Asymmetry analysis of charged pion production in PHENIX

Transverse single spin asymmetry in charged pions production at midrapidity in polarized p + p collisions at 200 GeV

Korea Univ.

Jaehee Yoo

The Proton Spin Structure

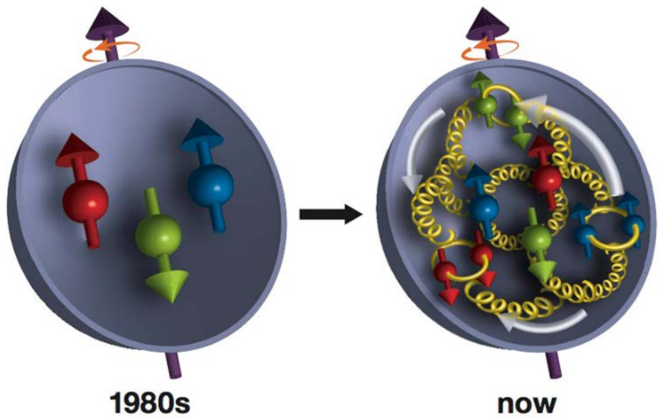


Image courtesy of Brookhaven National Laboratory

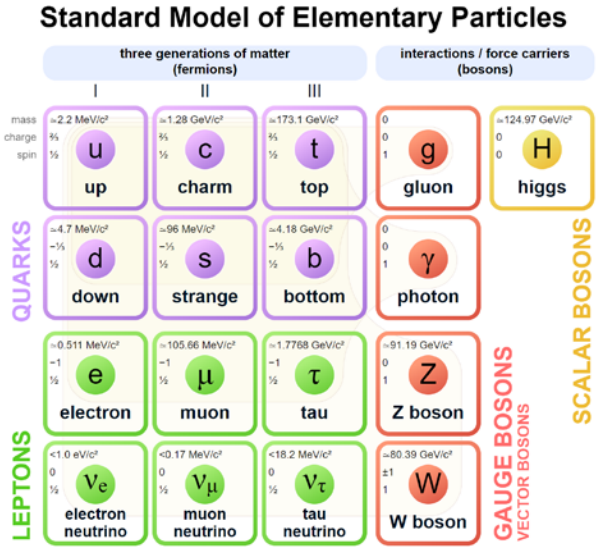
1988 EMC measured:

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

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

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

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

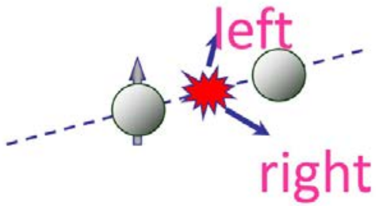


In the 1980s, the EMC experiment discovered that a proton's valance quarks account for only a fraction of the proton's overall spin. New measurements from RHIC experiment reveal that gluons contribute as much as or possibly more than the quarks.

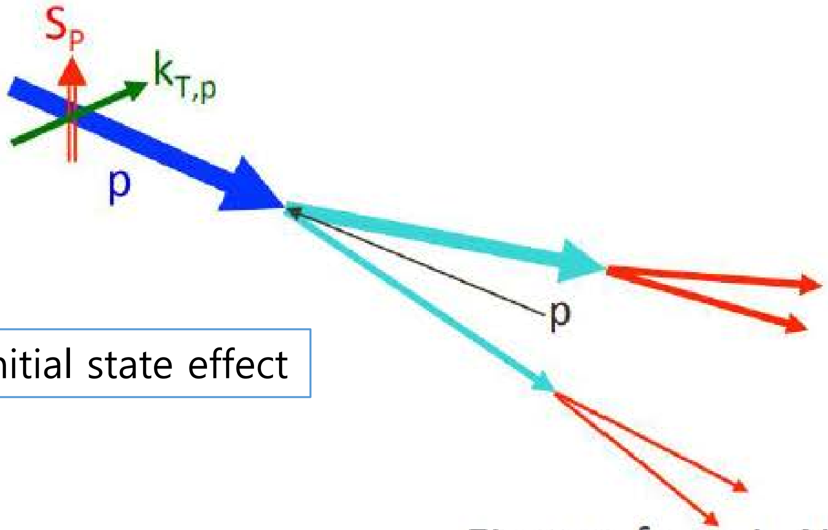
How is proton's spin correlated with the motion of quarks and gluons?
-> Transverse Momentum Dependent (TMD) Functions

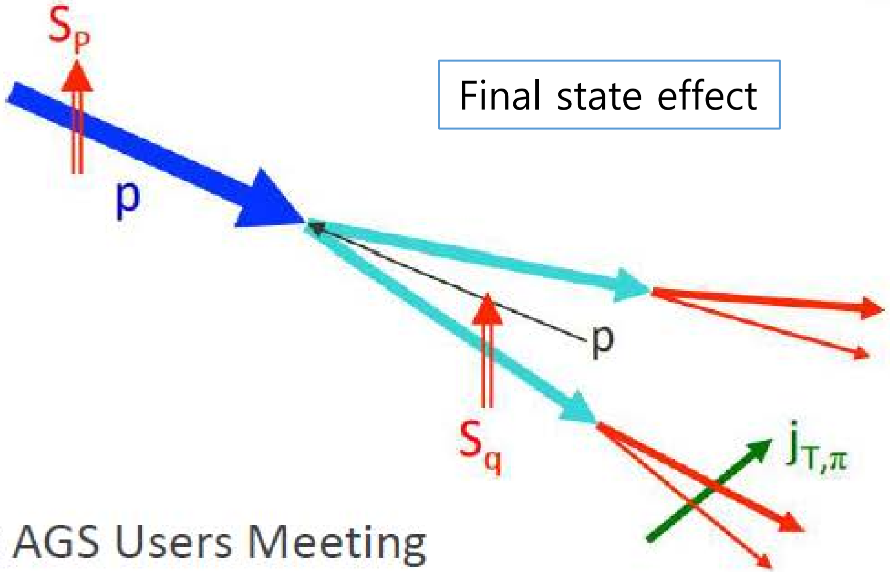
Transverse Single Spin Asymmetry

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



Sources of Transverse SSA's





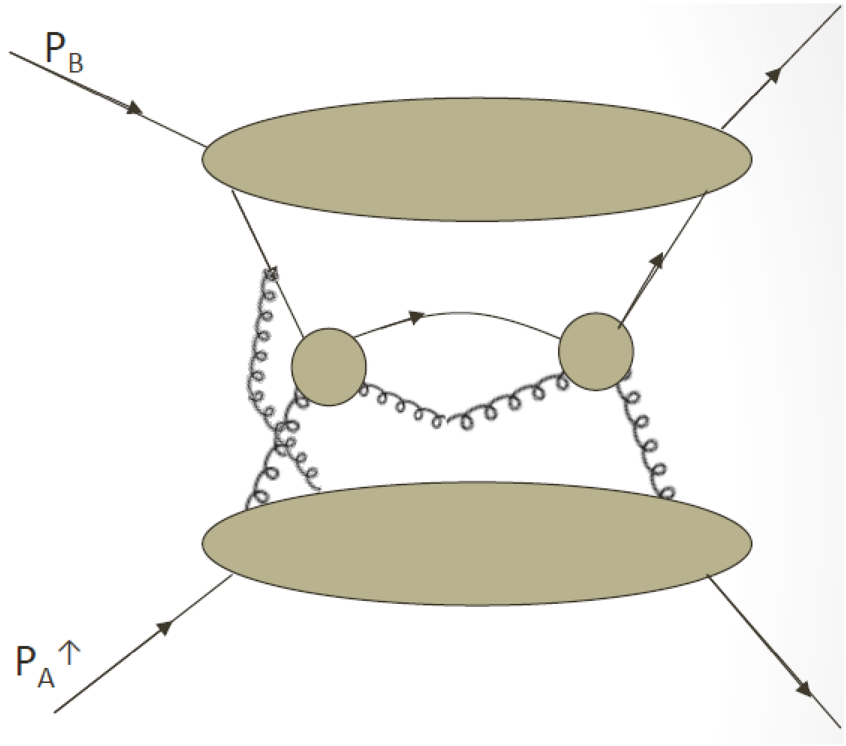
Figures from L. Nogach 2006 RHIC AGS Users Meeting

Sivers Function
- correlation between proton spin and parton k_T.

Collins Function
- Spin momentum correlation in a Fragmentation Function.

Transverse momentum dependent (TMD) framework
- two observed scales: . $\Lambda_{QCD} \ll Q_T^2\ (P_{h\perp}) \ll Q^2$
- applicable in SIDIS and Drell Yan

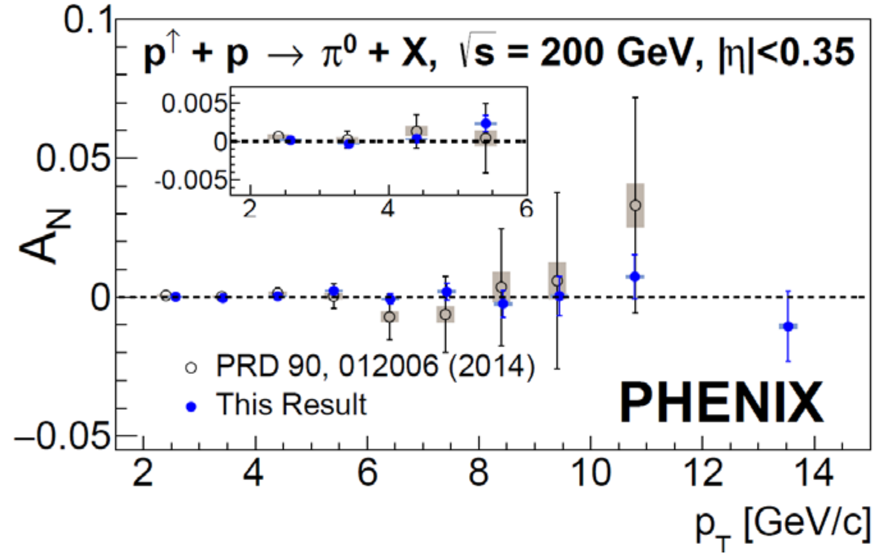
Higher Twist Effects

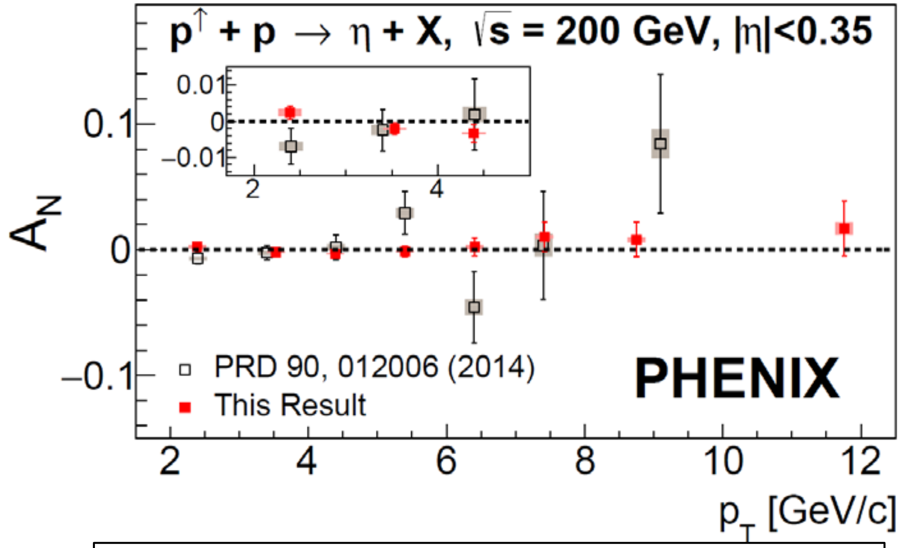


Twist-3 Function
- Multiparton correlations
- Power suppressed terms in factorization expansion by $\sim 1/Q$
- applicable when only single hard scale observed, such as in ANs in hadronic collisions. $(A_N \sim 1/p_T)$

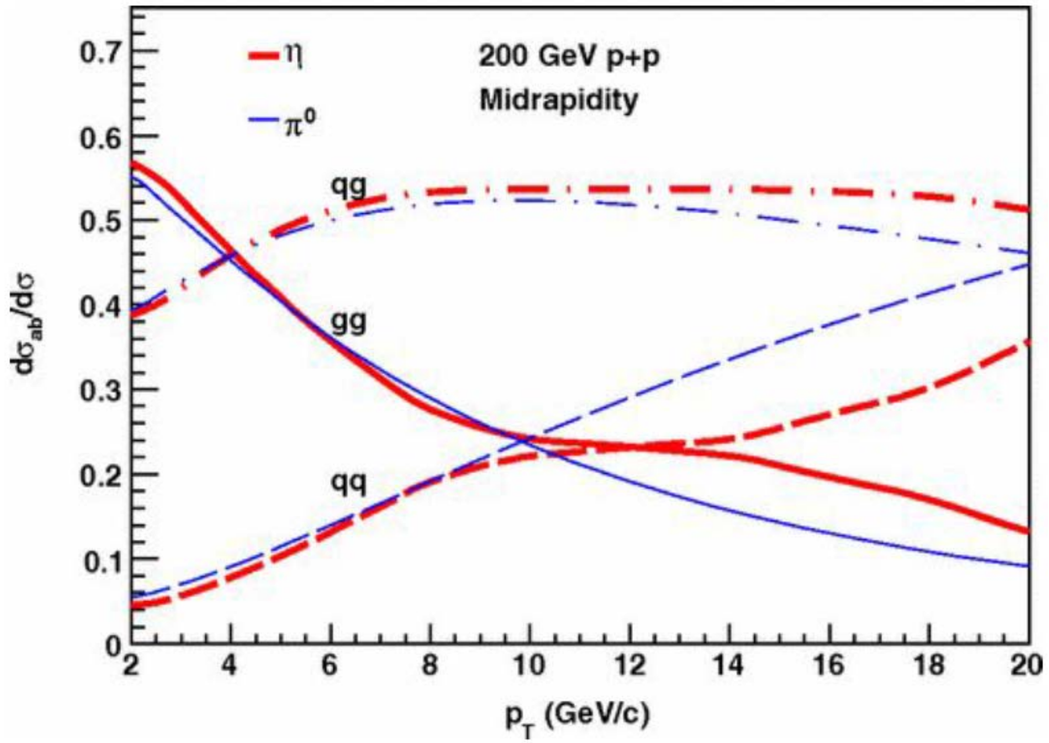
- **They also contain initial state (correlations in the nucleon) and final state (correlations in the fragmentation) effects**

Recent π^0 and η A_N results at 200 GeV with Run-15 data





(PHENIX Collaboration) Phys. Rev. D 103, 052009 (2021)



(PHENIX Collaboration) Phys. Rev. D 83, 032001 (2011)

- π^0 and η production
  - quark-gluon scattering is dominant process
  - A_N consistent with zero.
- These results are sensitive to initial and final state effects

→ Charged pion A_N can provide flavor sensitivity (u and d quarks)

Particle ID for $\pi^{\pm}$ and $e^{\pm}$

$\pi^{\pm}$ identification

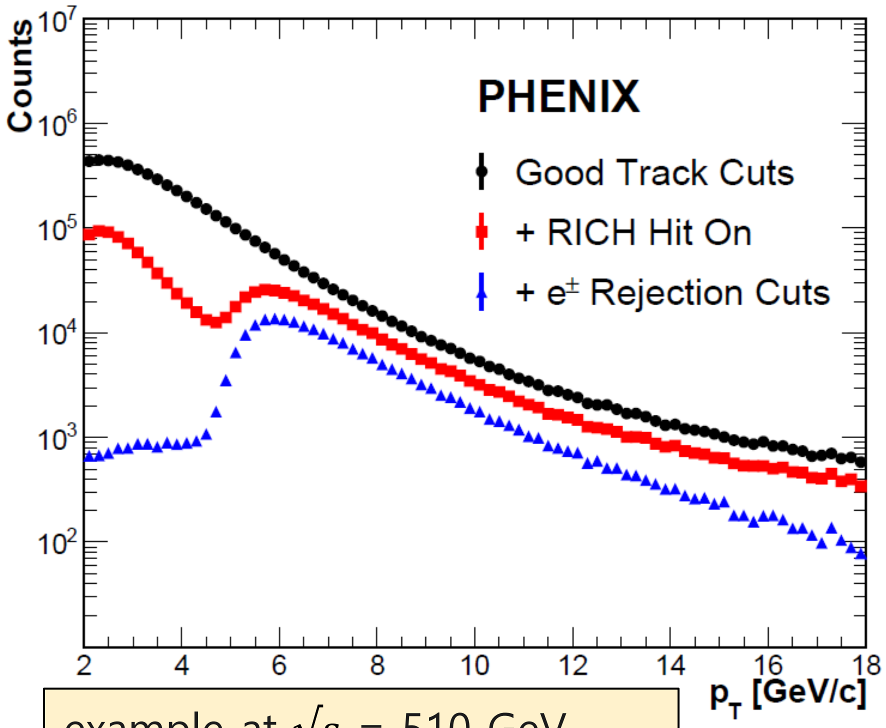
- Trigger $\pi^{\pm}$ with a BBC and EMCal.
- Track can be divided into two categories according to RICH response at pT 5~16GeV/c.
  - RICH Hit: $e^{\pm}$ and $\pi^{\pm}$.
  - No RICH Hit: $K^{\pm}$ and p.
- $0.2 < E/p < 0.8$
- EM shower shape probability < 0.1

$e^{\pm}$ identification

- Trigger $e^{\pm}$ with a BBC and EMCal.
- $|E\backslash p - \langle E/p \rangle| < 2\sigma_{E/p}$ at $(\langle E/p \rangle \sim 1)$
- RICH Hit: $e^{\pm}$ $(20\ MeV/c < p)$
- EM shower shape probability > 0.01
- Hit requirement in inner 2 layers of VTX
- Conversion veto cut on opening angle of nearby $e^{\pm}$ candidates

Energy threshold for the emission of Cherenkov radiation in RICH

Particle	***Electron***	***Pion***	**Kaon**	***Proton***
Threshold	*20MeV/c*	*4.9GeV/c*	*17.3GeV/c*	*33GeV/c*



example at $\sqrt{s}$ = 510 GeV

(PHENIX Collaboration) PRD 102, 032001

Calculation (Formula)

KOREA UNIVERSITY 1905

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)

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

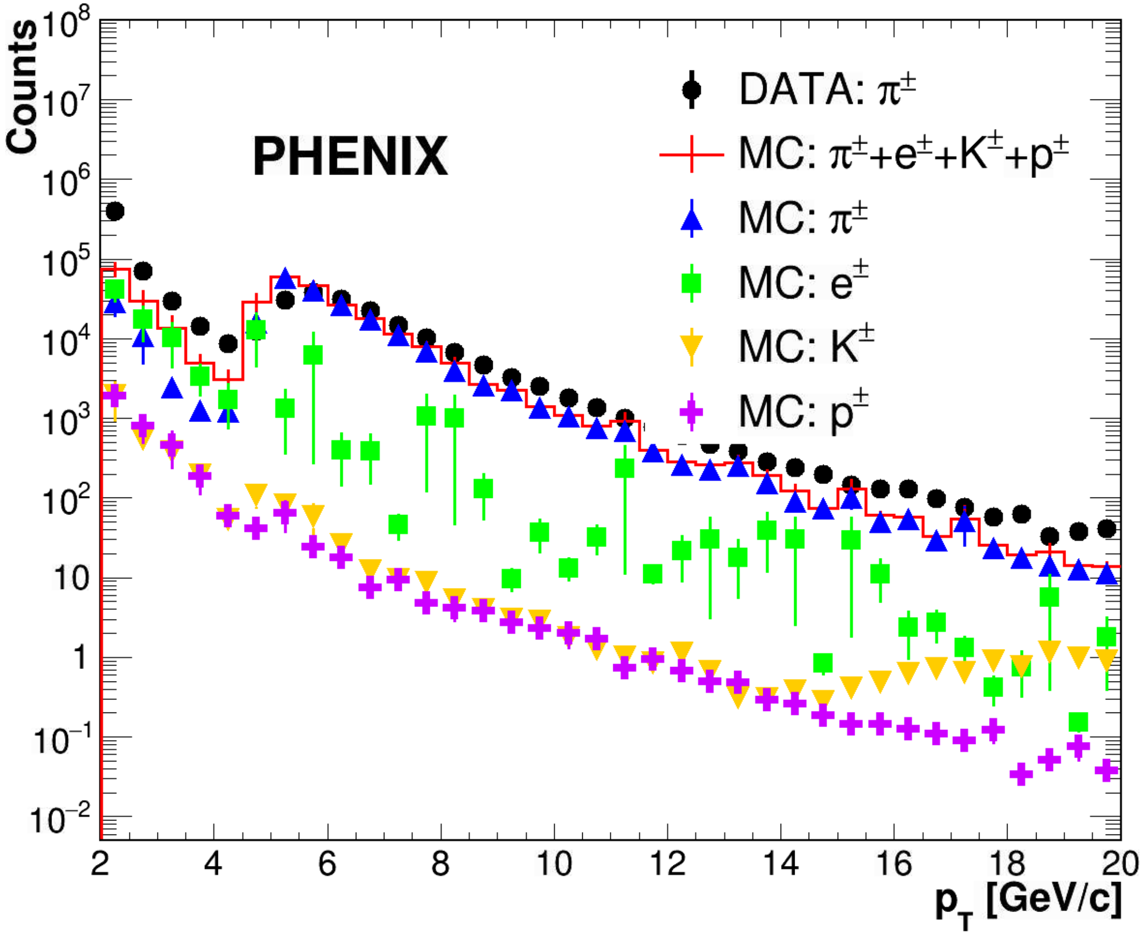
$$\sigma^2{}_{A_{N,average}} = \frac{1}{\sum_{i=Fill} 1 / \sigma^2{}_{A_{N,i}}}$$

Relative Luminosity Formula

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

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

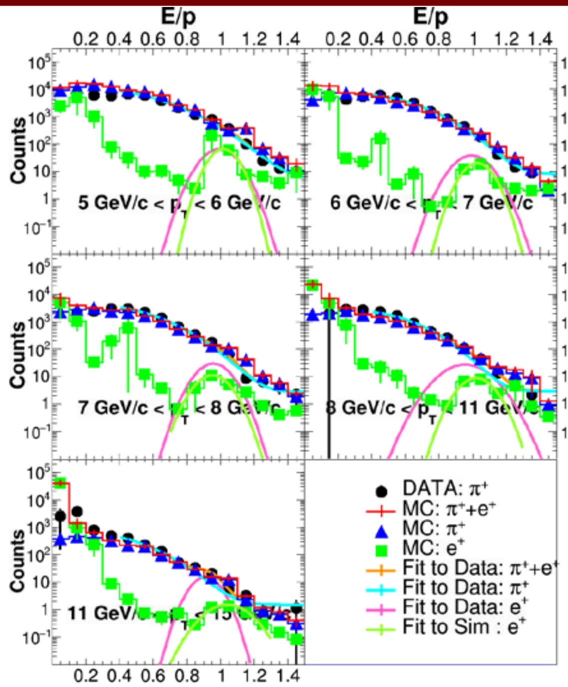
Charged pion background



Comparison of reconstructed particle momentum distributions as a function of the transverse momentum in the data and MC simulations.

- At low p_T below 5 GeV/c the distribution is dominated by electrons (kaons and protons is insignificant)
- At higher p_T, electrons are the dominant background.

Background_Fraction calculation



Energy over momentum ratio for pion candidates in bins of transverse momentum.

- e/p < 0.2 , electrons from photon conversion decay-in-flight are reconstructed with higher p_T
- e/p > 0.8 , considering that most pions do not deposit all their energy in the electromagnetic calorimeter in contrast to electrons.
- Calibrate electron background fraction from simulation by fitting E/p peak to data
- Correct for electron background using asymmetries from electron enhanced data sample

$$BF_{pion-sample} = \frac{A^e_{DATA(E/p\sim1)}}{A^e_{MC_{lumi\_scaled}(E/p\sim1)}} \times \frac{N^e_{MC_{lumi\_scaled}}}{N^{\pi+e}_{DATA}}$$

ScaleFactor for sys_unc.

$$\text{ScaleFactor} = \frac{Gaus\_amp_{data} + C \times Gaus\_amp\_err_{data}}{Gaus\_amp_{MC} + D \times Gaus\_amp\_err_{MC}}$$

where C, D = {-1,0,1}

BgkFrac = ScaleFactor * YieldRatio;

Background Fraction

$\frac{N^{\pi,Bg}}{N^{\pi,Sig}}$: Background Fraction in the pions enhanced sample

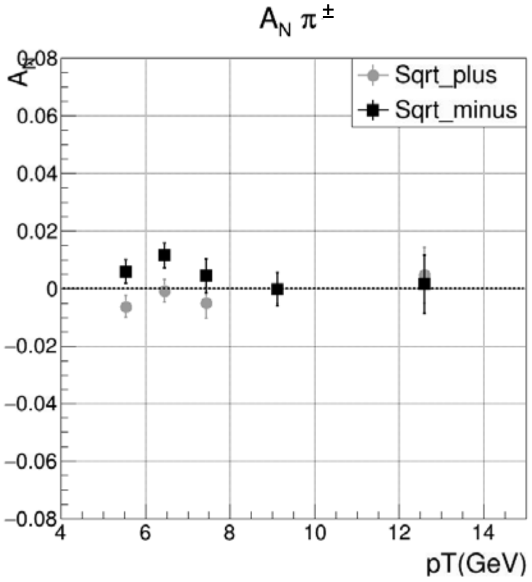
$\frac{N^{e,Bg}}{N^{e,Sig}}$: Background Fraction in the electrons enhanced sample

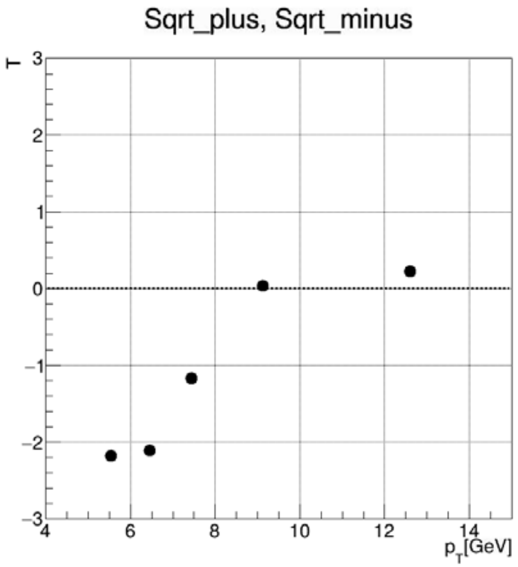
Background Subtraction

$$A_N^{\pi} = \frac{A_N^{\pi,Sig}\frac{N^{\pi,Sig}+N^{\pi,Bg}}{N^{\pi,Sig}} - A_N^{e,Sig}\frac{N^{\pi,Bg}}{N^{\pi,Sig}}\frac{N^{e,Sig}+N^{e,Bg}}{N^{e,Sig}}}{1-\frac{N^{\pi,Bg}}{N^{\pi,Sig}}\frac{N^{e,Bg}}{N^{e,Sig}}}$$

$$\Delta A_N^{\pi} = \frac{\sqrt{[\Delta A_N^{\pi,Sig}\frac{N^{\pi,Sig}+N^{\pi,Bg}}{N^{\pi,Sig}}]^2 - [\Delta A_N^{e,Sig}\frac{N^{\pi,Bg}}{N^{\pi,Sig}}\frac{N^{e,Sig}+N^{e,Bg}}{N^{e,Sig}}]^2}}{1-\frac{N^{\pi,Bg}}{N^{\pi,Sig}}\frac{N^{e,Bg}}{N^{e,Sig}}}$$

Charged pion vs eletron

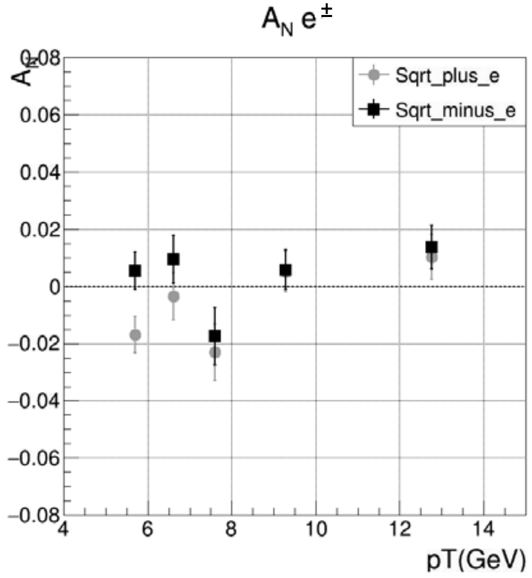


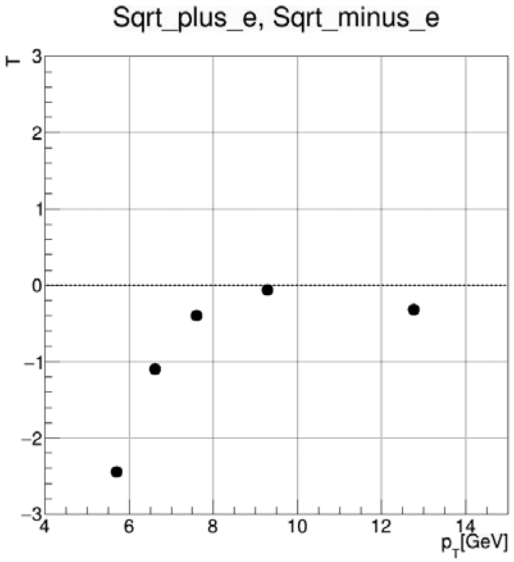


- Calculation A_N of pion enhancement sample by using pion PID cut

- T-test

$$T(p_T) = \frac{A_N^{\pi^-} - A_N^{\pi^+}}{\sqrt{\left|(\sigma^{\pi^-})^2 + (\sigma^{\pi^+})^2\right|}}$$



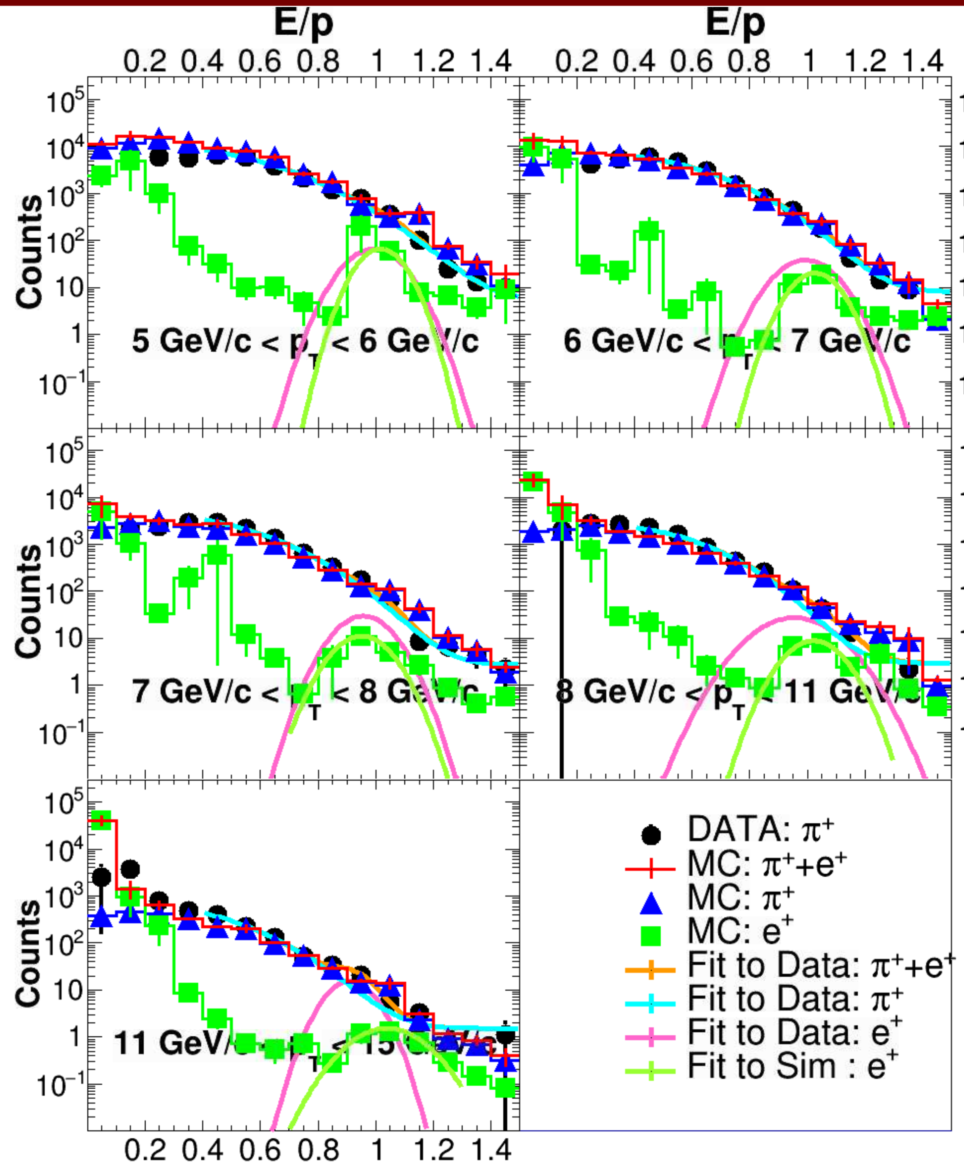


- Calculation A_N of electron enhancement sample by using electron PID cut

- T-test

$$T(p_T) = \frac{A_N^{e^-} - A_N^{e^+}}{\sqrt{\left|(\sigma^{e^-})^2 + (\sigma^{e^+})^2\right|}}$$

Background Subtraction



$$r_{\pi^\pm} \equiv \frac{N^{\pi^\pm,Bg}}{N^{\pi^\pm,Sig}} = \frac{A^{e^\pm}_{DATA(E/p\sim1)}}{A^{e^\pm}_{MC_{lumi\_scaled}(E/p\sim1)}} \times \frac{N^{e^\pm}_{MC_{lumi\_scaled}}}{N^{\pi^\pm+e^\pm}_{DATA}}$$

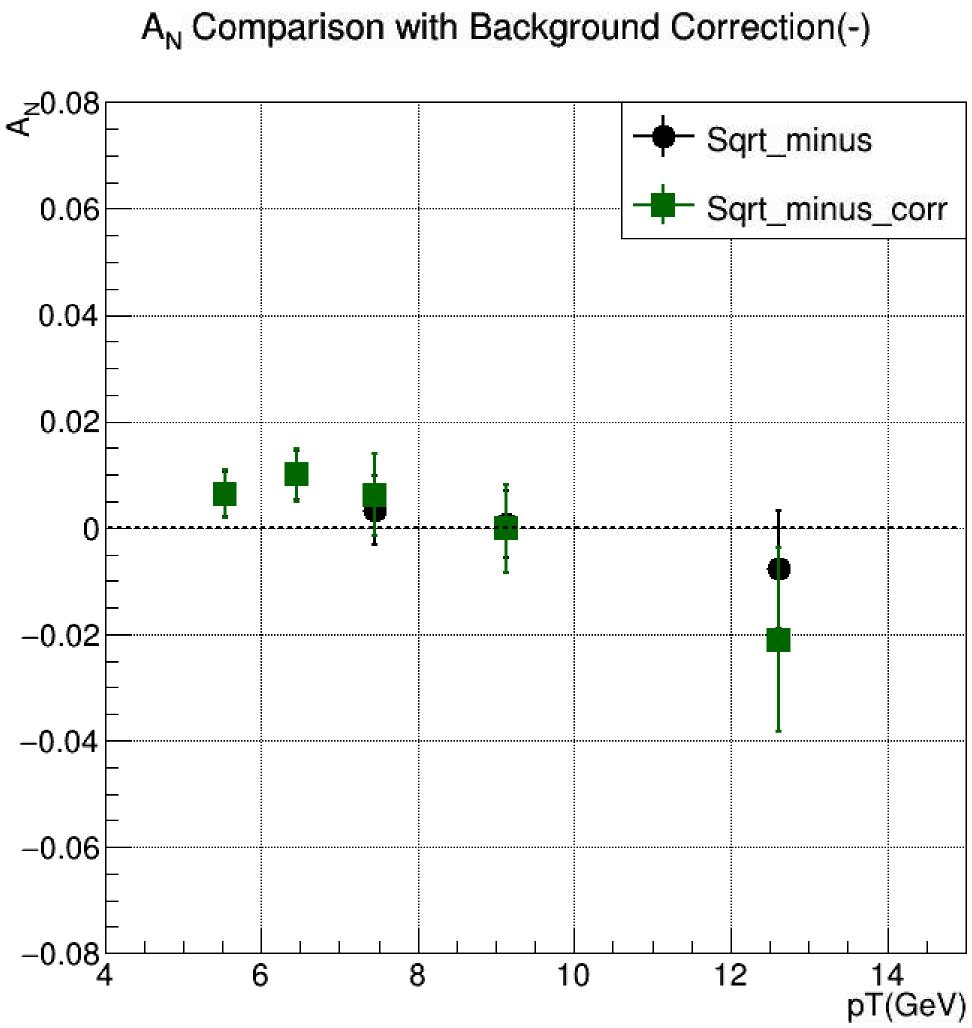
$$r_{e^\pm} \equiv \frac{N^{e^\pm,Bg}}{N^{e^\pm,Sig}} = \frac{A^{e^\pm}_{DATA(E/p\sim1)}}{A^{e^\pm}_{MC_{lumi\_scaled}(E/p\sim1)}} \times \frac{N^{\pi^\pm}_{MC_{lumi\_scaled}}}{N^{\pi^\pm+e^\pm}_{DATA}}$$

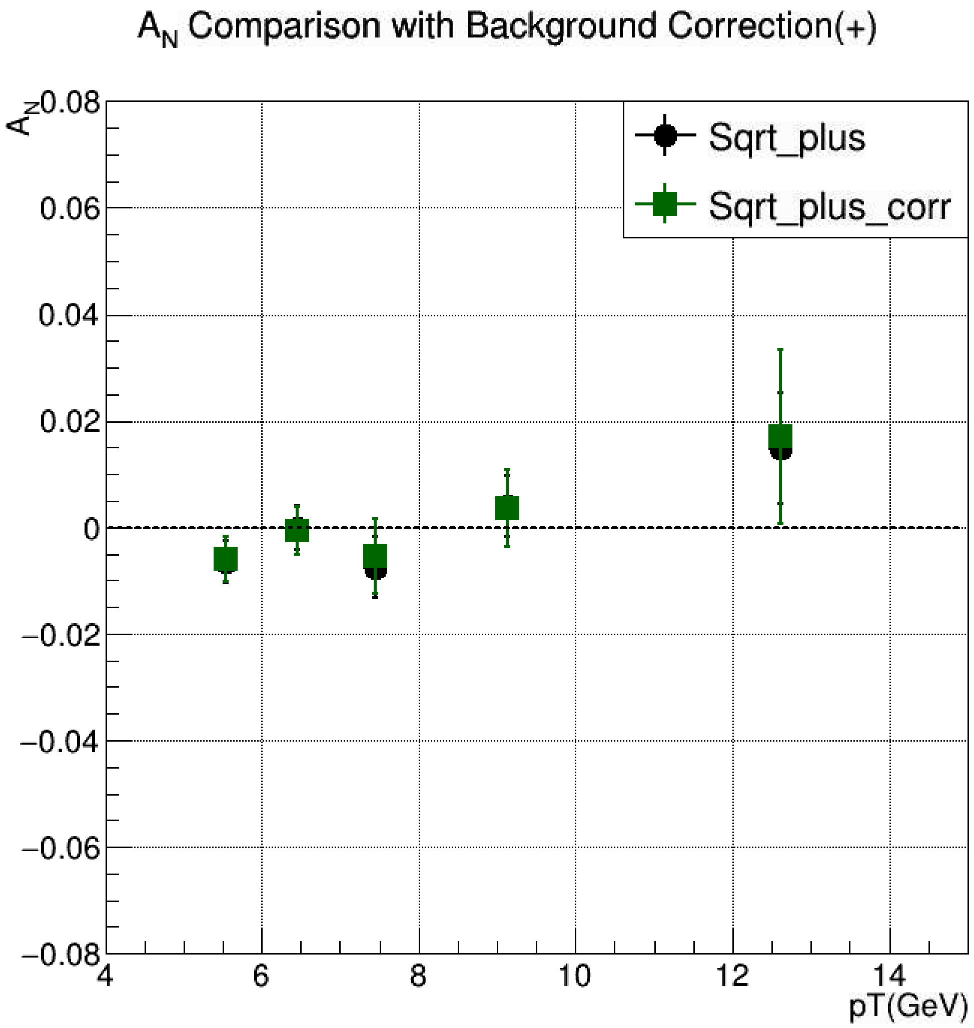
$$A_N^{\pi^\pm} = \frac{A_N^{\pi^\pm,Sig}\frac{N^{\pi^\pm,Sig}+N^{\pi^\pm,Bg}}{N^{\pi^\pm,Sig}} - A_N^{e^\pm,Sig}\frac{N^{\pi^\pm,Bg}}{N^{\pi^\pm,Sig}}\frac{N^{e^\pm,Sig}+N^{e^\pm,Bg}}{N^{e^\pm,Sig}}}{1-\frac{N^{\pi^\pm,Bg}}{N^{\pi^\pm,Sig}}\frac{N^{e^\pm,Bg}}{N^{e^\pm,Sig}}}$$

$$\sigma_{A_N^{\pi^\pm}} = \frac{\sqrt{\left(\sigma_{A_N^{\pi^\pm,Sig}}\frac{N^{\pi^\pm,Sig}+N^{\pi^\pm,Bg}}{N^{\pi^\pm,Sig}}\right)^2 + \left(\sigma_{A_N^{e^\pm,Sig}}\frac{N^{\pi^\pm,Bg}}{N^{\pi^\pm,Sig}}\frac{N^{e^\pm,Sig}+N^{e^\pm,Bg}}{N^{e^\pm,Sig}}\right)^2}}{1-\frac{N^{\pi^\pm,Bg}}{N^{\pi^\pm,Sig}}\frac{N^{e^\pm,Bg}}{N^{e^\pm,Sig}}}$$

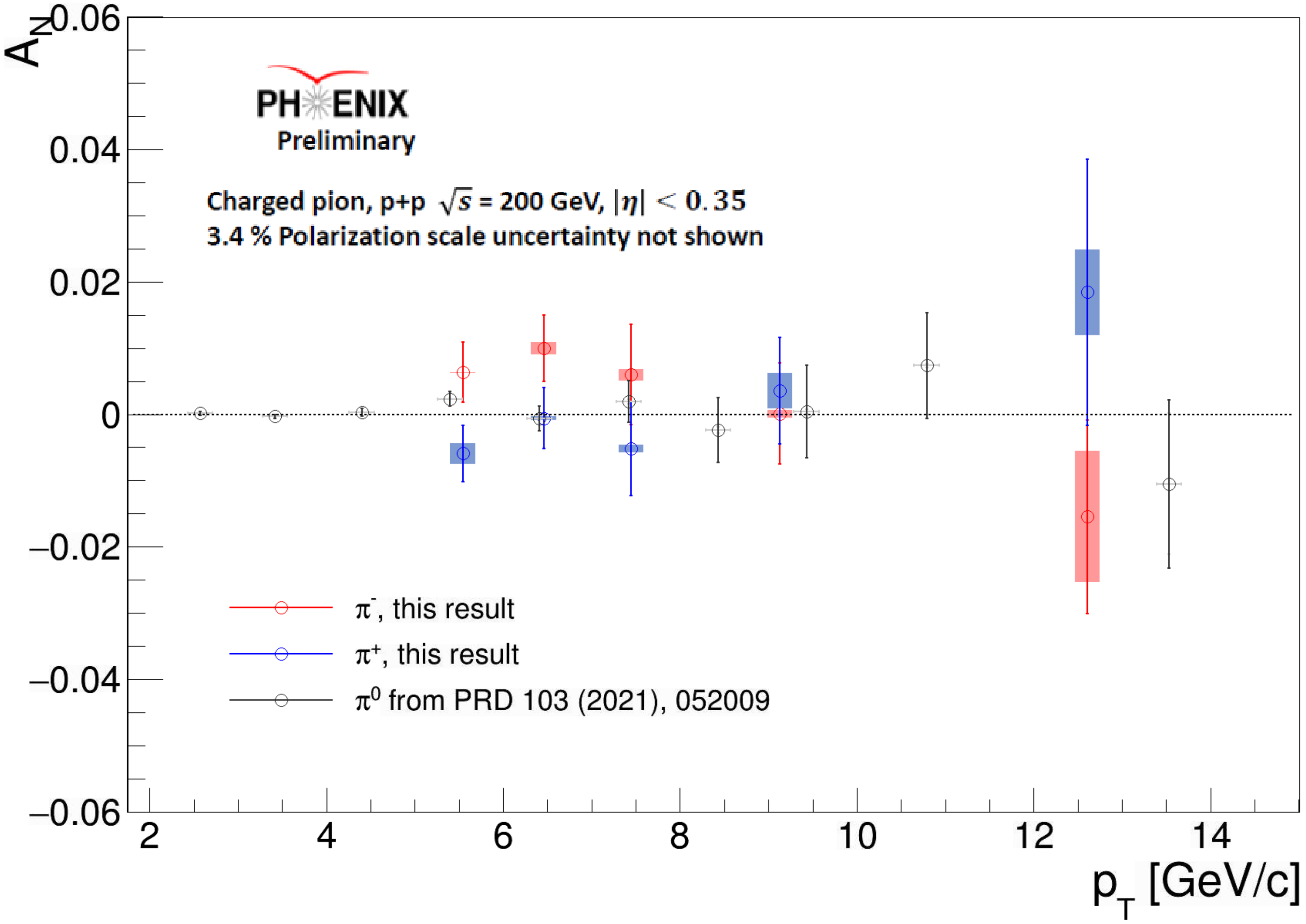
$$\sigma_{A_N^{\pi^\pm}} = \frac{\sqrt{\left\{\sigma_{A_N^{\pi^\pm,Sig}}\cdot(1+r_{\pi^\pm})\right\}^2 + \left\{\sigma_{A_N^{e^\pm,Sig}}\cdot r_{\pi^\pm}\cdot(1+r_{e^\pm})\right\}^2}}{1-r_{\pi^\pm}r_{e^\pm}}$$

Compare before/after background correction





Charged Pion A_N



- First central charged pion AN measurement at PHENIX
- A_N of each charge consistent with zero
- But slight indication of differences with each other. (particularly low P_T region)

Hint of different asymmetries from up and down quarks

Summary

- **First A_N measurements of $\pi^{\pm}$ at midrapidity**

- A_N in $\pi^{\pm}$ production are sensitive to quark flavors.

- With a complementary probe with improved statistics, might help to check the up and down quarks make a different asymmetries.

- It expands π^{+} and π^{-} for each quarks flavor.

Thank you.

BACKUP

Sys_Background_Fraction

pion_min

	pt	pion_bgkfrac	elec_bgkfrac	A_N	A_N_error
-	0	3.583.E-02	6.519.E-03	6.356.E-03	4.494.E-03
	1	4.189.E-02	6.569.E-02	9.972.E-03	4.841.E-03
	2	1.049.E-01	1.647.E-01	5.538.E-03	7.394.E-03
	3	5.568.E-02	8.560.E-01	2.882.E-04	7.161.E-03
	4	1.252.E-01	9.178.E-01	-1.473.E-02	1.430.E-02
+	0	3.583.E-02	6.519.E-03	-6.065.E-03	4.174.E-03
	1	4.189.E-02	6.569.E-02	-3.943.E-04	4.450.E-03
	2	1.049.E-01	1.647.E-01	-5.880.E-03	6.632.E-03
	3	5.568.E-02	8.560.E-01	3.893.E-03	6.338.E-03
	4	1.252.E-01	9.178.E-01	1.604.E-02	1.343.E-02

pion_max

	pt	pion_bgkfrac	elec_bgkfrac	A_N	A_N_error
-	0	5.358.E-02	6.519.E-03	6.326.E-03	4.581.E-03
	1	1.358.E-01	6.569.E-02	9.934.E-03	5.464.E-03
	2	1.775.E-01	1.647.E-01	7.100.E-03	8.188.E-03
	3	2.037.E-01	8.560.E-01	-9.079.E-04	9.989.E-03
	4	3.187.E-01	9.178.E-01	-3.012.E-02	2.192.E-02
+	0	5.358.E-02	6.519.E-03	-5.818.E-03	4.255.E-03
	1	1.358.E-01	6.569.E-02	-1.052.E-03	5.040.E-03
	2	1.775.E-01	1.647.E-01	-4.702.E-03	7.376.E-03
	3	2.037.E-01	8.560.E-01	3.384.E-03	8.985.E-03
	4	3.187.E-01	9.178.E-01	1.864.E-02	2.079.E-02

$$\varepsilon_\pi = (A_N^{\pi\,max} - A_N^{\pi\,min})/2$$

$$\varepsilon_e = (A_N^{e\,max} - A_N^{e\,min})/2$$

$$\sigma_{syst,bg\_frac} = \sqrt{(\varepsilon_\pi)^2 + (\varepsilon_e)^2}$$

elec_min

	pt	pion_bgkfrac	elec_bgkfrac	A_N	A_N_error
-	0	4.361.E-02	5.710.E-03	6.343.E-03	4.532.E-03
	1	6.883.E-02	5.732.E-02	9.961.E-03	5.001.E-03
	2	1.375.E-01	1.350.E-01	6.150.E-03	7.694.E-03
	3	1.192.E-01	6.518.E-01	-7.106.E-05	7.956.E-03
	4	2.154.E-01	6.421.E-01	-1.834.E-02	1.603.E-02
+	0	4.361.E-02	5.710.E-03	-5.957.E-03	4.209.E-03
	1	6.883.E-02	5.732.E-02	-5.782.E-04	4.600.E-03
	2	1.375.E-01	1.350.E-01	-5.419.E-03	6.913.E-03
	3	1.192.E-01	6.518.E-01	3.740.E-03	7.071.E-03
	4	2.154.E-01	6.421.E-01	1.665.E-02	1.510.E-02

elec_max

	pt	pion_bgkfrac	elec_bgkfrac	A_N	A_N_error
-	0	4.361.E-02	7.535.E-03	6.343.E-03	4.532.E-03
	1	6.883.E-02	7.579.E-02	9.961.E-03	5.009.E-03
	2	1.375.E-01	2.037.E-01	6.348.E-03	7.795.E-03
	3	1.192.E-01	1.160.E+00	-3.630.E-04	8.641.E-03
	4	2.154.E-01	1.243.E+00	-2.481.E-02	1.923.E-02
+	0	4.361.E-02	7.535.E-03	-5.956.E-03	4.209.E-03
	1	6.883.E-02	7.579.E-02	-5.871.E-04	4.607.E-03
	2	1.375.E-01	2.037.E-01	-5.269.E-03	7.007.E-03
	3	1.192.E-01	1.160.E+00	3.616.E-03	7.712.E-03
	4	2.154.E-01	1.243.E+00	1.775.E-02	1.819.E-02

	pt	σ_{syst,bg_frac}
-	0	1.509.E-05
	1	1.871.E-05
	2	7.875.E-04
	3	6.156.E-04
	4	8.349.E-03
+	0	1.236.E-04
	1	3.289.E-04
	2	5.937.E-04
	3	2.622.E-04
	4	1.412.E-03

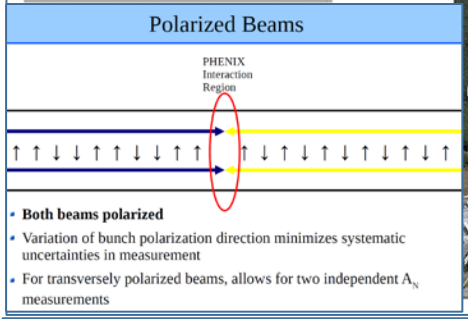
$$\text{ScaleFactor} = \frac{Gaus\_amp_{data} + C \times Gaus\_amp\_err_{data}}{Gaus\_amp_{MC} + D \times Gaus\_amp\_err_{MC}}$$ where C, D = {-1,0,1}

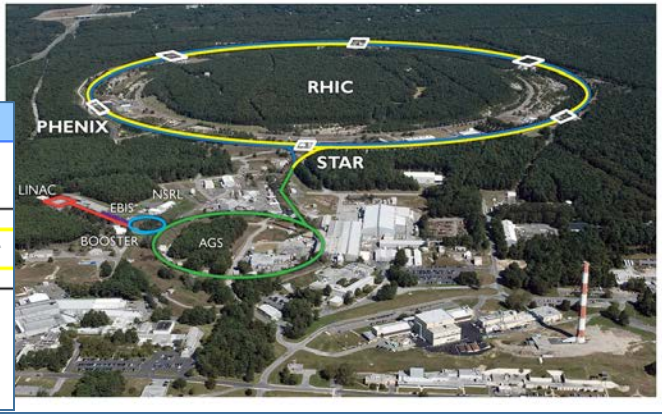
Where C =1 and D = -1 ---> max
Where C =-1 and D = 1 ---> max

Bunch shuffling

```
spin_blue[ cross ] ==  1 && spin_yellow[ cross ] ==  1 ) { //B down, Y down }
else if ( spin_blue[ cross ] ==  1 && spin_yellow[ cross ] == -1 ) { //B down, Y up   }
else if ( spin_blue[ cross ] == -1 && spin_yellow[ cross ] ==  1 ) { //B up,   Y down }
else if ( spin_blue[ cross ] == -1 && spin_yellow[ cross ] == -1 ) { //B up,   Y up   }
```

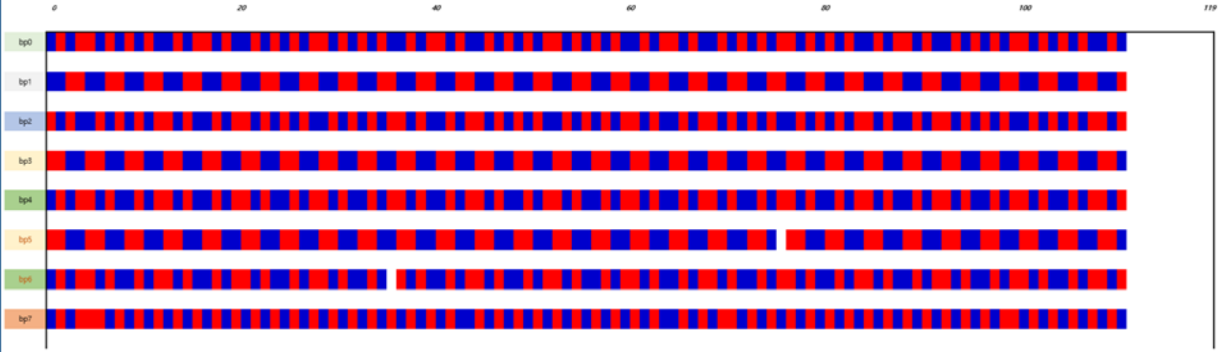
Blue = Clockwise
Yellow = Anti - Clockwise





Bunch shuffling : For each fill, the polarization directions of each crossing are randomized, and the asymmetry is calculated using the fill group method.

It involves randomizing the polarization directions of the beam such that the physics asymmetry disappears and all that is left are the statistical fluctuations present in the data.



• red = spins ↑ = -1

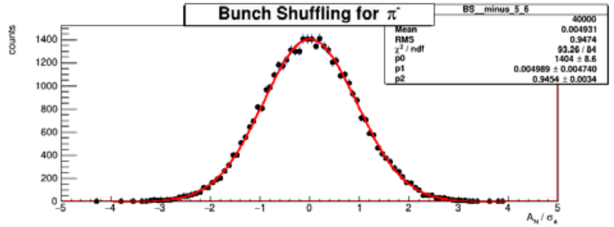
• Blue = spins ↓ = +1

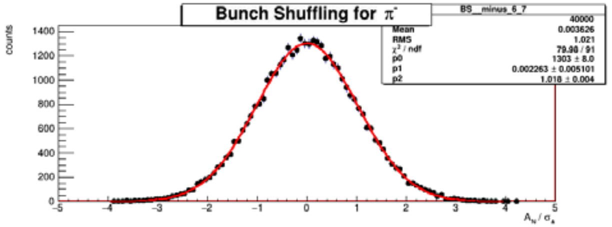
bp0	+ - + - - + - + - + - + + - + - - + - + + - + -	repeat 24
bp1	+ + - -	repeat 4
bp2	- + - + + - + - + - + - - + - + + - + - - + - +	repeat 24
bp3	- - + +	repeat 4
bp4	+ - + - - + - +	repeat 8
bp5	[illegible]	no repeat
bp6	[illegible]	no repeat
bp7	[illegible]	no repeat

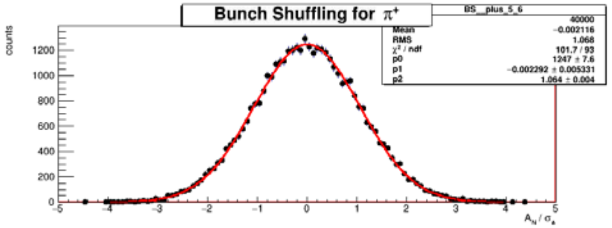
Pattern of each fillnumber (example)

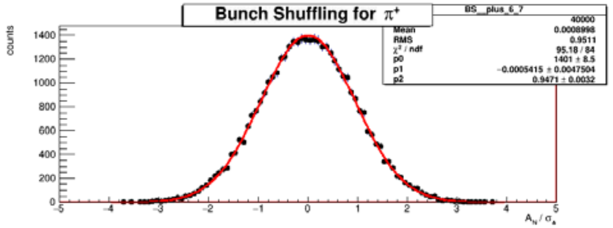
RunNumber	FillNumber	Crossing shift	# of pattern
430024	18893	5	1
430116	18894	5	7
430117	18894	5	7
430120	18894	5	7
430123	18894	5	7
430124	18894	5	7
430125	18894	5	7
430128	18894	5	7
430131	18894	5	7
430133	18895	5	3
430134	18895	5	3
430141	18895	5	3
430142	18895	5	3
430143	18895	5	3
430234	18897	5	8
430235	18897	5	8
430236	18897	5	8

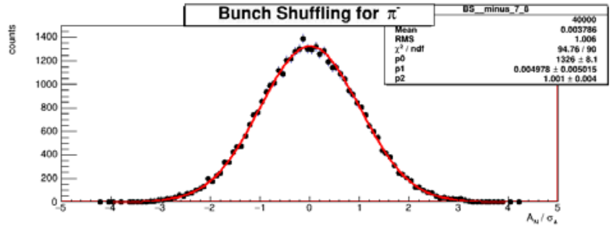
Sys. Unc. From Bunch shuffling

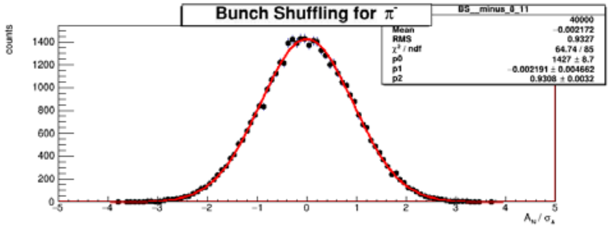


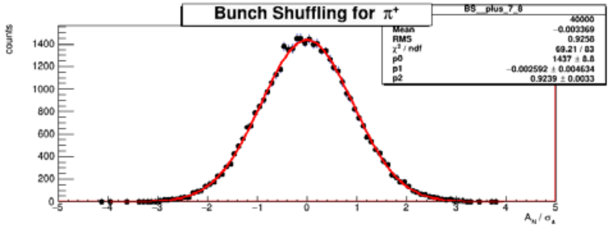


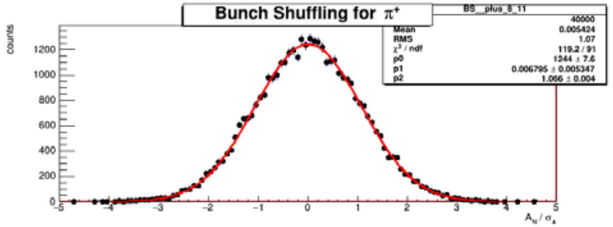


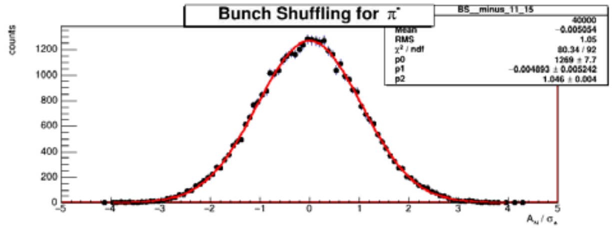




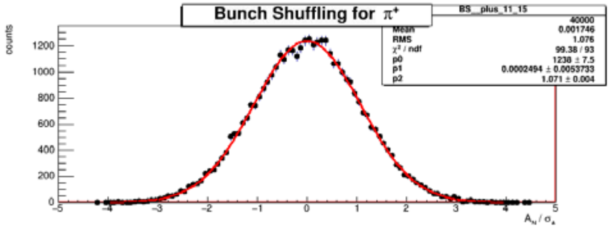








charge	pT (GeV)	mean	sigma	1-sigma
-	5~6	4.99.E-03	0.945	0.0546
	6~7	2.26.E-03	1.018	-0.0183
	7~8	4.98.E-03	1.001	-0.0006
	8~11	-2.19.E-03	0.931	0.0692
	11~15	-4.89.E-03	1.046	-0.0459



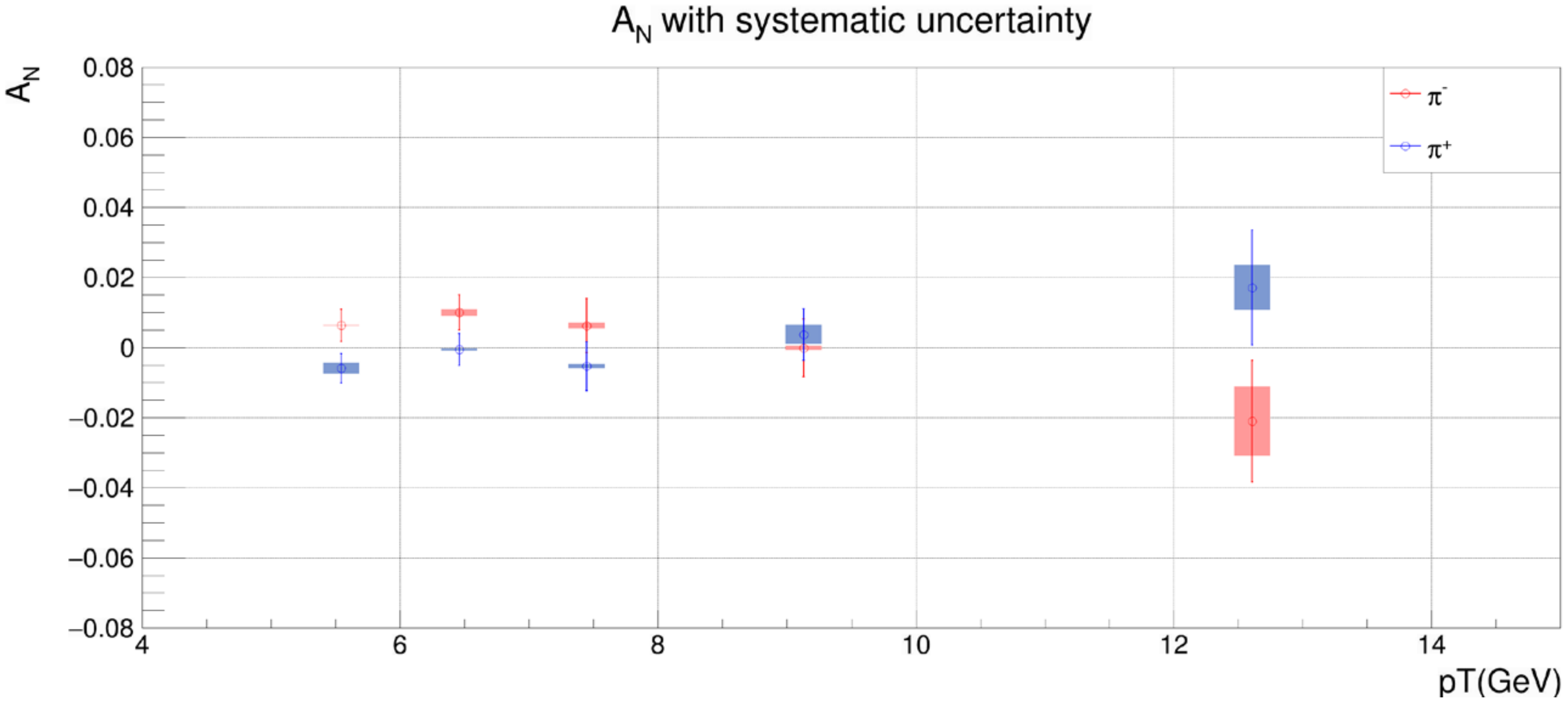
charge	pT (GeV)	mean	sigma	1-sigma
-	5~6	-2.29.E-03	1.064	-0.0635
	6~7	-5.41.E-04	0.947	0.0529
	7~8	-2.59.E-03	0.924	0.0761
	8~11	6.79.E-03	1.066	-0.0657
	11~15	2.49.E-04	1.071	-0.0713

Sys. Unc. From Bunch shuffling

Ex) $1.018\,\sigma_{stat} = \sqrt{(\sigma_{stat})^2+(\sigma_{syst})^2}$ for π^- 6~7 pt bin.

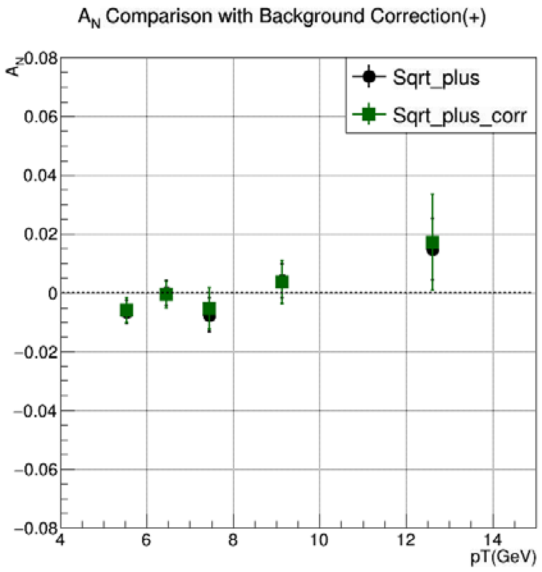
$$\sigma_{syst} = \sigma_{stat}\sqrt{(1.018)^2-(1)^2} \approx 0.000954$$

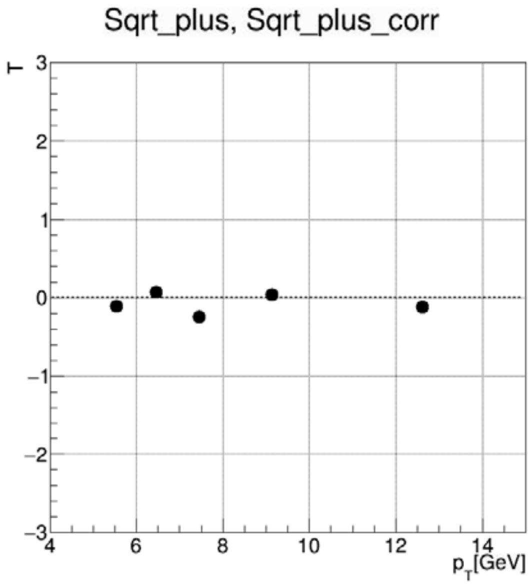
A_N with Systematic Uncertainty



	pt	<pt> in GeV/c	A_N (10^{-3})	Stat. (10^{-3})	Syst. (bg frraction) (10^{-3})	Syst. (bunch shuffling) (10^{-3})	Syst. (total) (10^{-3})
-	5~6	5.56	6.34	4.53	0.015		0.015
	6~7	6.46	9.96	5	0.019	0.954	0.954
	7~8	7.45	6.23	7.74	0.788	0.346	0.860
	8~11	9.08	-0.18	8.22	0.616		0.616
	11~15	12.42	-21.05	17.36	8.349	5.326	9.903
+	5~6	5.56	-5.96	4.21	0.124	1.530	1.535
	6~7	6.46	-0.58	4.6	0.329		0.329
	7~8	7.45	-5.35	6.95	0.594		0.594
	8~11	9.08	3.69	7.31	0.262	2.701	2.714
	11~15	12.42	17.11	16.38	1.412	6.280	6.437

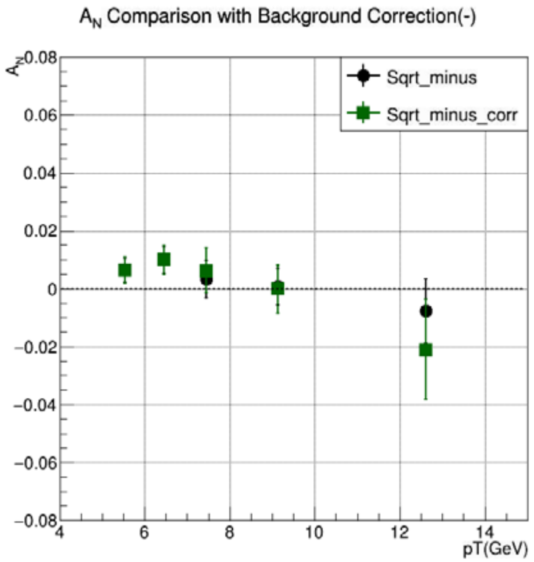
Compare before/after background correction

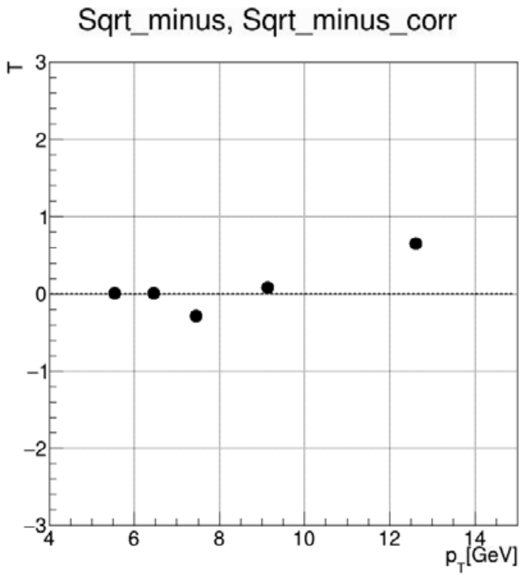




- Using pion enhancement sample by using pion PID cut

$$T(p_T) = \frac{A_N^{\pi^{before}} - A_N^{\pi^{after}}}{\sqrt{\left|(\sigma^{\pi^{before}})^2 + (\sigma^{\pi^{after}})^2\right|}}$$





- Using pion enhancement sample by using pion PID cut