The RHIC Spin Program Overview

- ✓ Nucleon helicity structure
- ✓ Transverse spin phenomena

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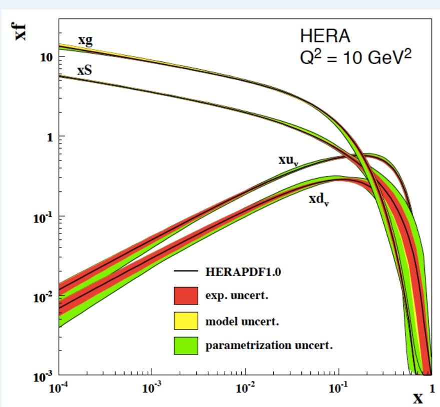
JAEA, Japan

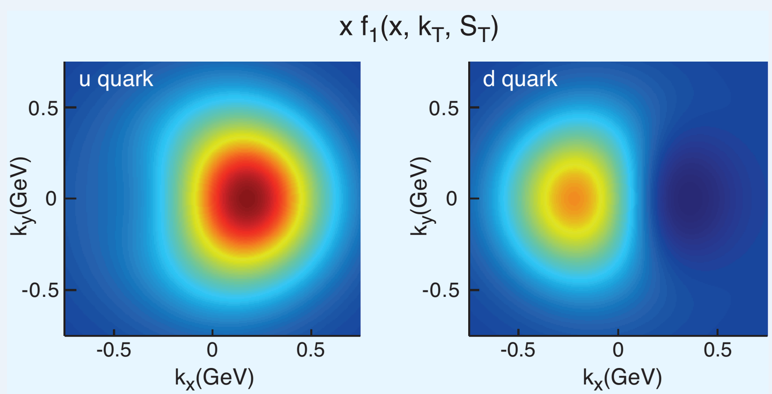
RHIC Spin

arXiv: 1501.01220

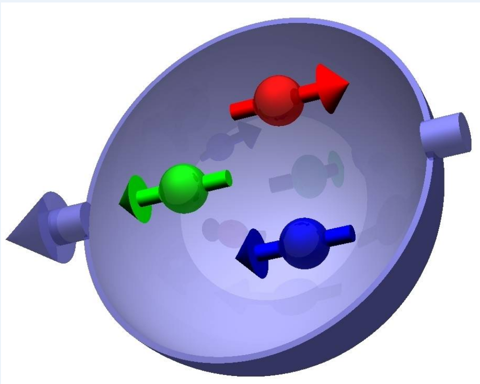
The RHIC Spin Program
Achievements and Future Opportunities

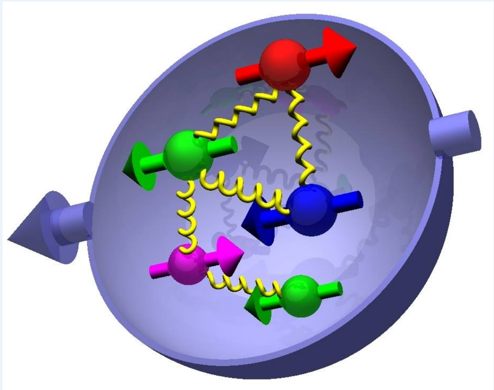
- How do quarks and gluons build the proton spin ½
- What do transverse spin phenomena teach us

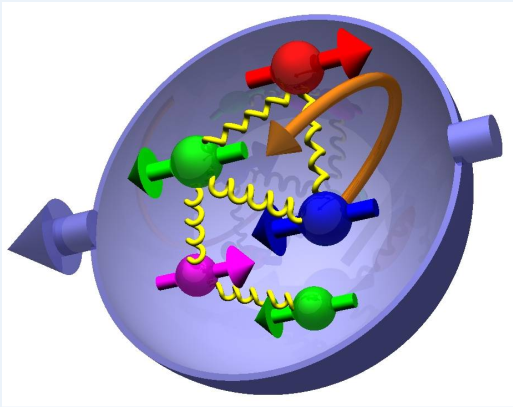




Nucleon Helicity Structure







Naïve parton model:

$$\frac{1}{2} = \frac{1}{2}\left(\Delta u_v + \Delta d_v\right)$$

1989 EMC (CERN):
ΔΣ=0.12±0.09±0.14

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s}$$

⇒ Spin Crisis

⇒ Gluons are polarized (ΔG)
⇒ Sea quarks are polarized:

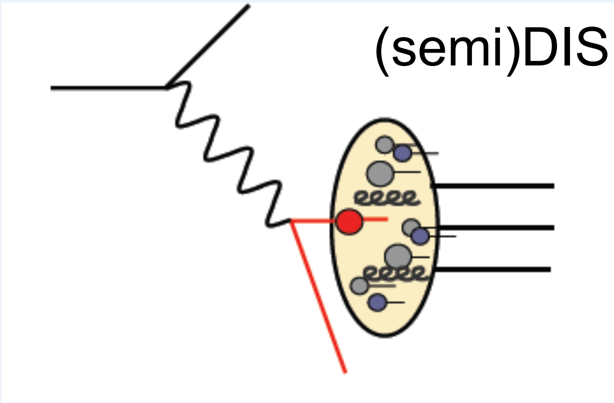
$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta\bar{q}\right) + \Delta G$$

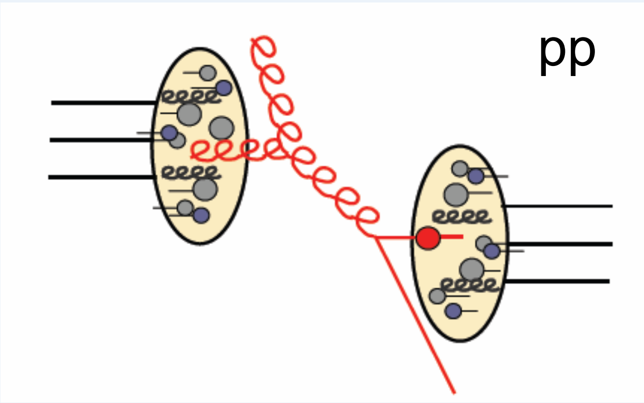
For complete description include parton orbital angular momentum L_Z:

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

Determination of ΔG and Δq-bar has been the main goal of longitudinal spin program at RHIC

From DIS to pp:





Probes ΔG:

Q^2 dependence of quark PDFs

Photon-gluon fusion

(Anti-)quark flavor separation:

Through fragmentation processes

Probes ΔG:

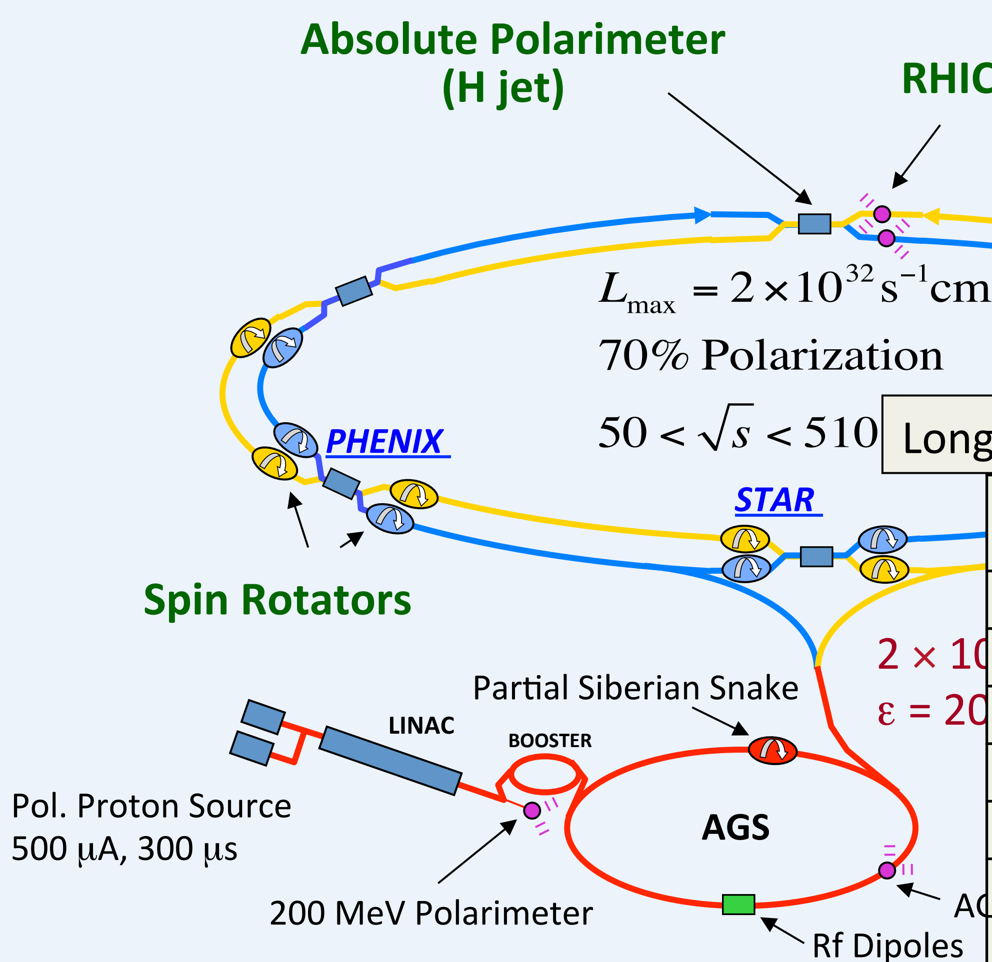
Directly from *gg* and *qg* scattering

(Anti-)quark flavor separation:

Through $u\bar{d} \rightarrow W^+$ and $\bar{u}d \rightarrow W^-$

Complementary approaches

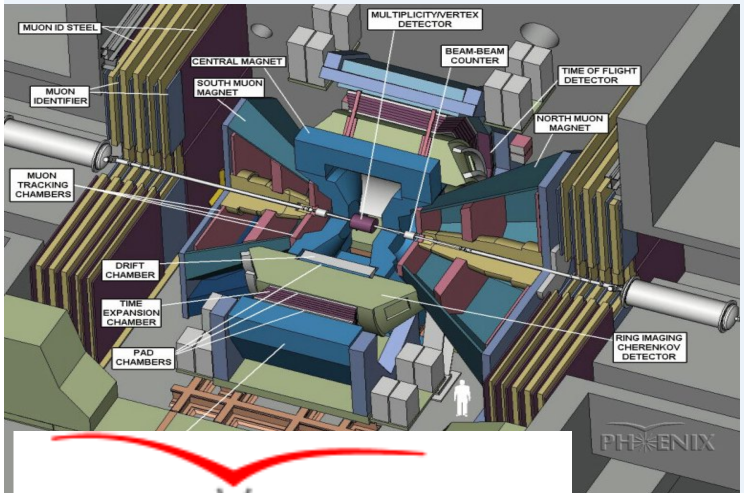
RHIC as polarized proton collider



Longitudinal Spin Running in PHENIX/STAR

Year	√s [GeV]	L [pb^{-1}] (recorded)	Pol. [%]
2003	200	0.35 / 0.3	27
2004	200	0.12 / 0.3	40
2005	200	3.4 / 3.1	49
2006	200	7.5 / 6.8	57
2006	**62.4**	**0.08 / -**	**48**
2009	200	16 / 25	55
2009	**500**	**14 / 10**	**39**
2011	**500**	**18 / 12**	**48**
2012	**510**	**32 / 82**	**53**
2013	**510**	**155 / 300**	**53**

PHENIX and STAR



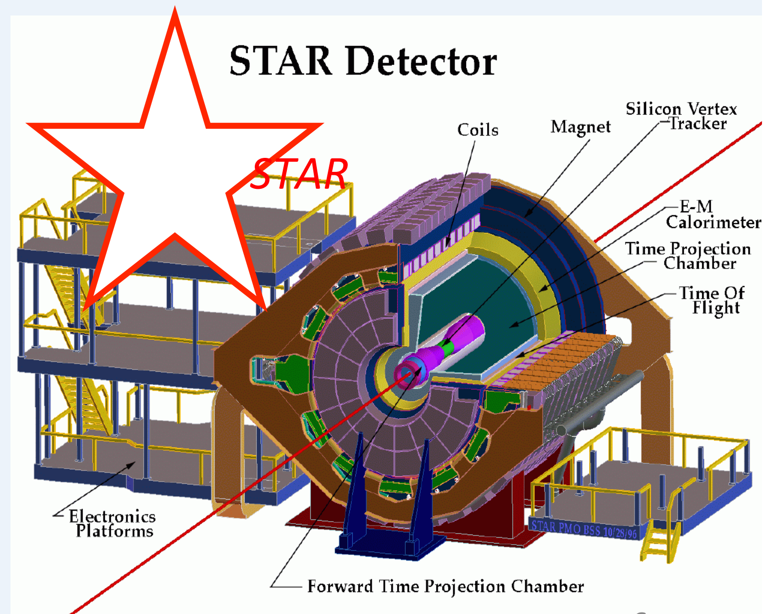
PHENIX

<u>PHENIX:</u>

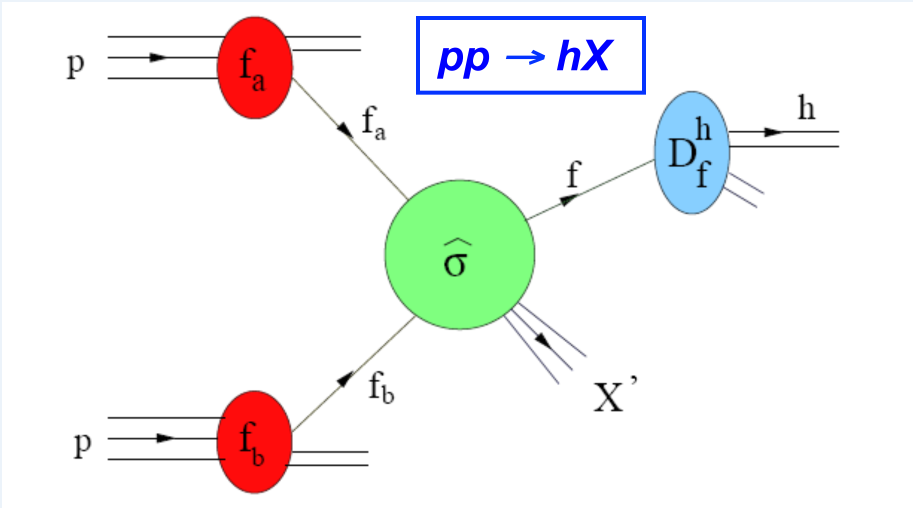
High rate capability
High granularity
Good mass resolution and PID
Limited acceptance
Upgrades to forward capabilities, inner tracking

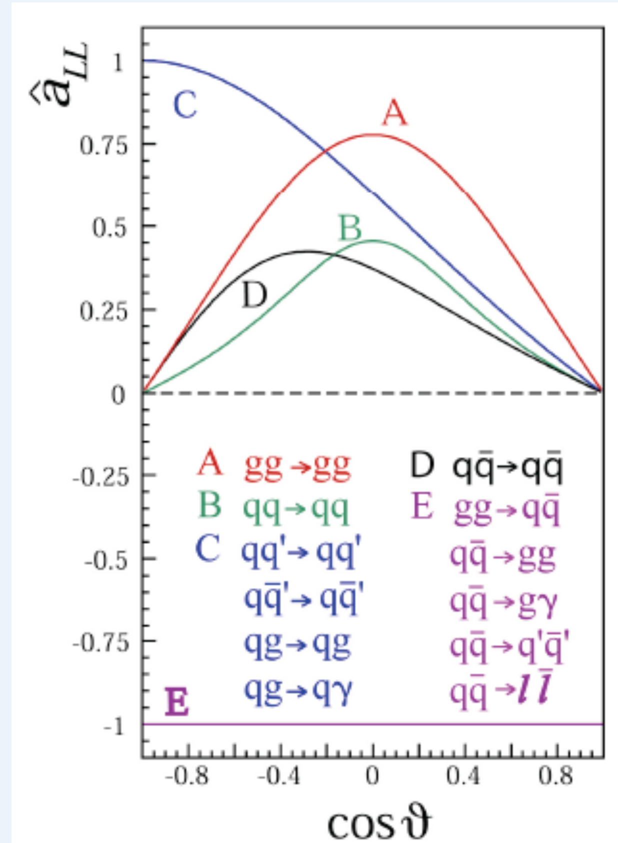
<u>STAR:</u>

Large acceptance with azimuthal symmetry
Good tracking and PID
Central and forward calorimetry
Upgrades to higher rate capabilities,
Inner tracking

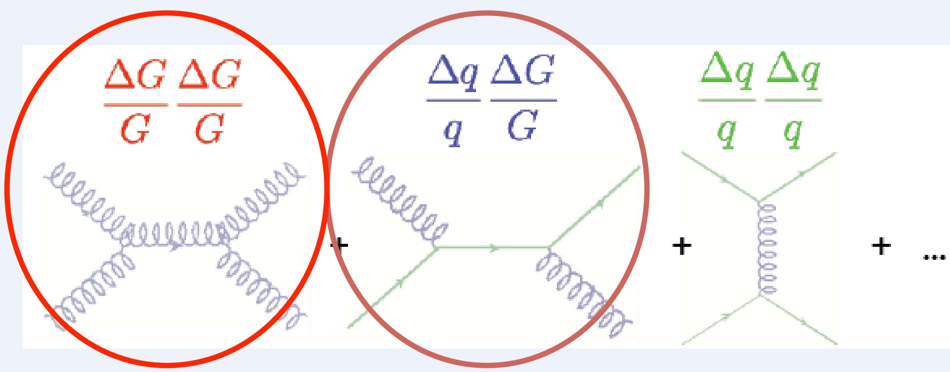


Probing ΔG in pol. pp collisions





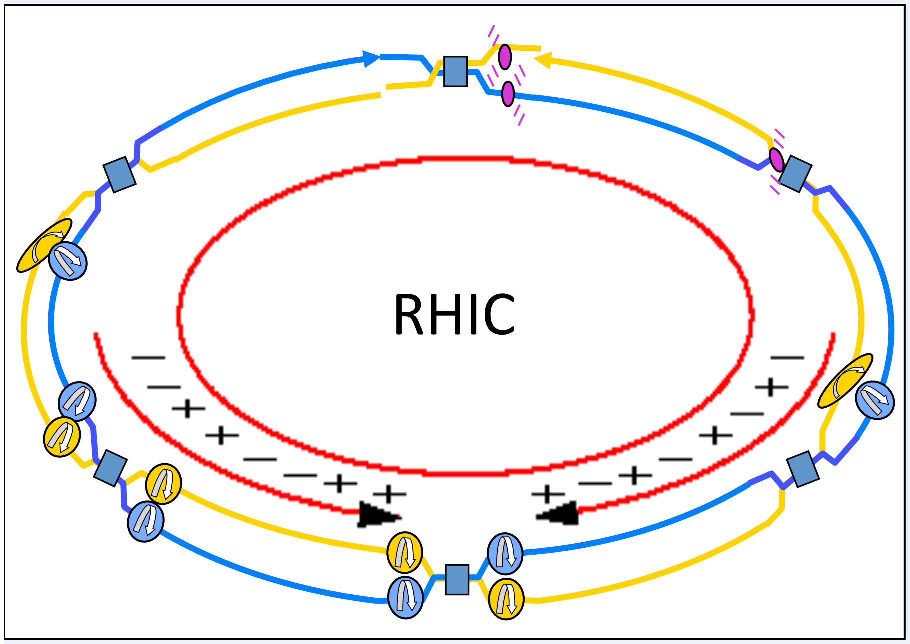
$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{\sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \cdot \hat{a}_{LL}^{f_a f_b \to fX} \otimes D_f^h}{\sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \otimes D_f^h}$$



Double longitudinal spin asymmetry A_{LL} is sensitive to ΔG

Measuring A_{LL}

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = \frac{1}{|P_1 P_2|} \frac{N_{++} - RN_{+-}}{N_{++} - RN_{+-}}; \qquad R = \frac{L_{++}}{L_{+-}}$$

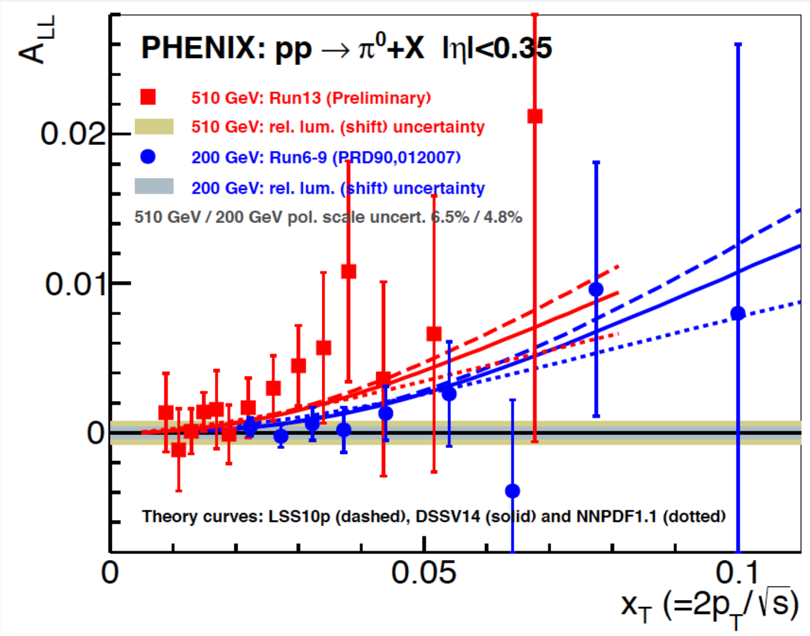


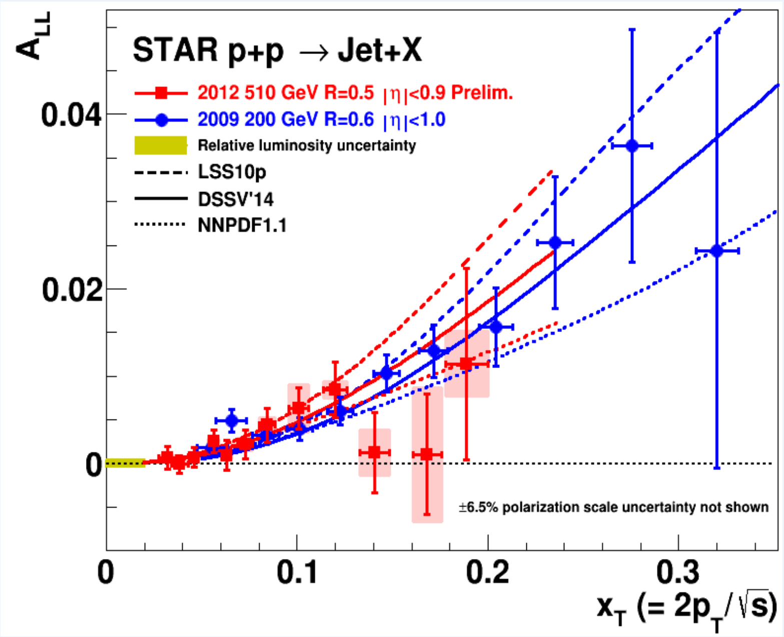
(N) Yield
(R) Relative Luminosity
(P) Polarization

✓ Bunch spin configuration (+ or - helicity) alternates every 106 ns
✓ Data for all bunch spin configurations are collected at the same time

⇒ Possibility for false asymmetries is greatly reduced

ΔG: π0 and jet A_{LL}

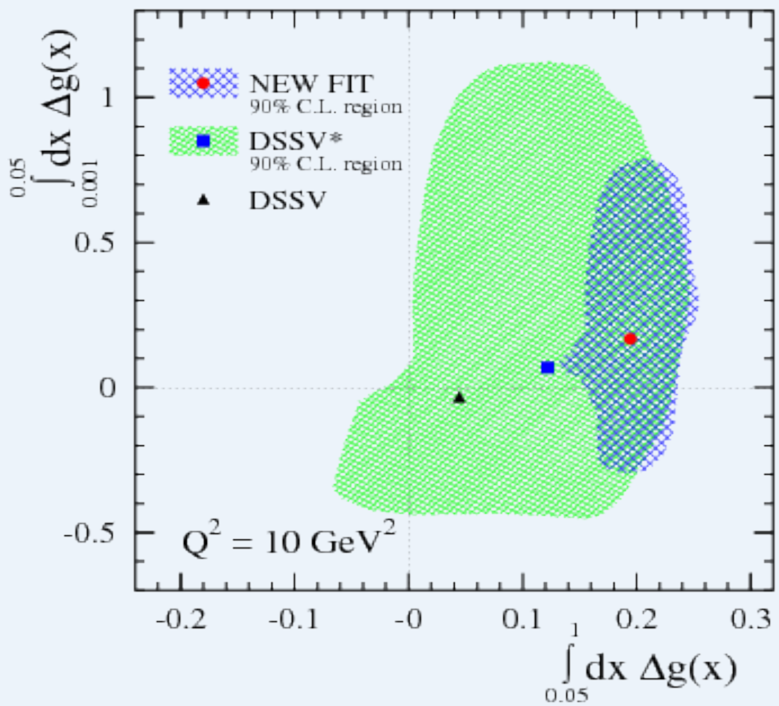




First observation of non-zero A_{LL} associated with non-zero ΔG !

ΔG: DIS+pp global QCD fit

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



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

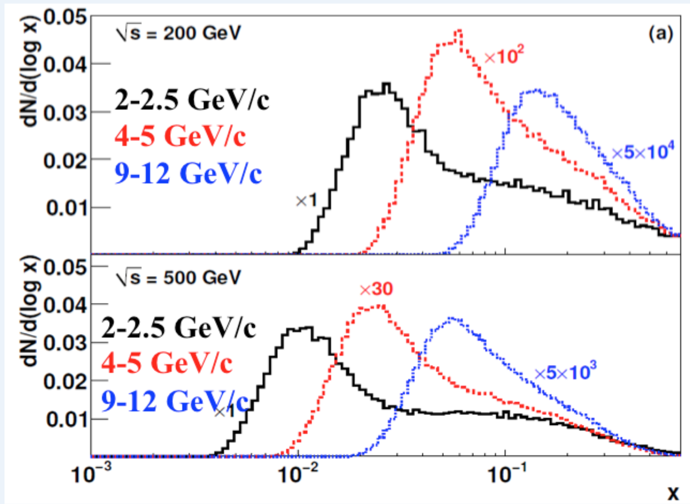
New DSSV: Phys Rev Lett, 113, 012001 (2014)
Data from up to 2009

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

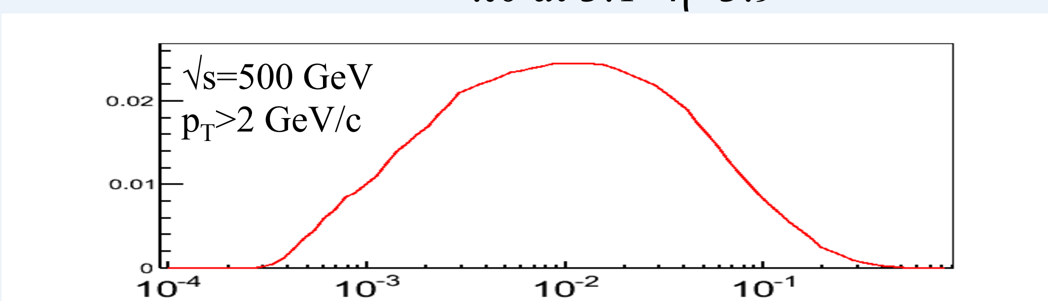
Significant non-zero Δg(x) in the kin. region probed by RHIC
Similar result from another global fit NNPDF
Still huge uncertainty in unmeasured region (x<0.05)
=> Measurements at higher √s and forward rapidity

ΔG: Towards lower x

π0 at |η|<0.35



π0 at 3.1<η<3.9

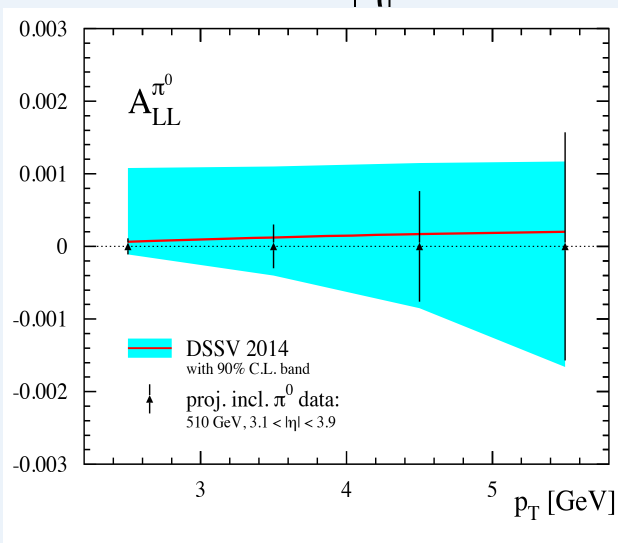


From √s=200 to 500 GeV

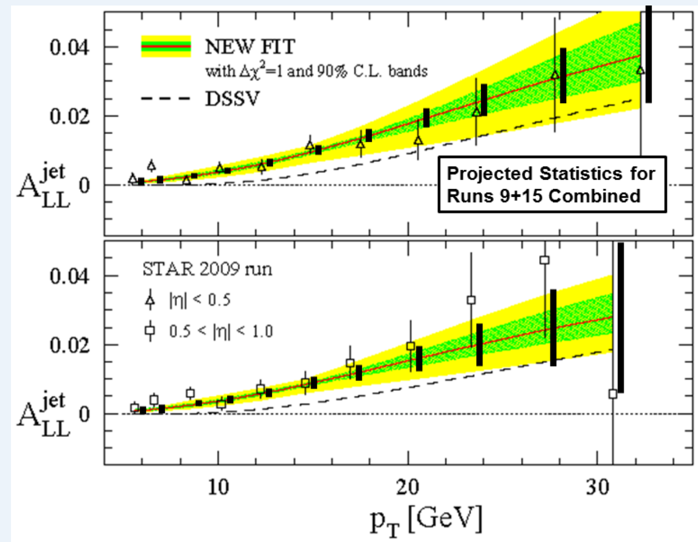
From central η to forward η

ΔG: Near Term Projections

π0: 3.1<|η|<3.9



Jets: |η|<1



π0 in forward region at √s=510 GeV (PHENIX):

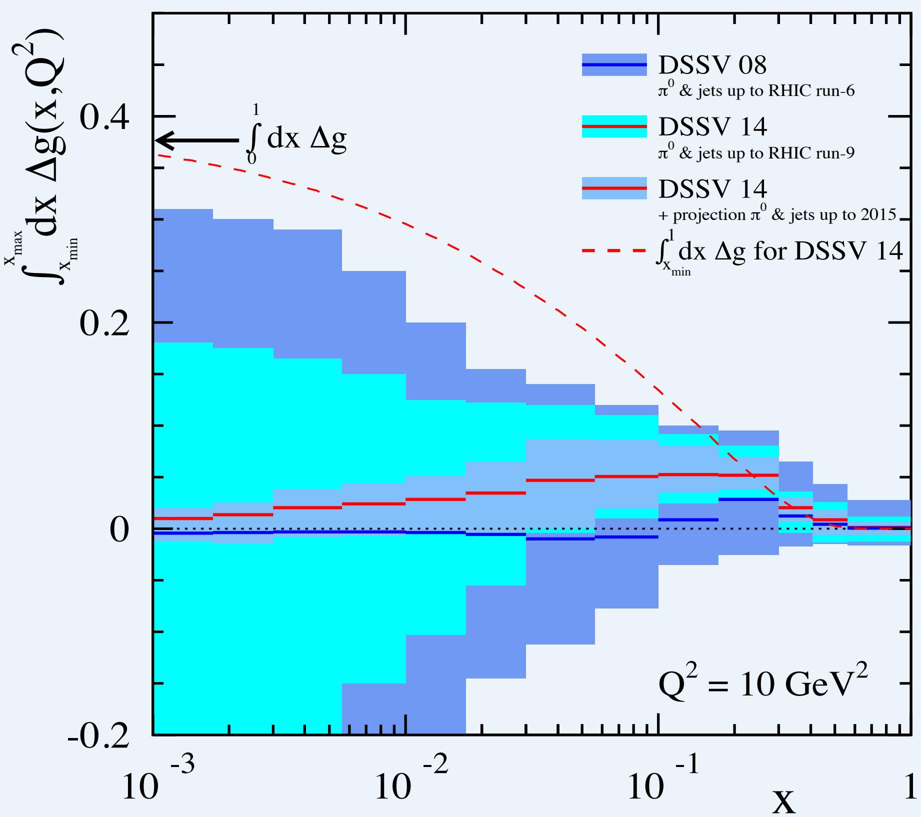
- Based on collected 2013 data
- Probes lower x down to ~10^{-3}

Inc. Jet at √s=200 GeV (STAR):

- Based on 2009/15 data
- Considerably improve exp. precisions

ΔG: Near Term Projections

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



ΔG fit in each x bin

Innermost band: after inclusion of projected data up to 2015

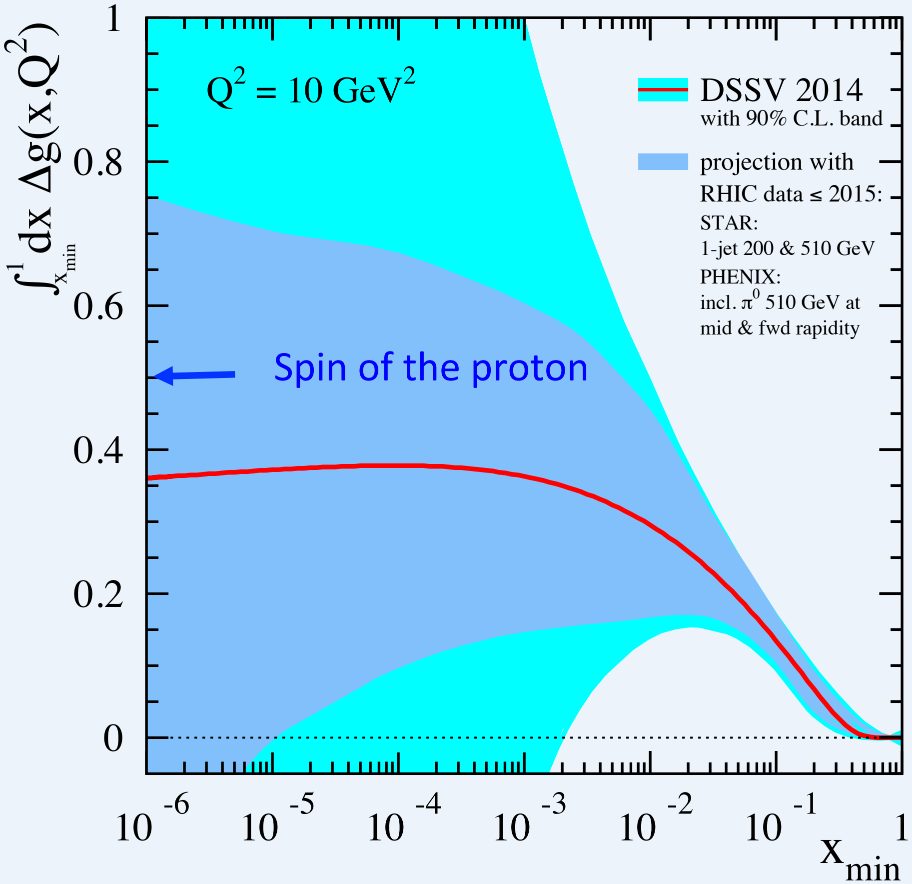
x>0.01 mainly from central rap. data
x<0.01 mainly from forward rap. data

Significant improvement expected soon, particularly at x<0.03

Other channels are also being measured
γ, η, π±, h±, heavy flavor through e and μ
jet-jet, h-h, γ-jet, γ-h
Will serve for syst. effects study in Δg(x) fit

ΔG: The status

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



Gluon contribution:

$$\int_{0.05}^{1.0} dx \Delta g \sim 0.20^{+0.06}_{-0.07} @\ 10\ \mathrm{GeV}^2$$

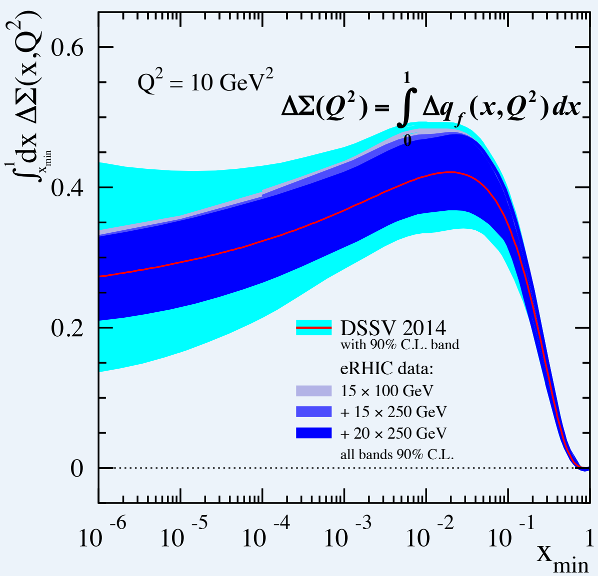
$$\int_{10^{-6}}^{1.0} dx \Delta g \sim 0.36 @\ 10\ \mathrm{GeV}^2 \qquad 72\%!$$

… Let's wait for RHIC new results to constrain ΔG down to x= 10^{-3}

What about quark+antiquark contribution ΔΣ

ΔΣ: The status

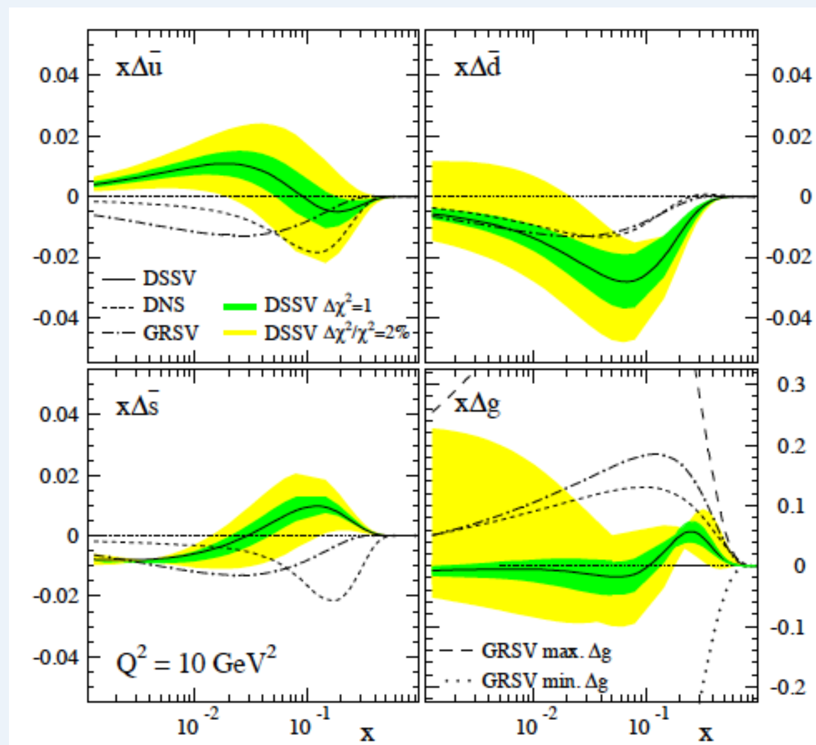
DSSV:
D. de Florian
R. Sassot
M. Stratmann
W. Vogelsang



$$\int_{0.001}^{1} dx\Delta\Sigma \sim 0.366 \pm^{0.042}_{0.062} @10GeV^2$$

$$\int_{10^{-6}}^{1} dx\Delta\Sigma \sim 0.242 @10GeV^2$$

Drop in the integral due to shape of polarized sea quark PDF

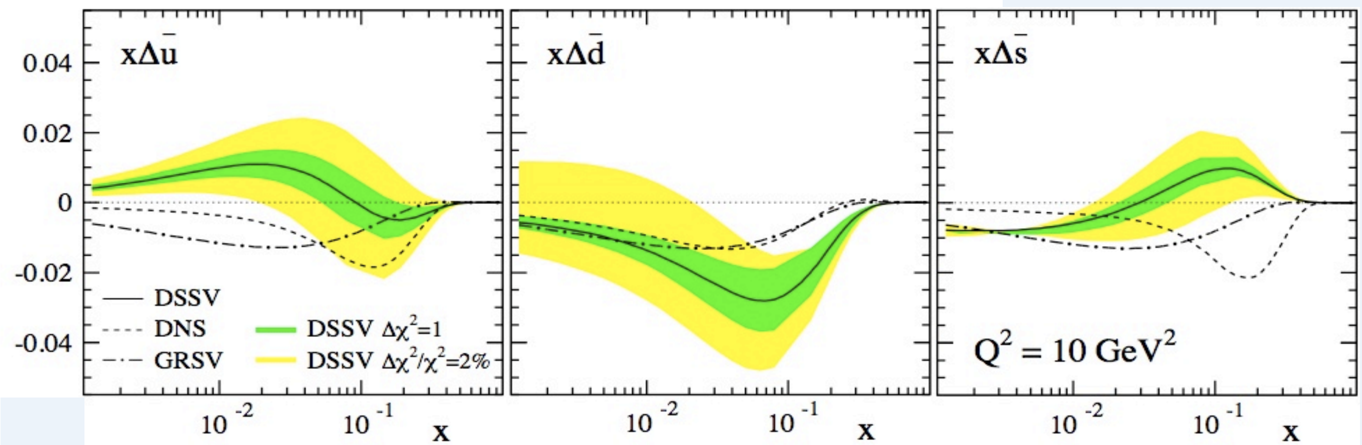


Important to measure flavor separated sea quark PDF

- ✓ To understand dynamics of the quark-antiquark fluctuations
- ✓ Unpolarized sea is not symmetric: $\bar{u} \neq \bar{d}$ => what about polarized sea?

(Anti)quark flavor separation

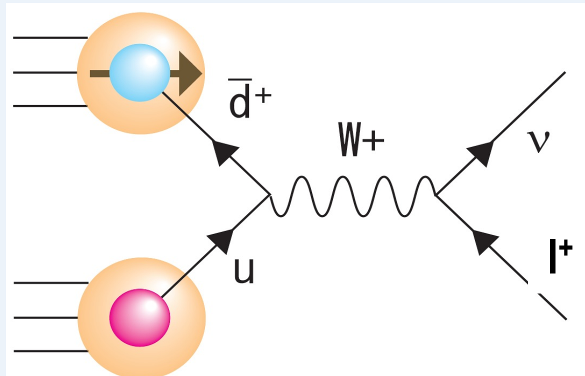
DSSV: PRL 101, 072001 (2008)



Mainly from SIDIS:

Fragmentation functions to tag (anti)quark flavor

p+*p* → W± → (*e*/*μ*)± + *ν*



- Parity violating W production:

  Fixes quark helicity and flavor:

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

- No fragmentation involved
- High Q² (set by W mass)

$$A_L^{W^+} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

Central region: $W^{\pm} \rightarrow e^{\pm}$

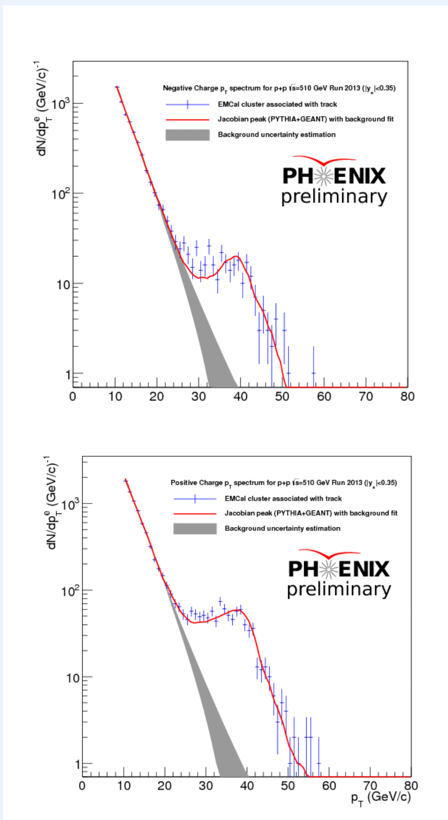
- Triggered by energy in EMCal
- Momentum from energy in EMCal
- Charge from tracking in B field

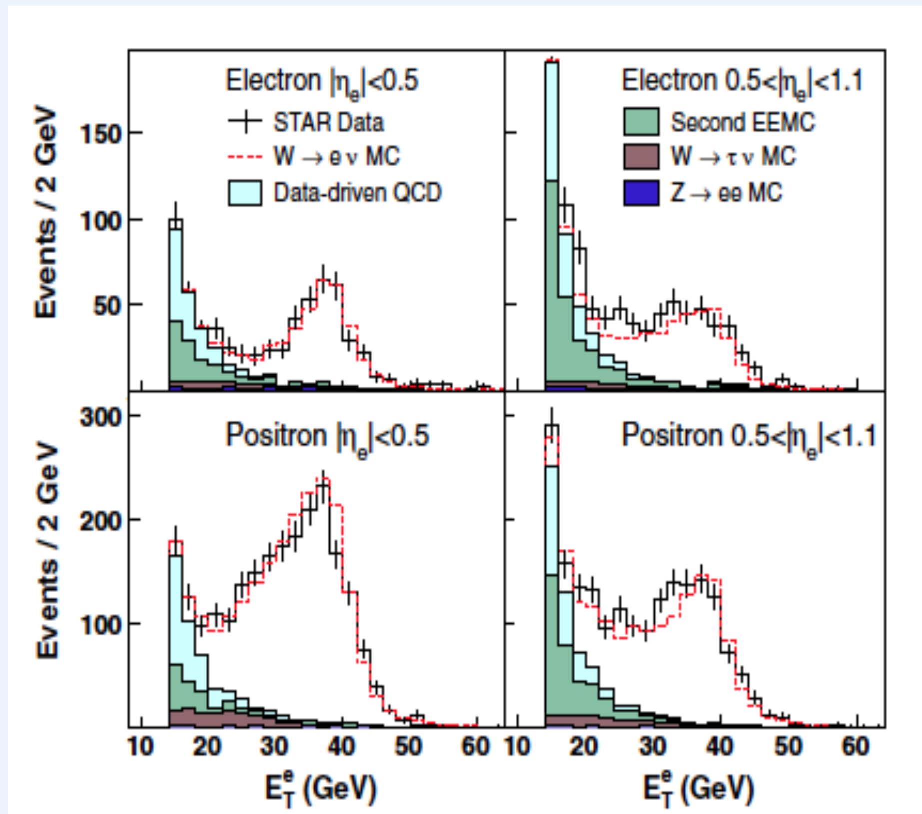
PHENIX: |η|<0.35

STAR: |η|<0.5 STAR: 0.5<|η|<1.1

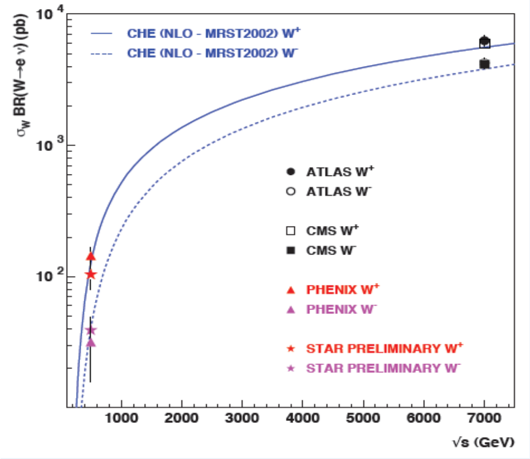
$W^{-} \rightarrow e^{-}$

$W^{+} \rightarrow e^{+}$



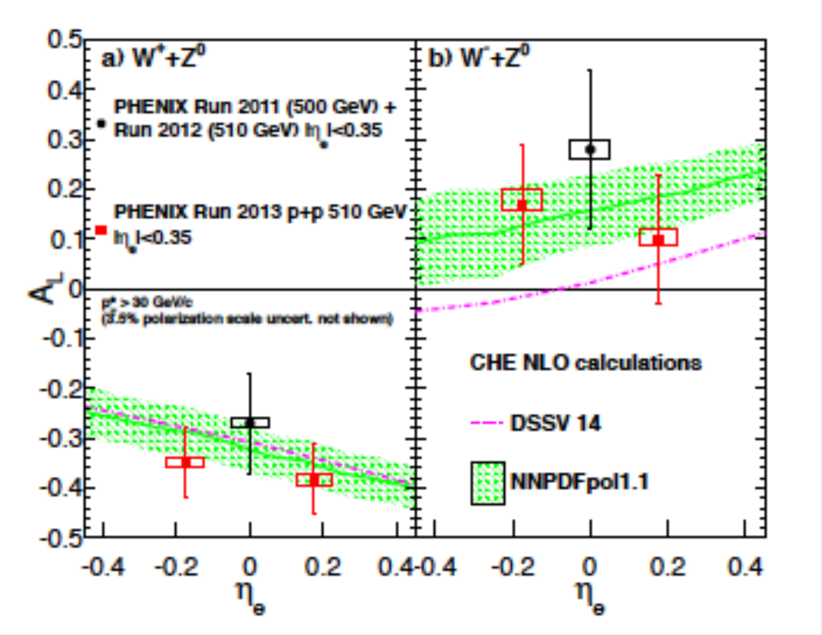


Cross section

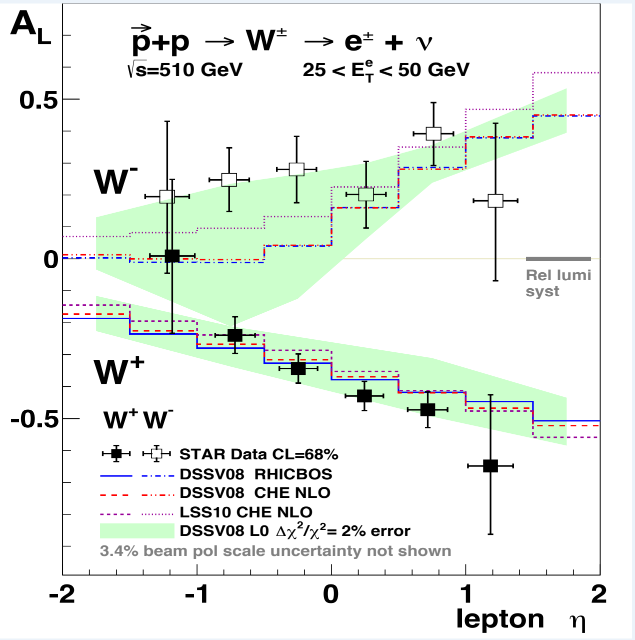


Central region: W± → e±

PHENIX: 2011-13
arXive: 1504.0745

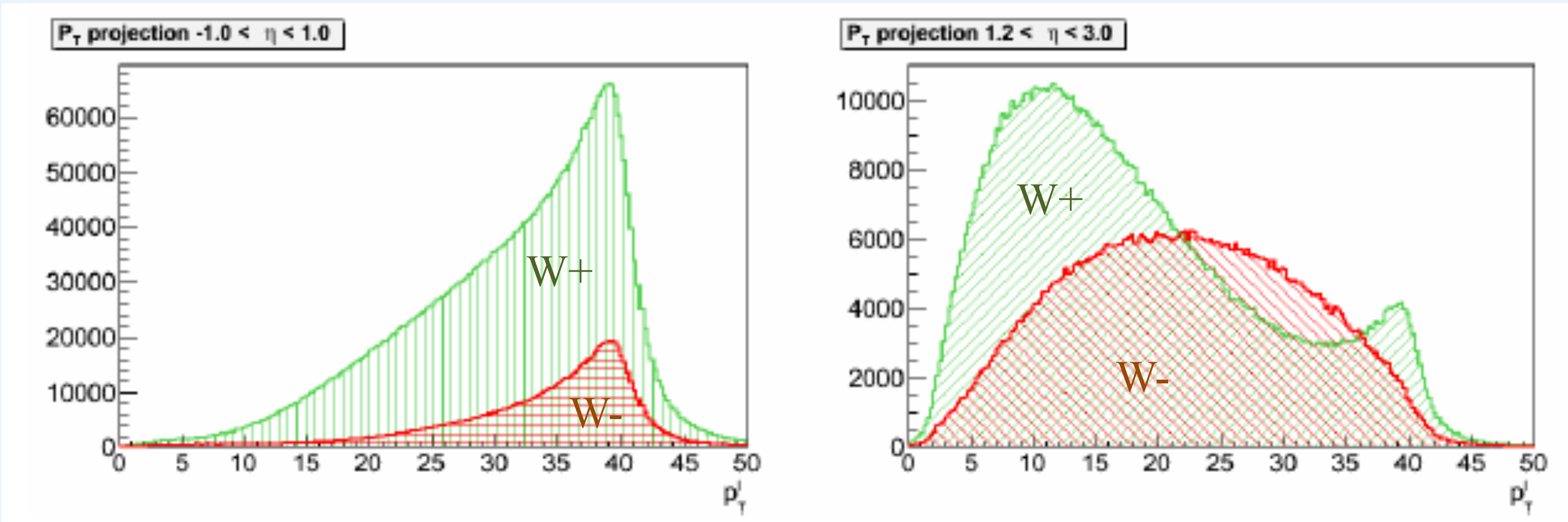


STAR: 2011/12
PRL 113 (2014), 072301



Δu-bar tends to be more positive
Symmetry breaking in polarized quarks?

W: Central vs Forward region

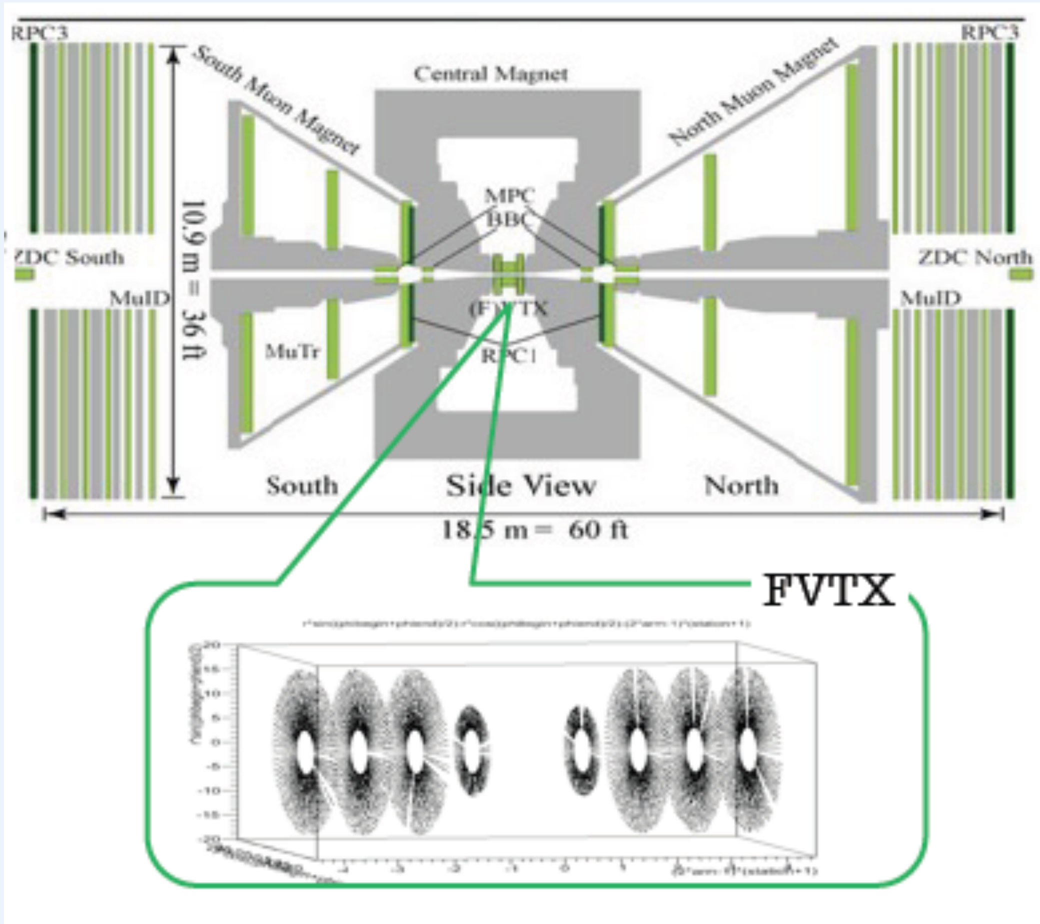


Clear Jacobian peak
at central rapidities

Suppressed/No Jacobean peak
at forward rapidities

Forward region: $W^{\pm} \rightarrow \mu^{\pm}$

PHENIX



Muon Arms: 1.2<|η|<2.4   Δφ=2π

Muon Tracker (MuTr)

Tracking, Momentum

Muon Identifier (MuID)

μ/h separation

Resistive Plate Chamber (RPC)

Timing, background rejection

Forward Vertex Detector (FVTX)

More precise tracking, background rejection

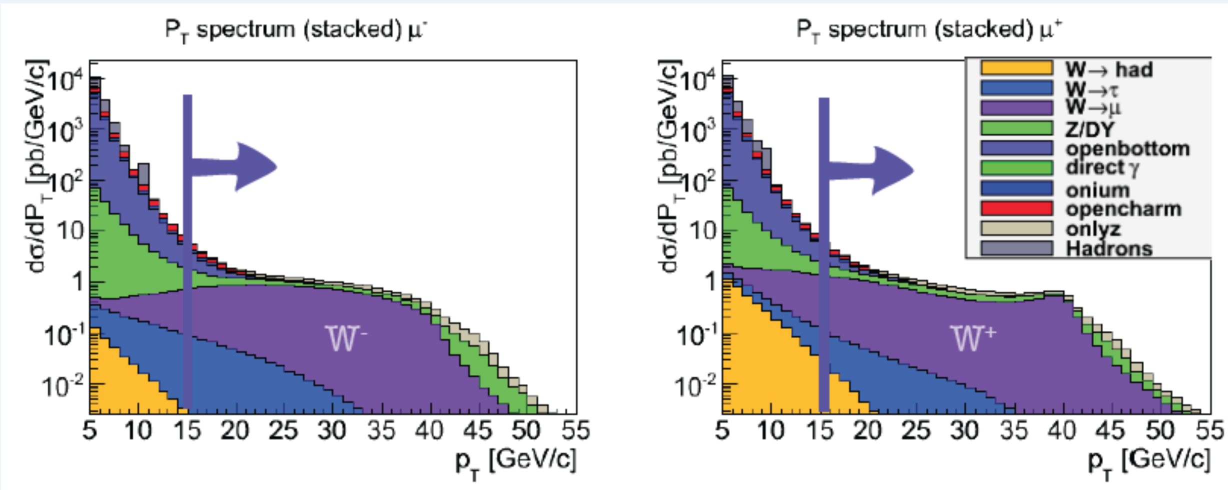
Dedicated Trigger

Based on MuTr and RPC

To tag high pT muons

Forward region: $W^{\pm} \rightarrow \mu^{\pm}$

PHENIX

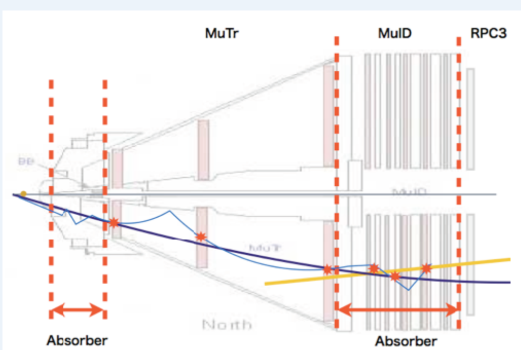


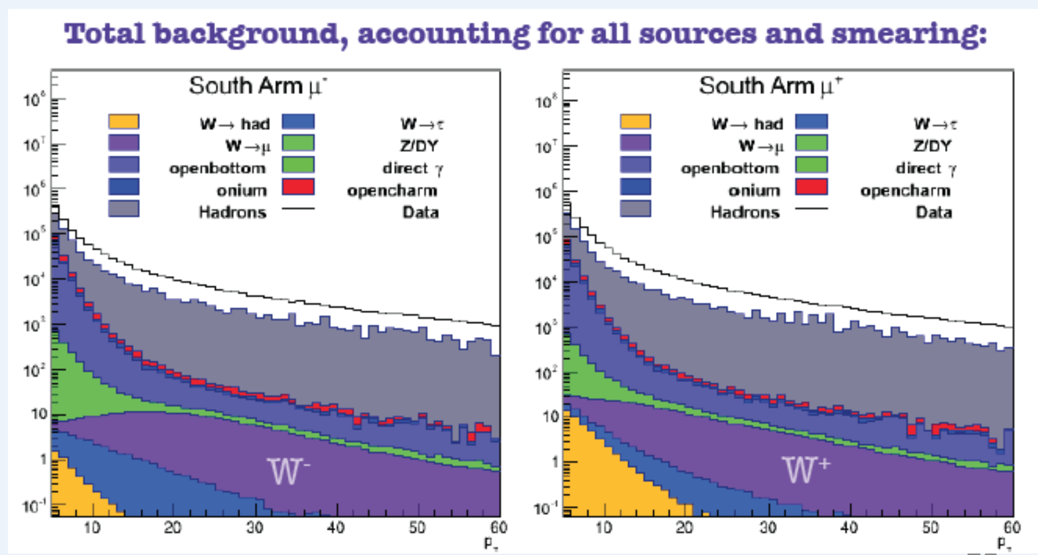
Muon background:

- Heavy flavor
- Quarkonia
- Decay muons
- Z/DY
- Etc.

Not significant at >15 GeV/c

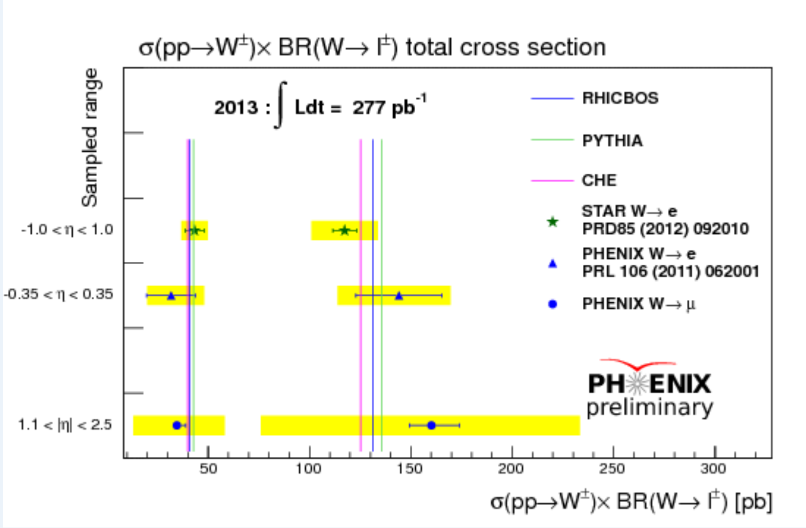
If include hadrons (misidentified as μ), h→μ (fake high pT) and pT smearing



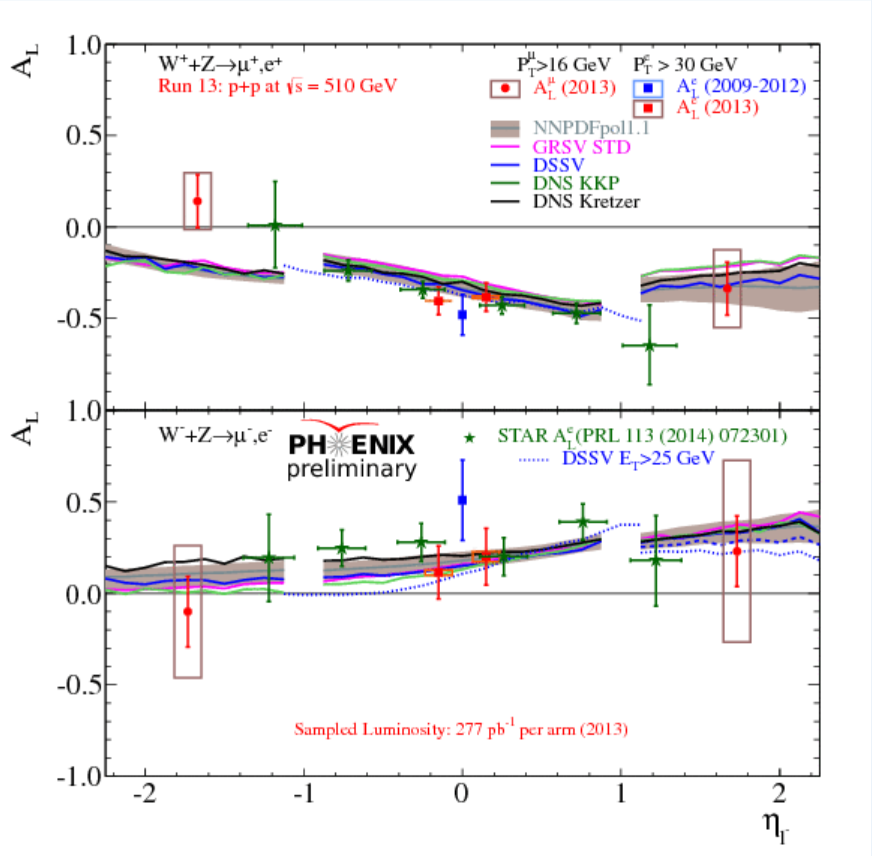


Forward region: $W^{\pm} \rightarrow \mu^{\pm}$

PHENIX



S/B = 0.2−1 depending on η

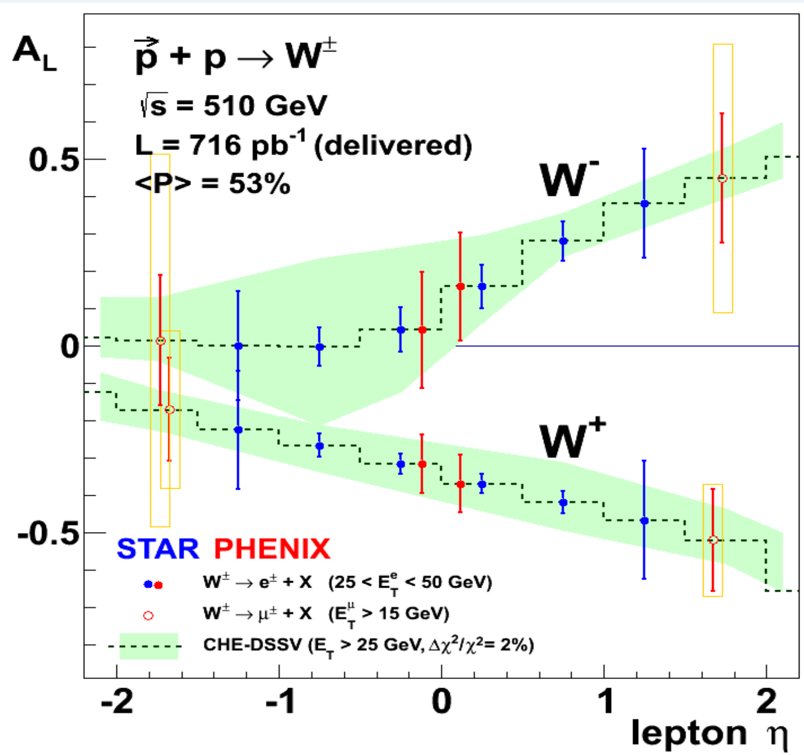


Measured cross section agrees with calculations within large uncertainties

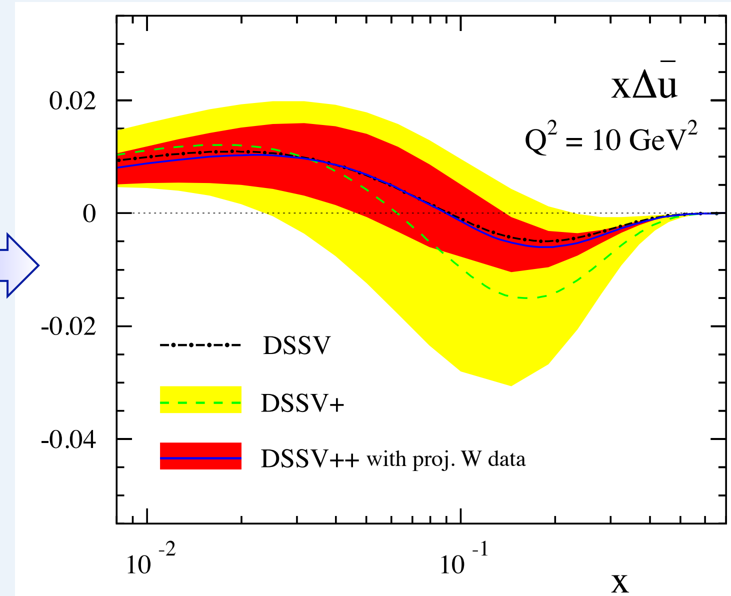
A_L uncertainties are still large

- Improve S/B
- Tracking alignment → reduce momentum smearing and improve charge reco

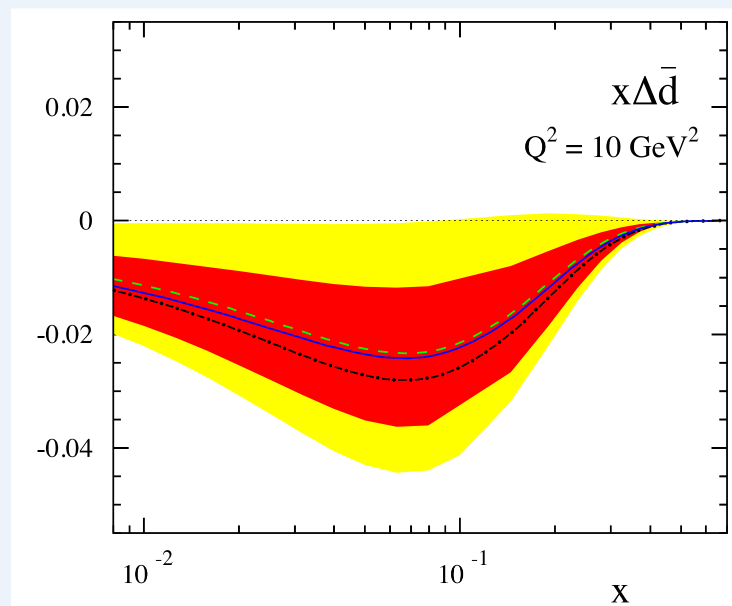
W: Projection



$\Delta\bar{u}$



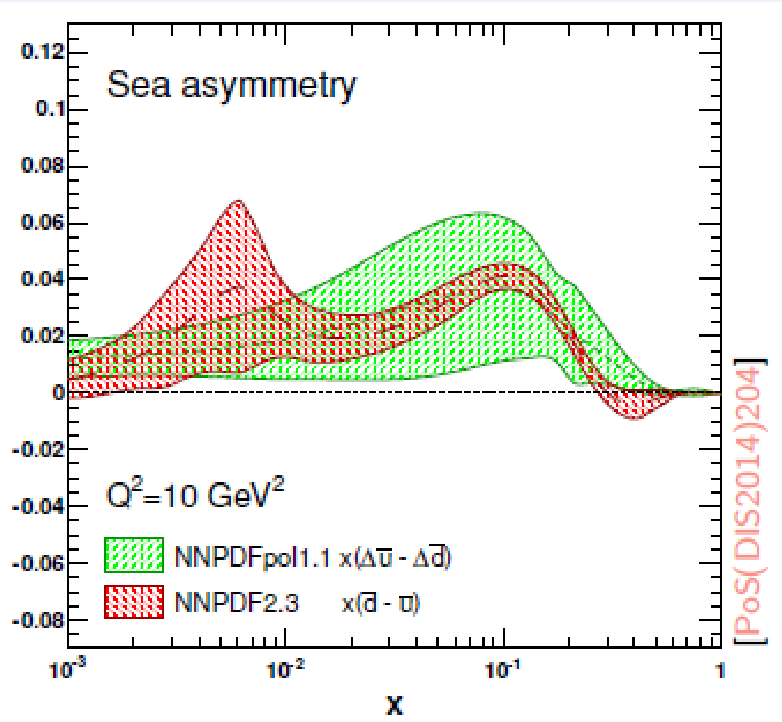
$\Delta\bar{d}$

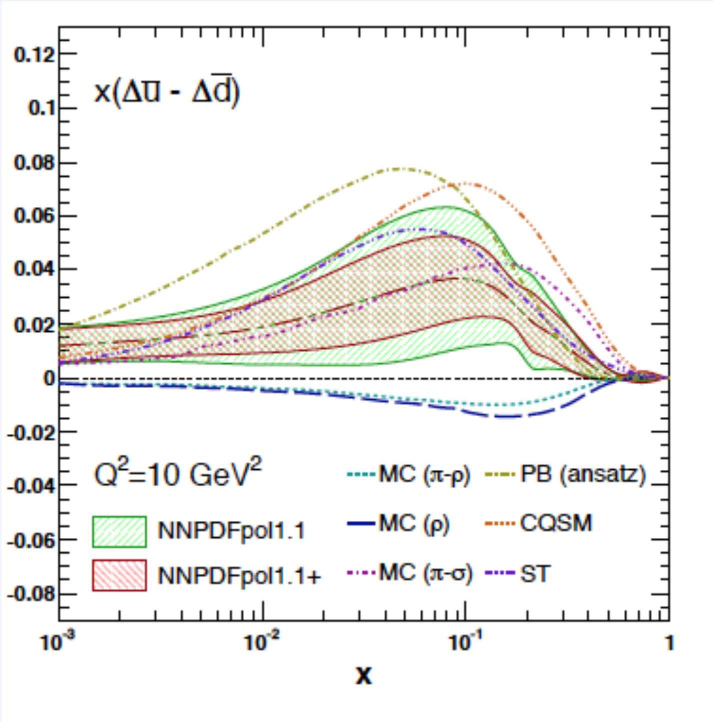


RHIC W-data will give a significant constraint on anti-quark polarization in the proton

Symmetry breaking in polarized sea?

Unpolarized sea is not symmetric





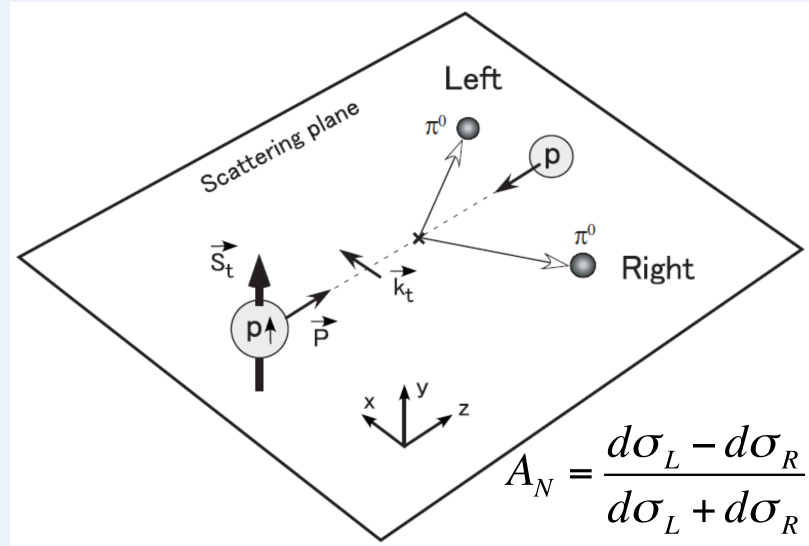
Polarized sea symmetric may be broken too!

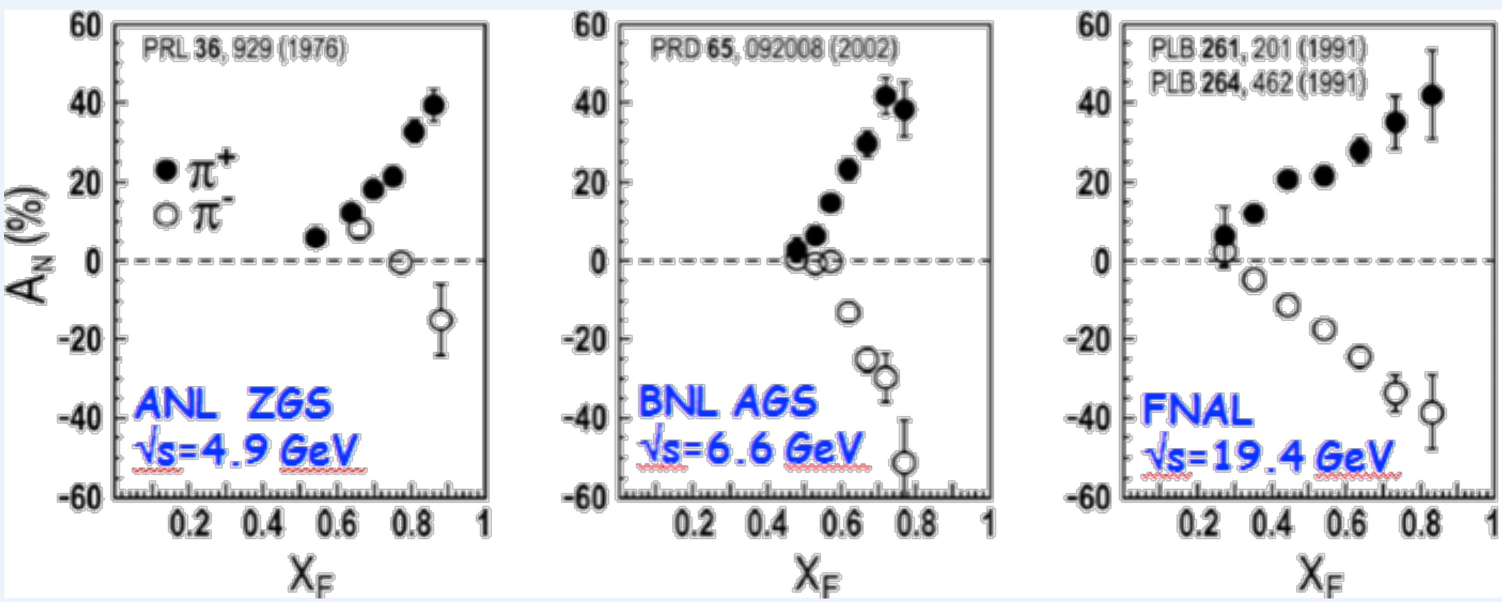
Already available data (Run13) will improve the measurement further

Transverse Spin

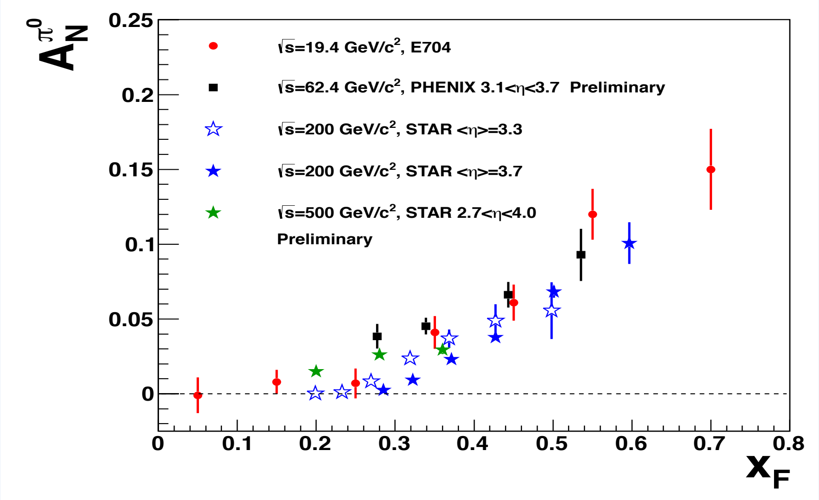
Transverse Spin Asymmetries

Large Transverse Spin Asymmetries have been observed in p↑p





Puzzles from RHIC



Naïve collinear pQCD predicts

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

Asymmetries survive at highest $\sqrt{s}$

Non-perturbative regime!

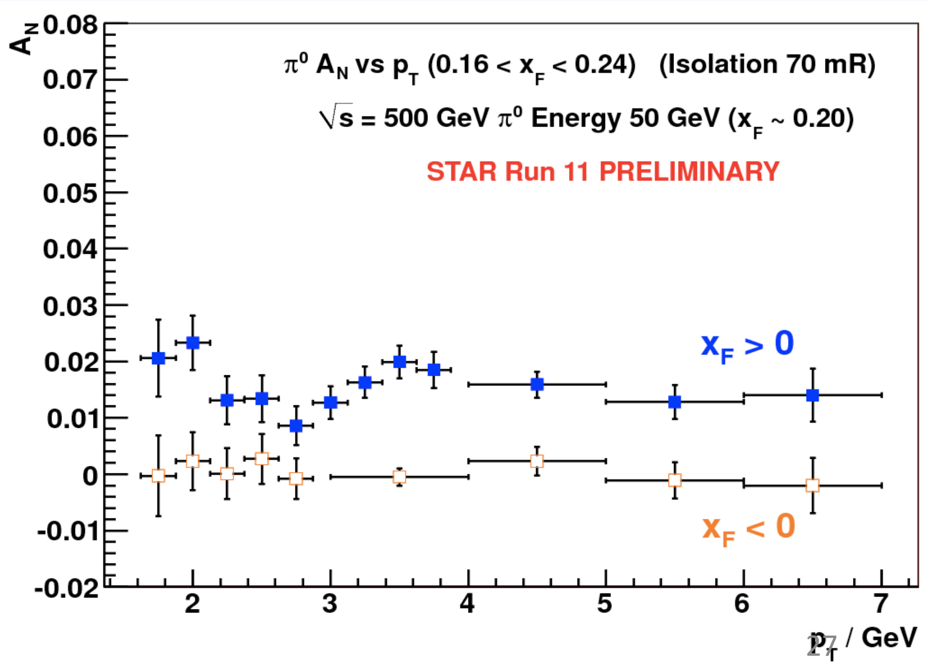
Asymmetries of the ~same size at all $\sqrt{s}$

Asymmetries scale with x_F

Collinear (higher twist) pQCD predicts

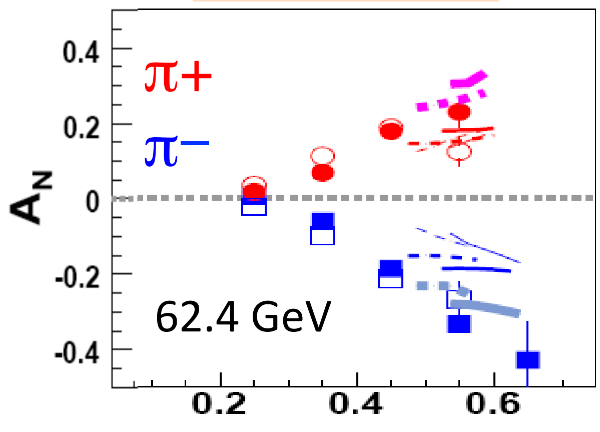
$$A_N \sim 1/p_T$$

No fall off is observed out to p_T ~7 GeV/c

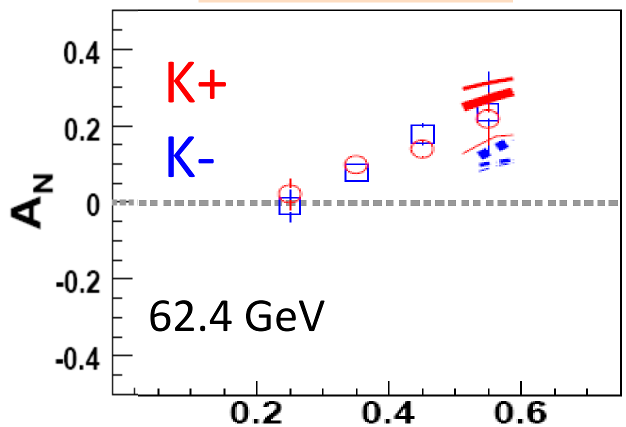


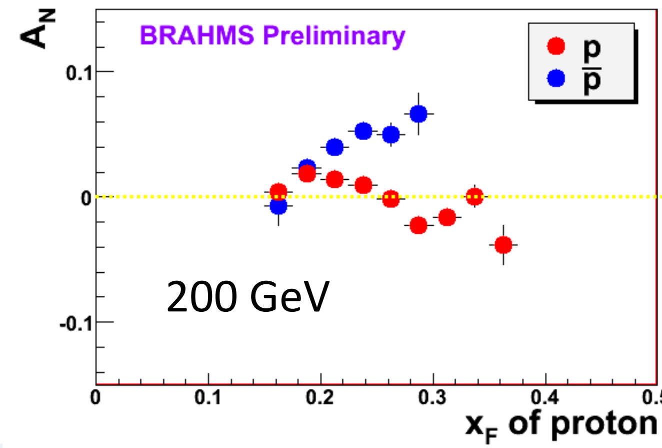
More puzzles from RHIC

PRL101, 042001



PRL101, 042001





π+ π- opposite asymmetries is believed to come from opposite spin-kT properties of valence u and d quarks

… But $K^- = \bar{u}s$ doesn't contain any valence quarks but still shows the same asymmetry as $K^+ = u\bar{s}$

Large antiproton asymmetry, while ~0 proton asymmetry??

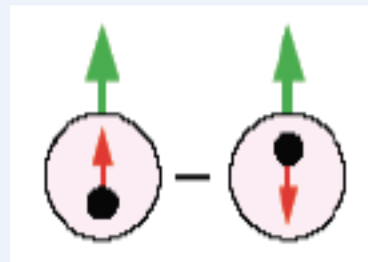
Sources

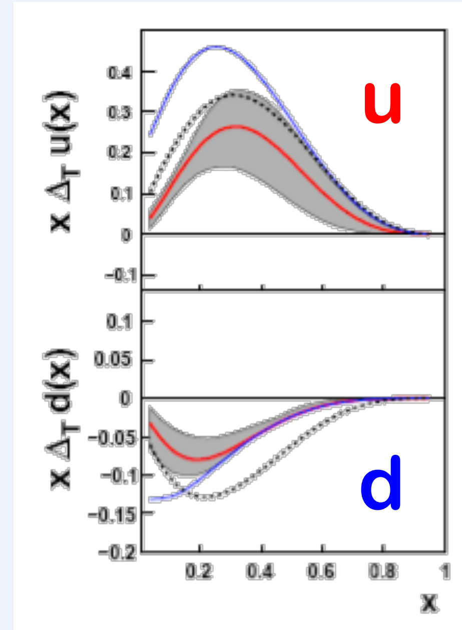
Collins effect (Nucl.Phys.B396,161):

Final state effect

Correlation between spin of the fragmenting parton and the hadron pT (spin dependent fragm. function)

Connected to tensor charge





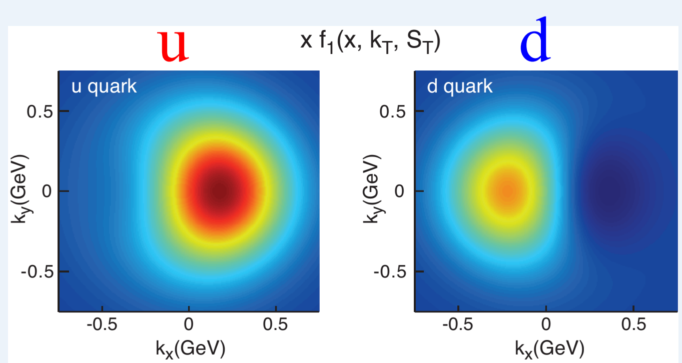
Anselmino et al., Eur. Phys. J. A39, 89 (2009)

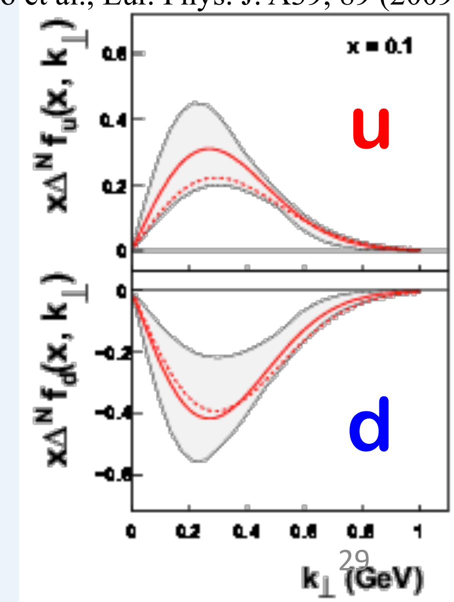
Sivers effect (Phys.Rev.D41,83):

Initial state effect

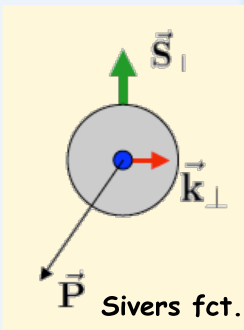
Correlation between proton spin and parton kT

Relates to parton motion => Connected to orbital momentum!



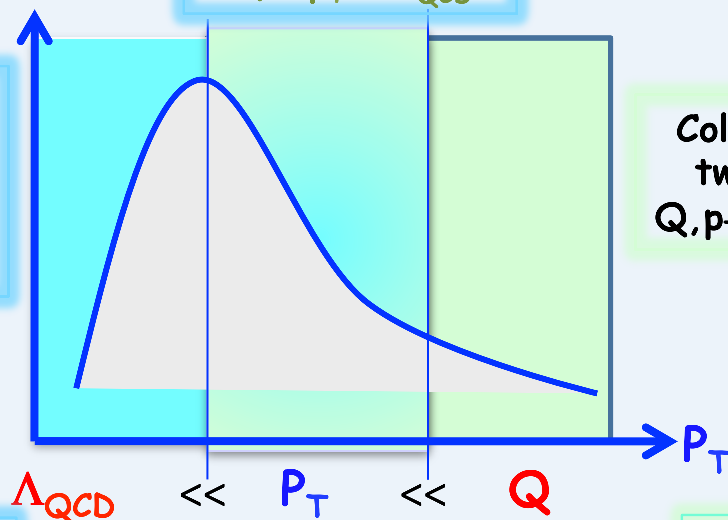


Initial State: TMD vs Twist3

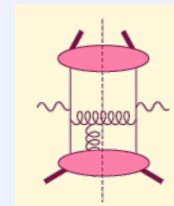


Transverse momentum dependent
$Q>>p_T>=\Lambda_{QCD}$

Intermediate p_T
$Q>>p_T>>\Lambda_{QCD}$



Collinear/ twist-3
$Q,p_T>>\Lambda_{QCD}$



Efremov, Teryaev; Qiu, Sterman

Need 2 scales
Q^2 and p_t
Remember pp:
several observables one scale
Exception:
DY, W/Z-production

Ji, Qiu, Vogelsang, Yuan,
PRL. **97**, 082002 (2006).

Need only 1 scale
Q^2 or p_t
But
should be of reasonable size

should be applicable to
pp observables
$A_N(\pi^0/\gamma/\text{jet})$

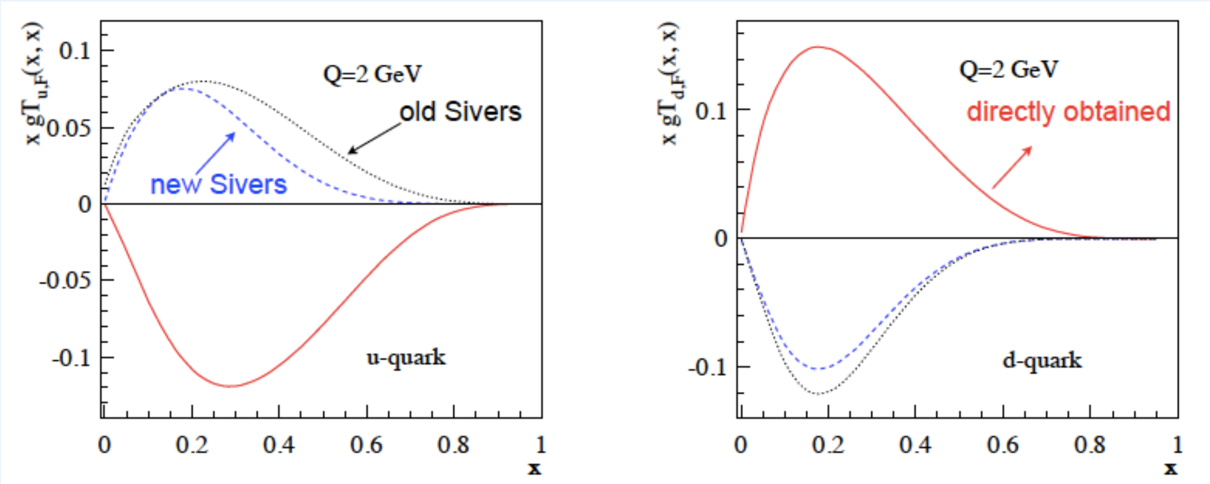
related through

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS} = T_{q,F}(x,x)$$

TMD vs Twist3: Sign Mismatch?

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS} = T_{q,F}(x,x)$$

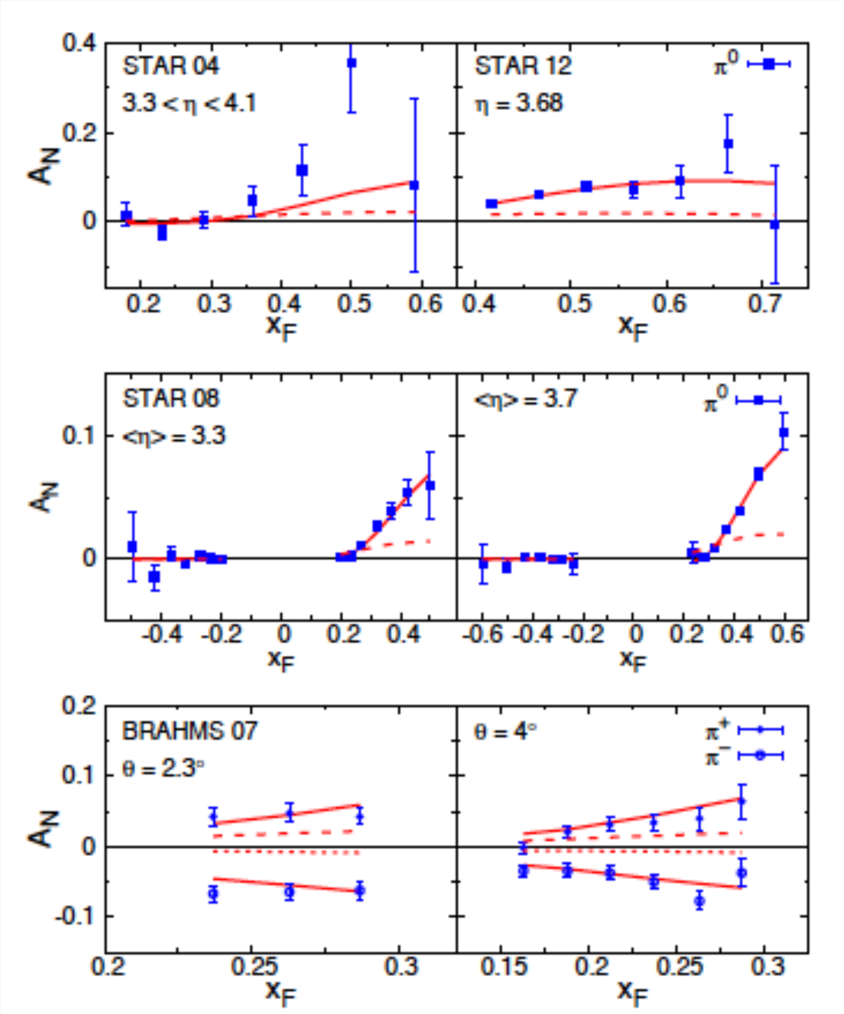
Kang, Qiu, Vogelsang, Yuan
PRD 83 (2011), 094011



pp→π X (Twist-3)
SIDIS (TMD)

Spin mismatch!
Sivers contribution is small in pp→π X ?
=> Collins dominate?

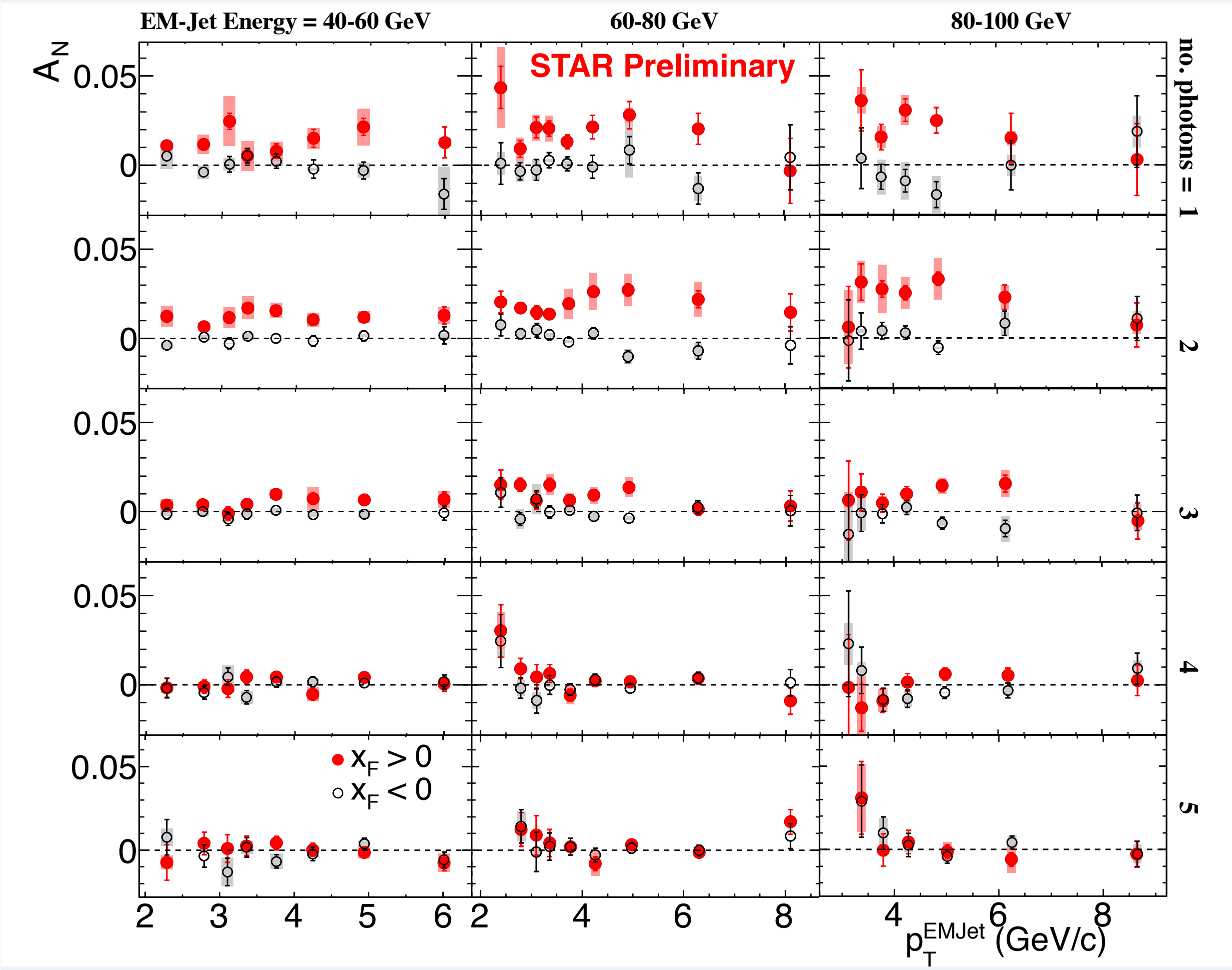
Collins dominate?



A_N from twist-3 fragmentation functions (Kanzawa, Koike, Metz, Pitoniak, arXiv:1404.1033)

Describes data well !

$pp \rightarrow \pi^0 X$



Largest A_N for isolated $\pi 0$

Smaller A_N for more complex events (more activity around $\pi 0$)

Smaller A_N with away side jet present

Does A_N come from $2 \rightarrow 2$ scattering?

May A_N come from hard diffraction:

$p\uparrow + p \rightarrow \pi^0 + p' + X$

STAR has already collected data in 2015 with Roman Pots to tag forward scattered p

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

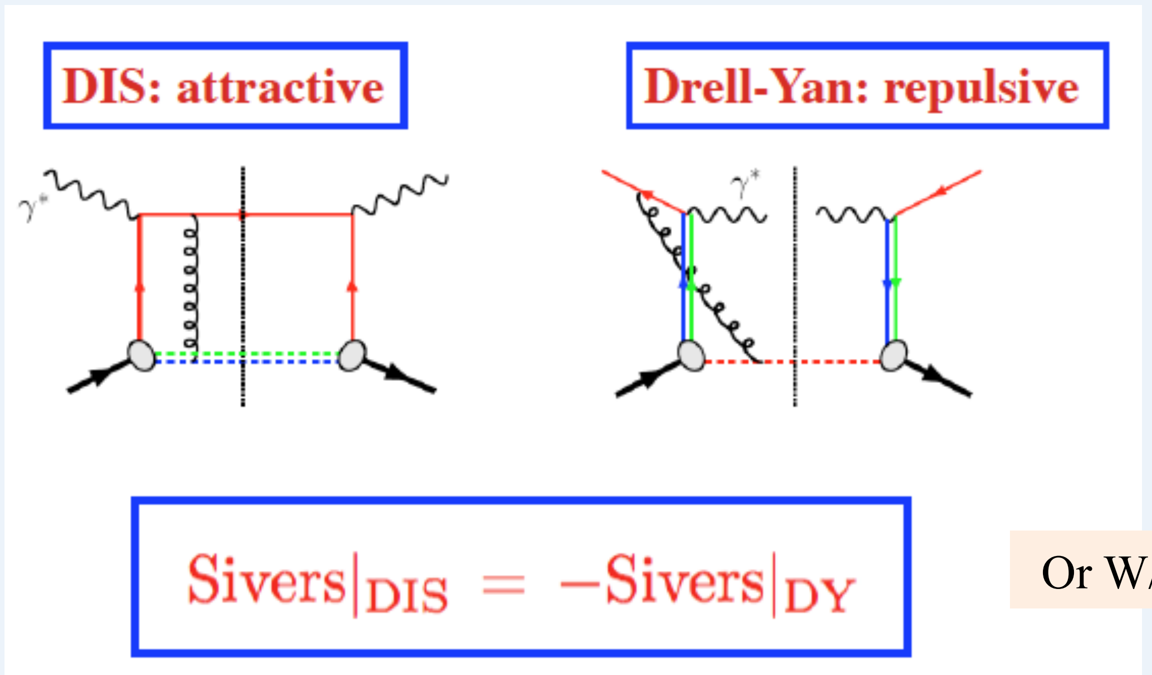
Fundamental Role of Sivers

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

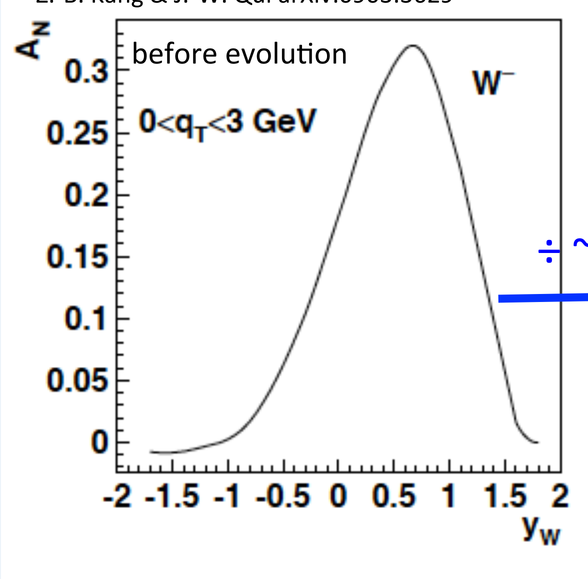


Or W/Z production

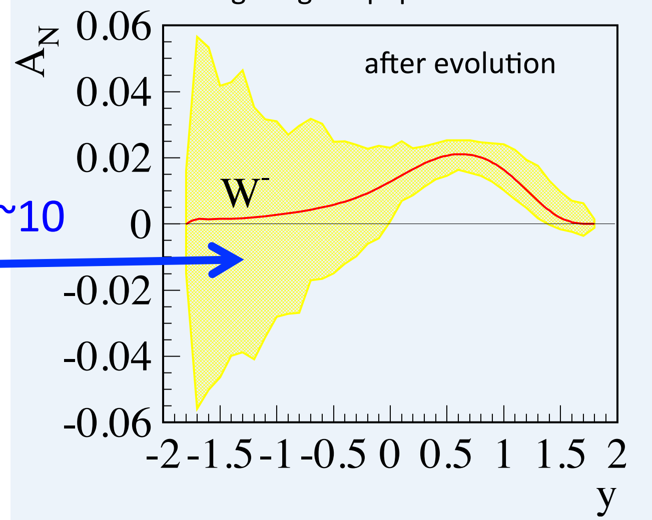
Critical test for our understanding of TMD's and TMD factorization

A_N for DY and W/Z, theory

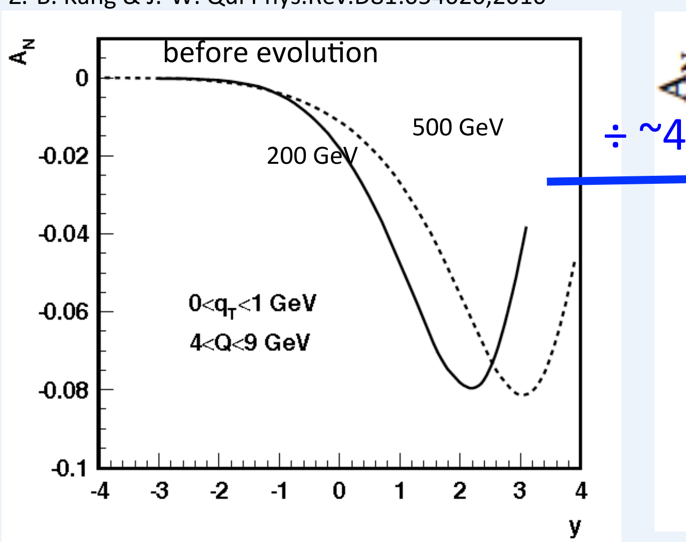
Z.-B. Kang & J.-W. Qui arXiv:0903.3629



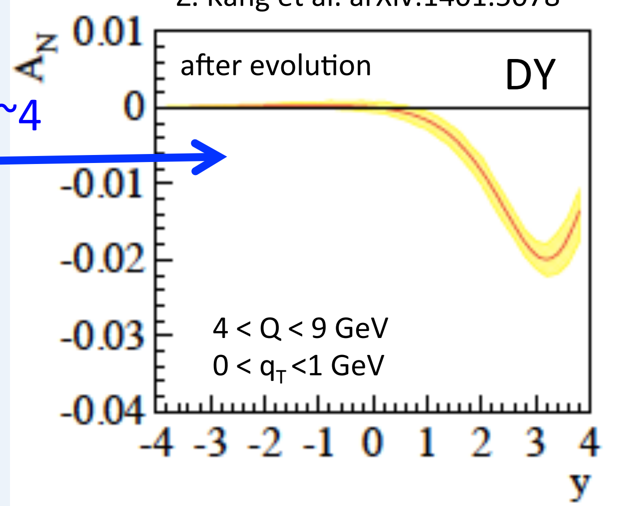
Z. Kang: original paper arXiv:1401.5078



Z.-B. Kang & J.-W. Qui Phys.Rev.D81:054020,2010



Z. Kang et al. arXiv:1401.5078

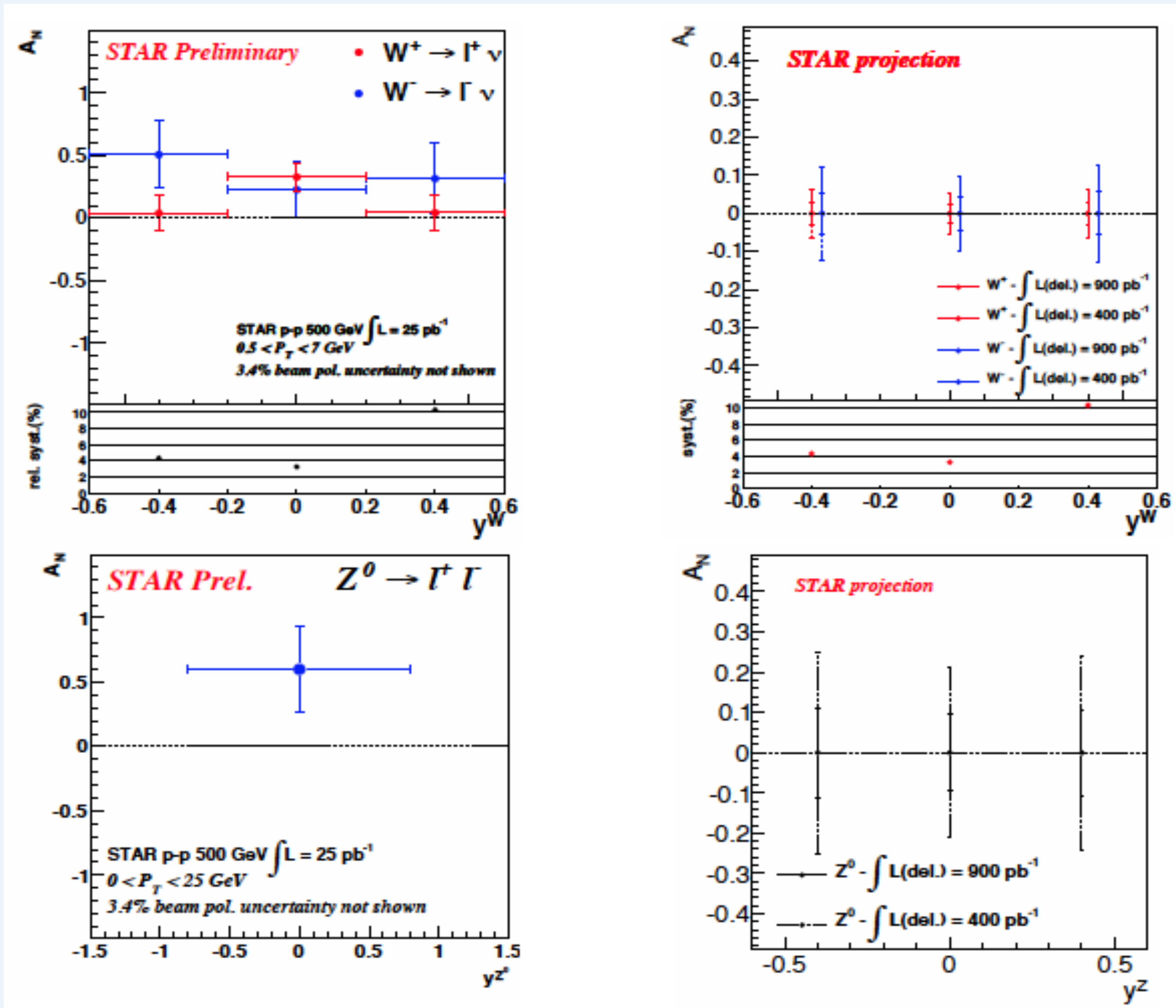


Too strong evolution effect ?

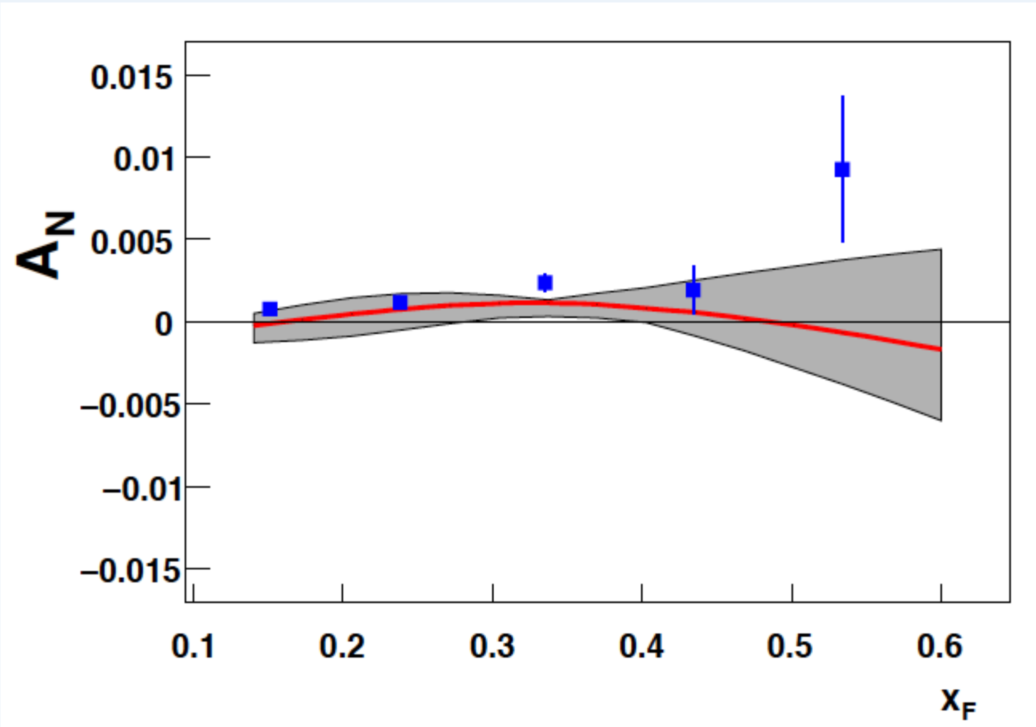
Need experimental data!

A_N for W/Z, data

Run-2009 | Proj. for Run-2017



A_N for Jets



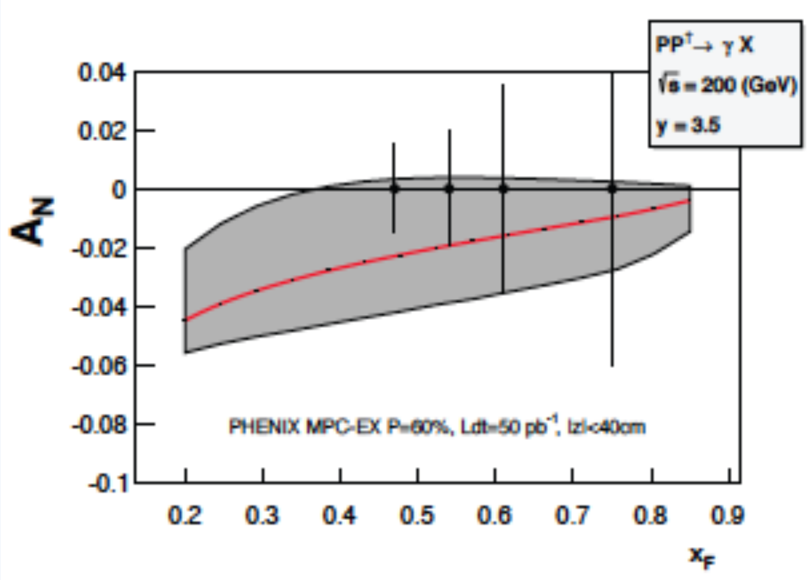
Data: AnDY arXiv: 1304.1454
Theory (from SISIS): arXiv:1302.3218

Cancelation of u and d Sivers TMDs => Small A_N

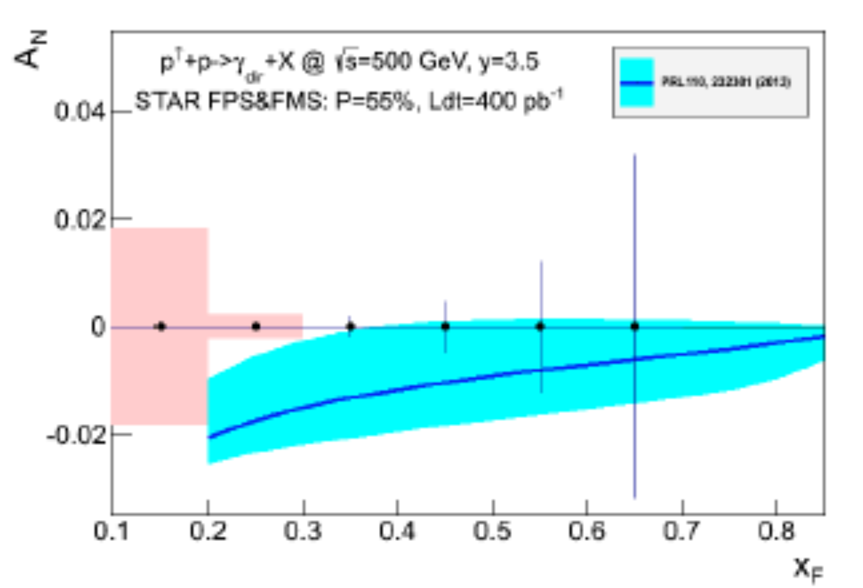
Would be good to measure u and d jets separately

A_N for Direct Photon

Proj for Run-2015



Proj for Run-2017

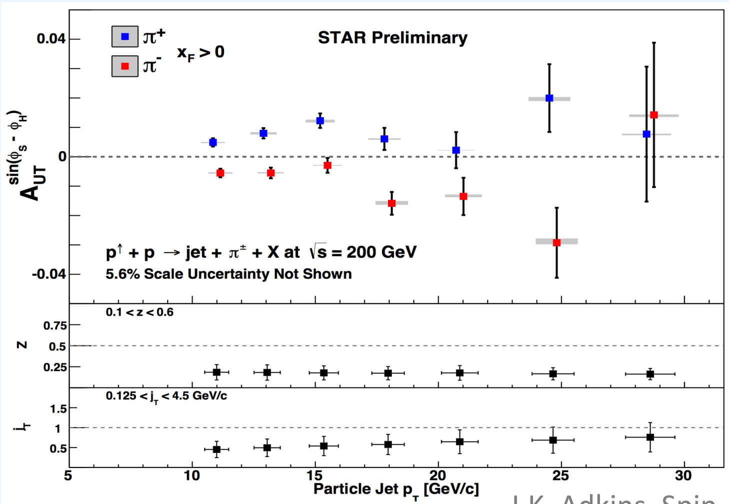


Data is already available!

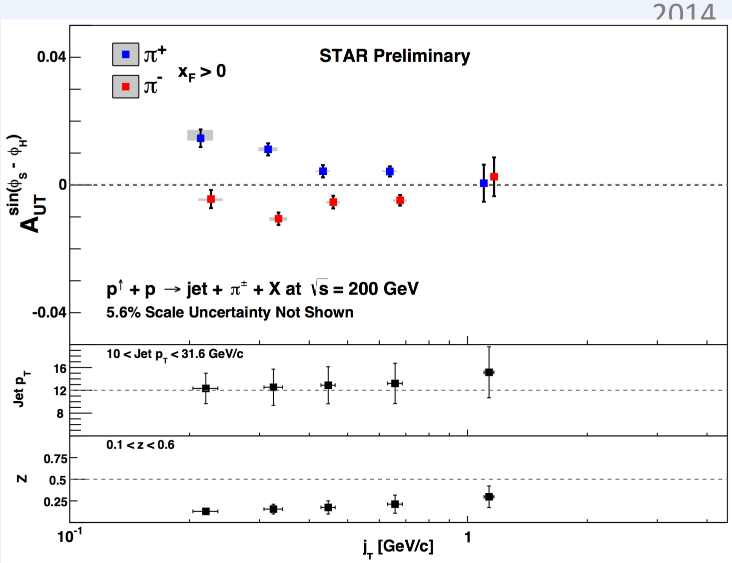
Analysis is ongoing

Collins FF

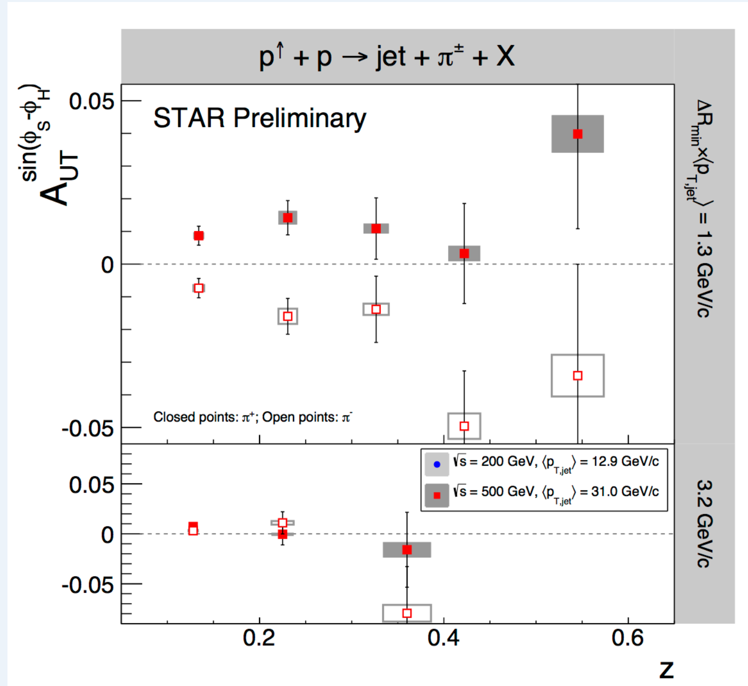
√s=200 GeV



J.K. Adkins, Spin 2014



√s=500 GeV



First Collins asymmetry in pp !

=> Access to transversity!

Strong dependence on j_T

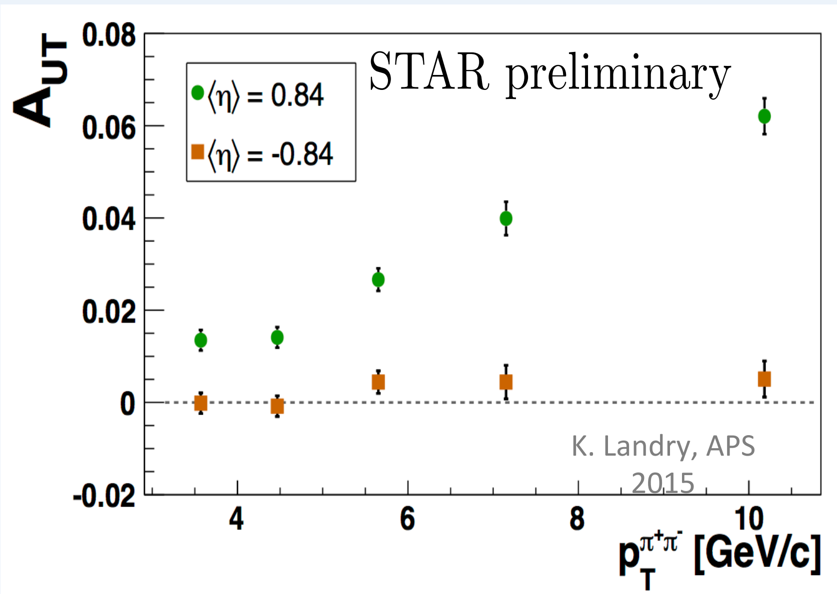
Asymmetry similar at 200 vs 500 GeV

=>TMD evolution is small?

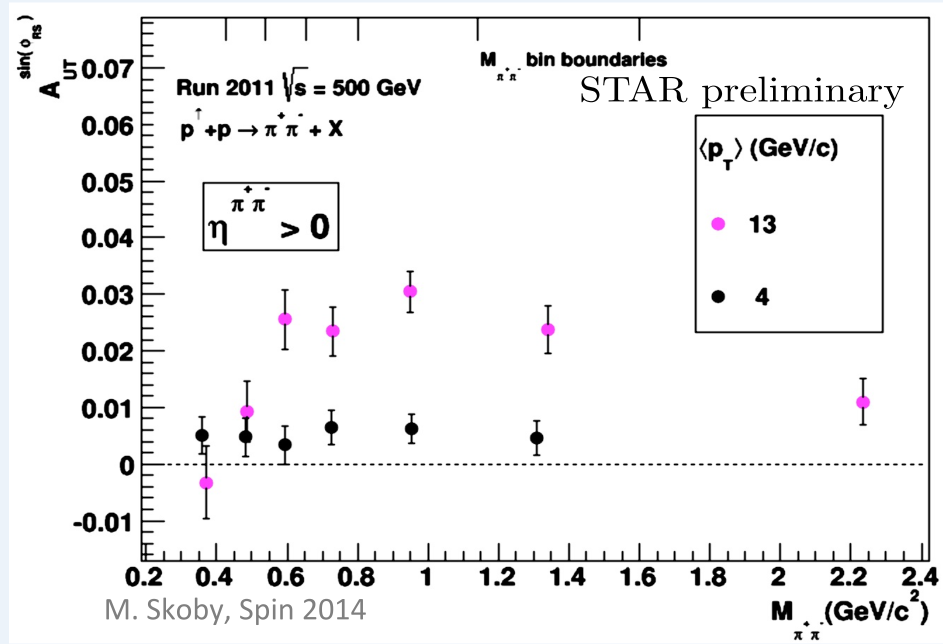
Interference FF

$$P^{\uparrow}P \rightarrow \pi^{+}\pi^{-} + X \text{ at } \sqrt{s} = 200 \text{ GeV}$$

√s=200 GeV



√s=500 GeV

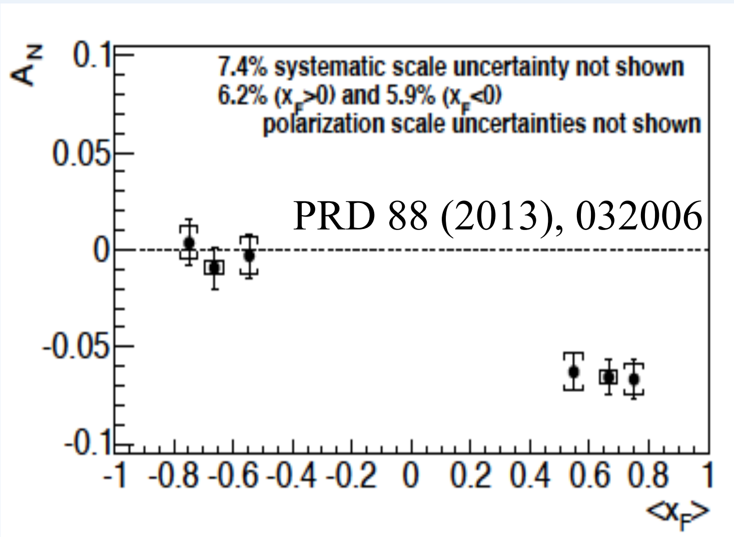


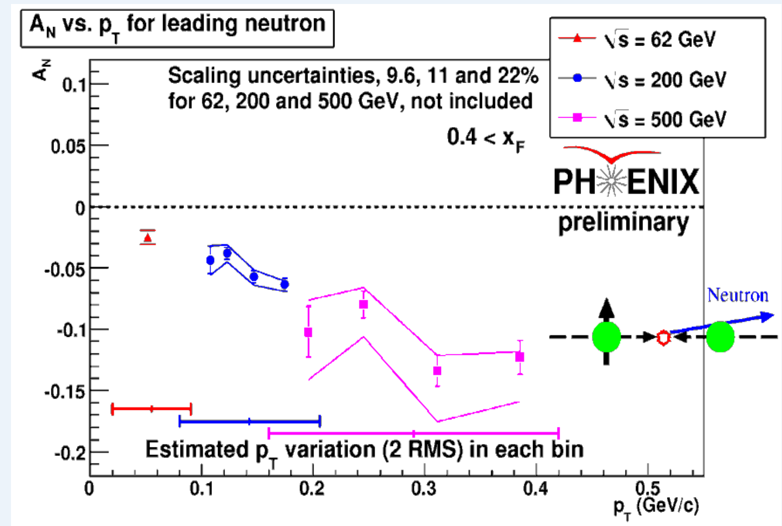
Another way to access transversity !

A_N for forward neutron

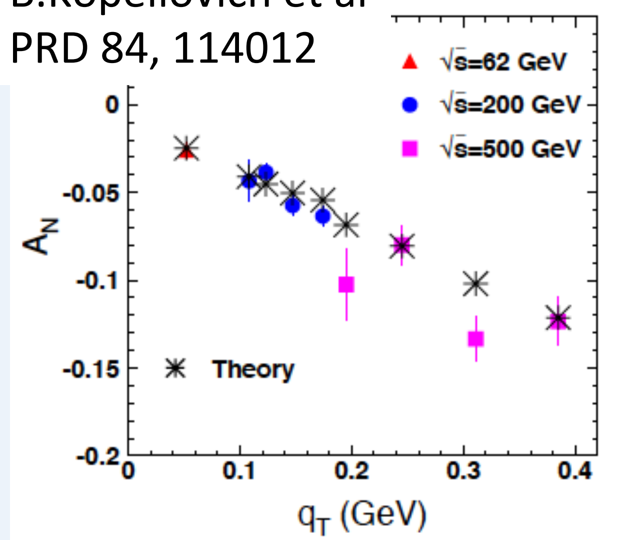
$pp \rightarrow nX$, $|\theta|<2.5$mrad

Discovered in 2002:
PLB 650, 325





B.Kopeliovich et al
PRD 84, 114012



Run-2015:

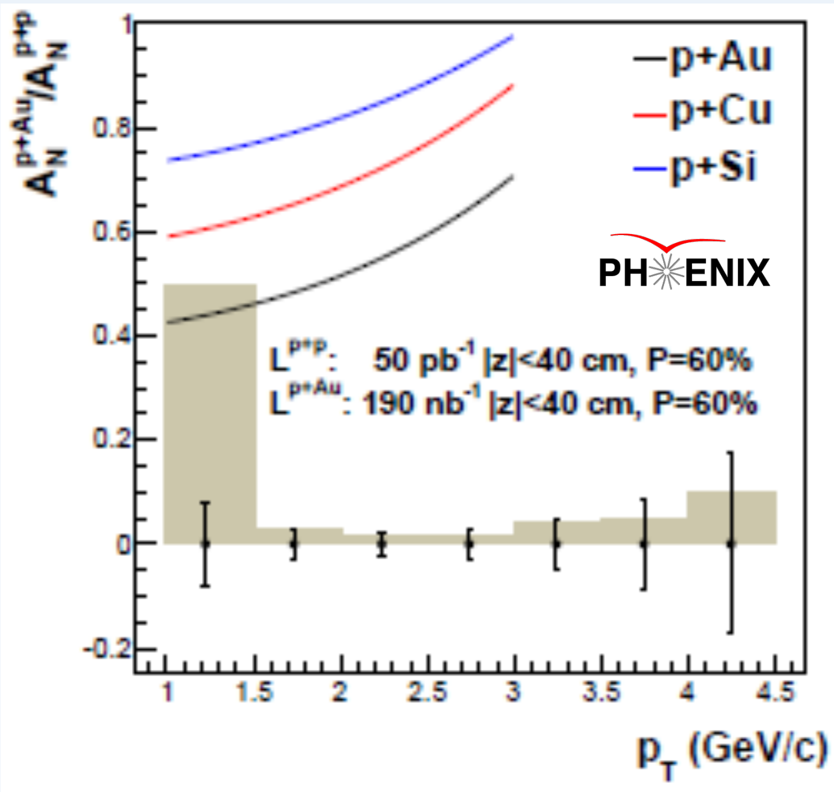
Collected data from p+Au and p+Al

Strong nuclear size dependence

Analysis ongoing

42

$\pi 0$ A_N in pA



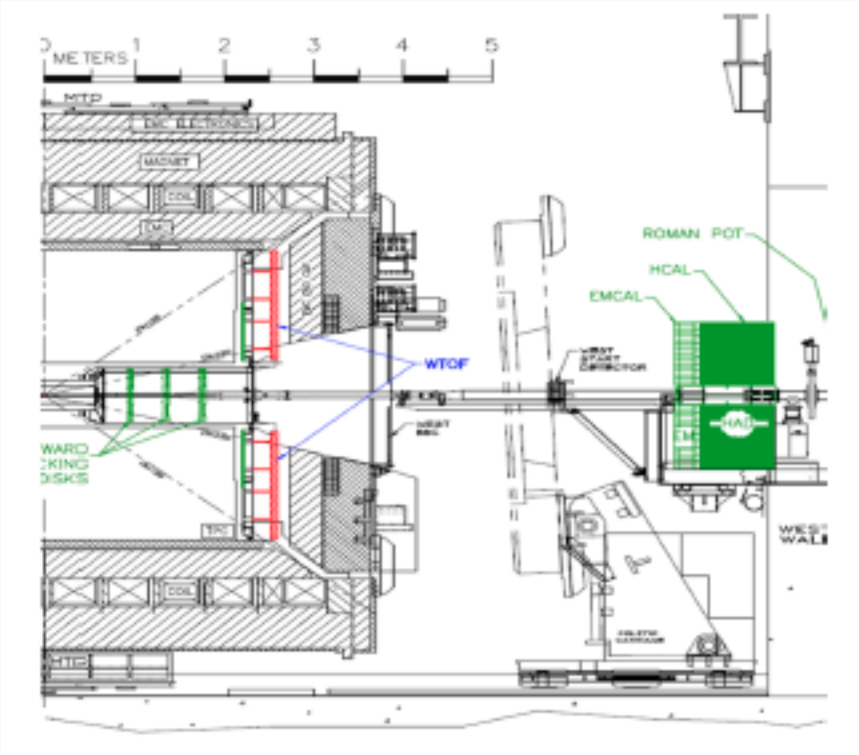
Probing gluon saturated matter, Color Glass Condensate (CGC) with polarized protons

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!

STAR: longer term plans

~2021-22

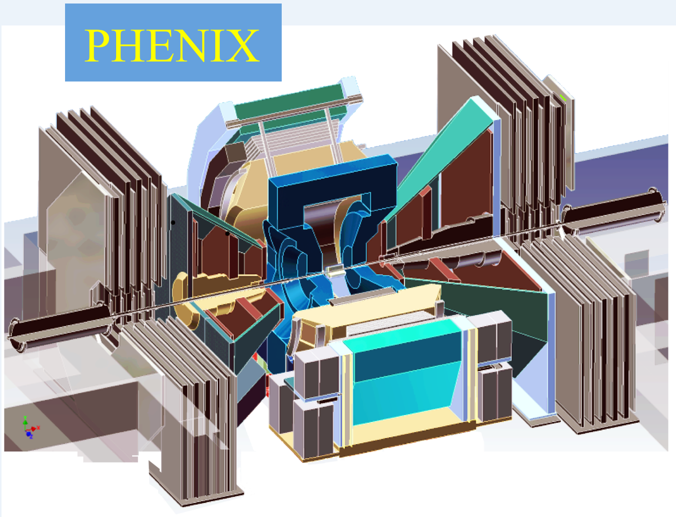


Forward instrumentation ($2.5<|\eta|<4.5$):

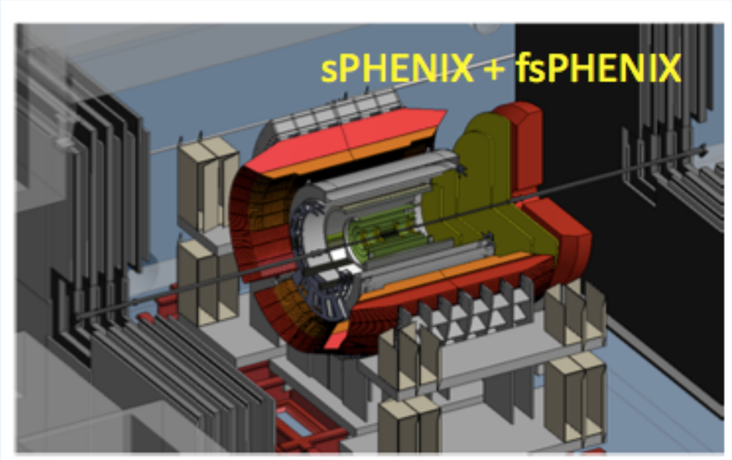
- ➢ EMCal+Hcal
- ➢ Tracking system

- ➢ High precision Sivers&Collins
- ➢ DY (Sivers sign change)
- ➢ Lowers x ΔG (from di-jets)

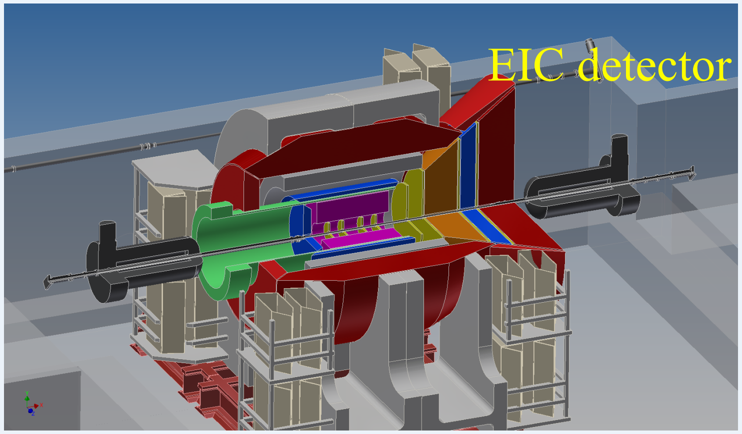
PHENIX: longer term plans



~2021-22



By ~2025

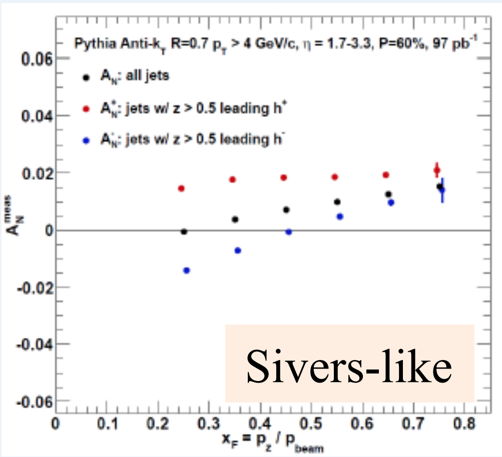


Evolve sPHENIX (pp and HI detector) to EIC Detector (ep and eA detector)

- 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

~2021-22

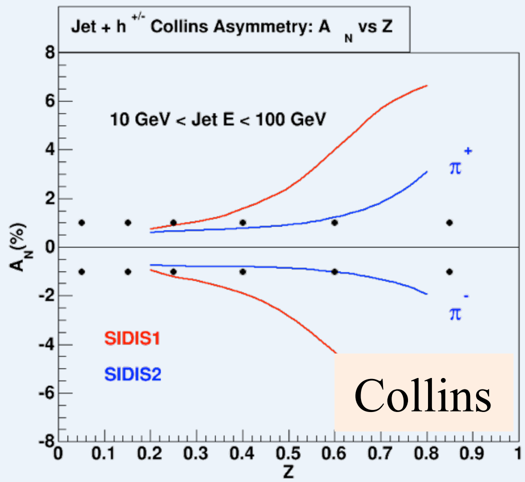


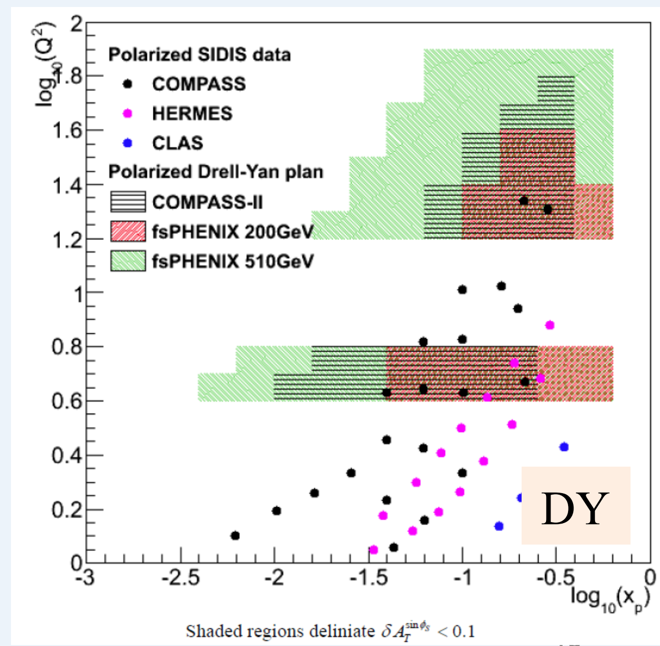
sPHENIX +

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

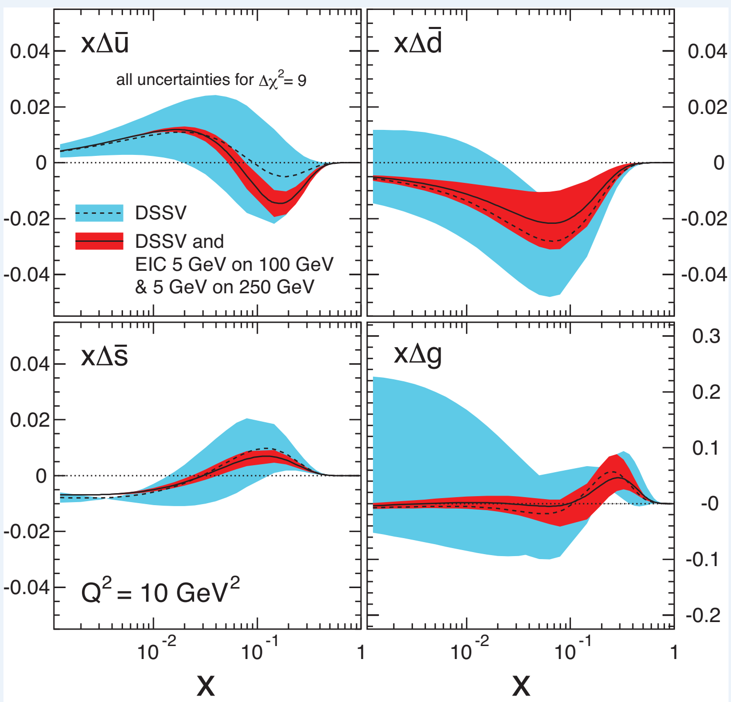
RHIC -> eRHIC

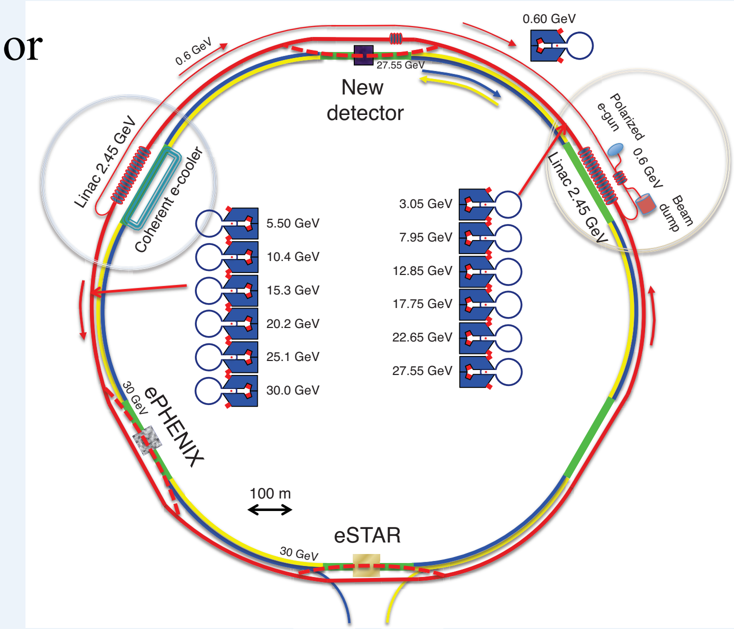
Electron – Ion Collider

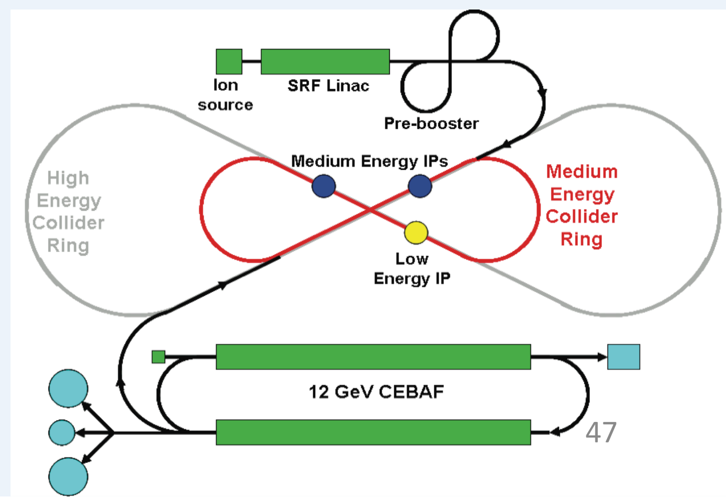
~2025

Add electron ring to existing RHIC proton/heavy_ion ring or
Add proton/heavy_ion ring to existing electron ring

Back to DIS but at much higher luminosity
(x100-1000 as HERA)
And much higher √s (with both beams polarized)







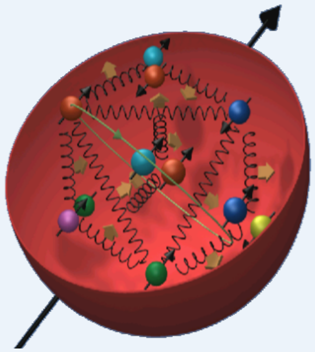
Summary

RHIC Spin program:

- How do gluon contribute to the proton Spin
  - Non-zero (in the limitted x-range) and comparable to (or larger than) quark contribution
  - Need to study lower x
- What is the flavor structure of polarized sea in the proton
  - Δu-bar tends to be positive, Δd-bar tends to be negative (symmetry breaking?)
  - Will see the more precise conclusion very soon
- What are the origins of transverse spin phenomena in QCD
  - Hadron A_N persists to high $\sqrt{s}$, and survives at high p_T
  - First observation of Collins and IFF asymmetries in pp (access to transversity!)
  - A_N for DY and W - fundamental QCD test
  - Other mechanisms for hadron A_N (dffractive?)

Many other results from PHENIX, STAR, BRAHMS and AnDY
Much more expected in EIC era !

Outlook

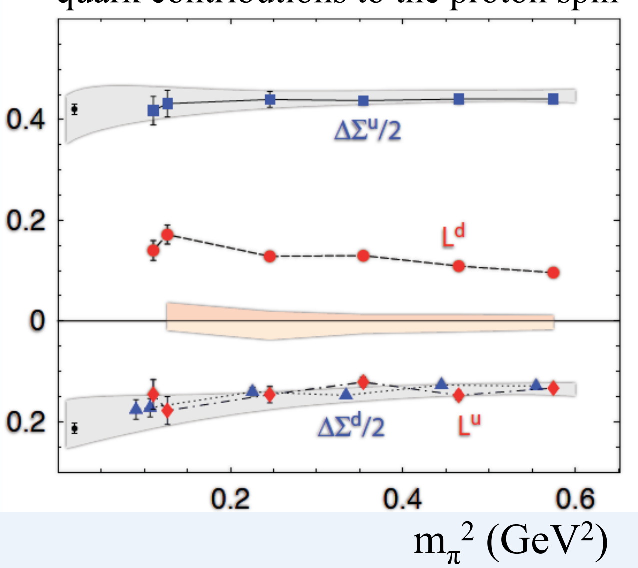


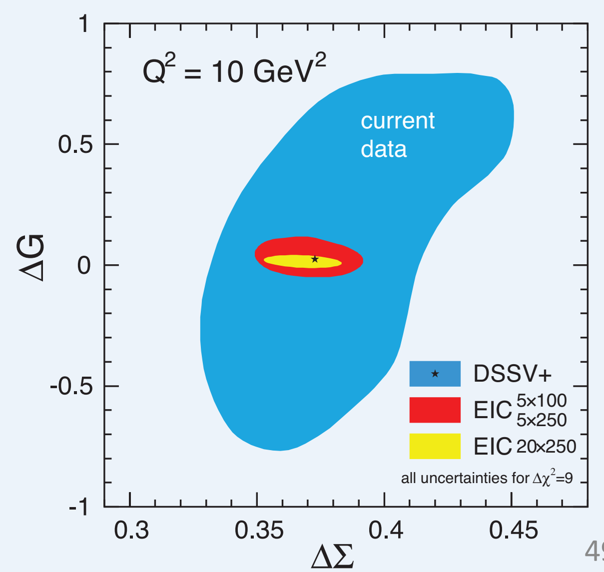
Proton Spin

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

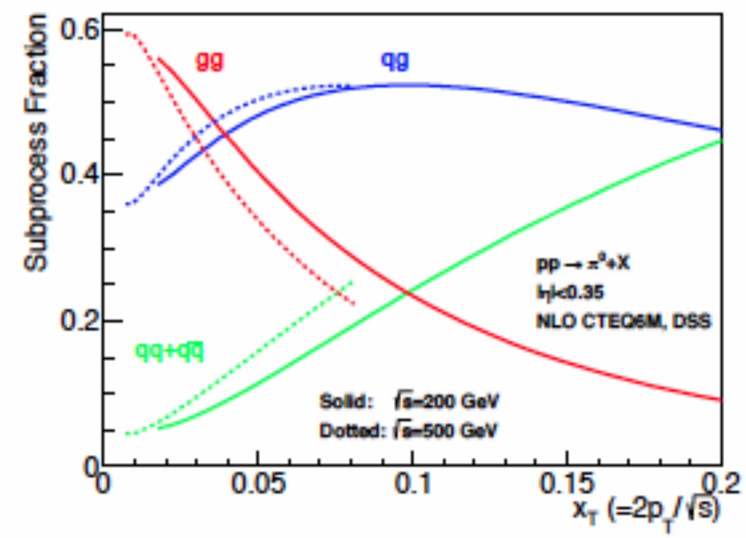
(Anti)quark Contribution: 0.15-0.20	Gluon Contribution: 0.2 in x>0.05	Parton Orbital Momentum: ???

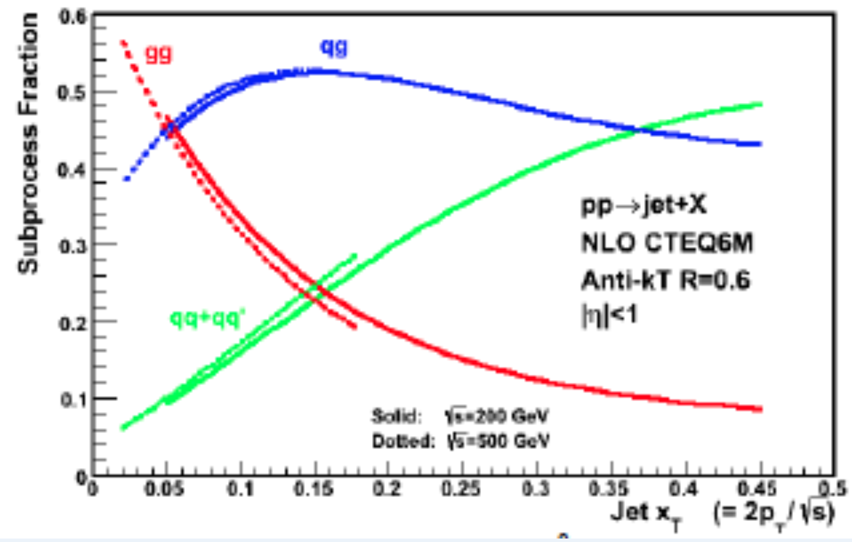
Lattice QCD:
quark contributions to the proton spin





Backup


Subprocess Fraction
gg
qg
qq+qq̄
pp → π⁰+X
|η|<0.35
NLO CTEQ6M, DSS
Solid: √s=200 GeV
Dotted: √s=500 GeV
0
0.2
0.4
0.6
0.05
0.1
0.15
0.2
x_T (=2p_T/√s)


Subprocess Fraction
gg
qg
qq+qq'
pp→jet+X
NLO CTEQ6M
Anti-kT R=0.6
|η|<1
Solid: √s=200 GeV
Dotted: √s=500 GeV
0
0.1
0.2
0.3
0.4
0.5
0.6
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Jet x_T (= 2p_T / √s)

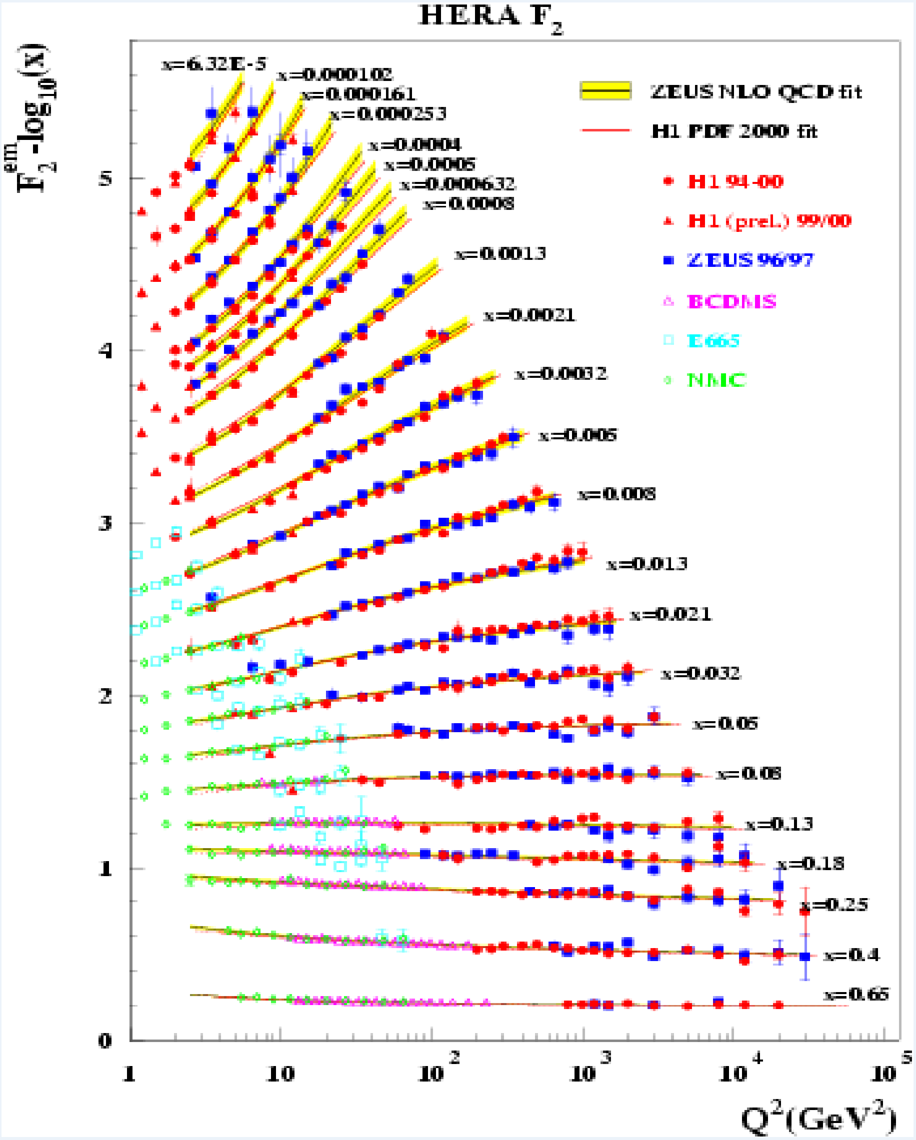
DSSV: PRL 101, 072001 (2008)

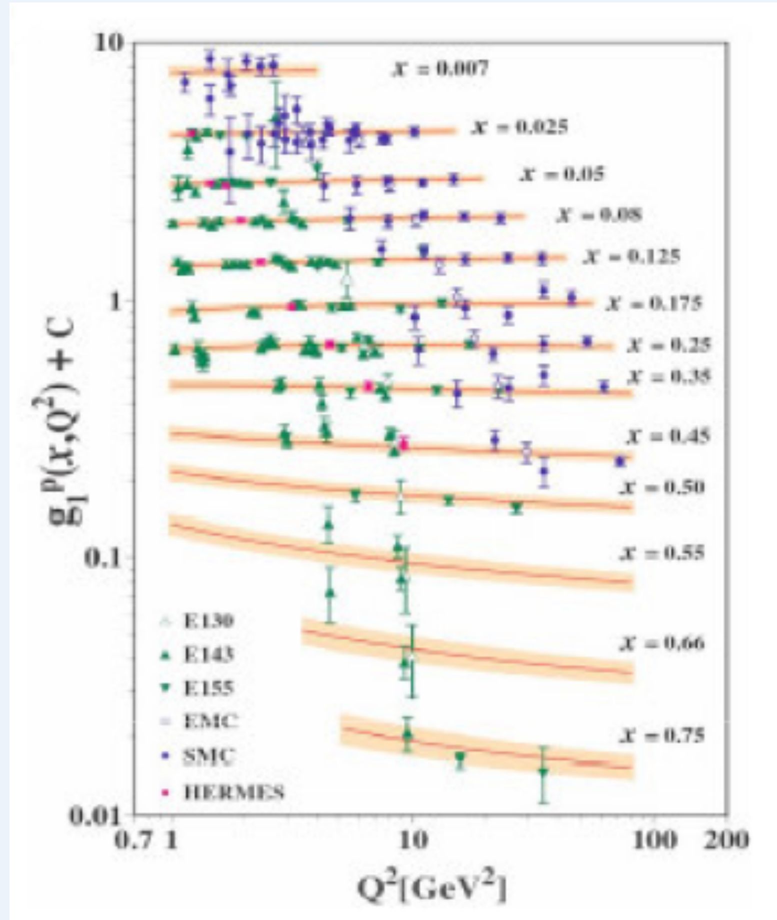
TABLE II. First moments $\Delta f_j^{1,[x_{\min}\to 1]}$ at $Q^2 = 10$ GeV^2.

	$x_{\min} = 0$ best fit	$x_{\min} = 0.001$ $\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793^{+0.011}_{-0.012}$	$0.793^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	−0.458	$-0.416^{+0.011}_{-0.009}$	$-0.416^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028^{+0.021}_{-0.020}$	$0.028^{+0.059}_{-0.059}$
$\Delta\bar{d}$	−0.115	$-0.089^{+0.029}_{-0.029}$	$-0.089^{+0.090}_{-0.080}$
$\Delta\bar{s}$	−0.057	$-0.006^{+0.010}_{-0.012}$	$-0.006^{+0.028}_{-0.031}$
Δg	−0.084	$0.013^{+0.106}_{-0.120}$	$0.013^{+0.702}_{-0.314}$
$\Delta\Sigma$	0.242	$0.366^{+0.015}_{-0.018}$	$0.366^{+0.042}_{-0.062}$

Before RHIC Run9 data for ΔG
No W data yet

From Inclusive Pol. DIS

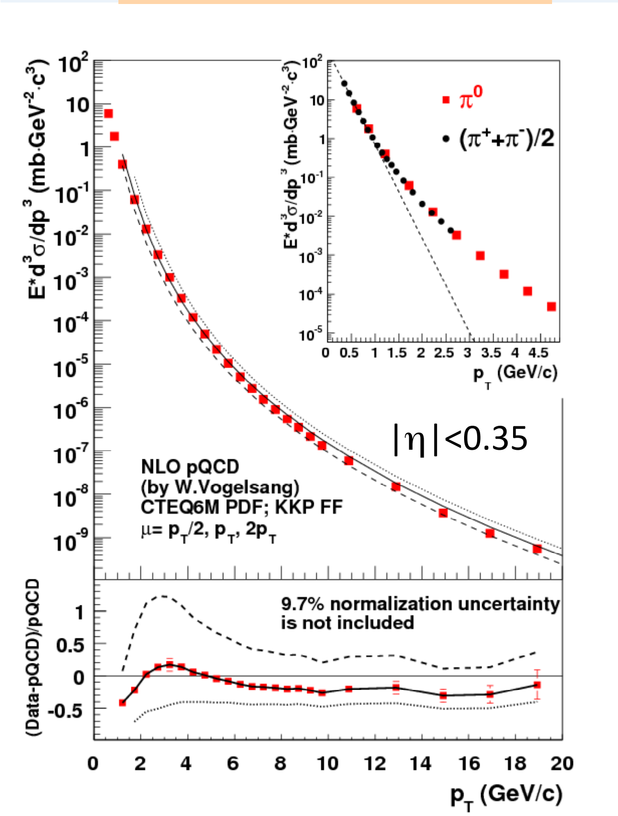


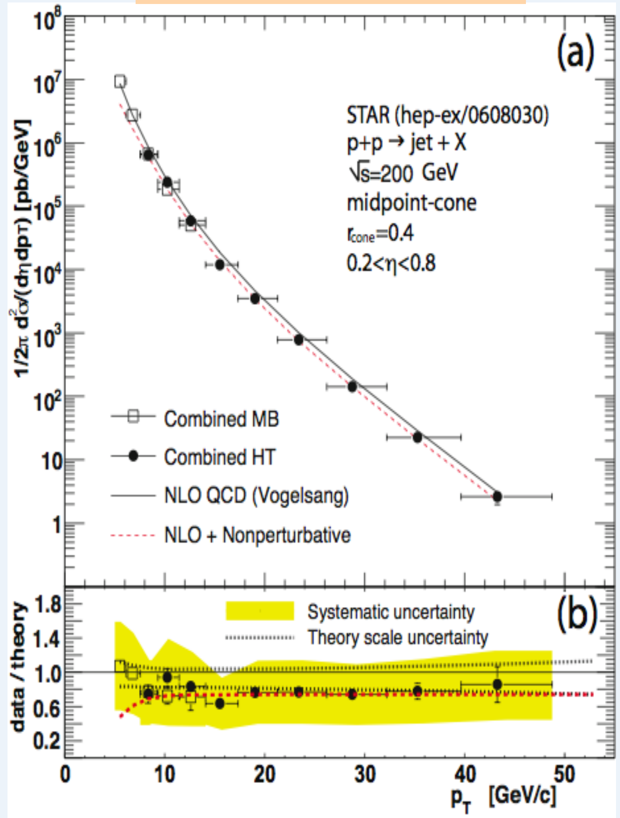


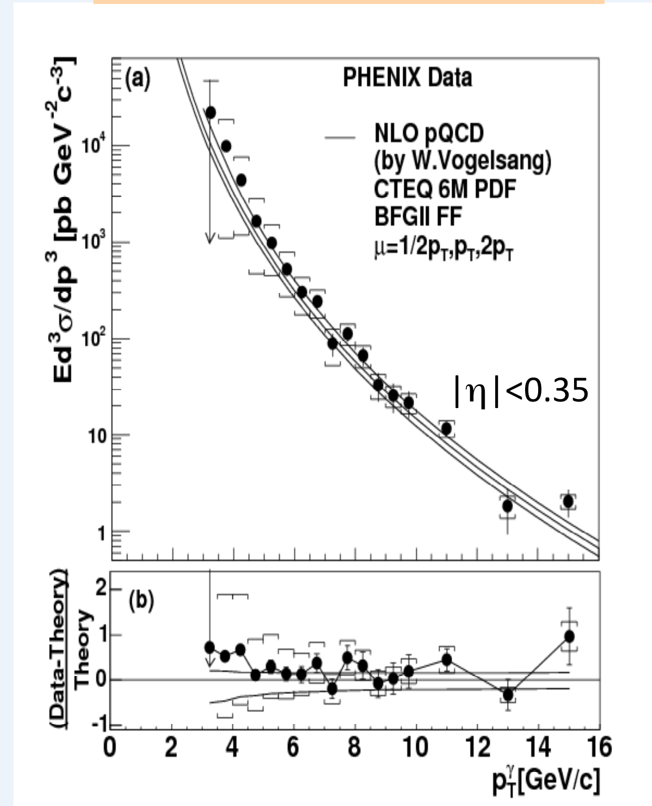
$$\frac{d}{d\ln Q^2}\begin{pmatrix}\Delta q\\ \Delta g\end{pmatrix} = \begin{pmatrix}\Delta P_{qq} & \Delta P_{qg}\\ \Delta P_{gq} & \Delta P_{gg}\end{pmatrix}\otimes\begin{pmatrix}\Delta q\\ \Delta g\end{pmatrix}$$

Unpol. Cross Section and pQCD in pp

PHENIX pp→ π^0 X PRD76, 051106	STAR: pp→jet X PRL 97, 252001	PHENIX pp→γ X PRL 98, 012002



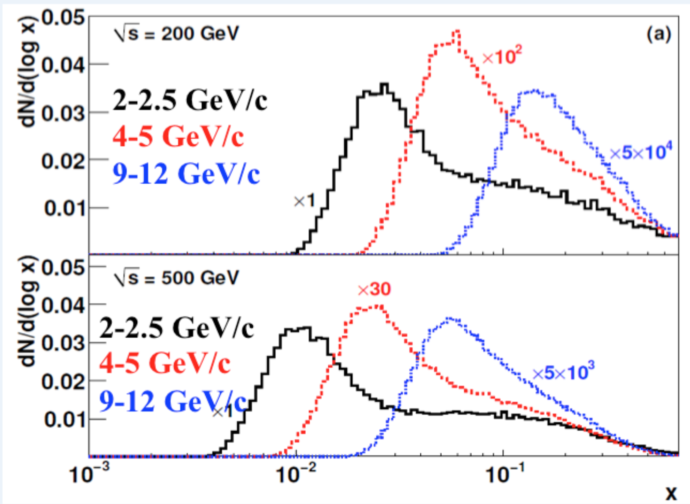


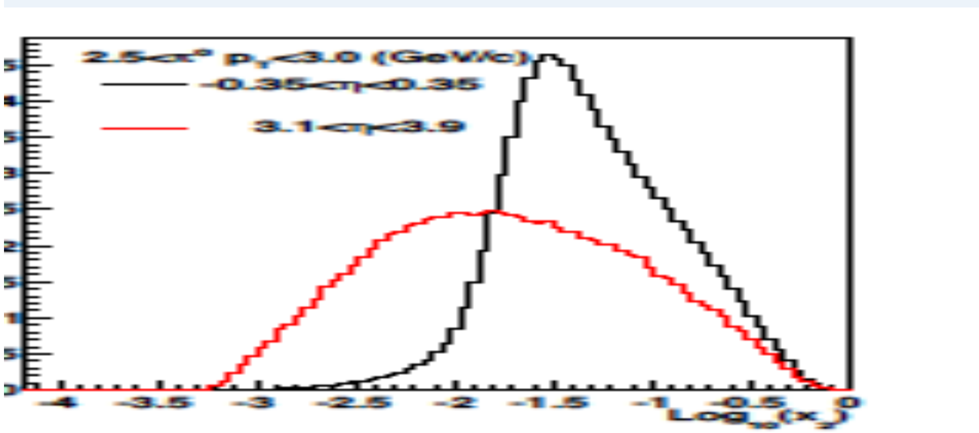


Good agreement between NLO pQCD calculations and data ⇒ pQCD can be used to extract spin dependent pdf's from RHIC data.

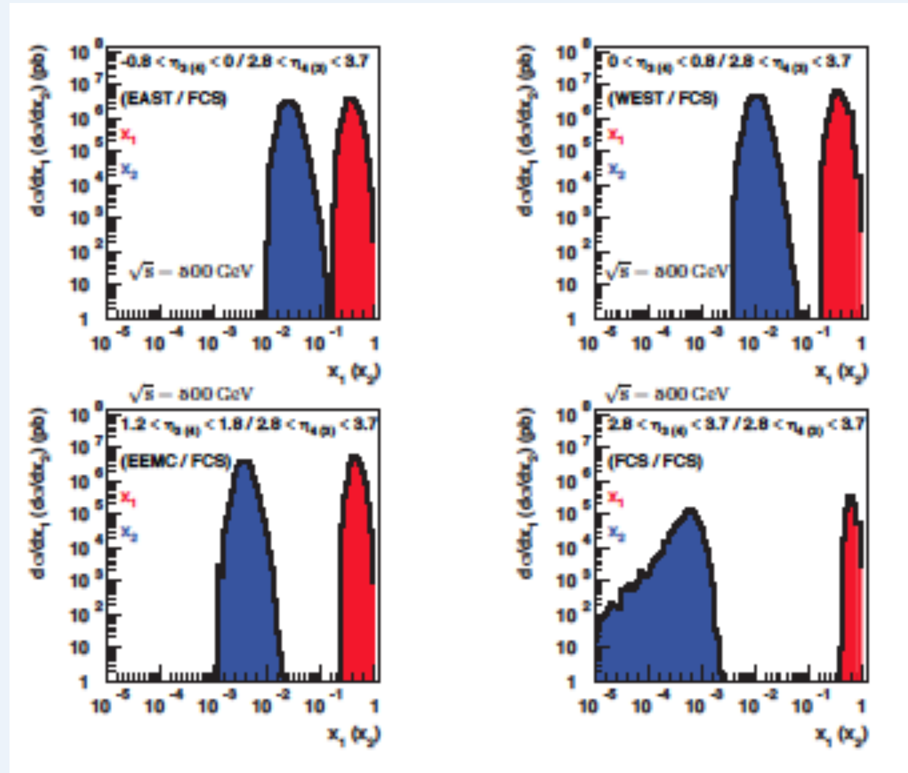
ΔG: Towards lower x

From incl. π0

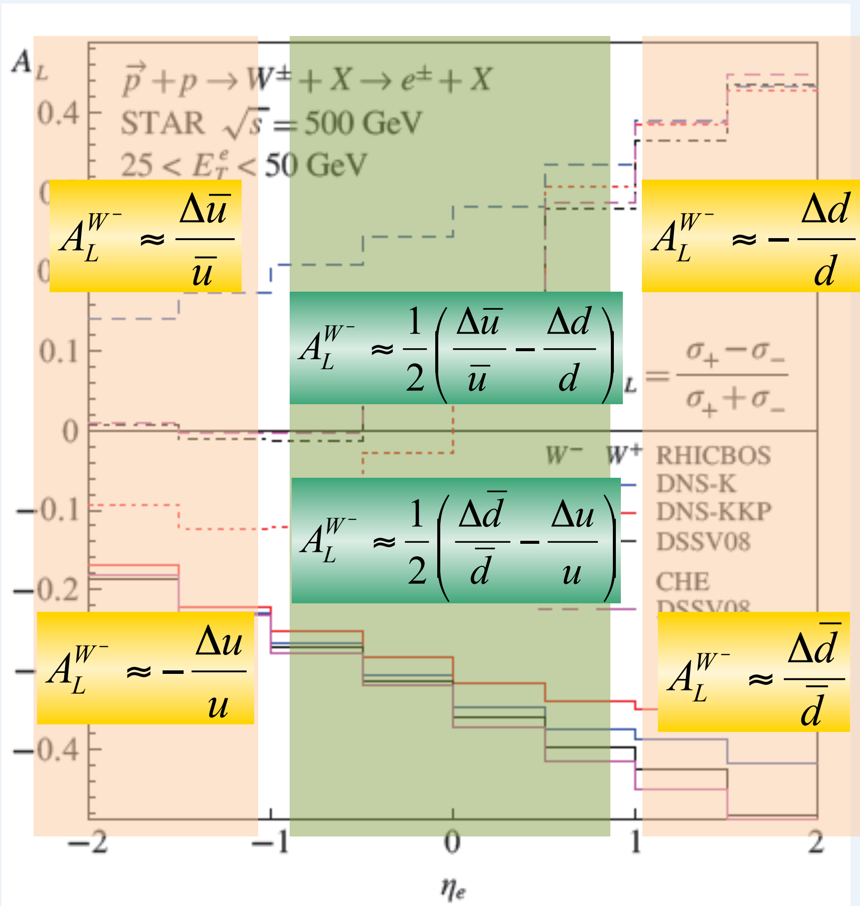




From di-jets



W: A_L vs η_l



STAR

Central (barrel) region (W→e$^{\pm}$, |η|<1)

First data from 2009: **PRL106, 062002 (2011)**

Forward (endcup) region (W→e$^{\pm}$, 1<|η|<2) :

Forward tracker upgrade, first data in 2012

PHENIX

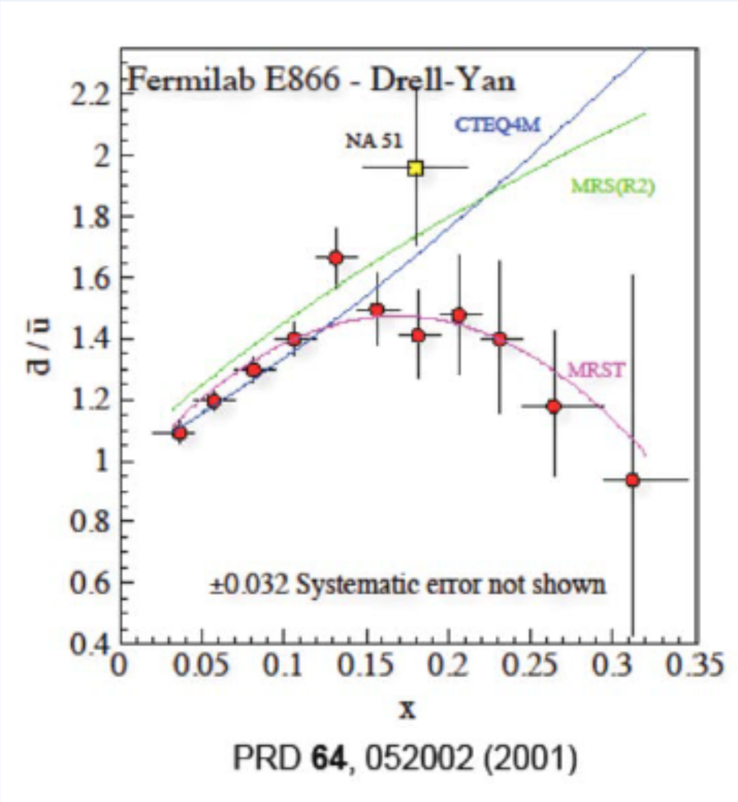
Central Arms (W→e$^{\pm}$, |η|<0.35)

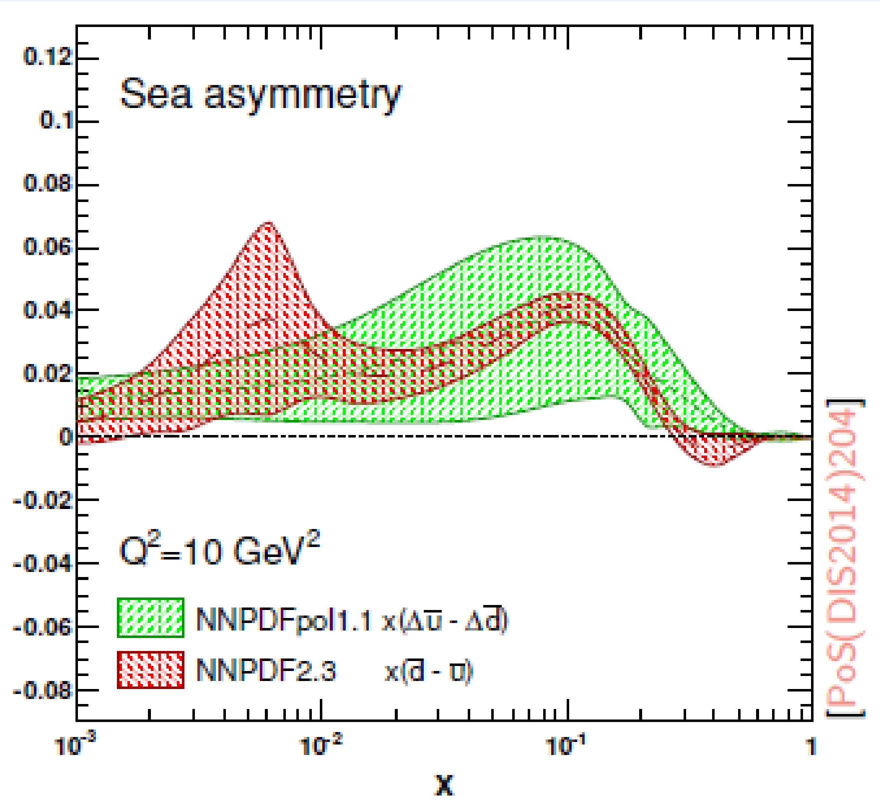
First data from 2009: **PRL106, 062001 (2011)**

Forward Arms (W→μ$^{\pm}$, 1.2<|η|<2.4) :

Trigger upgraded, first data from 2011

Symmetry breaking in pol. sea?

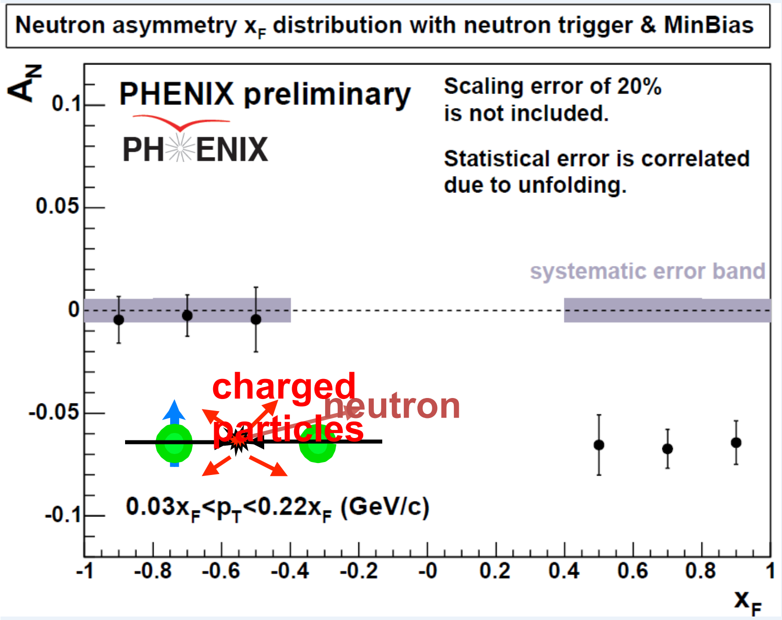




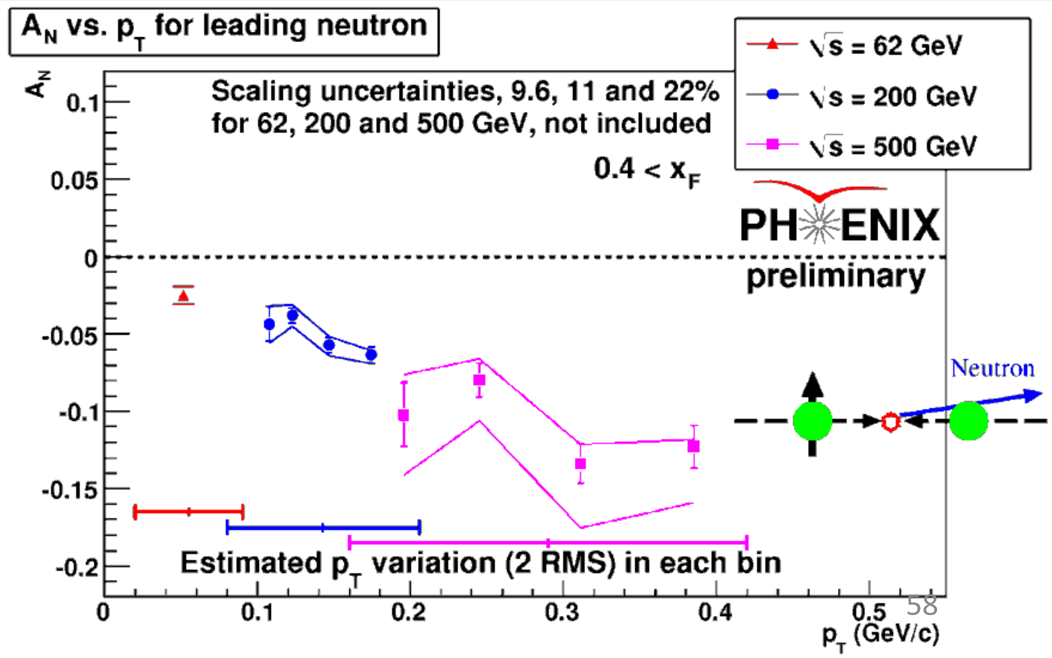
Unpolarized sea is not symmetric

Symmetry breaking in polarized sea?

Neutron A_N



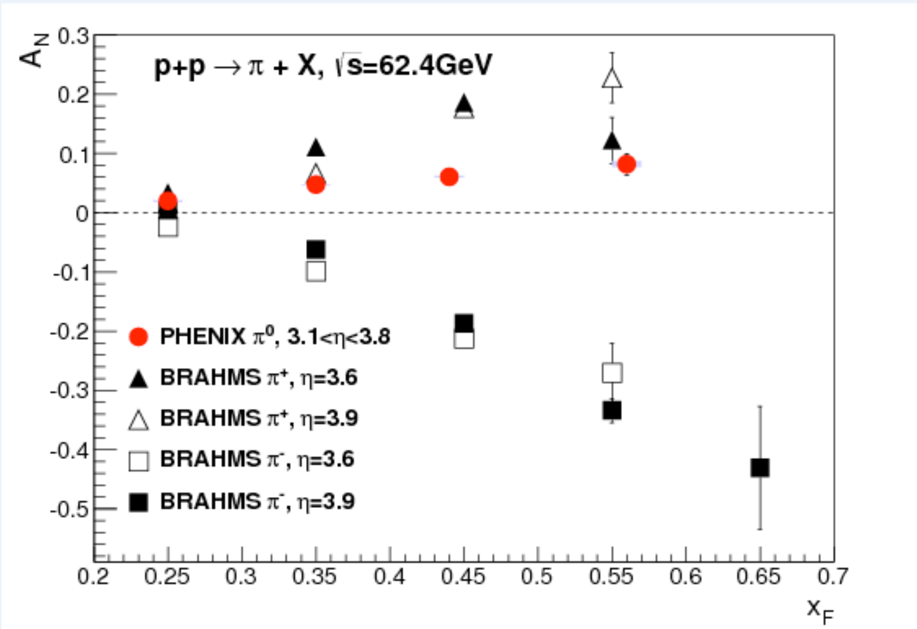
Neutron asymmetry x_F distribution with neutron trigger & MinBias
A_N
PHENIX preliminary
PHENIX
Scaling error of 20% is not included.
Statistical error is correlated due to unfolding.
systematic error band
charged particles
neutron
0.03x_F<p_T<0.22x_F (GeV/c)
0.1
0.05
0
-0.05
-0.1
-1
-0.8
-0.6
-0.4
-0.2
-0
0.2
0.4
0.6
0.8
1
x_F



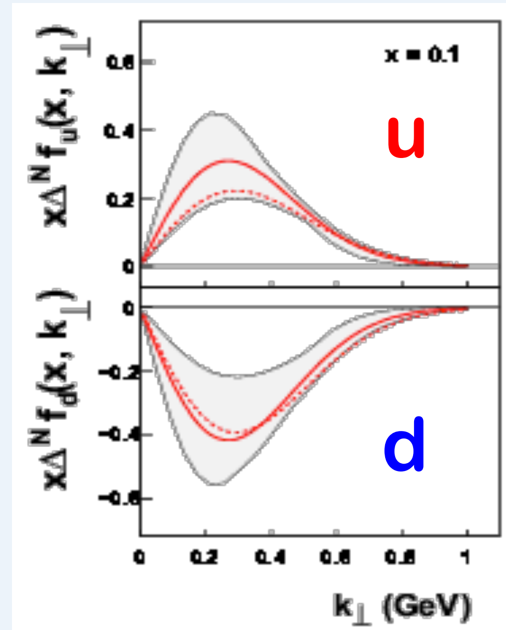
A_N vs. p_T for leading neutron
√s = 62 GeV
√s = 200 GeV
√s = 500 GeV
A_N
Scaling uncertainties, 9.6, 11 and 22% for 62, 200 and 500 GeV, not included
0.4 < x_F
PHENIX
preliminary
Neutron
Estimated p_T variation (2 RMS) in each bin
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
0.1
0.2
0.3
0.4
0.5
p_T (GeV/c)

A_N: pp→π X

PRD90 (2014), 012006



Anselmino et al., Eur. Phys. J. A39, 89 (2009)



PYTHIA:

π+ mainly produced from u

π- equally produced from d and u

=> $|A_N(\pi+)| >> |A_N(\pi-)|$

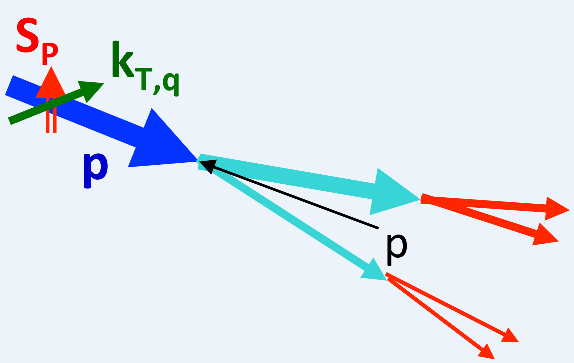
Sivers contribution is small in pp→π X ?

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



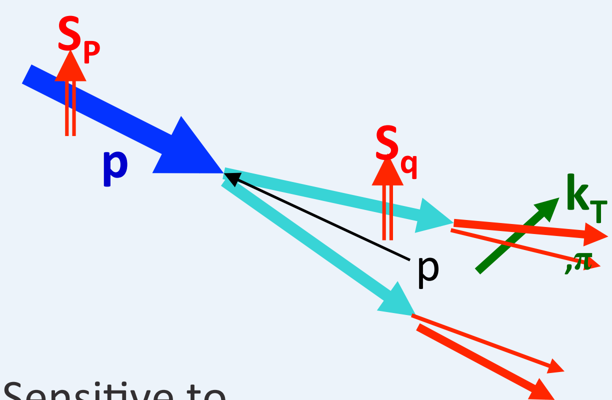
Sensitive to correlations
proton spin – parton **transverse motion**

Not universal between SIDIS & pp

Final State:

Collins mechanism

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

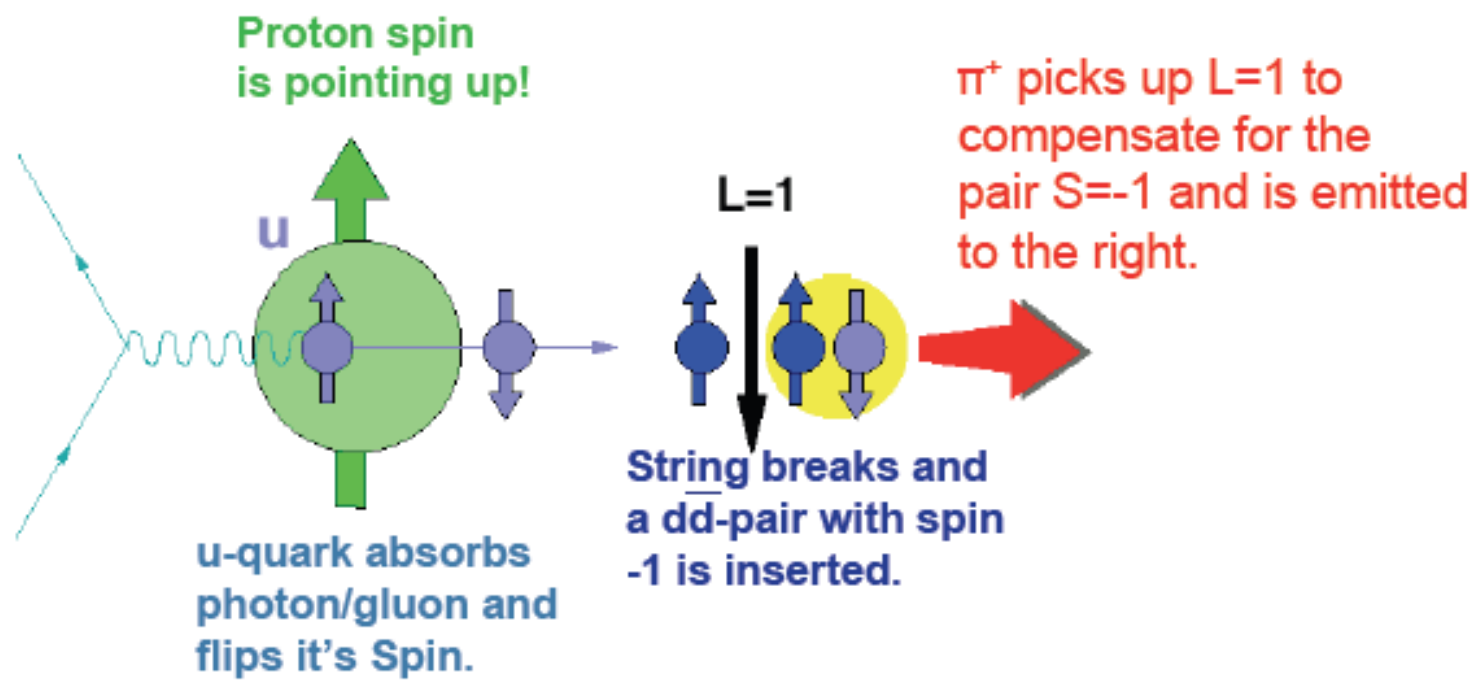


Sensitive to
transversity x spin-dependent FF

Universal between SIDIS & pp & e+e-

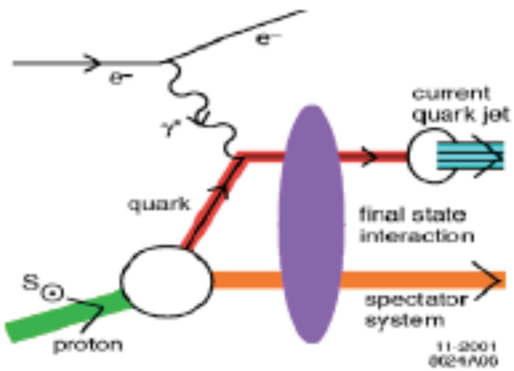
The Collins Effect in the Artru Fragmentation Model

A simple model to illustrate that spin-orbital angular momentum coupling can lead to left right asymmetries in spin-dependent fragmentation:

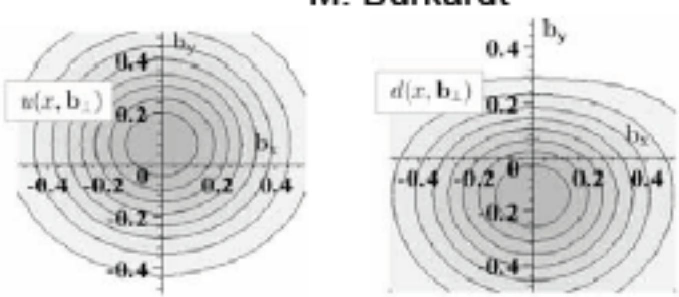


Naïve Sivers Interpretation

Sivers effect is an interference with a final state interaction of quark with spectator system.



(Int.J.Mod.Phys.A18:1327-1334,2003)
M. Burkardt



(Nucl.Phys. A735 (2004) 185-199)

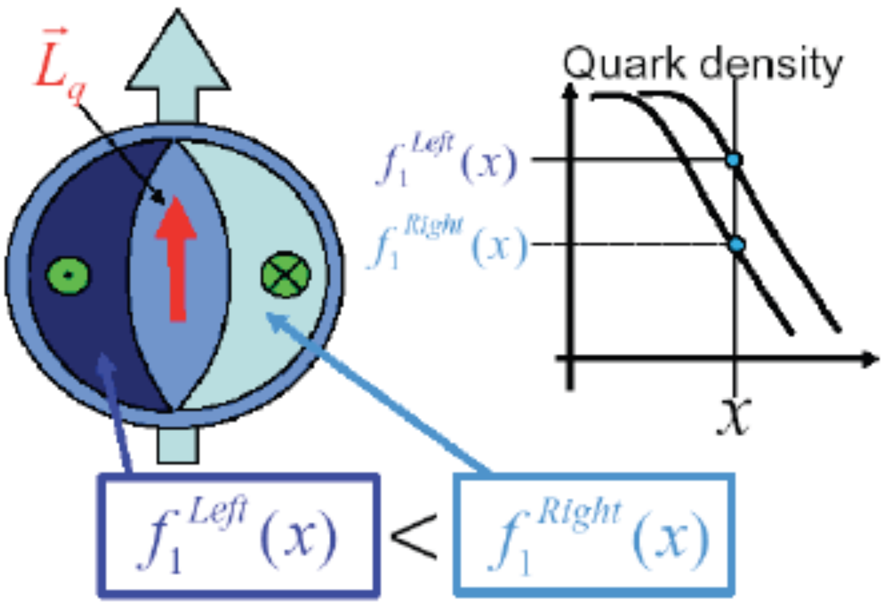
Can be understood as soft-gluon exchange in final state.

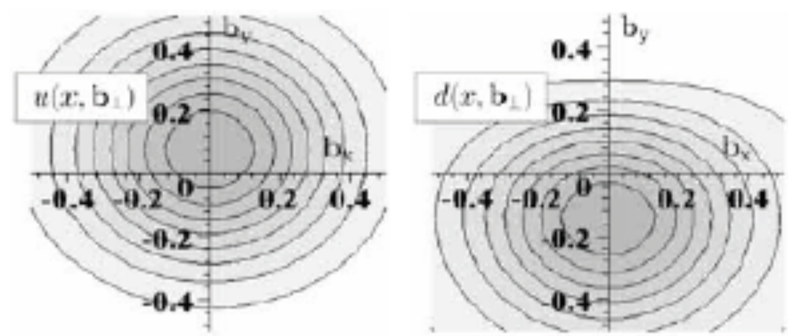
Sivers effect generates single spin asymmetries scattered off transversely polarized target.

Sivers effect and Orbital Angular Momentum

Semi-classical picture :

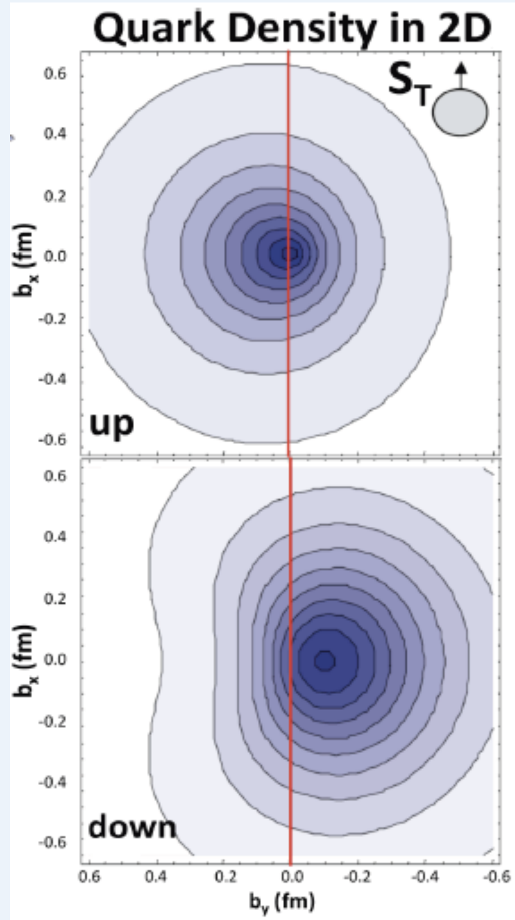
If quarks have L_q , probability to find quark which carries momentum fraction of "x" is different between left & right sides in the nucleon (viewed from virtual photon).





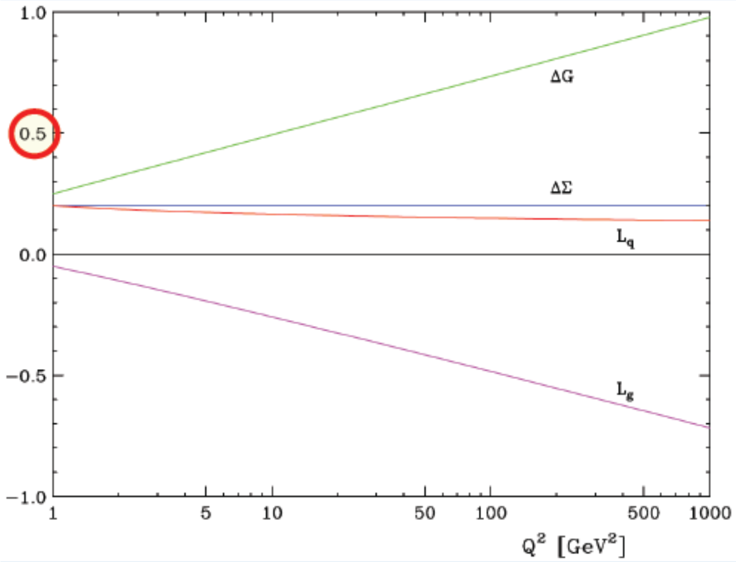
M. Burkardt
(Nucl.Phys. A735 (2004) 185-199)

→ Sivers function can be viewed an impact-parameter dependent PDF.



Lattice QCD PRL98:222001,2007.

Q2 dependence



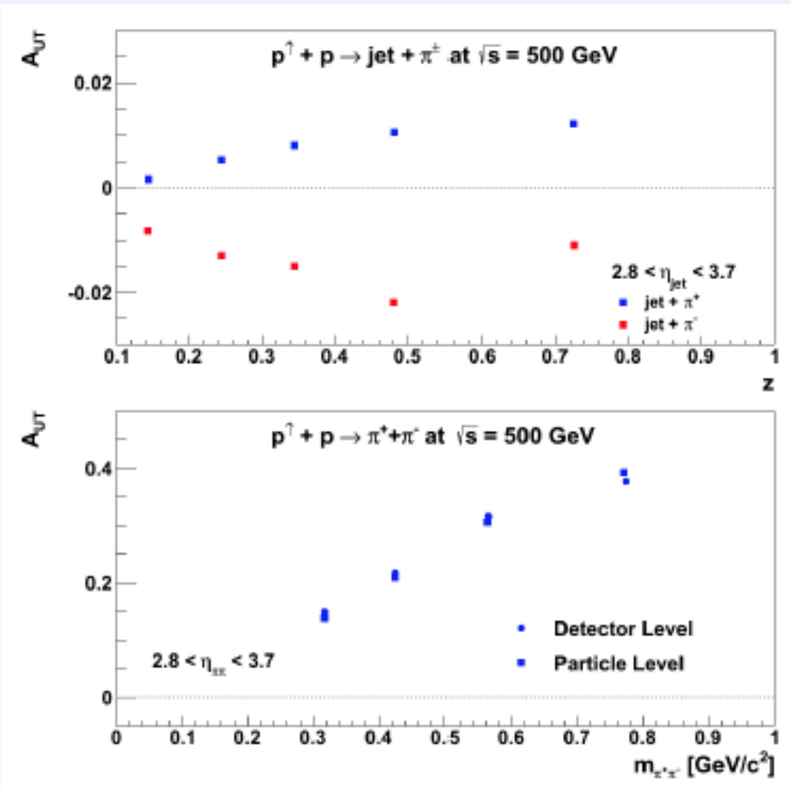
ΔG is dynamic value – Q^2 dependent
ΔG can be large at large Q^2 (and can be >>1/2) no matter how small it is at some low Q^2
Large ΔG at large Q^2 is compensated by L_g

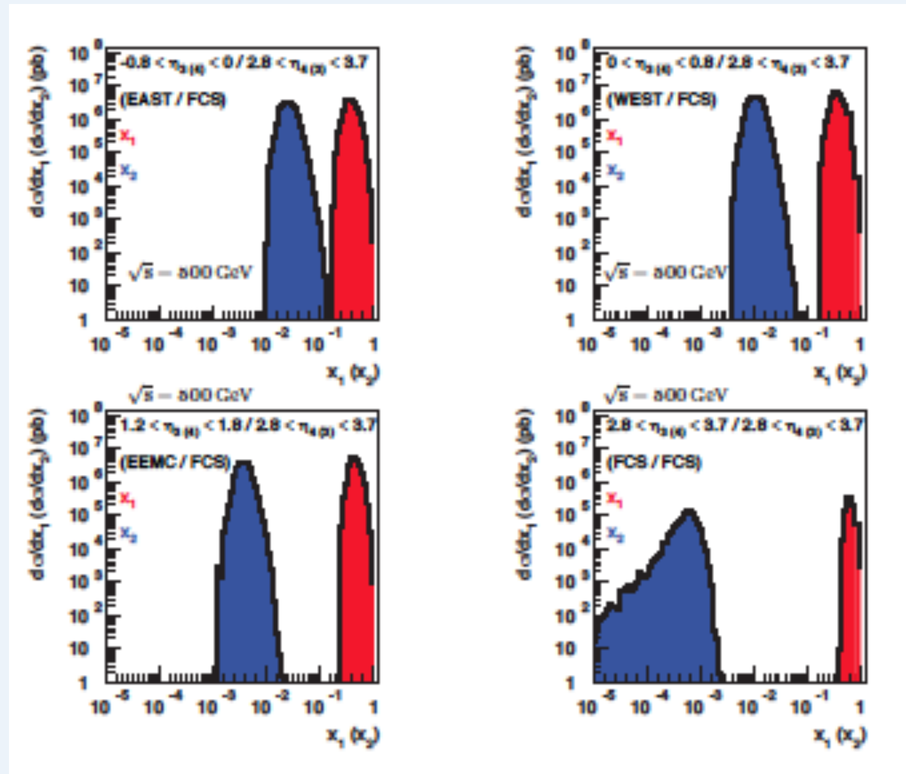
$$\frac{1}{2}^{proton} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$$

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

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

STAR forward upgrade





PHENIX forward upgrade