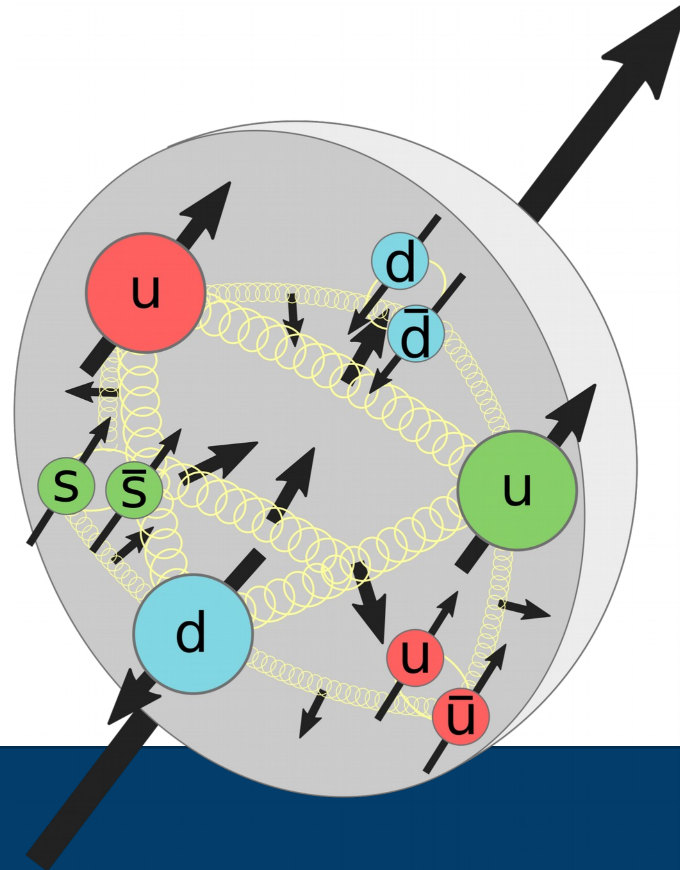


RESULTS FROM RHIC-SPIN

24 AUG 2019 | MARIA ŻUREK | LAWRENCE BERKELEY NATIONAL LABORATORY

11TH WORKSHOP ON HADRON PHYSICS IN CHINA AND OPPORTUNITIES WORLDWIDE

SPIN PHYSICS PROGRAM AT RHIC

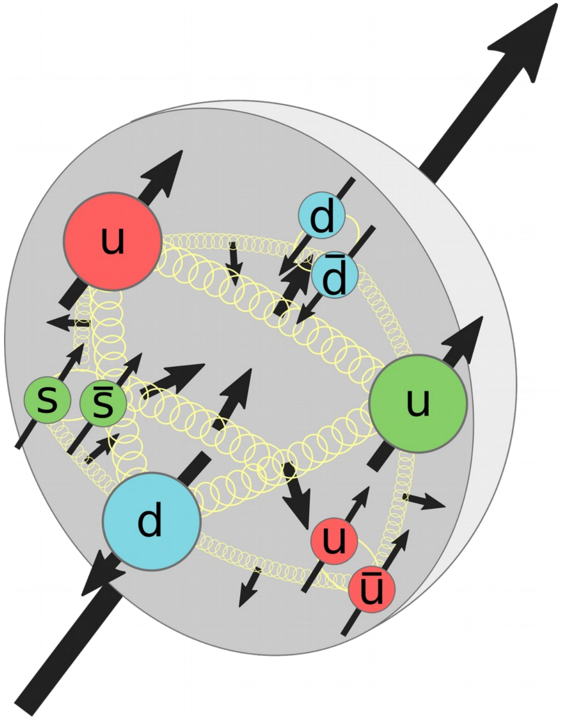
Goal:

Using spin as a unique probe to unravel the internal structure and the QCD dynamics of nucleons with unprecedented precision

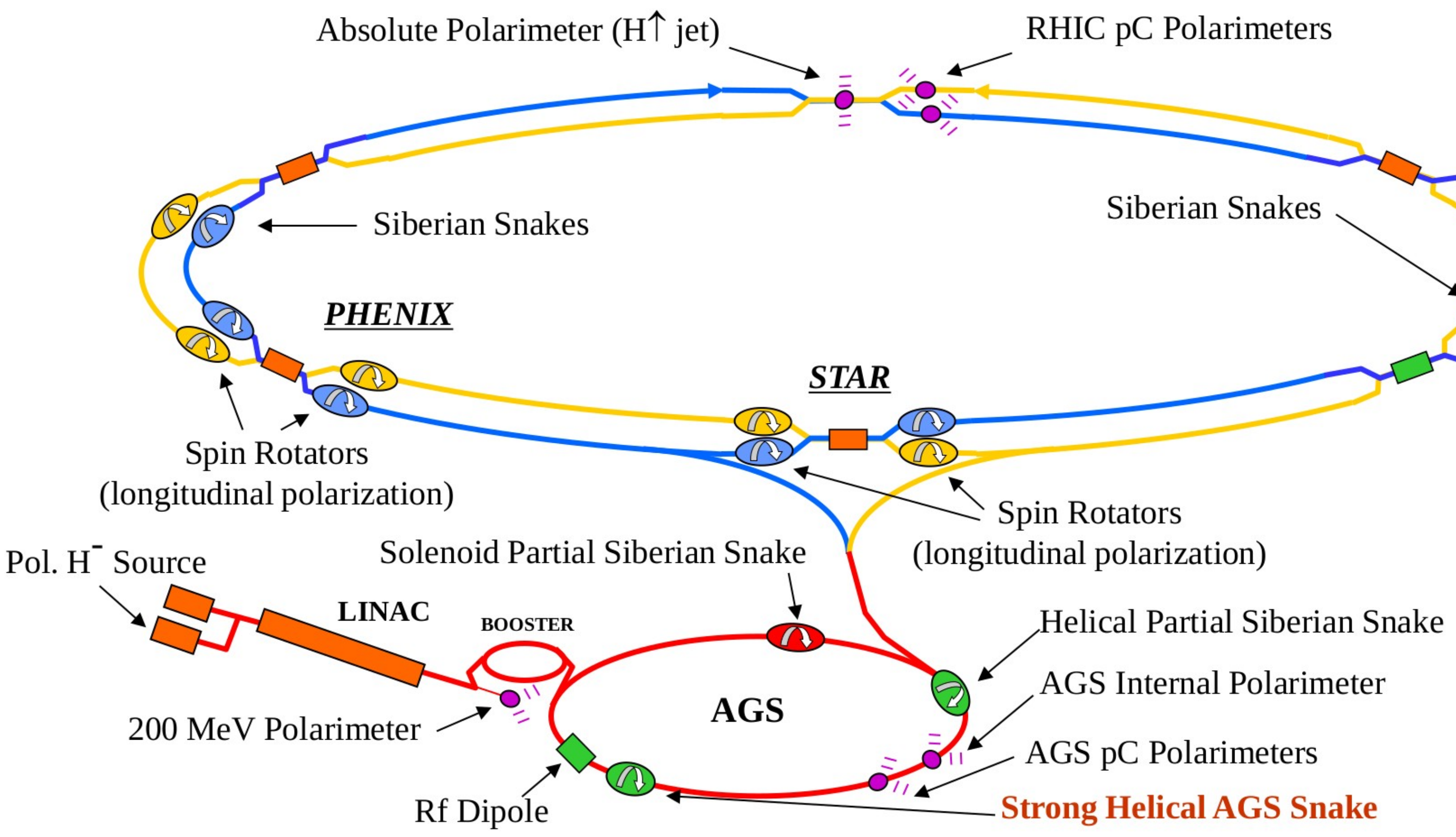
Questions:

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

- How do gluons contribute to the proton spin?
- What is the landscape of the polarized quark-sea in the nucleon?
- What do transverse-spin phenomena teach us about the structure of proton?



RHIC – POLARIZED PROTON COLLIDER

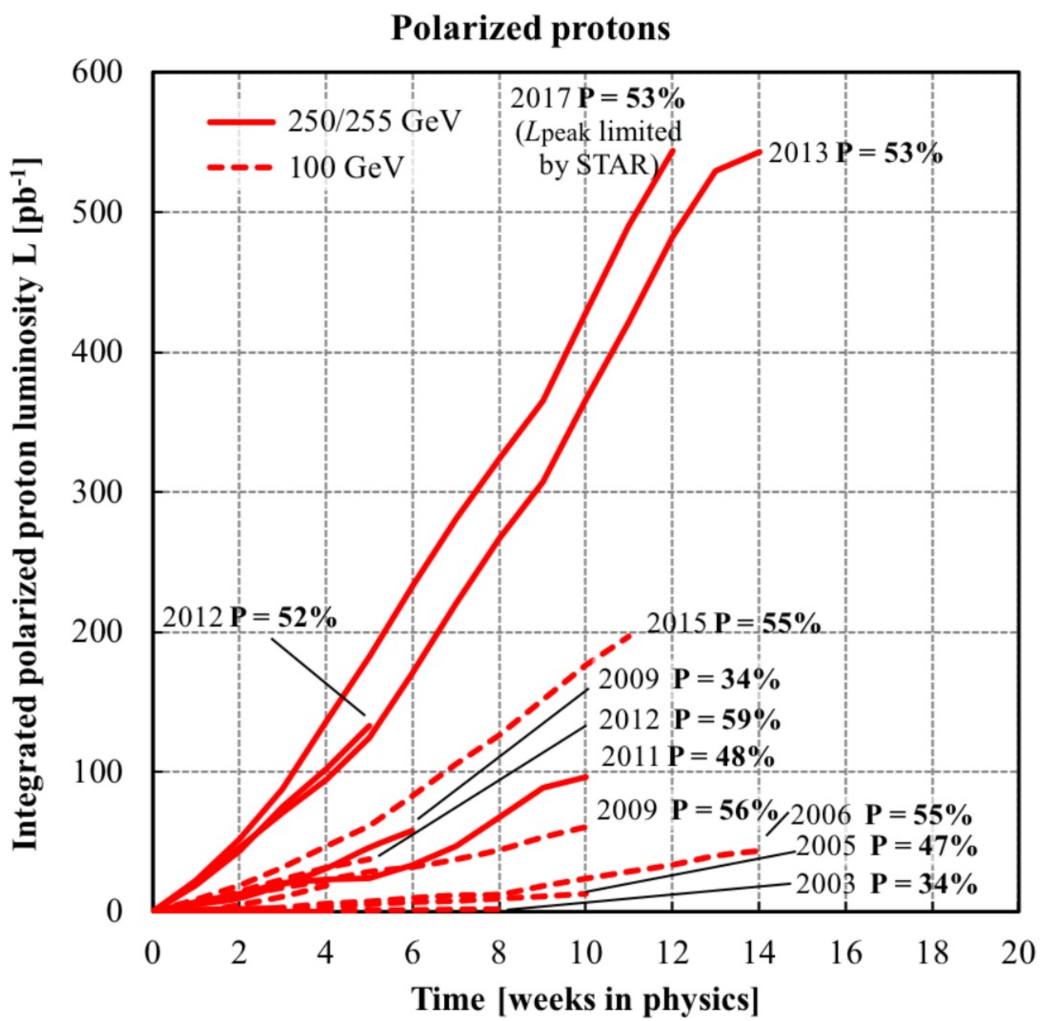


- Polarized proton √s = 62, 200, 500 GeV
- Transverse and longitudinal polarization
- Alternating spin configurations bunch by bunch and fill by fill

Hard scattering processes with control of systematic effects

RHIC – POLARIZED PROTON COLLIDER

Year and √s	STAR L [pb^{-1}]	PHENIX L [pb^{-1}]
Longitudinal runs		
√s = 200 GeV		
2009	25	16
2015	50	-
√s = 500/510 GeV		
2009	10	14
2011	12	18
2012	82	32
2013	300	155
Transverse runs		
√s = 200 GeV		
2012	22	10
2015	50	40
√s = 500/510 GeV		
2011	25	-
2017	320	-



SOLENOIDAL TRACKER AT RHIC

Electromagnetic Calorimeter
- $\Delta\varphi = 2\pi$, $1 < \eta < 2$
- Barrel ($|\eta| < 1$) and Endcap ($-1 < \eta < 2$)
- Energy measurement, trigger

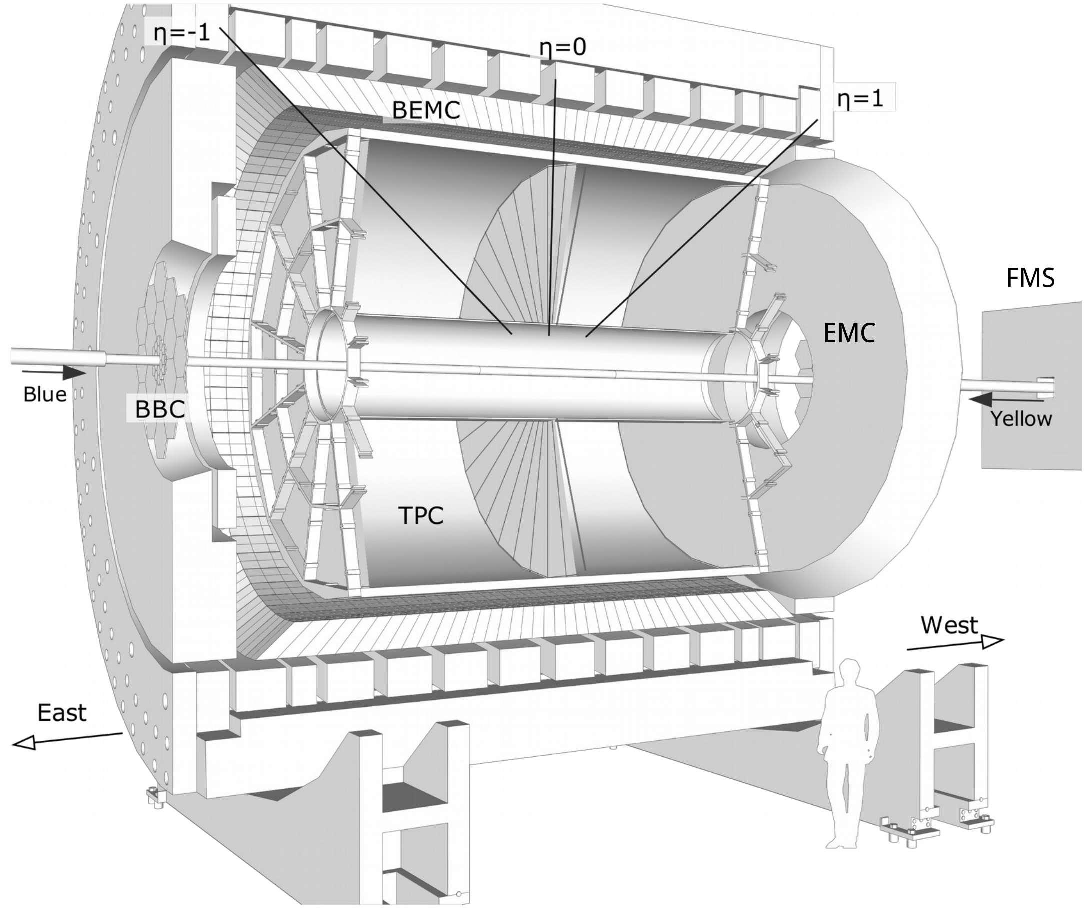
Time Projection Chamber
- $\Delta\varphi = 2\pi$, $|\eta| < 1$, 0.5 T
- PID, tracking, vertex reconstruction

Time of Flight Barrel
- $\Delta\varphi = 2\pi$, $|\eta| < 1$
- PID

Forward Meson Spectrometer
- $\Delta\varphi = 2\pi$, $2.6 < \eta < 4$
- Energy measurement, trigger

Beam-Beam Counter
Vertex Position Detector
- Relative luminosity and MB trigger

Zero Degree Calorimeter
- Relative luminosity and local polarimetry



Characteristics
- Large acceptance (PID and calorimetry)
- Good for jets and correlations
- Upgrades: iTPC, EPD, ETOF

PHENIX DETECTOR

Took data up to 2016

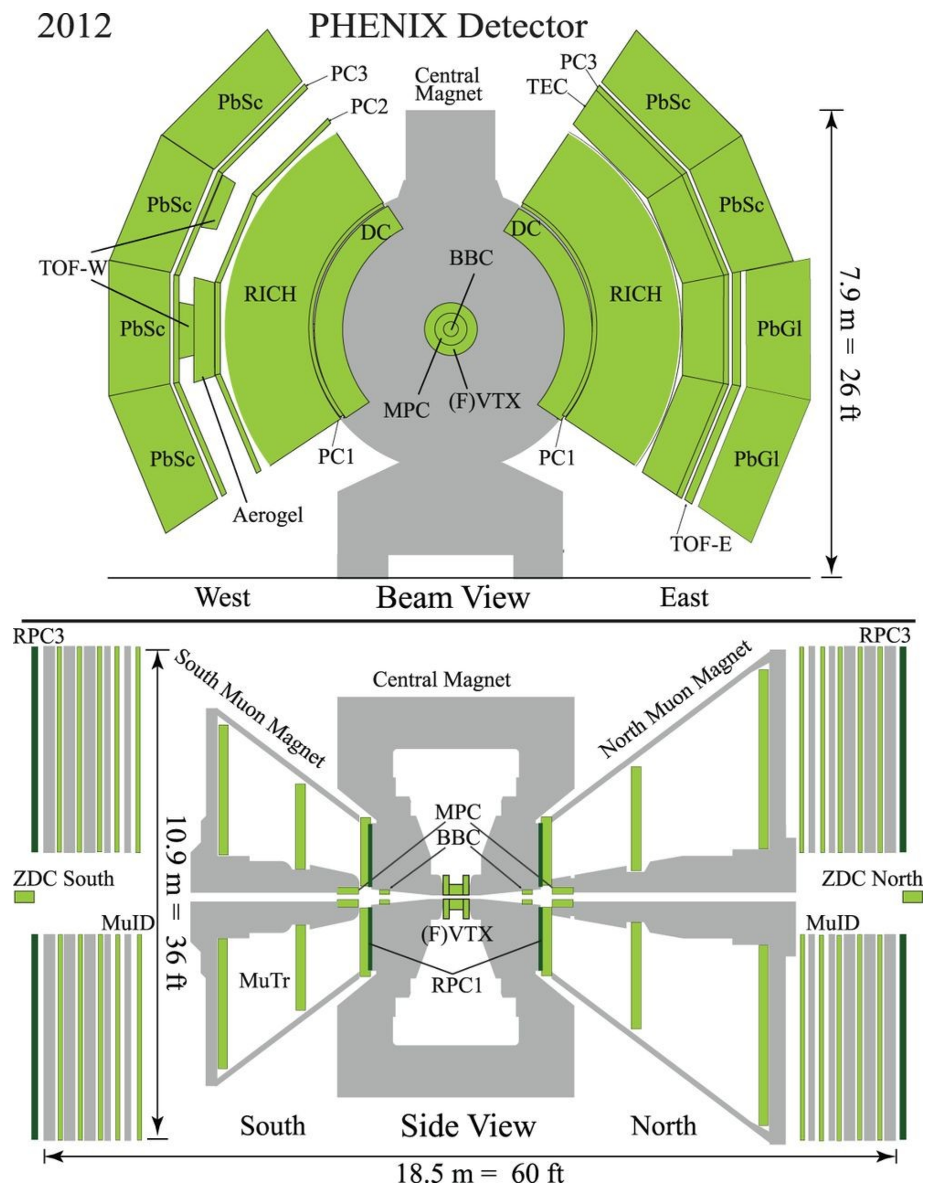
Central Arm
- $|\eta| < 0.35$, $\Delta\varphi = 2 \times \pi/2$, 0.78 T
- VTX detector
- Electromagnetic Calorimeter
- Tracking: Drift chambers, Pad chambers
- PID: RICH, ToF

Muon Arm
- $1.2 < |\eta| < 2.4$, $\Delta\varphi = 2\pi$, 0.72 T
- Muon PID and Tracking
- PID, tracking, vertex reconstruction

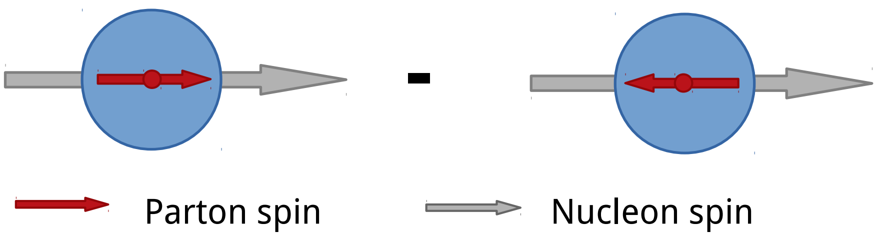
Muon Piston Calorimeter
- $\Delta\varphi = 2\pi$, $3.1 < |\eta| < 3.9$

Beam-Beam Counter
Zero Degree Calorimeter
- Relative luminosity

Characteristics
- High rate capabilities + good resolution
- Central arms: π^0 and η
- Muon arms



HELICITY STRUCTURE OF PROTON



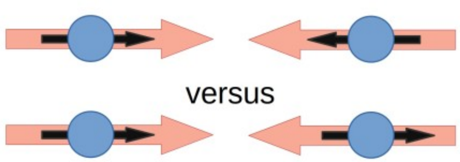
Helicity $\Delta f(x)$

Density of partons with spin aligned with a longitudinally polarized proton that carry a fraction x of proton momentum

How do gluons contribute to the proton spin?

Double polarization

$$\vec{p} + \vec{p} \rightarrow \text{jet/dijet/hadrons} + X$$

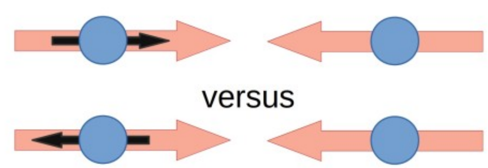


$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

What is the landscape of the polarized sea in the proton?

Single polarization + weak interaction

$$\vec{p} + p \rightarrow W^{+/-} \rightarrow e^{+/-} + \nu$$

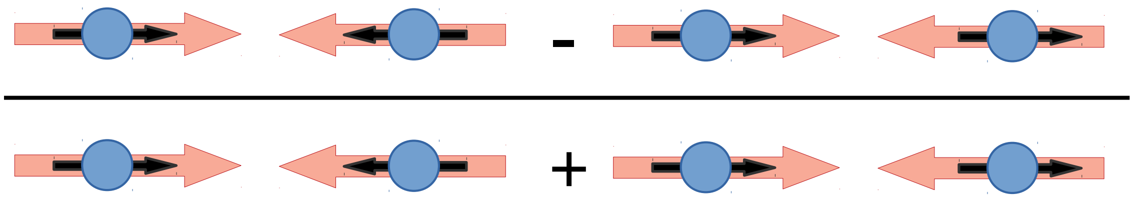


$$A_L = \frac{\sigma_{+} - \sigma_{-}}{\sigma_{+} + \sigma_{-}}$$

HOW TO ACCESS ΔG?

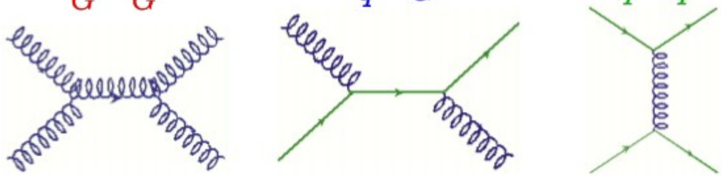
HOW TO ACCESS ΔG?

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} =$$

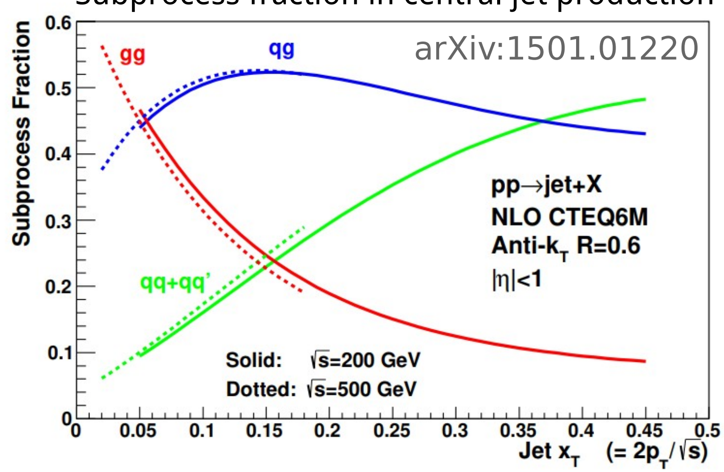


Which processes dominate at RHIC?

$\frac{\Delta G}{G} \frac{\Delta G}{G}$ $\quad$ $\frac{\Delta q}{q} \frac{\Delta G}{G}$ $\quad$ $\frac{\Delta q}{q} \frac{\Delta q}{q}$

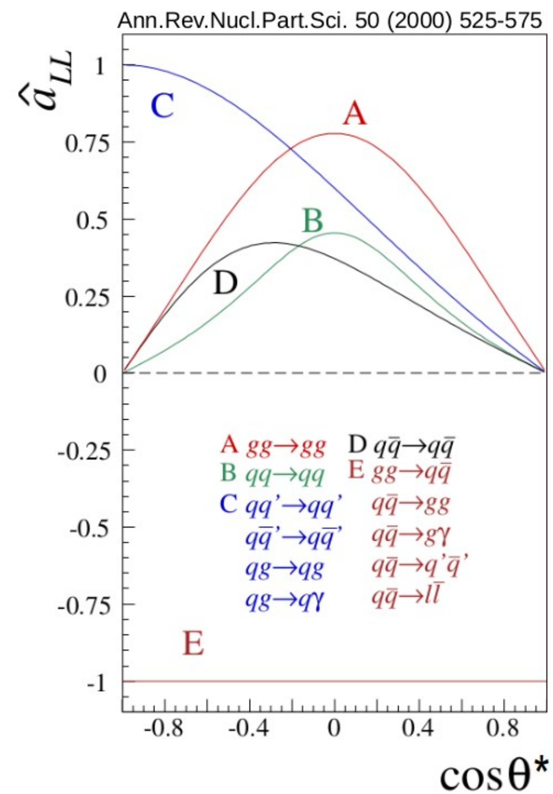


Subprocess fraction in central jet production



Sensitive to qg and gg – Access to **ΔG/G**

What are a_{LL} for these processes?

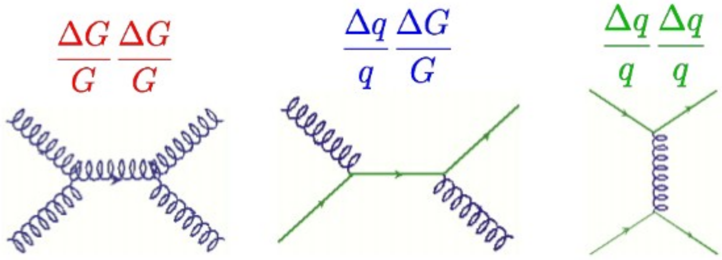


HOW TO ACCESS ΔG?

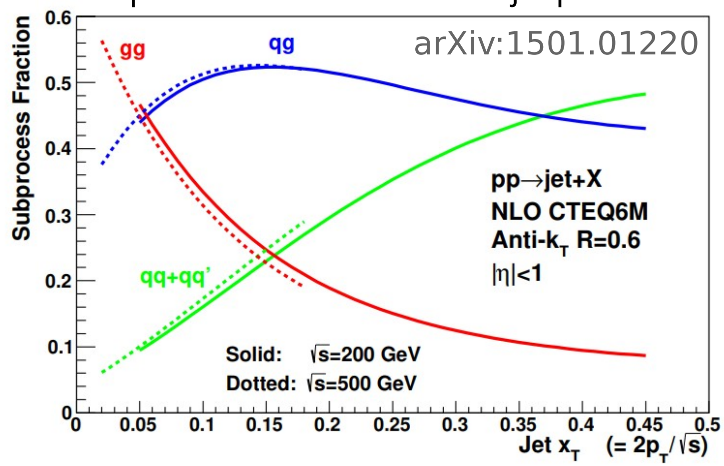
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} a\hat{_{LL}} \otimes D}{\Sigma f_a \otimes f_b \otimes \hat{\sigma} \otimes D}$$

LO for illustration

Which processes dominate at RHIC?



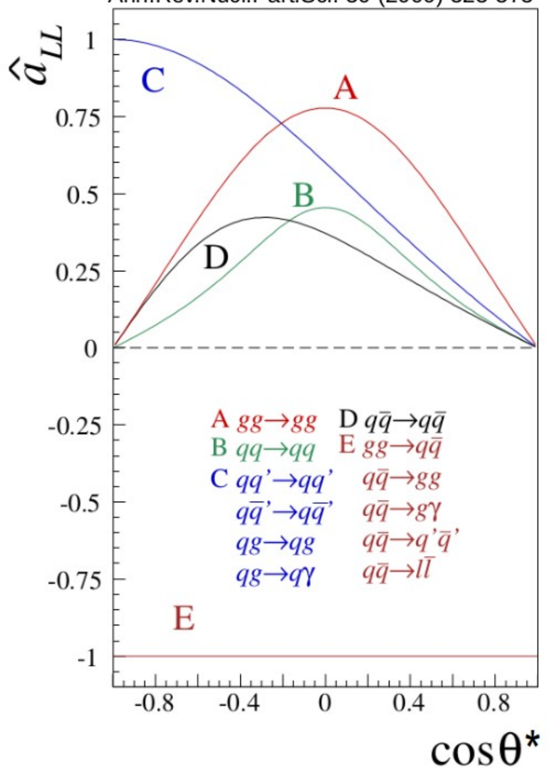
Subprocess fraction in central jet production



Sensitive to qg and gg – Access to **ΔG/G**

What are a_{LL} for these processes?

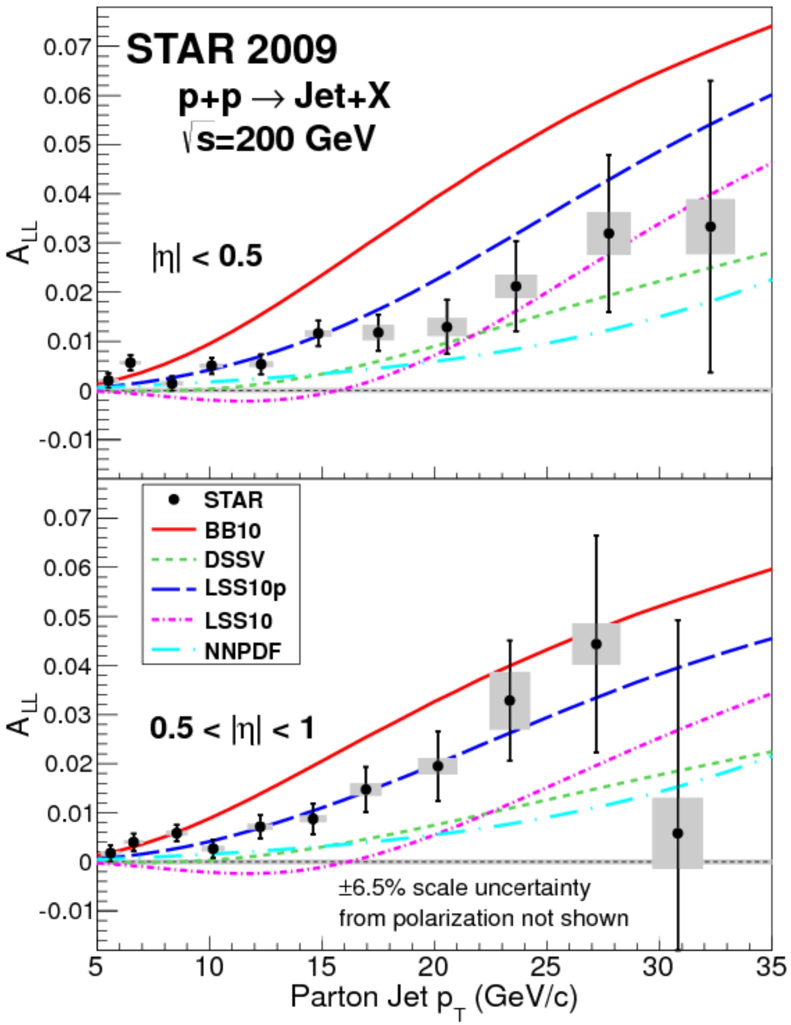
Ann.Rev.Nucl.Part.Sci. 50 (2000) 525-575



STATUS OF ΔG

Precision A_{LL}

PRL 115 (2015) 9, 092002



In the PDF fit also PHENIX π^0 A_{LL} included PRD 90, 012007 (2014)

1. Significant advance in respect to old data:
- About an order in precision
- Extended kinematic range
- Initial sensitivity to different x_g from rapidities

2. A_{LL} positive for large p_T - **positive gluon polarization**

3. Included in DSSV and the NNPDF **PDF fits** (NLO)
- These data drive the constraints on ΔG in both fits

$$\text{DSSV:} \quad 0.20^{+0.06}_{-0.05}, \quad \text{at } 90\% \text{ C.L. }, x > 0.05$$
$$\text{NNPDF:} \quad 0.23 \pm 0.07, \quad 0.05 < x < 0.5$$

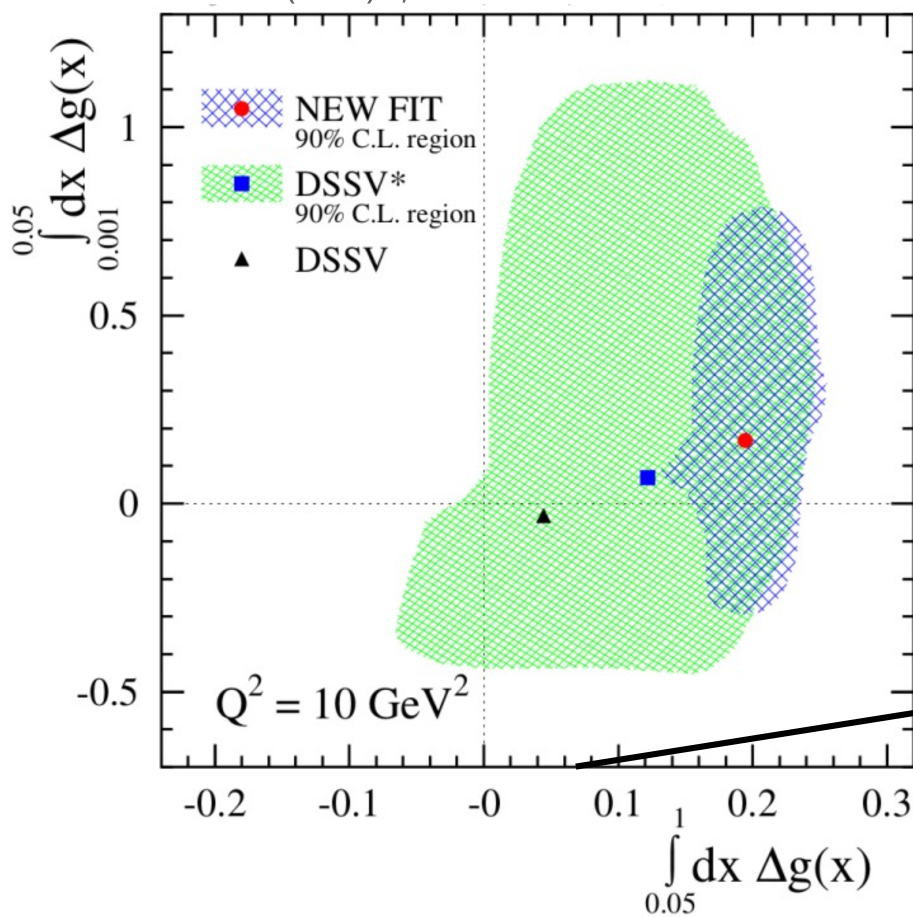
Evidence for **positive gluon polarization** in the x range 0.05 < x < 0.2 and at $Q^2 = 10$ GeV^2

Run 2009 - 25 pb^{-1}
Further precision: Run 2015 – 50 pb^{-1}

STATUS OF ΔG

Impact of A_{LL} from 2009 data on ΔG

PRL 113 (2014) 1, 012001



$$\Delta G = \int_0^1 \Delta g(x) \mathrm{d}x$$

Low-x range

Improving constrain for **x < 0.05**

Extend sensitivity to smaller x_g:

- forward rapidity

$$x_g \propto \exp(-\eta)$$

- √s = 510 GeV data

$$x_g \propto 1/\sqrt{(s)}$$

High-x range

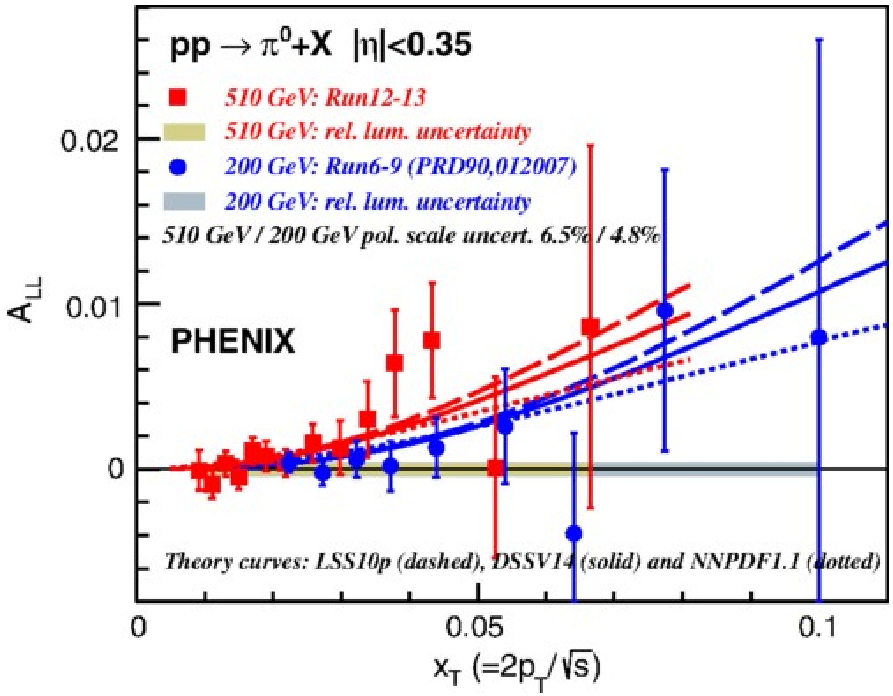
Further precision from:

- Jet and neutral pion probes
- Complementary probes

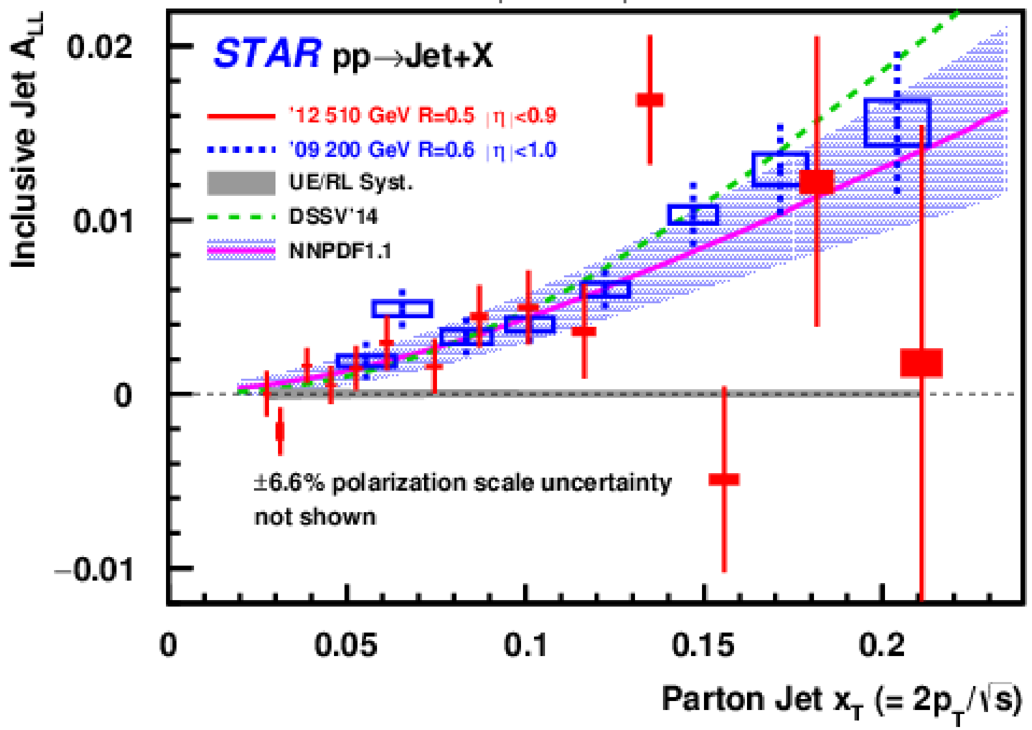
CENTRAL π^0 AND JETS AT 510 GEV

Towards smaller x_g

PRD 93 (2016), 011501



arXiv:1906.02740, Accepted for publication in PRD



- Consistent result from both energies and both experiments
- **Higher √s pushes sensitivity to lower x > 0.02**
- More to come:
  - 2013 data: High luminosity 510 GeV: STAR and PHENIX
  - 2015 data: Double 2009 statistics 200 GeV: STAR

STAR: A_{LL} of π^0 at 510 GeV with FMS ($2.6 < \eta < 4$, $x > 0.001$) PRD 98 (2018), 032013

STAR: A_{LL} of π^0 at 200 GeV at midrapidity PRD 80 (2009), 111108

DI-JET MEASUREMENT

Towards smaller x_g and complementary probes

- Di-jets give stricter constraints to underlying **partonic kinematics**

- May place better constraints on **functional form of Δg(x)**
- More-forward production - **lower x down to 0.01,** 2 – likely gluon, 1 – likely quark
- **Narrow ranges** of initial state partonic momentum tested

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

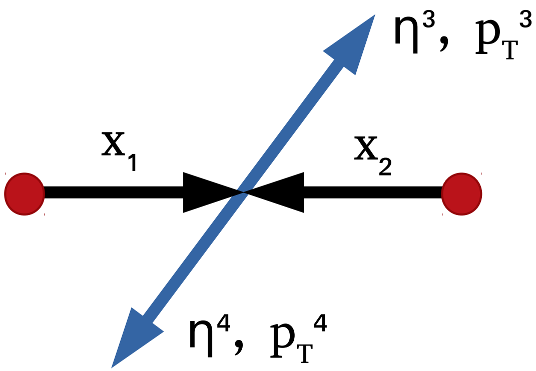
$$\eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$

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

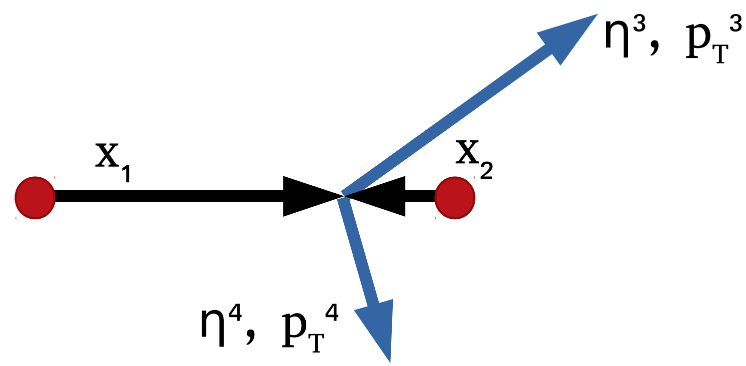
$$x_2 = \frac{1}{\sqrt{s}}(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4})$$

(LO)

Unlike-sign topology



Same-sign topology

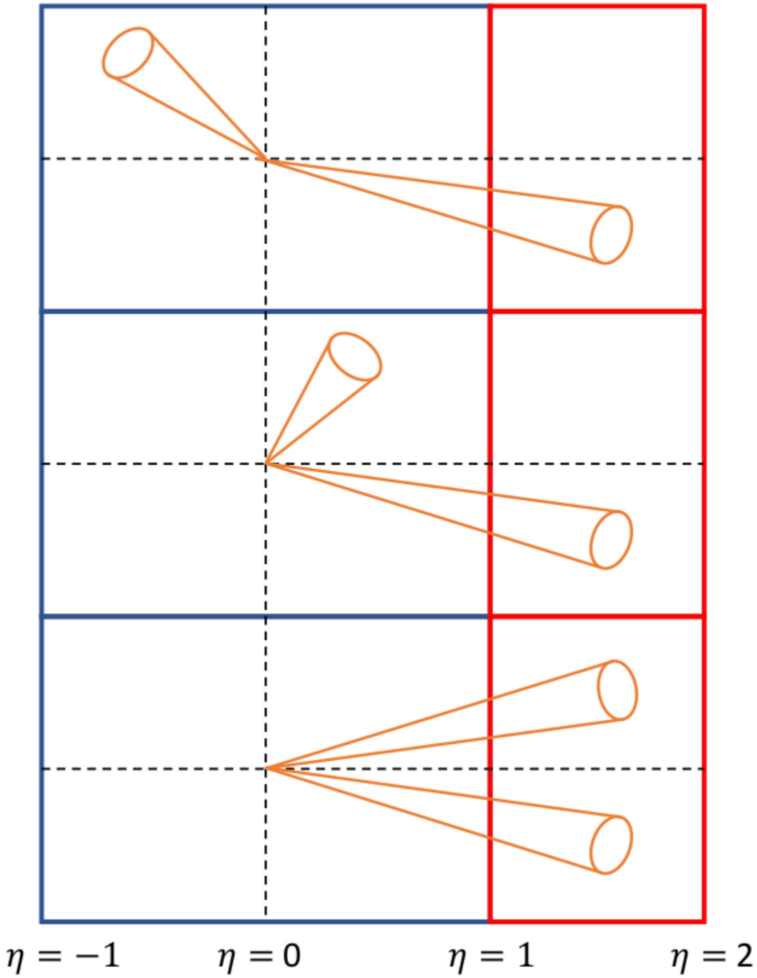


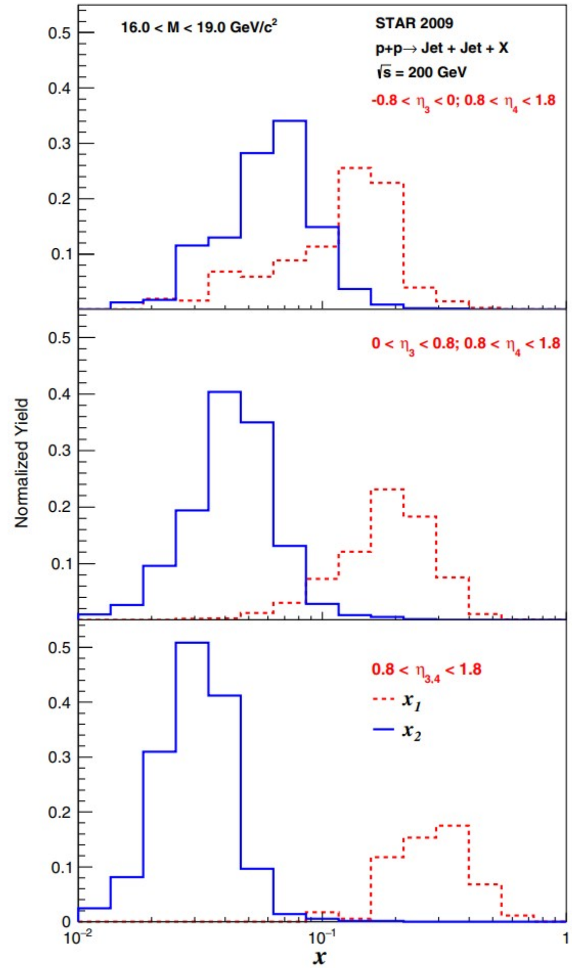
Forward jets probe lower values of x_g

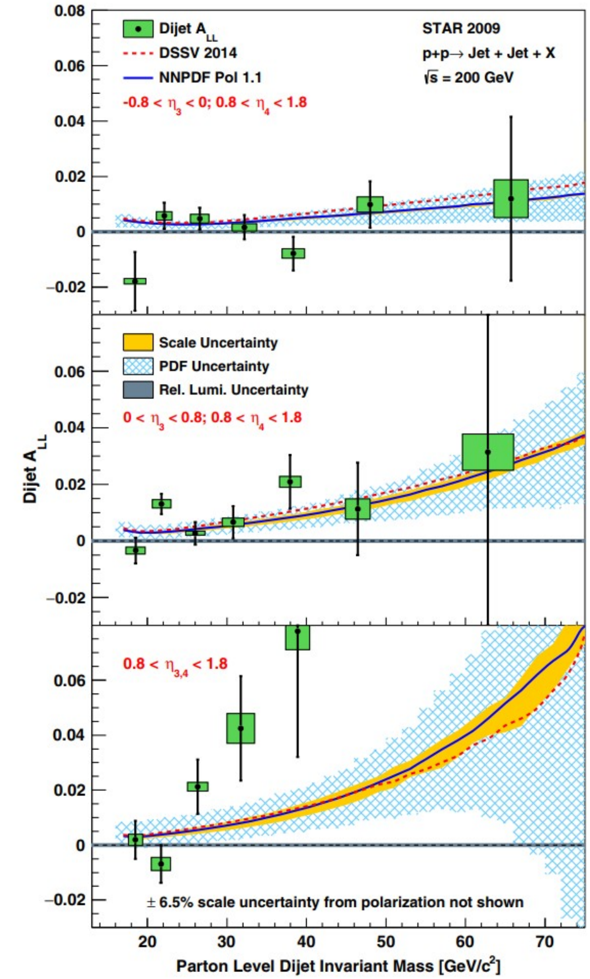
DI-JET MEASUREMENT

Towards smaller x_g and complementary probes

PRD 98 (2018), 032011





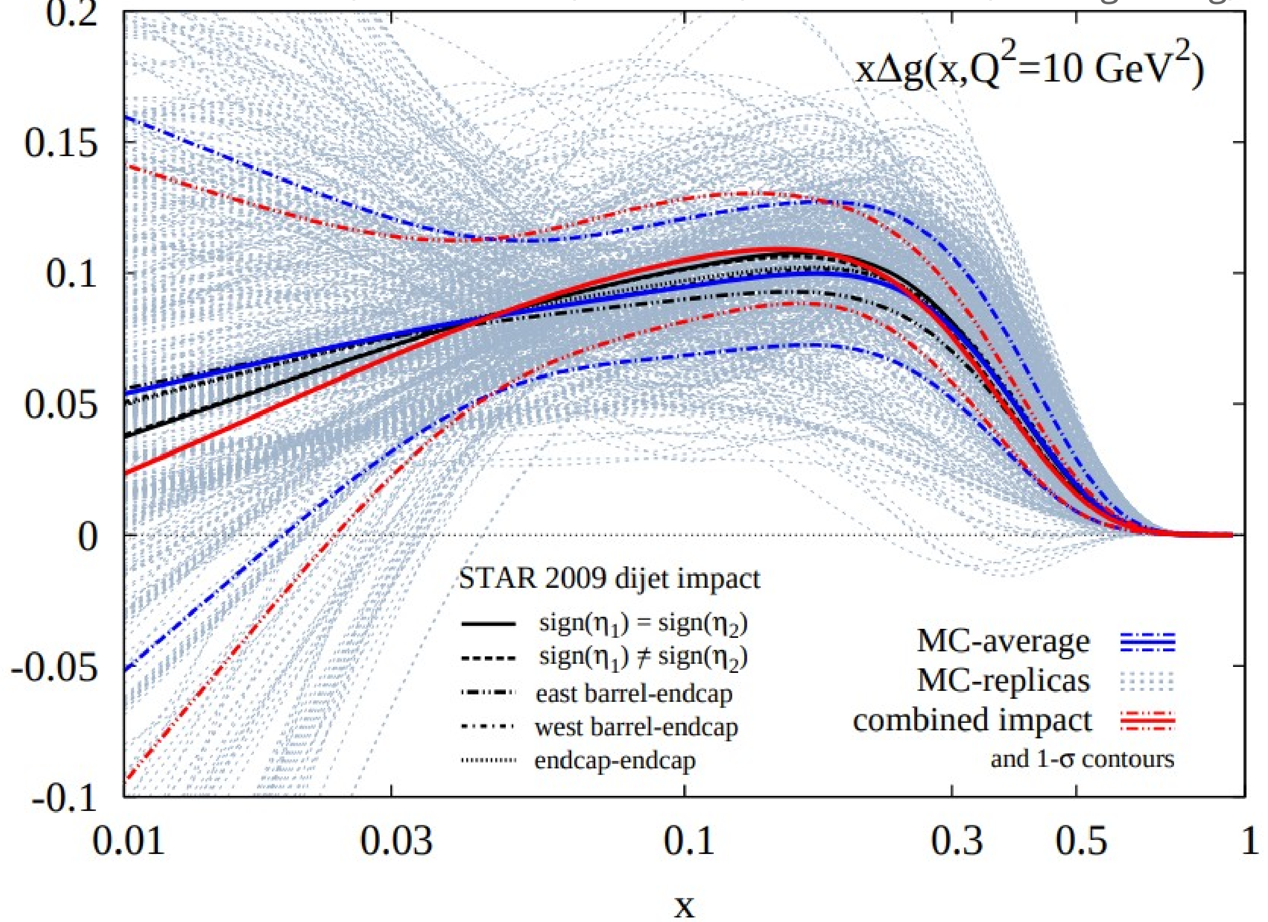


- Central di-jet measurement Run 2009 √s = 200 GeV : PRD 95 (2017), 071103
- Central di-jet measurement Run 2012 √s = 510 GeV : arXiv:1906.02740, Accepted for publication in PRD
- Further precision: Run 2015 √s = 200 GeV – x 1.5 statistics

DI-JET MEASUREMENT

Impact on Δg(x)

arXiv 1902.10548
D. de Florian, G. A. Lucero, R. Sassot, M. Stratmann, W. Vogelsang,



- Influence of central and forward di-jets from 2009 data √s = 200 GeV on DSSV caculations

QUARK-SEA HELICITIES

QUARK HELICITIES

Single spin asymmetry and cross sections for W production

Goal: Constrain the sea-quark helicity

Separation of quark flavour

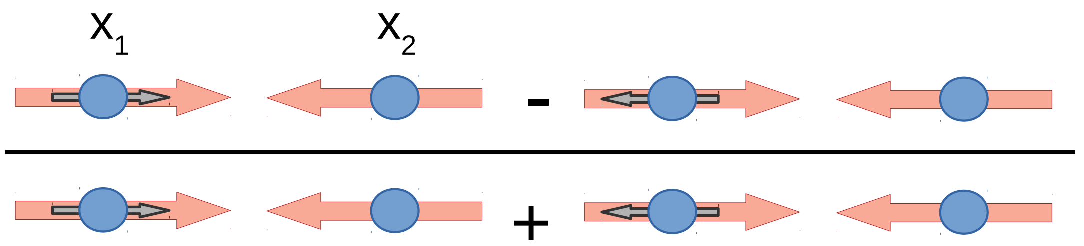
- $W^+(W^-)$: predominantly u(d) and $\bar{d}(\bar{u})$

Maximal parity violation

- W couples to left-handed particles or right-handed antiparticles

The decay process is calculable

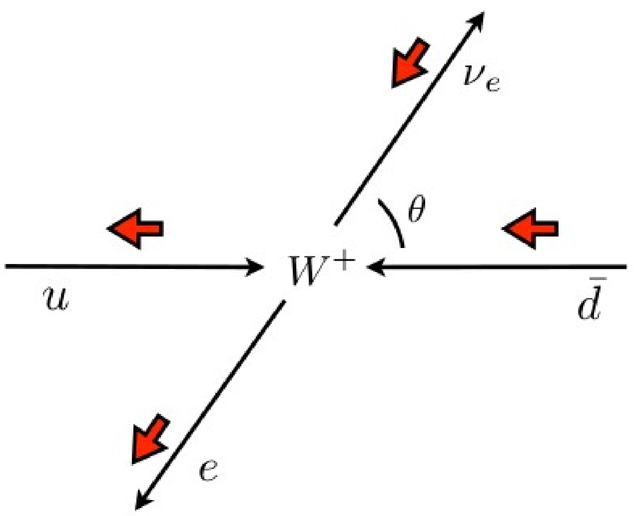
Free from fragmentation function



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

(LO)

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



Experiment Signature:

- Large p_T lepton, missing E_T

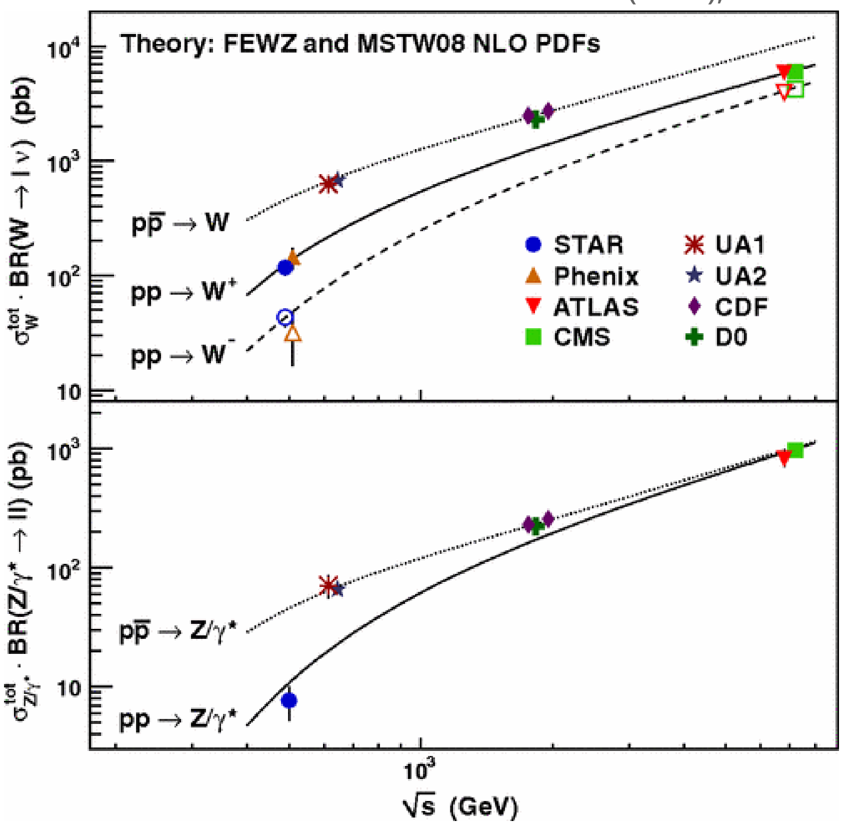
Experiment Challenges:

- Charge-ID at large |η|
- Electron-hadron discrimination
- High luminosity needed

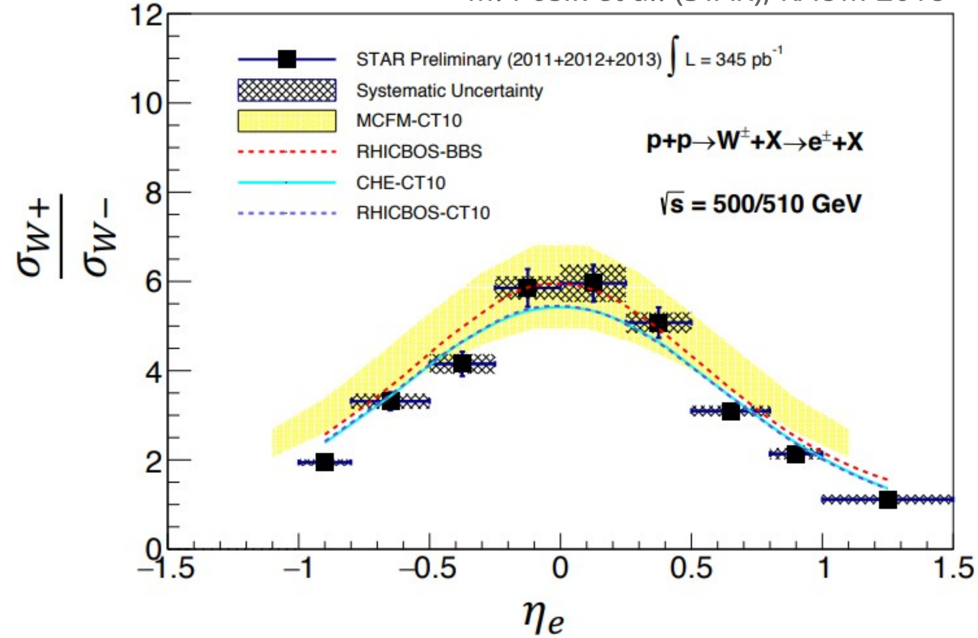
QUARK HELICITIES

Cross sections for W production

PRD 85 (2011), 092010



M. Posik et al. (STAR), RAUM 2018



$$\frac{\sigma_{W^+}}{\sigma_{W^-}} \approx \frac{u(x_1)\bar{d}(x_2) + u(x_2)\bar{d}(x_1)}{d(x_1)\bar{u}(x_2) + d(x_2)\bar{u}(x_1)}$$

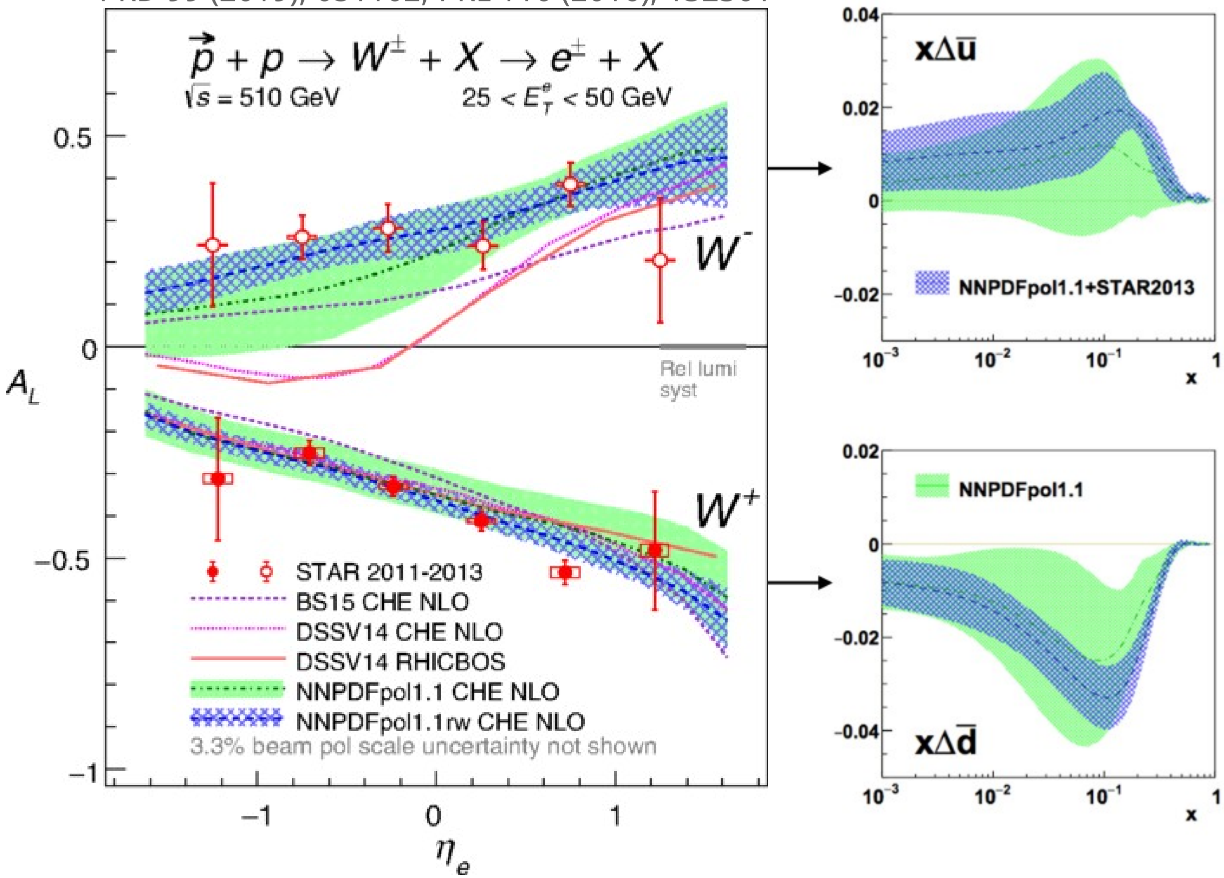
- Agreement with NLO pQCD theory and with other experiments
- Support for the NLO pQCD interpretation of asymmetry measurements

- W+/W-: Probing the $\bar{d}(x)/\bar{u}(x)$ ratio
- Complementary to NA51, E866, and SeaQuest
- STAR data cover ~0.1 < x < ~0.3, $|\eta_e| < 1$
- Run 17: 350 pb^{-1} of polarized data

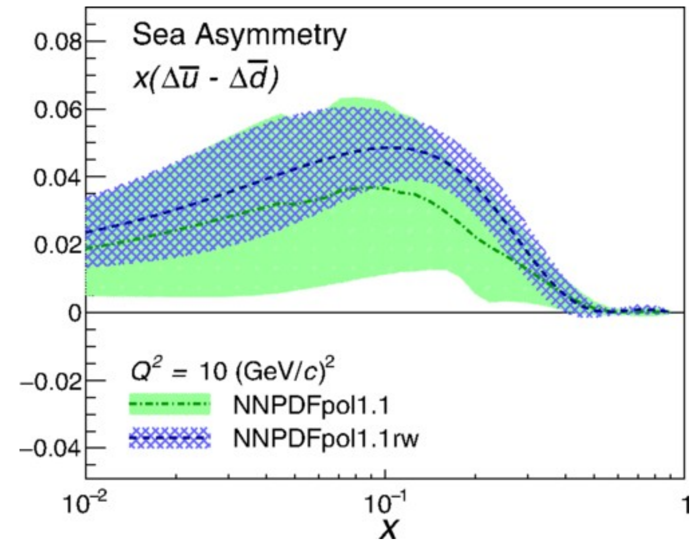
QUARK HELICITIES

Single spin asymmetry for W production at STAR

PRD 99 (2019), 051102; PRL 116 (2016), 132301



For covered lepton η: $0.05 < x_1 < 0.25$



- Significant preference for $\Delta\bar{u}$ over $\Delta\bar{d}$
- Opposite to the spin-averaged quark-sea distributions
- Verification of different nucleon structure models

- 2013 data (300 pb^{-1}) – Most precise data to date
- Combined precision (full available data set) – **important constraint on sea asymmetry**
- Predictions from DSSV and NNPDF agree with data
- Data agrees with DIS results in the valence region

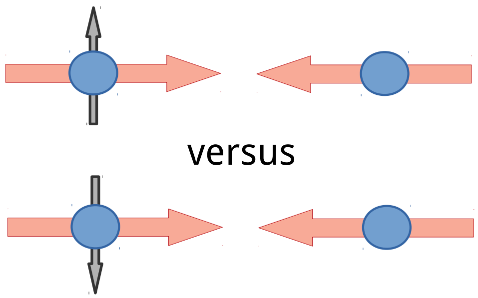
TRANSVERSITY

TRANSVERSITY

For a complete picture of nucleon spin structure at leading twist: **transversity**

Methods to access it at RHIC

Single spin asymmetries of the azimuthal distributions $\mathbf{A_{UT}}$



Spin-dependent modulation of hadrons in jets
Collins function (TMD FF)

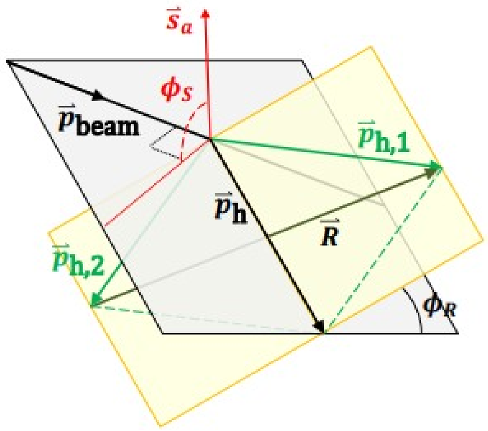
Correlation of transverse spin of fragmenting quark and transverse momentum kick given to fragmentation hadron

Di-hadron correlation measurements
"interference FF" (collinear framework)

Correlation of transverse spin of fragmenting quark and and momentum cross-product of di-hadron pair

TRANSVERSITY

Interference Fragmentation Function (IFF)

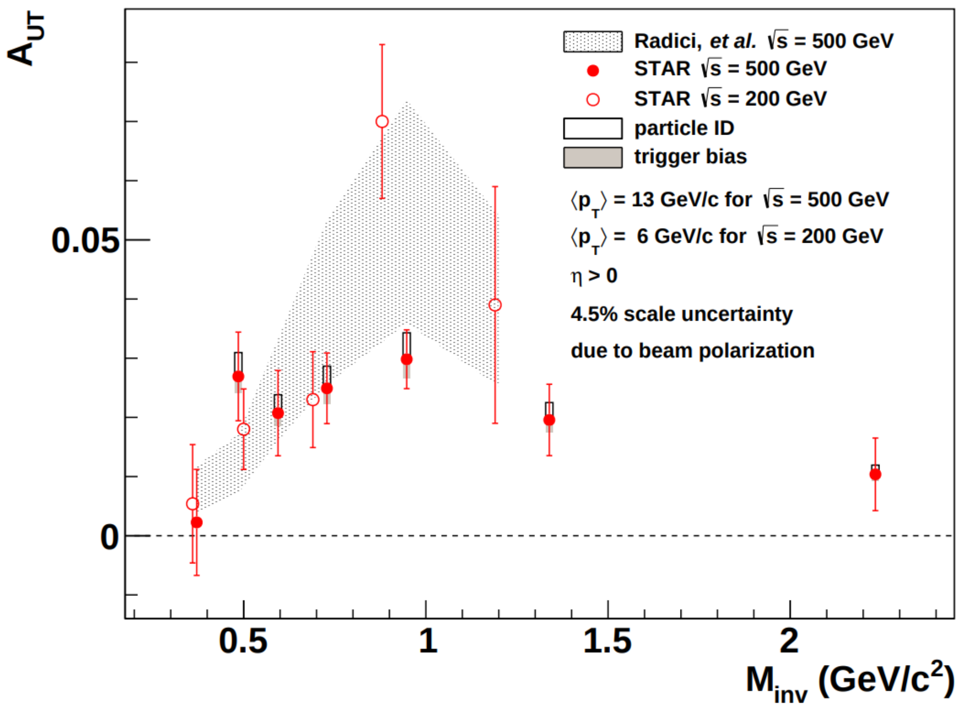


- The angle $\varphi_{RS} = \varphi_R - \varphi_S$ modulates the asymmetry due to the product of transversity and the IFF by $\sin(\varphi_{RS})$

- First **significant transversity signal** measured in the central detector in pp collisions
- Well described by **recent IFF asymmetry calculations** incorporating SIDIS and Belle e^+e^- data

- **Gobal analysis** including the IFF results from 200 GeV pp collisions
  M. Radici and A. Bacchetta, PRL 120, (2018) 192001
  - Reduction of the uncertainty for h_1^u
  - uncertainty for h_1^d: dominated by $g \rightarrow \pi^+\pi^-$ FF

PLB 780 (2018), 332



TRANSVERSITY

Interference Fragmentation Function (IFF)

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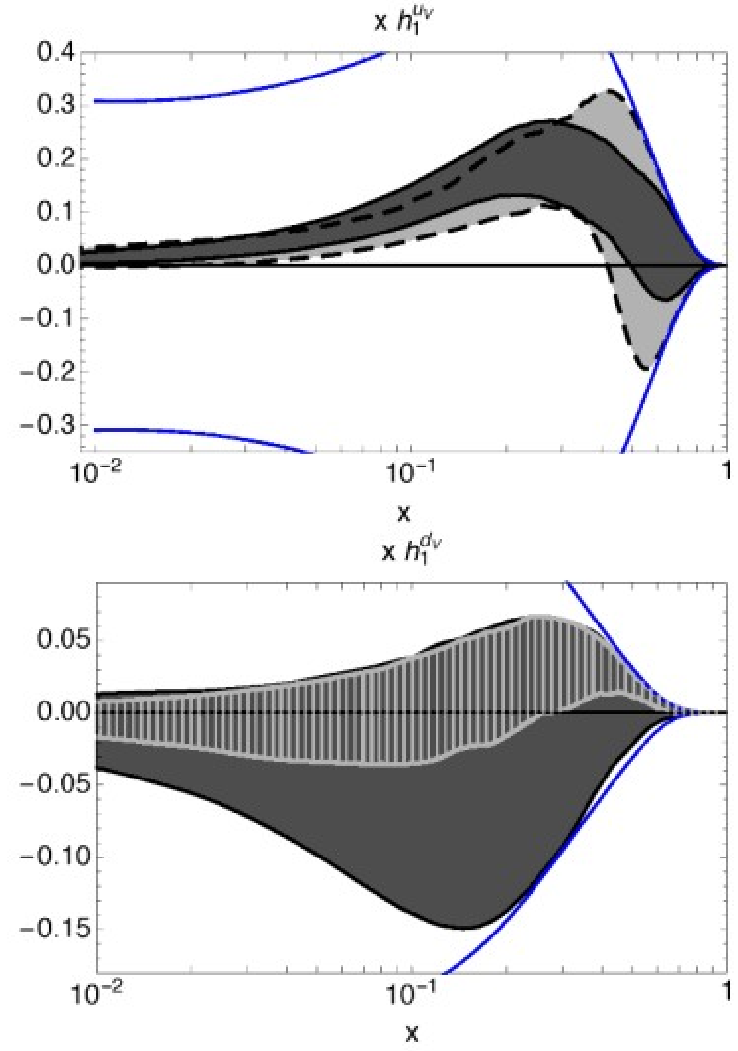
M. Radici and A. Bacchetta
PRL 120 (2018), 192001



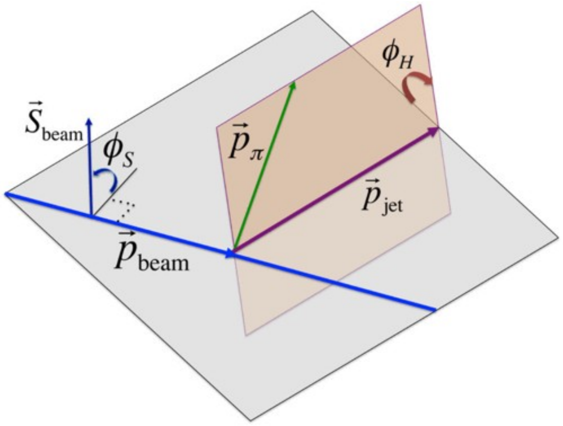
TRANSVERSITY

Collins asymmetry

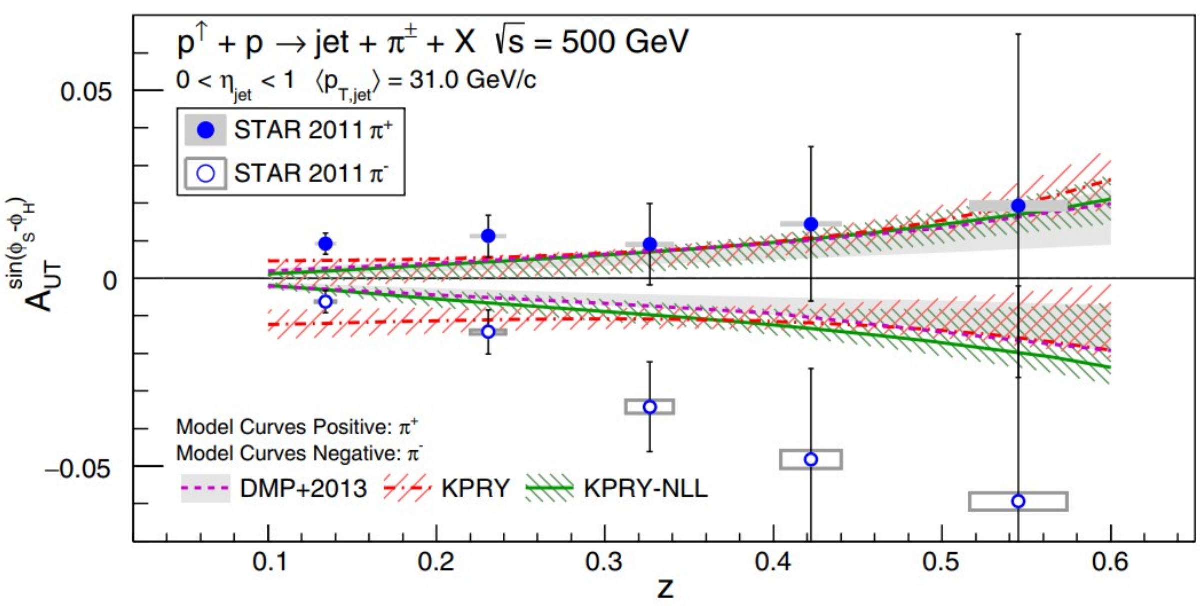
Transversity x Collins

$$d\sigma_{UT} \sim d\sigma_{UU}[1 + A'_{UT}\sin(\phi_s - \phi_h) + A''_{UT}\sin(\phi_s - 2\phi_h)]$$

The angle $\varphi_{SH} = \varphi_S - \varphi_H$ modulates the asymmetry due to the product of transversity and the Collins function by $\sin(\varphi_{RS})$



PRD 97 (2018), 032004



D'Alesio, Murgia & Pisano
PLB 773 (2017), 300

Kang, Prokudin, Ringer & Yuan,
PLB 774 (2017), 635
without and with evolution

- Theory predistions using transversity and Collins FF extracted from SIDIS and e^+e^-
- TMD Evolution effects appear to be small

TRANSVERSITY

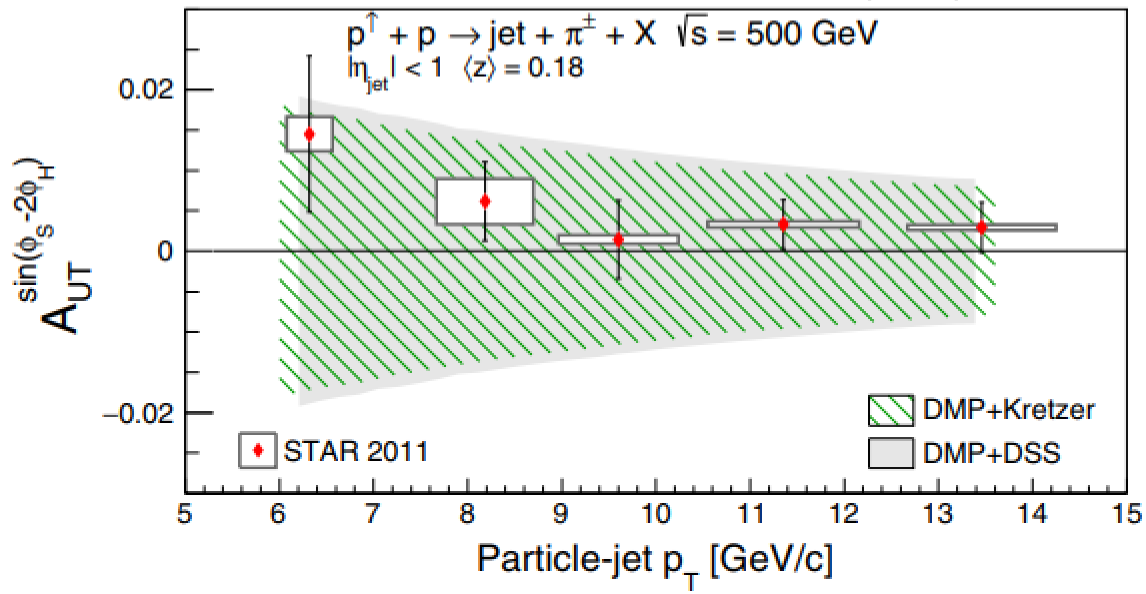
Collins-like Asymmetry

Linearly polarized gluons x Collins-like

$$d\sigma_{UT} \sim d\sigma_{UU}[1 + A'_{UT}\sin(\phi_s - \phi_h) + A''_{UT}\sin(\phi_s - 2\phi_h)]$$

- First ever measured Collins-like Asymmetry
- First limit on linearly polarized gluons in a polarized proton
- Best sensitivity at low p_T
- First input to constrain models

PRD 97 (2018), 032004



More from STAR on IFF and Collins

- Collins results from 2012 200 GeV being finalized
- 200 GeV data from 2015 (x 2 more then 2012)
- 500 GeV data from 2017 (x 12 more)

Precision data at fixed x and different √s → ideal to constrain TMD evolution

SIVERS FUNCTION – SIGN CHANGE

SIVERS FUNCTION – SIGN CHANGE

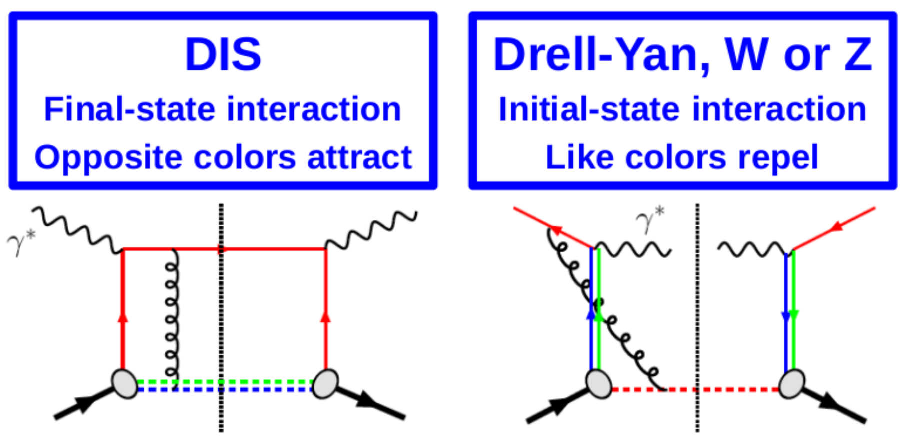
Transverse spin structure

- Most observables in pp only related through **Twist-3 formalism**: collinear quark-gluon-quark correlations (1 hard scale needed, e.g., p_T of hadron or jet)
- **TMD parton distributions**: e.g. Collins or Sivers functions (require 2 scales, e.g., p_T and M of W)

Sivers function - describes correlation between parton's **transverse momentum** inside the proton with proton **transverse spin** (initial state TMD)

Not universal in hard scattering
Rescattering of the stuck parton in the color field of the remnant of polarized proton

$\text{Sivers}_{DIS} = - \text{Sivers}_{DY/W/Z}$



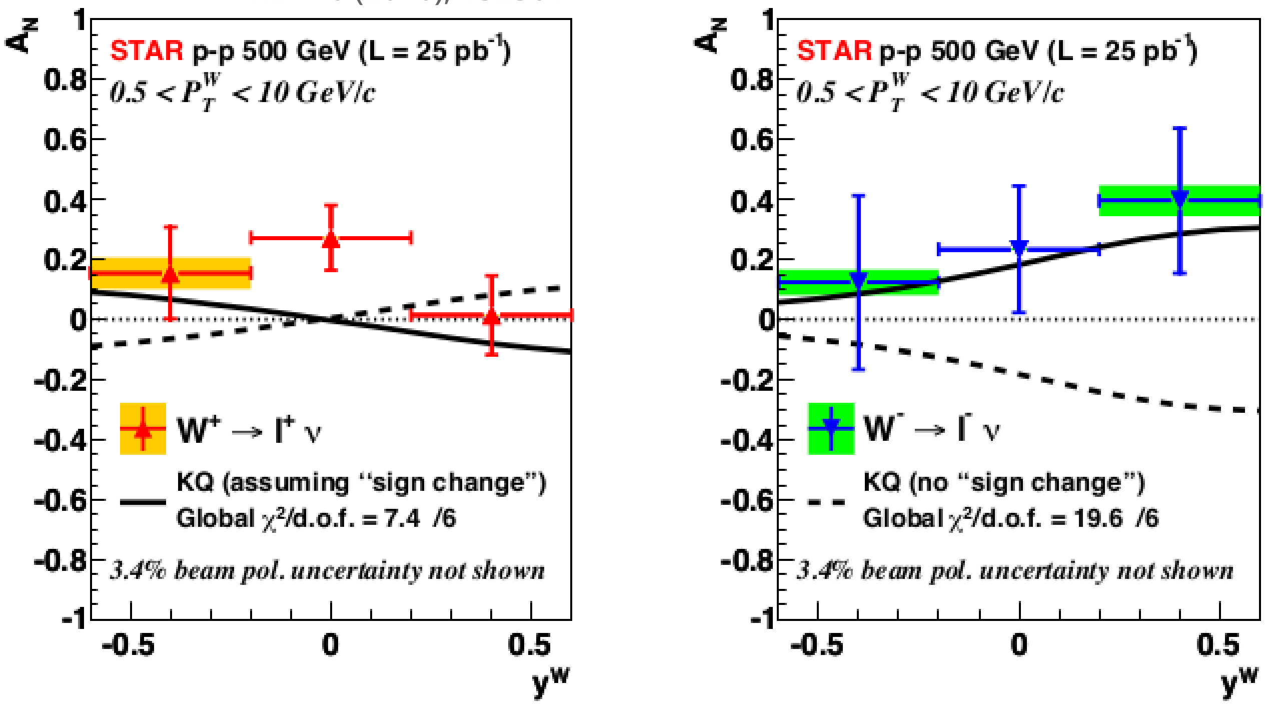
Fundamental prediction about the nature of QCD

SIVERS FUNCTION – SIGN CHANGE

Nonuniversality of Sivers function in QCD: $\text{Sivers}_{DIS} = -\,\text{Sivers}_{DY/W/Z}$

→ Critical test of k_T factorization

PRL 116 (2016), 132301



- STAR: A_N for W production with 25 pb^{-1} of data – W kinematics fully reconstructed
- **2017 results** will be based on 350 pb^{-1} data – more definite test
- **Other opportunities**, e.g. photons (sign change in the Twist-3 formalism), Drell-Yan
- Gradual **upgrades** to existing STAR forward instrumentation

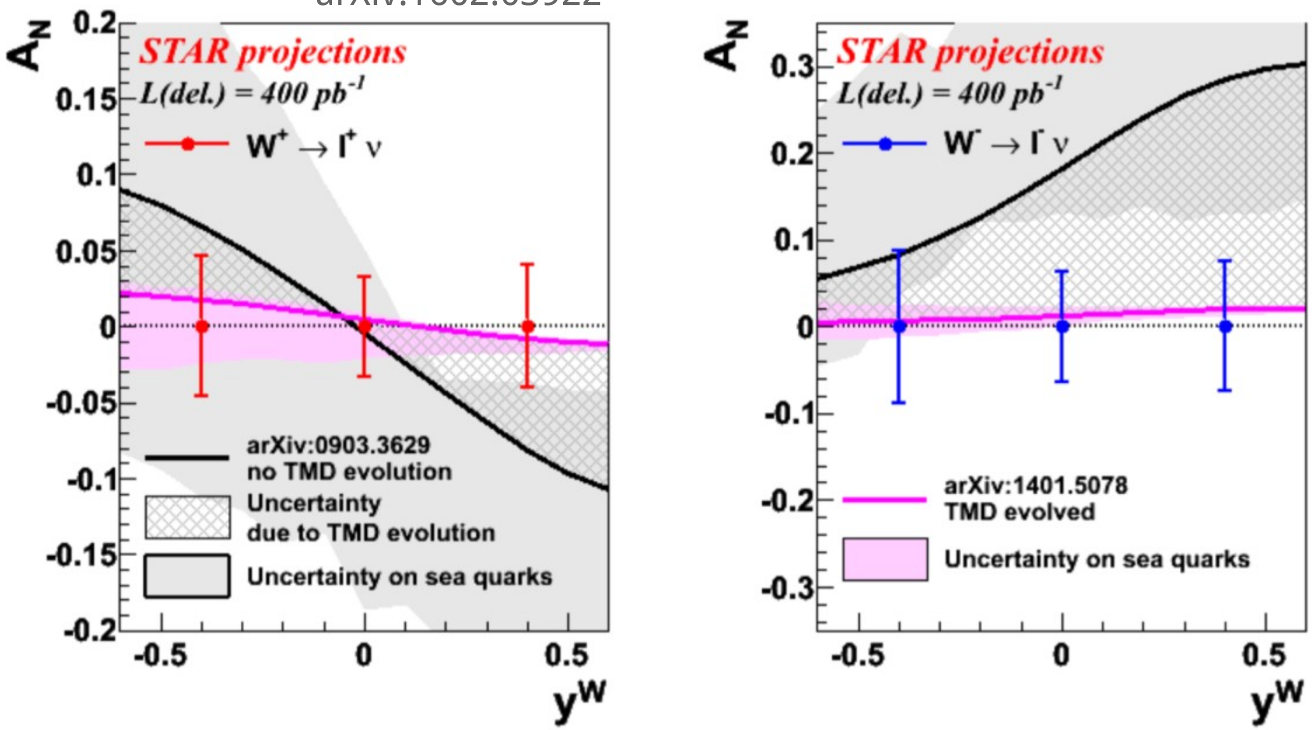
- Fit based on Kang-Qiu (KQ) model Z. Kang and J. Qiu, PRL 103 (2009), 172001
- Results **favor sign change** if evolution effects are not large

SIVERS FUNCTION – SIGN CHANGE

Nonuniversality of Sivers function in QCD: $\text{Sivers}_{DIS} = -\ \text{Sivers}_{DY/W/Z}$

→ Critical test of k_T factorization

arXiv:1602.03922



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- **Other opportunities**, e.g. photons (sign change in the Twist-3 formalism), Drell-Yan
- Gradual **upgrades** to existing STAR forward instrumentation

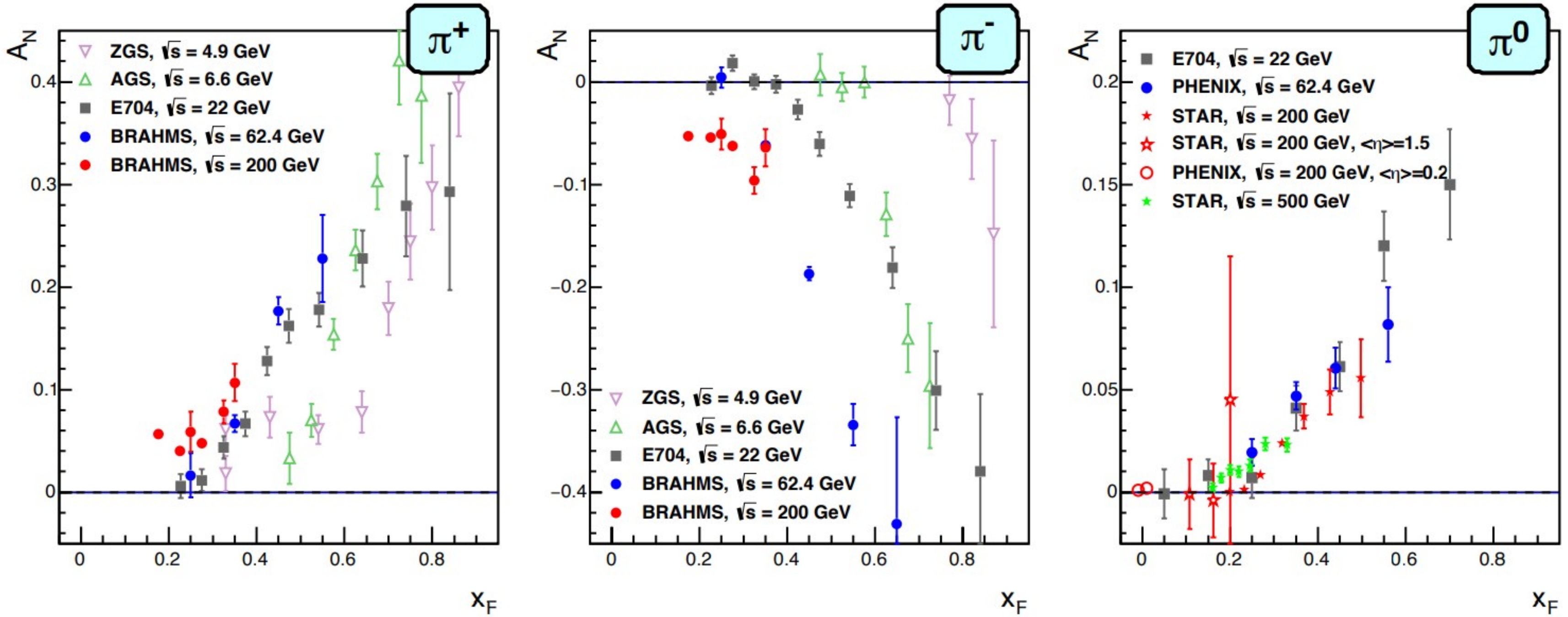
- Kang-Qiu (KQ) model Z. Kang and J. Qiu, PRL 103 (2009), 172001
  → No TMD evolution
- EIKV model M. Echevarria, A. Idilbi, Z. Kang and I. Vitev, PRD 89 (2014), 074013
  → TMD evolved

ORIGIN OF LARGE FORWARD A_N

ORIGIN OF LARGE FORWARD A_N

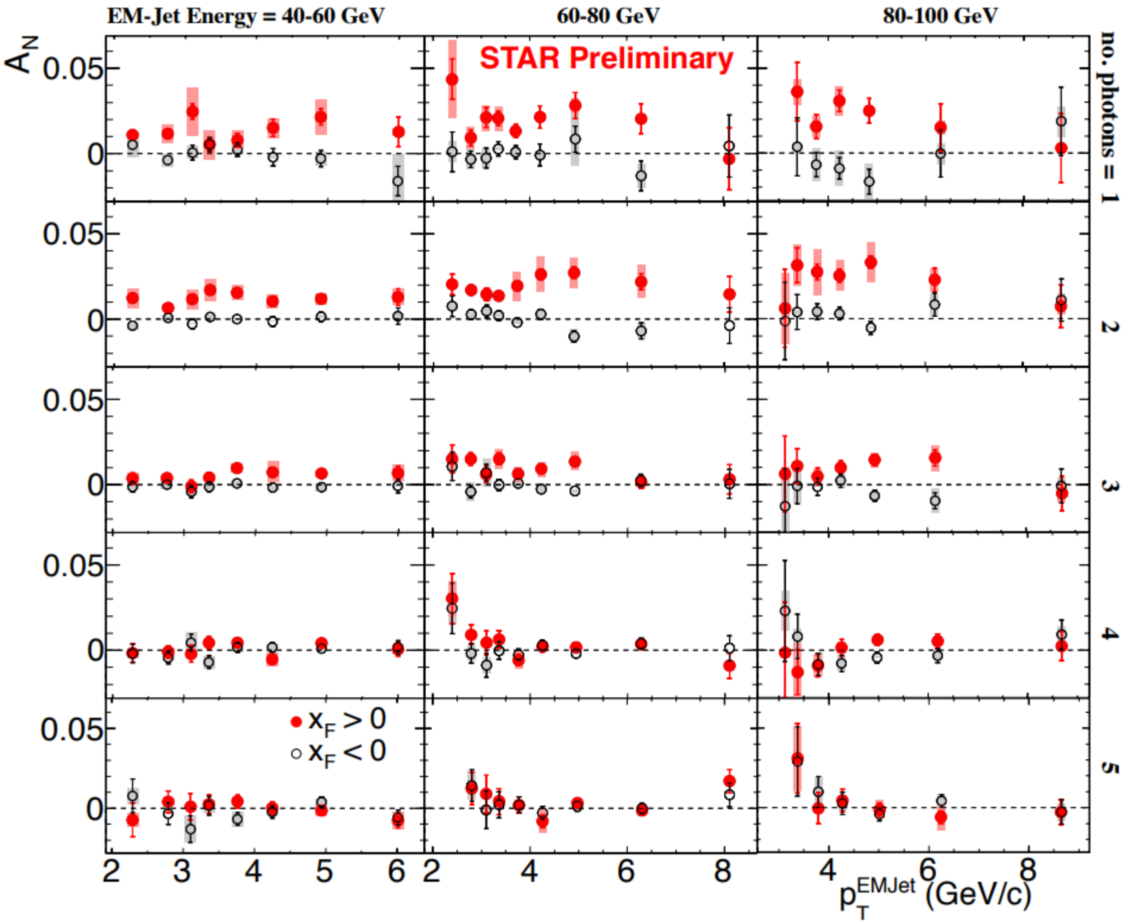
Puzzle since E704

arXiv:1602.03922

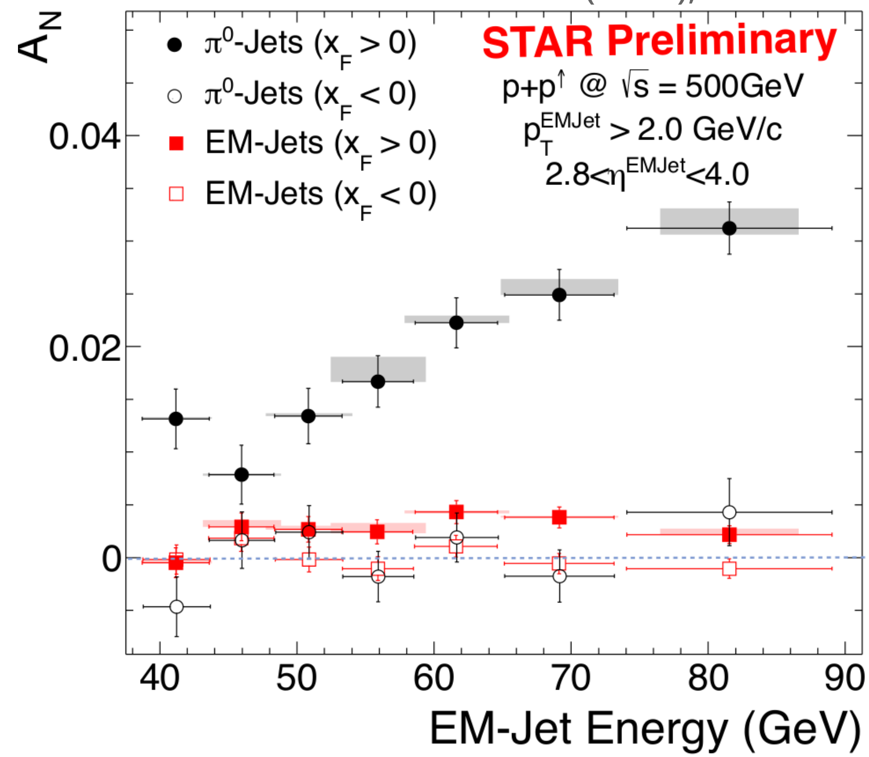


- Large asymmetries nearly independent on √s (especially π^0)
- Interpretations within Twist-3 formalism:
  - K. Kanazawa, Y. Koike, A. Metz and D. Pitonyak, PRD 89 (2014), 111501(R) – 3-parton collinear FF fit to RHIC data + soft-gluon pole term fixed – good description of π A_N
  - L. Gamberg, Z.-B. Kang, and A. Prokudin, PRL 110 (2013), 232301 – description of forward jet A_N from A_NDY Collaboration, PLB 750 (2015), 660 – Twist-3 parton correlation function for u and d valence quarks cancel - opposite sign but equal magnitude of Sivers functions from SIDIS

ORIGIN OF LARGE FORWARD A_N



M. Mondal et al. (STAR), DIS 2014



- Description of A_N beyond pQCD 2 → 2 process
- Low-multiplicity observation suggests diffraction mechanism
- STAR Roman Pots + FMS ($2.6 < \eta < 4$) – direct access to diffractive A_N

NUCLEAR DEPENDENCE OF A_N

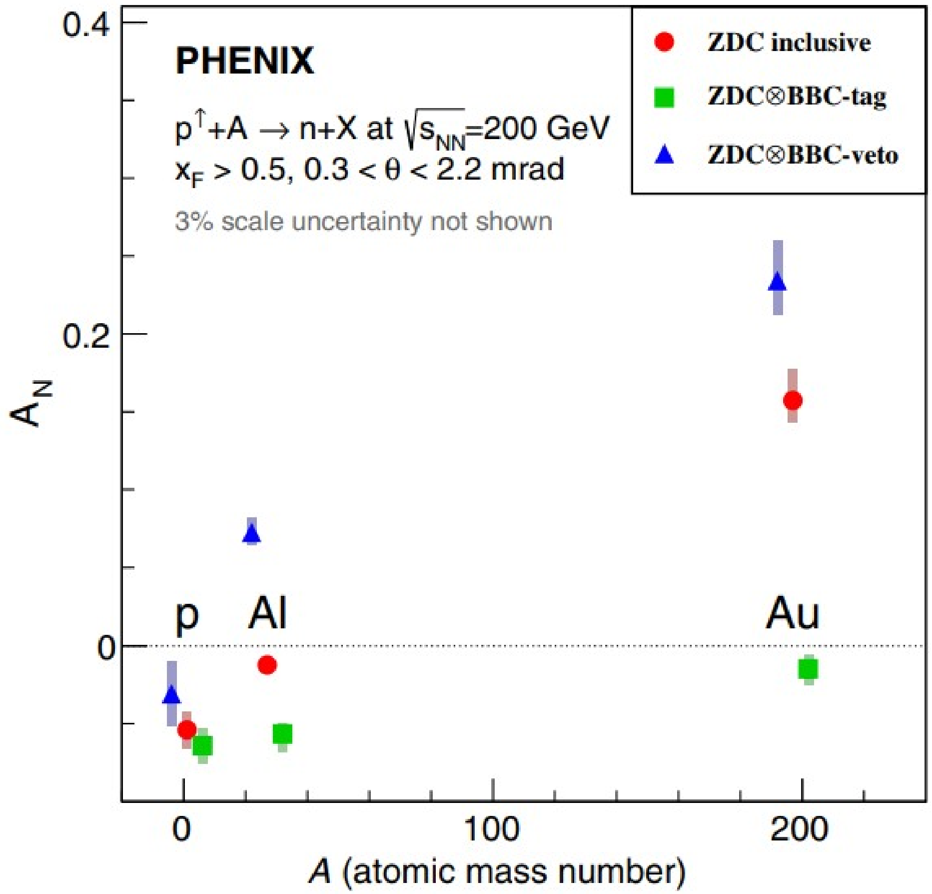
Very forward neutron

In the **perturbative** region:

- color-glass-condensate models: hadronic A_N should decrease with increasing A
  e.g. Y. V. Kovchegov and M. D. Sievert, PRD 86, 034028 (2012)

- Some approaches based on pQCD factorization: A_N would stay approximately the same
  J.-W. Qiu, in Proceedings of the RIKEN/RBRC Workshop: Forward Physics at RHIC, 2012

No studies in **nonperturbative** region or diffractive scattering



Possible explanation:

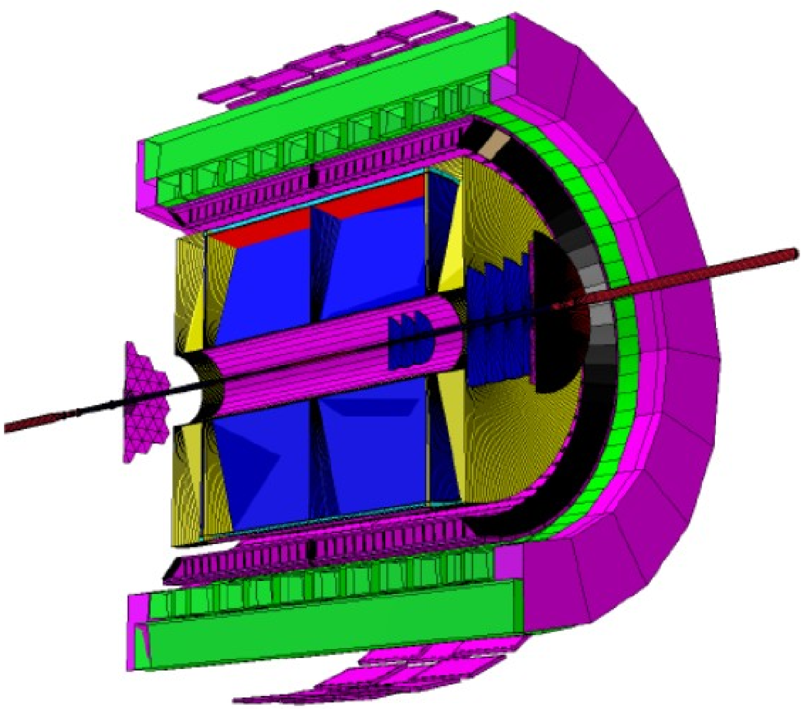
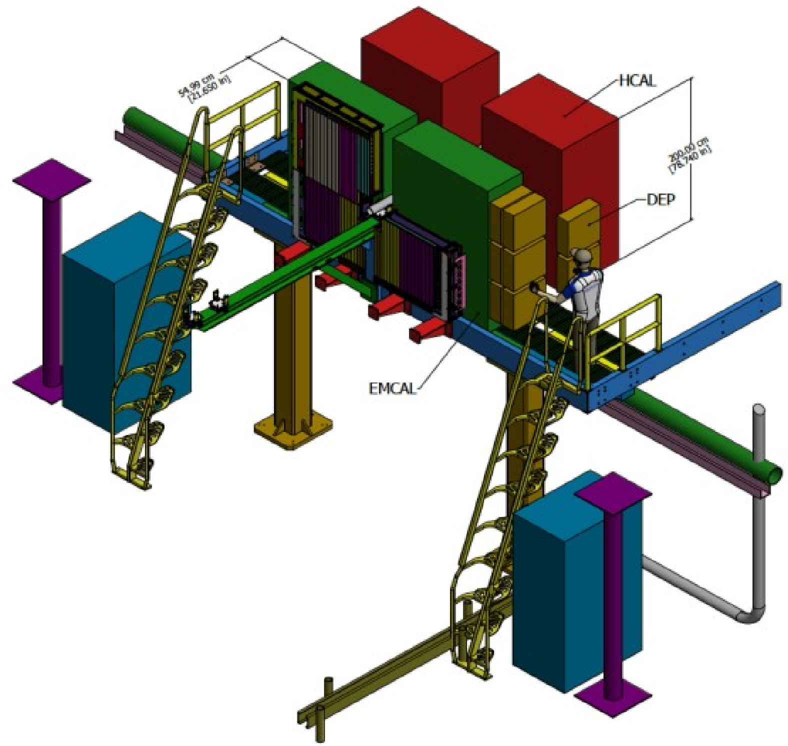
- EM processes important at large Z
- nonresonant photo-π^+ production and n from from photonucleon excitation - Δ resonance

OUTLOOK

STAR Forward Upgrade

- Access to the charged hadron asymmetries up to the highest √s at RHIC
- Full jets in forward direction at √s = 200 and 500 GeV - TMDs at low and high x and Δg(x) at small x
- Precision A_N (Drell-Yan) to complete the Sivers measurements

- **Tracking:** Si disks + small Thin Gap Chambers
- **Calorimetry:** hadronic and electromagnetic

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648

SUMMARY

RHIC - critical and complimentary role in resolving the spin structure of the proton.

From **longitudinal** polarized p+p collisions RHIC has provided unique insight into:

- The **polarized sea quark** distributions via W/Z production.
- Constraints on the **polarized gluon distribution** through jet and di-jet A_{LL}
  - ➔ Towards lower x: high luminosity 2013 data at √s = 510 GeV
  - ➔ Towards precision in current x region: 2015 data at √s = 200 GeV

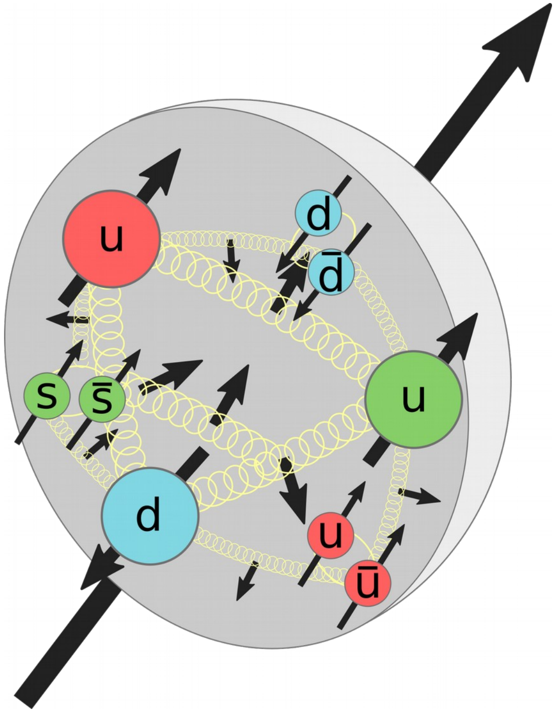
Transverse polarized p+p collisions at RHIC have accessed the transverse spin processes:

- **Sivers' sign-change** from W-boson data
  - ➔ Sivers' measurements with W-bosons, Drell-Yan, and photons in 2017 (x 12 more data)
- **Transverity** sensitive quantities through the **Collins asymmetry and IFF**
- **Gluon linear polarization** through the first measurement of the **Collins-like asymmetry**
  - ➔ More data from 2015 run (x 1.5 for √s = 200 GeV and x 12 for 510 GeV)

Ongoing forward upgrades to STAR

- Aiming for complete upgrade for potential polarized pp run at 500 GeV in 2022 and future data taking periods

THANK YOU



mariakzurek@lbl.gov

@mariakzurek

PLANS

RHIC cold-QCD plan for 2017-2023 (arXiv:1602.03922):

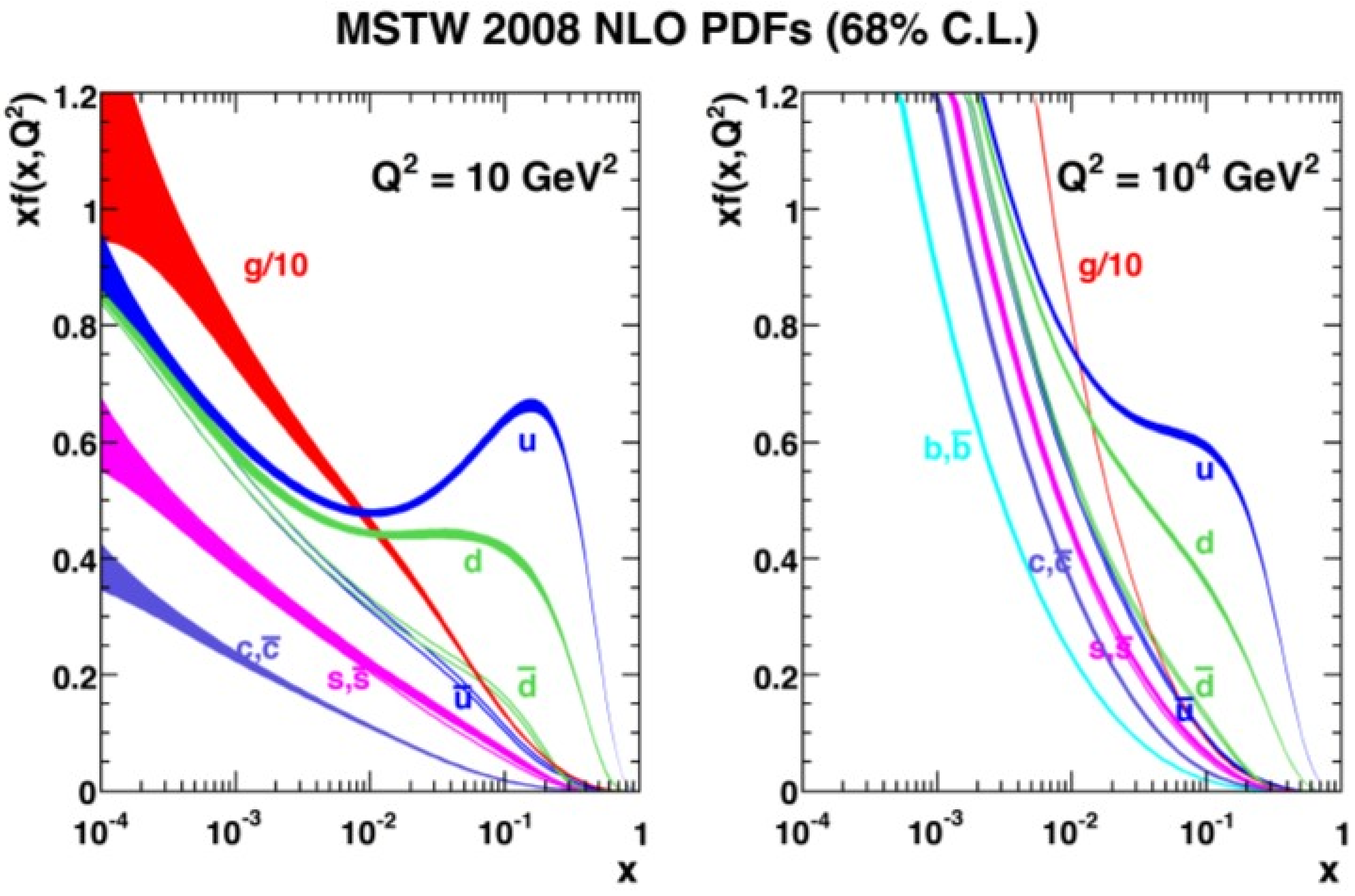
	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3 First look at GPD Eg	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/Ψ in UPC	A_N^{DY}: Postshower to FMS@STAR **None** **None**
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η evolution of ETQS fct. properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for γ A_N for diffractive events	Yes Forward instrum. **None** **None**
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAu}(DY):Yes Forward instrum. **None** Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl}: direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAl}(DY): Yes Forward instrum. **None** Yes Forward instrum.

PLANS

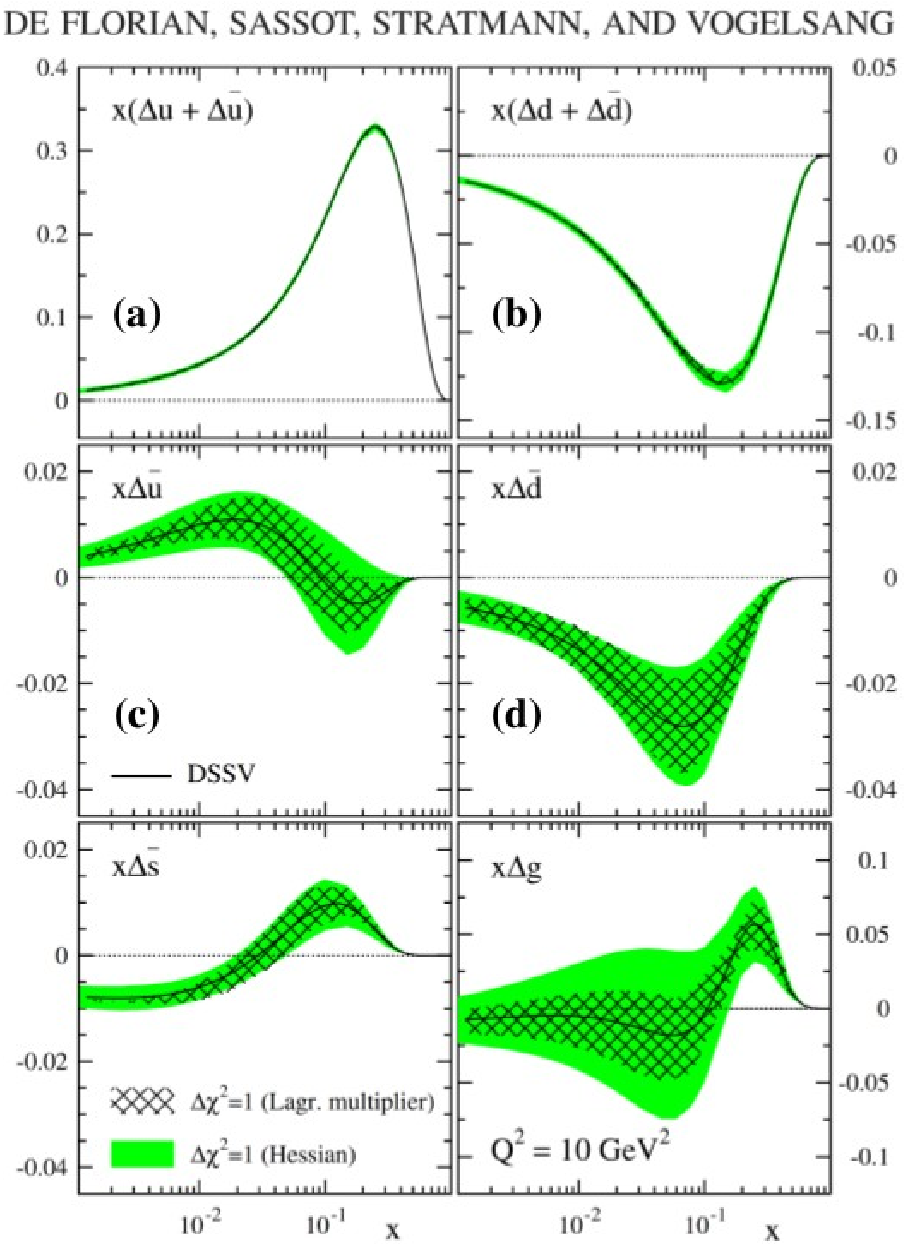
K. N. Barish - Spin 2018, Ferrara

	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	Subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Forward instrum. ECal+HCal+Tracking
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Clear signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+Hcal+Tracking
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking
Potential future running	2021	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Forward instrum. ECal+HCal+Tracking
	2021	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Forward instrum. ECal+HCal

UNPOLARIZED PDFs



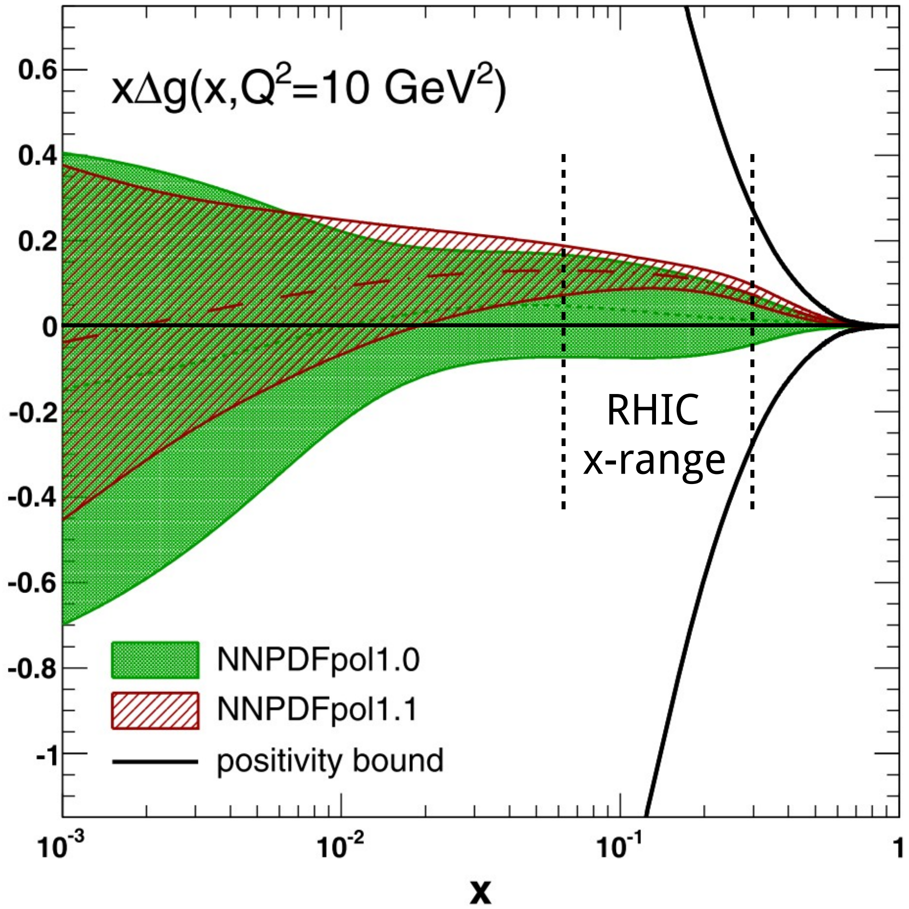
HELICITY DEPENDENT PDFs



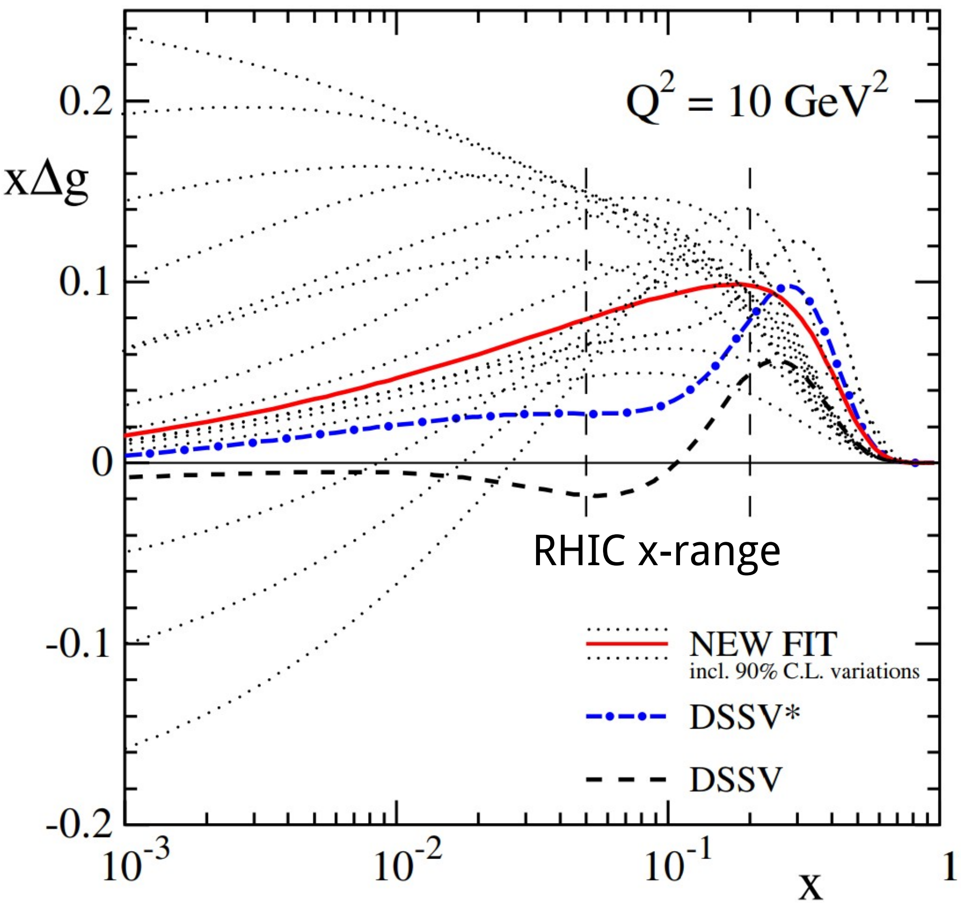
STATUS OF ΔG

Impact of ALL from 2009 data on ΔG

Nucl. Phys. B 887 (2014) 276-308



PRL 113 (2014) 1, 012001

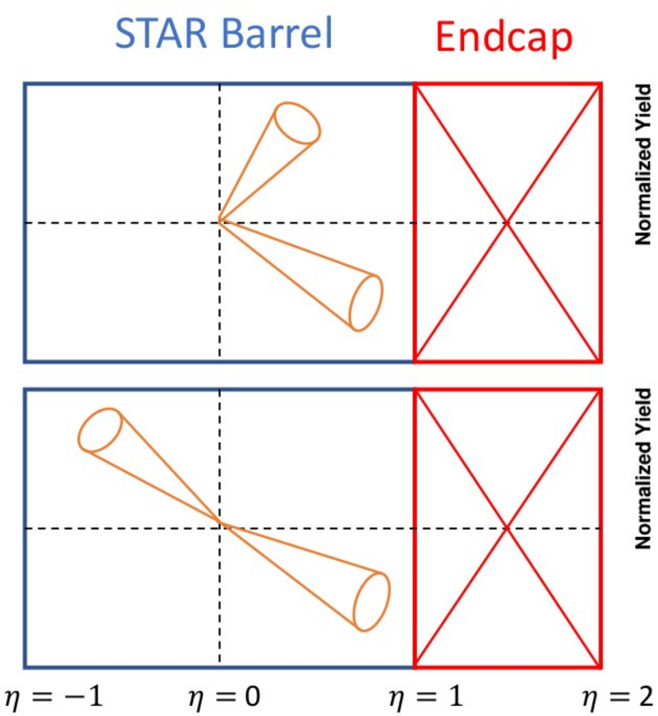


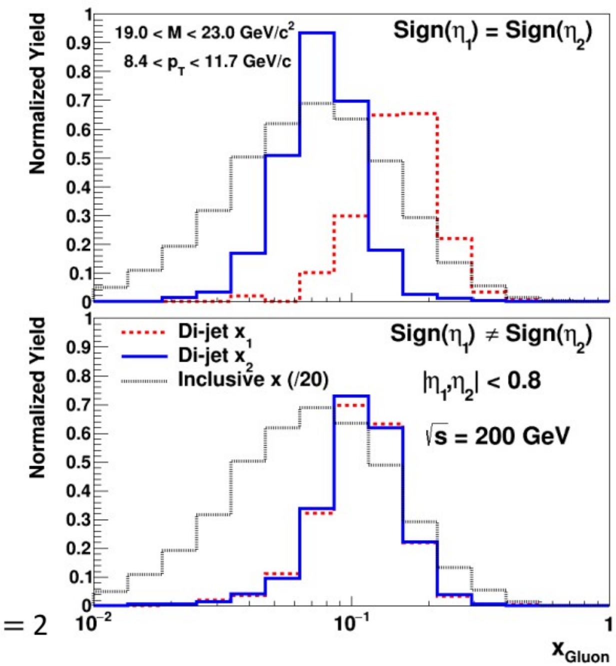
DI-JETS MEASUREMENT

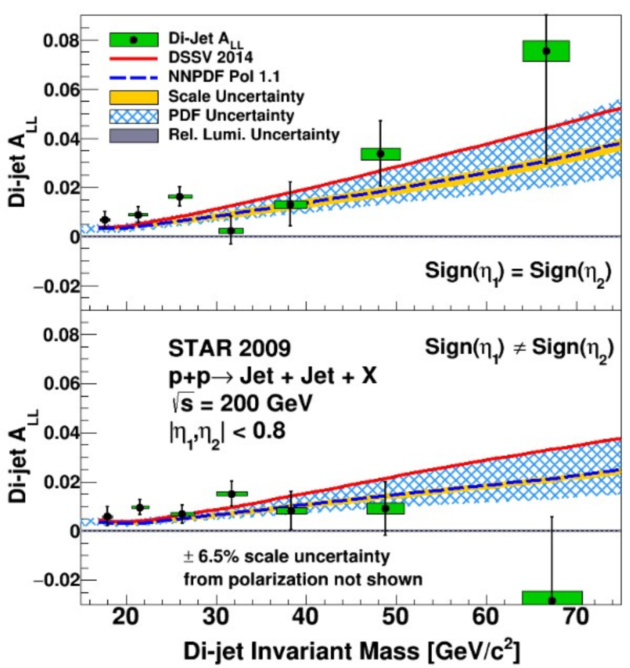
Towards smaller x_g and complementary probes

- Di-jets give stricter constraints to underlying **partonic kinematics**
- May place better constraints on **functional form of Δg(x)**
- Much narrower ranges of initial state partonic momentum tested
- Different di-jet topologies enhances sensitivity of the data to selected x

Phys. Rev. D 95, 071103 (2017)





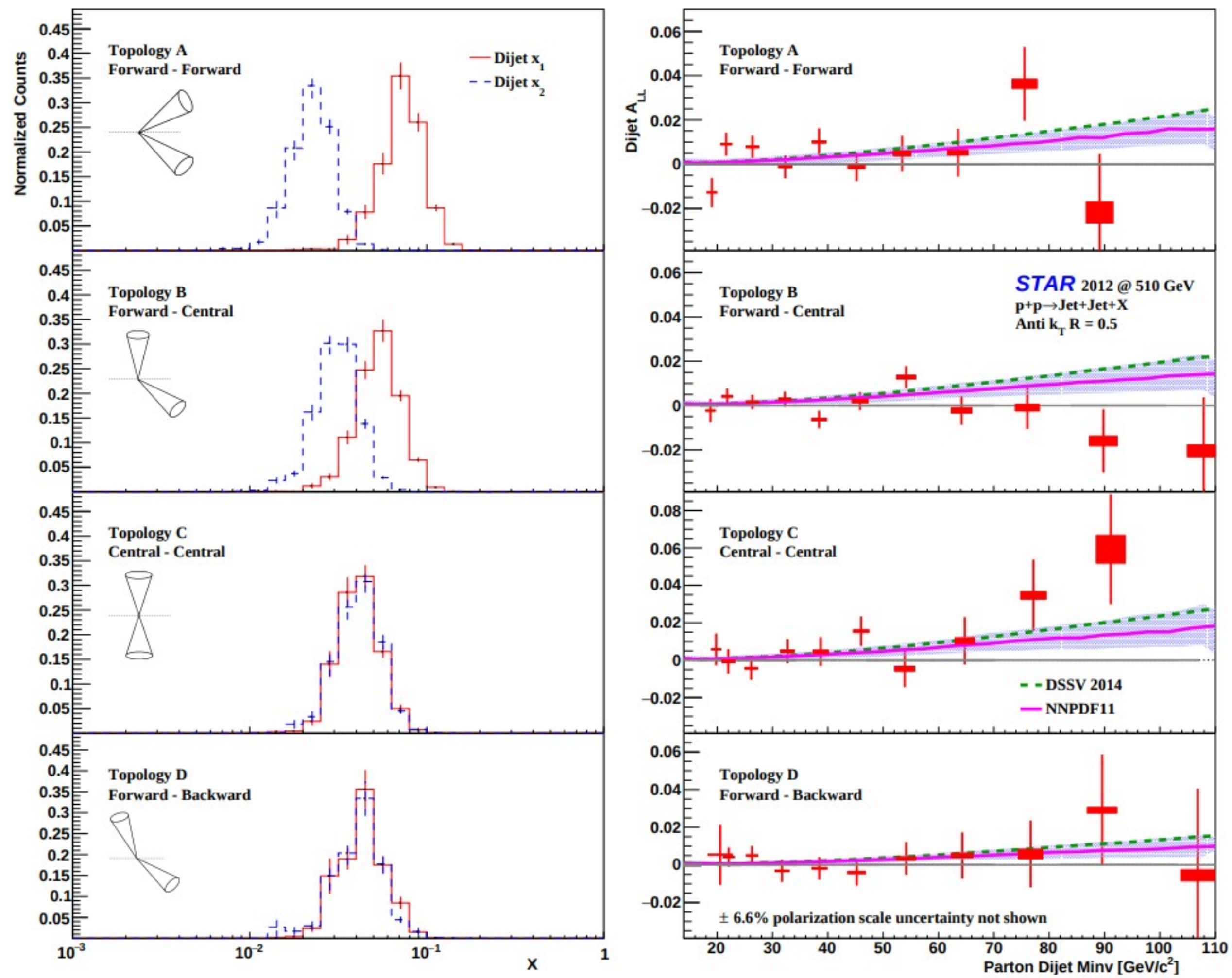


2015 data at 200 GeV (2x statistics)

DI-JET MEASUREMENT

Towards smaller x_g and complementary probes: $\sqrt{s}$ = 510 GeV

ArXiv:1906.02740, Accepted to publication in PRD



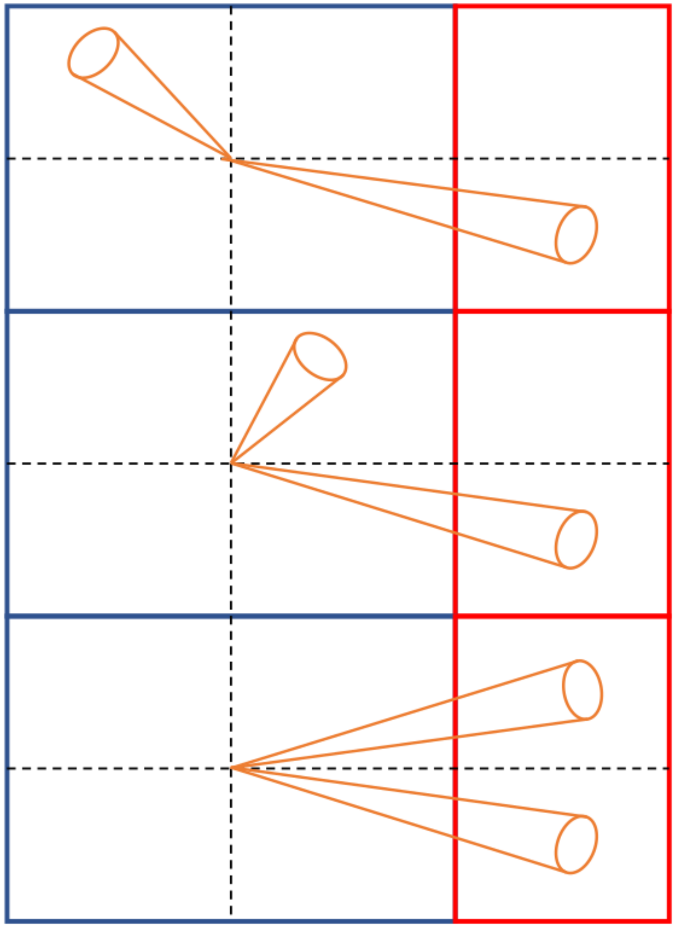
Used topology

η_3 and η_4 Regions	Physics Description
$0.3 < \|\eta_{3,4}\| < 0.9$; $\eta_3 \cdot \eta_4 > 0$	Forward-Forward
$\|\eta_{3,4}\| < 0.3$; $0.3 < \|\eta_{4,3}\| < 0.9$	Forward-Central
$\|\eta_{3,4}\| < 0.3$	Central-Central
$0.3 < \|\eta_{3,4}\| < 0.9$; $\eta_3 \cdot \eta_4 < 0$	Forward-Backward

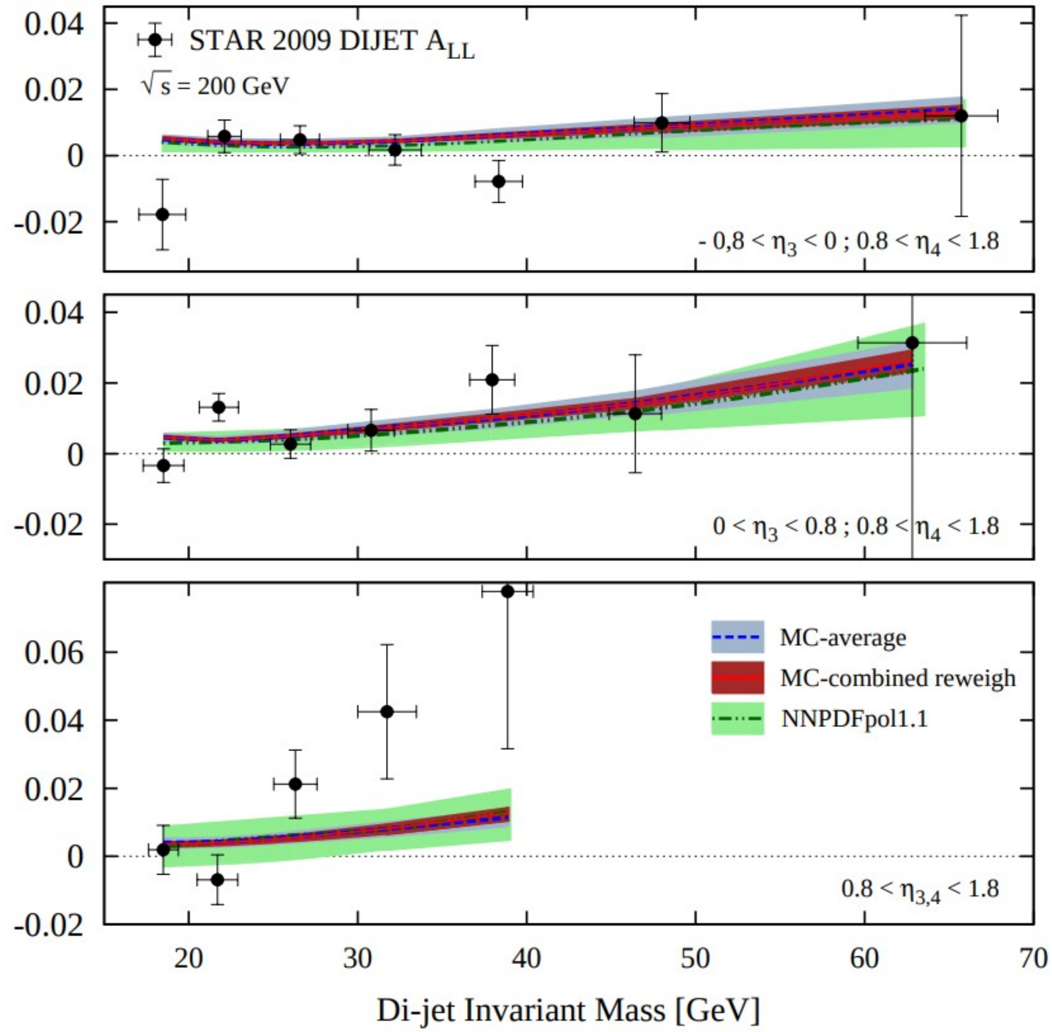
- Analysis with 2013 data - high luminosity 510 GeV: ongoing

DI-JET MEASUREMENT

Impact on Δg(x)



arXiv 1902.10548

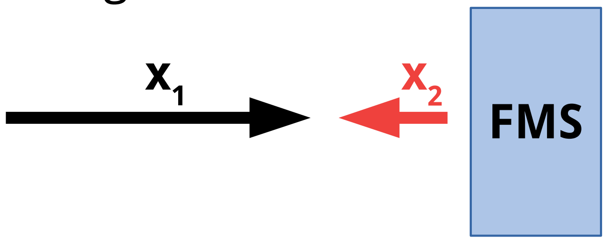


- Influence of central and forward di-jets from 2009 data √s = 200 GeV on DSSV calculations

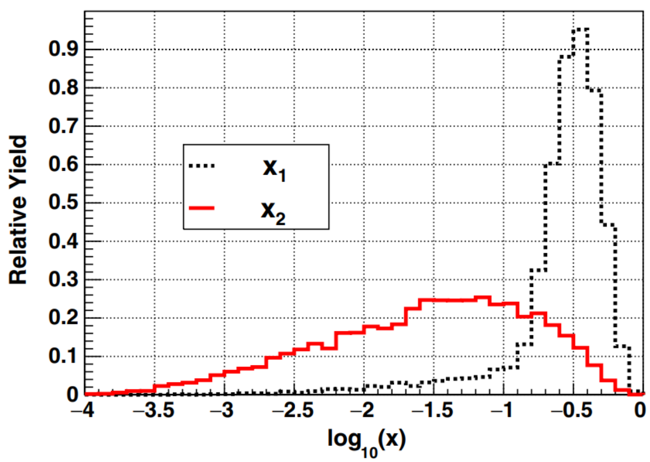
FORWARD PION PRODUCTION

Towards smaller x_g and complementary probes

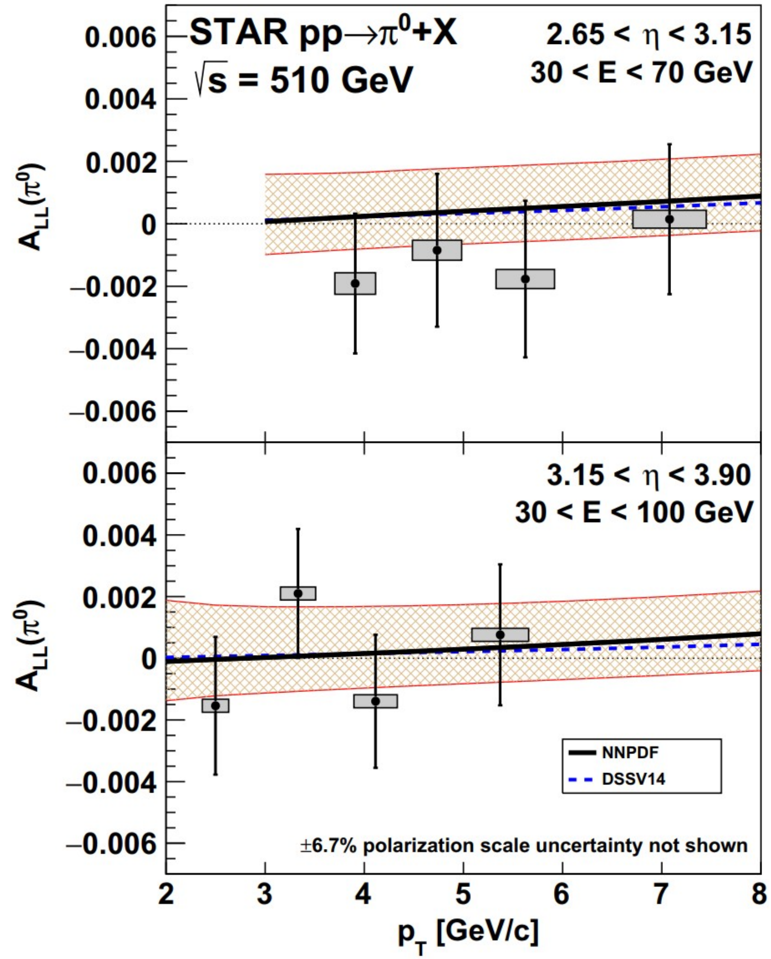
- A_{LL} of neutral pions at 510 GeV
- Measured with FMS ($2.6 < \eta < 4$)
- Access to gluons **x > 0.001**



1 – likely quark, 2 – likely gluon



PRD 98, (2018) 032013



- All available 510 GeV analyzed: run 2012 (82 pb^{-1}) and 2013 (300 pb^{-1})
- Run 2015 at 200 GeV (50 pb^{-1}) – analysis underway. Can probe $x > 0.0025$.

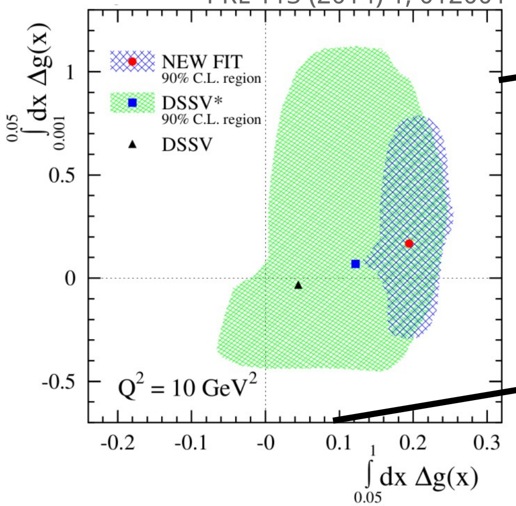
HELICITY OUTLOOK

Helicity structure of proton from STAR

1. Non-perturbative sea-quark polarization at W-mass scale, free of fragmentation uncertainties

2. Insight into gluon polarization:

PRL 113 (2014) 1, 012001



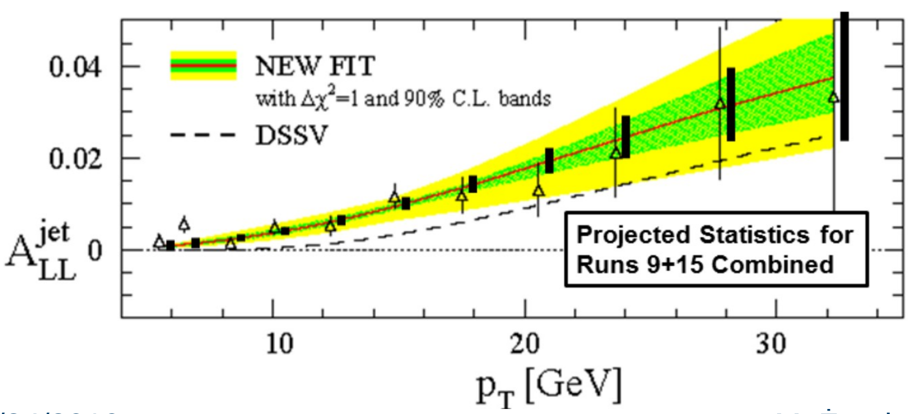
Low-x range

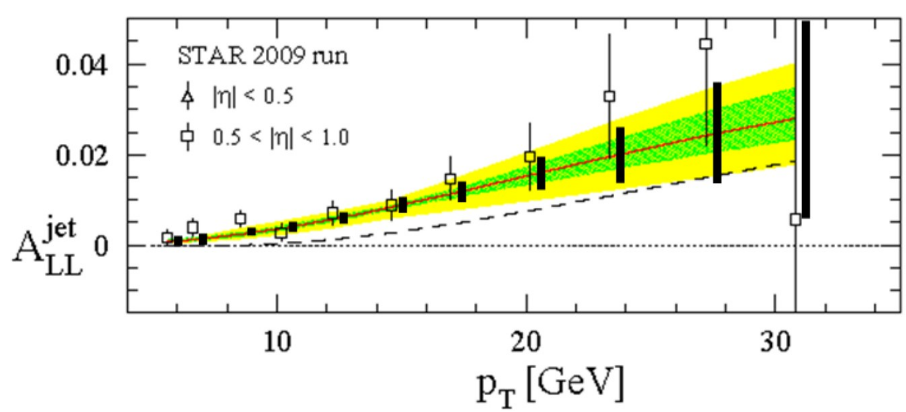
- Iclusive jets at 510 GeV
- Di-jets at 510 GeV in mid-rapidity region
- Forward pion measurements with FMS

High-x range

Run 2015 at 200 GeV (50 pb^{-1})
Further precision:

- Central inclusive jet measurement
- Central di-jet measurement

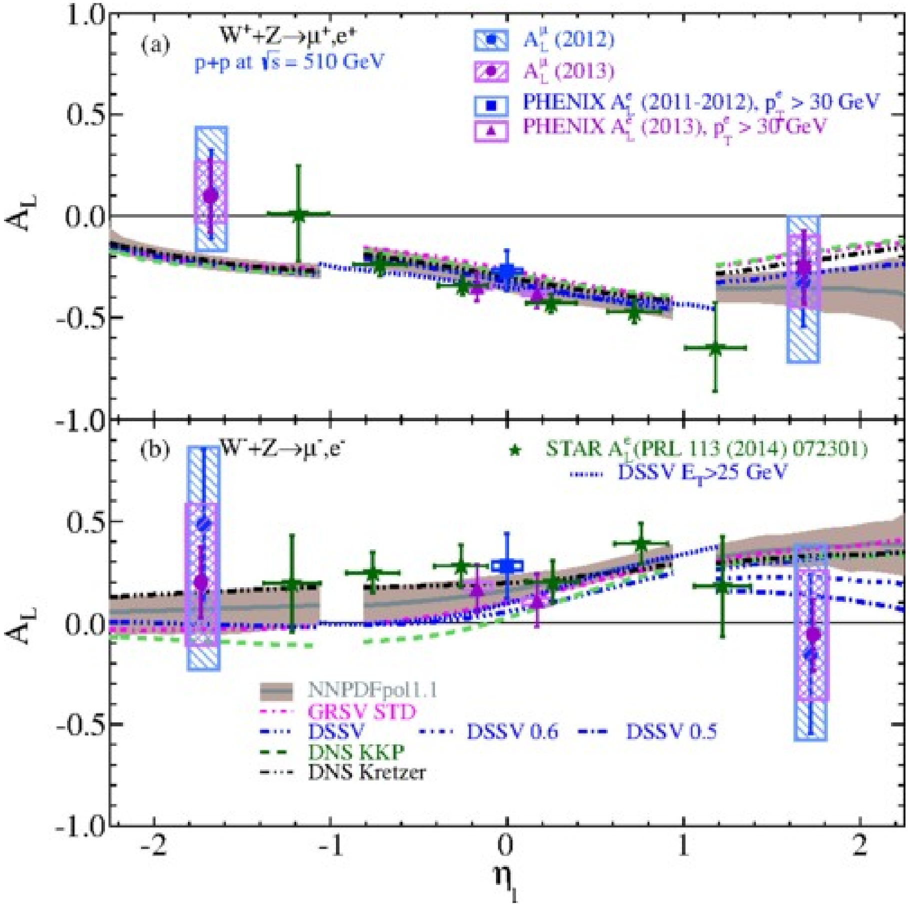




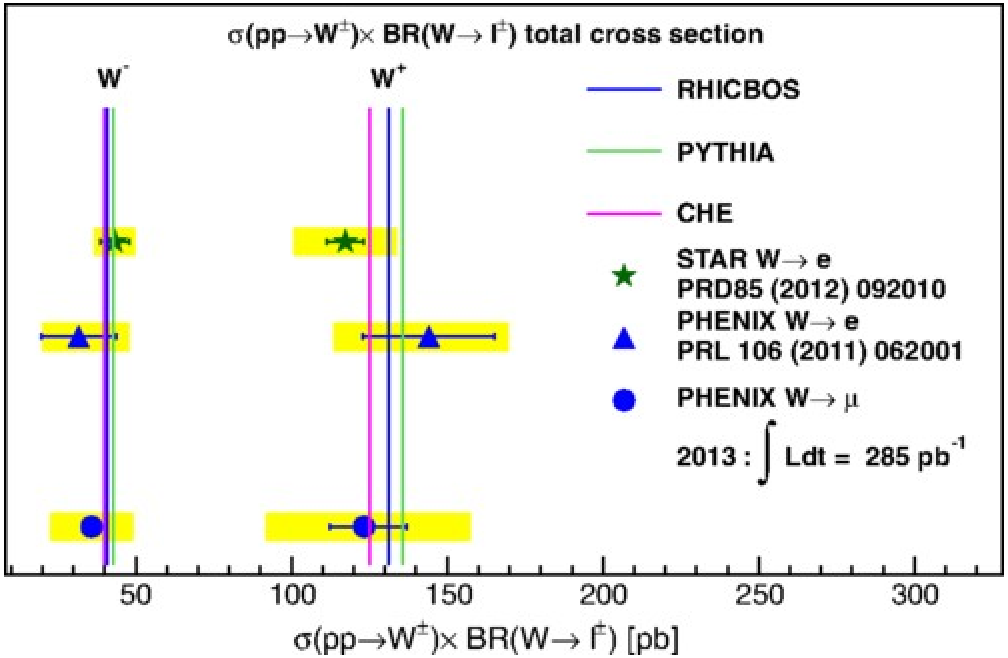
QUARK HELICITIES

Single spin asymmetry and cross sections for W production

PRD 98 (2018), 032007



PRD (2018) 98, 032007



- Cross sections well-described by NLO pQCD theory (FEWZ + MSTW08),
- Support NLO pQCD interpretation of the asymmetry measurements

- PHENIX:
  W → μ A_L, σ, 1.2 <|η| < 2.4, PRD98, 032007 (2018)
  W → e A_L , |η| < 0.35, PRD93, 051103 (2016)
  W → e σ, PRL106 062001 (2011)
- STAR:
  W → e A_L , |η| < 1, PRL113, 072301 (2014)
  W → e σ, PRD85 092010 (2011)

TRANSVERSE SPIN MEASUREMENTS

TMD formalism

Sivers function – correlation between parton transverse momentum and nucleon transverse spin

Collins function – correlation of the transverse spin of a fragmenting quark and the transverse momentum of a hadron

Requires **2 scales**: hard scale Q^2 and soft scale p_T
Where: $\lambda_{QCD} < p_T << Q$

Observables: azimuthal dependences of hadrons within a jet, Drell-Yan, W/Z

Twist-3 formalism

ETQS function – transverse momentum integrated distribution Twist-3 analog

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

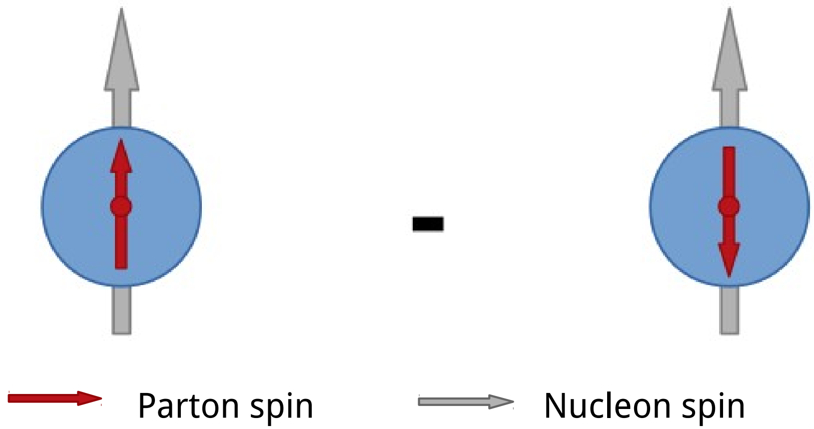
Twist-3 analog fragmentation function

Requires **1 scale**: Q^2 or p_T
Where: $\lambda_{QCD} << p_T, Q$

Observables: Inclusive A_N (π^0 , γ, jet, charmed mesons)

TRANSVERSITY

For a complete picture of nucleon spin structure at leading twist: transversity

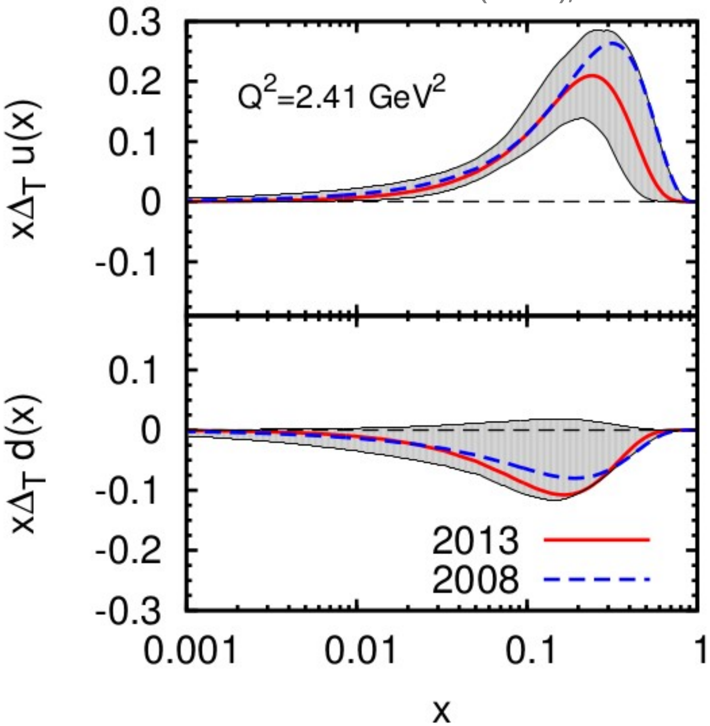


Transversity: $\delta q(x)$
Net density of quarks with spin aligned with the transversely polarized nucleon

- Difficult to access - **chiral-odd nature**
- Couples to chiral-odd fragmentation functions

- Much less data than for helicity
- Before observed in SIDIS combined with e^+e^-
- First **global analyses:** simultaneously the transversity and polarized FF
  - Phys. Rev. D 87, 094019 (2013)
  - Phys. Rev. Lett. 107, 012001 (2011)
- All show large uncertainties

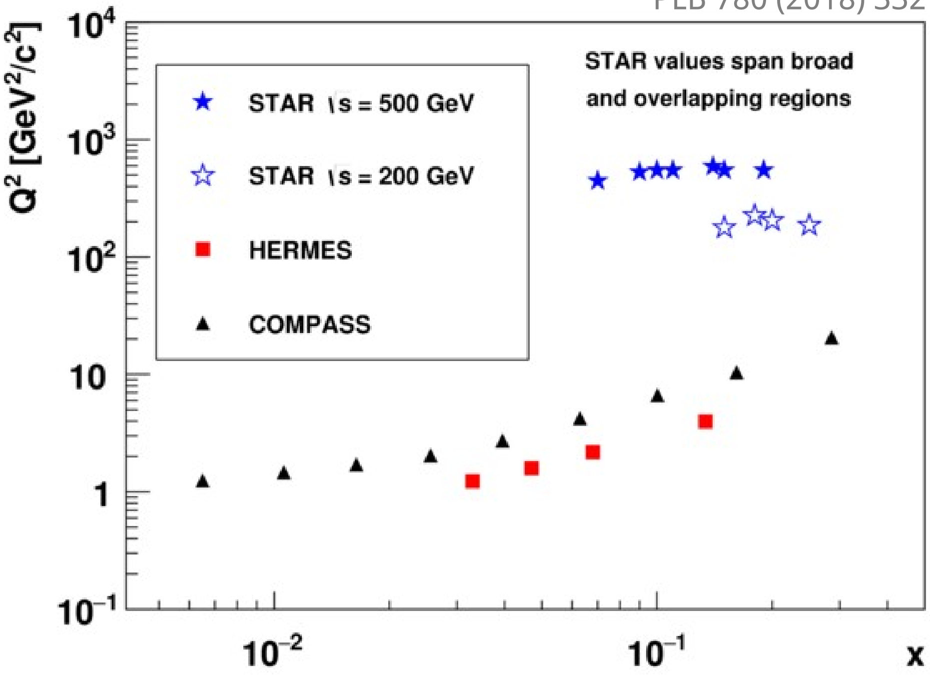
PRD 87 (2013), 094019



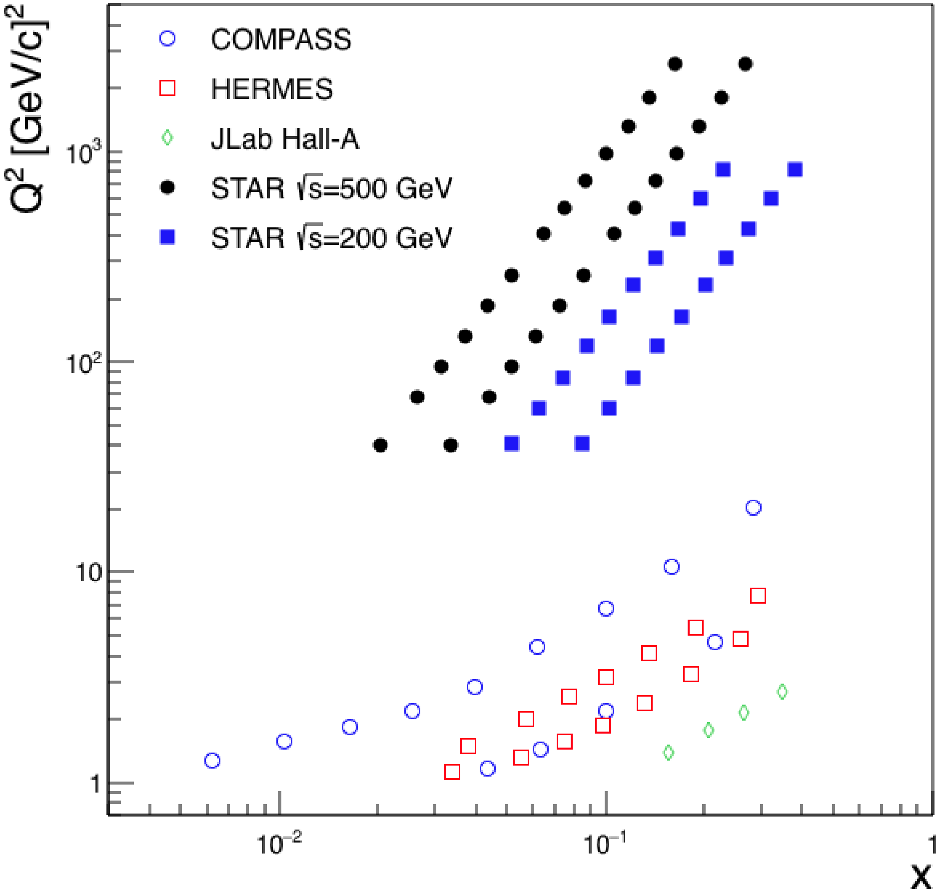
STAR: KINEMATIC COVERAGE

IFF and Collins asymmetry

PLB 780 (2018) 332



PRD 97 (2018), 032004

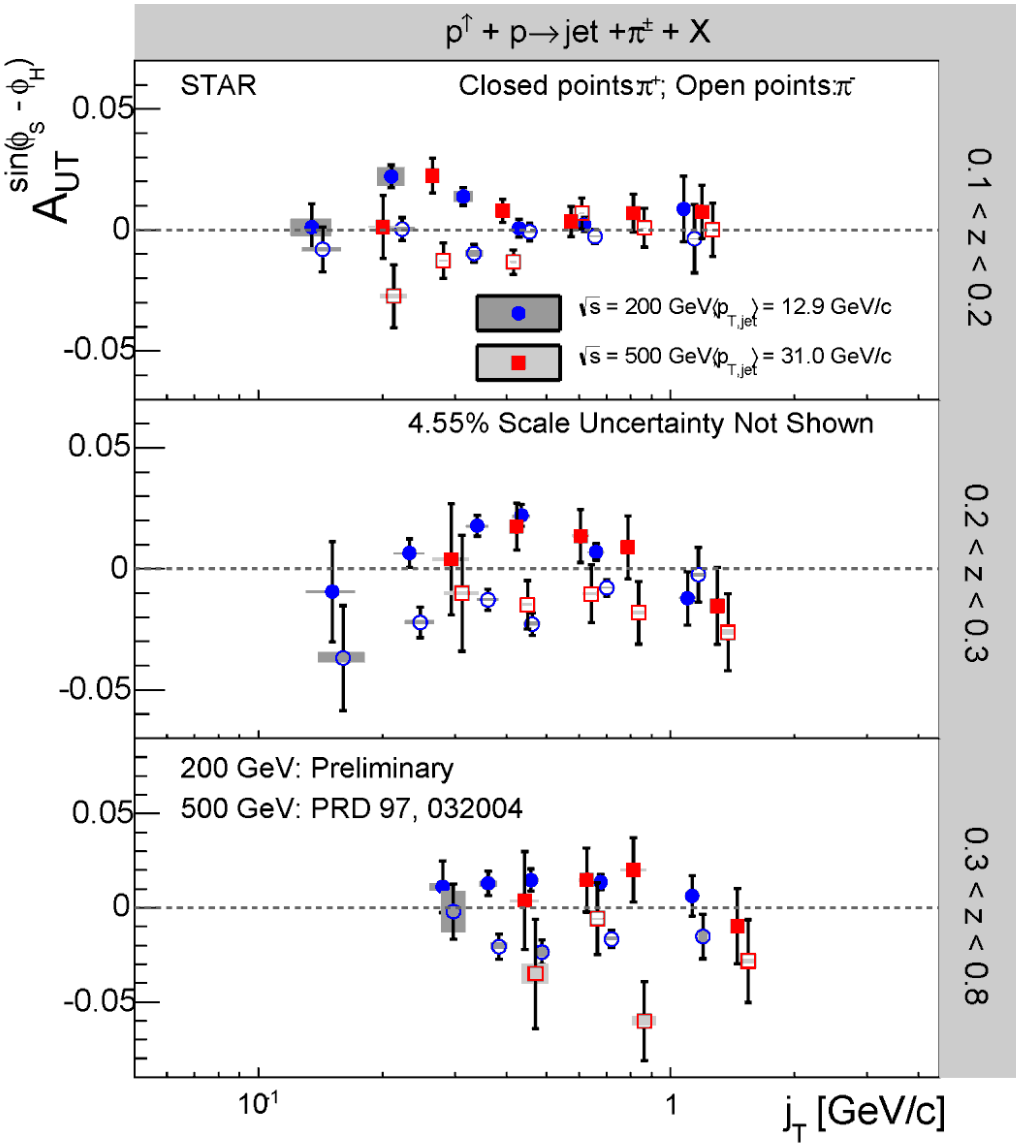


TRANSVERSITY

Collins asymmetry

PRD 97 (2018), 032004
K. Adkins (STAR), SPIN 2014

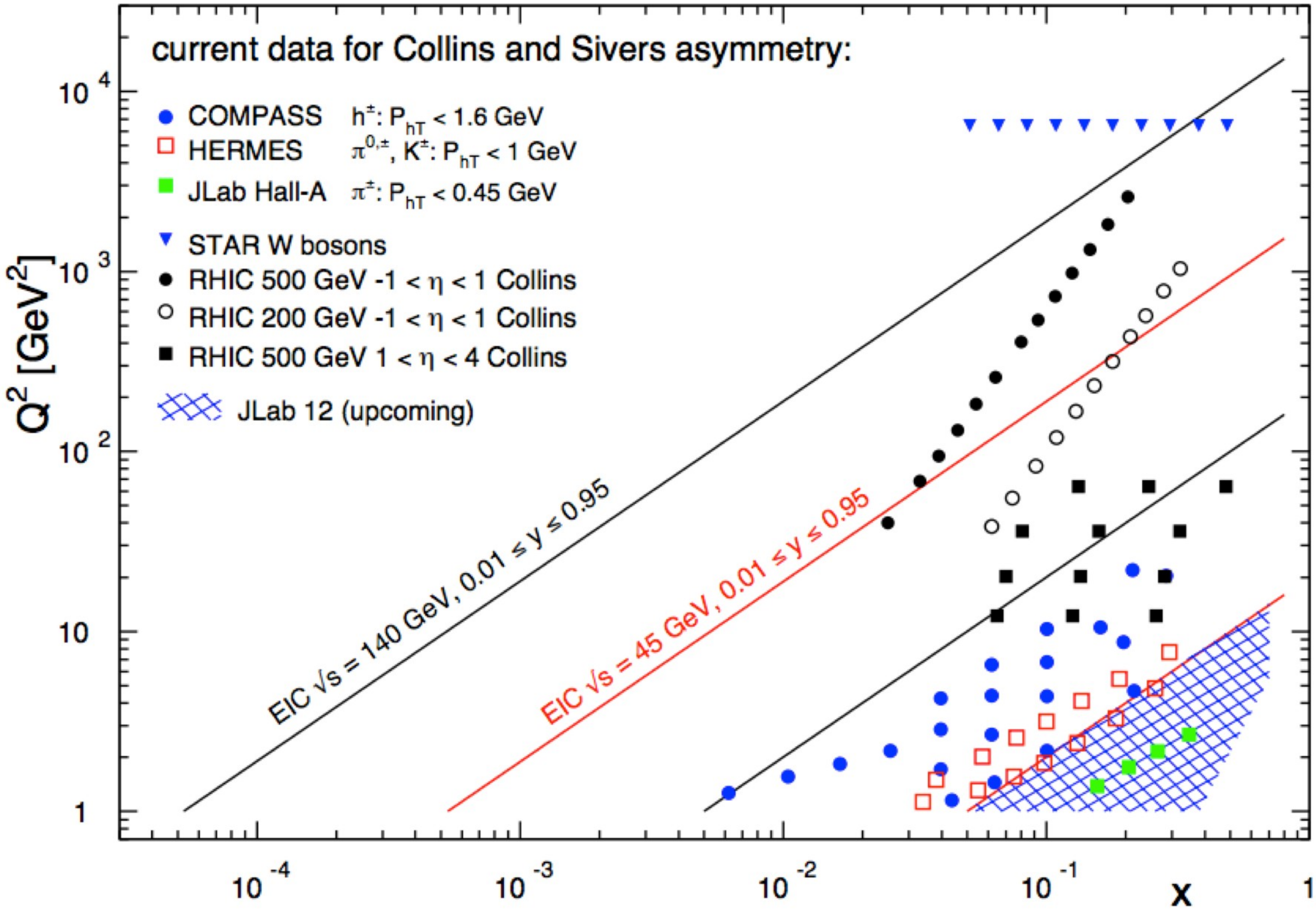
- 500 GeV pp results hinted the A_{UT} peak shifts to higher j_T as z increases
- Preliminary 200 GeV pp results show similar behavior
- Hadron j_T is independent of initial state transverse momentum
- Additional statistics for both 200 (x 2.5) and 500 GeV (x 12) available



RHIC KINEMATIC

Collins and Sivers asymmetry

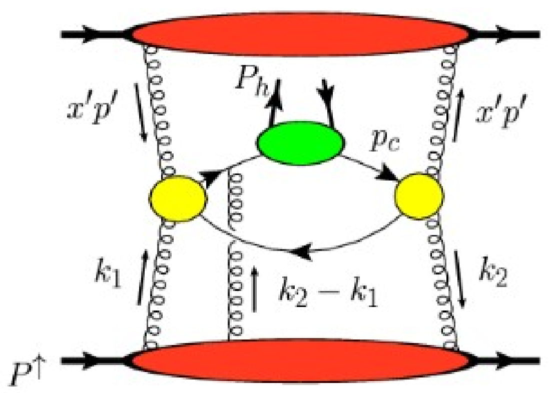
arXiv:1602.03922

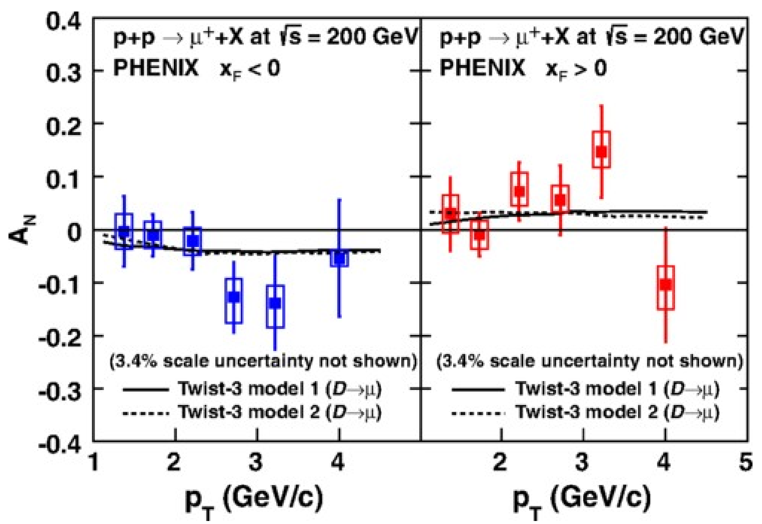


TWIST-3

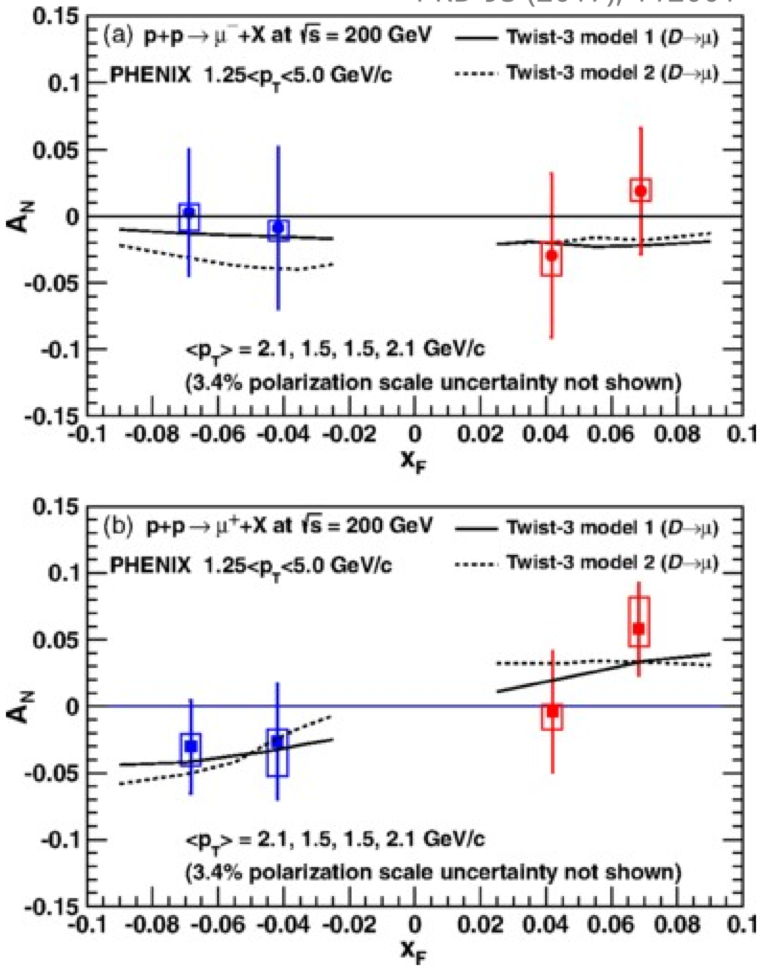
Heavy flavor A_N

- PHENIX: A_N μ asymmetries from open heavy-flavor decays at √s = 200 GeV.
- Heavy flavor asymmetries sensitive to twist-3 tri-gluon correlator





PRD 95 (2017), 112001



Asymmetries were found to be small and in agreement with model calculations for twist-3 (D→ μ)