Overview of transverse spin physics in the PHENIX experiment

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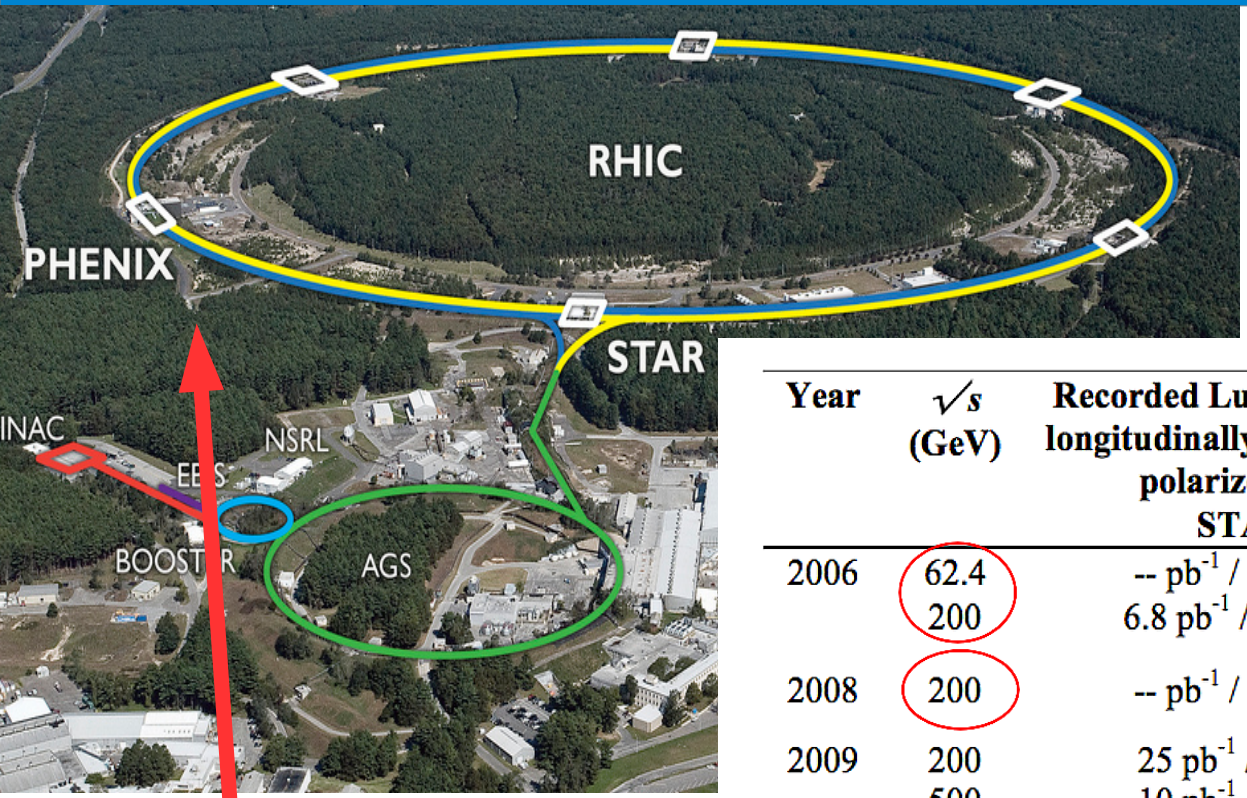
on behalf of the PHENIX collaboration.

Deep Inelastic Scattering Conference, April 3 – 7, 2017, Birmingham, UK.

The PHENIX experiment at RHIC and runs with polarized proton beam



View of the Brookhaven National Laboratory, NY, USA

PHENIX experimental Hall

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

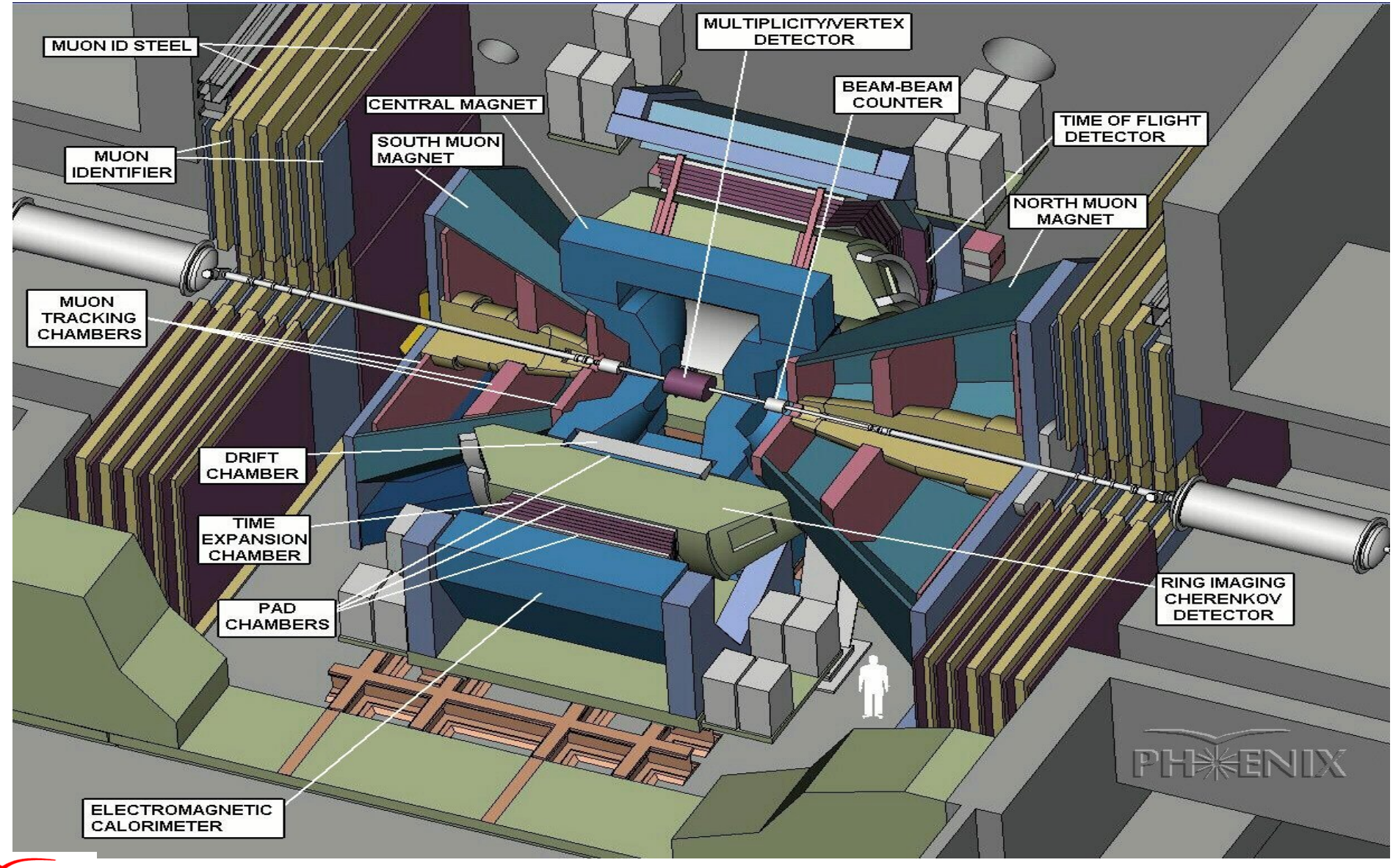
Run 2015 : for the first time, polarized p+A collisions.

PHENIX spectrometer, cut view

Mid rapidity, central arm: |η| < 0.35 => charged hadrons with PID, π°, η...

Forward rapidity, muon arms: 1.2 < |η| < 2.4 => charged hadrons, muons, J/ψ...

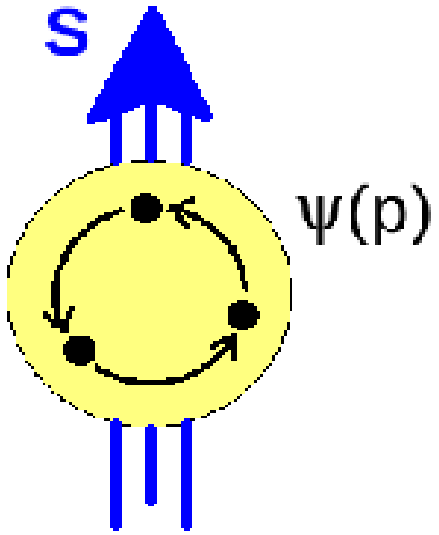
Forward rapidity, muon Piston Calorimeters: 3.1 < |η| < 3.9 => π°, η



Transverse spin physics and non zero asymmetry effects

Goal: transverse structure of the nucleon with transverse spin asymmetries.
Single transverse spin asymmetry A_N in p+p (A) collisions could be induced by:

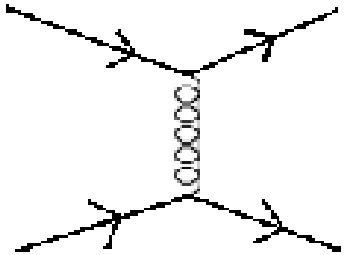
Sivers Effect



Polarized hadron generates asymmetric PDF

Coupling of quark orbital motion to nucleon spin. Initial state effect in hadron-hadron collisions.

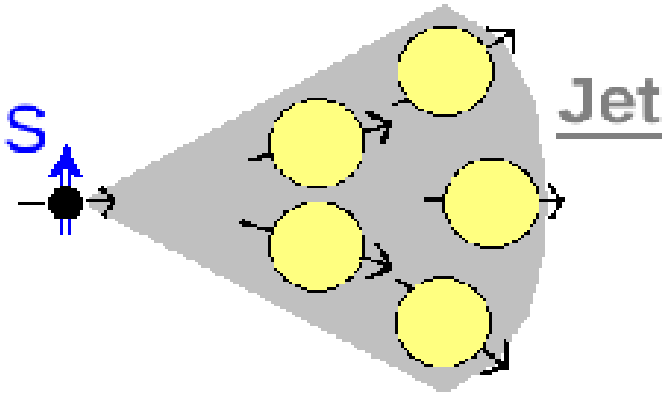
Interaction Effects



Parton-level asymmetric scattering

Gluon exchanges, Initial and final state q+g and g+g coupling.

Collins Effect



Polarized parton undergoes asymmetric fragmentation

Fragmentation of polarized quarks in polarized nucleon into hadrons. Final state effect.

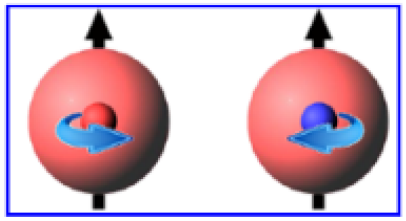
Fig. : Y. Kovchegov, et al. Phys.Rev. D86 (2012) 034028

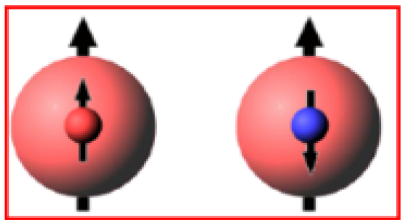
Transverse Momentum Distributions versus Collinear factorization framework: low / high p_T approach

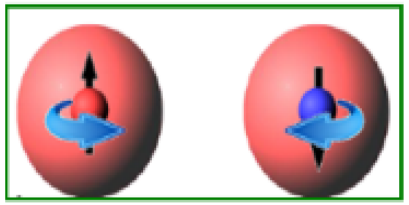
Transverse Momentum Distributions – k_T dependent approach

Transversity h_1: quark and nucleon spin correlation

=> transversity * Collins fragmentation effect : quark spin and hadron k_T correlation



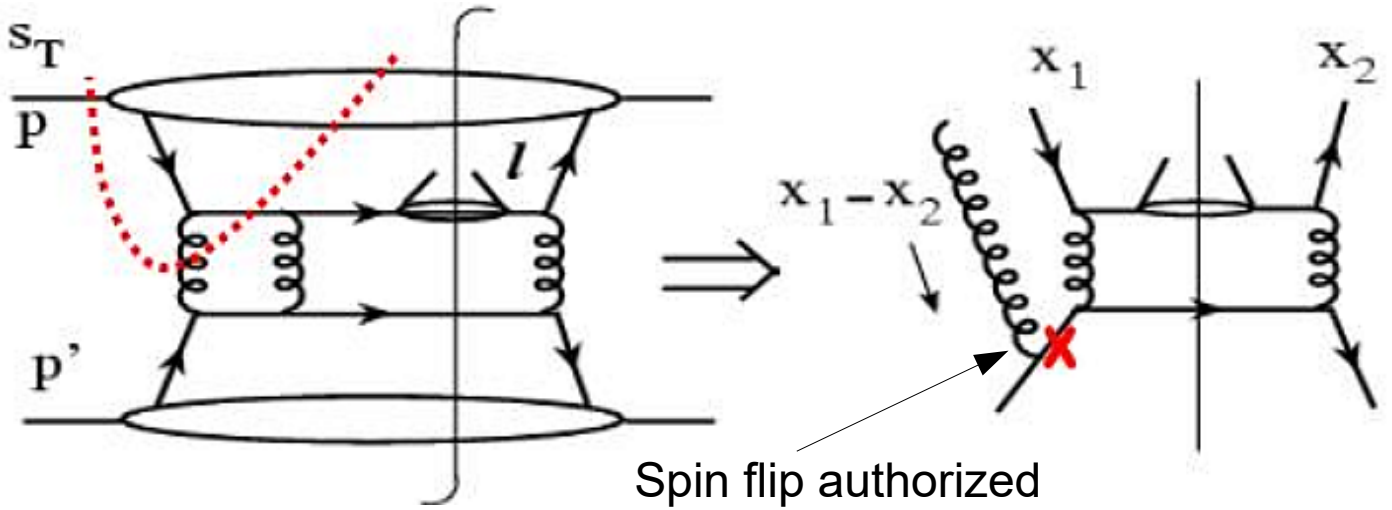




Sivers $f_{1T}^{\perp}$: correlation between proton transverse spin and non zero transverse momentum of quarks

Boer-Mulders $h_1^{\perp}$: correlation between quarks transverse spin and their non-zero momentum k_T

Twist 3 multiparton correlation functions and fragmentation functions correspond to initial and final state interactions and correspond to k_T moments of integrals of TMDs.

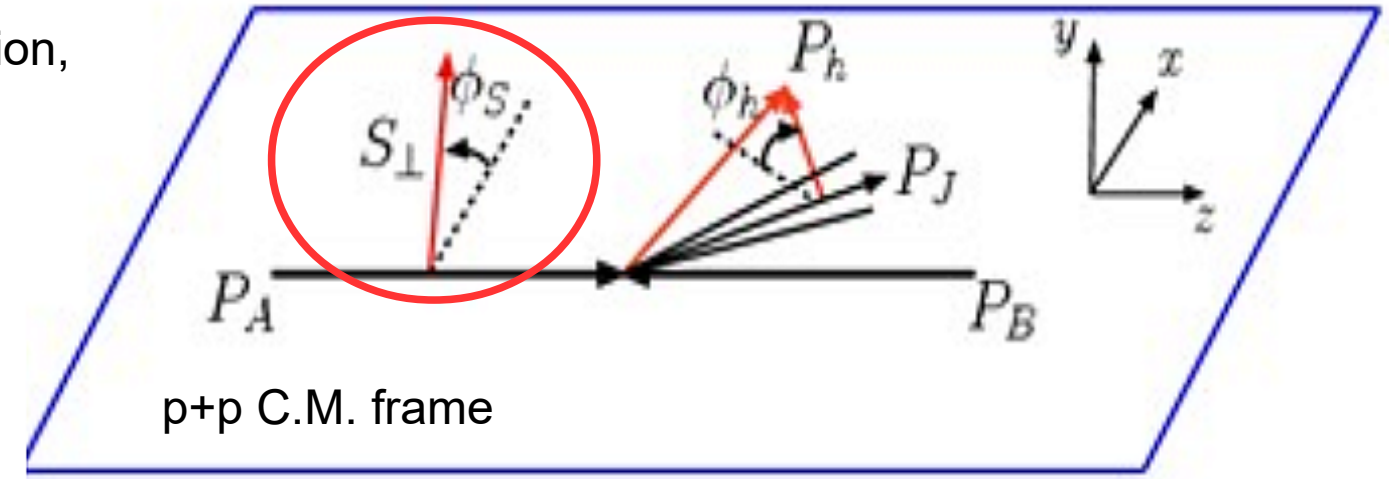


Diagrams:
J.Qiu talk at BNL, 2005

Higher twist effect and gg + gq correlations must be dominant at RHIC energies

Azimuthal dependences in p+p collisions and observables

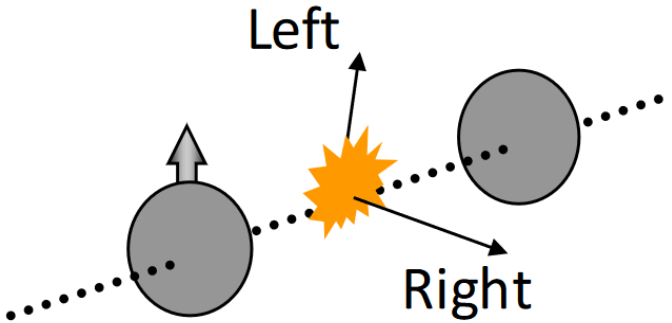
Scheme of p+p collision,
Φ_s = spin angle.



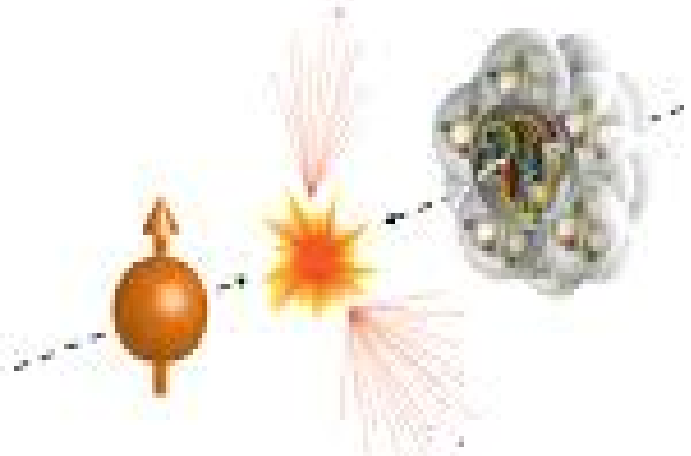
What we are measuring:
Transversely polarized
Single Spin Asymmetry

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

$p^{\uparrow}$+p collisions



$p^{\uparrow}$+A collisions



Azimuthal dependence of unpolarized and polarized cross sections and spin asymmetries comes from non zero quark transverse momentum k_T and nucleon spin

Recent PHENIX results with transversely polarized beam

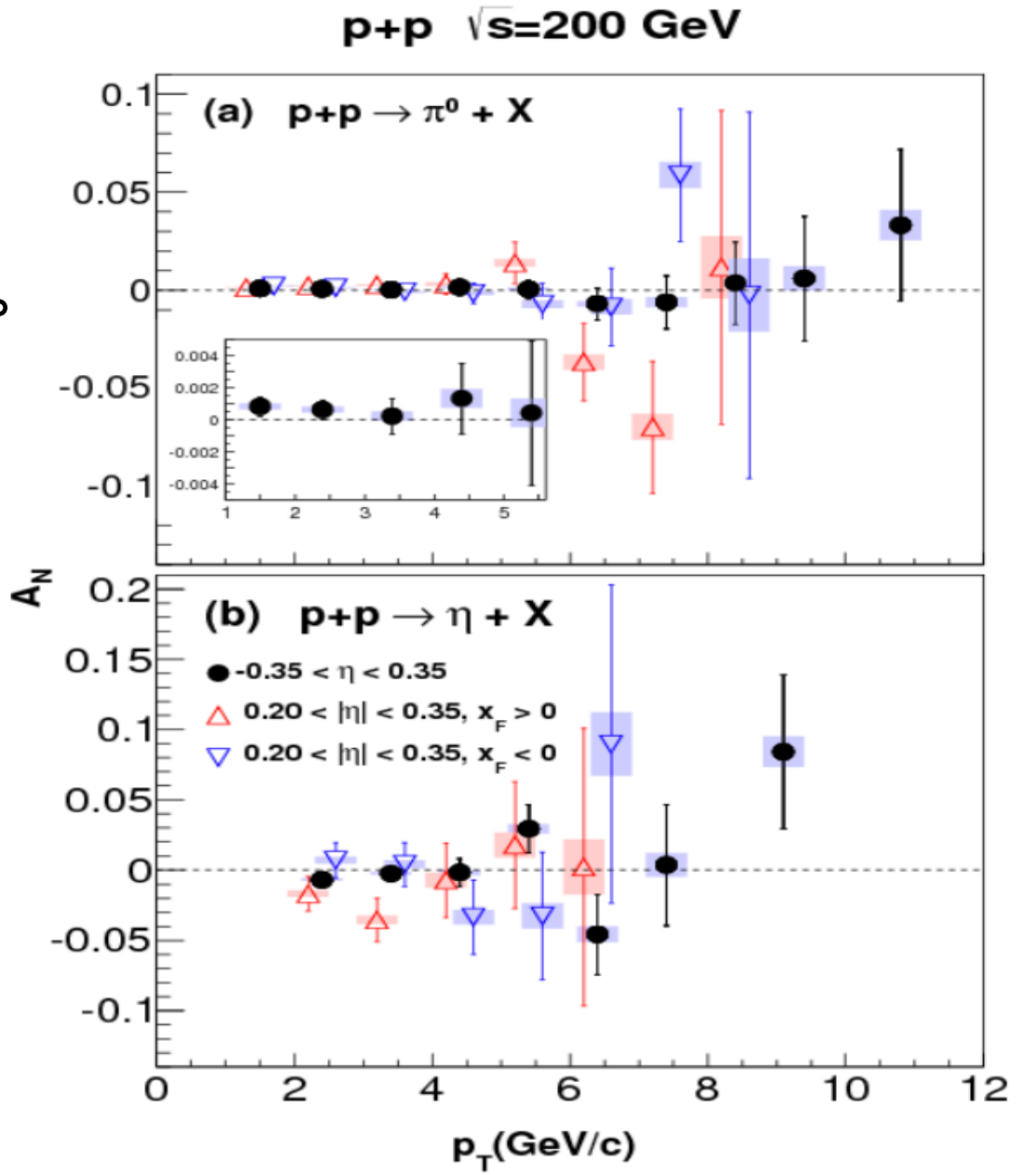
1) Transverse spin asymmetry in light hadrons production: inclusive π° and η mesons production at mid- and forward- rapidity in p+p collisions, and nuclear dependences in p+A collisions.

2) Transverse spin asymmetry in open heavy flavor production: inclusive D-mesons production (dominant) at forward rapidity in p+p collisions.

3) Transverse spin asymmetry in inclusive J/ψ production at forward rapidity in p+p collisions.

4) Transverse spin asymmetry in neutron production and nuclear dependences: see Gaku Mitsuka presentation later in this session.

1) Transverse spin asymmetry in light hadrons production : π° and η



π°

η

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

Mid-rapidity: |η| < 0.35

π° and η A_N in p+p at 200 GeV

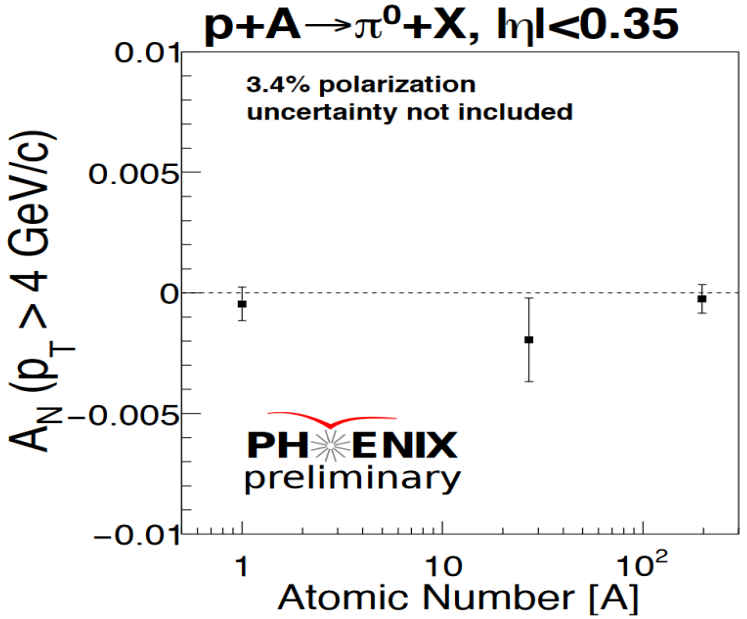
A_N were found consistent with zero for the whole p_T range in p+p collisions within statistic uncertainties.

Nuclear dependence at mid-rapidity of A_N (π^0)

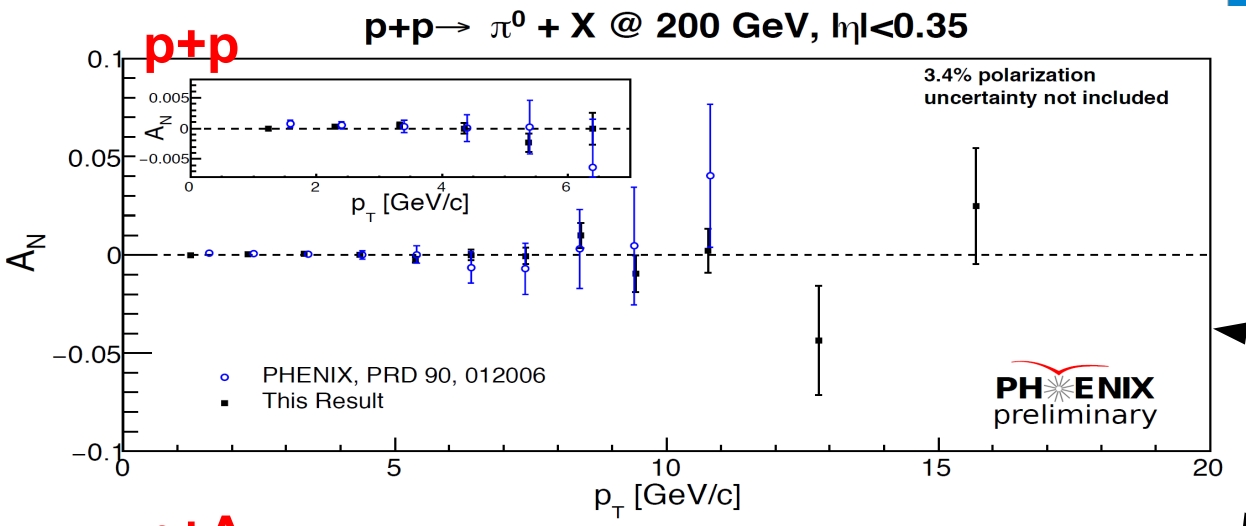
p+Au and p+Al collisions

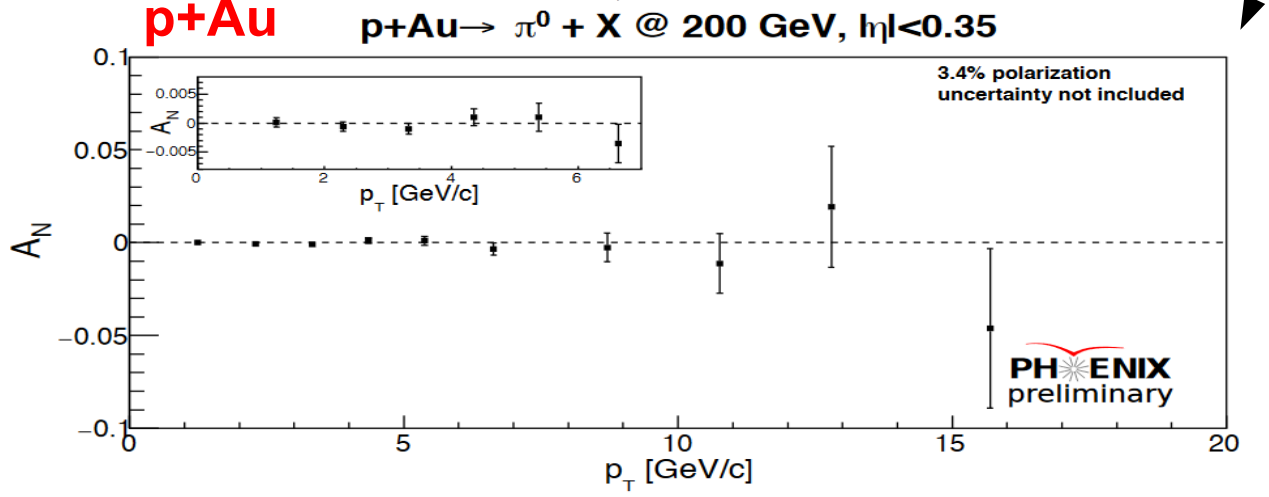
A_N versus p_T for p+p, p+Au, p+Al

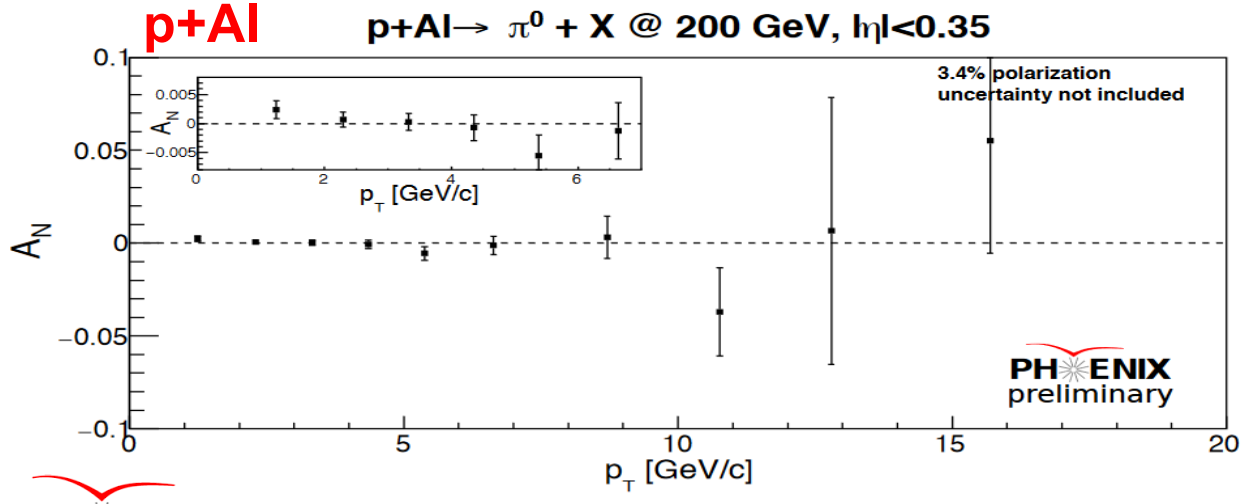
A_N integrated over p_T as a function of A :



Results are consistent with zero asymmetry for p+p, p+Au and p+Al collisions, and no quantifiable nuclear dependence.



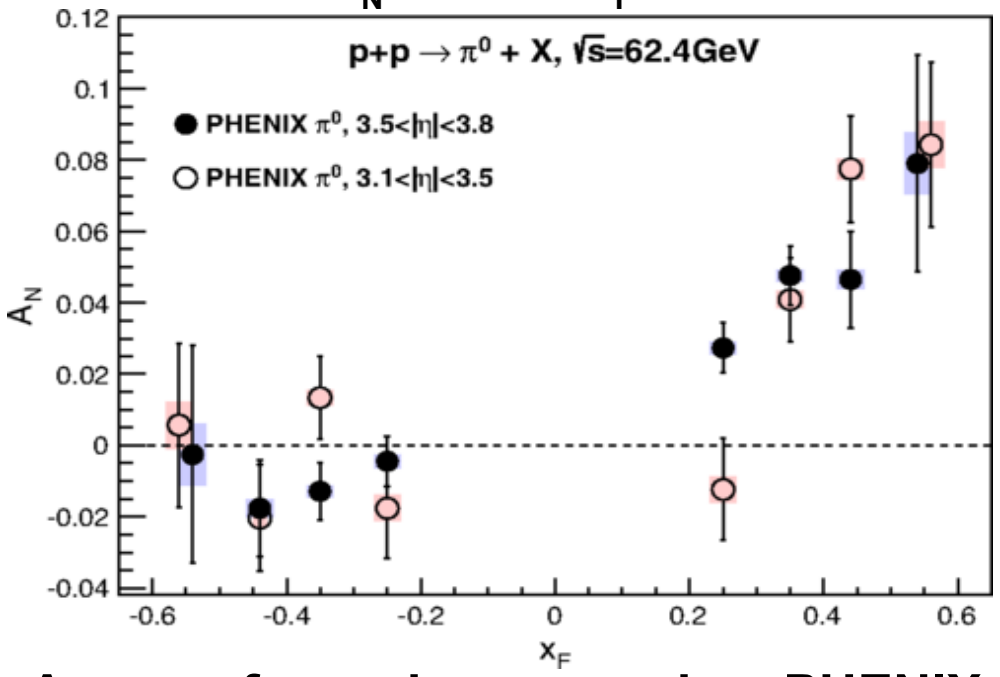




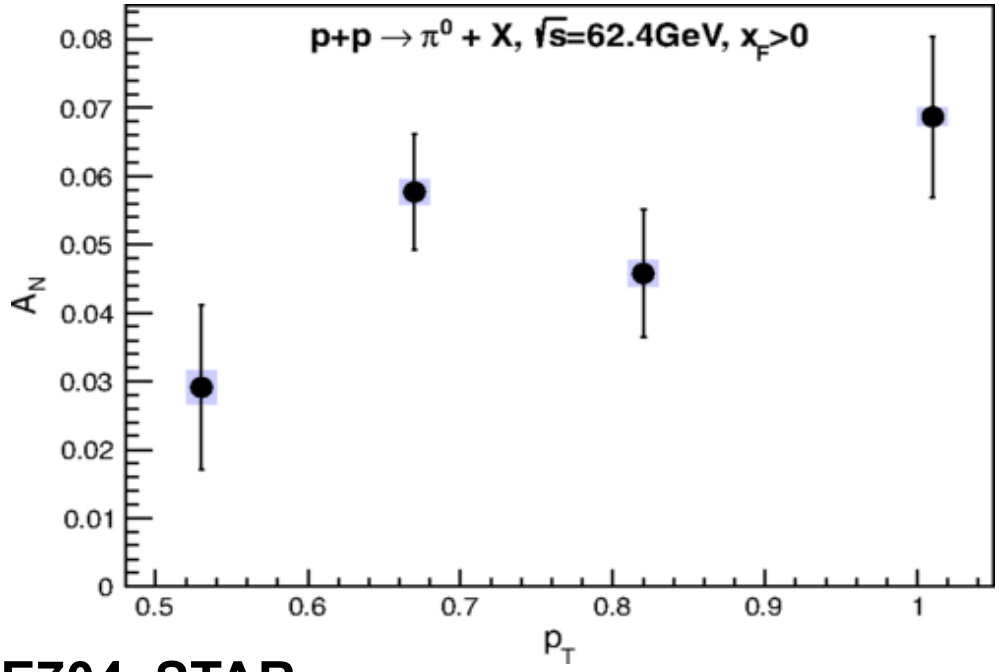
1) Transverse spin asymmetry in light hadrons production : π° and η

π° at forward rapidity

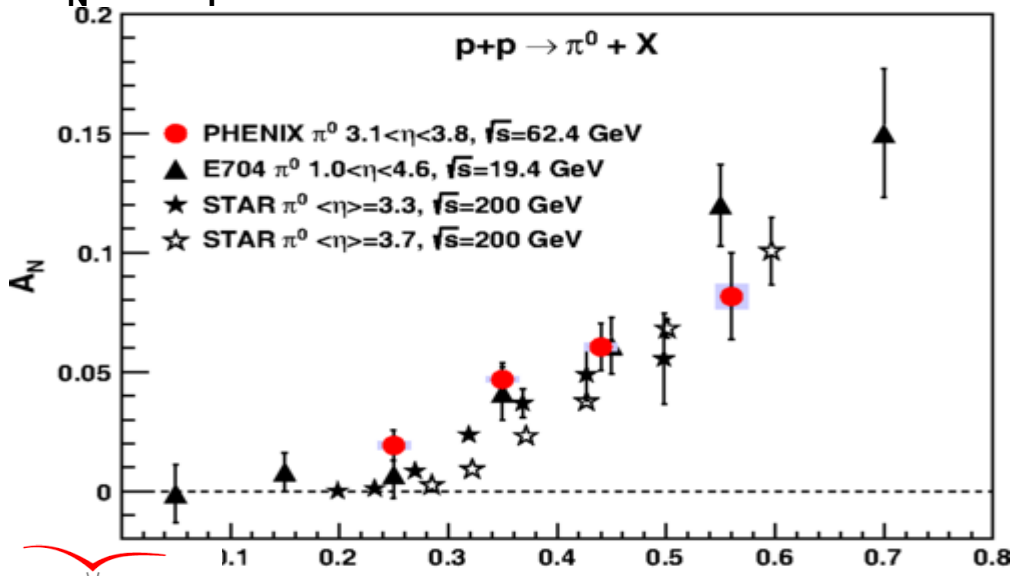
A_N versus x_F



Integrated forward A_N versus p_T



A_N vs x_F for various energies: PHENIX, E704, STAR



Unexpected large A_N at PHENIX energy!

- Large asymmetries measured at forward rapidity, while zero at mid- (last slide) and backward rapidity.

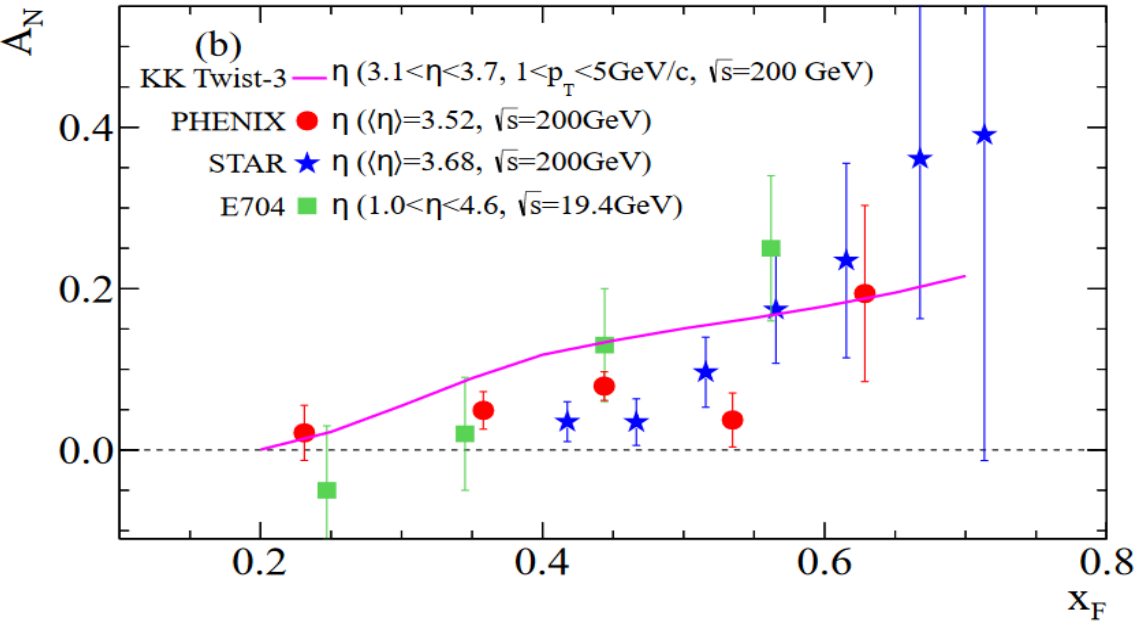
- weak energy dependence

- tend to increase with $x_F > 0$ and p_T

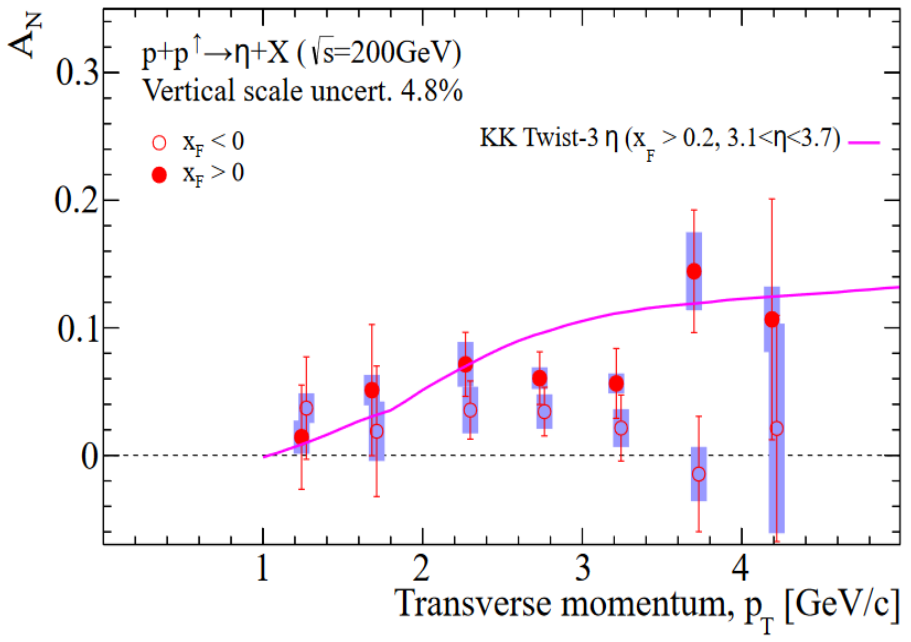
Phys. Rev. D 90, 012006 (2014)

1) Transverse spin asymmetry in light hadrons production : π° and η
η at forward rapidity

A_N vs x_F various energies, PHENIX, STAR, E704



A_N versus p_T



Large asymmetry at forward rapidity in both π° and η production, at same level.

Pink fit: twist-3 calculations using quark-gluon correlation functions

PhysRevD.90.072008 (2015)

2) Open heavy flavor transverse spin asymmetry

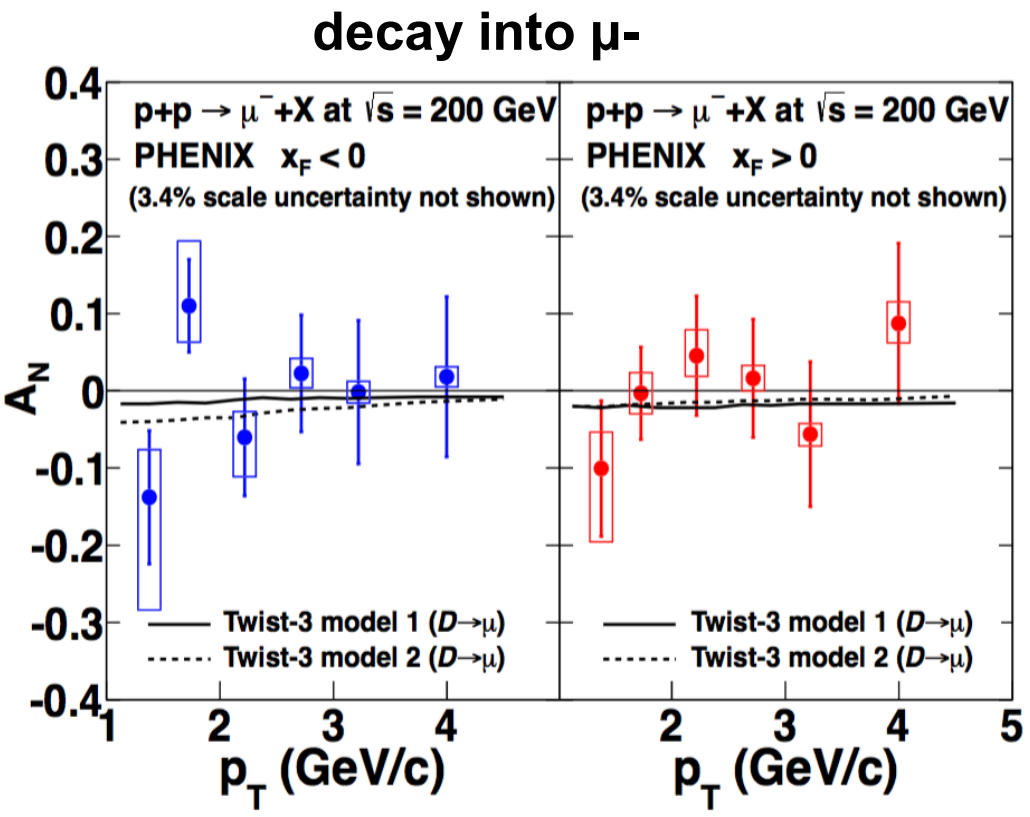
Dominated by gluon-gluon interactions

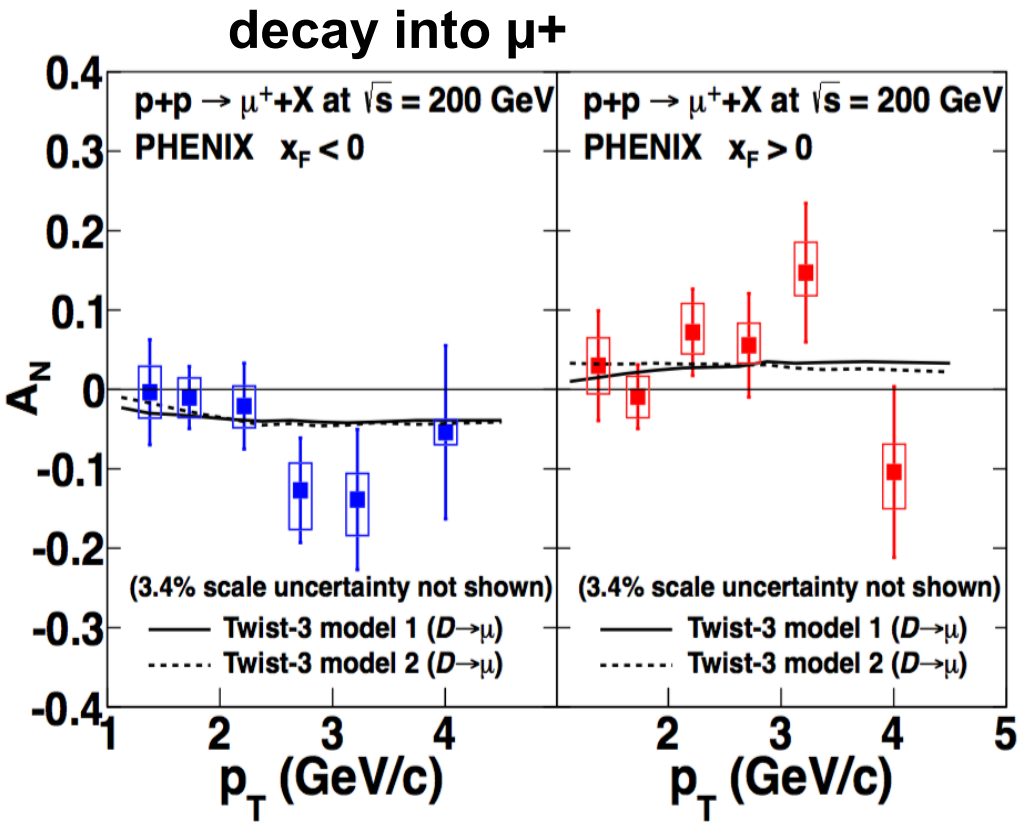
Collinear factorization approach : production dominated by tri-gluon correlation

Sensitive to gluon Sivers function, as moment related to correlation function
(see btw Kang et al, Phys.Rev.D83:094001,2011)

=> non zero asymmetry would be expected from initial state effect in case gluon function is large

2) Open heavy flavor transverse spin asymmetry (vs pT)





- Main contribution to single muons: D-meson decay (~ 60% to 92% at lower p_T)

- Decay into μ+ and μ- comparison

- Results consistent with zero within uncertainties

- Model predictions at twist 3 within collinear factorization framework consistent with measurement. Original calculations for D meson translated to single μ decay.

Twist 3 model: Y. Koike, S. Yoshida, PRD84:014021 (2011)

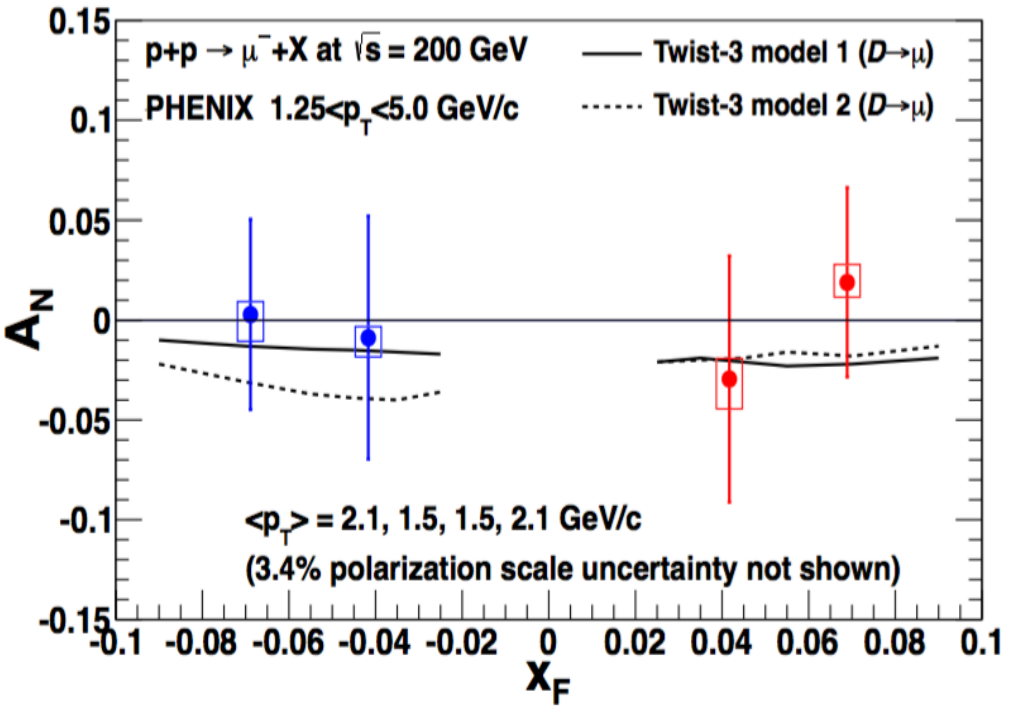
AN calculations for D mesons provided by S. Yoshida.

New result !

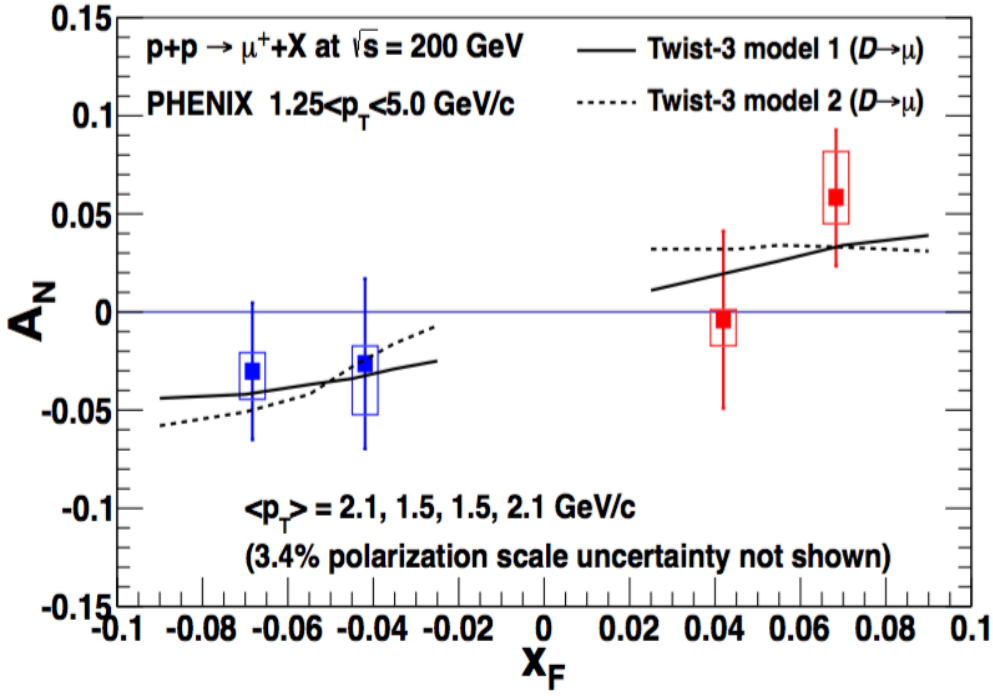
arXiv:1703.09333

2) Open heavy flavor transverse spin asymmetry (vs xF)

decay into μ-



decay into μ+



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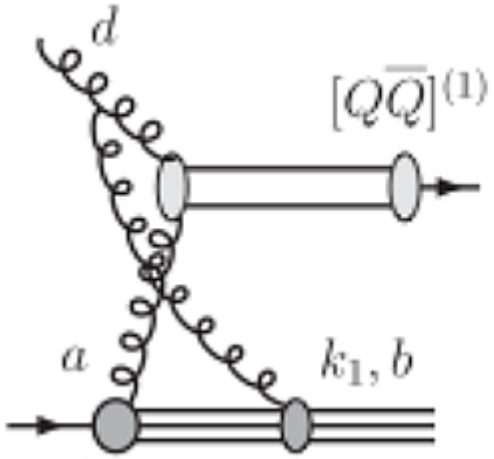
3) Transverse spin asymmetry in inclusive J/ψ production

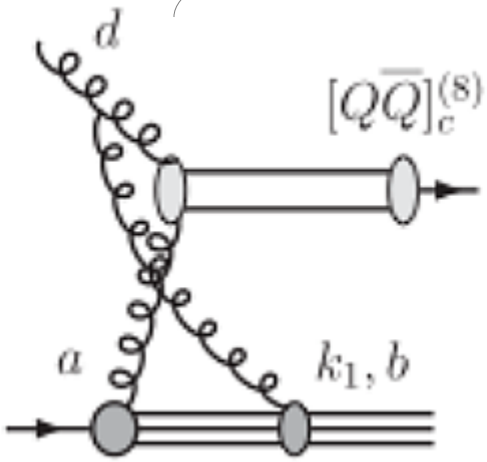
Sensitive to production mechanism: only color singlet produce non zero A_N

Color singlet

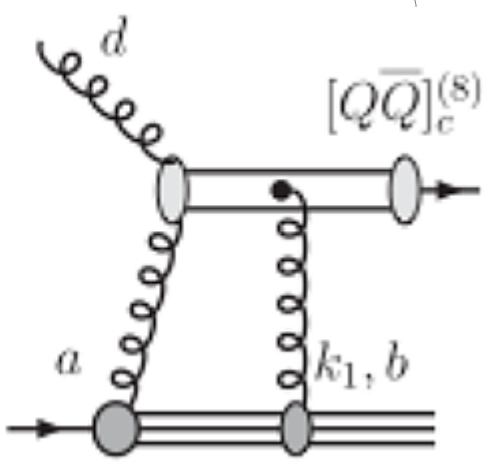


Initial state interaction

Color octet



Initial state interaction



Final state interaction

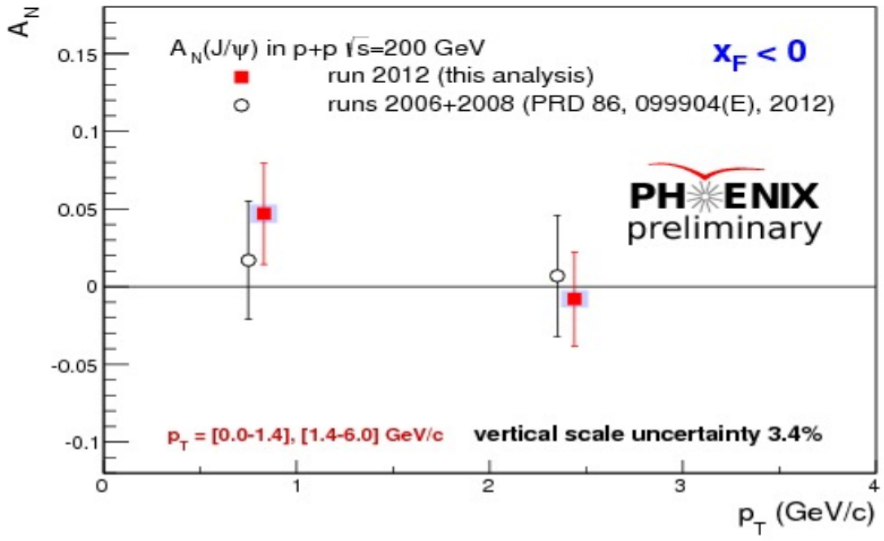
Comparison :

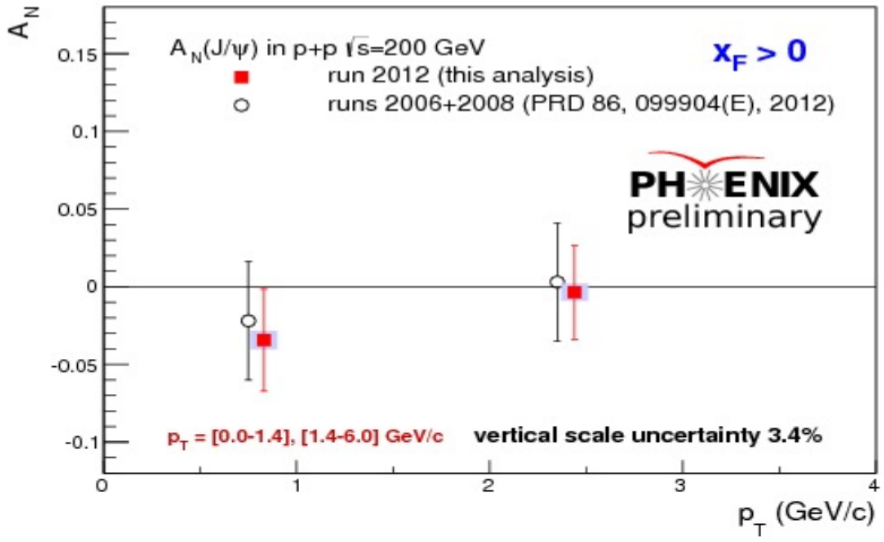
4 data sets, last one in 2015 with x5 improved luminosity

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%

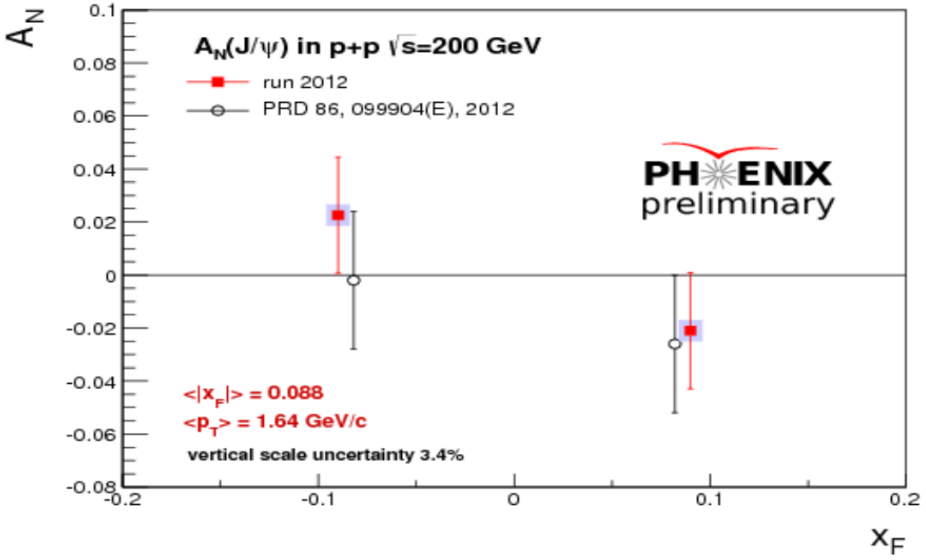
3) Transverse spin asymmetry in inclusive J/ψ production in p+p

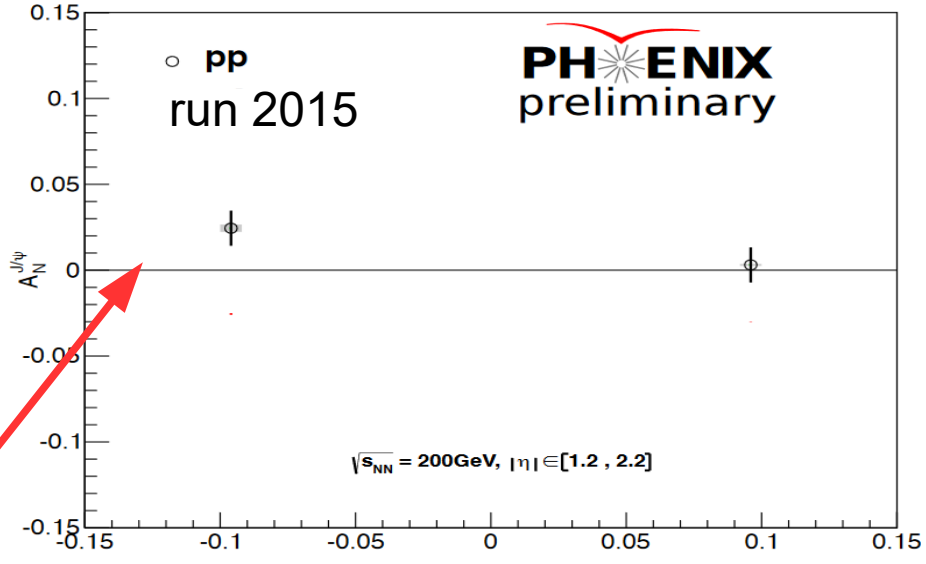
A_N versus pT, 2006+2008 and 2012 data





A_N vs xF, 2006+2008, 2012 (top) 2015 (bottom)





Run 2015: x5 statistics compared to all other sets. Small stat. errors

A_N consistent with 0 within stat. uncertainties

Phys. Rev. D 82, 112008 (2010)

Summary and Perspectives

Transverse spin asymmetries in light hadron production

- Measured from inclusive π° and η production in p+p and recently in p+A,
- Asymmetries are found compatible with zero at mid-rapidity, and no significant nuclear dependence is measured,
- Large asymmetries at forward rapidity: unexpected at PHENIX energy,
- Forward asymmetries are well described by twist 3 models.

Transverse spin asymmetries in heavy quarks production

- Open heavy flavor (D-mesons): compatible with zero within uncertainties,
- J/Ψ: compatible with zero within uncertainties.

Perspectives

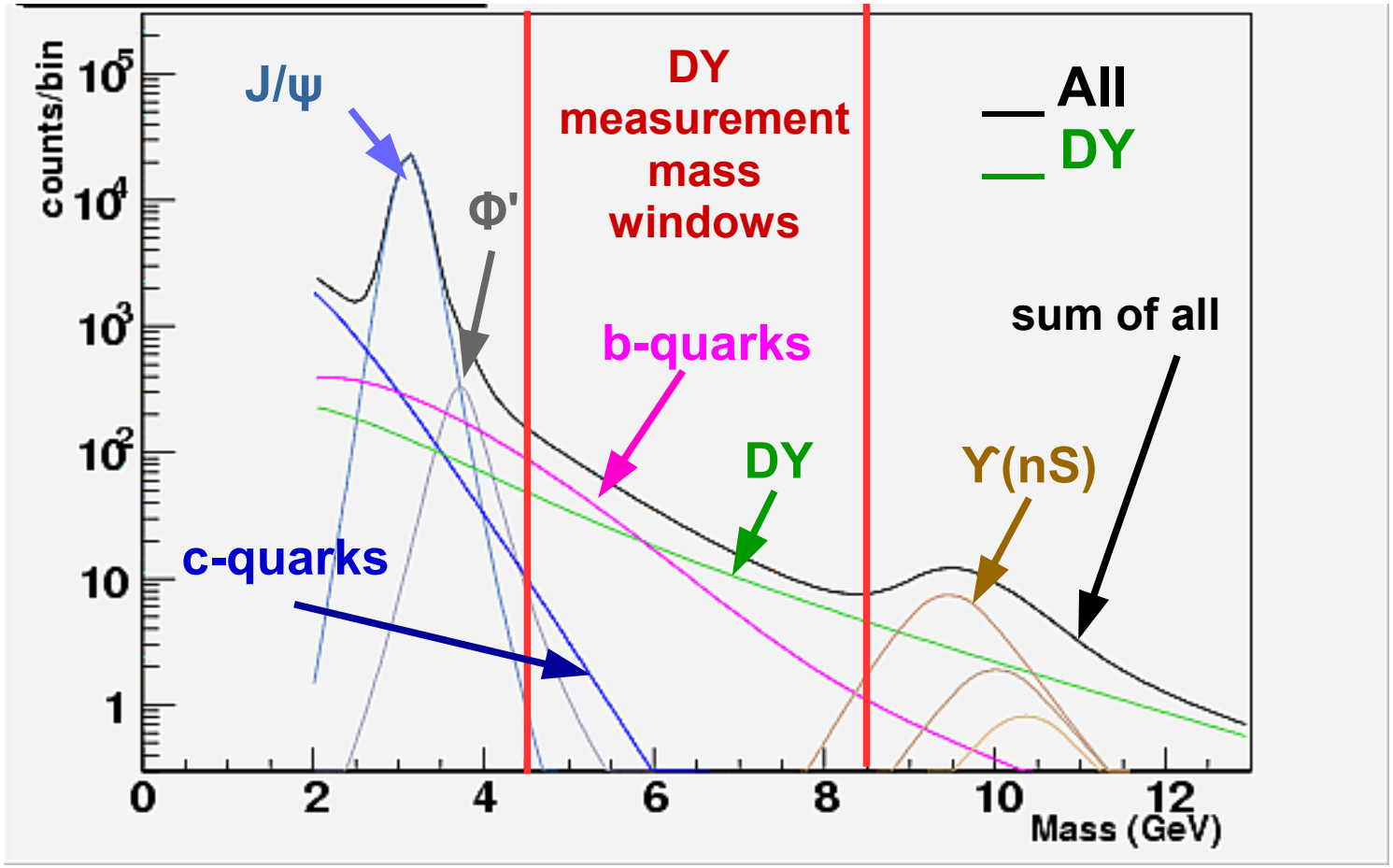
- Ongoing analysis of processes presented here with new data, with p+p and p+A improved statistics: more interesting results in perspective !
- Ongoing forward single hadron analysis in broad rapidity range: results soon !
- Ongoing analysis of forward Drell-Yan A_N for Sivers-like effect and comparison with SIDIS measurements: result very soon. See next slide.

Don't miss G. Mitsuka presentation on neutron A_N !

Outlook: Drell-Yan analysis in PHENIX

Ongoing analysis of Drell-Yan A_N, sensitive to Sivers effect. Goal: compare to SIDIS mes.

Mass distribution and various signal + background contributions to the dimuons spectrum



Kinematics at $\sqrt{s}$ = 200 GeV:

$1.2 < |y| < 2.2$

$x_F \sim 10^{-1}$

$0.5 < q_T < \sim 5$ GeV

Fig. from PHENIX DY proposal, courtesy of Ming Liu. Simulations using Pythia 6 event generator.

Main challenge: background reduction and limited statistics available (run 2015 p+p).

Drell-Yan A_N result coming very soon : keep in touch !

Thank you !

Please address any further questions to: mboer@rcf.rhic.bnl.gov
or to any member of the PHENIX collaboration