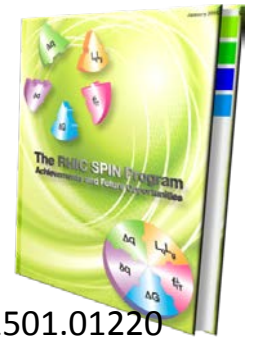
RHIC Spin Program: Highlights of Recent achievements and future prospects

Sanghwa Park

(Stony Brook University)

RHIC Spin Program



arxiv:1501.01220

Spin: a tool for fundamental tests of QCD

- Spin is one of the fundamental properties of particles
- Spin plays an important role in QCD: Interplay between the intrinsic properties and interactions of quarks and gluons
- RHIC polarized p+p data provides unique data sets for various processes: stringent tests of factorization and universality
  - Spin adds control and precision

RHIC spin program addresses key questions such as:

- How do gluons and sea quarks contribute to the proton spin?
- What is the momentum and position distribution of the polarized sea in the nucleon?
- What do transverse spin phenomena teach us about proton structure?

From 1D structure of nucleon …

- Collinear parton picture: three parton distribution functions unveil the information on the internal structure of hadrons

$$q(x) \quad f_1^q(x) = q^{\vec{\Rightarrow}}(x) + q^{\vec{\Leftarrow}}(x)$$

Unpolarized parton distribution functions (PDFs)

$$\Delta q(x) \quad g_1^q(x) = q^{\vec{\Rightarrow}}(x) - q^{\vec{\Leftarrow}}(x)$$

Helicity PDFs

$$\delta q(x) \quad h_1^q(x) = q^{\uparrow\Uparrow}(x) - q^{\uparrow\Downarrow}(x)$$

Transversity PDFs

slide stloen from
E. C. Aschenauer

... to 3D imaging

2+1 DIMENSIONAL IMAGING OF QUARKS & GLUONS

Wigner function
$W(x,b_T,k_T)$

QCD genetic map

$\int d^2b_T$

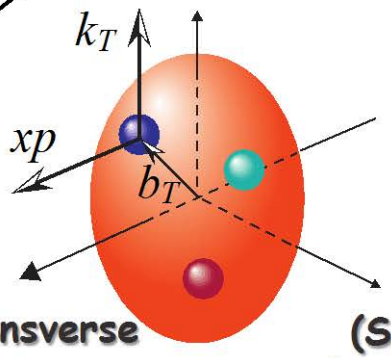
$\int d^2k_T$

Momentum space

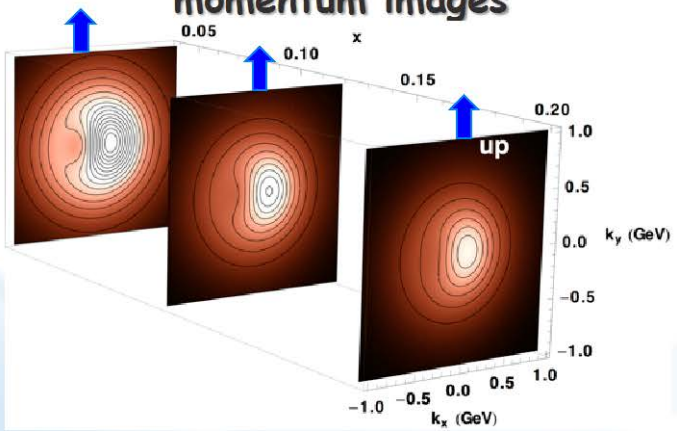
Coordinate space

$f(x,k_T)$
TMDs

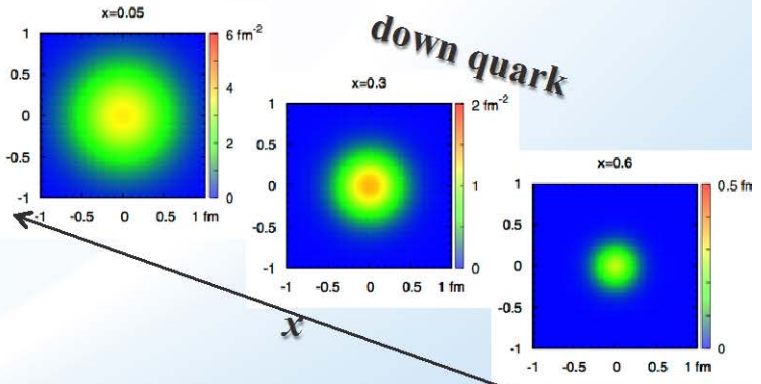
$f(x,b_T)$
GPDs



(Spin-dependent) 2+1D transverse momentum images



(Spin-dependent) 2+1D spatial images from exclusive scattering



Recent theoretical work indicates direct access to Gluon Wigner function through diffractive di-jets in UPC (arXiv:1706.01765)

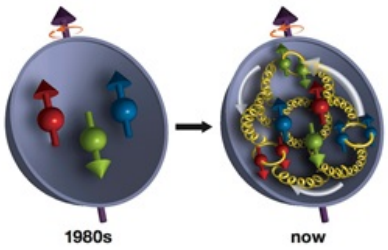
Longitudinal Spin Program:

How do gluon and antiquarks contribution to the proton spin?

Is gluon spin contribution zero?

What is the role of antiquarks?

Proton Spin Puzzle



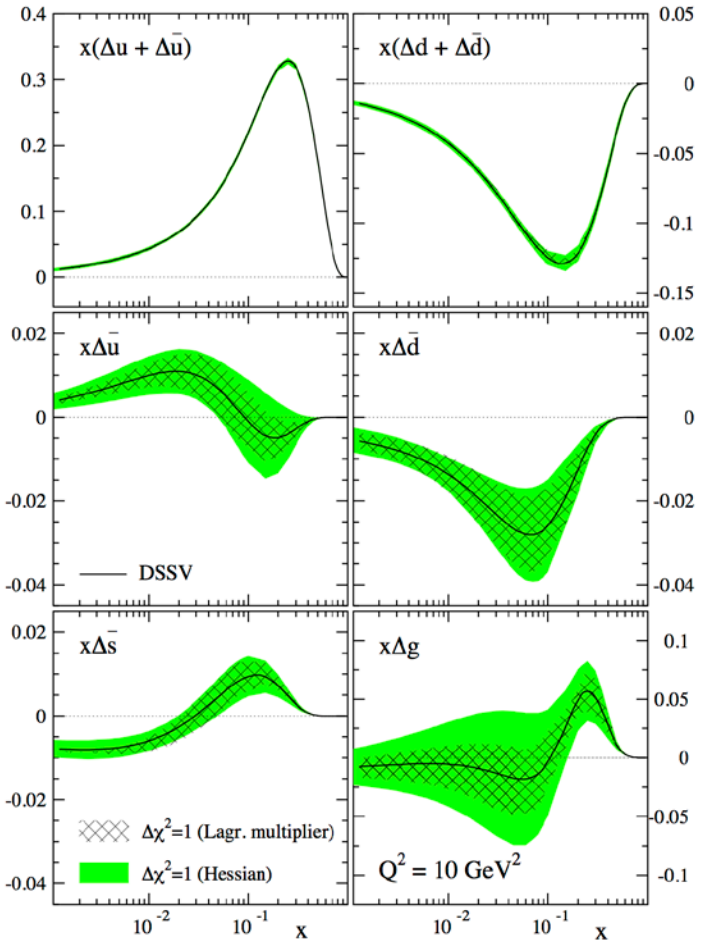
total quark spin

orbital angular momentum

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

gluon spin

- Combined quark and antiquark contribution ~ 30%
- Antiquark mostly extracted by SIDIS, RHIC W data comes in.
- gluon only poorly constrained by DIS (small x-Q^2 reach) - direct access allowed in p+p



D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, Phys. Rev. D 80, 034030 (2009)

Longitudinal Spin Program:

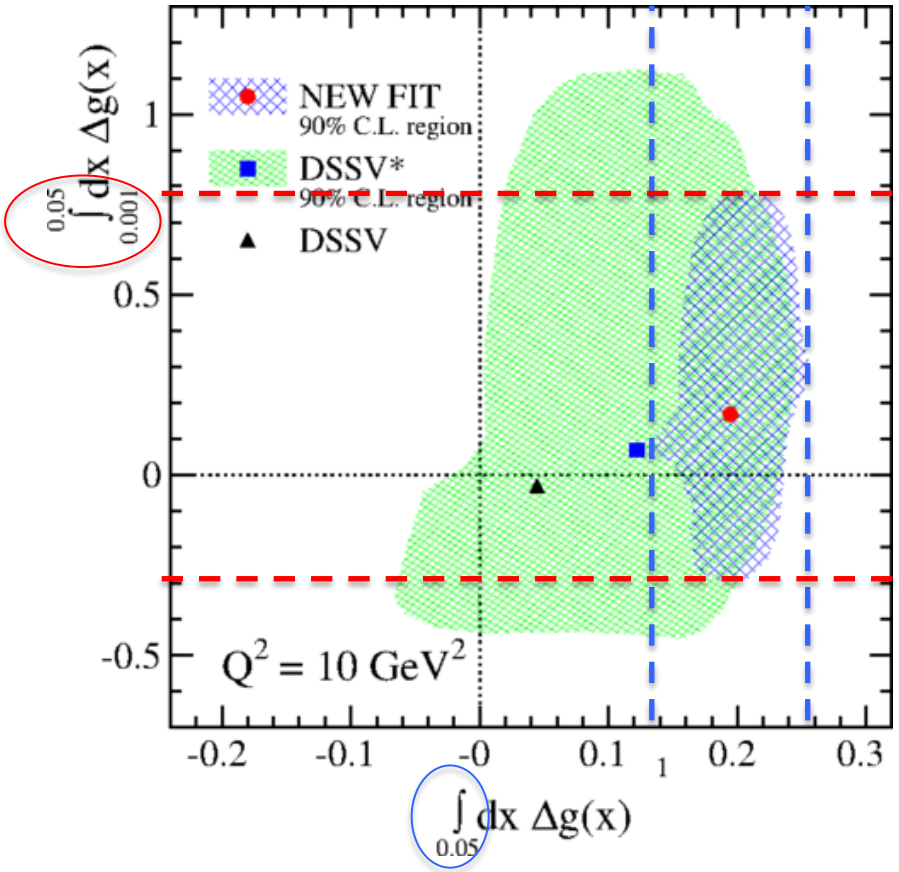
How do gluon and antiquark contribution to the proton spin?

Is gluon spin contribution zero?

What is the role of antiquarks?

First evidence of non-zero gluon spin at x > 0.05

Only included RHIC 200GeV data
500 GeV data not yet included!



Phys. Rev. Lett. 113 (2014) 012001

RHIC data directly access gluons: STAR jet and PHENIX pi0 production dominated by gg and qg scatterings

RHIC 200GeV data shed light on non-zero gluon spin for x > 0.05!

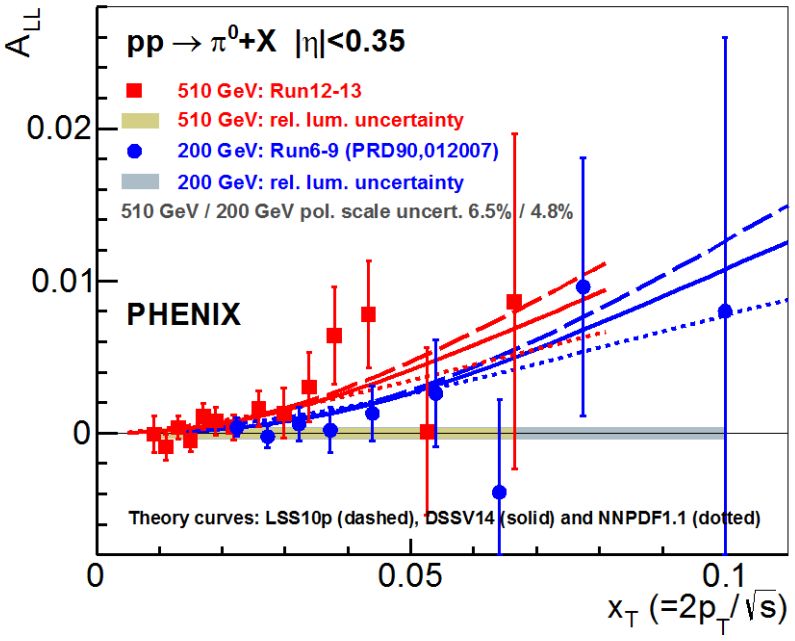
Included in the DSSV global analysis, significant constraint on gluon spin

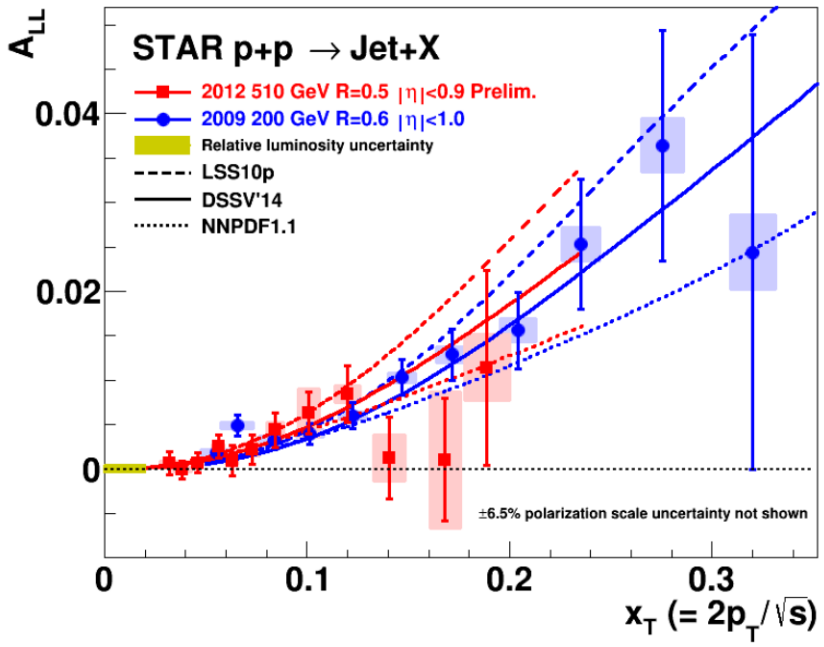
$$\int_{0.05}^{1} dx \Delta g(x) = 0.2^{+0.06}_{-0.07} (Q^2 = 10 GeV^2)$$

Also similarly confirmed by NNPDFpol fit

Access low x: Higher energy

Phys.Rev. D93 (2016) no.1, 011501



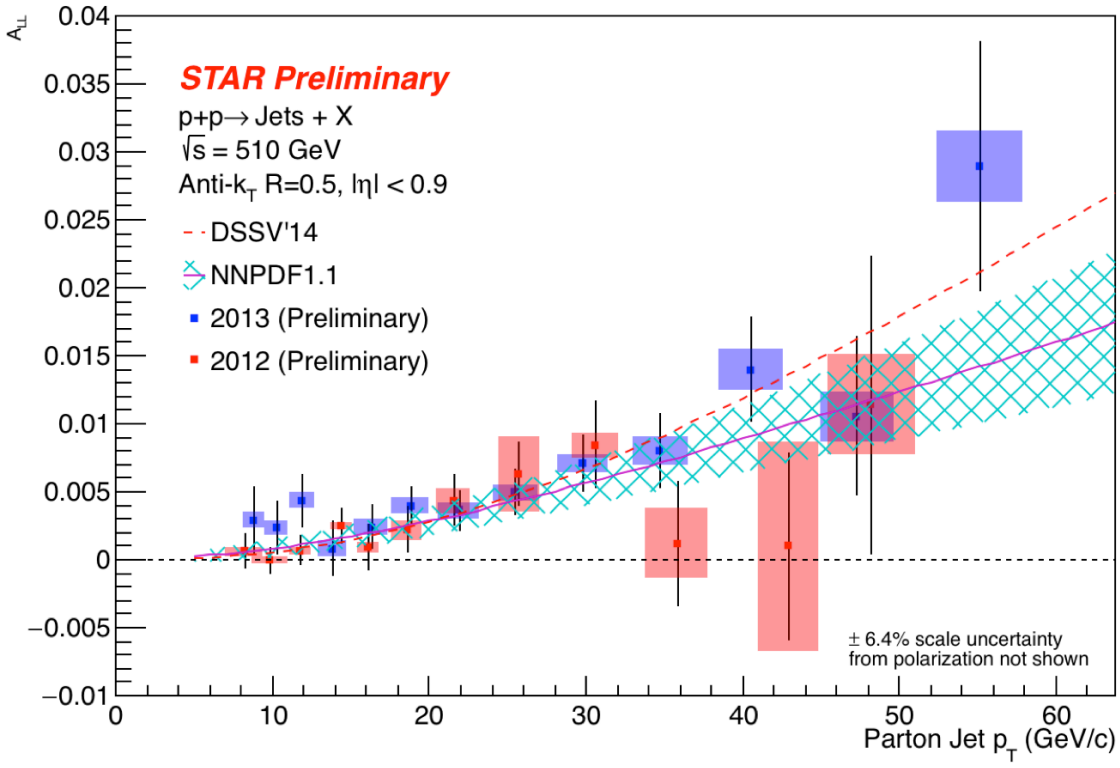


- Access low x by higher energy (x down to ~10^{-2})
- Inclusive measurements have the most statistical power
- In excellent agreement with latest global fit results

Access low x: Higher energy

New!

Check out the poster session!



- New Run13 STAR inclusive Jet A_{LL} preliminary result
- Consistent with DSSV14 and NNPDF1.1 curves and Run12 preliminary result

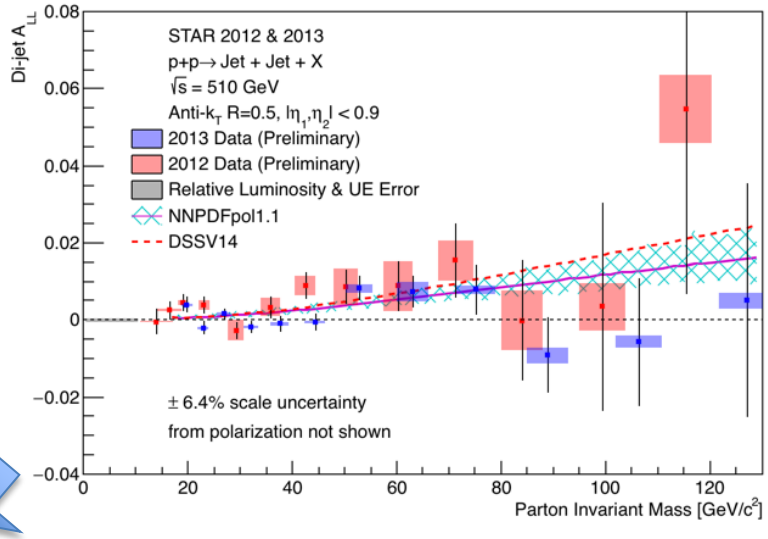
Shape of x: Correlation measurement

- Access parton kinematics at LO

$$M = \sqrt{s}\sqrt{x_1 x_2}$$

$$\eta_3 + \eta_4 = \ln(x_1 / x_2)$$

- access x_{min} ~ 0.02

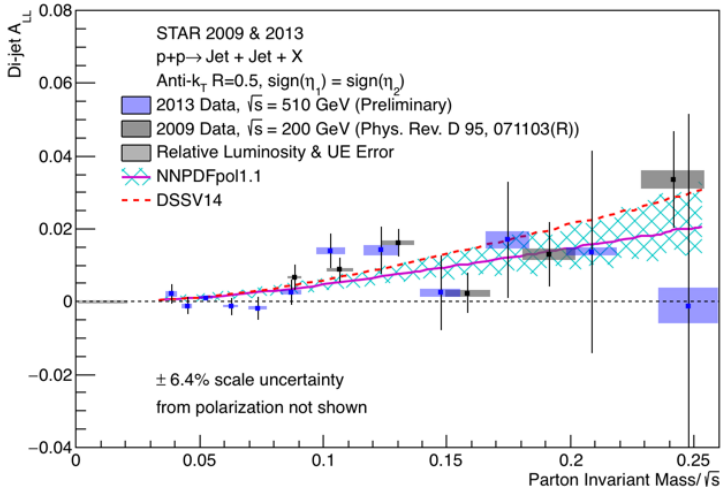


New!

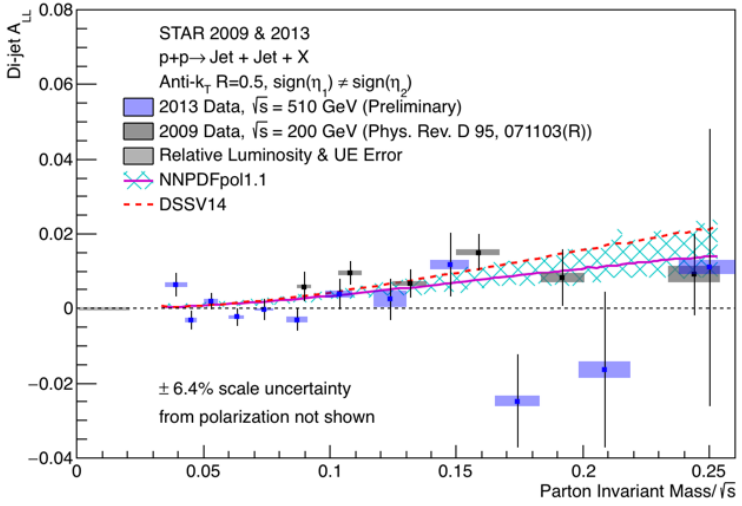
Run13 di-jet Results

Check out the poster session!

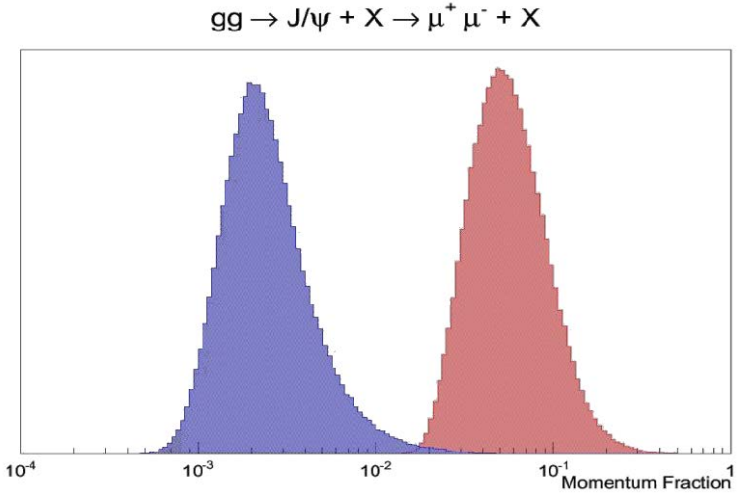
Sign(η_1)=Sign(η_2)

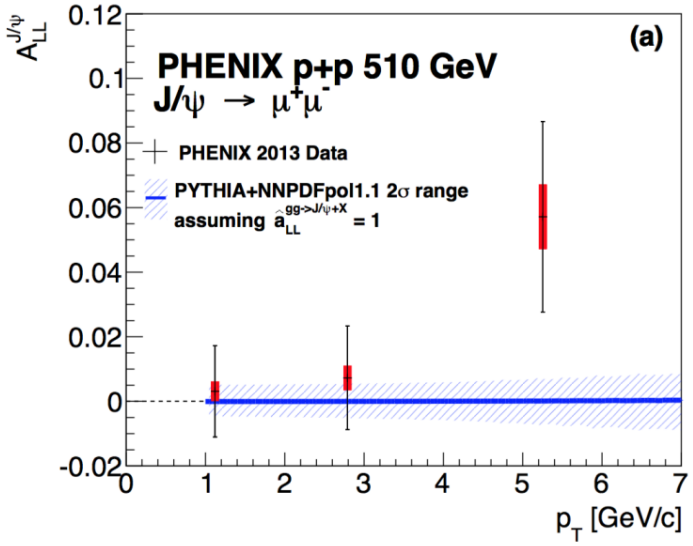


Sign(η_1)≠Sign(η_2)



Access low x: Go forward





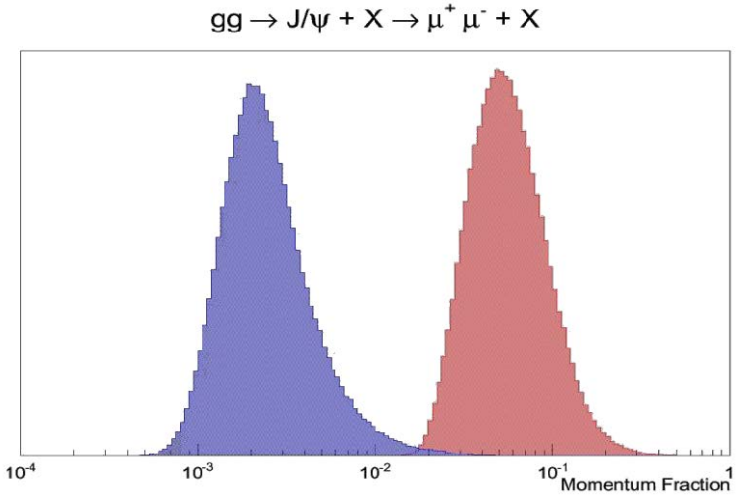
Forward rapidity measurement allows us to access lower x region

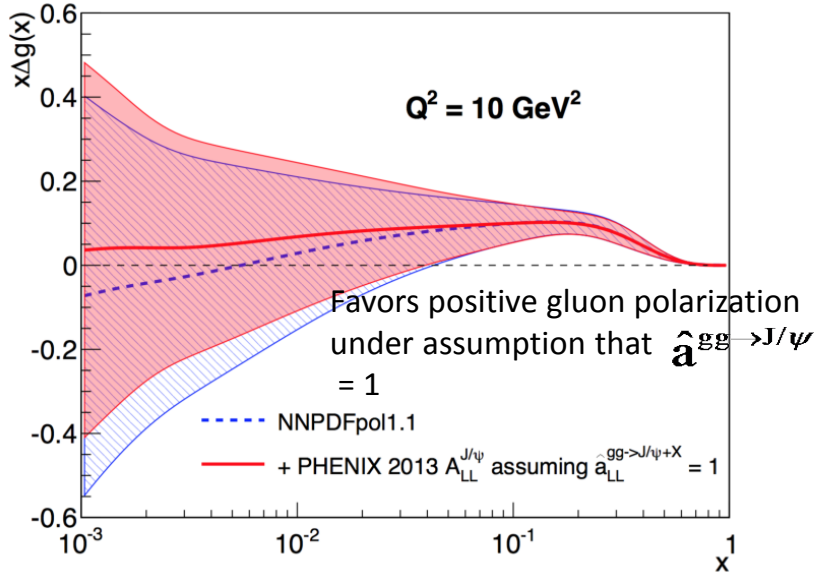
PHENIX J/psi measurement

$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \hat{a}^{gg\to J/\psi}\frac{\Delta g(x1)}{g(x1)}\frac{\Delta g(x2)}{g(x2)}$$

- At RHIC energies, J/psi production dominated by gluon-gluon fusion
- Extend x down to ~2×10^{-3}
- Measurement limited by large production mechanism uncertainty

Access low x: Go forward





Forward rapidity measurement allows us to access lower x region

PHENIX J/psi measurement

$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \hat{a}^{gg\to J/\psi}\frac{\Delta g(x1)}{g(x1)}\frac{\Delta g(x2)}{g(x2)}$$

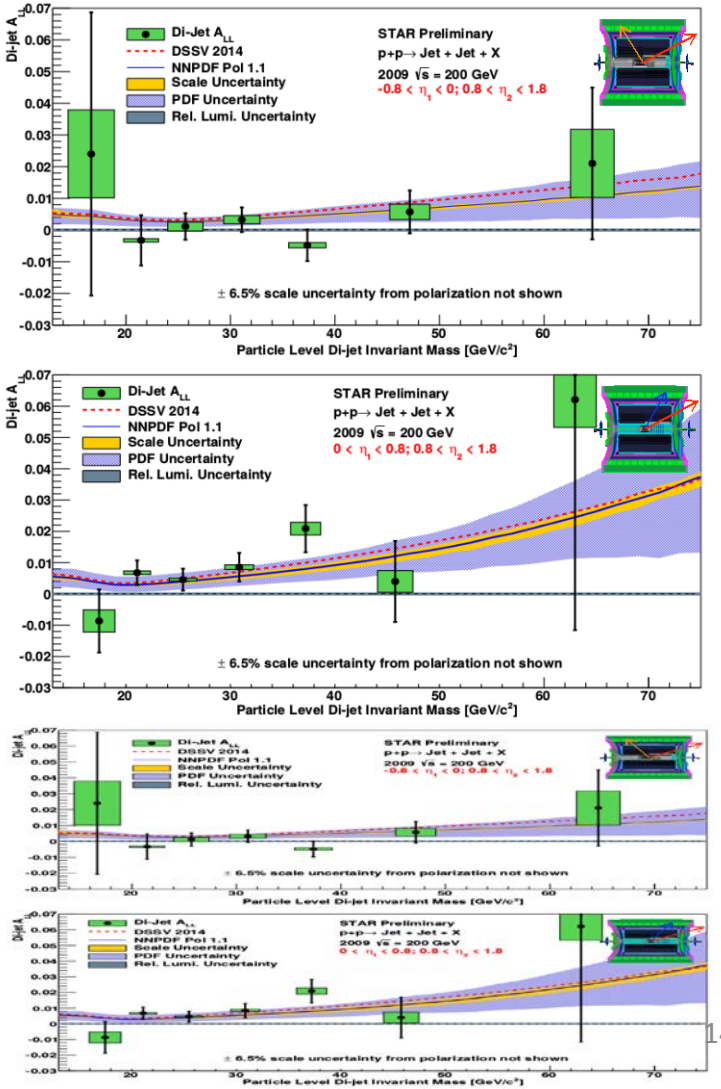
- At RHIC energies, J/psi production dominated by gluon-gluon fusion
- Extend x down to ~2×10^{-3}
- Measurement limited by large production mechanism uncertainty

Further forward Run13 MPC pi0 ALL (3.1 <|η|< 3.9) analysis accesses x ~ 10^{-3}

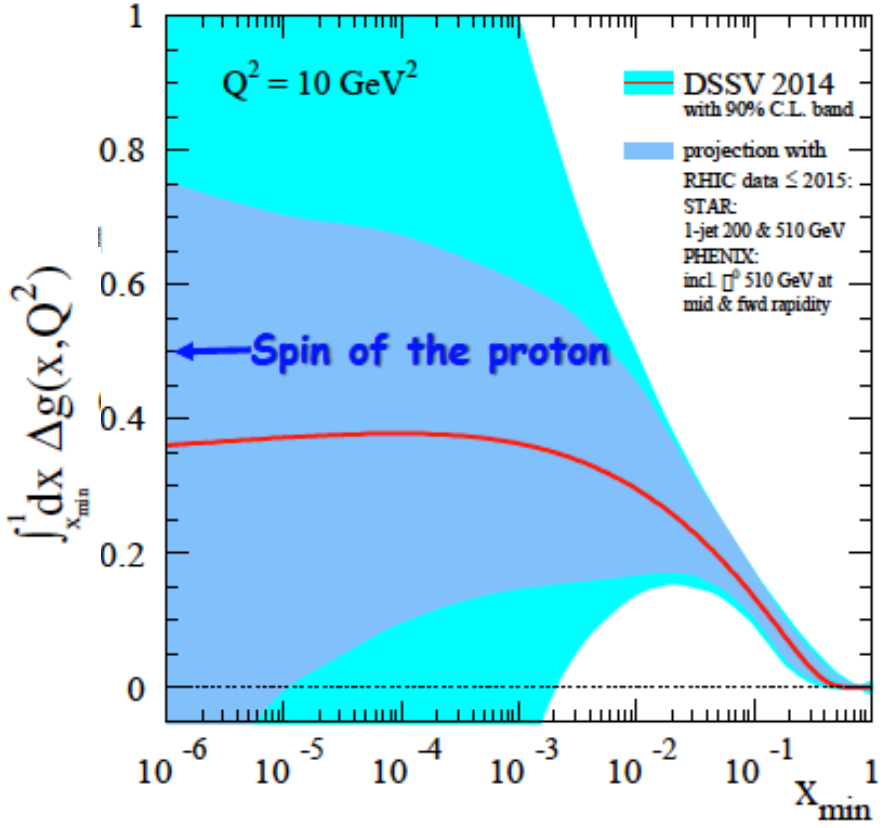
Access low x: Go forward

- STAR Forward di-jet A_{LL} measurement with Barrel and Endcap Electromagnetic Calorimeters
  - consistent with global fit results constrained by Run9 A_{LL} 2009 data

- Also, Forward Meson Spectrometer pi0 measurement ($2.5 < |\eta| < 4.0$)



Future constraint on ΔG



RHIC p+p data significantly contribute to contraint on gluon spin

More to come! Ongoing analyses:

STAR:
- finalize 510 GeV inclusive and di-jet for Run12 and Run13
- finalize 510 GeV pi0 ALL at forward rapidities (2.4 to 4)
- Increase precision at 200 GeV with Run15 data

PHENIX:
- Finalized Run11 500 GeV MPC pi0 ALL at forward rapidity (3.1 to 3.9)
- Run13 MPC pi0 analysis ongoing
- Ongoing 510 GeV mid-rapidity analyses: charged pions, direct photon, jet, di-pi0

Longitudinal Spin Program:

How do gluon and antiquark contribution to the proton spin?

Is gluon spin contribution zero?

What is the role of antiquarks?

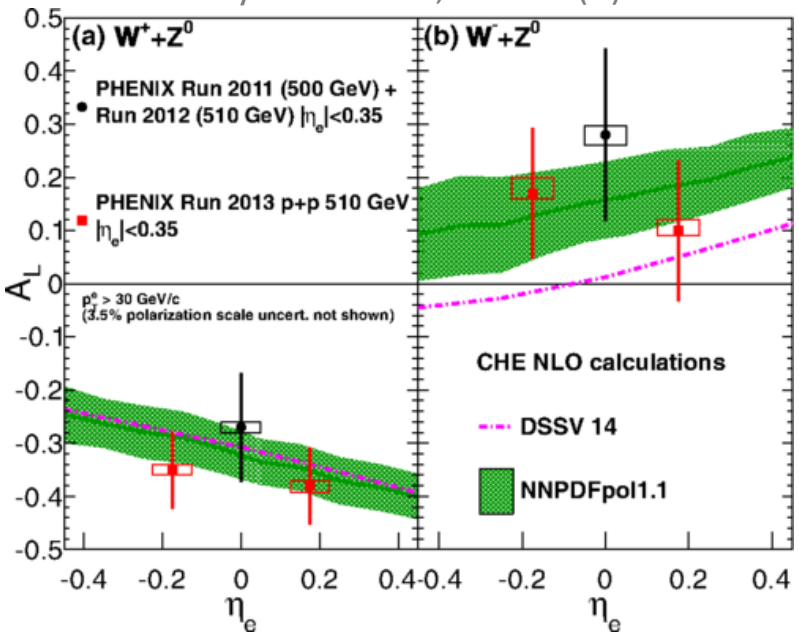
W Program: Separating quark flavor

- Clean and direct sensitivity to antiquark helicity PDFs via parity violating W production
- Flavor asymmetry of the sea: unpolarized sea asymmetry → Is polarized sea symmetric?

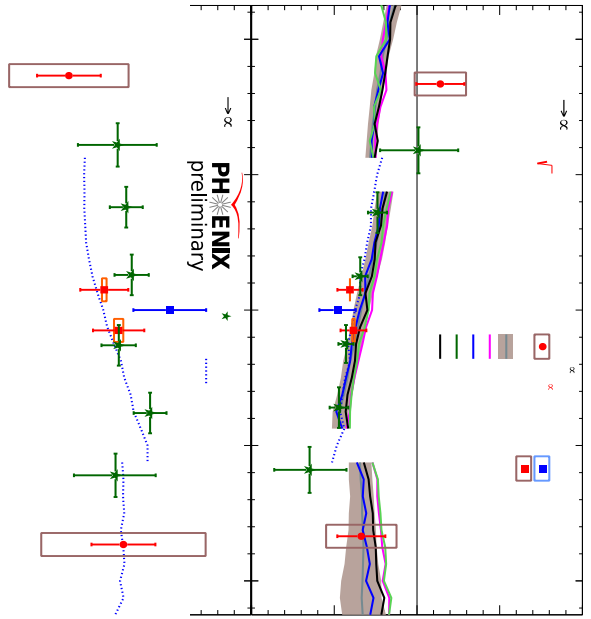
$$u_L \bar{d}_R \rightarrow W^+$$

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

Phys. Rev. D 93, 051103(R)



Forward rapidity coverage (1.2 < |η| < 2.4)

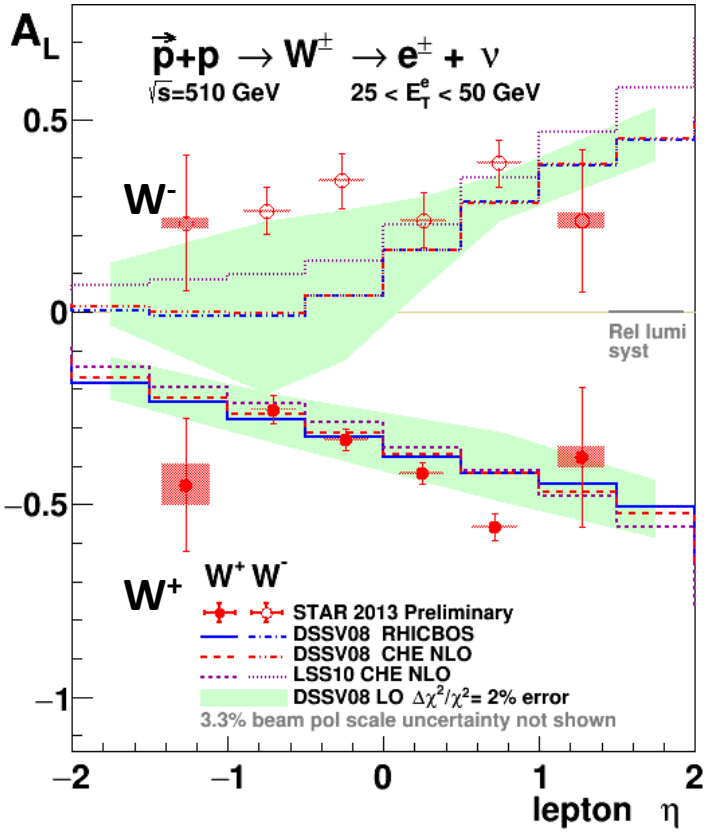


W Program: Separating quark flavor

- Clean and direct sensitivity to antiquark helicity PDFs via parity violating W production
- Flavor asymmetry of the sea: unpolarized sea asymmetry → Is polarized sea symmetric?

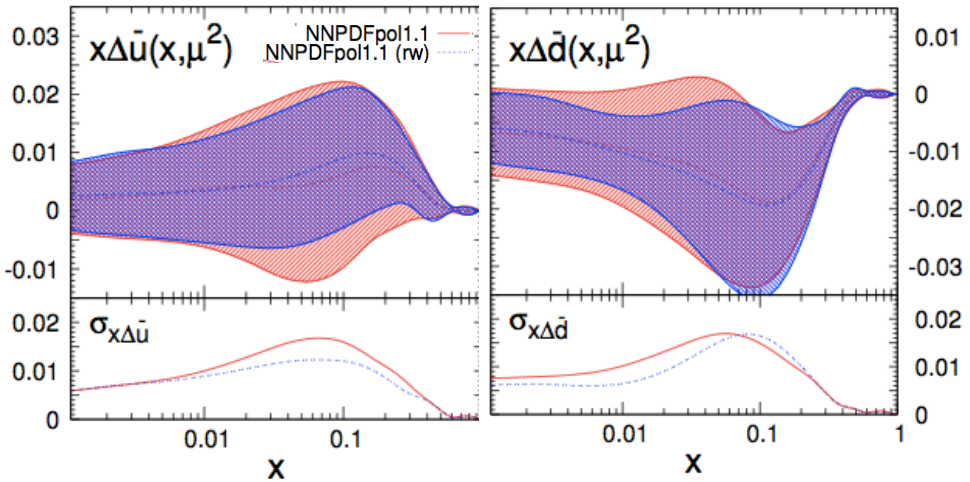
$$u_L \bar{d}_R \rightarrow W^+$$

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



New Run13 mid-rapidity data preliminary result

NNPDFpol1.1 arXiv:1702.05077



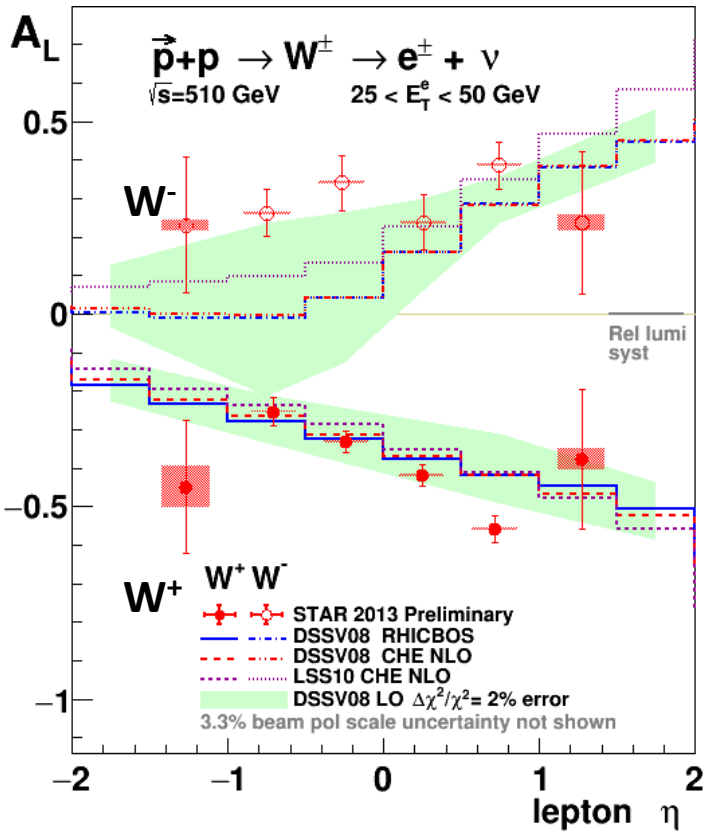
New! Run13 preliminary at near-forward rapidity

W Program: Separating quark flavor

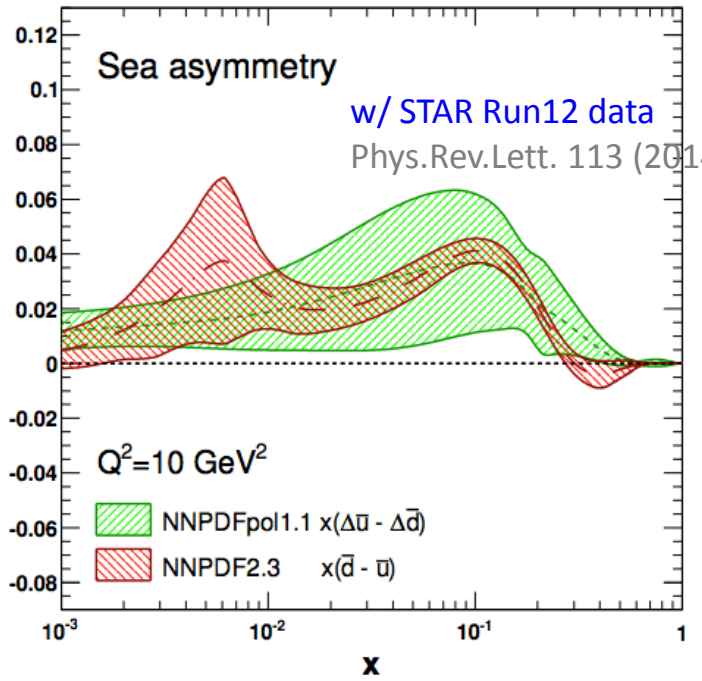
- Clean and direct sensitivity to light sea quark helicity PDFs via parity violating W production
- Flavor asymmetry of the sea: unpolarized sea asymmetry → Is polarized sea symmetric?

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

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



arXiv:1406.7122



- Polarized light sea quark asymmetry
- Almost same size as its unpolarized counterpart, but opposite sign

Transverse Spin Program:

Are TMDs universal?

How do TMD distributions evolve?

How can we access sea quark Sivers function?

Gluon Sivers/twist-3

Transversity

TMD vs Collinear

Ann.Rev.Nucl.Part.Sci. 65 (2015) 429-456

Transverse Momentum Dependent distributions

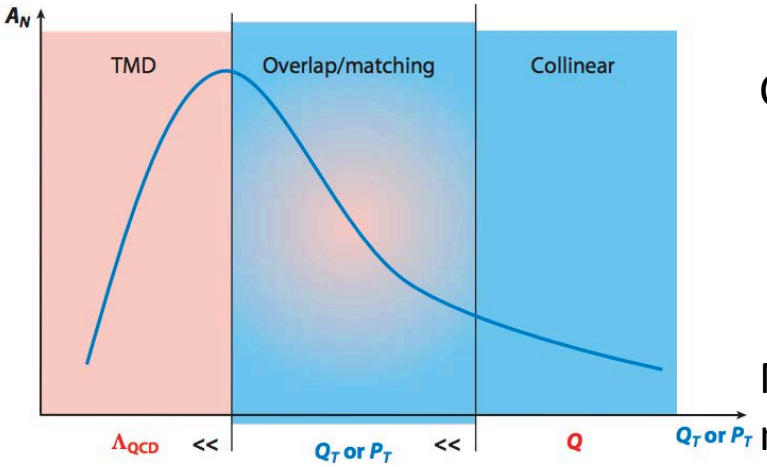
$$f(x, k_\perp; Q^2)$$

Need two observed scales Q^2 and p_T

$Q >> Q_T \sim \Lambda_{QCD}$

CSS (Collins-Soper-Sterman) evolution

Observables:
DY, W/Z production
hadrons within jets (TMD FF)



pT << Q

pT ~ Q

both formalisms are applicable and related

Collinear distributions

$$f(x; Q^2)$$

Need one observed momentum scale

$Q, Q_T >> \Lambda_{QCD}$

DGLAP evolution

Beyond leading twist: Twist-3 effects

Observables:
Inclusive jet and hadrons, HF, direct photon

Sivers Sign change

$$f_{q/h^{\uparrow}}^{SIDIS}(x,k_T,Q^2) = -f_{q/h^{\uparrow}}^{DY/W^{\pm}/Z}(x,k_T,Q^2)$$

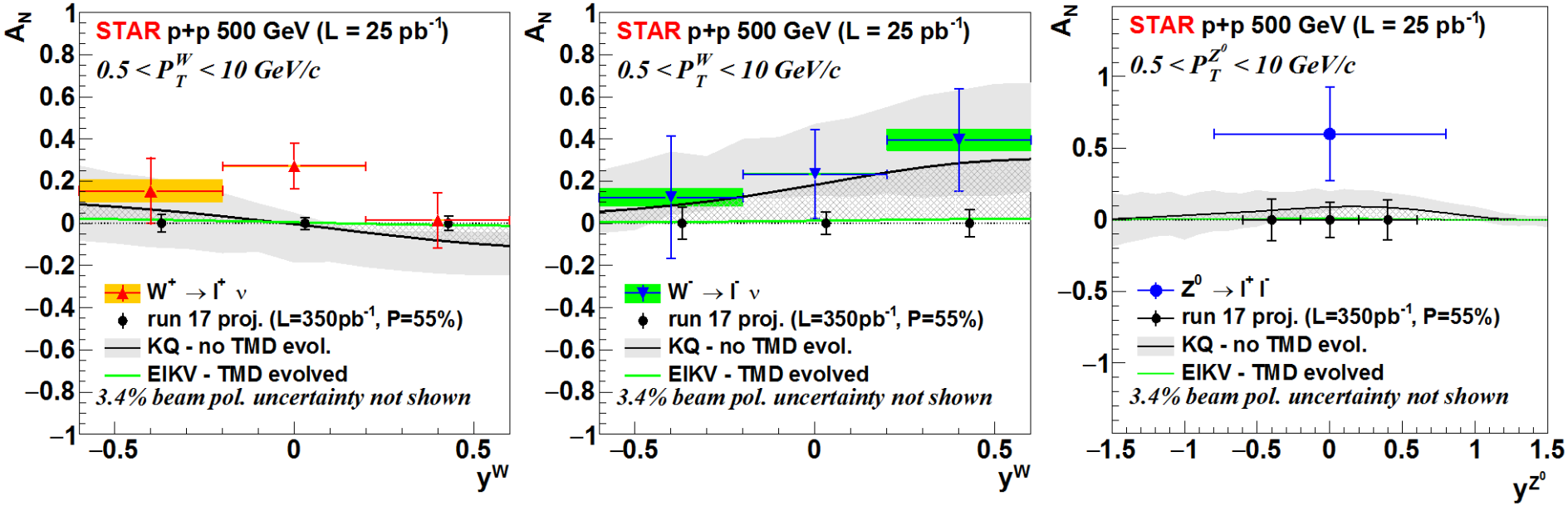
associated with final state effect through gluon exchange between struck parton and the target nucleon remanants

Sivers asymmetry appears as an initial state interaction effect

- Test nonuniversality of Sivers function
- Sivers sign change: fundamental prediction from the gauge invariance of QCD, direct verification of QCD factorization
- DY, W/Z production in p+p: provide two scales (mass, pT)
- First STAR 500 GeV W/Z data published (PRL.116,.132301.(2016))
- 200 and 500 GeV direct photon data: independent access through Twist-3 parton correlation functions

Sivers Sign change

Phys. Rev. Lett. 116, 132301 (2016)



- STAR Run11 500 GeV result with fully reconstructed W kinematics via its recoil
- The result favors sign change, if TMD evolution effect is small
- Run17 data of 350 pb-1 (14 times larger than Run11 data) will also provides a test of unknown TMD evolution and access to the sea quark Sivers functions

Transverse Spin Program:

Are TMDs universal?

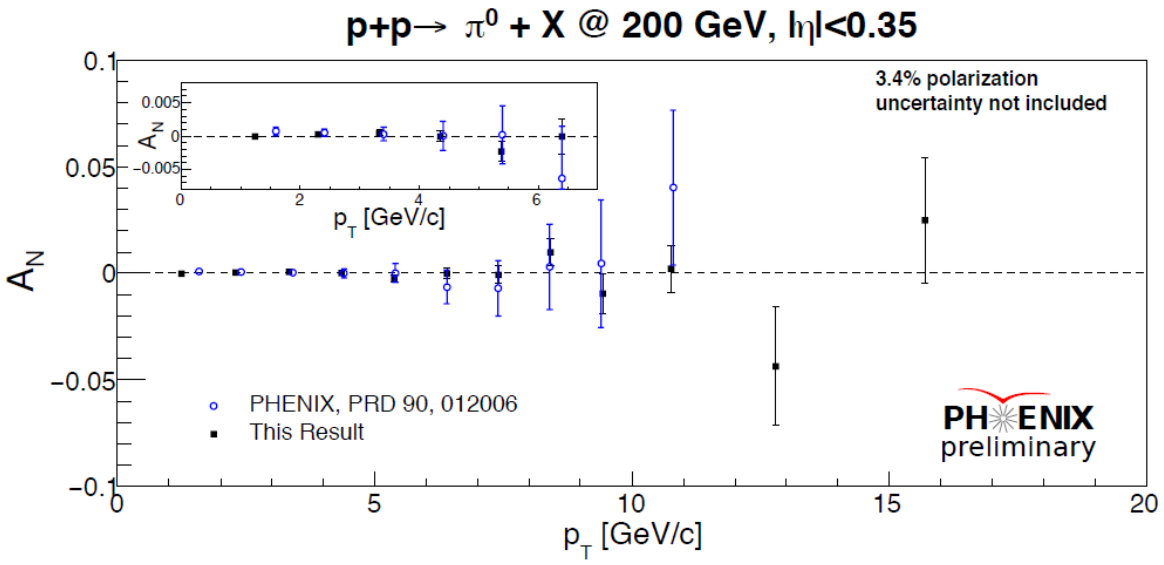
How do TMD distributions evolve?

How can we access sea quark Sivers function?

Gluon Sivers/twist-3

Transversity

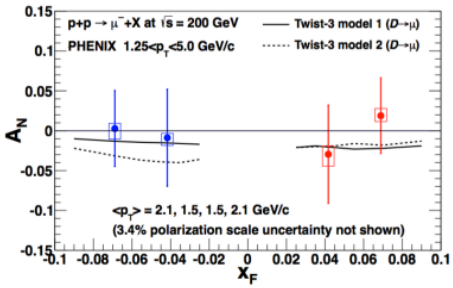
Mid-rapidity pi0

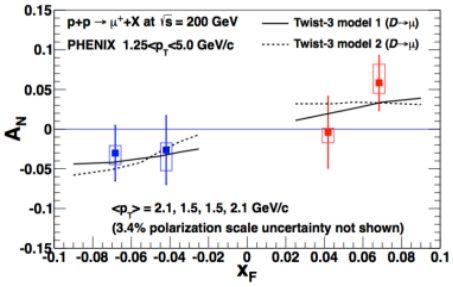


- gg, qg scattering dominant at RHIC
- Higher twist function related to the (gluon) Sivers moments seems to be constrained
- Run15 high precision data (3 times more statistics than the previous measurement)

Heavy Flavor decay muon and J/psi

- Heavy flavor A_N: ideal to investigate gluon distribution
- Twist-3 tri-gluon correlation in the collinear factorization framework
- Recently published Run12 forward rapidity Heavy flavor decay muon results (J/psi contribution removed) consistent with zero within the uncertainty.
- Run15 data analysis ongoing 6.5 times more statistics

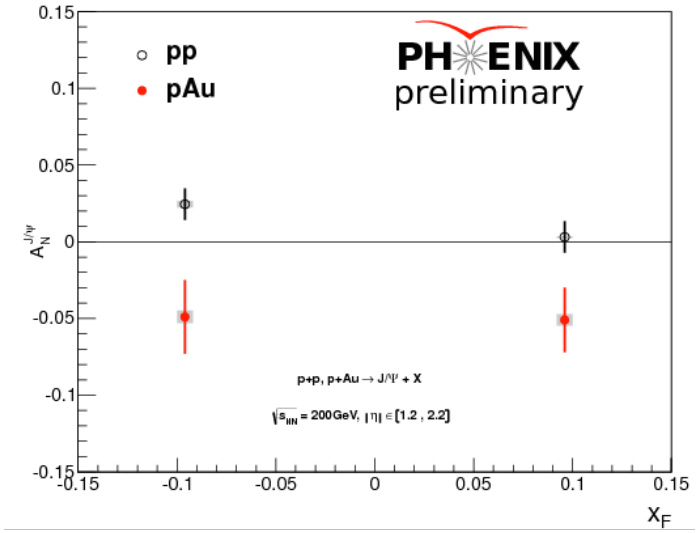


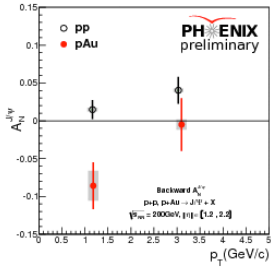


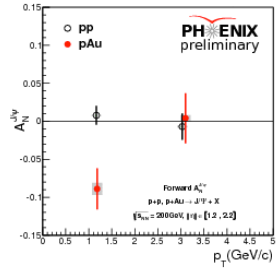
Phys.Rev. D95 (2017) no.11, 112001

Twist-3 model calculations agree with our data

- Run15 J/psi data in p+p and p+Au at 200 GeV
- p+p results consistent with previous results
- 2-sigma level A_N observed in p+Au in both forward and backward
- large unexpected effect from low pT







Transverse Spin Program:

Are TMDs universal?

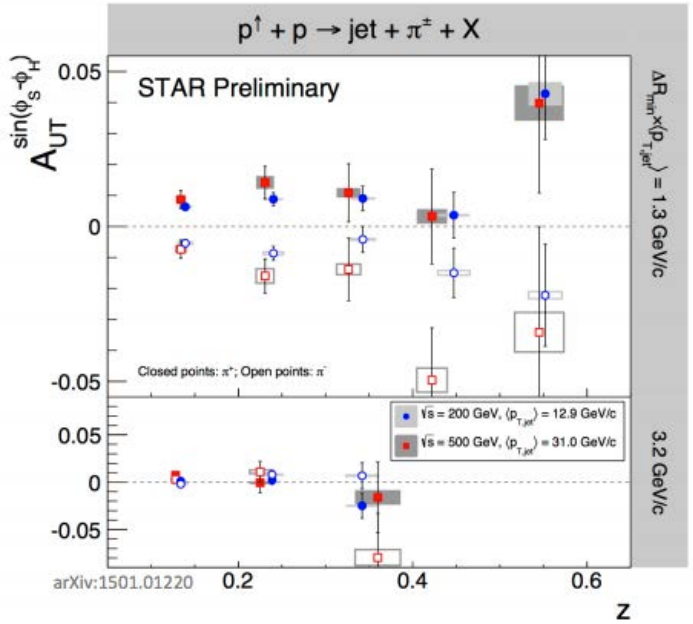
How do TMD distributions evolve?

How can we access sea quark Sivers function?

Gluon Sivers/twist-3

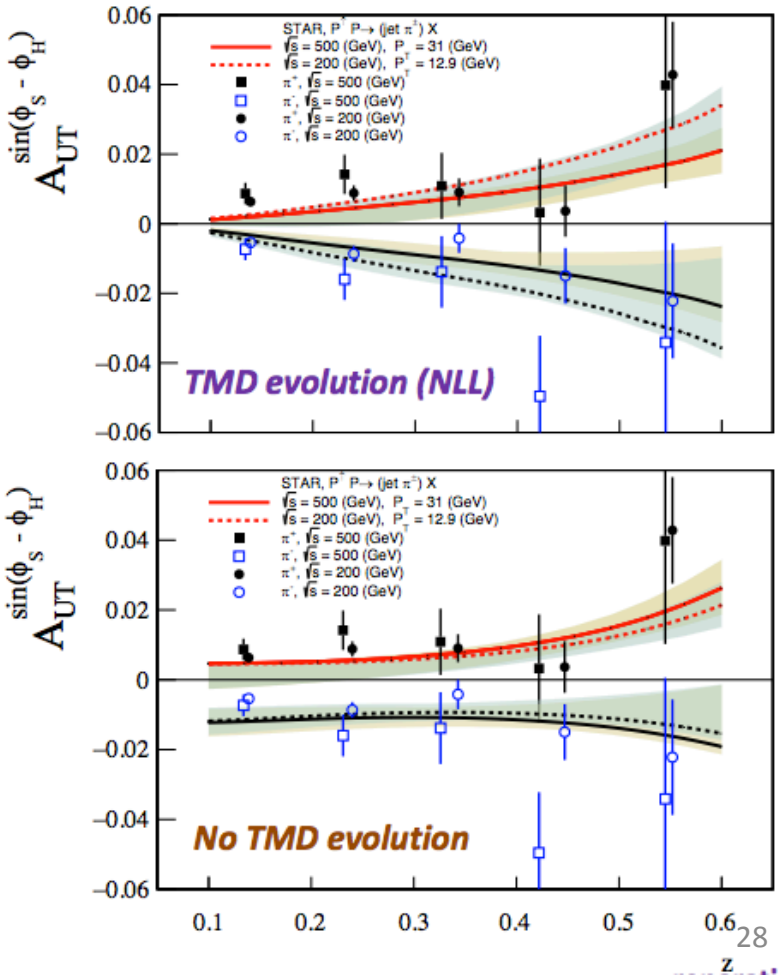
Transversity via Collins FF and IFF

Transversity via Collins FF



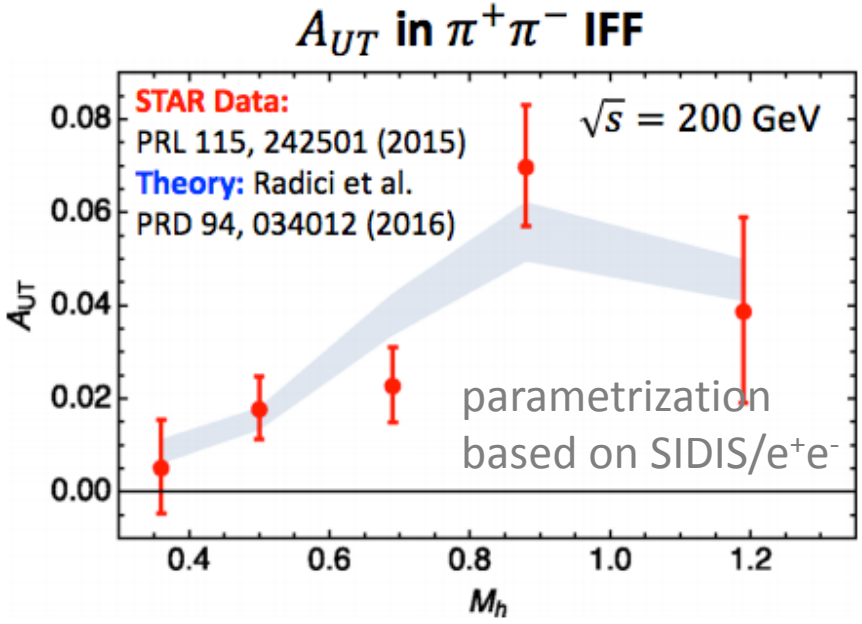
$$j_{T,\min} \approx z \times \Delta R_{\min} \times \langle p_T \rangle,$$

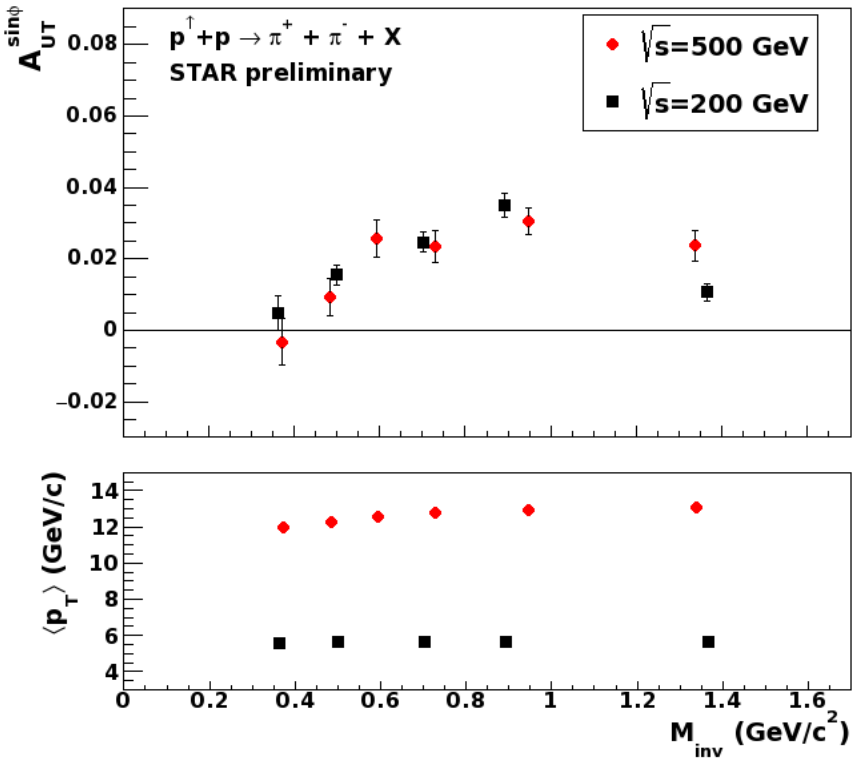
$$\Delta R = \sqrt{\left(\eta_{\text{jet}} - \eta_{\pi}\right)^2 + \left(\phi_{\text{jet}} - \phi_{\pi}\right)^2}$$



- Transverse spin asymmetries of the azimuthal distribution of pions inside of jets
- Non-zero Collins asymmetries at 500 GeV!
- Strong dependence on j_T
- Consistent with 200 GeV results
- Compare with models based on SIDIS/e^+e^- : universality and factorization
- Generally good agreement with STAR data
- No sign of strong TMD evolution in the asymmetries

Transversity via Interference FF



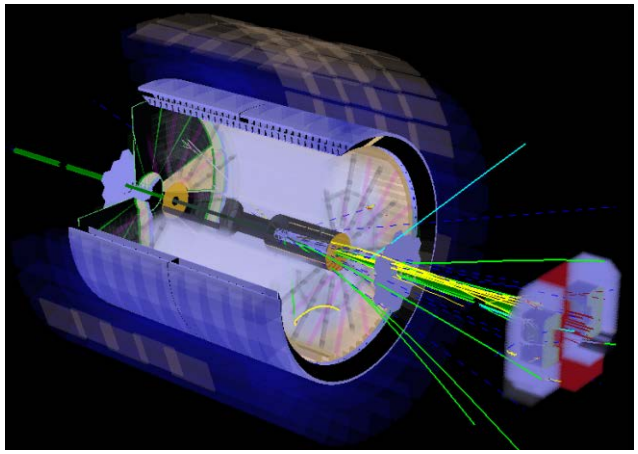


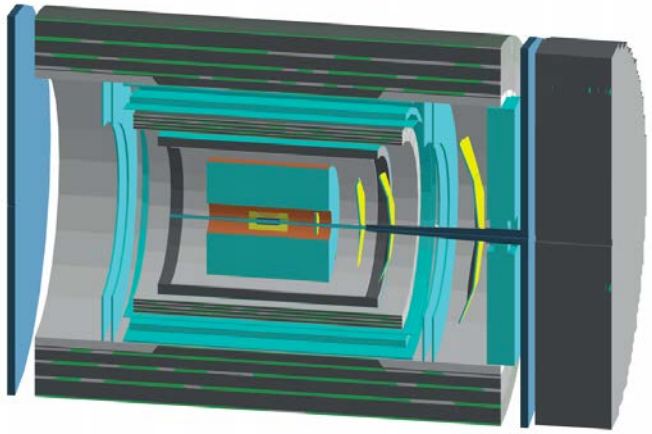
- Independent access to transversity
- Utilizes collinear factorization
- Significant non-zero di-hadron asymmetries at Run12 200 and Run11 500 GeV

- Theory groups begins to include the RHIC IFF results into global tranversity extractions!

Future RHIC Spin

- RHIC is the world's only polarized hadron hadron collider arXiv:1602.03922
- Unique physics opportunities in pp and pA
- pp/pA program essential to fully realize the scientific promise of the EIC:
  - inform the physics program
  - quantify experimental requirements
- Require moderate forward upgrade of sPHENIX and STAR: EMCal + Hcal + Tracking
  - Reuse PHENIX EM calorimeter
  - Detector evolves to an EIC detector with PID and electron direction detector





Cold QCD Plan

arXiv:1602.03922

cs program propsed in the years 2017 and 2023 and if an additional 500 GeV run would become possible.

Summary

RHIC Spin Program has been playing a key role for our understanding of QCD with unique data sets

- RHIC data has the largest impact on ΔG
- RHIC W program to disentangle quark and antiquark helicity functions and study sea symmetry
- Transverse spin program: tests of TMD evolution and color interactions in QCD

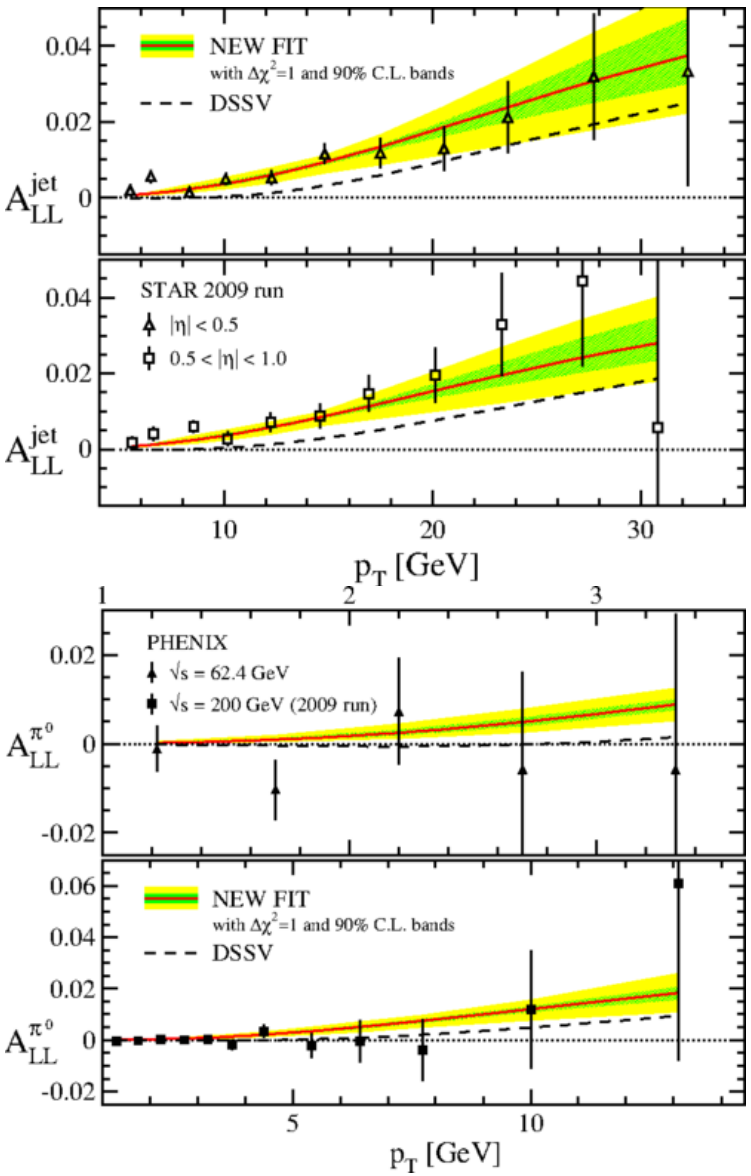
More exiting results are coming. Stay tuned!

RHIC Cold QCD Program with forward upgrade:

- forward pp/pA unique program addressing several fundamental questions in QCD
- essential to complete the mission of the RHIC physics program
- essential to fully realize the scientific promise of the EIC

Backup

First evidence of non-zero gluon spin



RHIC data directly access gluons: STAR jet and PHENIX pi0 production dominated by gg and qg scatterings

RHIC 200GeV data shed light on non-zero gluon spin for x > 0.05!

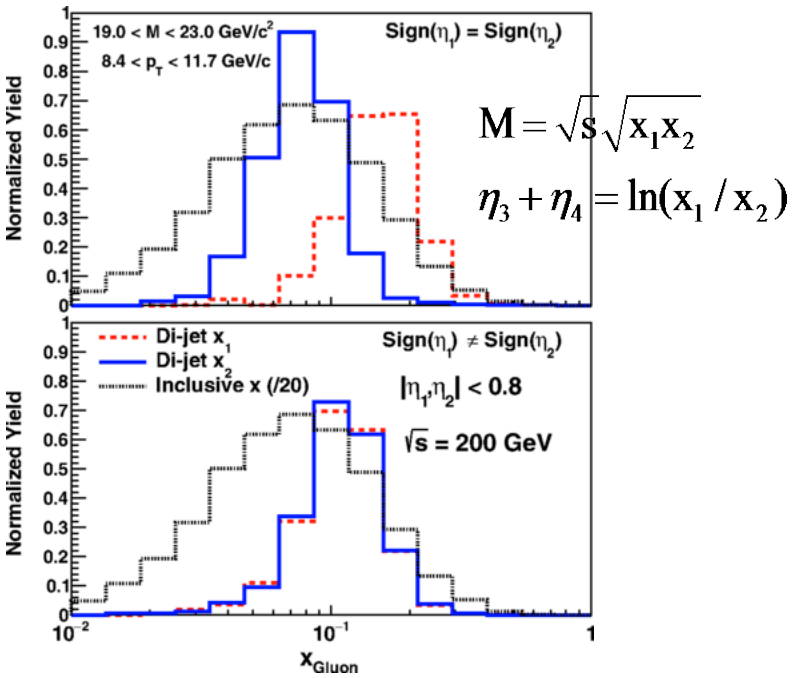
Included in the DSSV global analysis, significant constraint on gluon spin

$$\int_{0.05}^{1} dx\Delta g(x) = 0.2^{+0.06}_{-0.07}(Q^2 = 10\mathrm{GeV}^2)$$

Similarly confirmed by NNPDFpol fit

Correlation measurement

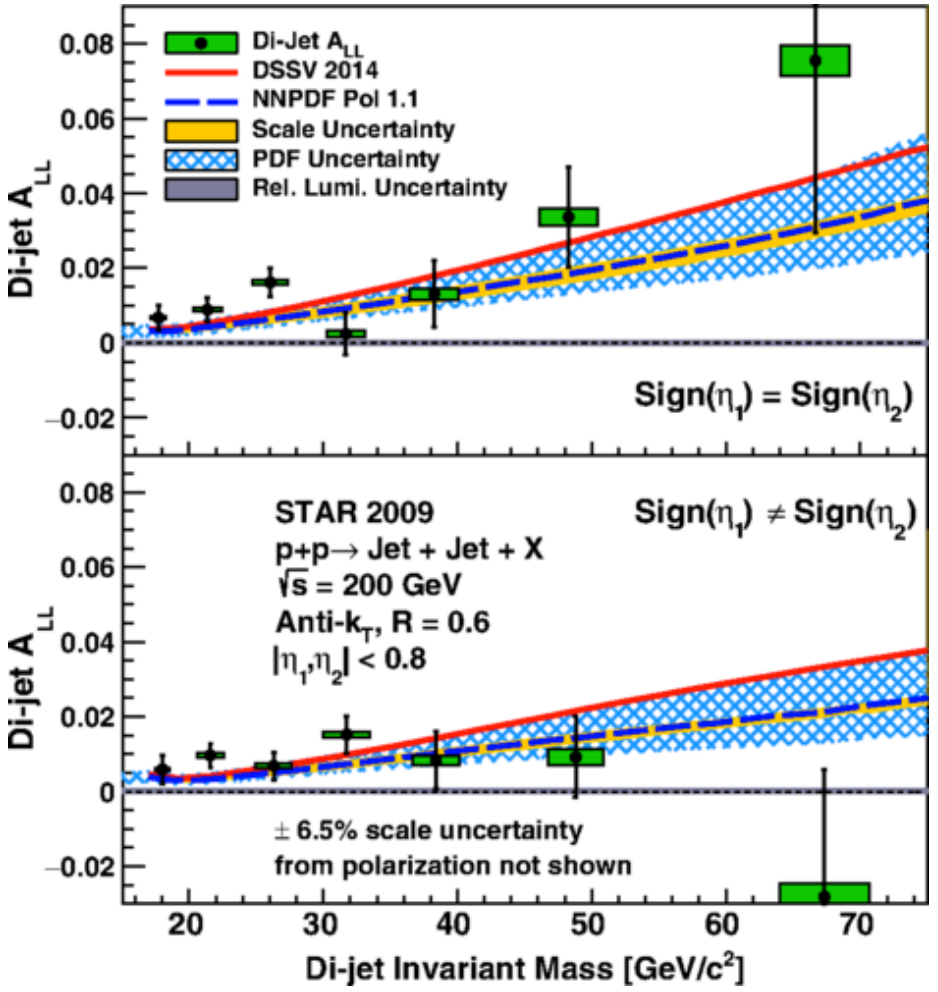
- Access parton kinematics at LO
- Sign(η_1)≠Sign(η_2): select relatively symmetric partonic collisions
- Sign(η_1)=Sign(η_2): asymmetric collisions
- DSSV14 and NNPDFpol 1.1 consistent with dijet measurements



$$M = \sqrt{s}\sqrt{x_1 x_2}$$

$$\eta_3 + \eta_4 = \ln(x_1 / x_2)$$

Phys. Rev. D 95, 071103(R)



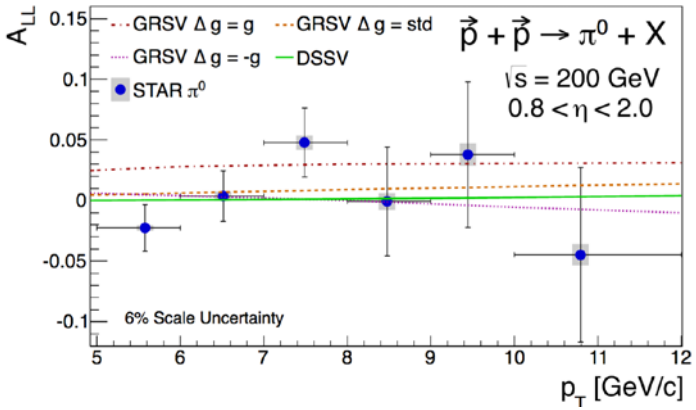
Access low x: Go forward

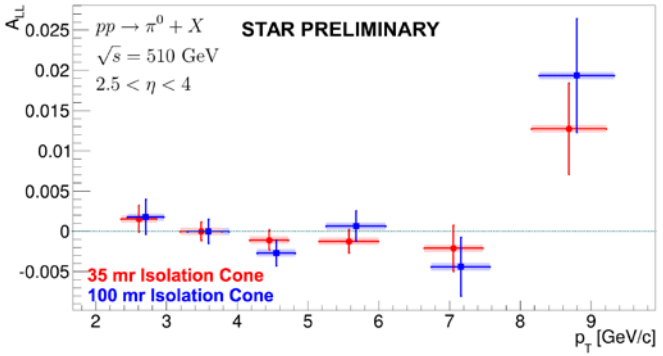
- Forward rapidity measurement allows us to access lower x region ($x_{min} \sim 10^{-3}$)

- STAR Forward pi0 results:
  - 0.8 < |η| < 2.0 at 200 GeV using Run6 data
  - further forward rapidity measurement with Forward Meson Spectrometer (2.5 < |η| < 4.0) using Run12 and Run13 510 GeV data

- STAR Forward di-jet ALL measurement with Barrel and Endcap Electromagnetic Calorimeters
  - consistent with global fit results including 2009 inclusive jet data

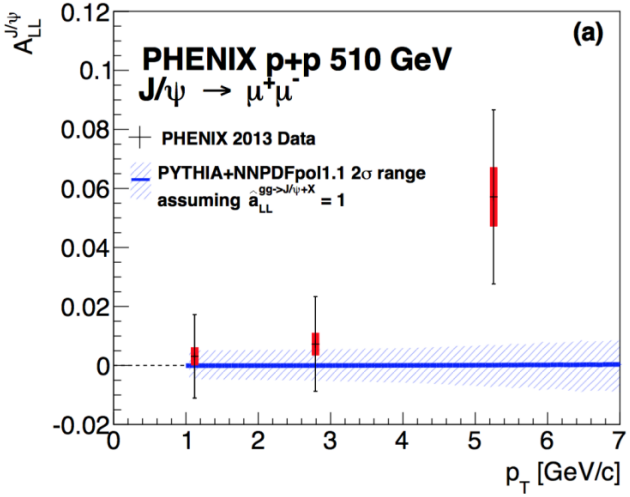
Phys. Rev. D 89, 012001 (2014)

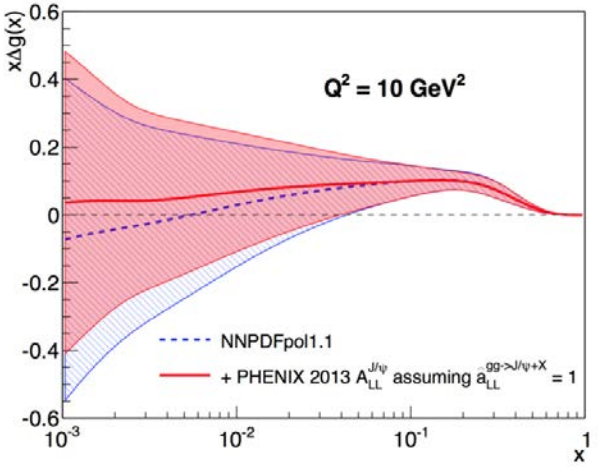


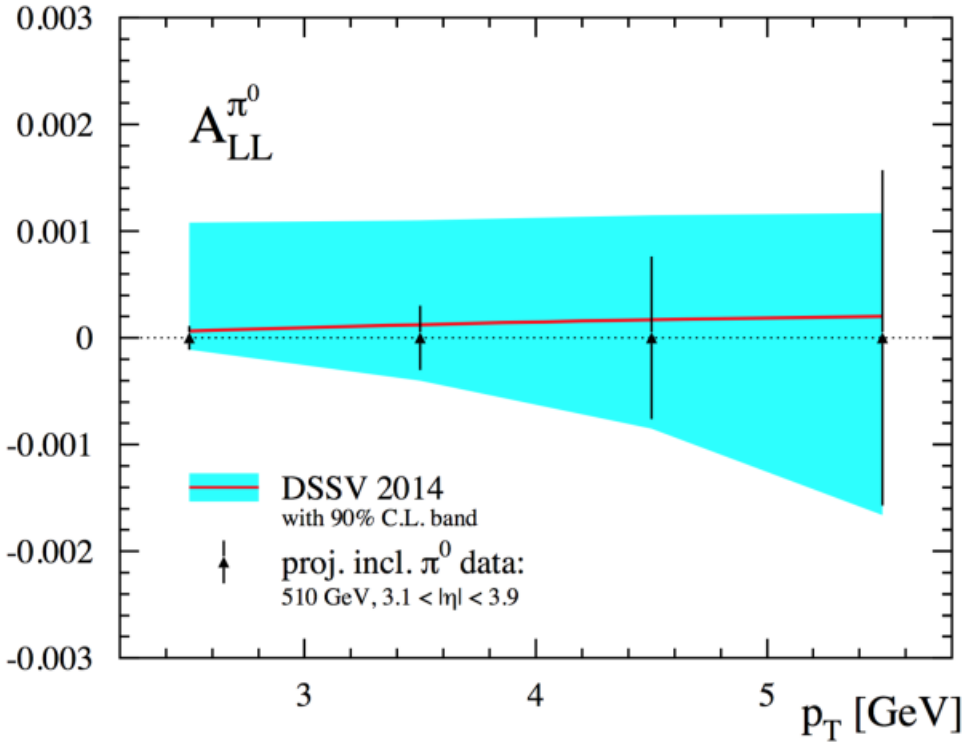


Access low x: Go forward

Phys. Rev. D 94, 112008 (2016)







ion

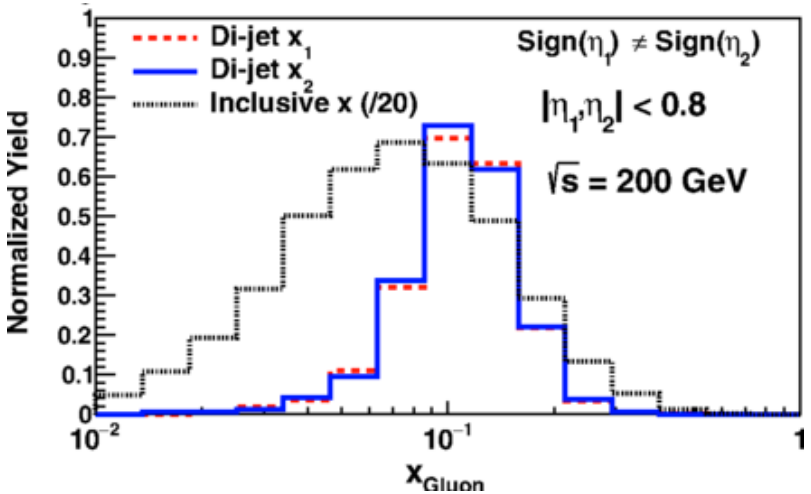
pi0 in MPC:

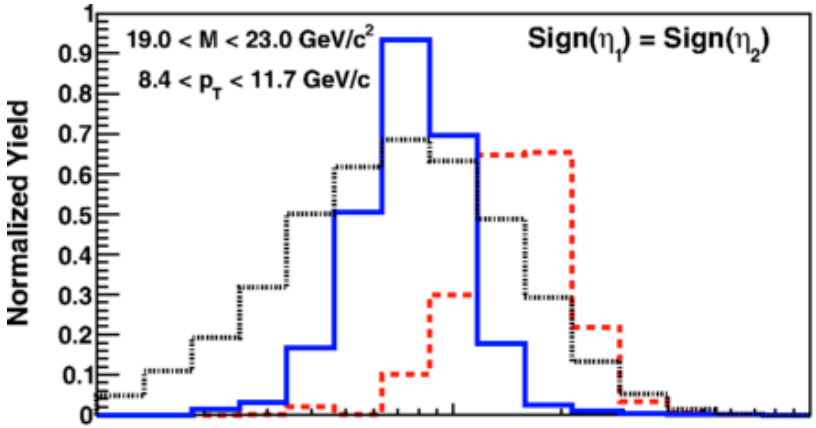
- Further forward Run13 MPC pi0 ALL (3.1 <|η|< 3.9) analysis accesses x ~ 10^{-3}

Shape of x: Correlation measurement

Access parton kinematics at LO

Phys.Rev. D95 (2017) no.7, 071103



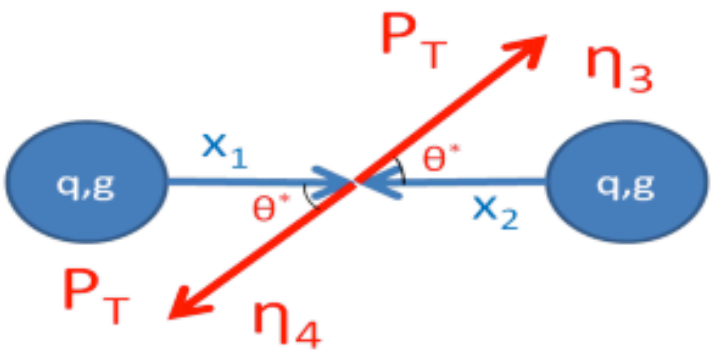


$$M = \sqrt{s}\sqrt{x_1 x_2} \qquad \eta_3 + \eta_4 = \ln(x_1 / x_2)$$

Sign(η_1)≠Sign(η_2): select relatively symmetric partonic collisions

Sign(η_1)=Sign(η_2): asymmetric collisions

Dijet Kinematics



- Correlation measurements such as di-jets capture more information from the hard scattering – di-jet may place better constraints on the functional form of $\Delta g(x,Q^2)$
- Forward rapidity jets arise from asymmetric partonic collisions and probe lower momentum gluons

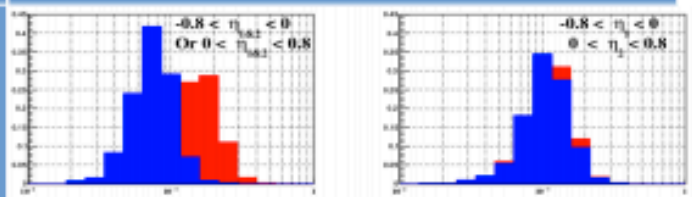
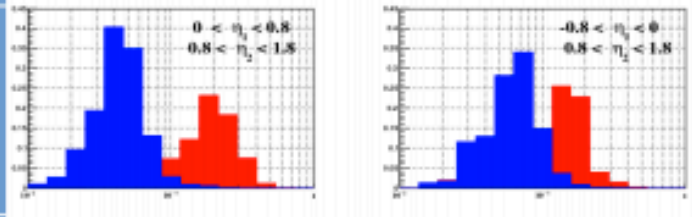
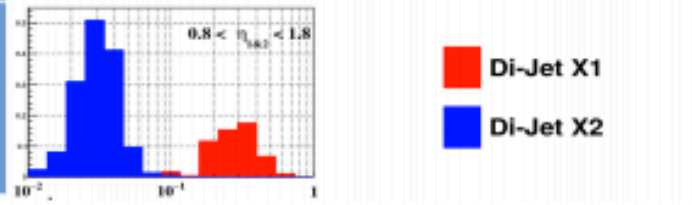
$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4}\right)$$

$$M = \sqrt{x_1 x_2 s}$$

$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2}$$

$$\left|\cos\theta^*\right| = \tanh\left|\frac{\eta_3 - \eta_4}{2}\right|$$

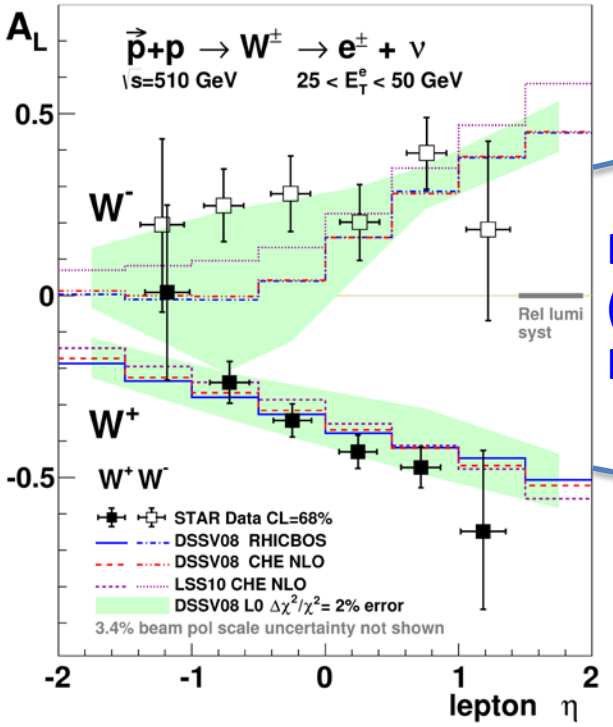
Dijet Configuration	Minimum X1/X2 ($\sqrt{s}$ = 200 GeV)
Barrel-Barrel	
Barrel-Endcap	
Endcap-Endcap	

W Program: Separating quark flavor

- Clean and direct sensitivity to light sea quark helicity PDFs via parity violating W production
- Flavor asymmetry of the sea: unpolarized sea asymmetry → Is polarized sea symmetric?

STAR Run12 results

PRL113,072301(2014)



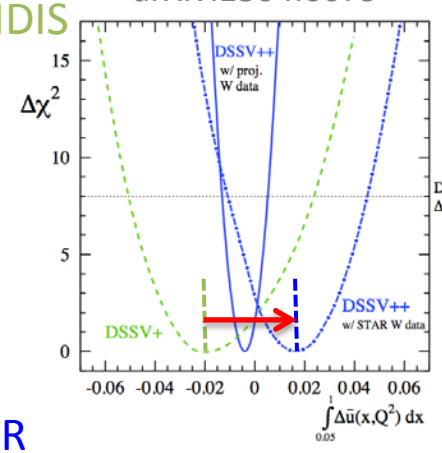
$\Delta\bar{u}$

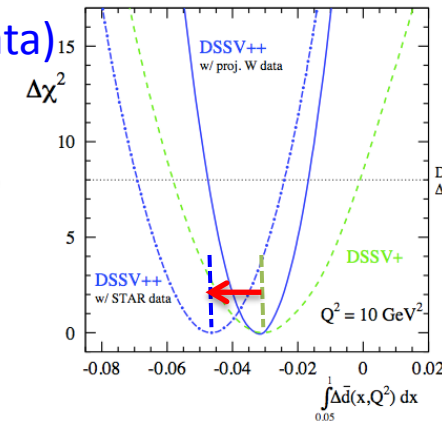
$\Delta\bar{d}$

DSSV++ (with STAR Run12 data)

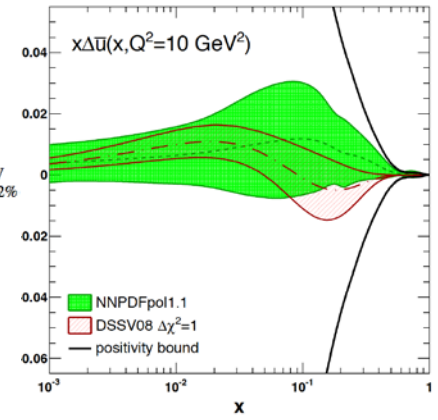
DIS+SIDIS

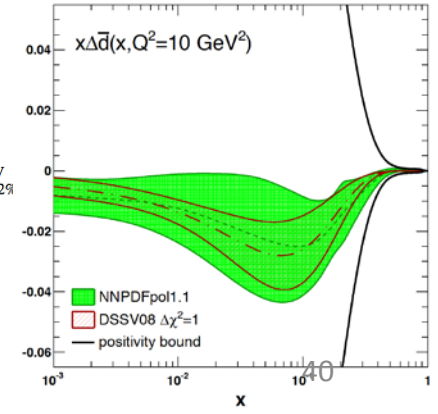
arXiv:1304.0079





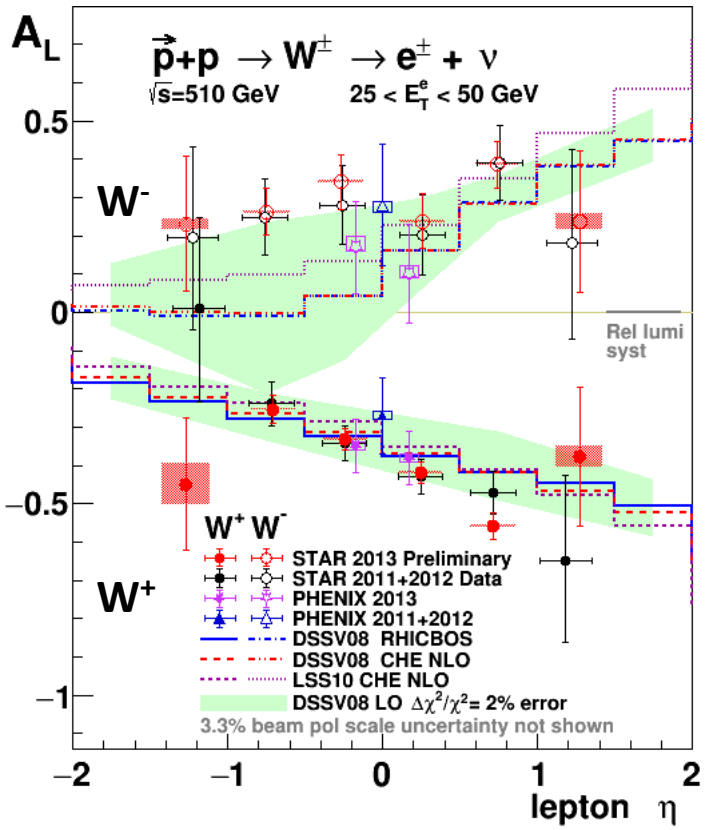
Nucl.Phys. B887 (2014) 276-308



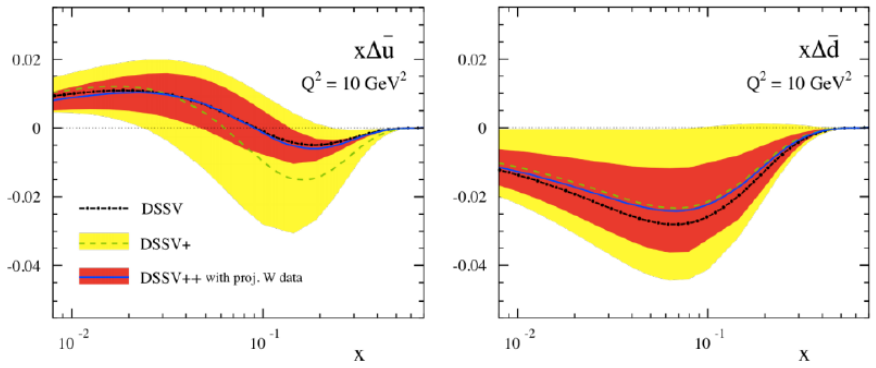


W Program: Separating quark flavor

- Clean and direct sensitivity to light sea quark helicity PDFs via parity violating W production
- Flavor asymmetry of the sea: unpolarized sea asymmetry → Is polarized sea symmetric?

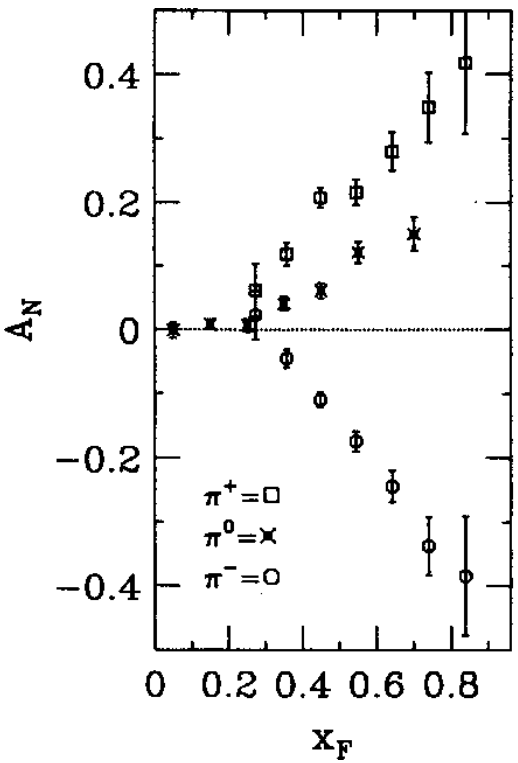


- Run11-Run13 STAR and PHENIX W data will further constraint $\Delta\bar{u}$ and $\Delta\bar{d}$
- Impact of RHIC 2009-2013 W data:

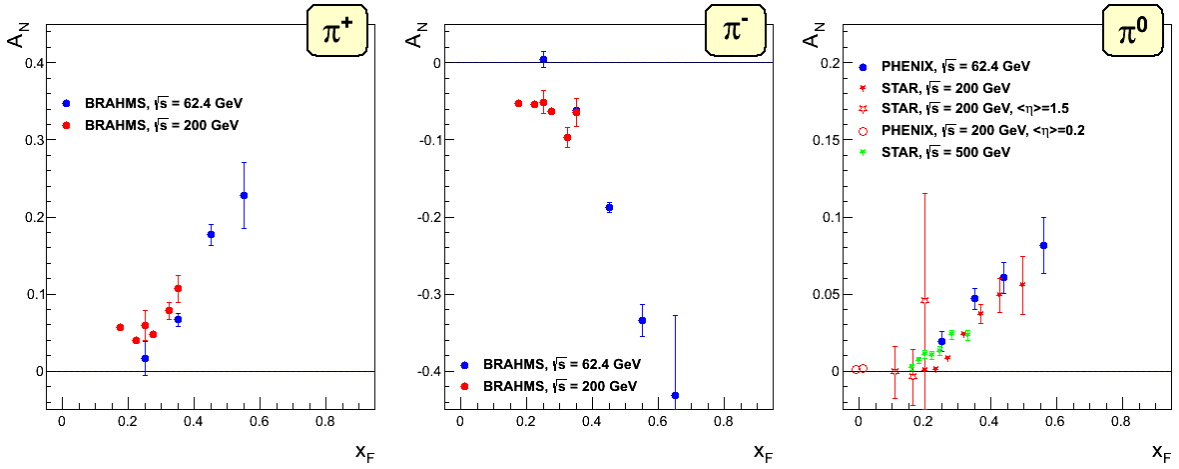


Transverse Spin Phenomena

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$



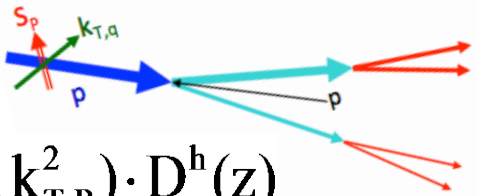
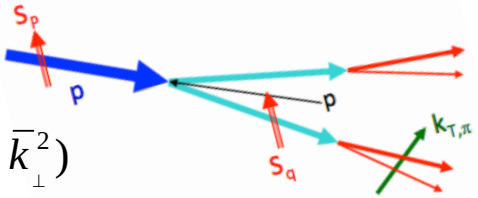
- Naïve QCD Predicted very small asymmetry $\propto \frac{\alpha_s m_q}{p_T}$
- Surprisingly large TSSAs observed (A_N ~ 40% @ √s = 19.1 GeV)
- Asymmetry survived with higher energies: nearly independent of √s



Adams D L et al. (FNAL-E704)
1991 Phys. Lett. B264 462466

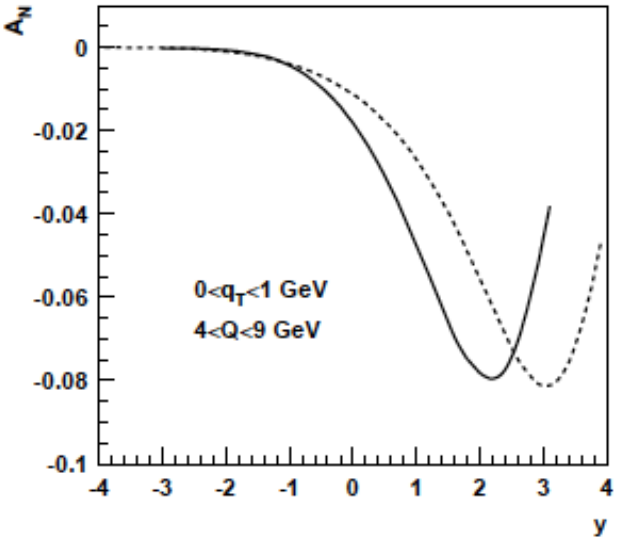
Understanding the large TSSAs?

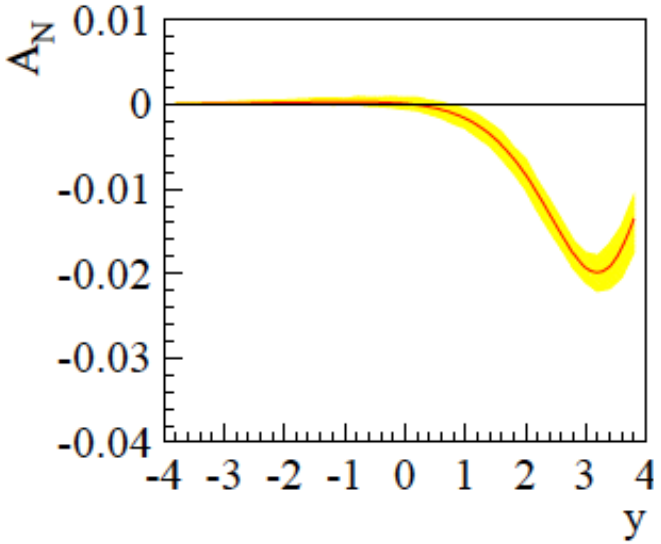
Beyond the leading twist collinear parton picture

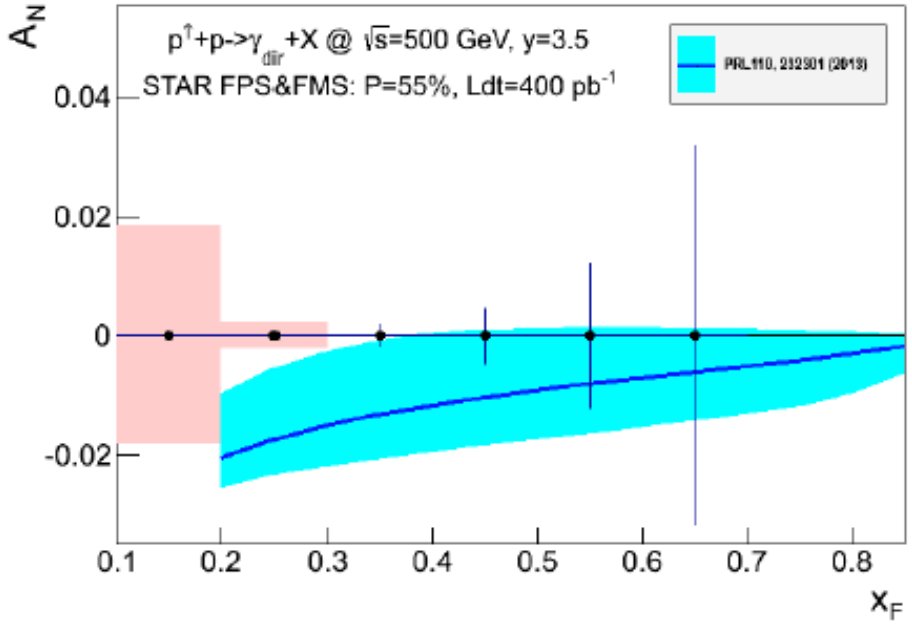
Initial state	**Final state**
Sivers effect Correlation between Parent spin (S_p) and intrinsic parton transverse momentum $k_{T,q}$	Collins effect Correlation between Parent spin (S_p) and quark spin (S_q) + spin dependent fragentation function (FF)
 $\bar{f}_{1T}^{\perp q}(x, k_{T,P}^2) \cdot D_q^h(z)$	 $\delta q(x) \cdot H_1^{\perp}(z_2, \bar{k}_{\perp}^2)$ transversity x Collins FF
Multiparton correlation (twist-3) functions	Multiparton correlation (twist-3) fragmentation functions

$$A_N \propto \sigma(p_T, S_\perp) - \sigma(p_T, -S_\perp)$$

$$\propto T^{(3)}(x, x, S_\perp) \otimes \hat{\sigma}_T \otimes D(z) + \delta q(x, S_\perp) \otimes D^{(3)}(z, z) + ..$$


A_N
0
-0.02
-0.04
-0.06
-0.08
-0.1
-4 -3 -2 -1 0 1 2 3 4
y
$0<q_T<1$ GeV
$4<Q<9$ GeV


A_N
0.01
0
-0.01
-0.02
-0.03
-0.04
-4 -3 -2 -1 0 1 2 3 4
y


A_N
$p^{\uparrow}+p\rightarrow\gamma_{dir}+X$ @ $\sqrt{s}$=500 GeV, y=3.5
STAR FPS&FMS: P=55%, Ldt=400 pb^{-1}
PRL110, 232301 (2013)
0.04
0.02
0
-0.02
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
x_F