



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

Radiation Lab. meeting



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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

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

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

Averaging Over Fills (The Weighted Mean Formula)

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

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

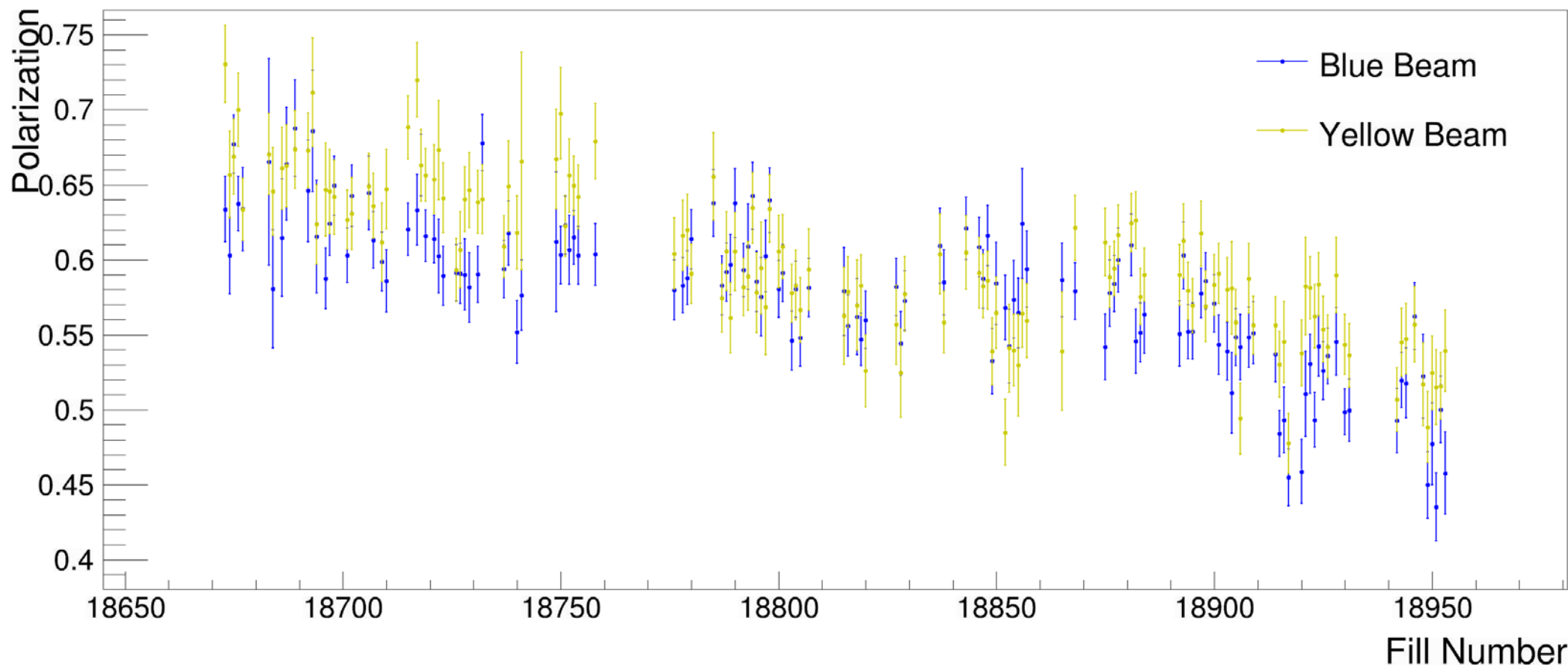
Relative Luminosity Formula

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

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

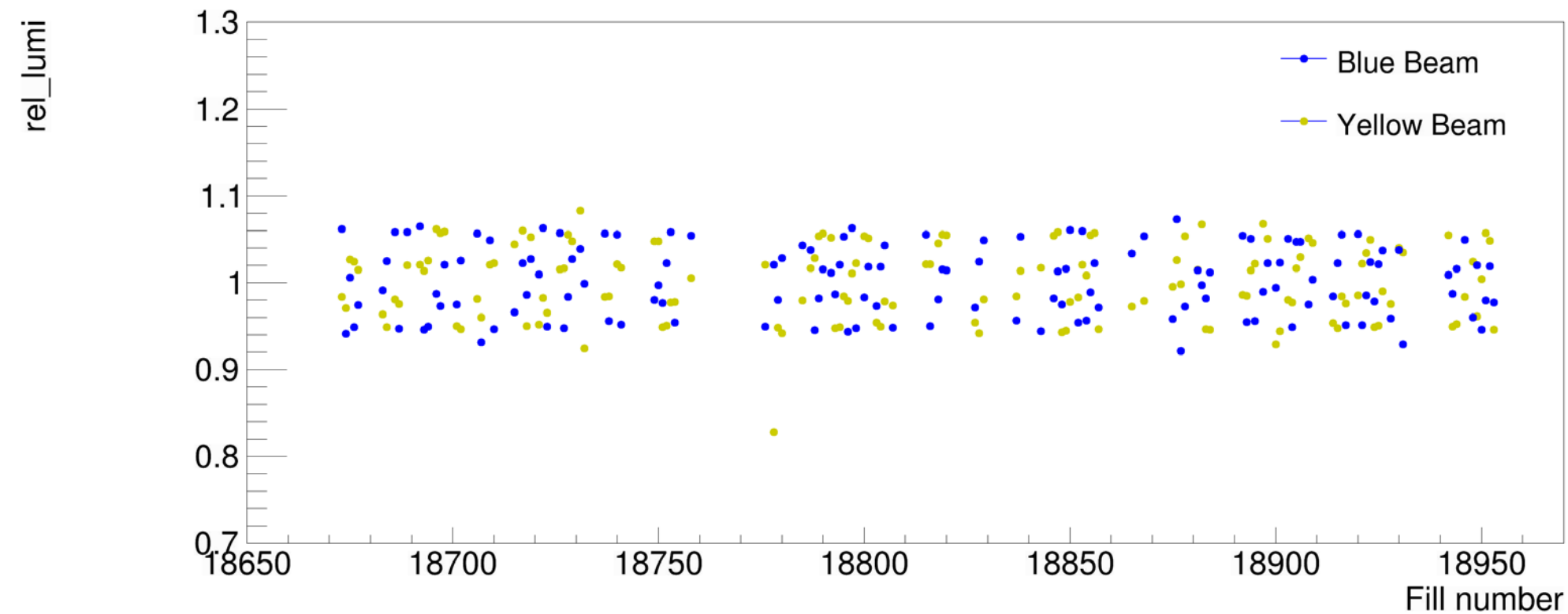
Polarization vs filnumber

Polarization



- 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 filnumber

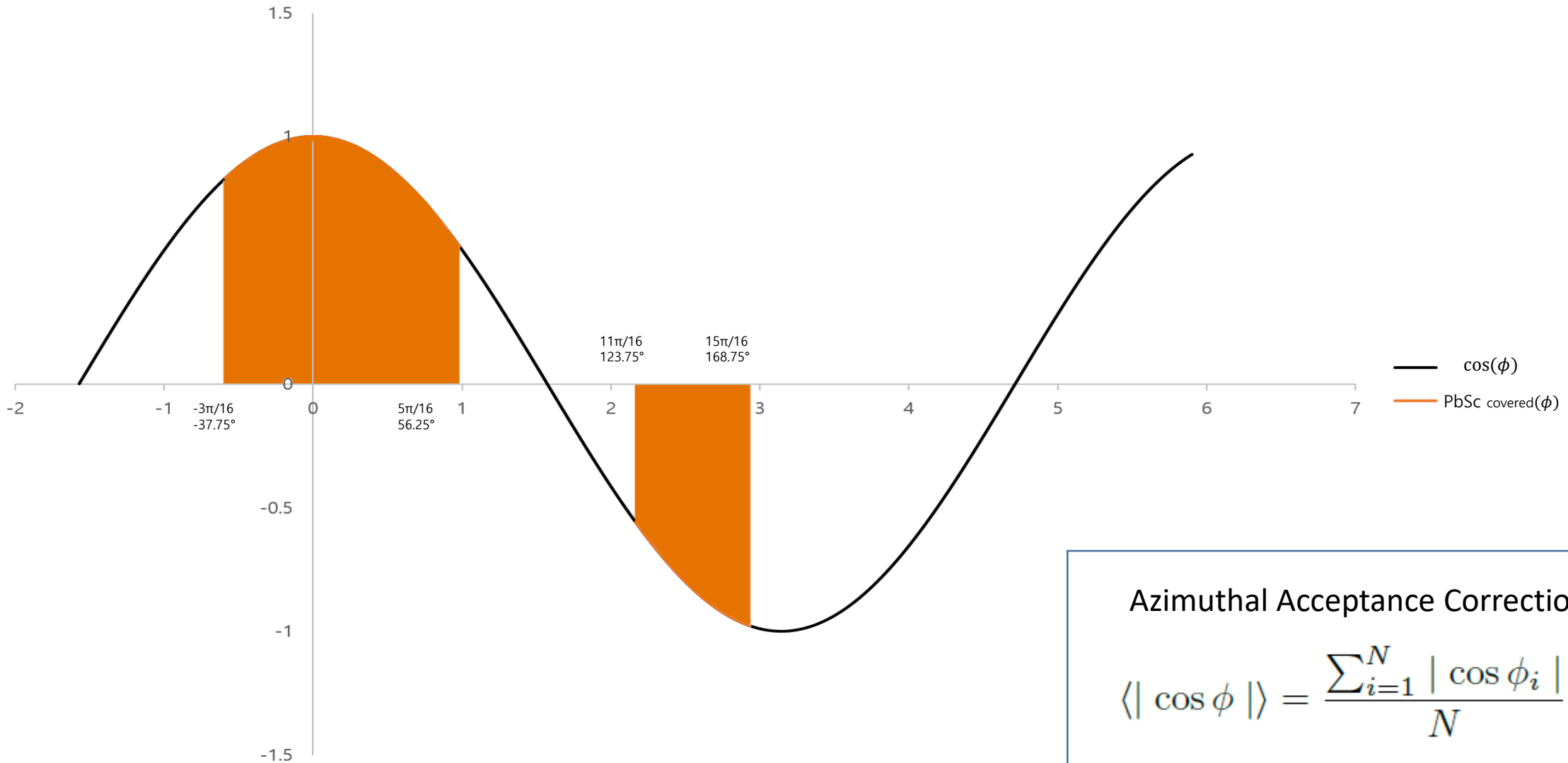


$$R = L_{\uparrow} / L_{\downarrow}$$

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

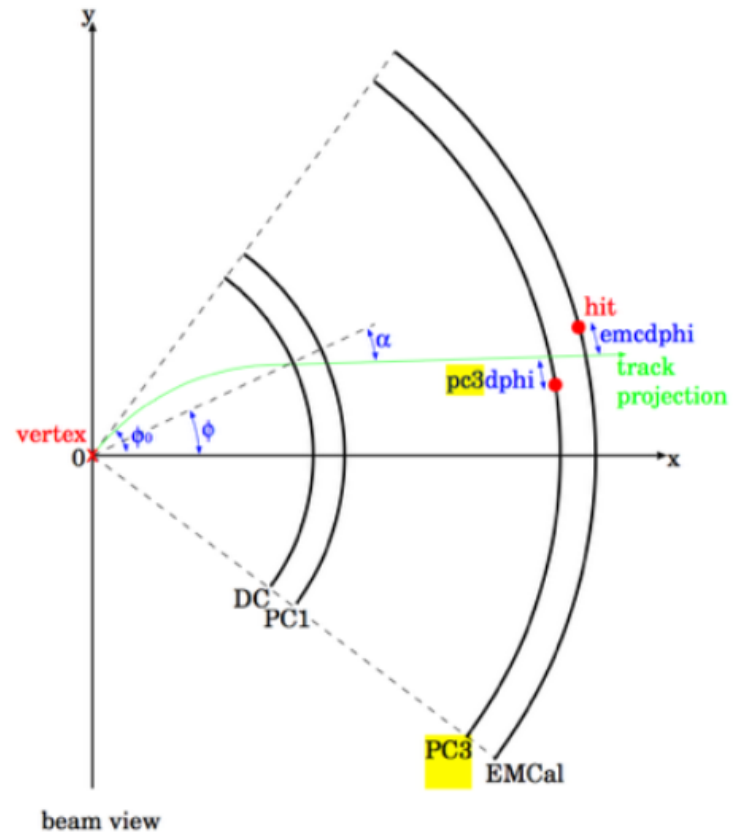


Azimuthal Acceptance Correction

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

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`.

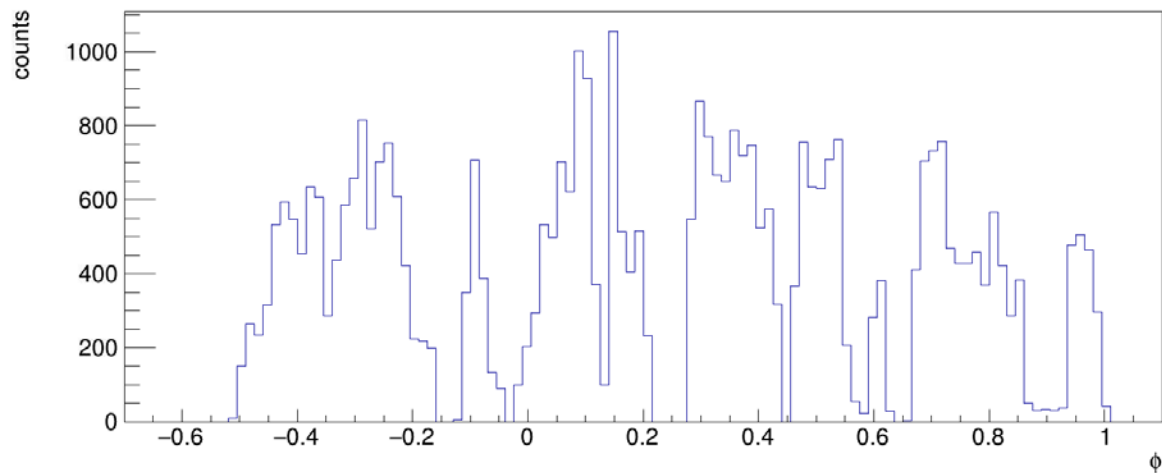


I using "phi0"

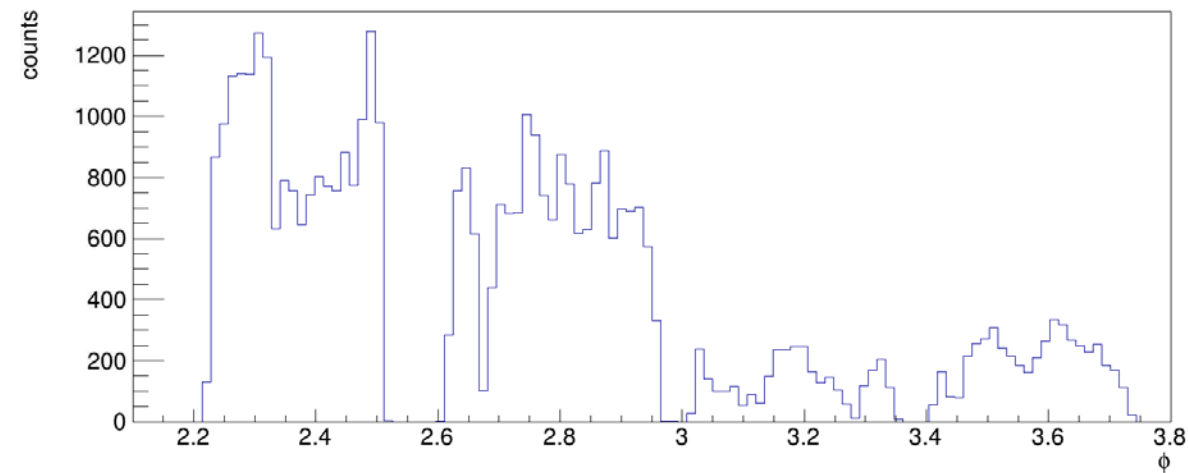
By Using " `_trk->get_phi0();` "

Phi distribution $5 \text{ GeV} < p_T < 6 \text{ GeV}$

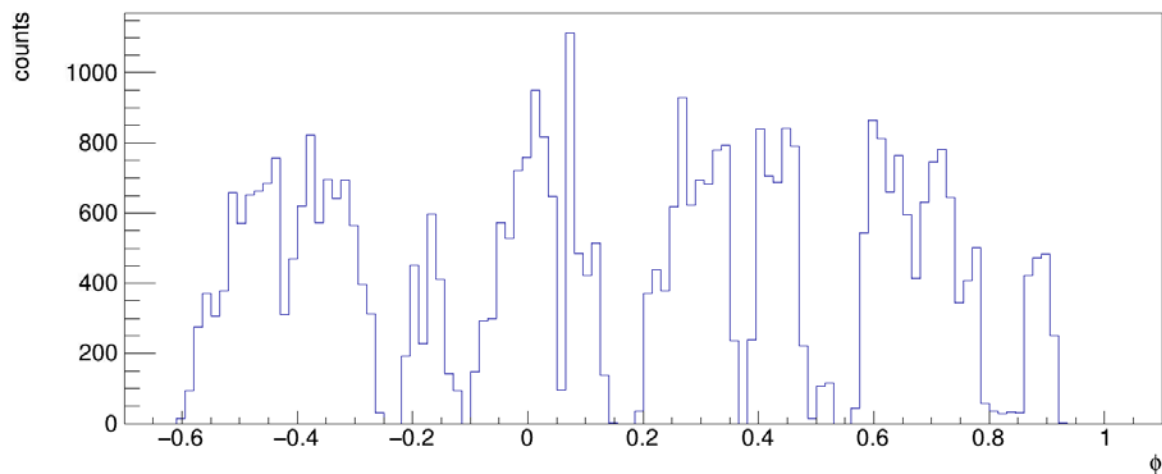
ϕ (West, π^-), $5 \text{ GeV} < p_T < 6 \text{ GeV}$



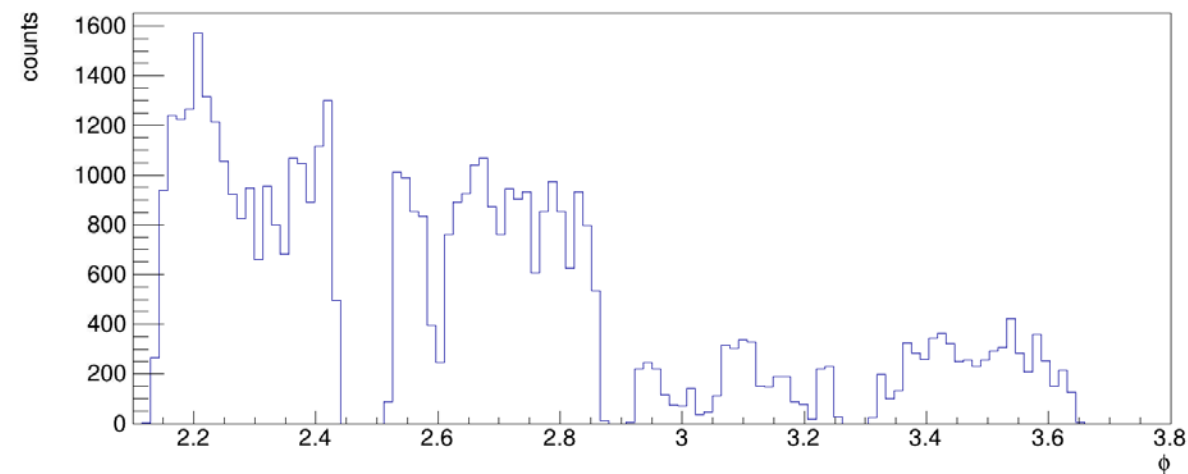
ϕ (East, π^-), $5 \text{ GeV} < p_T < 6 \text{ GeV}$



ϕ (West, π^+), $5 \text{ GeV} < p_T < 6 \text{ GeV}$

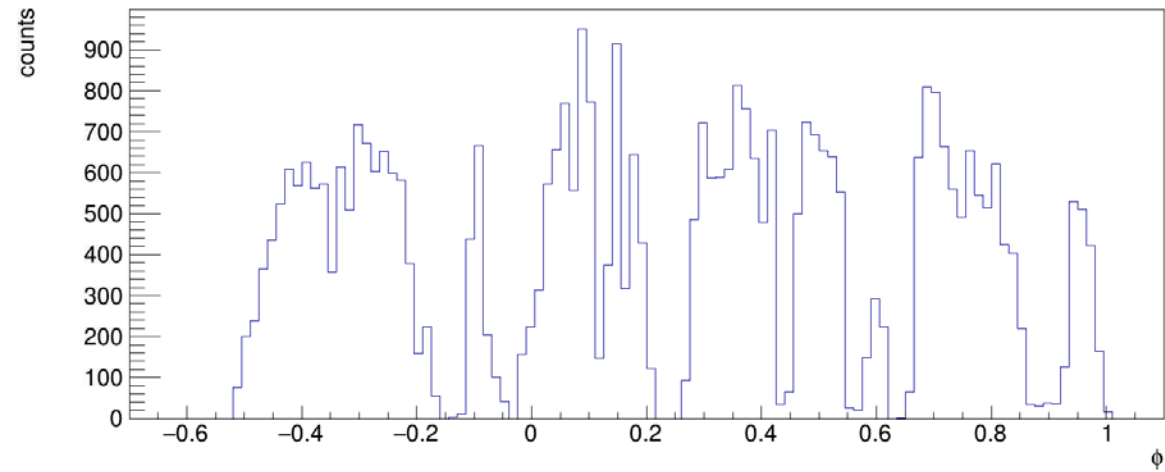


ϕ (East, π^+), $5 \text{ GeV} < p_T < 6 \text{ GeV}$

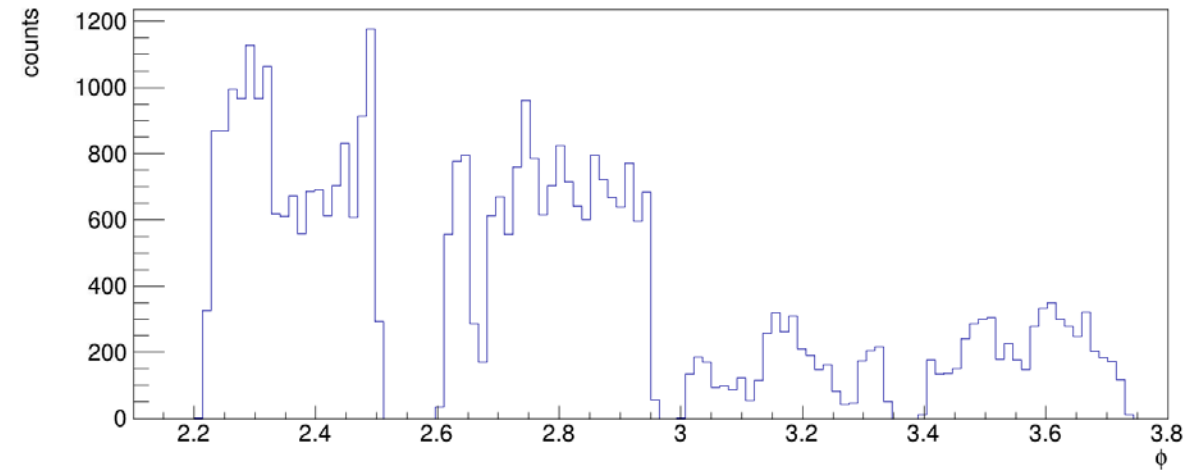


Phi distribution $6 \text{ GeV} < p_T < 7 \text{ GeV}$

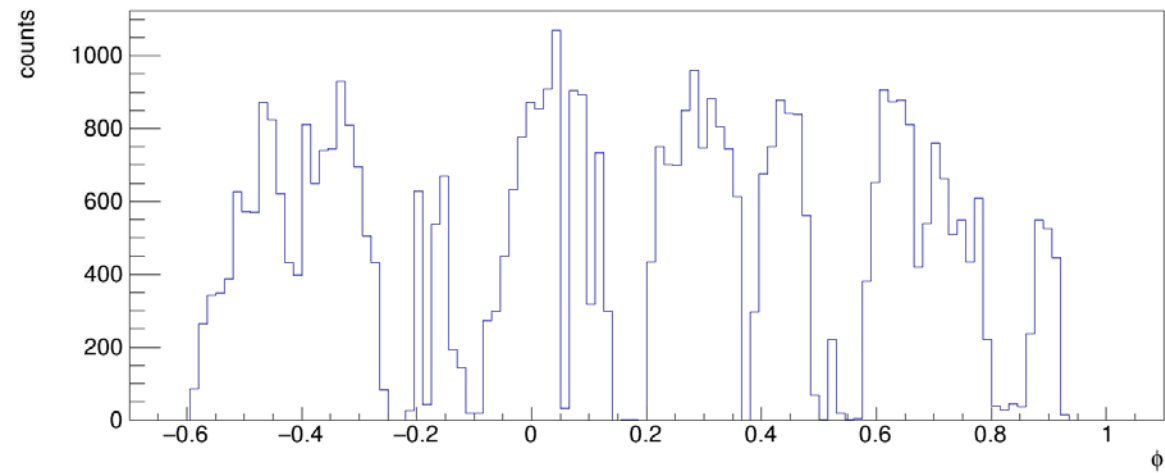
ϕ (West, π^-), $6 \text{ GeV} < p_T < 7 \text{ GeV}$



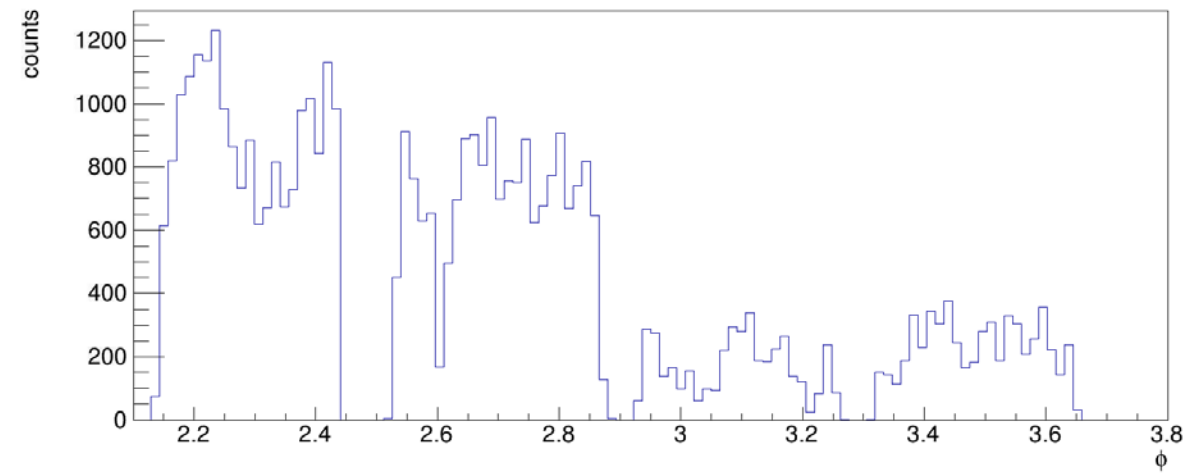
ϕ (East, π^-), $6 \text{ GeV} < p_T < 7 \text{ GeV}$



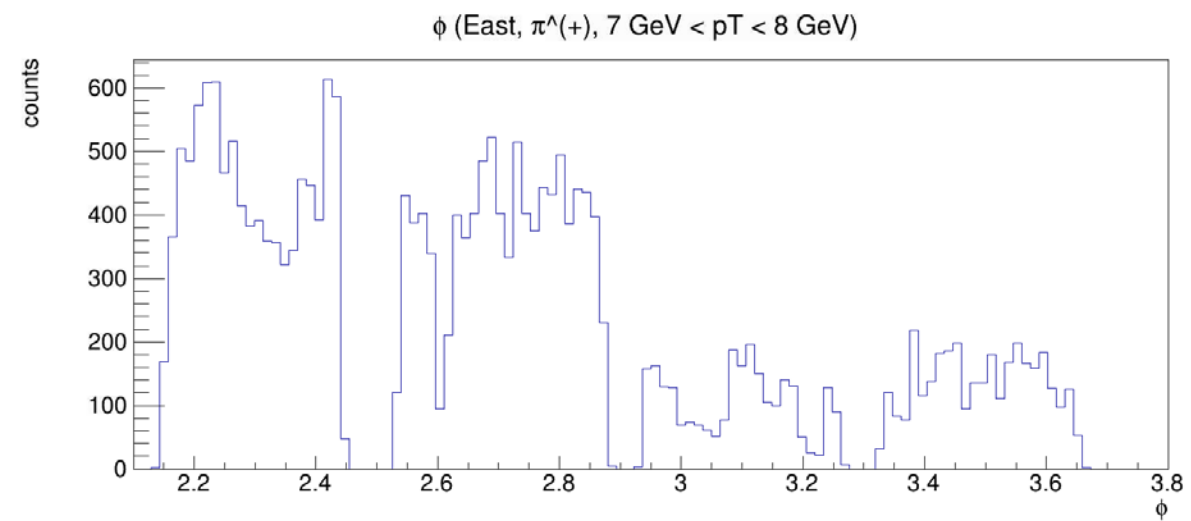
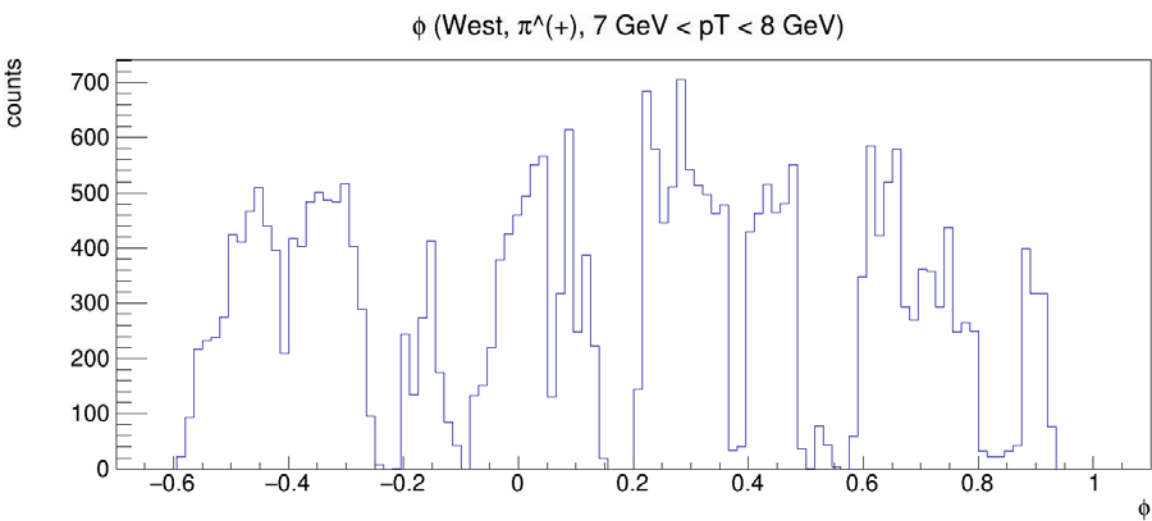
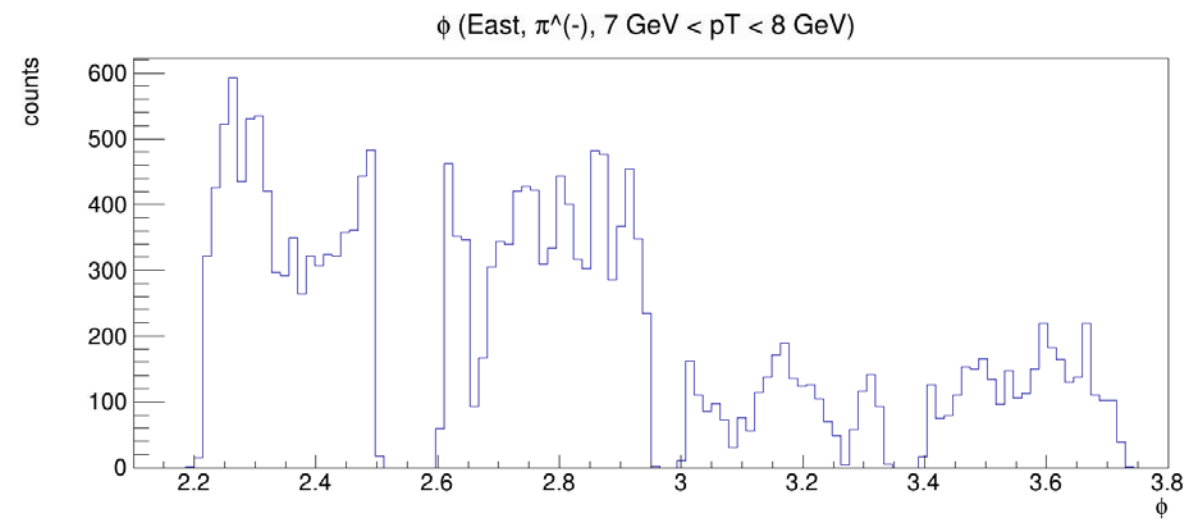
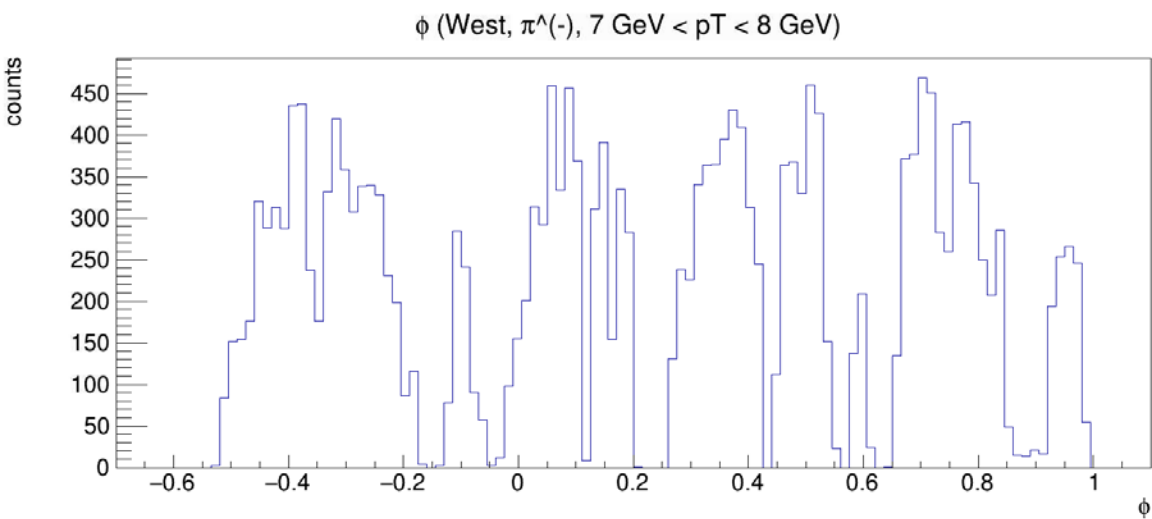
ϕ (West, π^+), $6 \text{ GeV} < p_T < 7 \text{ GeV}$



ϕ (East, π^+), $6 \text{ GeV} < p_T < 7 \text{ GeV}$



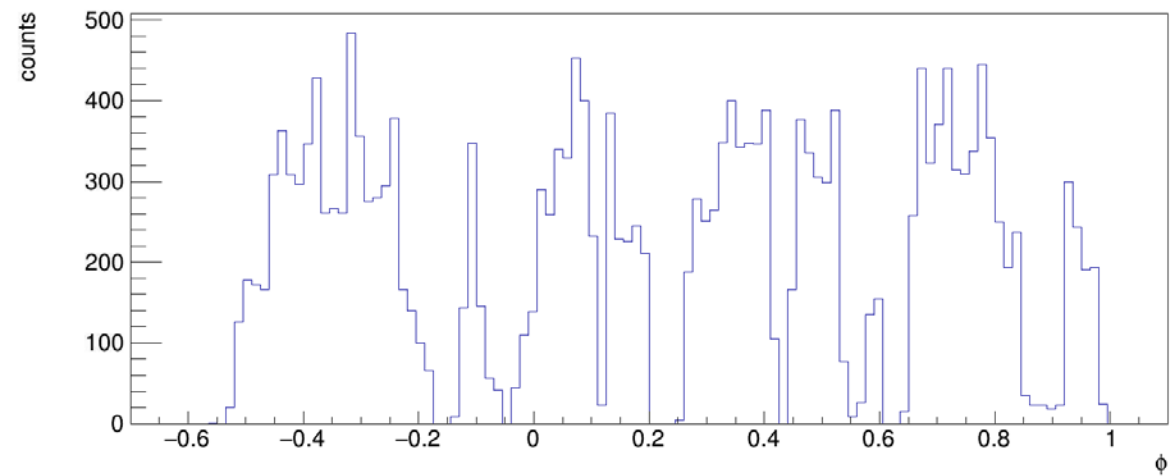
Phi distribution $7 \text{ GeV} < p_T < 8 \text{ GeV}$



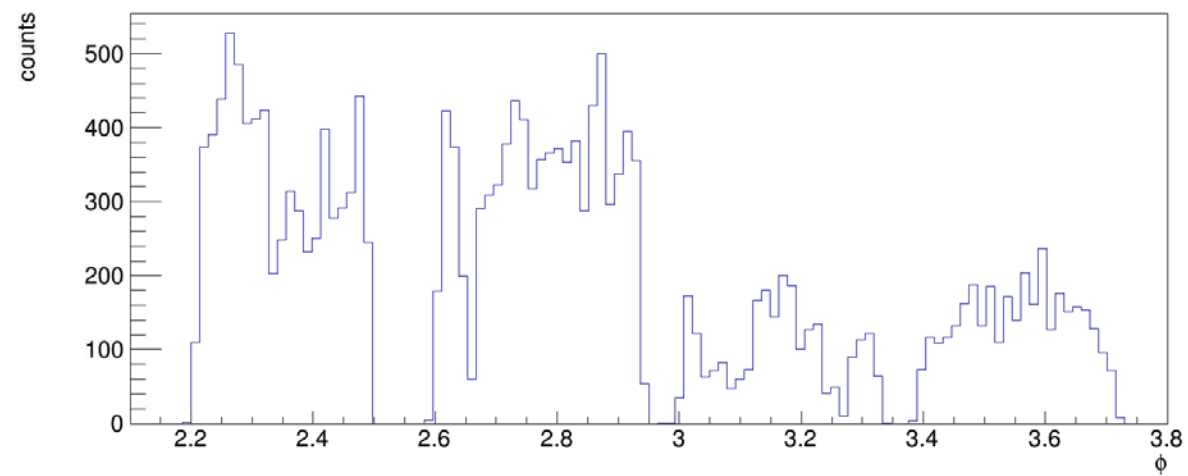
Phi distribution $8 \text{ GeV} < p_T < 11 \text{ GeV}$



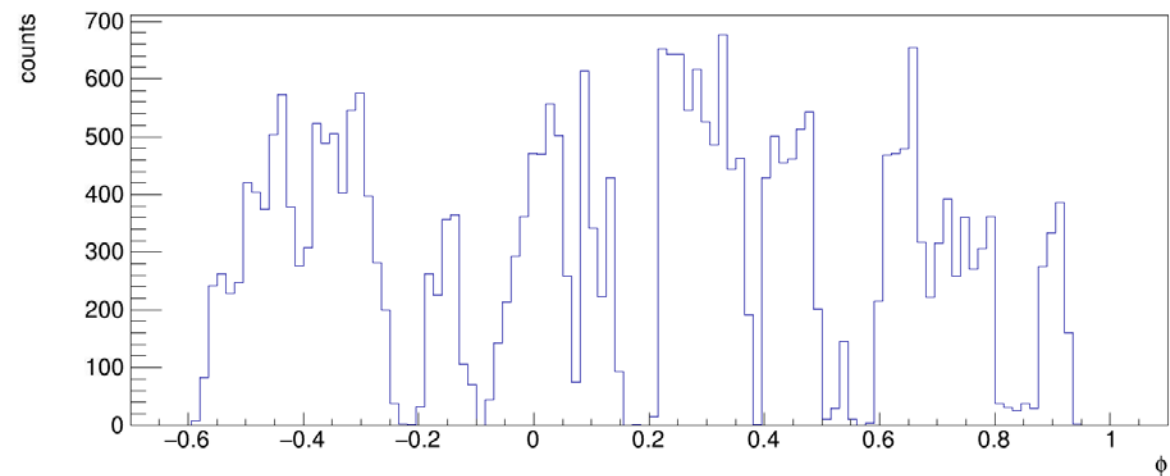
ϕ (West, π^-), $8 \text{ GeV} < p_T < 11 \text{ GeV}$



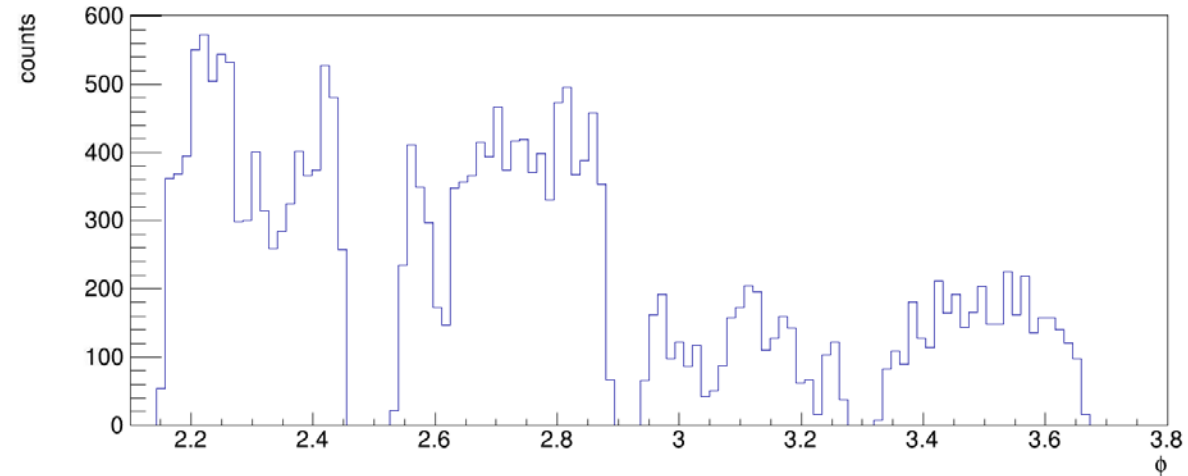
ϕ (East, π^-), $8 \text{ GeV} < p_T < 11 \text{ GeV}$



ϕ (West, π^+), $8 \text{ GeV} < p_T < 11 \text{ GeV}$

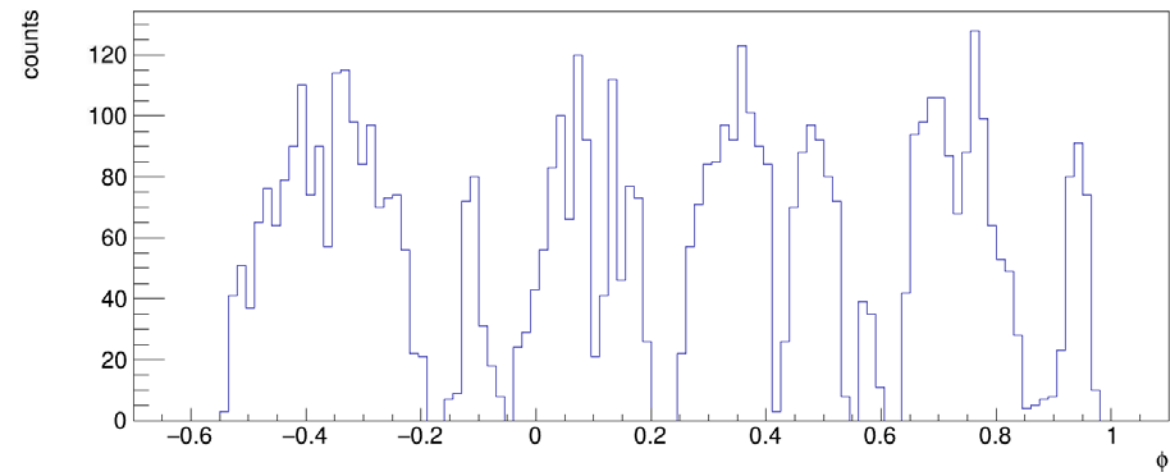


ϕ (East, π^+), $8 \text{ GeV} < p_T < 11 \text{ GeV}$

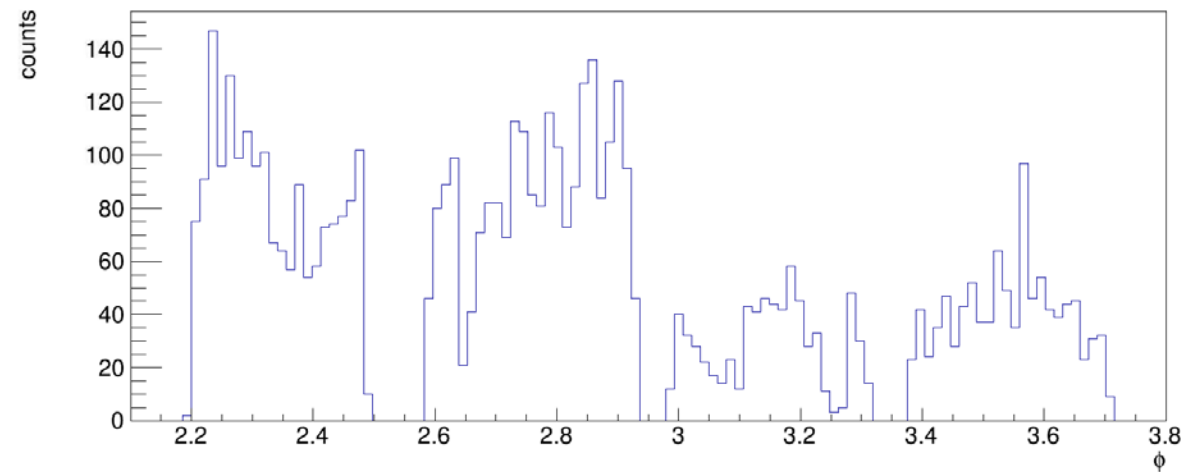


Phi distribution $11 \text{ GeV} < p_T < 15 \text{ GeV}$

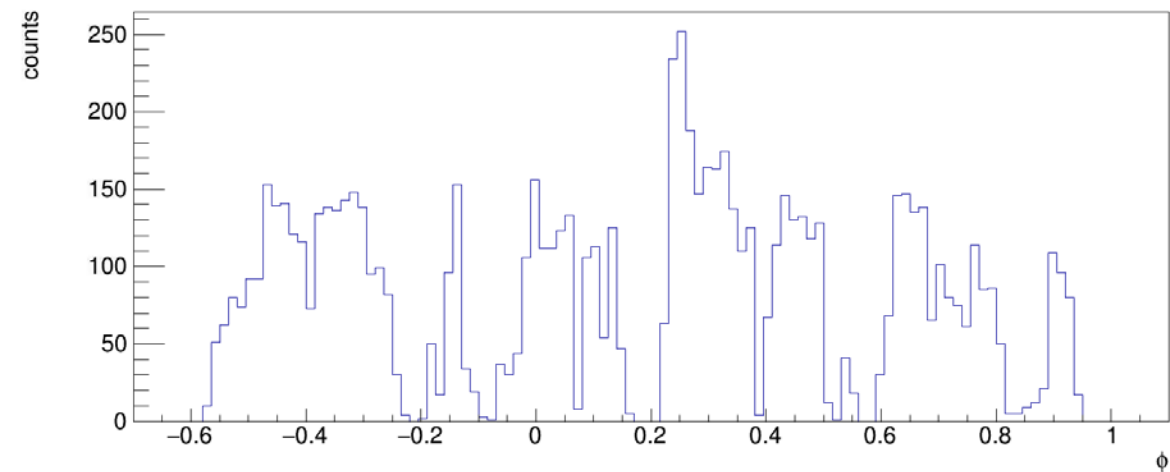
ϕ (West, π^-), $11 \text{ GeV} < p_T < 15 \text{ GeV}$



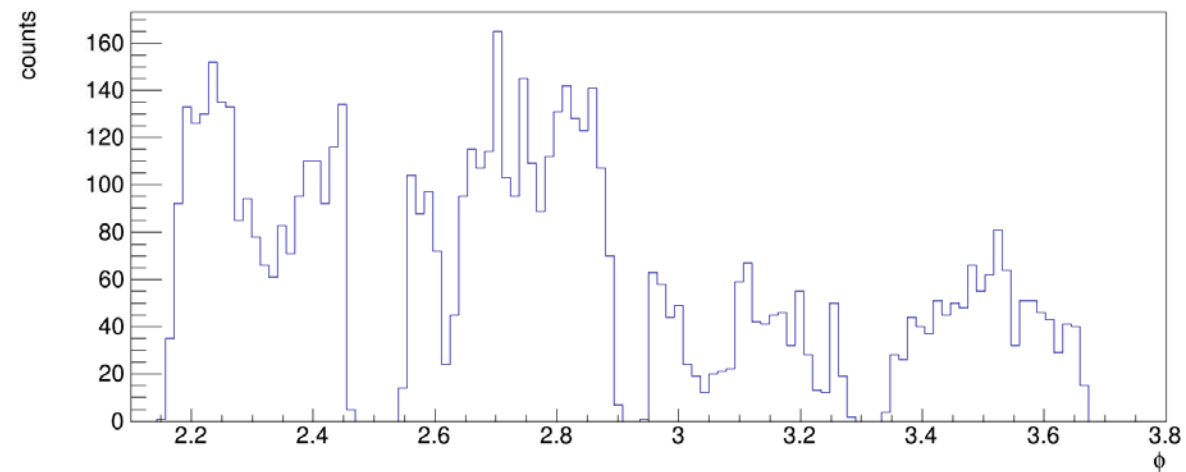
ϕ (East, π^-), $11 \text{ GeV} < p_T < 15 \text{ GeV}$

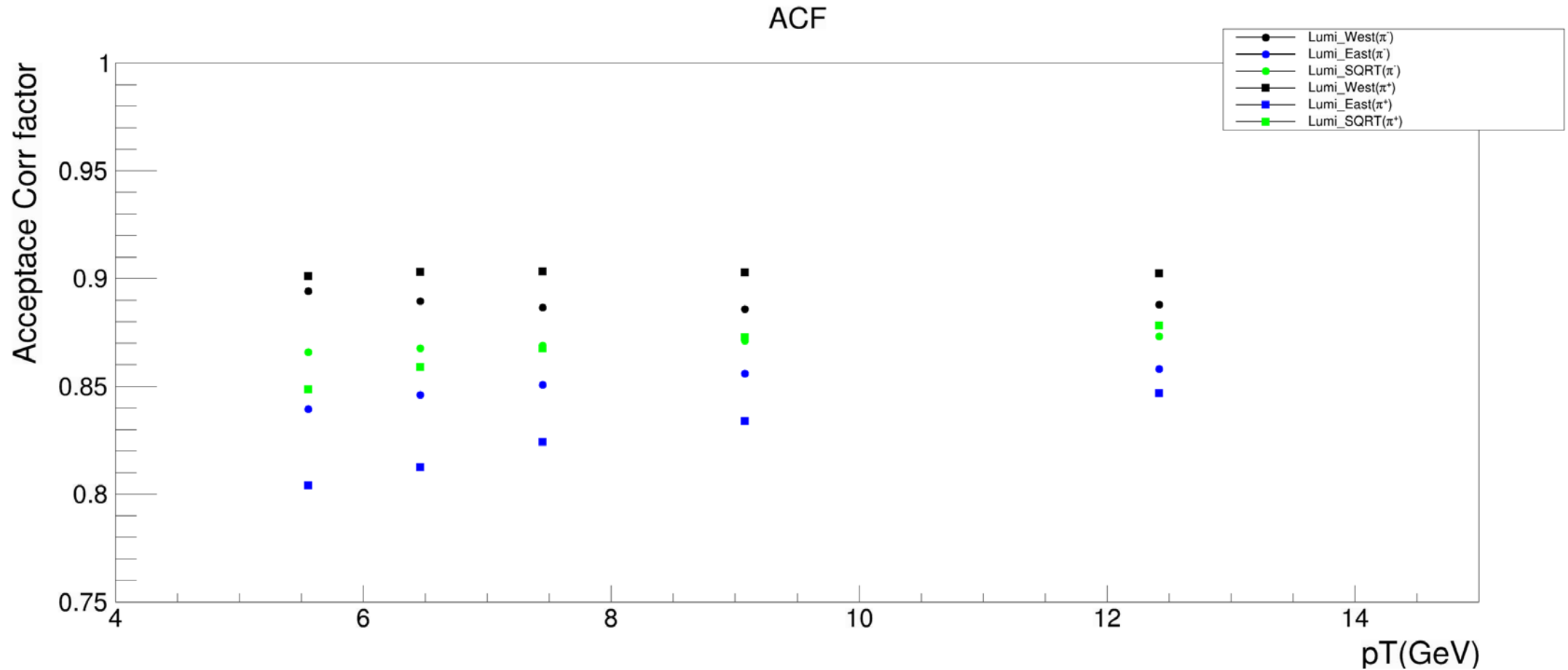


ϕ (West, π^+), $11 \text{ GeV} < p_T < 15 \text{ GeV}$



ϕ (East, π^+), $11 \text{ GeV} < p_T < 15 \text{ GeV}$



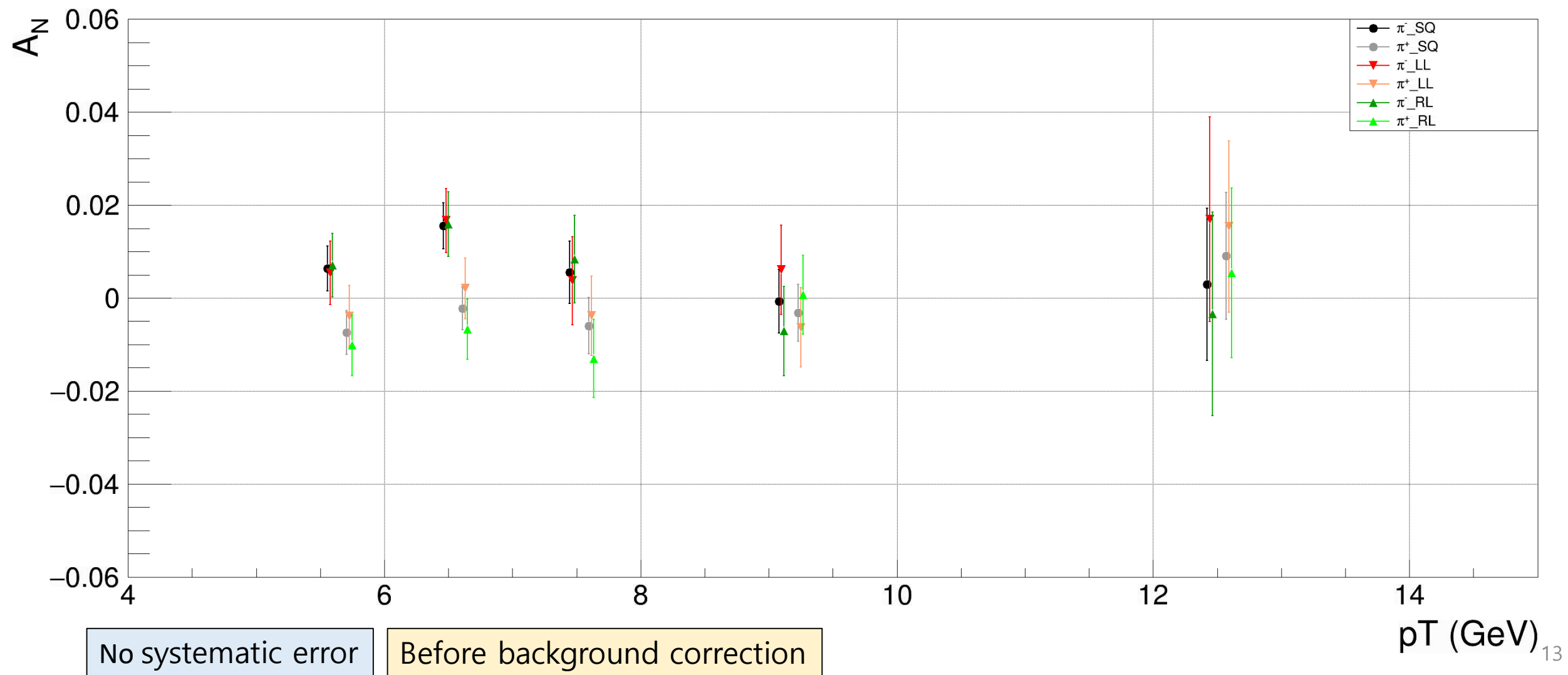


No systematic error

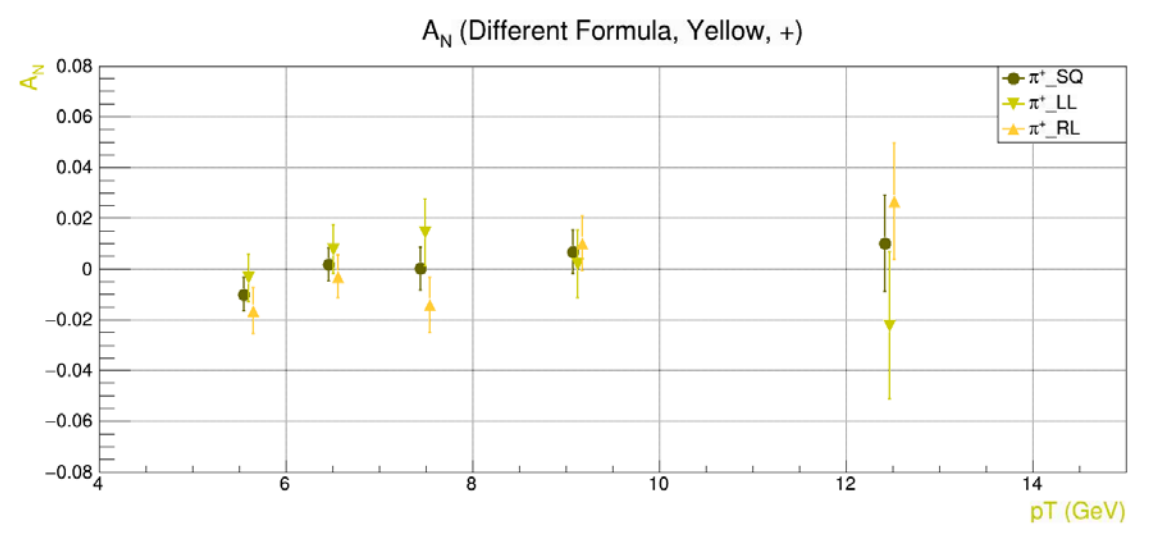
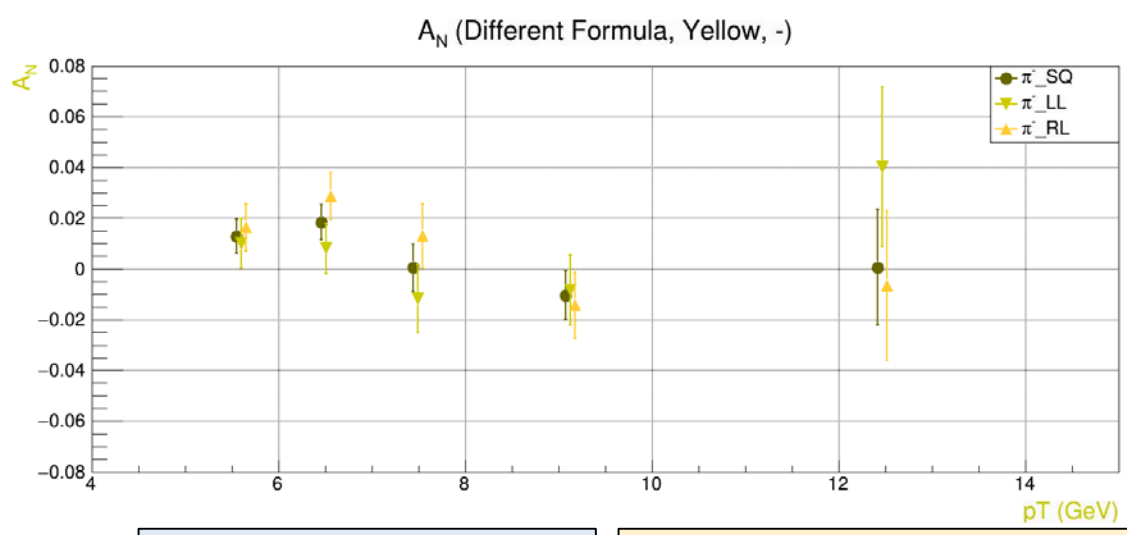
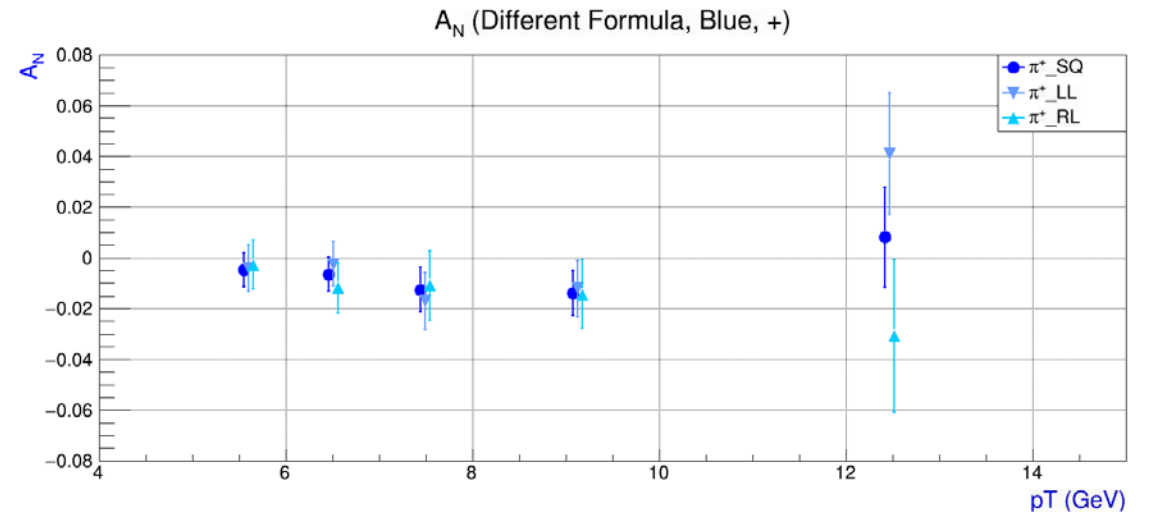
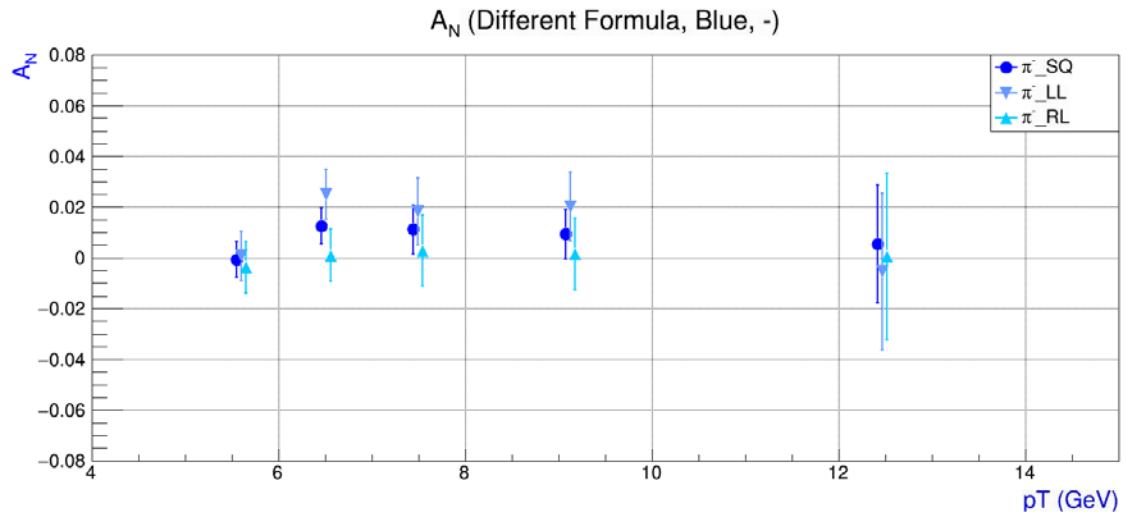
Before background correction

A_N after merging beam

A_N (Different Formula, -)



A_N with different beam, charge and formula

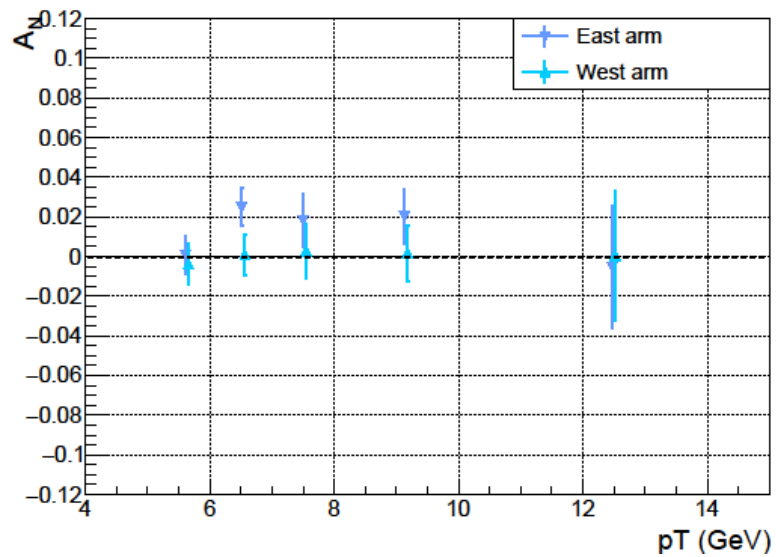


No systematic error

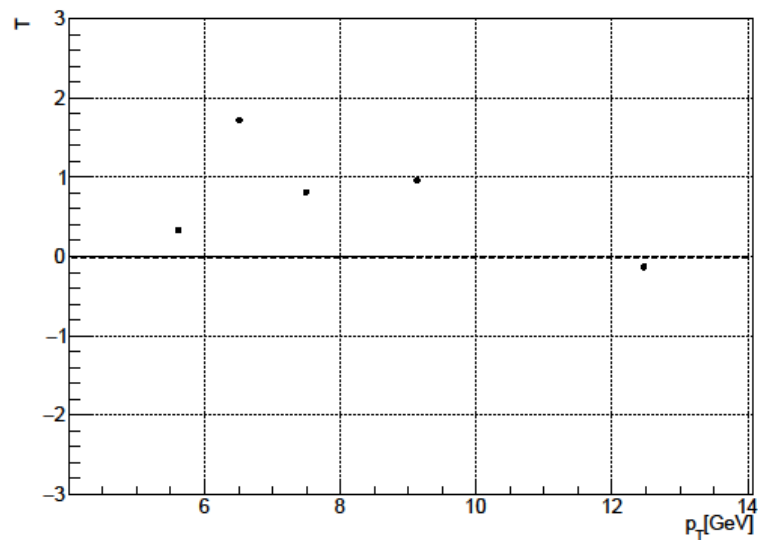
Before background correction

Relative Luminosity Formula (Blue)

A_N (Rel_lumi, blue beam, -)

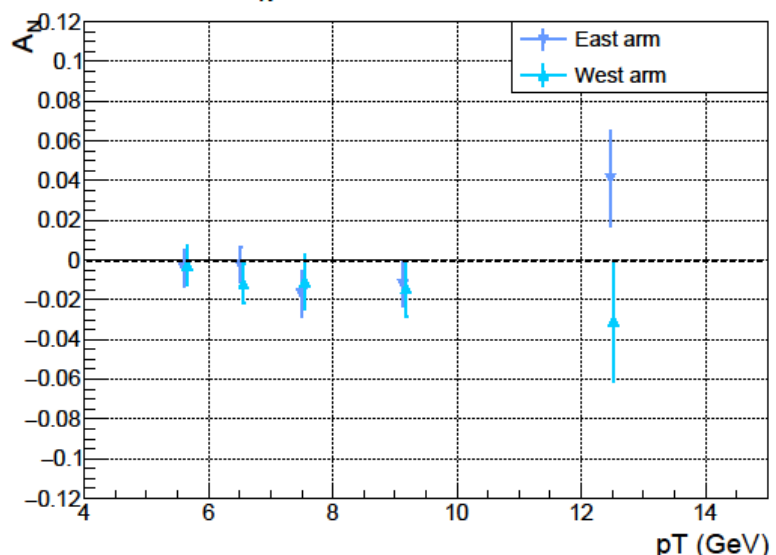


Rel_lumi(Blue beam, π^-)

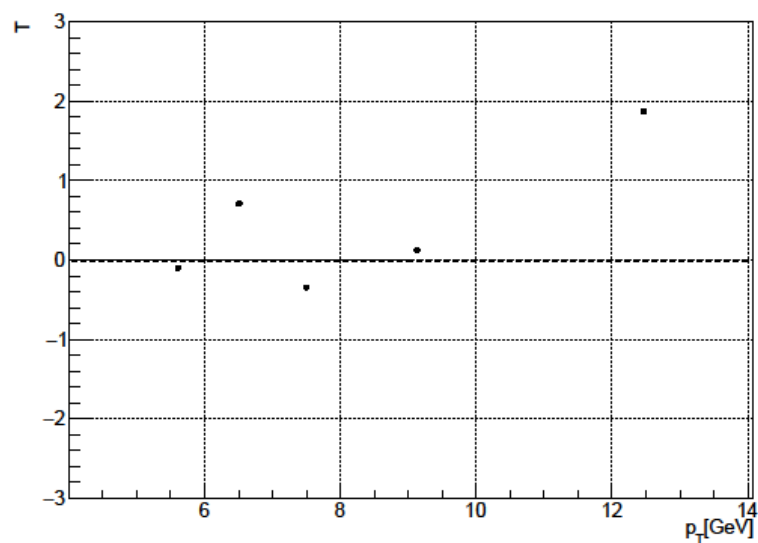


$$T(p_T) = \frac{A_N^{Left} - A_N^{Right}}{\sqrt{(\sigma^{Left})^2 + (\sigma^{Right})^2}}$$

A_N (Rel_lumi, blue beam, +)



Rel_lumi(Blue beam, π^+)

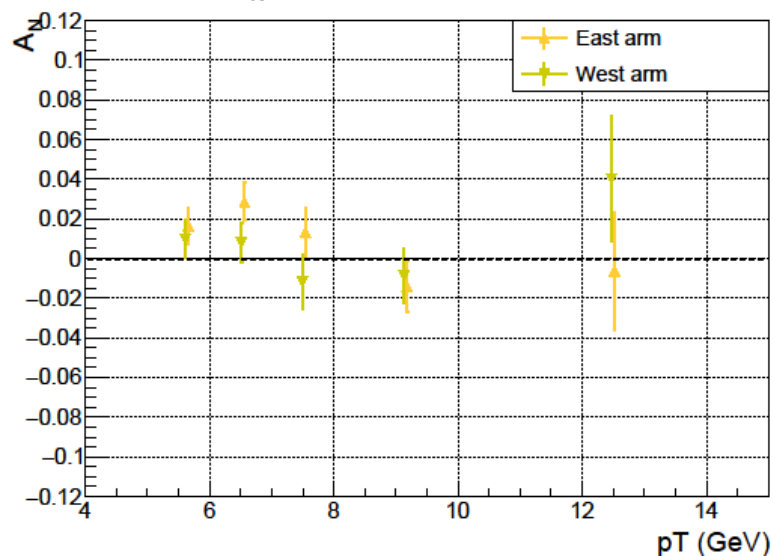


No systematic error

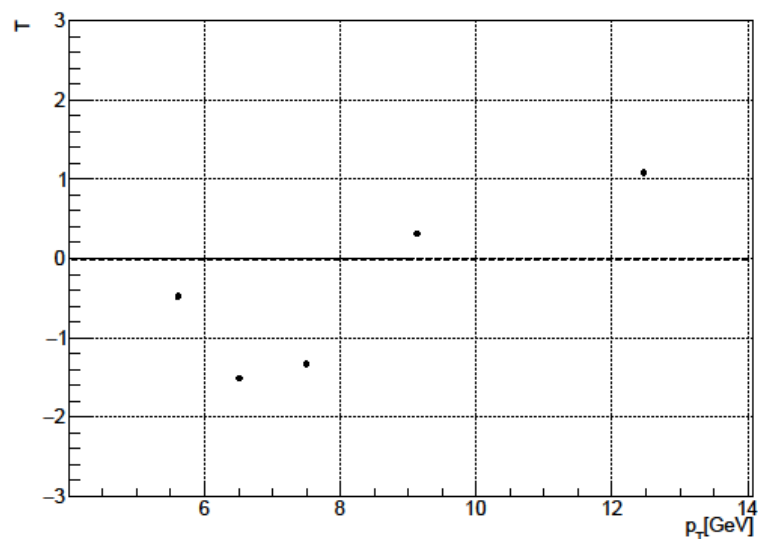
Before background correction

Relative Luminosity Formula (Yellow)

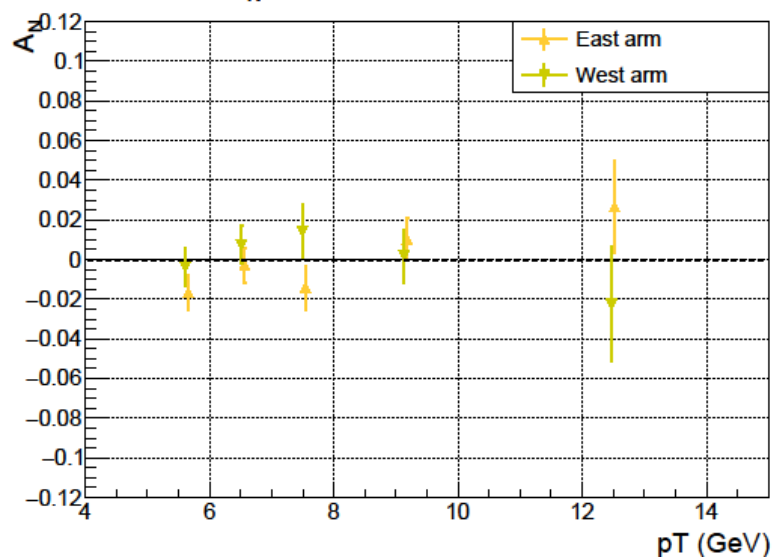
A_N (Rel_lumi, yellow beam, -)



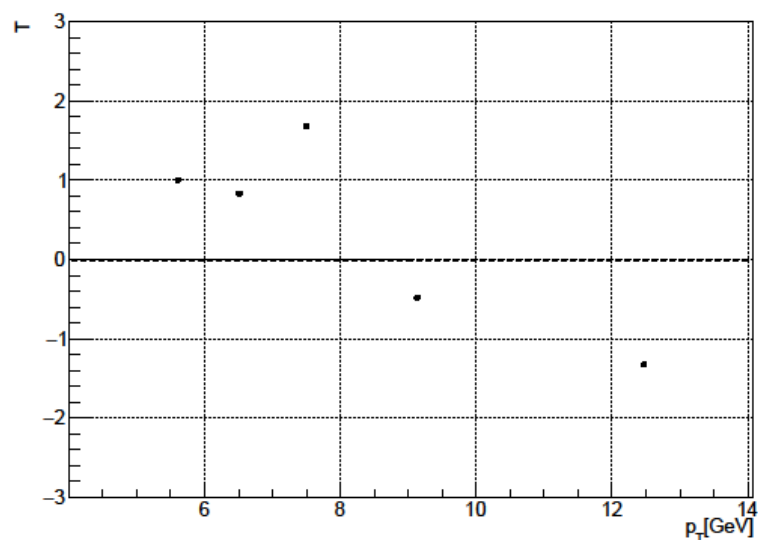
Rel_lumi(Yellow beam, π^-)



A_N (Rel_lumi, yellow beam, +)



Rel_lumi(Yellow beam, π^+)



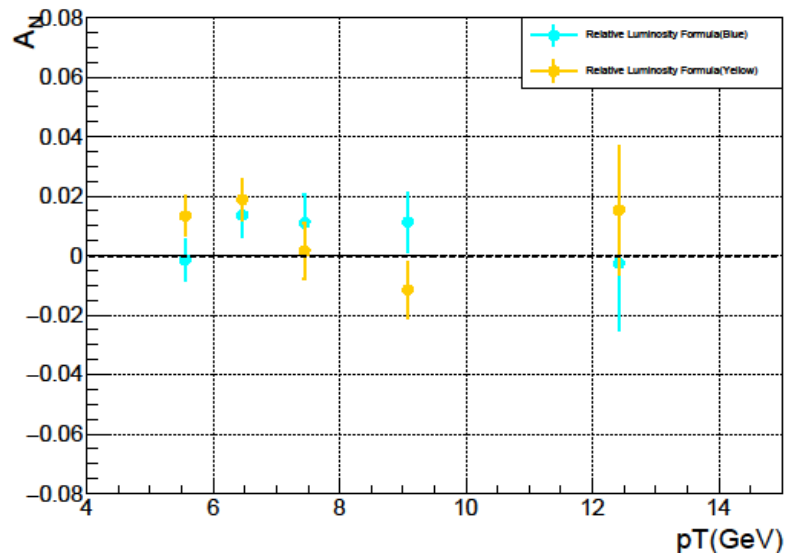
$$T(p_T) = \frac{A_N^{Left} - A_N^{Right}}{\sqrt{(\sigma^{Left})^2 + (\sigma^{Right})^2}}$$

No systematic error

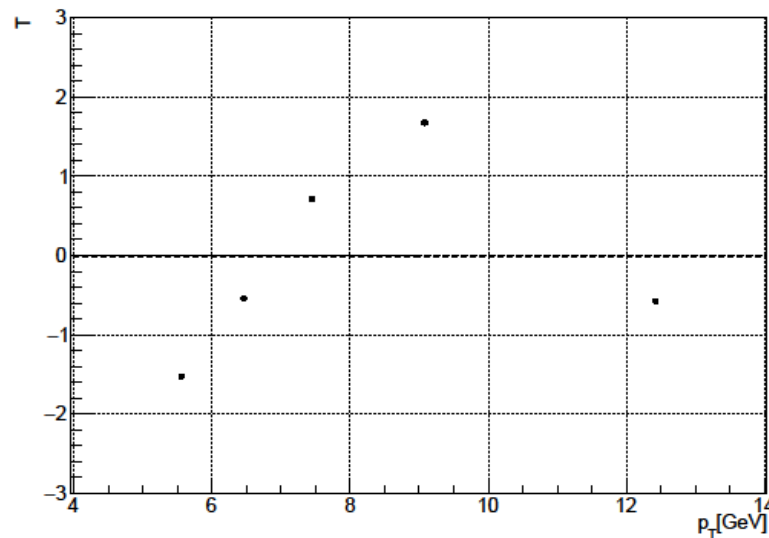
Before background correction

Relative Luminosity Formula

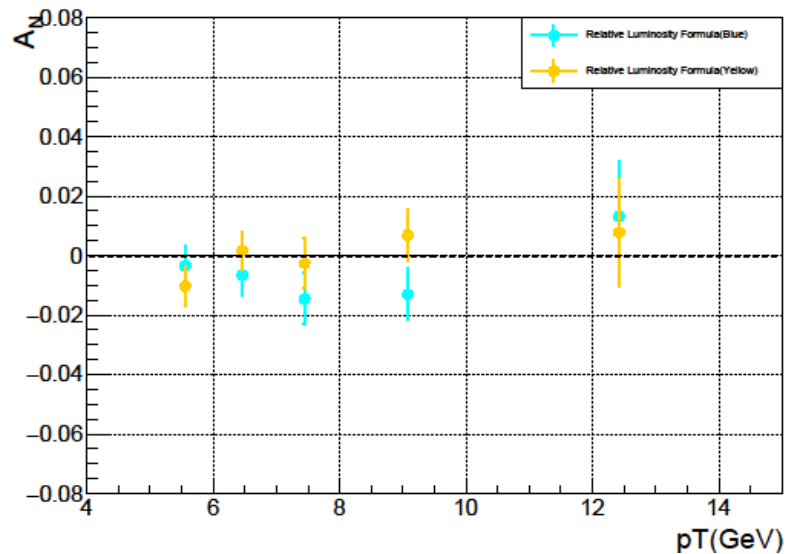
Lumi_B_c0



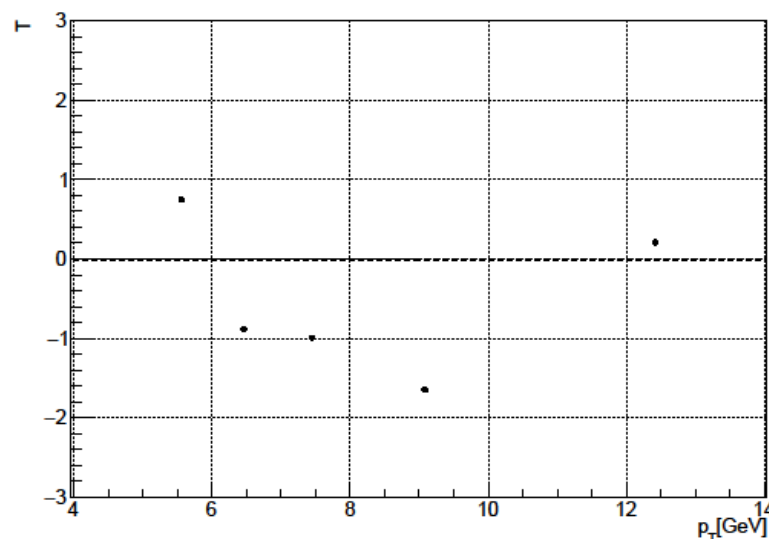
t-testRL_0, π^-



Lumi_B_c1



ttestRL_1, π^+



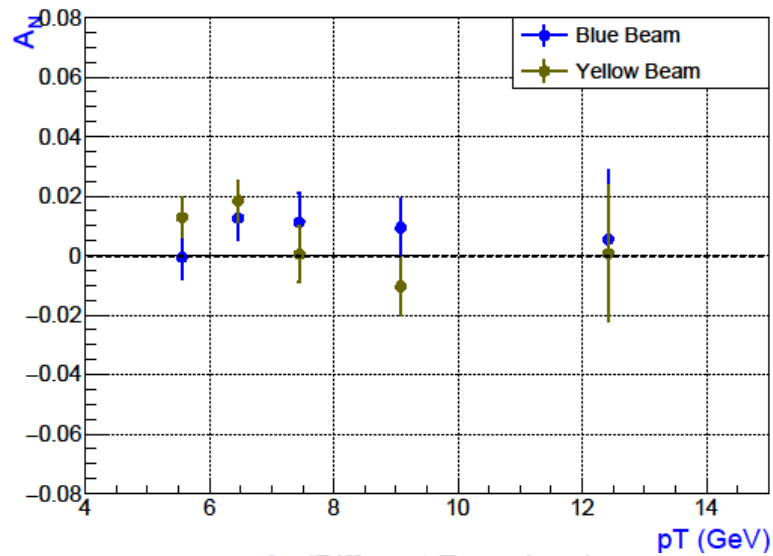
$$T(p_T) = \frac{A_N^{Yellow} - A_N^{Blue}}{\sqrt{(\sigma^{Yellow})^2 + (\sigma^{Blue})^2}}$$

No systematic error

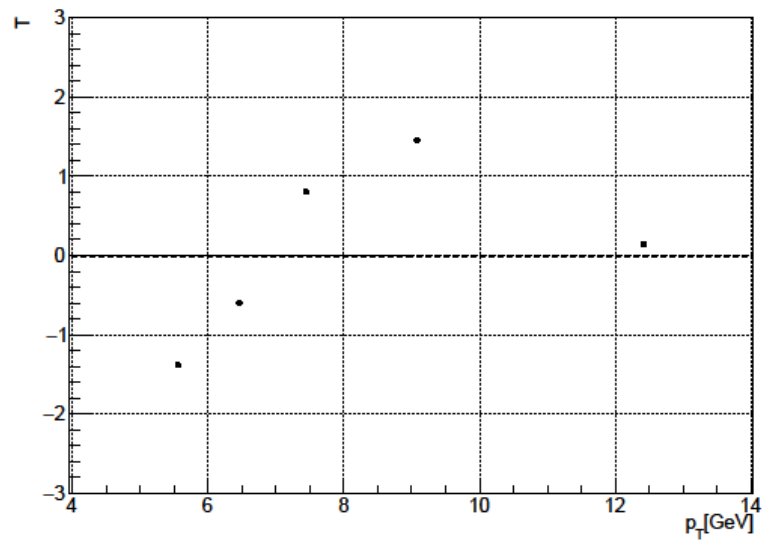
Before background correction

Square Root Formula

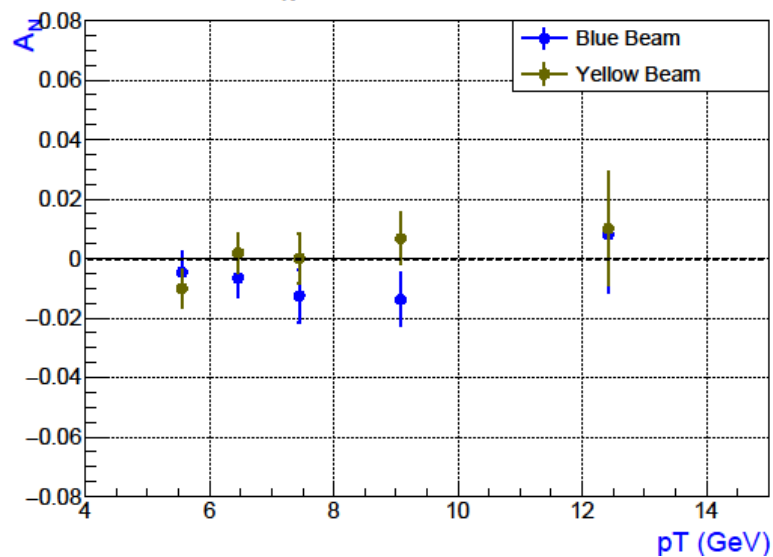
A_N (Different Formula, -)



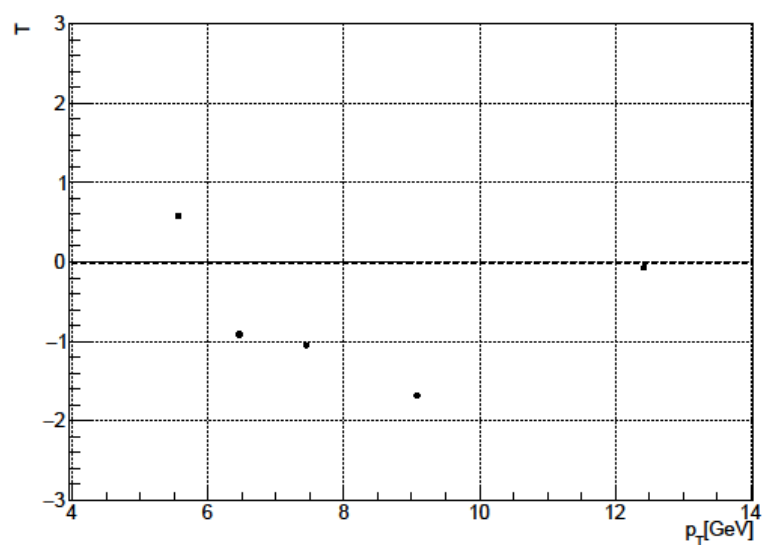
Square Root, π^-



A_N (Different Formula, +)



Square Root, π^+



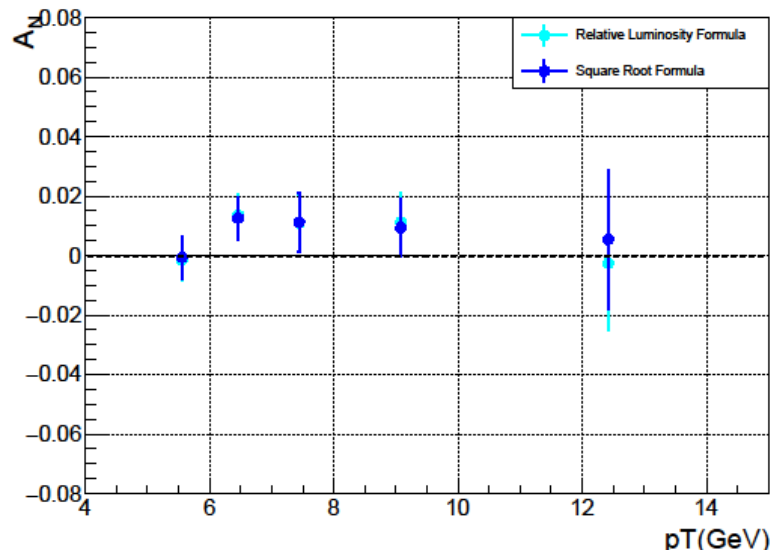
$$T(p_T) = \frac{A_N^{Yellow} - A_N^{Blue}}{\sqrt{(\sigma^{Yellow})^2 + (\sigma^{Blue})^2}}$$

No systematic error

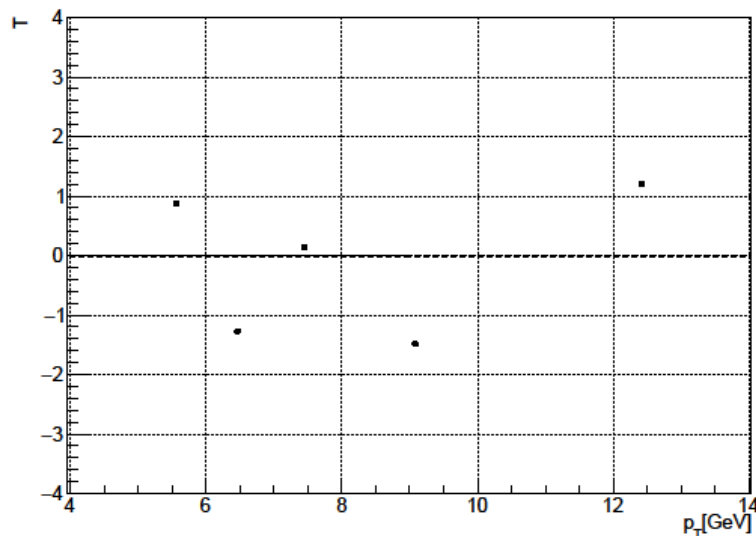
Before background correction

A_N - Formula Comparison (Blue)

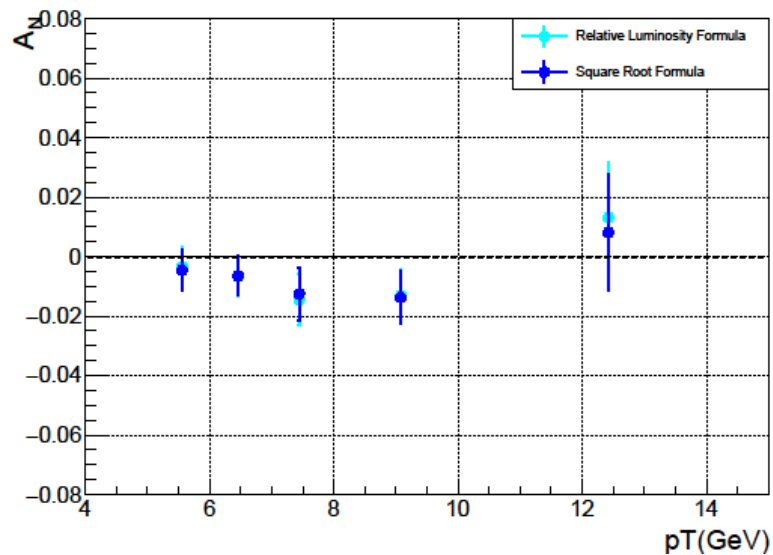
Lumi_B_c0



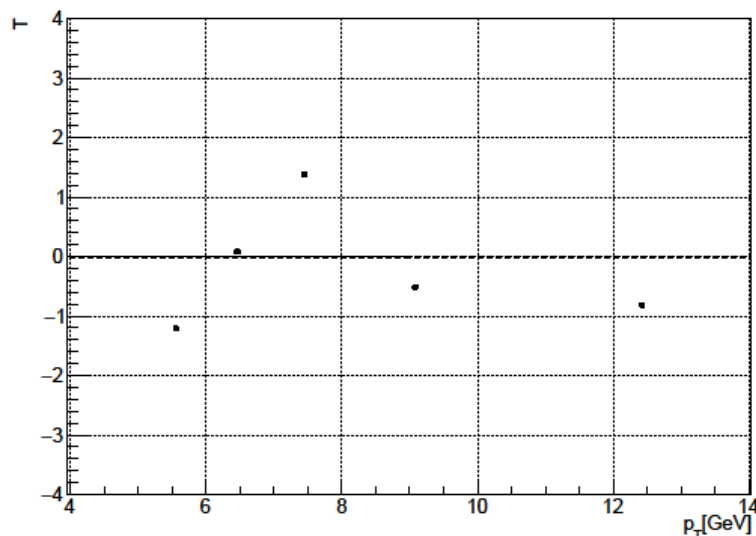
t-test_B_0, π^-



Lumi_B_c1



ttest_B_1, π^+



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

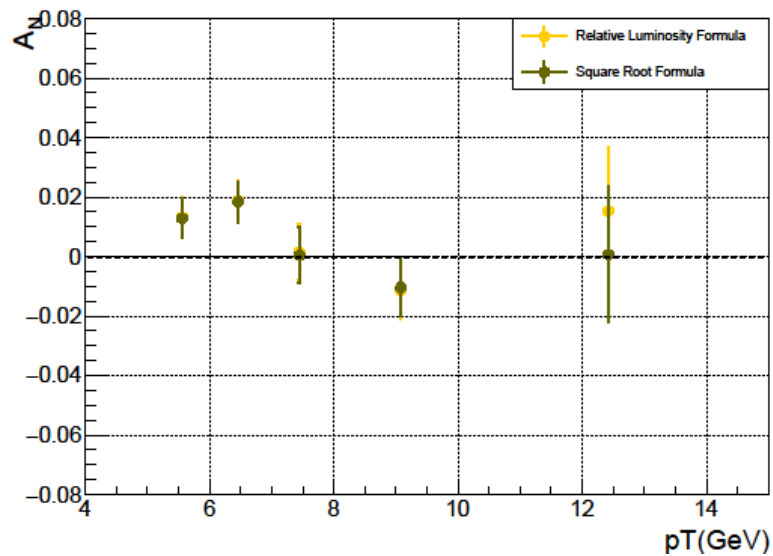
No systematic error

Before background correction

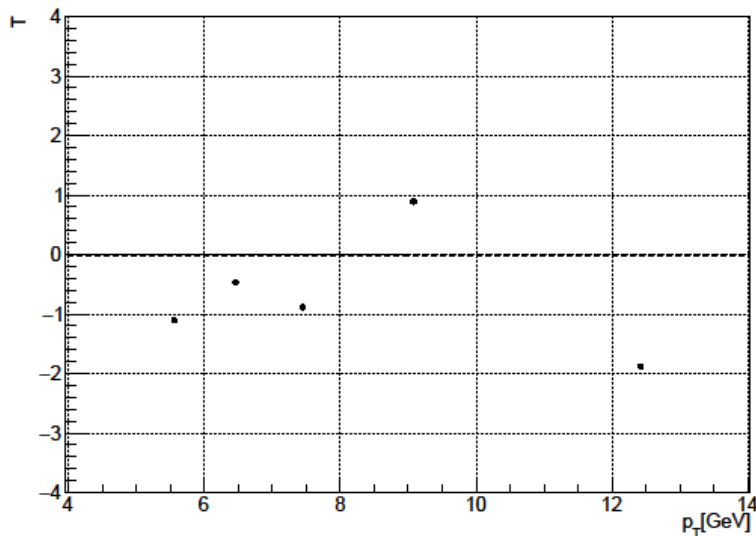
A_N - Formula Comparison (Yellow)



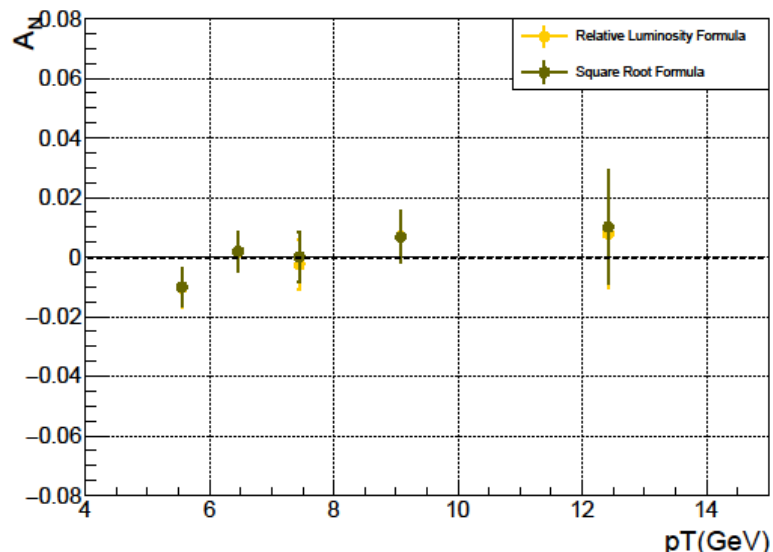
Lumi_Y_c0



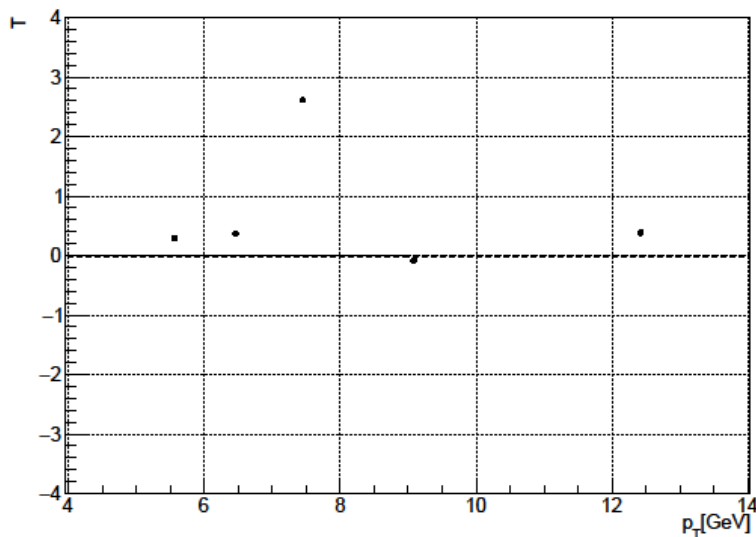
t-test_Y_0, π^-



Lumi_Y_c1



ttest_Y_1, π^+



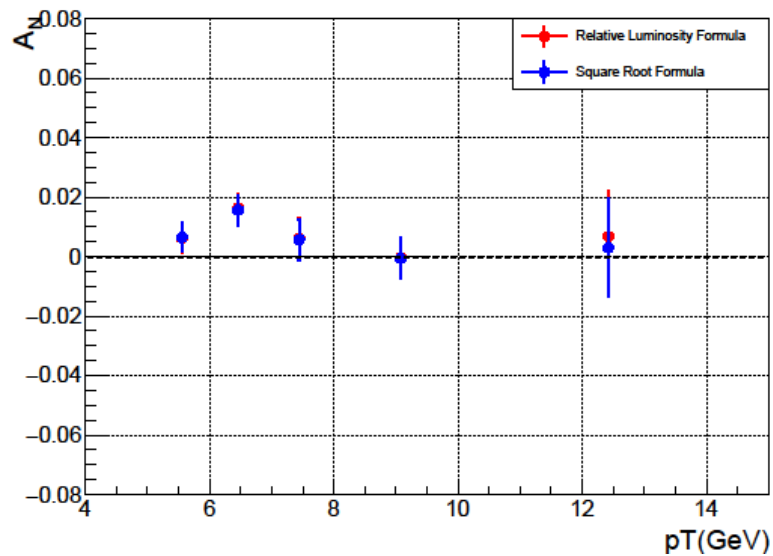
$$T(p_T) = \frac{A_N^{Sqrt} - A_N^{Lumi}}{\sqrt{|(\sigma^{Sqrt})^2 - (\sigma^{Lumi})^2|}}$$

No systematic error

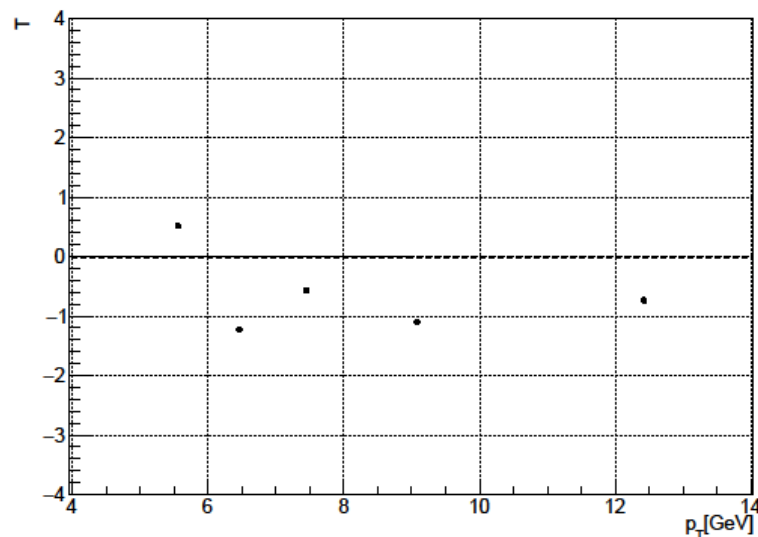
Before background correction

A_N - Formula Comparison (Averaged)

Lumi_Y_c0

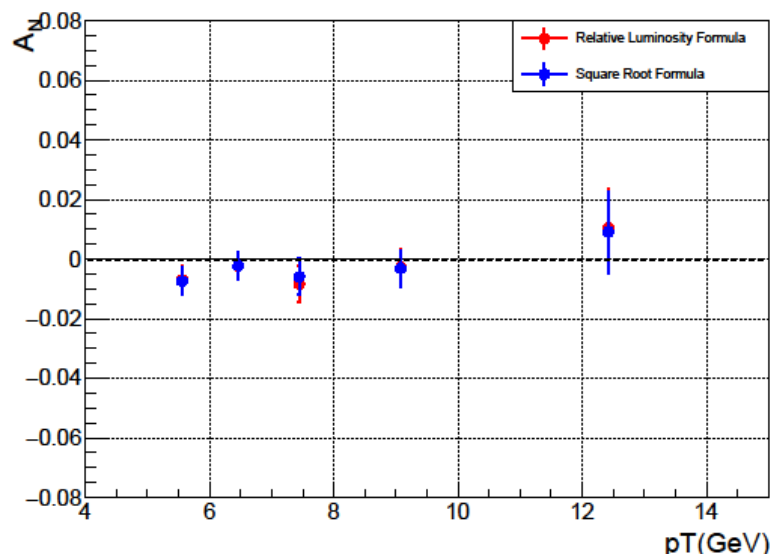


t-test_0, π^-

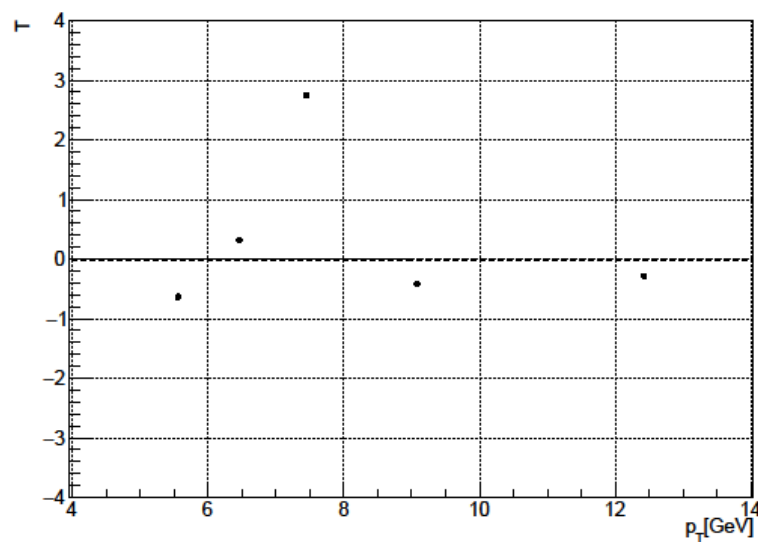


$$T(p_T) = \frac{A_N^{Sqrt} - A_N^{Lumi}}{\sqrt{|(\sigma^{Sqrt})^2 - (\sigma^{Lumi})^2|}}$$

Lumi_c1



ttest_1, π^+



No systematic error

Before background correction



Thank you.



BACK UP

The Proton Spin Structure

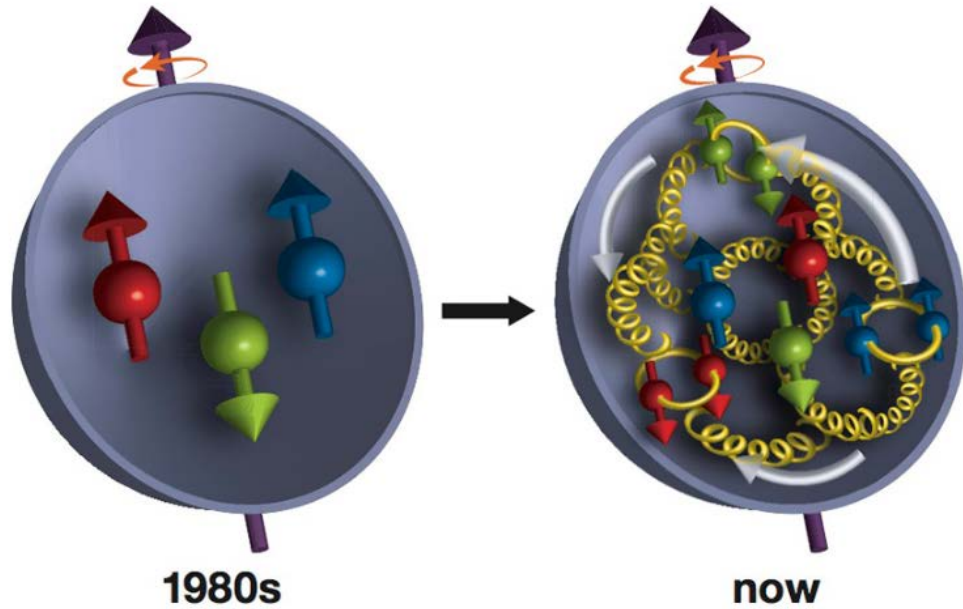


Image courtesy of Brookhaven National Laboratory

Standard Model of Elementary Particles

		three generations of matter (fermions)			interactions / force carriers (bosons)	
		I	II	III		
QUARKS	mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
	charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
		u up	c charm	t top	g gluon	H higgs
		$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
		$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		d down	s strange	b bottom	γ photon	
LEPTONS	mass	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	charge	-1	-1	-1	0	
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		e electron	μ muon	τ tau	Z Z boson	
		$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
		0	0	0	± 1	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

SCALAR BOSONS

GAUGE BOSONS VECTOR BOSONS

In the 1980s, scientists discovered that a proton's three valence 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

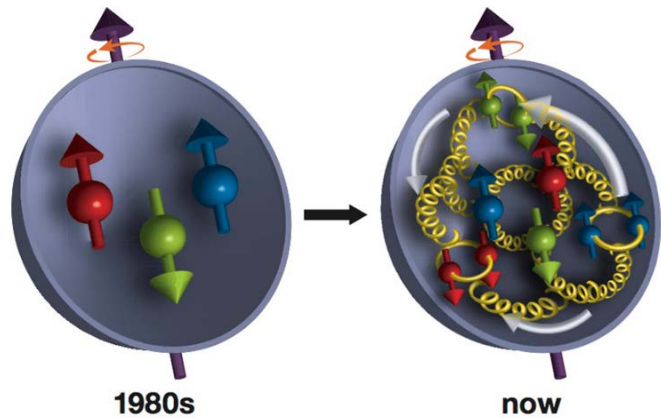


Image courtesy of Brookhaven National Laboratory

1988 EMC measured:
 $\Sigma = 0.123 \pm 0.013 \pm 0.019 \implies$ Spin Puzzle!

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

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

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

Standard Model of Elementary Particles

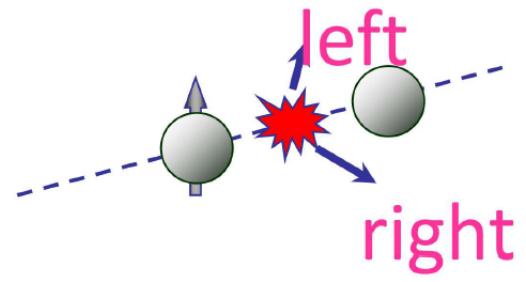
	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0	0
QUARKS	u up	c charm	t top	g gluon	H higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	d down	s strange	b bottom	γ photon	
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					SCALAR BOSONS
					GAUGE BOSONS VECTOR BOSONS

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

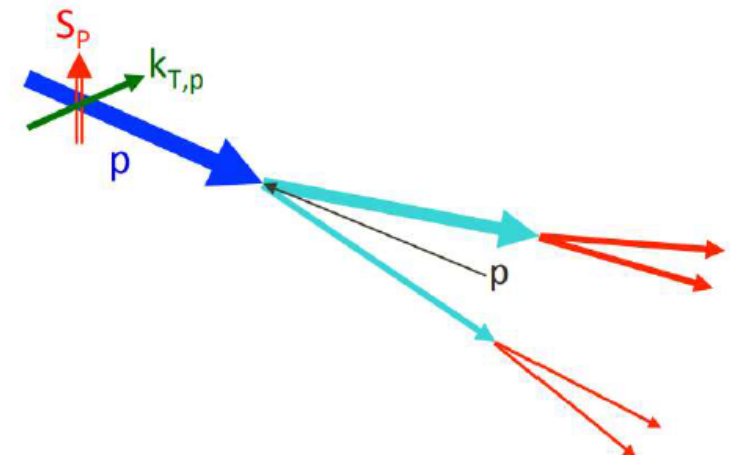
Transverse Single Spin Asymmetry

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

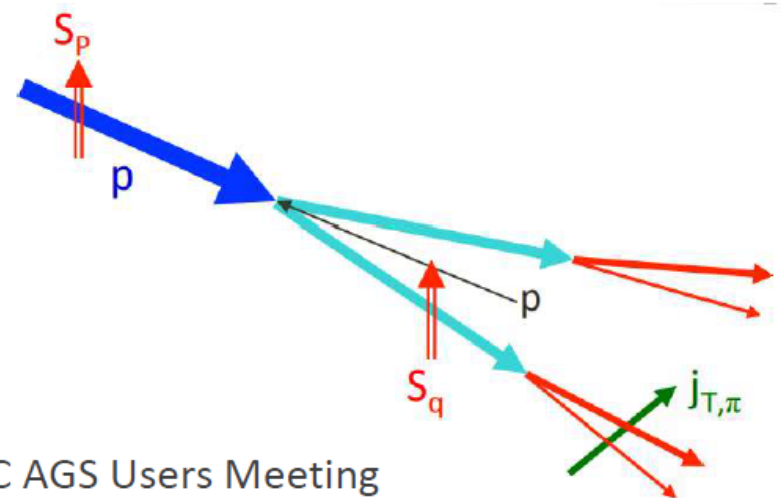


Sources of Transverse SSA's

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



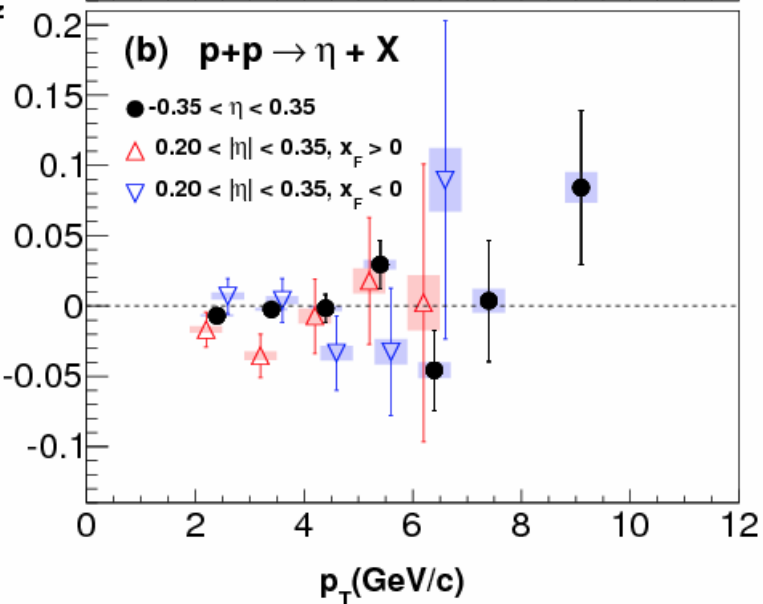
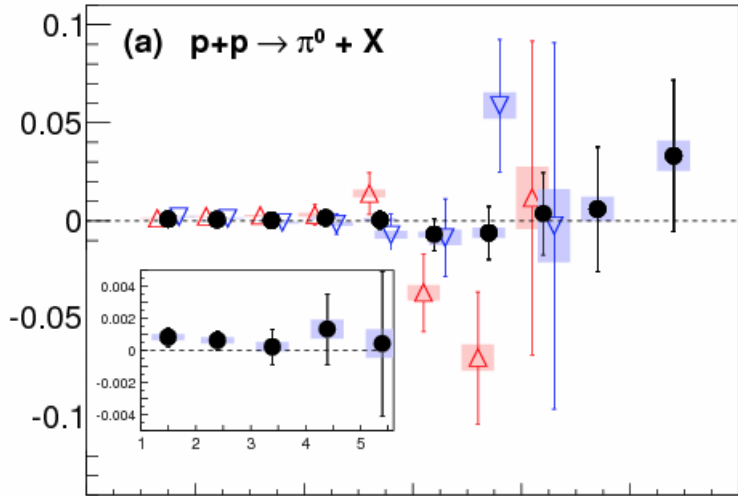
Final State effects:
Collins Function: spin momentum correlation in a Fragmentation Function



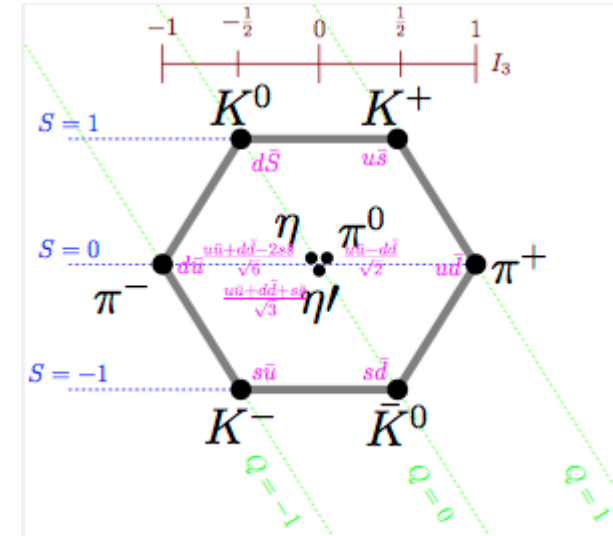
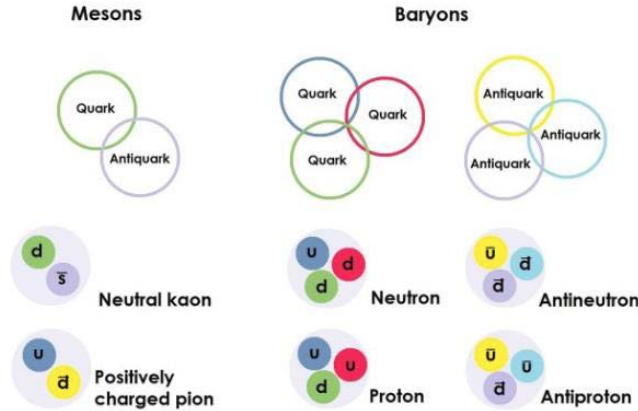
Figures from L. Nogach 2006 RHIC AGS Users Meeting

Transverse Single Spin Asymmetry

p+p $\sqrt{s}=200$ GeV



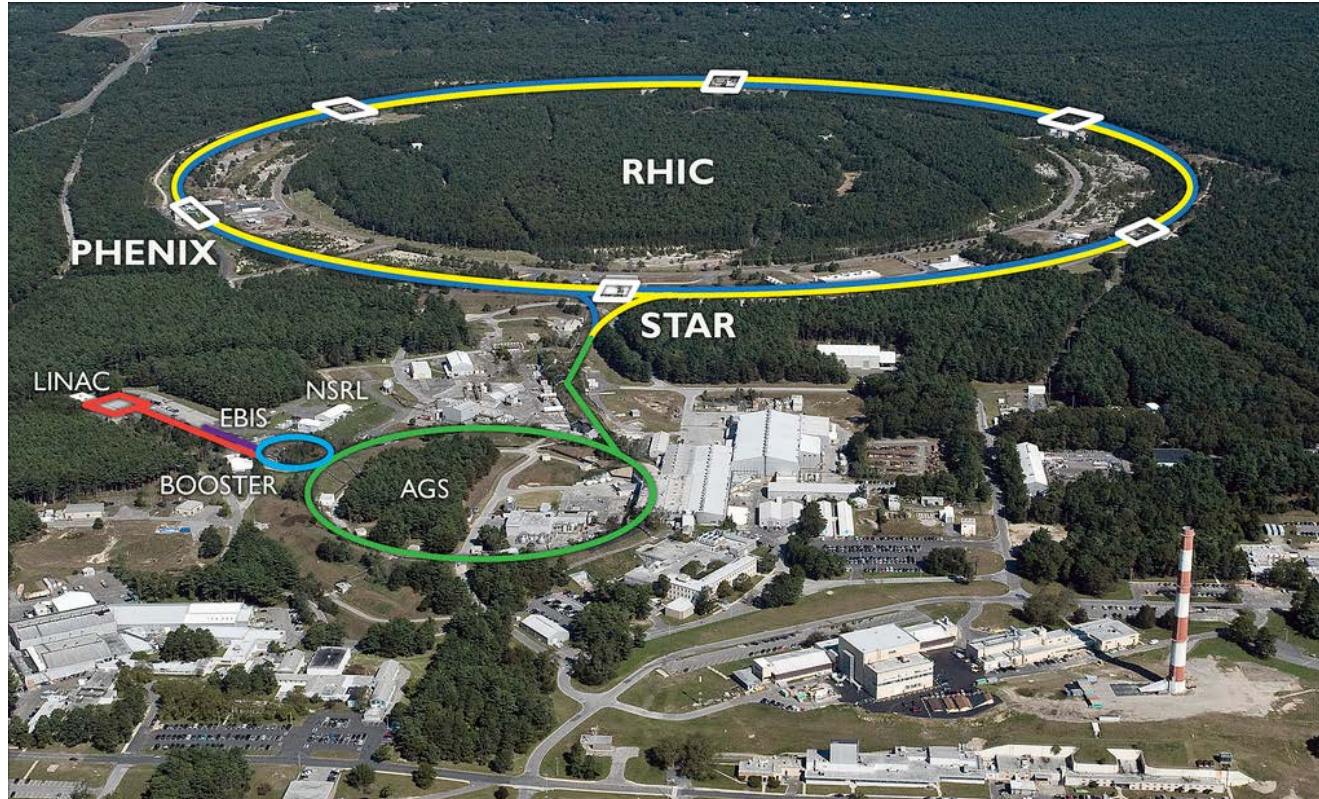
Hadrons



The asymmetry of π^0 and η in midrapidity:

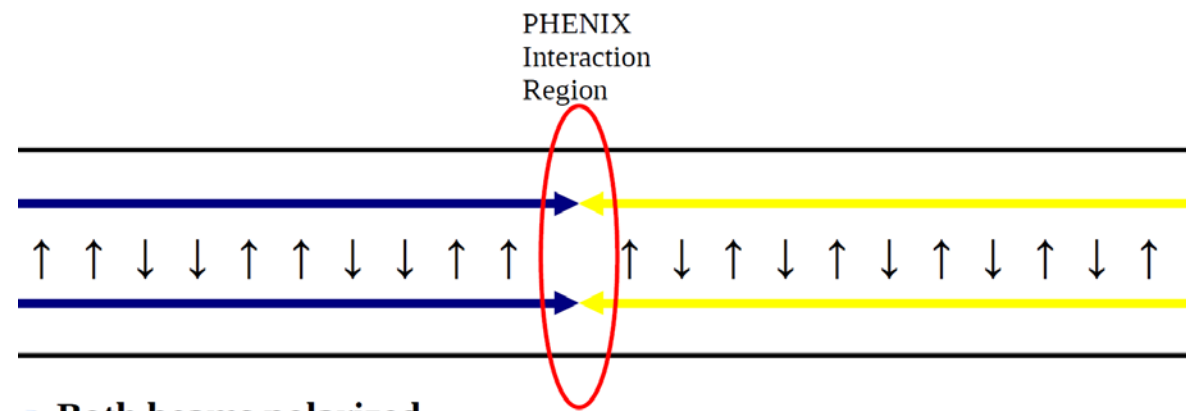
- Consistent with zero within errors

How does it change from neutral to charged hadron?



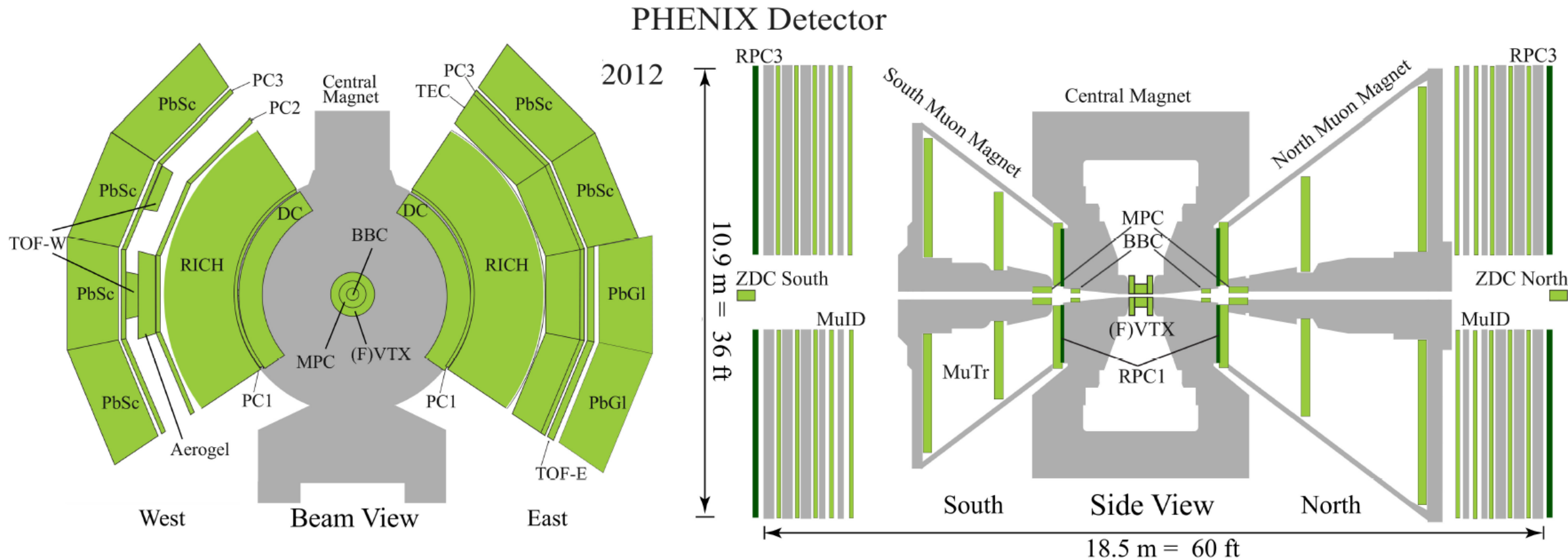
View of the Brookhaven National Laboratory, NY, USA

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

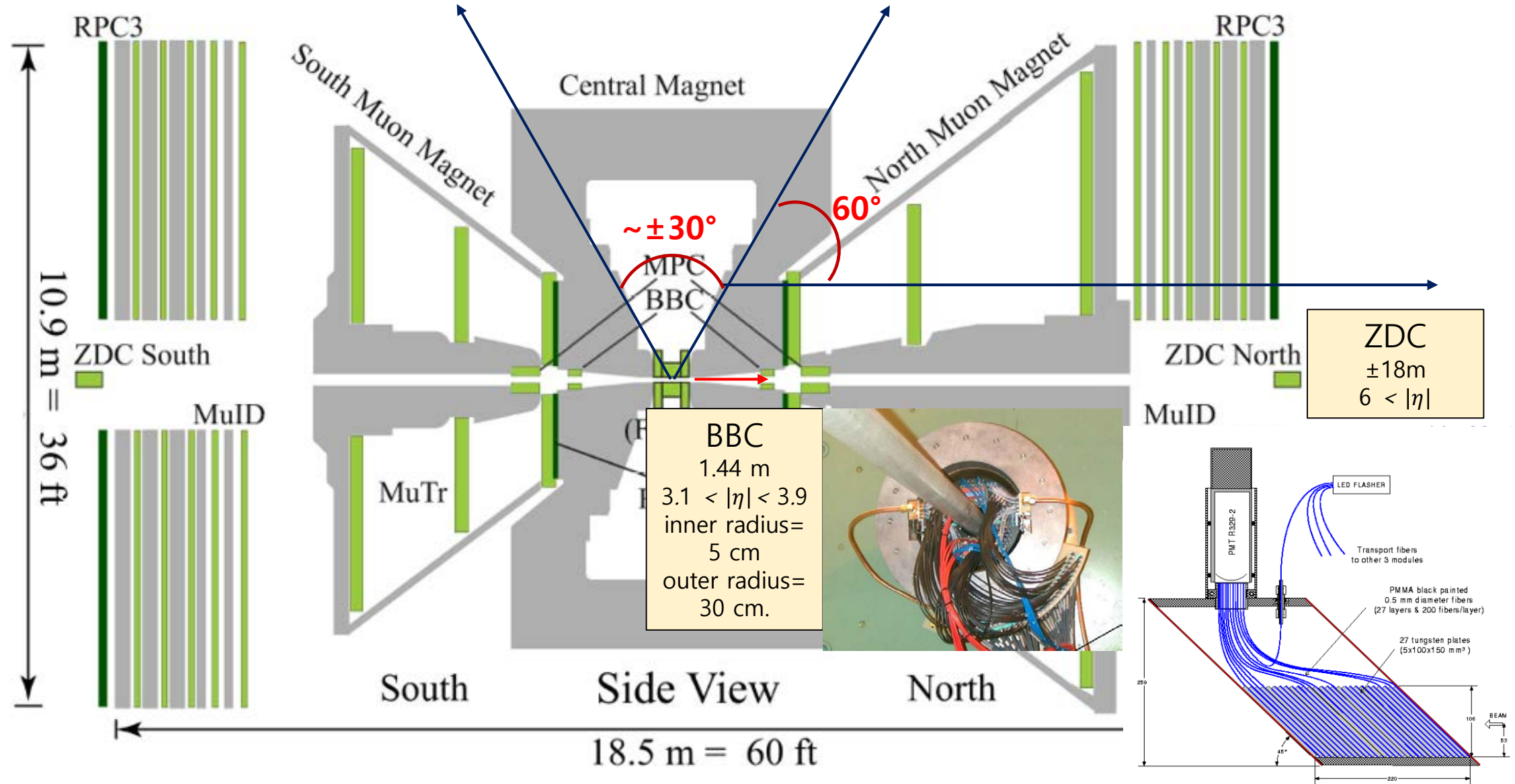
PHENIX Detector System



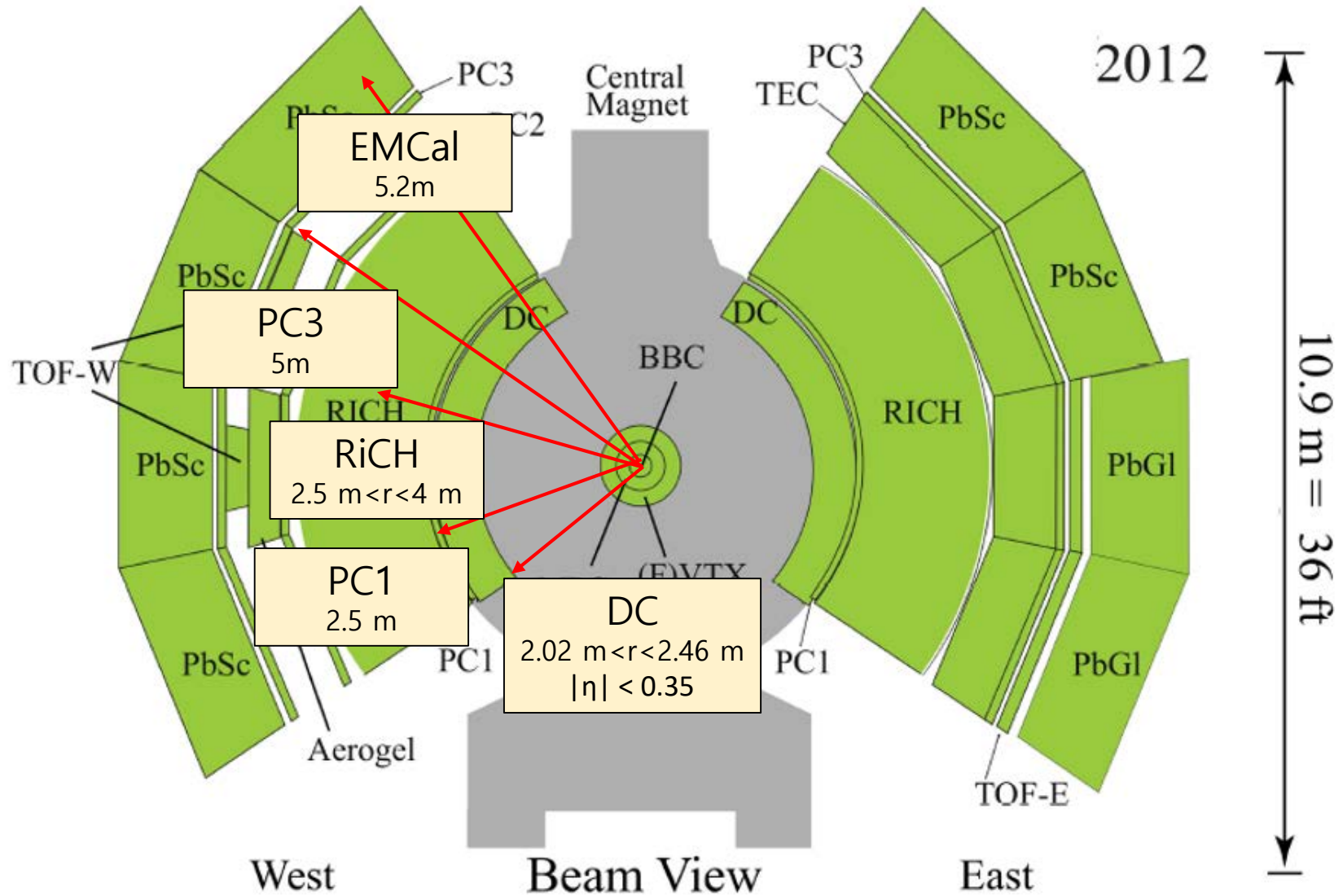
2 central arm: Mid rapidity, $|\eta| < 0.35$

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

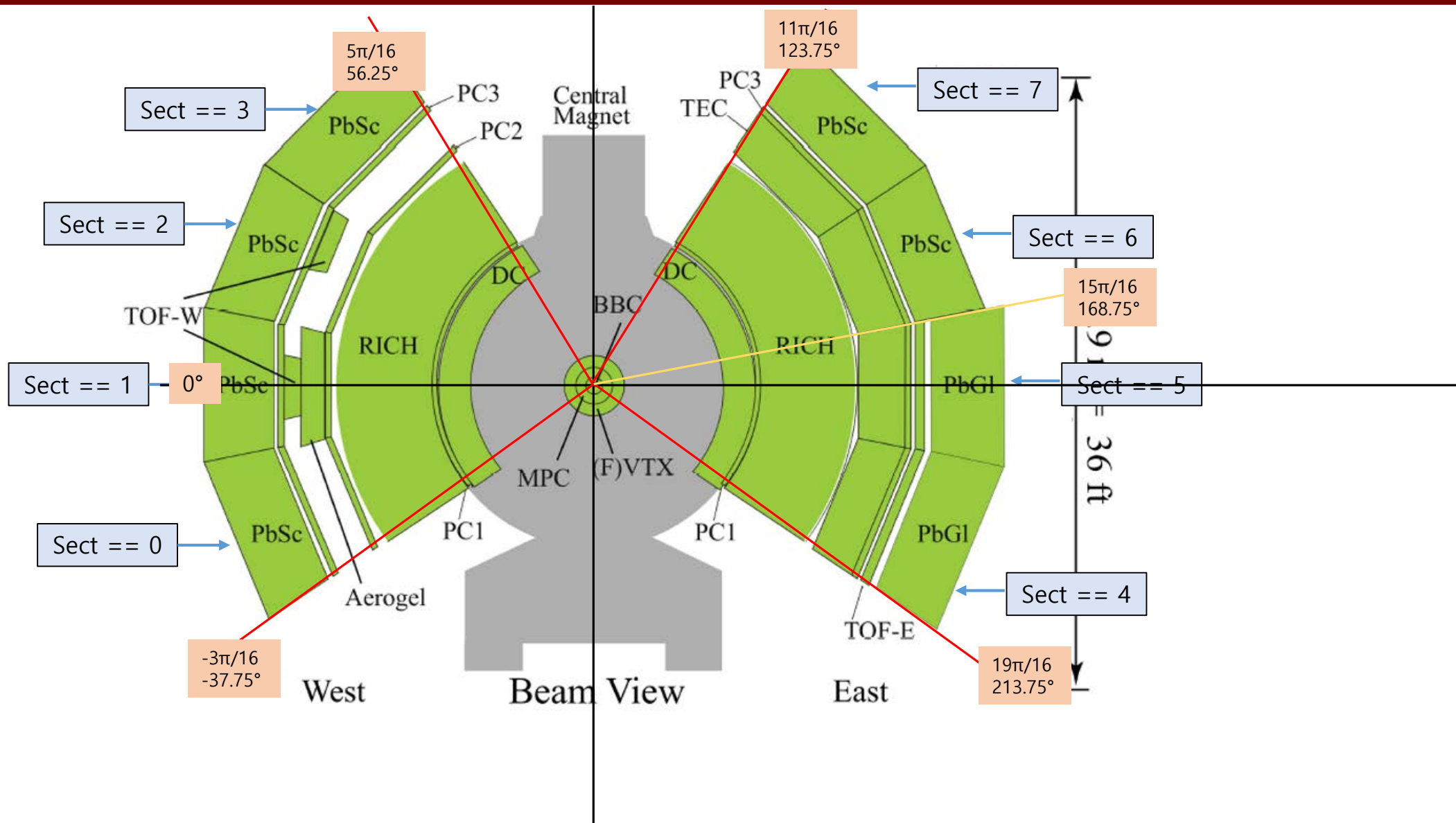
PHENIX Detector System



PHENIX Detector System



PHENIX Detector System



Rel. luminosity(Norbert's)

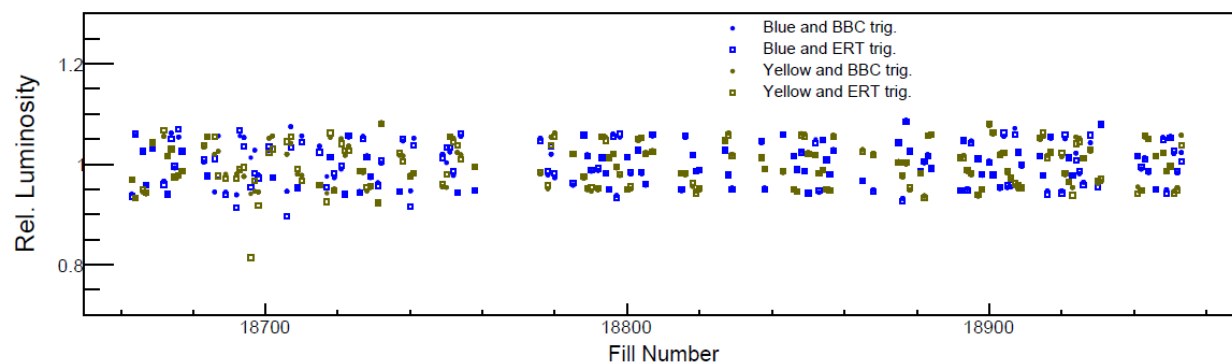


Figure 41: Relative luminosity factor calculated for each fill in Run-15 $p + p$.

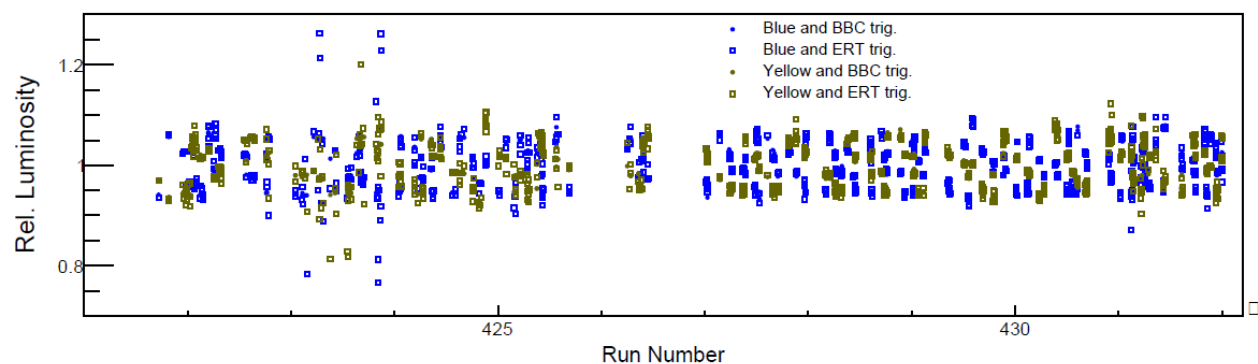


Figure 42: Relative luminosity factor calculated for each run in Run-15 $p + p$.