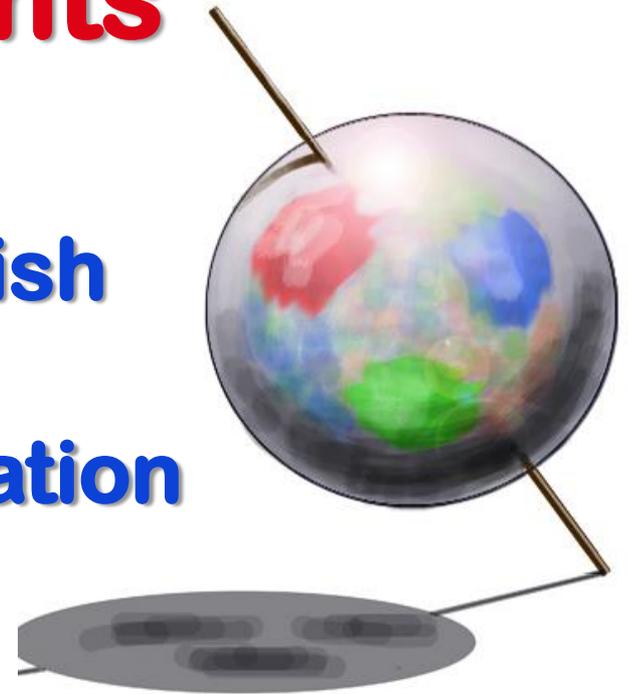


# PHENIX Transverse Spin Measurements

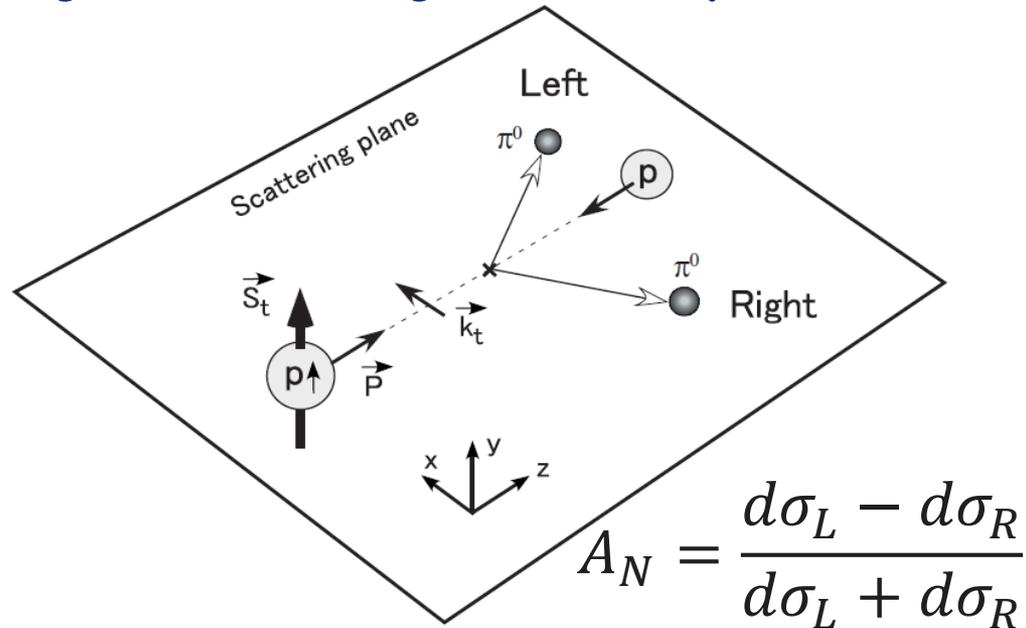
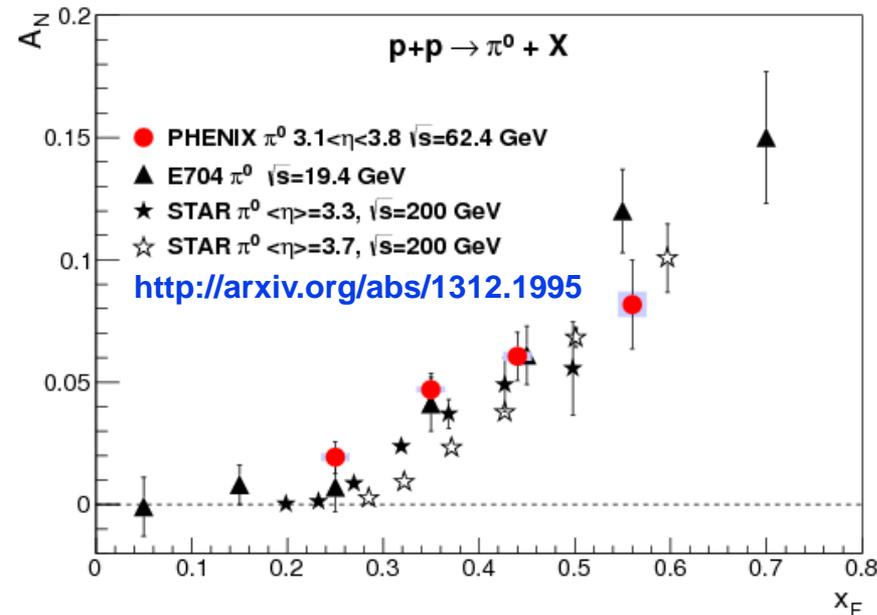
**Kenneth N. Barish  
for the  
PHENIX Collaboration**



**XXII. International Workshop on Deep-  
Inelastic Scattering and Related Subjects  
Warsaw, Poland April 28-May 2, 2014**

# Transverse Spin Asymmetries

- The persistence of large transverse asymmetries at RHIC energies, where collinear pQCD describes the cross-sections well, was a surprise.
- The transverse structure of the nucleon is largely unknown
- Large transverse asymmetries carry potential information about QCD dynamics beyond 1-D picture



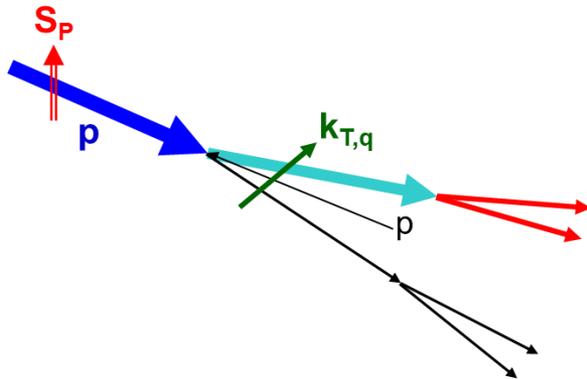
# Transverse Spin Asymmetry Sources

## (I) Initial State Effects: "Sivers"

Correlation between proton-spin and intrinsic transverse quark momentum

$$\propto \underbrace{\bar{f}_{1T}^{\perp q}(x, k_{\perp}^2)}_{\text{Sivers distribution (initial state)}} \cdot D_q^h(z)$$

Sivers distribution (initial state)



D. Sivers, Phys. Rev. D **41**, 83 (1990)

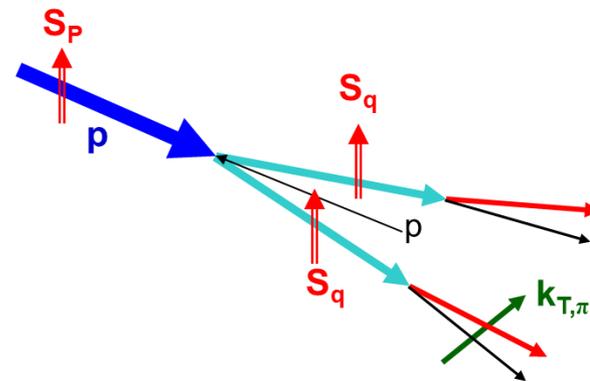
Twist-3 quark-gluon/gluon-gluon correlators in polarized hadron.

## (II) Final State Effects: "Collins"

Correlation between proton & quark spin + spin dependant fragmentation function

$$\propto \underbrace{\delta q(x)}_{\text{Quark transverse spin distribution}} \cdot \underbrace{H_1^{\perp}(z_2, \bar{k}_{\perp}^2)}_{\text{Collins FF (final state)}}$$

Quark transverse spin distribution Collins FF (final state)

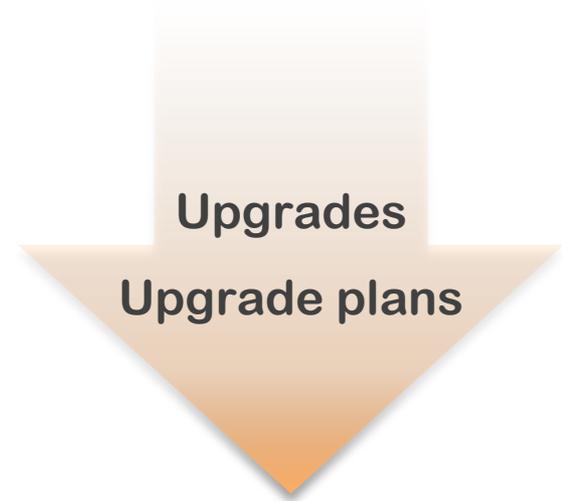


J. C. Collins, Nucl. Phys. **B396**, 161 (1993)

Twist-3 quark-gluon fragmentation function.

# Transverse Spin Measurements

- **Inclusive  $A_N$  (central/forward)**
  - Central  $\pi^0, \eta$
  - Forward  $\pi^0$ , EM clusters,  
 $\eta, \mu, J/\psi$
- **Photon  $A_N$  (MPC-EX)**
- **Jet correlations/structure,  
DY (fsPHENIX)**



# The PHENIX Detector

## Central Arms

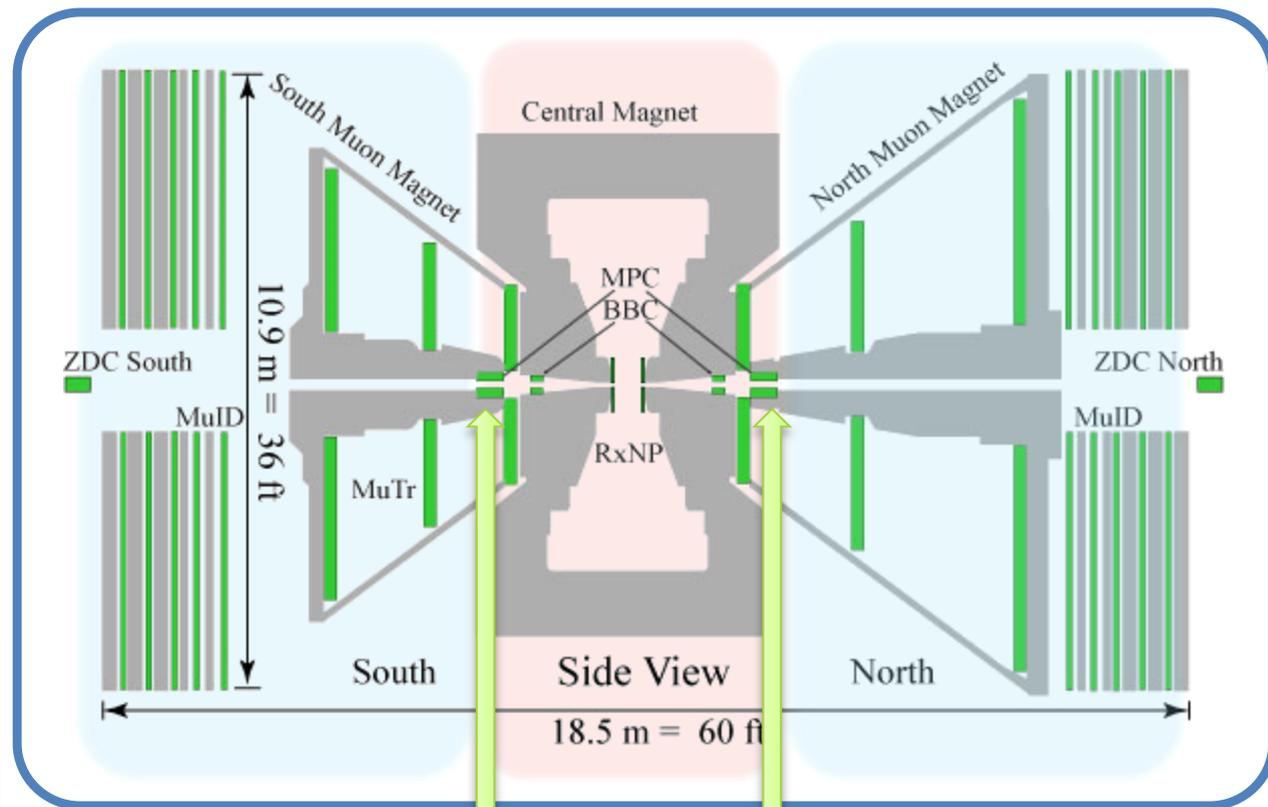
$$|\eta| < 0.35$$

- ❖ charged hadrons
- ❖  $\pi^0, \eta$
- ❖ direct photon
- ❖  $J/\psi$
- ❖ heavy flavor

## Muon Arms

$$1.2 < |\eta| < 2.4$$

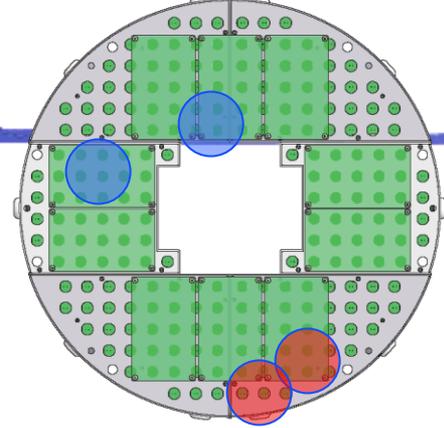
- ❖  $J/\psi$
- ❖ charged hadrons
- ❖ heavy flavor



MPC  $3.1 < |\eta| < 3.9$

- ❖  $\pi^0, \eta$

# MPC detectors

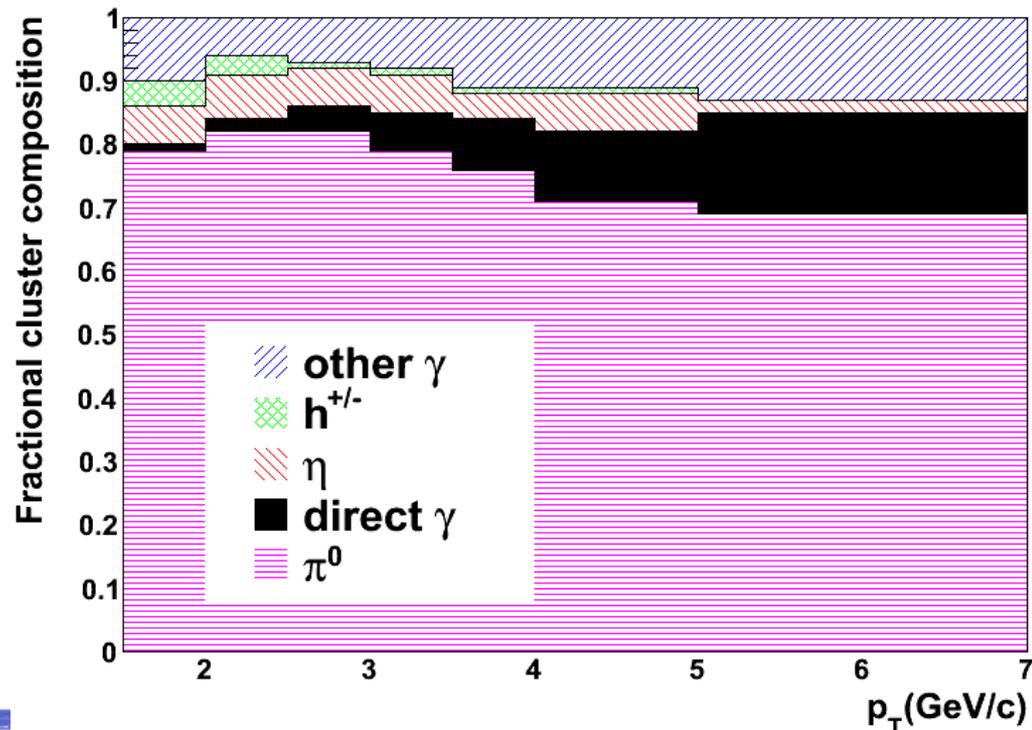


tower size  $2.25^2 \text{ cm}^2$   
220 cm from vertex

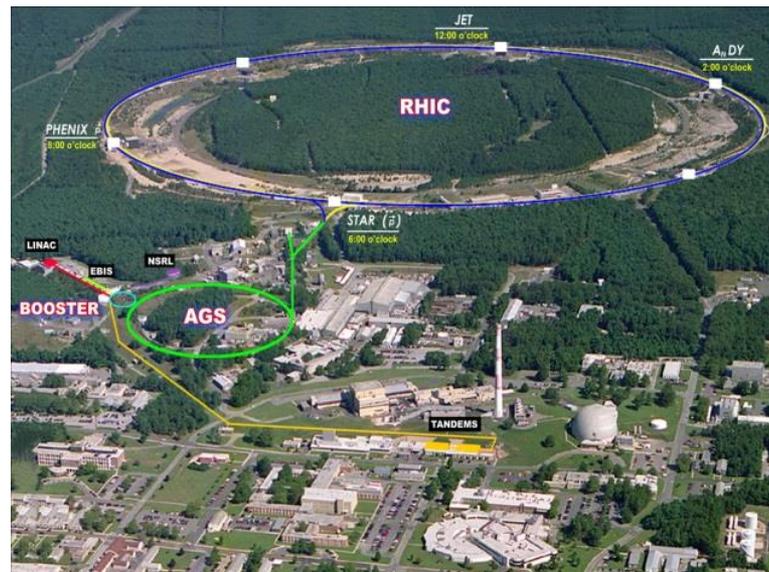
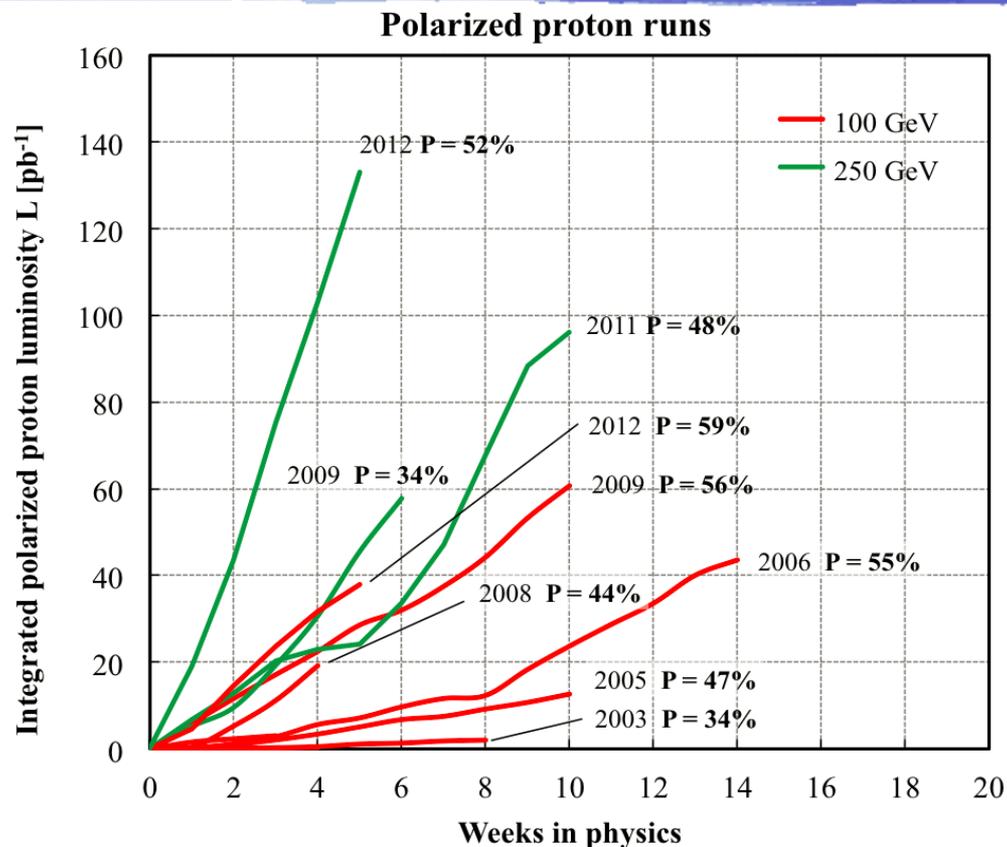
- **Lead-tungstate EMCal ( $3.1 < |\eta| < 3.8$ )**
  - » Enables measurements of forward  $\pi^0$  and  $\eta$  mesons
- **Photon merging effects significant for  $E > 20 \text{ GeV}$  ( $p_T > 2 \text{ GeV}/c$ )**
  - » For  $\sqrt{s} = 62 \text{ GeV}$ ,  $20 \text{ GeV} \rightarrow 0.65 x_F \Rightarrow$  two photon  $\pi^0$  analysis
  - » For  $\sqrt{s} = 200 \text{ GeV}$ ,  $20 \text{ GeV} \rightarrow 0.20 x_F \Rightarrow$  “Single clusters”

## ➤ Single Clusters

- »  $\pi^0$ 's are dominant source.
- » With increasing  $p_T$ , there is a sizable increase in contributions from direct and other photons.

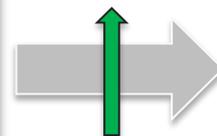


# Polarized Protons at RHIC-PHENIX



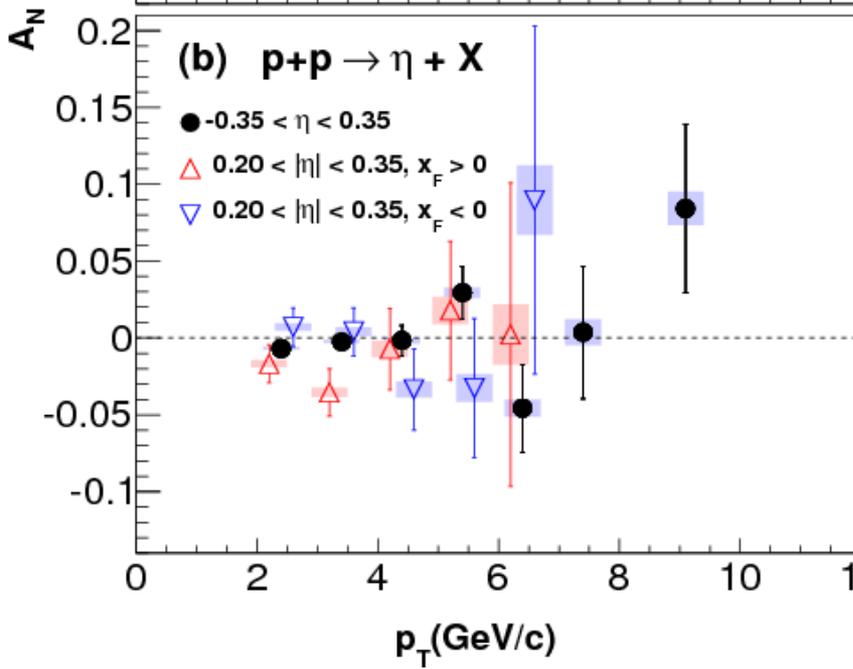
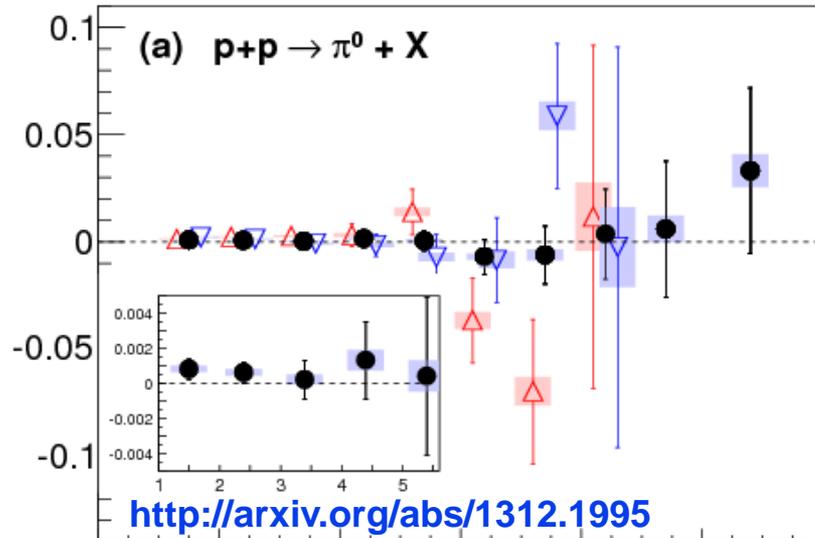
## Transverse Data

Year	$\sqrt{s}$ (GeV)	$L$ ( $\text{pb}^{-1}$ )	P	FoM ( $P^2L$ )
2006	62.4	0.02	48%	0.0046
2006	200	2.7	51%	0.7
2008	200	5.2	46%	1.1
2012	200	9.2	58%	3.1

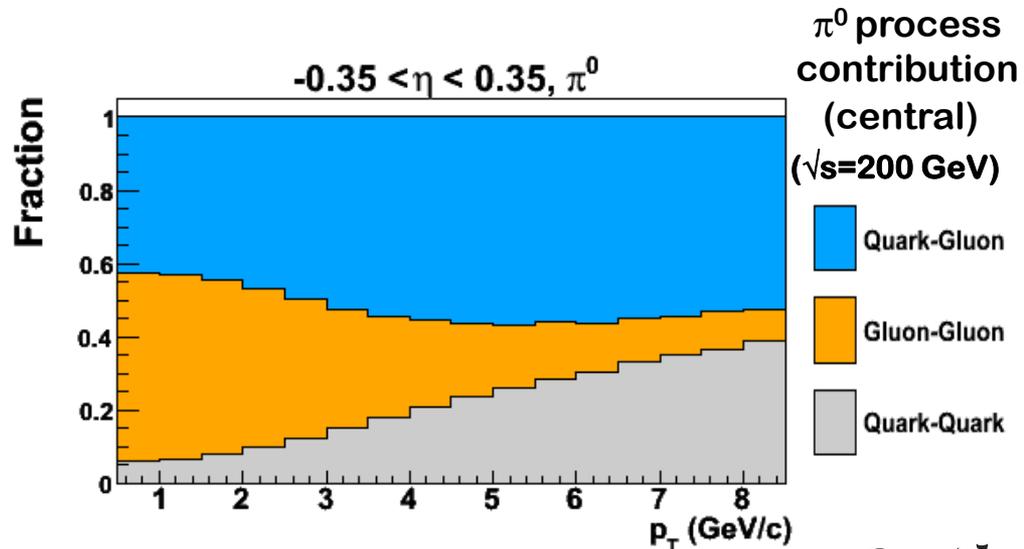


# $A_N$ : mid-rapidity $\pi^0$ and $\eta$

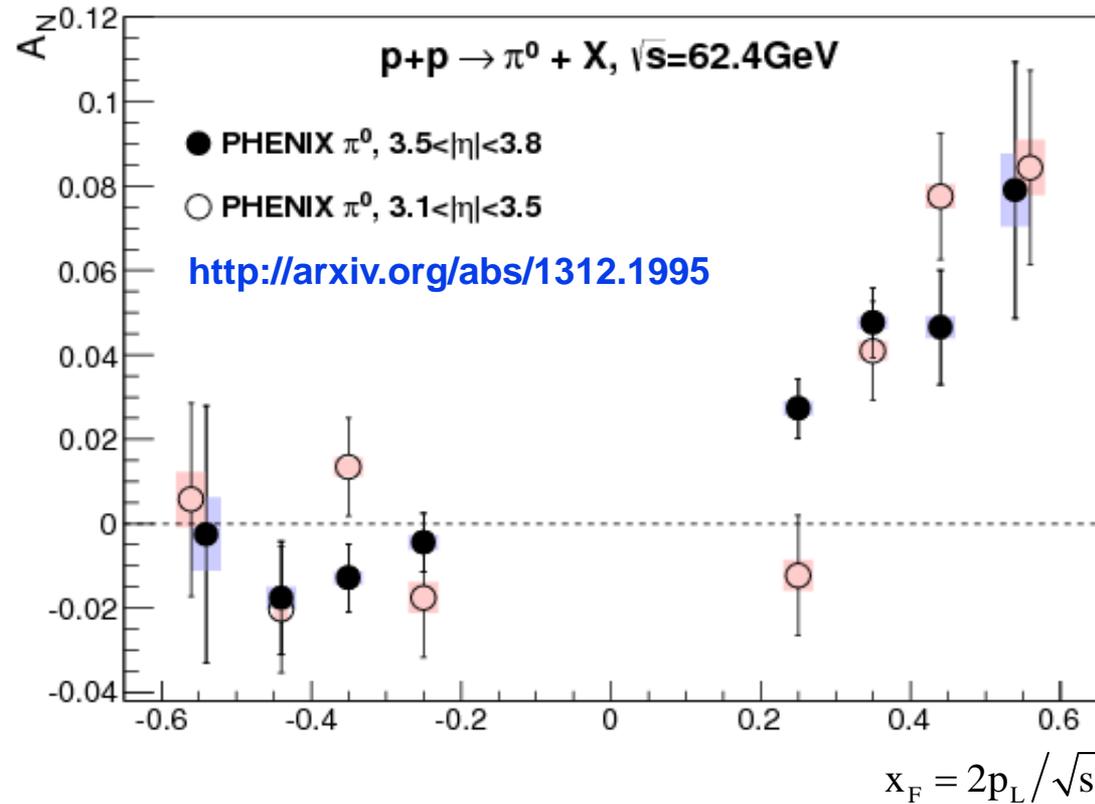
p+p  $\sqrt{s}=200$  GeV



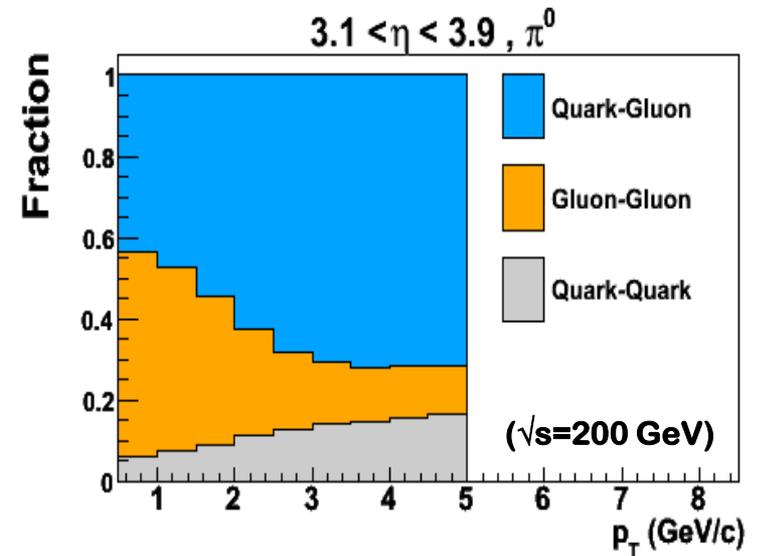
- $\pi^0$  asymmetries consistent with zero observed over a wide  $p_T$  range
- Exceed precision of previous publication (Phys. Rev. D 74, 094011) by a factor of 20 and extends  $p_T$  range.
- Constrains gluon Sivers
- $\eta$  asymmetries are also consistent with zero.



# Forward $\pi^0$ $A_N$ (62.4 GeV)



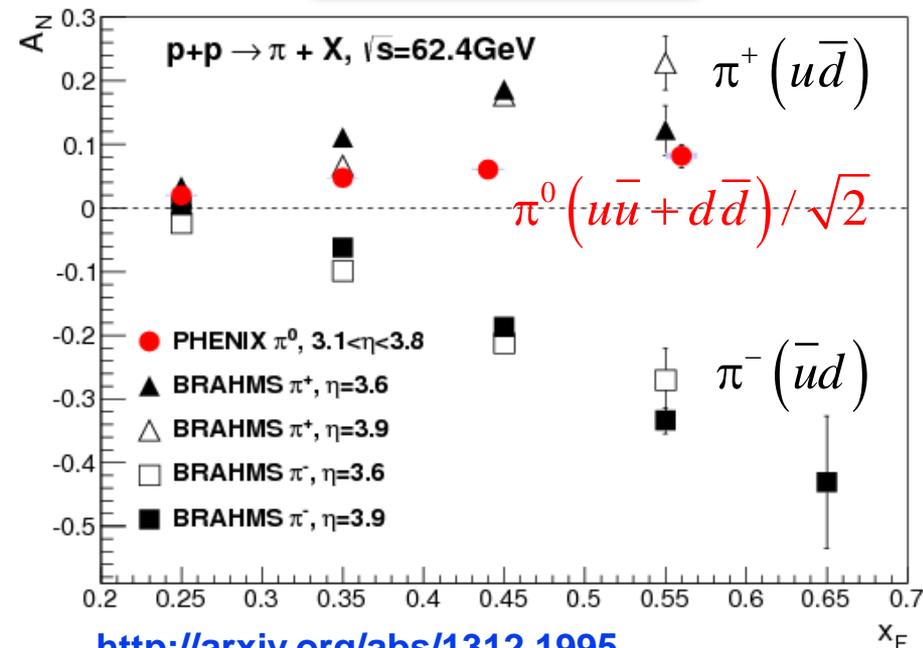
## $\pi^0$ process contribution in PHENIX forward arms



- Significant asymmetries for  $x_F > 0$  ( $\sim$  linear for  $x_F > 0.2$ )
- $A_N$  consistent with zero for  $x_F < 0$
- Quark-gluon is the dominant partonic component.

# Isospin Comparison of pion $A_N$

$\sqrt{s} = 62.4 \text{ GeV}$

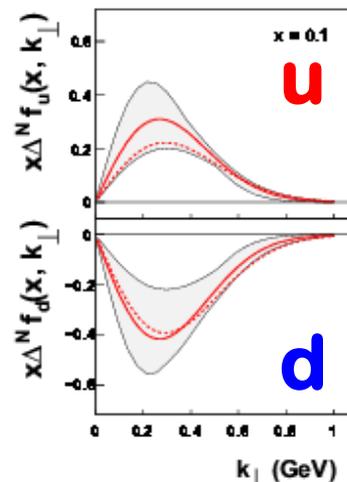


Quark origins of pions (PYTHIA):

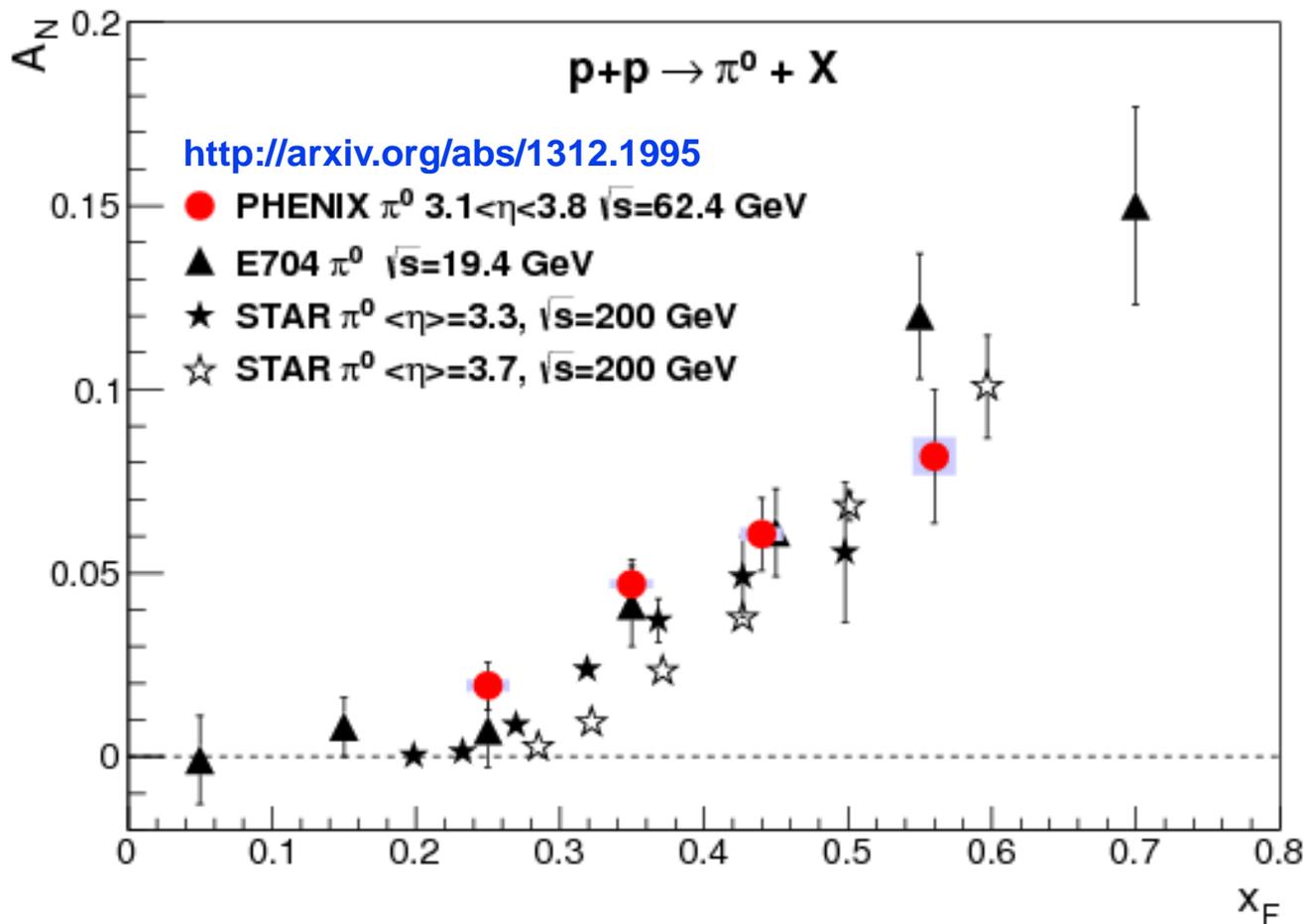
- $u \rightarrow \pi^+ / d \rightarrow \pi^+ : 100 / 0$
- $u \rightarrow \pi^0 / d \rightarrow \pi^0 : 75 / 25$
- $u \rightarrow \pi^- / d \rightarrow \pi^- : 50 / 50$

Data cannot be explained by initial state effects of quarks (Sivers) alone (assuming u and d quark Sivers functions extracted from SIDIS)

Sivers



# Forward $\pi^0$ $A_N$ $\sqrt{s}$ dependence

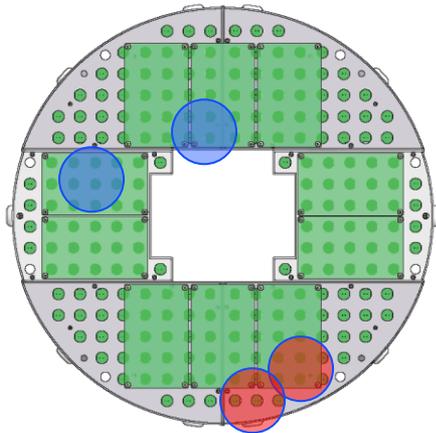


- Sizable forward non-zero asymmetries
- No dependence on  $\sqrt{s}$  apparent from 19.6 GeV to 200 GeV
- Slight differences in pseudorapidity and/or  $p_T$

# Forward $A_N$ for EM Clusters

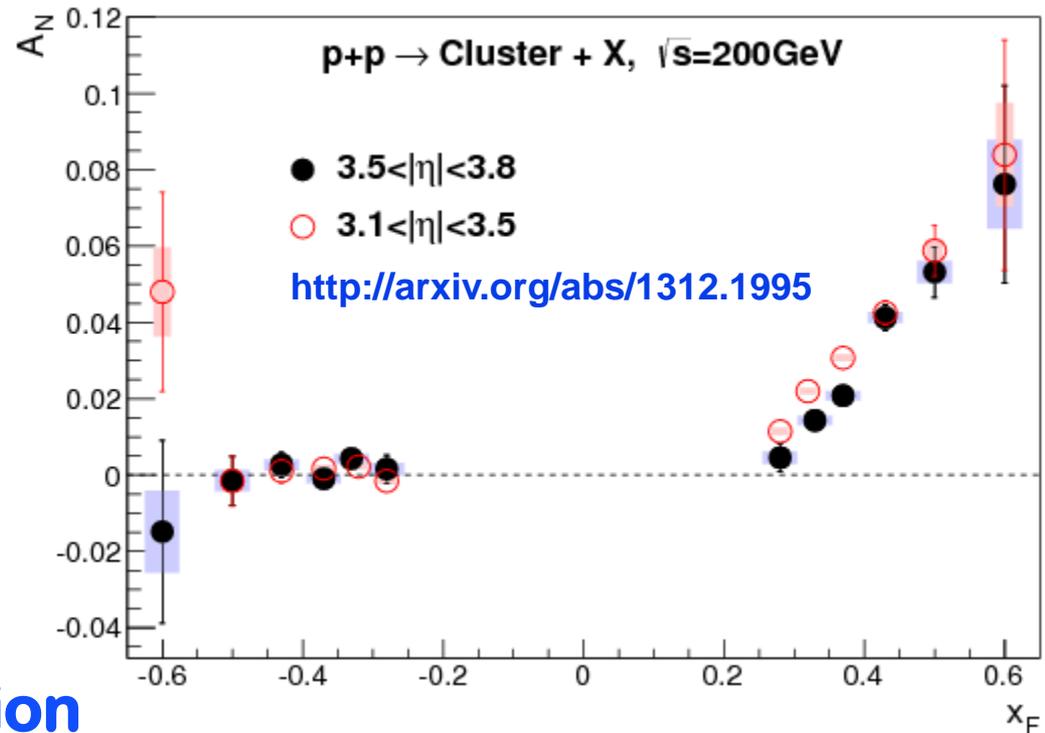
## MPC

tower size  $2.25^2 \text{ cm}^2$   
220 cm from vertex

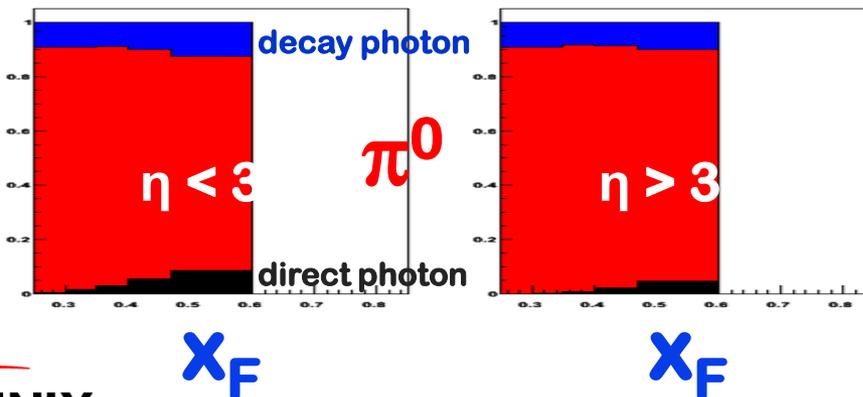


Decay photon impact positions  
for low and high energy  $\pi^0$ 's.

$\sqrt{s} = 200 \text{ GeV}$

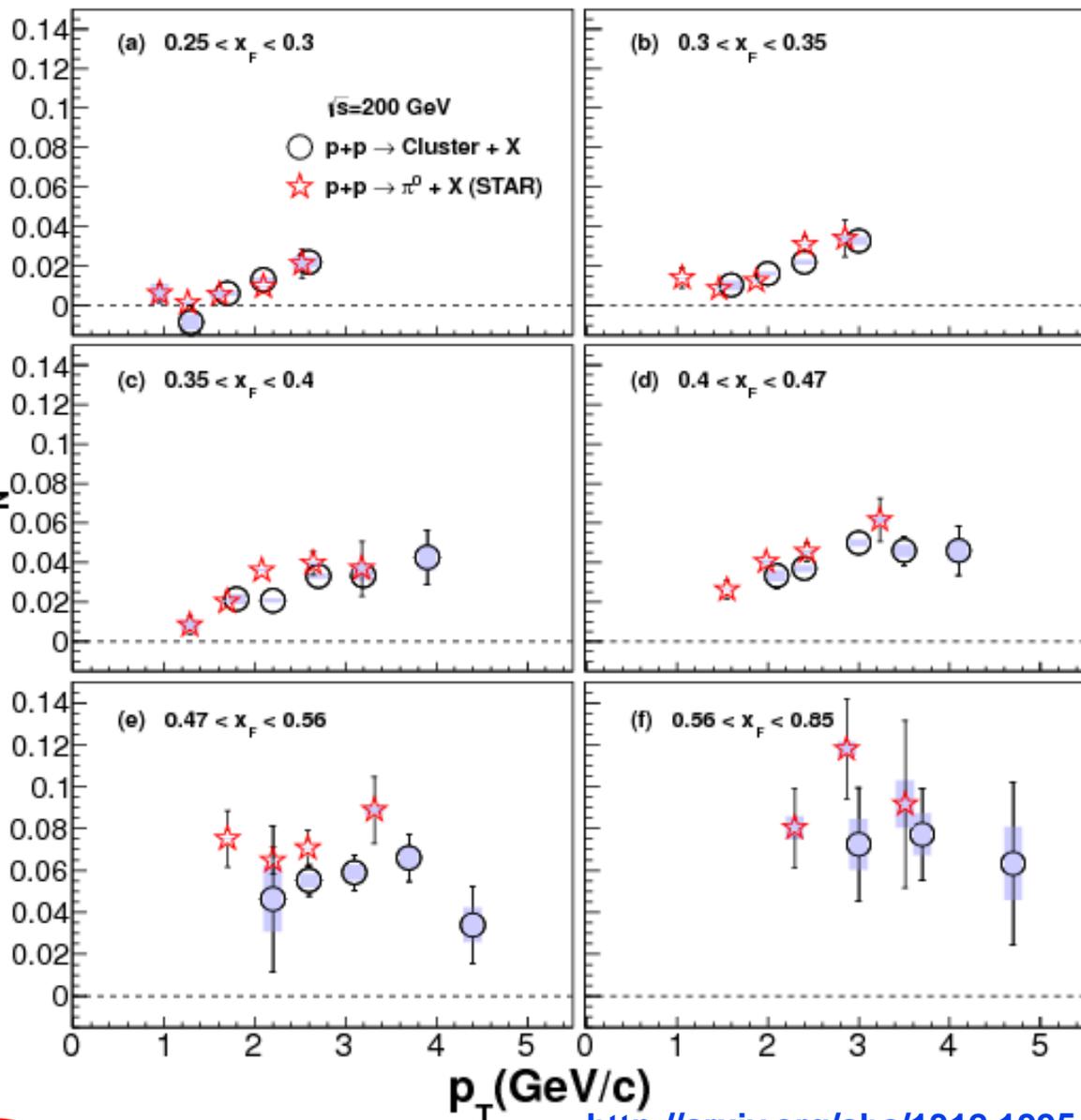


## EM Cluster contribution

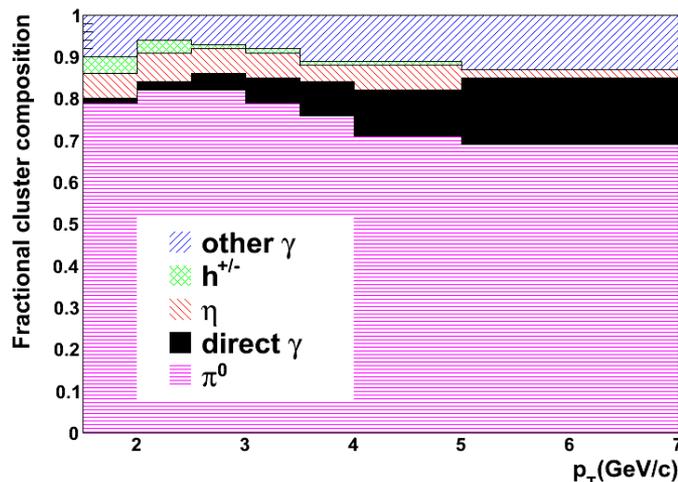


Magnitude of forward  
asymmetries similar to  
E704 ( $19.4 \text{ GeV}/c^2$ ) and  
STAR at ( $200\text{GeV}/c^2$ )

# Comparison of clusters with STAR $\pi^0$



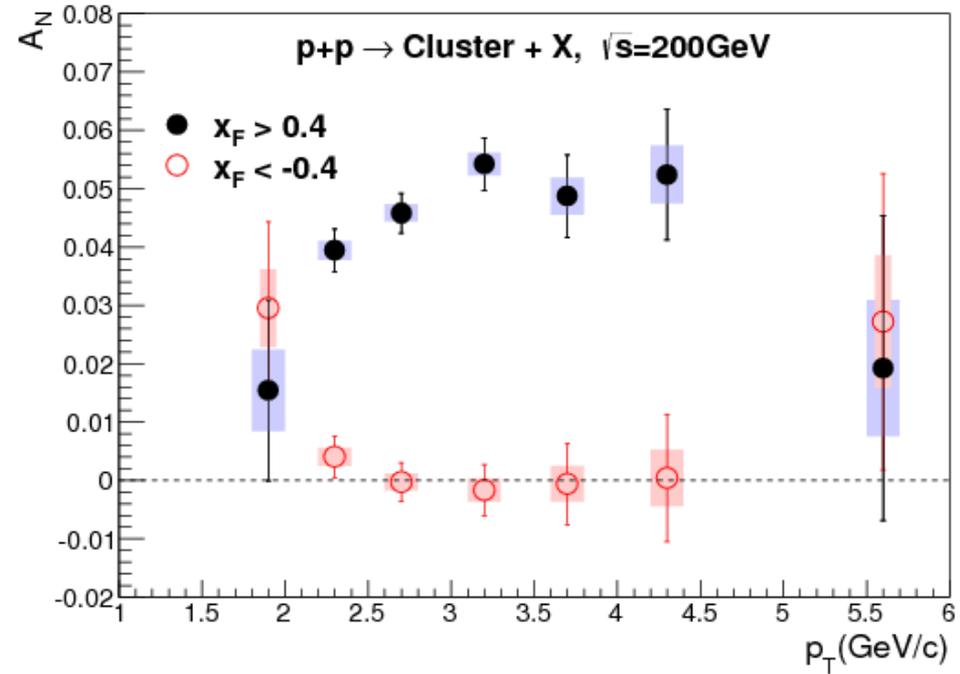
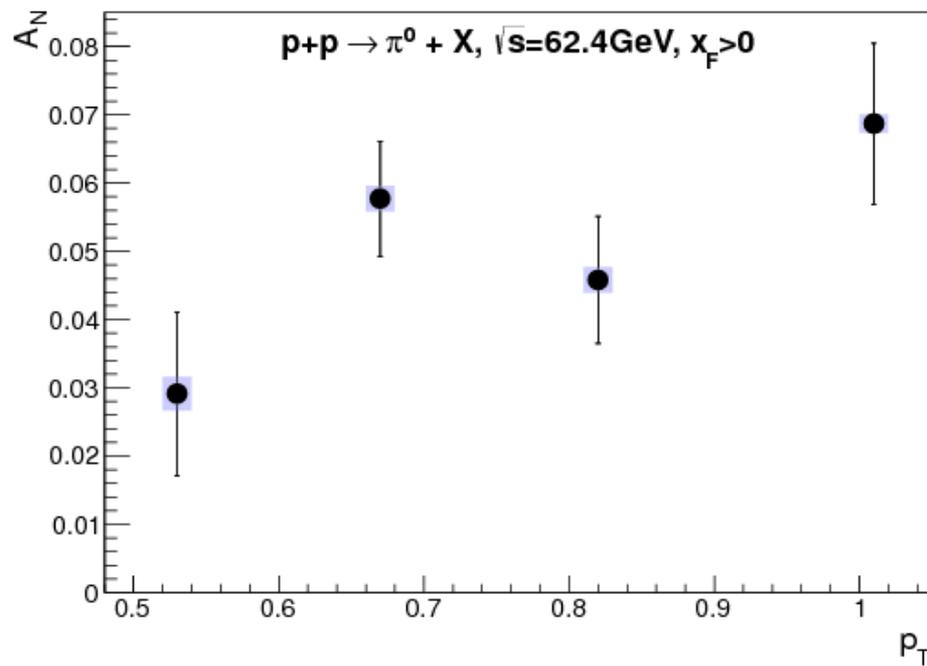
- Good agreement for  $x_F < 0.4$ .
- For  $x_F > 0.4$ , statistically limited, but there is a possible difference between clusters and  $\pi^0$ 's, leaving room a direct photon contribution.



<http://arxiv.org/abs/1312.1995>

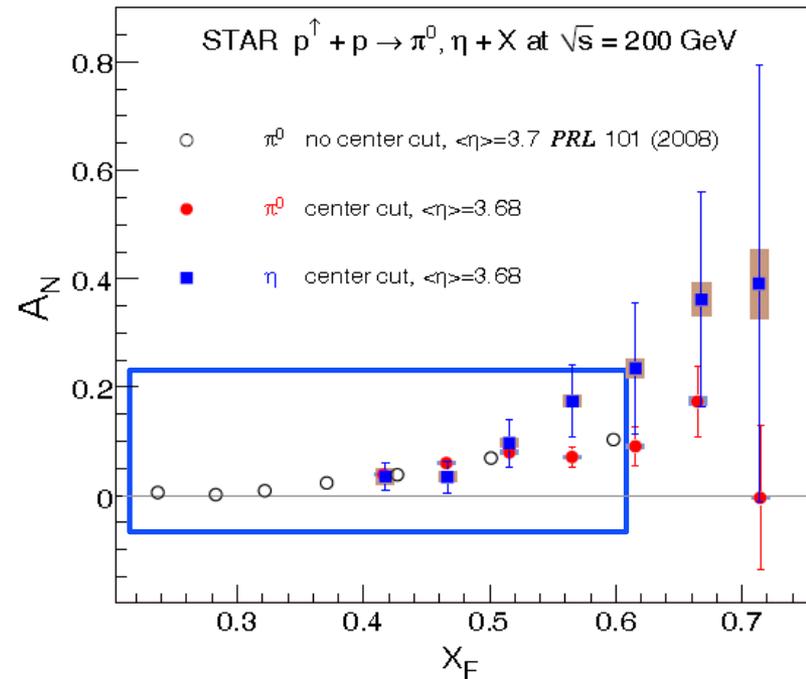
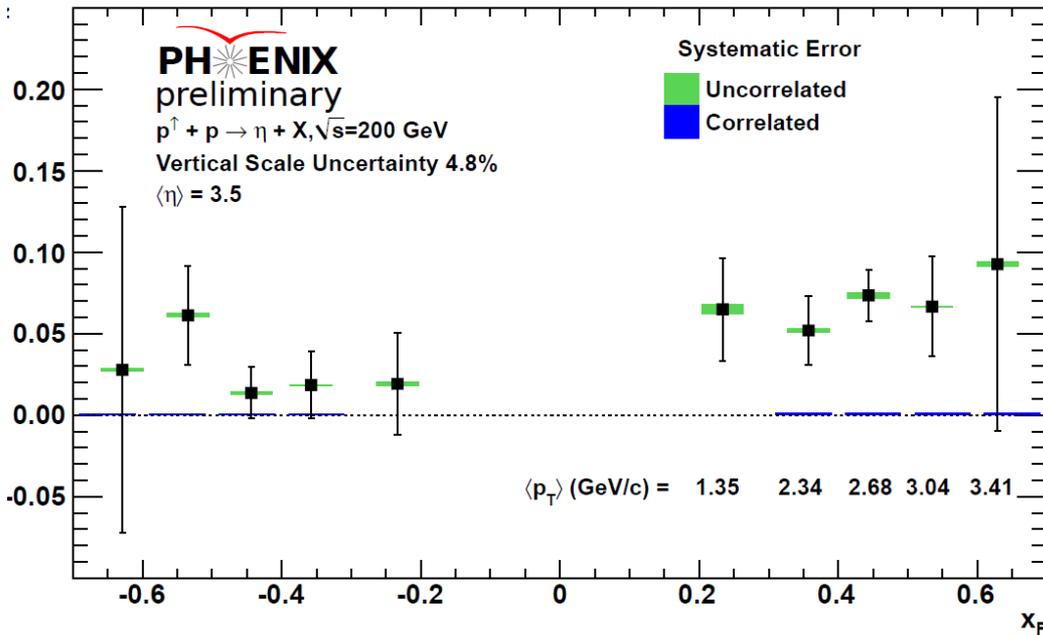
# $A_N$ as a function of $p_T$

<http://arxiv.org/abs/1312.1995>



**A significant decrease of the asymmetry as expected from higher twist calculations is not conclusive.**

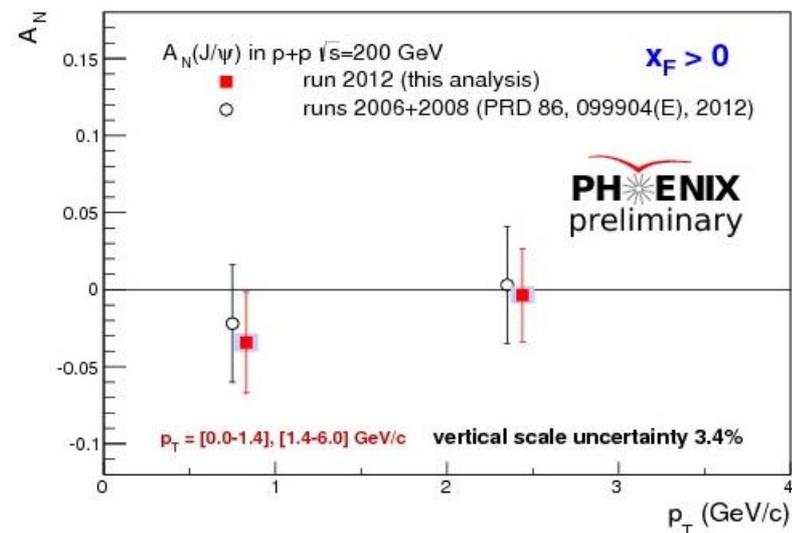
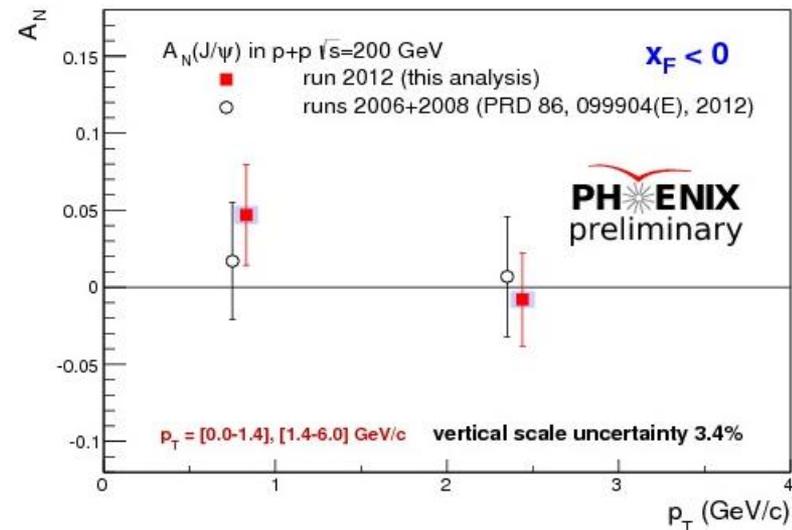
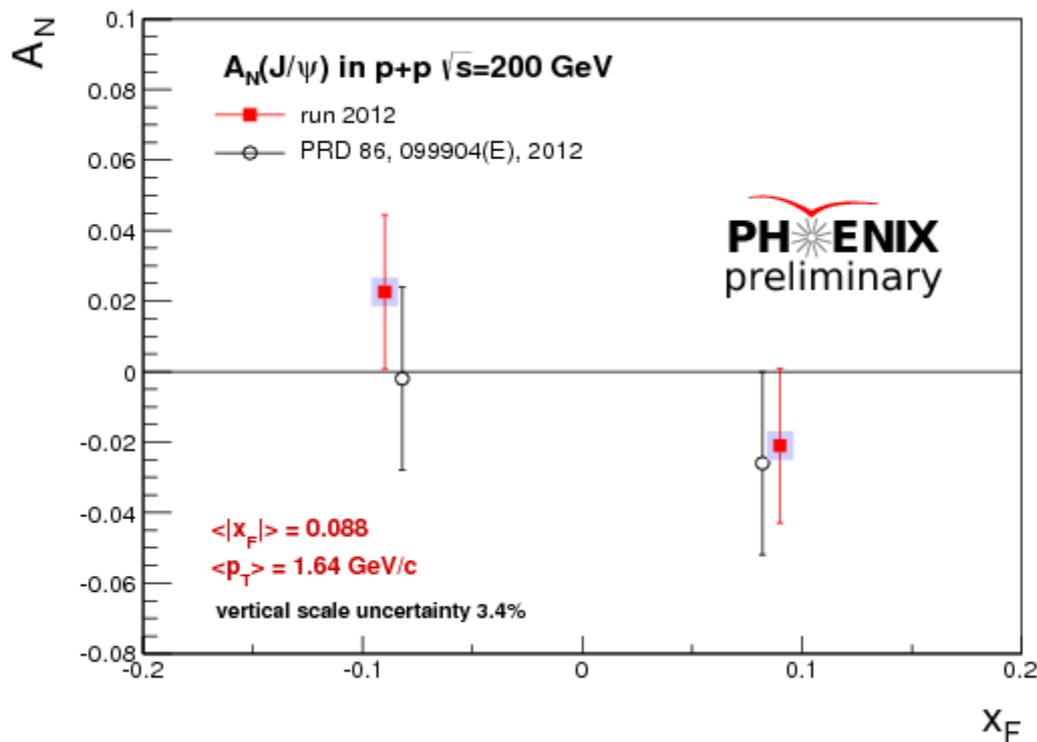
# Forward $A_N(\eta)$



PRD86 (2012) 051101

- Significant asymmetries observed for positive  $x_F$
- Asymmetries consistent with PHENIX  $\pi^0$  measurements
- Difference in fragmentation mass, strangeness, isospin
- Final asymmetry and cross-section results on expected soon.

# $A_N$ Forward $J/\psi$ at 200 GeV (Run 12)



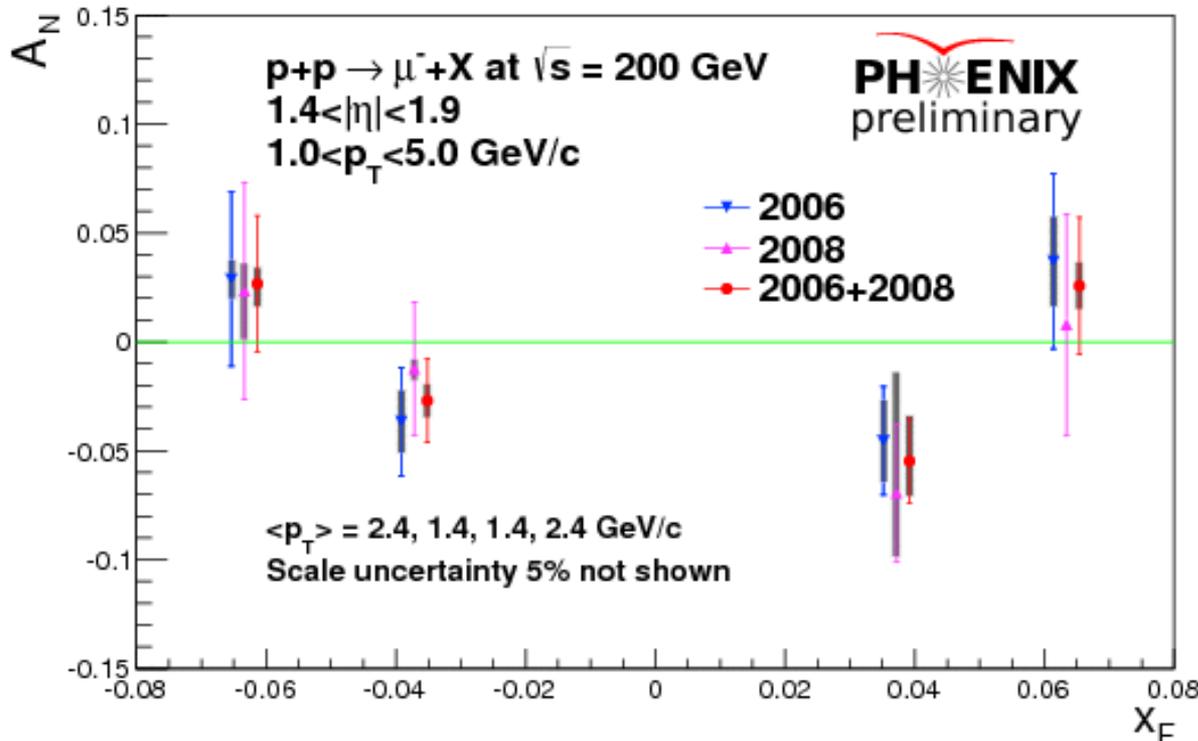
- Only color single generates SSA  $\Rightarrow$  sensitive to production mechanism.
- $A_N$  is consistent with zero.

# $A_N$ Forward single muon (200 GeV)

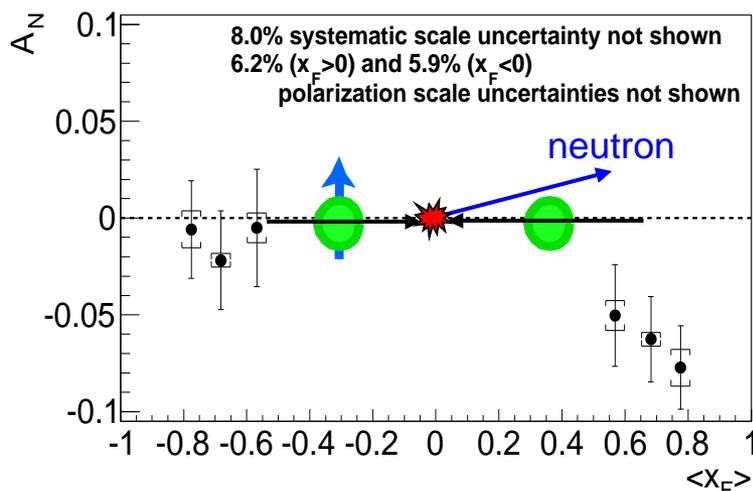
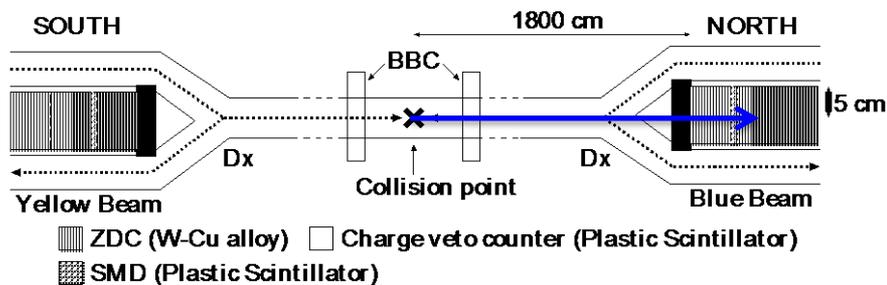
## Single muon $A_N$ from D meson decay

- » Production dominated by gg fusion
- » Probes gluon related correlation functions (initial state)
  - Koike and Yoshida, Phys Rev. D84 (2011) 014026.
- » Sensitive to gluon Sivers distribution

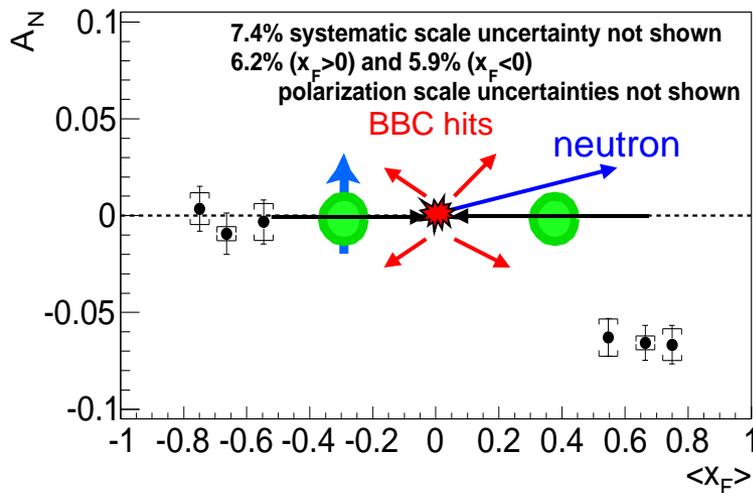
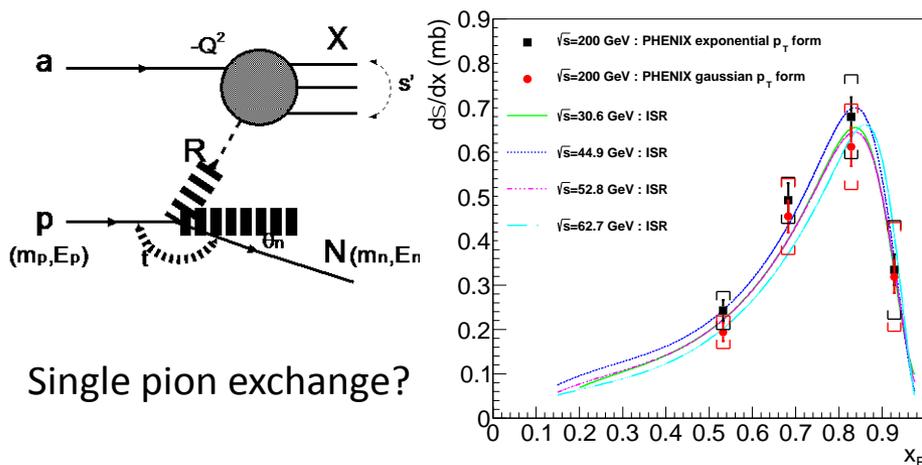
- $A_N$  consistent with zero
- A large 2012 data sample will increase sensitivity.
- A new Forward Silicon Vertex Detector (FVTX) will help in rejecting hadronic decay background in Run 15.



# $A_N$ very forward leading neutrons



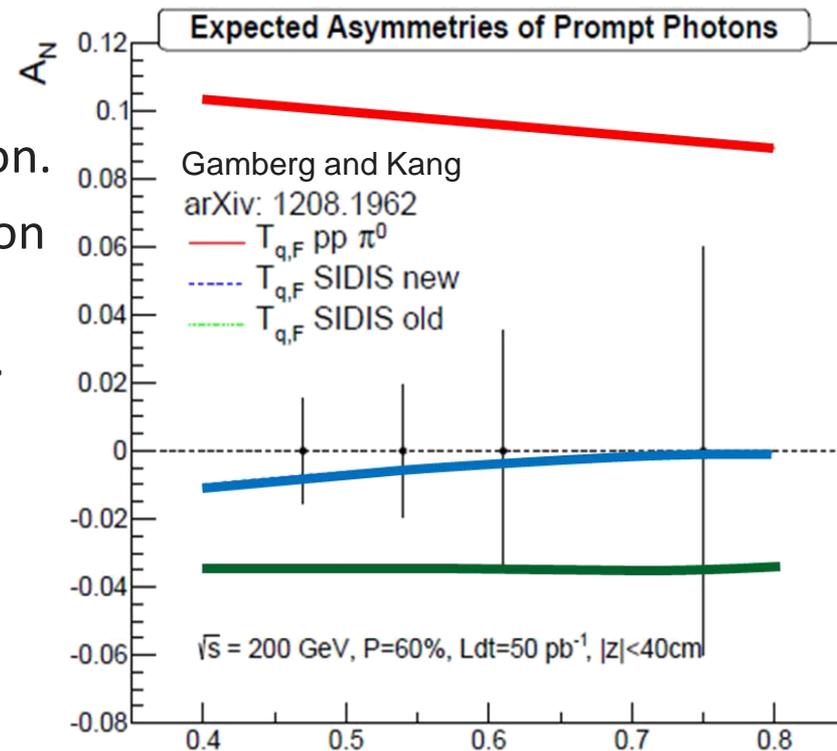
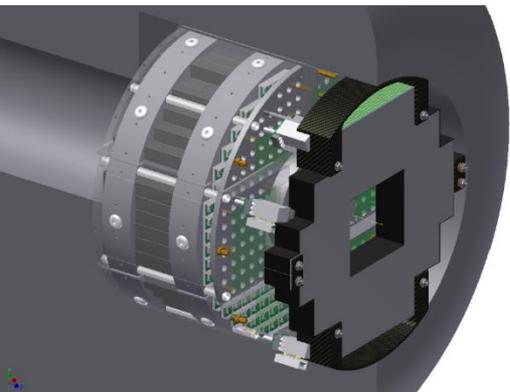
Phys. Rev. D88, 032006 (2013)



Large negative asymmetry used for local polarimetry

# $A_N$ : forward $\gamma$ (MPC-EX)

- 8 layer Silicon minipad Tungsten sandwich pre-shower in front of lead-tungstate MPC electromagnetic calorimeter ( $3.1 < |\eta| < 3.8$ )
  - Reconstruct and reject  $\pi^0$  mesons  $\Rightarrow$  enhances  $\pi^0/\gamma$  separation (up to  $>80\text{GeV}$ )
- Spin Physics Motivation:
  - Sign mismatch between twist-3 quark gluon distribution functions  $T_{q,F}(x, x)$  extracted from RHIC (assuming no Collins) and moments of the Sivers function from SIDIS measurements.
  - The Collins fragmentation functions in the p+p measurements may be the reason.
  - $A_N$  of prompt photons (free of contribution from the Collins effect) can be used to verify this & check consistency of theory.
- Timescale: Expected for Run 15.



# Summary and Outlook

## ➤ Central rapidity measurements

- $A_N$  for  $\pi^0$  and  $\eta \Rightarrow$  constrain gluon Sivers

## ➤ Forward rapidity measurements

- $A_N$  for  $\pi^0$ , EM Clusters including  $p_T$ ,  $x_F$  dependence
  - Comparison with data at different  $\sqrt{s}$  and charged pions
  - Provides info to constrain Collins, Sivers, and twist-3 effects

## ➤ Upgrades will significantly extend physics capabilities

- FVTX will enhance forward heavy-flavor program ( $\mu$ ,  $J/\psi$ )
- MPC-EX will enable forward  $A_N(\gamma)$  measurements
  - Polarized  $p + A$  measurements sensitive to gluon saturation
- Proposed new Forward Spectrometer (fsPHENIX) for jet correlations/structure and Drell-Yan measurements (talk by John Lajoie)
- The fsPHENIX would also be well matched with ePHENIX (talk by Sasha Bazilevsky)