Progress at RHIC on studying the spin of the proton

Jianwei Qiu

Brookhaven National Laboratory

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Based on presentations at Workshop 4 – RHIC and the spin of the proton, …

U.S. DEPARTMENT OF ENERGY | Office of Science

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Proton spin

❑ Proton is NOT elementary, but, a composite particle:

✧ **Proton-spin = Proton's angular momentum when it is at rest**

✧ **Proton-spin = One number touches every part of the quantum world**

from the quantum mechanics to the quantum field theory and QCD

$S(\mu) = \frac{1}{2}$

$\mu \Rightarrow \infty$

✧ **Proton-spin = One number carries every secrets of QCD dynamics**

from the "unknown" confinement to the "well-known" asymptotic freedom

❑ Quark Model:

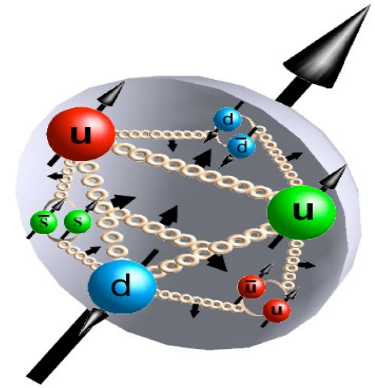
✧ **Expectation:** $S_p \equiv \langle p\uparrow | S | p\uparrow \rangle = \frac{1}{2}, \qquad S = \sum_i S_i$

✧ **Wave function:** $|p\uparrow\rangle = \sqrt{\frac{1}{18}}\left[u\uparrow u\downarrow d\uparrow + u\downarrow u\uparrow d\uparrow - 2u\uparrow u\uparrow d\downarrow + \text{perm.}\right]$

Skyrmion Model, MIT Bag Model, Chiral Bag Model, …

Proton spin in QCD

❑ Complexity of the proton in QCD:



Known from QCD

$$S(\mu) = \sum_f \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu)$$

From QCD, But, unknown

$$\vec{J}_q = \int d^3x \left[\psi_q^\dagger \vec{\gamma}\gamma_5\psi_q + \psi_q^\dagger(\vec{x}\times(-i\vec{D}))\,\psi_q\right] \qquad \vec{J}_g = \int d^3x \left[\vec{x}\times(\vec{E}\times\vec{B})\right]$$

❑ Asymptotic limit:

Ji, 2005

$$J_q(\mu\to\infty) \Rightarrow \frac{1}{2}\frac{3N_f}{16+3N_f} \sim \frac{1}{4} \qquad J_g(\mu\to\infty) \Rightarrow \frac{1}{2}\frac{16}{16+3N_f} \sim \frac{1}{4}$$

❑ Spin sum rule – not unique!

$$S(\mu) = \frac{1}{2}\Sigma(\mu) + L_q(\mu) + \Delta G(\mu) + \overbrace{[J_g(\mu) - \Delta G(\mu)]}^{L_g(Q^2)}$$

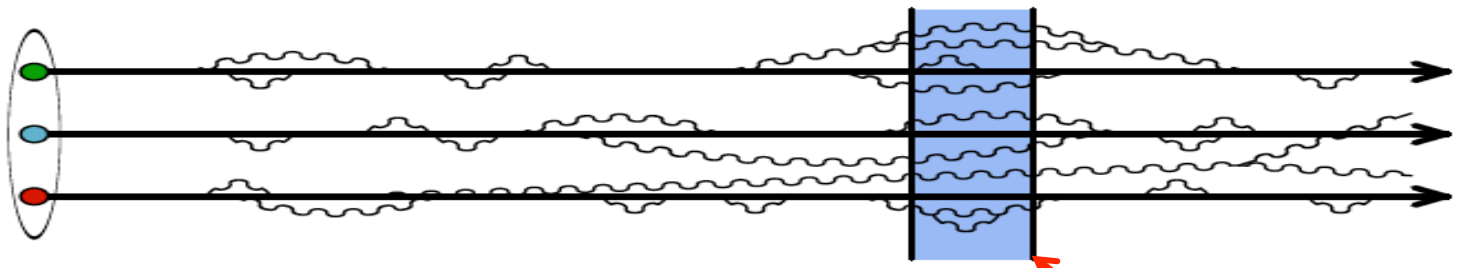
Intrinsic parton's spin: $\Sigma(Q^2) = \sum_q \left[\Delta q(Q^2) + \Delta\bar{q}(Q^2)\right], \quad \Delta G(Q^2)$

dynamical parton motion: $L_q(Q^2), \quad L_g(Q^2)$

- **Matrix elements of quark and gluon fields are NOT physical observables!**
- **Infinite possibilities of decompositions – connection to observables?**

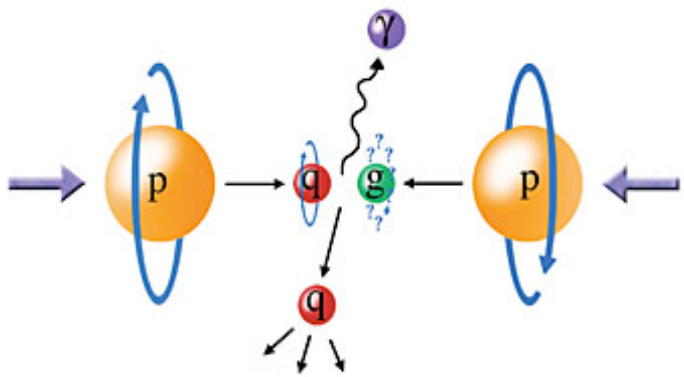
How to probe quarks and gluons?

❑ From cross sections to quarks and gluons – QCD factorization:



Boost
Time-dilation

Hard probe: t ~ 1/Q < 1/10 fm



$$\frac{d\Delta\sigma}{dydp_T^2} = \int \frac{dx}{x}\Delta q(x) \int \frac{dx'}{x'}\Delta g(x') \frac{d\Delta\hat{\sigma}_{qg\to\gamma g}}{dydp_T^2} \times \left[1 + \mathcal{O}\left(\alpha_s^2\right) + \mathcal{O}\left(\frac{1}{p_T^n}\right)\right]$$

❑ Contribution to proton's helicity: Proton is NOT at rest!

✧ Elementary particles' spin – helicity: $\Sigma(Q^2) = \sum_q \left[\Delta q(Q^2) + \Delta\bar{q}(Q^2)\right]$

(intrinsic effect – longitudinal motion) $\Delta G(Q^2)$

+

✧ Motion of the particles – projection of orbital angular momentum

(dynamical – fundamental interaction – transverse motion)

RHIC spin program

Research

Status a

S

In this report we present the r
science of the RHIC spin prog
ments for the RHIC spin progr
evolution of the spin program

Christine Aidala[a], Mei Bai[b], I
Abhay Deshpande[c,e], Dougla
Matthias Grosse Perdekamp[c
Kistenev[b], Stefan Kretzer[b,c],
Vladimir Rykov[h], Naohito Sa
Surrow[n], Atsushi Taketani[c,l
Fleming Videbaek[b], Steve Vig

(see next page for institutions)

Plans for the RHIC

June

The following is meant to provi
tion of the 2007 Nuclear Physi
presentation in the 2005 Resea

http://spin.ri

In addition to the material pre
celeration of polarized protons
developing area of the transve
both proton helicity and transv

Gerry Bunce and Werner Vog
pande, Wolfram Fischer, Mat
Bernd Surrow
(see also: authors of Research

Al

This report gives a RHIC spin plan for the
nificantly advance our understanding of the
expected toward an understanding of the glu
violating measurements would greatly impac
up and anti-down quark polarizations in the
a precision stage studying asymmetries con
transversity.

The entire plan rests on running. The plan
tained running is necessary to build the requi
to build the level of polarization anticipated,
ity recorded by the experiments, both at $\sqrt{s}$
Support for development of higher proton-p
program envisioned for beyond 2013.

Writers, for the RI
and the PHENIX a

Gerry Bunce (chair), Alexander Bazilevsky, L
Gagliardi, Yuji Goto, Matthias Grosse-Perd
Roser, Ralf Seidl, Jim Sowinski, Marco Strat

2012

The RHIC SPIN Program

Achievements and Future Opportunities

Writers, for the RHIC Spin Collaboration[1]

Elke-Caroline Aschenauer, Alexander Bazilevsky, Kieran Boyle, Kjeld Oleg Eyser, Renee Fatemi, Carl Gagliardi, Matthias Grosse-Perdekamp, John Lajoie, Zhongbo Kang, Yuri Kovchegov, John Koster, Itaru Nakagawa, Rodolfo Sassot, Ralf Seidl, Ernst Sichtermann, Marco Stratmann, Werner Vogelsang, Anselm Vossen, Scott W. Wissink, and Feng Yuan

Goals of RHIC spin program

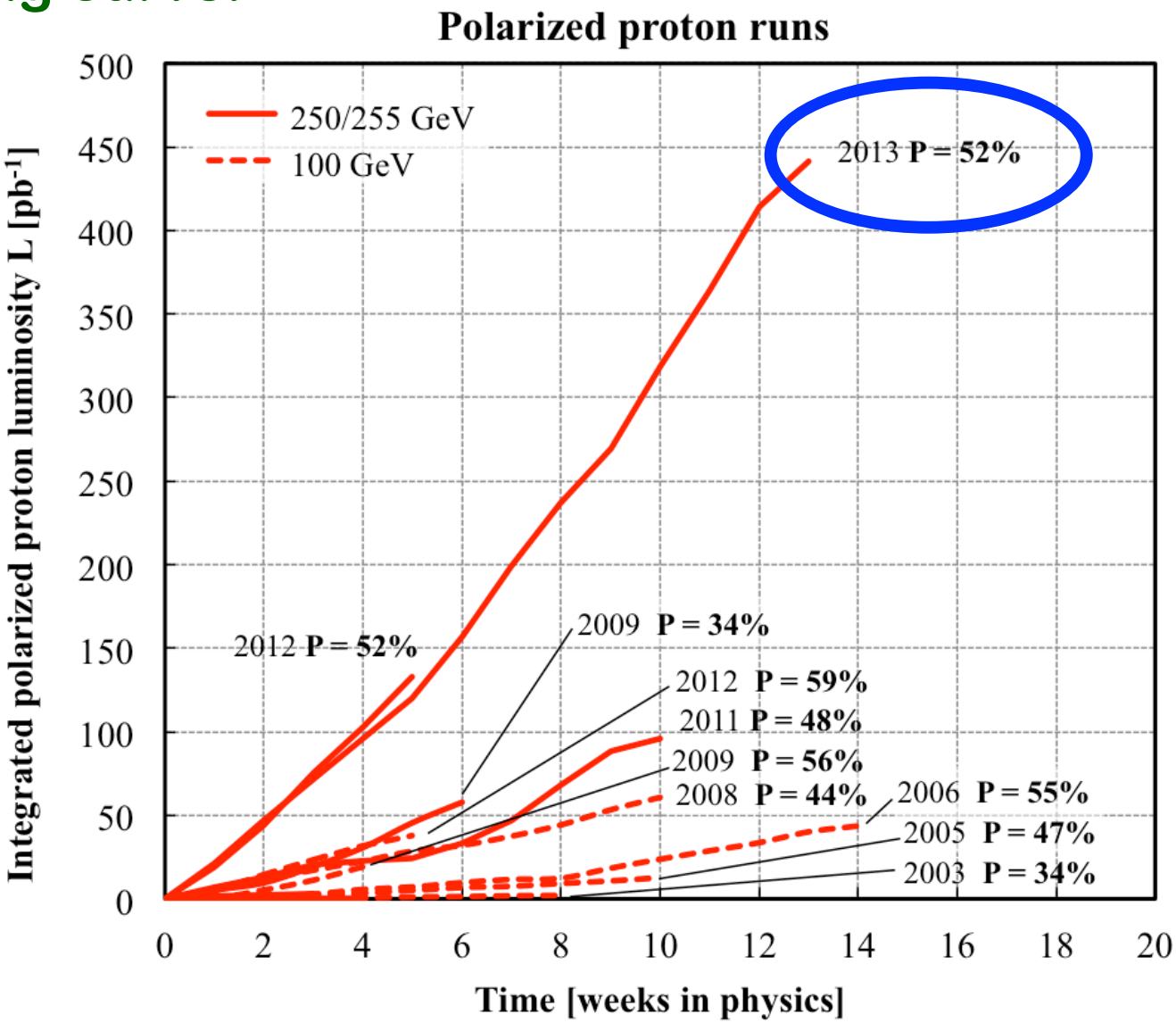
- Determination of polarized gluon distribution (ΔG) over a large range of momentum fraction x, using multiple probes

- Determination of flavor identified quark and anti-quark polarization using parity violating production of $W^{\pm}$

- Transverse spin phenomena in QCD: transversity (δq), parton orbital angular momentum (L_q), and etc.

What has RHIC delivered?

- Learning curve:



- Maturity and discovery:

What a year of 2013!

What have we learned?

Workshop 4 - RHIC and the spin of the proton

Go Back

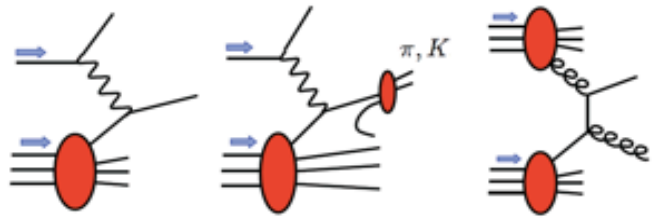
Date: Tuesday, June 25, 2013
Organizers: Pibero Djawotho, Mickey Chiu, Xiaorong Wang and Jim Drachenberg
Time: Afternoon Session 1:30 p.m. to 5:35 p.m.
Location: Building 463B, Biosciences Seminar Room (157)

Agenda

Session: I: Spin Sessions		
1:30 - 2:15	Theory overview of spin physics at RHIC	Marco Stratmann, BNL
2:15 - 2:40	PHENIX DeltaG	Scott Wolin, University of Illinois @ Urbana-Champaign
2:40 - 3:05	STAR DeltaG	Grant Webb, University of Kentucky
3:05 - 3:30	PHENIX W production	Mikhail Stepanov, University of Massachusetts @ Amherst
3:30 - 3:55	STAR W production and FGT	Xuan Li, Temple University
3:55 - 4:20	**Coffee Break**	
	End of Session I	
Session: II: Spin Sessions		
4:20 - 4:45	AnDY	Akio Ogawa, BNL
4:45 - 5:10	PHENIX Transverse Spin	Ming Liu, LANL
5:10 - 5:35	STAR Transverse Spin	Jim Drachenberg, Valparaiso University
	Adjourn	

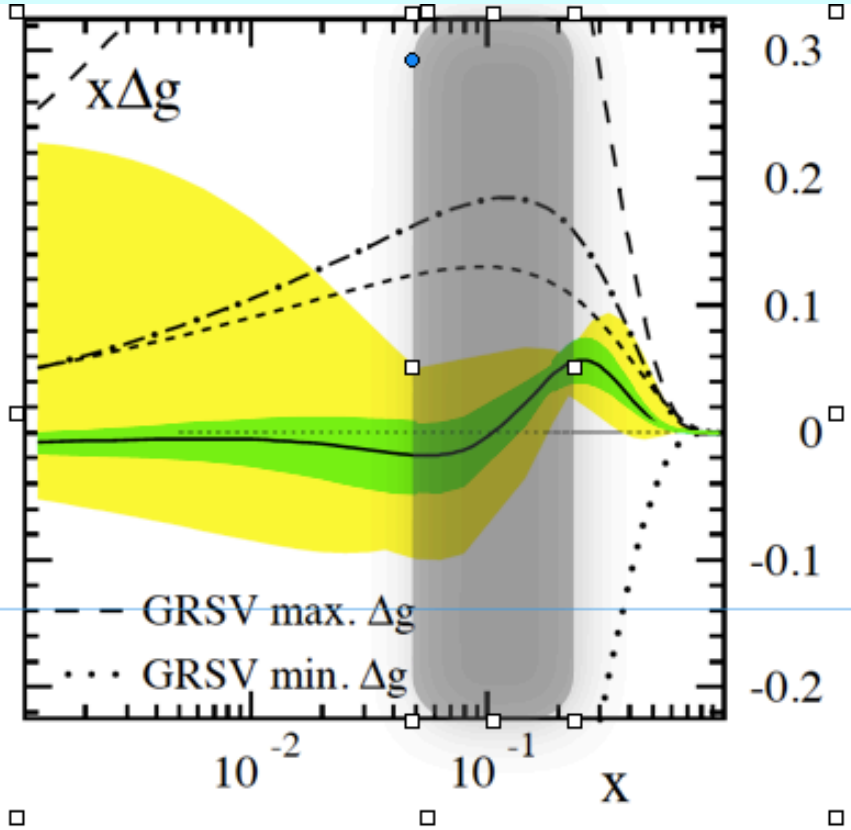
Recent helicity PDF fits @ NLO

Stratmann's talk



				uncertainties	last update
NNPDF Ball, Forte, Guffanti, Nocera, Rodolfi, Rojo	✓	✗	✗	100 replicas stat. approach	1303.7236
DSSV de Florian, Sassot, MS, Vogelsang	✓	✓	✓	L.M. $\Delta\chi^2 = 8$ (1) (Hessian $\Delta\chi^2 = 1$)	0904.3821 [DSSV+/++: 1112.0904 1304.0079]
LSS Leader, Sidorov, Stamenov	✓	✓	✗	Hessian $\Delta\chi^2 = 1$	1010.0574
BB Blumlein, Bottcher	✓	✗	✗	Hessian $\Delta\chi^2 = 1$	1010.3113
⋮		⋮			⋮
GRSV Gluck, Reya, MS, Vogelsang	✓	✗	✗	✗	1st NLO analysis 9508347

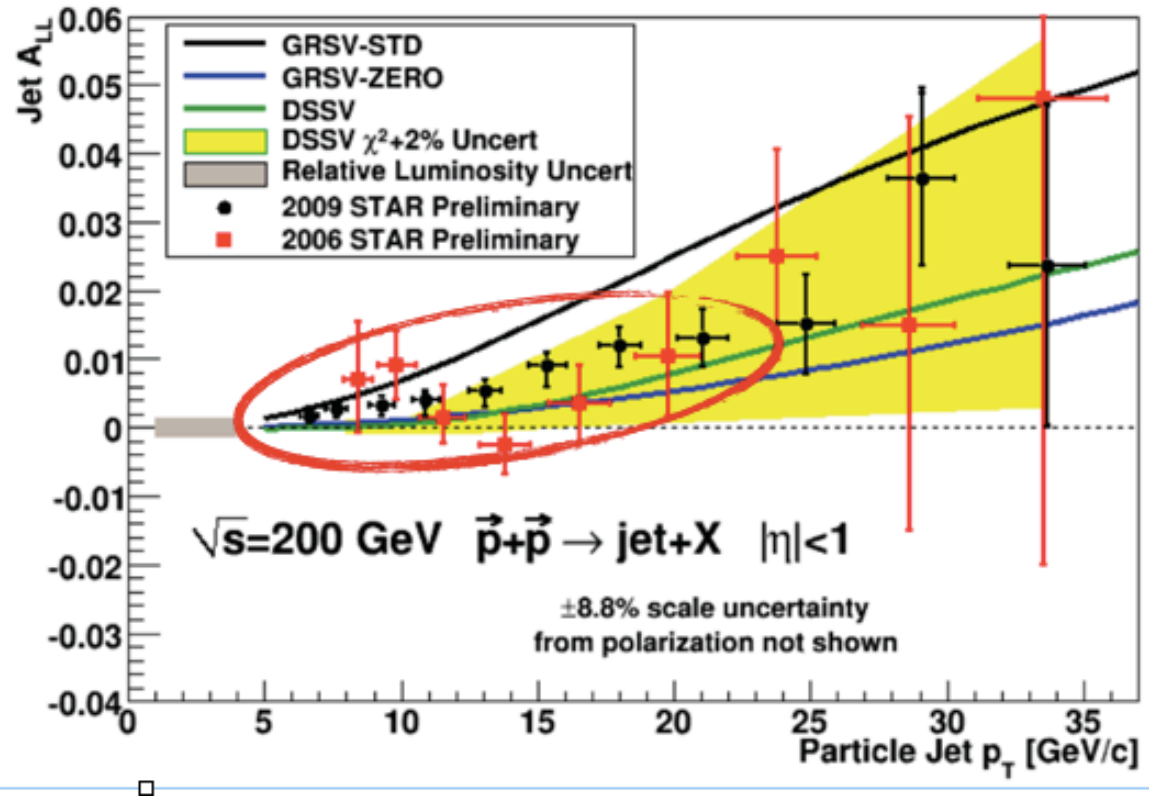
RHIC Measurements on ΔG



- ☑ 200 GeV data mainly probe gluon in x=0.05-0.2
- ☑ found to be small, but uncertainties still large

$$\int_{0.05}^{0.2} dx\, \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2) = 0.005^{+0.129}_{-0.164}$$

from DSSV 2008/09 analysis

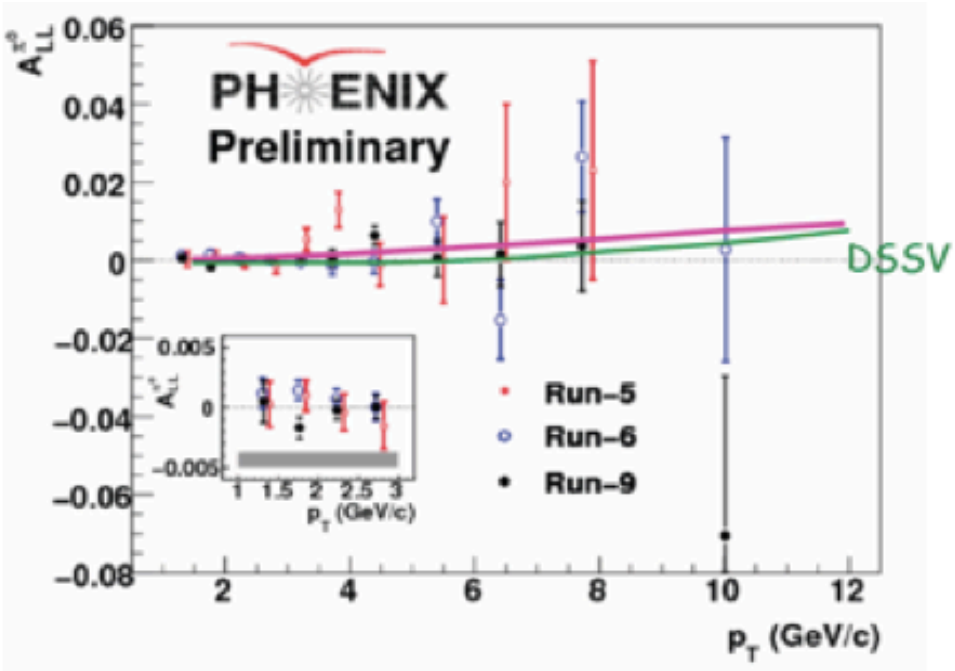


- ☑ new data consistently above DSSV
- ☑ considerably smaller errors

what's the impact?

Stratmann's talk

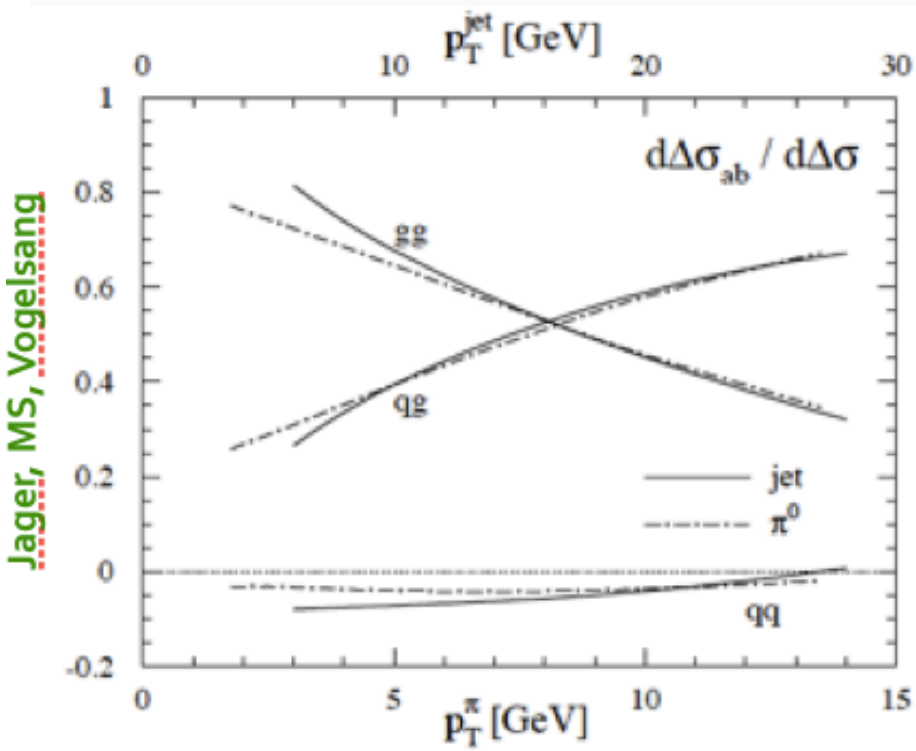
Consistency between PHENIX and STAR data

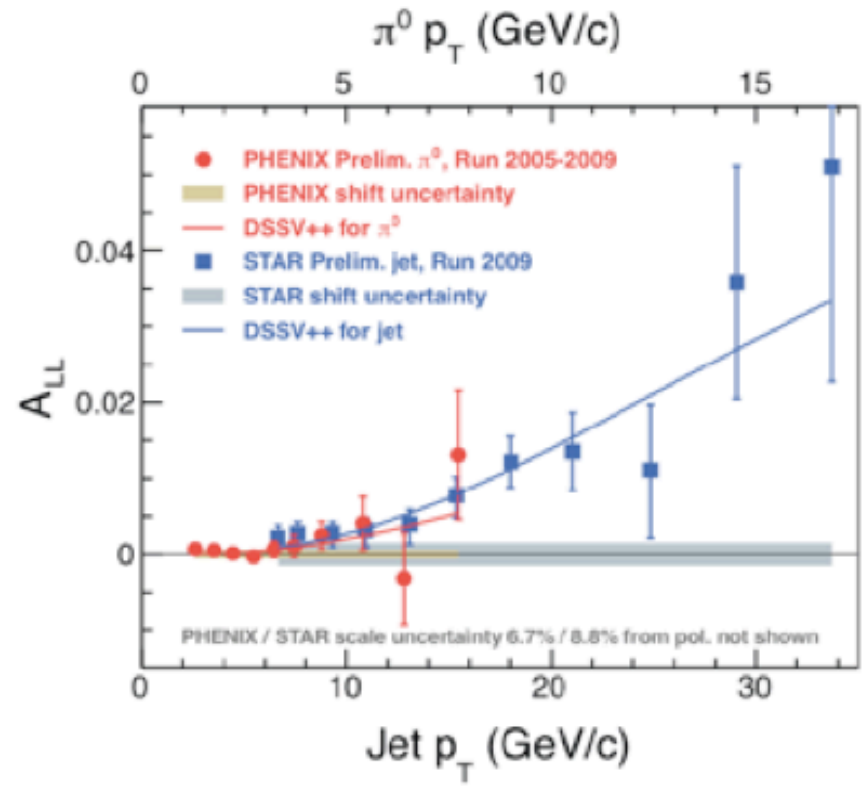


Stratmann's talk

- mid rapidity π^0 and jet data closely related
- π's carry approx. 1/2 of parton's momentum

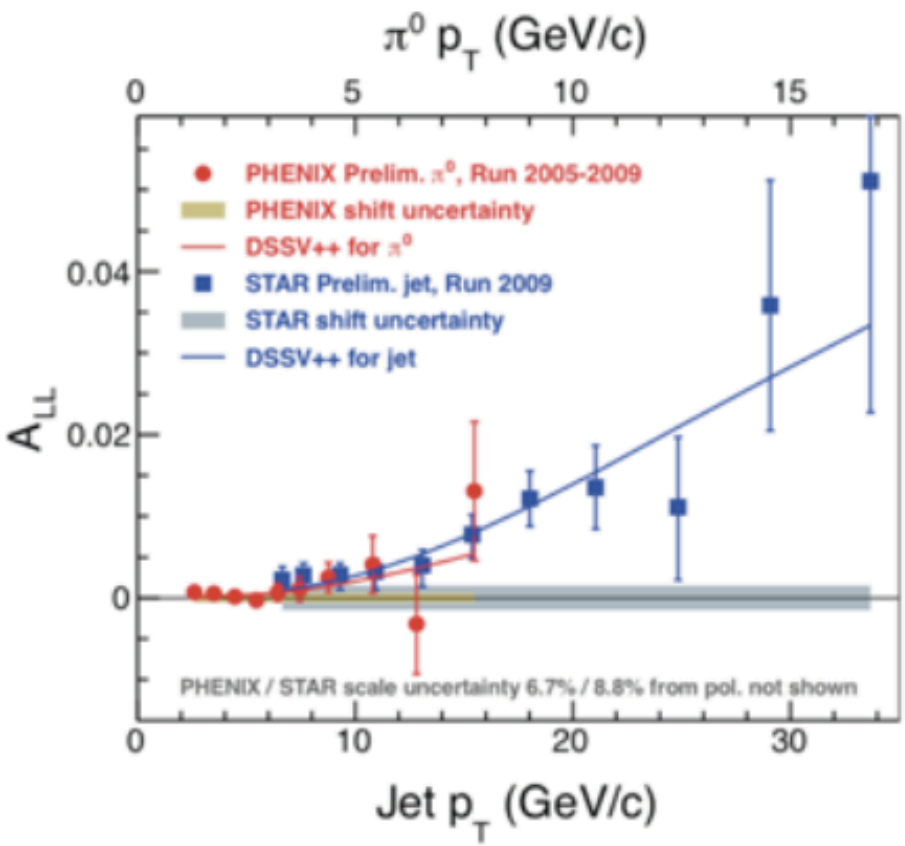
- jet and π^0 data can be put into one plot
- PHENIX probes lower p_T (slightly lower x)



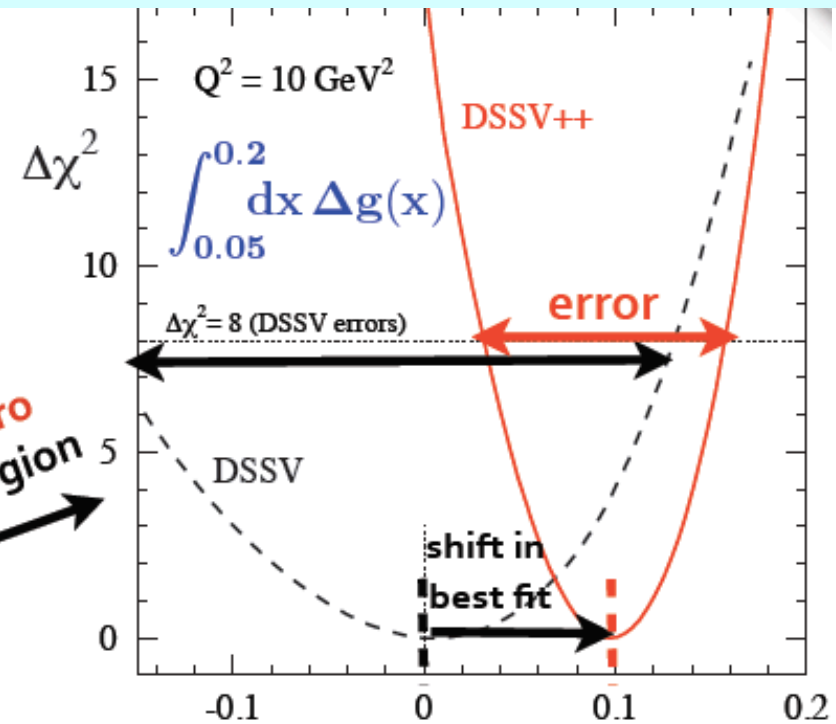


Impact of RHIC measurements

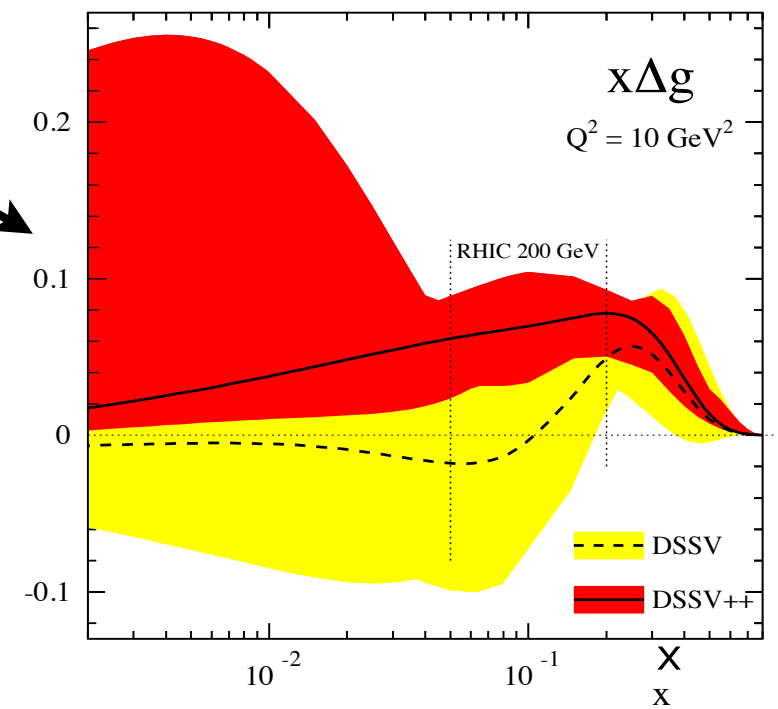
new RHIC data included in DSSV++



lead to non-zero Δg in RHIC x-region



positive Δg in RHIC x-region



$$\int_{0.05}^{0.2} dx\, \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2) = 0.1^{+0.06}_{-0.07}$$

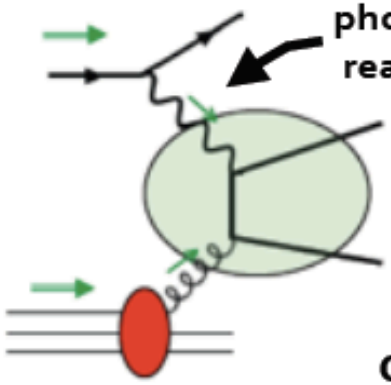
fully compatible with old DSSV error estimate

Stratmann's talk

Role of DIS measurements

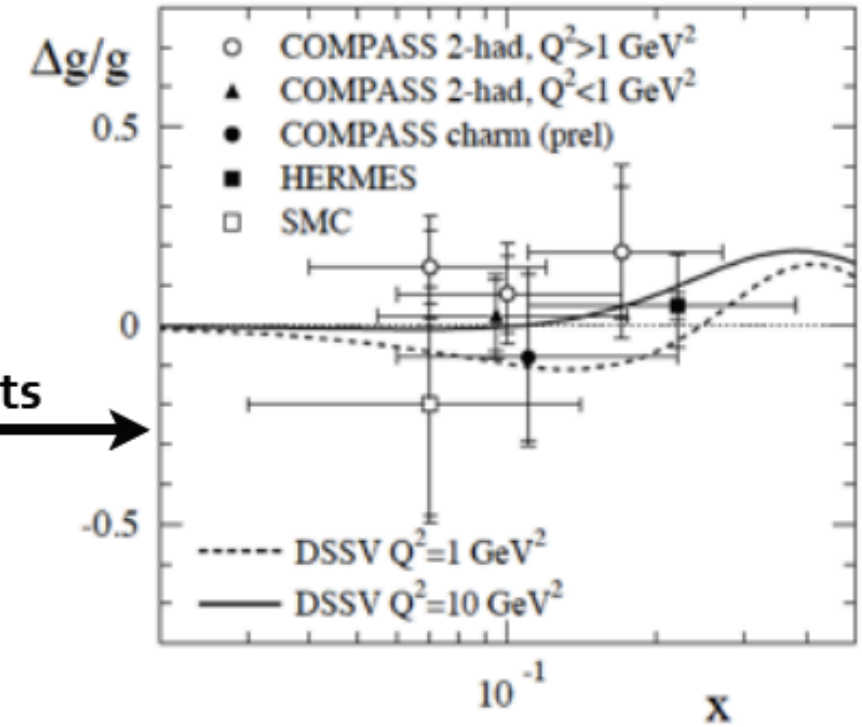
Stratmann's talk

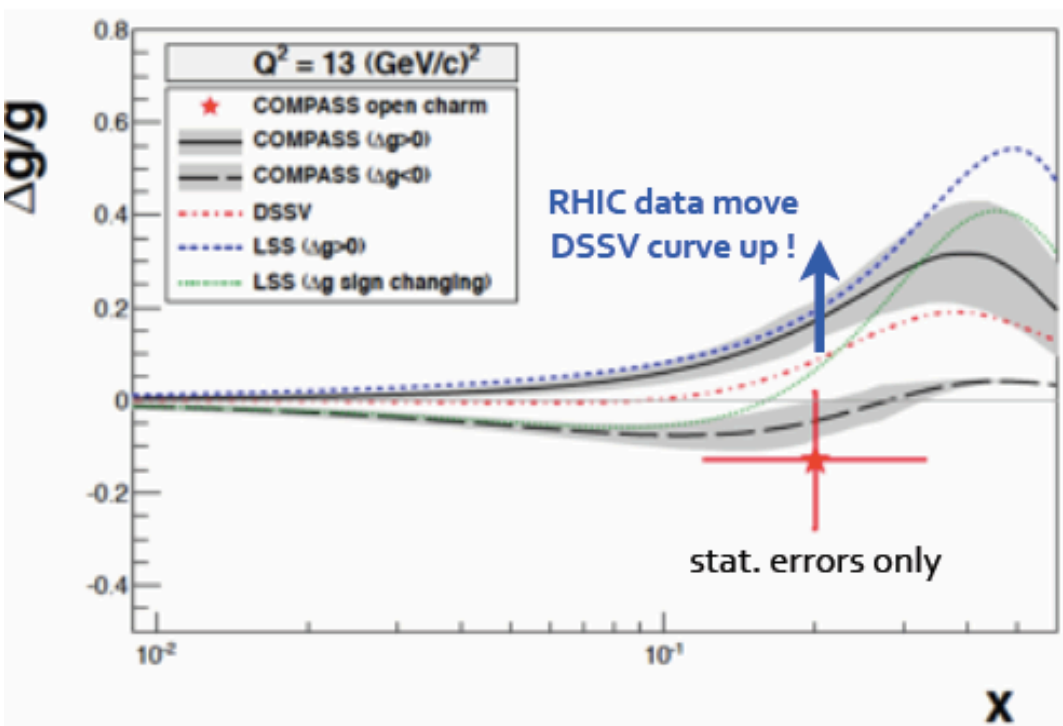
idea: processes with (dominant) contributions from γg-fusion



open charm
hadrons

compilation of existing results





new result

1211.6849

$$\langle \frac{\Delta g}{g} \rangle = -0.13 \pm 0.15 \pm 0.15$$

$$\langle x \rangle = 0.2 \quad \langle \mu^2 \rangle = 13\,\mathrm{GeV}^2$$

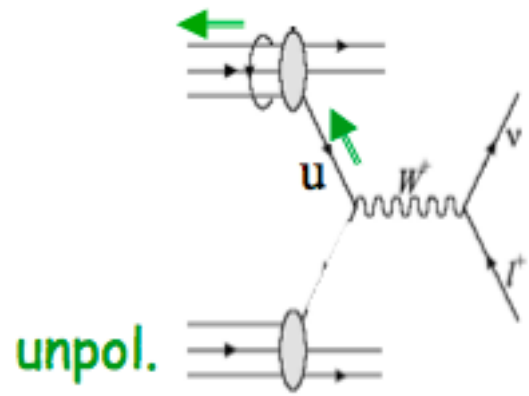
from some "hybrid MC/NLO" extraction

Quark flavor decomposition

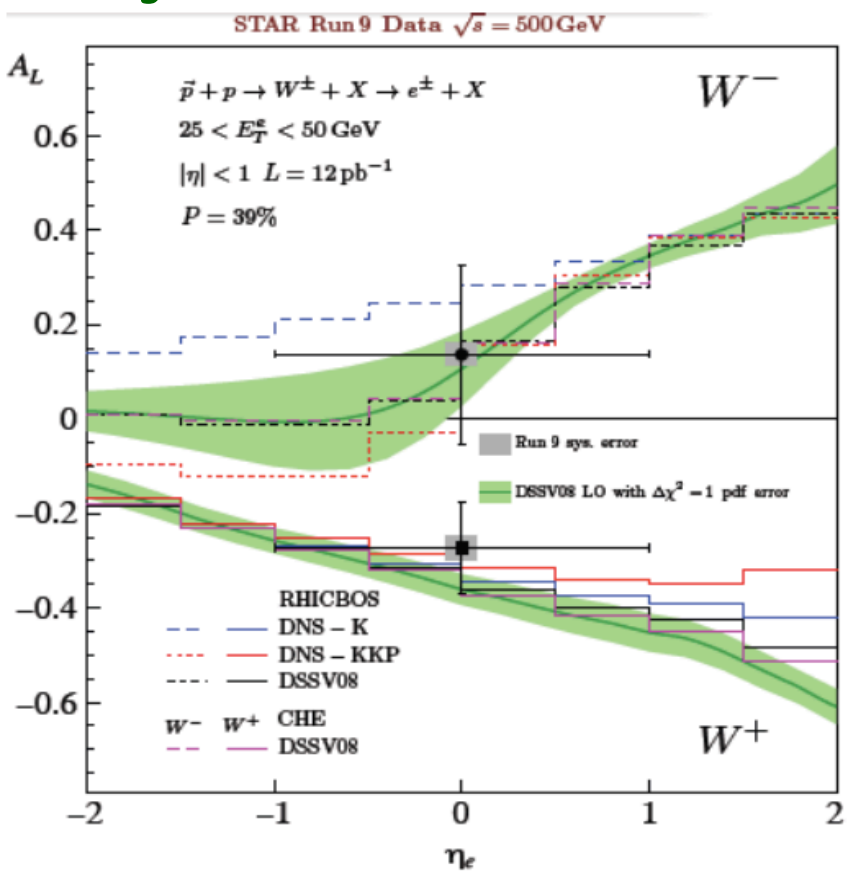
- **Single longitudinal spin asymmetries:**

$$A_L = \frac{[\sigma(+) - \sigma(-)]}{[\sigma(+) + \sigma(-)]} \quad \text{for } \sigma(s)$$

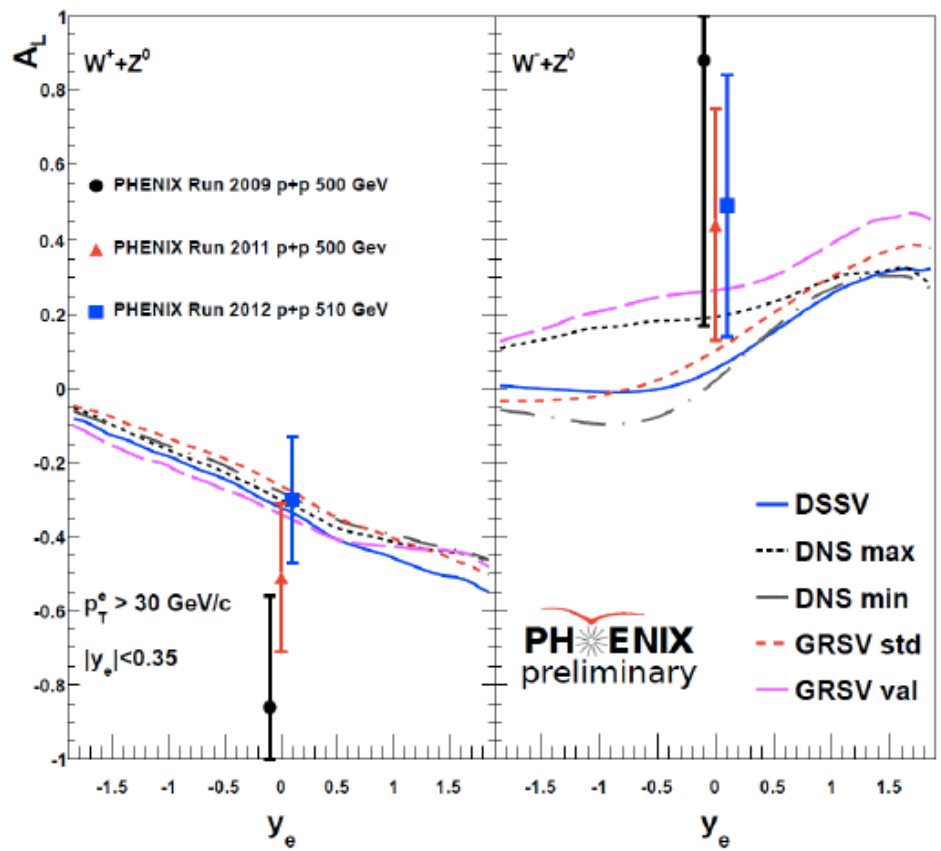
Parity violating weak interaction



- **Early RHIC results:**



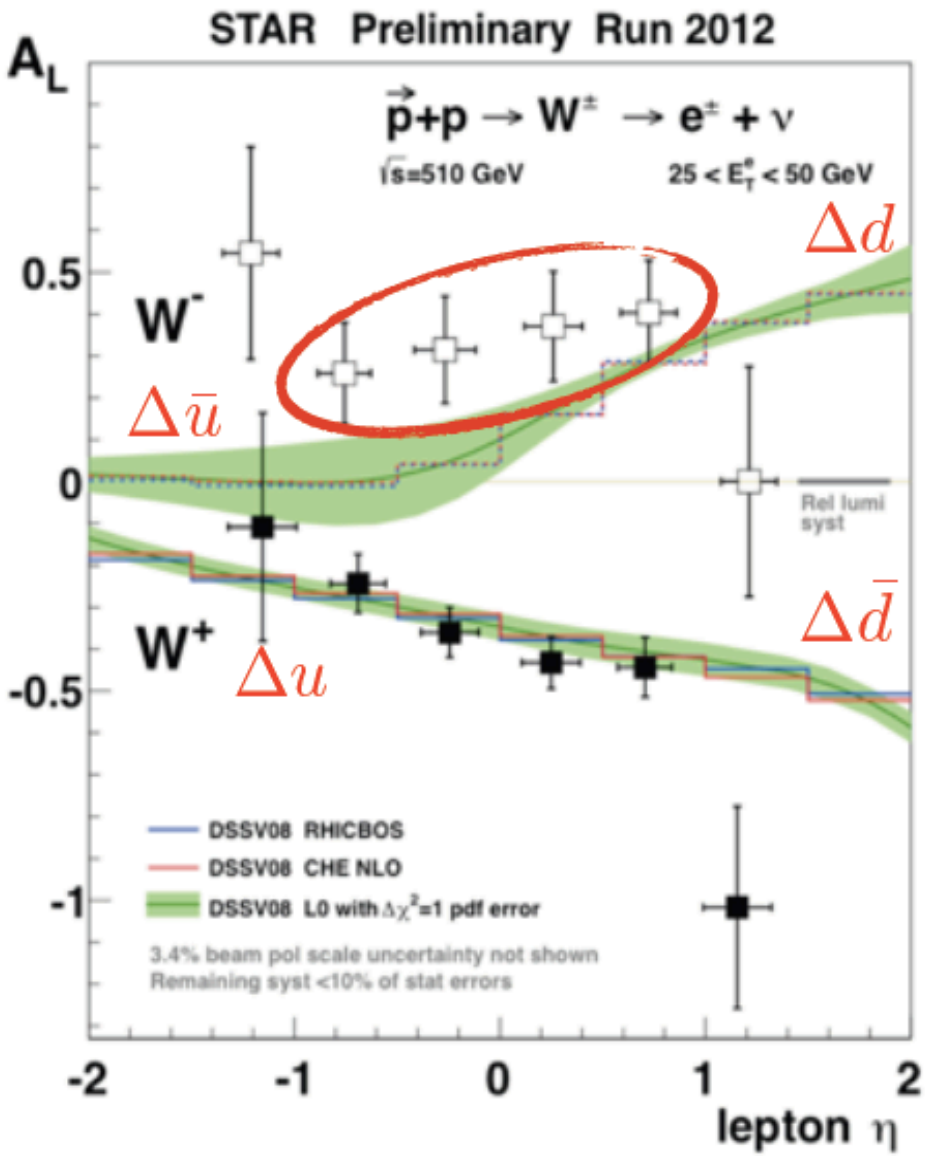
STAR - Xuan Li

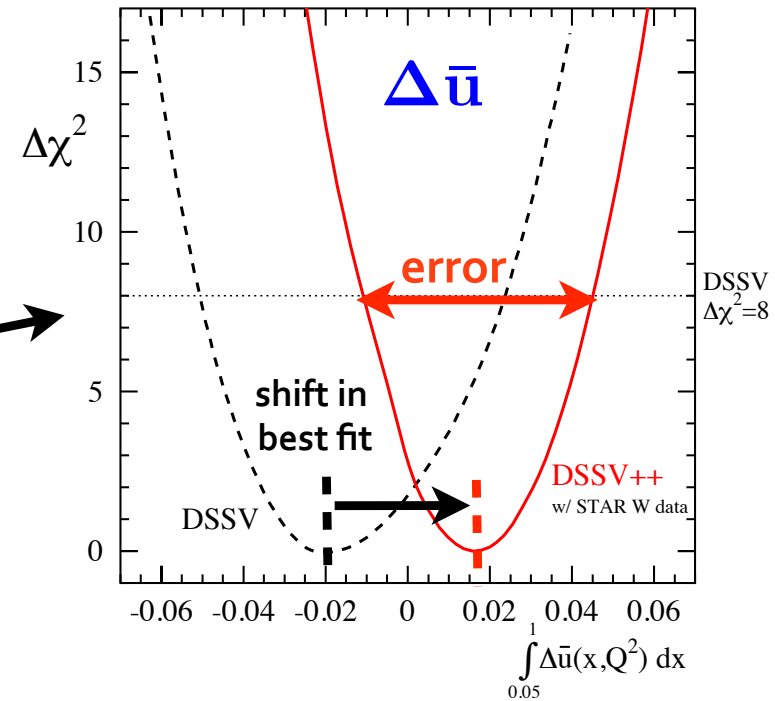


PHENIX - Mikhail Stepanov

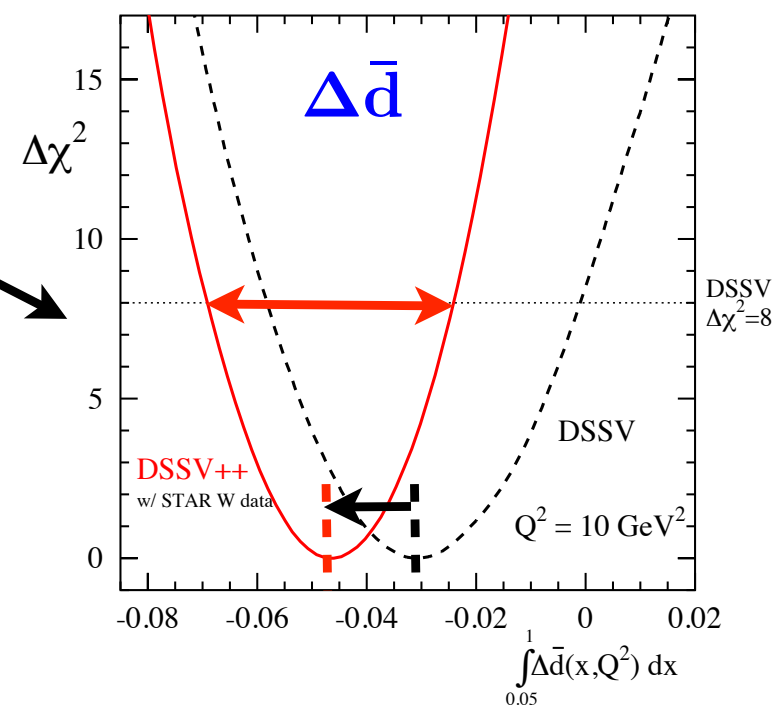
Impact of preliminary 2012 STAR data

Stratmann's talk





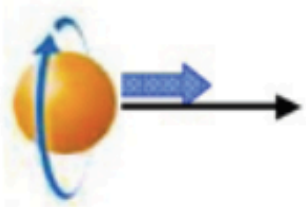
run 12 data already have a significant impact



much more to come from RHIC run-13

✔ DOE milestone for 2013

status of proton spin sum rule



$$\frac{1}{2} = \langle P, \frac{1}{2} | \hat{J}_z | P, \frac{1}{2} \rangle$$

raging controversy in past 2 years
(often semantics)
Jaffe, Manohar; Ji; ....; Chen et al.;
Wakamatsu; Leader; Lorce;
Hatta, Yoshida; Leader; Ji, Xiong, Yuan; ...

in a nutshell

Ji $\quad \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$ gauge invariant

same "number"

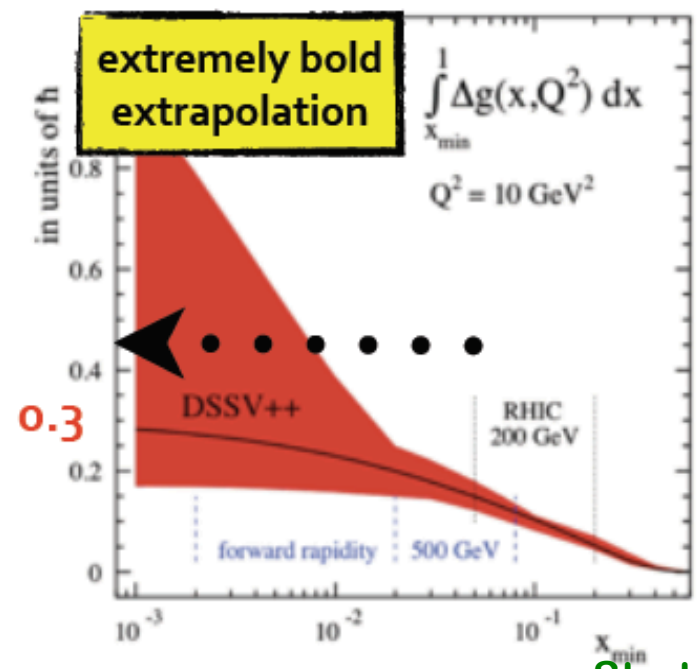
Jaffe Manohar $\quad \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + \mathcal{L}_q + \mathcal{L}_g$ "partonic" A^+=0 gauge

all quantities depend on scale Q & factorization scheme

- ✓ $\Delta\Sigma = \sum_q \int_0^1 dx\, [\Delta q(x) + \Delta\bar{q}(x)]$
- ✓ $J_{q,g}$ <-> GPD's (exclusive processes)
- ✓ $\Delta g = \int_0^1 dx\, \Delta g(x)$
- ✓ ✗ $\mathcal{L}_{q,g}$ <-> twist-3 GPD's
  Ji, Xiong, Yuan

where do we stand on ΔΣ and Δg ?

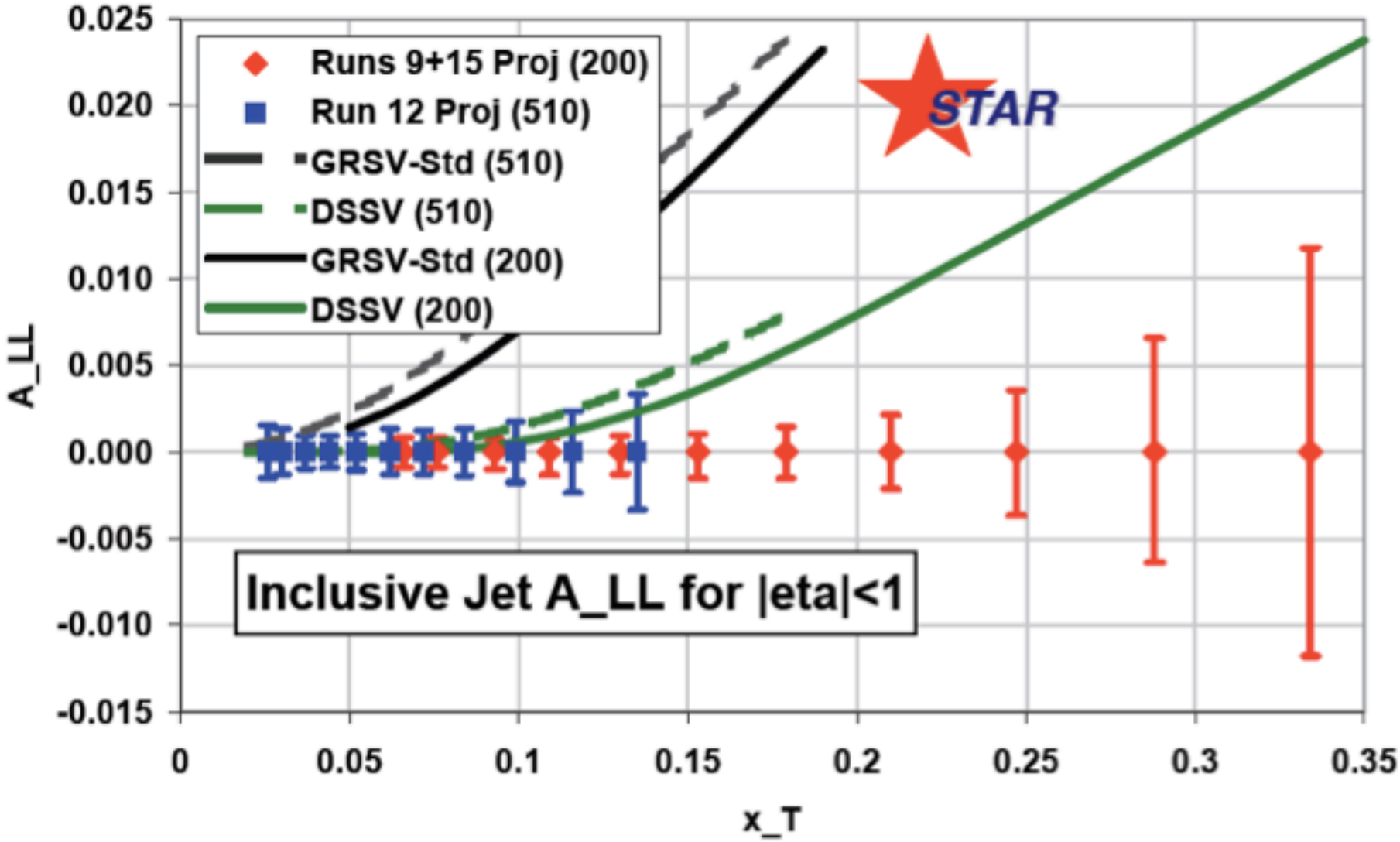
- all fits find $\Delta\Sigma \approx 0.25$
  beware of LARGE small x & 3F-D uncertainties
- Δg is anybody's guess (apart from x=0.05-0.2 region)
- even non-singlet BJ sum has large errors
  $\Delta u + \Delta\bar{u} - (\Delta d + \Delta\bar{d}) = 1.19 \pm 0.22$
  NNPDF



little room for OAM ?

Stratmann's talk

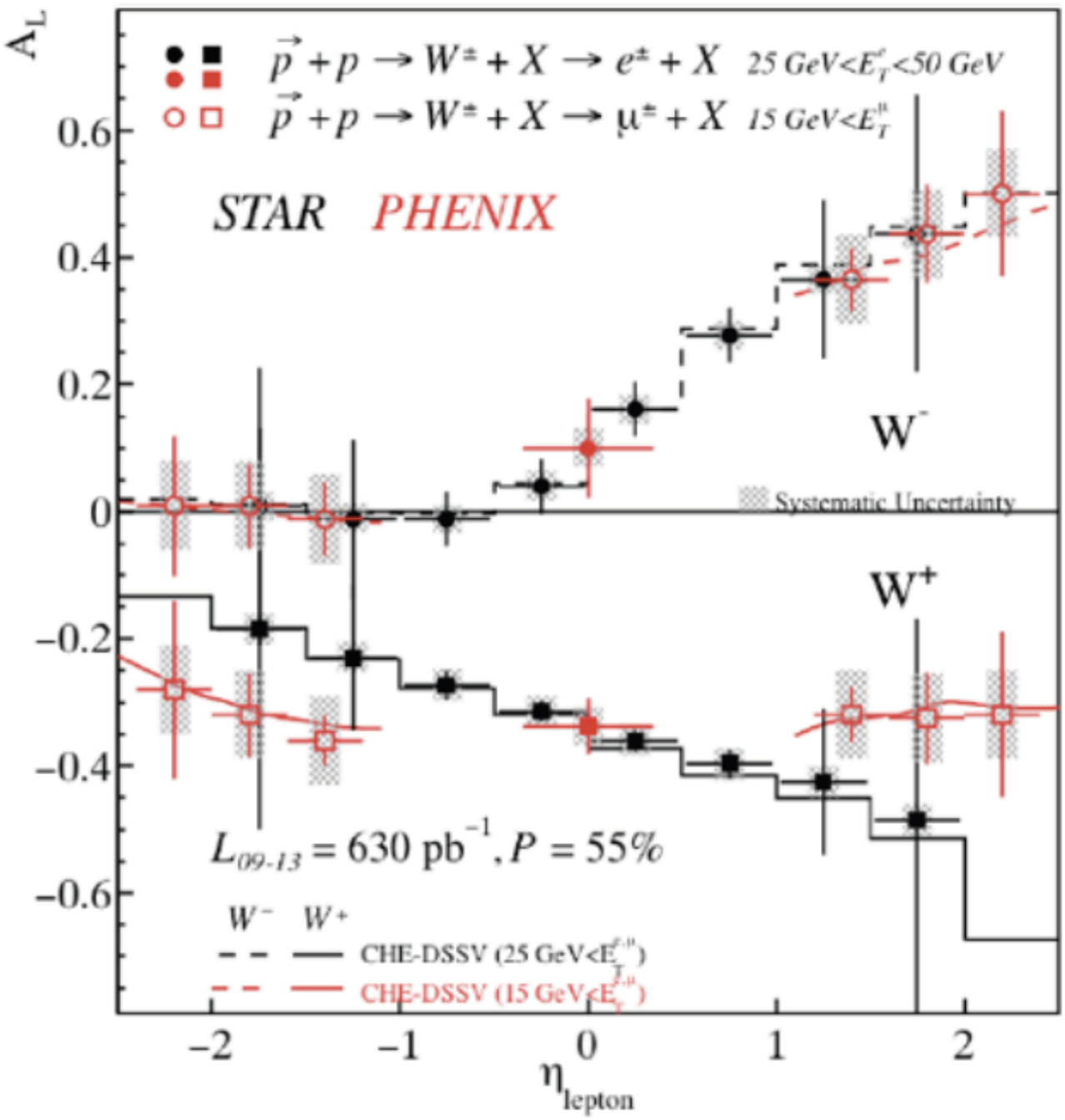
Future RHIC measurements on ΔG



- ✧ Expect to reduce ΔG uncertainty by a factor of 2 by end of run-15
- ✧ Expect to expand the x-coverage from mid rapidity jet data to [0.01-0.2]

Talks by Li, Stratmann

Expectation from 2013 data on A_L

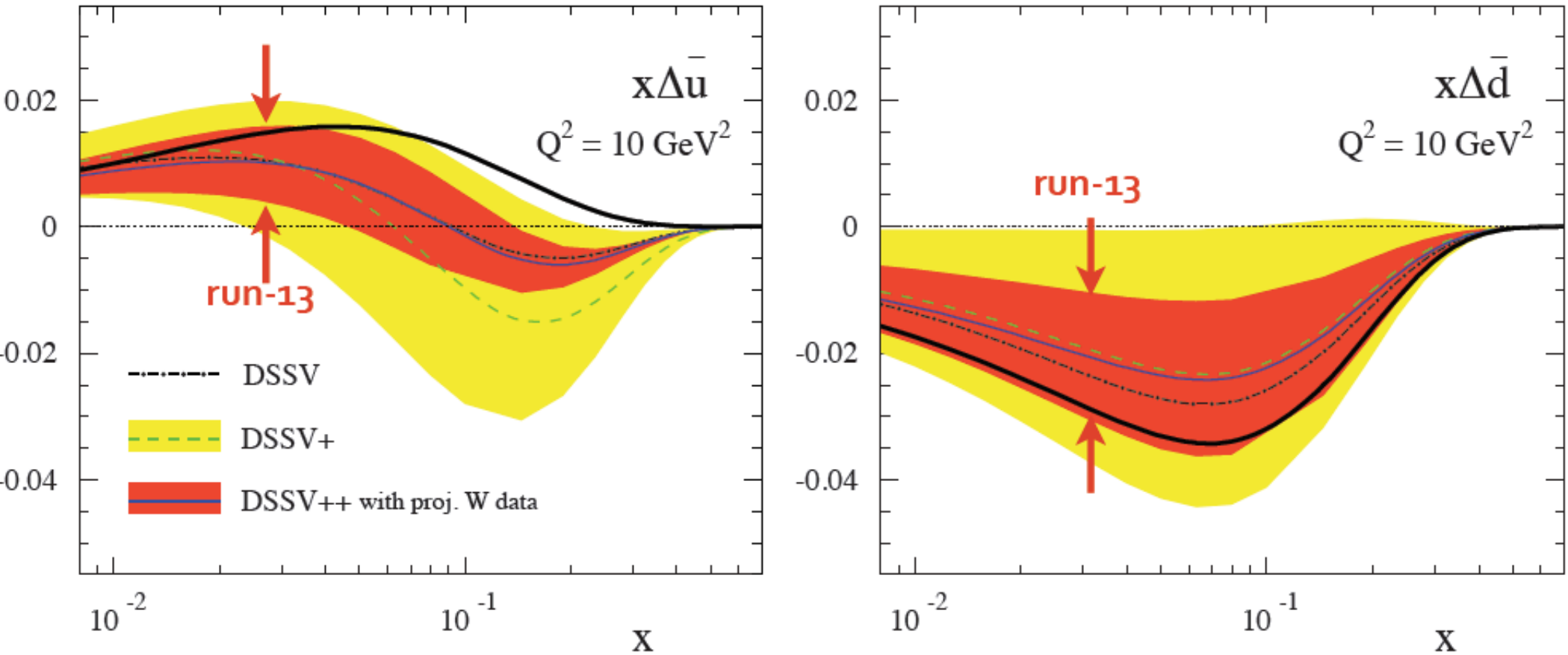


+ other observables

Potential impact from 2013 data

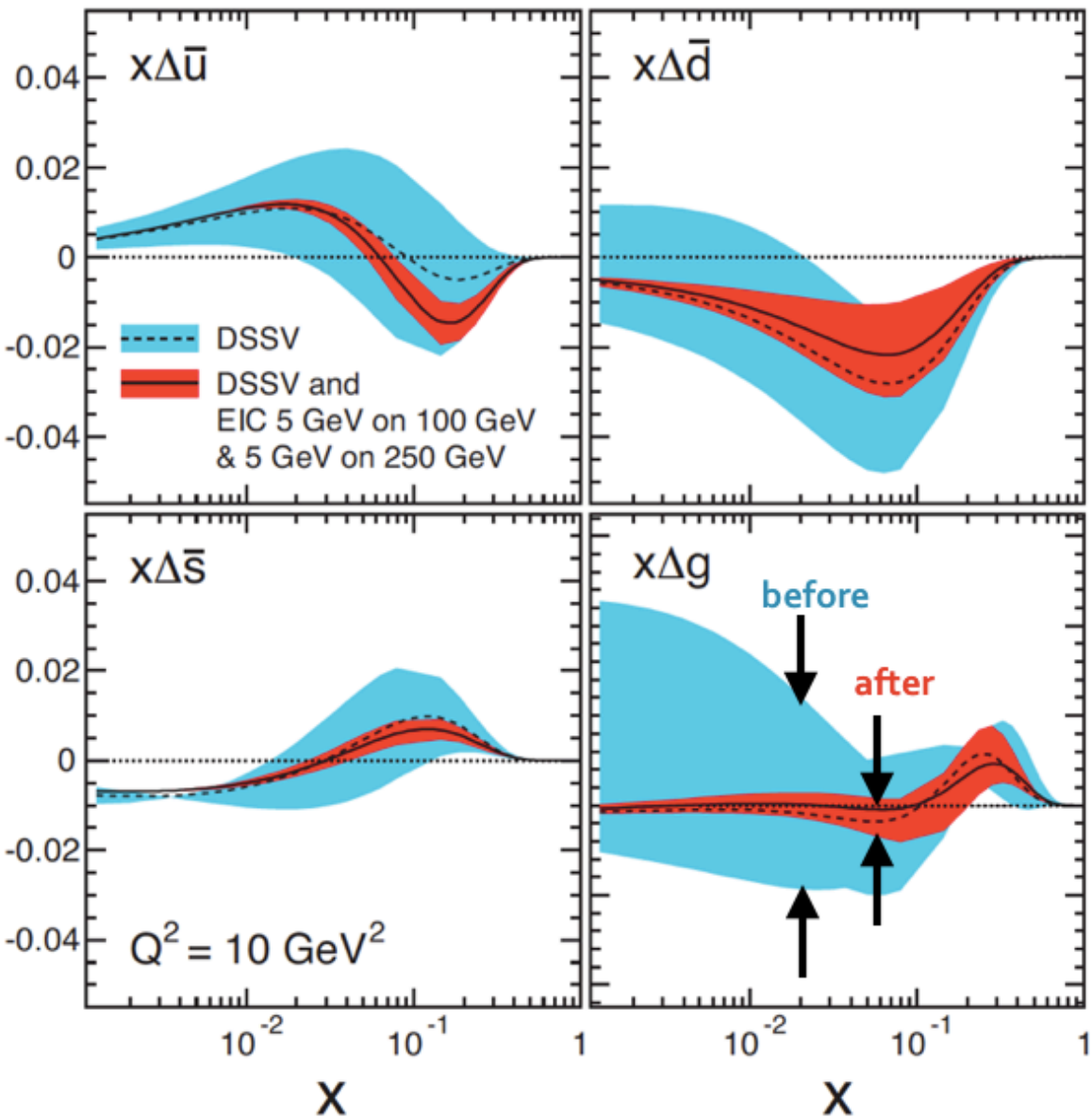
Stratmann's talk

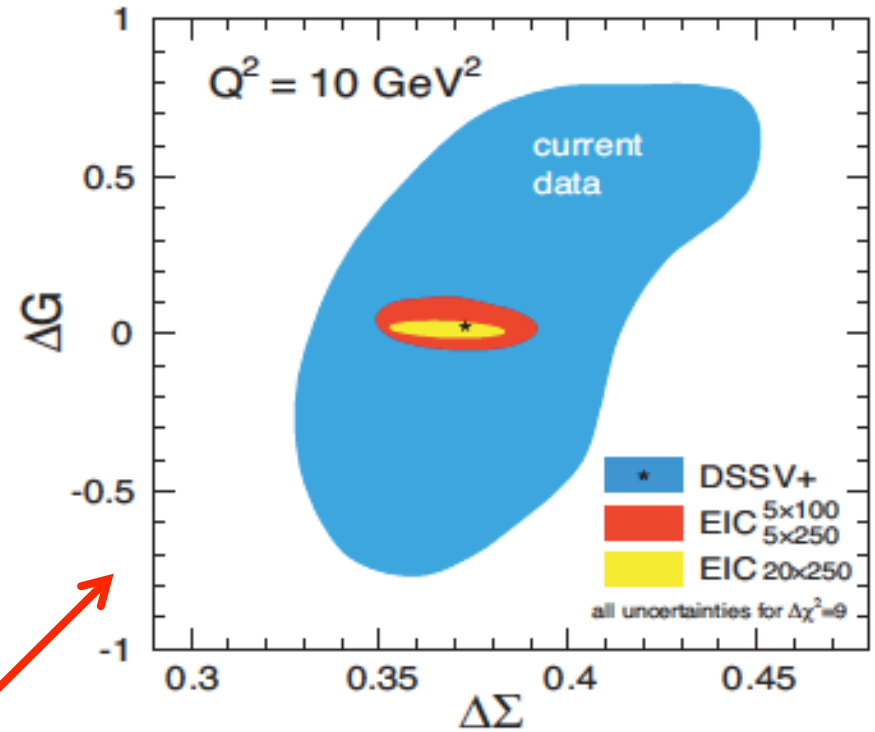
preliminary study!



compatibility with SIDIS data can be tested

Future on proton spin - eRHIC

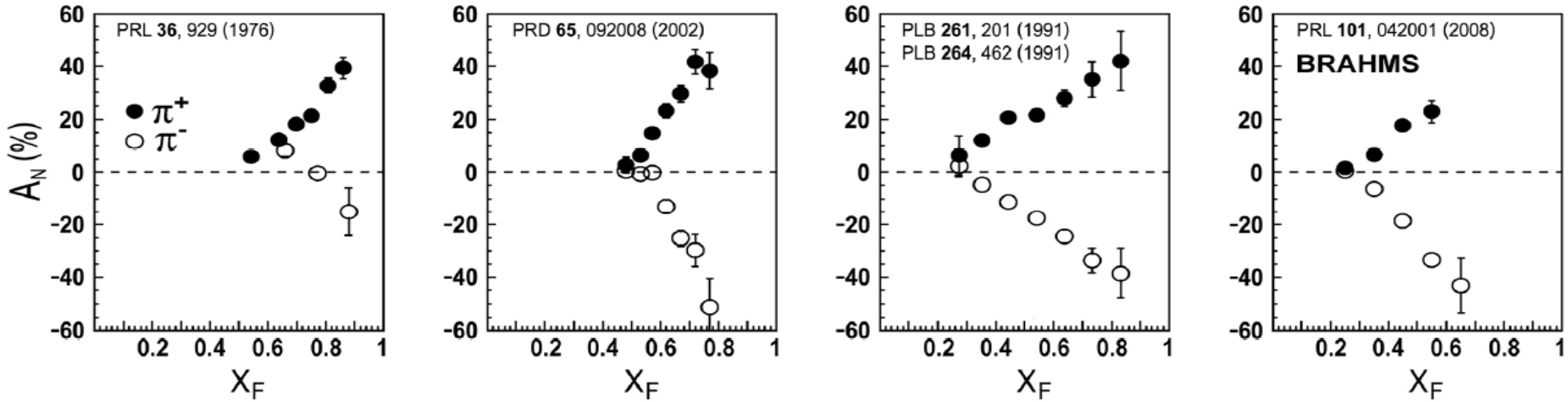




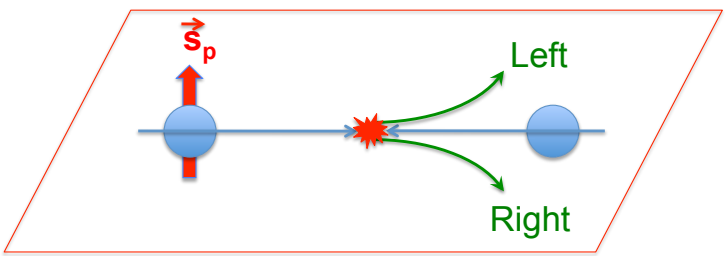
Transverse single-spin asymmetry (SSA)

- **Consistently observed for over 35 years!**

ANL – 4.9 GeV | BNL – 6.6 GeV | FNAL – 20 GeV | BNL – 62.4 GeV



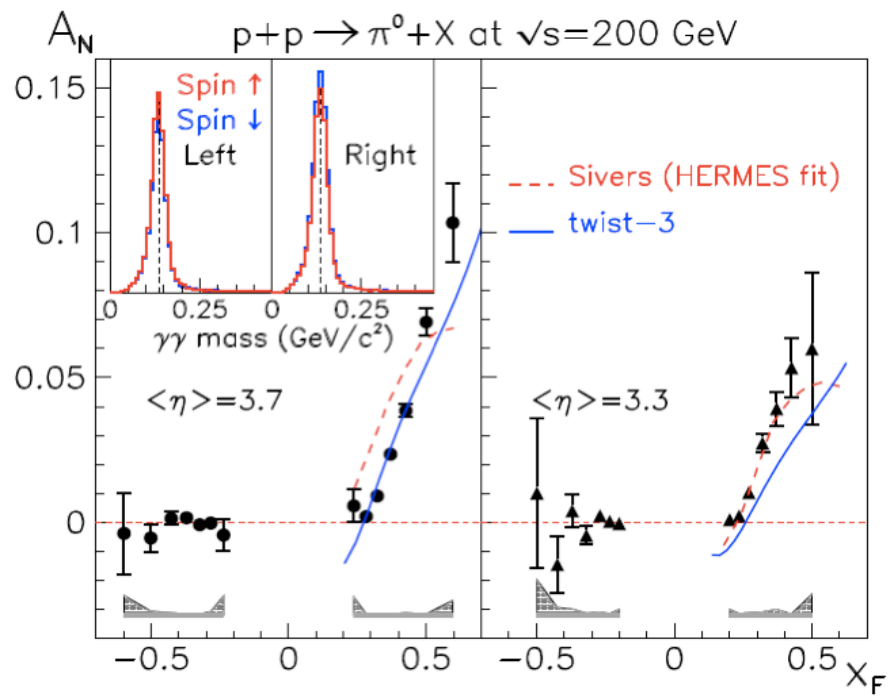
- **Definition:**



$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s}) - \sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s}) + \sigma(\ell,-\vec{s})}$$

Do we understand this?

BNL – 200 GeV

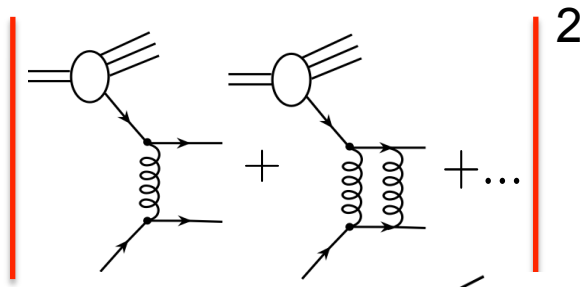


Do we understand it?

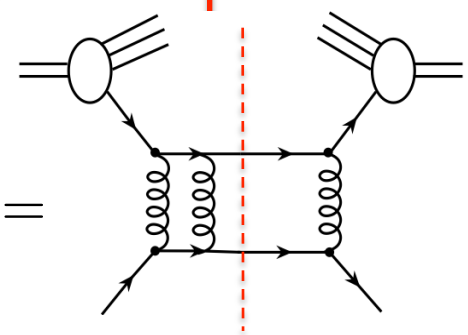
Kane, Pumplin, Repko, PRL, 1978

❑ Early attempt:

Cross section: $\sigma_{AB}(p_T, \vec{s}) \propto$



Asymmetry: $\sigma_{AB}(p_T, \vec{s}) - \sigma_{AB}(p_T, -\vec{s}) =$



$\propto \alpha_s \dfrac{m_q}{p_T}$

Too small to explain available data!

❑ What do we need?

$$A_N \propto i\vec{s}_p \cdot (\vec{p}_h \times \vec{p}_T) \Rightarrow i\epsilon^{\mu\nu\alpha\beta} p_{h\mu} s_\nu p_\alpha p'_{h\beta}$$

Need a phase, a spin flip, enough vectors

❑ Vanish without parton's transverse motion:

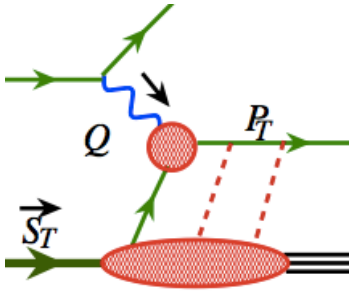
➡ **A direct probe for parton's transverse motion,**

Spin-orbital correlation, QCD quantum interference

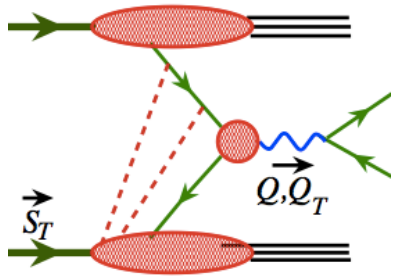
Current understanding of SSAs

Talks by Liu, Drachenberg, …

- Two scales observables – $Q_1 >> Q_2 \sim \Lambda_{QCD}$:



SIDIS: $Q >> P_T$

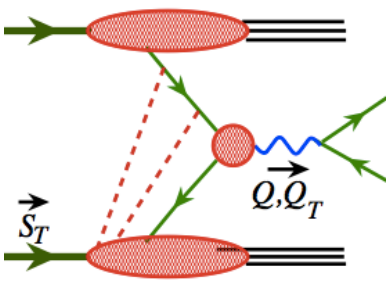


DY: $Q >> Q_T$

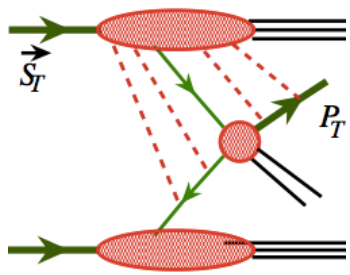
→ **TMD factorization**
TMD distributions

Direct information on parton k_T

- One scale observables – $Q >> \Lambda_{QCD}$:



DY: $Q \sim Q_T$

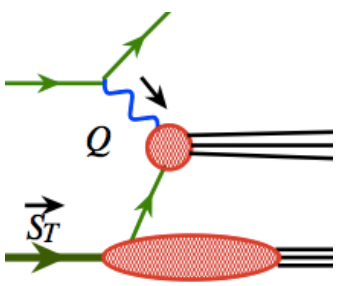


Jet, Particle: P_T

→ **Collinear factorization**
Twist-3 distributions

Information on moments of parton k_T

- Symmetry plays important role:



Inclusive DIS
Single scale
Q

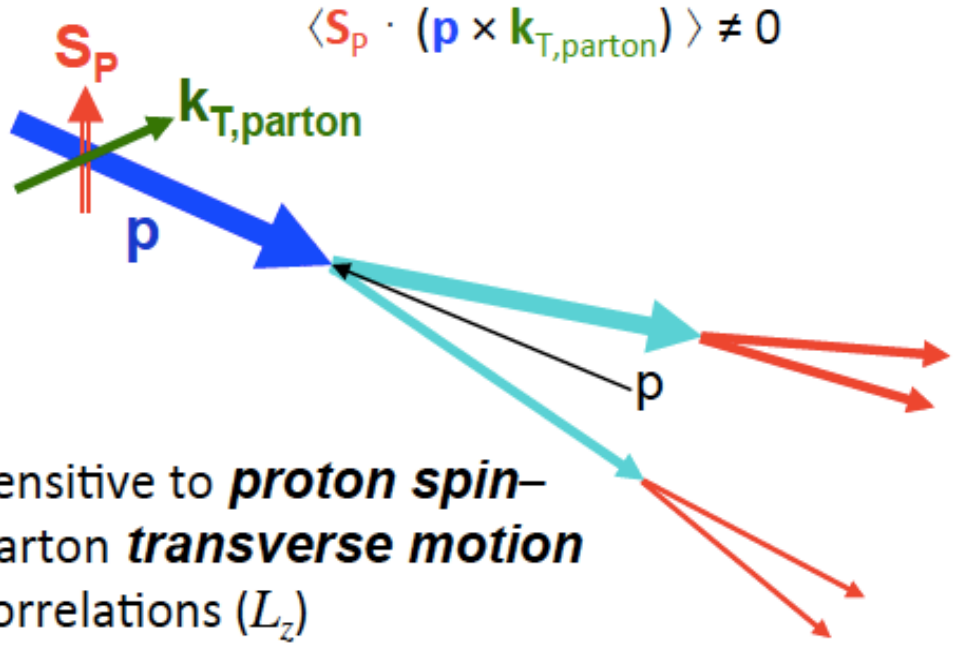
Parity
Time-reversal

→ $A_N = 0$

Transverse motion and TMDs

Sivers mechanism: asymmetry in the forward jet or γ *production*

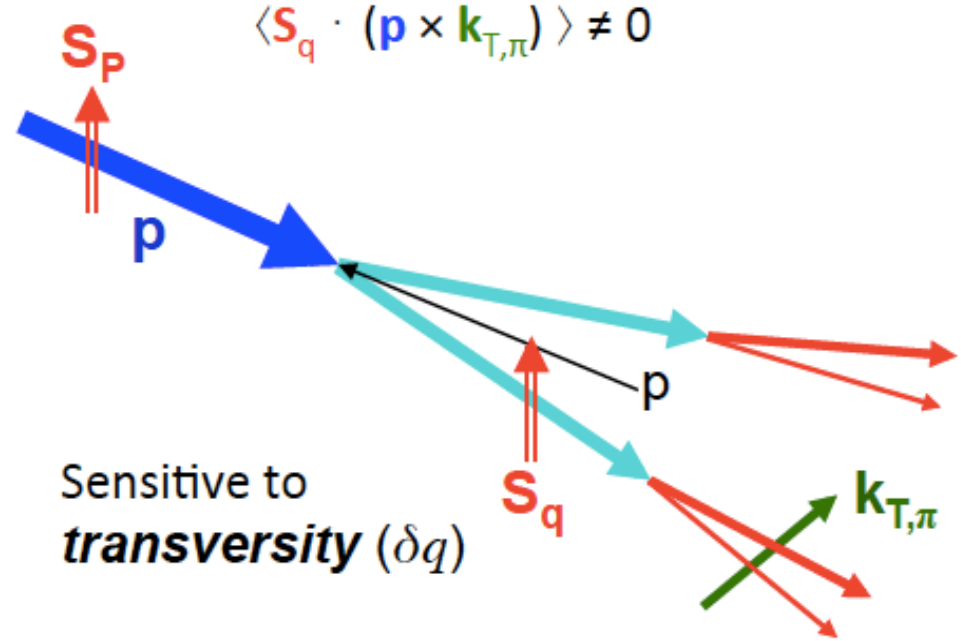
$\langle S_P \cdot (p \times k_{T,parton}) \rangle \neq 0$



Sensitive to ***proton spin***–parton ***transverse motion*** correlations (L_z)

Collins mechanism: asymmetry in the forward jet *fragmentation*

$\langle S_q \cdot (p \times k_{T,\pi}) \rangle \neq 0$



Sensitive to ***transversity*** (δq)

Inclusive hadrons:

Observed transverse single-spin asymmetries could arise from the **Sivers effect** or **Collins effect**, or from a **linear combination of the two**

Sivers or Collins ~ $\sin(\phi_S)$

ϕ_S—*angle between spin and event plane*

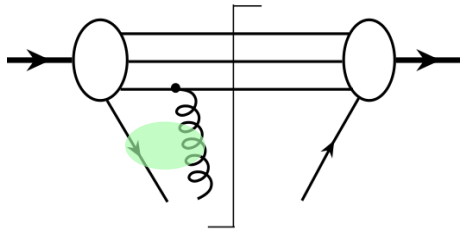
STAR – Drachenberg's talk

Twist-3 correlation functions

- **Twist-3 polarized correlation functions:**

Efremov, Teryaev, 1982, …
Qiu, Sterman, 1991, …

$T^{(3)}(x, x, S_\perp) \propto$

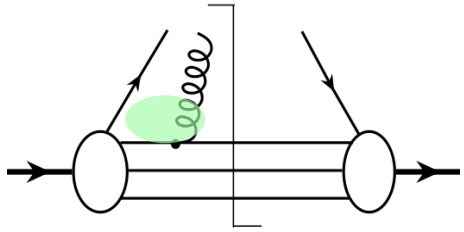


Moment of Sivers function

- **Twist-3 unpolarized correlation functions:**

Kanazawa, Koike 2000, …

$T^{(3\sigma)}(x', x') \propto$

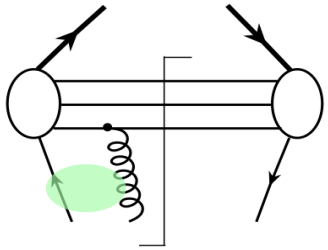


Moment of Boer-Mulders function

- **Twist-3 fragmentation functions:**

Kang, Yuan, Zhou, 2010

$D^{(3)}(z, z) \propto$



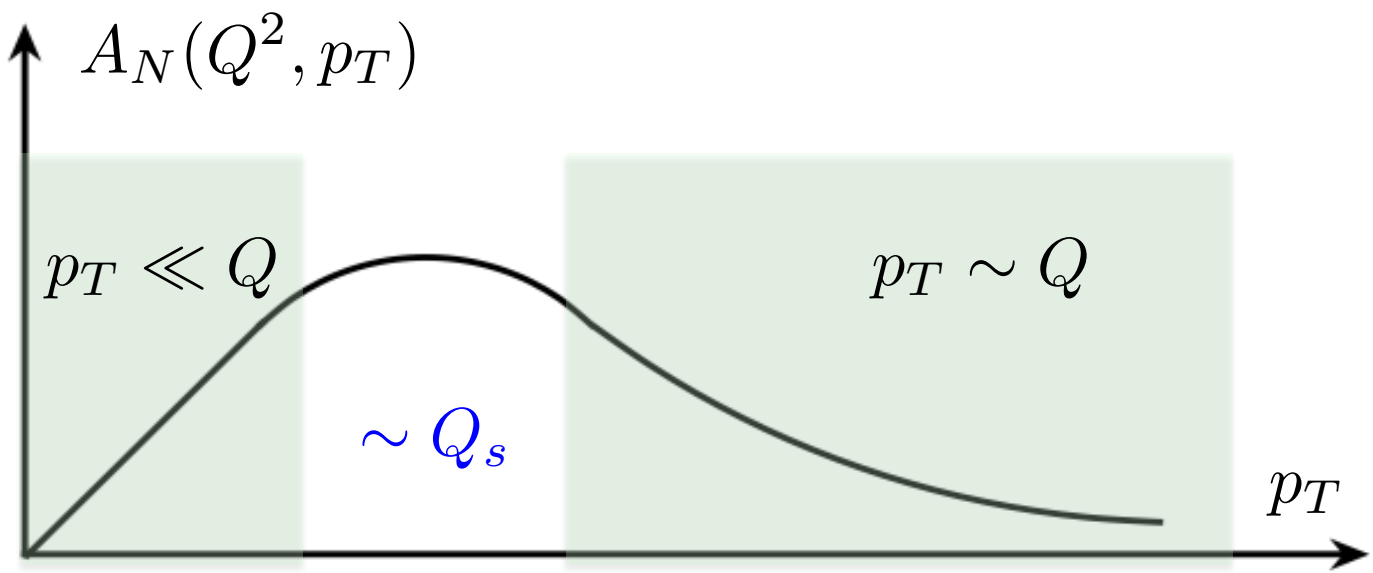
Moment of Collins function?

All these correlation functions have No probability interpretation!

Quantum interference between a single and a composite state

Transition from low p_T to high p_T

- Two-scale becomes one-scale:



TMD Collinear Factorization

- TMD factorization to collinear factorization:

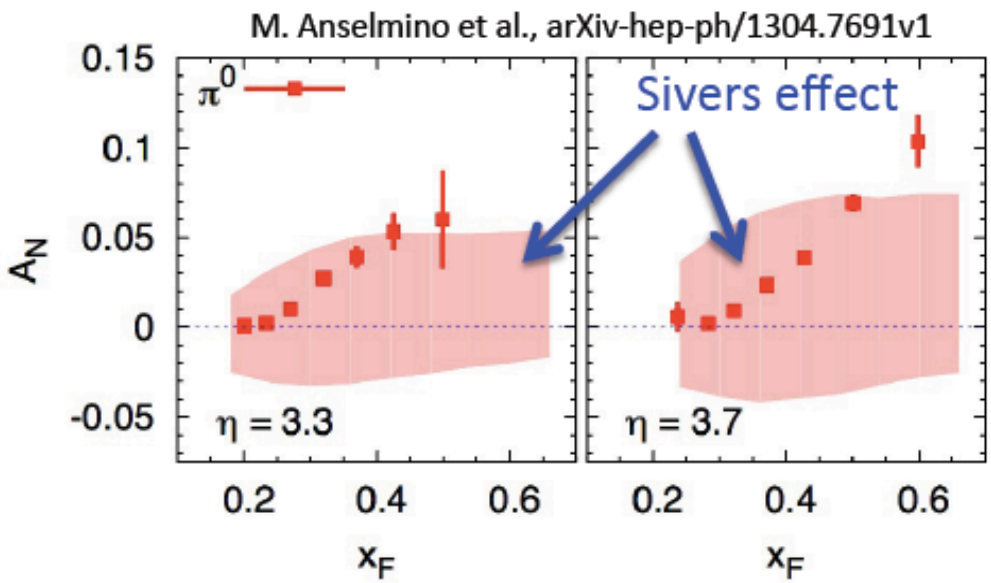
Ji,Qiu,Vogelsang,Yuan,
Koike, Vogelsang, Yuan

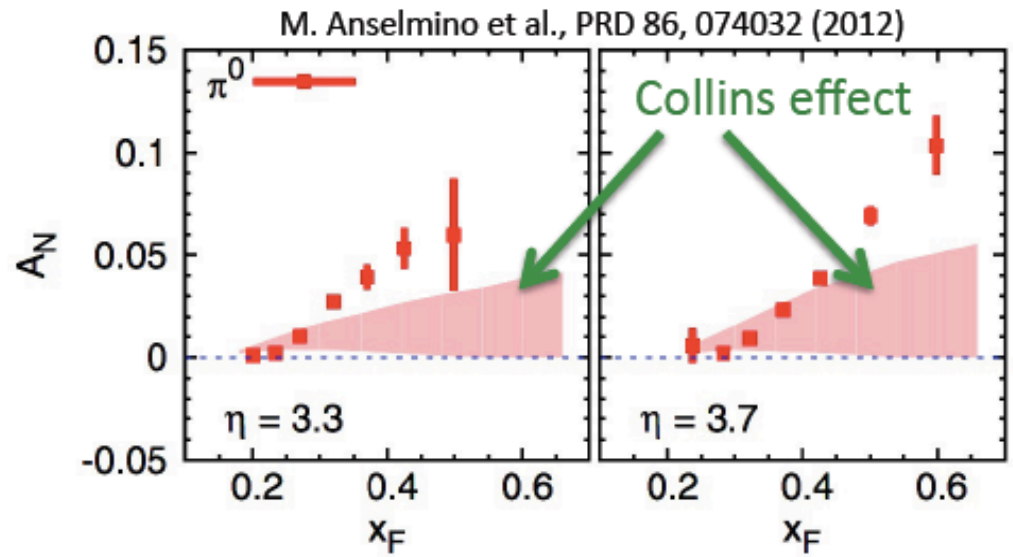
Two factorization are consistent in the overlap region: $\Lambda_{\rm QCD} \ll p_T \ll Q$

A_N finite – requires correlation of multiple collinear partons

New opportunities!

STAR Transverse Asymmetries at Forward Pseudorapidity





STAR data from PRL 101, 222001 (2008)

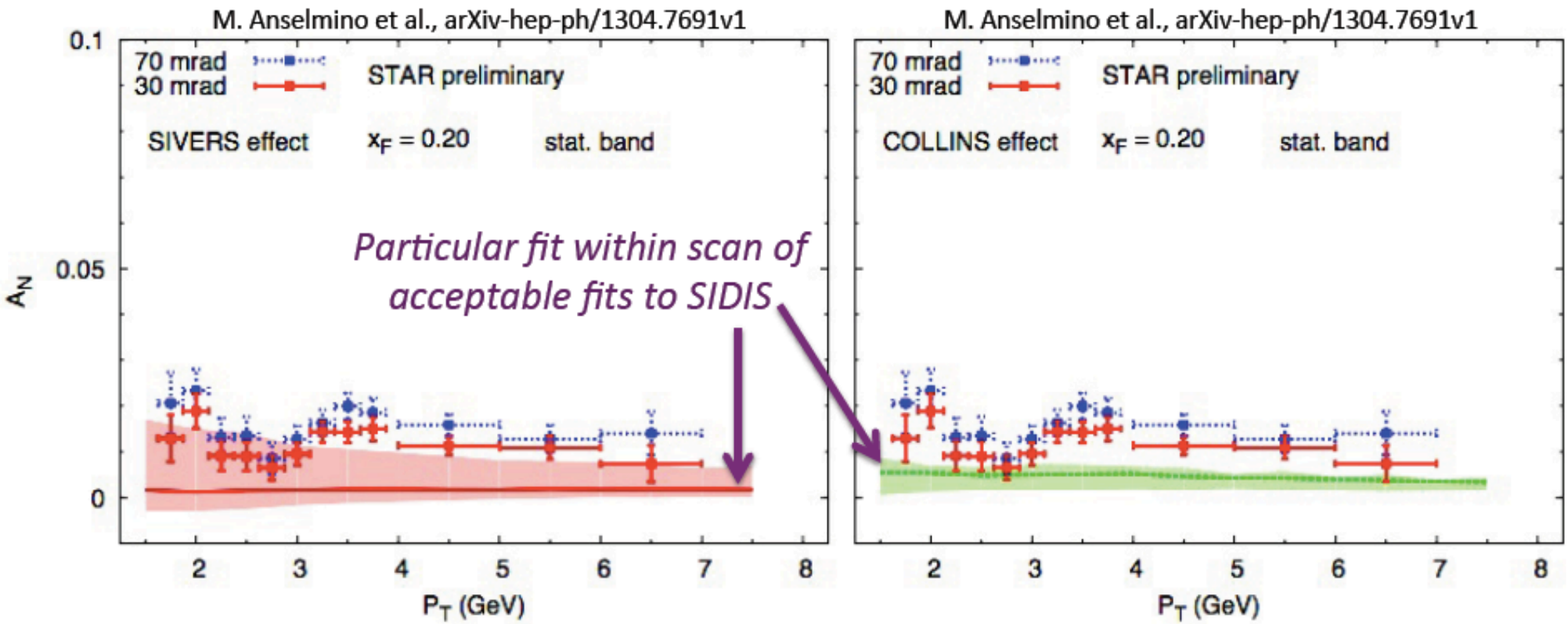
Current models based on fits to SIDIS and e^+e^-:

- *"The Collins effect…is not sufficient for the medium-large x_F range of STAR data, $x_F \gtrsim 0.3$"*
- *"The Sivers effect alone might in principle be able to explain…almost the full amount of STAR π^0 data on A_N"*

Theoretical questions remain about applicability to p+p data of Sivers extractions from SIDIS

(*e.g. Kang et al., PRD 83, 094001 (2011)*)

STAR Transverse Asymmetries at Forward Pseudorapidity



Recent models based on SIDIS fits suggest flat p_T-dependence for **Sivers effect** out to $p_T \sim 7$ GeV/c but at ***lower magnitude than data***

Similar behavior for **Collins effect** in some parameterizations

→ ***possible hint of Collins+Sivers effect?***

Twist-3 models also see flat p_T dependence out to $p_T \sim 15$ GeV/c

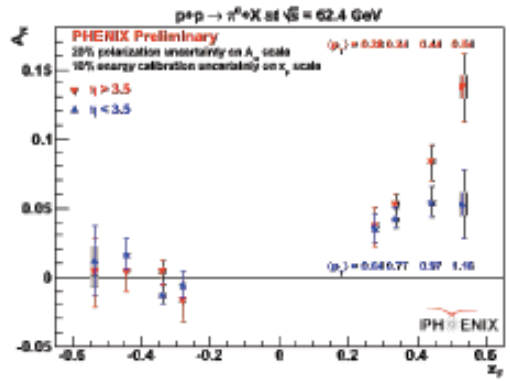
[*e.g. Kanazawa and Koike, PRD 83, 114024 (2011)*]

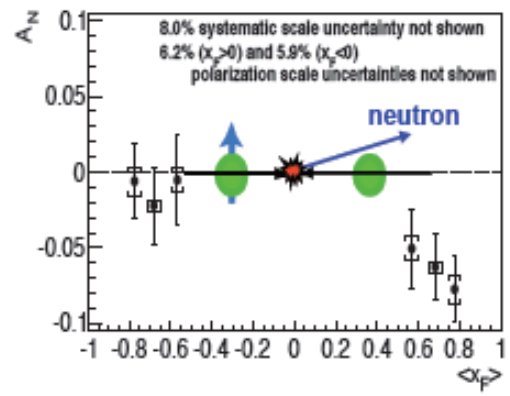
Future transverse spin @ STAR

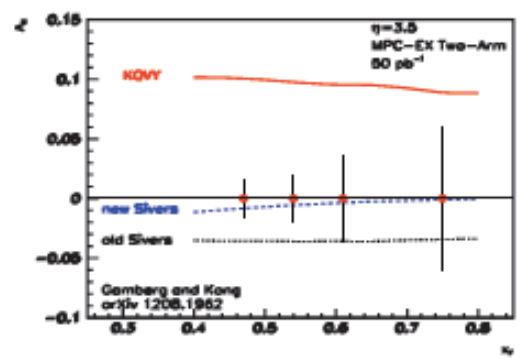
- STAR investigation of large transverse asymmetries at forward-η:
  - Persistence of sizable asymmetries at forward pseudorapidity to $p_T \sim 10$ GeV/c
  - Precise investigation of A_N dependence of on event topology
    → ***asymmetries in jet-like π^0 are smaller than asymmetries in isolated π^0***
  - Investigation of forward calorimeter jets at $\sqrt{s} = 500$ GeV underway
  - Measurement of π^0 A_N for the first time at intermediate pseudorapidity ($1 < \eta < 2$)
- STAR investigation of transverse spin effects at central-η:
  - Hints of transversity in inclusive jet and di-hadron asymmetries
  - Investigation of transverse single-spin asymmetries for the first time in inclusive jets at central pseudorapidity and $\sqrt{s} = 500$ GeV
  - Extension of existing Collins and IFF analyses to higher statistical precision and reduced systematics (Run-12)
- Future endeavors include direct photons at forward-η and investigation of transverse-spin phenomena in p+Au collisions

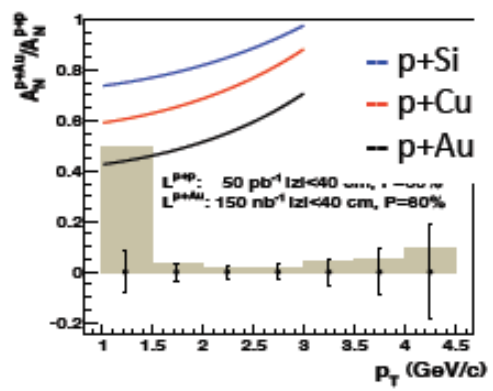
Future transverse spin @ PHENIX

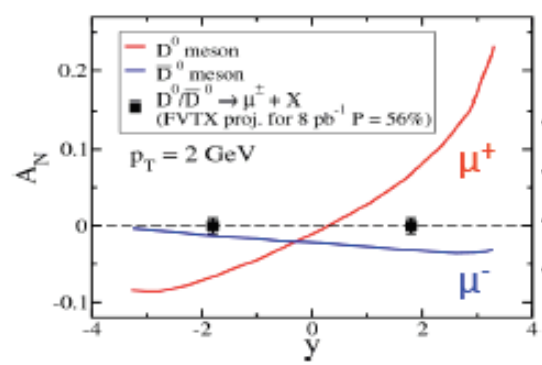
- Significant TSSA observed in the forward rapidity
  - Pion and eta via MPC
  - Leading neutrons in ZDC
- Expect much improved measurements w/ forward MPC-EX
  - larger pT, xF coverage; dir-photon
  - Quarks' Sivers and Collins effects
- Forward muons with FVTX
  - Gluon Sivers
  - Charm vs anti-Charm & tri-gluon
  - Drell-Yan to test QCD
- Forward s/ePHENIX
  - New spin program

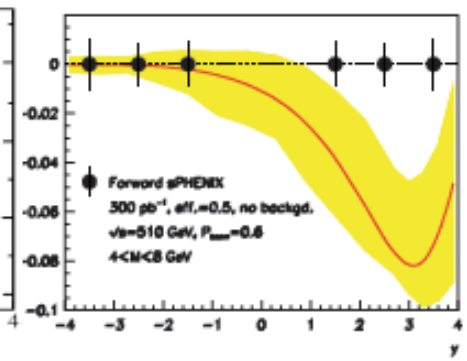










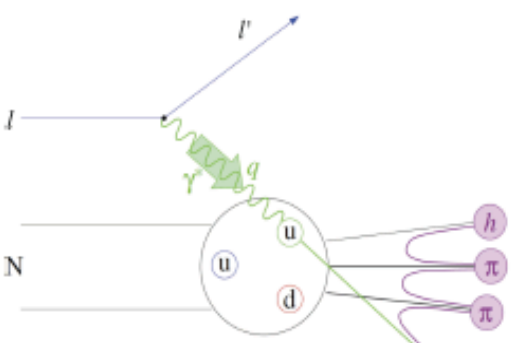


Future Forward Dimuon Drell-Yan A_N Study

fundamentally important test of QCD factorization and gauge-link

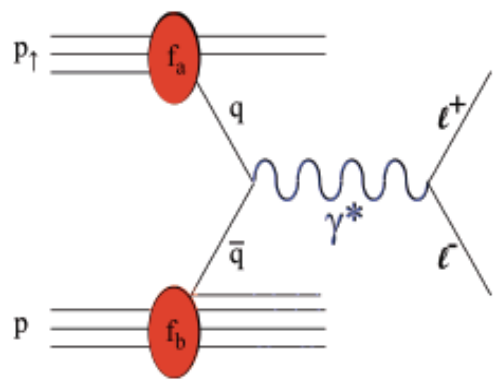
- Drell-Yan A_N accesses quark Sivers effect ($f_{1T}^{\perp}$) in proton
- $f_{1T}^{\perp}$ expected to reverse in sign from SIDIS to DY meas.

$$f_{1T}^{\perp q}\,|_{SIDIS} = -f_{1T}^{\perp q}\,|_{DY}$$



$ep^{\uparrow} \to e'\pi X$

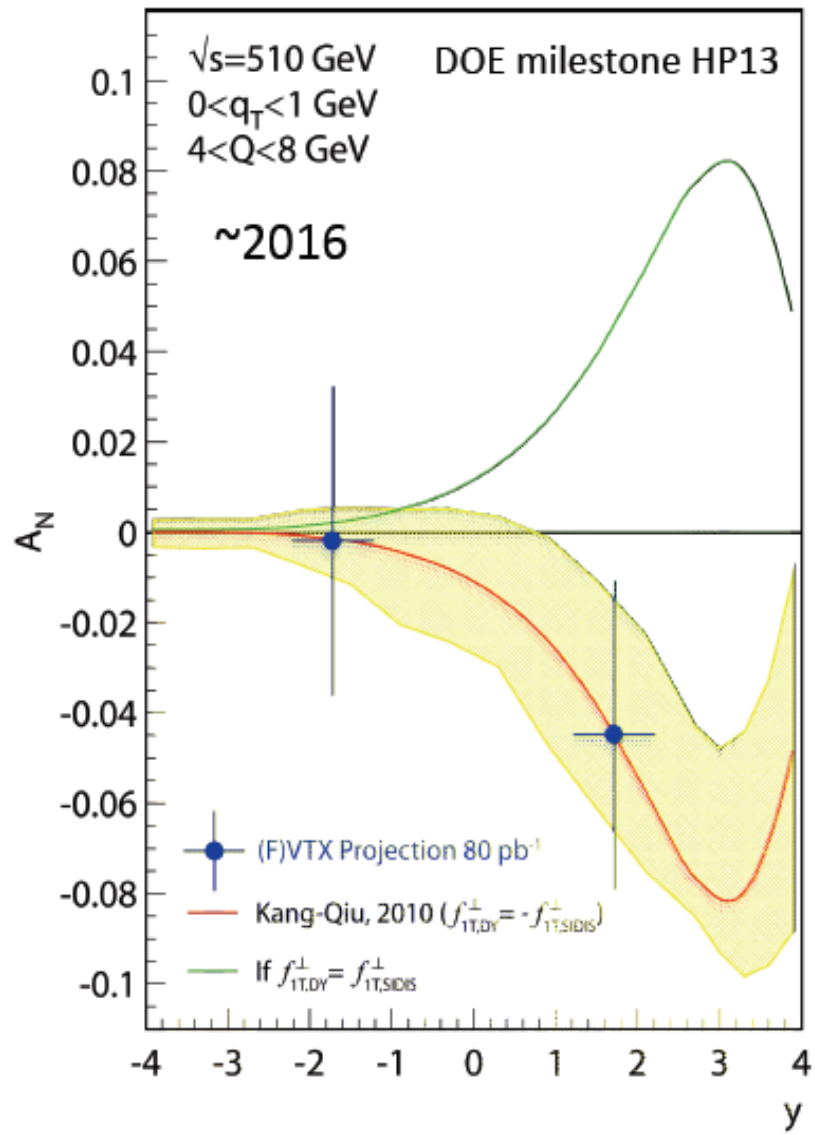
Semi-inclusive DIS (SIDIS)



$pp^{\uparrow} \to \mu^+\mu^- X$

Drell-Yan

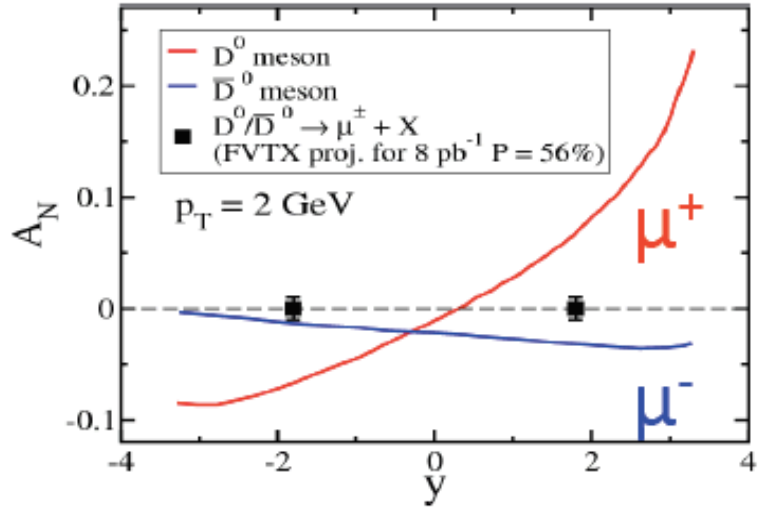
RHIC 1-year running projection

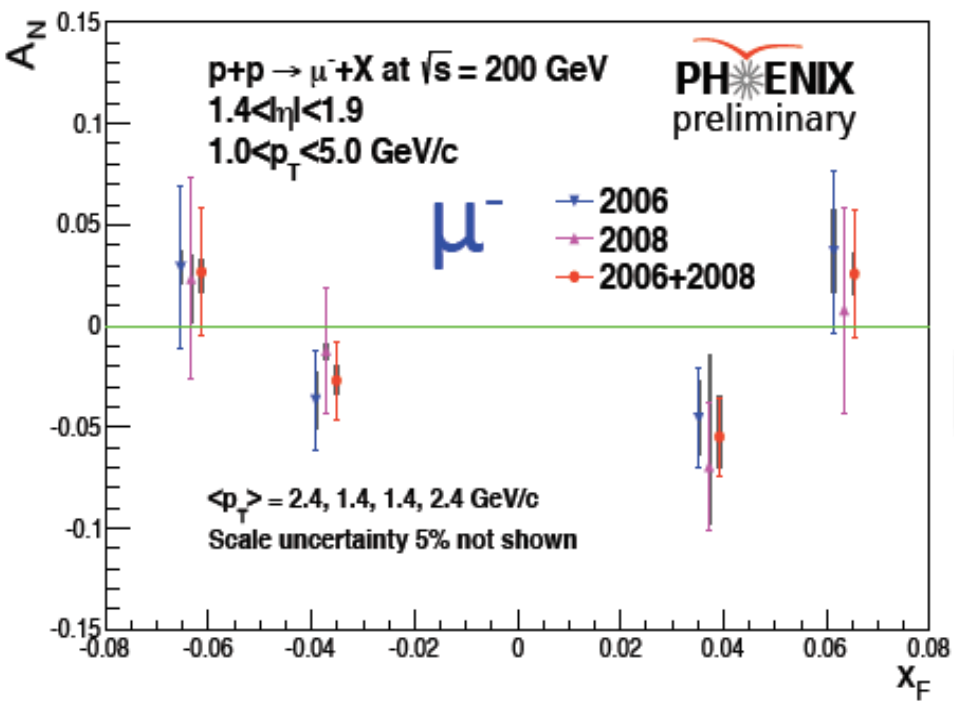


Projected Open Charm TSSA with FVTX

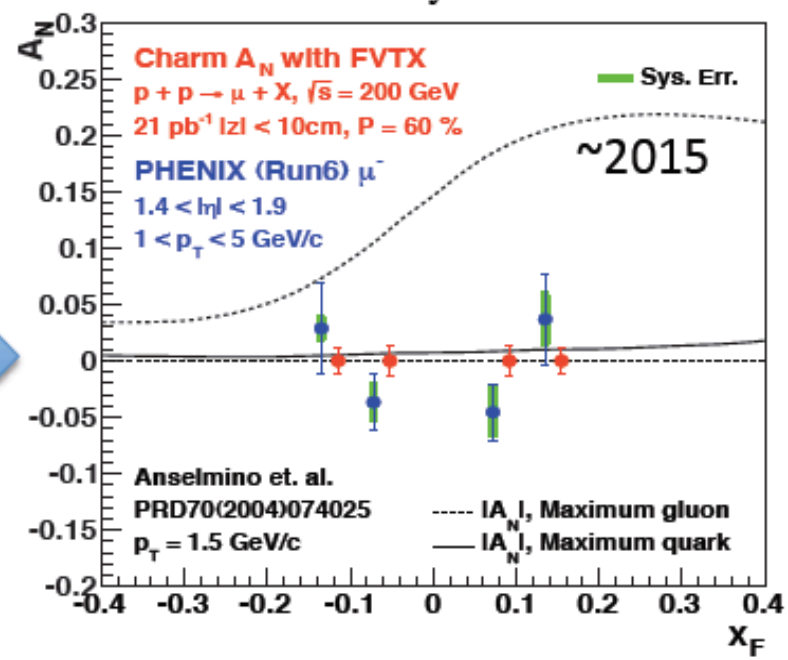
Unique opportunity to study gluon Sivers distributions at RHIC

- Forward Muon arms
  - Run6, 8
  - Run12 work in progress
  - Much improved w/FVTX (Run15)





FVTX



Summary

- After almost 40 years, we have learned a lot of QCD dynamics, but, only at very short-distance - less than 0.1 fm, and limited information on non-perturbative parton structure

- Understanding proton spin could provide the first complete example to describe the fundamental properties of hadrons at various distance scale

- Transverse spin opens a new domain to test QCD dynamics and new observables for extracting partonic structure beyond PDFs

- RHIC spin program is rich, and has a clear path forward to the future EIC.

Thank you!

Backup slices

Global QCD analysis for PDFs

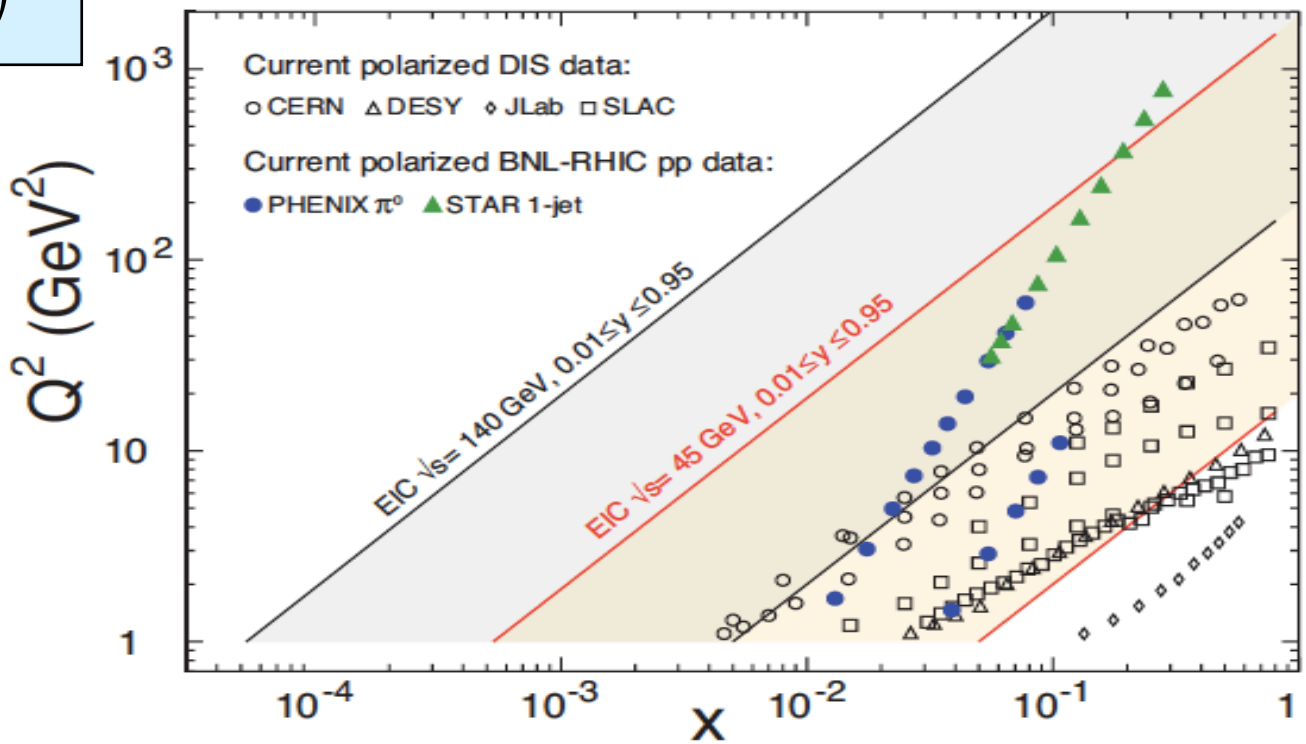
Input DPFs at Q_0

$$\Delta\varphi_{f/h}\left(x,\{a_j\}\right)$$

Vary $\{a_j\}$

Minimize Chi^2

DGLAP



$\Delta\varphi_{f/h}\left(x\right)$ **at $Q>Q_0$**

QCD calculation

Comparison with Data at various x and Q

Procedure: Iterate to find the best set of $\{a_j\}$ for the input DPFs

Determination of ΔG

❑ Double longitudinal spin asymmetries:

$$A_{LL} = \frac{[\sigma(+,+) - \sigma(+,-)] - [\sigma(-,+) - \sigma(-,-)]}{[\sigma(+,+) + \sigma(+,-)] + [\sigma(-,+) + \sigma(-,-)]} \quad \text{for } \sigma(s_1, s_2)$$

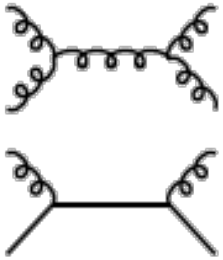
❑ Physical channels sensitive to ΔG:

$\vec{p} + \vec{p} \rightarrow \pi + X$

$\vec{p} + \vec{p} \rightarrow \text{jet} + X$

$\vec{g}\vec{g} \rightarrow gg$

$\vec{q}\vec{g} \rightarrow qg$



Pion or jet production

high rates

$\vec{p} + \vec{p} \rightarrow \gamma + X$

$\vec{p} + \vec{p} \rightarrow \gamma + \text{jet} + X$

$\vec{q}\vec{g} \rightarrow \gamma q$

Direct photon production

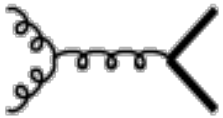
low rates

$\vec{p} + \vec{p} \rightarrow D + X$

$\vec{p} + \vec{p} \rightarrow B + X$

$\vec{g}\vec{g} \rightarrow c\bar{c}$

$\vec{g}\vec{g} \rightarrow b\bar{b}$



Heavy-flavour production

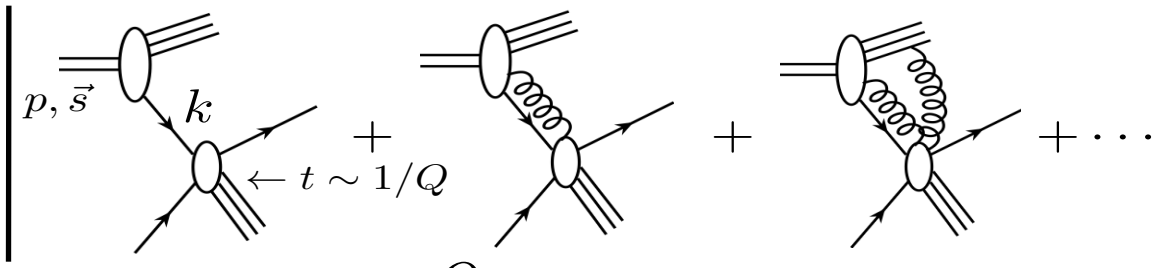
separated vertex detection required

Many NLO pQCD calculations are available

Integrated transverse motion

- **Cross section with one large momentum transfer: Q >> Λ_{QCD}**

$\sigma(Q,\vec{s}) \propto$



$Q_s^2 \sim \langle k^2 \rangle, \langle k_T^2 \rangle$

$$\approx H^{\rm LP} \otimes f_2 \otimes f_2 + \frac{Q_s}{Q} H^{\rm NLP} \otimes f_2 \otimes f_3 + \ldots$$

pQCD factorization

- **Single transverse spin asymmetry:**

$$A_N \propto \sigma(Q, S_\perp) - \sigma(Q, -S_\perp)$$
$$\propto H(Q)\, [\, \langle p, S_\perp | \mathcal{O}(\psi, A^\mu) | p, S_\perp \rangle - \langle p, -S_\perp | \mathcal{O}(\psi, A^\mu) | p, -S_\perp \rangle \,]$$

- **Dominated by the derivative term – forward region:**

$$E \frac{d\Delta\sigma}{d^3\ell} \propto \epsilon^{\ell_T s_T n \bar{n}}\, D_{c\to\pi}(z) \otimes \left[-x \frac{\partial}{\partial x} T_F(x,x) \right]$$
$$\otimes \frac{1}{-\hat{u}} \left[G(x') \otimes \Delta\hat{\sigma}_{qg\to c} + \sum_{q'} q'(x') \otimes \Delta\hat{\sigma}_{qq'\to c} \right]$$

$$A_N \propto \left(\frac{\ell_\perp}{-\hat{u}} \right) \frac{n}{1-x} \quad \text{if } T_F(x,x) \propto q(x) \propto (1-x)^n$$

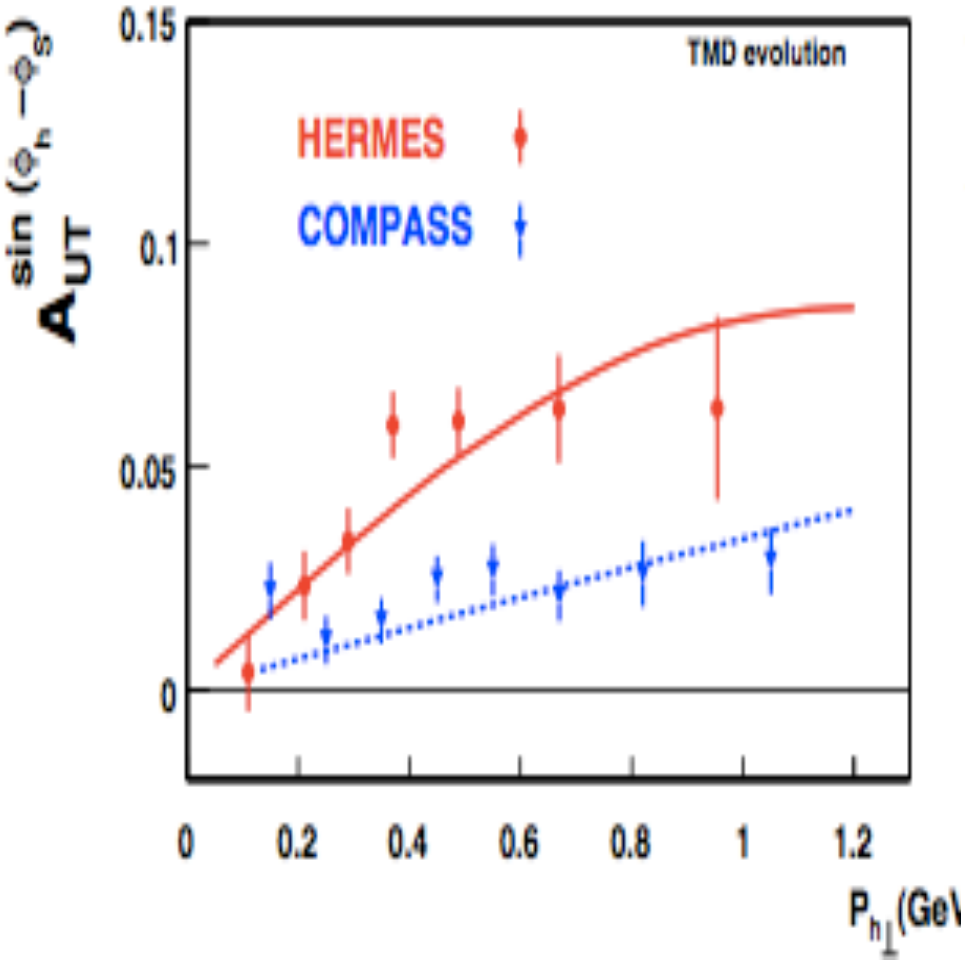
Qiu, Sterman, 1998, …

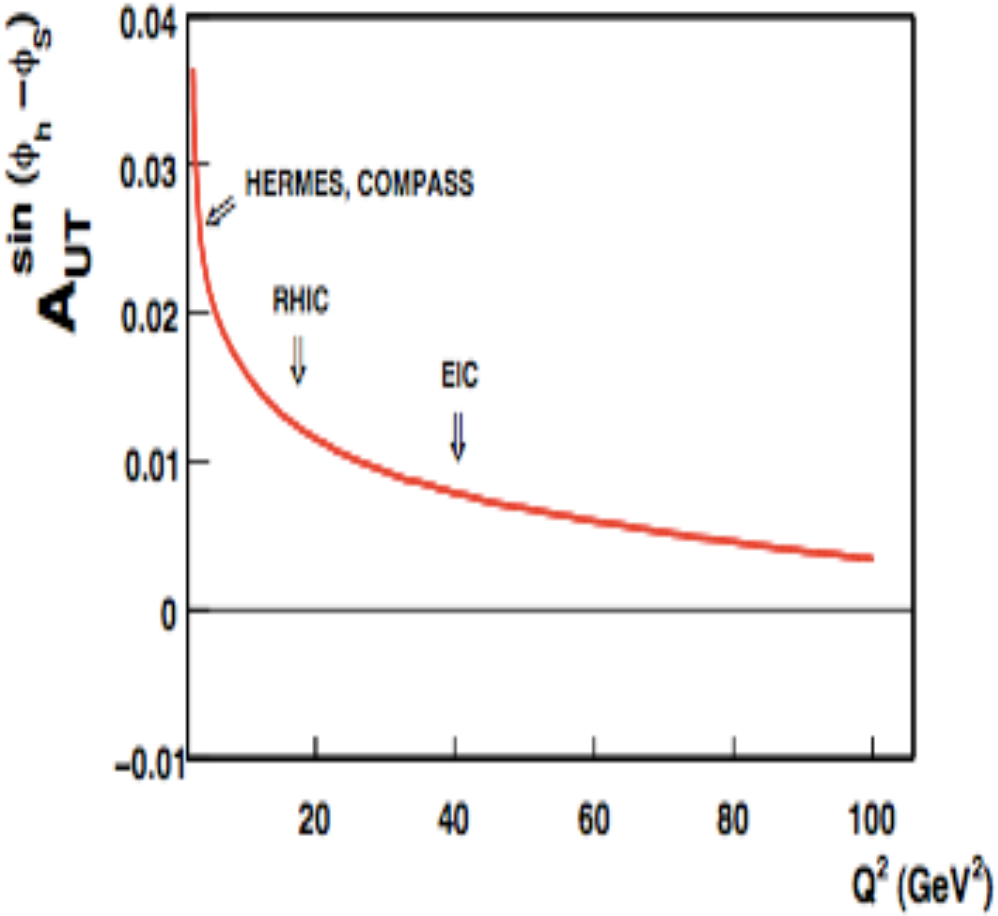
Kouvaris, Qiu, Vogelsang, Yuan, 2006

Importance of the evolution

Aybat, Rogers, 2012

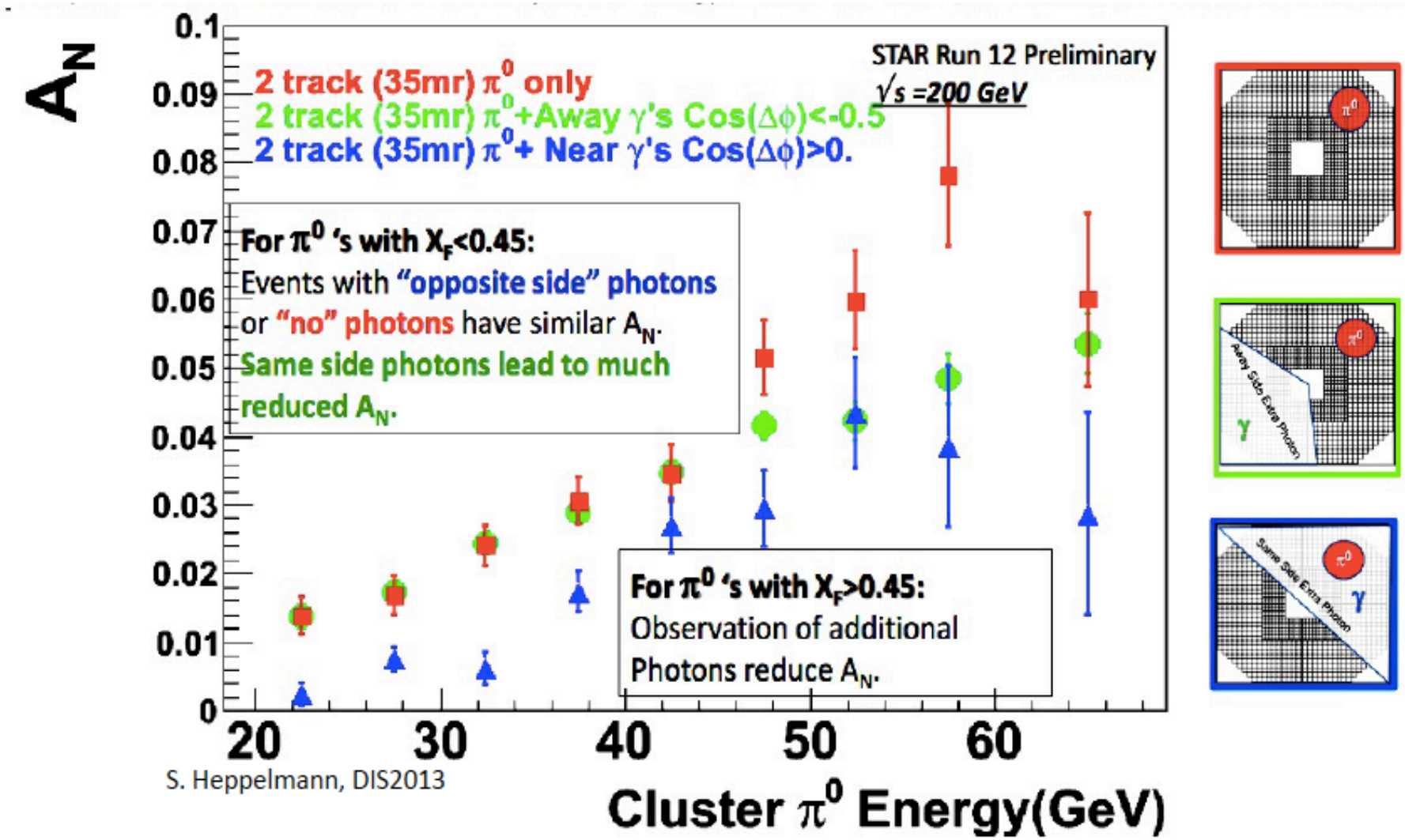
❑ SSAs – Sivers function:





Q^2 dependence – effectiveness of the probe?

Forward Inclusive Neutral Pions at 200 GeV



S. Heppelmann, DIS2013

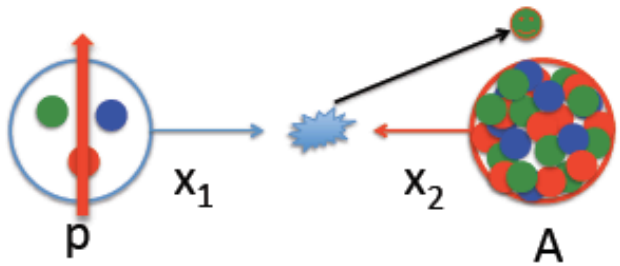
Recent data from Run-12 suggest that asymmetries for pions with additional near-side energy deposit have *lower asymmetries than those of more isolated pions*

Polarized p+A at RHIC(2015+)

"Polarized p+A @RHIC" workshop, Jan., 2013
https://indico.bnl.gov/conferenceDisplay.py?ovw=True&confId=553

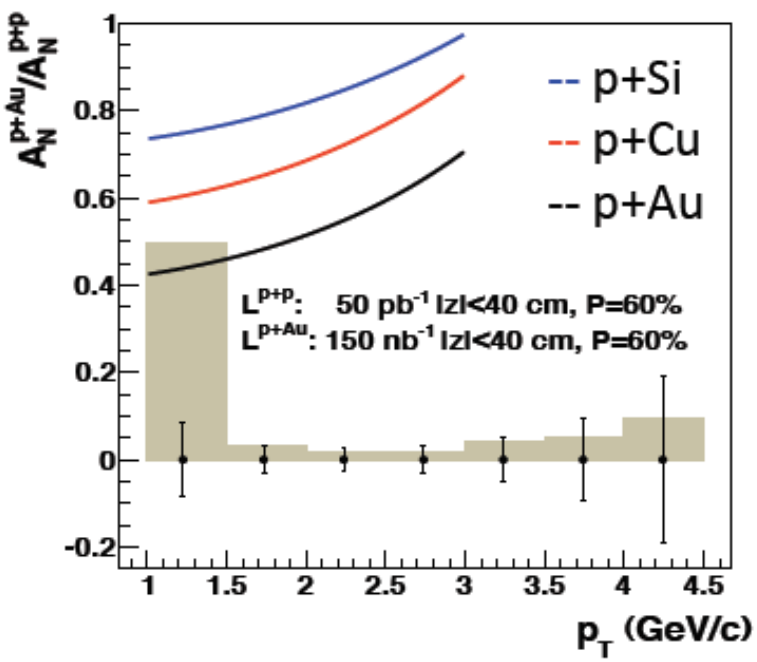
- Large transverse spin asymmetry A_N at forward rapidity – a large analyzing power at large x_1
- Gluon saturation/CGC probed at forward rapidity in p+A – small x_2 in A

A new probe – using a large spin asymmetry to study CGC effects in the forward rapidity



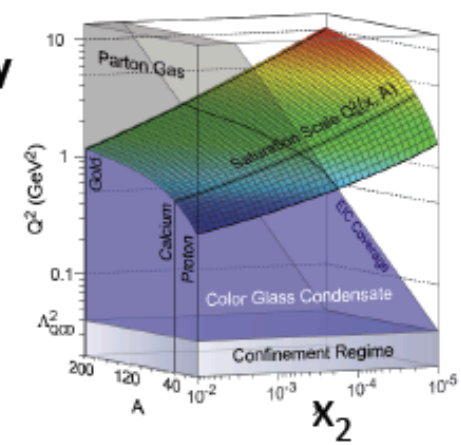
projectile: $x_1 \sim \frac{p_\perp}{\sqrt{s}} e^{+y} \sim 1$ valence

target: $x_2 \sim \frac{p_\perp}{\sqrt{s}} e^{-y} \ll 1$ gluon



$$\Delta\sigma_{forward} \sim \Delta f(x_1) \otimes g(x_2); \quad x_1 >> x_2$$

Forward Pion Single-Spin Asymmetry

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 \ll Q_s^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{\frac{P_{h\perp}^2 \delta^2}{Q_{sp}^4}}$$

Kang, Yuan (2011)