Transverse Spin Results from PHENIX

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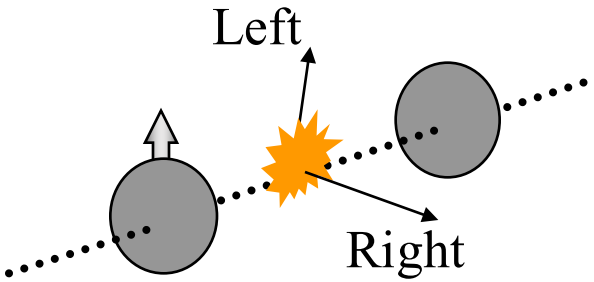
Outline

- Introduction
- PHENIX measured A_N
  - mid/forward rapidity π^0, η
  - open heavy flavor
  - J/ψ
- First PHENIX p+A Transverse Spin results
  - **Forward neutron A_N in p+p, p+Au and p+Al**

Transverse Single Spin Asymmetry A_N

Transverse Single Spin Asymmetries A_N

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



Theory Expectation:

Small asymmetries at high energies

(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

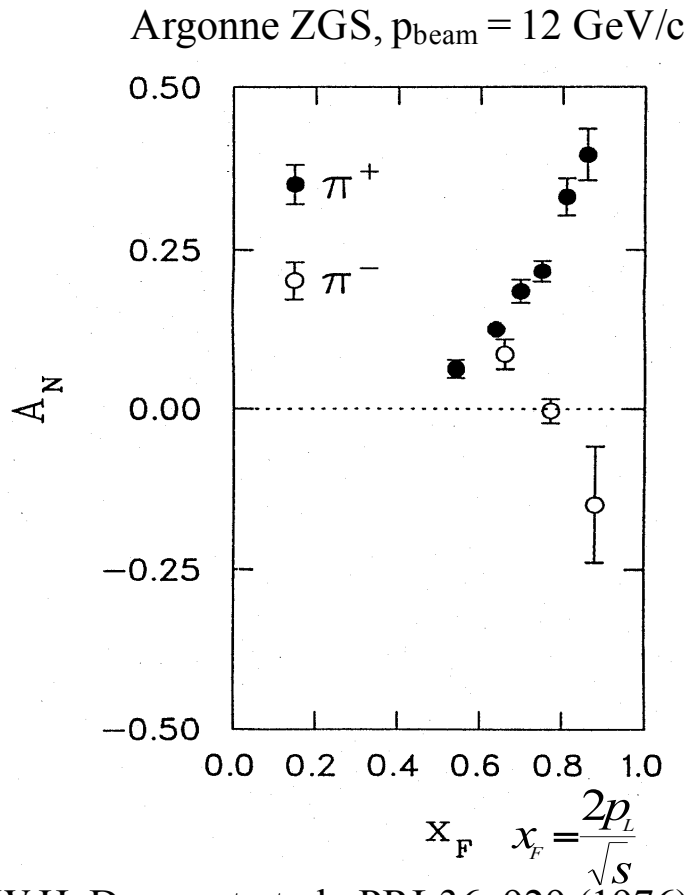
$A_N \sim O(10^{-4})$ theory

Experiments:

ZGS, AGS, FERMILAB to RHIC

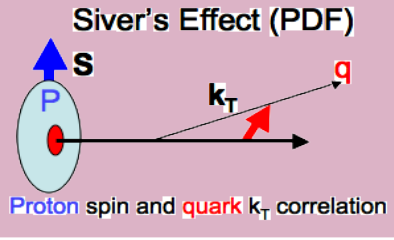
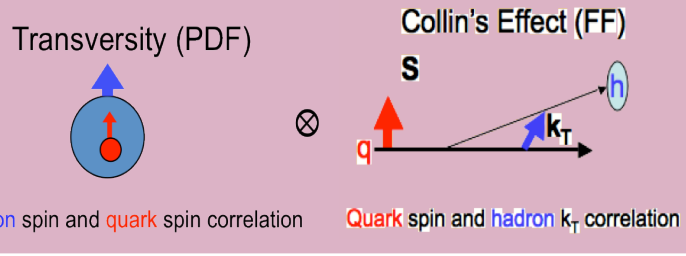
$A_N \sim O(10^{-1})$ observed

$\sqrt{s} = 5 \sim 500$ GeV



W.H. Dragoset et al., PRL36, 929 (1976)

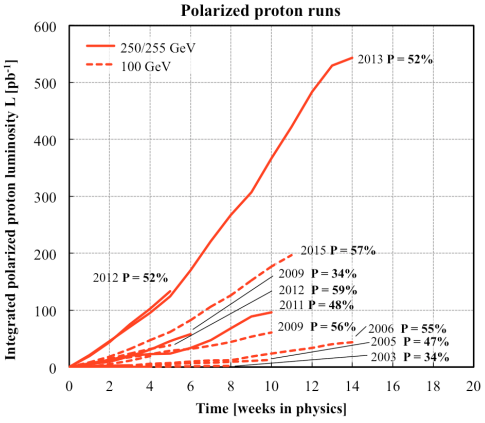
Mechanisms for A_N

	Initial State	Final State
Transverse Momentum Dependent function approach	**Sivers mechanism** D. Sivers, PR D41 (1990) 83; D43 (1991) 261 $A_N \propto f_T^q(x,k_\perp^2)\cdot D_q^h(z)$ 	**Collins mechanism** John Collins, Nucl Phys B396 (1993) 161 $A_N \propto \delta q(x)\cdot H_1^\perp(z_2,\bar{k}_\perp^2)$ 
Collinear Factorization $k_\perp$ is integrated ➔ represents integrated spin dependence of the parton's transverse motion	**Twist-3 distribution** $d\sigma(\mathbf{S}_\perp) = H\otimes f_{a/p^\uparrow(3)}\otimes f_{b/p(2)}\otimes D_{h/c(2)}$ $+ H'\otimes f_{a/p^\uparrow(2)}\otimes f_{b/p(3)}\otimes D_{h/c(2)}$ $+ H''\otimes f_{a/p^\uparrow(2)}\otimes f_{b/p(2)}\otimes D_{h/c(3)},$ works at $Q >> \Lambda_{QCD}$, Twist-3 quark-gluon correlation function $T_{q,F}$ and two independent tri-gluon correlation functions $T_G^{(f)}$, $T_G^{(d)}$ are related through $T_F^q(x,x) = -\int d^2\mathbf{p}_\perp \frac{\mathbf{p}_\perp^2}{M} f_{1T}^{\perp q}(x,\mathbf{p}_\perp^2)\vert_{\text{SIDIS}}$	**Twist-3 fragmentation** Twist-3 fragmentation function $\hat{H}$ is related to the $k_\perp$-moment of the TMD Collins function $H_1^{\perp h/q1}$ as $\hat{H}^{h/q}(z) = z^2\int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{2M_h^2} H_1^{\perp h/q}(z, z^2\vec{k}_\perp^2)$

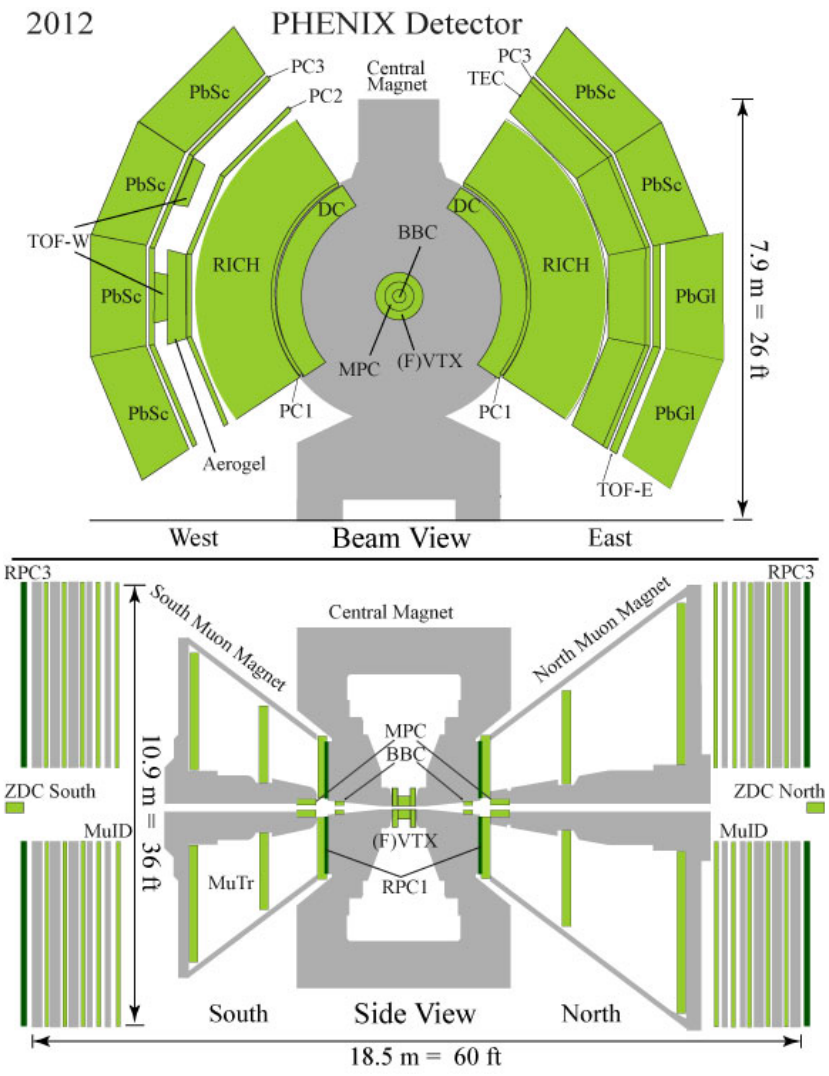
PHENIX Transverse Spin Runs

Year	$\sqrt{s}$ (GeV)	Recorded Luminosity for longitudinally / transverse polarized p+p STAR	Recorded Luminosity for longitudinally / transverse polarized p+p PHENIX	<P> in %
2006	62.4	-- pb^{-1} / 0.2 pb^{-1}	0.08 pb^{-1} / 0.02 pb^{-1}	48
	200	6.8 pb^{-1} / 8.5 pb^{-1}	7.5 pb^{-1} / 2.7 pb^{-1}	57
2008	200	-- pb^{-1} / 7.8 pb^{-1}	-- pb^{-1} / 5.2 pb^{-1}	45
2009	200	25 pb^{-1} / -- pb^{-1}	16 pb^{-1} / -- pb^{-1}	55
	500	10 pb^{-1} / -- pb^{-1}	14 pb^{-1} / -- pb^{-1}	39
2011	500	12 pb^{-1} / 25 pb^{-1}	18 pb^{-1} / -- pb^{-1}	48
2012	200	-- pb^{-1} / 22 pb^{-1}	-- pb^{-1} / 9.7 pb^{-1}	61/56
	510	82 pb^{-1} / -- pb^{-1}	32 pb^{-1} / -- pb^{-1}	50/53
2013	510	300 pb^{-1} / -- pb^{-1}	155 pb^{-1}/ -- pb^{-1}	51/52
2015	200	52 pb^{-1} / 52 pb^{-1}	-- pb^{-1}/ 60 pb^{-1}	53/57
2015	200 *p* Au	total delivered Luminosity = 1.27 pb^{-1}		60
2015	200 *p* Al	total delivered Luminosity = 3.97 pb^{-1}		54

O : Trasversely polarized



PHENIX Detectors



- Philosophy
  - high resolution & high-rate
  - trigger for rare events
- Central Arms
  - $|\eta| < 0.35$, $\Delta\varphi \sim \pi$
  - Momentum, EM Energy, PID
  - π^0 and η
- Muon Arms
  - $1.2 < |\eta| < 2.4$
  - Momentum
  - High p_T muons
- Muon piston calorimeter
  - $3.1 < |\eta| < 3.9$
  - EM Energy
  - π^0 and η

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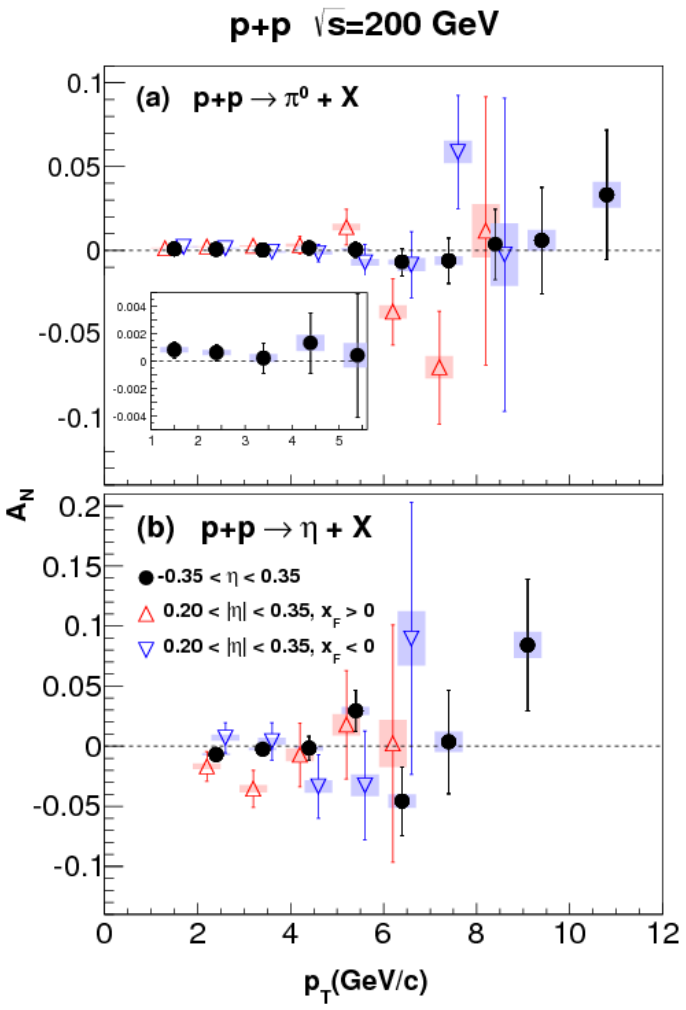
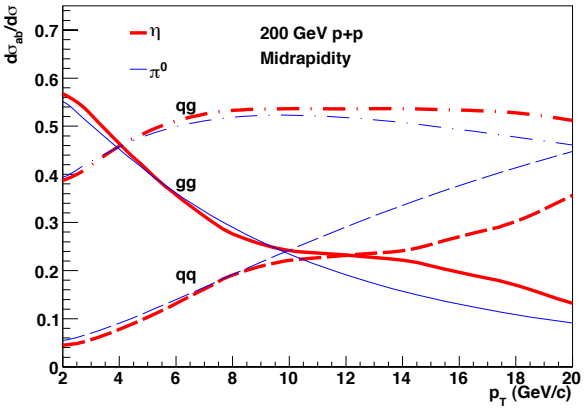
Mid-rapidity π^0 and η A_N

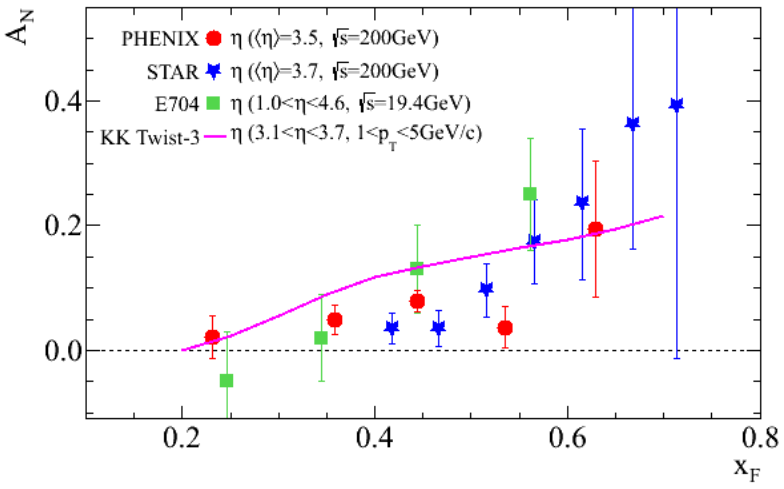


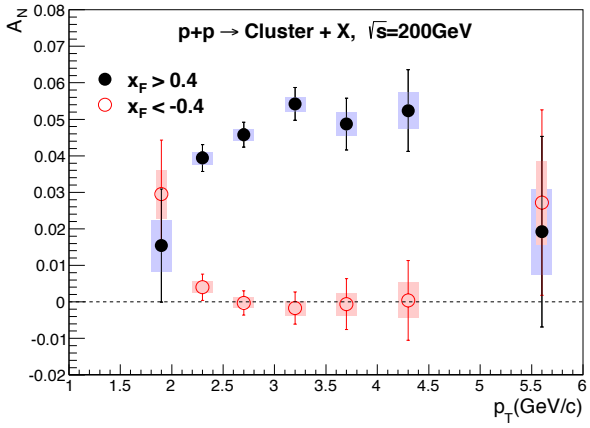
A. Adare et al. (PHENIX Collaboration) PRD 90, 012006 (2014)



- The π^0 and η production is sensitive to qg and gg process
- Consistent with zero for both π^0 and η

Forward-rapidity π^0 and η A_N





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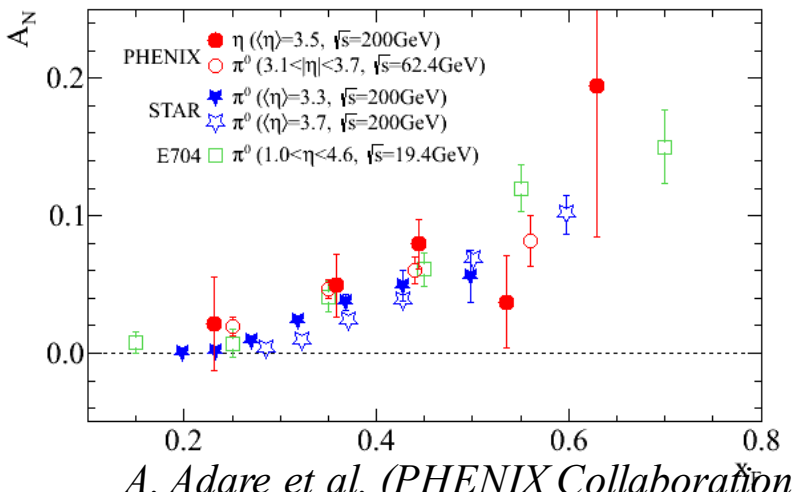

A. Adare et al. (PHENIX Collaboration) PRD 90, 072008 (2014)

- A_N is independent of collision energy
- Similar for π^0 and η
- No obvious p_T dependence

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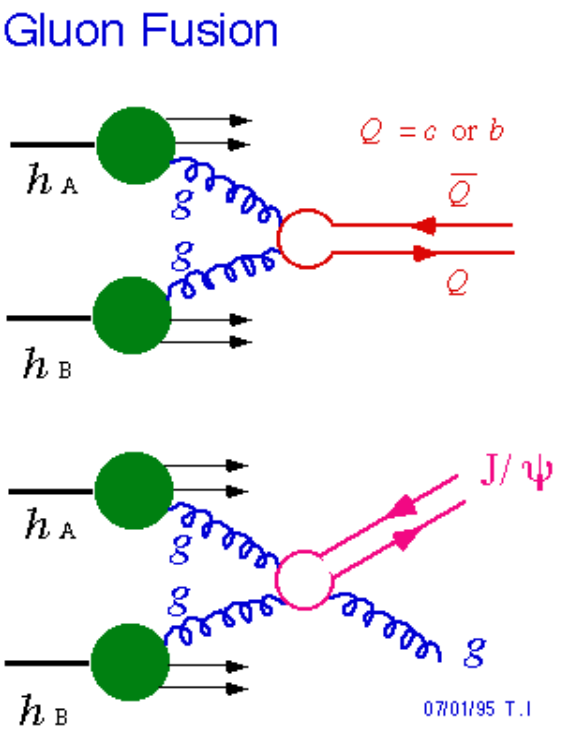
Heavy Flavor A_N

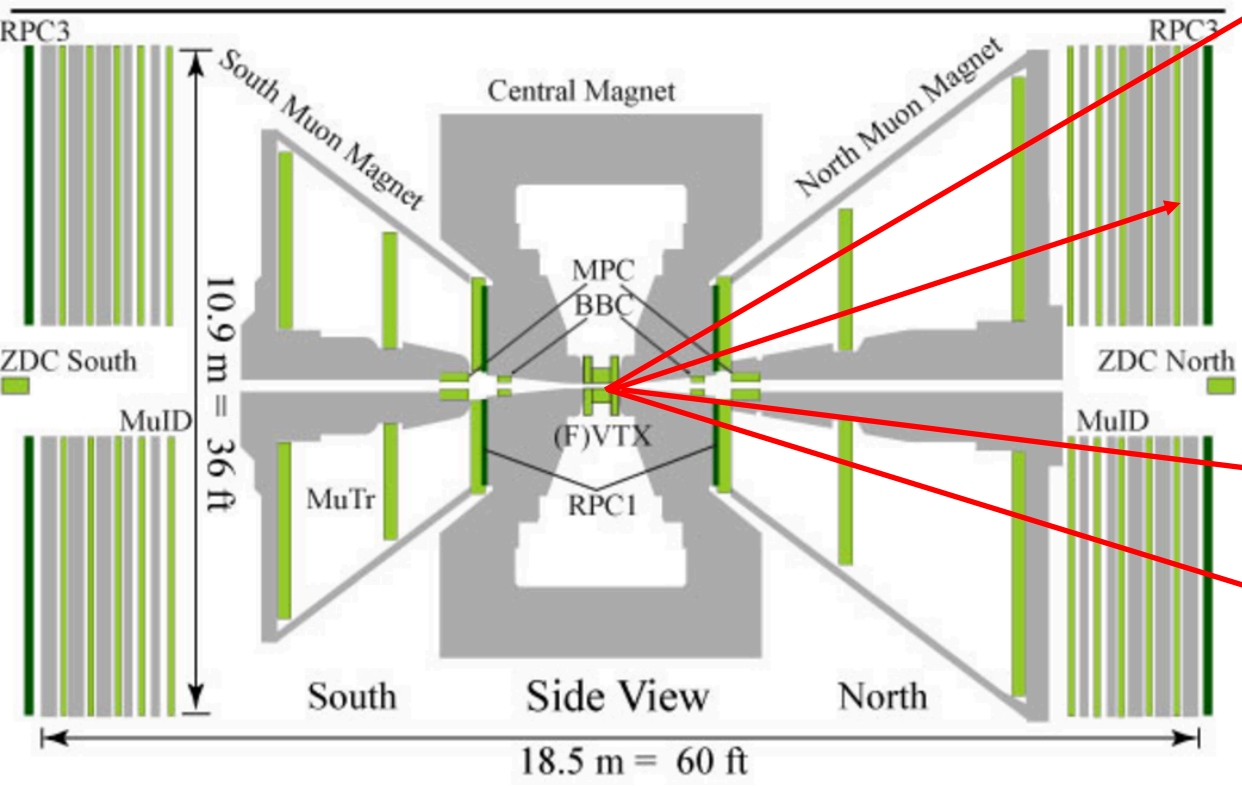


Heavy flavor production is dominated by gluon-gluon fusion at RHIC energies

- Heavy Flavor (especially D meson) production is an ideal tool to investigate gluon distribution.
- A_N in heavy flavor production is sensitive to the tri-gluon correlations by using the twist-3 collinear factorization framework
  - *Z. Kang, J. Qiu, W. Vogelsang, F. Yuan, PRD78:114013 (2008)*
  - *Y. Koike, S. Yoshida PRD84:014026 (2011)*

Open Heavy Flavor A_N

Sources of muon-like tracks



(1) Open Heavy Flavor
($D, B \rightarrow \mu$ signal)

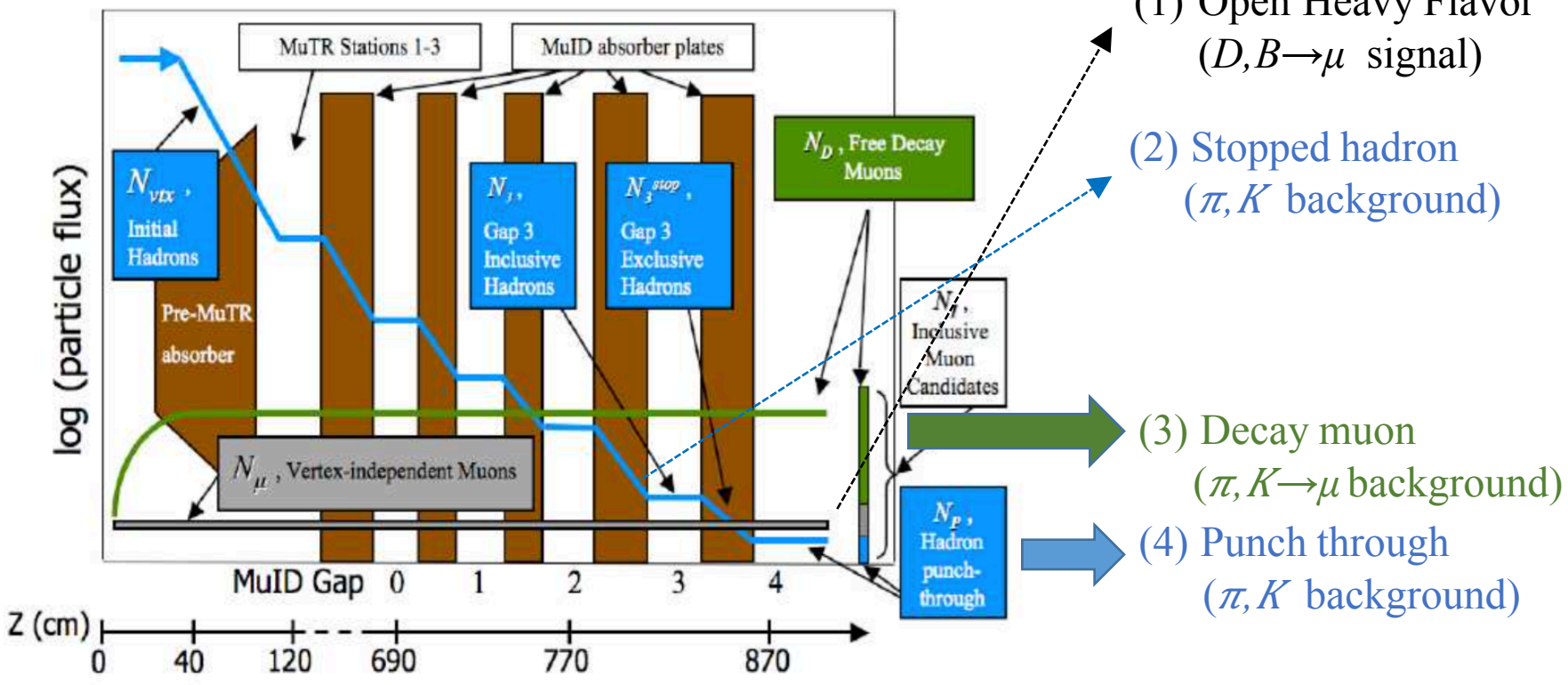
(2) Stopped hadron
(π, K background)

(3) Decay muon
($\pi, K \rightarrow \mu$ background)

(4) Punch through
(π, K background)

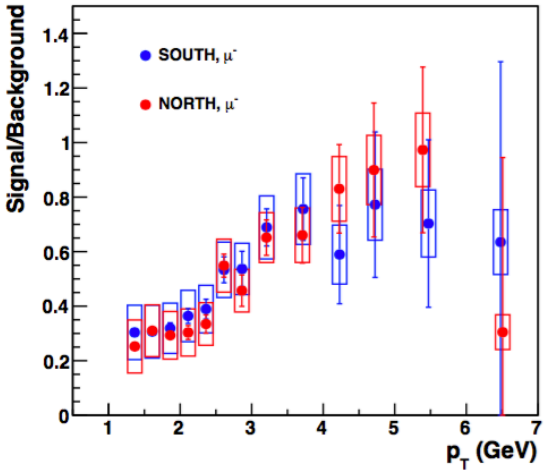
Open Heavy Flavor A_N

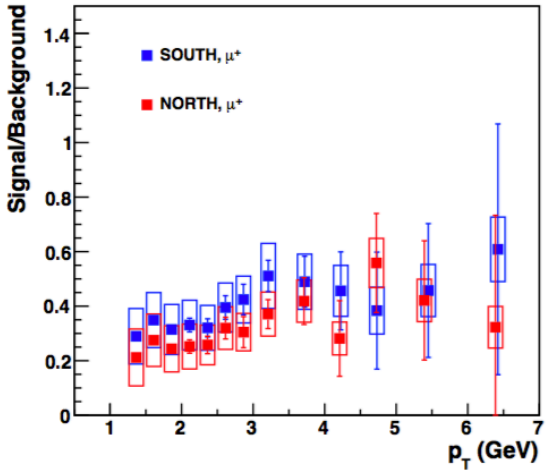
Relative contributions of signal and backgrounds



- Signal : (1)Open Heavy Flavor
- Distinguished Background : (2)Stopped Hadron
- Non-distinguished background : (3)Decay Muon, (4)Punch Through

Open Heavy Flavor A_N





signal-to-background ratio
Run12 *p*+*p* 200 GeV

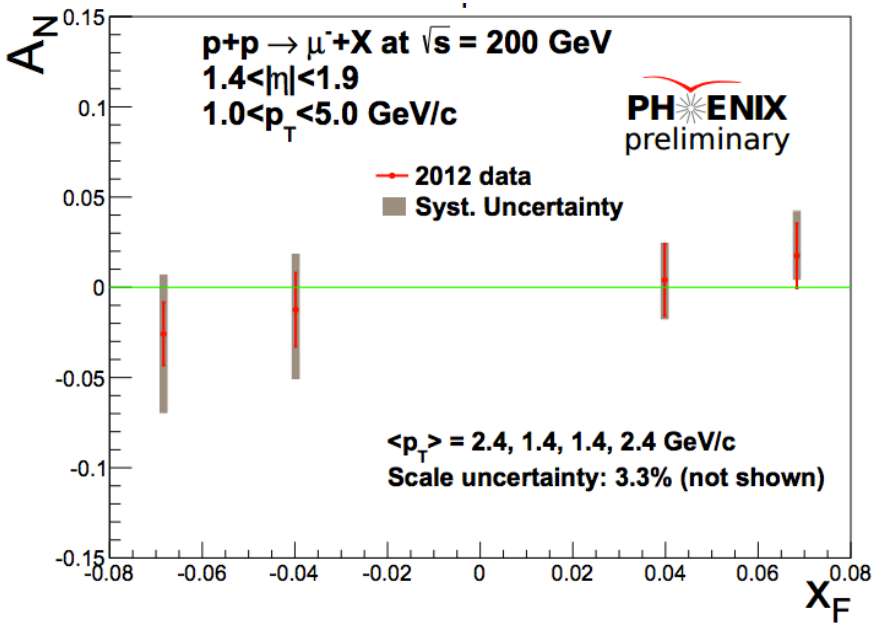
$$A_N^{Phys} = \frac{A_N^{incl} - r \cdot A_N^{BG}}{1 - r}$$

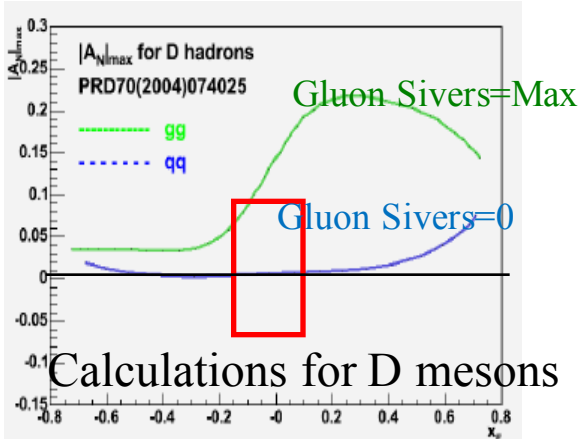
$$r = N^{BG}/N^{incl} = (N^{incl} - N^{signal})/N^{incl}$$

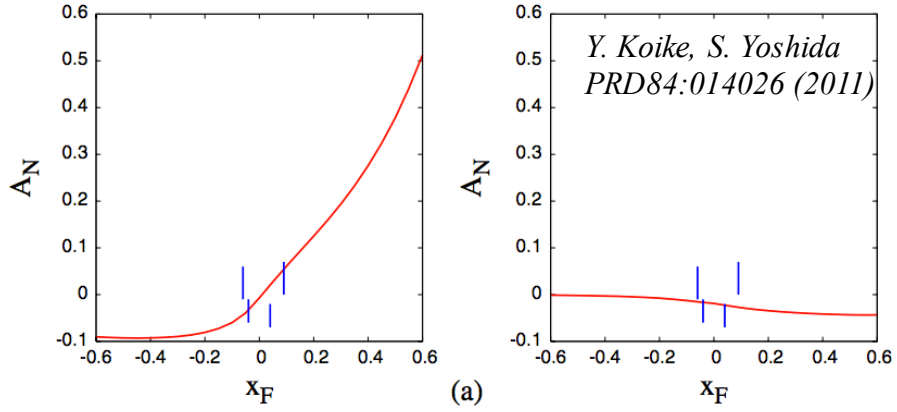
- A_N^{Incl} : Inclusive MUID gap4 tracks
- A_N^{BG} : Background (gap2,3 stopped hadron)
- ***r*** : non-distinguished background fraction in gap4 inclusive tracks
- Each A_N is calculated by Maximum Likelihood Method

Open Heavy Flavor A_N

- Both charges are studied for Run12 *p*+*p* 200 GeV, result will be released soon
- Run15 *p*+A 200 GeV analysis is ongoing







?

$$A_N(D) \neq A_N(\bar{D})$$

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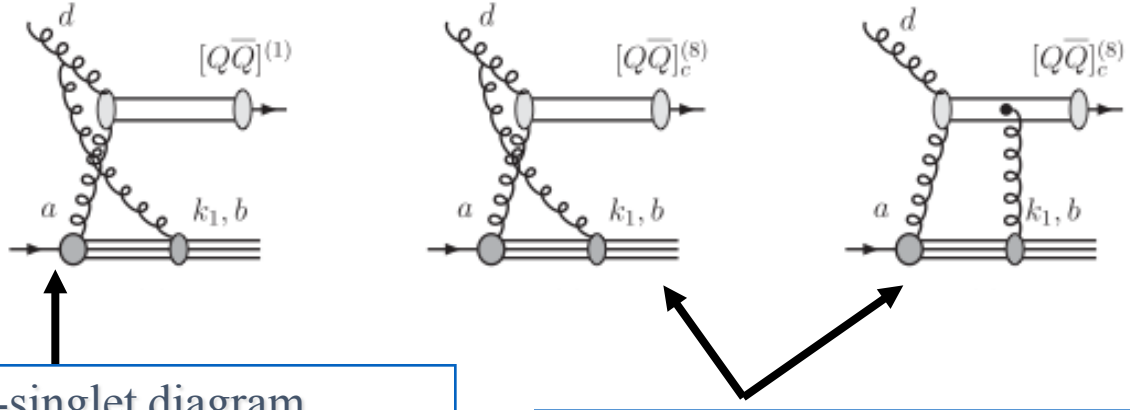
J/ψ A_N

- J/ψ A_N is sensitive to the production mechanisms
  - Assuming a non-zero gluon Sivers function, in pp scattering, J/ψ A_N vanishes if the pair are produced in a color-octet model but survives in the color-singlet model
  - *Feng Yuan, Phys. Rev D78, 014024(2008)*



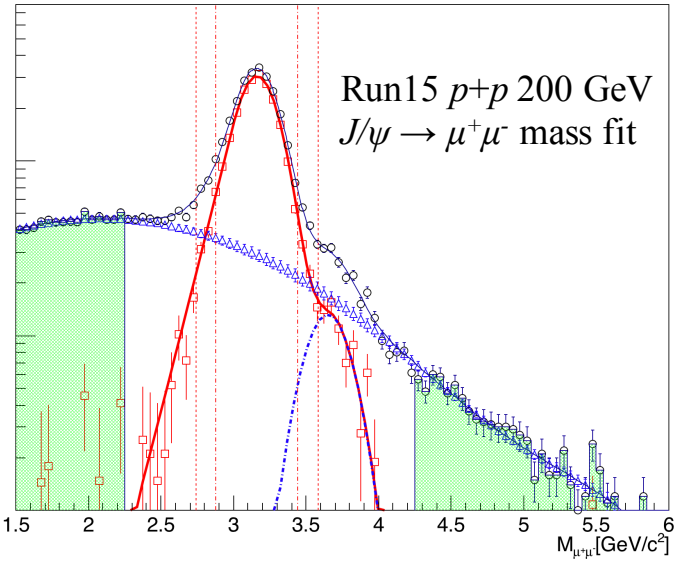
One color-singlet diagram
— no cancellation, asymmetry generated by the initial state interaction, $A_N \neq 0$

Two color-octet diagrams
— cancellation between initial and final state interactions, no asymmetry $A_N = 0$

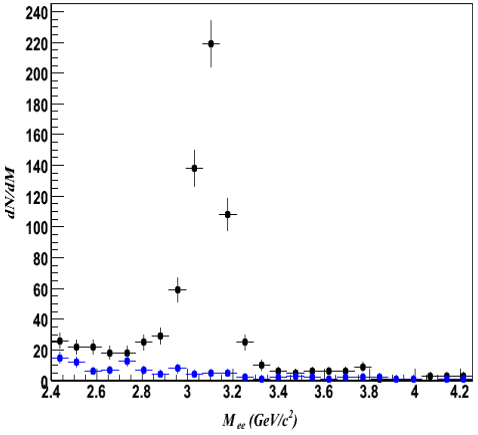
J/ψ A_N

- In Muon Arm ($J/\psi \rightarrow \mu^+\mu^-$)
  - A_N^{Incl} : oppositely-charged muon pairs in the invariant mass range ±2σ around J/ψ mass.
  - A_N^{BG} : oppositely-charged muon pairs in the invariant mass range 2.0<m<2.5 along with charged pairs of the same sign in invariant mass range 2.0<m<3.6 in p+p analysis

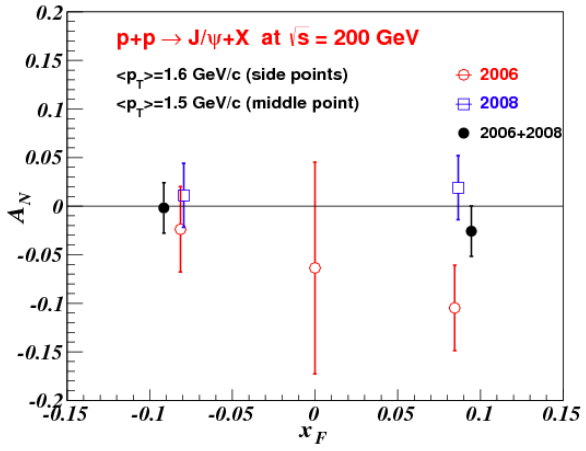
$$A_N^{J/\psi} = \frac{A_N^{Incl.} - r \cdot A_N^{BG}}{1 - r}$$



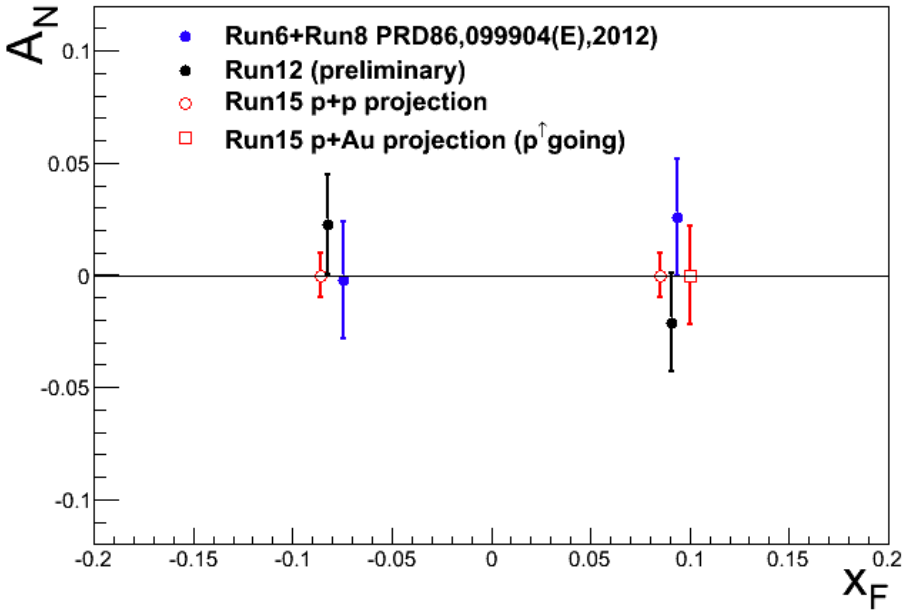
- In Central Arm ($J/\psi \rightarrow e^+e^-$)
  - A_N^{BG} : remaining continuum background is small, does not make a significant contribution



J/ψ A_N



Run	Luminosity	Pol
Run6	1.8 pb^{-1}	53%
Run8	4.5 pb^{-1}	45%
Run12	9.2 pb^{-1}	60%
Run15	50 pb^{-1}	60%



- The result is consistent with 0, statistical uncertainty is dominant
- We expect improved result from ongoing Run15 p+p analysis (>5x statistics) as well as J/ψ A_N result in Run15 $p^{\uparrow}$+A

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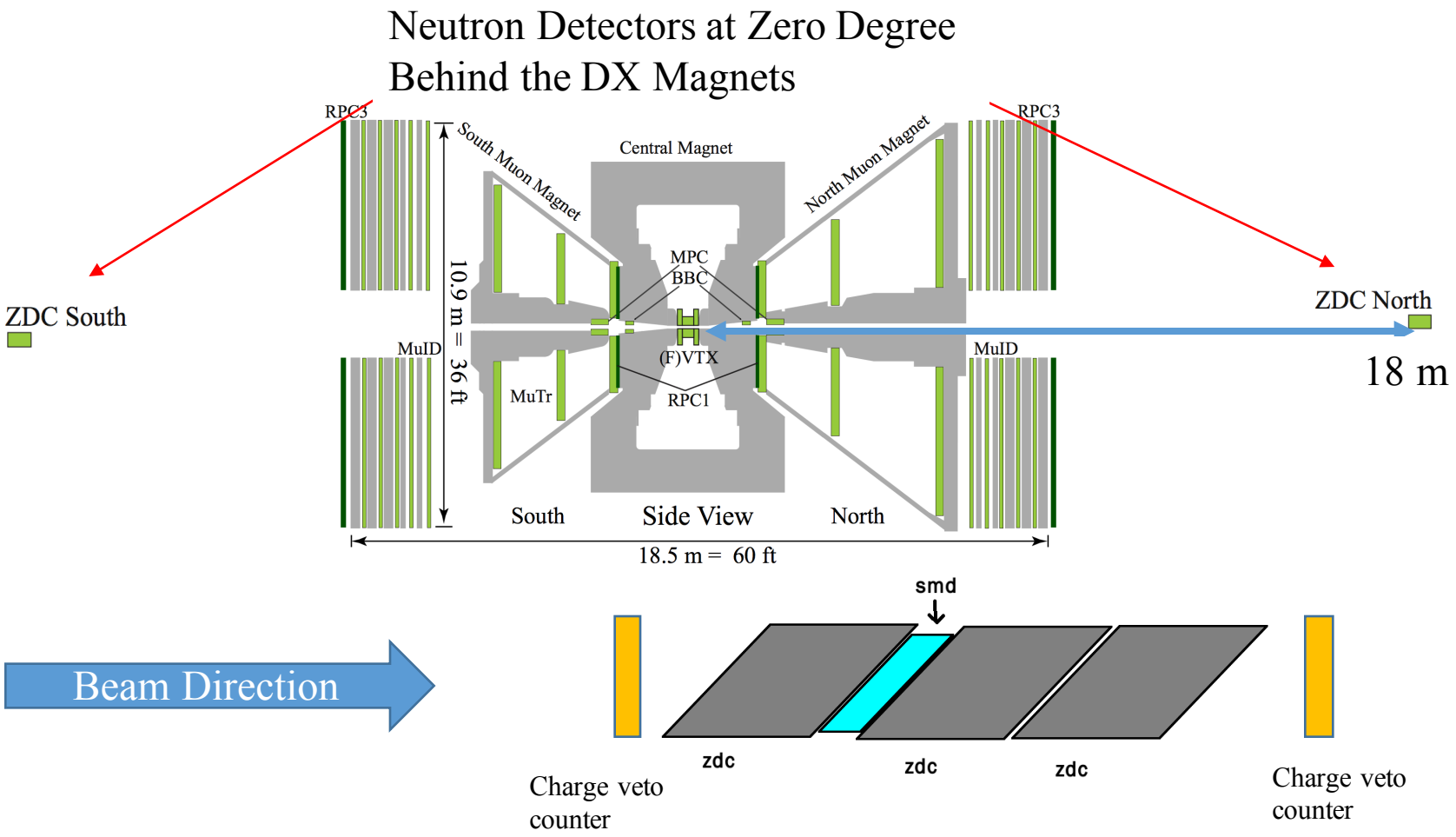
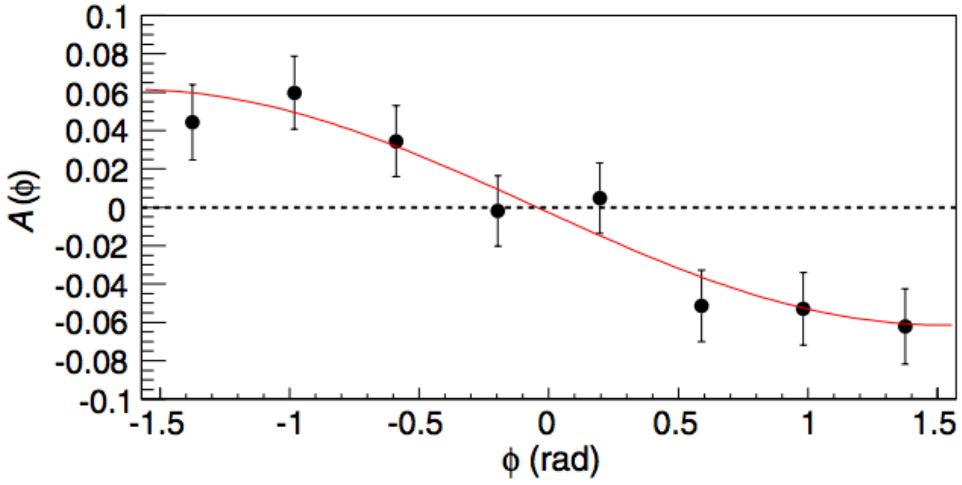
Forward neutron A_N

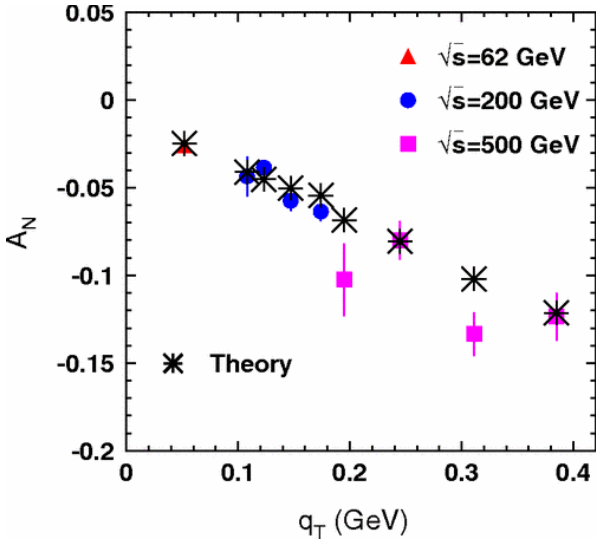


Forward Neutron A_N

PRD 88, 032006 (2013) PHENIX



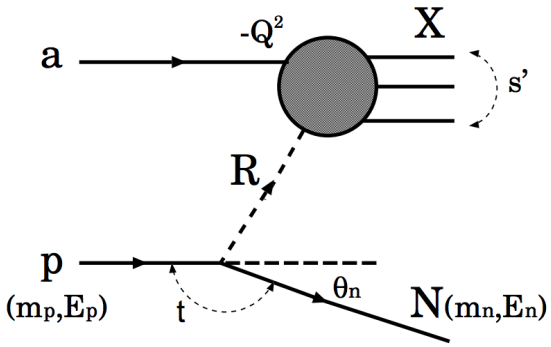
PRD 84, 114012 (2011) Kopeliovich et al.



- Large asymmetry not expected before the measurements
- Large forward neutron A_N discovered @ RHIC IP12 experiment (2002)
- Large forward neutron A_N measured @ PHENIX with dedicated neutron detectors (2006)
- pQCD is not applicable for p_T<0.22GeV at 200 GeV
- π-a_1 interference in Reggeon framework explains asymmetry result for p+p data well.

Origin of Nonzero A_N

$$A_N \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{\sum_X |< nX|T|\uparrow>|^2 - \sum_X |< nX|T|\downarrow>|^2}{\sum_X |< nX|T|\uparrow>|^2 + \sum_X |< nX|T|\downarrow>|^2}$$



$p^{\uparrow} + a \rightarrow n + X$

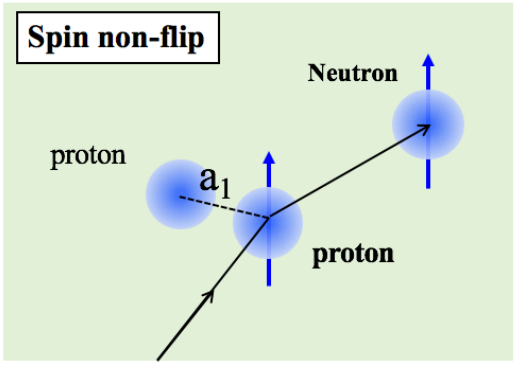
Reggeon exchange model

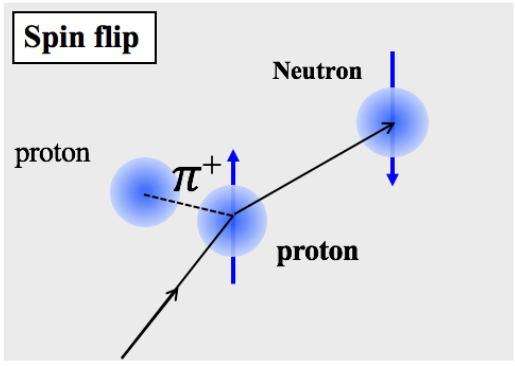
Using

$$|\uparrow> = \frac{1}{\sqrt{2}}(|+> + i|->) \quad \& \quad |\downarrow> = \frac{1}{\sqrt{2}}(|+> - i|->)$$

$$\sum_X |< nX|T|\uparrow>|^2 - \sum_X |< nX|T|\downarrow>|^2 =$$
$$\mathbf{-2Im\sum_X < nX|T|-><+|T^{+}|nX>}$$

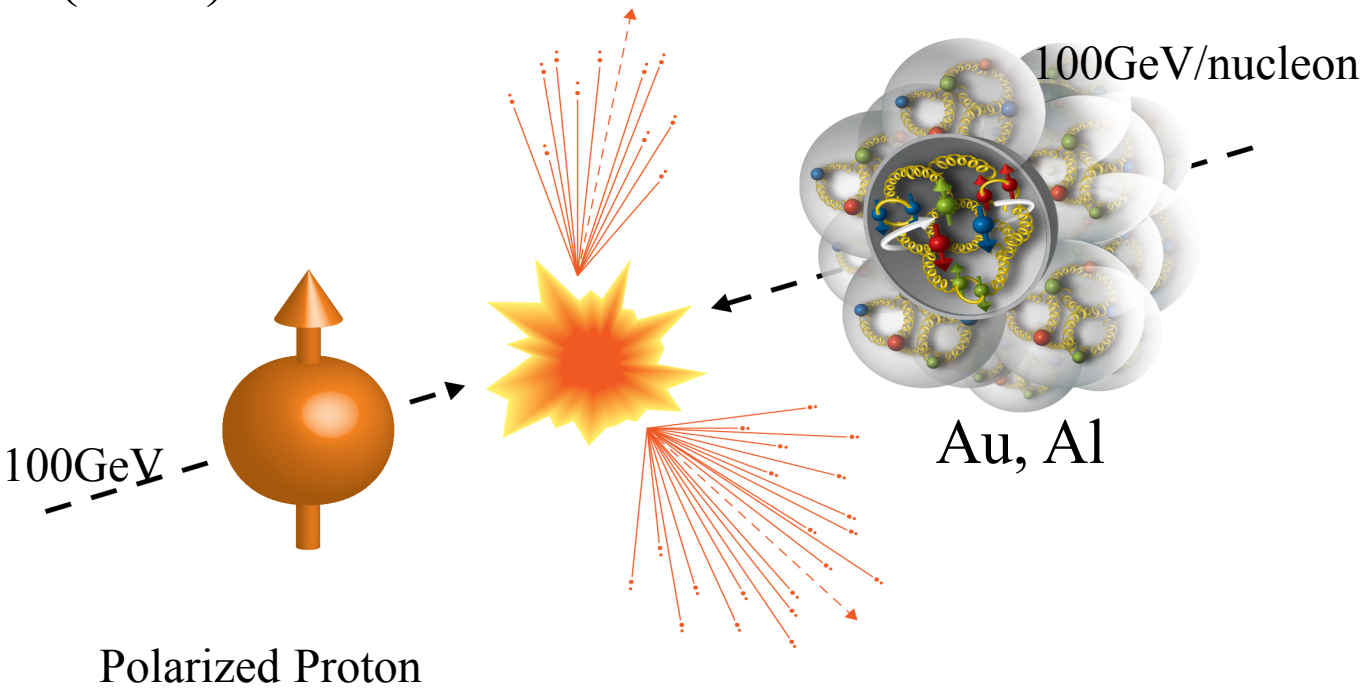
$A_N \neq 0$ if
Nonzero term for interference between spin-flip and nonflip interaction with different phase



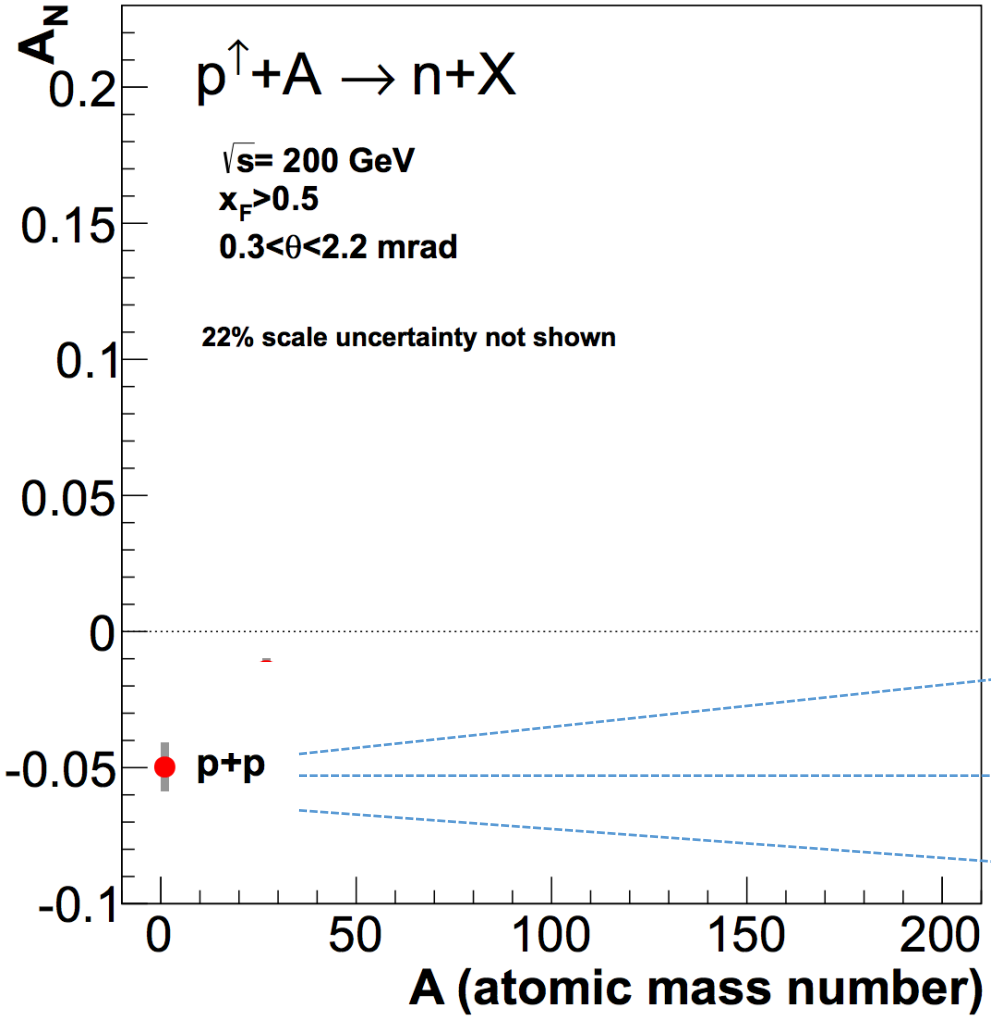


First Polarized *p*+*A* at RHIC

Run15 (2015)



A-dependent A_N (inclusive)



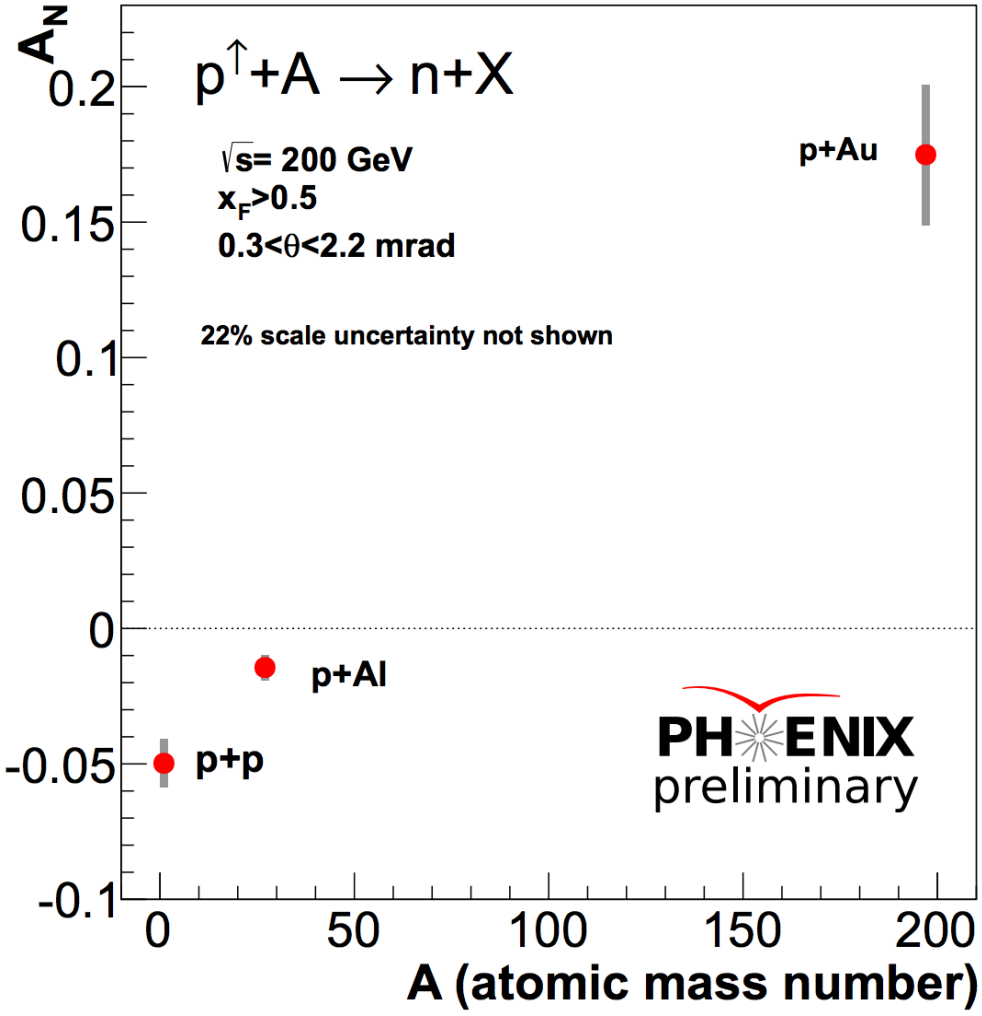
	# of proton	# of neutron
p	1	0
Al	13	14
Au	79	118

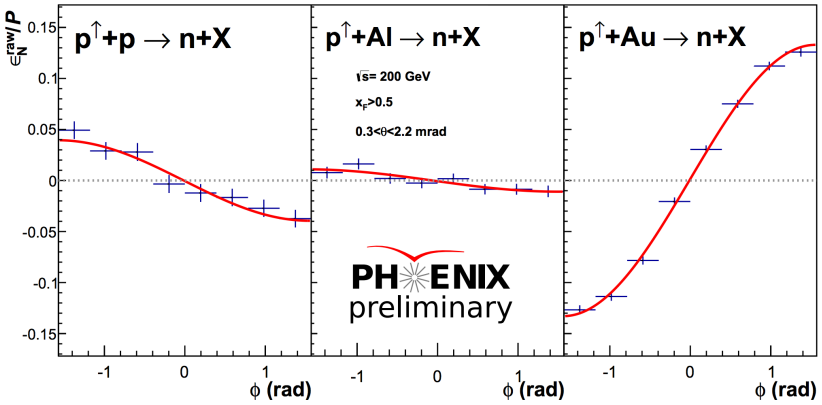
Present Framework (π-a_1 interference)

No A-dependence ?

Stronger gluonic field?

A-dependent A_N (inclusive)

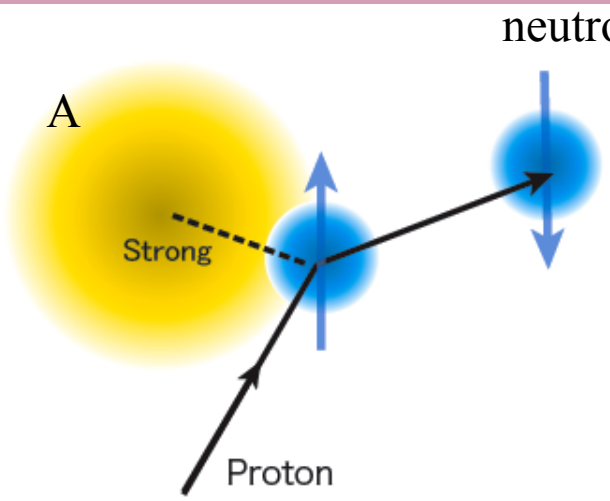


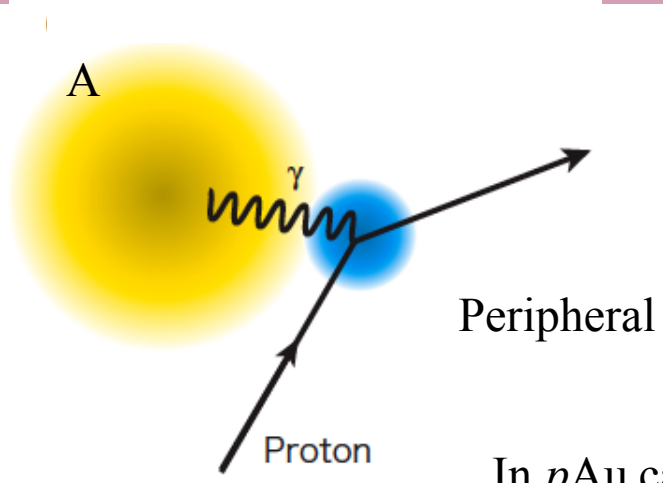


Analysis by Minjung Kim (SNU/RIKEN)

- Surprise — huge dependence on A
  - Even sign changes
- Simple π-a_1 interference predicts small dependence
- Mechanism? Why?

EM Ultra Peripheral Collision

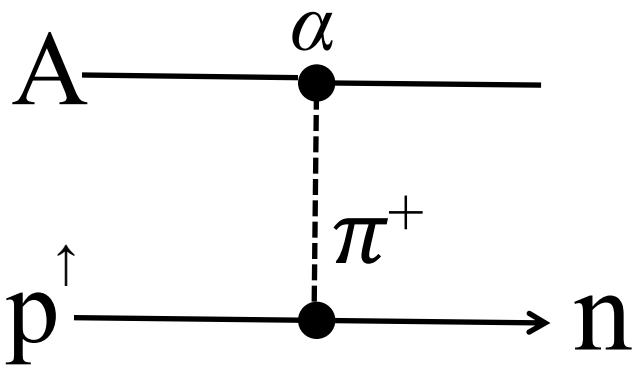


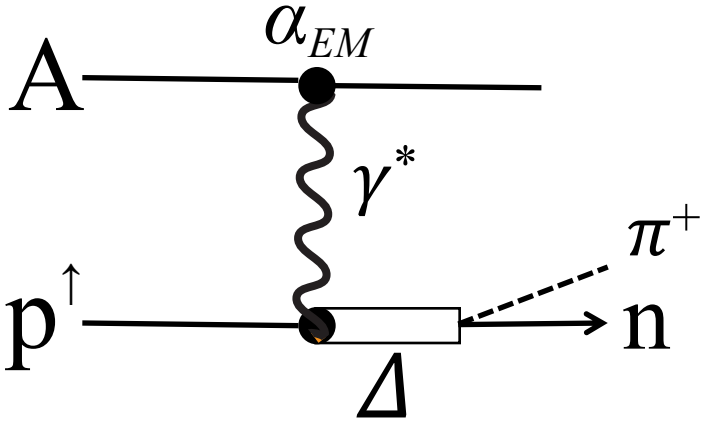


$t \rightarrow 0$

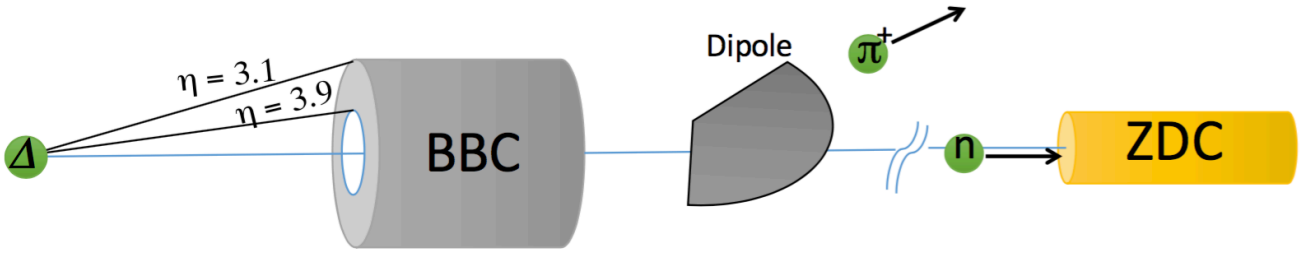
In pAu case

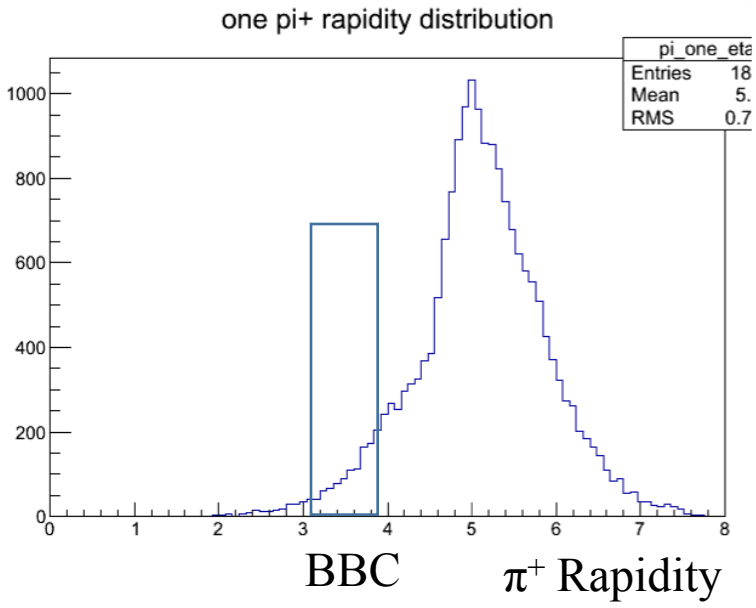
$Z^2 \bullet \alpha_{EM} \sim 79^2/137 \sim 45$





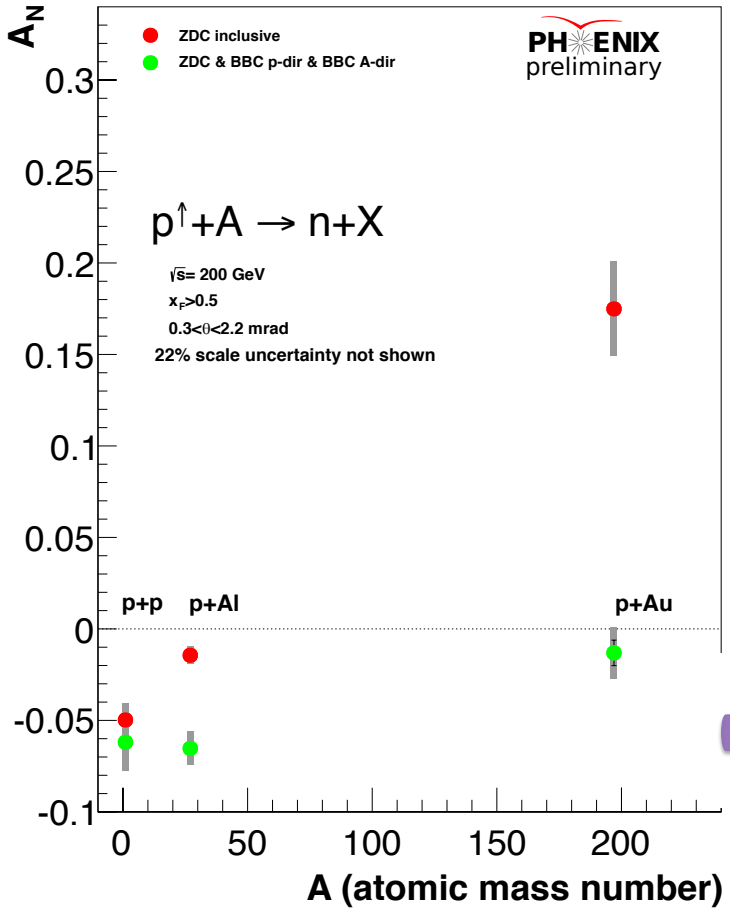
Identify UPC





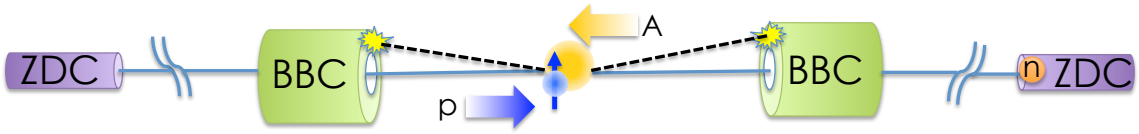
- π^+ via UPC process is substantially boosted towards the proton beam direction
- Most of π^+ from Δ decay go through BBC hole and will be swept away by the dipole magnet (DX).
- *Eur. Phys. J. C (2015) 75:614, Gaku Mitsuka*
- UPC (SOPHIA) Monte Carlo includes high N* states though Δ dominates

BBC Tagging



- Large A_N vanished in p+Au
- No sign flip in A_N
- A_N for p+p and p+Al are comparable

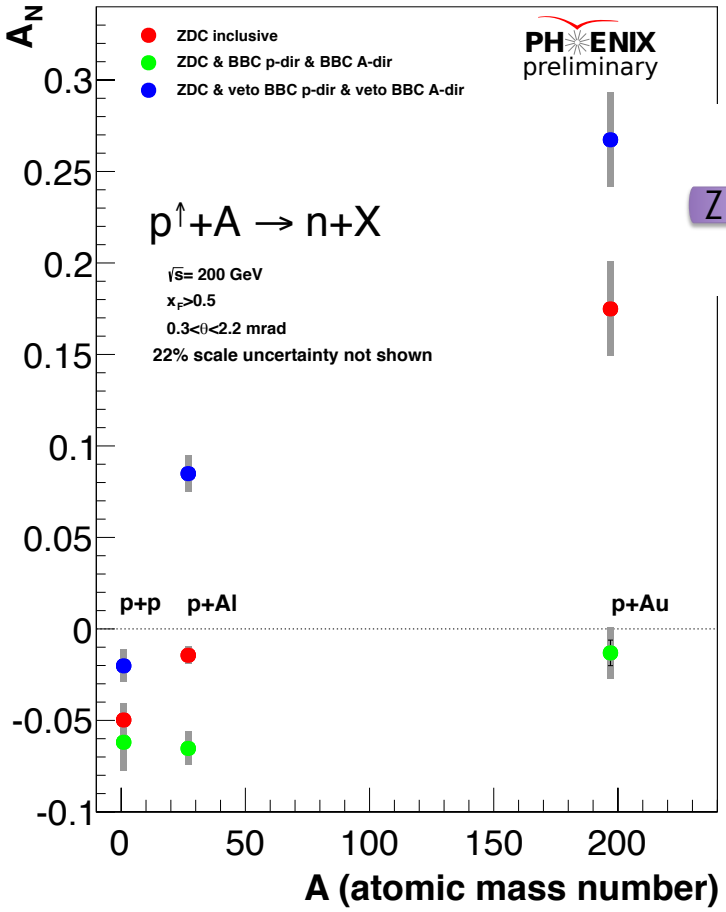
BBC Tagging



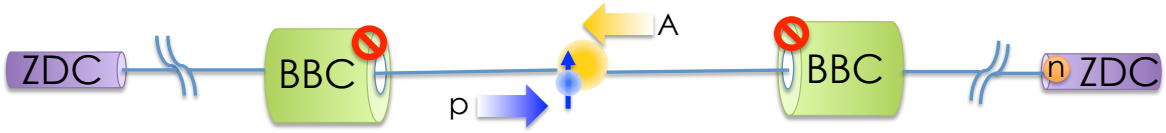
EM surpressed

$$A_N \sim had * had + had * EM + EM * had + EM * EM$$

BBC Vetoing



BBC Vetoing

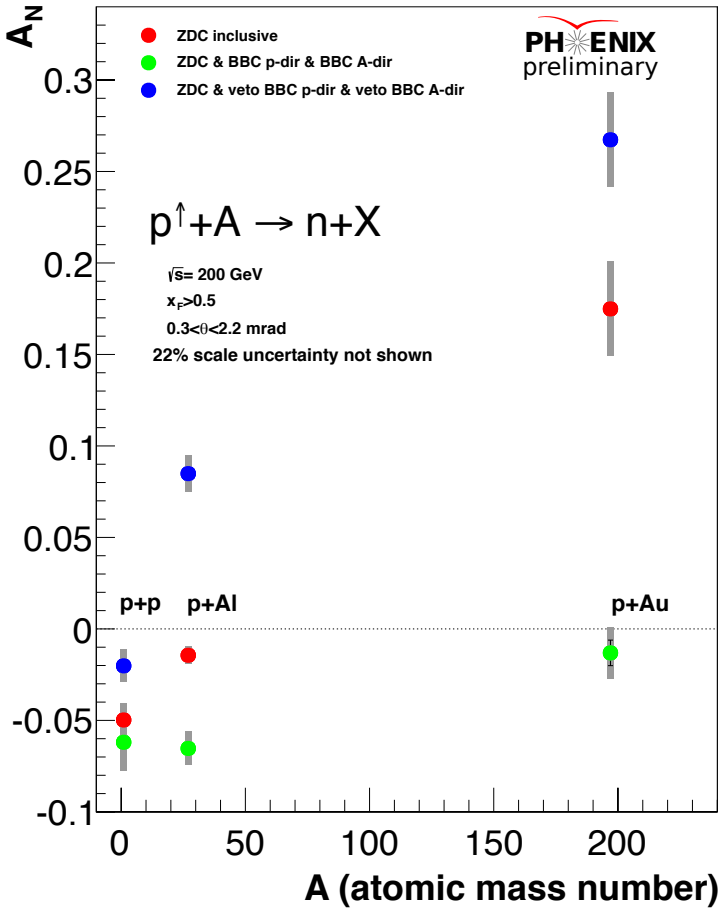


- Even larger $A_N \sim 0.28$ in p+Au
- Sign flip occurs between p+p and p+Al
- A_N for p+p gets even smaller ~ 0.02

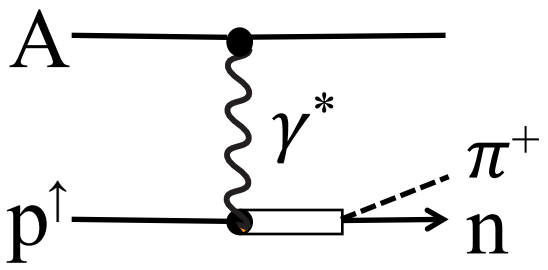
EM enhanced

$$A_N \sim had * had + \boxed{had * EM + EM * had + EM * EM}$$

BBC Tagging, Vetoing



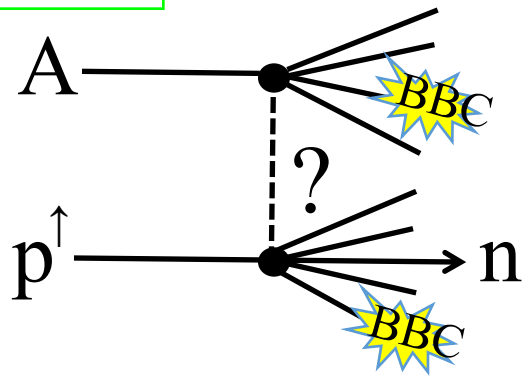
BBC Vetoing



$A_N > 0$

… but why?

BBC Tagging



$A_N < 0$

$$A_N \sim \boxed{had * had} + \boxed{had * EM + EM * had + EM * EM}$$

Summary

- PHENIX observed
  - mid/forward rapidity π^0, η showed similar A_N for π^0 *and* η, no collision energy dependence
  - J/ψ A_N is sensitive to production mechanism, expect improved statistics in Run15 data as well as first p+A result
  - Open heavy flavor measurement, both charges are studied for Run12 p+p 200 GeV, result will be released soon. p+A analysis is ongoing
- Forward Neutron - First p+A result in PHENIX
  - strong A-dependence large forward neutron A_N observed in forward neutron measurement
  - A_N changes sign from p+p to p+Au, A_N magnitude increases by factor of ~3 from p+p to p+Au
  - A_N behaved quite differently by enhancing/suppressing UPC like events (BBC correlation)
  - The A_N result is unexpected from current theory. Theoretical development is ongoing

Thank you !