# PHENIX recent results from polarized pp and pA collisions

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

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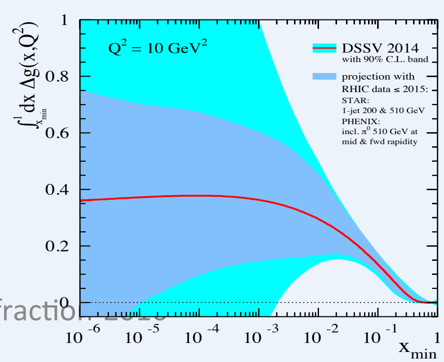
September 2-8, 2016, Acireale (Italy)
International Workshop on Diffraction
in High-Energy Physics

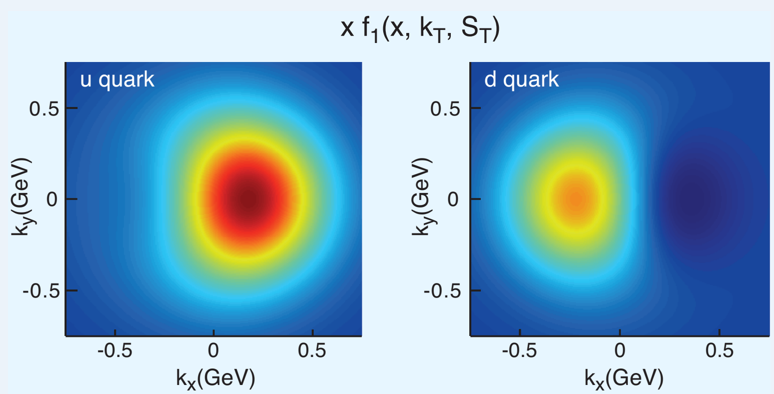
# RHIC Spin

arXiv: 1602.03922

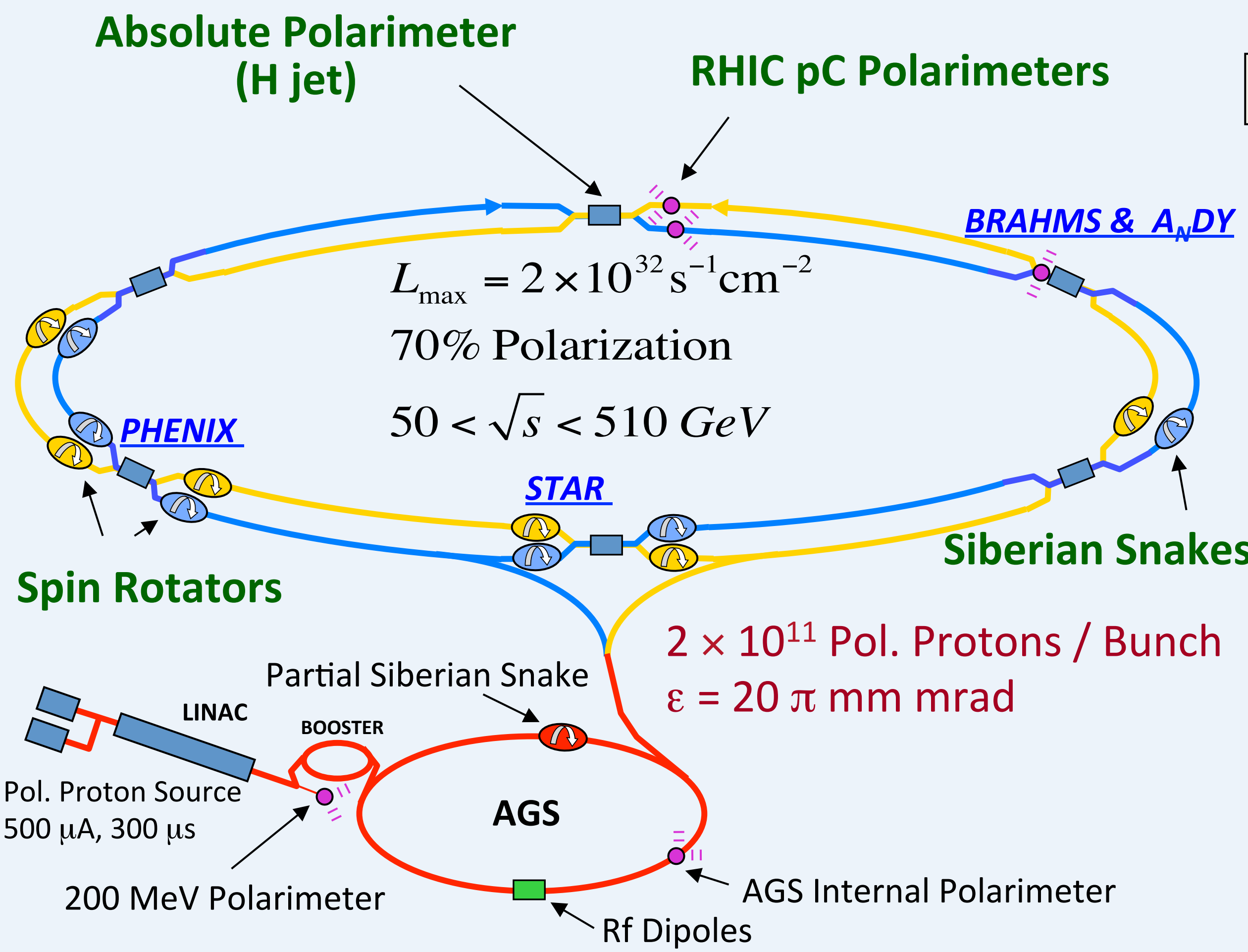

- How do quarks and gluons build the proton spin ½
- What do transverse spin phenomena teach us

arXiv: 1501.01220

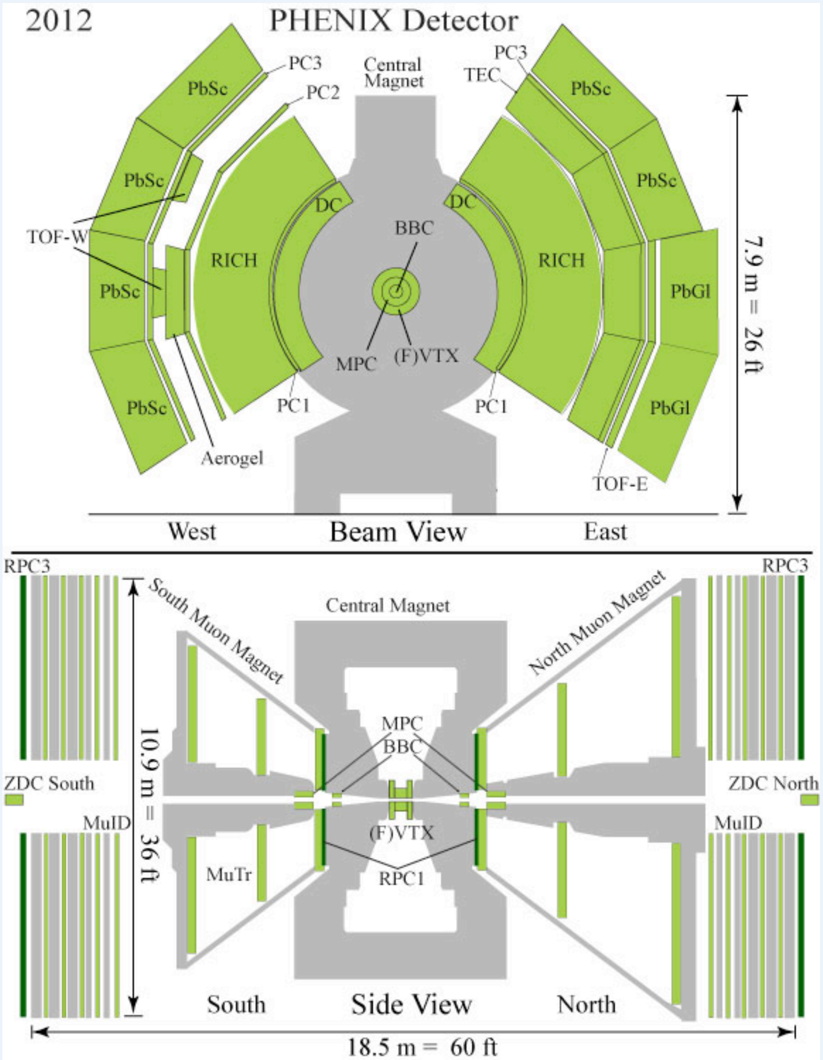
# PHENIX Spin @ RHIC




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




$\pi^0, \gamma, \eta$

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

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

Muon Id/Muon Tracker
FVTX

## Relative Luminosity

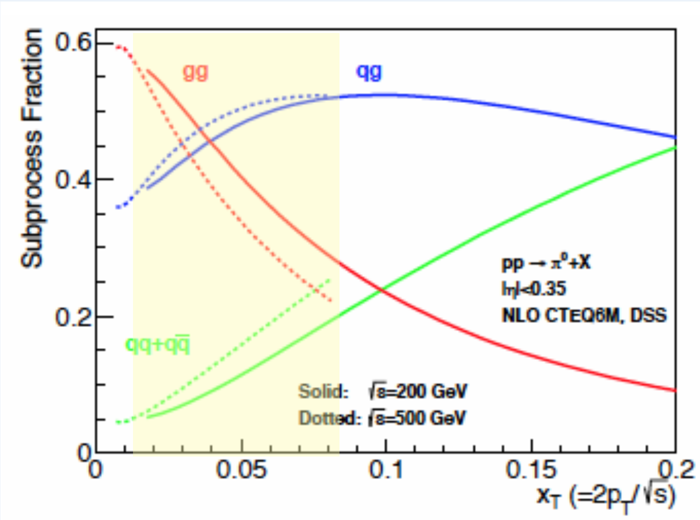
Beam Beam Counter (BBC)
Zero Degree Calorimeter (ZDC)

## Local Polarimetry – ZDC & SMD

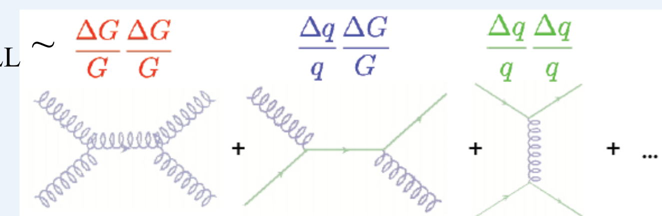
Spin direction control

# ΔG: π0 $A_{LL}$

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



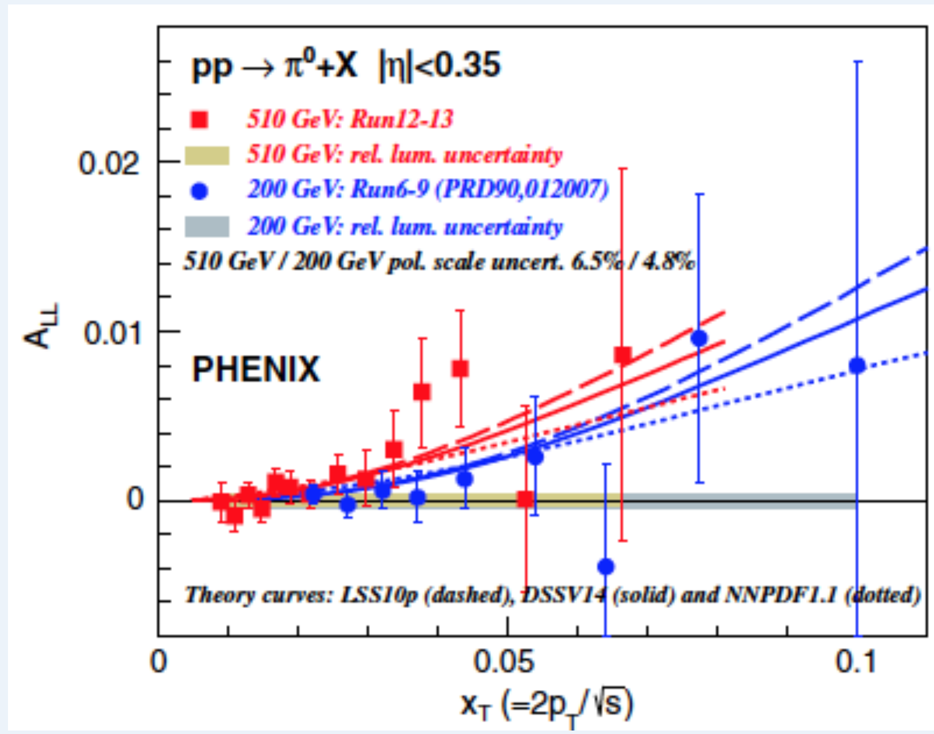

$A_{LL} \sim$




## The most abundant probe in PHENIX

(triggering + identification capability)

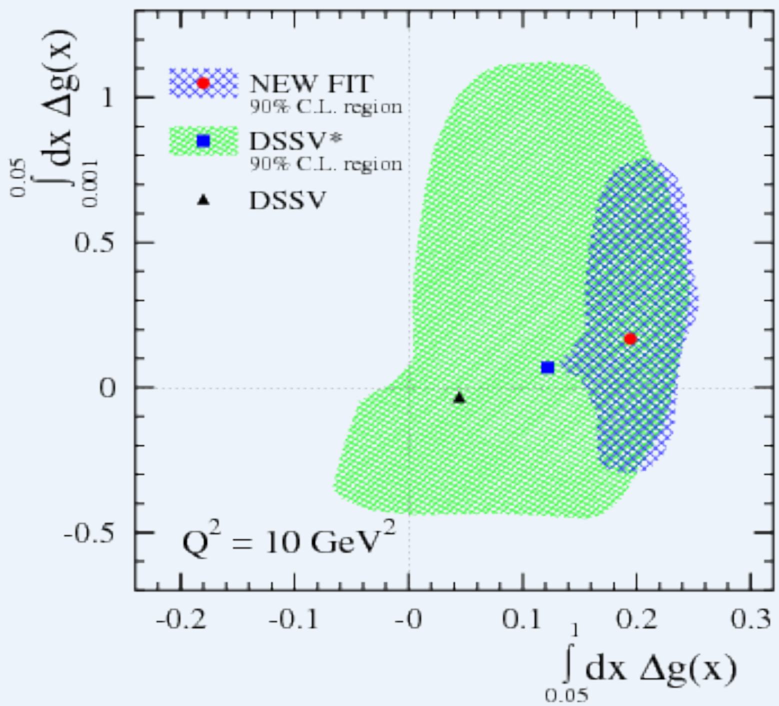
PRD93, 011501 (2016)




**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

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

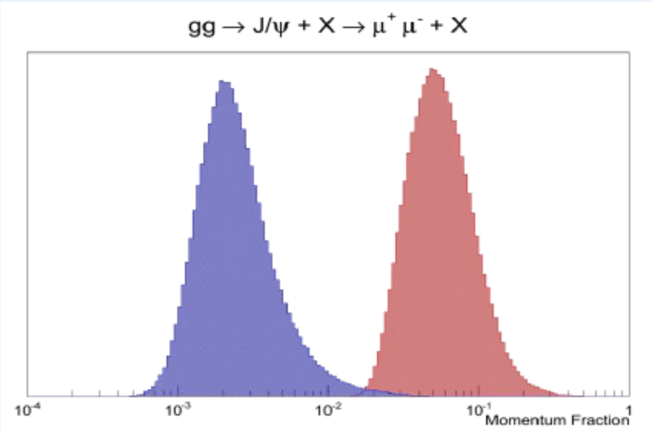
Significant non-zero Δg(x) in the kin. region probed by RHIC
Similar result from another global fit NNPDF
Still huge uncertainty in unmeasured region (x<0.05)
=> Measurements at higher √s and forward rapidity

# ΔG: Towards lower x

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

pp → *J/ψ* at √s=510 GeV 1.2<|η|<2.4

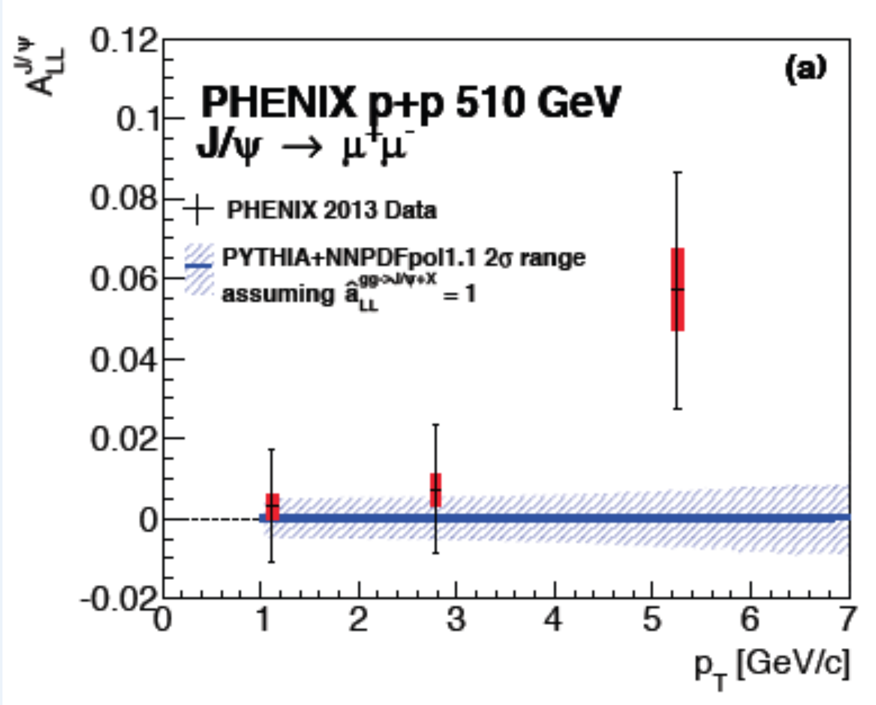
arXiv: 1606.01815




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

Get access to x down to $2\times10^{-3}$

Already constrained by RHIC



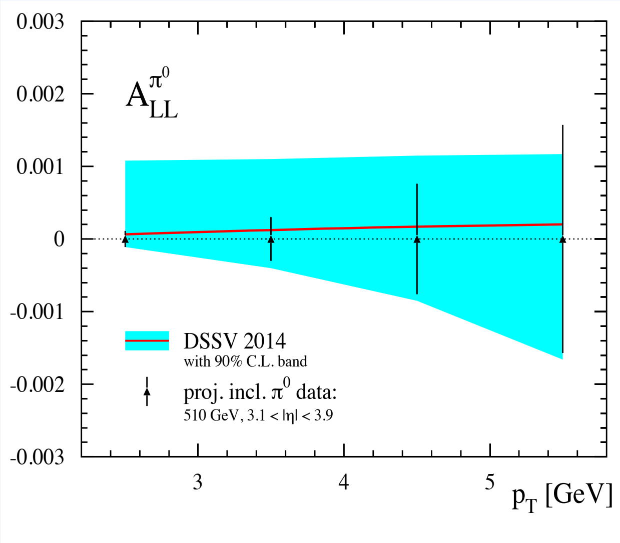

*J/ψ* production mechanism uncertainty
Not yet in the global fit

# ΔG: Towards lower x

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

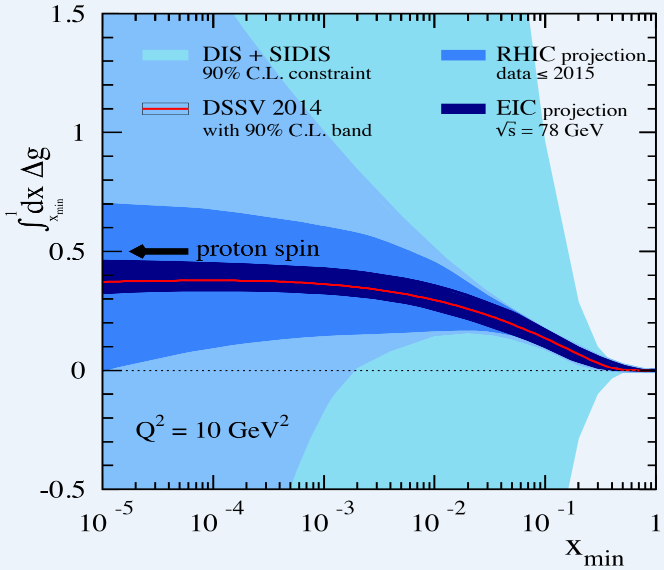
Projection

π0: 3.1<|η|<3.9




From available PHENIX+STAR data from 2011-15

Aschenauer, Stratmann,Sassot
arXiv: 1509.06489




π0 in forward region at √s=510 GeV:

Based on collected 2013 data

Probes lower x down to $\sim 10^{-3}$

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

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

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

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

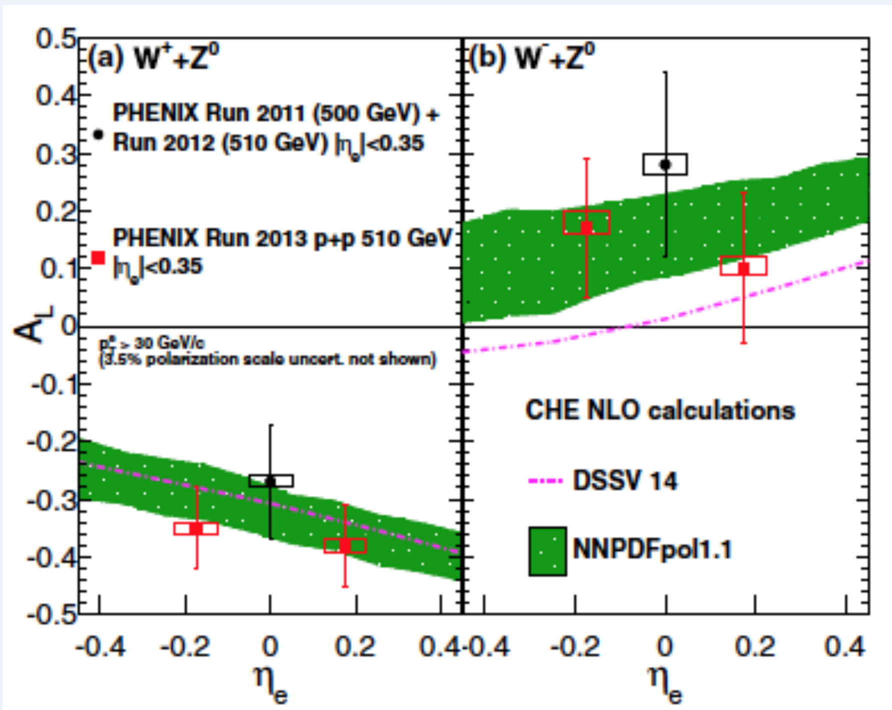
# Δq-bar: W± → e±

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

|η|<0.35

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

PRD93, 051103 (2016)



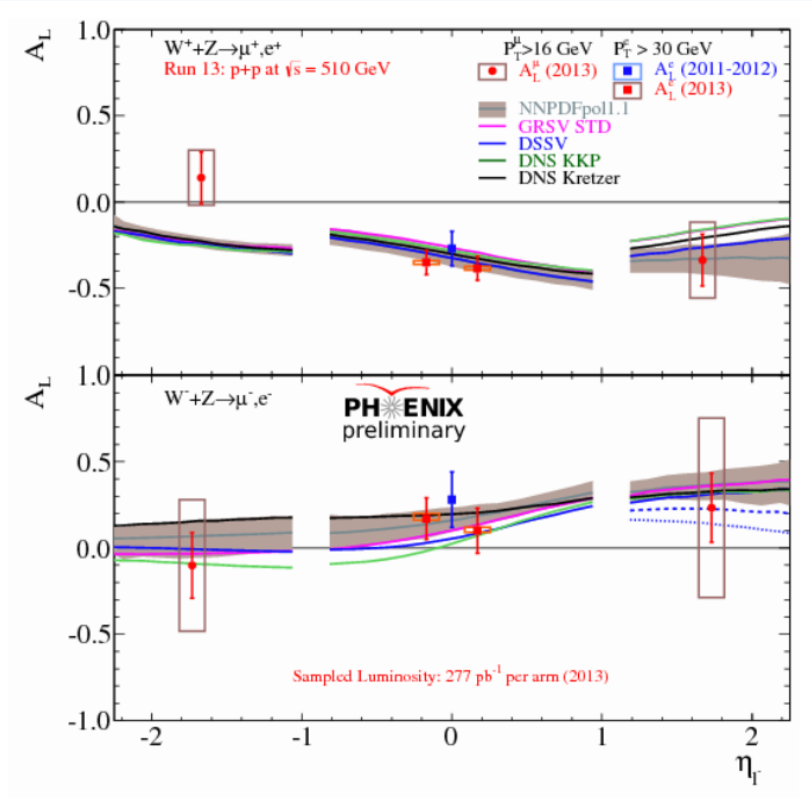
$$d_L \bar{u}_R \rightarrow W^-$$
$$u_L \bar{d}_R \rightarrow W^+$$

# Δq-bar: $W^\pm \rightarrow \mu^\pm$

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

$1.2<|\eta|<2.4$

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



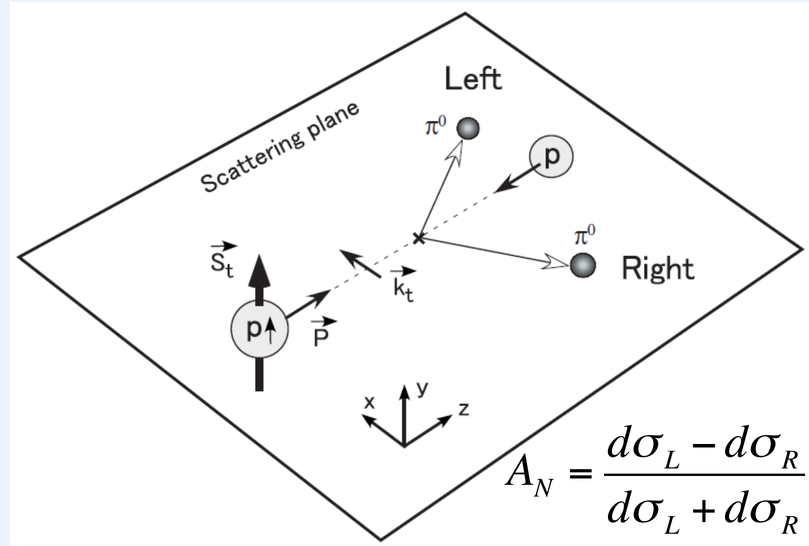

Uncertainties are large due to sizable background (S/B= 0.2−1)

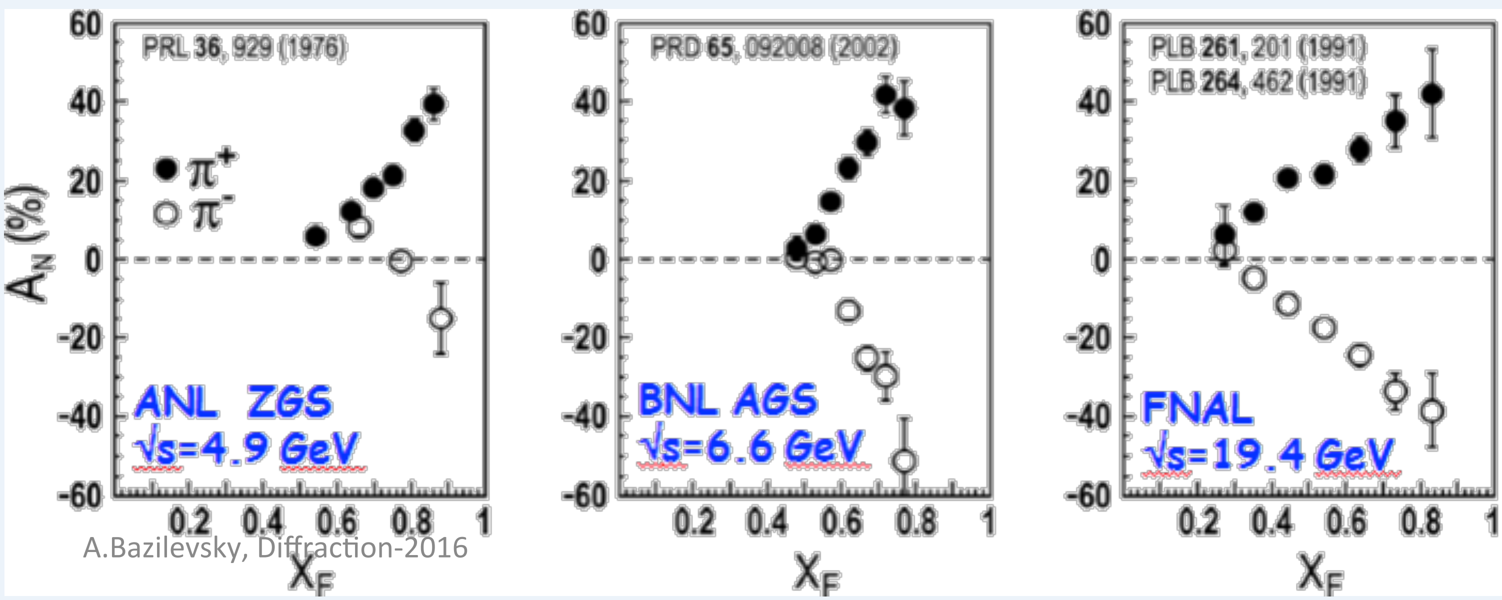
Working to reduce syst. uncertainties

Publication in preparation

# Transverse Spin Asymmetries

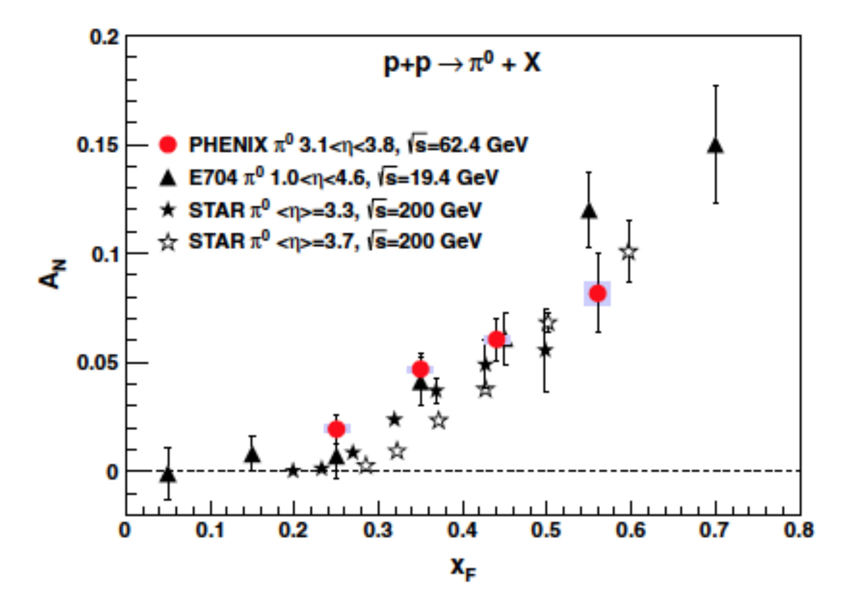
Large Transverse Spin Asymmetries have been observed in $p^{\uparrow}p$



# 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 $\sqrt{s}$

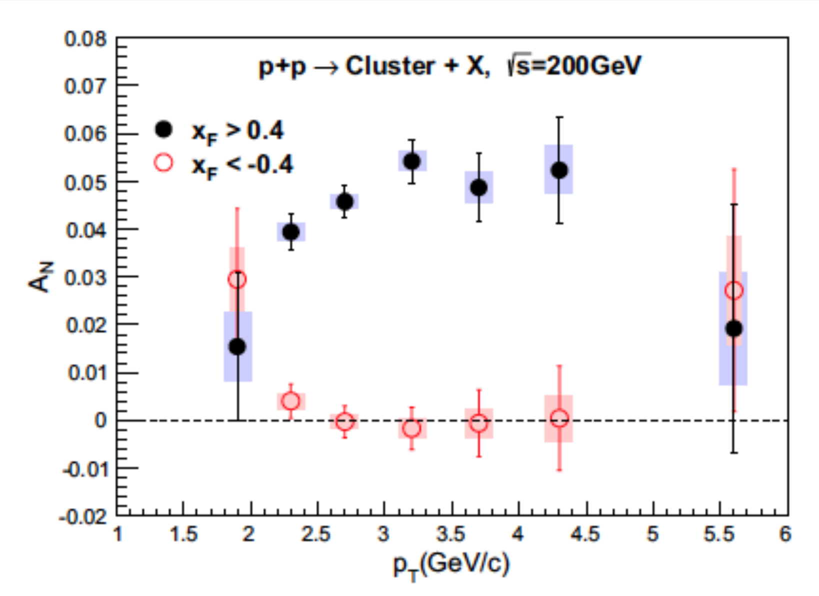
Asymmetries scale with $x_F$

Collinear (higher twist) pQCD predicts

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

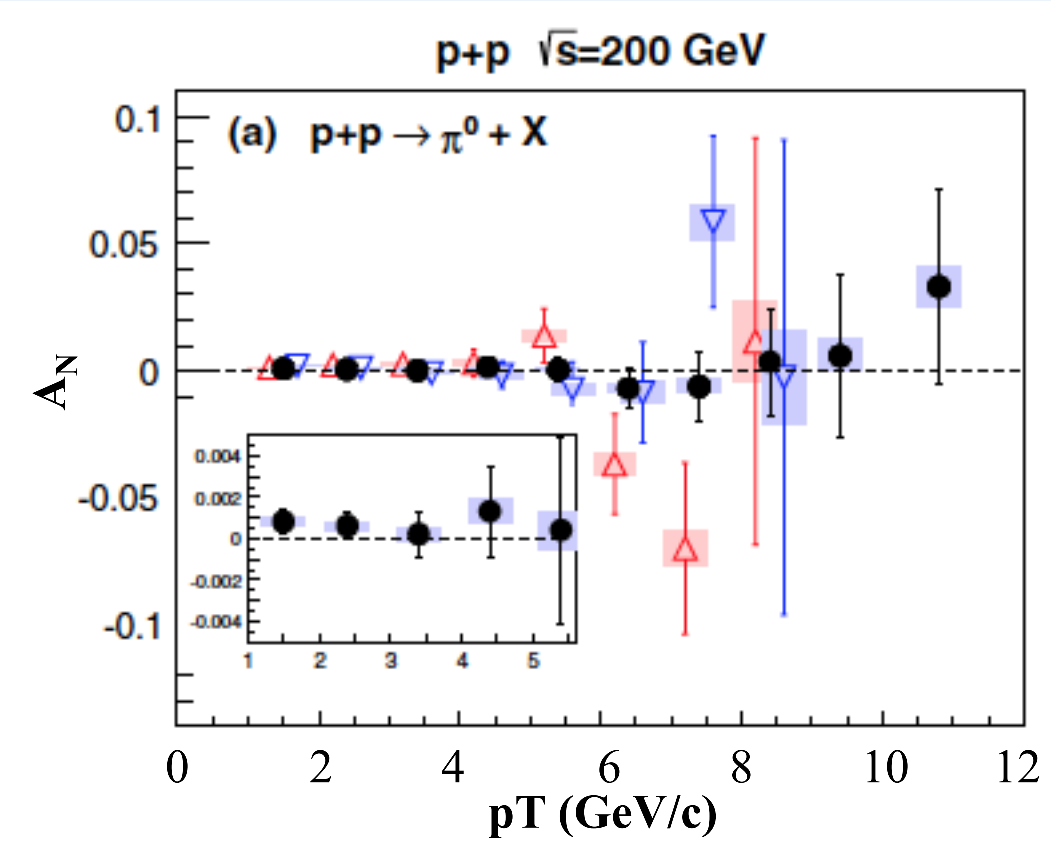
No fall off is observed out to $p_T$ ~5 GeV/c

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 $p_T$

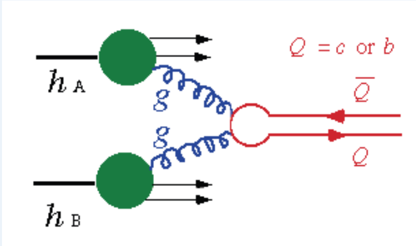
Sensitive to gluons

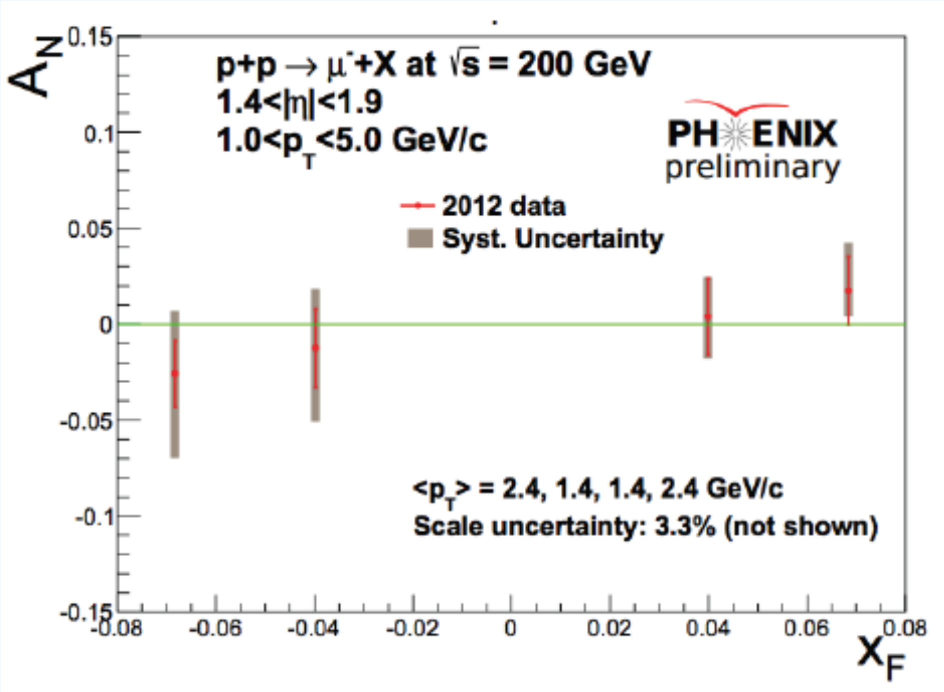
Used to constrain gluon Sivers effect:

Anselmino et al, PRD 74 (2006), 094011

D'Alesio et al, JHEP 1509 (2015), 119

# Heavy Flavor $A_N$




Dominated by gluon-gluon fusion

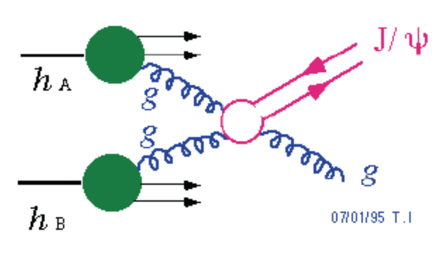
Used to constrain tri-gluon correlation in the Twist-3 collinear framework

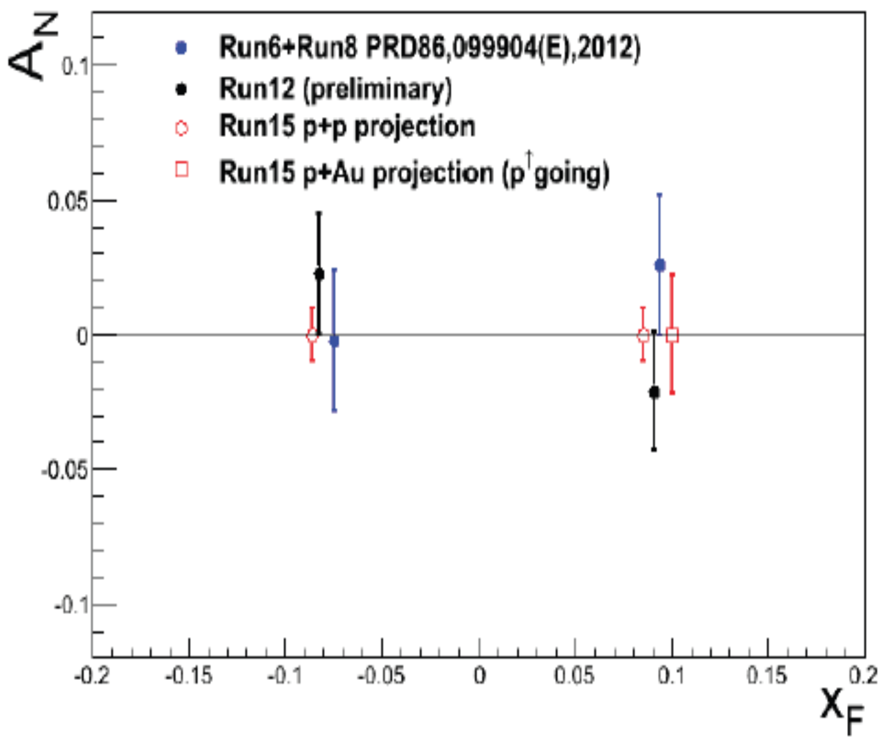
Z.Kang, J.Qiu, W.Vogelsang, F.Yuan, PRD78,114013

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

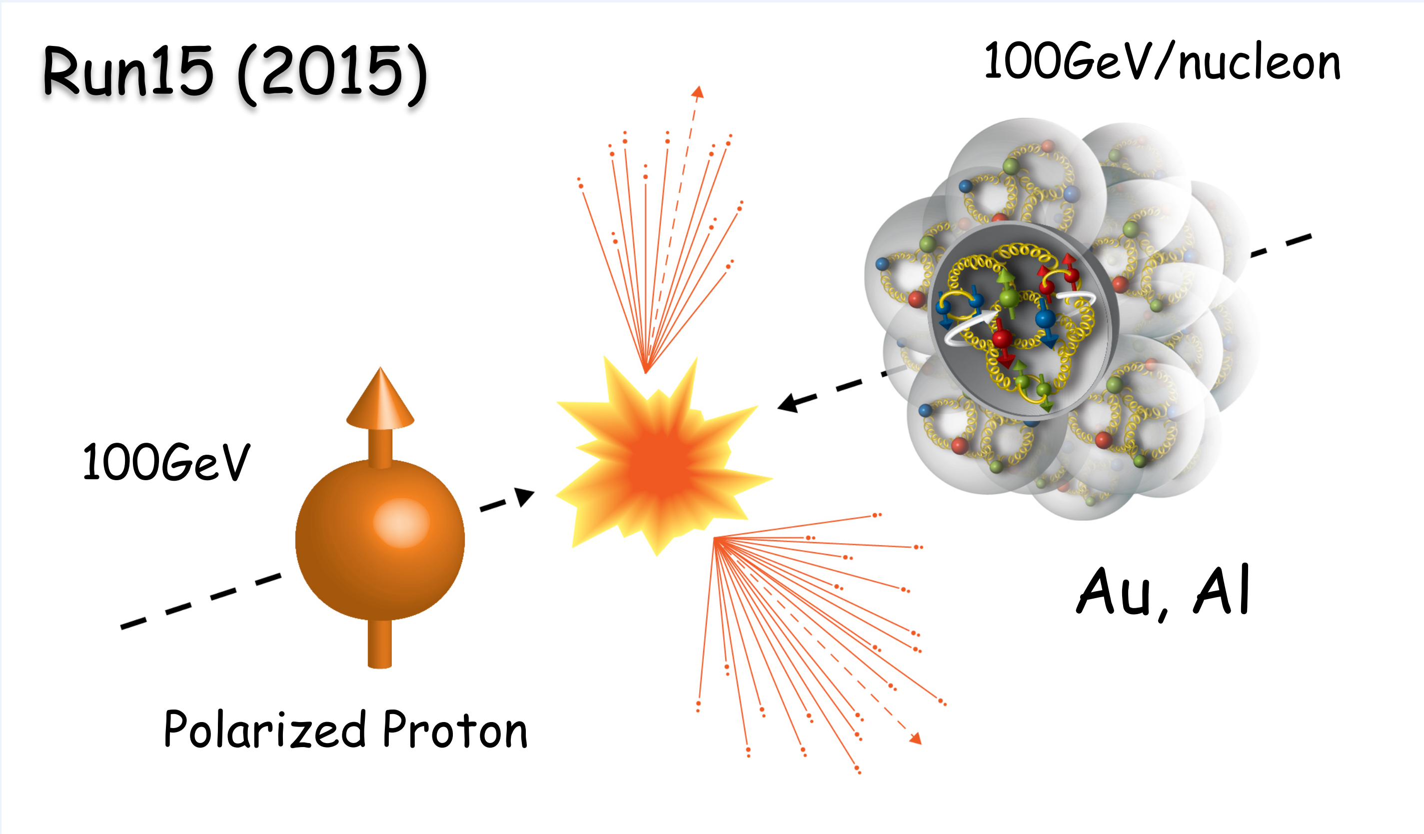
F.Yuan, PRD78, 014024:

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 !!!



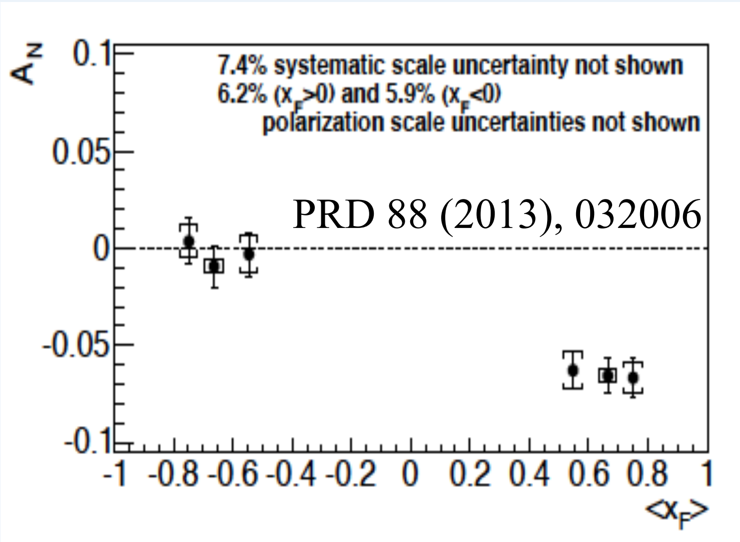

Many results expected soon

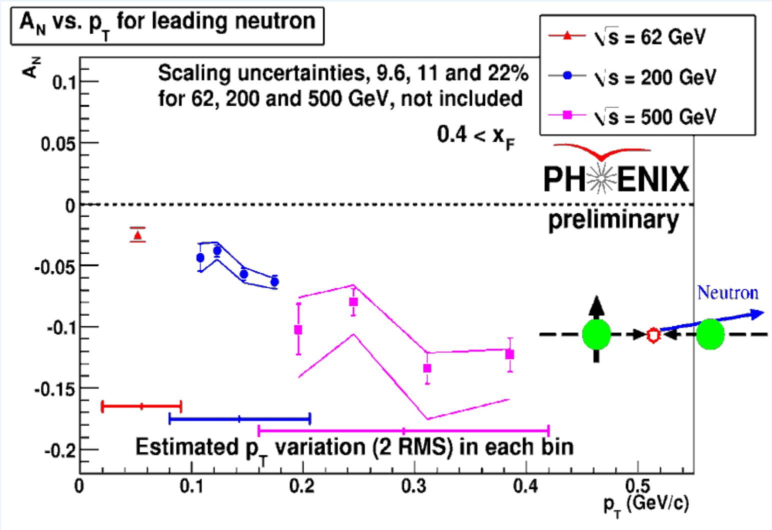
In the following: **first results on very forward neutron $A_N$**

# pp: forward neutron $A_N$

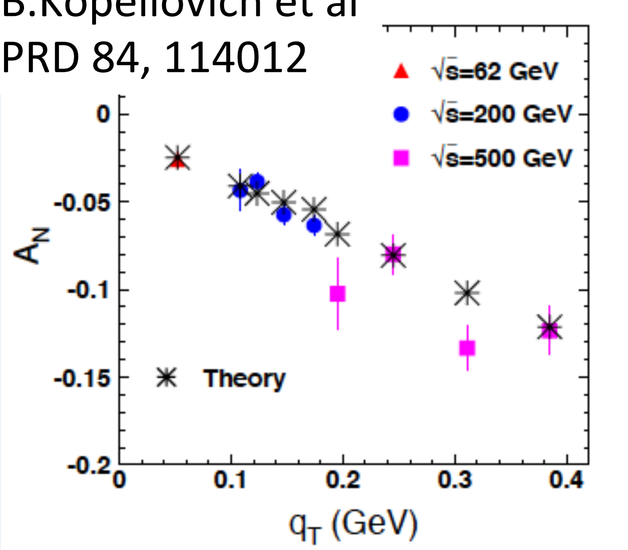
pp→nX, |θ|<2.5mrad

Discovered at RHIC in 2002: PLB 650, 325




B.Kopeliovich et al PRD 84, 114012

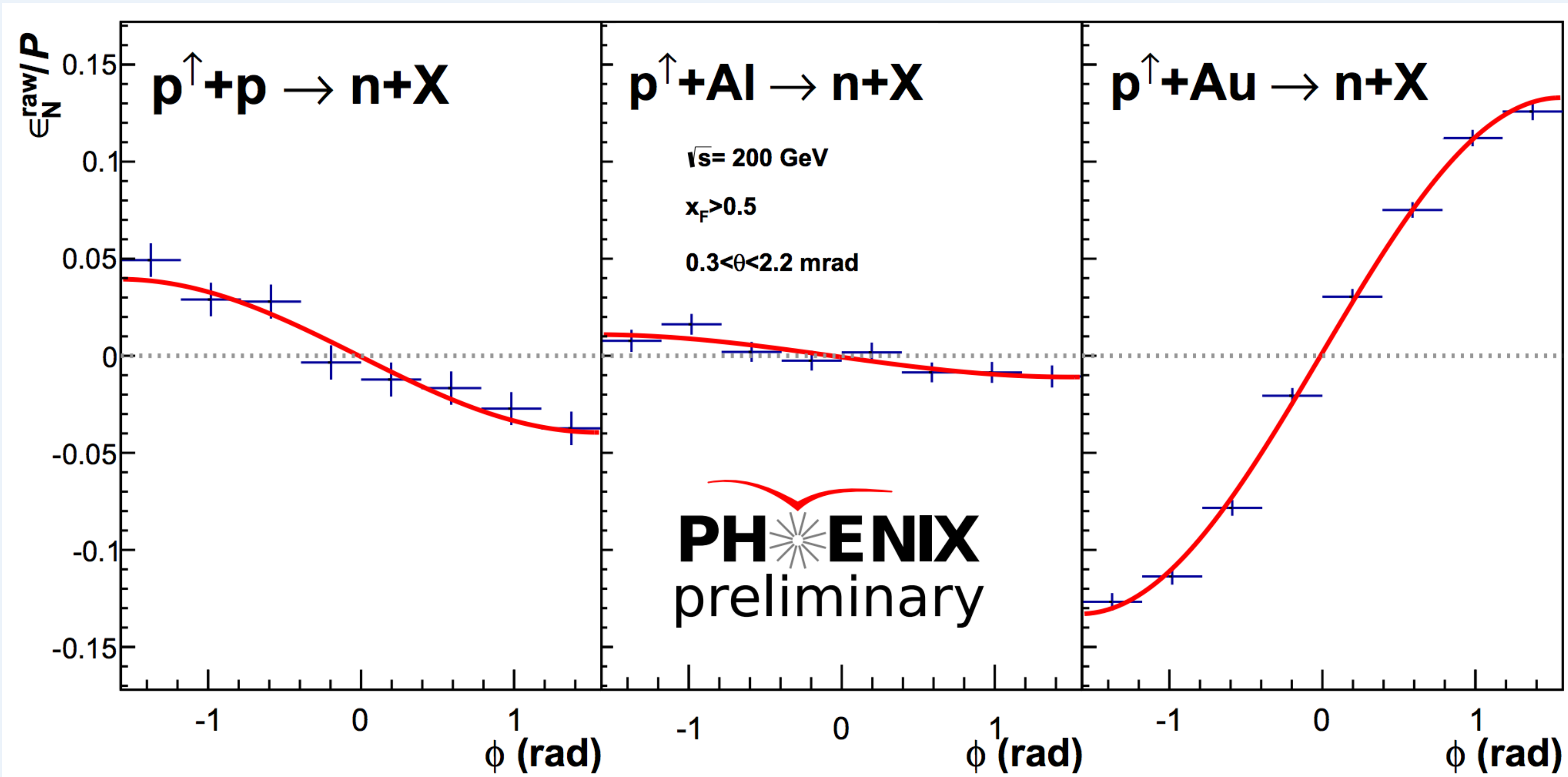



One pion Exchange model in Regge framework model

(interference between pion and a1-reggeon exchange)

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

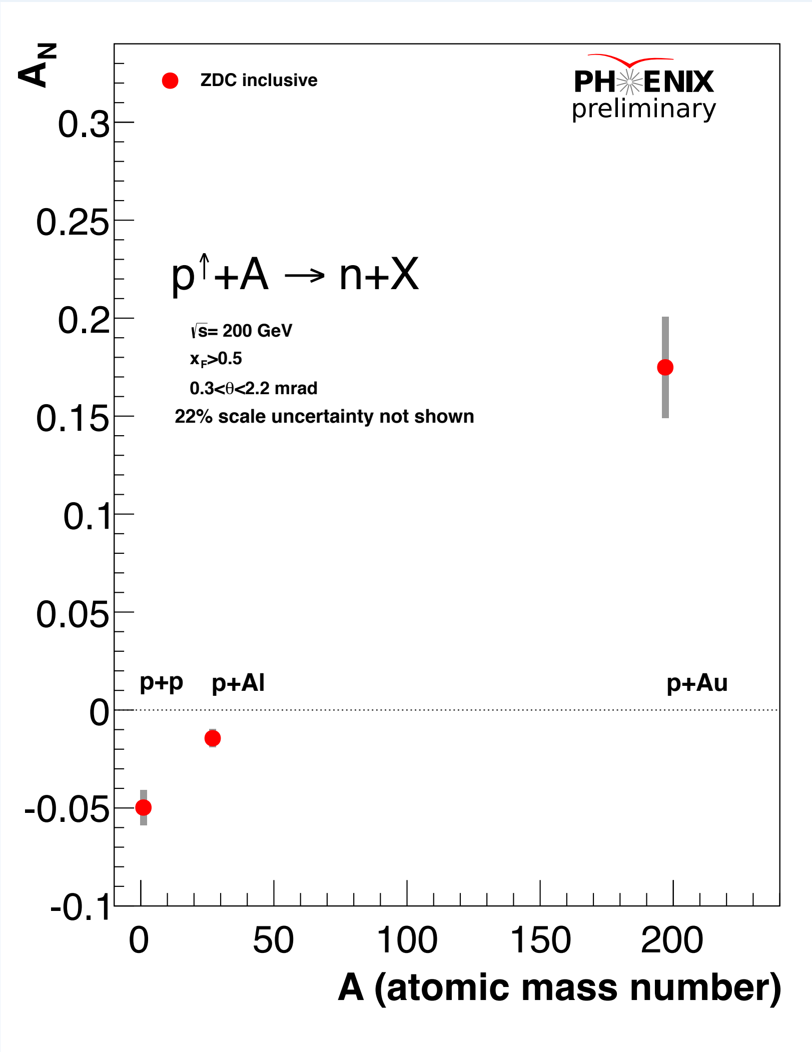
$$A = A(\varphi) = A_N \bullet \sin(\varphi)$$

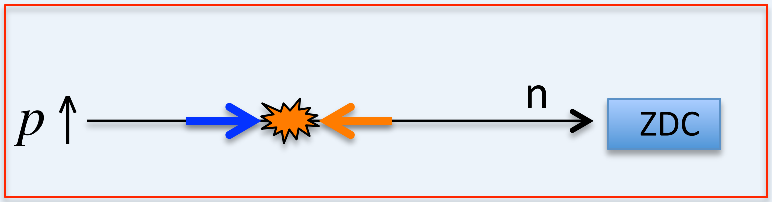



$A_N<0$ $A_N<0$ $A_N>0$

# $A_N$ vs nucleus mass

ZDC: η>6.5
BBC: 3.0<|η|<3.9



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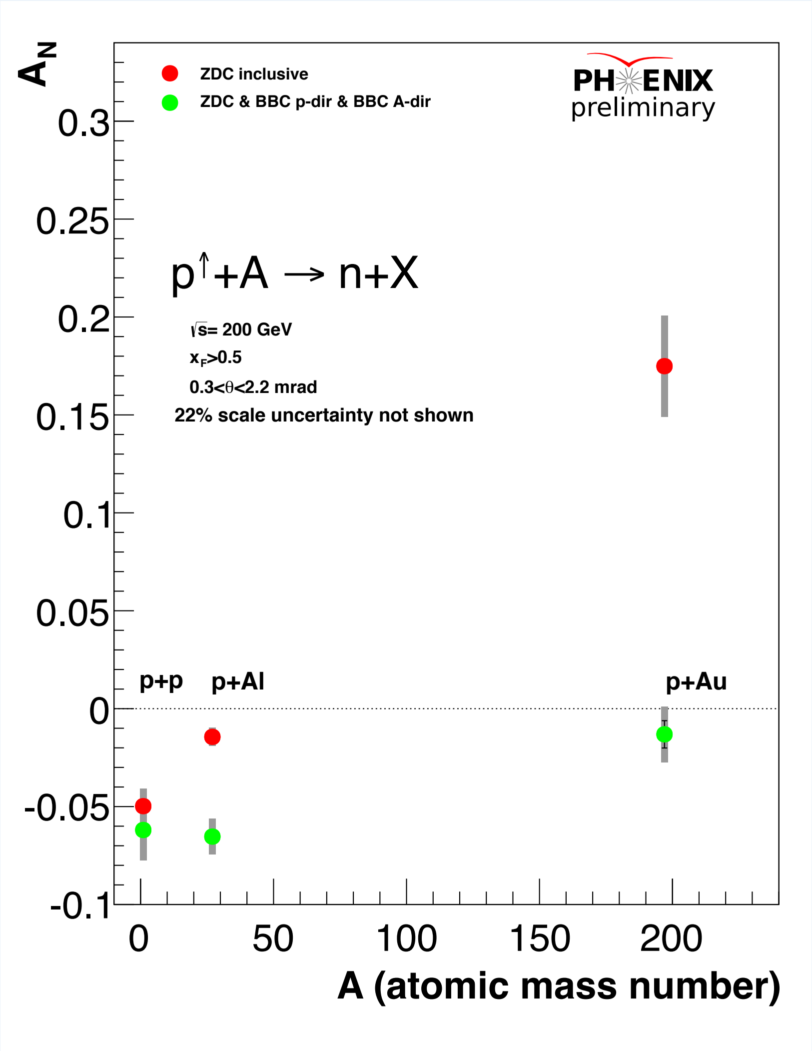


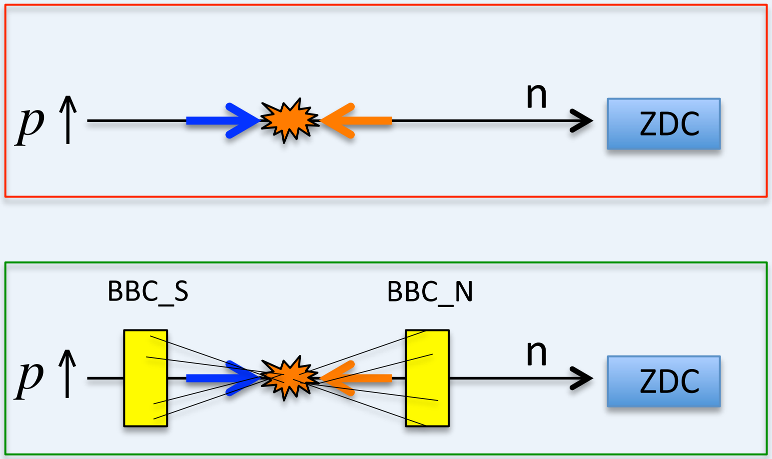

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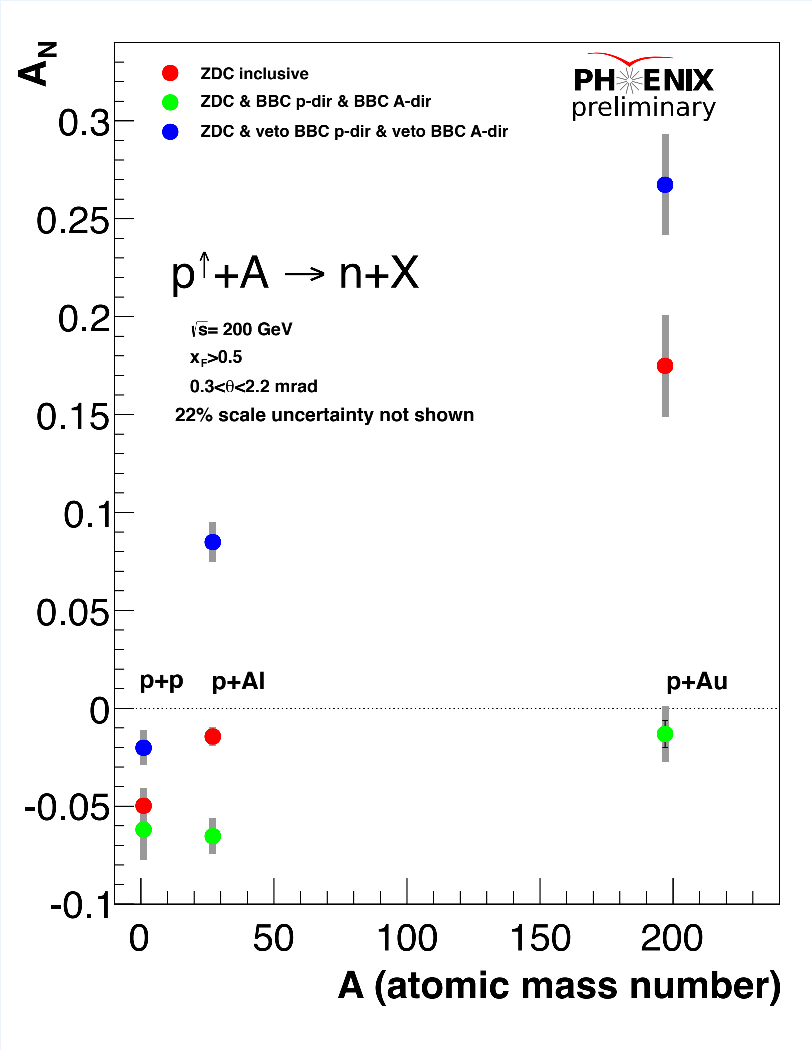


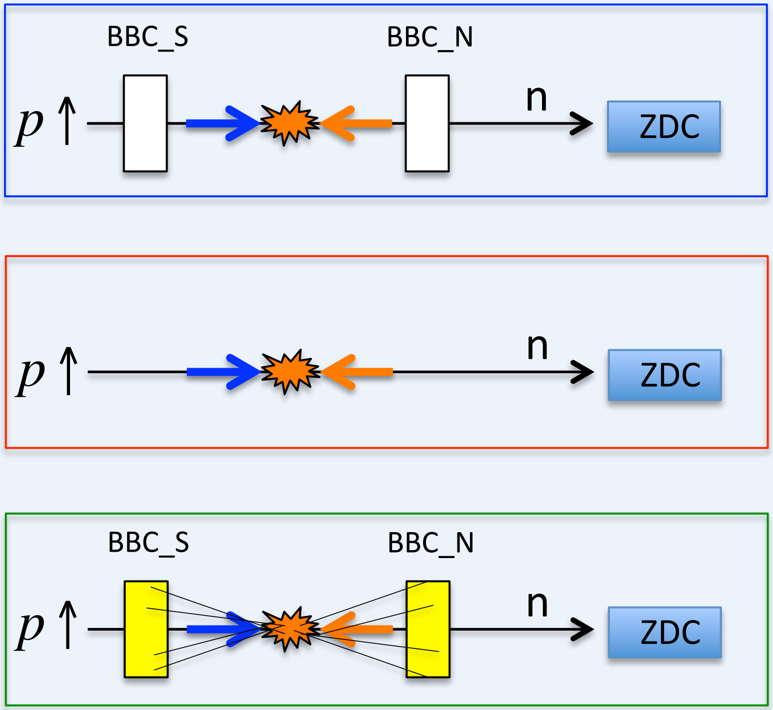

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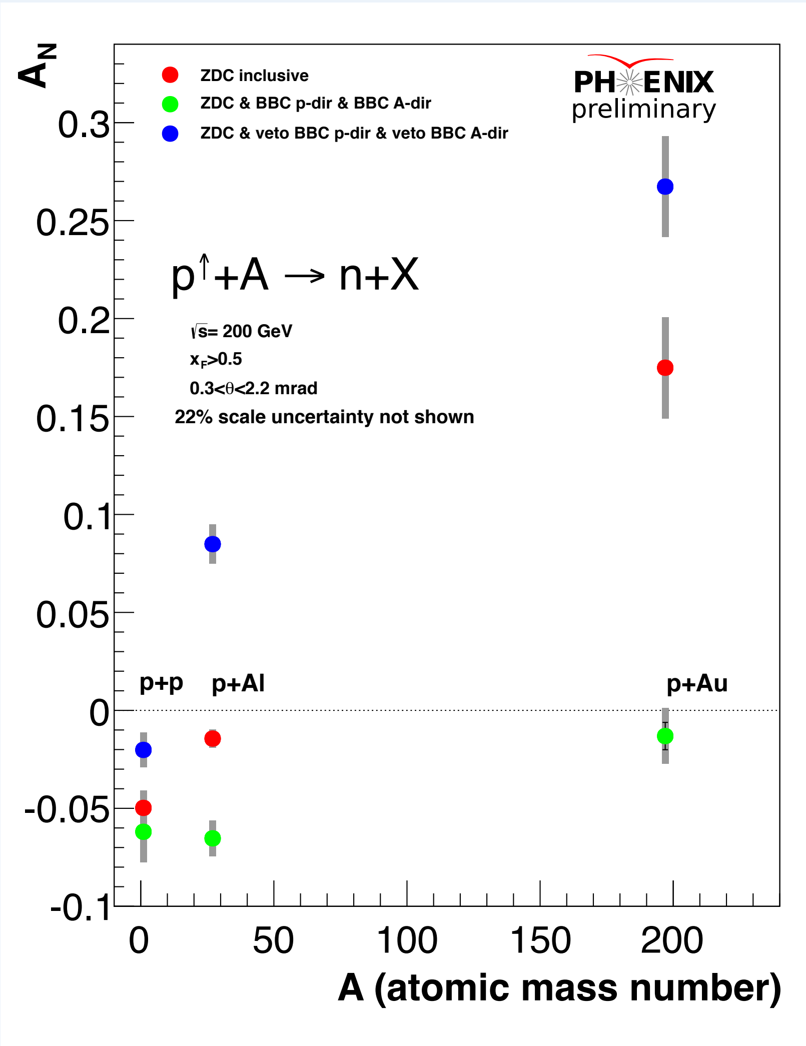
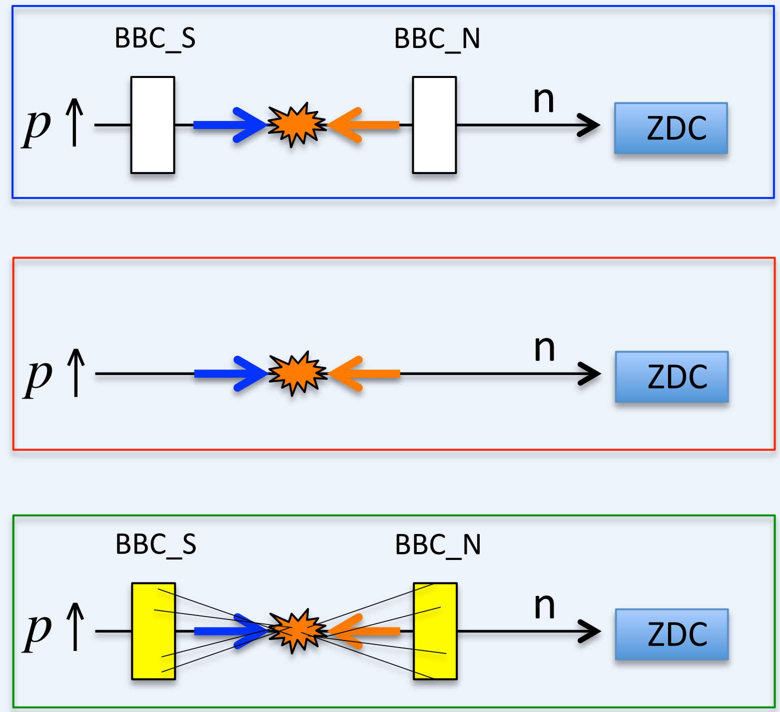
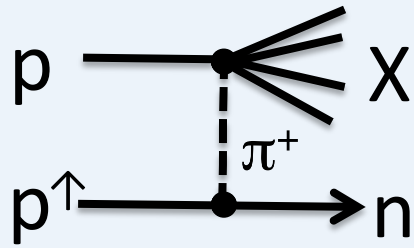


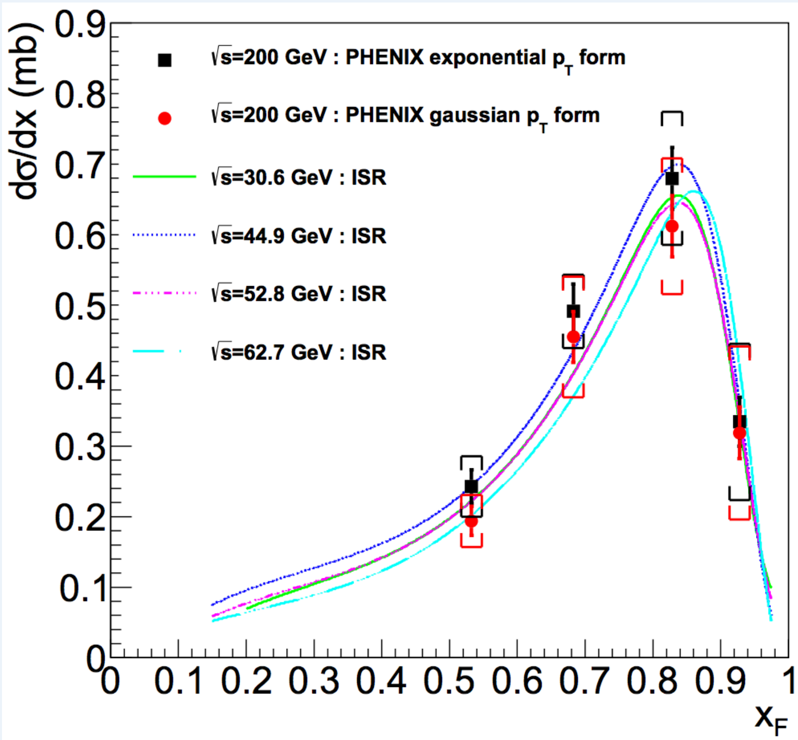




Likely multiple mechanisms contribute

# Forward neutrons: One Pion Exchange




PHENIX: PRD 88 (2013), 032006



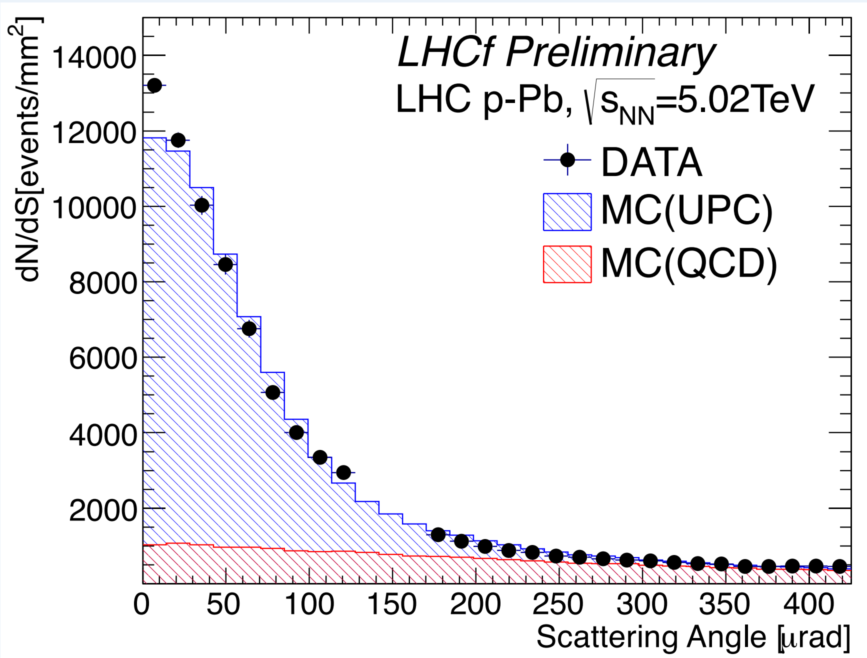

p+p: One Pion Exchange (OPE) model successful for x-section

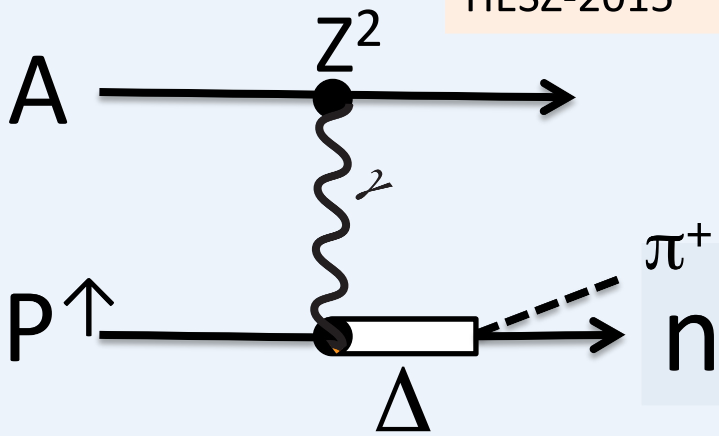
Does it work for p+A ?

Other mechanisms definitely exist, at least in p+A

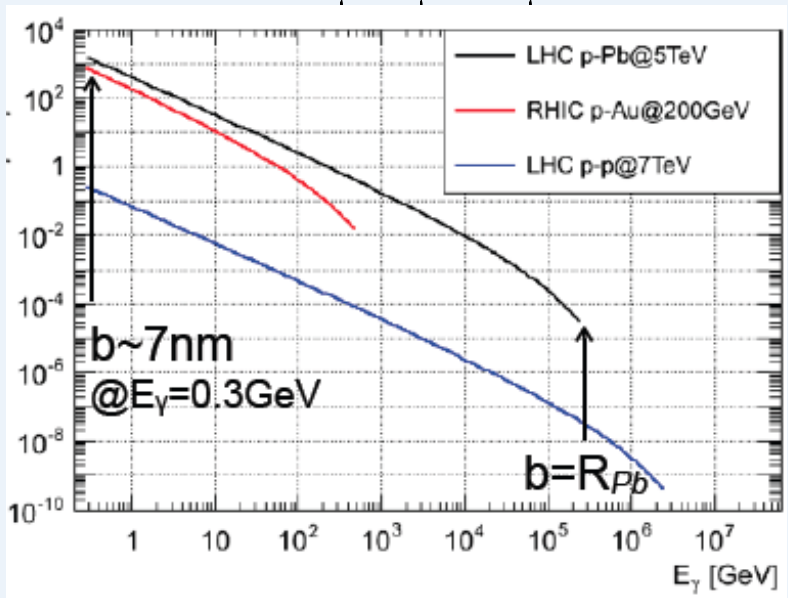
# Forward neutrons: Ultra Peripheral Collisions

Hiroaki Menjo
HESZ-2015




dN$_\gamma$/dE$_\gamma$ vs E$_\gamma$




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

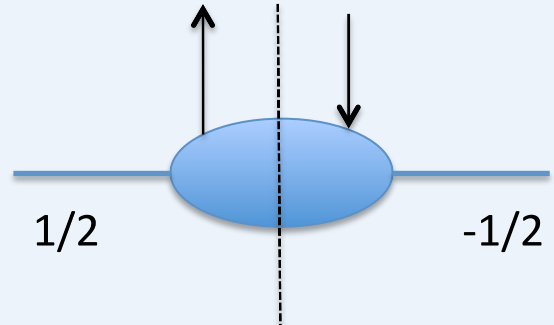
| Physics process | Neutron ($\mu$b) |
|---|---|
| $qq \to qq$ | 35 |
| $q\bar{q} \to q\bar{q}$ | <1 |
| $q\bar{q} \to gg$ | <1 |
| $qg \to qg$ | 268 |
| $gg \to q\bar{q}$ | 9 |
| $gg \to gg$ | 352 |

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

Mainly from gluon scattering

$\Delta^0, \Delta^+, \Delta^-, \Lambda^0 \rightarrow n$

# $A_N$




Requires interference between helicity flip and helicity non-flip amplitudes

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

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

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

---

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

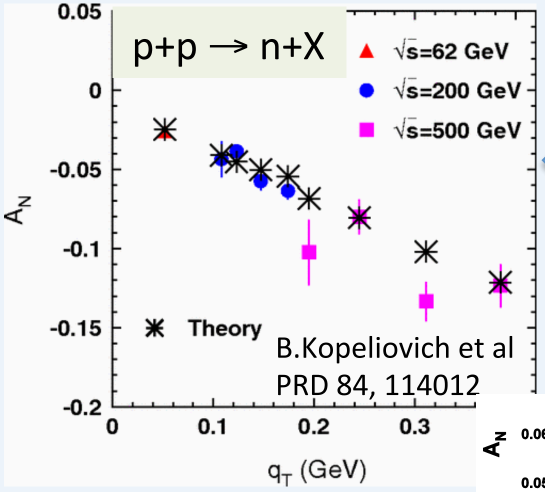
$$A_N \propto \mathrm{Im}(\phi^{HAD}_{non-flip}\phi^{HAD}_{flip} + \phi^{HAD}_{non-flip}\phi^{EM}_{flip} + \phi^{EM}_{non-flip}\phi^{HAD}_{flip} + \phi^{EM}_{non-flip}\phi^{EM}_{flip})$$

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

Need input from theorists

# $A_N$

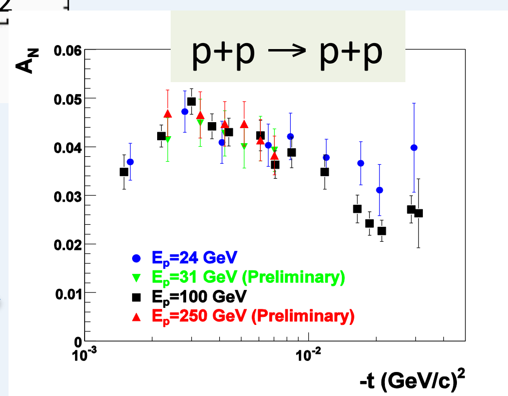
$A_N$~Im(HAD*HAD)

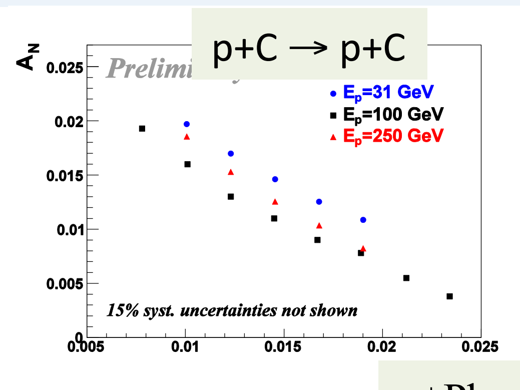



PHENIX data:
interference between
pion and a1-reggeon
exchange

$A_N$~Im(EM*HAD)

RHIC CNI data:
Elastic scattering in
Coulomb Nuclear
Interference region




$A_N$~Im(EM*EM)

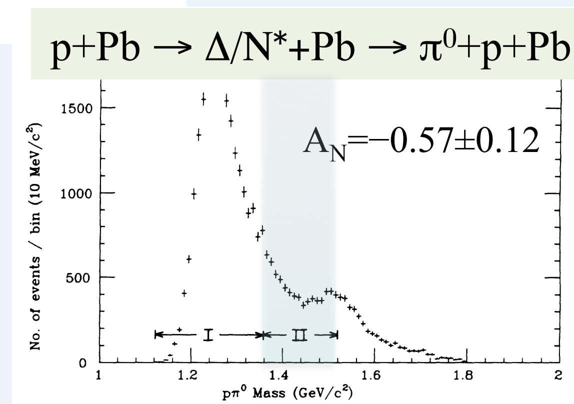



FIG. 2. The invariant-mass spectrum of the $\pi^0$-$p$ system in $p$+Pb→ $\pi^0$+$p$+Pb for $|t'| < 1\times10^{-3}$ (GeV/$c$)$^2$. Peaks due to the $\Delta^+(1232)$ and $N^*(1520)$ resonances are shown. Regions I and II are defined in the text.

Fermilab, PRL64, 357 (1990):

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

# 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

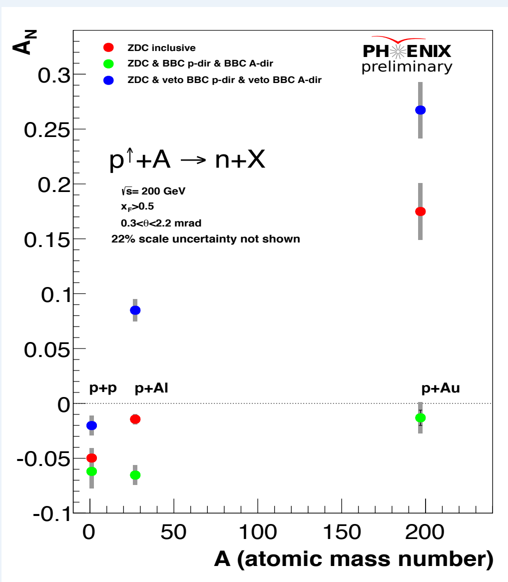
- What is the flavor structure of polarized sea in the proton

  $A_L(W)$ 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, $J/\psi$) => gluon Sivers

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



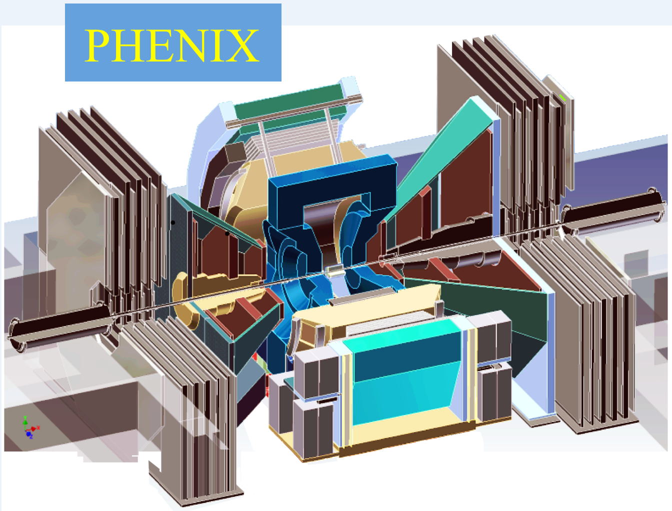

## $A_N$ of forward neutron production: from pp to pA

- 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

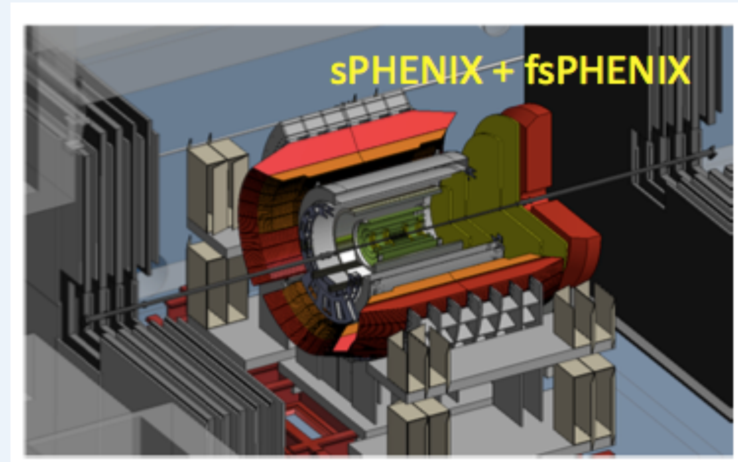
Need theoretical input ! => B.Kopeliovich talk next

# Backup

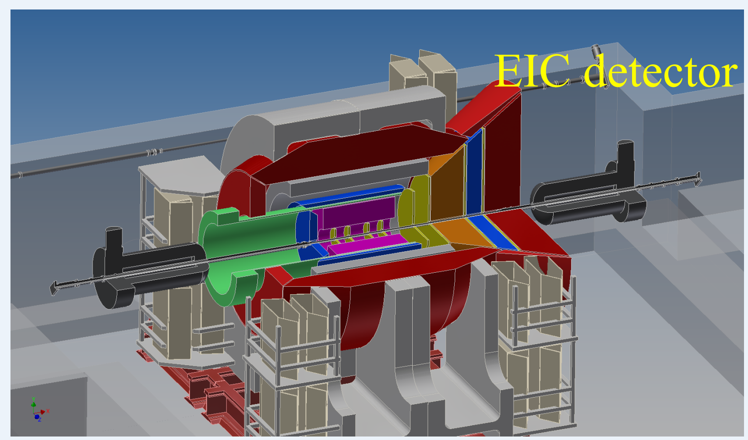
# PHENIX: longer term plans




~2021-22




By ~2025

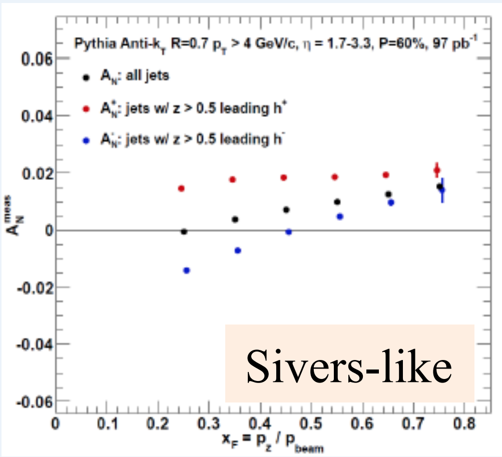



Evolve sPHENIX (pp and HI detector) to EIC Detector (ep and eA detector)

- 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

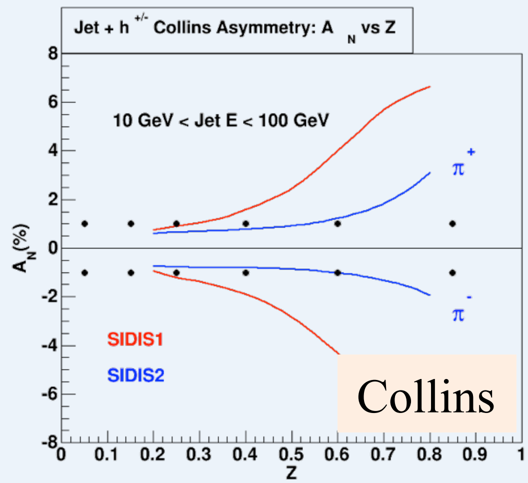


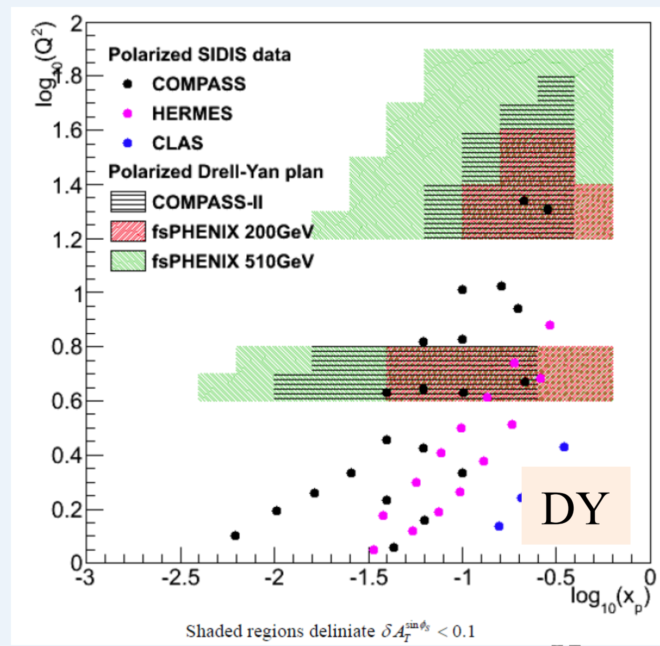

sPHENIX +

PHENIX reconfigured: forward Si tracker and Muon ID

EIC Detector forward systems: GEMs and HCal

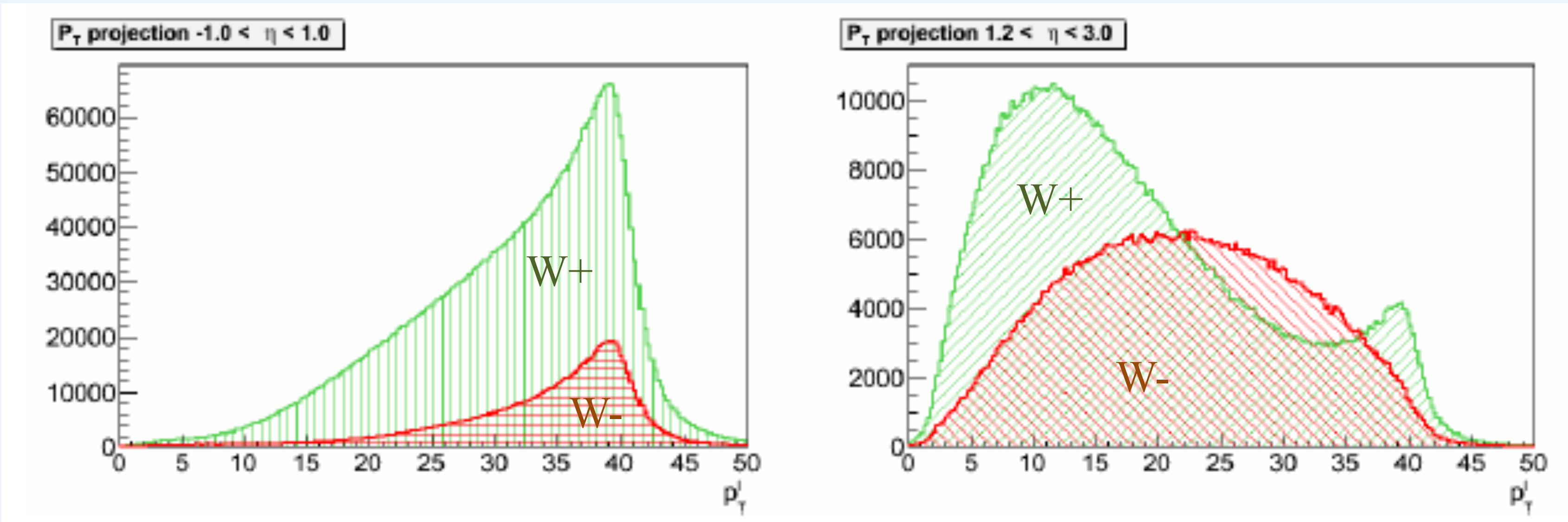
90% of the cost common with EIC detector




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

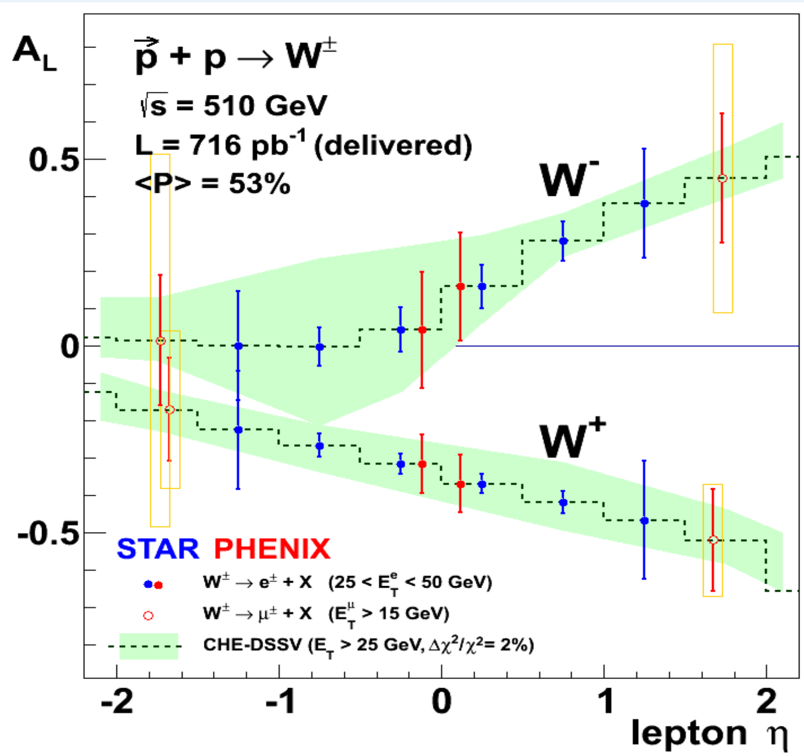
# W: Central vs Forward region



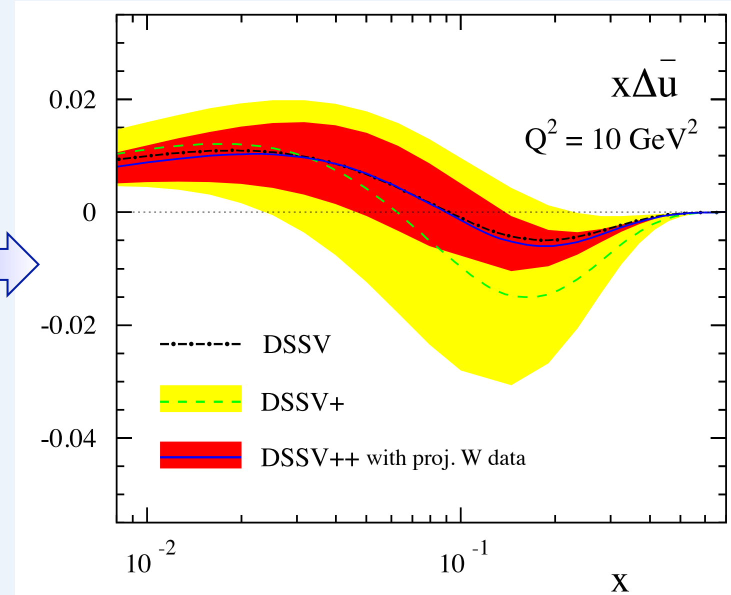

Clear Jacobian peak
at central rapidities

Suppressed/No Jacobean peak
at forward rapidities

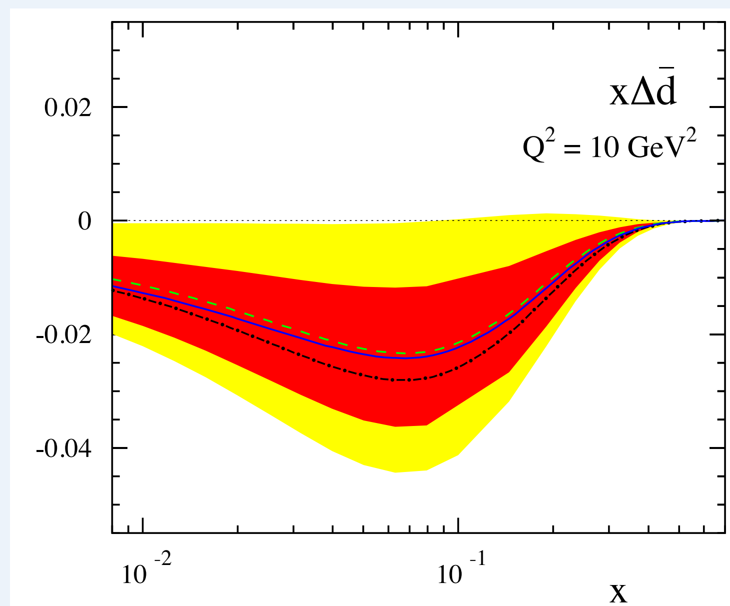
# W: Projection




$\Delta\bar{u}$



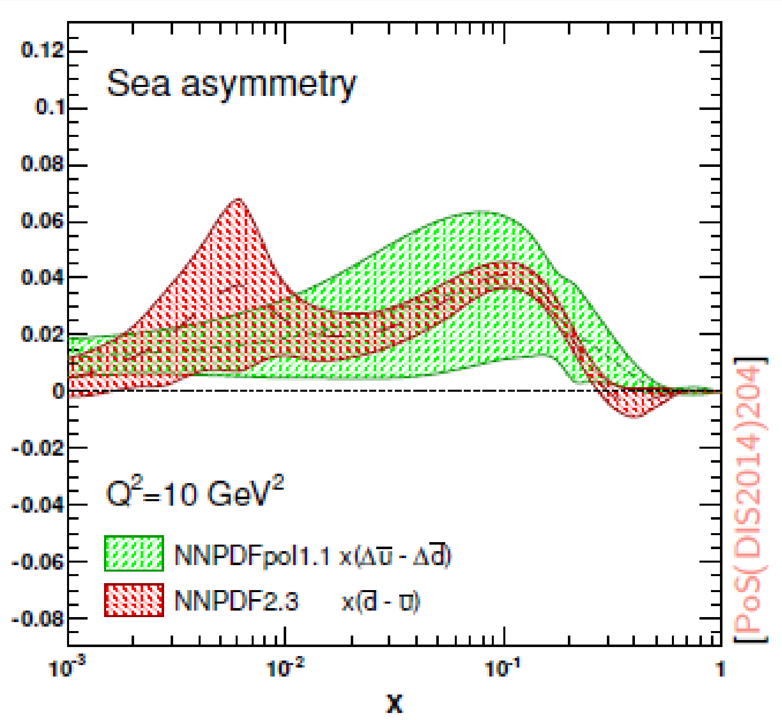

$\Delta\bar{d}$

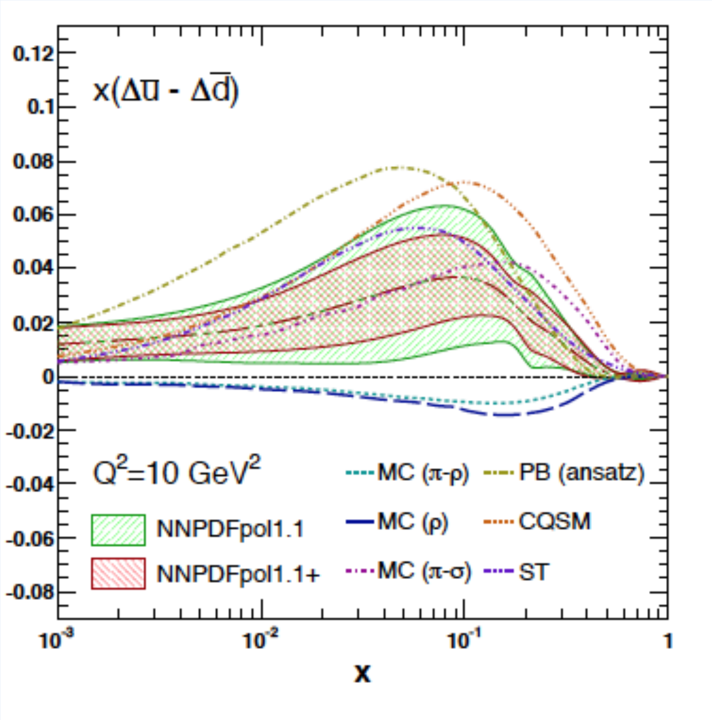



RHIC W-data will give a significant constraint on anti-quark polarization in the proton

# Symmetry breaking in polarized sea?

Unpolarized sea is not symmetric



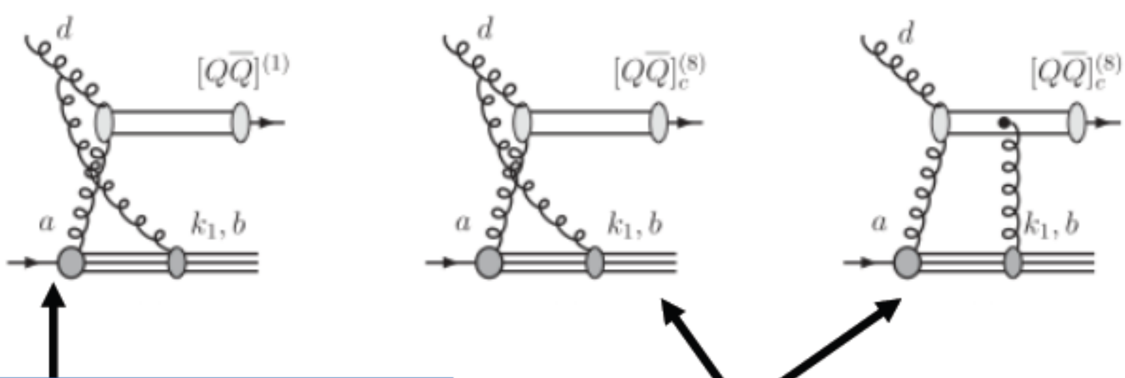




Polarized sea symmetric may be broken too!

Already available data (Run13) will improve the measurement further

# $J/\psi\ A_N$

- $J/\psi$ $A_N$ is sensitive to the production mechanisms
  - Assuming a non-zero gluon Sivers function, in pp scattering, $J/\psi$ $A_N$ 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

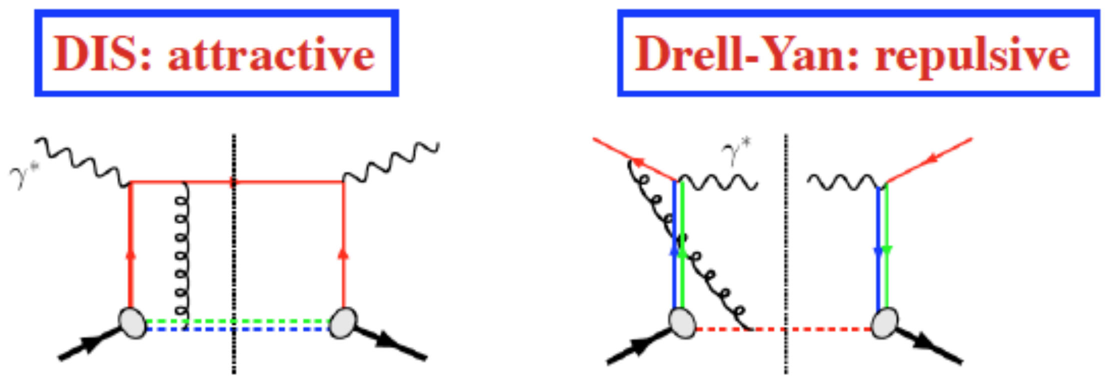
# Fundamental Role of Sivers

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

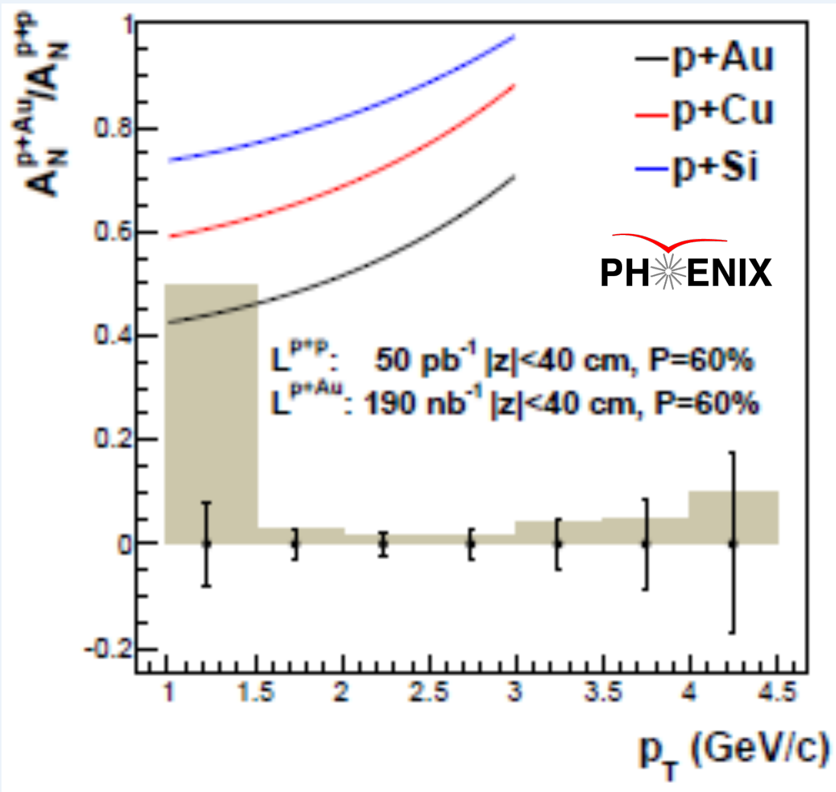



$$\text{Sivers}|_{DIS} = -\text{Sivers}|_{DY}$$

Or W/Z production

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

# π0 $A_N$ in pA

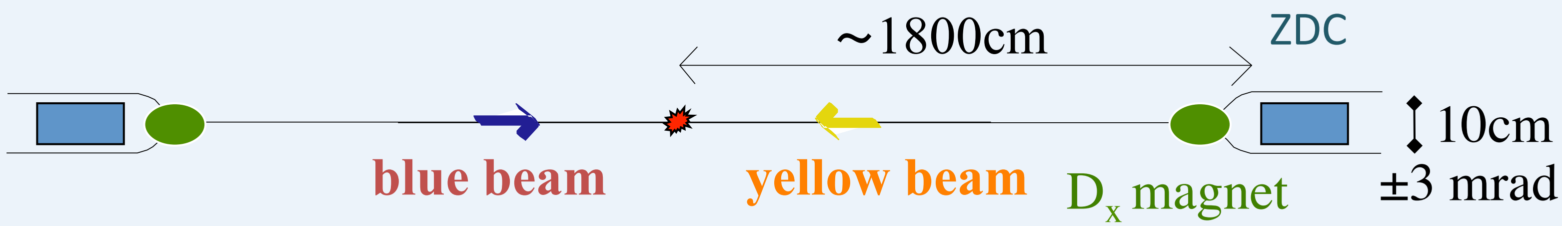



Probing gluon saturated matter, Color Glass Condensate (CGC) with polarized protons

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!

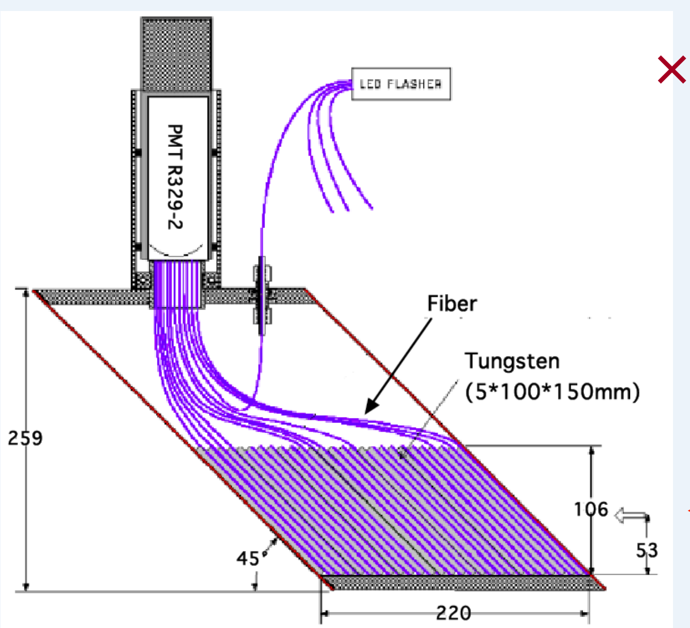
# Forward Neutron Measurements




Hadron sampling calorimeter made of Tungsten plate and fibers

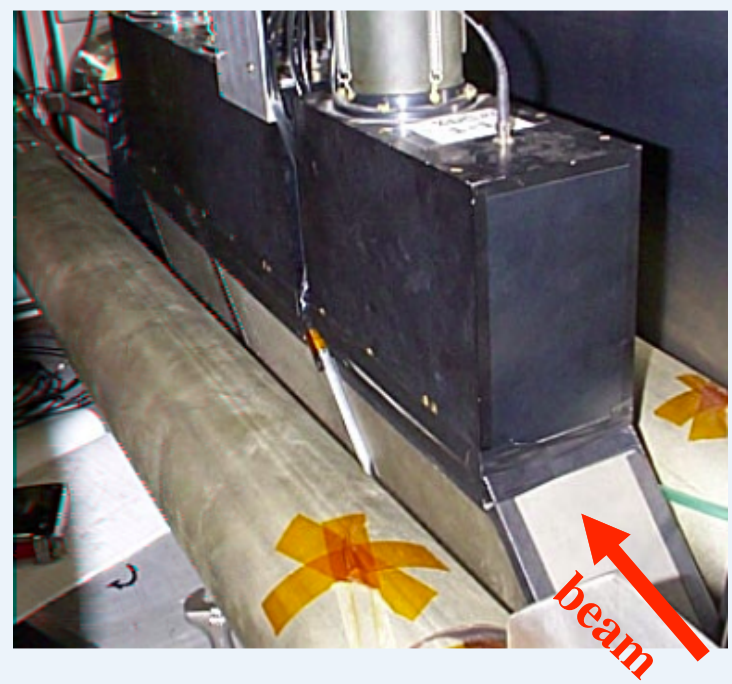
**Detects neutrons and measure their energy**

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



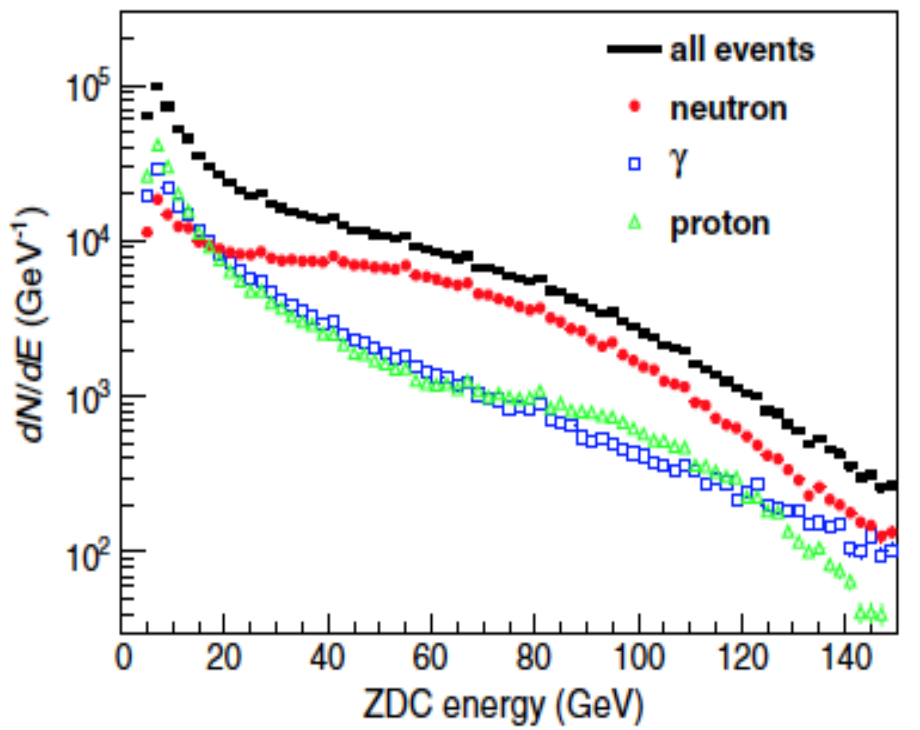

× 3 modules →

**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

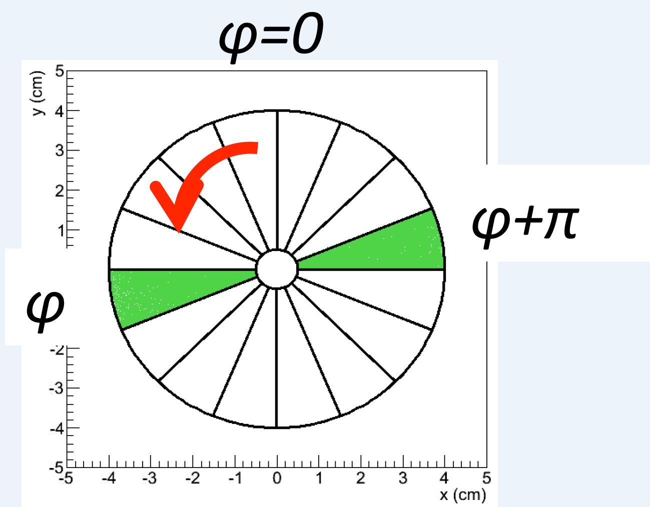
>1 SMD strip fired

Suppresses photon background

**Neutron purity >97%**

Residual background: protons, $K^0$

# $A_N$ Measurements




$A = A(\varphi) = \mathrm{A_N} \bullet \sin(\varphi)$

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

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

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

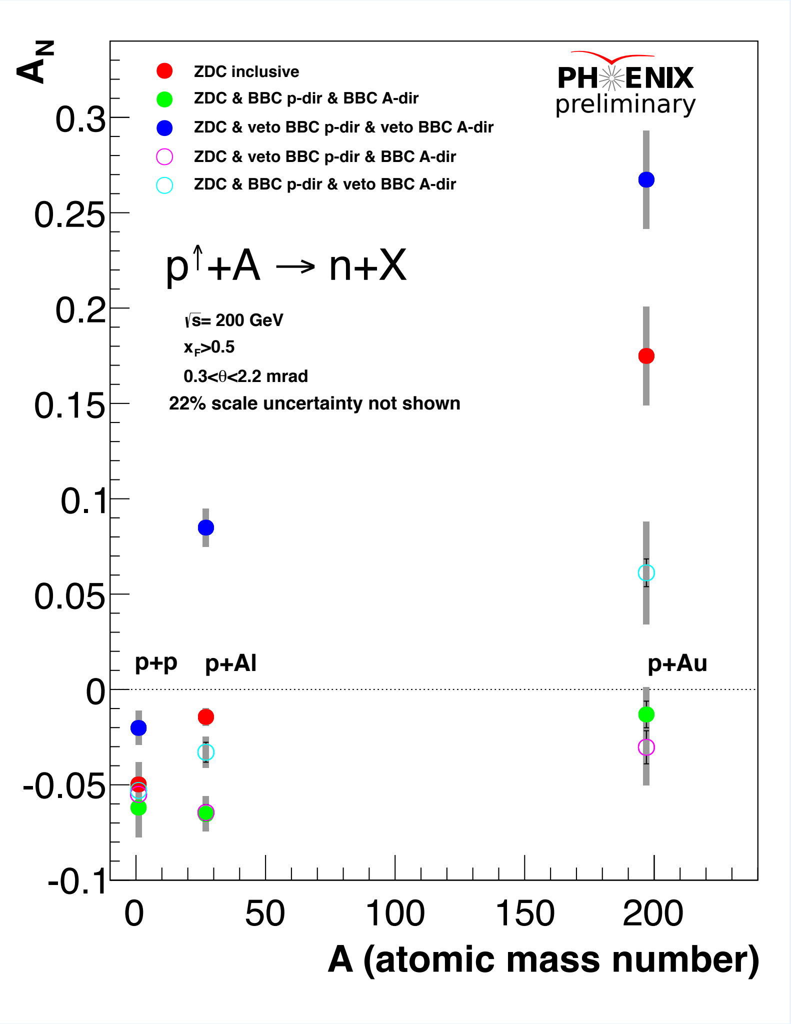
$$A_N = \frac{d\sigma_L^{\uparrow} - d\sigma_L^{\downarrow}}{d\sigma_L^{\uparrow} + d\sigma_R^{\uparrow}} = \frac{1}{P}\frac{N_L^{\uparrow} - R_{lum}N_L^{\downarrow}}{N_L^{\uparrow} + R_{\det}N_R^{\uparrow}}, \quad R_{lum} = \frac{L^{\uparrow}}{L^{\downarrow}}$$

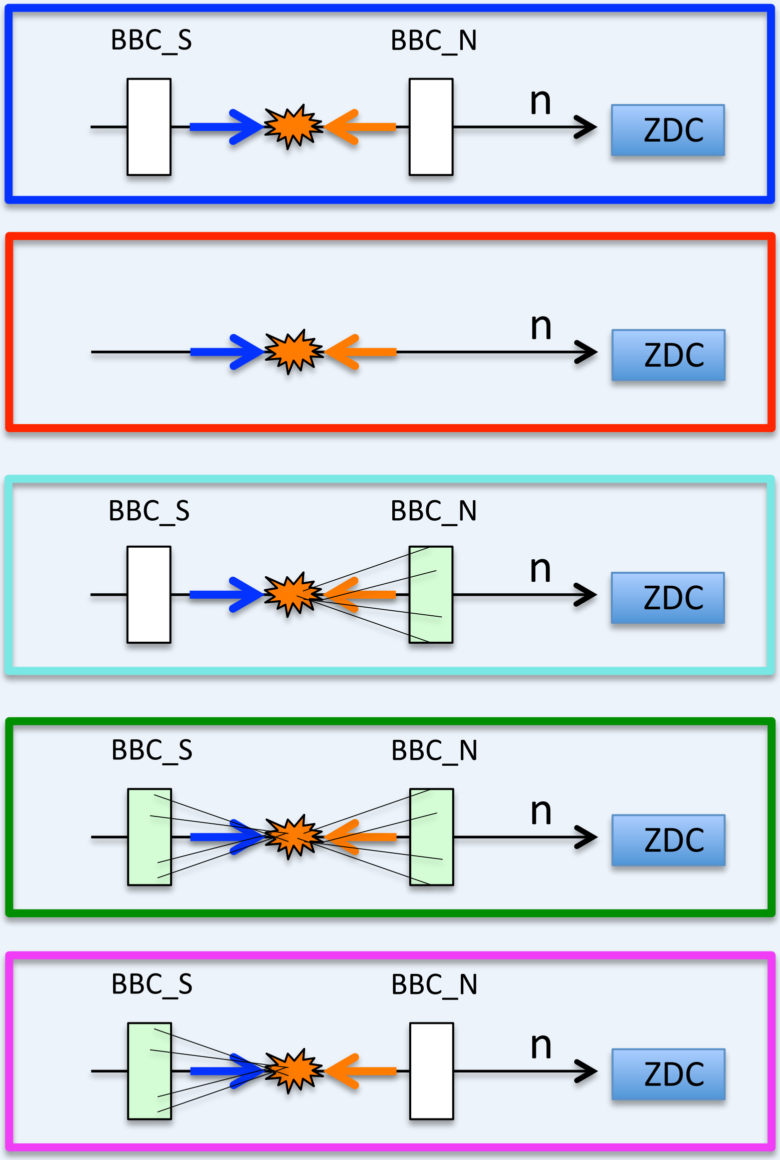
- Square root formula: cancels acceptance and luminosity effects

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

ZDC: η>6.5

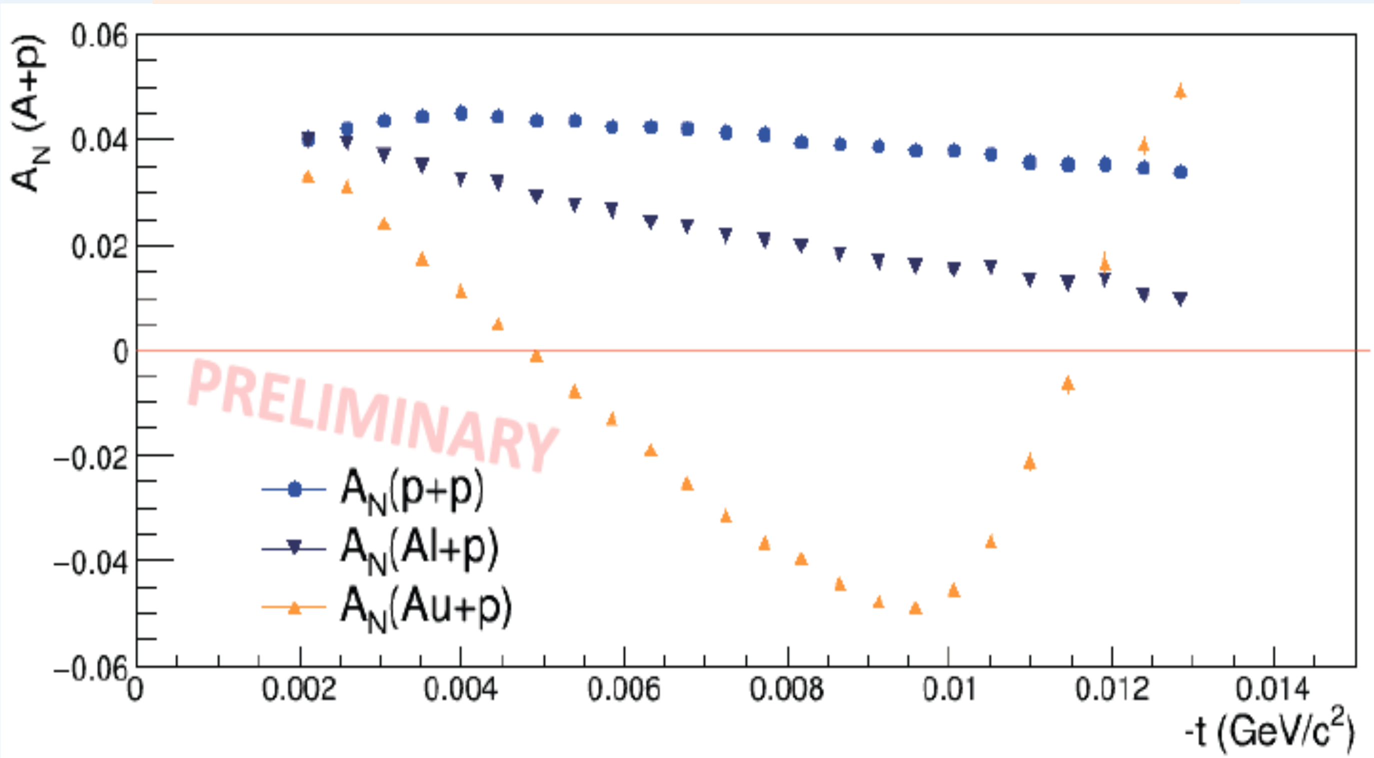
BBC: 3.0<|η|<3.9



# New CNI measurements from Run15

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

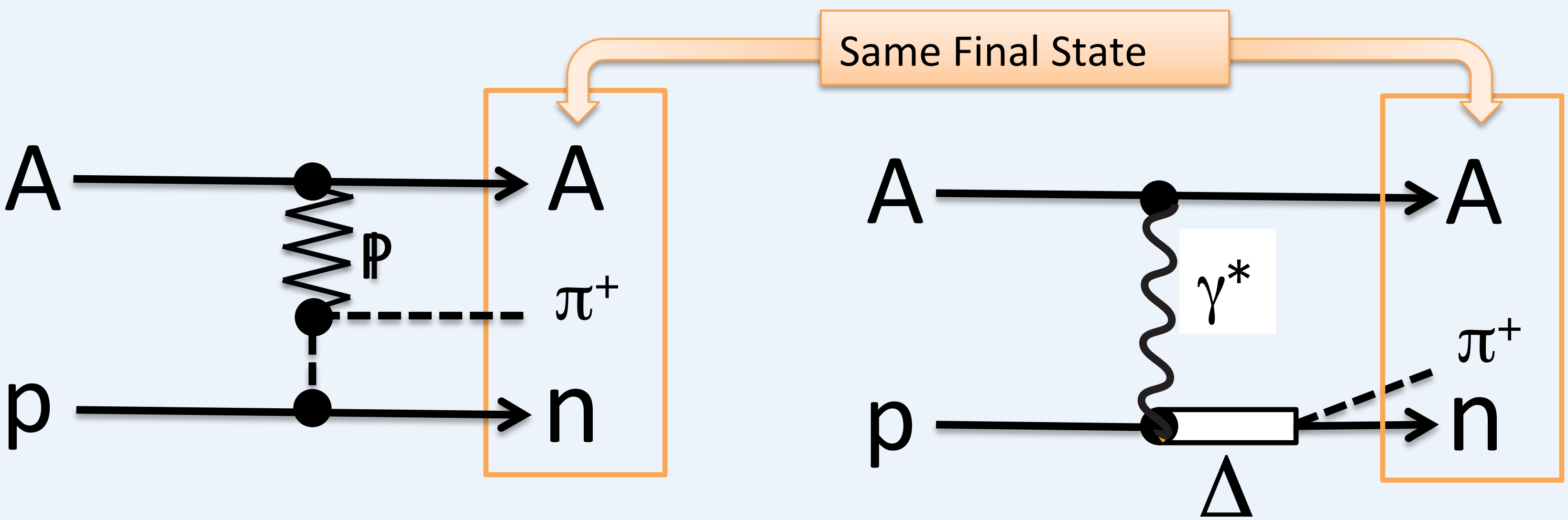



Fixed target with 100 GeV p(A) beam

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

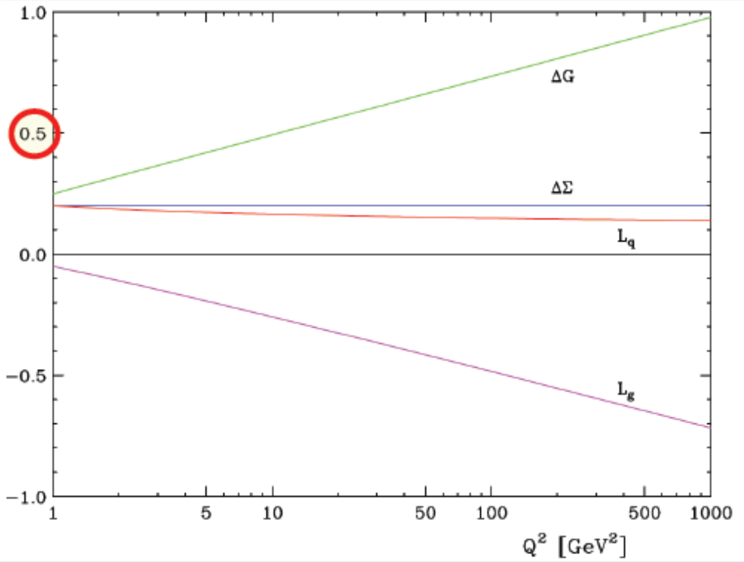
Also strong A-dependence

# Coulomb-Nuclear Interference in Forward Neutron Production




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

# Q2 dependence




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

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

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

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