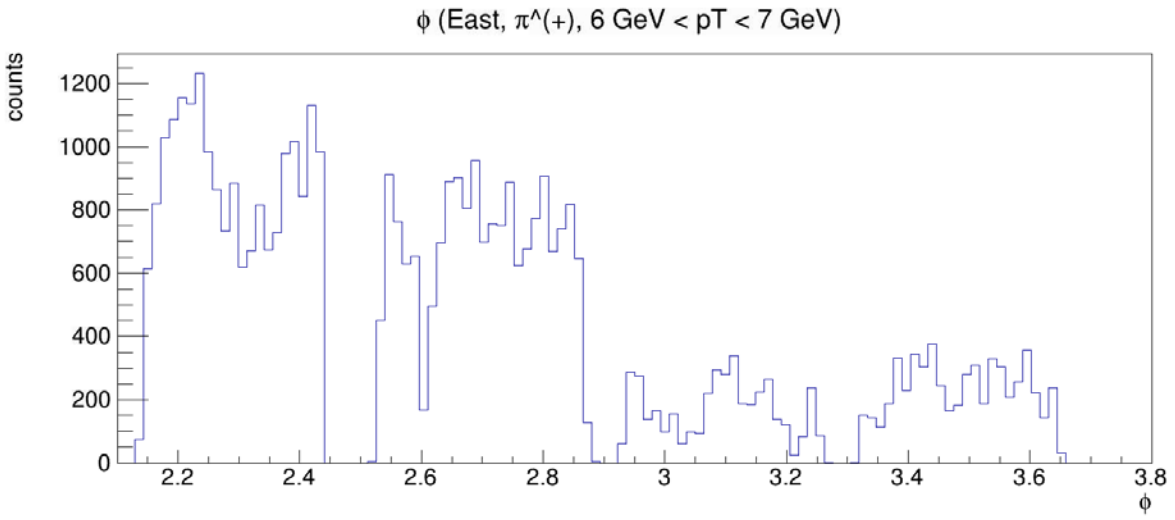


Phi distribution 6 GeV < pT < 7 GeV

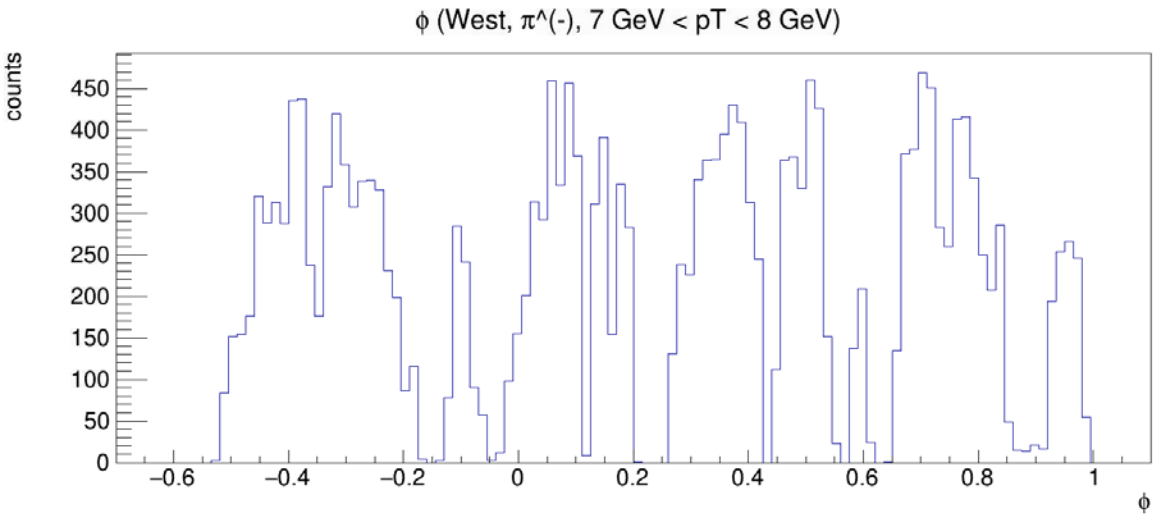


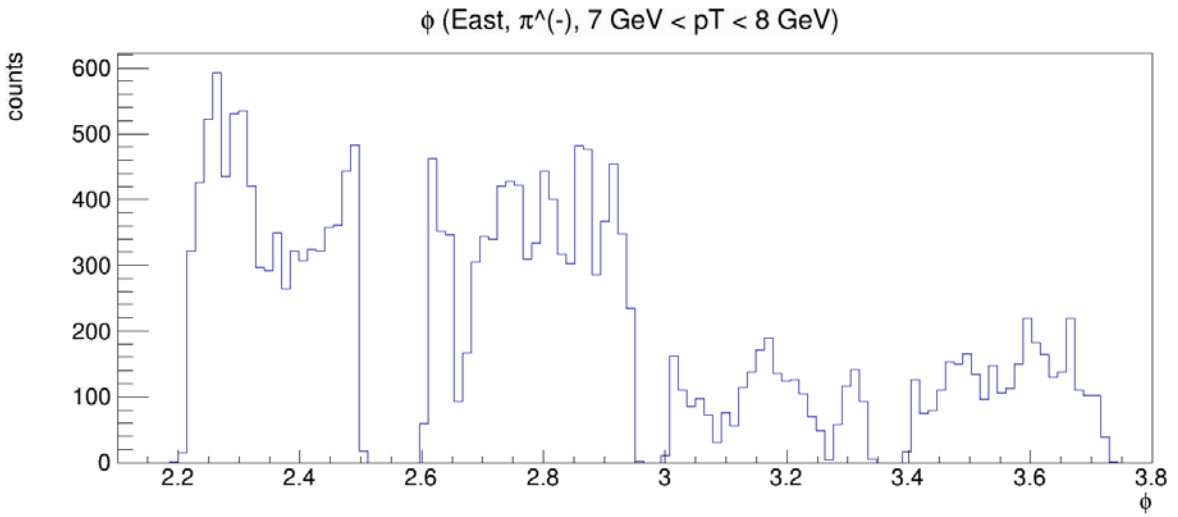


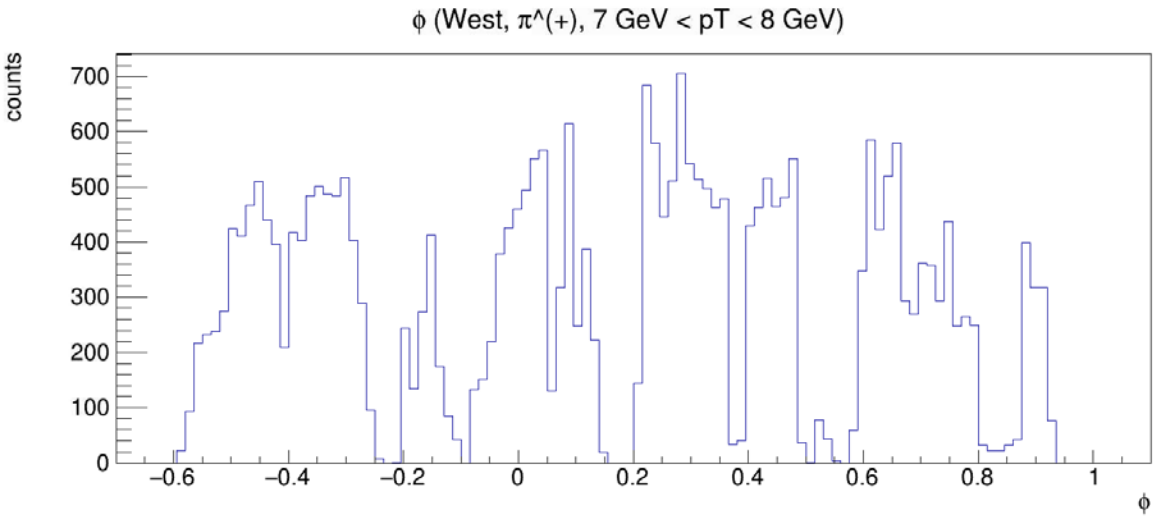


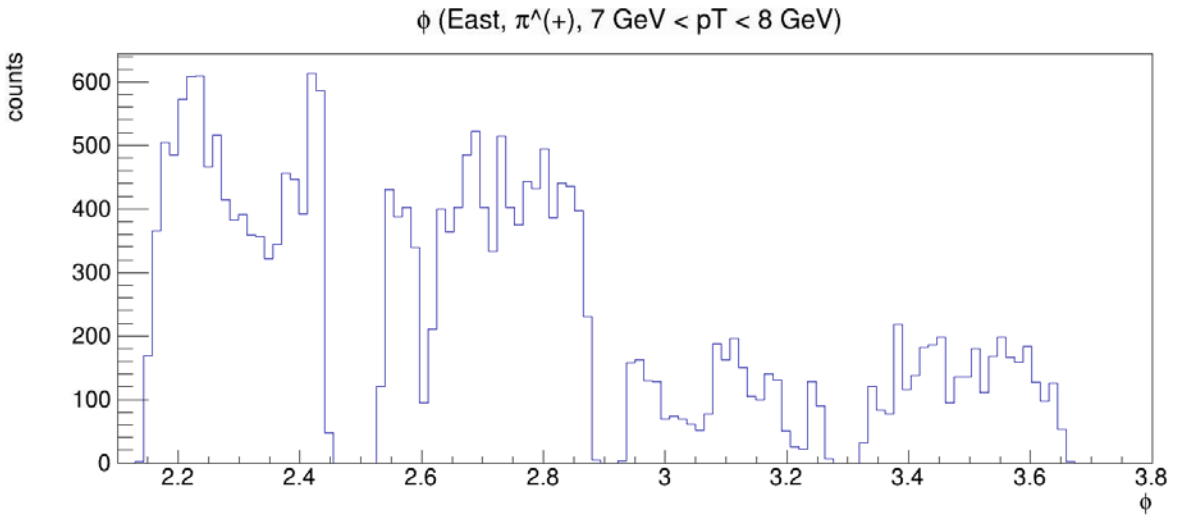


Phi distribution 7 GeV < pT < 8 GeV

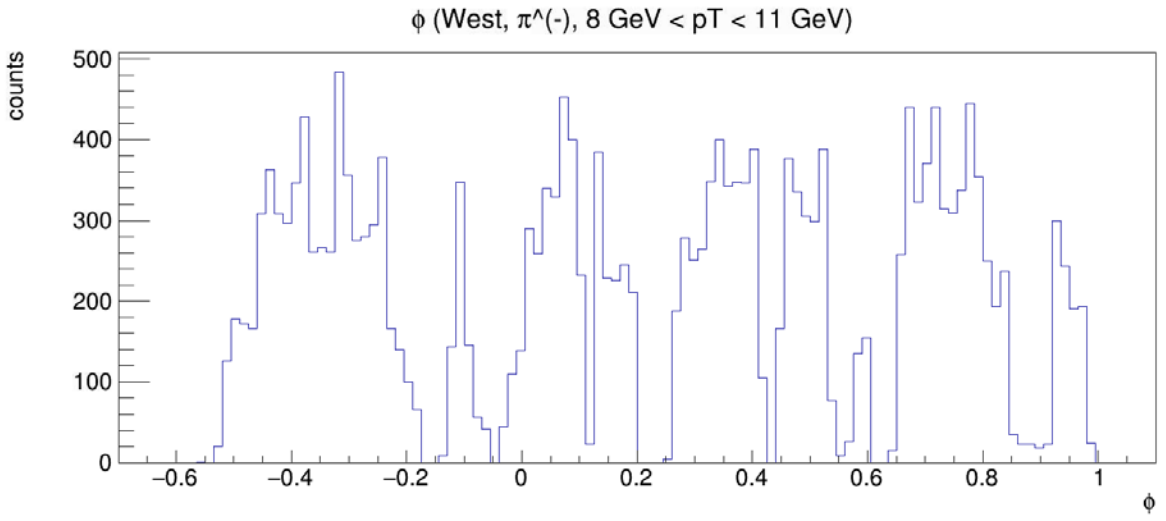


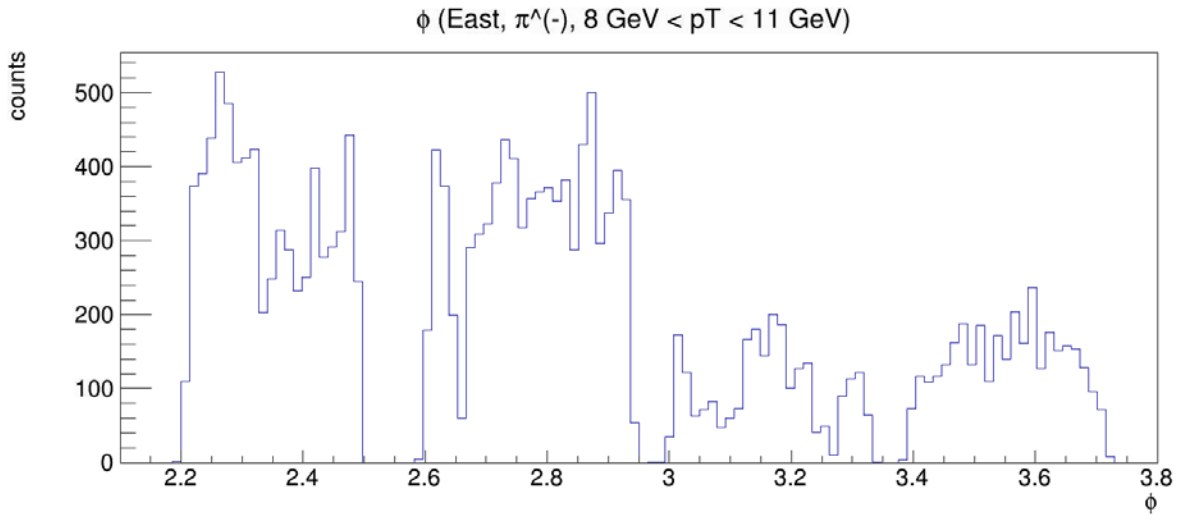


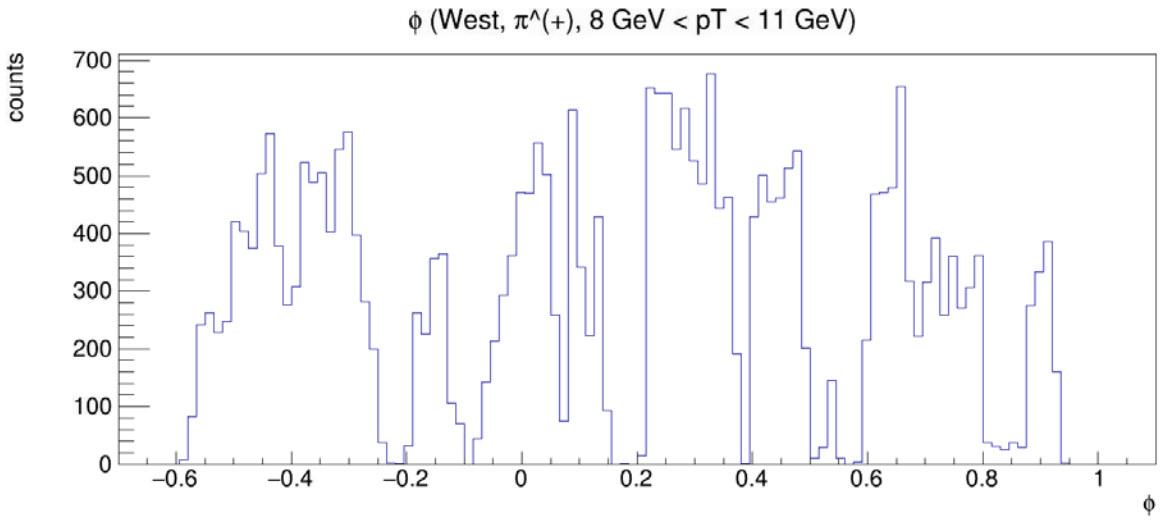


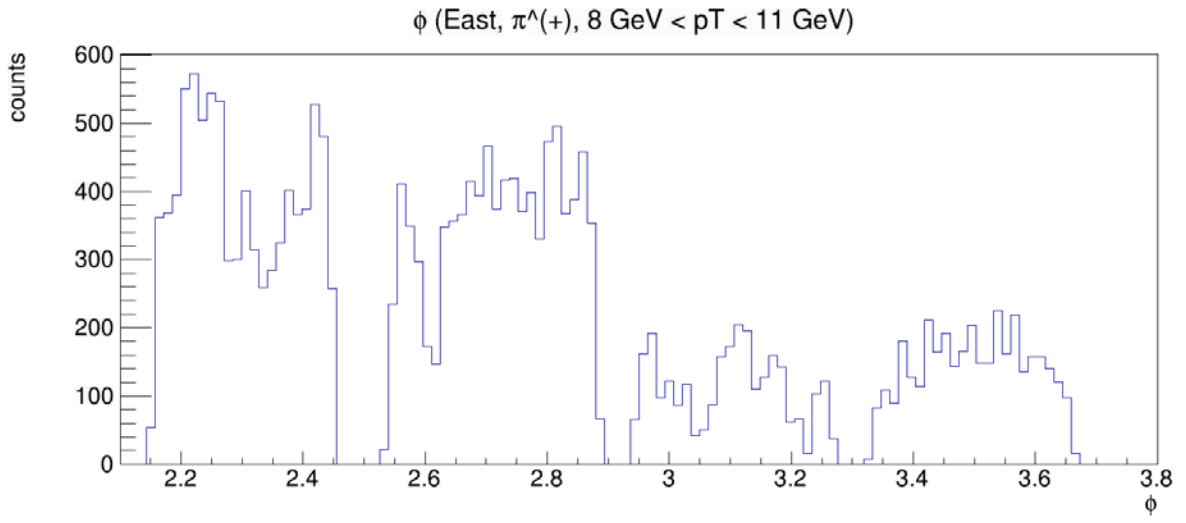


Phi distribution 8 GeV < pT < 11 GeV

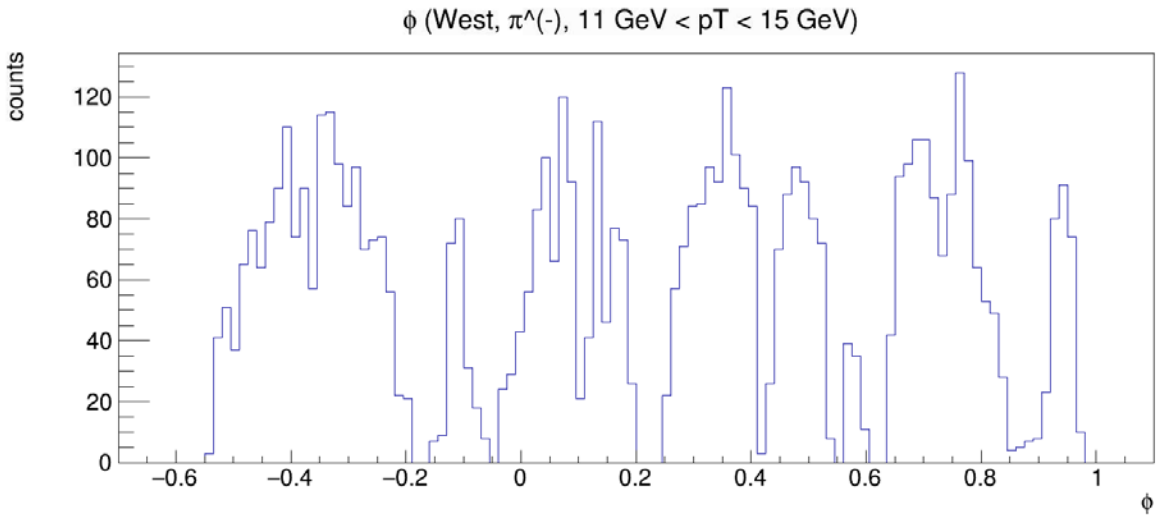


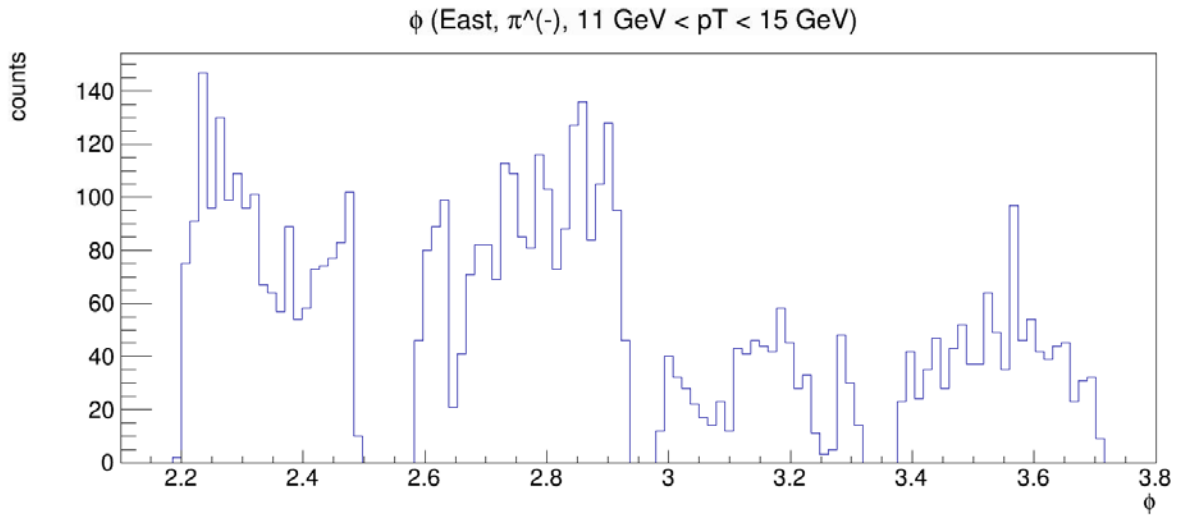


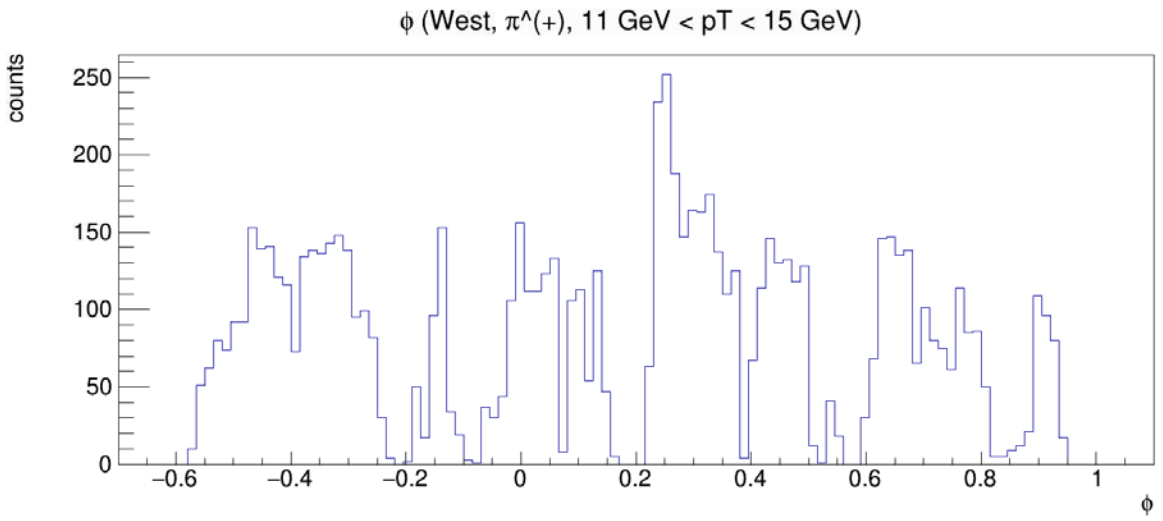


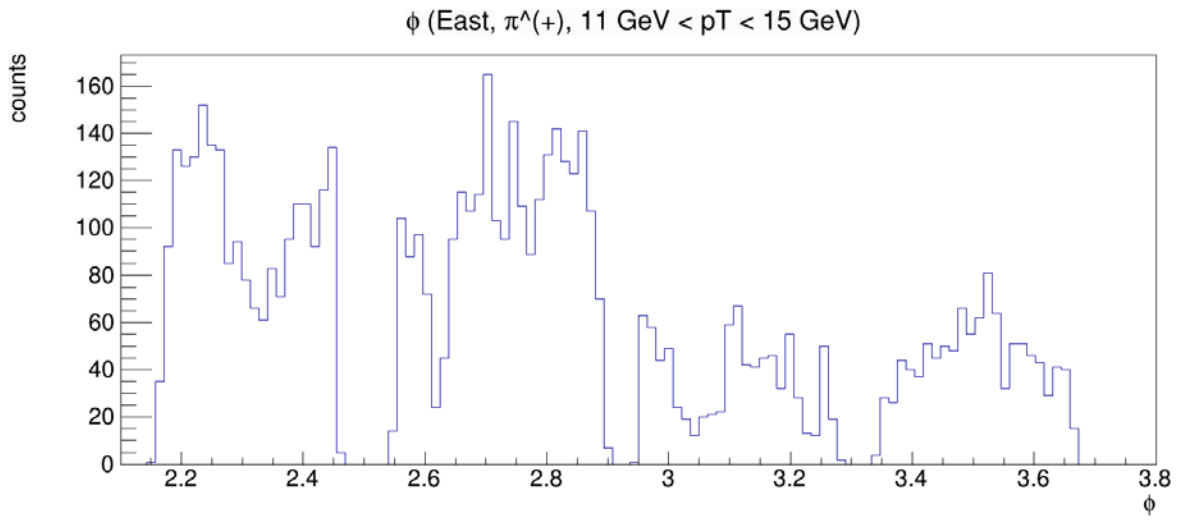


Phi distribution 11 GeV < pT < 15 GeV

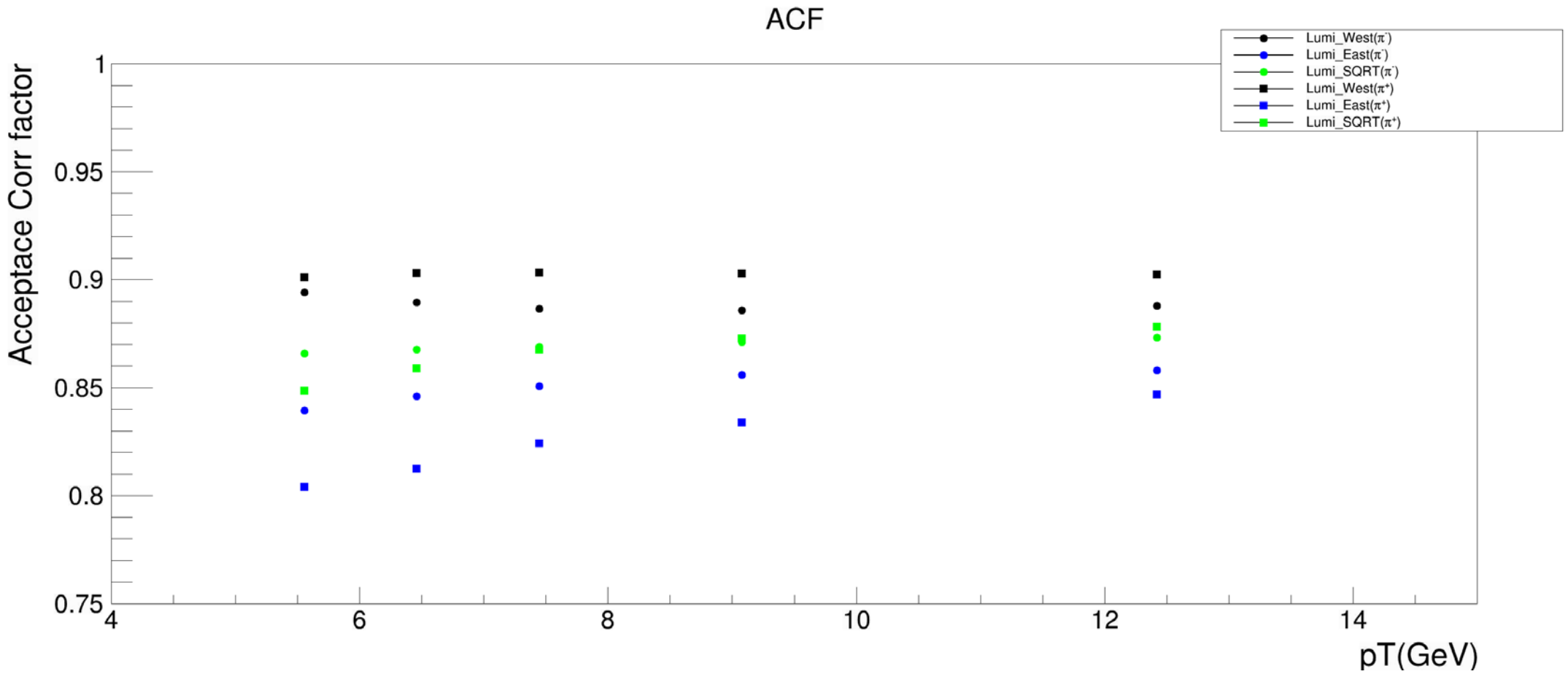








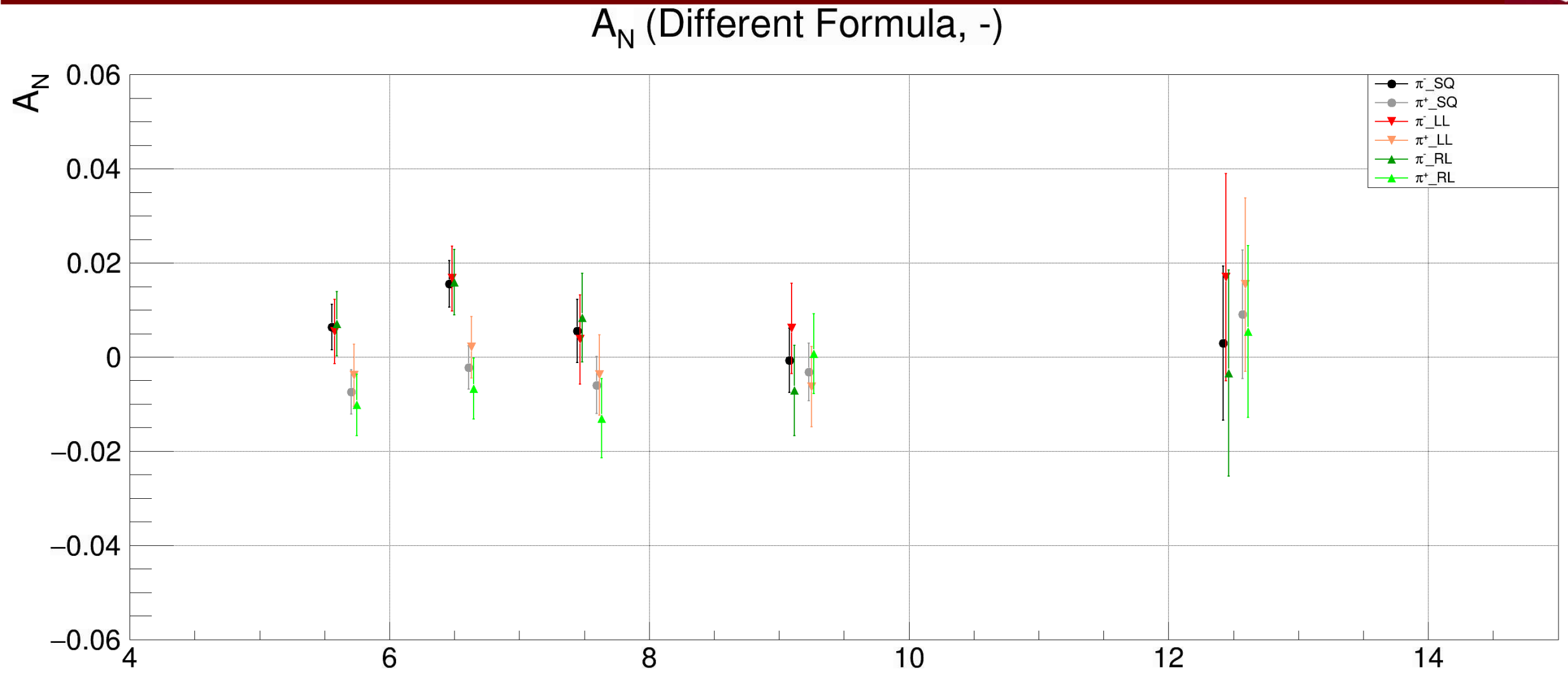
ACF



No systematic error

Before background correction

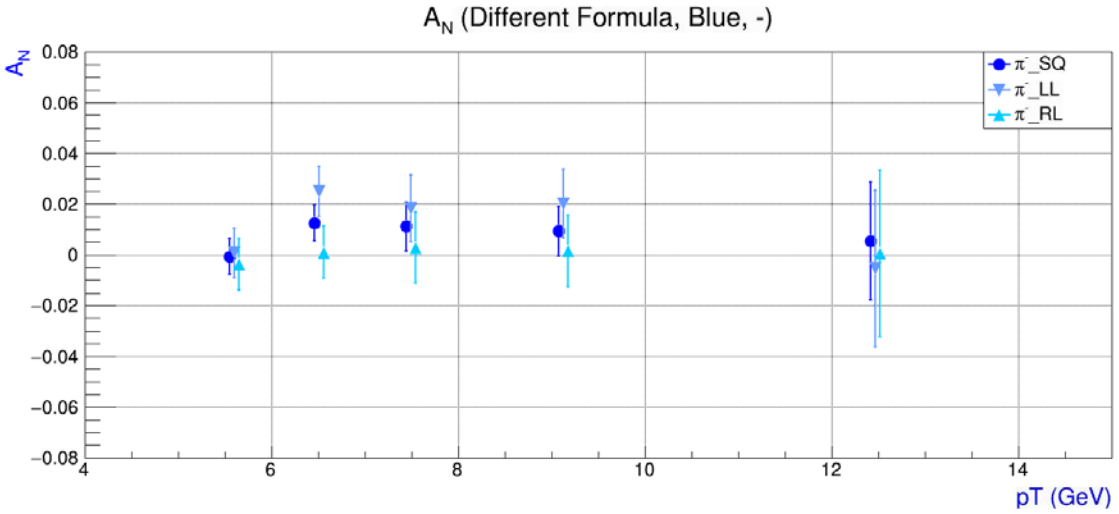
A_N after merging beam

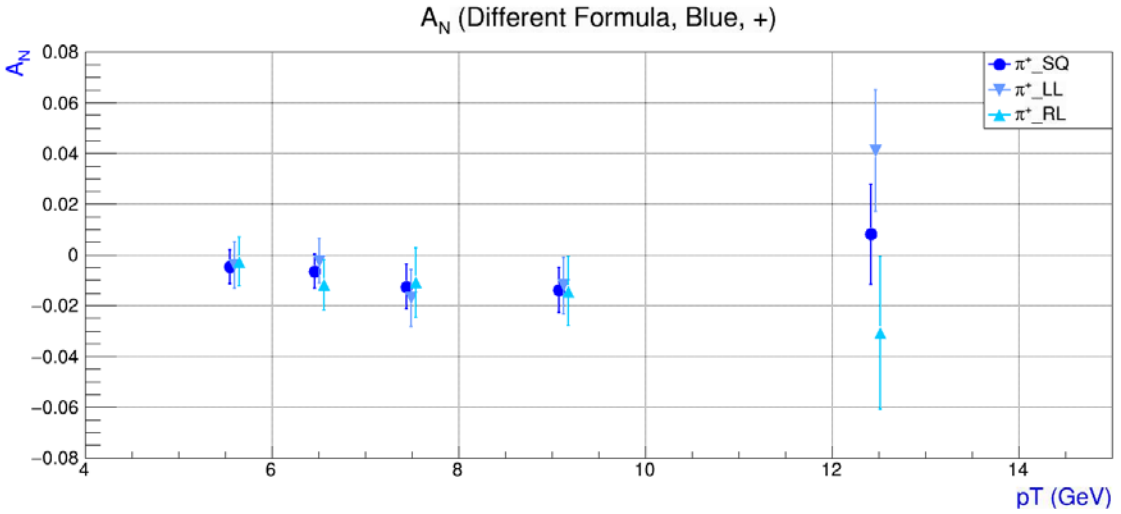


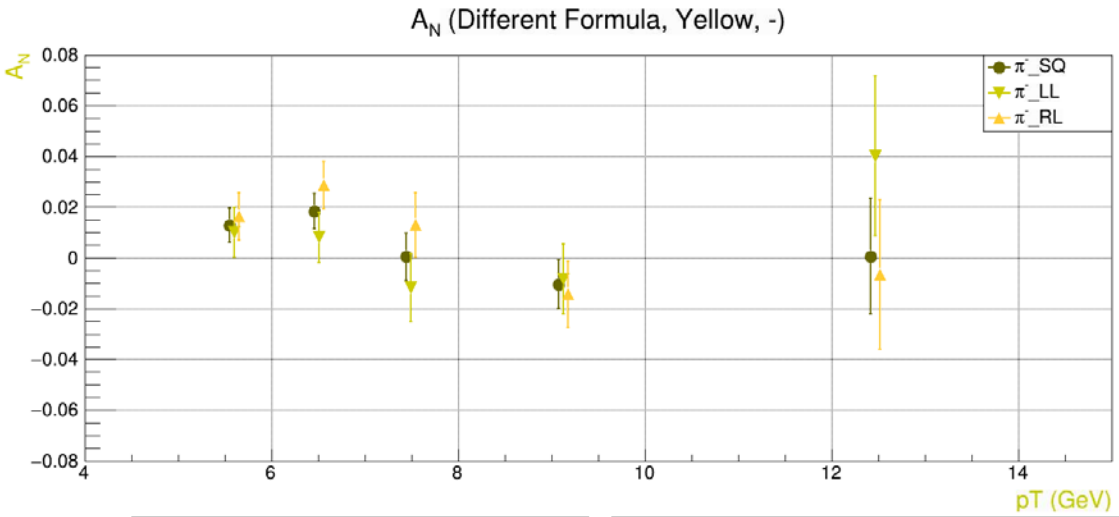
No systematic error

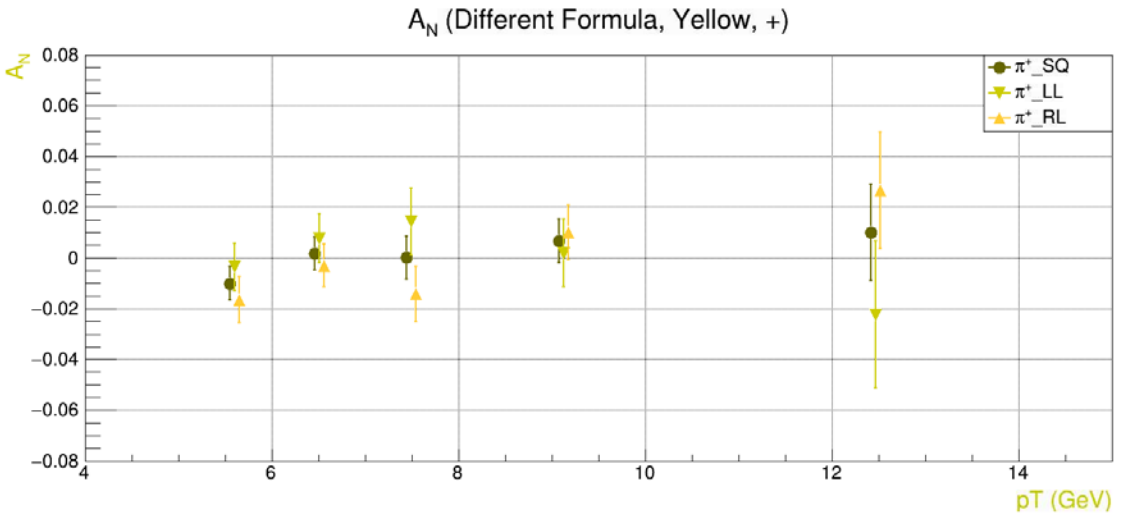
Before background correction

A_N with different beam, charge and formula





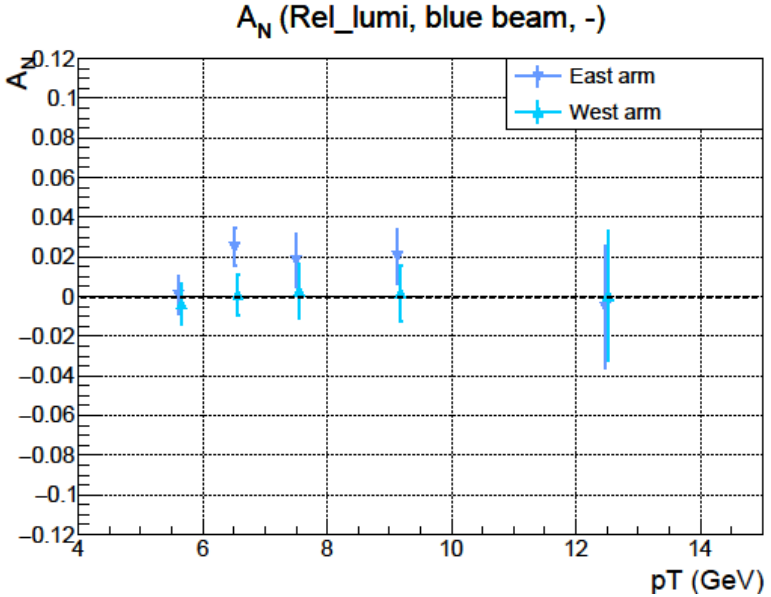


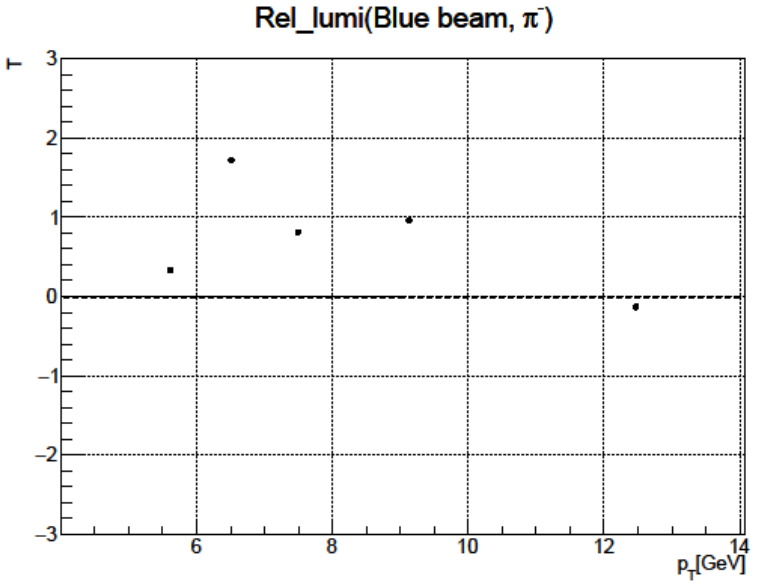


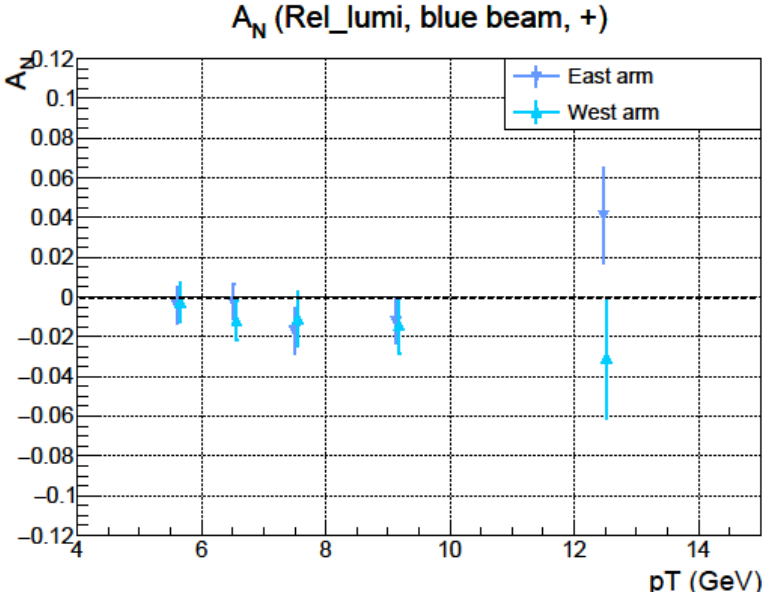
No systematic error

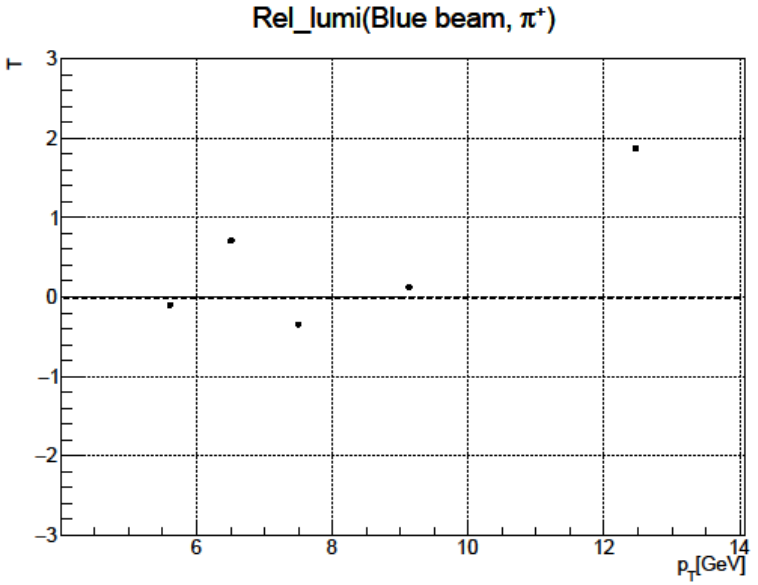
Before background correction

Relative Luminosity Formula (Blue)







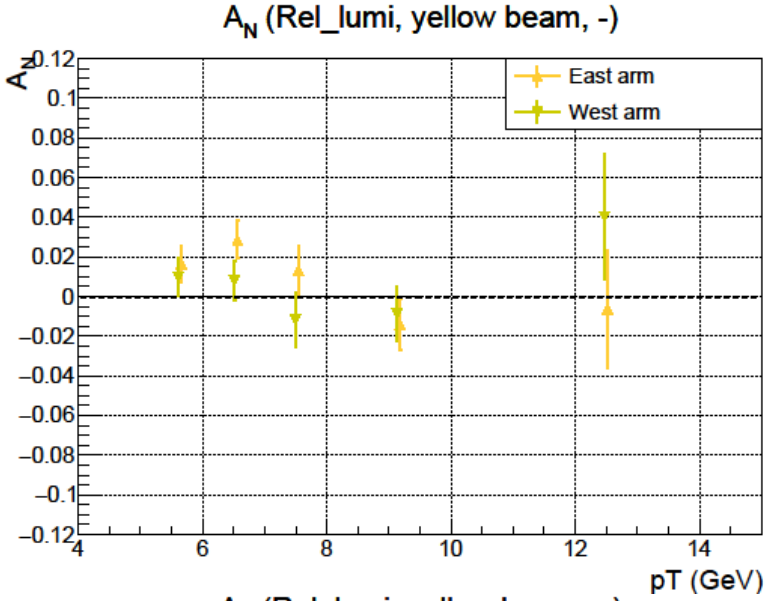


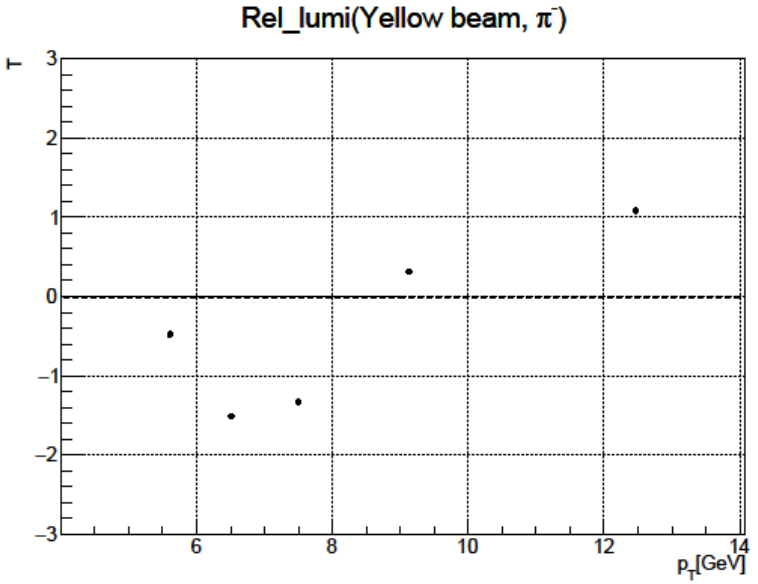
$$T(p_T) = \frac{A_N^{Left} - A_N^{Right}}{\sqrt{(\sigma^{Left})^2 + (\sigma^{Right})^2}}$$

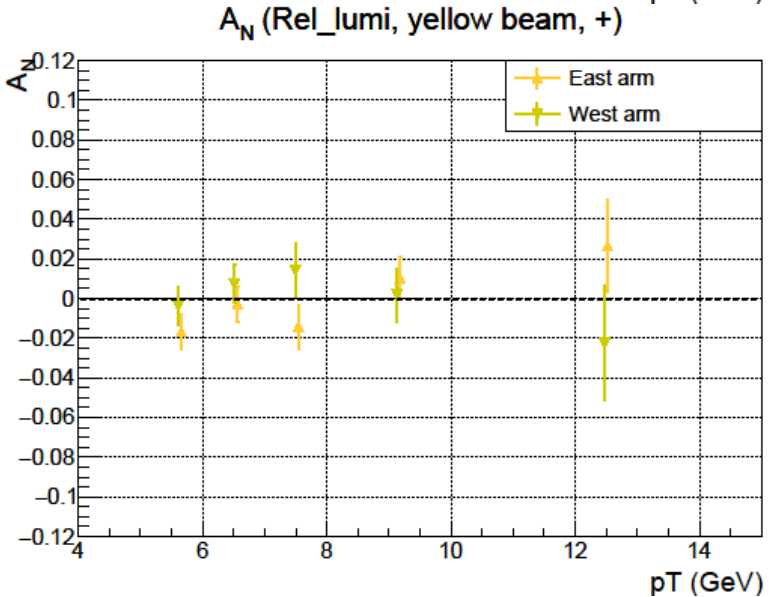
No systematic error

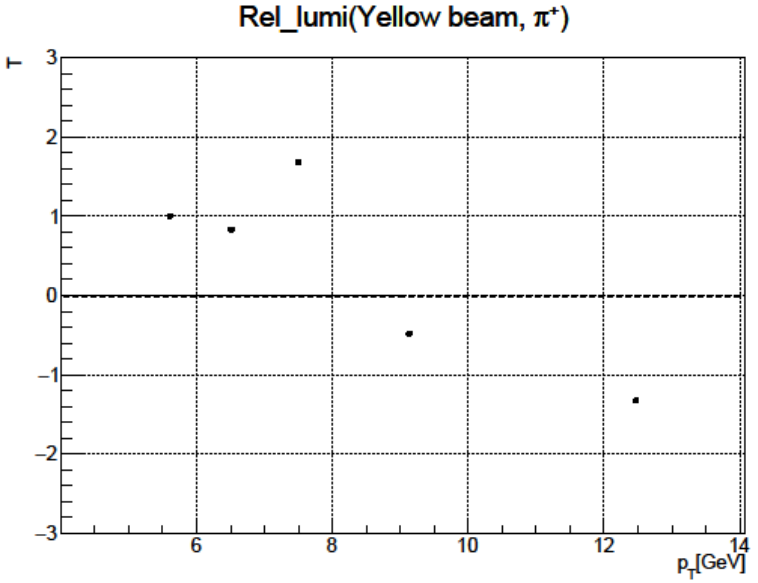
Before background correction

Relative Luminosity Formula (Yellow)







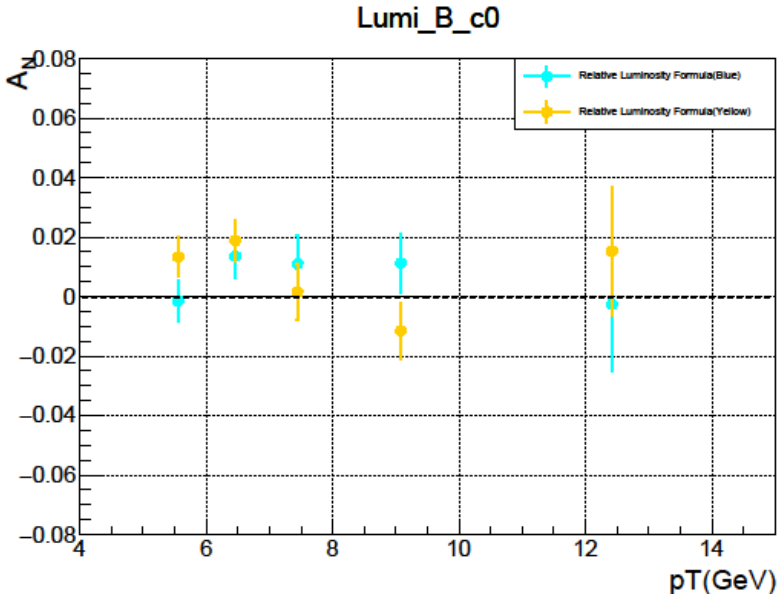


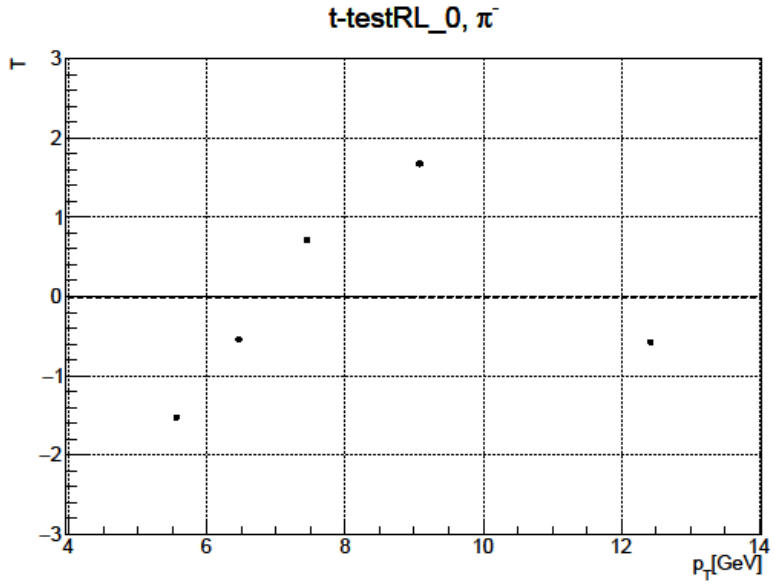
$$T(p_T) = \frac{A_N^{Left} - A_N^{Right}}{\sqrt{(\sigma^{Left})^2 + (\sigma^{Right})^2}}$$

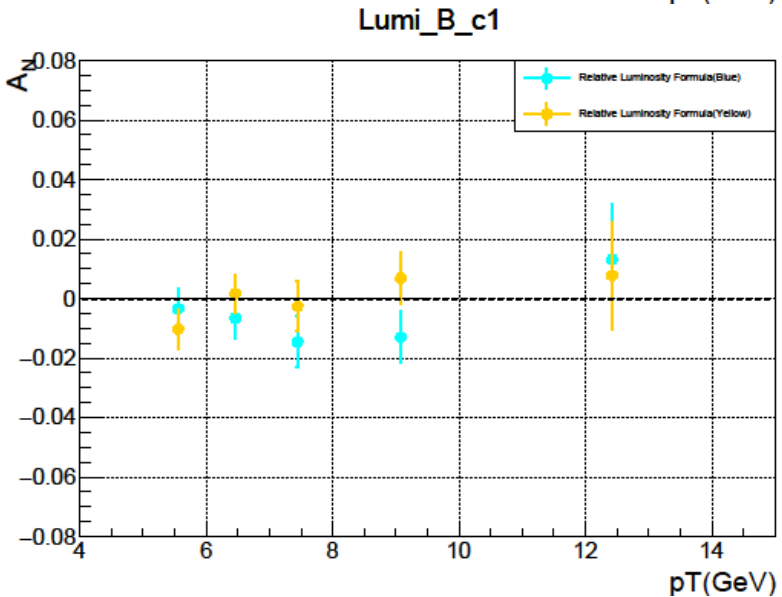
No systematic error

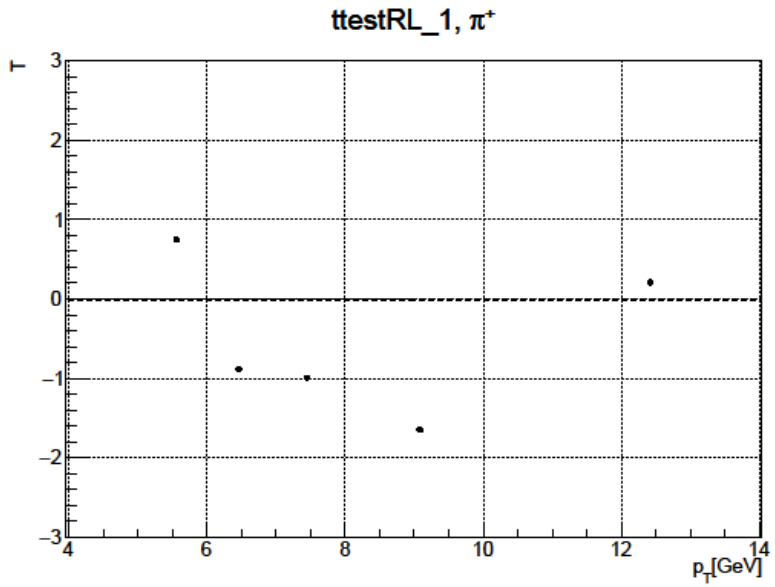
Before background correction

Relative Luminosity Formula







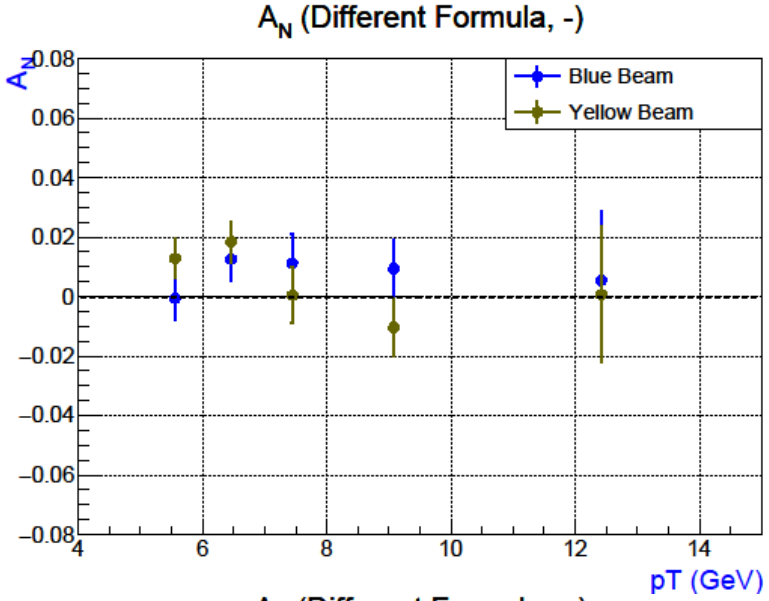


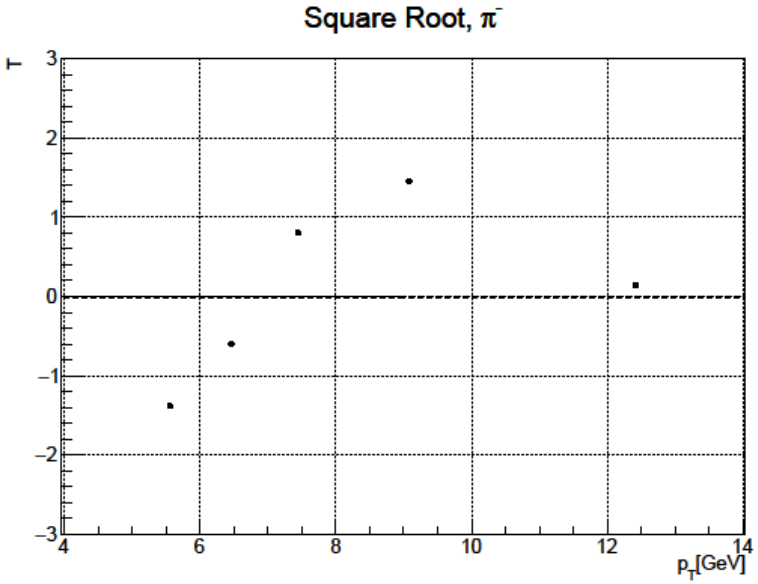
$$T(p_T) = \frac{A_N^{Yellow} - A_N^{Blue}}{\sqrt{(\sigma^{Yellow})^2 + (\sigma^{Blue})^2}}$$

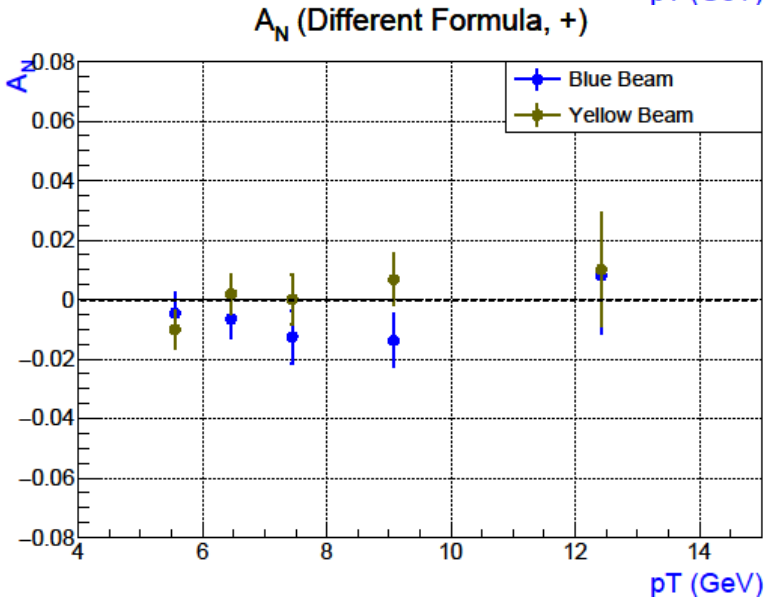
No systematic error

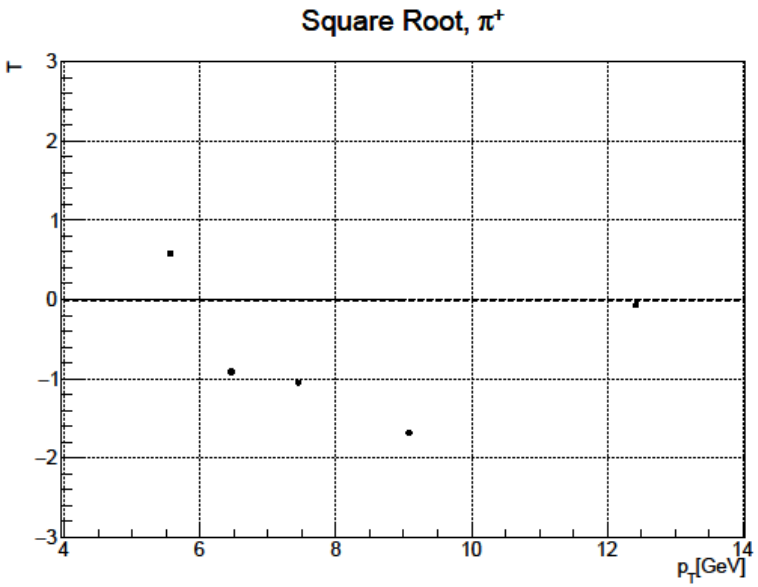
Before background correction

Square Root Formula







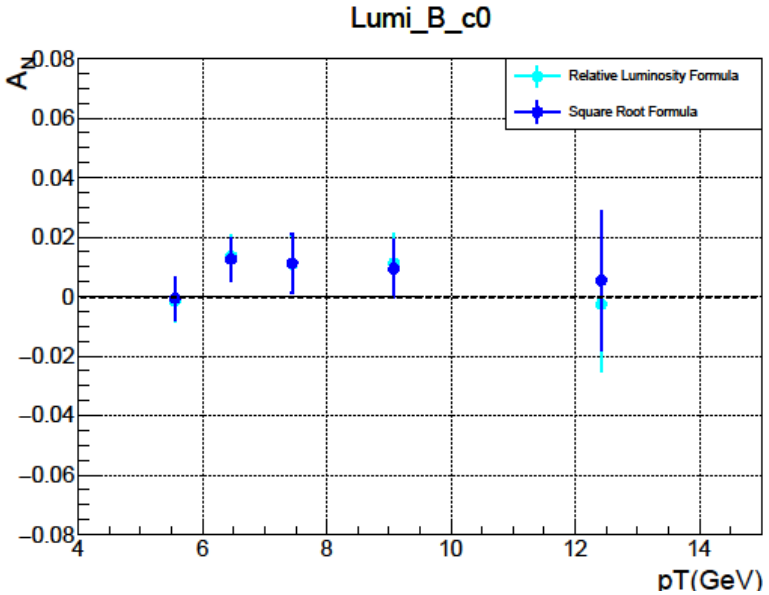


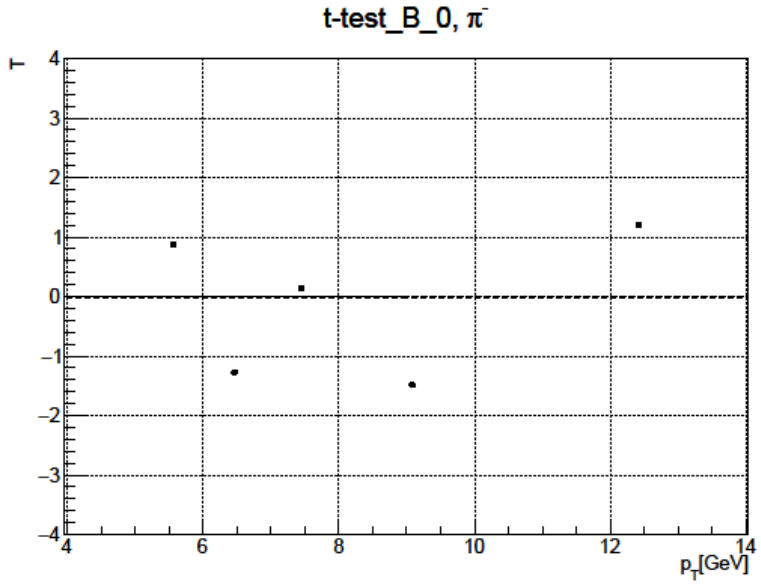
$$T(p_T) = \frac{A_N^{Yellow} - A_N^{Blue}}{\sqrt{(\sigma^{Yellow})^2 + (\sigma^{Blue})^2}}$$

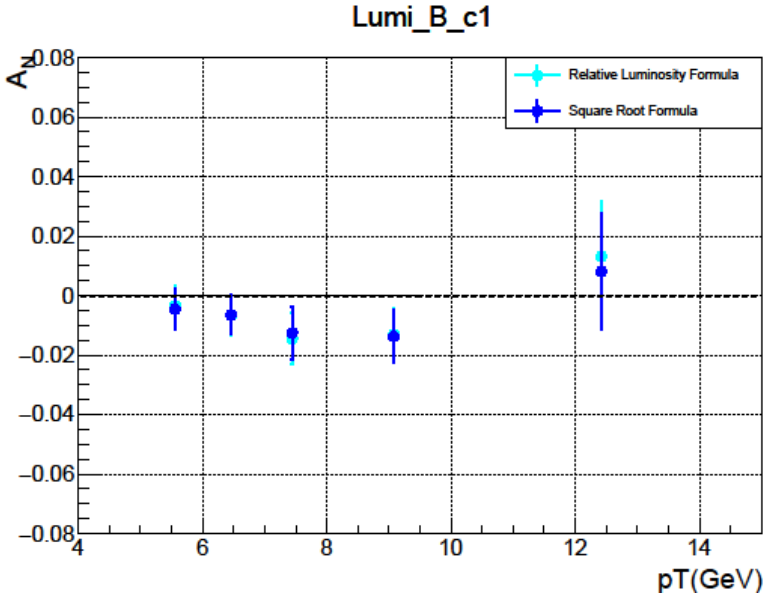
No systematic error

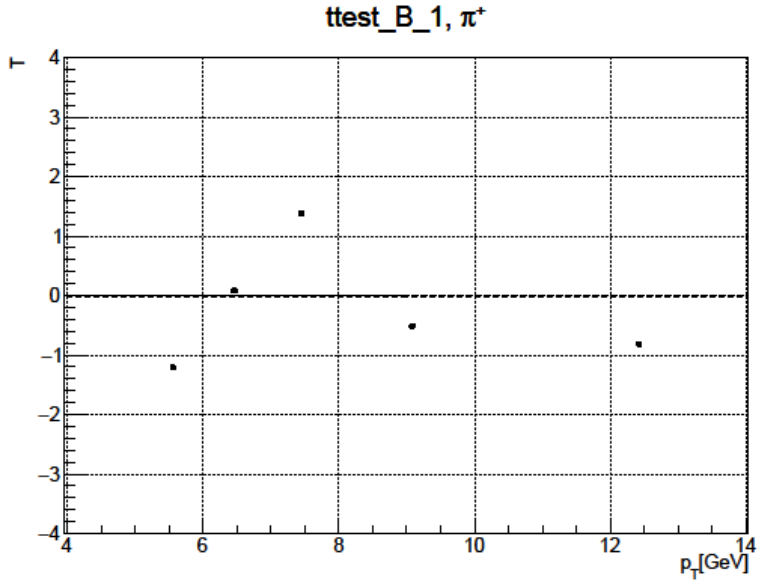
Before background correction

A_N - Formula Comparison (Blue)







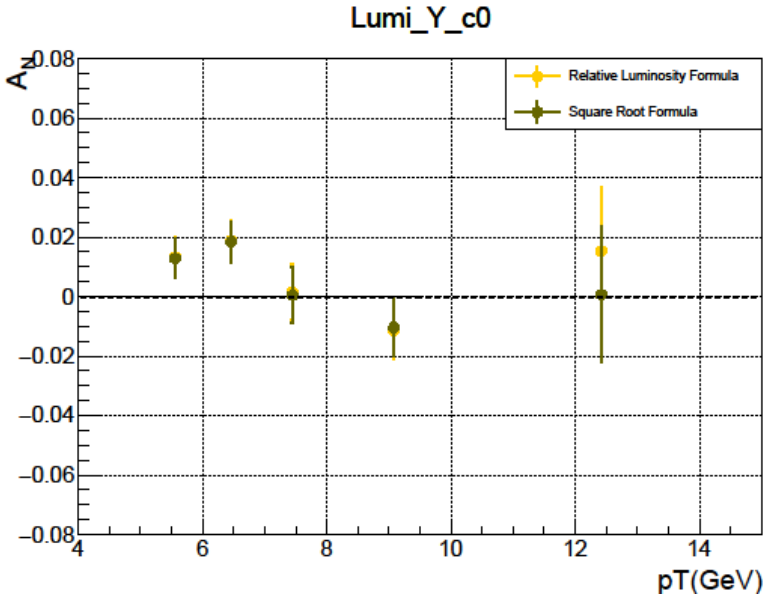


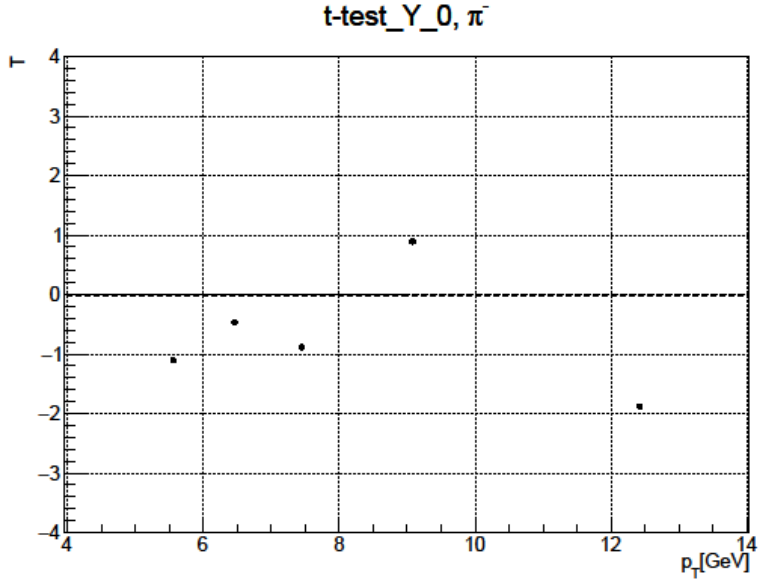
$$T(p_T) = \frac{A_N^{Sqrt} - A_N^{Lumi}}{\sqrt{|(\sigma^{Sqrt})^2 - (\sigma^{Lumi})^2|}}$$

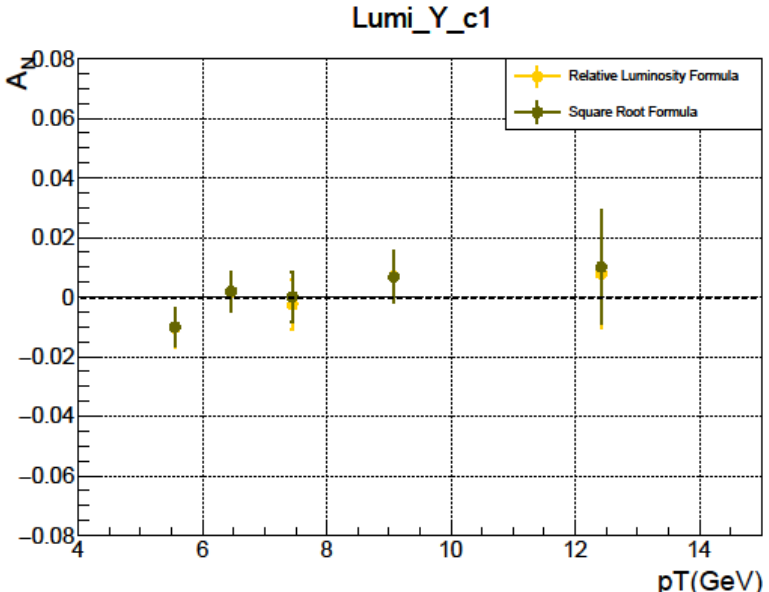
No systematic error

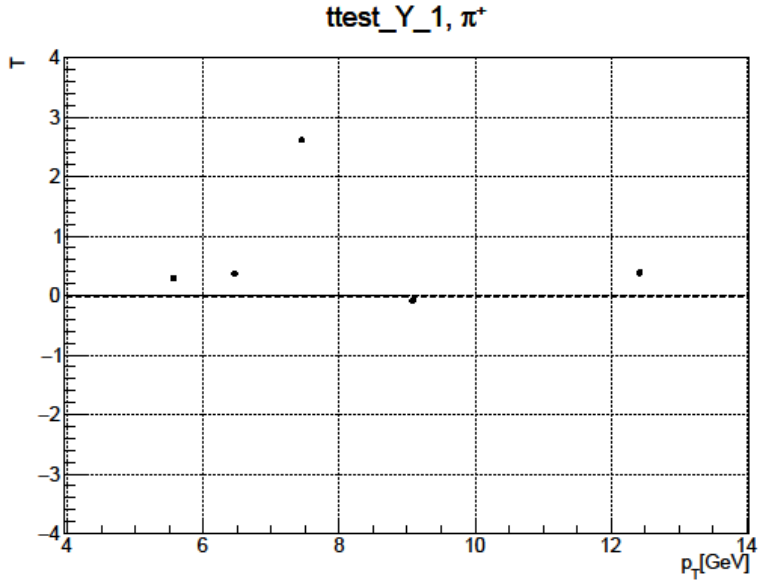
Before background correction

A_N - Formula Comparison (Yellow)







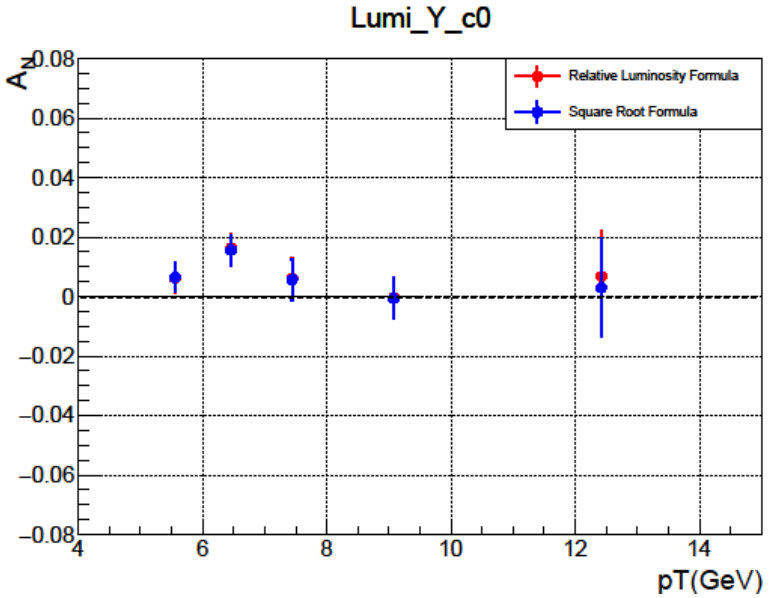


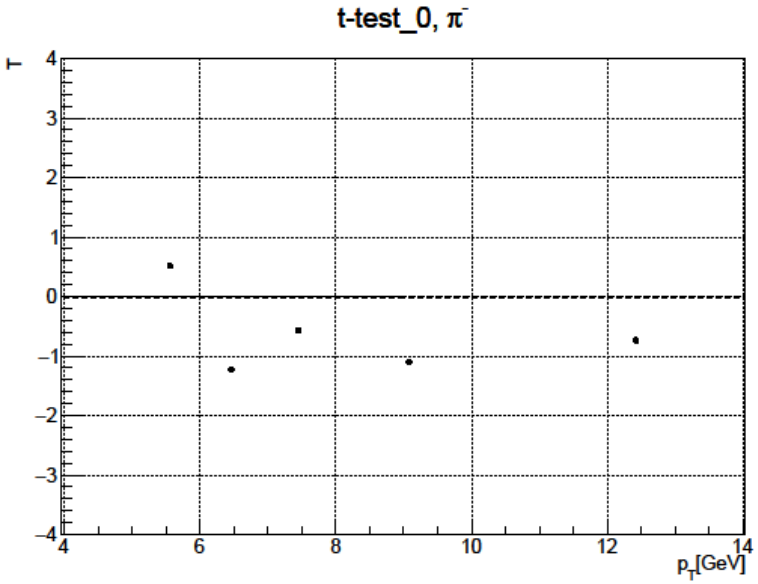
$$T(p_T) = \frac{A_N^{Sqrt} - A_N^{Lumi}}{\sqrt{|(\sigma^{Sqrt})^2 - (\sigma^{Lumi})^2|}}$$

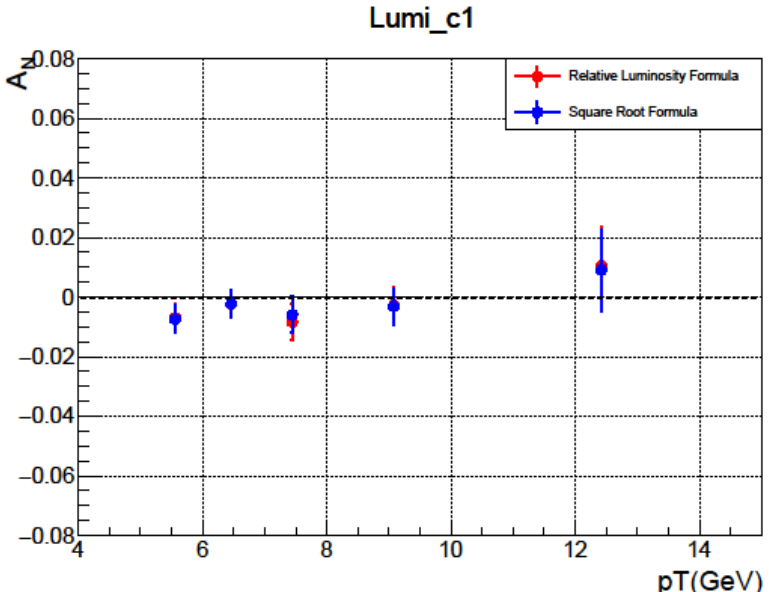
No systematic error

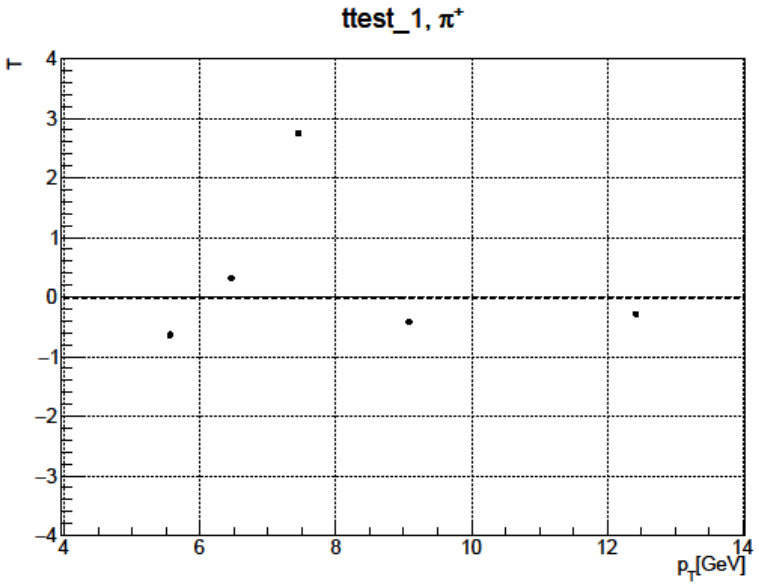
Before background correction

A_N - Formula Comparison (Averaged)









$$T(p_T) = \frac{A_N^{Sqrt} - A_N^{Lumi}}{\sqrt{|(\sigma^{Sqrt})^2 - (\sigma^{Lumi})^2|}}$$

No systematic error

Before background correction

Thank you.

BACK UP

The Proton Spin Structure

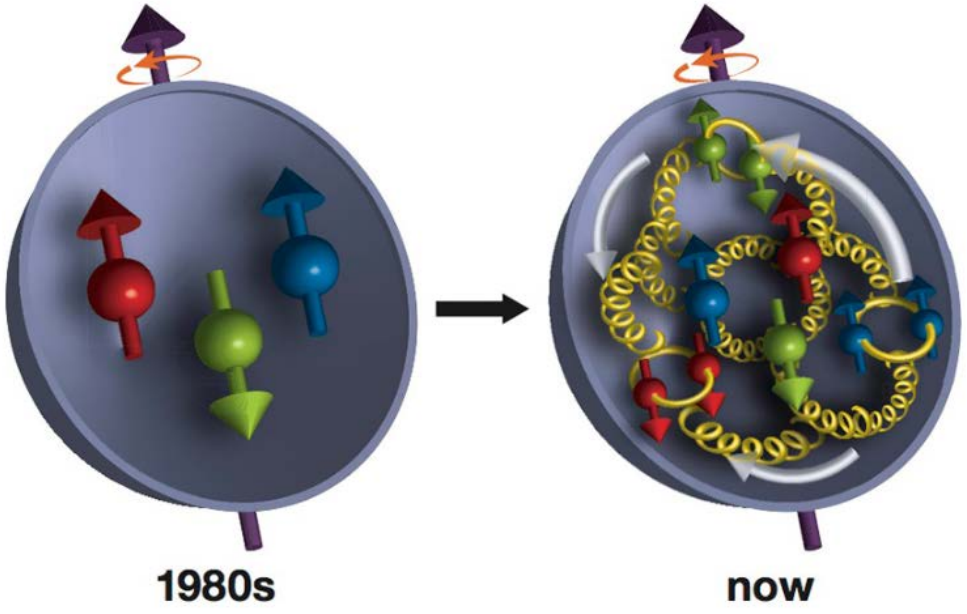
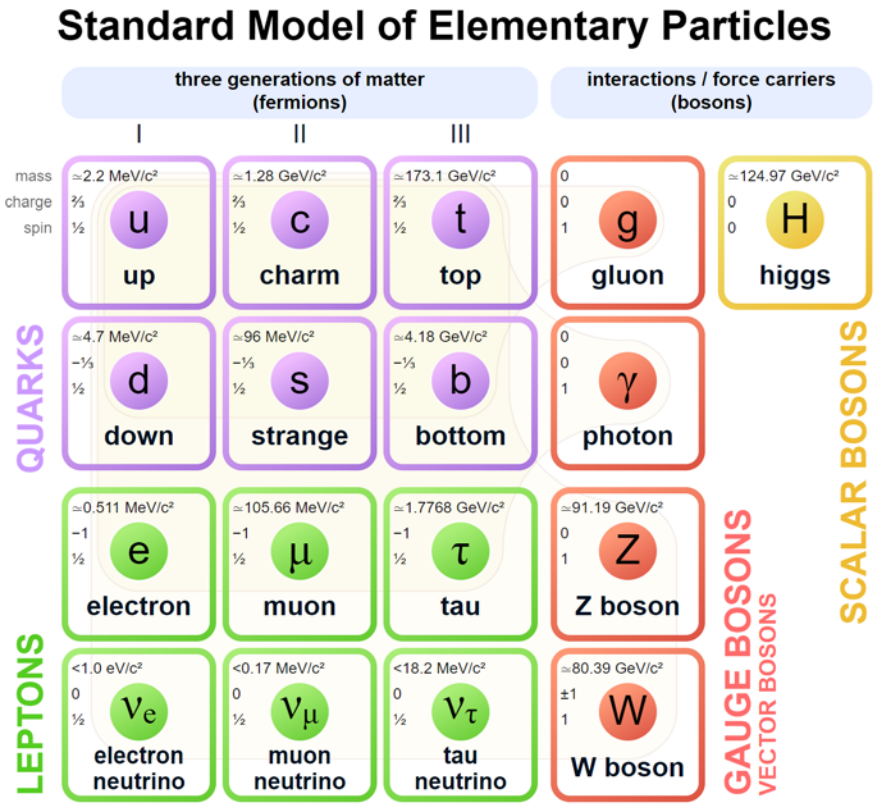


Image courtesy of Brookhaven National Laboratory



In the 1980s, scientists discovered that a proton's three valance quarks (red, green, blue) account for only a fraction of the proton's overall spin. New measurements from RHIC's PHENIX experiment reveal that gluons (yellow corkscrews) contribute as much as or possibly more than the quarks.

The Proton Spin Structure

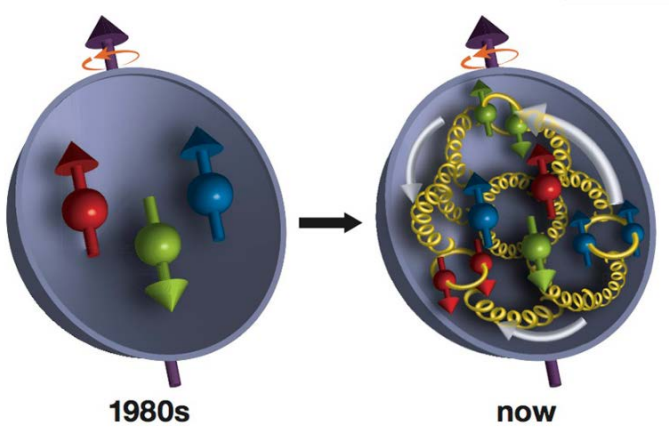


Image courtesy of Brookhaven National Laboratory

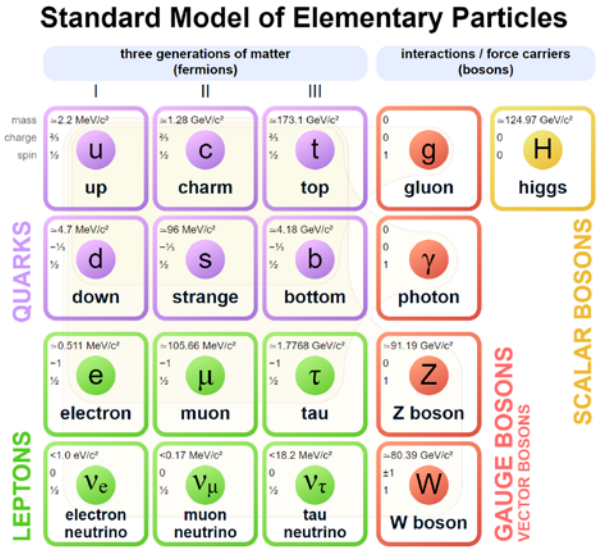
1988 EMC measured:

$\Sigma = 0.123 \pm 0.013 \pm 0.019$ $\Longrightarrow$ Spin Puzzle!

$$S_{proton} = \frac{1}{2} = \frac{1}{2}\Delta q + \Delta G + L_{q,g}$$

$$\frac{1}{2} = \frac{1}{2}\left(\Delta u_v + \Delta d_v + \underbrace{\Delta q_s}\right) + \Delta G + L_q + L_g$$

$$\Delta u_v + \Delta d_v + \Delta q_s + \Delta \bar{u}_s + \Delta \bar{d}_s + \Delta \bar{s}_s$$

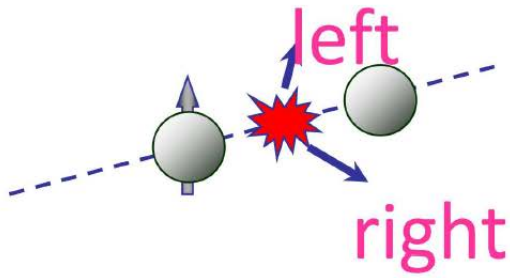


Full description of proton's spin needs
orbital angular momentum

How is proton's spin correlated with the motion of quarks and gluons?
-> Transverse Momentum Dependent (TMD) Functions

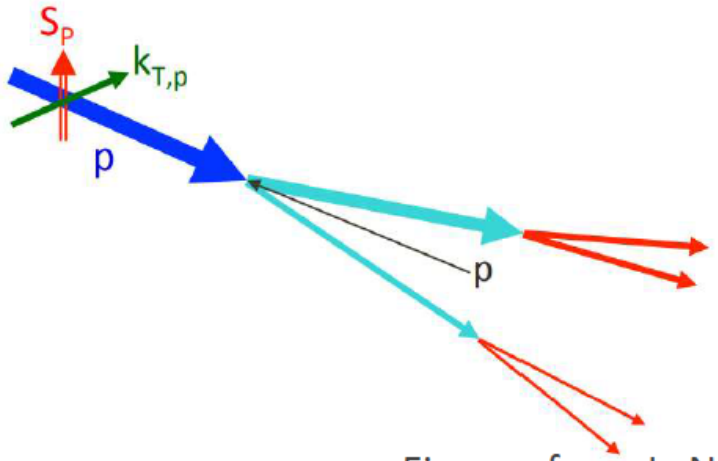
Transverse Single Spin Asymmetry

$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

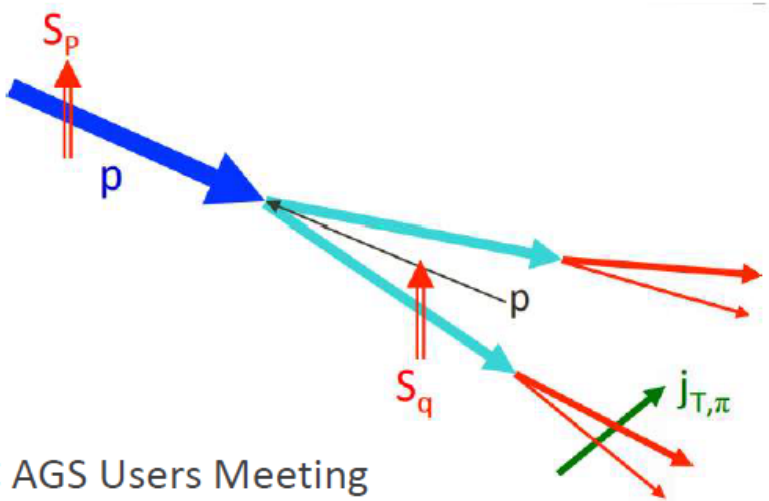


Sources of Transverse SSA's

Initial State Effects:
For example Sivers functions: correlation between proton spin and parton k_T

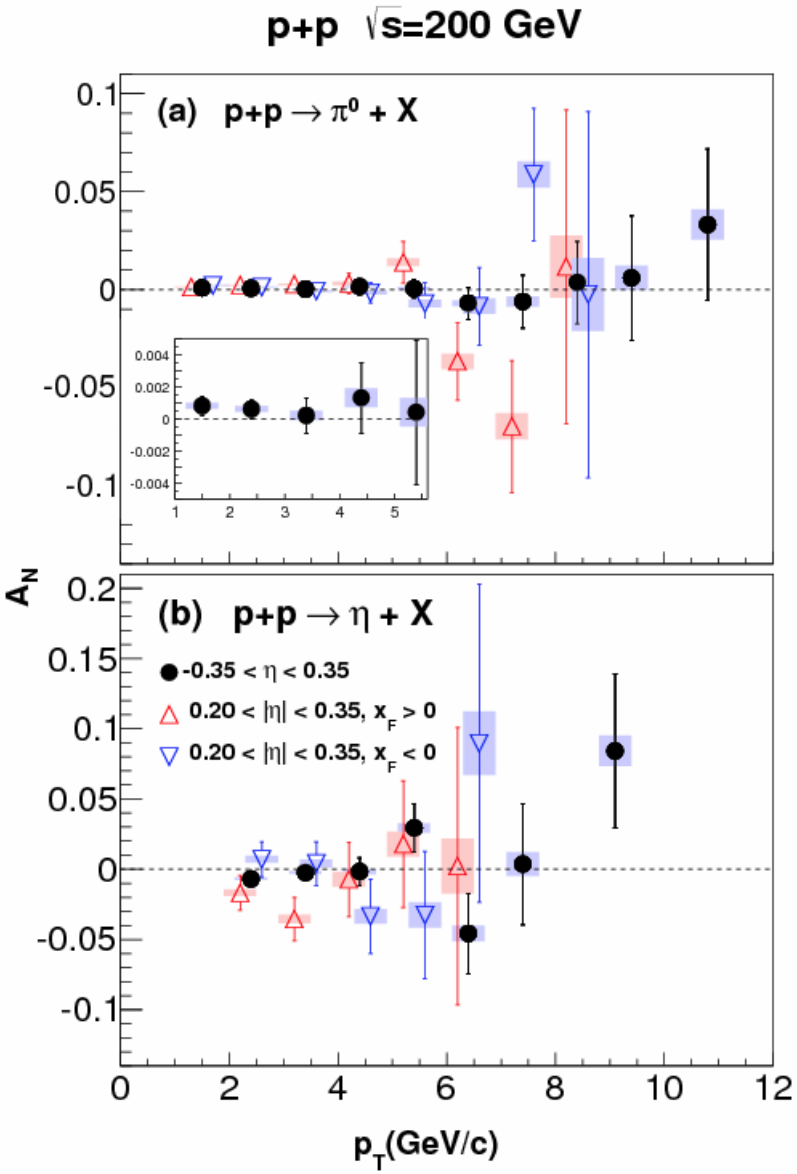


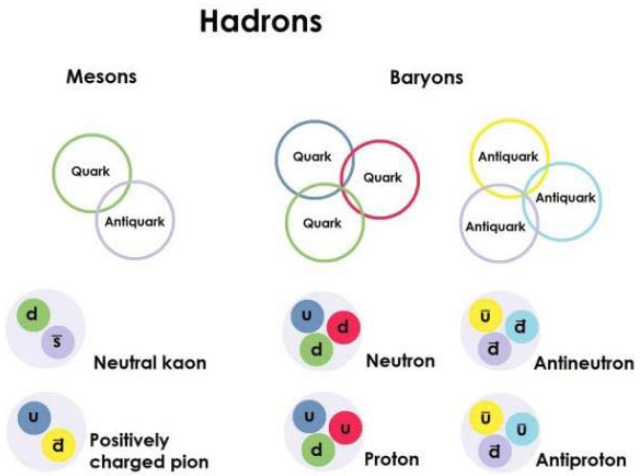
Final State effects:
Collins Function: spin momentum correlation in a Fragmentation Function

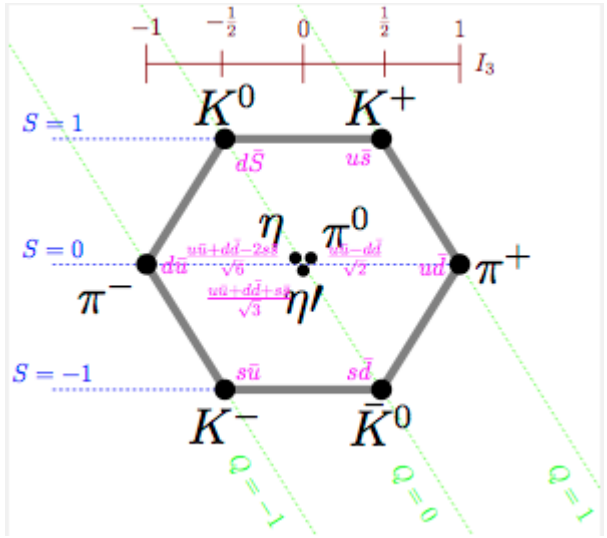


Figures from L. Nogach 2006 RHIC AGS Users Meeting

Transverse Single Spin Asymmetry







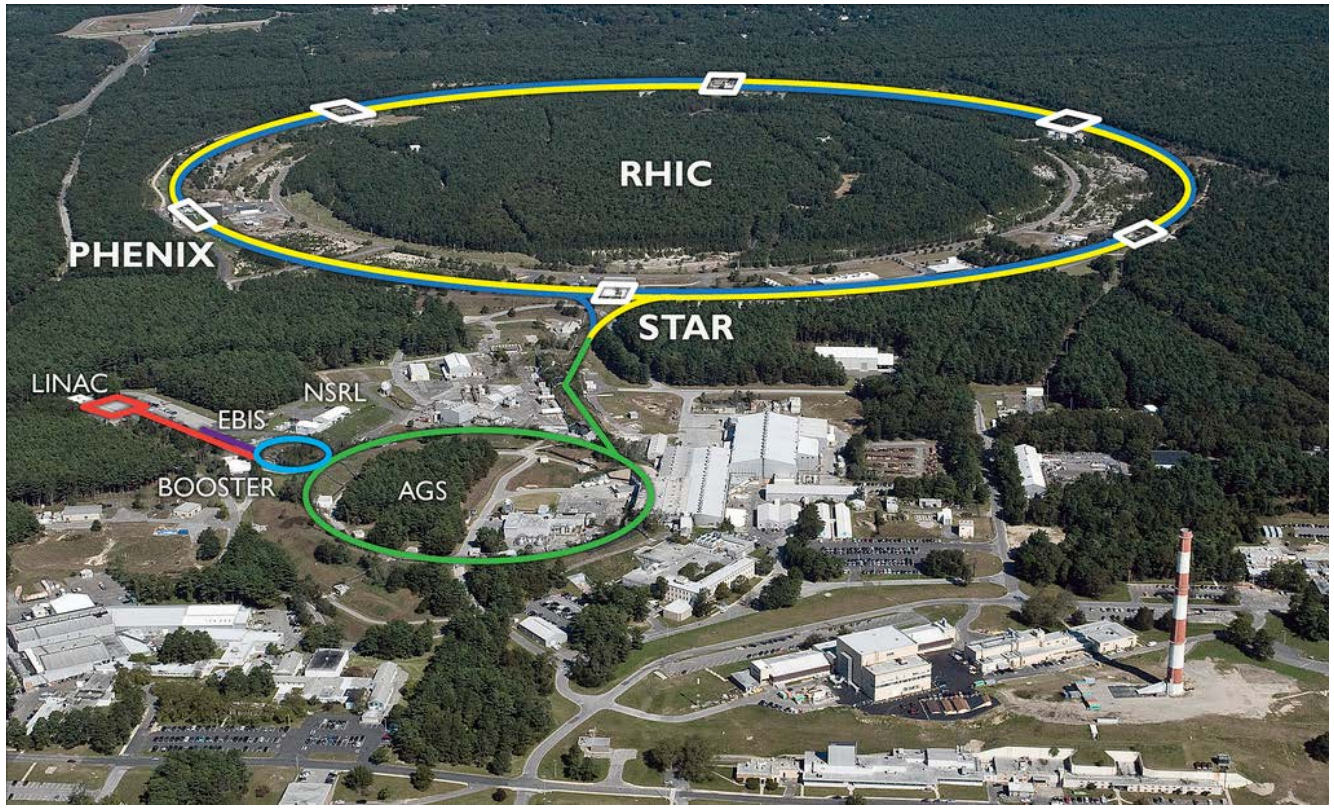
The asymmetry of π0 and η in midrapidity:

- Consistent with zero within errors

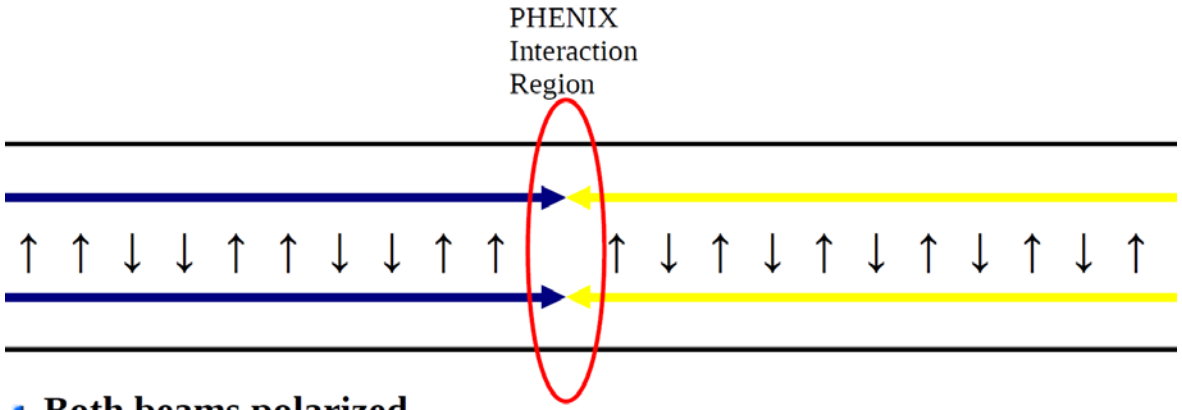
How does it change from neutral to charged hadron?

PRD90, 012006 (2014)

RHIC



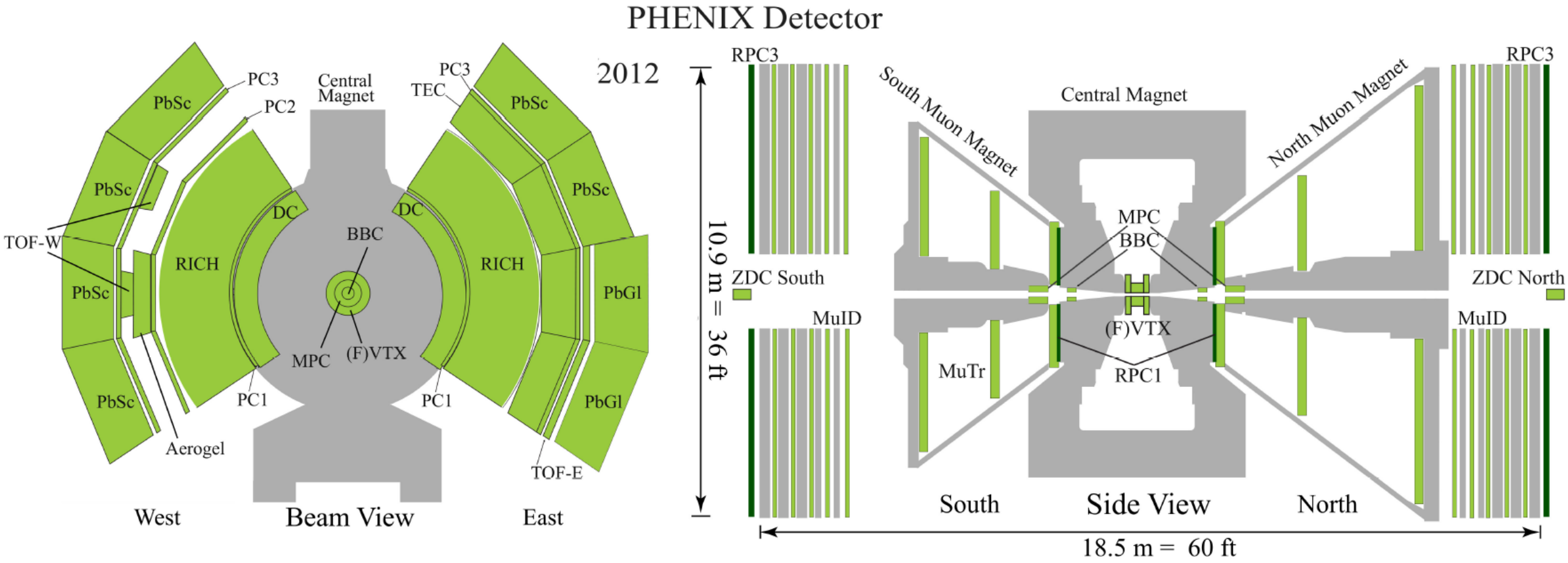
Polarized Beams



- **Both beams polarized**
- Variation of bunch polarization direction minimizes systematic uncertainties in measurement
- For transversely polarized beams, allows for two independent A_N measurements

View of the Brookhaven National Laboratory, NY, USA

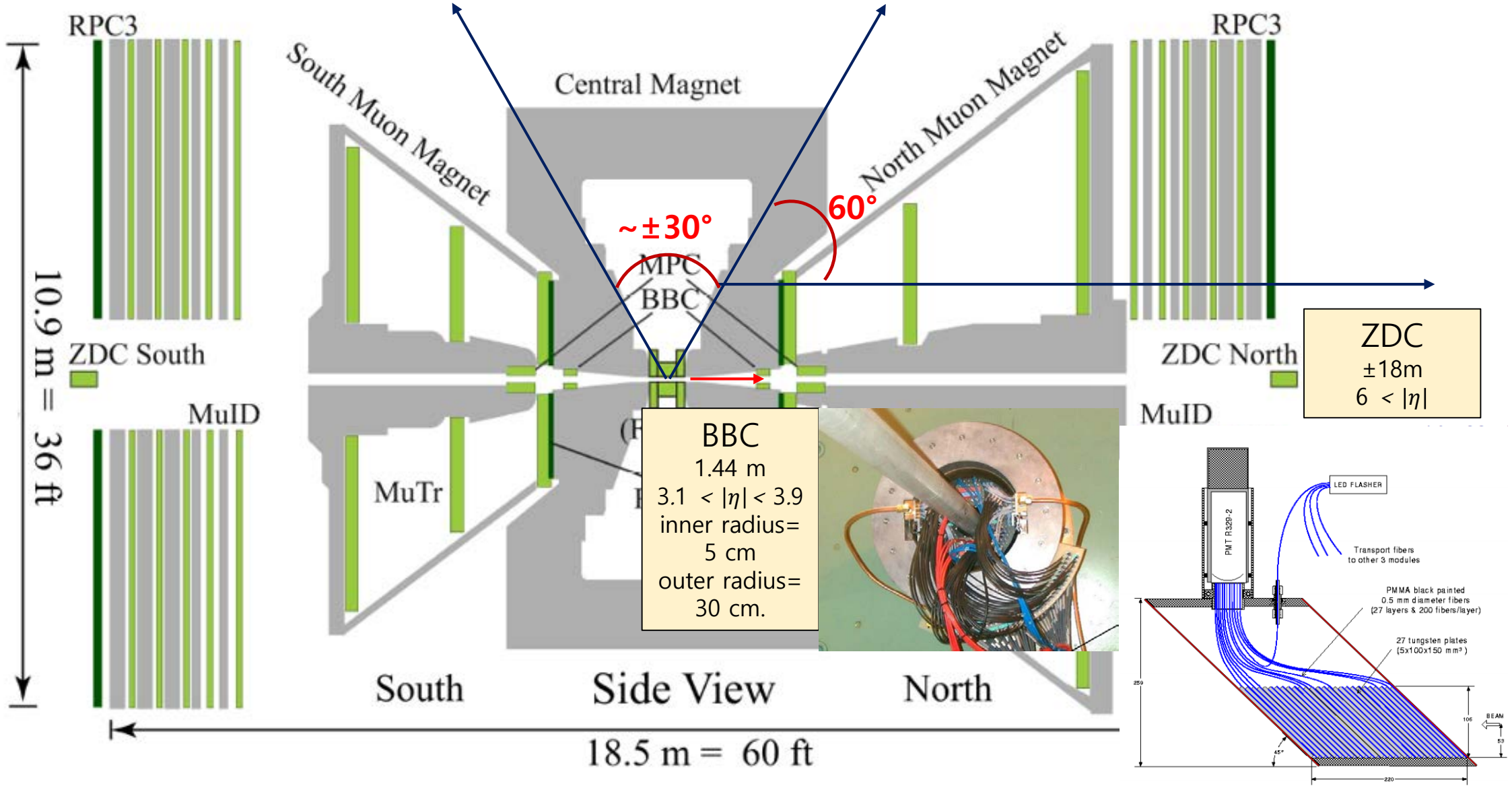
PHENIX Detector System



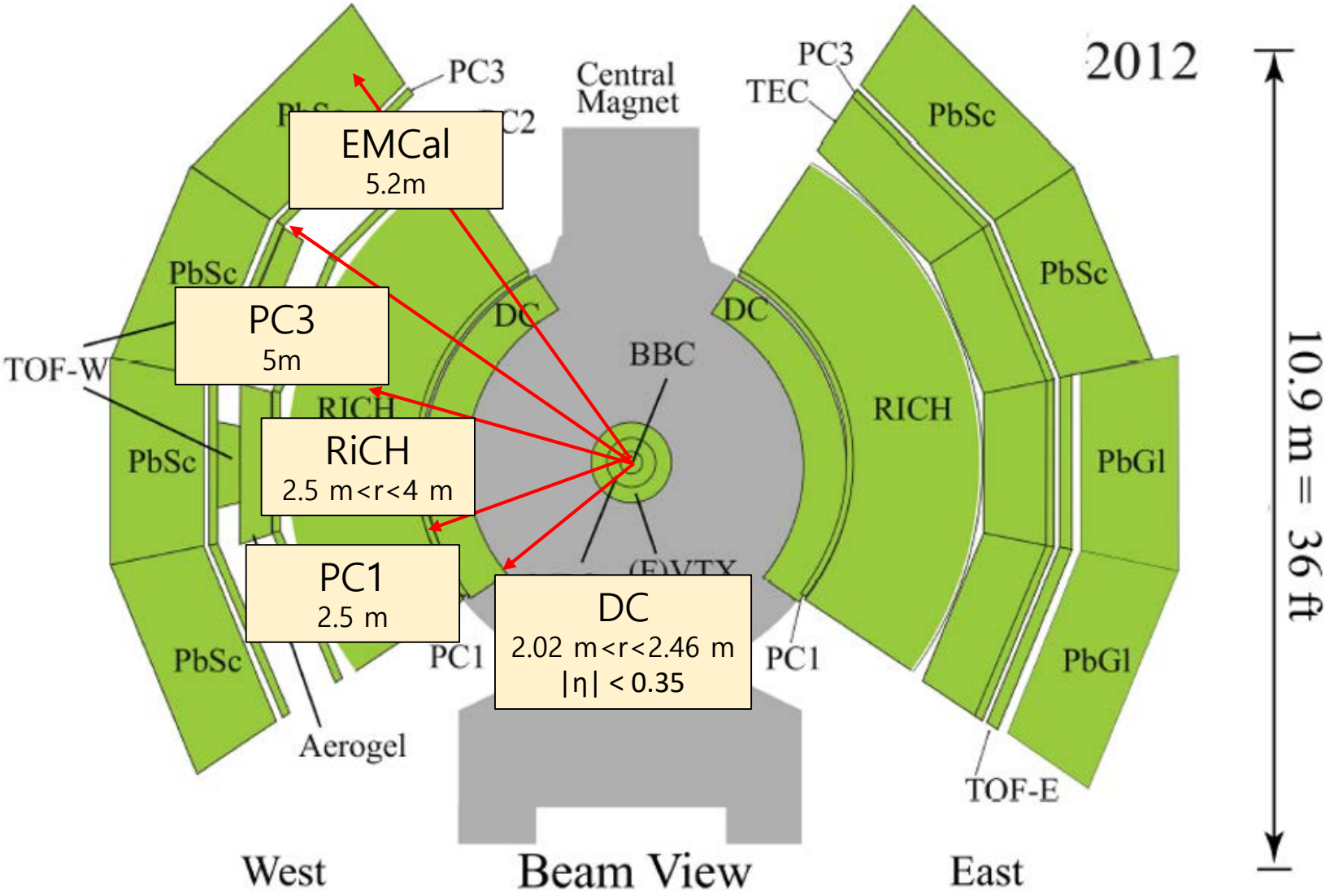
2 central arm: Mid rapidity, $|\eta| < 0.35$

- Identified charged hadrons : π^0, η, direct photon, J/ψ, heavy flavor.

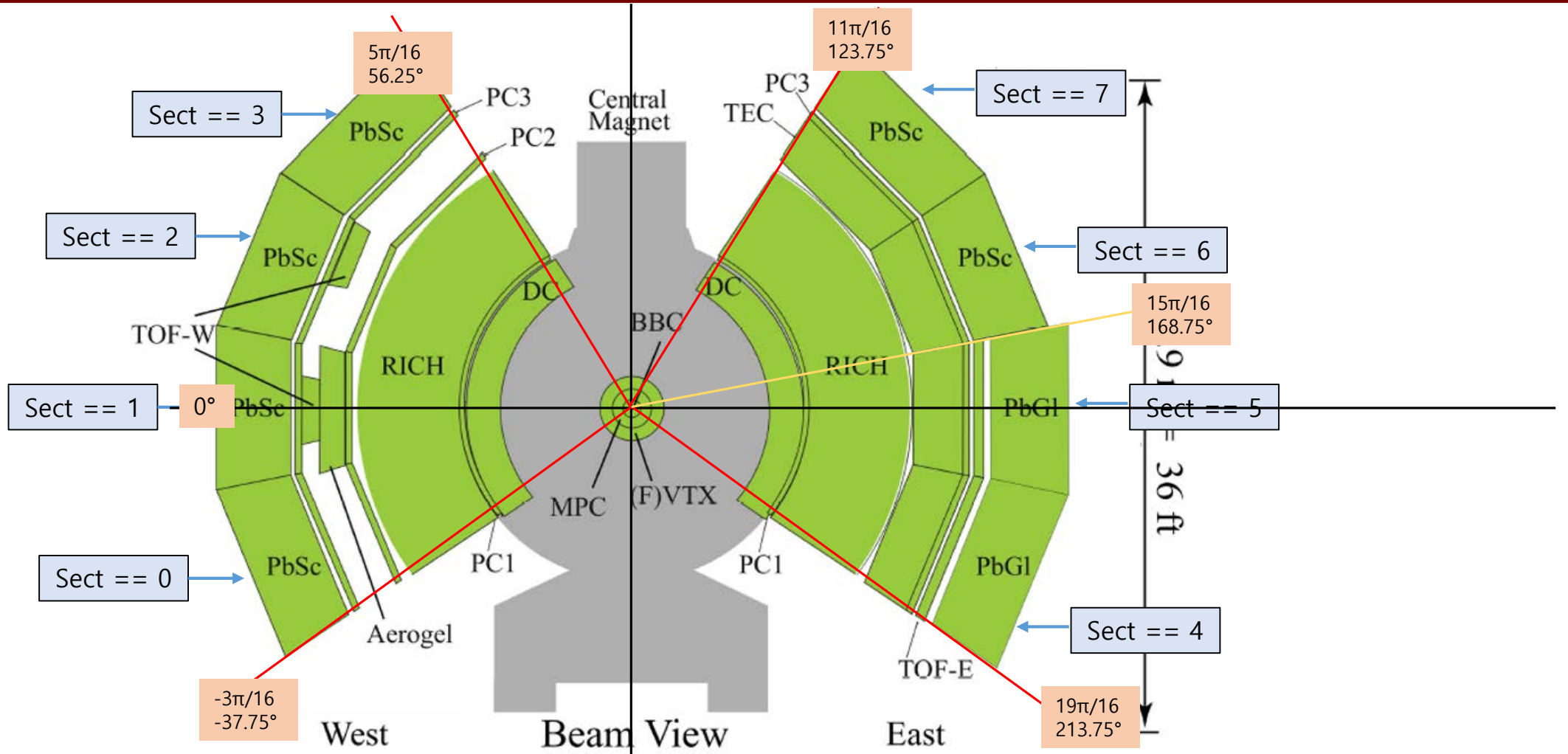
PHENIX Detector System



PHENIX Detector System



PHENIX Detector System



Rel. luminosity(Norbert's)

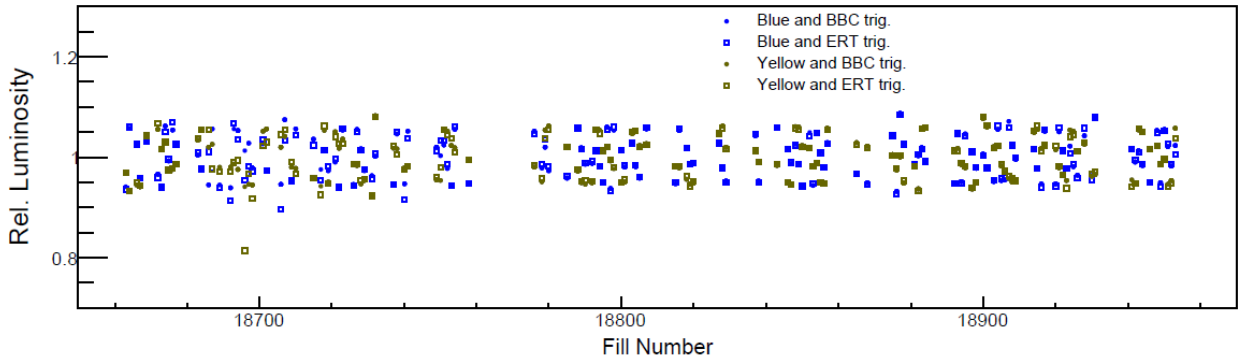


Figure 41: Relative luminosity factor calculated for each fill in Run-15 $p+p$.

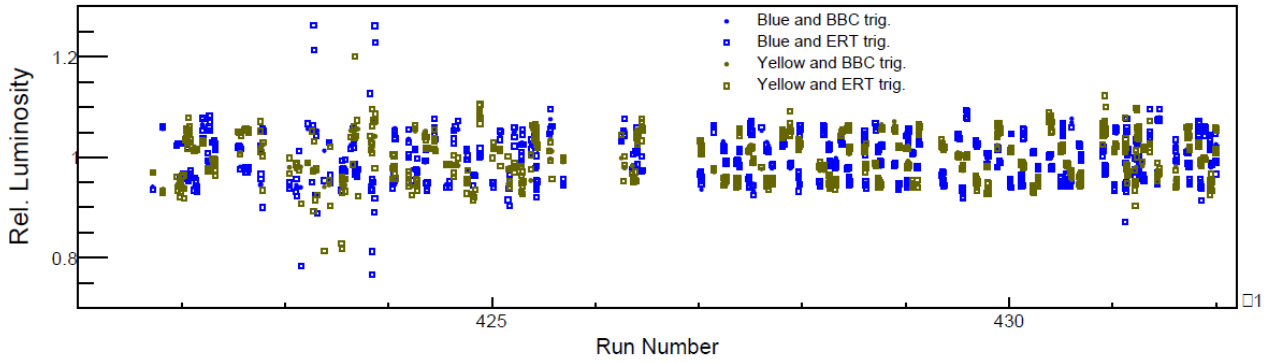


Figure 42: Relative luminosity factor calculated for each run in Run-15 $p+p$.

AN 1269(Norbert's)