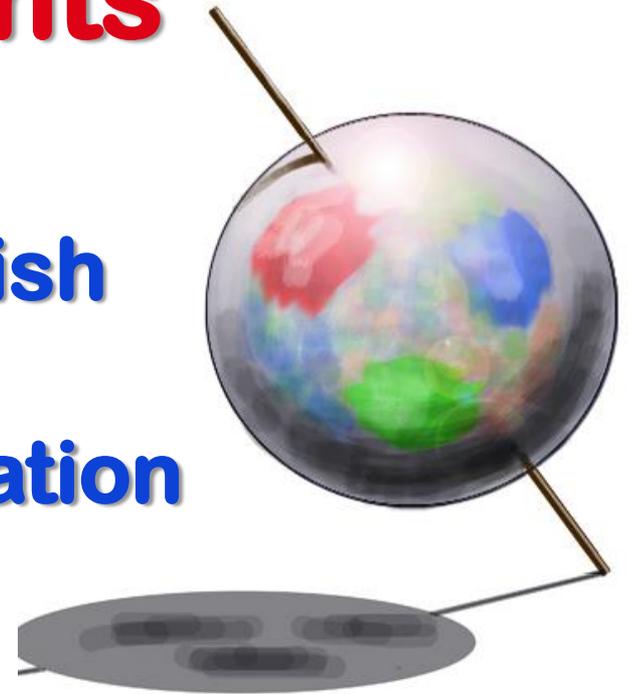


PHENIX Transverse Spin Measurements

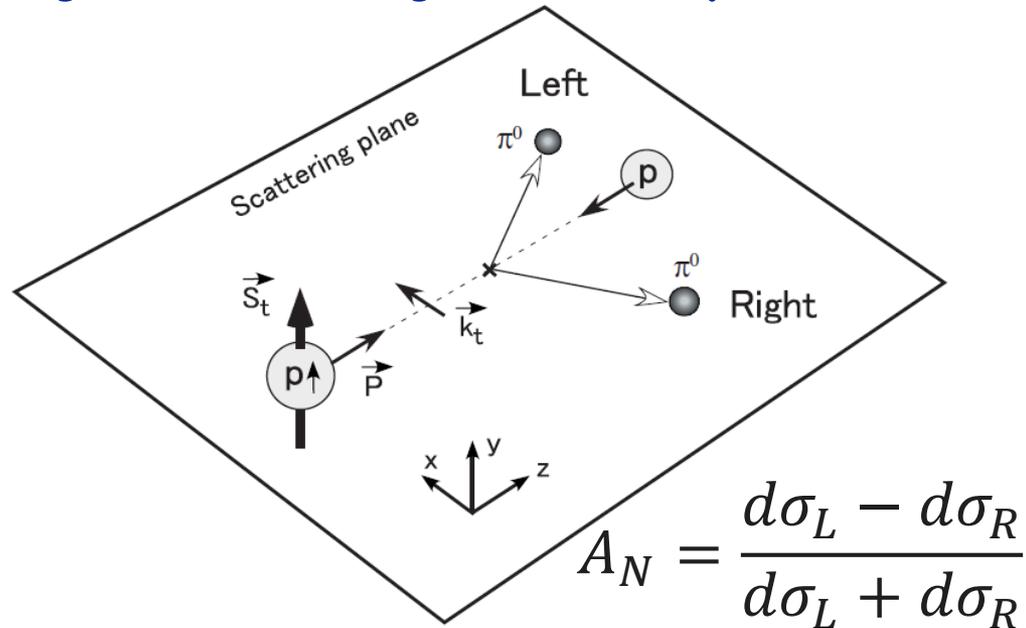
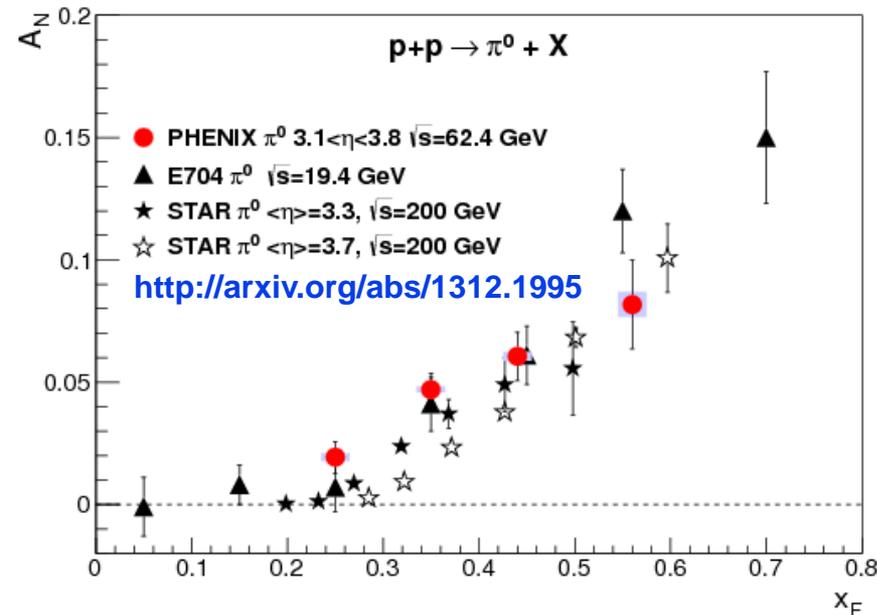
**Kenneth N. Barish
for the
PHENIX Collaboration**



**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



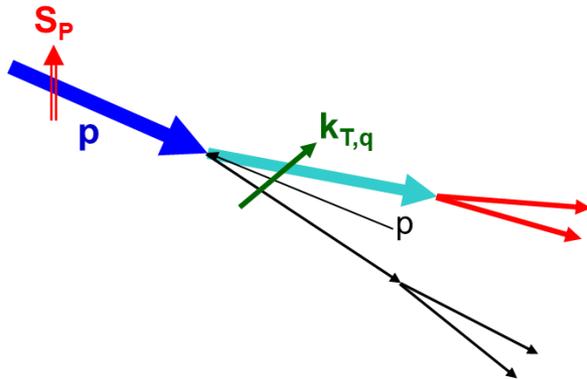
Transverse Spin Asymmetry Sources

(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)

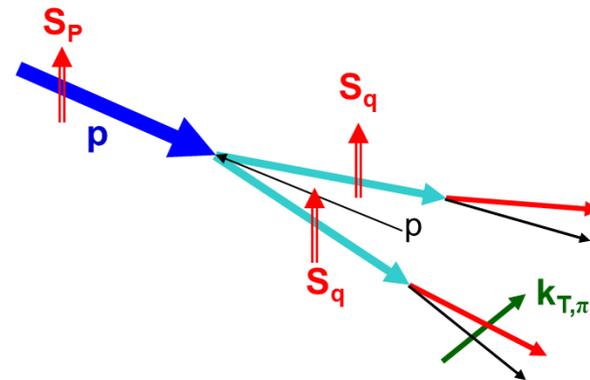
Twist-3 quark-gluon/gluon-gluon correlators in polarized hadron.

(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)

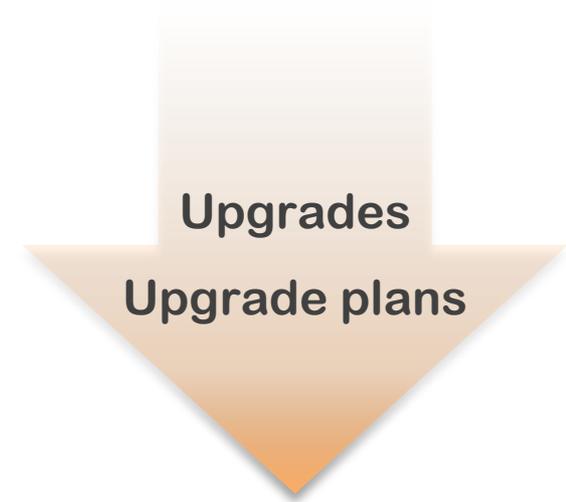


J. C. Collins, Nucl. Phys. **B396**, 161 (1993)

Twist-3 quark-gluon fragmentation function.

Transverse Spin Measurements

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



The PHENIX Detector

Central Arms

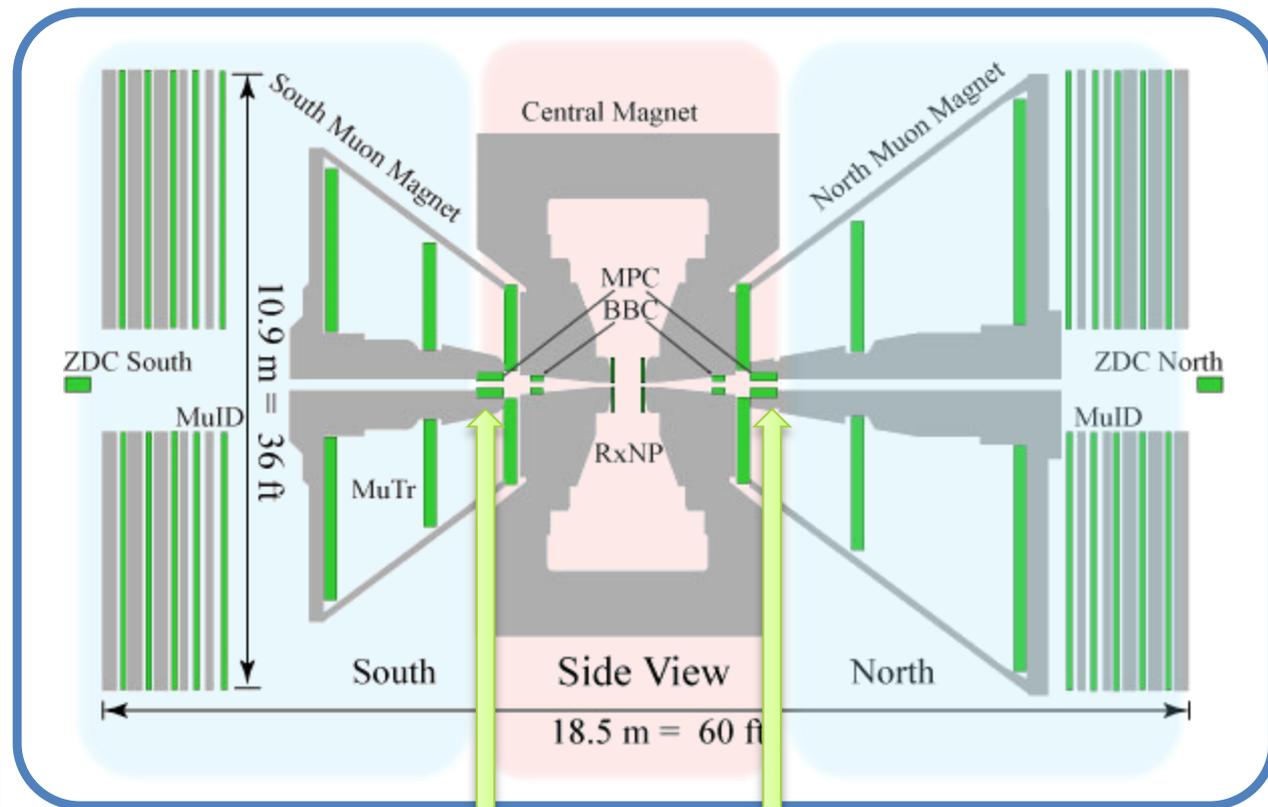
$$|\eta| < 0.35$$

- ❖ charged hadrons
- ❖ π^0, η
- ❖ direct photon
- ❖ J/ψ
- ❖ heavy flavor

Muon Arms

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

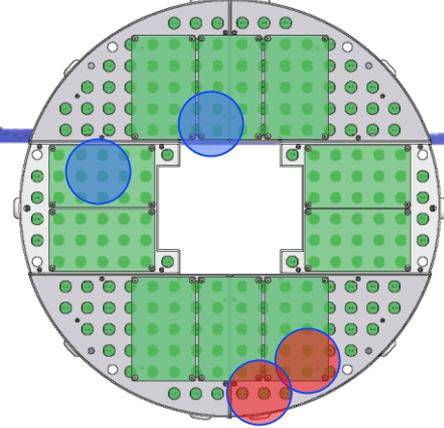
- ❖ J/ψ
- ❖ charged hadrons
- ❖ heavy flavor



MPC $3.1 < |\eta| < 3.9$

- ❖ π^0, η

MPC detectors

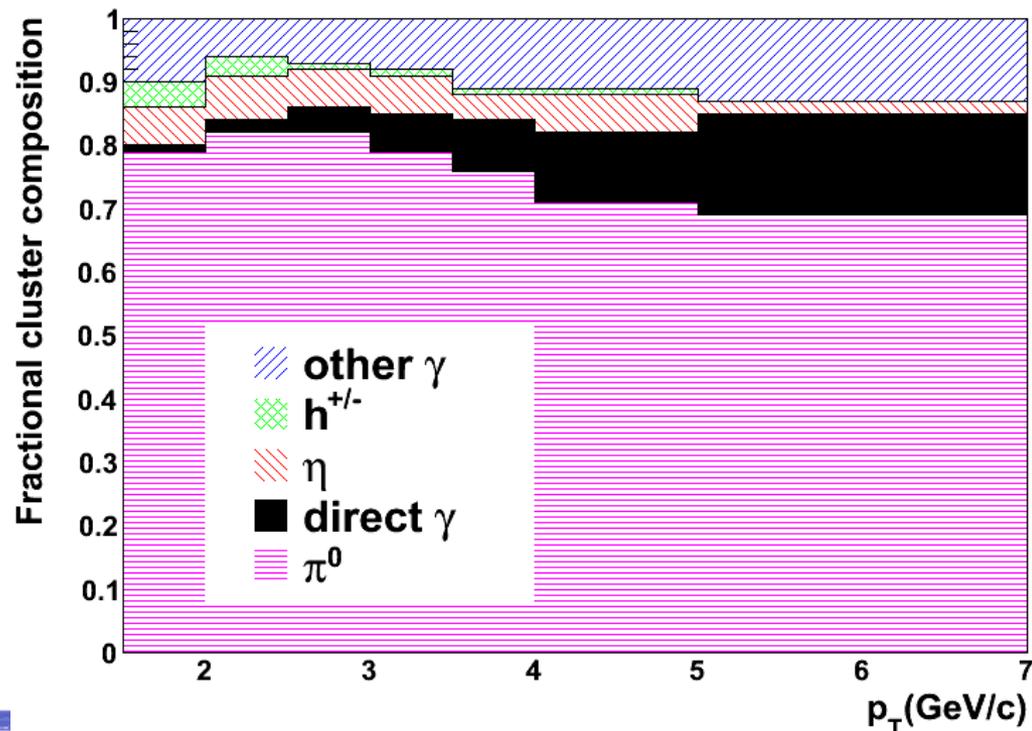


tower size 2.25^2 cm^2
220 cm from vertex

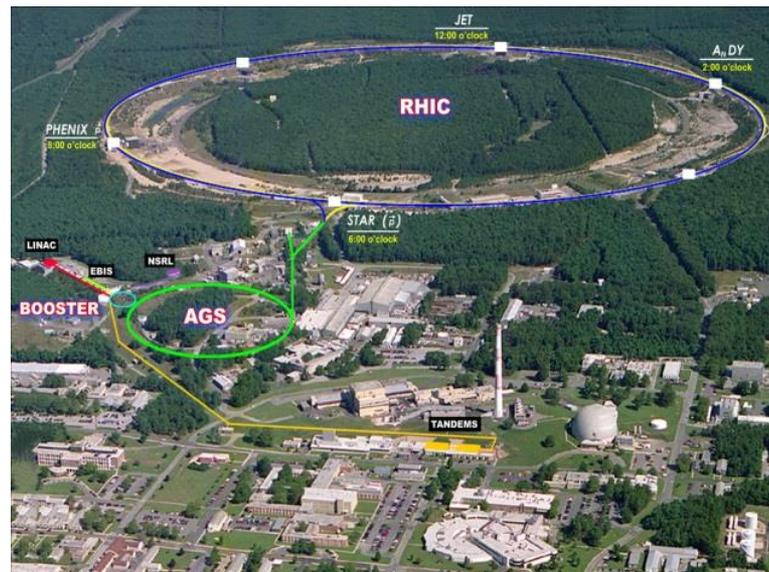
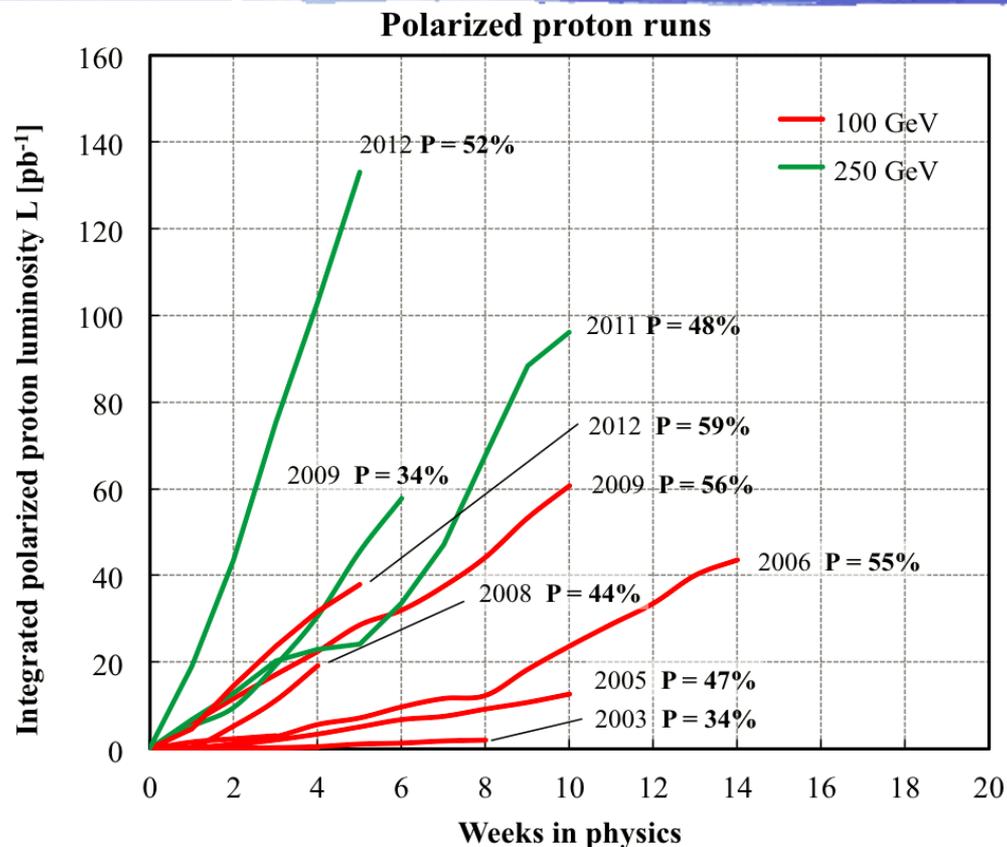
- **Lead-tungstate EMCal ($3.1 < |\eta| < 3.8$)**
 - » Enables measurements of forward π^0 and η mesons
- **Photon merging effects significant for $E > 20 \text{ GeV}$ ($p_T > 2 \text{ GeV}/c$)**
 - » For $\sqrt{s} = 62 \text{ GeV}$, $20 \text{ GeV} \rightarrow 0.65 x_F \Rightarrow$ two photon π^0 analysis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

➤ Single Clusters

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

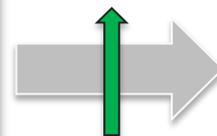


Polarized Protons at RHIC-PHENIX



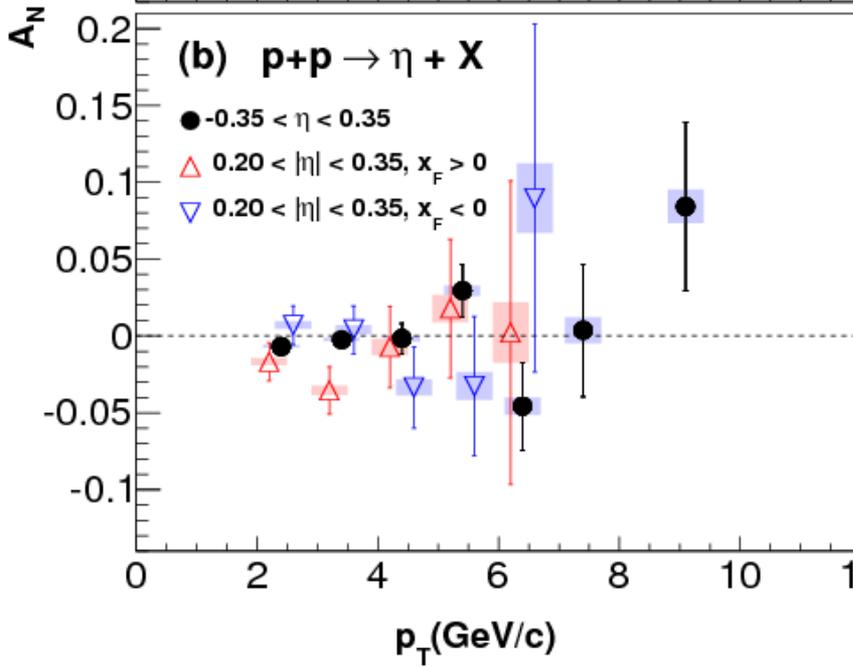
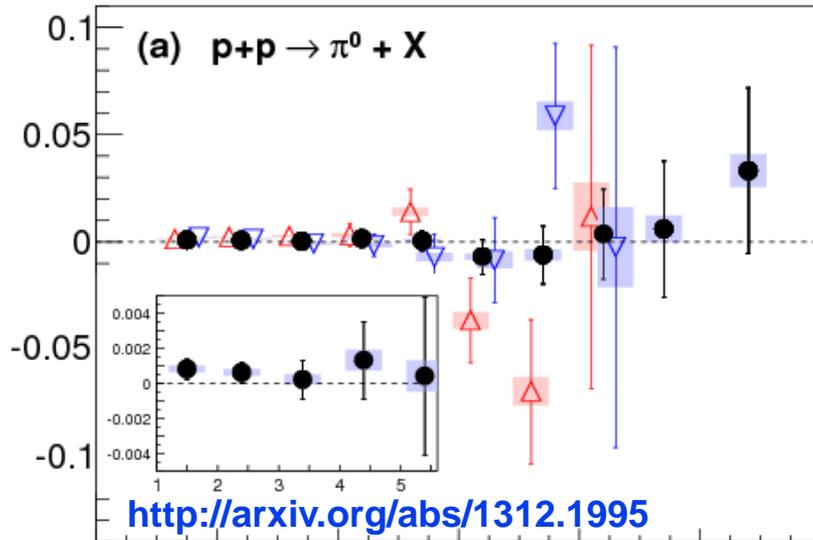
Transverse Data

Year	\sqrt{s} (GeV)	L (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

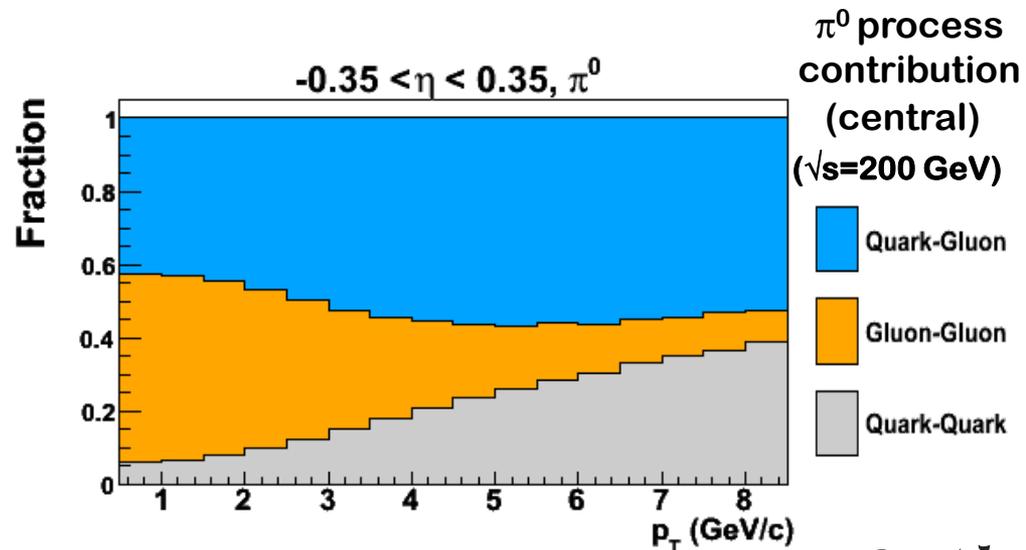


A_N : mid-rapidity π^0 and η

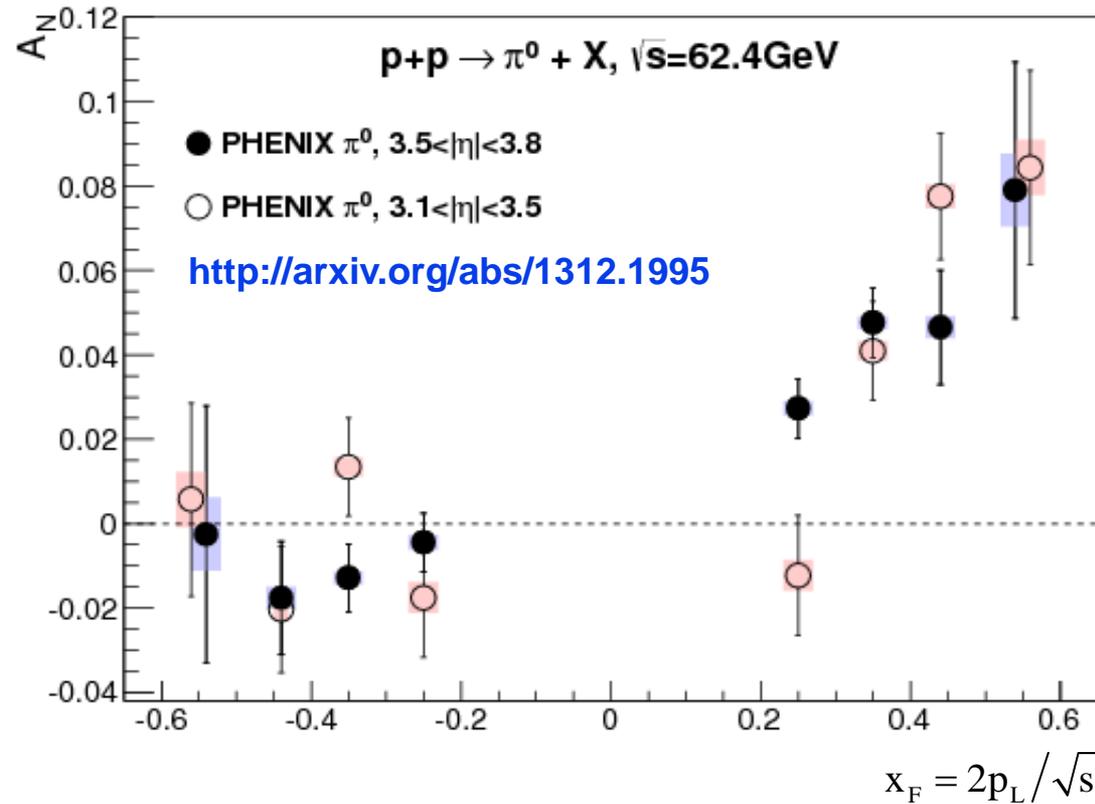
p+p $\sqrt{s}=200$ GeV



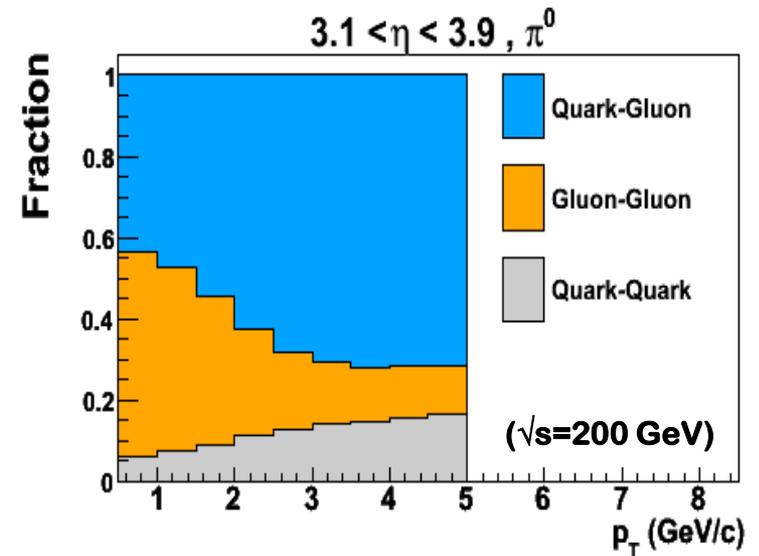
- π^0 asymmetries consistent with zero observed over a wide p_T range
- Exceed precision of previous publication (Phys. Rev. D 74, 094011) by a factor of 20 and extends p_T range.
- Constrains gluon Sivers
- η asymmetries are also consistent with zero.



Forward π^0 A_N (62.4 GeV)



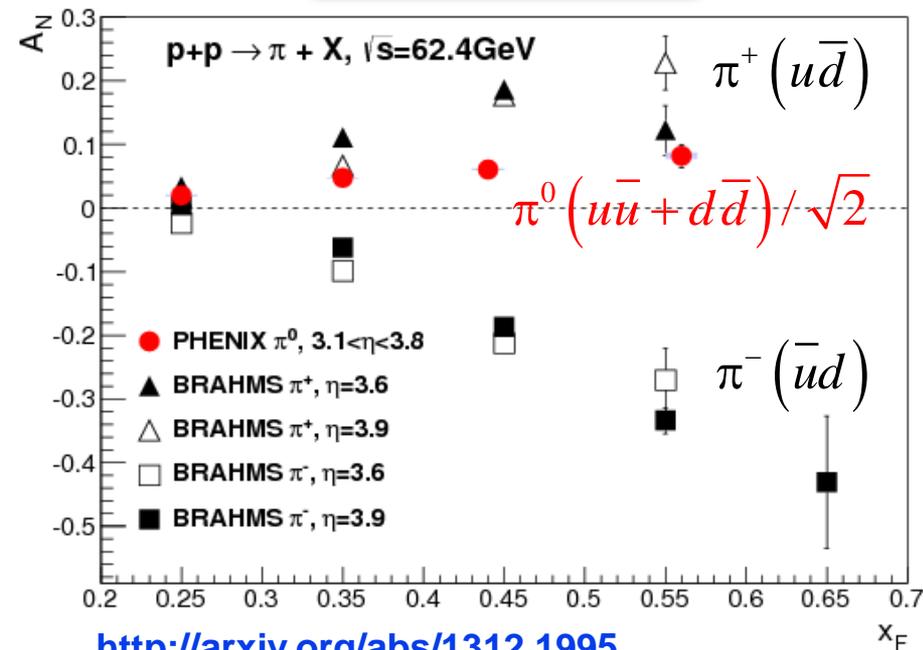
π^0 process contribution in PHENIX forward arms



- 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

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



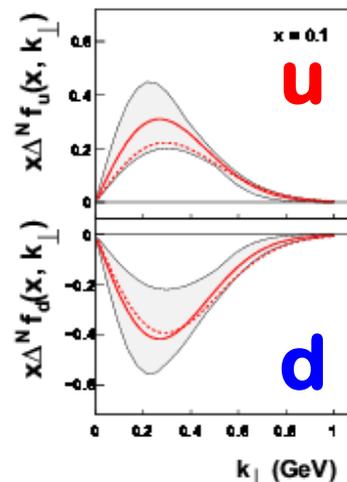
<http://arxiv.org/abs/1312.1995>

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

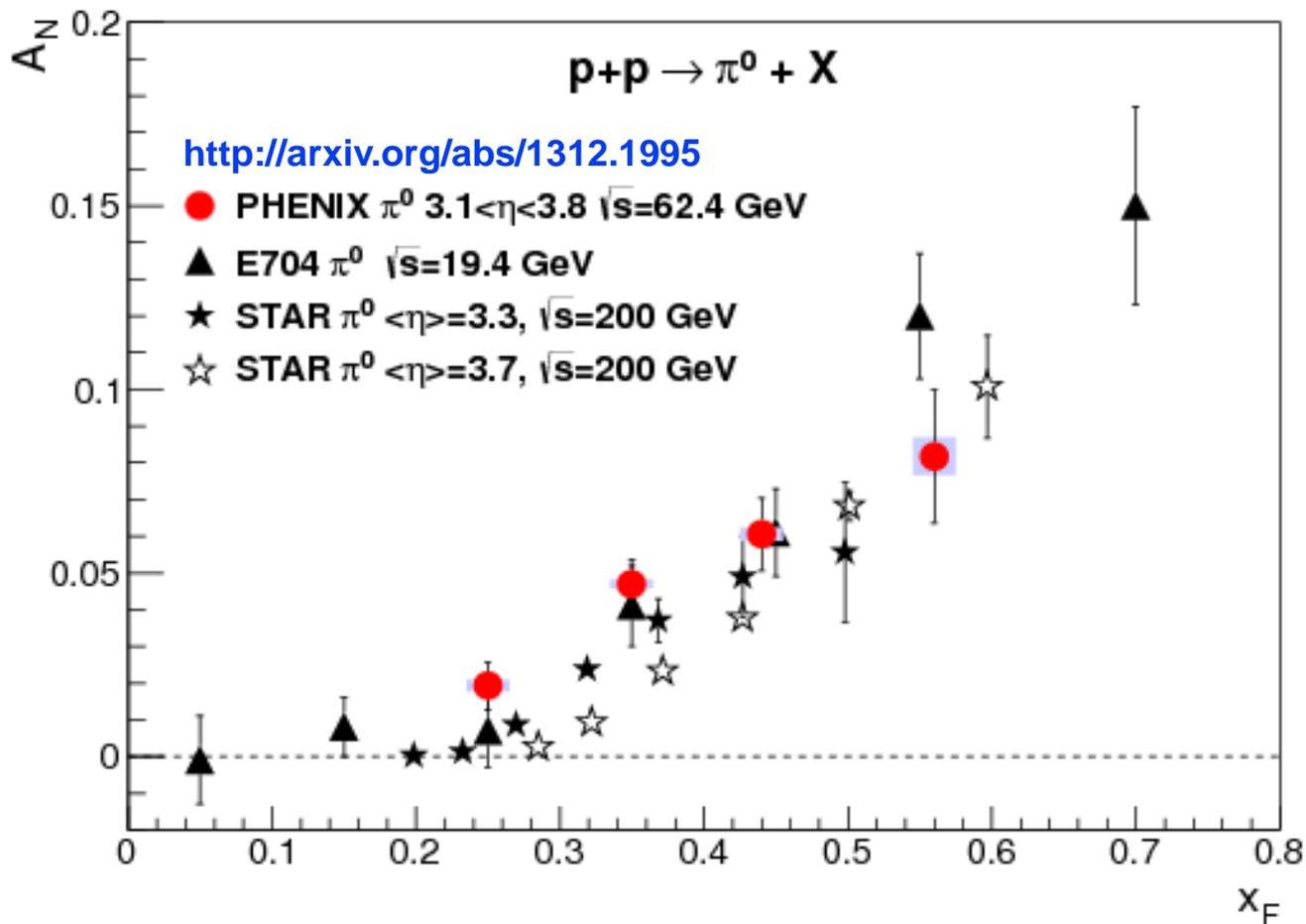
Quark origins of pions (PYTHIA):

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

Sivers



Forward π^0 A_N \sqrt{s} dependence

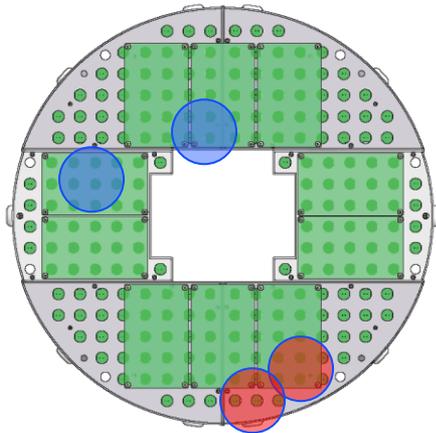


- Sizable forward non-zero asymmetries
- No dependence on \sqrt{s} apparent from 19.6 GeV to 200 GeV
- Slight differences in pseudorapidity and/or p_T

Forward A_N for EM Clusters

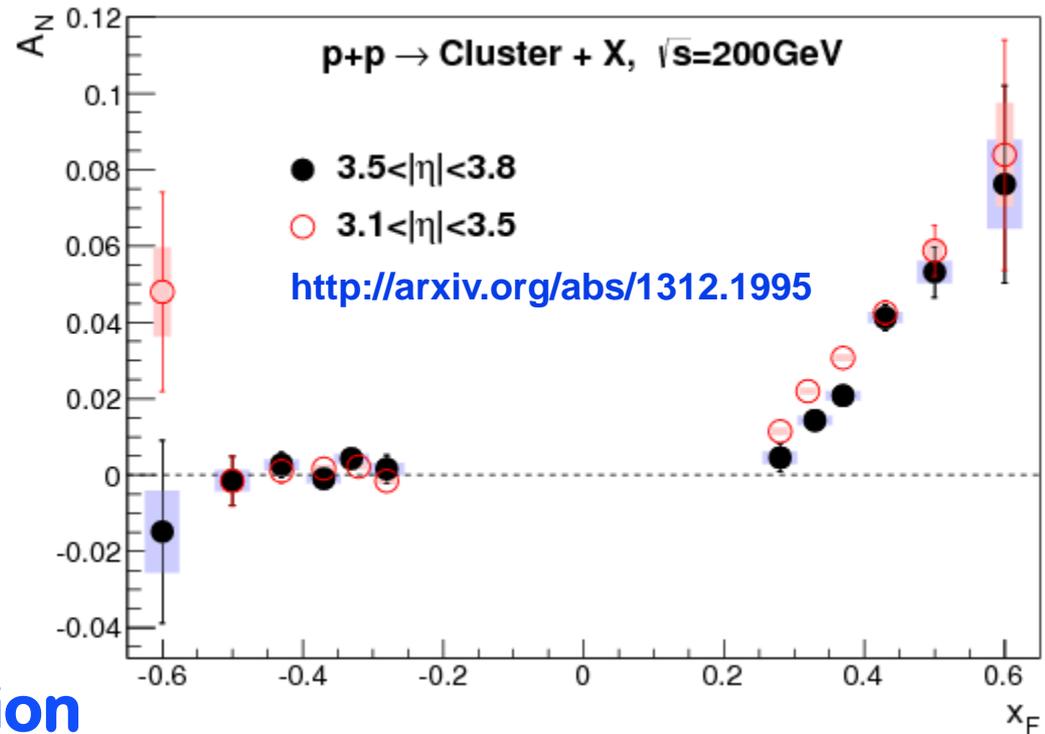
MPC

tower size 2.25^2 cm^2
220 cm from vertex

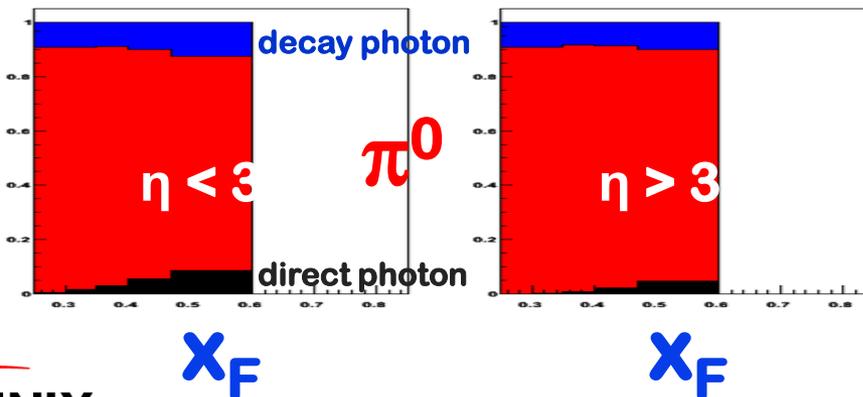


Decay photon impact positions
for **low** and **high** energy π^0 's.

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

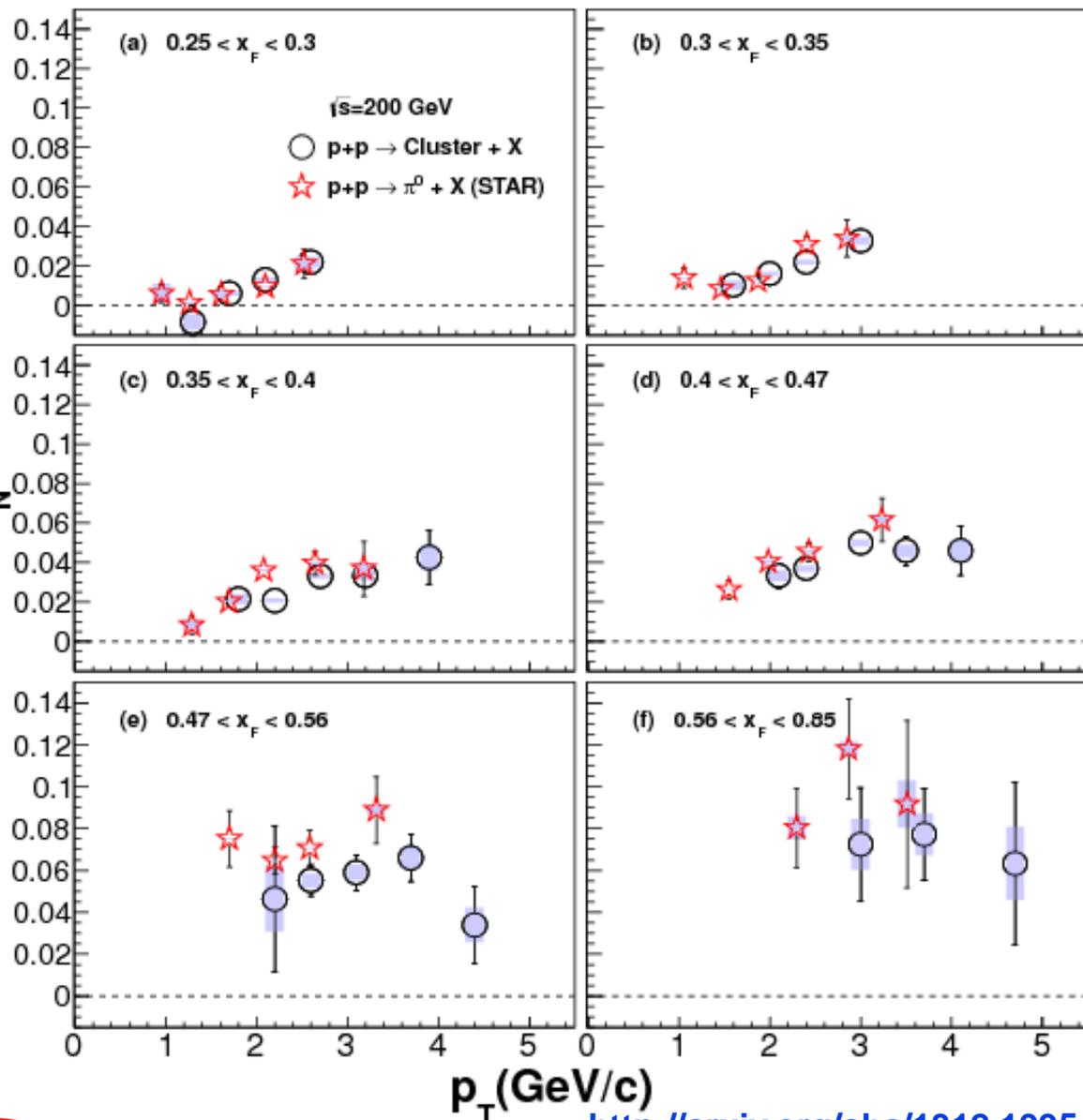


EM Cluster contribution

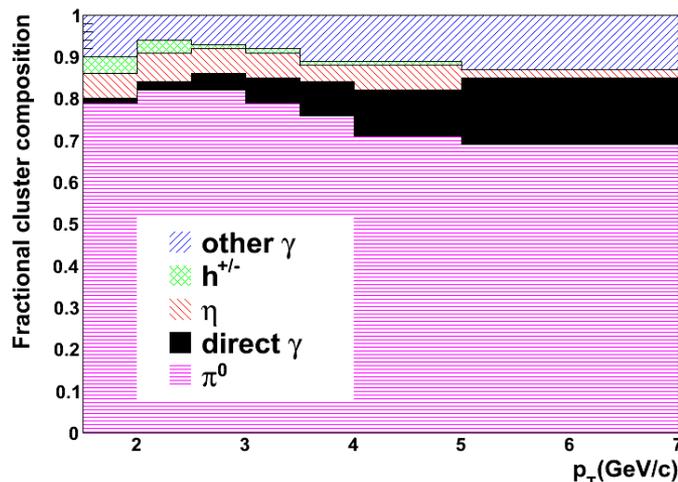


Magnitude of forward
asymmetries similar to
E704 ($19.4 \text{ GeV}/c^2$) and
STAR at ($200 \text{ GeV}/c^2$)

Comparison of clusters with STAR π^0



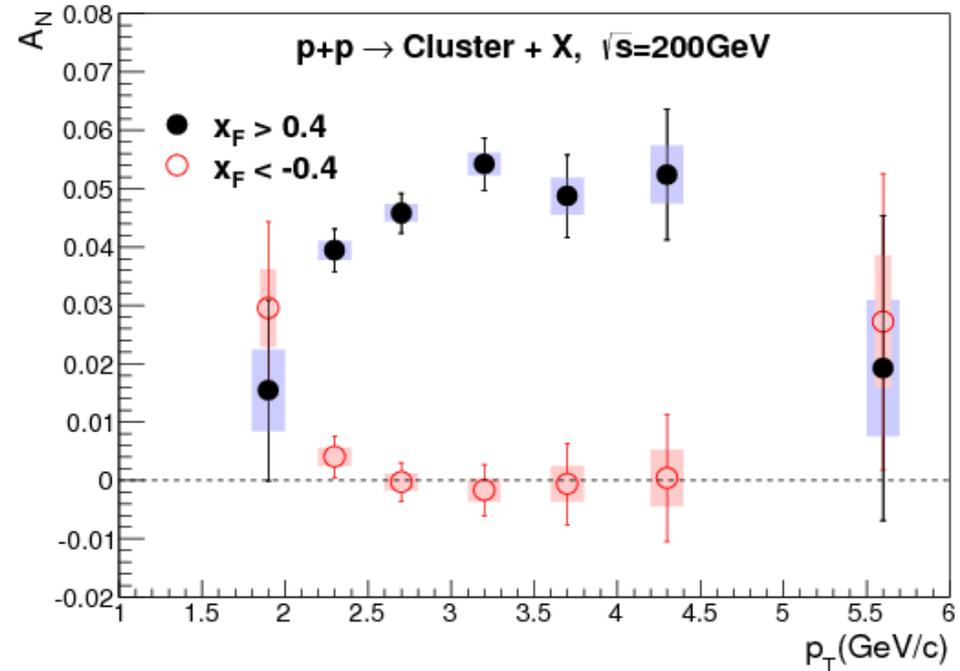
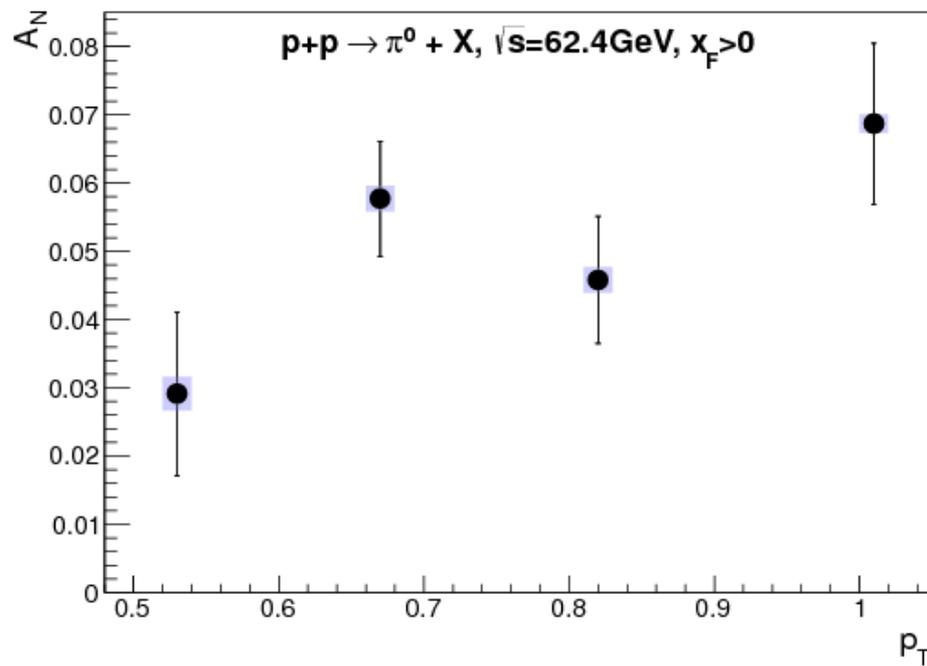
- Good agreement for $x_F < 0.4$.
- For $x_F > 0.4$, statistically limited, but there is a possible difference between clusters and π^0 's, leaving room a direct photon contribution.



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

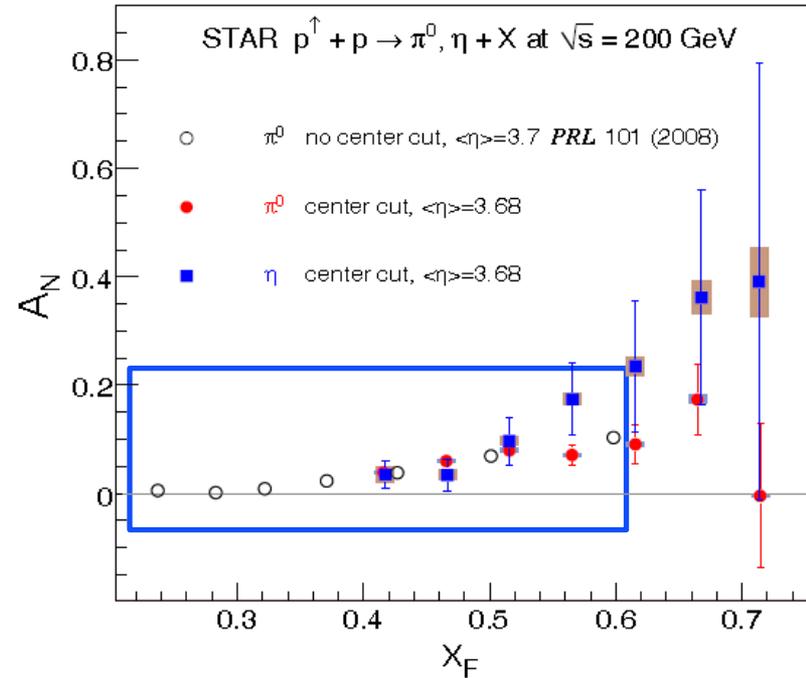
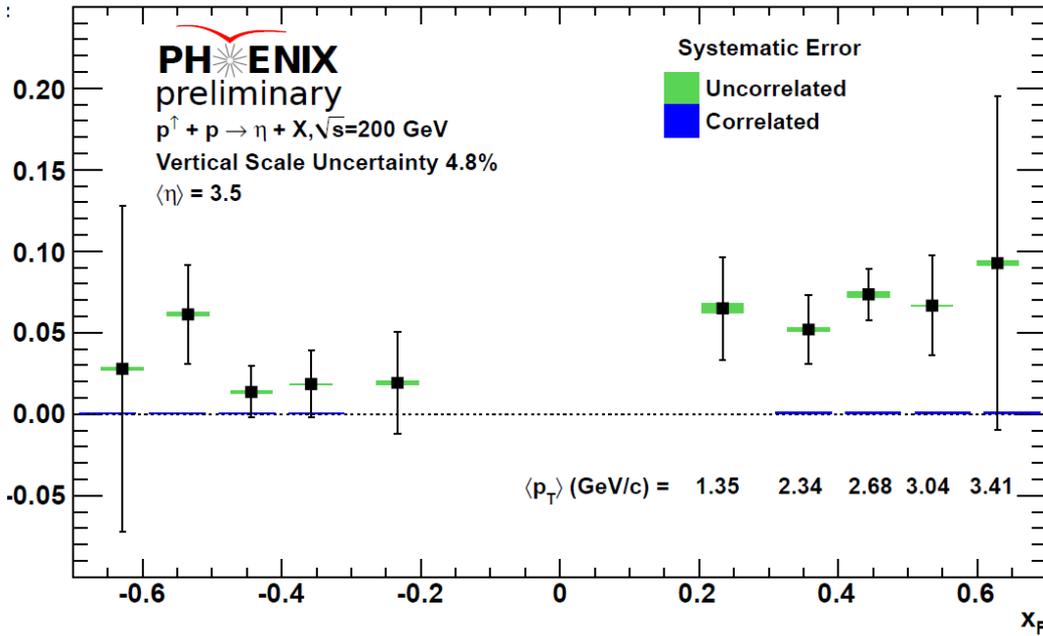
A_N as a function of p_T

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



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

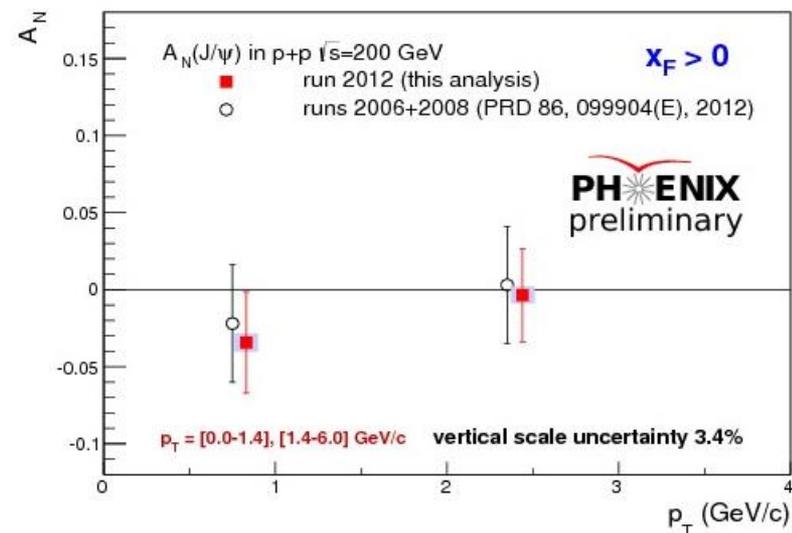
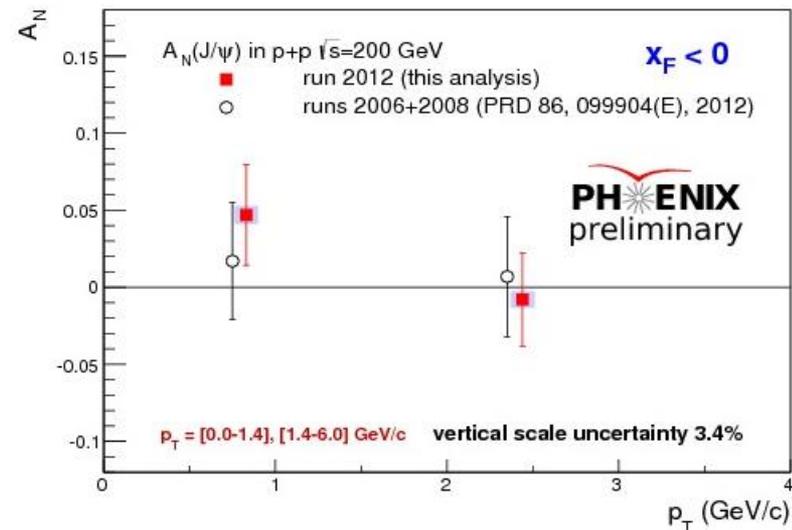
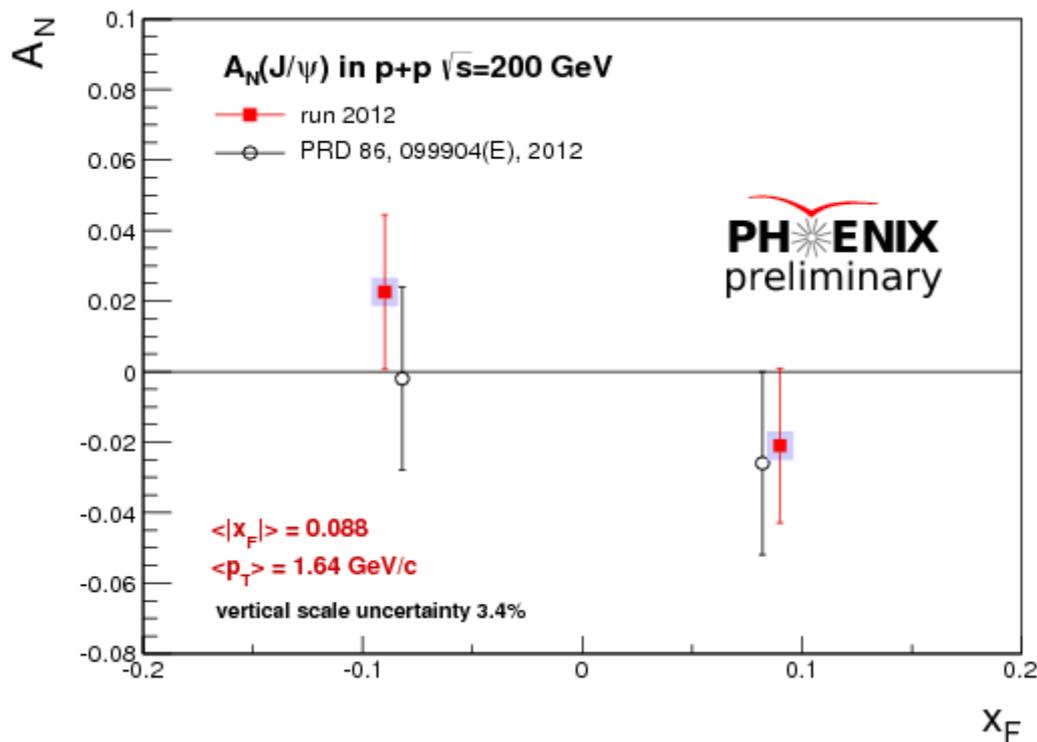
Forward $A_N(\eta)$



PRD86 (2012) 051101

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

A_N Forward J/ψ at 200 GeV (Run 12)



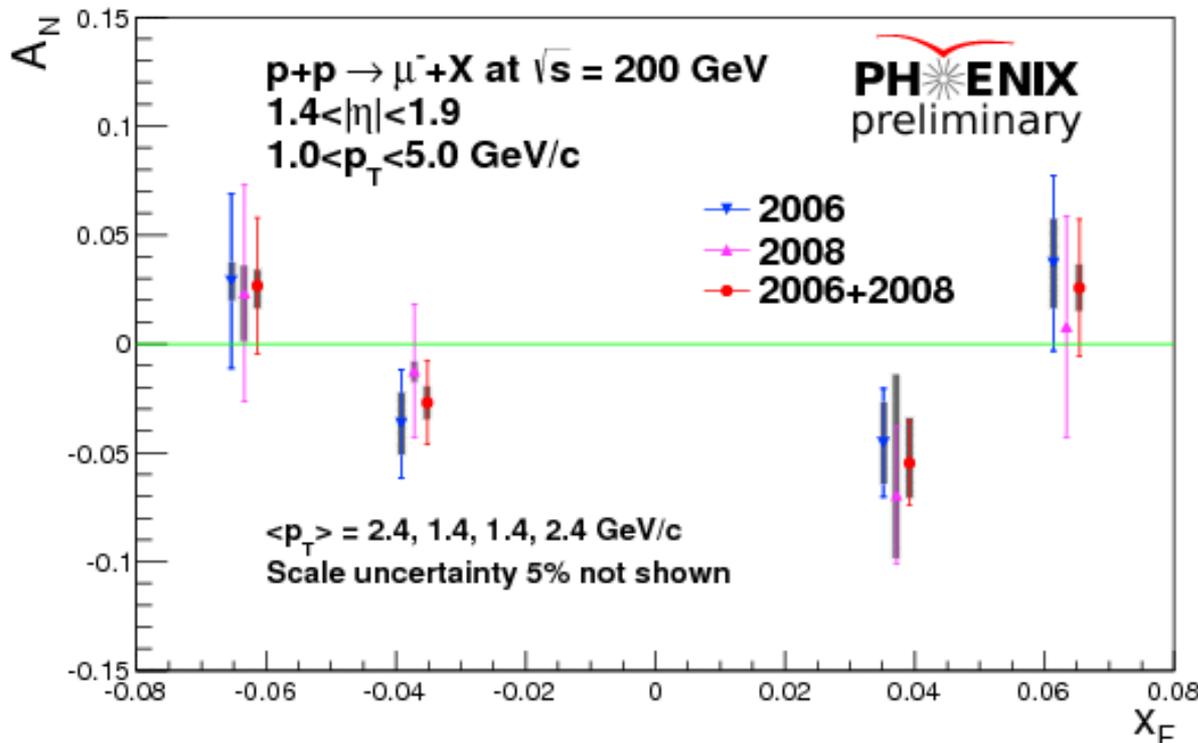
- Only color single generates SSA \Rightarrow sensitive to production mechanism.
- A_N is consistent with zero.

A_N Forward single muon (200 GeV)

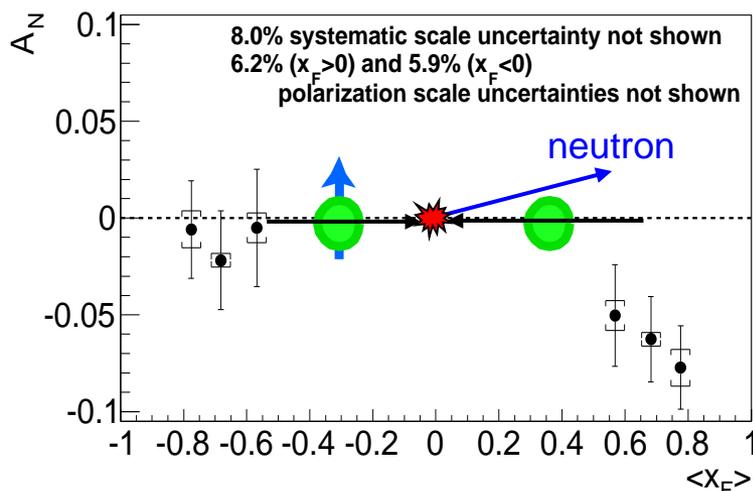
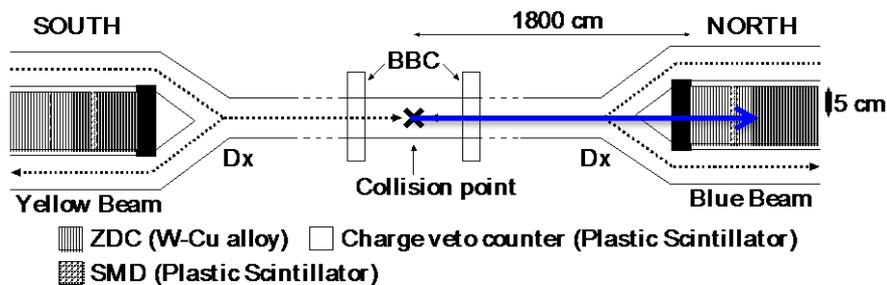
Single muon A_N from D meson decay

- » 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

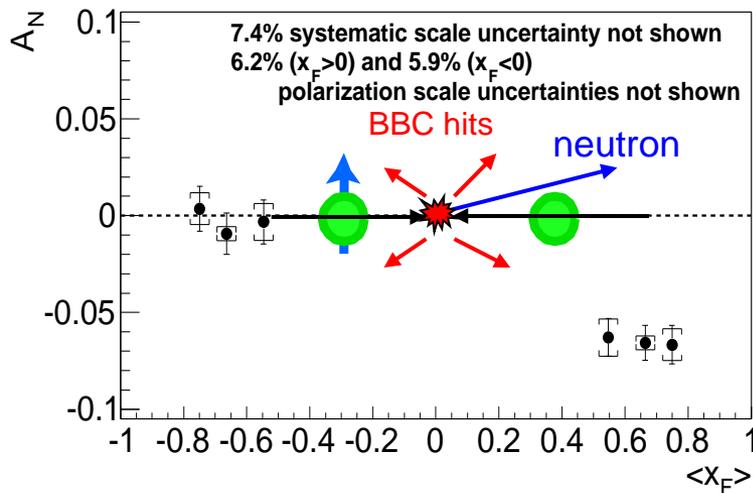
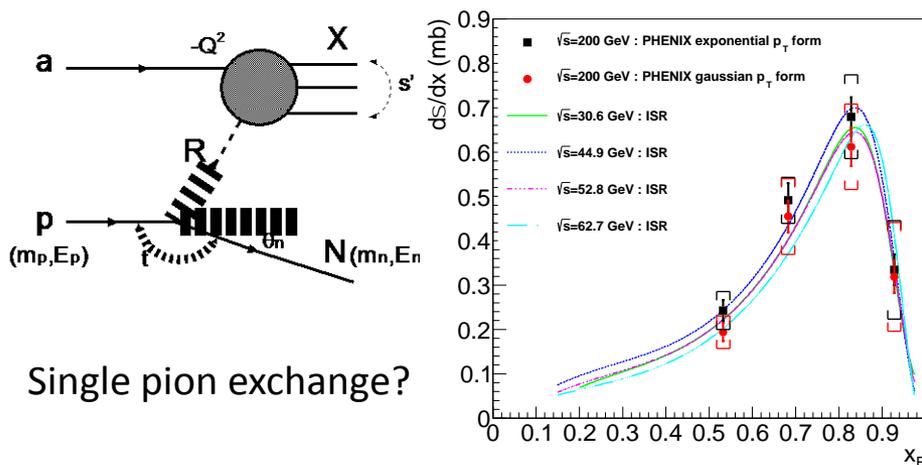
- A_N consistent with zero
- A large 2012 data sample will increase sensitivity.
- A new Forward Silicon Vertex Detector (FVTX) will help in rejecting hadronic decay background in Run 15.



A_N very forward leading neutrons



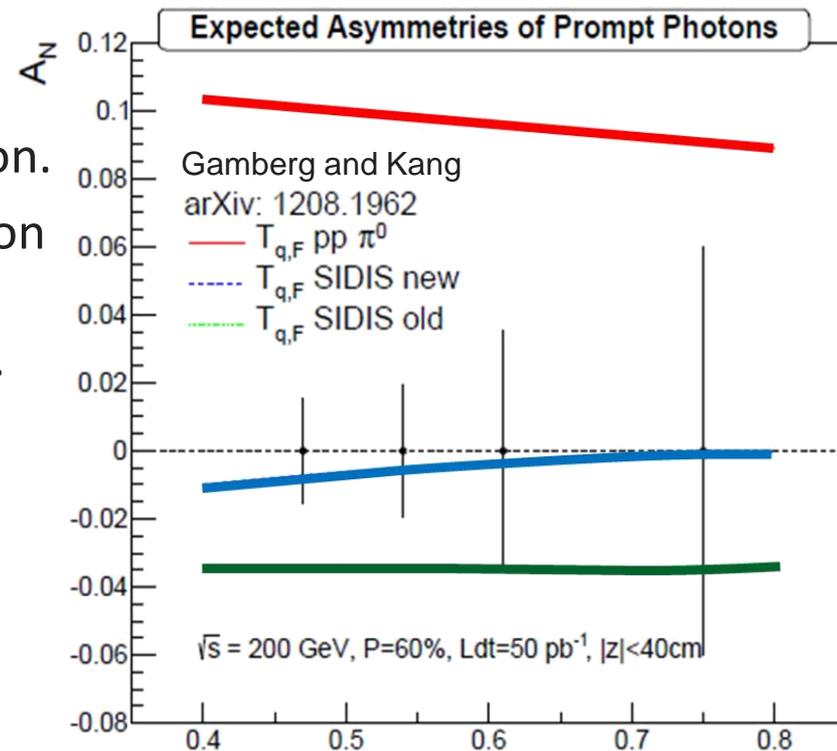
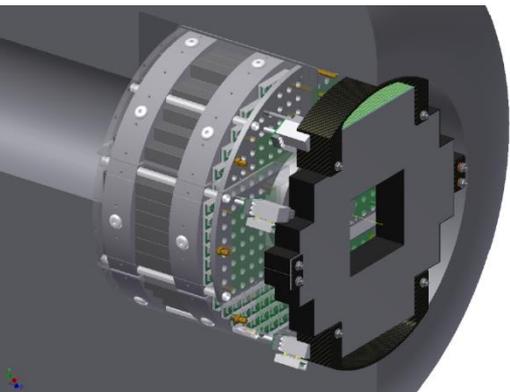
Phys. Rev. D88, 032006 (2013)



Large negative asymmetry used for local polarimetry

A_N : forward γ (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 π^0 mesons \Rightarrow enhances π^0/γ 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 π^0 and $\eta \Rightarrow$ constrain gluon Sivers

➤ Forward rapidity measurements

- A_N for π^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 (μ , J/ψ)
- 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)