XXI. Workshop on Deep Inelastic Scattering
and Related Subjects

# Highlights of Transverse Spin Physics in PHENIX

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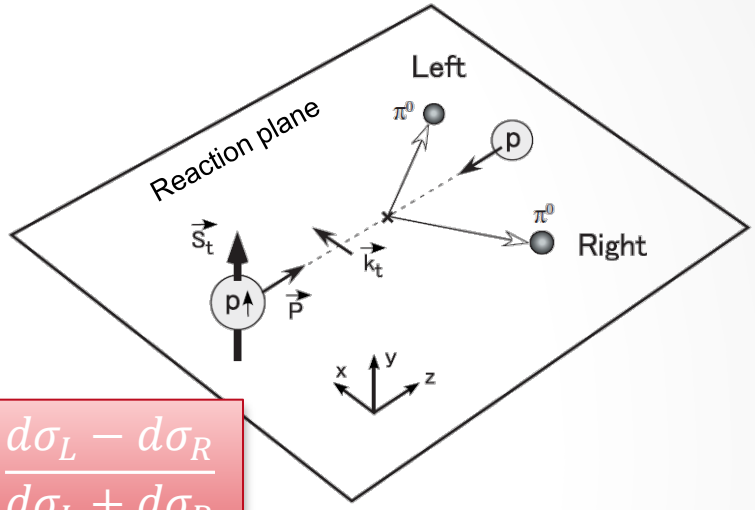
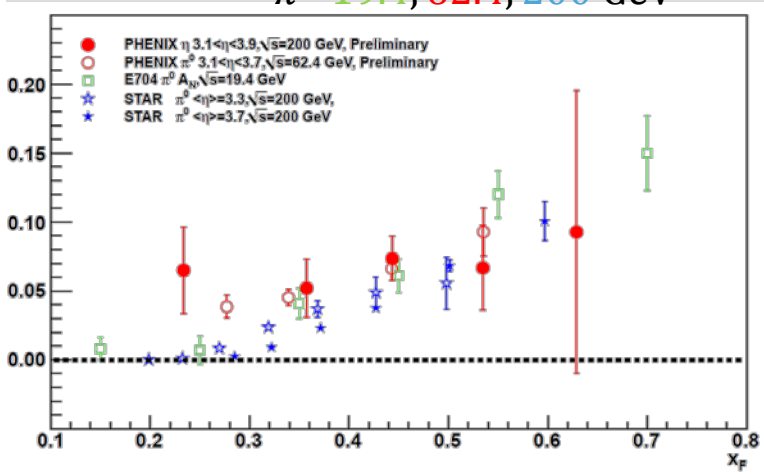
# Transverse Spin Asymmetries

- The transverse structure of the nucleon is largely unknown
- Transversity is chiral odd
- Large transverse asymmetries carry potential information about QCD dynamics beyond 1-d picture

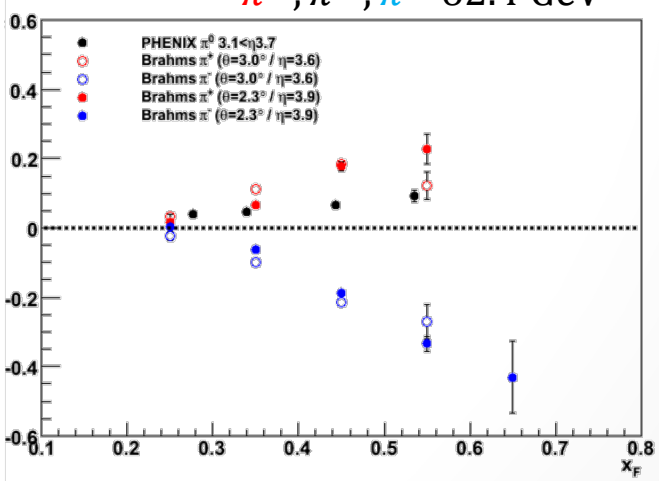



$$A_N = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$

$\pi^0$ 19.4, 62.4, 200 GeV



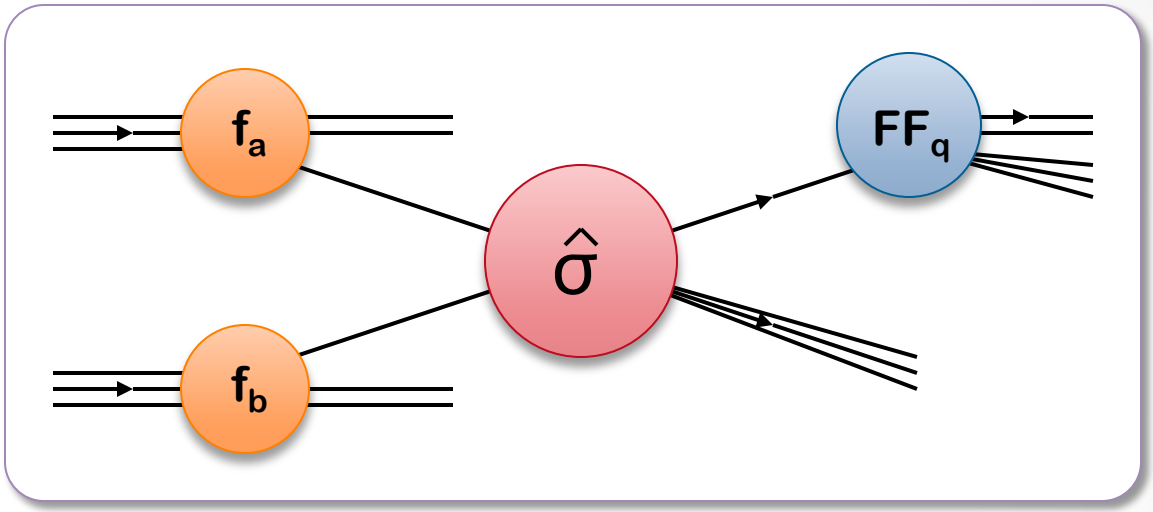

$\pi^+, \pi^0, \pi^-$ 62.4 GeV

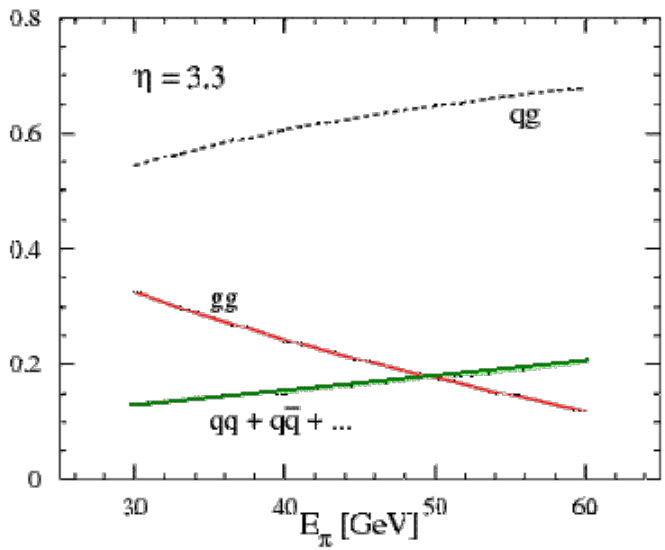



$x_F = 2p_l/\sqrt{s}$

# Proton-Proton Collisions

- Initial State
- pQCD
- Final State



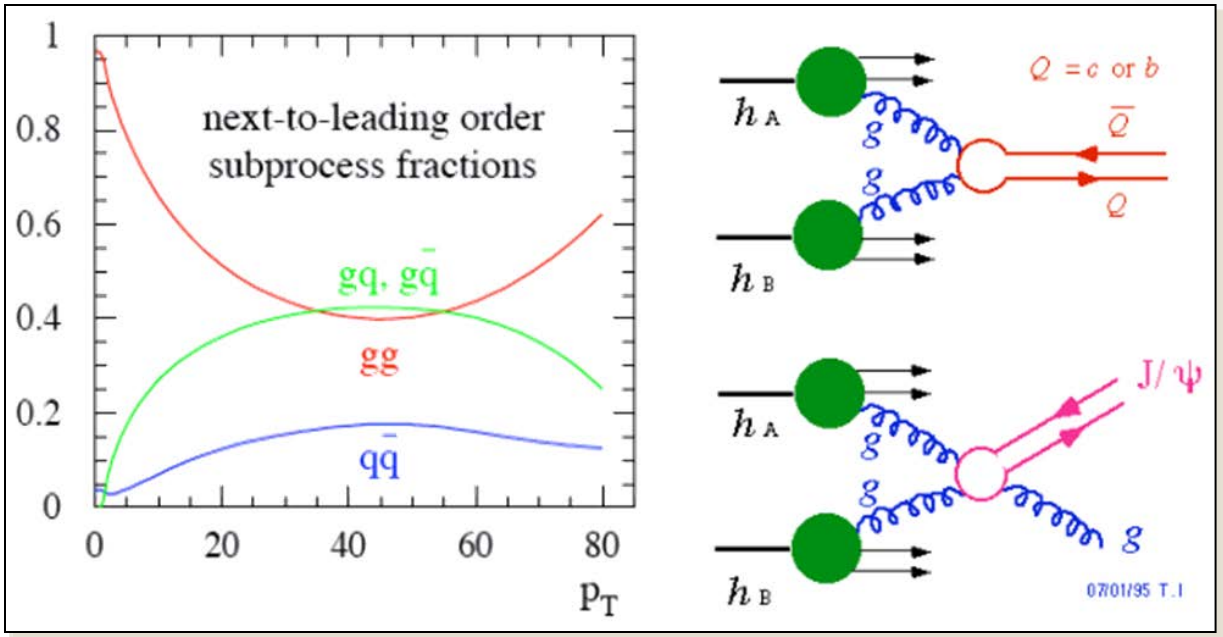

Process contribution in $\pi^0$ production

Disentangle effects from

- kinematics
- processes
- probes

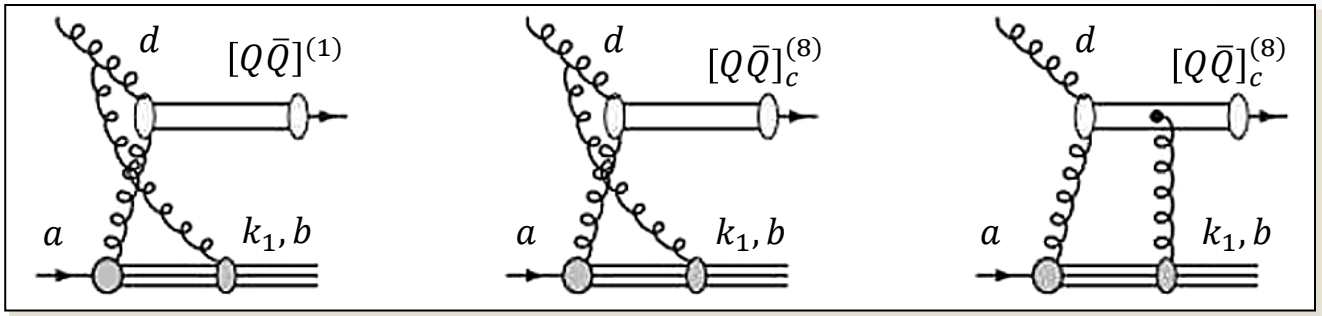
# Heavy Flavor

- In leading order
  - o $gg \to c\bar{c} \approx 95\%$
  - o $gg \to b\bar{b} \approx 85\%$
- Gluon has no transversity (suppressed Collins effect)
- Only sensitive to Sivers effect

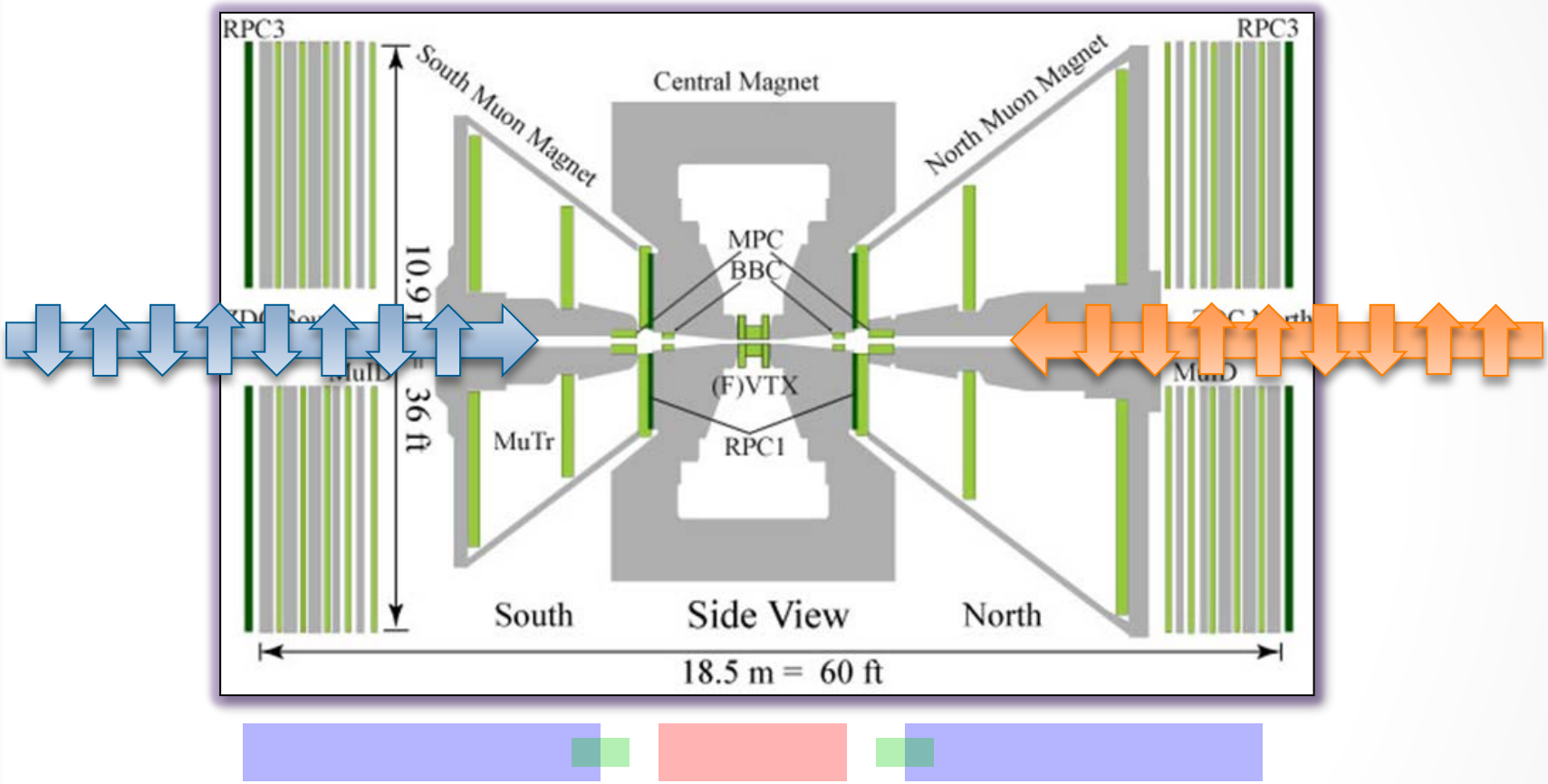



- Cancellation of initial and final state interactions [PRD78, 014024, 2008]

No color-octet in asymmetry



# The PHENIX Detector

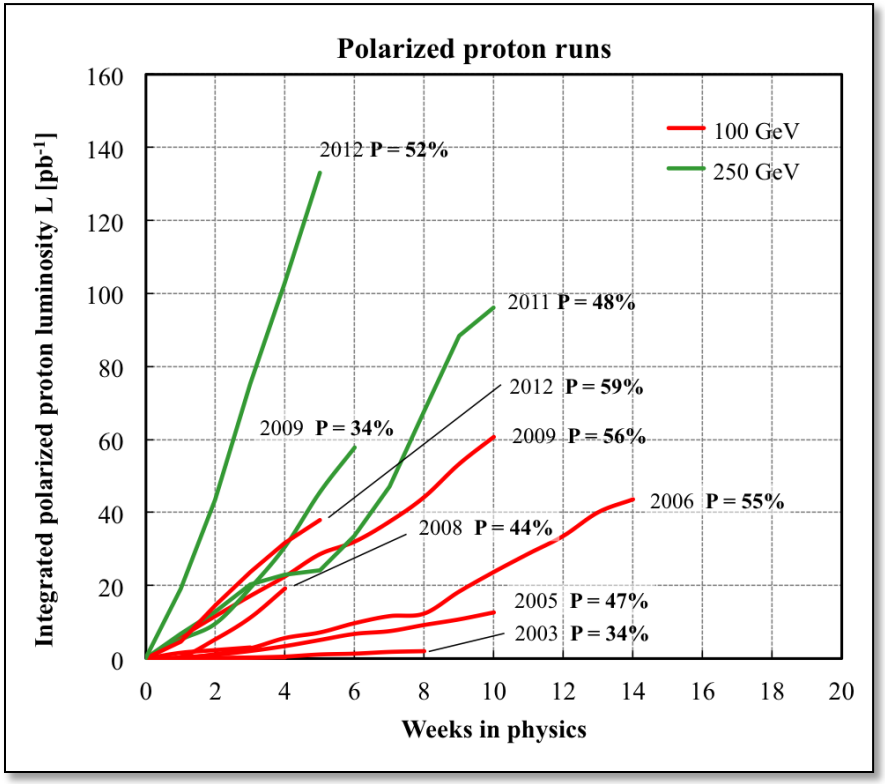


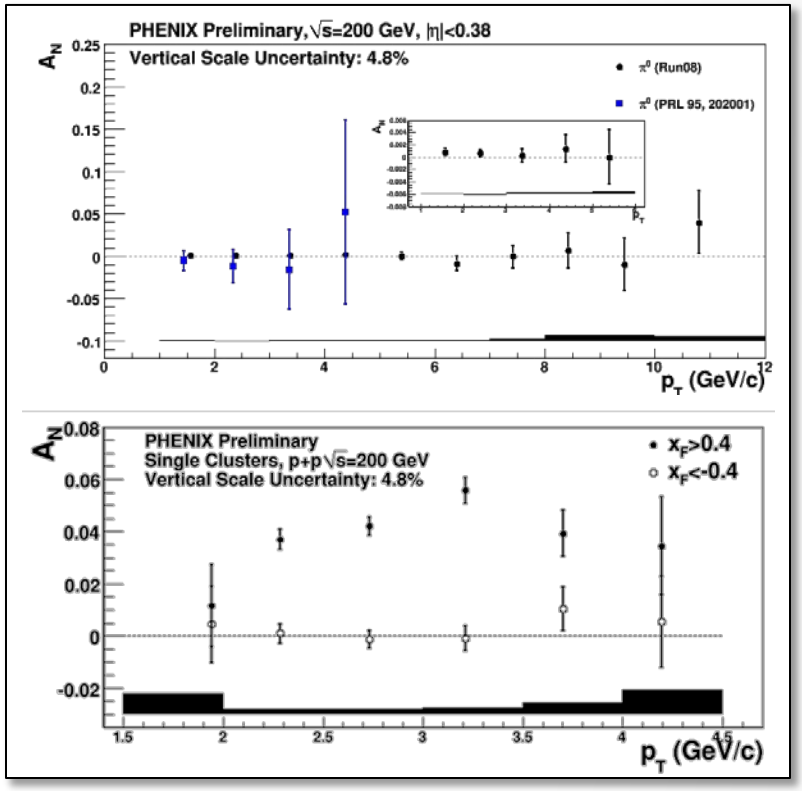

$-0.35 < \eta < 0.35, \Delta\varphi = 2 \times {}^{\pi}/_{2}$: tracking and EM-cal

$1.2 < |\eta| < 2.4, \Delta\varphi = 2\pi$: tracking and μ-ID

$3.1 < |\eta| < 3.9, \Delta\varphi = 2\pi$: EM-cal

# $\vec{p} + p$ @ PHENIX




| Year | $\sqrt{s}$ (GeV) | Pol. (%) | L (pb-1) | $P^2L$ ($pb^{-1}$) |
|---|---|---|---|---|
| 2006 | 62 | 48 | 0.02 | 0.005 |
| 2006 | 200 | 57 (51) | 2.7 | 0.7 |
| 2008 | 200 | 46 | 5.2 | 1.1 |
| 2012 | 200 | 58 | 9.2 | 3.1 |

# Asymmetry Determination

- Conventional square-root method
  - Needs assumptions for integration of cross section

$$\varepsilon = \frac{1}{\langle \cos\varphi \rangle} \cdot \frac{\sqrt{N_l^{\uparrow} \cdot N_R^{\downarrow}} - \sqrt{N_l^{\downarrow} \cdot N_R^{\uparrow}}}{\sqrt{N_l^{\uparrow} \cdot N_R^{\downarrow}} + \sqrt{N_l^{\downarrow} \cdot N_R^{\uparrow}}}$$

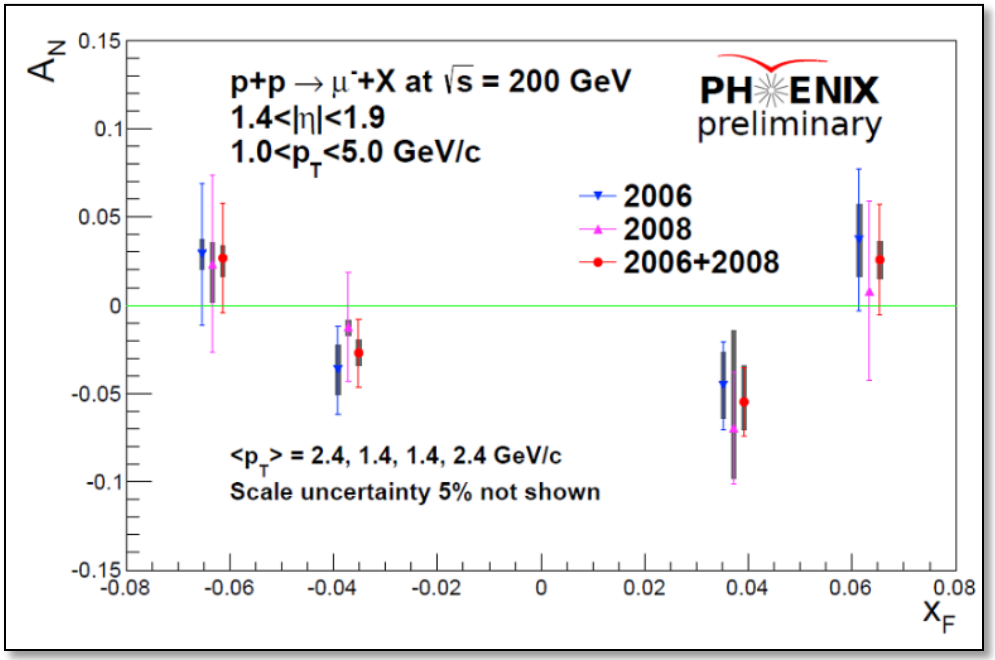
- Unbinned maximum likelihood method
  - Sensitive to differences in luminosity of polarization states

$$-\log \mathcal{L}(\varepsilon|\varphi) = -\sum_i \log[e \cdot (1 + \varepsilon \cdot \cos\varphi_i)]$$

- Background correction

$$\varepsilon = \frac{\varepsilon^{inc} - r \cdot \varepsilon^{bg}}{1 - r} \implies A_N = \frac{\varepsilon}{P_{beam}}$$

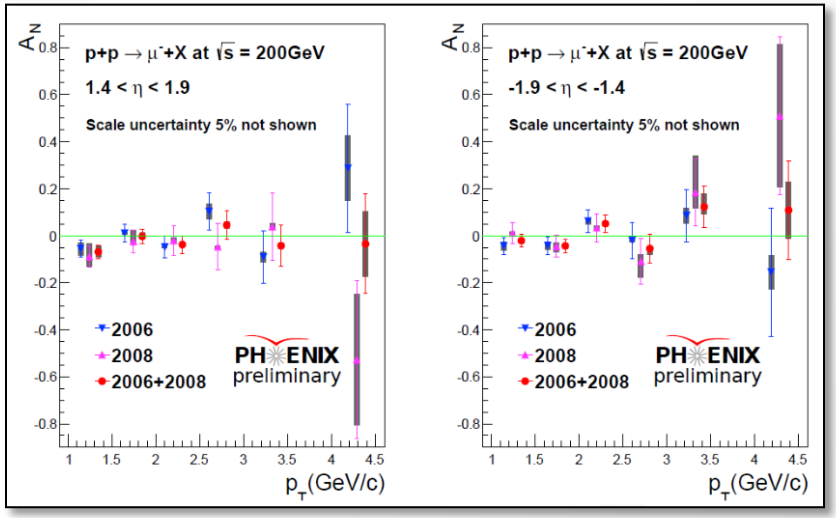
# Single Muons




Background from hadrons

- Monte-Carlo studies for hadron decays and punch through hadrons
- Compare with stopped hadrons
- Correct asymmetry

$p_T$ dependence

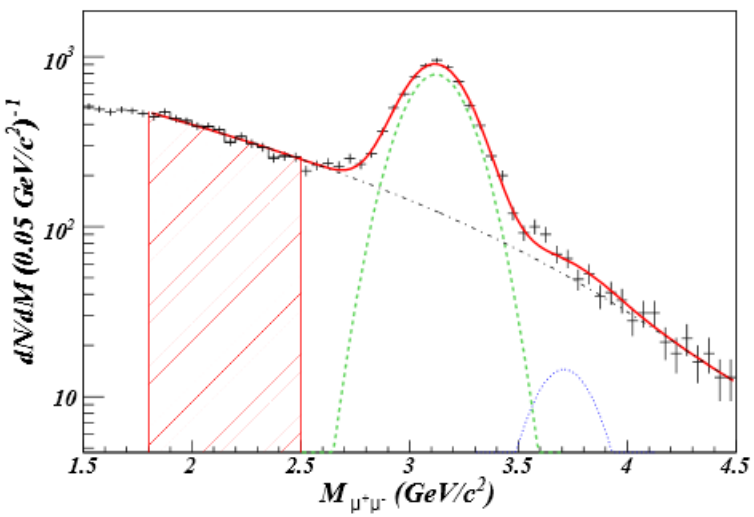


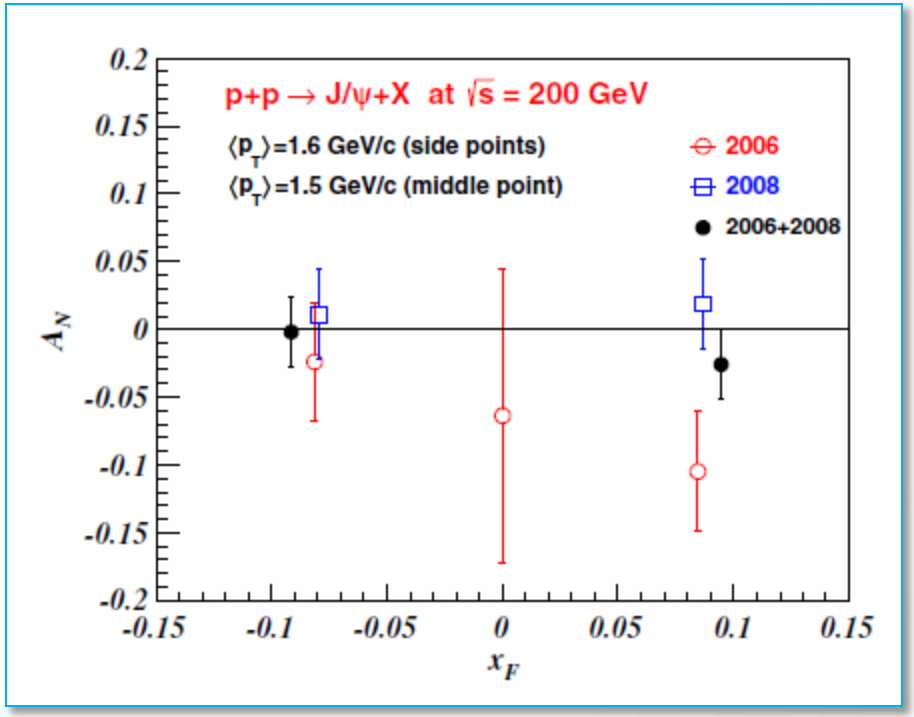

- Observed $A_N$ are consistent with zero
- 2012 data will increase sensitivity
- FVTX for background rejection in future data

# $J/\psi$ Transverse Asymmetries

- PRD 86, 099904 (E), 2012

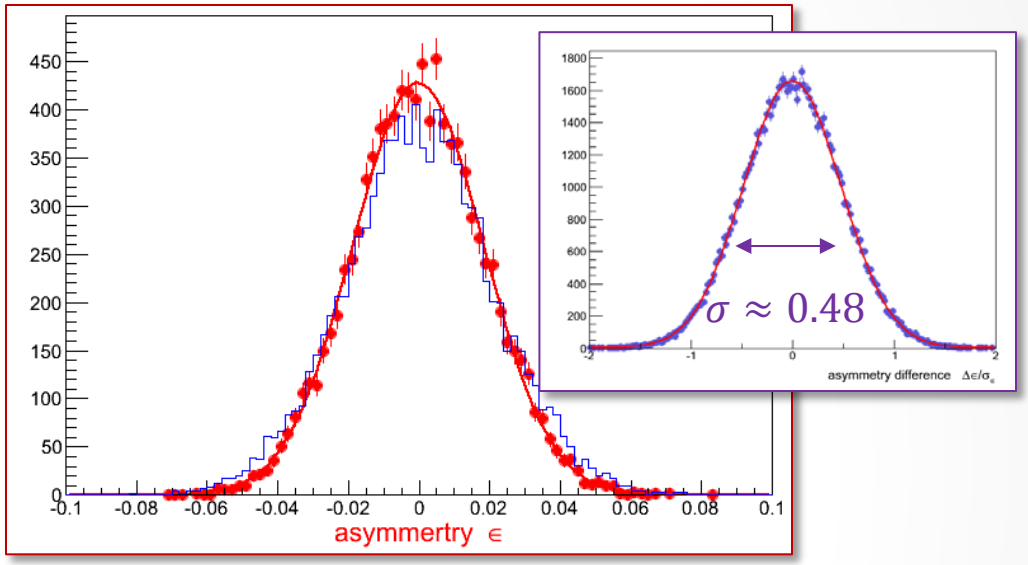
  2006 vs. 2008 results at $x_F > 0$ problematic?

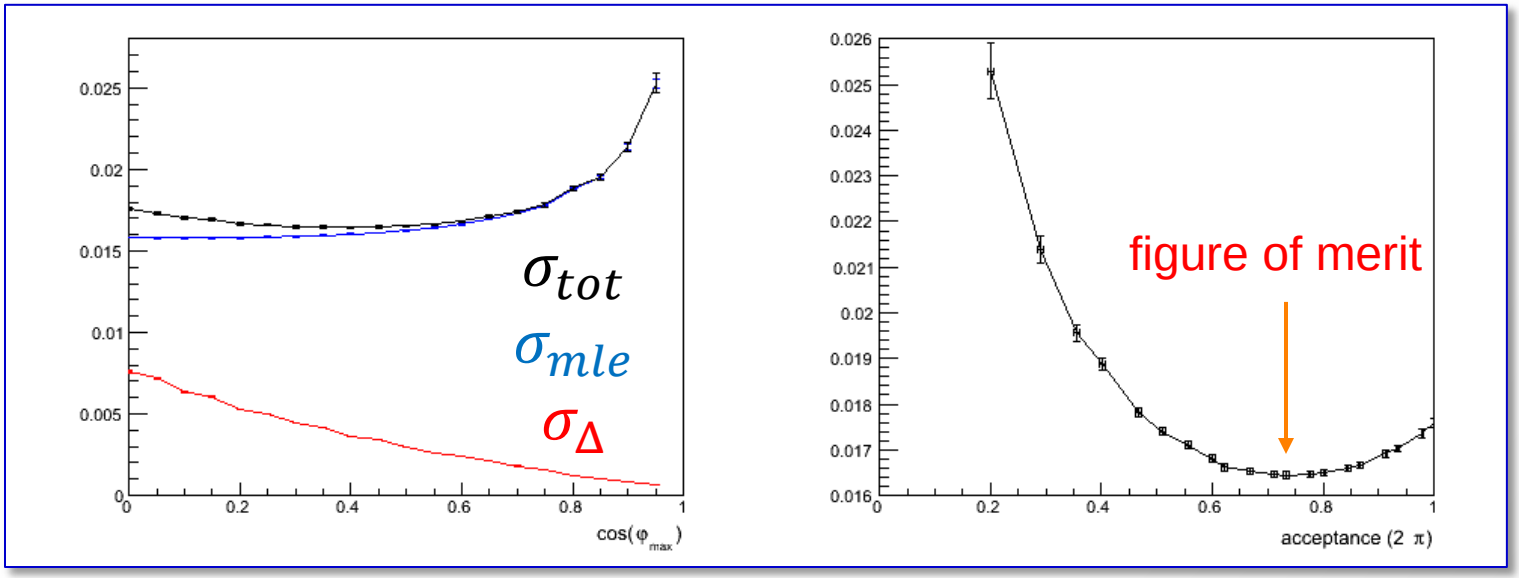


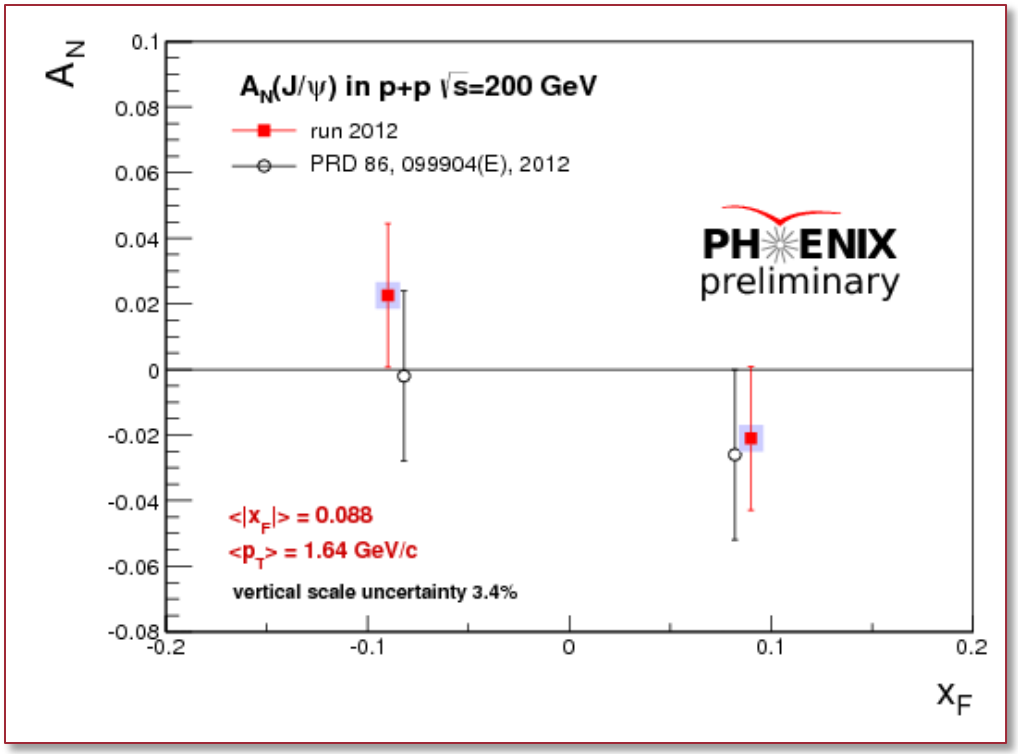
# Asymmetry Reproducibility

- Toy Monte Carlo simulation
  - max. like & sqrt asymmetries
- Difference is not zero
  - Driven by acceptance where asymmetry is small
  - Limit acceptance symmetrically $|\cos\varphi| > c_{threshold}$

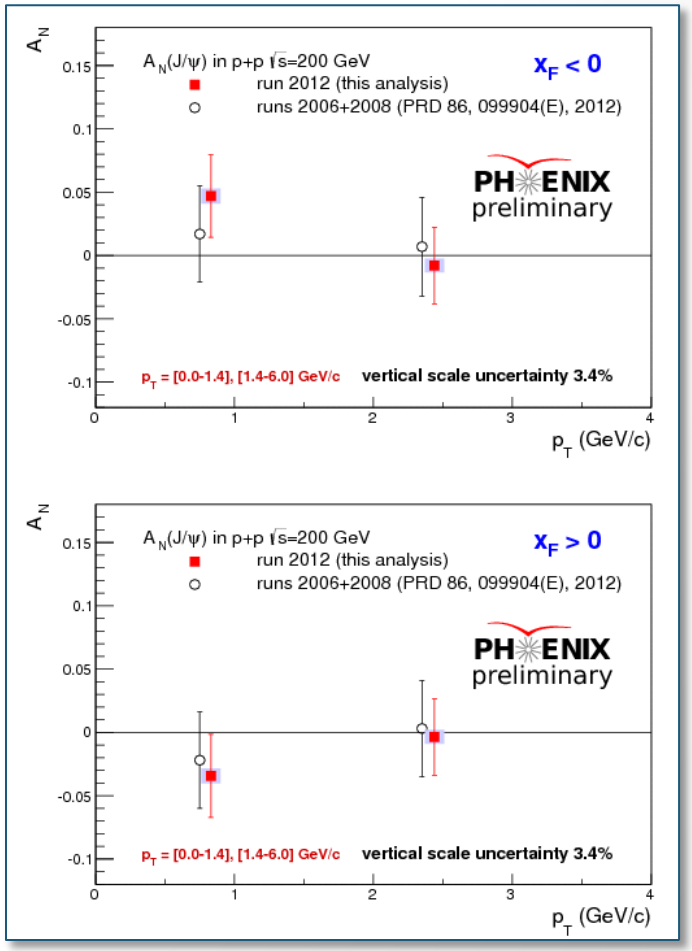


# Comparison of Results




$p_T$ dependence




- Observed $A_N$ are consistent with zero
  - Higher moments consistent with zero
- Measured asymmetries are consistent between data sets

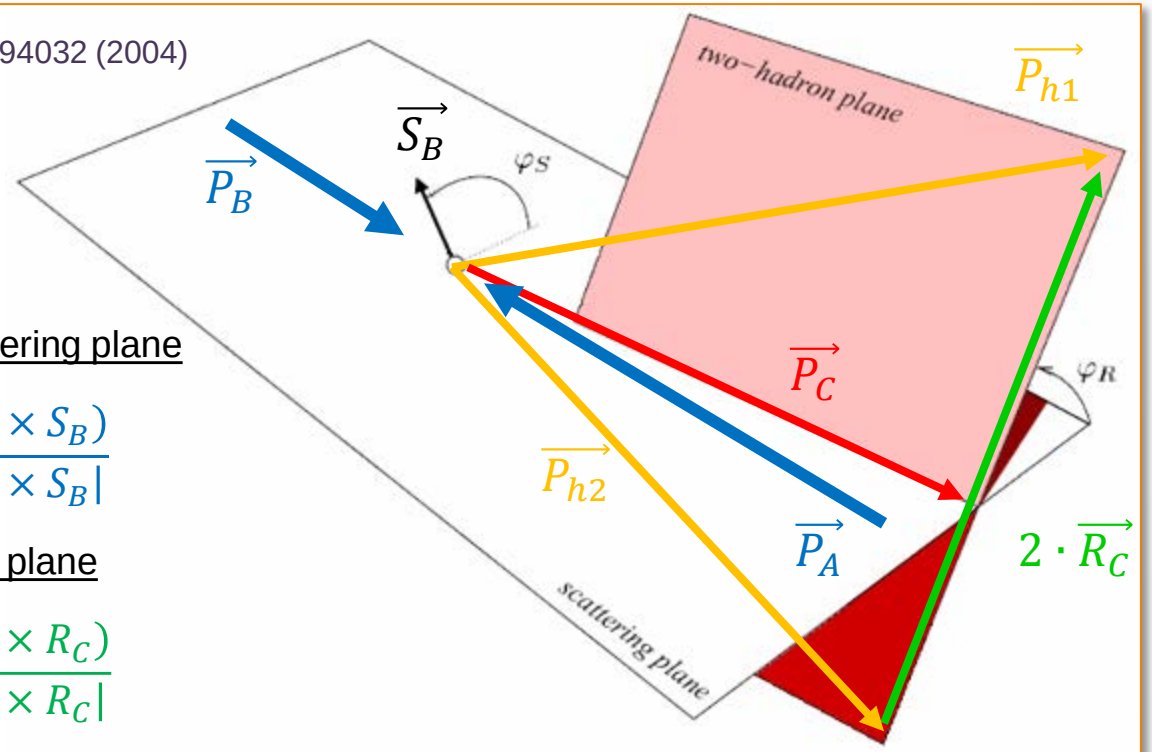
# Interference Fragmentation

$$d\sigma_{UT} = 2|P_{C\perp}||S_{BT}|\sin(\varphi_S - \varphi_R)\sum_{a,b,c,d}\int \frac{dx_a dx_b}{16\pi z_c} f_1^a(x_a) h_1^b(x_b) \frac{d\Delta\hat{\sigma}_{ab^\uparrow\to c^\uparrow d}}{d\hat{t}} H_{1,ot}^{\sphericalangle c}(\bar{z}_c, M_C^2)$$

$$A_{UT} = \frac{\sigma_{UT}}{\sigma_{UU}}$$

$$d\sigma_{UU} = 2|P_{C\perp}|\sum_{a,b,c,d}\int \frac{dx_a dx_b}{4\pi^2 z_c} f_1^a(x_a) f_z^b(x_b) \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}} D_{1,00}(\bar{z}_c, M_C^2)$$

A. Bacchetta, M. Radici, PRD 70, 094032 (2004)




<u>from polarization vector to scattering plane</u>

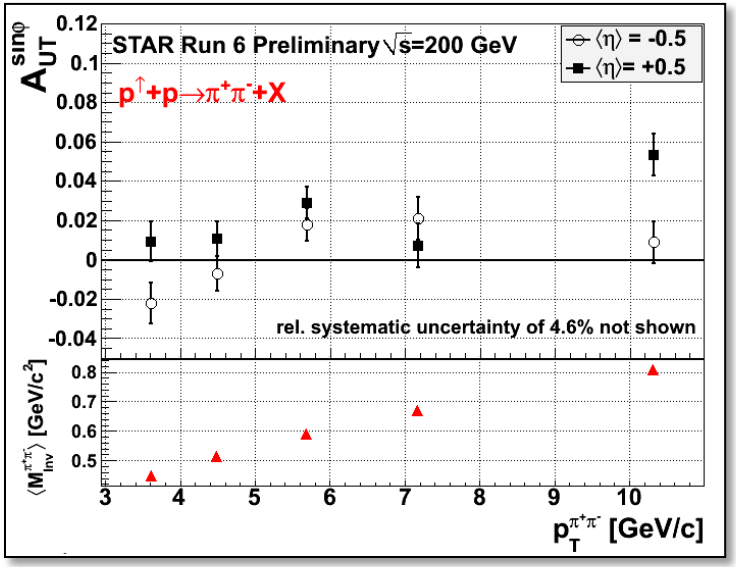
$$\cos\varphi_S = \frac{(P_B \times P_C)}{|P_B \times P_C|}\cdot\frac{(P_B \times S_B)}{|P_B \times S_B|}$$

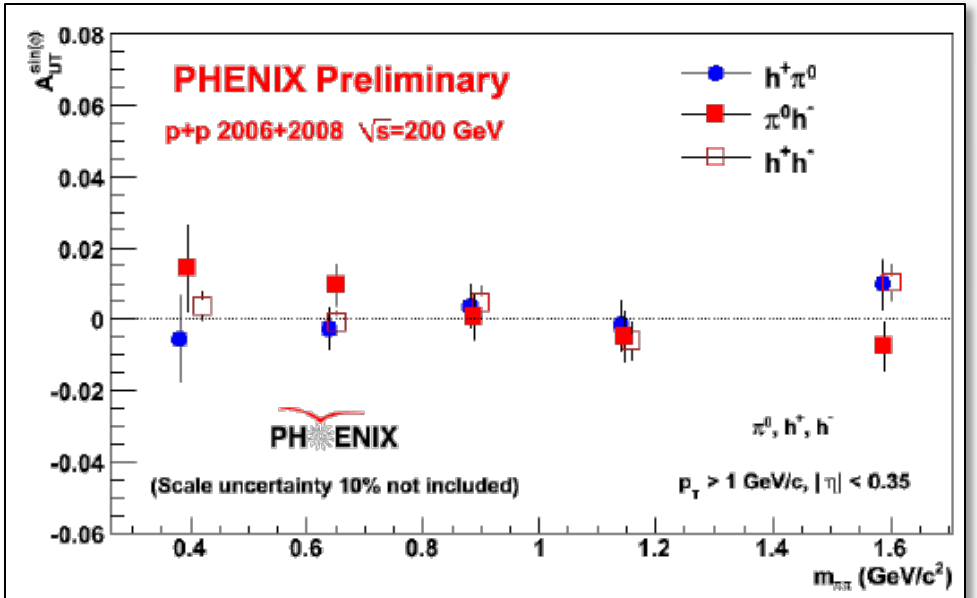
<u>from scattering plane to hadron plane</u>

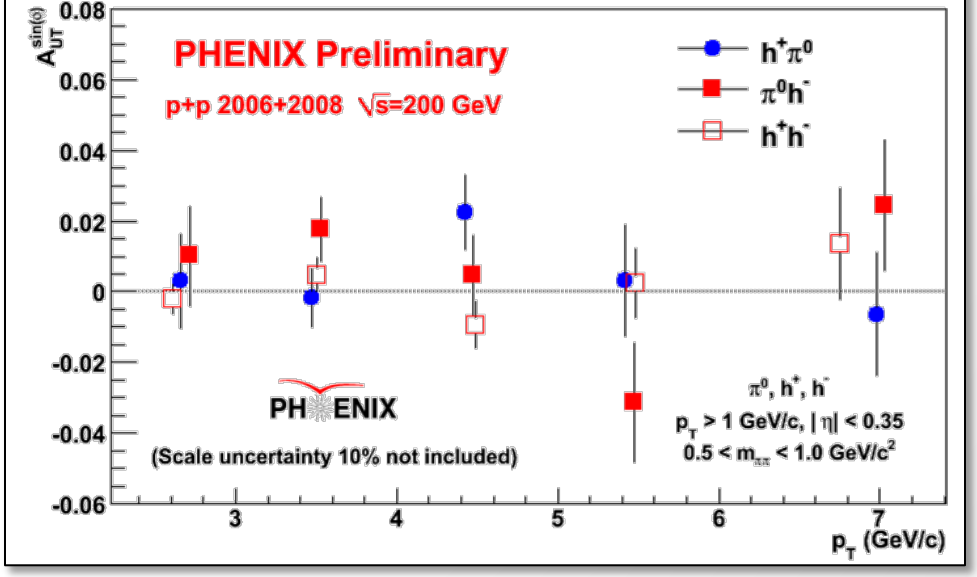
$$\cos\varphi_R = \frac{(P_C \times P_A)}{|P_C \times P_A|}\cdot\frac{(P_C \times R_C)}{|P_C \times R_C|}$$

# IFF @ RHIC

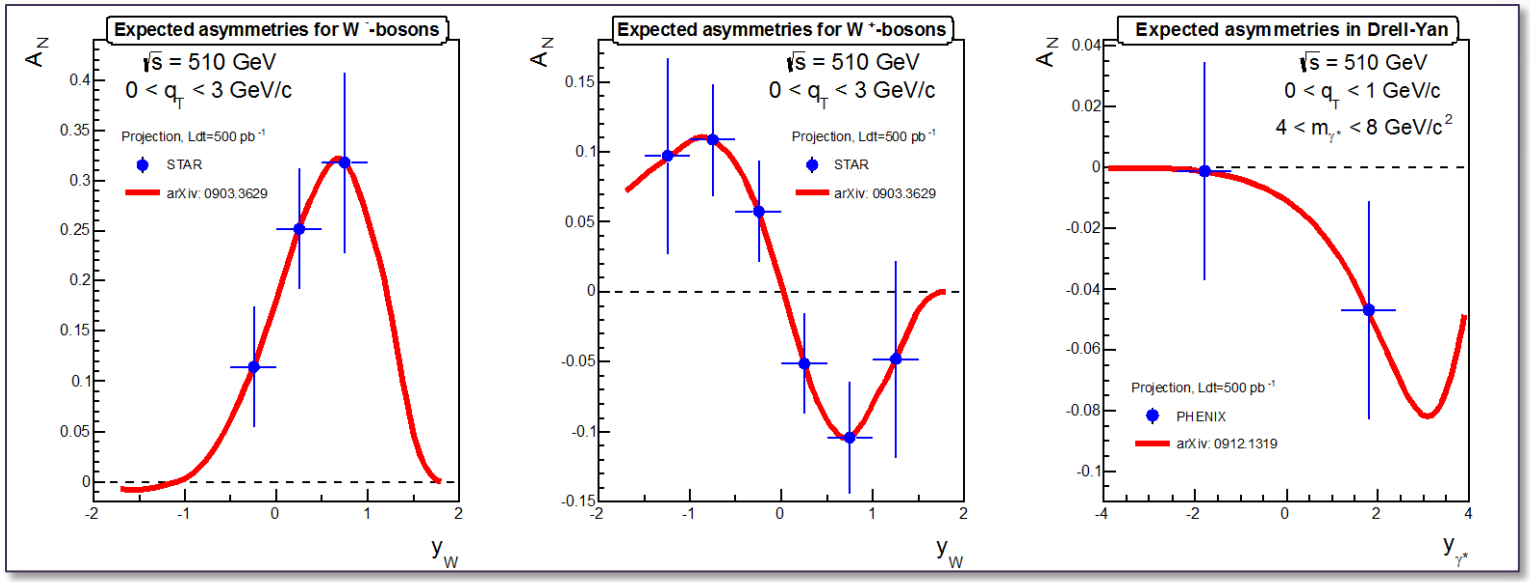
- PHENIX data 2006/2008
- $A_{UT} \approx 0$
- STAR sees significant $A_{UT}$
- Analysis of 2012 is on-going



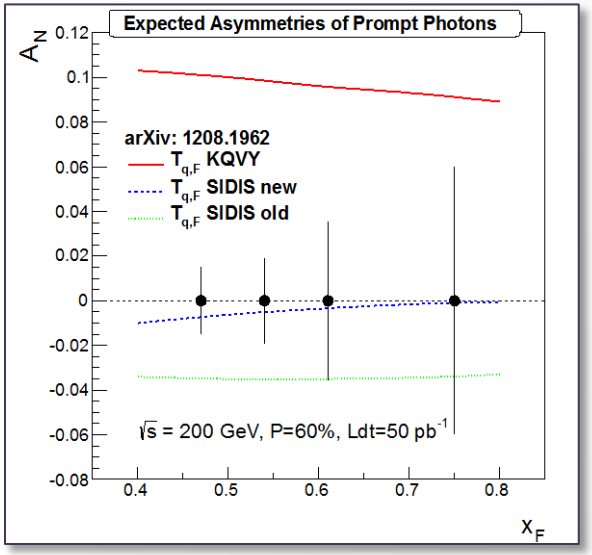



# Sivers Asymmetries

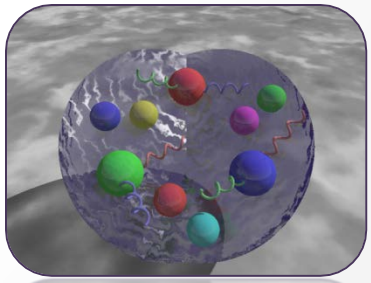



- Projected asymmetries with current setup / moderate upgrades in 500 pb$^{-1}$
- Test scale dependence / evolution
- Map out functional form / high-*x*
- The RHIC Spin Program: Achievements and Future Opportunities (arXiv: 1304.0079)



# What to take home…

- Non-vanishing transverse single spin asymmetries have been measured over a wide range of energies
  - Previous $A_N$ at mid- and forward rapidities are being prepared for publication
- Need to disentangle and quantify contributions from different effects
- PHENIX has measured $A_N$ in heavy flavor production
  - Statistics of single μ still limited, 2012 data not included yet
  - Previous $A_N(J/\psi)$ have been published, consistent with 2012 data
- Expect updated results of interference fragmentation functions soon
  - Can extract transversity in combination with IFF from Belle
- Future measurements of transverse asymmetries at RHIC can provide essential input to our understanding of (p)QCD



# Higher Moments in Asymmetry

$$-\log \mathcal{L}(\varepsilon|\varphi) = -\sum_i \log\left(1 + \varepsilon_\varphi \cdot \cos\varphi_i + \varepsilon_{2\varphi} \cdot \cos 2\varphi_i + \varepsilon_{3\varphi} \cdot \cos 3\varphi_i\right)$$

unpolarized

cos(φ) moment

cos(3φ) moment

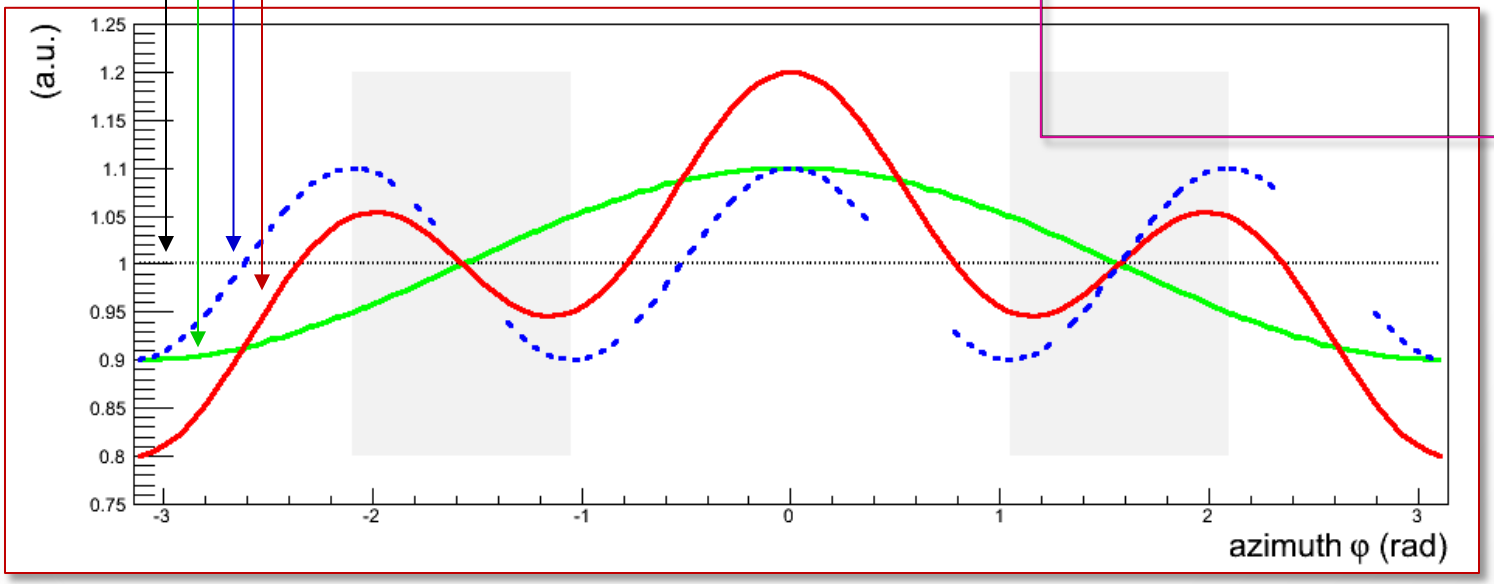
total asymmetry

Toy MC input

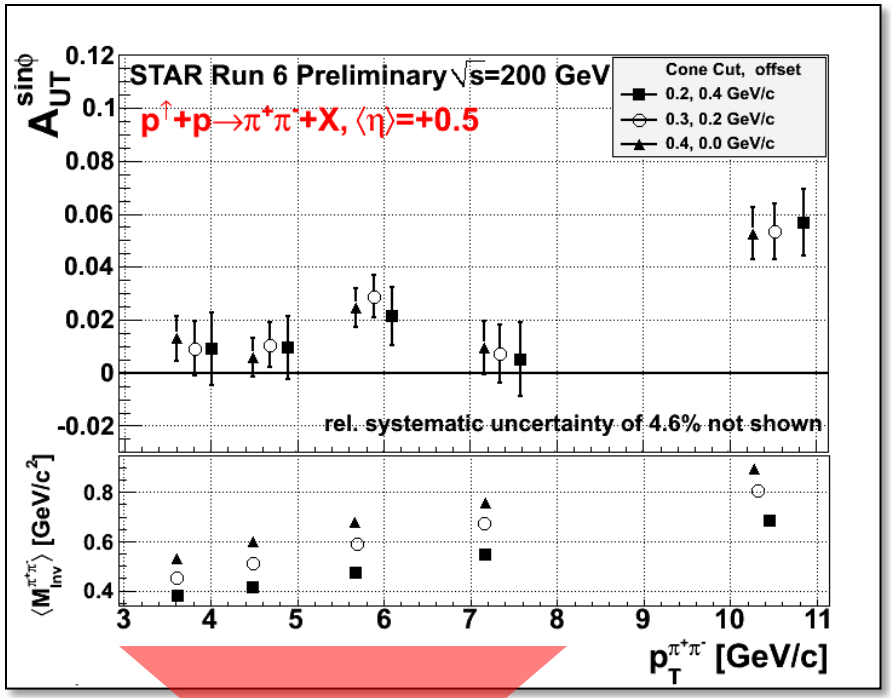
$\varepsilon_\varphi = 0.02$

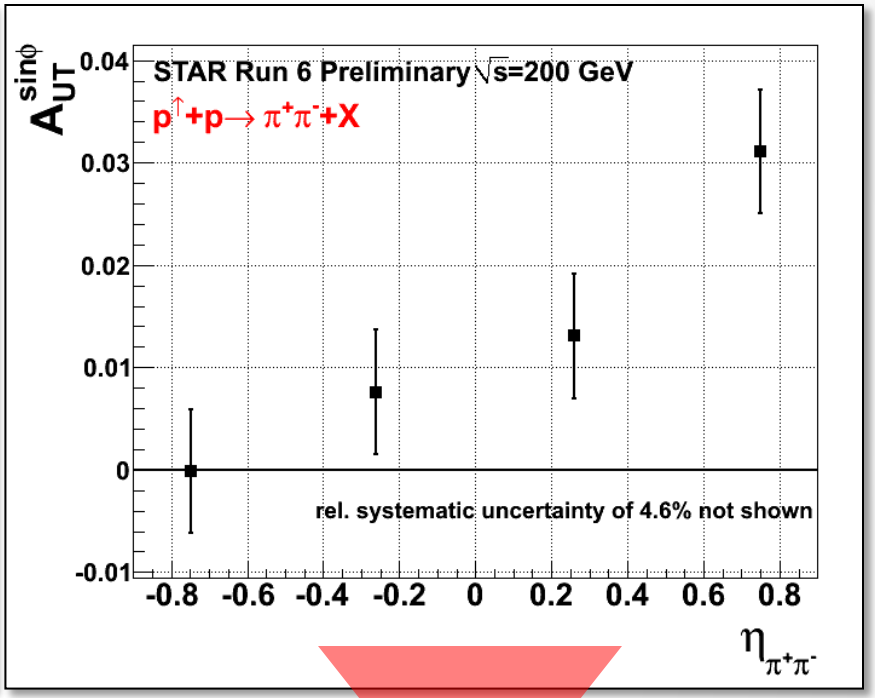
$\varepsilon_{3\varphi} = 0.10$

mle sqrt



# IFF @ STAR




Current PHENIX range/acceptance