PHENIX recent results from polarized pp and pA collisions

- ✓ Nucleon helicity structure
- ✓ Transverse spin phenomena in pp
- ✓ Polarized p + A

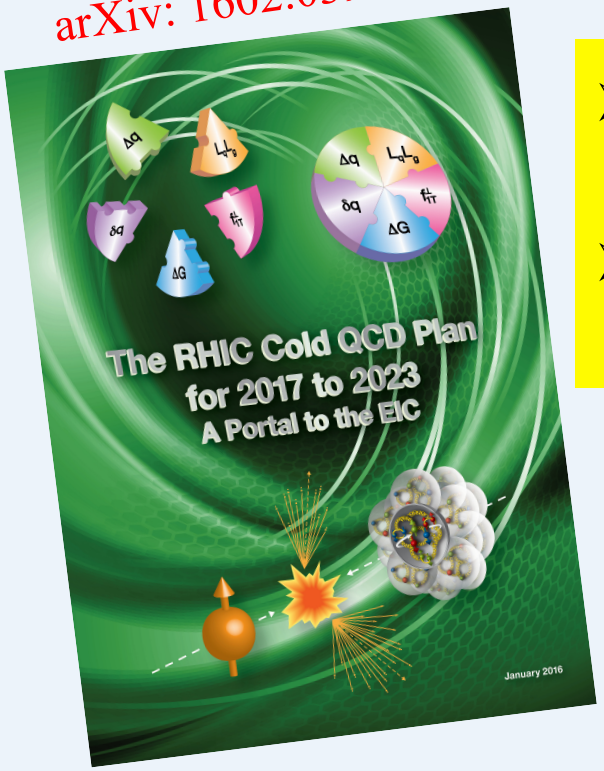
A.Bazilevsky (BNL)

September 2-8, 2016, Acireale (Italy)
International Workshop on Diffraction
in High-Energy Physics

gaetanoracitifoto.com © 2014

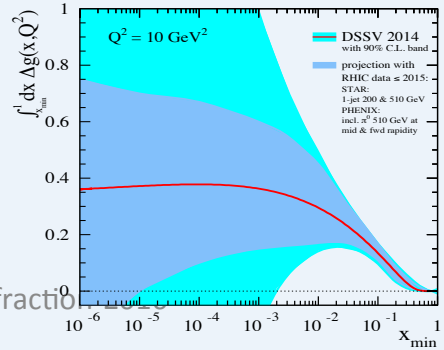
RHIC Spin

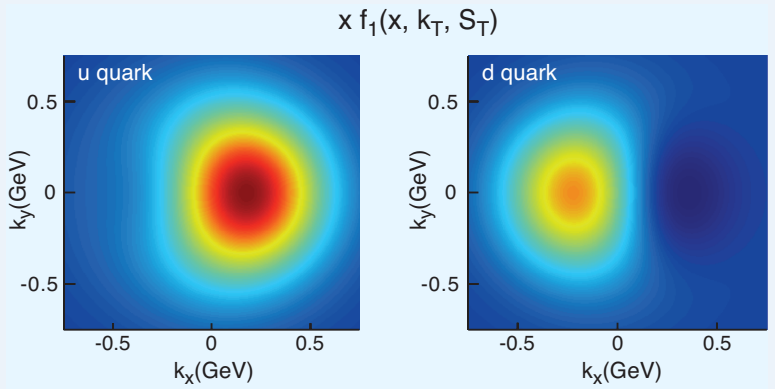
arXiv: 1602.03922



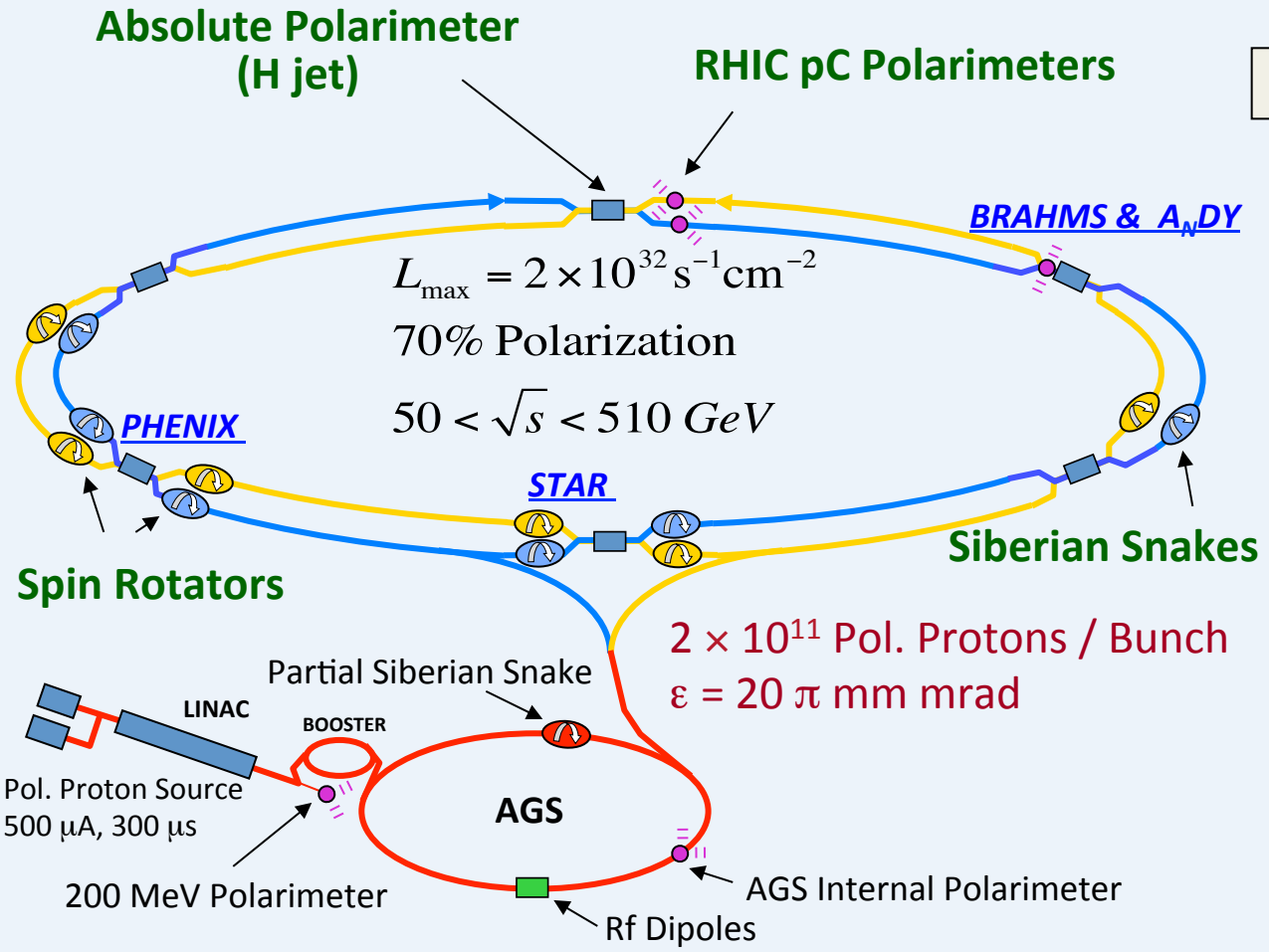
- How do quarks and gluons build the proton spin ½
- What do transverse spin phenomena teach us

arXiv: 1501.01220





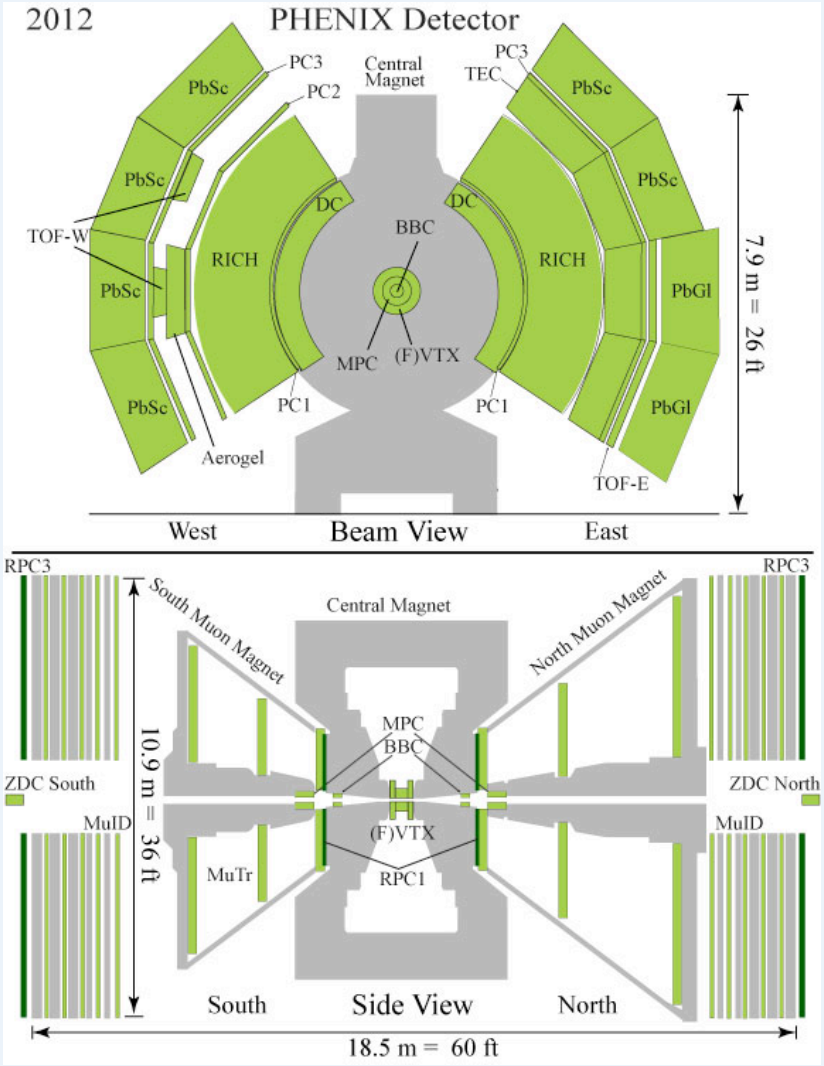
PHENIX Spin @ RHIC



Spin Running in PHENIX, long./trans.

Year	√s [GeV]	L [pb^{-1}] (recorded)	Pol. [%]
2002	200	– / 0.15	15
2003	200	0.35 / –	27
2004	200	0.12 / –	40
2005	200	3.4 / 0.2	49
2006	200	7.5 / 2.7	57
2006	**62.4**	**0.08 / 0.02**	**48**
2008	200	– / 5.2	45
2009	200	16 / –	55
2009	**500**	**14 / –**	**39**
2011	**500**	**18 / –**	**48**
2012	200	– / 9.7	56
2012	**510**	**32 / –**	**50**
2013	**510**	**155 / –**	**51**
2015	200	– /50	57
2015	pAu@200	– /1.3	60
2015	pAl@200	– /4.0	54

PHENIX Detector



π^0, γ, η

Electromagnetic Calorimeter: **$|\eta|<0.35$**

Muon Piston Calorimeter: **$3.1<|\eta|<3.9$**

$\pi^{\pm}$, e, $J/\psi \rightarrow e^+e^-$, $W \rightarrow e$: **$|\eta|<0.35$**

Drift, Pad Chambers, VTX ($|\eta|<1$)

Ring Imaging Cherenkov Counter, ToF

Electromagnetic Calorimeter

μ, $J/\psi \rightarrow \mu^+\mu^-$, $W \rightarrow \mu$: **$1.2<|\eta|<2.4$**

Muon Id/Muon Tracker

FVTX

Relative Luminosity

Beam Beam Counter (BBC)

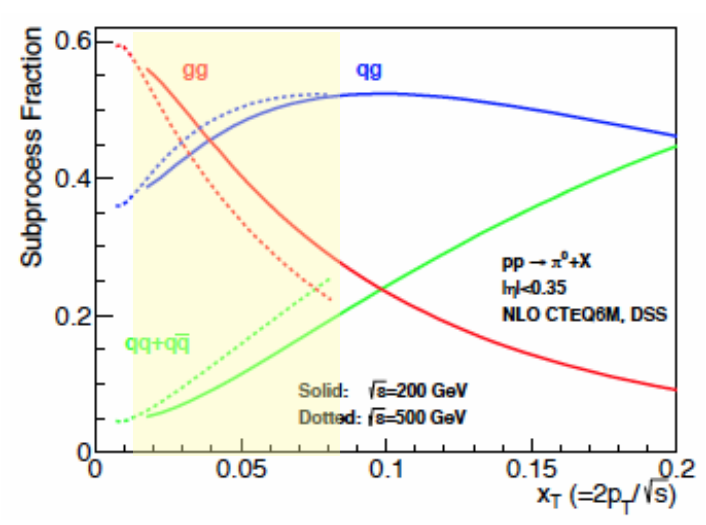
Zero Degree Calorimeter (ZDC)

Local Polarimetry – ZDC & SMD

Spin direction control

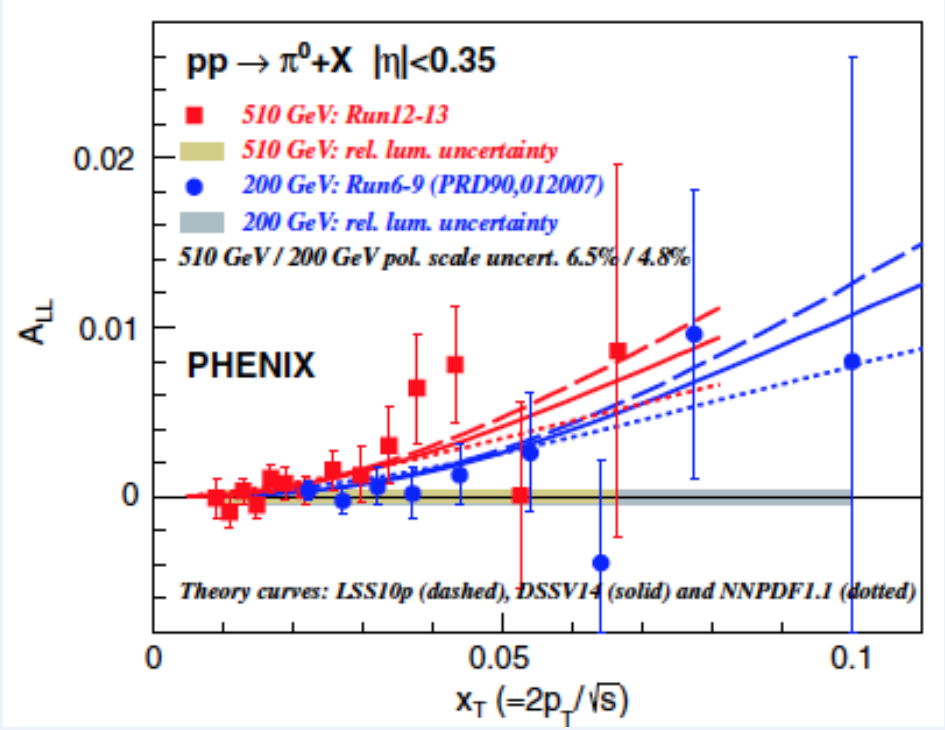
ΔG: π0 A_{LL}

$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta \bar{q}\right) + \Delta G + L_z$$

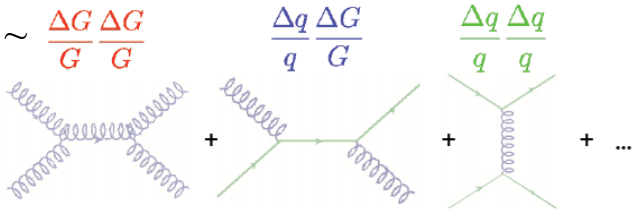


The most abundant probe in PHENIX
(triggering + identification capability)

PRD93, 011501 (2016)



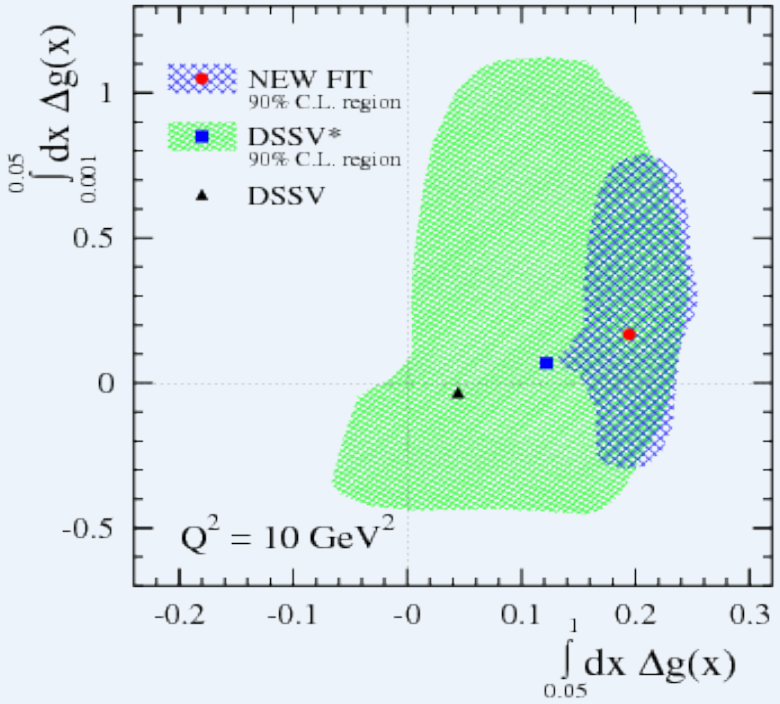
$A_{LL} \sim \frac{\Delta G}{G}\frac{\Delta G}{G} + \frac{\Delta q}{q}\frac{\Delta G}{G} + \frac{\Delta q}{q}\frac{\Delta q}{q} + \ldots$



Non-zero A_{LL} associated with non-zero ΔG !

ΔG: DIS+pp global QCD fit

DSSV:
D. de Florian
R. Sassot
M. Stratmann
W. Vogelsang



pp: PHENIX + STAR

DSSV: Phys Rev Lett, 101, 072001 (2008)
Data from up to 2006

New DSSV: Phys Rev Lett, 113, 012001 (2014)
Data from up to 2009

$$\int_{0.05}^{1} dx\Delta g(x) = 0.2^{+0.06}_{-0.07} \qquad \text{(90\% CL)}$$

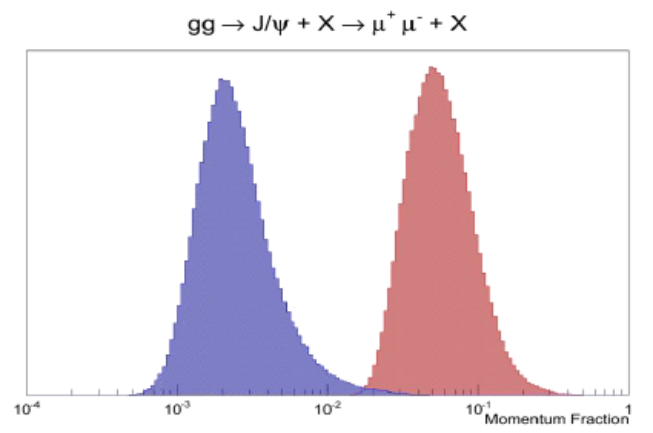
Significant non-zero Δg(x) in the kin. region probed by RHIC
Similar result from another global fit NNPDF
Still huge uncertainty in unmeasured region (x<0.05)
=> Measurements at higher √s and forward rapidity

ΔG: Towards lower x

$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta \bar{q}\right) + \Delta G + L_z$$

pp → *J/ψ* at √s=510 GeV 1.2<|η|<2.4

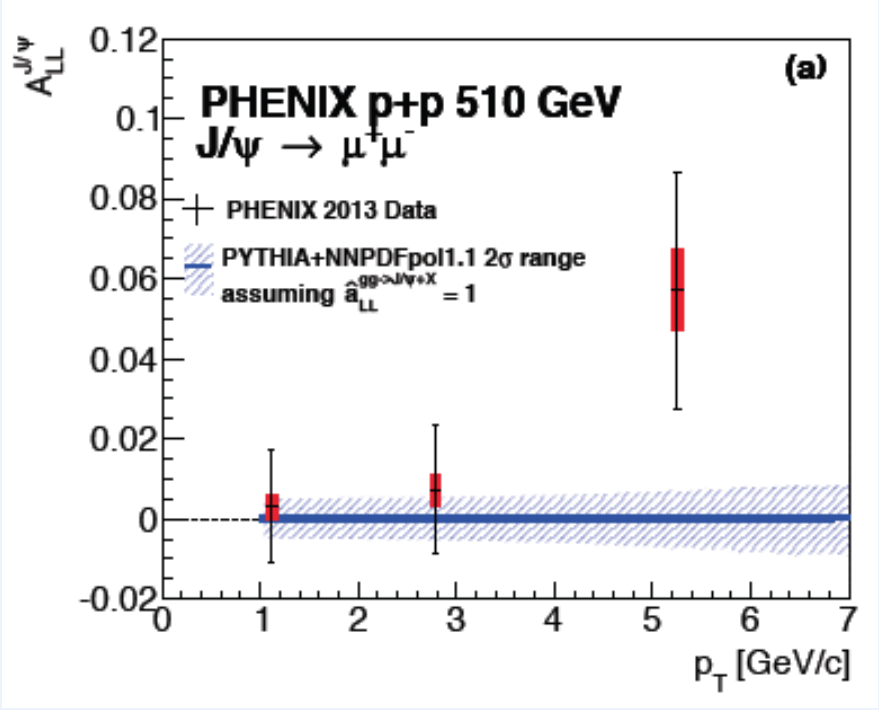
arXiv: 1606.01815



$$A_{LL} \propto \frac{\Delta g(x_1)}{g(x_1)} \cdot \frac{\Delta g(x_2)}{g(x_2)}$$

Get access to x down to 2×10^{-3}

Already constrained by RHIC



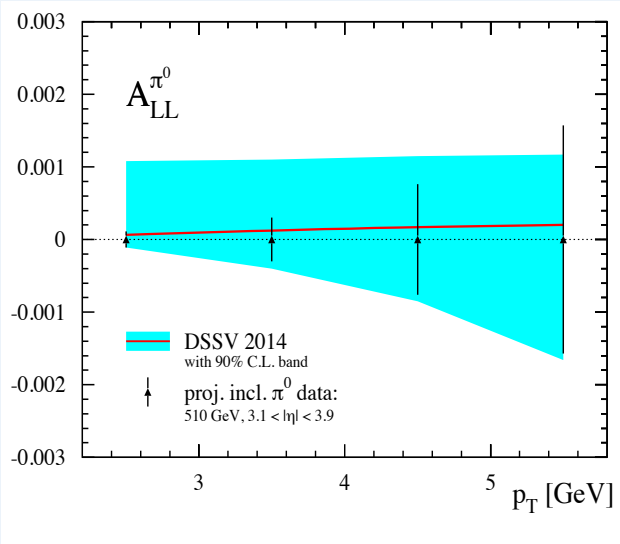
J/ψ production mechanism uncertainty
Not yet in the global fit

ΔG: Towards lower x

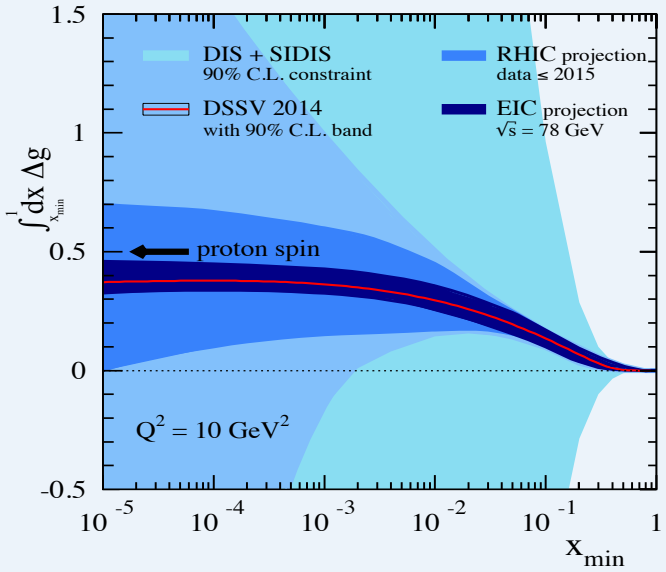
$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta \bar{q}\right) + \Delta G + L_Z$$

Projection

π0: 3.1<|η|<3.9



From available PHENIX+STAR data from 2011-15



π0 in forward region at √s=510 GeV:

Based on collected 2013 data

Probes lower x down to ~10^{-3}

Other channels also being measured (but with weaker stat. power)

γ, η, π±, h±, heavy flavor through e and μ, h-h, γ-h

$$d_L \bar{u}_R \rightarrow W^-$$
$$u_L \bar{d}_R \rightarrow W^+$$

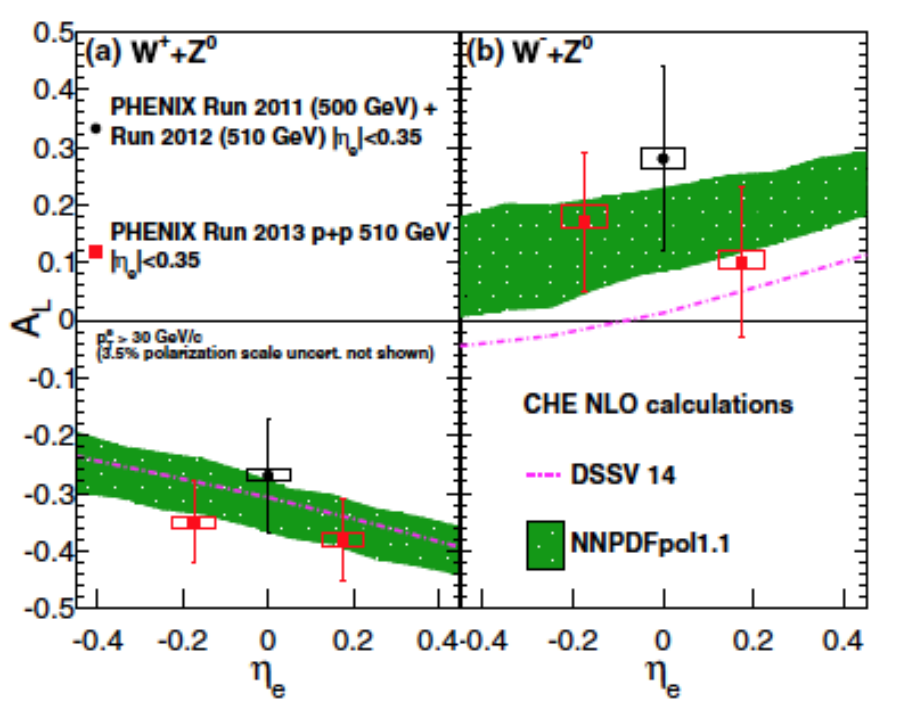
Δq-bar: $W^{\pm} \rightarrow e^{\pm}$

$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta \bar{q}) + \Delta G + L_z$$

$|\eta|<0.35$

Constrains flavor separated (anti-)quark polarization at high $Q \sim M_W$ at $x>0.05$, with no fragmentation involved (as in SIDIS)

PRD93, 051103 (2016)



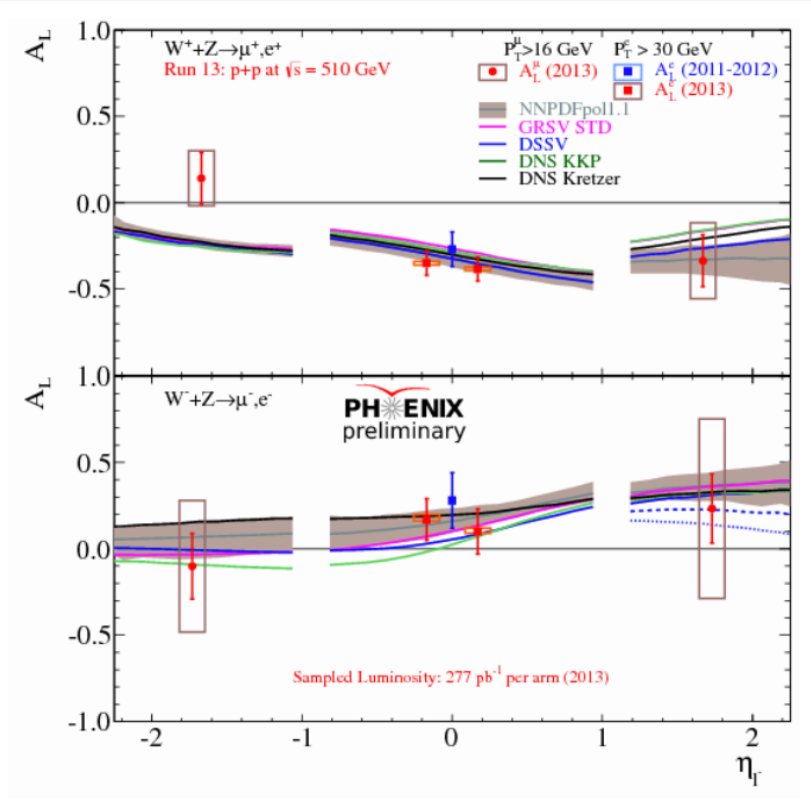
$$d_L \bar{u}_R \rightarrow W^-$$
$$u_L \bar{d}_R \rightarrow W^+$$

Δq-bar: W± ⟶ μ±

$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta \bar{q}) + \Delta G + L_z$$

1.2<|η|<2.4

Constrains flavor separated (anti-)quark polarization at high Q~M_W at x>0.05, with no fragmentation involved (as in SIDIS)



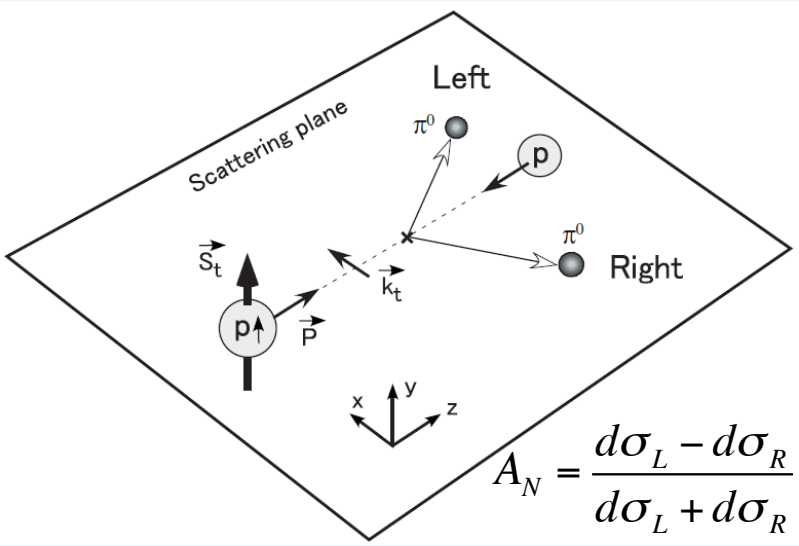
Uncertainties are large due to sizable background (S/B= 0.2−1)

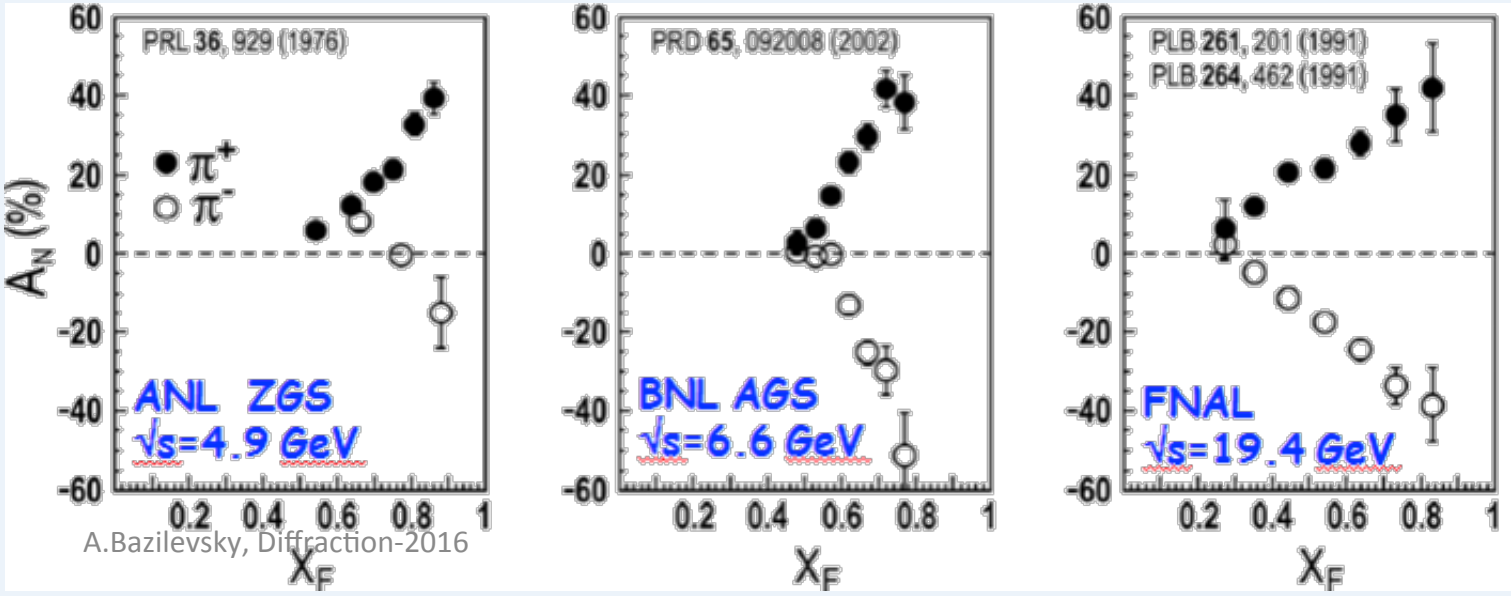
Working to reduce syst. uncertainties

Publication in preparation

Transverse Spin Asymmetries

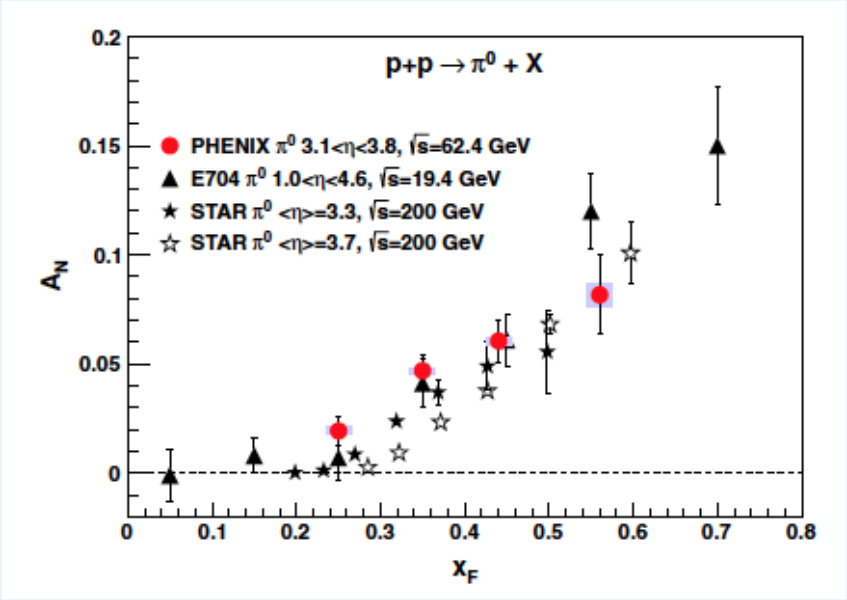
Large Transverse Spin Asymmetries have been observed in $p^{\uparrow}p$





Forward-rapidity π0 A_N

PRD90, 012006 (2014)



Naïve collinear pQCD predicts

$$A_N \sim \alpha_s m_q / p_T \sim 0$$

Asymmetries survive at highest $\sqrt{s}$

Non-perturbative regime!

Asymmetries of the ~same size at all $\sqrt{s}$

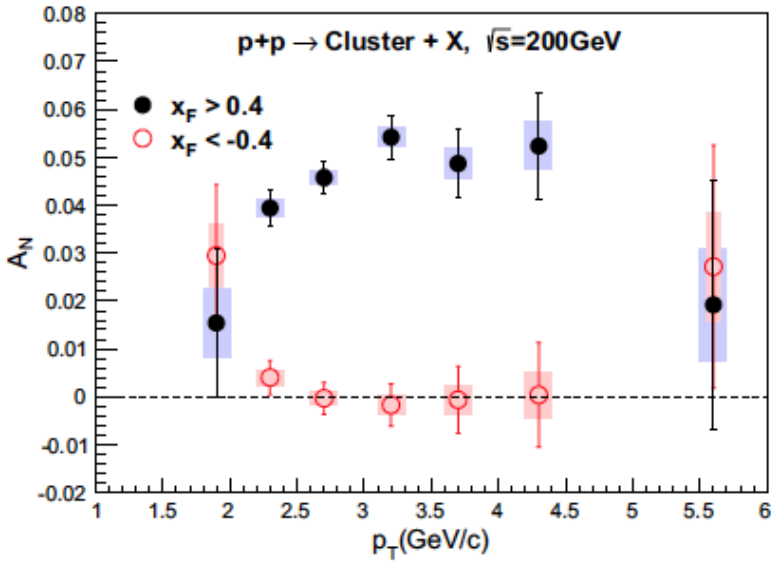
Asymmetries scale with x_F

Collinear (higher twist) pQCD predicts

$$A_N \sim 1/p_T \ ?$$

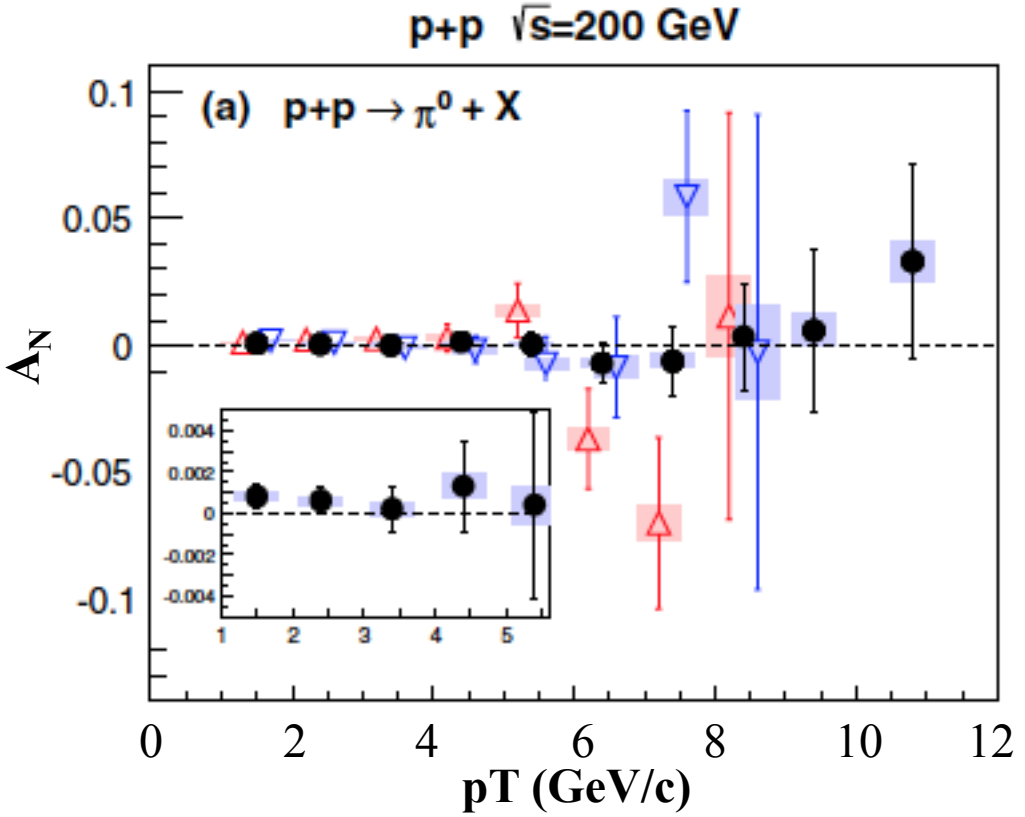
No fall off is observed out to p_T ~5 GeV/c

STAR showed no fall off up to ~7 GeV/c



Mid-rapidity π0 A_N

PRD90, 012006 (2014)



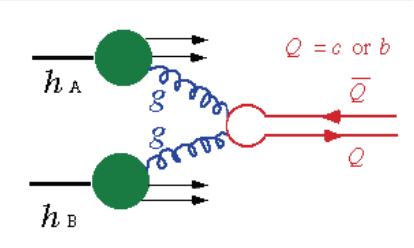
Consistent with 0

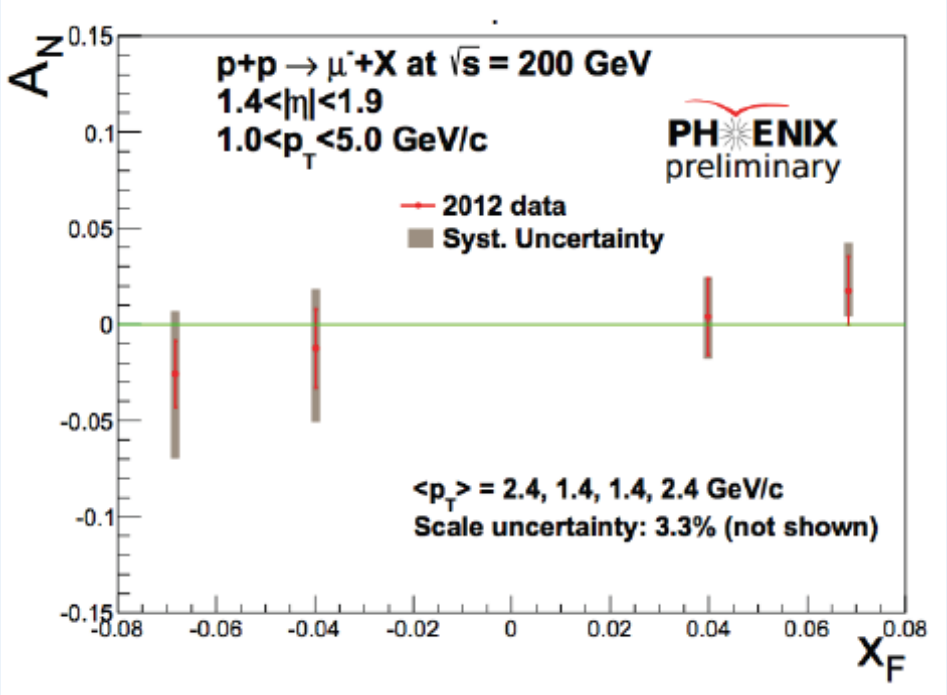
To $<10^{-3}$ precision level at low p_T

Sensitive to gluons

Used to constrain gluon Sivers effect (Anselmino et al, PRD 74, 094011)

Heavy Flavor A_N





Dominated by gluon-gluon fusion

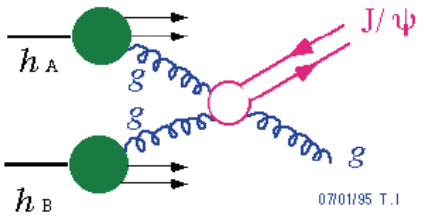
Used to constrain tri-gluon correlation in the Twist-3 collinear framework

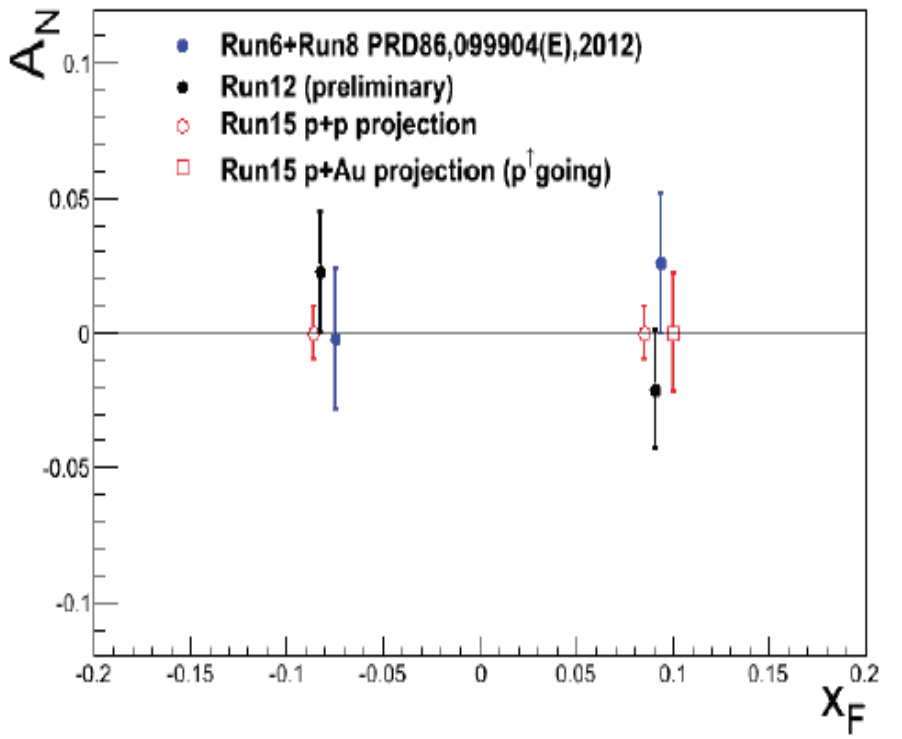
Z.Kang, J.Qiu, W.Vogelsang, F.Yuan, PRD78,114013

Y.Koike, S.Yoshida, PRD84,014026

Significant reduction in uncertainties expected from 2015 data

J/ψ A_N





A_N sensitive to J/ψ production mechanism

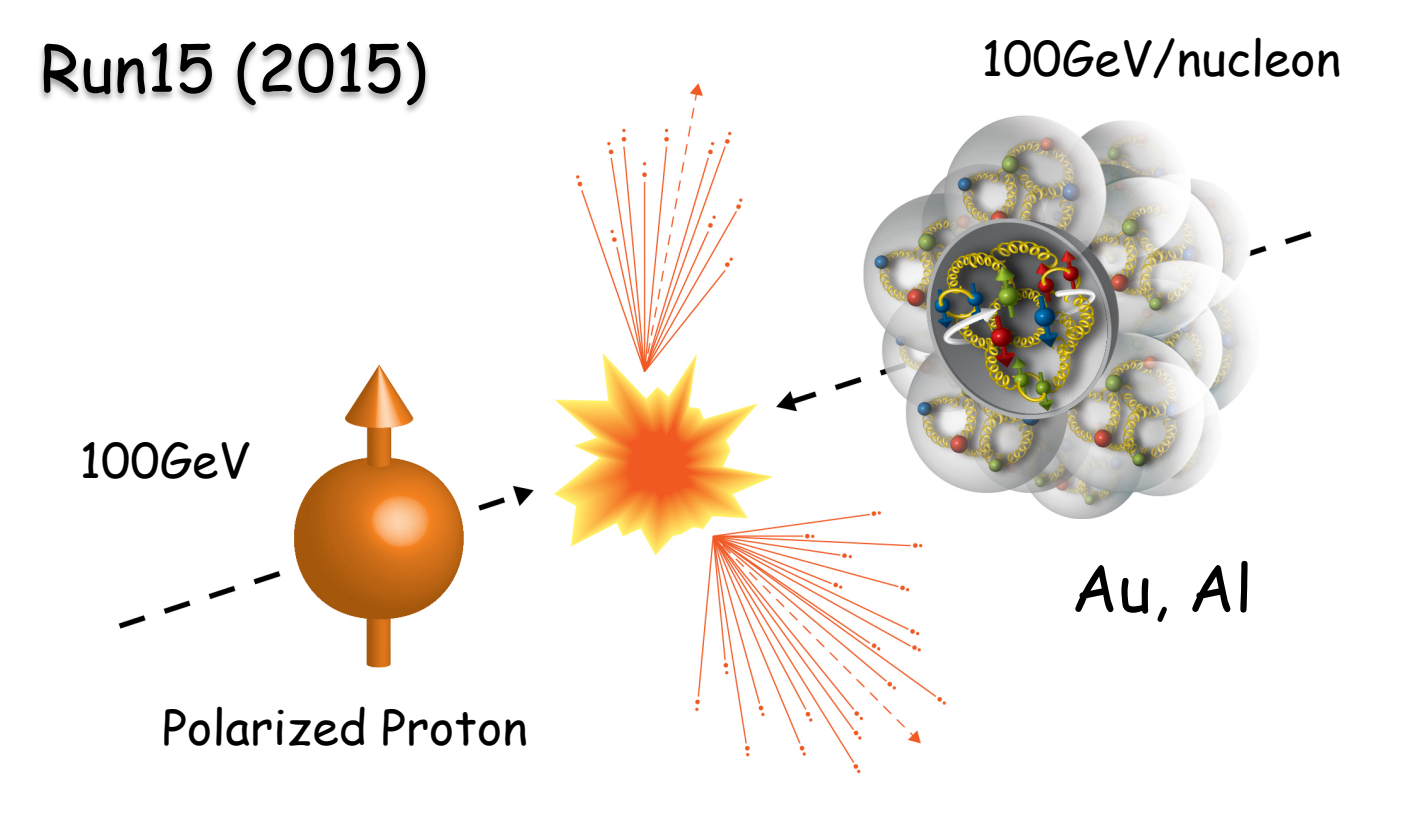
F.Yuan, PRD78, 014024:

For non-zero gluon Sivers, A_N vanishes in color octet model, but survives in color singlet model

Considerable improvements expected from 2015 data

Also pA data from 2015!

First $p^{\uparrow} + A$ data !!!



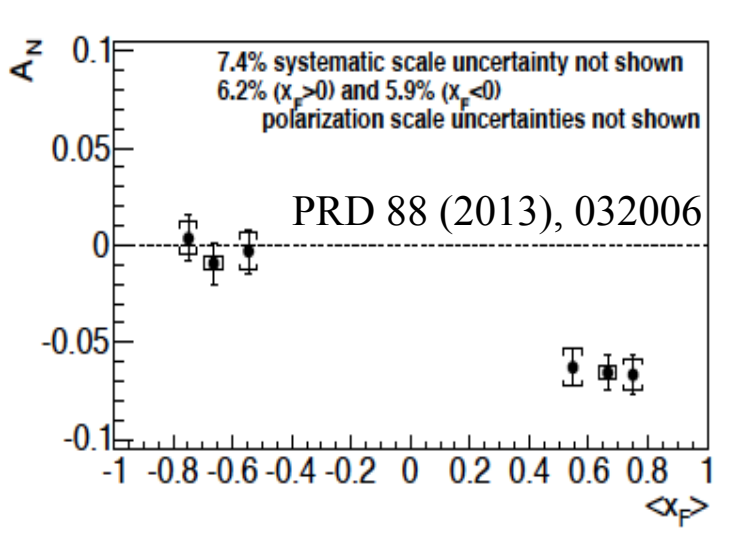
Many results expected soon

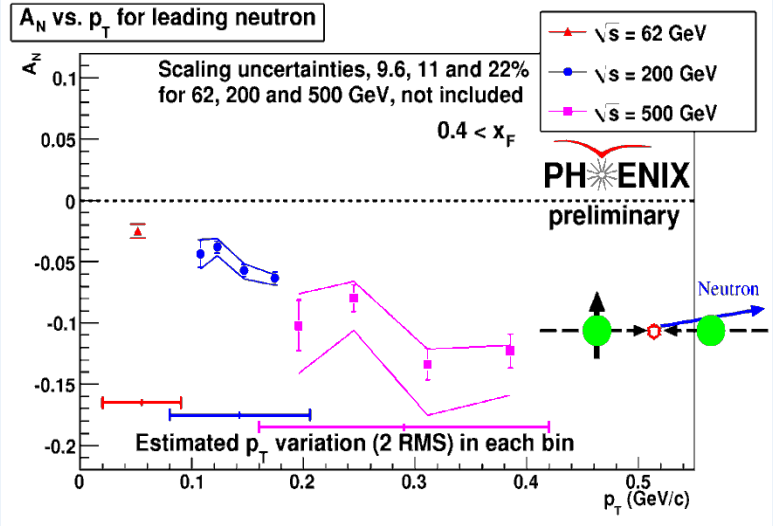
In the following: **first results on very forward neutron A_N**

pp: forward neutron A_N

Discovered at RHIC in 2002: PLB 650, 325

pp→nX, |θ|<2.5mrad

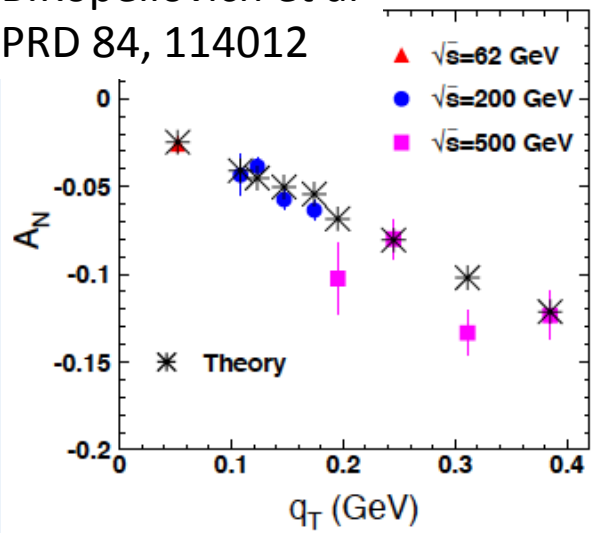




One pion Exchange model in Regge framework model

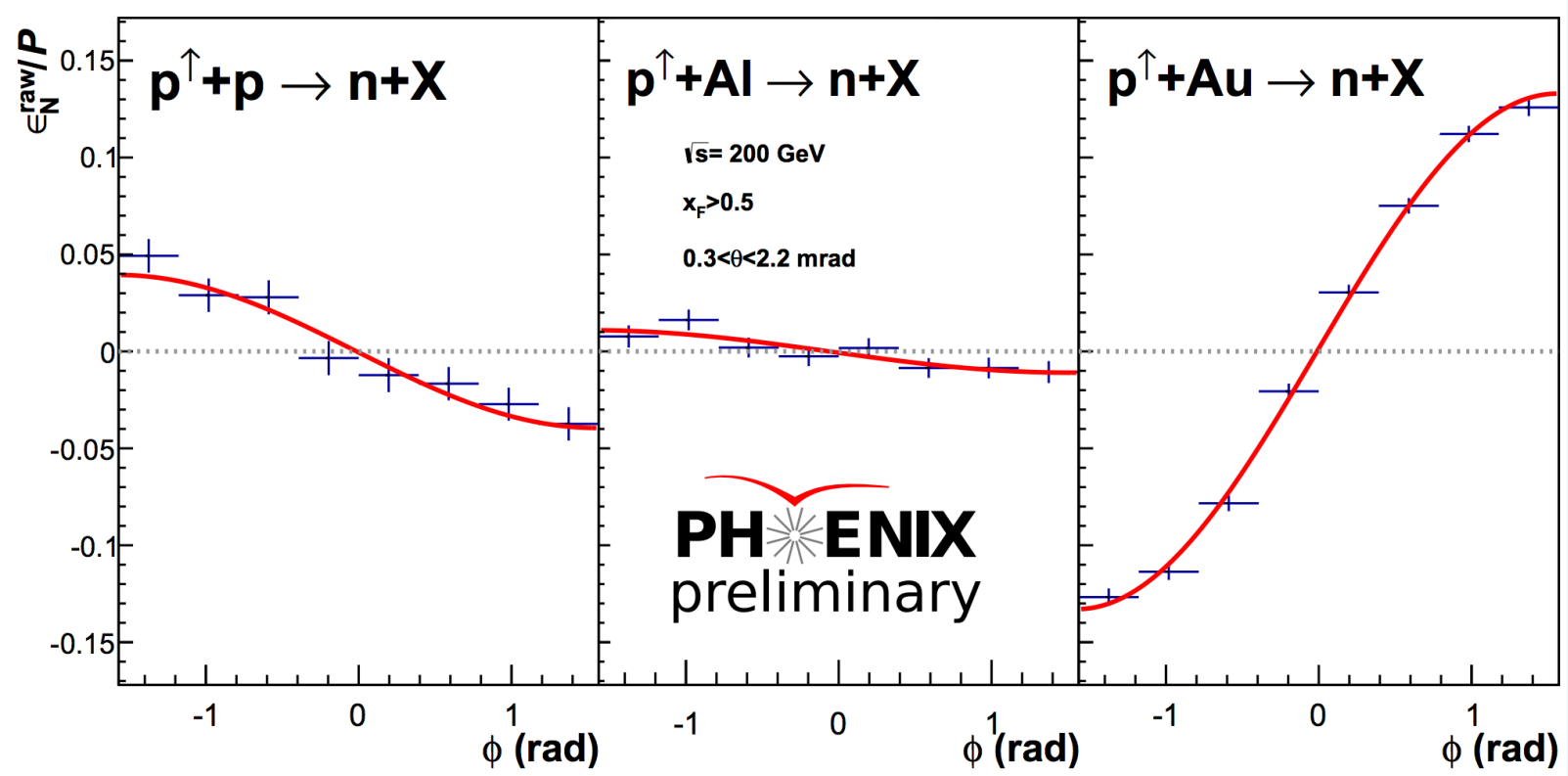
(interference between pion and a1-reggeon exchange)

B.Kopeliovich et al
PRD 84, 114012



p+p *vs* p+Al *vs* p+Au

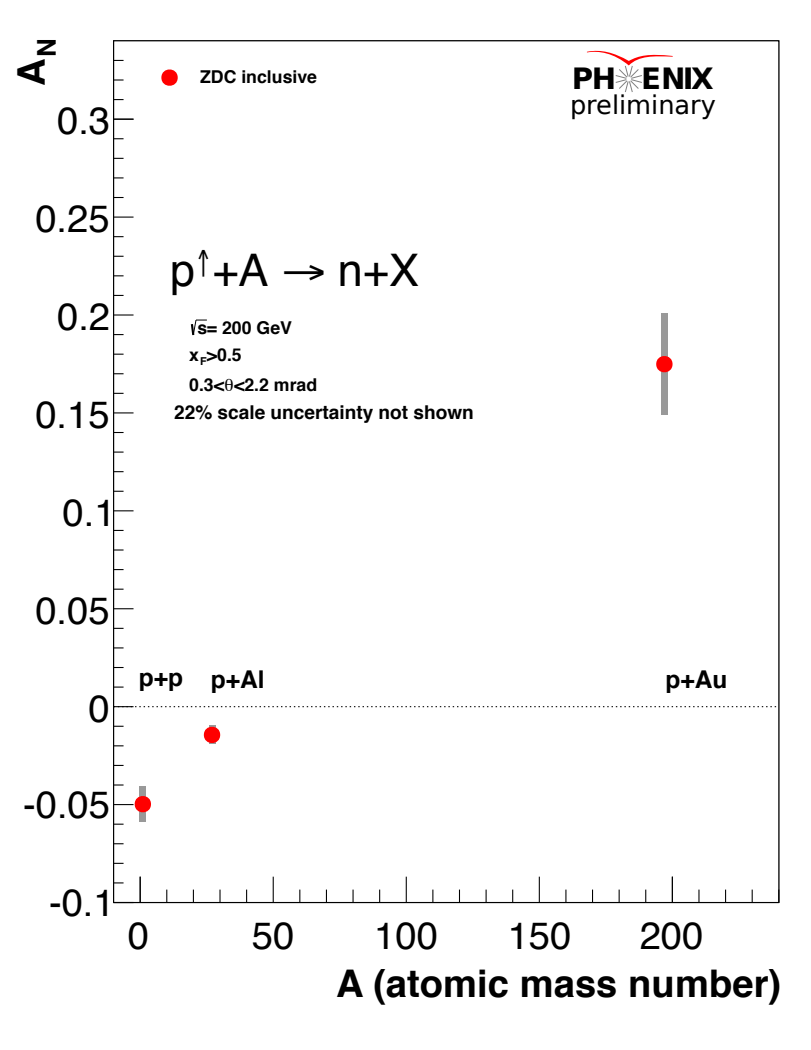
$$A = A(\varphi) = A_N \cdot \sin(\varphi)$$

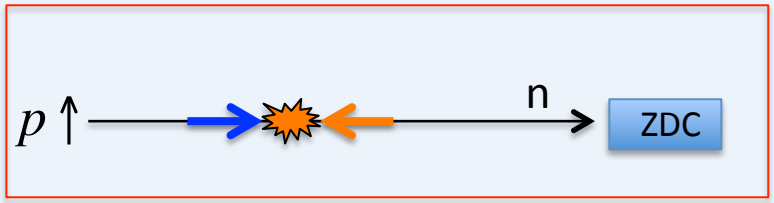


$A_N<0$ $A_N<0$ $A_N>0$

A_N vs nucleus mass

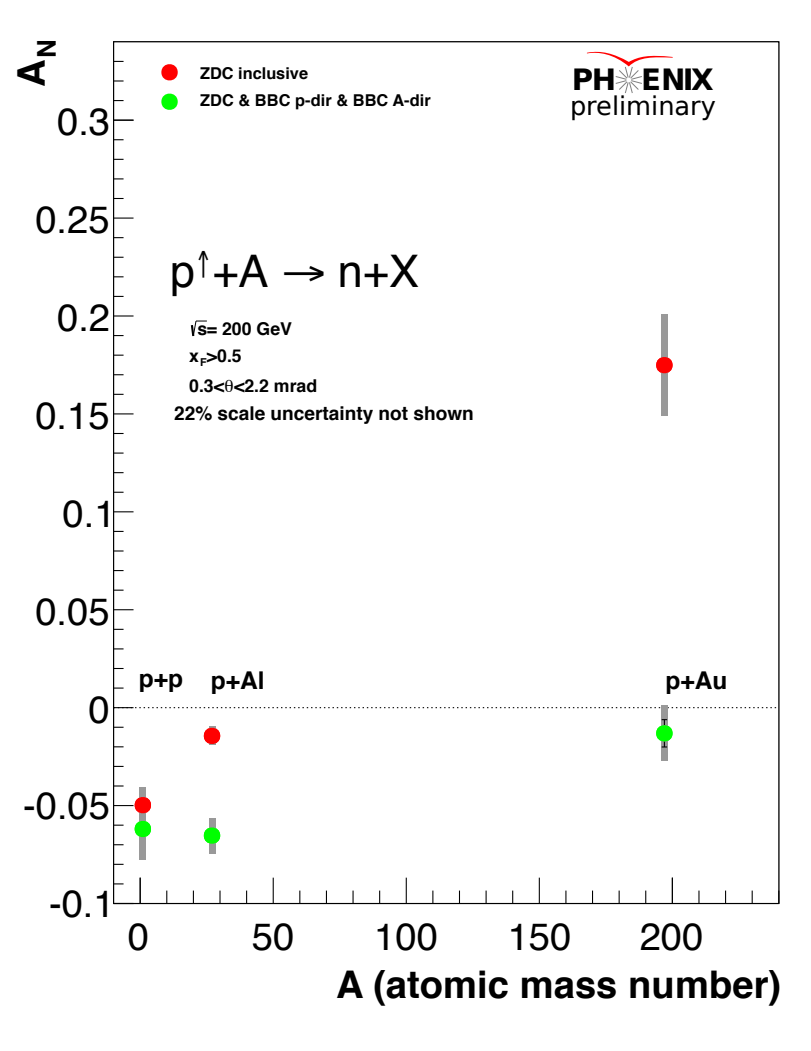
ZDC: η>6.5
BBC: 3.0<|η|<3.9

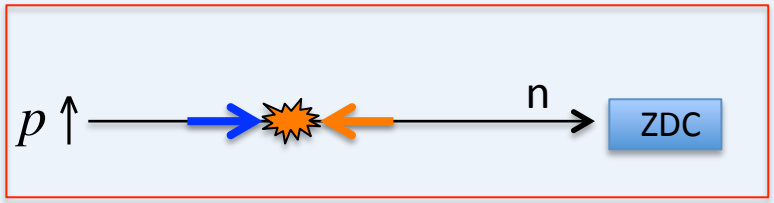


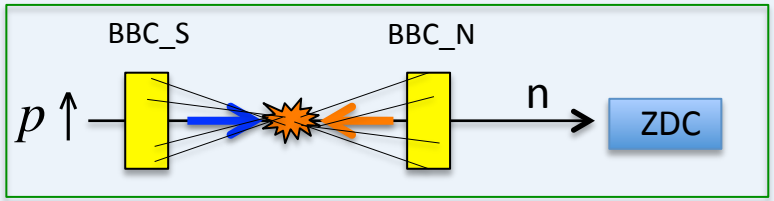


A_N vs nucleus mass

ZDC: η>6.5
BBC: 3.0<|η|<3.9

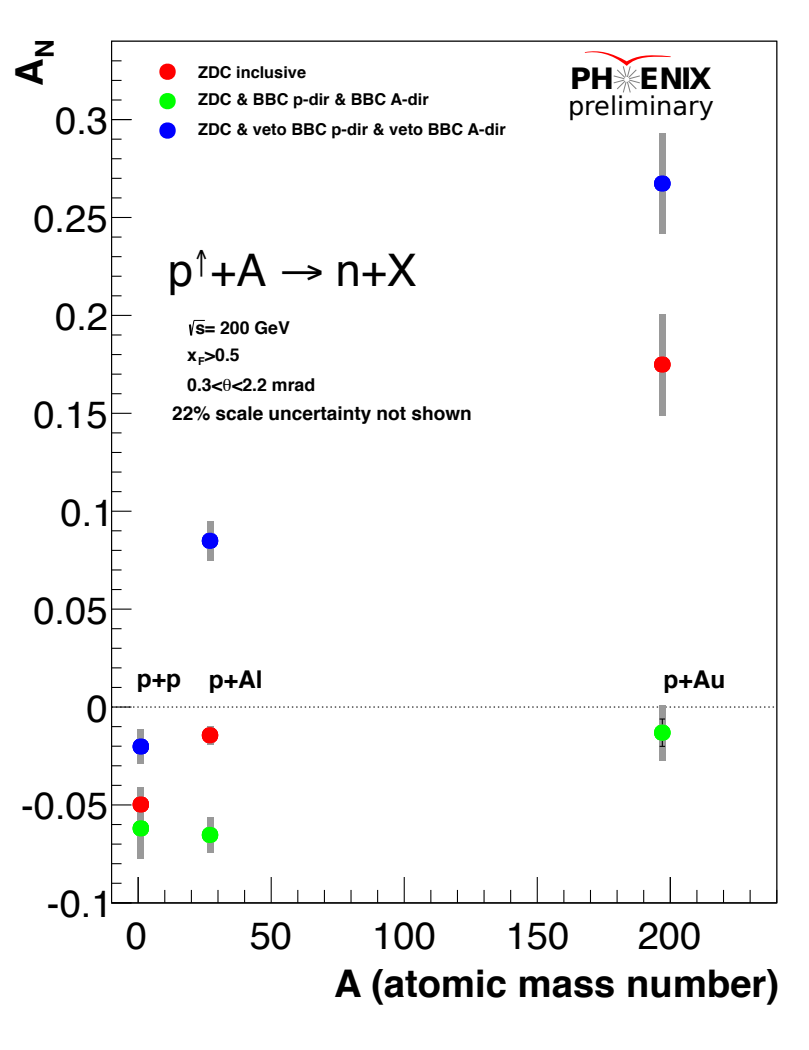


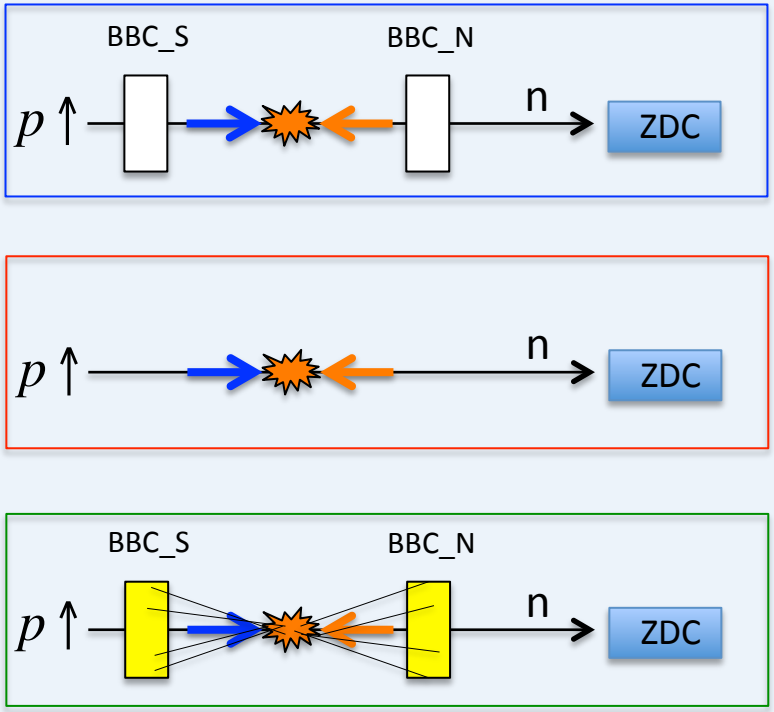




A_N vs nucleus mass

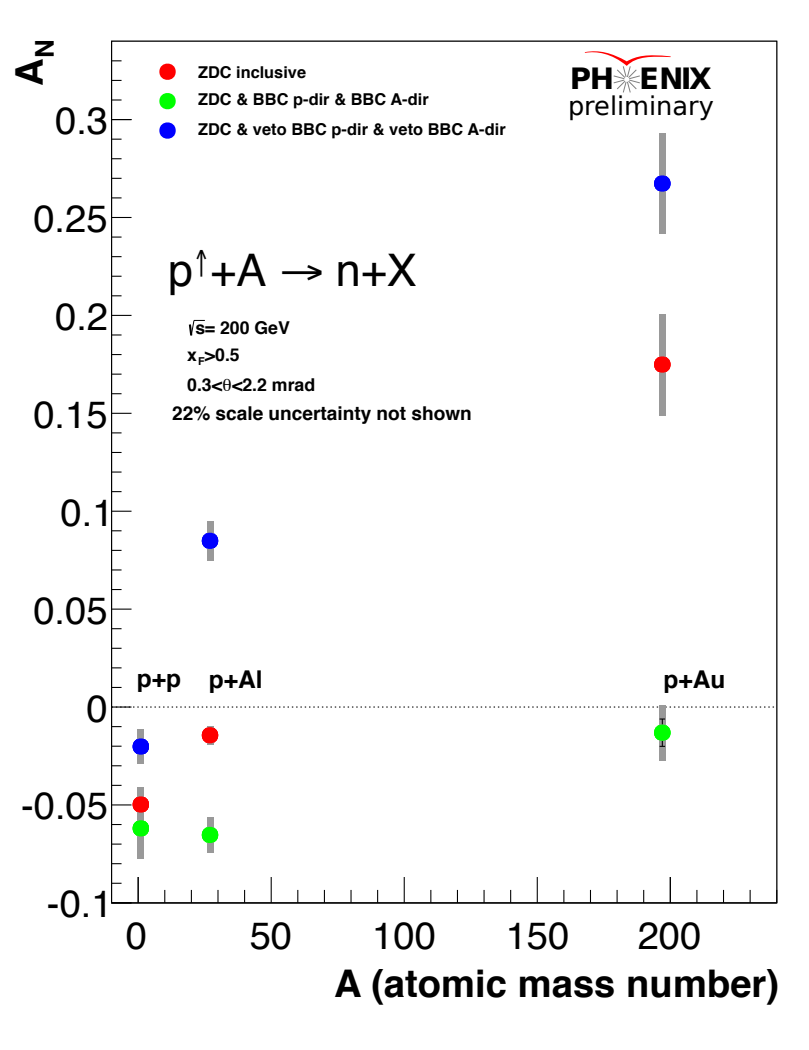
ZDC: η>6.5
BBC: 3.0<|η|<3.9

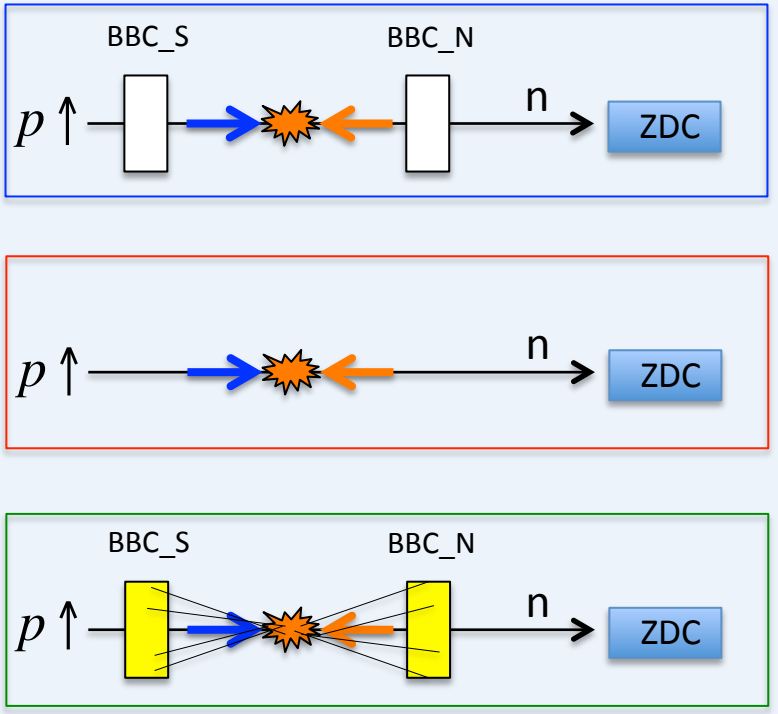




A_N vs nucleus mass

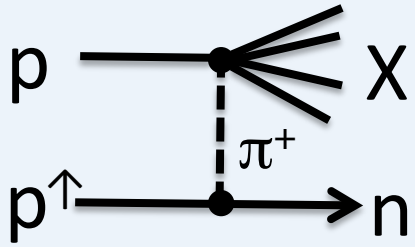
ZDC: η>6.5
BBC: 3.0<|η|<3.9



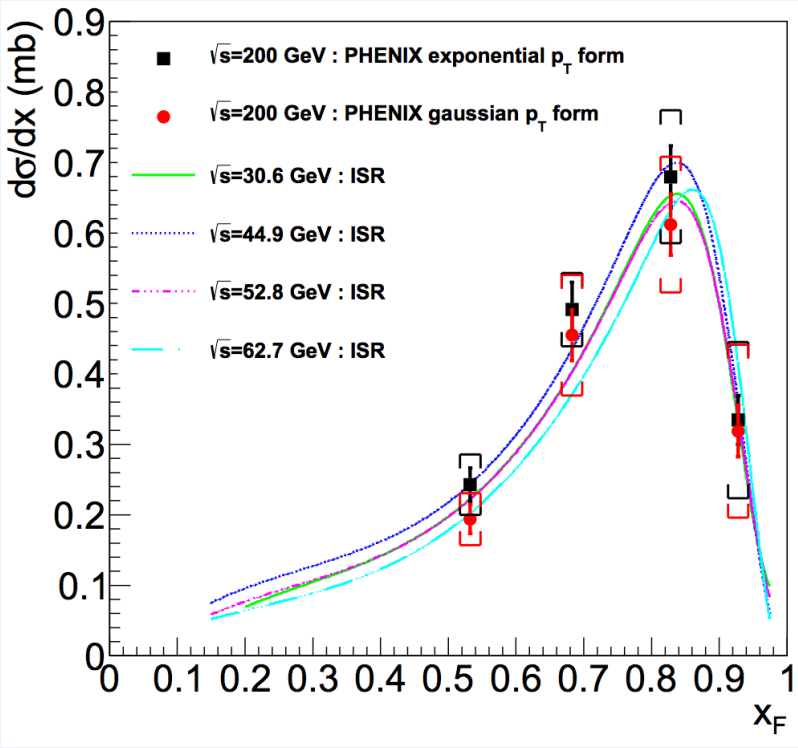


Likely multiple mechanisms contribute

Forward neutrons: One Pion Exchange



PHENIX: PRD 88 (2013), 032006



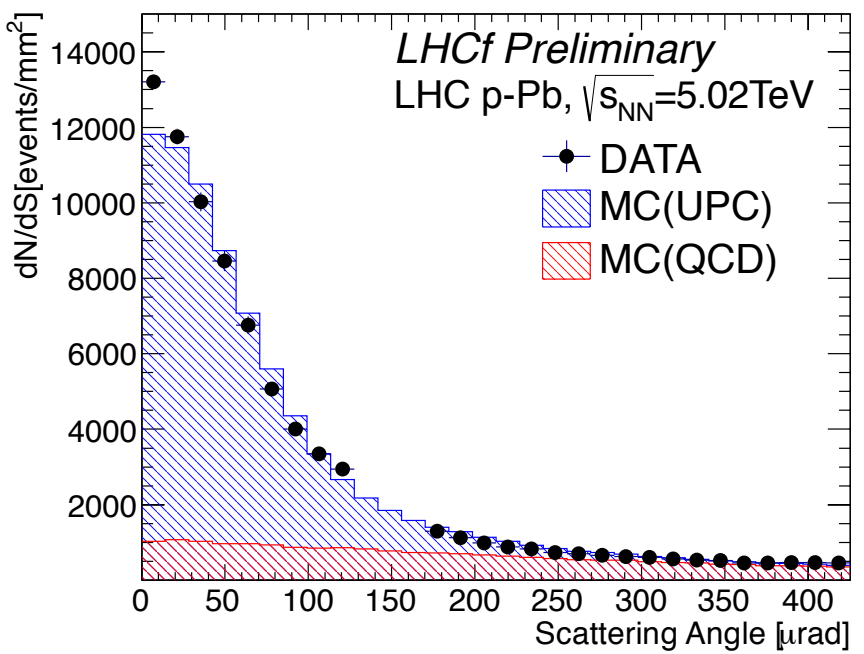
p+p: One Pion Exchange (OPE) model successful for x-section

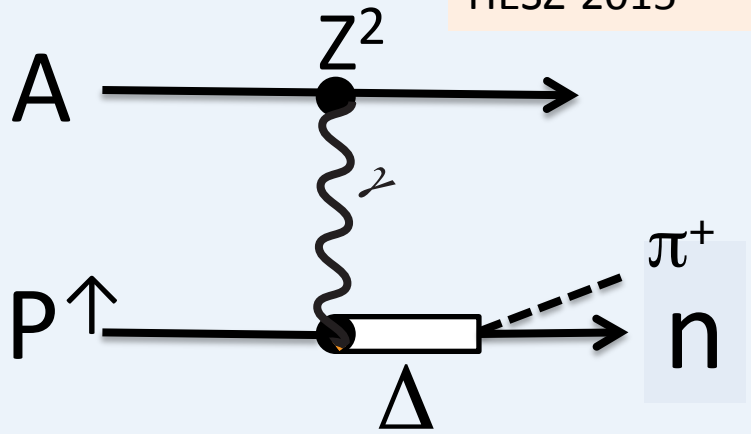
Does it work for p+A ?

Other mechanisms definitely exist, at least in p+A

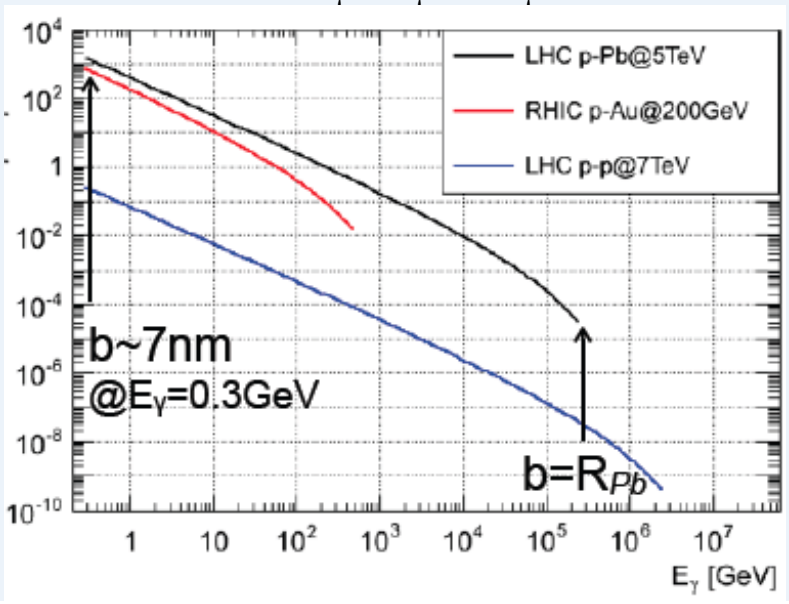
Forward neutrons: Ultra Peripheral Collisions

Hiroaki Menjo
HESZ-2015





dN_γ/dE_γ vs E_γ



Photon flux similar at LHC and RHIC

UPC – the dominant source of forward neutron production in p+A

Forward neutrons: QCD scattering

From Manabu Togawa's thesis

PYTHIA+GEANT simulation, $E_{ZDC} > 5$ GeV

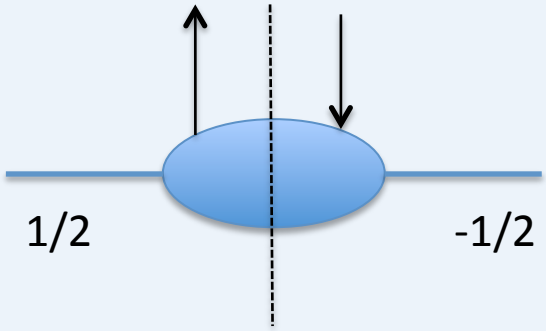
Physics process	Neutron (μb)
$qq \to qq$	35
$q\bar{q} \to q\bar{q}$	<1
$q\bar{q} \to gg$	<1
$qg \to qg$	268
$gg \to q\bar{q}$	9
$gg \to gg$	352

PYTHIA: 30% of neutron production in pp in ZDC acceptance

Mainly from gluon scattering

Δ^0, Δ^+, Δ^-, Λ^0 –> n

A_N



Requires interference between helicity flip and helicity non-flip amplitudes

$$|\uparrow\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle + i|-\rangle\right)$$

$$|\uparrow\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle - i|-\rangle\right)$$

$$A_N \propto \mathrm{Im}(\phi^{*}_{non-flip}\phi_{flip})$$

$$\phi_{non-flip} = \phi^{HAD}_{non-flip} + \phi^{EM}_{non-flip} \qquad \phi_{flip} = \phi^{HAD}_{flip} + \phi^{EM}_{flip}$$

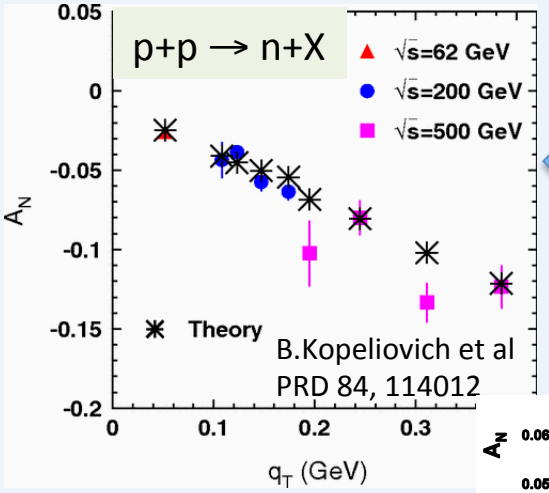
$$A_N \propto \mathrm{Im}(\phi^{HAD}_{non-flip}\phi^{HAD}_{flip} + \phi^{HAD}_{non-flip}\phi^{EM}_{flip} + \phi^{EM}_{non-flip}\phi^{HAD}_{flip} + \phi^{EM}_{non-flip}\phi^{EM}_{flip})$$

Which pair(s) of interfering amplitudes would produce forward neutron A_N ?

Need input from theorists

A_N

A_N~Im(HAD*HAD)

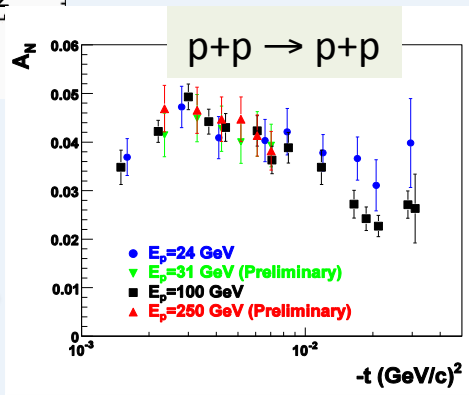


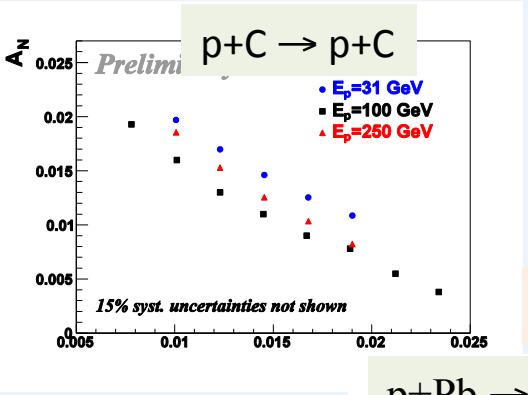
B.Kopeliovich et al
PRD 84, 114012

PHENIX data:
interference between
pion and a1-reggeon
exchange

A_N~Im(EM*HAD)

RHIC CNI data:
Elastic scattering in
Coulomb Nuclear
Interference region





A_N~Im(EM*EM)

p+Pb → Δ/N*+Pb → π^0+p+Pb

Fermilab, PRL64, 357 (1990):

185 GeV polarized protons
Nuclear Coulomb coherent production
$|t|<0.001$ (GeV/c)^2

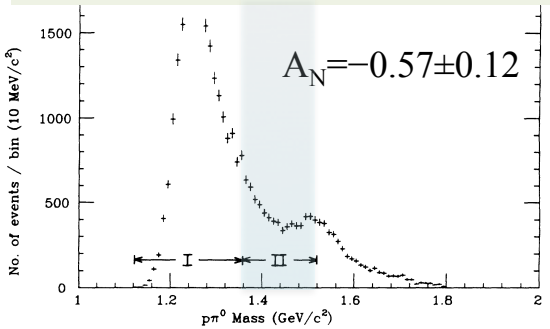
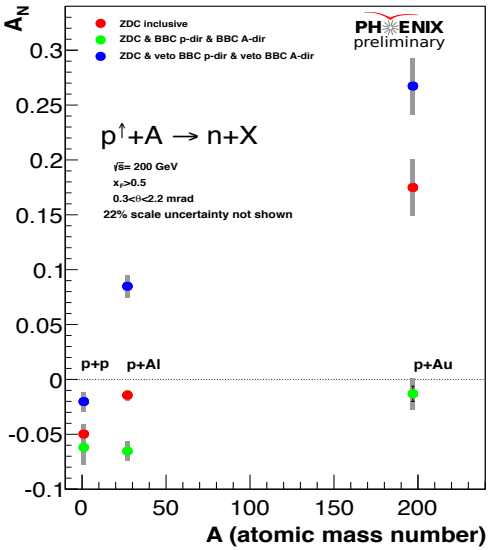


FIG. 2. The invariant-mass spectrum of the π^0-p system in $p+\mathrm{Pb}\to\pi^0+p+\mathrm{Pb}$ for $|t'|<1\times10^{-3}$ (GeV/c)^2. Peaks due to the $\Delta^+(1232)$ and $N^*(1520)$ resonances are shown. Regions I and II are defined in the text.

Summary

- How do gluon contribute to the proton Spin
  - Non-zero (in the limitted x-range) and comparable to (or larger than) quark contribution
  - Data at lower x coming
- What is the flavor structure of polarized sea in the proton
  - A_L(W) will contribute to $\Delta\bar{u}$ and $\Delta\bar{d}$
- What are the origins of transverse spin phenomena in QCD
  - $A_N(\pi^0,\eta)$, central and forward; A_N(Heavy Flavor, J/ψ) => gluon Sivers
- First $p^{\uparrow}A$ data !



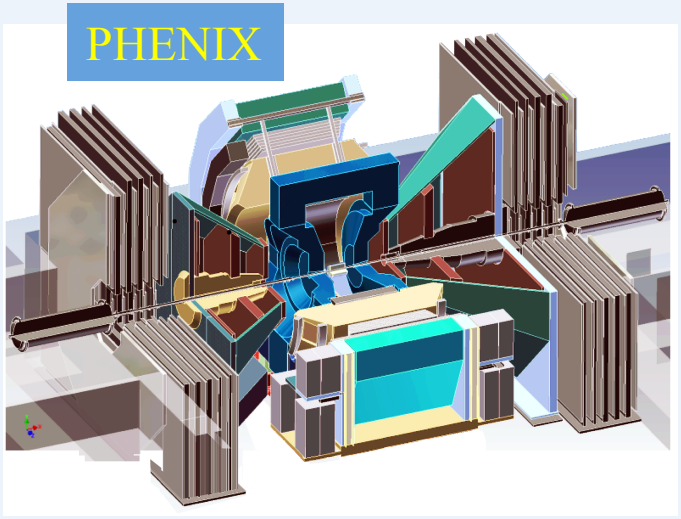
A_N of forward neutron production: from pp to pA

- Strong dependence on nucleus mass (or Z?) and particle production in other rapidity regions
- Likely multiple mechanisms contribute
- Correlations with particle production in other rapidities will help to isolate different channels

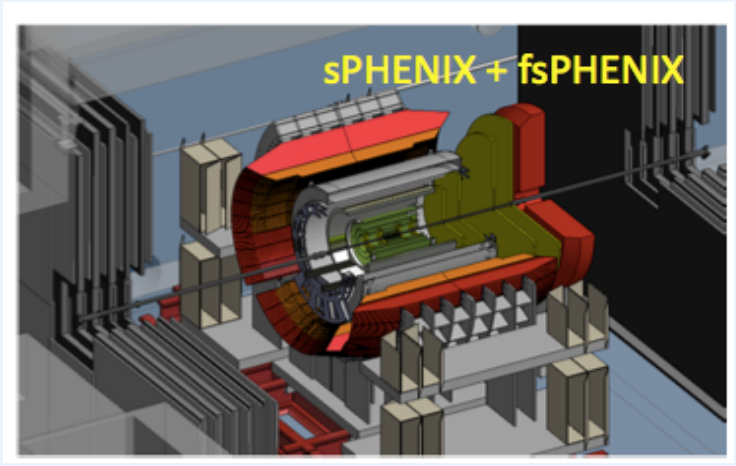
Need theoretical input ! => B.Kopeliovich talk next

Backup

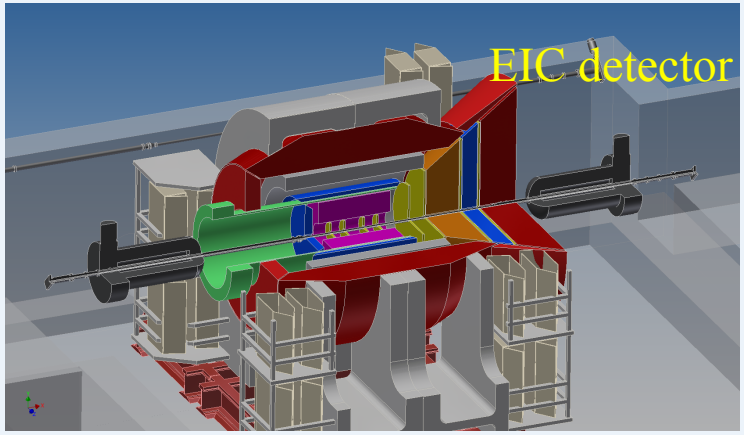
PHENIX: longer term plans



~2021-22



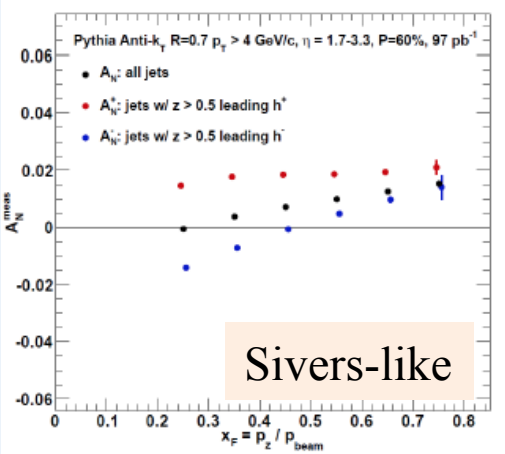
By ~2025



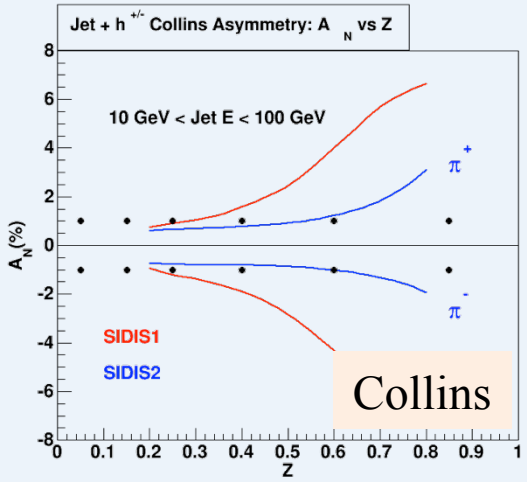
Evolve sPHENIX (pp and HI detector) to EIC Detector (ep and eA detector)

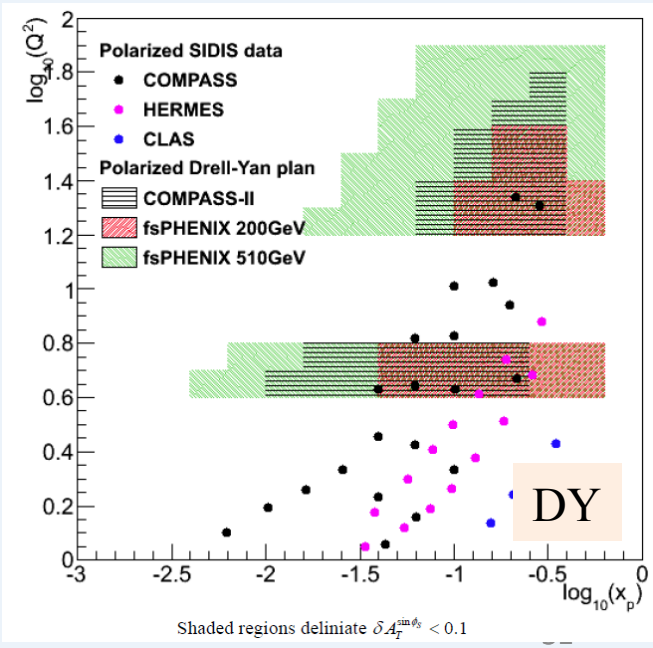
- To utilize e and p (A) beams at eRHIC with *e*-energy up to 15 GeV and *p*(*A*)-energy up to 250 GeV (100 GeV/n)
- *e*, *p*, *He*3 polarized
- Stage-1 luminosity ~10^{33} cm^{-2} s^{-1} (~1fb^{-1} /month)

fsPHENIX = “forward” sPHENIX ~2022-23



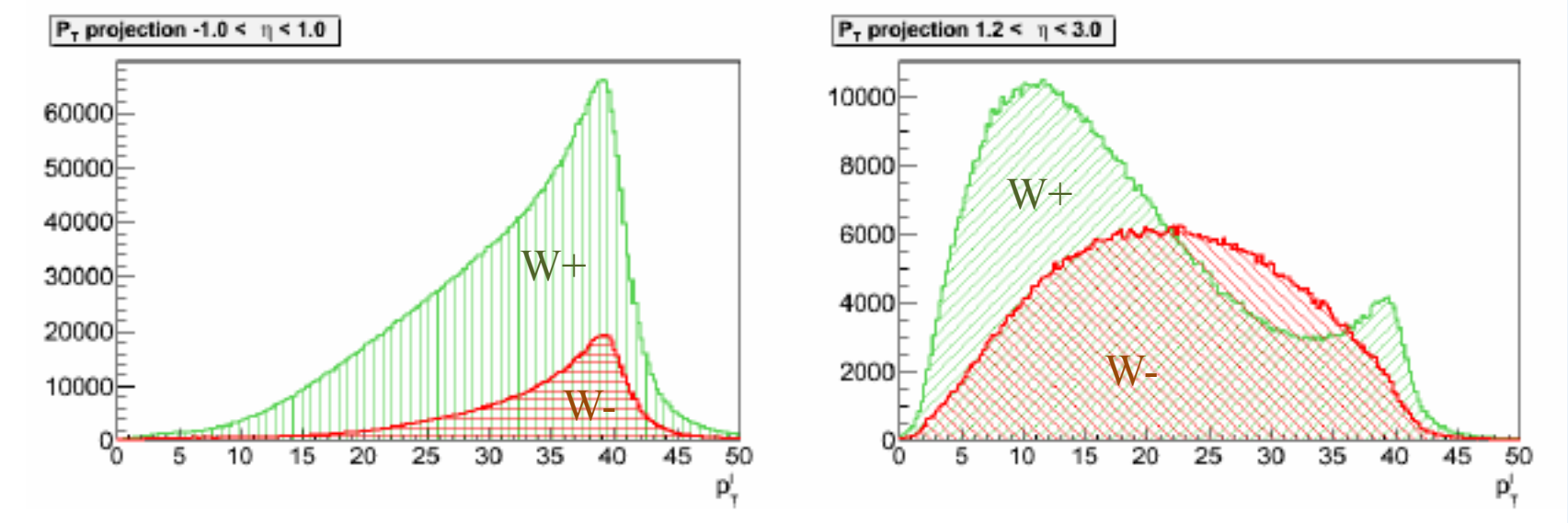
sPHENIX +
PHENIX reconfigured: forward Si tracker and Muon ID
EIC Detector forward systems: GEMs and HCal
90% of the cost common with EIC detector





- Explore the source of large A_N in hadronic collisions
- Critical TMD test with polarized DY –> $\mu\mu$
- Cold nuclear matter studies in pA

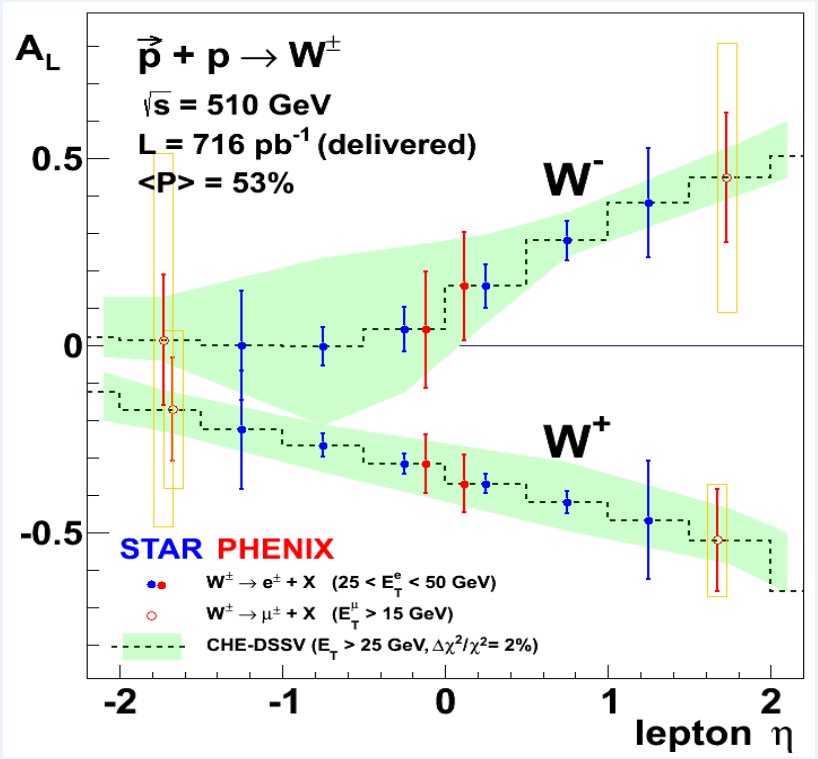
W: Central vs Forward region



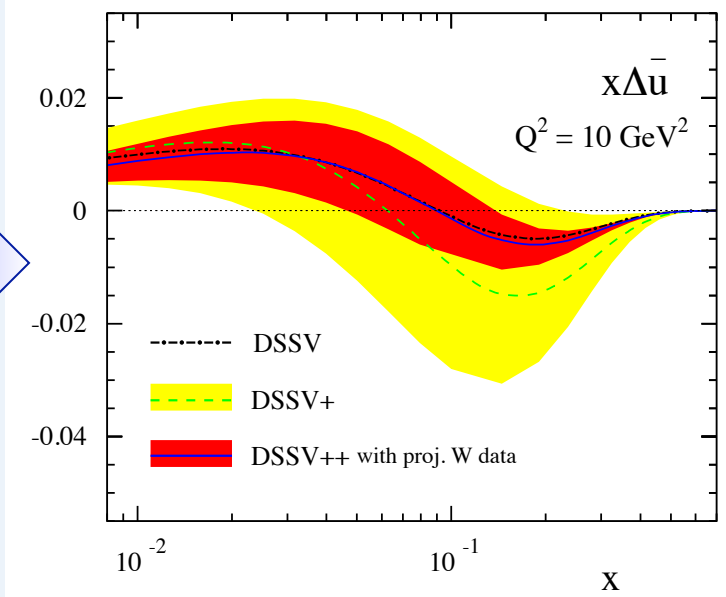
Clear Jacobian peak
at central rapidities

Suppressed/No Jacobean peak
at forward rapidities

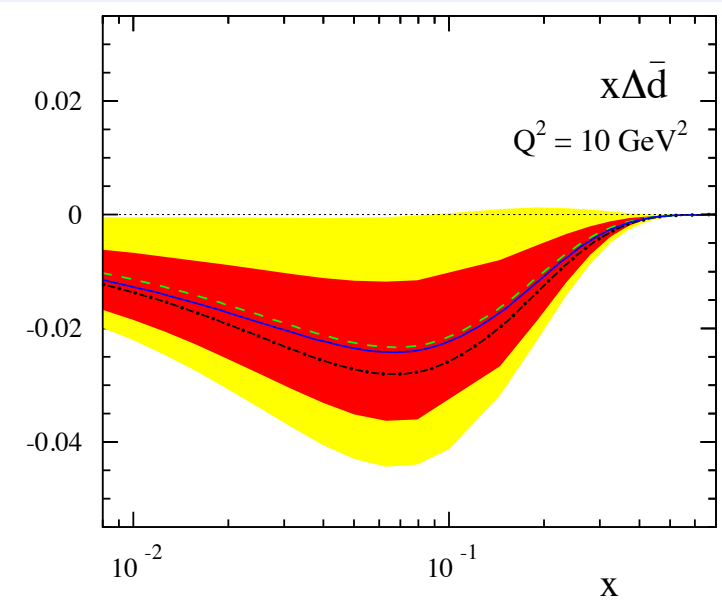
W: Projection



$\Delta\bar{u}$



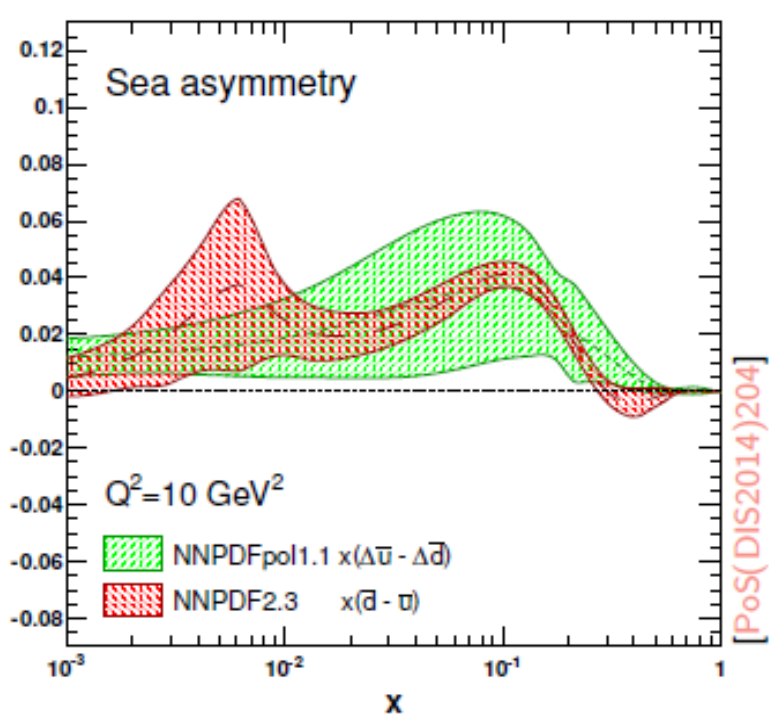
$\Delta\bar{d}$

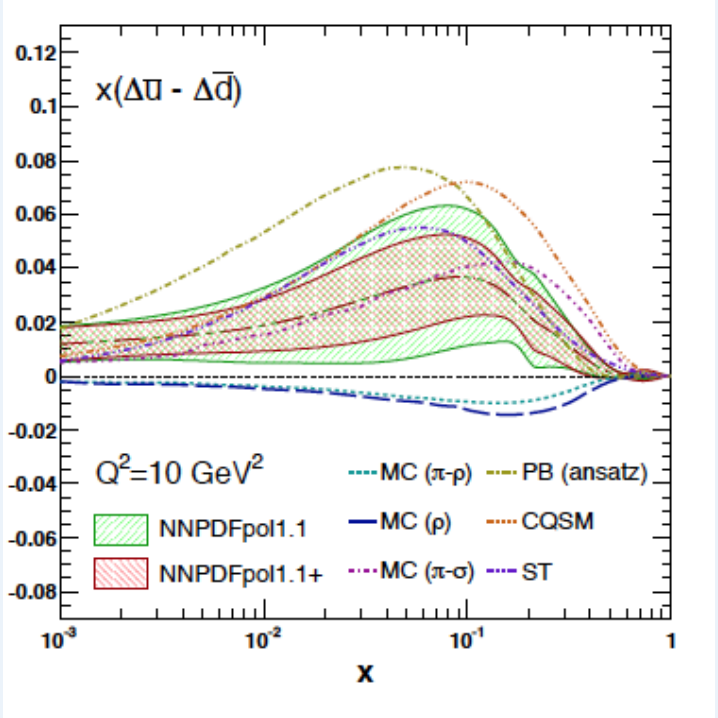


RHIC W-data will give a significant constraint on anti-quark polarization in the proton

Symmetry breaking in polarized sea?

Unpolarized sea is not symmetric



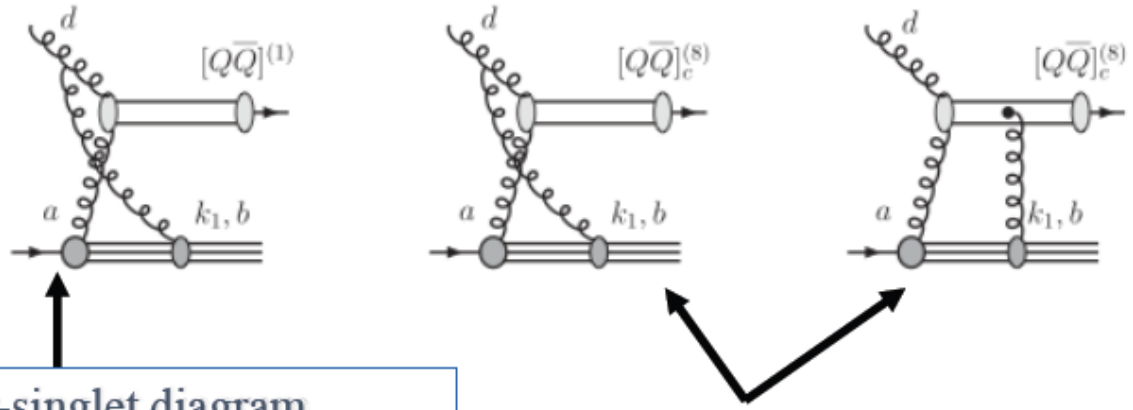


Polarized sea symmetric may be broken too!

Already available data (Run13) will improve the measurement further

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 $A_N = 0$

To measure at RHIC

Initial State:

Sivers/Twist3 mechanism

- A_N for jets, direct photons
- A_N for heavy flavor ➔ gluon
- A_N for W, Z, DY

Sensitive to correlations
proton spin – parton **transverse motion**

Not universal between SIDIS & pp

Final State:

Collins mechanism

- Hadron azimuthal asymmetry in jet
- Hadron pair azimuthal asymmetry (Interference fragmentation function)

Sensitive to
transversity x spin-dependent FF

Universal between SIDIS & pp & e+e-

Other mechanisms

- Diffraction

Fundamental Role of Sivers

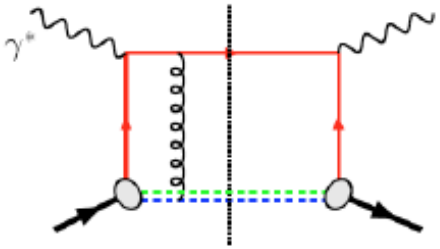
Brodsy, Hwang, Schmidt (Phys.Let.B530,99):

Sivers function in DIS can arise from interference with diagrams with soft gluon exchange between outgoing quark and target spectator

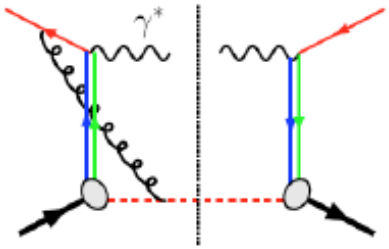
Collins (Phys.Let.B536,43):

Sivers asymmetry is revered in sign in Drell-Yan process

DIS: attractive



Drell-Yan: repulsive

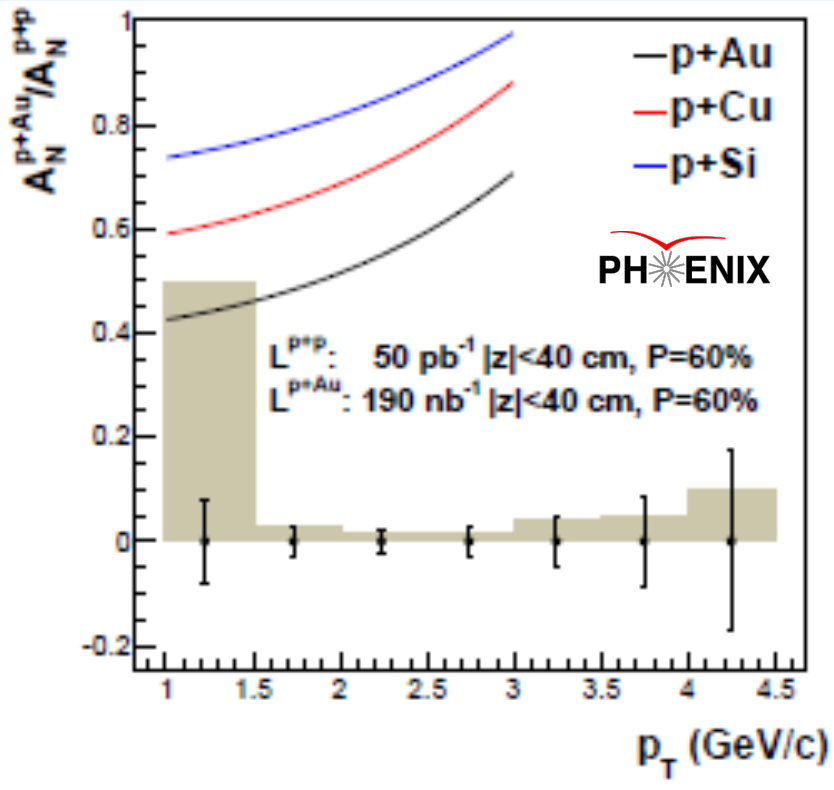


$$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$$

Or W/Z production

Critical test for our understanding of TMD's and TMD factorization

π0 A_N in pA

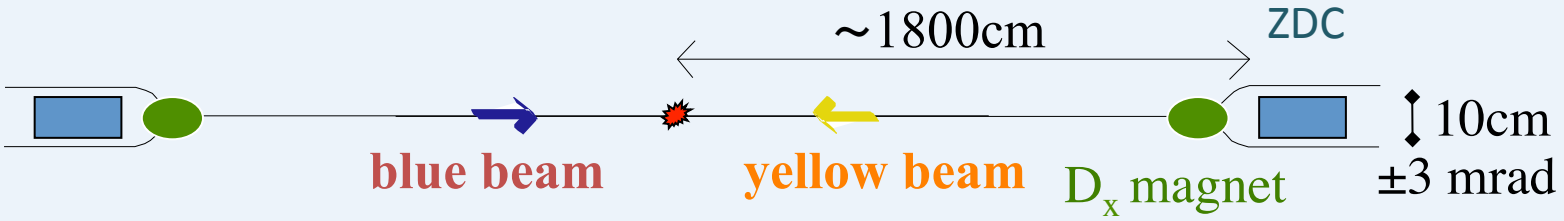


Probing gluon saturated matter, Color Glass Condensate (CGC) with polarized protons

Kang, Yuan: PRD84, 034019
Kovchegov, Sievert: PRD86, 034028

- Unique RHIC possibility p$^{\uparrow}$A
- Synergy between CGC based theory and transverse spin physics
- Suppression of A_N in p$^{\uparrow}$A provides sensitivity to Q_s
- Data already collected in Run-2015!

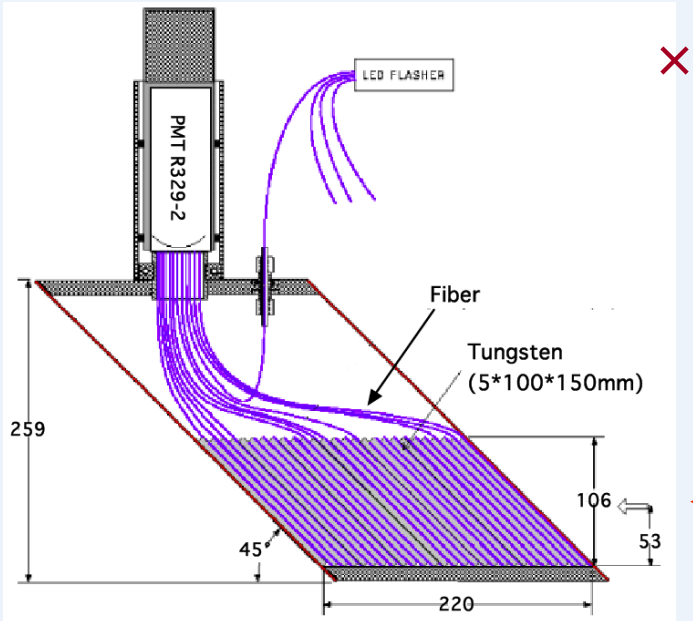
Forward Neutron Measurements



Hadron sampling calorimeter made of Tungsten plate and fibers

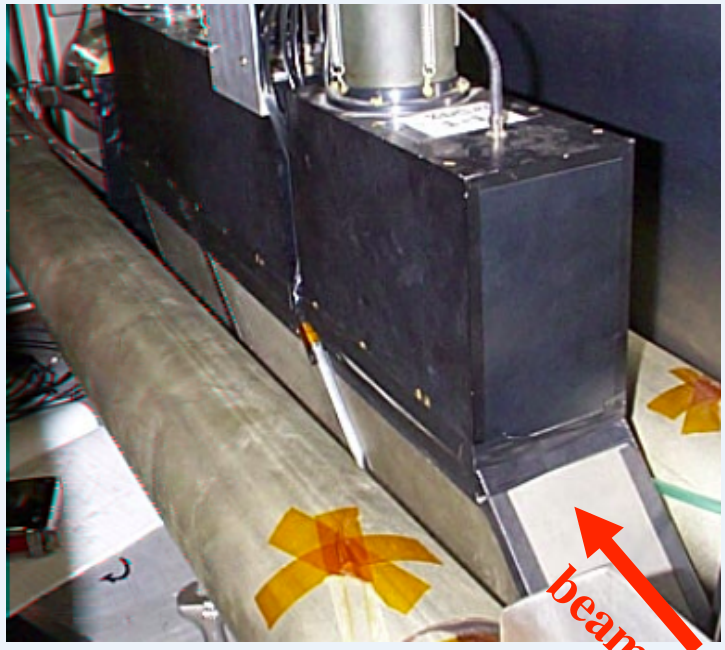
Detects neutrons and measure their energy

$5.1\lambda_T$ $149X_0$ (3 ZDCs), Energy resolution ~ 20% @ 100GeV



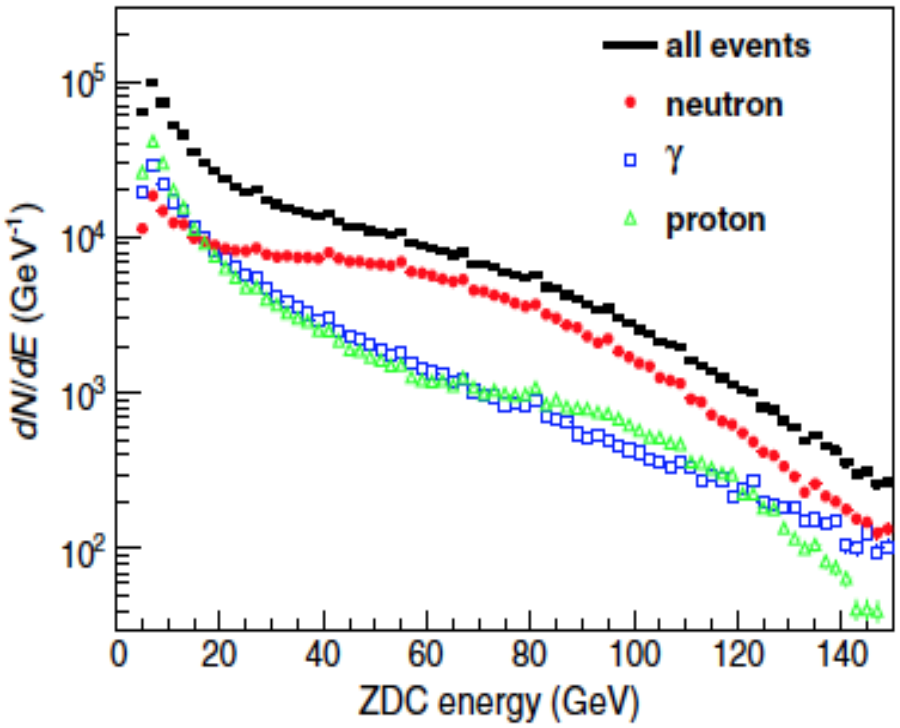
× 3 modules ➔

beam



Neutron ID

ZDC energy response
from PYTHIA+GEANT



$40 < E_{ZDC} < 120$ GeV

Minimizes background contribution

Charged veto

Rejects charged background

No/little energy in ZDC-2

Suppresses photon background

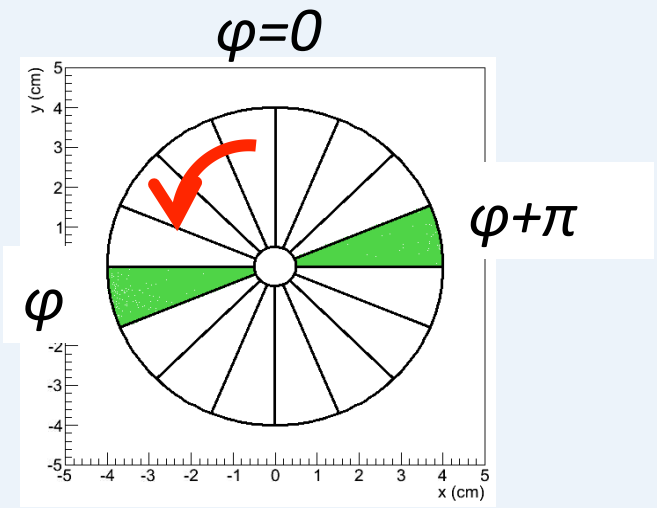
>1 SMD strip fired

Suppresses photon background

Neutron purity >97%

Residual background: protons, K^0

A_N Measurements



$$A = A(\varphi) = A_N \cdot \sin(\varphi)$$

$$N_L \rightarrow N(\varphi)$$
$$N_R \rightarrow N(\varphi+\pi)$$

- Detector Left-Right asymmetries or Spin Up-Down asymmetry

$$A_N = \frac{d\sigma_L^{\uparrow} - d\sigma_R^{\uparrow}}{d\sigma_L^{\uparrow} + d\sigma_R^{\uparrow}} = \frac{1}{P}\frac{N_L^{\uparrow} - R_{\det} N_R^{\uparrow}}{N_L^{\uparrow} + R_{\det} N_R^{\uparrow}}, \quad R_{\det} = \frac{\varepsilon_L}{\varepsilon_R}$$

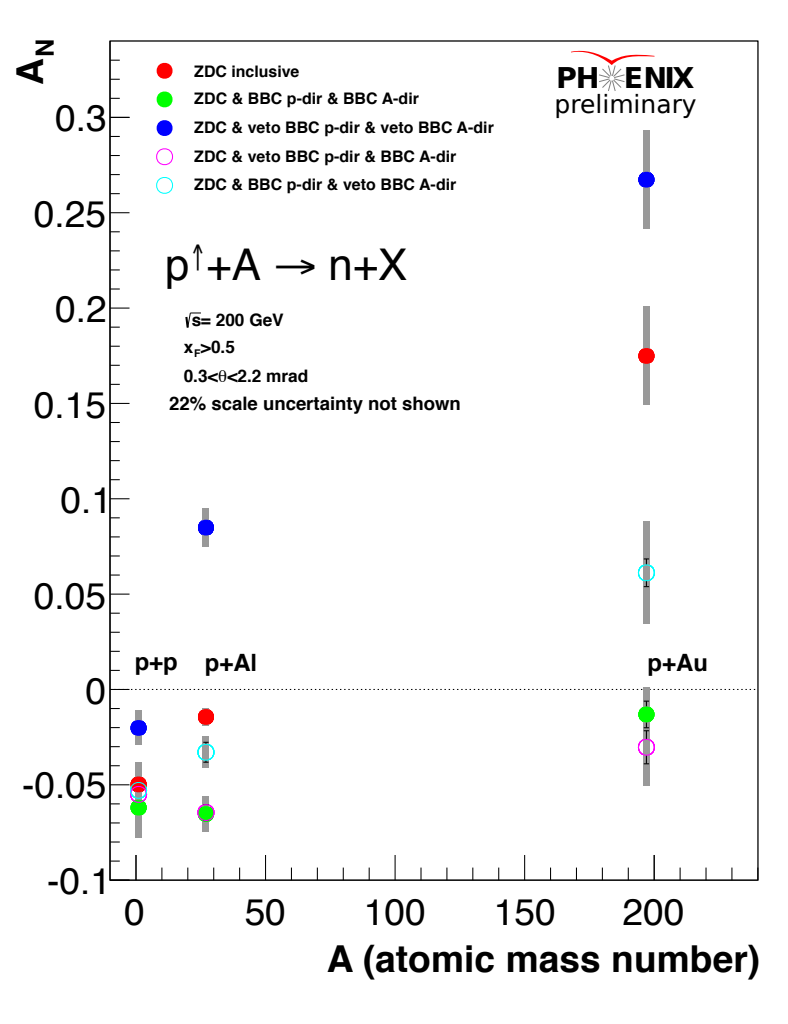
$$A_N = \frac{d\sigma_L^{\uparrow} - d\sigma_L^{\downarrow}}{d\sigma_L^{\uparrow} + d\sigma_R^{\uparrow}} = \frac{1}{P}\frac{N_L^{\uparrow} - R_{lum} N_L^{\downarrow}}{N_L^{\uparrow} + R_{\det} N_R^{\uparrow}}, \quad R_{lum} = \frac{L^{\uparrow}}{L^{\downarrow}}$$

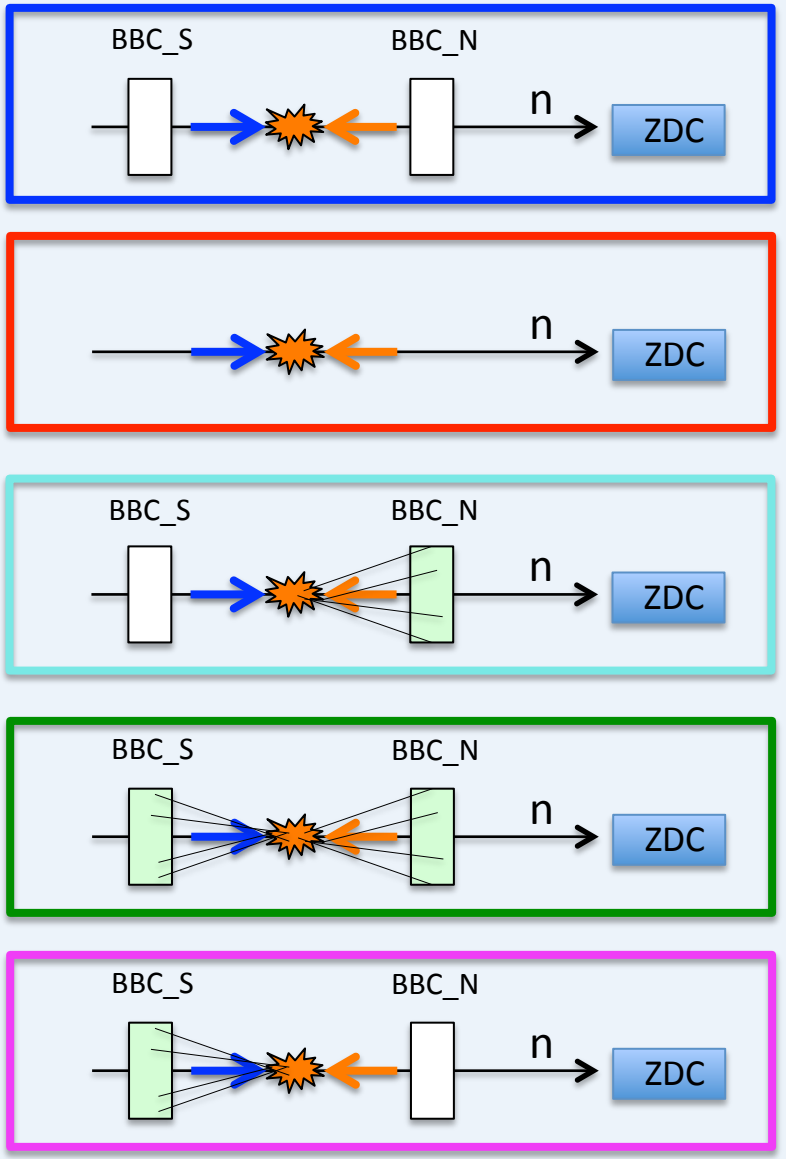
- Square root formula: cancels acceptance and luminosity effects

$$A_N = \frac{1}{P}\frac{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} \cdot N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} \cdot N_R^{\uparrow}}}$$

ZDC: η>6.5

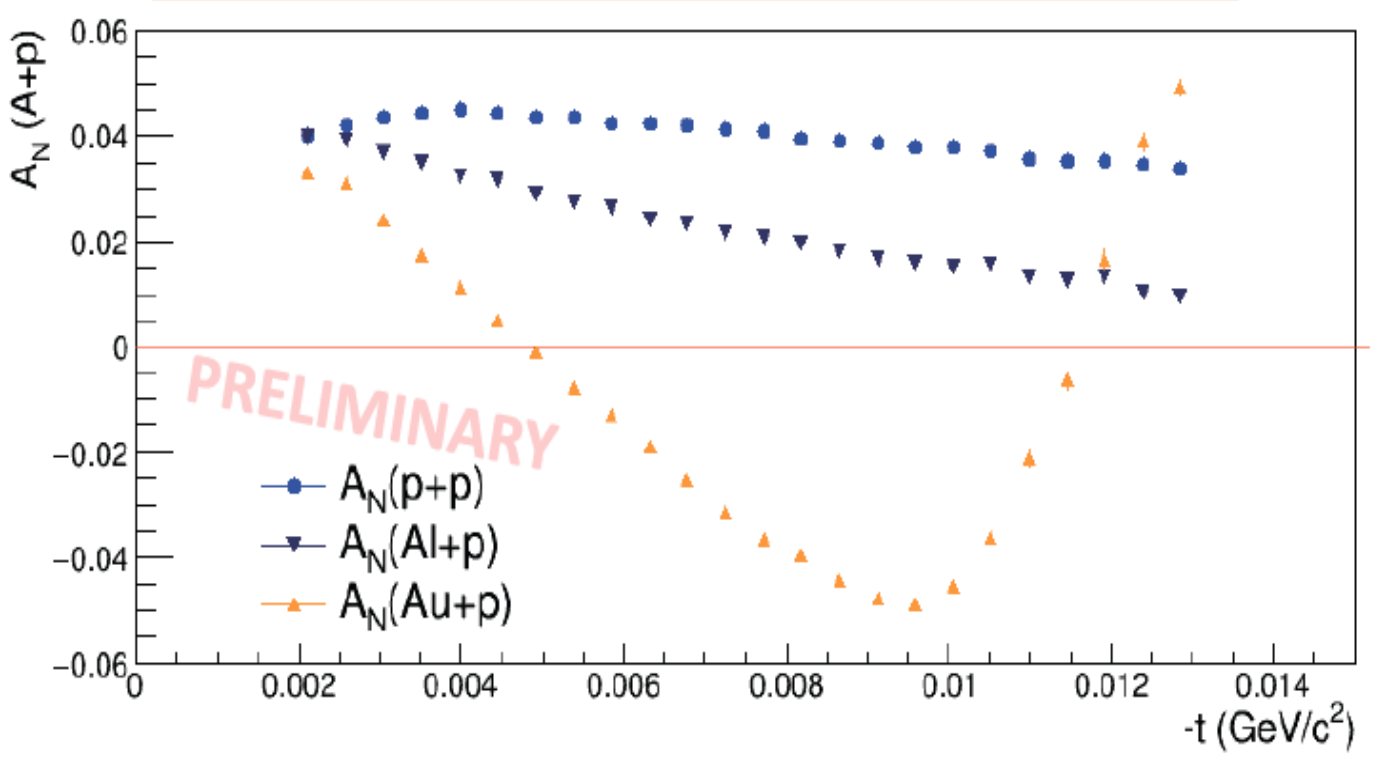
BBC: 3.0<|η|<3.9





New CNI measurements from Run15

Run15 Hjet results: Oleg Eyser (PSTP-2015 workshop)

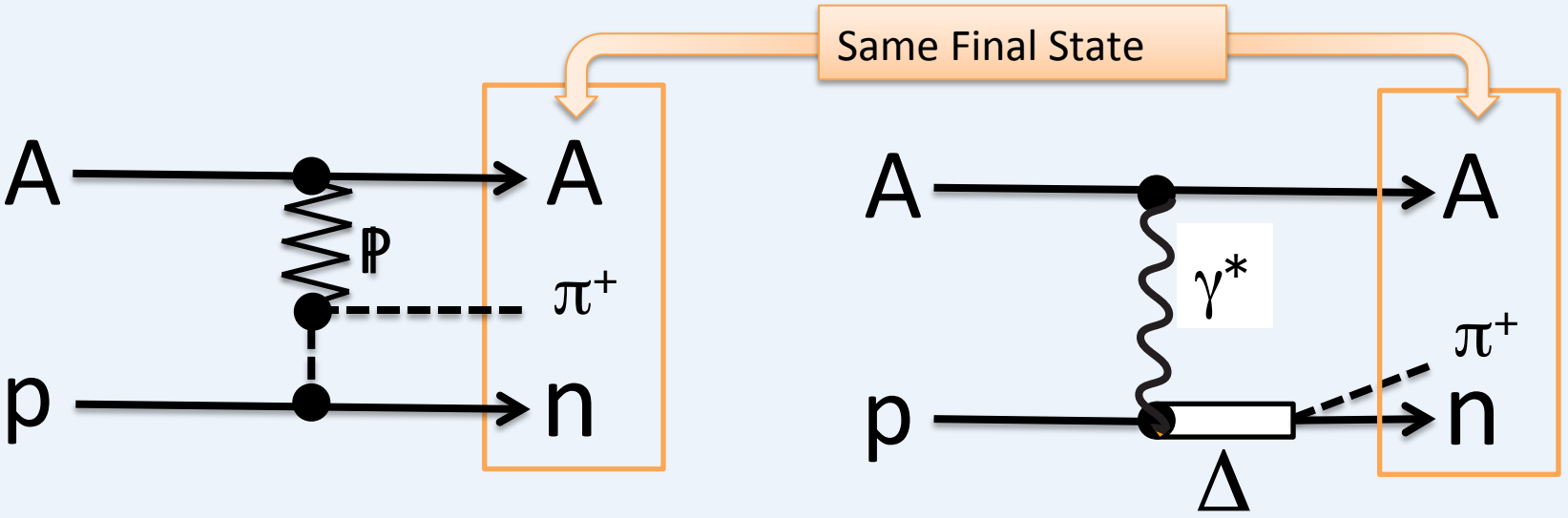


Fixed target with 100 GeV p(A) beam

Forward neutron measurements are at $t \sim 0.02$ - 0.5 (GeV/c) ^{2}

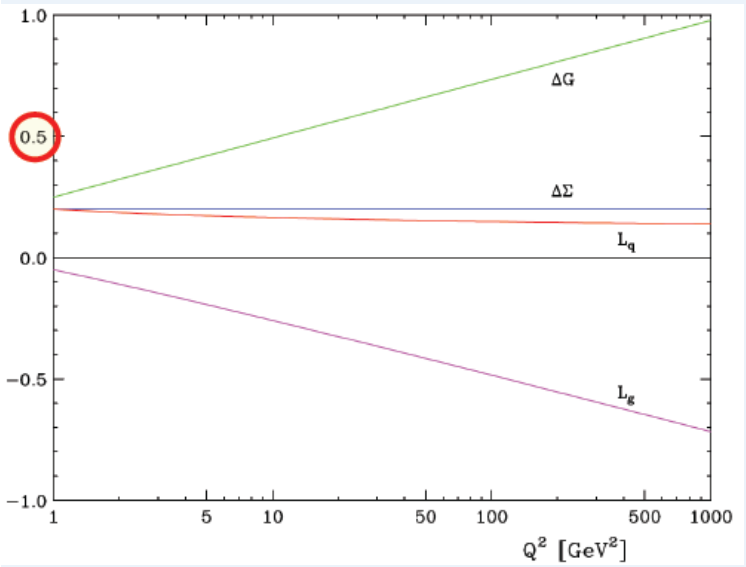
Also strong A-dependence

Coulomb–Nuclear Interference in Forward Neutron Production



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

Q2 dependence



ΔG is dynamic value – Q^2 dependent
ΔG can be large at large Q^2 (and can be >>1/2) no matter how small it is at some low Q^2
Large ΔG at large Q^2 is compensated by L_g

$$\frac{1}{2}^{proton} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$$

$$\frac{1}{2}\Delta\Sigma + L_q = \frac{1}{2}\frac{3n_f}{3n_f + 16} = 0.18$$

$$\Delta g + L_g = \frac{1}{2}\frac{16}{3n_f + 16} = 0.32$$