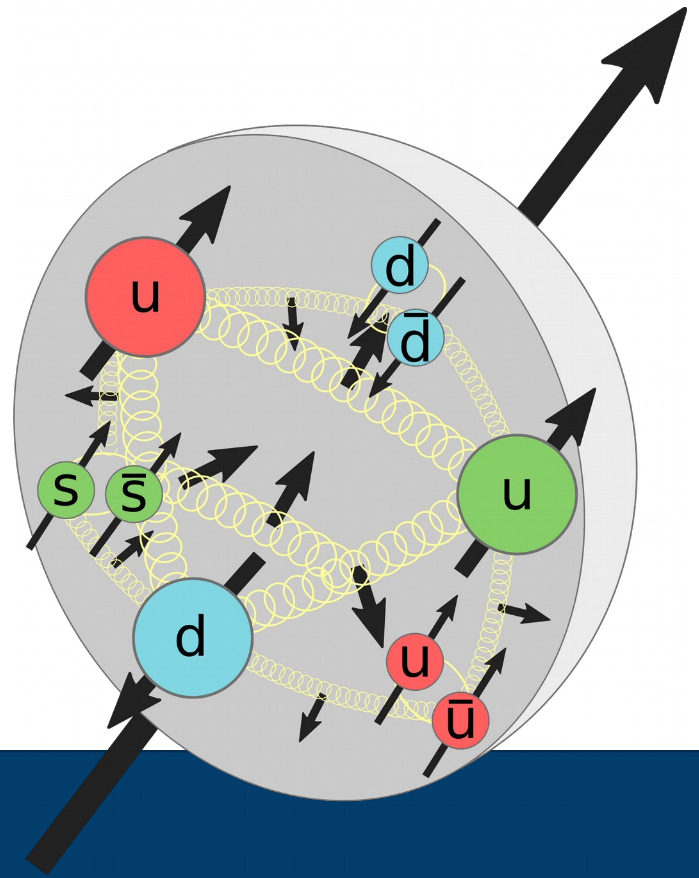


RHIC-SPIN PROGRAM

14 NOV 2019 | MARIA ŻUREK | LAWRENCE BERKELEY NATIONAL LABORATORY

SPIN PHYSICS PROGRAM AT RHIC

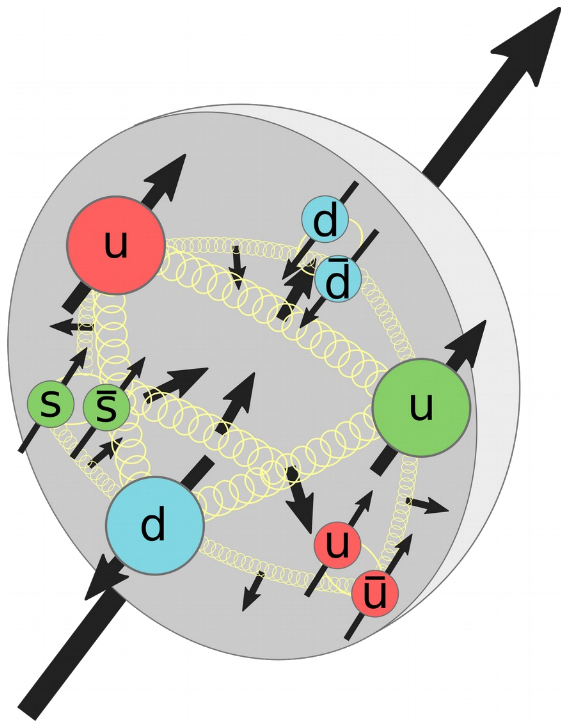
Goals:

- Using spin as a unique probe to unravel the internal structure of nucleon
- Understanding the role of spin in QCD

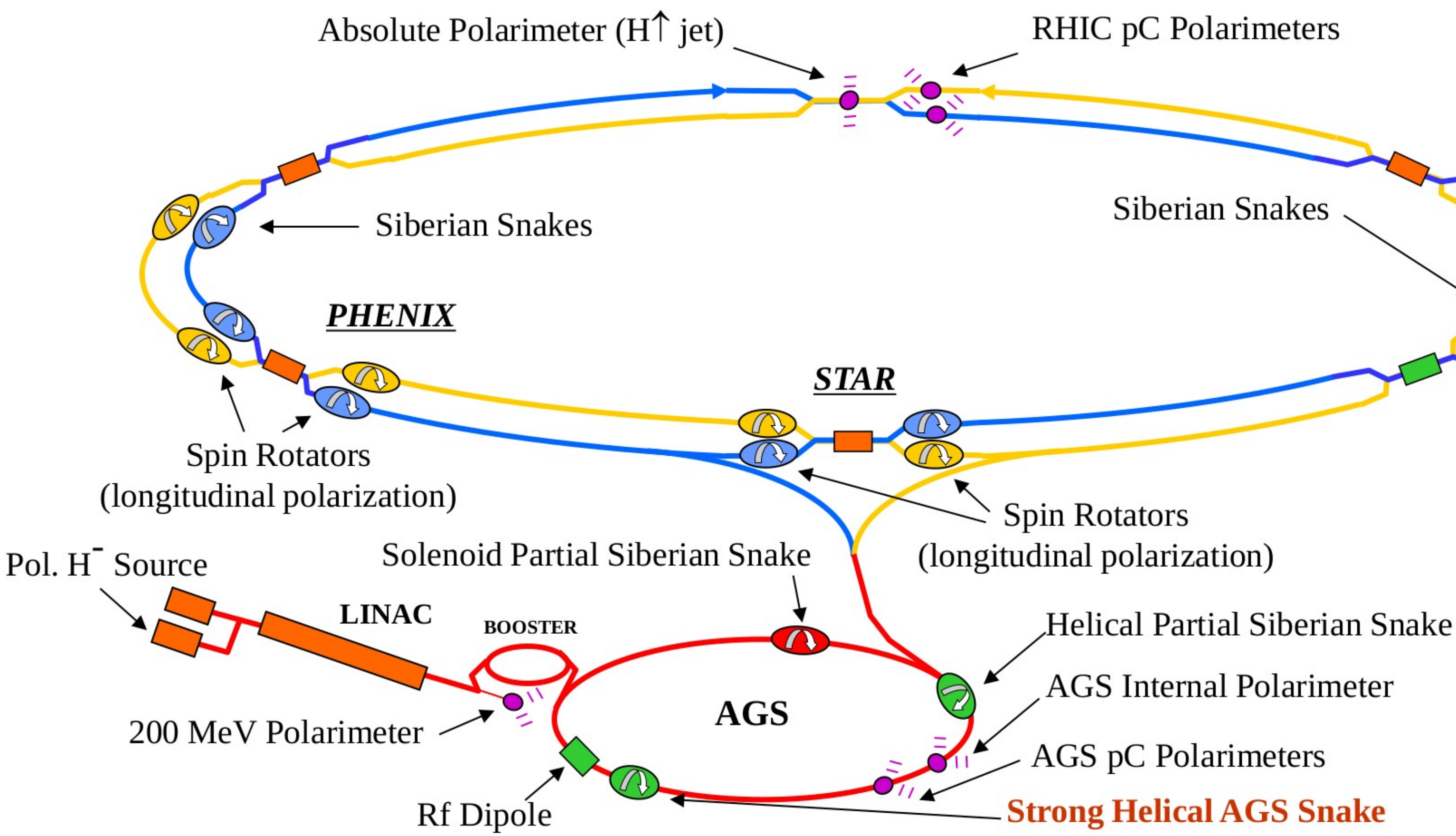
Questions:

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

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



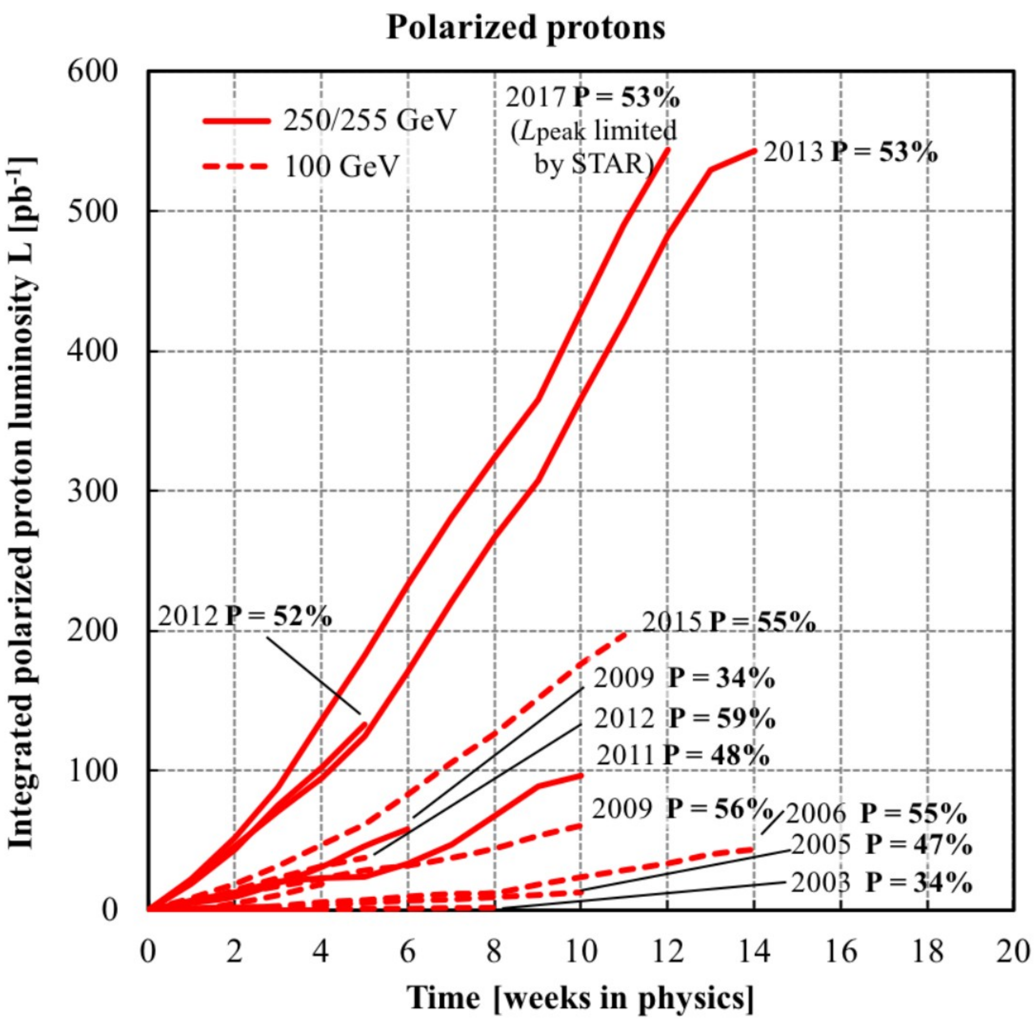
RHIC – POLARIZED PROTON COLLIDER



- Polarized protons √s = 62, 200, 500 GeV
- Transverse and longitudinal polarization
- Alternating spin configurations bunch by bunch and fill by fill
- The only polarized high-energy proton-proton collider

Hard scattering processes with control of systematic effects

RHIC – POLARIZED PROTON COLLIDER



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

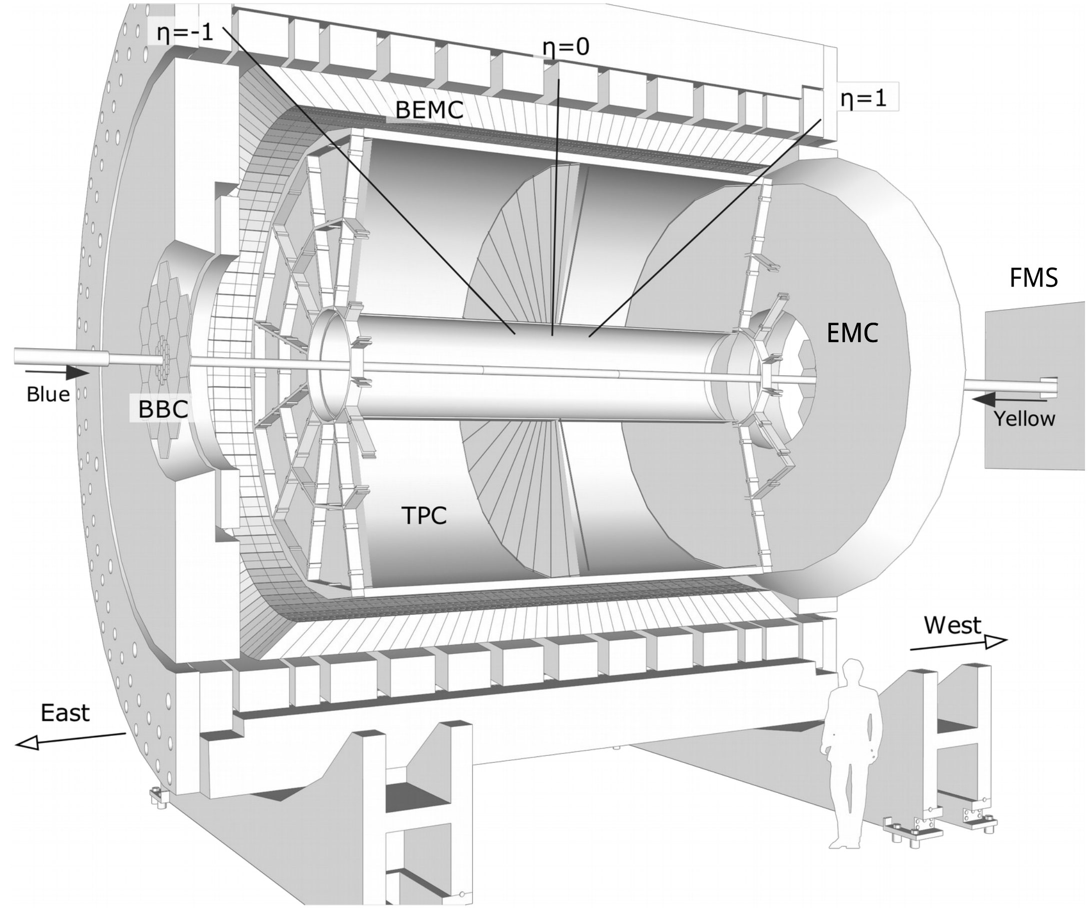
Forward Meson Spectrometer
- $\Delta\varphi = 2\pi$, $2.6 < \eta < 4$
- Energy measurement, trigger

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

Zero Degree Calorimeter
- Relative luminosity and local polarimetry

Roman Pots

Forward Upgrade (discussed later)



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

PHENIX DETECTOR

Took data up to 2016
Being replaced by sPHENIX

Central Arm
- |η| < 0.35, Δφ = 2 x π/2, 0.78 T
- VTX detector
- Electromagnetic Calorimeter
- Tracking: Drift chambers, Pad chambers
- PID: RICH, ToF

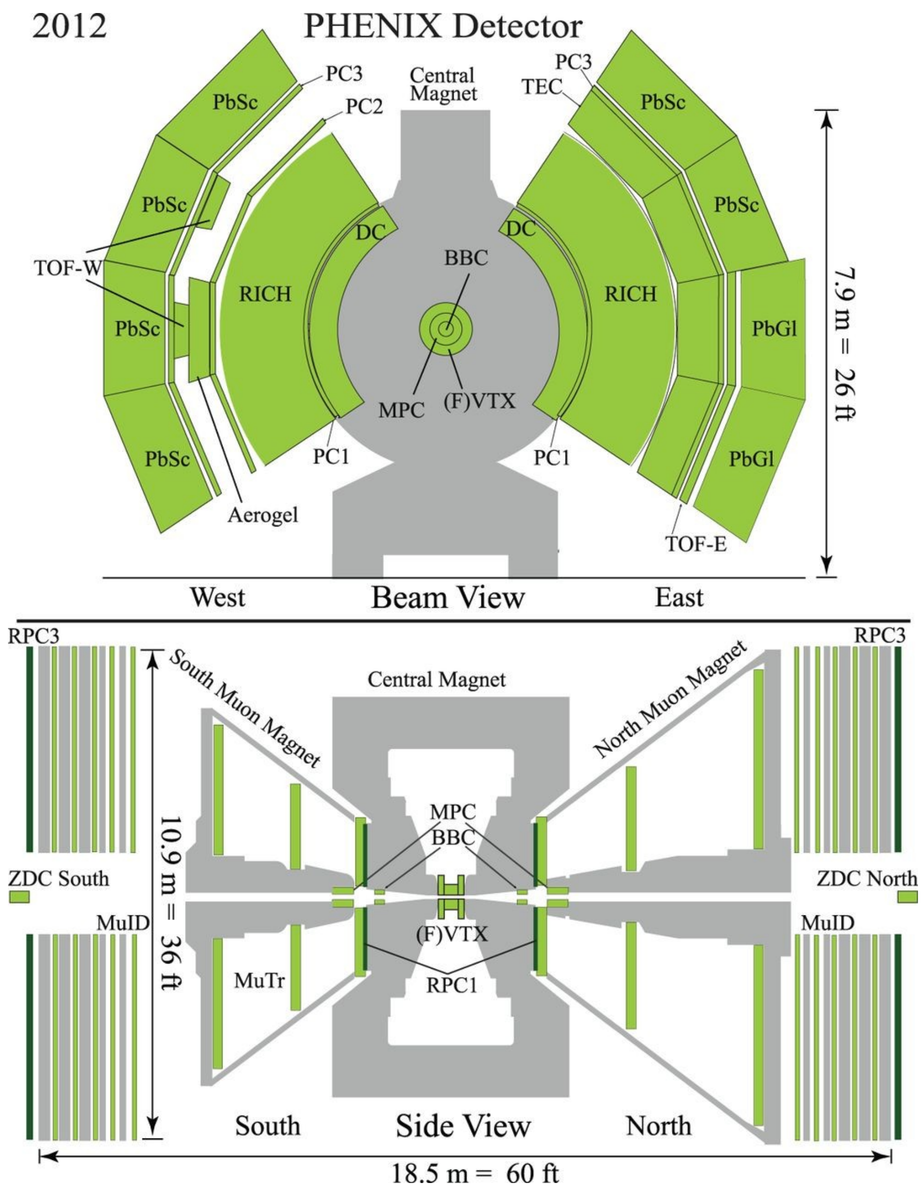
Muon Arm
- 1.2 < |η| < 2.4, Δφ = 2π, 0.72 T
- Muon PID and Tracking
- PID, tracking, vertex reconstruction

Muon Piston Calorimeter
- Δφ = 2π, 3.1 <|η| < 3.9

Beam-Beam Counter
Zero Degree Calorimeter
- Relative luminosity

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

I do not discuss BRAHMS, A_NDY, pp2pp here



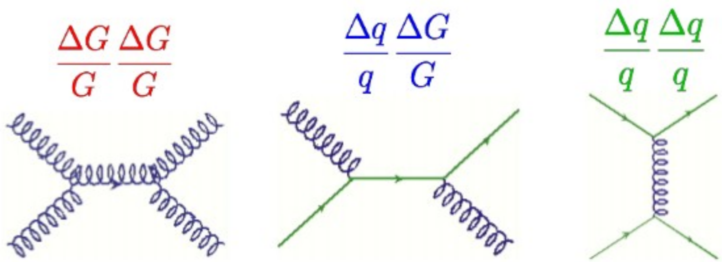
HOW TO ACCESS GLUON HELICITY?

HOW TO ACCESS ΔG?

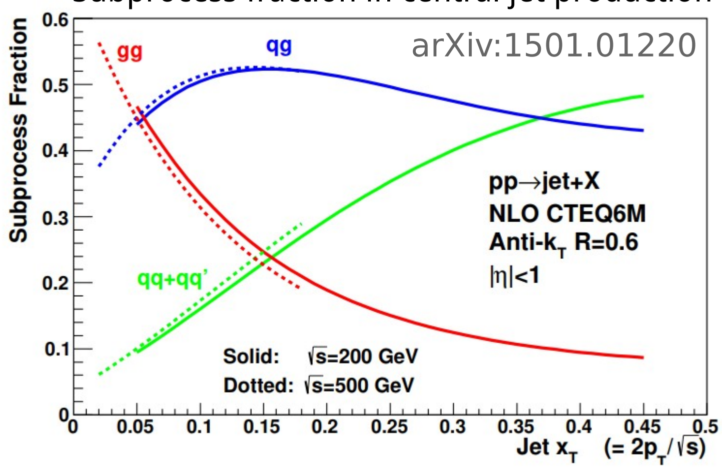
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} a\hat{_{LL}} \otimes D}{\Sigma f_a \otimes f_b \otimes \hat{\sigma} \otimes D}$$

LO for illustration

Which processes dominate at RHIC?



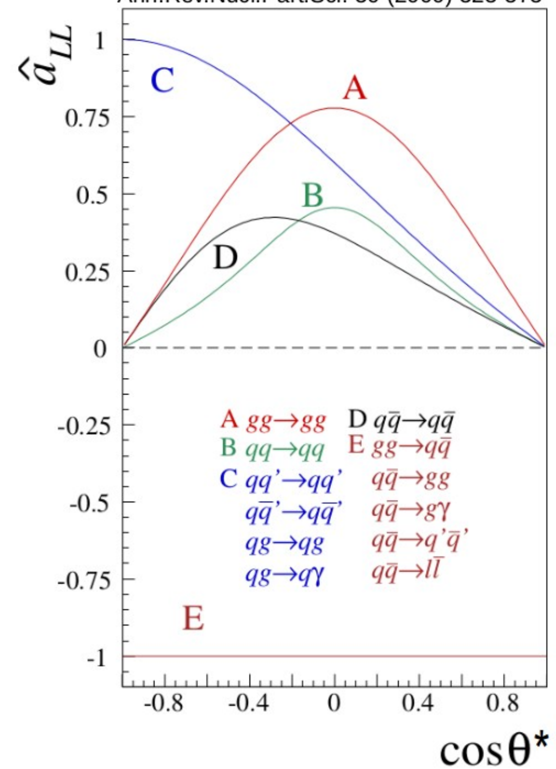
Subprocess fraction in central jet production



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

What are a_{LL} for these processes?

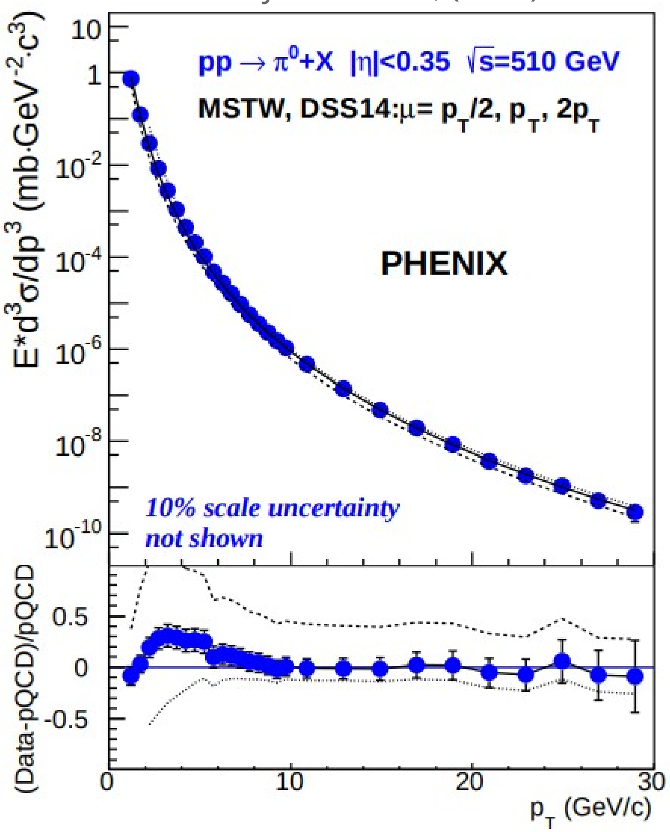
Ann.Rev.Nucl.Part.Sci. 50 (2000) 525-575



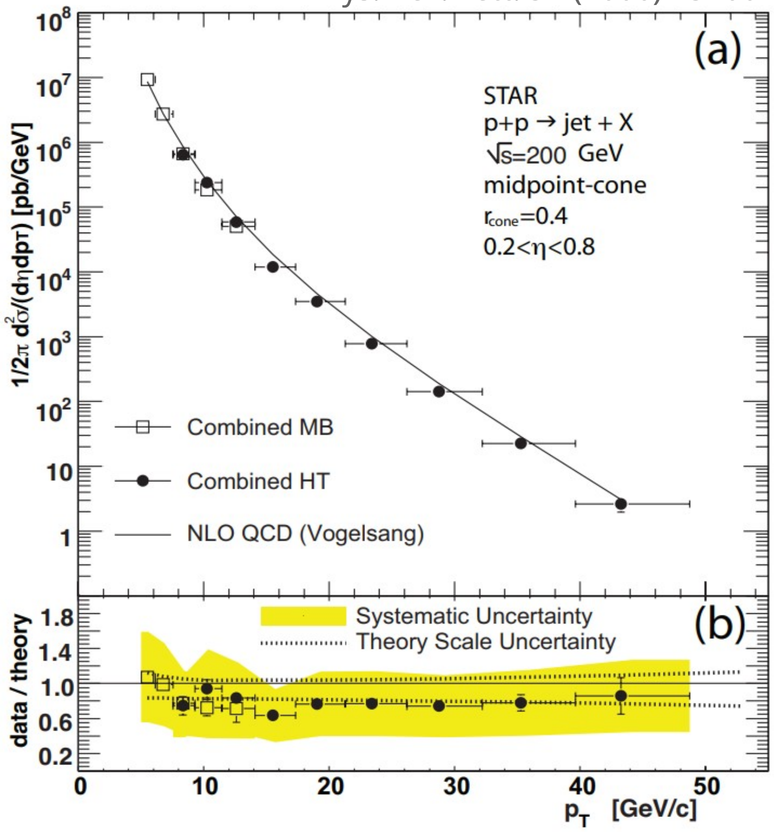
CROSS-SECTIONS

Jet and π^0 production

Phys. Rev. D93, (2016) 011501



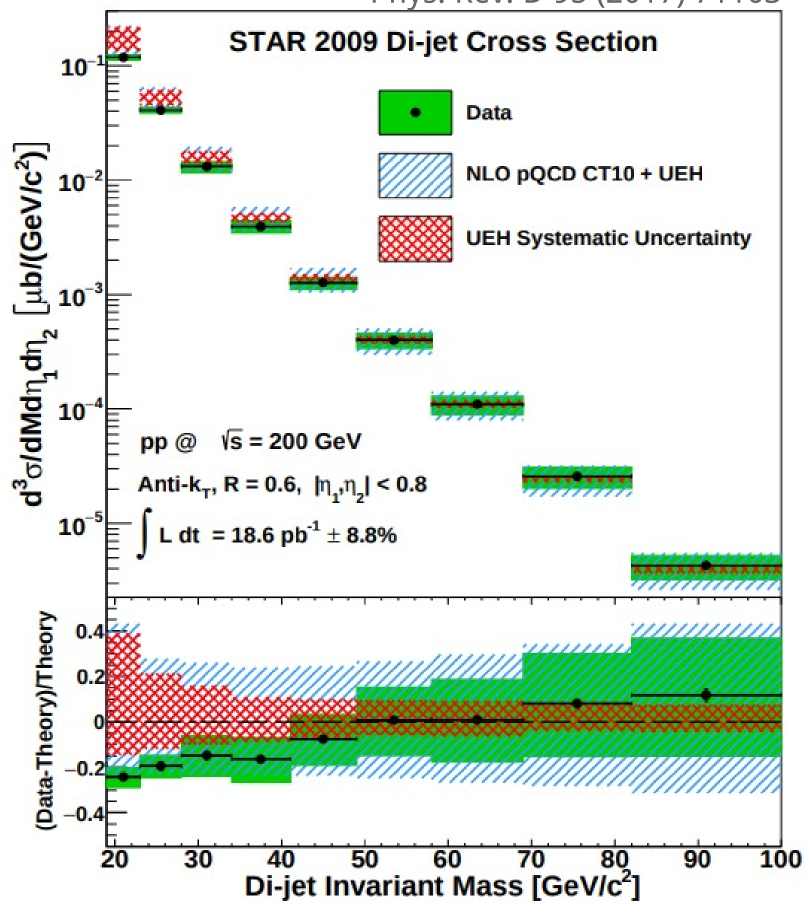
Phys. Rev. Lett. 97 (2006) 252001



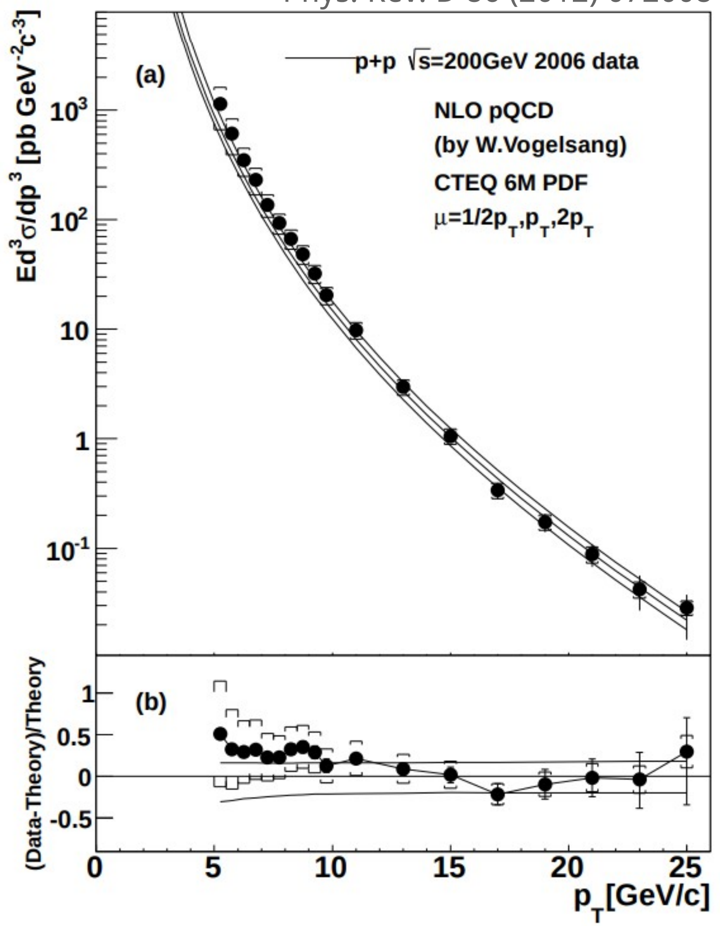
- Cross-section measurement to support the **NLO pQCD** interpretation of asymmetries
- Theoretical error includes the PDF uncertainty and sensitivity to the variation of the factorization and renormalization scales (altered simultaneously by factors of 0.5 and 2.0)

CROSS-SECTIONS
di-jet production and photon

Phys. Rev. D 95 (2017) 71103



Phys. Rev. D 86 (2012) 072008

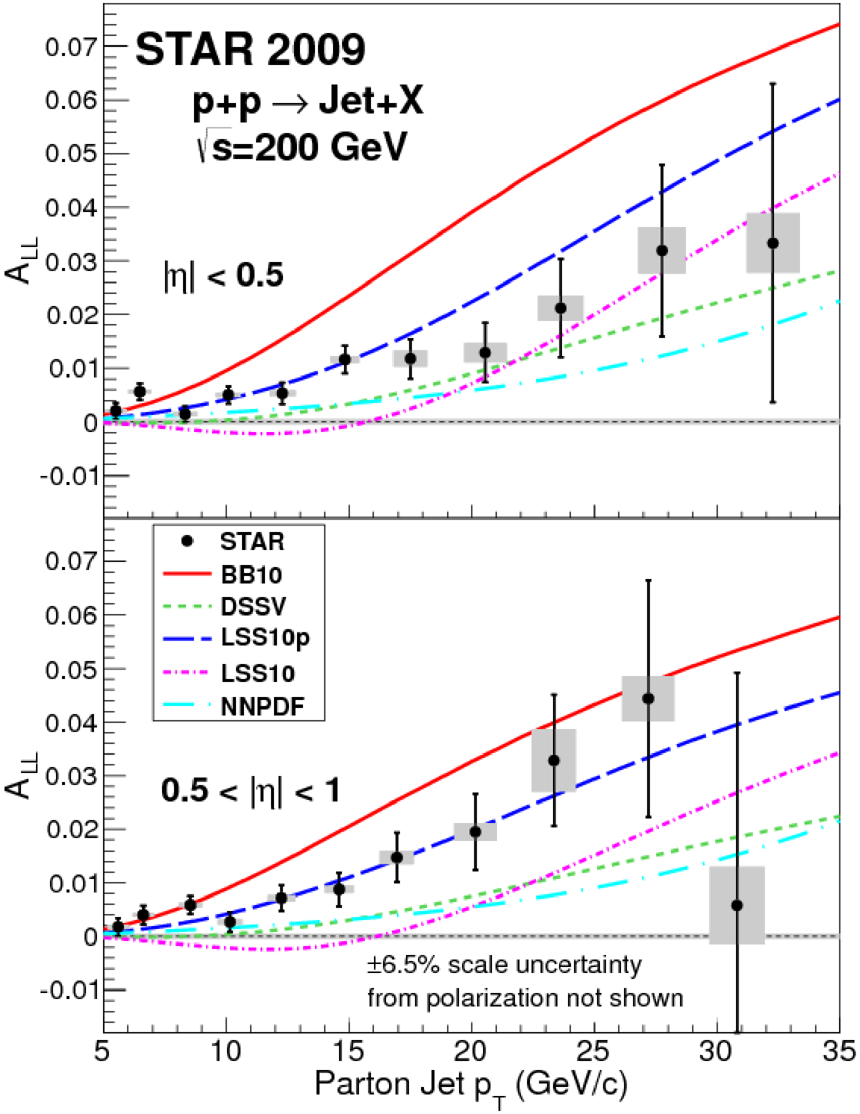


- Cross-section measurement to support the **NLO pQCD** interpretation of **asymmetries of correlations and rare probes**

STATUS OF ΔG

Precision A_{LL}

PRL 115 (2015) 9, 092002



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

2. Included in DSSV and the NNPDF **PDF fits** (NLO)
- These data drive the constraints on ΔG in both fits
- Initial sensitivity to different x_g from rapidities
- In the PDF fit also PHENIX π^0 A_{LL} included PRD 90, 012007 (2014)

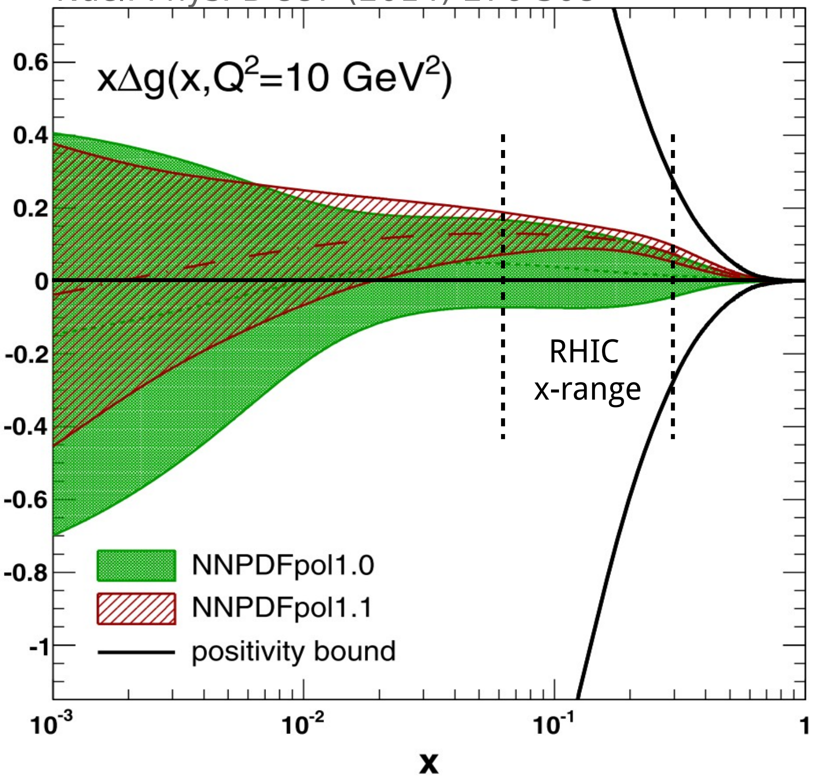
Evidence for **positive gluon polarization** in the x range $0.05 < x < 0.2$ and at $Q^2 = 10$ GeV^2

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

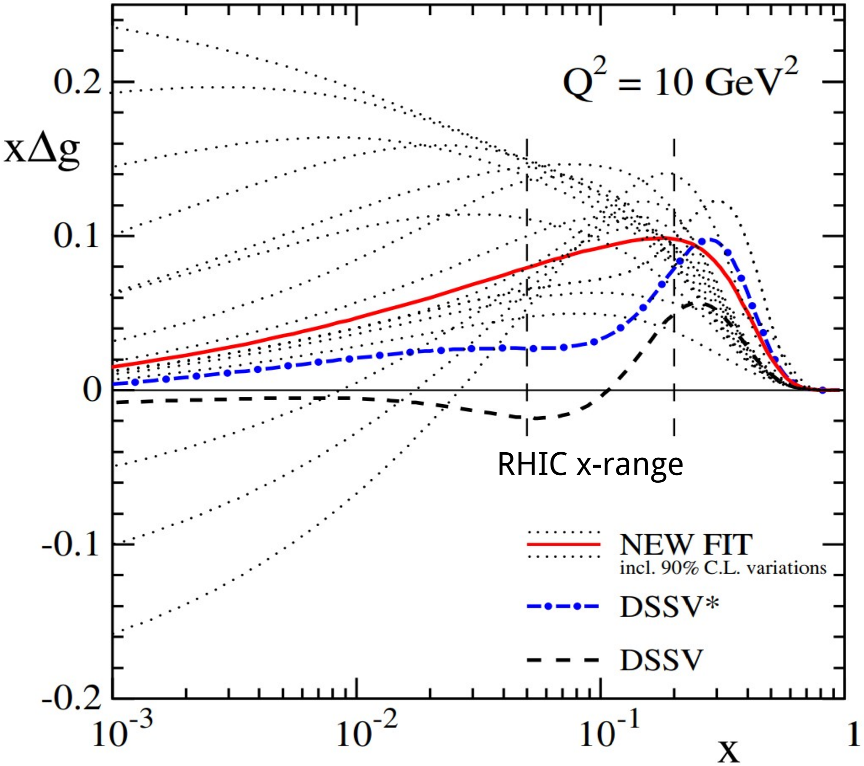
STATUS OF ΔG

Impact of ALL from 2009 data on ΔG

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



PRL 113 (2014) 1, 012001

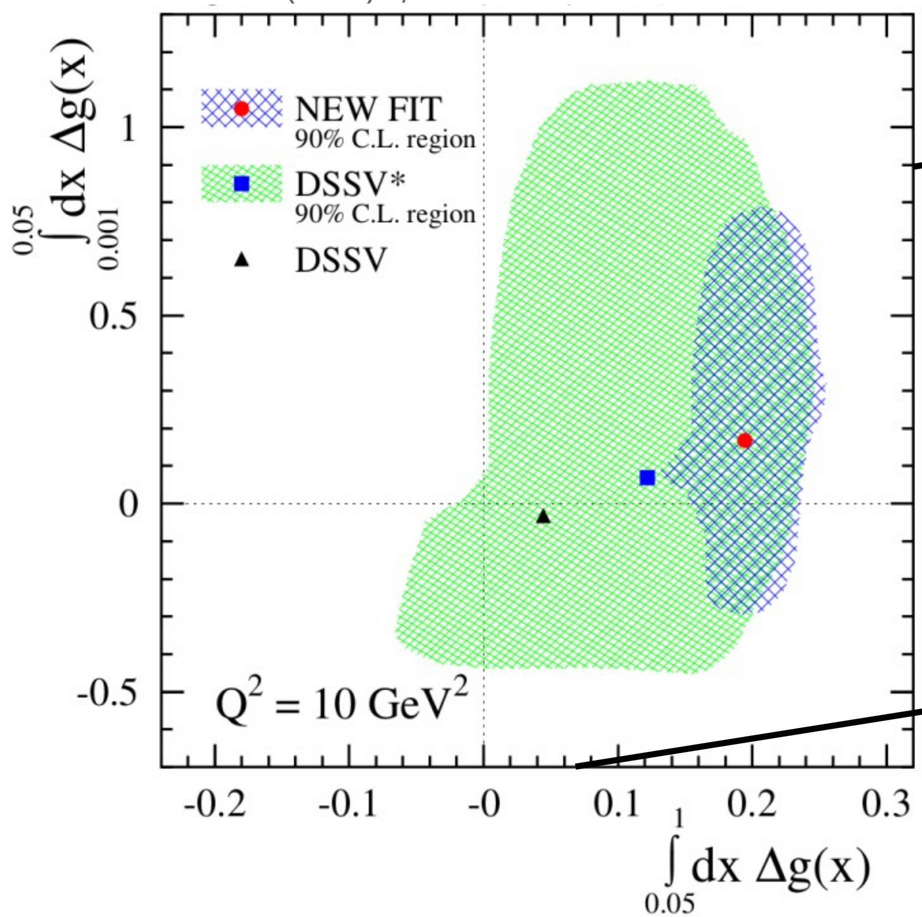


$$\text{DSSV:} \quad 0.20^{+0.06}_{-0.05}, \quad \text{at } 90\% \text{ C.L. }, x > 0.05$$
$$\text{NNPDF:} \quad 0.23 \pm 0.07, \quad 0.05 < x < 0.5$$

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

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

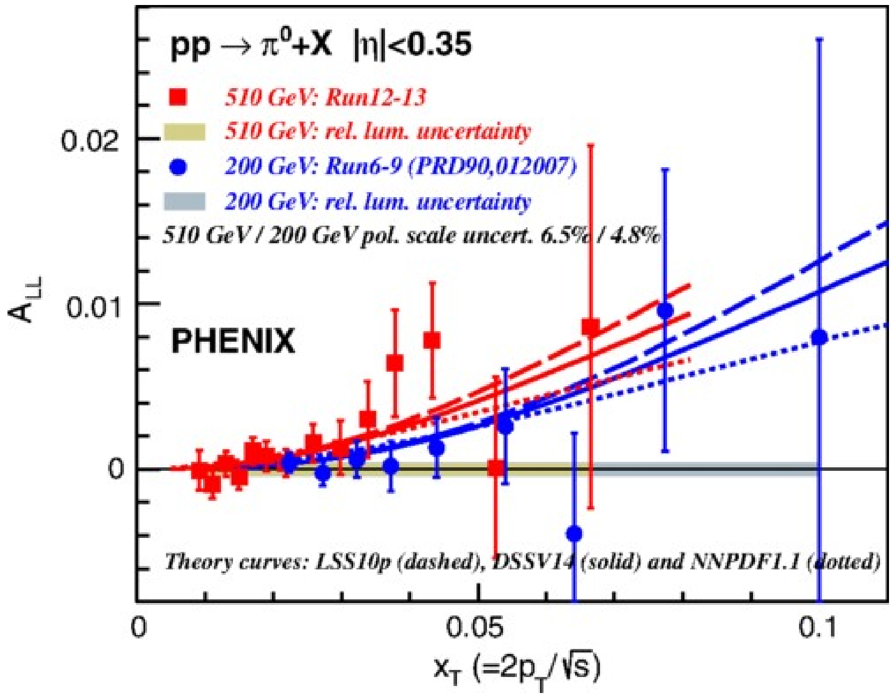
Further precision from:

- Jet and neutral pion probes
- Complementary probes

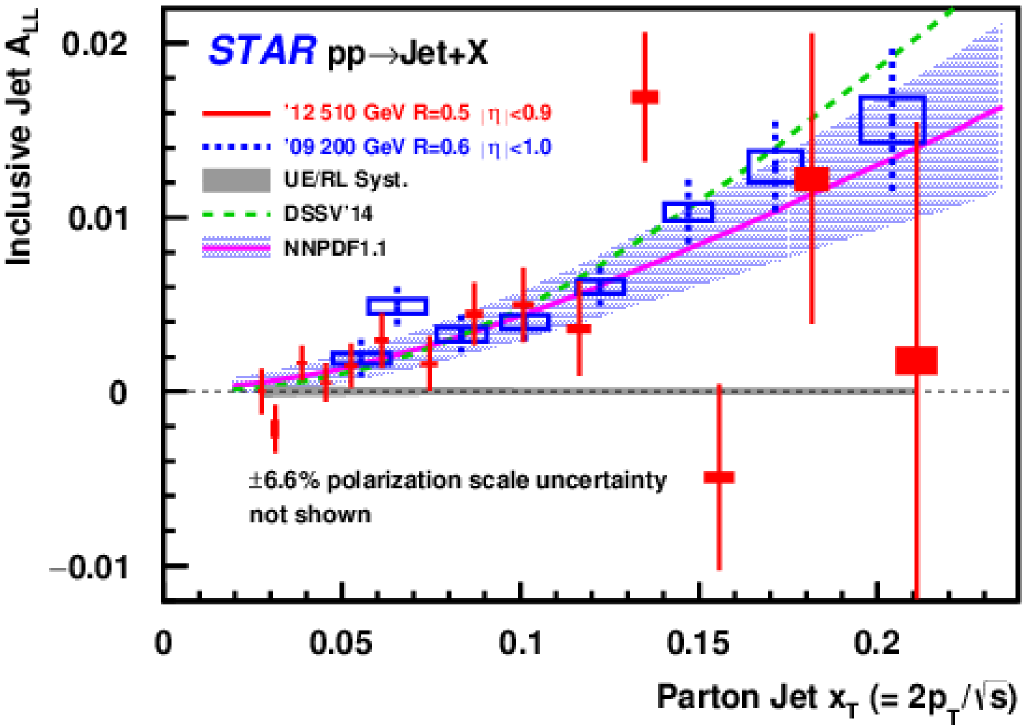
CENTRAL π^0 AND JETS AT 510 GEV

Towards smaller x_g

PRD 93 (2016), 011501



PRD 100 (2019), 052005



- Consistent result from both energies and both experiments
- **Higher $\sqrt{s}$ pushes sensitivity to lower x > 0.02**
- More to come:
  - 2013 data: High luminosity (300 pb^{-1}) 510 GeV STAR
  - 2015 data: Double 2009 statistics 200 GeV: STAR

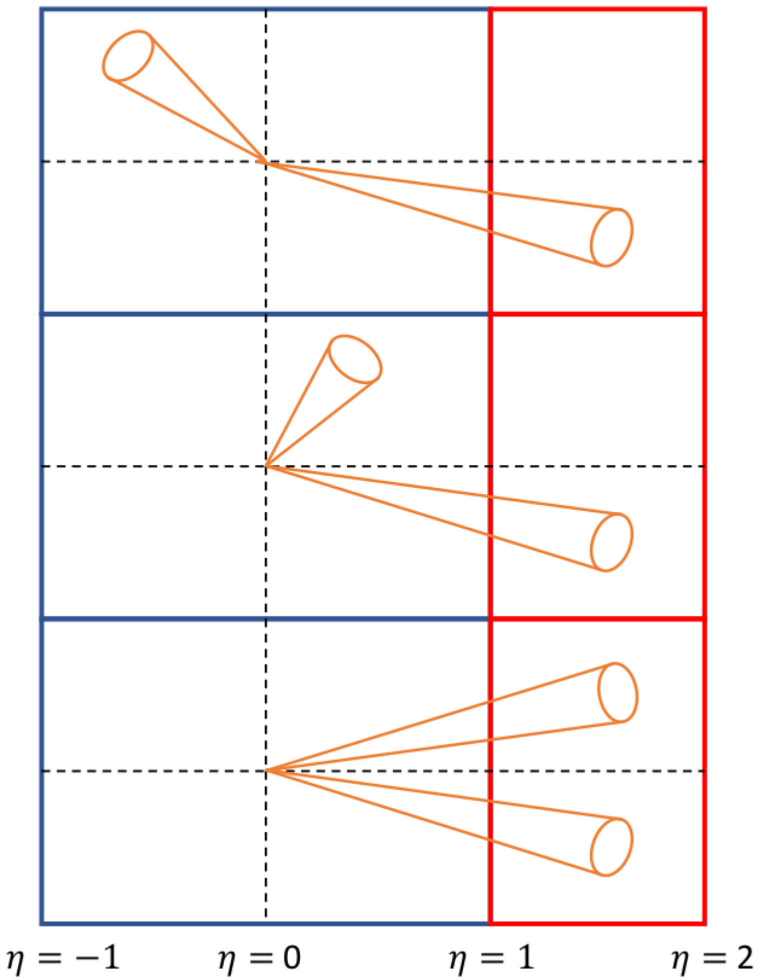
STAR: A_{LL} of π^0 at 510 GeV with FMS ($2.6 < \eta < 4$), $x > 0.001$, run 2012 (82 pb^{-1}) and 2013 (300 pb^{-1})

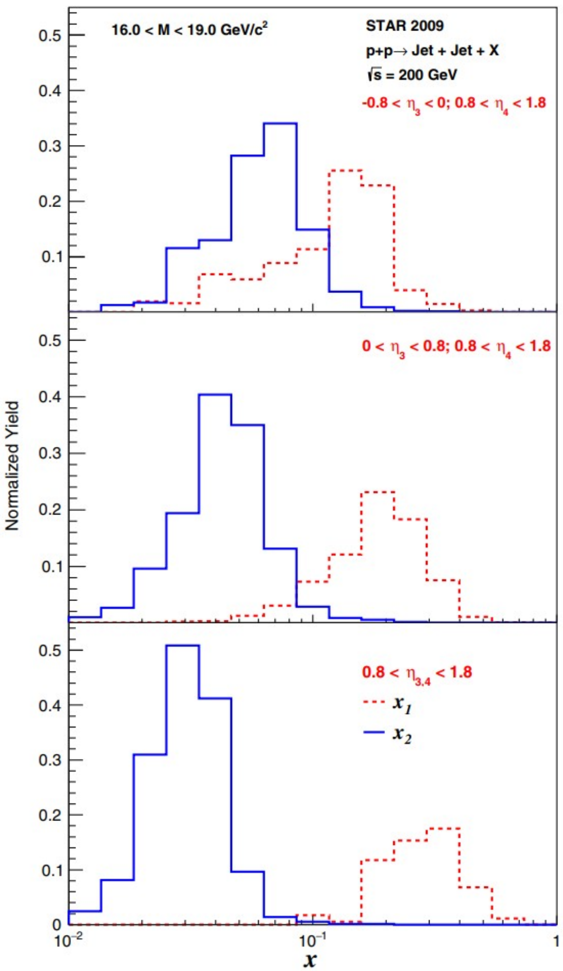
PRD 98 (2018), 032013

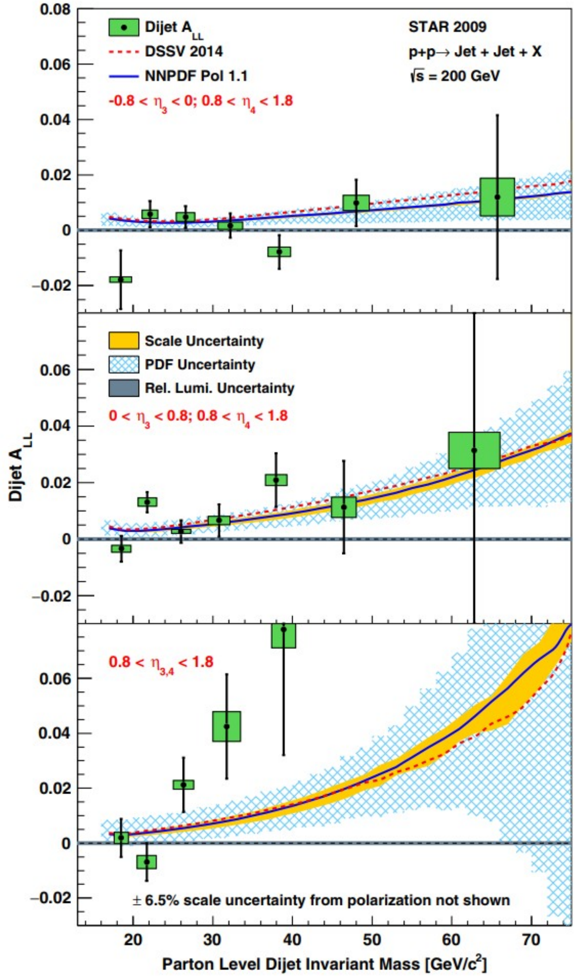
DI-JET MEASUREMENT

Towards smaller x_g and complementary probes

PRD 98 (2018), 032011







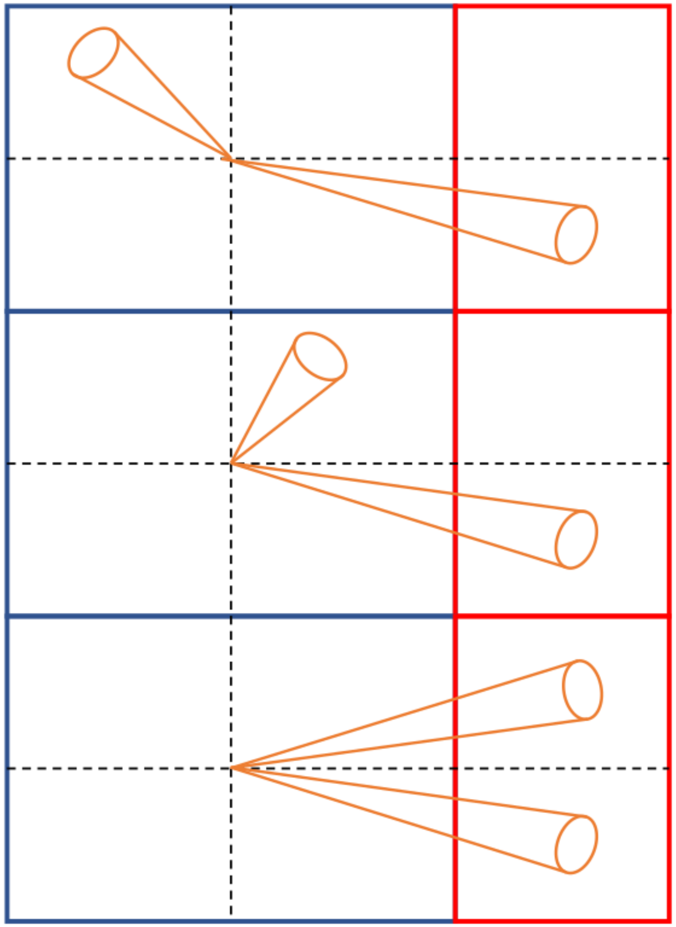
Di-jets give stricter constraints to underlying **partonic kinematics**

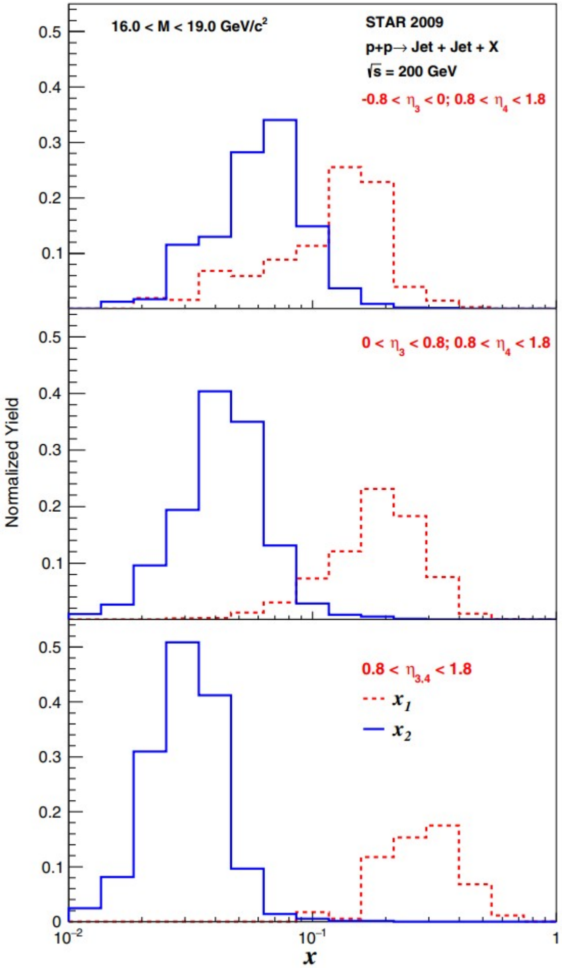
- May place better constraints on **functional form of Δg(x)**
- More-forward production - **lower x down to 0.01,** x_2 – likely gluon, x_1 – likely quark
- **Narrow ranges** of initial state partonic momentum tested

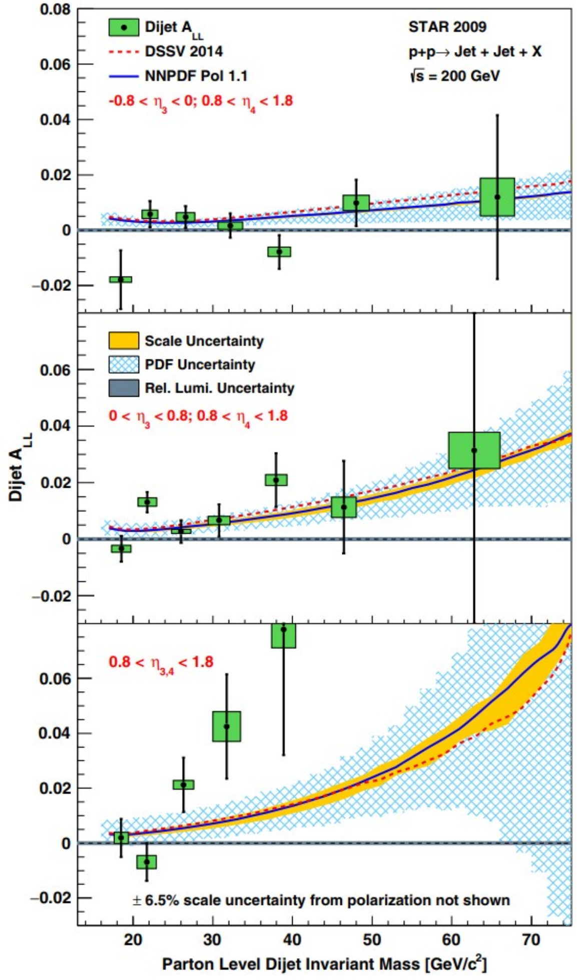
DI-JET MEASUREMENT

Towards smaller x_g and complementary probes

PRD 98 (2018), 032011



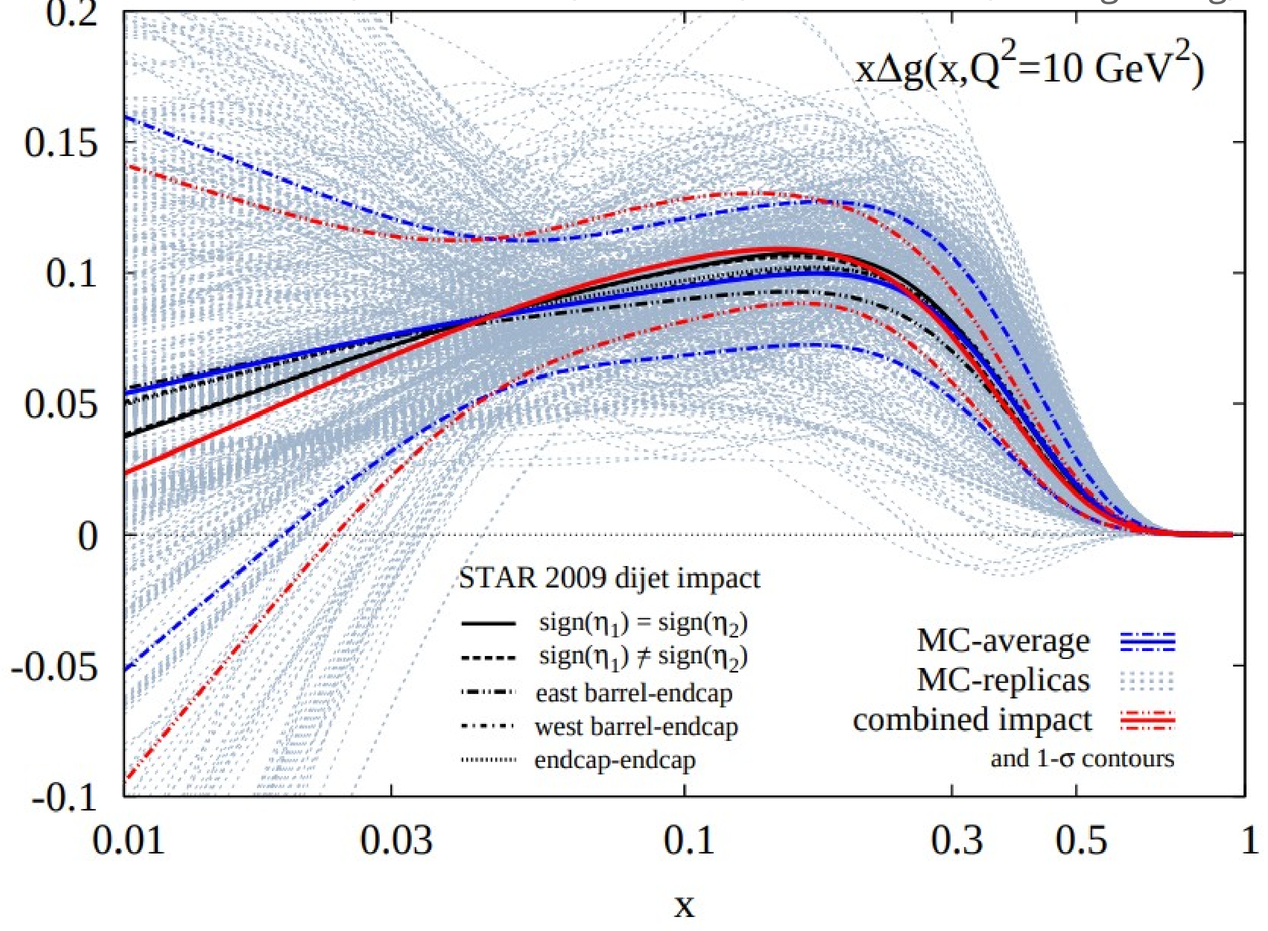




- Central di-jet measurement Run 2009 √s = 200 GeV (25 pb^{-1}): PRD 95 (2017), 071103
- Central di-jet measurement Run 2012 √s = 510 GeV (82 pb^{-1}): PRD 100 (2019), 052005
- Further precision: Run 2015 √s = 200 GeV – x 1.5 statistics, Run 2013 √s = 510 GeV – x 3.2 statistics

DI-JET MEASUREMENT
Impact on Δg(x)

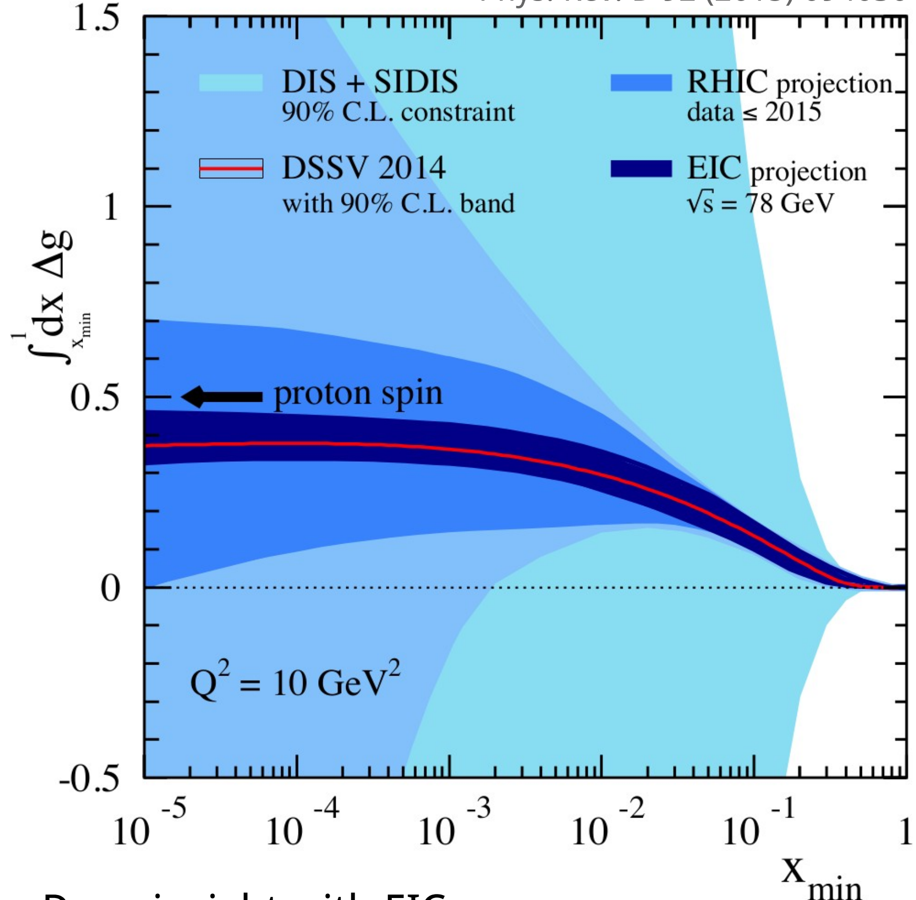
arXiv 1902.10548
D. de Florian, G. A. Lucero, R. Sassot, M. Stratmann, W. Vogelsang,



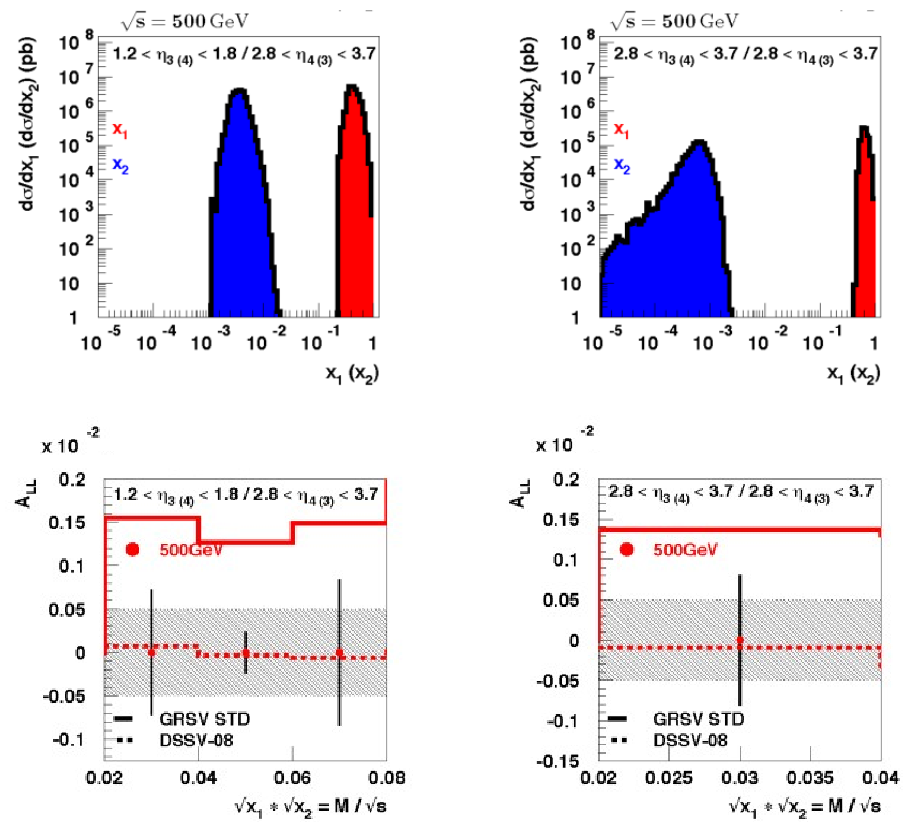
- Influence of central and forward di-jets from 2009 data (25 pb^{-1}) $\sqrt{s}$ = 200 GeV on DSSV calculations

FUTURE OPPORTUNITIES

Phys. Rev. D 92 (2015) 094030



arXiv:1602.03922



Deep insight with EIC

- Scaling violation in inclusive DIS: $g_1(x, Q^2)$

Predictions for: Luminosity: 10 fb^{-1}, Polarization: 70%, Efficiency: 50%

Potential future with forward upgrade

- Di-jet asymmetries with x up to 10^{-3}
- Luminosity: 1 fb^{-1}, Polarization: 60%, Efficiency: 66%

HOW TO ACCESS QUARK-SEA?

QUARK HELICITIES

Single spin asymmetry and cross sections for W production

Goal: Constrain the sea-quark helicity

Separation of quark flavour

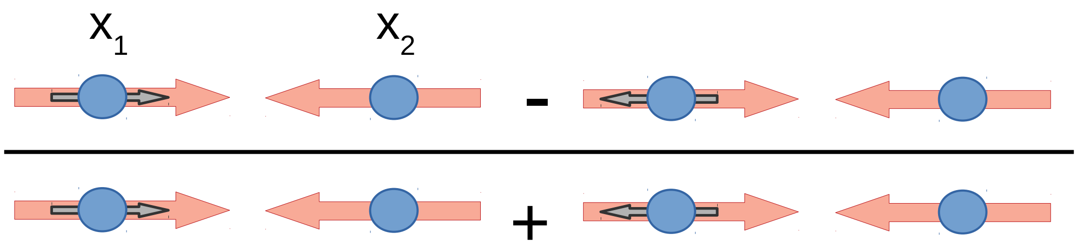
- $W^+(W^-)$: predominantly $u(d)$ and $\bar{d}(\bar{u})$

Maximal parity violation

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

The decay process is calculable

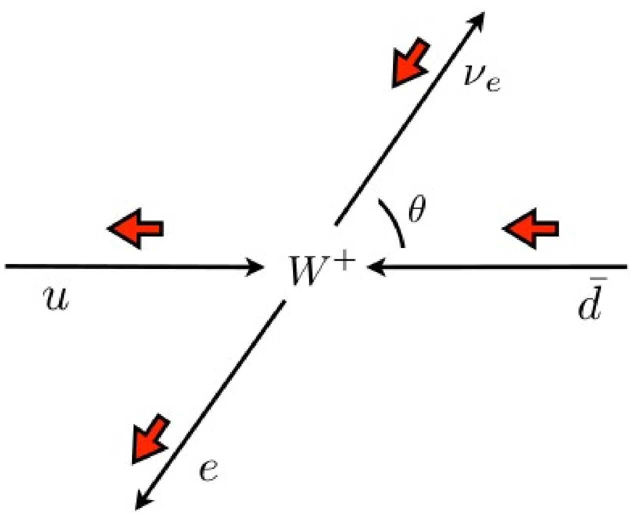
Free from fragmentation function



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

(LO)

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



Access both to sea and valence quarks

Experiment Signature:

- Large p_T lepton, missing E_T

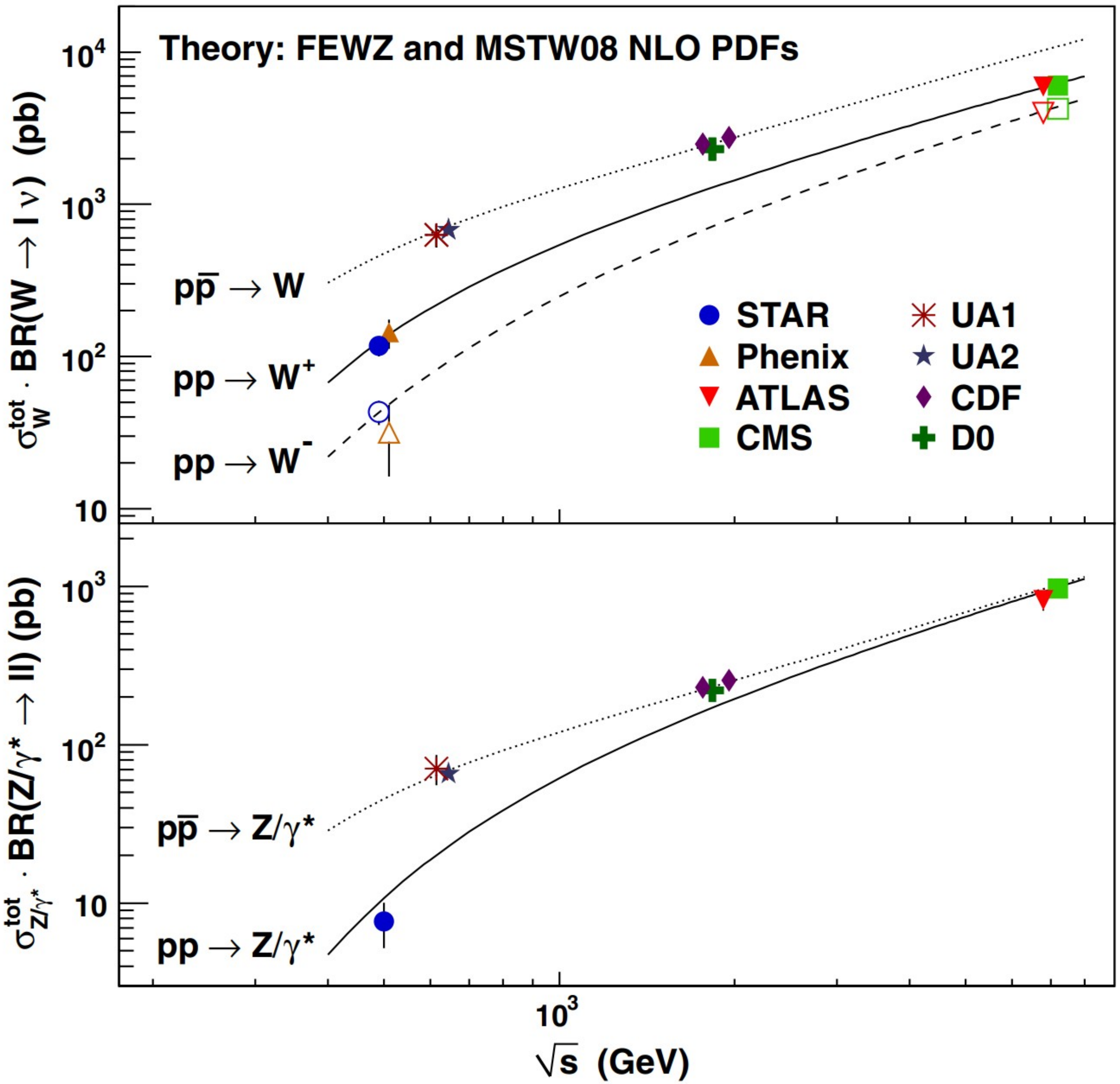
Experiment Challenges:

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

QUARK HELICITIES

Cross sections for W production

PRD 85 (2011), 092010

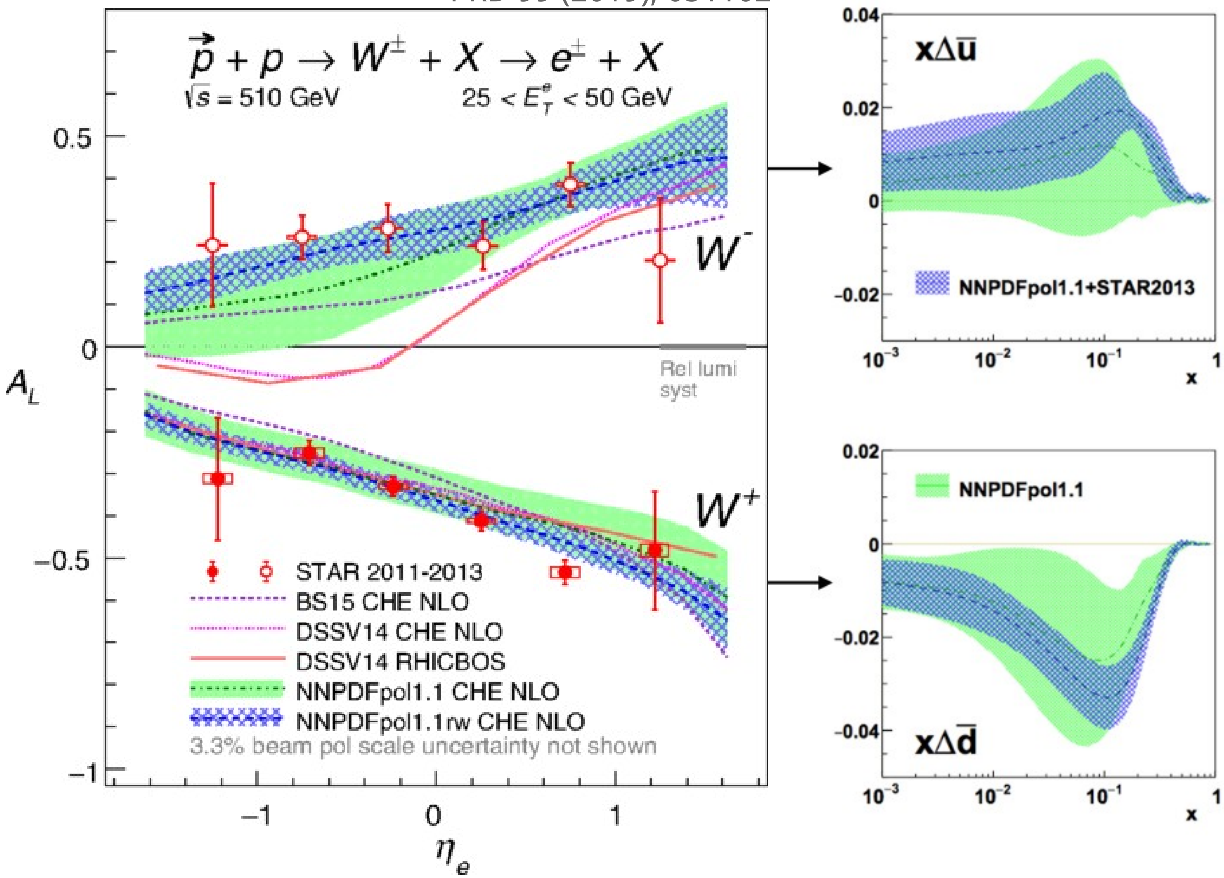


- Agreement between theory and experiment for different bosons, for different collision systems, and over a wide energy range
- Support for the NLO pQCD interpretation of asymmetry measurements
- Ratio measurements may provide insights in unpolarized light quark distributions
- **PHENIX:**
  $W \to \mu$ A_L, σ, $1.2 < |\eta| < 2.4$, PRD98, 032007 (2018)
  $W \to e$ A_L , $|\eta| < 0.35$, PRD93, 051103 (2016)
  $W \to e$ σ, PRL106 062001 (2011)
- **STAR:**
  $W \to e$ σ, PRD85 092010 (2011)
  $W \to e$ A_L , $|\eta| < 1$, PRL113, 072301 (2014)
  $W \to e$ A_L, PRL116, 132301 (2016)
  $W \to e$ A_L, PRD 99, 051102 (2019)

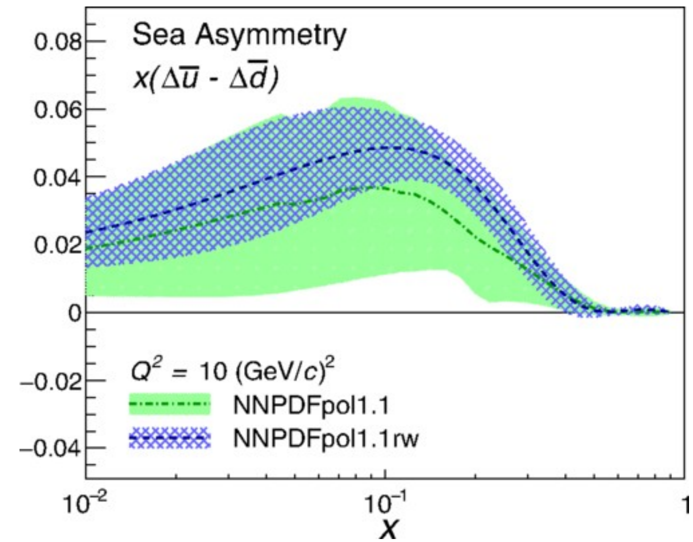
QUARK HELICITIES

Single spin asymmetry for W production at STAR

PRD 99 (2019), 051102



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



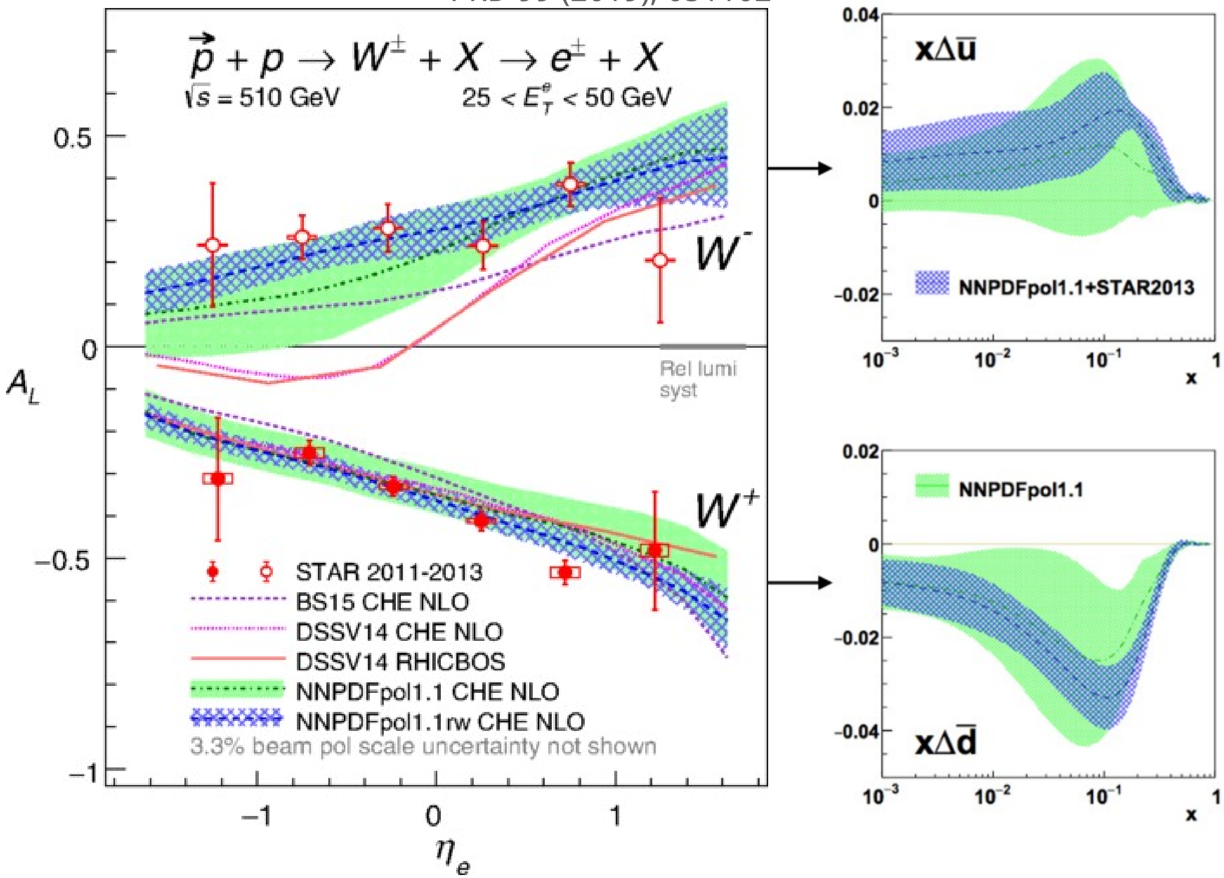
- Significant preference for $\Delta\bar{u}$ over $\Delta\bar{d}$
- Opposite to the spin-averaged quark-sea distributions
- Verification of different nucleon structure models

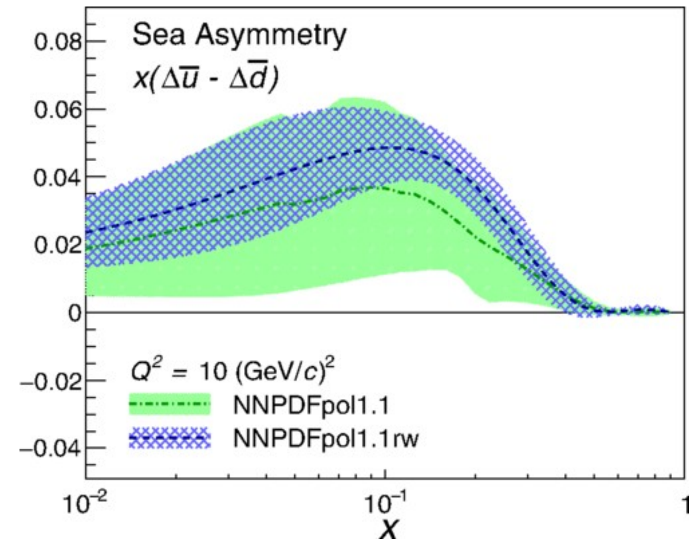
- 2013 data (300 pb^{-1}) – Most precise data to date
- Combined precision (full available data set) – **important constraint on sea asymmetry**
- Predictions from DSSV and NNPDF agree with data
- Data agrees with DIS results in the valence region

QUARK HELICITIES

Single spin asymmetry for W production at STAR

PRD 99 (2019), 051102





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

Motivation to investigate further the sea asymmetry

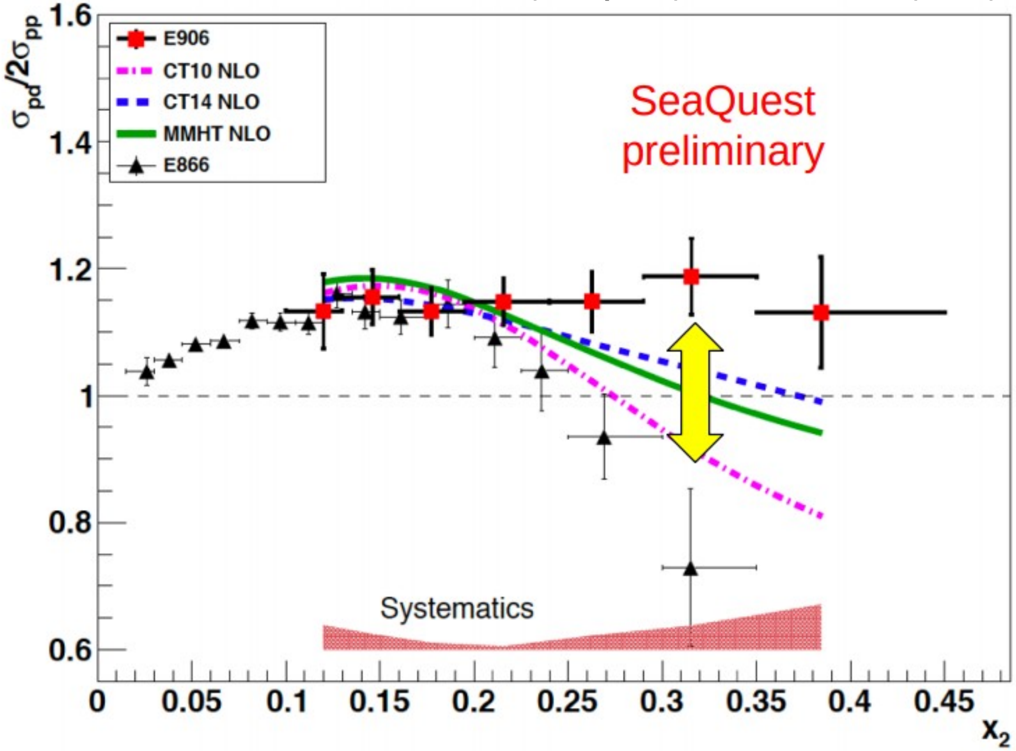
Opportunities at EIC

- Accurate determination of $\Delta\bar{u}$ and $\Delta\bar{d}$ through CC DIS and SIDIS with pions
- Access to strangeness: SIDIS with kaons and CC mediated charm production in DIS: $W^+s \to c$

UNPOLARIZED SEA-QUARK DISTRIBUTIONS

Probing the $\bar{d}(x)/\bar{u}(x)$ ratio

W. Lorenzon (SeaQuest), Hadron-China (2019)



Drell–Yan cross sections
NA51, E866, SeaQuest
Ratio of cross-sections with proton and deuteron target gives access to $\bar{d}(x)/\bar{u}(x)$

$$\frac{\sigma_{dp}}{2\sigma_{pp}} \sim \frac{1}{2}\left(1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right)$$

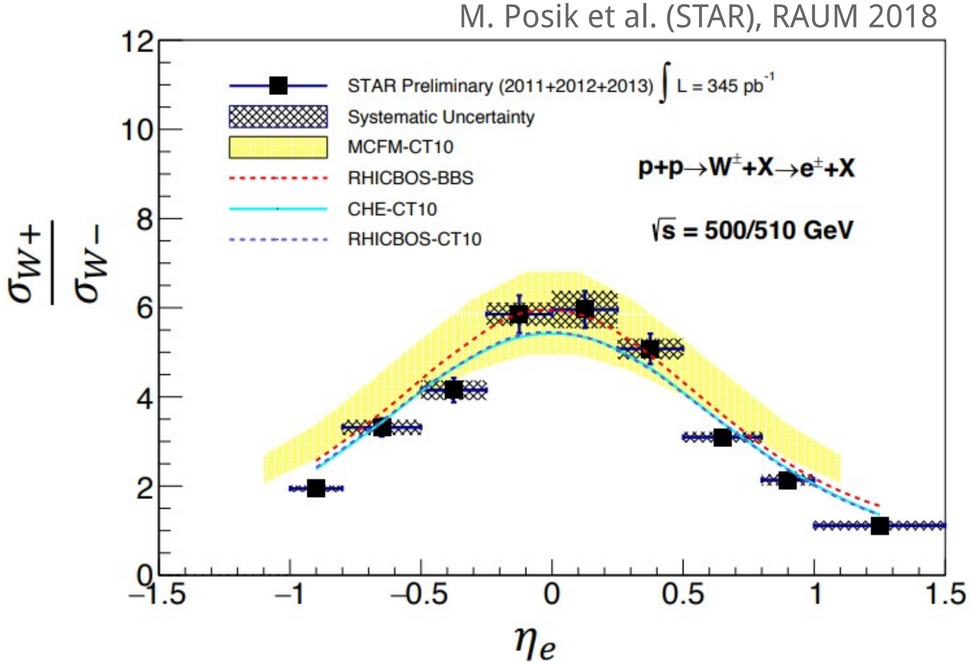
W^+/W^- cross section ratio at STAR

- Complementary to NA51, E866, and SeaQuest
- STAR data cover ~0.1 < x < ~0.3, $|\eta_e| < 1$
- Higher $Q^2 = M_W^2$

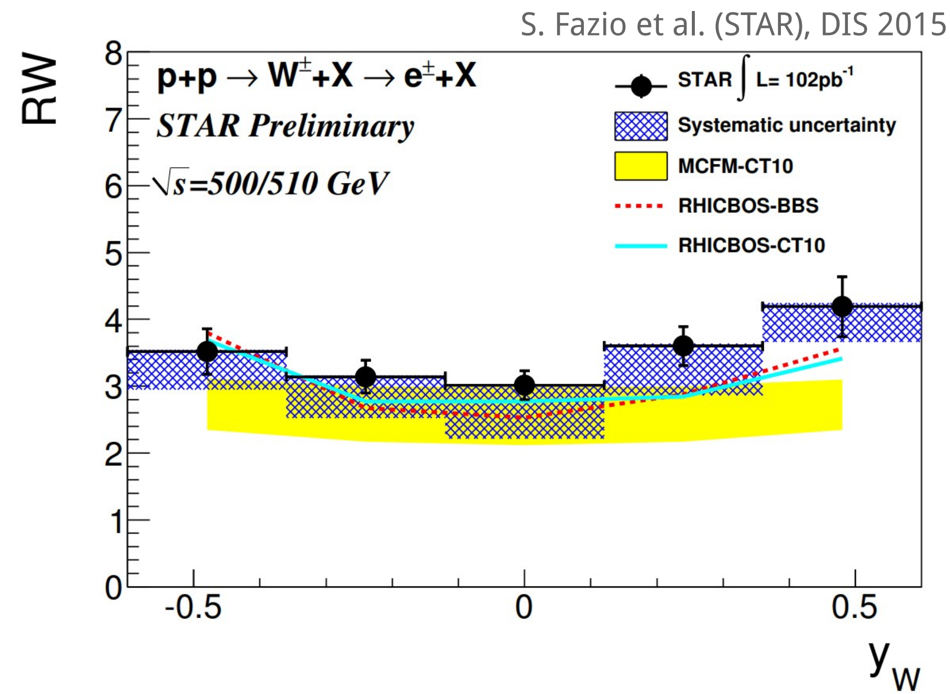
UNPOLARIZED SEA-QUARK DISTRIBUTIONS

Cross sections for W production

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



S. Fazio et al. (STAR), DIS 2015



Publication in preparation

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

- W-boson kinematics determined by reconstructing its recoil
- Rapidity determined from data combined with simulations

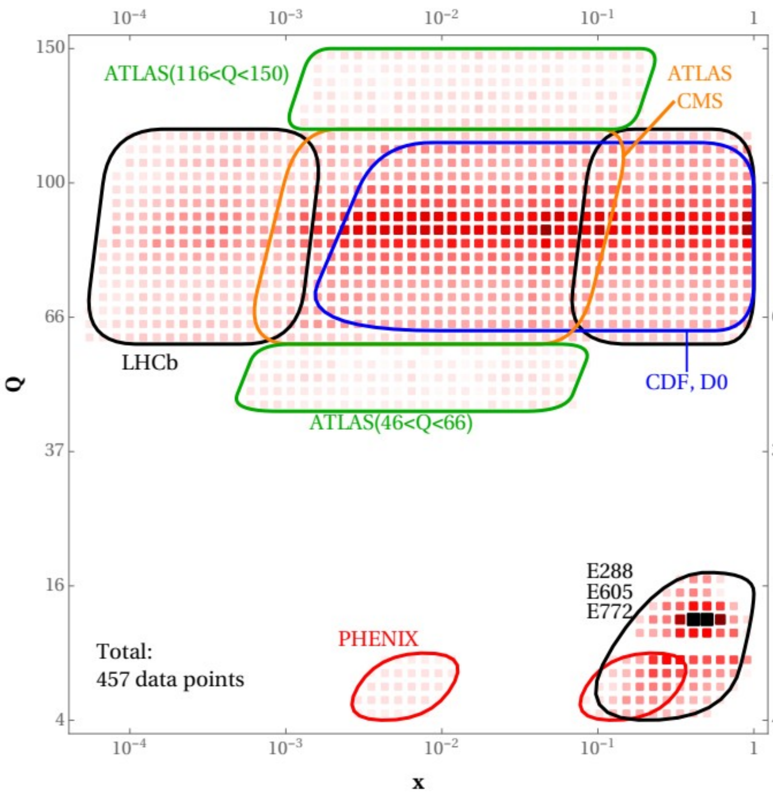
- Constraints on global PDF fitting for $\bar{u}$ and $\bar{d}$ quarks through W production at higher Q^2 than SeaQuest and NuSea and overlapping x region: 0.1 – 0.3.

SIVERS FUNCTION – SIGN CHANGE

TMD FACTORIZATION AT WORK

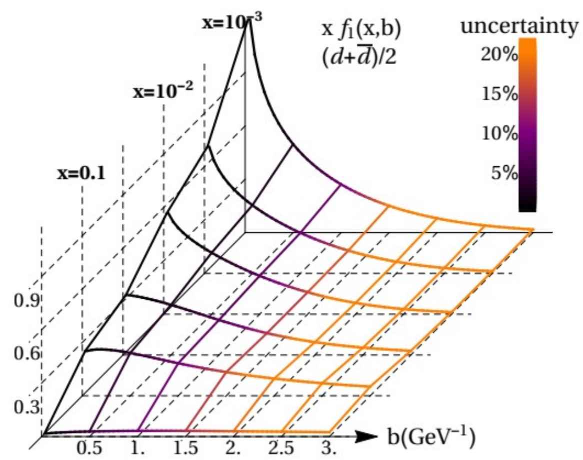
TMD factorization formalism used to extract universal **TMDPDFs** and **non-perturbative evolution kernel** from DY/Z boson production

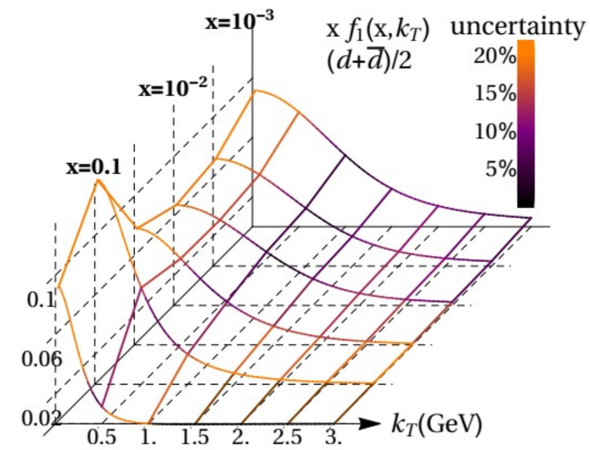
JHEP 1906 (2019) 028
V. Bertone, I. Scimemi, A. Vladimirov



State-of-the-art implementation of TMD factorization

- Analysis performed at NNLO in pQCD
- Scale fixation within the ζ-prescription approach
  → non-perturbative evolution values can be used in, e.g., the analysis of polarized TMDPDFs





- 457 data points with restrictive cut on kinematics
  → well within TMD factorization range

SIVERS FUNCTION – SIGN CHANGE

Transverse spin structure

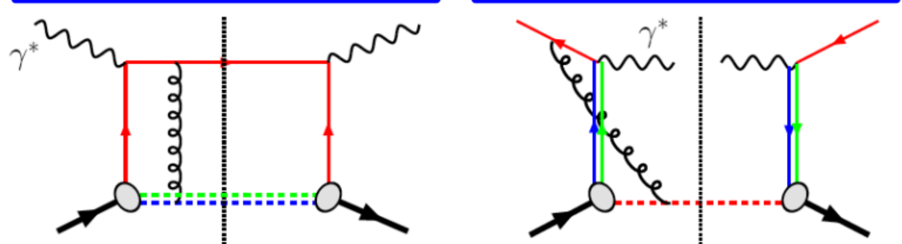
- Most observables in pp only related through **Twist-3 formalism**: collinear quark-gluon-quark correlations (1 hard scale needed, e.g., p_T of hadron or jet)
- **TMD parton distributions**: e.g. Collins or Sivers functions (require 2 scales, e.g., p_T and M of W)

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

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

DIS	**Drell-Yan, W or Z**
Final-state interaction	**Initial-state interaction**
Opposite colors attract	**Like colors repel**



Fundamental prediction about the nature of QCD

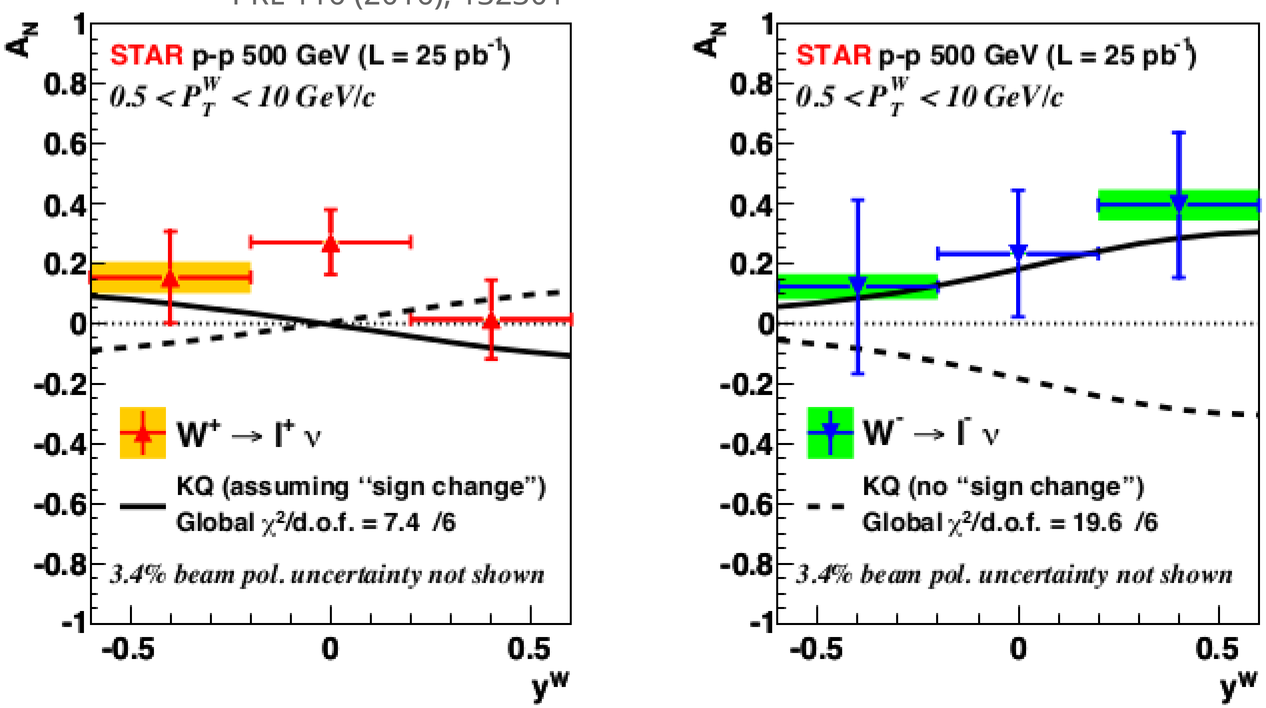
SIVERS FUNCTION – SIGN CHANGE

A_N for W^+ and W^- at STAR

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

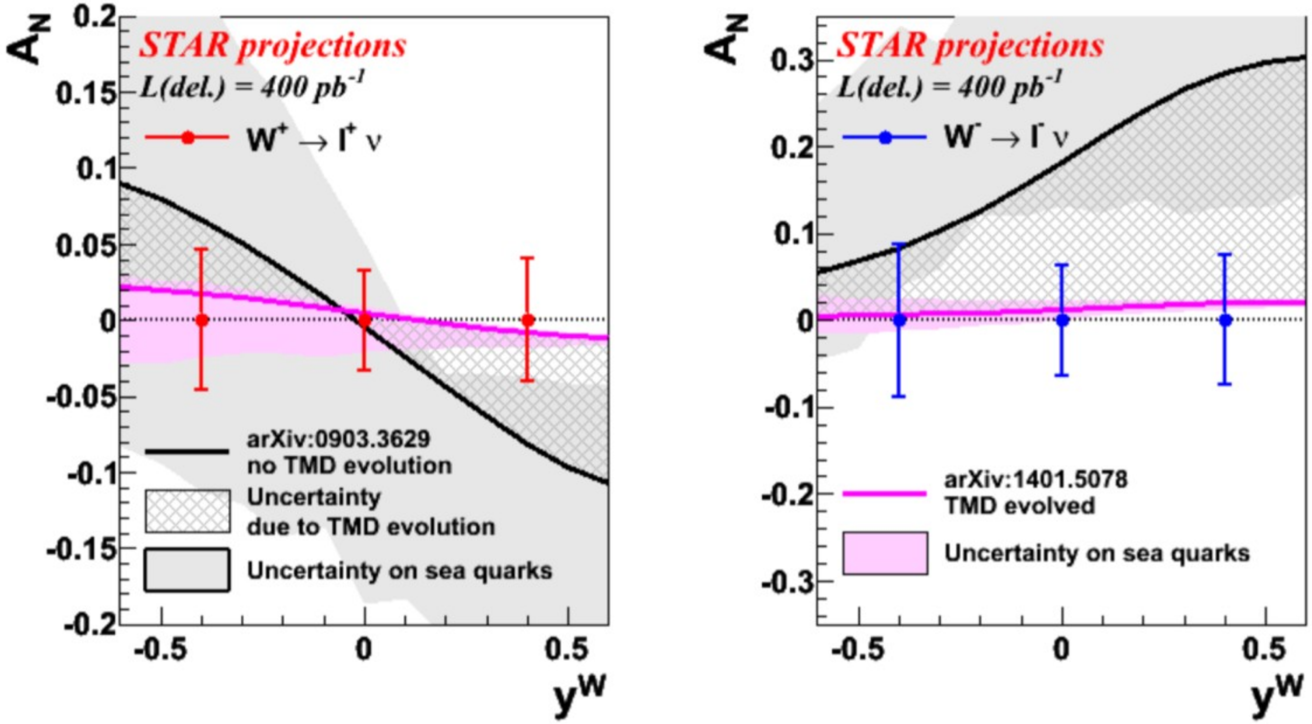
SIVERS FUNCTION – SIGN CHANGE

A_N for W^+ and W^- at STAR

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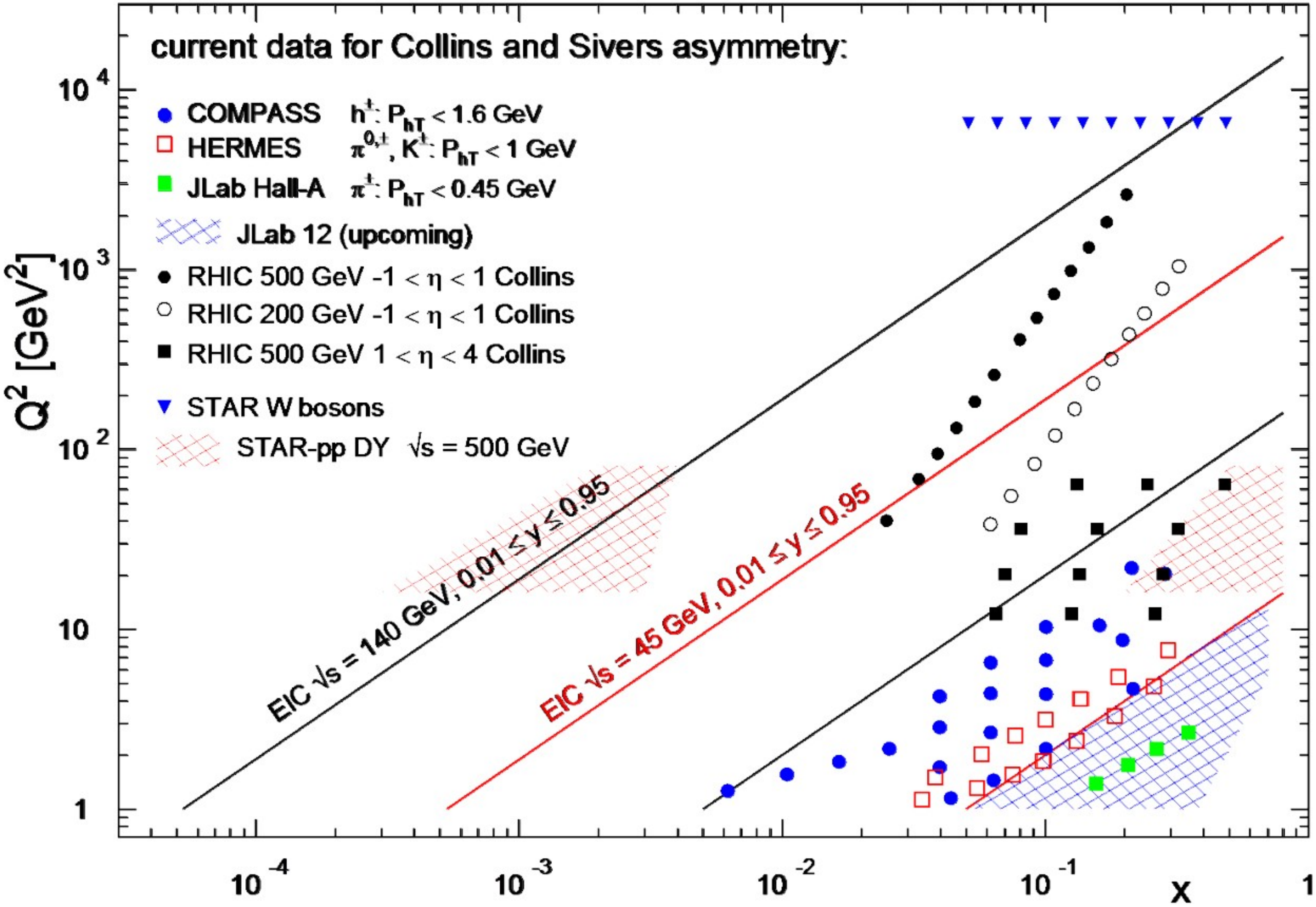
- **2017 results** will be based on 350 pb^{-1} data – more definite test
- **Other opportunities**, e.g. photons (sign change in the Twist-3 formalism), Drell-Yan
- Gradual **upgrades** to existing STAR forward instrumentation

- Uncertainties on sea quarks from DIS and SIDIS measurements large
- Precision data on from DIS from EIC
- 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

COLLINS AND SIVERS ASYMMETRY

arXiv:1602.03922



- Fixed-target DIS, RHIC-spin, and EIC are truly complementary
- RHIC-spin has a unique role in hadro-production with kinematics from high to low x at high Q^2
- Precision tests of universality when EIC data become available

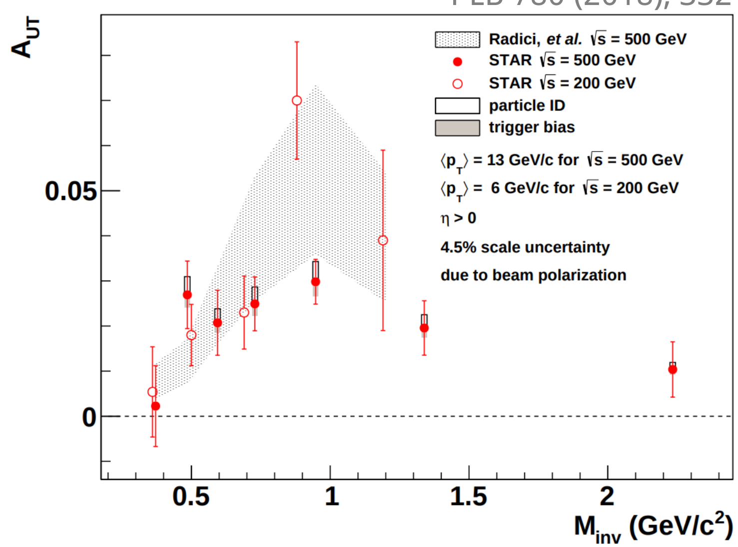
TRANSVERSITY

TRANSVERSITY

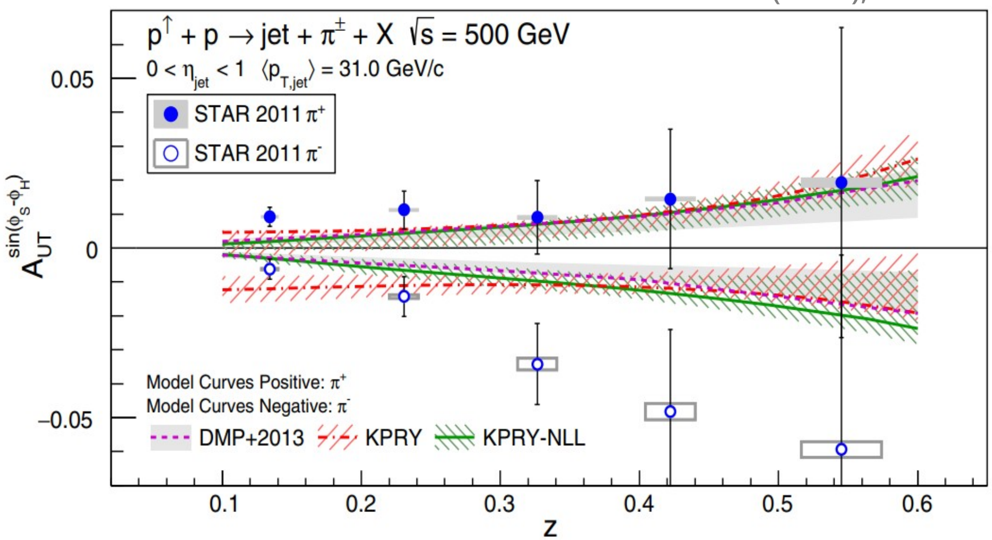
Methods to access it at RHIC: Single spin asymmetries of the azimuthal distributions A_{UT}

- Spin-dependent modulation of hadrons in jets → **Collins function** (TMD FF)
- Di-hadron correlation measurements → **“interference FF”** (collinear framework)

PLB 780 (2018), 332



PRD 97 (2018), 032004



- Well described by **recent IFF asymmetry calculations** incorporating SIDIS and Belle e^+e^- data
- 200 GeV data included in **gobal analysis**:
  M. Radici and A. Bacchetta, PRL 120, (2018) 192001

- Theory predictions using transversity and Collins FF extracted from SIDIS and e^+e^-
  D’Alesio, Murgia & Pisano PLB 773 (2017), 300
  Kang, Prokudin, Ringer & Yuan, PLB 774 (2017), 635
  without and with evolution

More from STAR on IFF and Collins

- Collins results from 2012 200 GeV (22 pb^{-1}) being finalized
- 200 GeV data from 2015 (x 2 more then 2012) & 500 GeV data from 2017 (x 12 more)

TRANSVERSITY

Connection to BSM physics

Tensor charge for a quark type q: first moment of the transversity distribution for valence quarks

$$\int_0^1 dx\left(h_1^q(x,Q^2)-h_1^{\bar{q}}(x,Q^2)\right)$$

Intensity frontier: search for low-energy footprint of BSM physics at higher scales

Neutron EDM d_n: estimate CP violation induced by quark chromo-EDM d_q

$$\delta\mathcal{L}_{\mathrm{CPV}} \supset -\frac{ie}{2}\sum_{f=u,d,s,e} d_f\,\bar{f}\sigma_{\mu\nu}\gamma_5 F^{\mu\nu} f$$

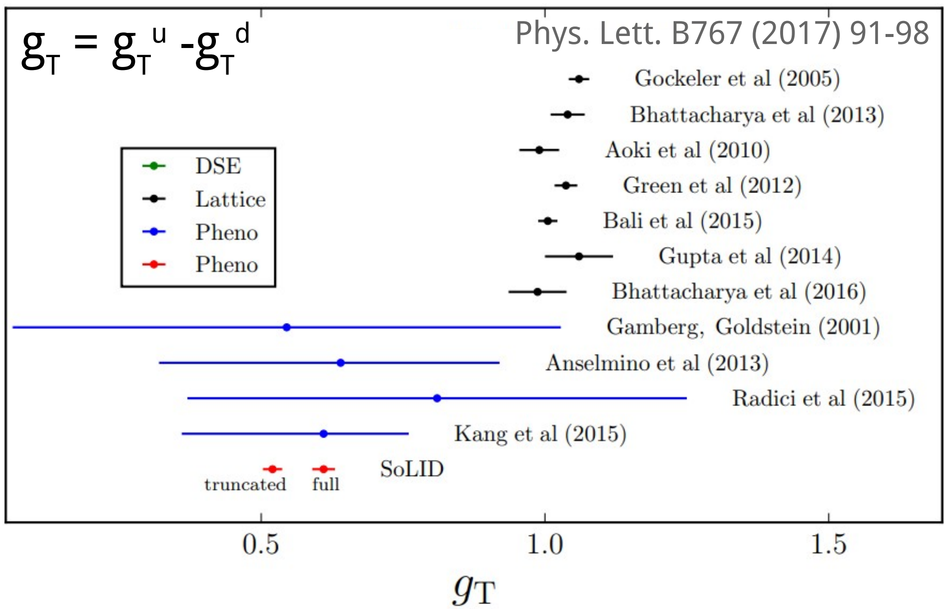
$$d_n = g_T^u d_u + g_T^d d_d + g_T^s d_s$$

Experimental bounds

Tensor charge

Bounds on CPV sources encoded in quark EDM

Gobal analysis including 200 GeV IFF STAR data:
$g^T = 0.53(25)$ at $Q^2 = 4$ GeV^2
M. Radici and A. Bacchetta, PRL 120, (2018) 192001



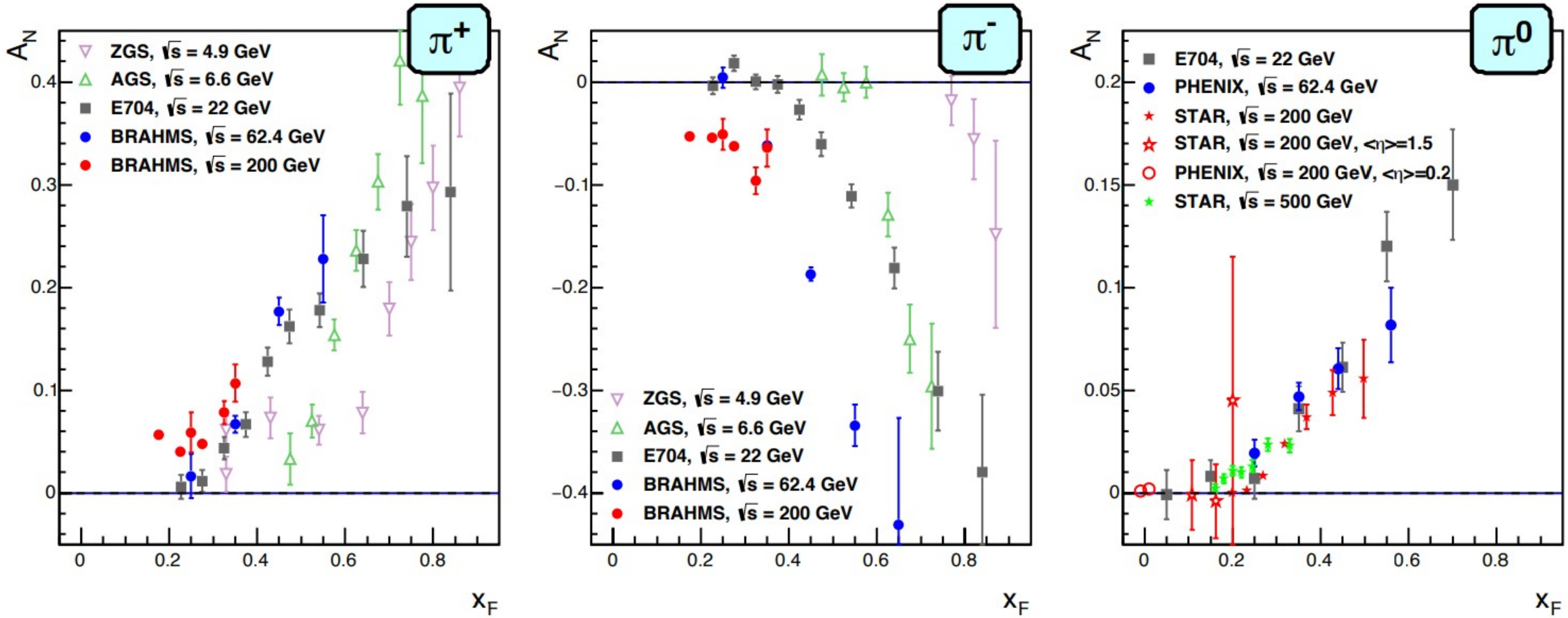
Comparison to the lattice QCD calculations

ORIGIN OF LARGE FORWARD A_N

ORIGIN OF LARGE FORWARD A_N

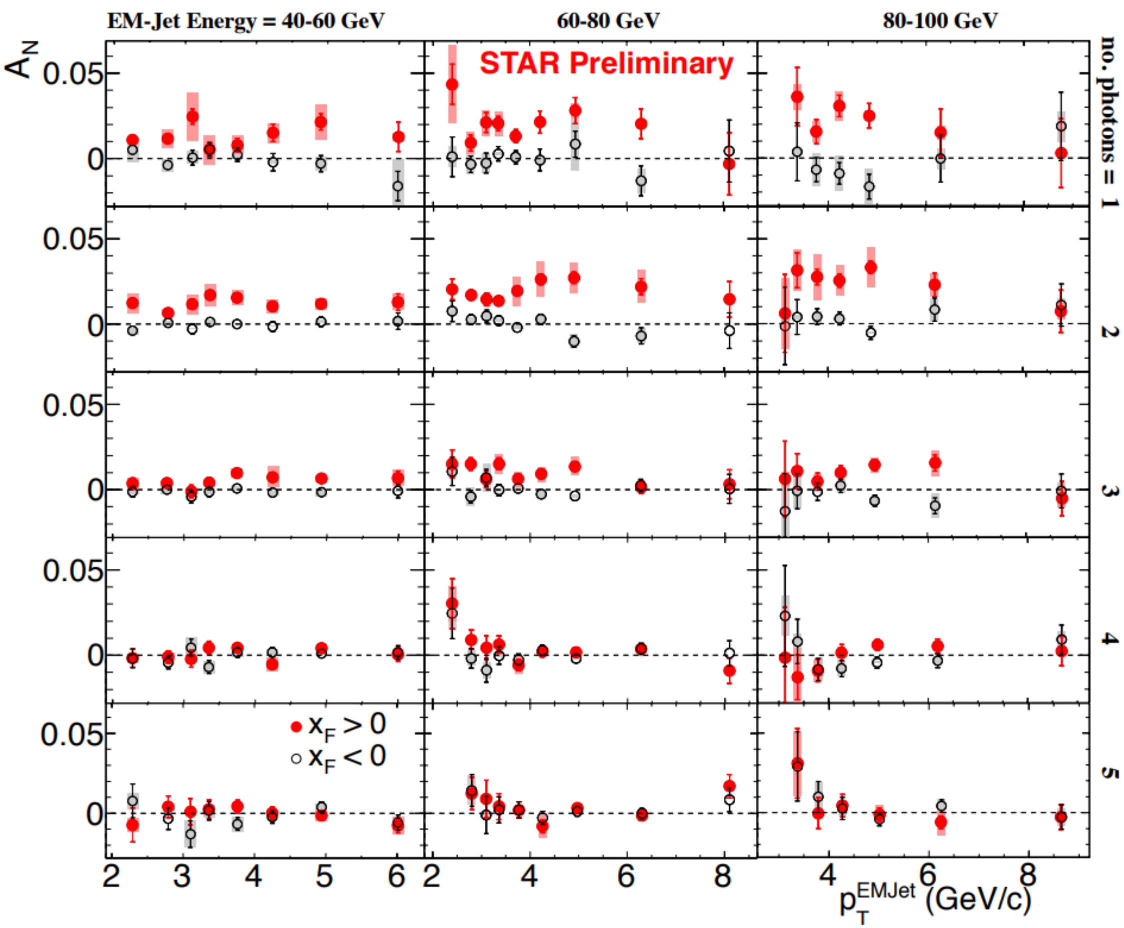
Puzzle since E704

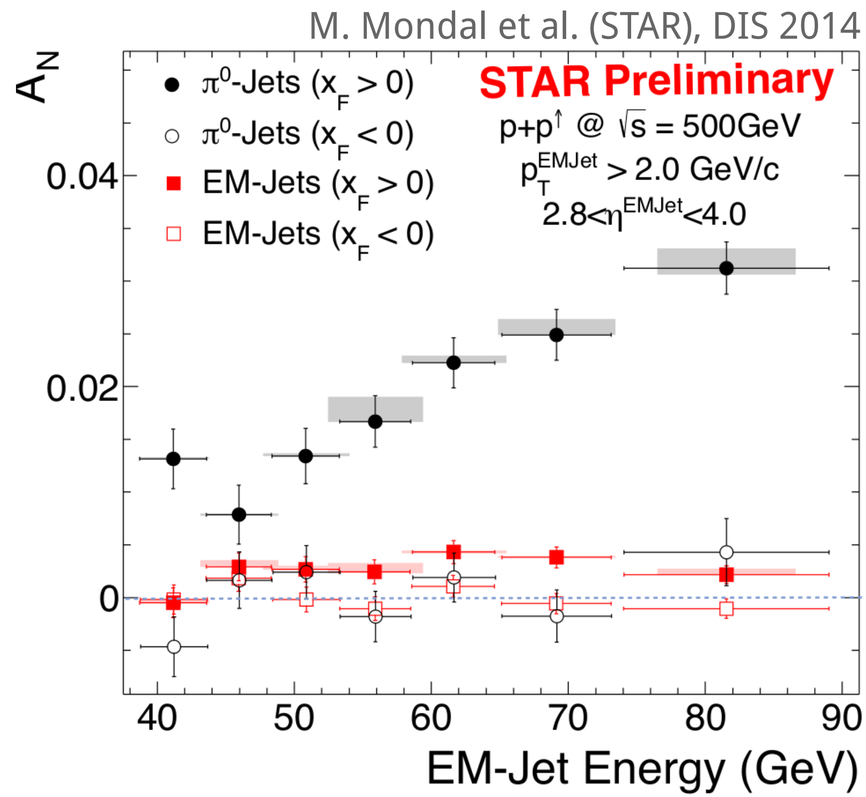
arXiv:1602.03922



- 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





- 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

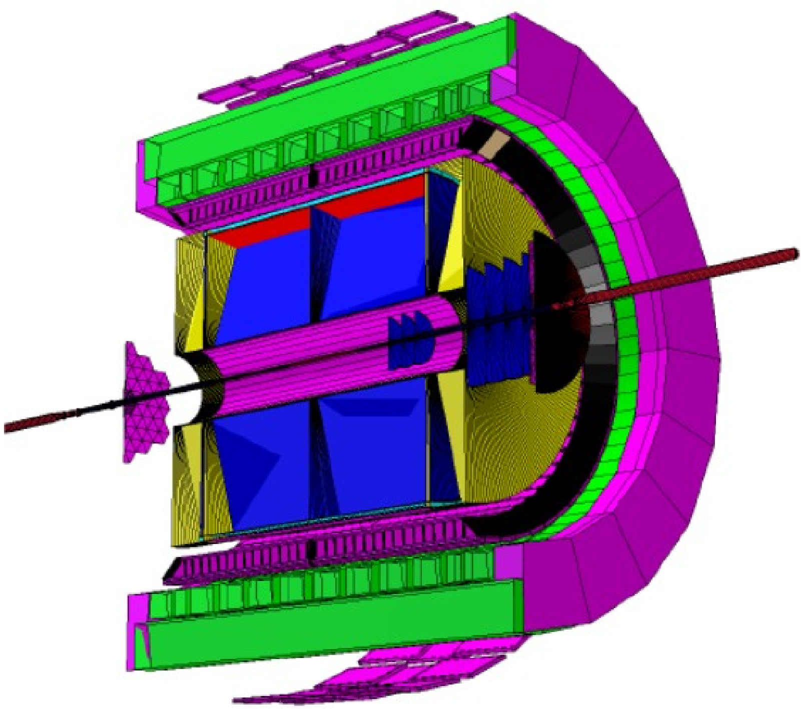
OUTLOOK

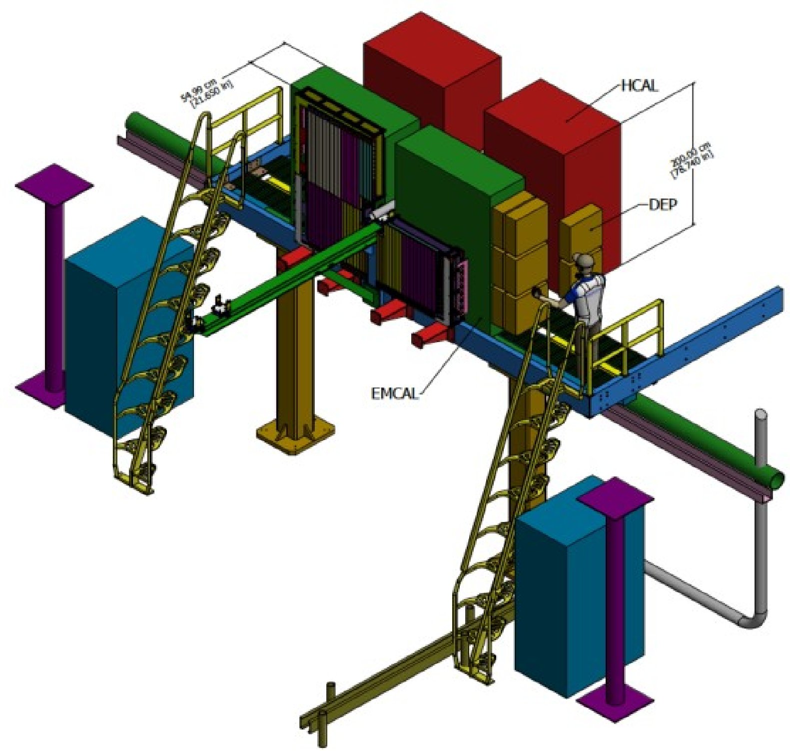
Experts at the workshop: E.-C. Aschenauer, Z. Ye

STAR Forward Upgrade

- Ensure jet ($\sqrt{s}$ = 500 GeV) and Drell-Yan capability, and charge-sign discrimination
- Access to the charged hadron asymmetries and flavor-enhanced jets up to the highest $\sqrt{s}$ at RHIC
- Drell-Yan and direct photon – initial state and hadronization in nuclear collisions, Sivers sign change
- Full jets in forward direction – TMDs at low and high x and $\Delta g(x)$ at small x

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





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

PLANS WITH FORWARD UPGRADE

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

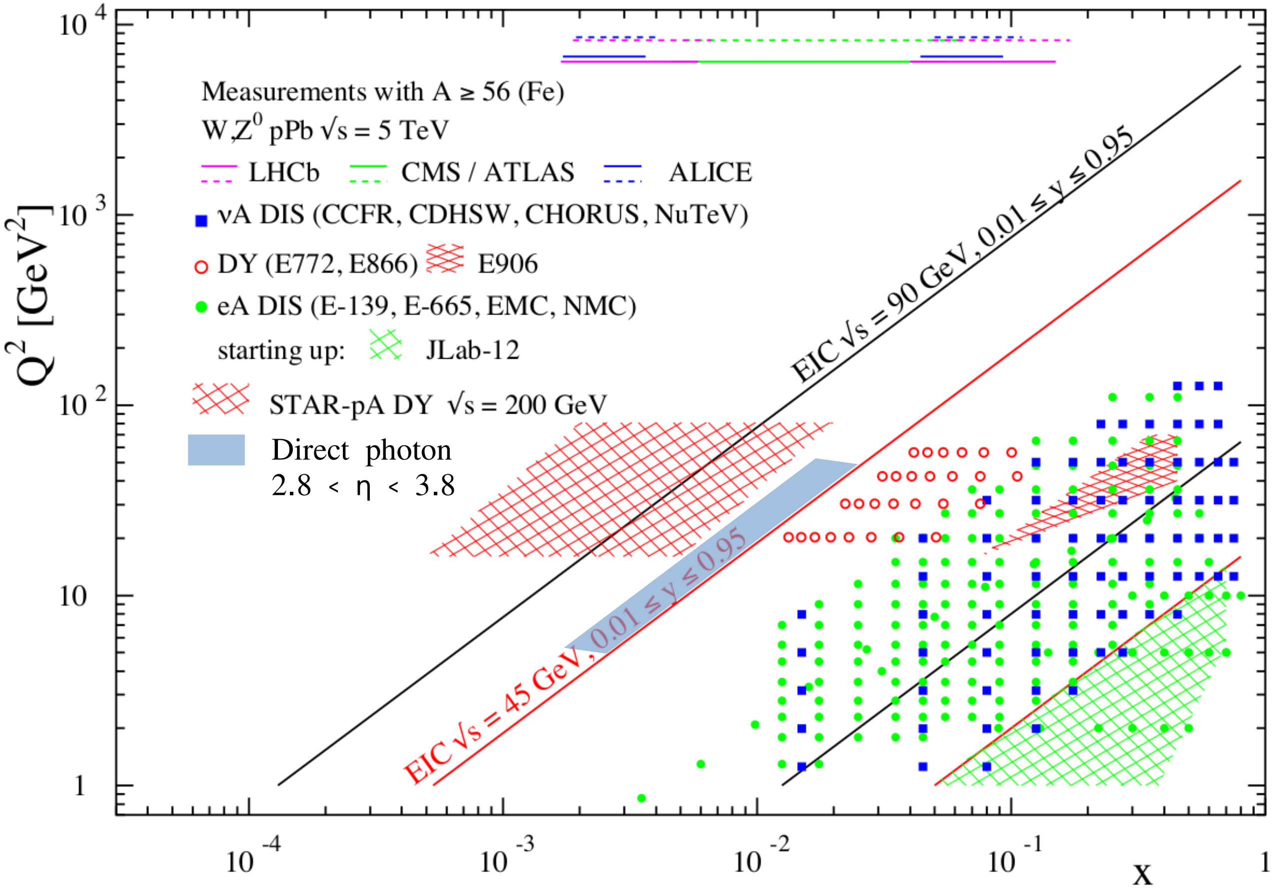
	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	Subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Forward instrum. ECal+HCal+Tracking
	2023	$p^{\uparrow}Au$ @ 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

- 2023: Concurrent with sPHENIX run: opportunities with and without forward instrumentation
- 2021/22 (potential): More high-impact science with unique forward capabilities of STAR following the completion of the ongoing BES-II campaign and before RHIC running with sPHENIX

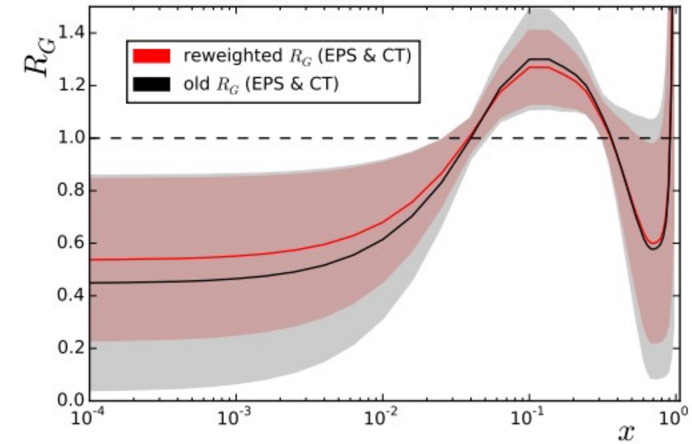
PROTON-NUCLEUS COLLISIONS

Probing initial state in AA collisions

Adapted from arXiv:1602.03922



Armesto, N. et al. EPJC (2016) 76, 218



- Understanding of initial state: critical for LHC and RHIC program
- Our knowledge about nPDFs still limited

Opportunities at RHIC:

- pAl, pAu
  → A-dependence of nPDFs
  → Test saturation models predictions of A-dependence
- moderate Q^2 and medium and low x → nuclear effects large

R_{pA} for Drell-Yan → nuclear modification of sea-quarks

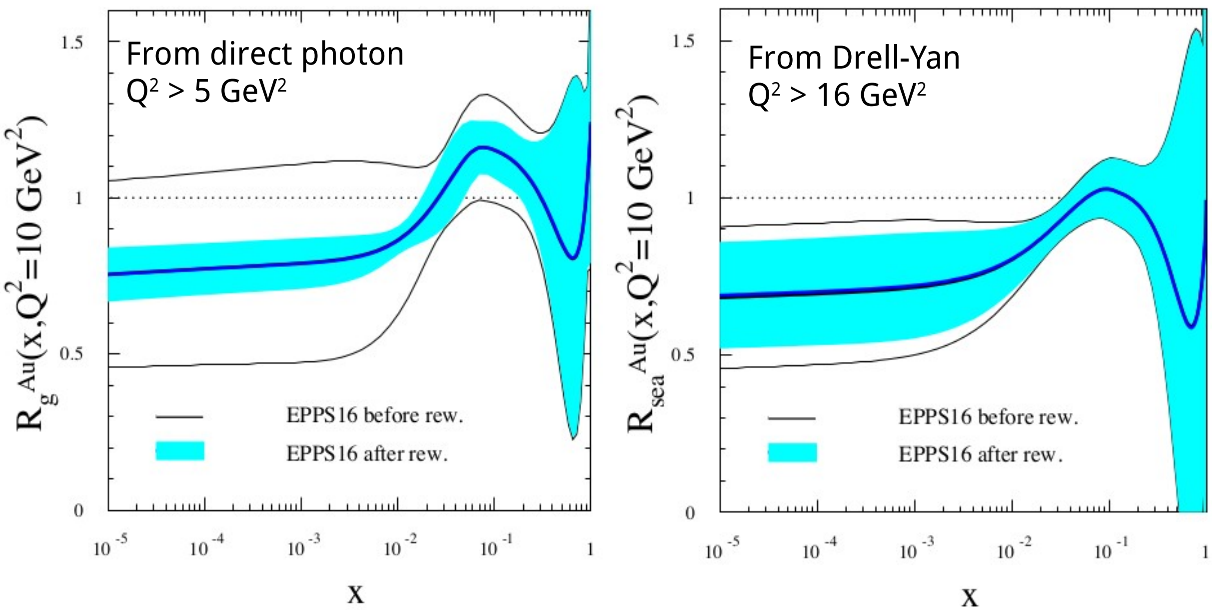
R_{pA} for direct forward photon → gluons

Free of final state effects

PROTON-NUCLEUS COLLISIONS

Probing initial state in AA collisions

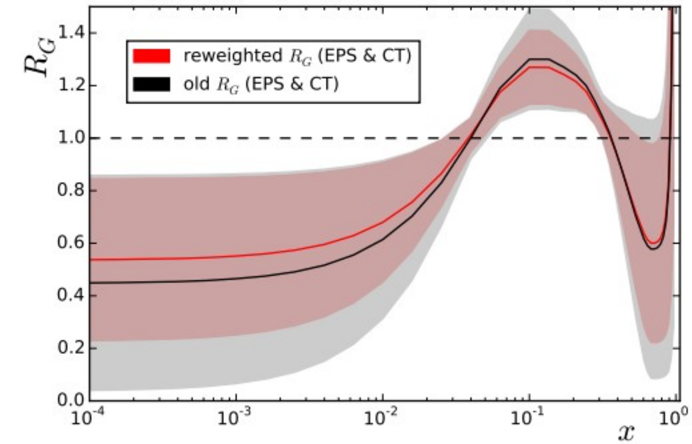
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648



- Predicted impact of the RHIC 2015 and 2023 data
- Complimentary with future EIC data
- Precision of pA data enable test of nPDF universality with future EIC results

R_{pA} for Drell-Yan → nuclear modification of sea-quarks
R_{pA} for direct forward photon → gluons
Free of final state effects

Armesto, N. et al. EPJC (2016) 76, 218



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  → Test saturation models predictions of A-dependence
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SUMMARY

RHIC-spin program has provided unique insight into:

- The **polarized sea quark** distributions via W/Z production
- Constraints on the **polarized gluon distribution**
  - Towards lower x: high luminosity 2013 data at √s = 510 GeV
  - Towards precision in current x region: 2015 data at √s = 200 GeV
- **Sivers' sign-change** from W-boson data
  - Sivers' measurements with W-bosons, Drell-Yan, and photons in 2017 (x 12 more data)
- **Transverity** through the **Collins and IFF asymmetry** and **gluon linear polarization** through the 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 will provide unique physics opportunities in:

- Understanding the origin on **large forward A_N**
- Testing **TMD evolution**
- Constraining tensor charge through **transversity at high x**
- Accessing **gluon helicities** at lower x
- Understanding nature of **initial state** and **hadronization** in pA collisions

Precision measurements at RHIC important for meaningful comparisons and interpretation with future EIC data to test the **factorization** and **universality**.

Polarized proton program at RHIC is an important precursor to EIC

THANK YOU

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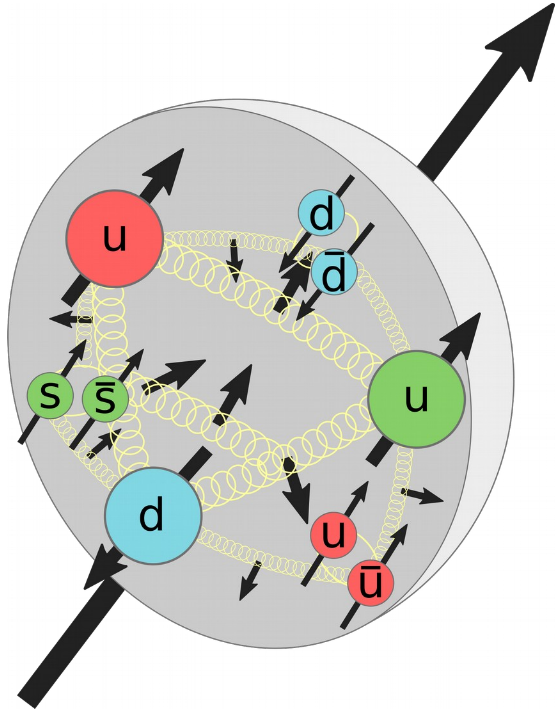
@mariakzurek

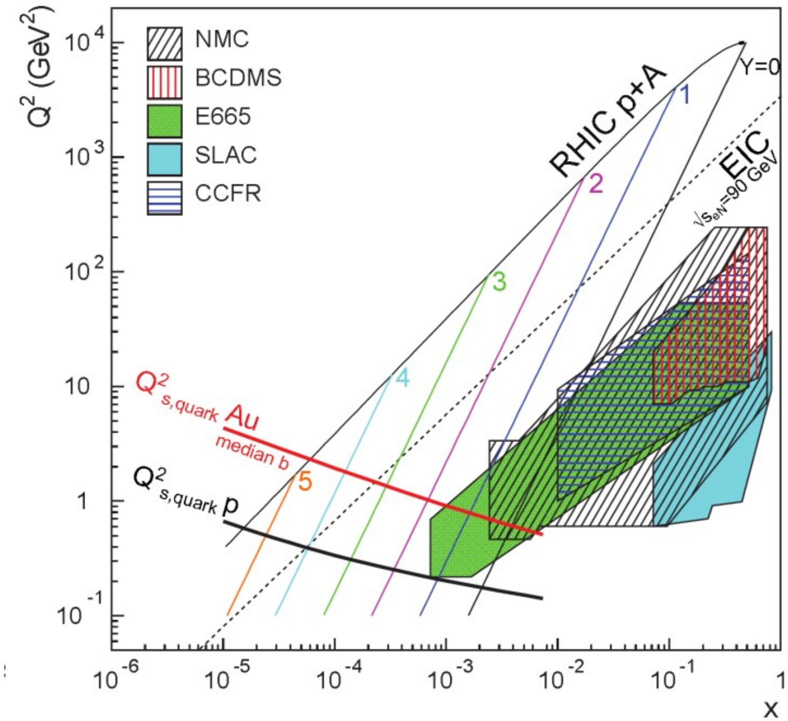


PROTON-NUCLEUS COLLISIONS

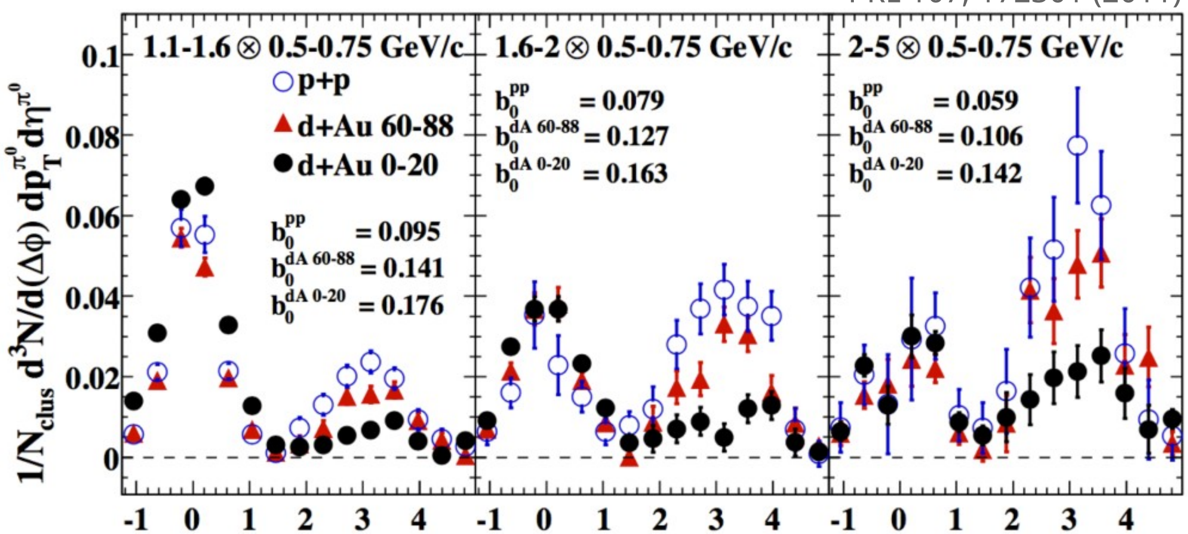
Saturation

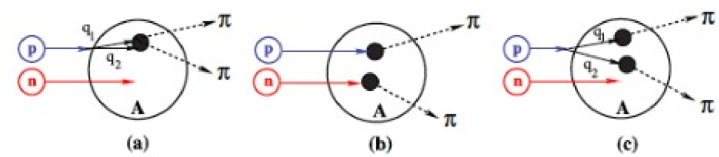
arXiv:1602.03922

- Evidence seen at HERA, RHIC, and LHC alternative explanations remain
- Key observable at RHIC: **di-hadron correlations**
- CGC predicts suppression
- Study the evolution of Q_s^2 in x and A-dependence
- Resolve ambiguity what causes the suppression in dAu



PRL 107, 172301 (2011)





Contributions through the double-interaction mechanism

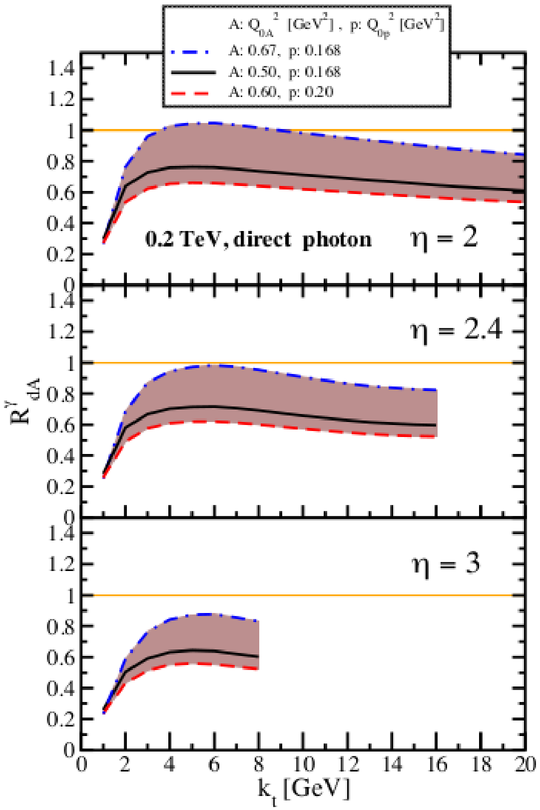
Increased luminosity with **forward upgrade**
Additional probes: photon, photon-jet, photon-hadron and di-jet correlations

PROTON-NUCLEUS COLLISIONS

Saturation

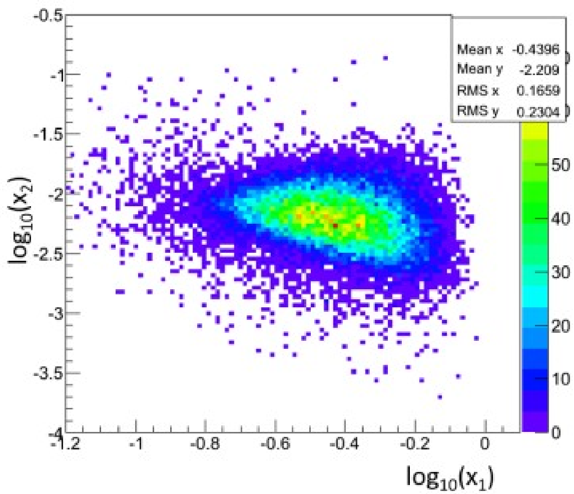
Increased luminosity with **forward upgrade**
Additional probes: photon, photon-jet, photon-hadron and di-jet correlations

photon



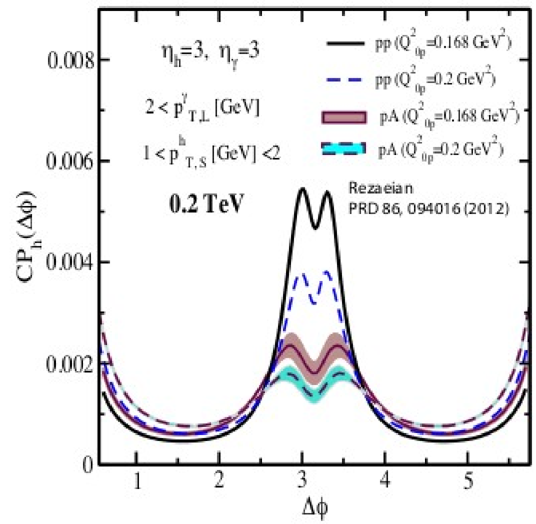
Nuclear modification factor
J. Jalilian-Marian and A.H. Rezaeian, Phys. Rev. D86 (2012) 034016 (CGC)

γ+jet



- Sensitive to gluon dipole
- Expected 1M forward γ+jet events in 2023 pAu and pAl
- 0.001 < x < 0.005
- arXiv:1602.03922

hadron+jet



- Correlation in minimum bias pp and pAu

A. Rezaeian, Phys. Rev. D86 (2012) 094016

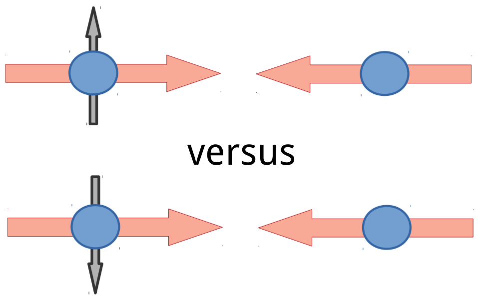
Error estimation: variation of Q_s^2 from studies of DIS structure functions and particle production in min-bias pp, pA and AA collisions in the CGC formalism

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)

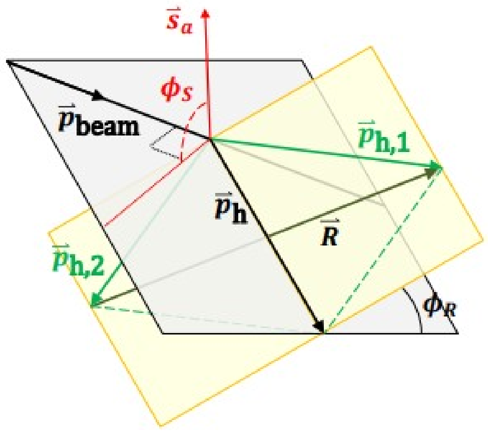
Correlation of transverse spin of fragmenting quark and transverse momentum kick given to fragmentation hadron

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)

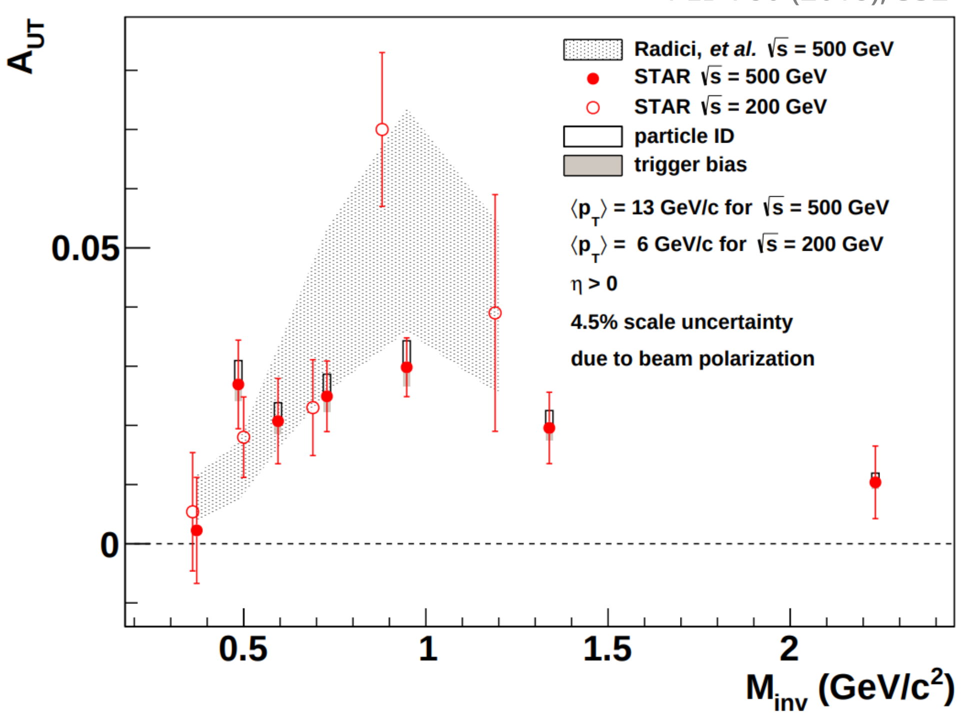


- The angle $\varphi_{RS} = \varphi_R - \varphi_S$ modulates the asymmetry due to the product of transversity and the IFF by $\sin(\varphi_{RS})$

- 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 $g \to \pi^+\pi^-$ FF

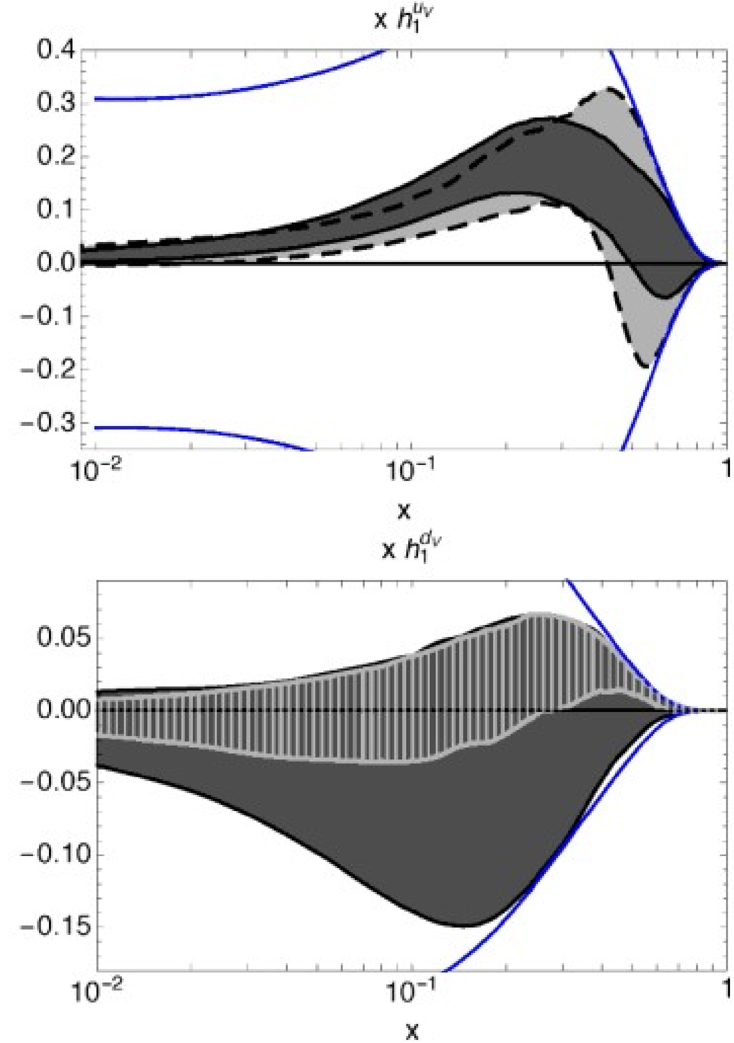
PLB 780 (2018), 332



TRANSVERSITY

Interference Fragmentation Function (IFF)

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



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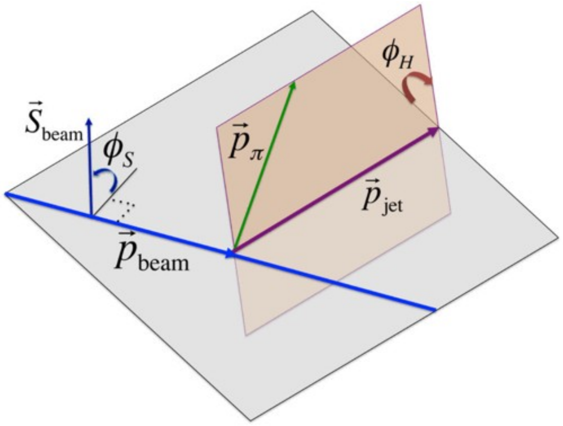
TRANSVERSITY

Collins asymmetry

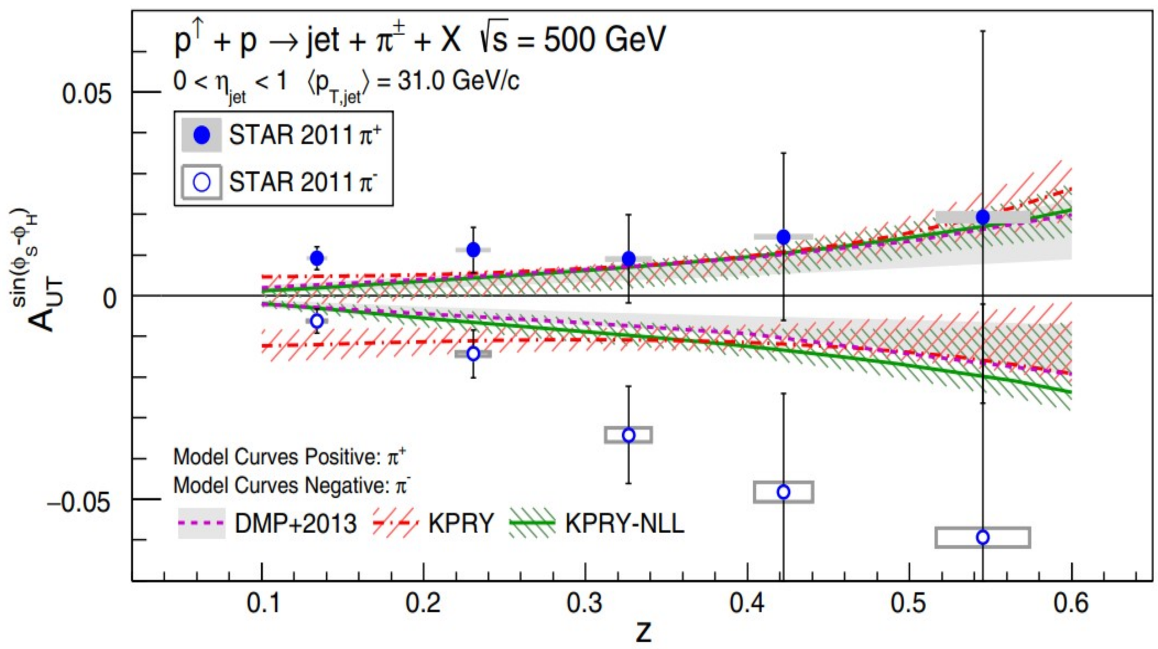
Transversity x Collins

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



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

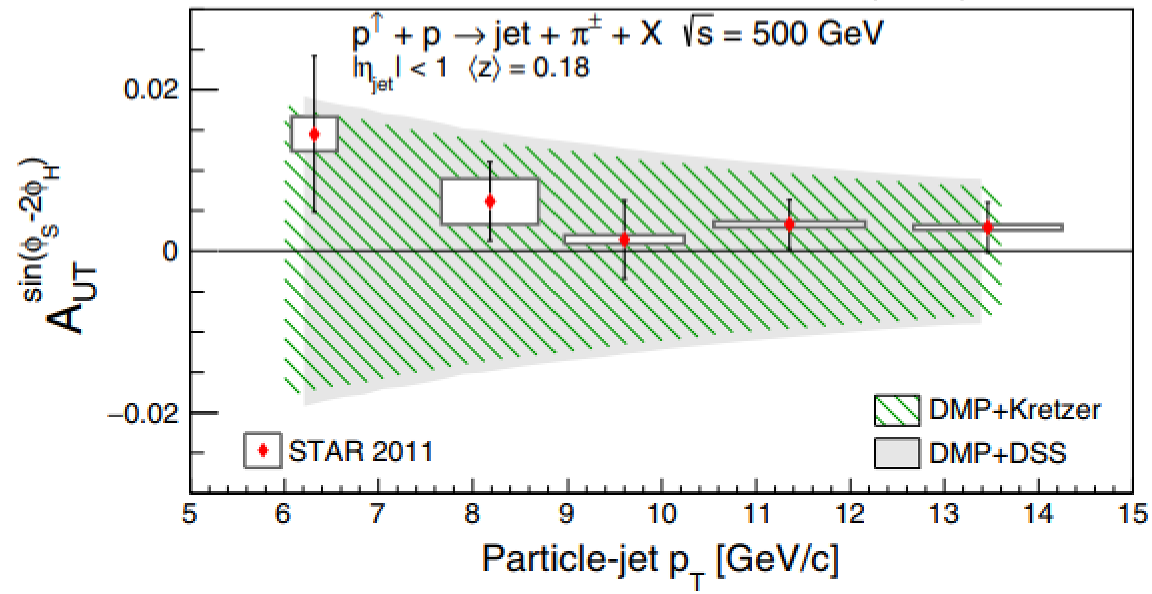
Collins-like Asymmetry

Linearly polarized gluons x Collins-like

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

- 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

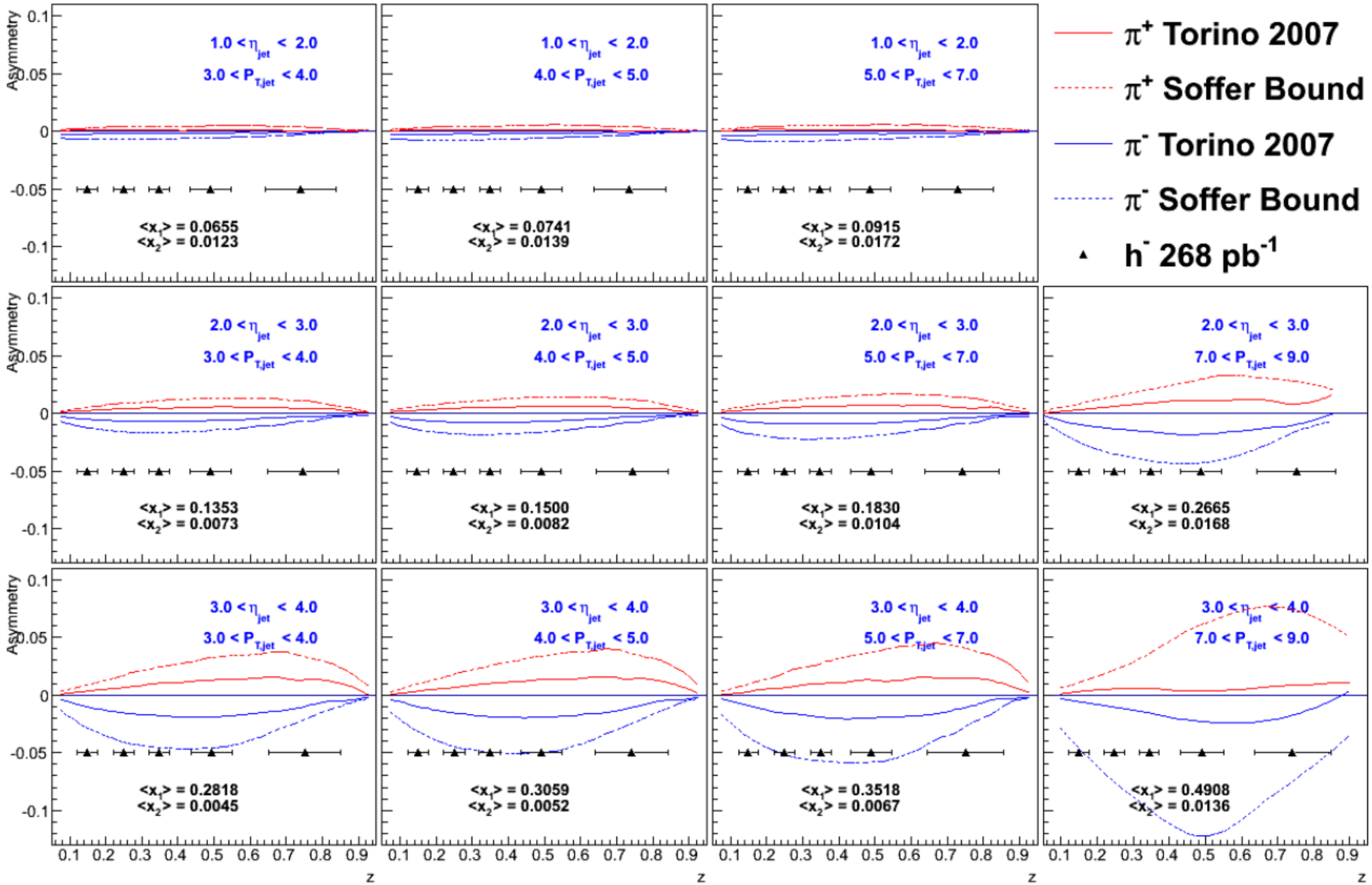


More from STAR on IFF and Collins

- 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)

COLLINS ASYMMETRY

arXiv:1602.03922



Opportunities with a future 500 GeV Run

- Statistical uncertainties based on an accumulated luminosity of 268 pb^{-1}

PROTON-NUCLEUS COLLISIONS

Nuclear parton distrubution function

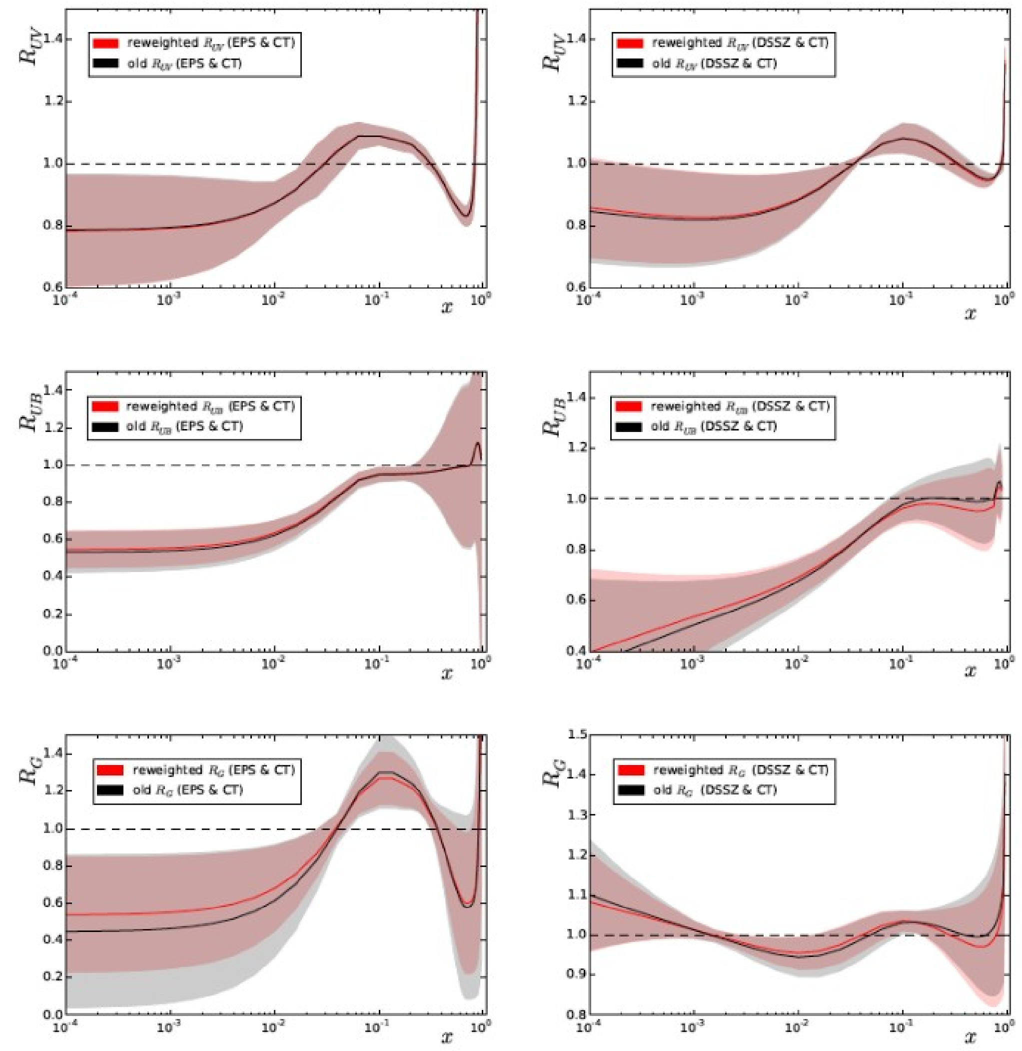
Current understanding of nPDFs still limited

- LHC: p+Pb, very high Q^2, nuclear effects reduced by evolution

- RHIC: p+Al, p+Au (A-dependence), moderate Q^2, medium and low x

Golden channels:

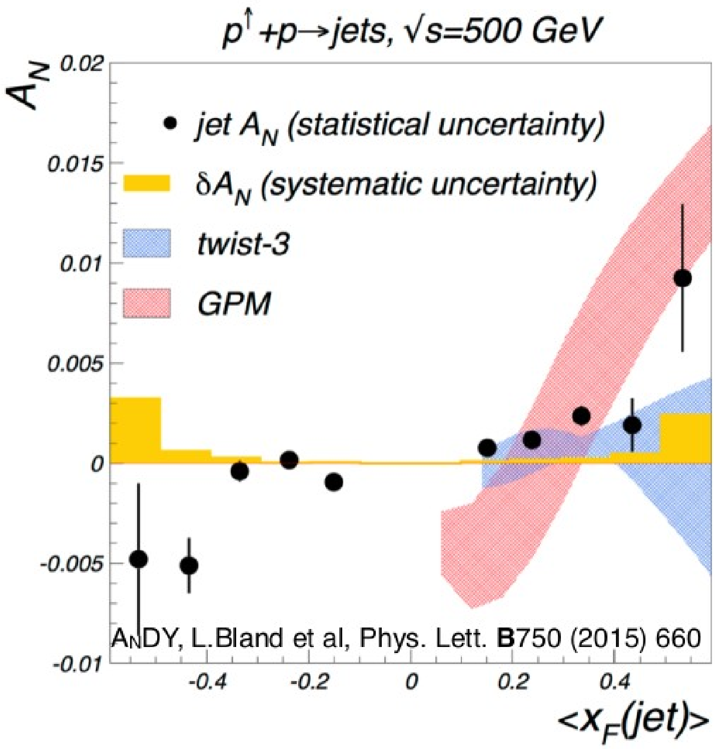
- R_{pA} for Drell-Yan → nuclear modification of sea-quarks
- R_{pA} for direct forward photon → gluons

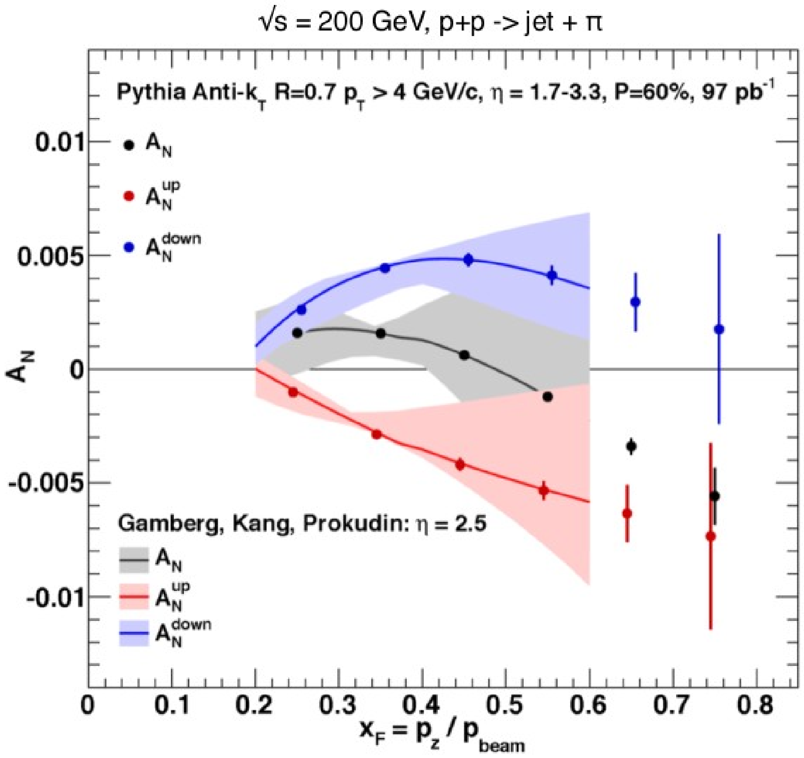


Impact of the LHC Run-I data on the nPDFs

ORIGIN OF LARGE FORWARD A_N

Small forward jet A_N from A_NDY Collaboration, PLB 750 (2015), 660





- L. Gamberg, Z.-B. Kang, and A. Prokudin, PRL 110 (2013), 232301 – Twist-3 parton correlation function for u and d valence quarks cancel
- Pursue charged-pion enhanced jets, and possible Twist-3 origin of forward A_N with improved photon A_N measurements
- Diffractive origin: Roman-Pot data (exist on tape) + full forward jet-capability and tracking are needed to pursue cancellation scenarios

NUCLEAR DEPENDENCE OF A_N

Very forward neutron

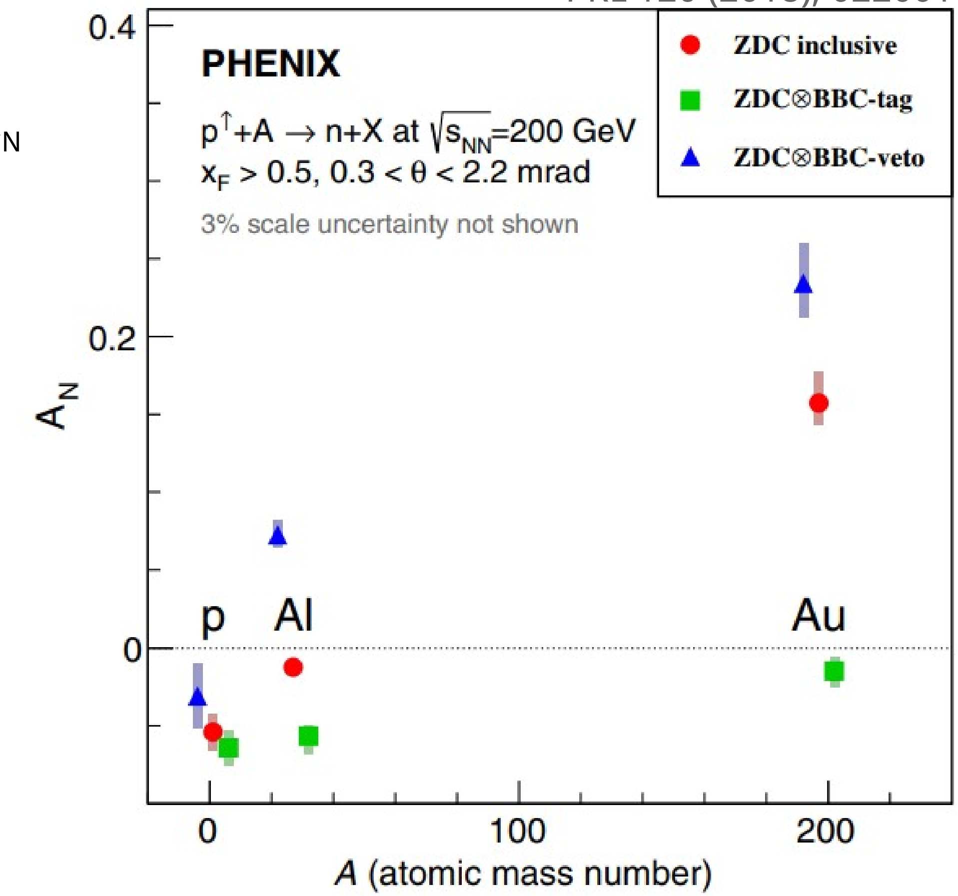
In the **perturbative** region:

- 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

PRL 120 (2018), 022001

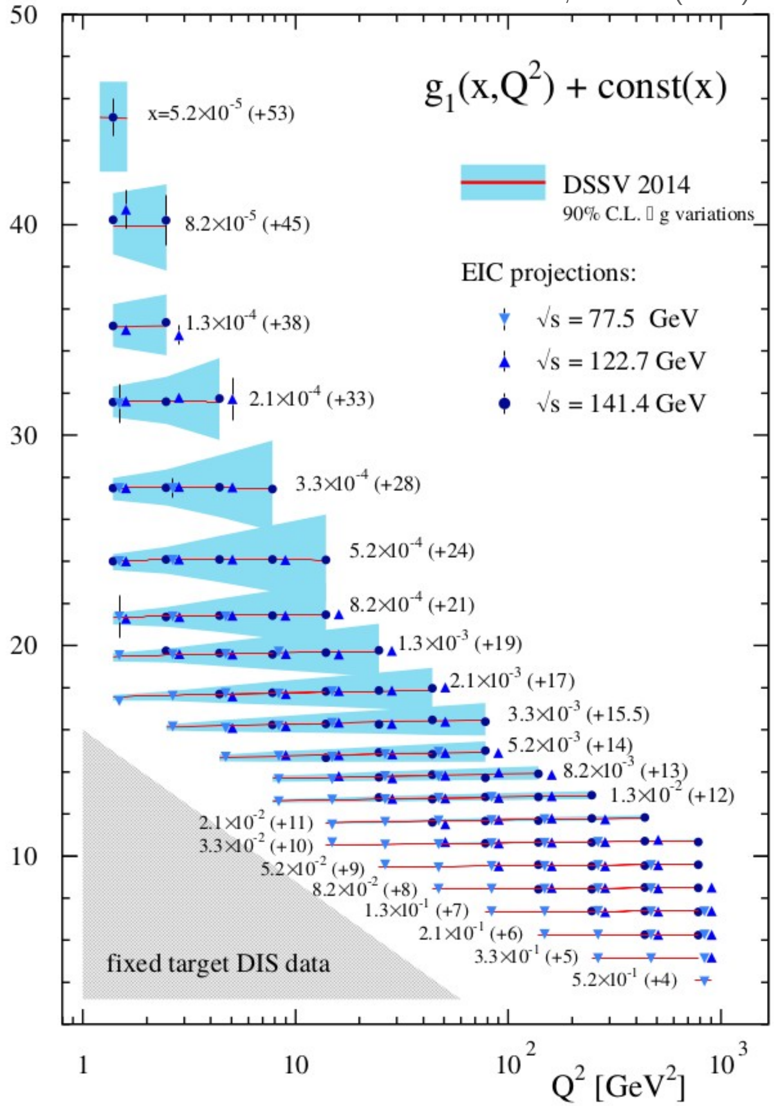


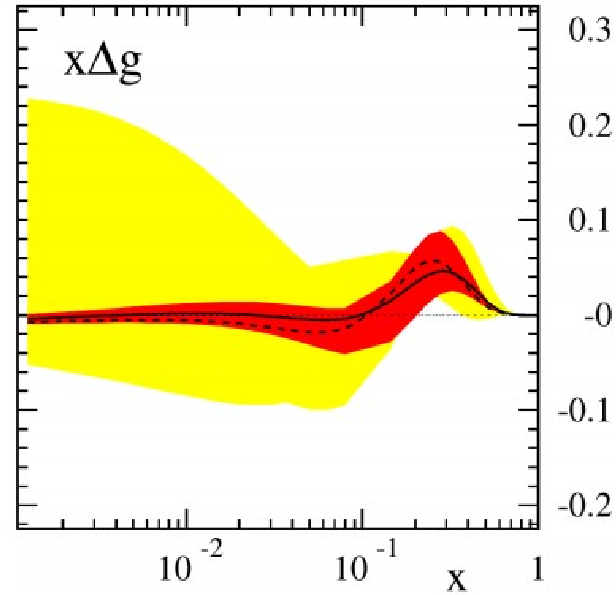
Possible explanation:

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

ΔG AT EIC

PRD 92, 094030 (2015)





[Figures taken from PRD 86 (2012) 054020]

Constrain Δg through scaling violations of g_1

full NNLO [NPB 417 (1994) 61; NPB 889 (2014) 351]

map Δg with an accuracy of 10% (or better) at $x \gtrsim 10^{-4}$

may be advantageous to measure $\Delta\sigma$ instead of A_1^p or g_1^p

Study possible deviations from DGLAP evolution

not clear if EIC kinematic range is large enough

the shape of Δg at small x may change significantly

DI-JET MEASUREMENT

Towards smaller x_g and complementary probes

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

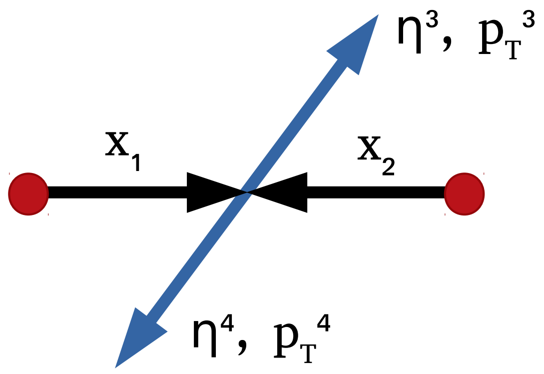
- May place better constraints on **functional form of Δg(x)**
- More-forward production - **lower x down to 0.01,** 2 – likely gluon, 1 – likely quark
- **Narrow ranges** of initial state partonic momentum tested

$$M = \sqrt{x_1 x_2 s} \qquad x_1 = \frac{1}{\sqrt{s}}(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4})$$

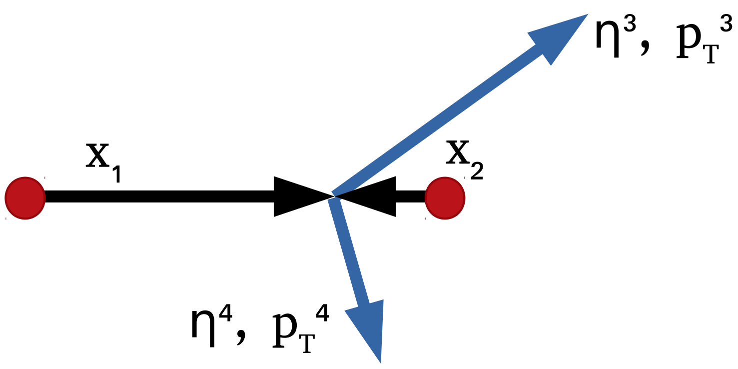
$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2} \qquad x_2 = \frac{1}{\sqrt{s}}(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4})$$

(LO)

Unlike-sign topology



Same-sign topology



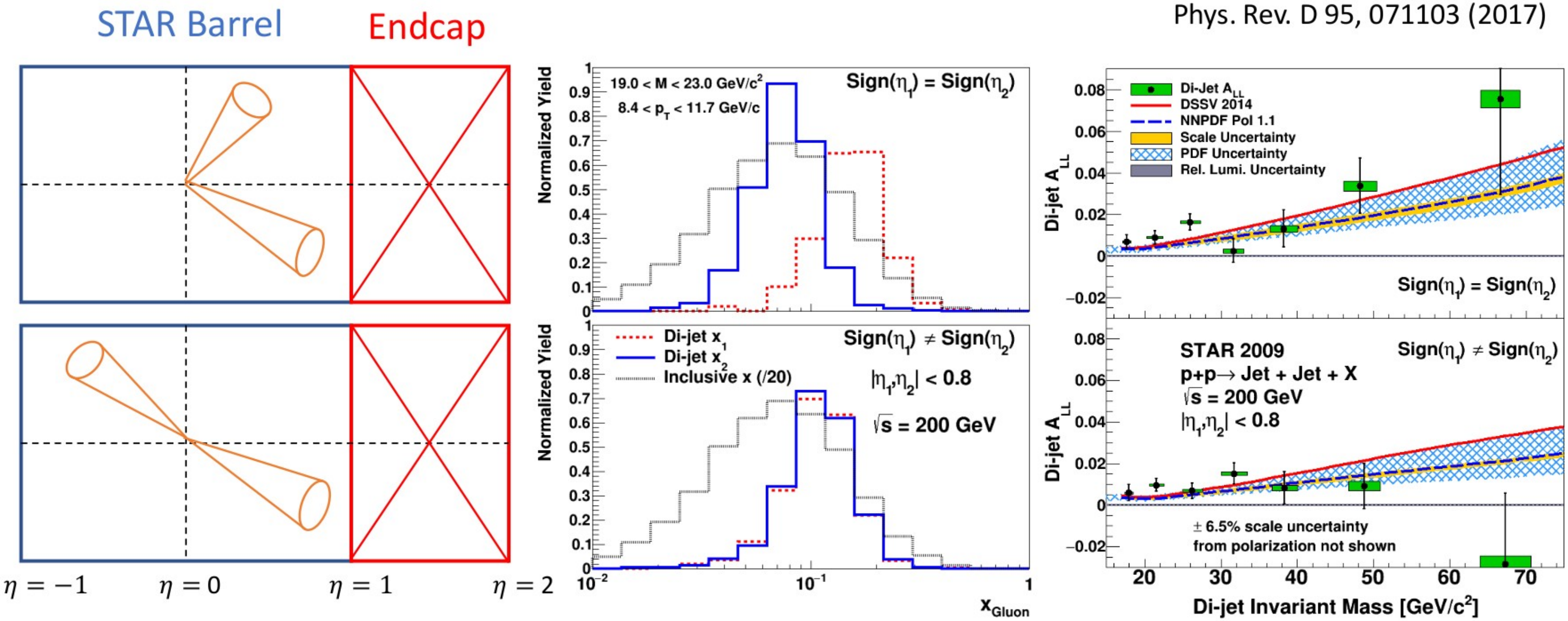
Forward jets probe lower values of x_g

DI-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)

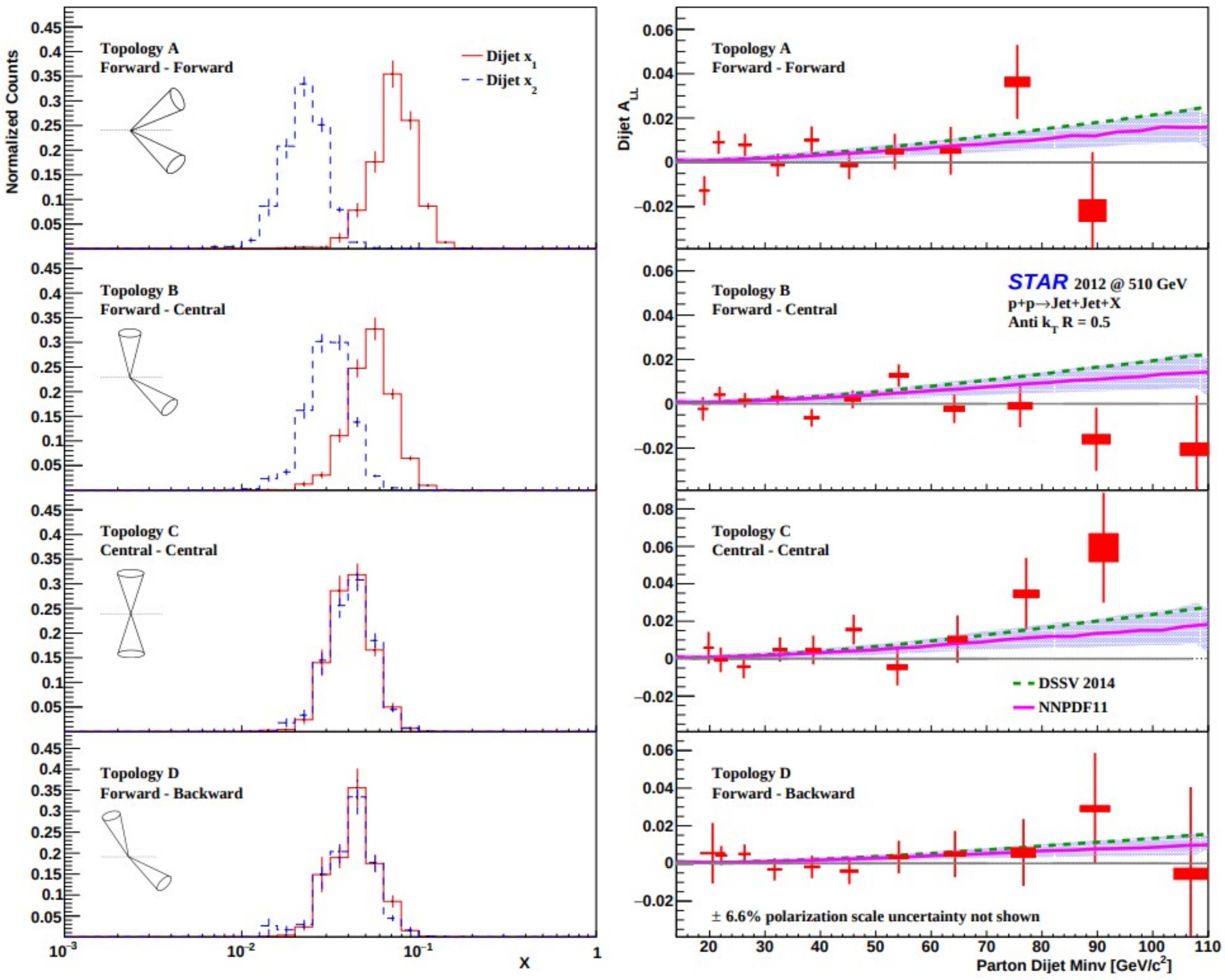


2015 data at 200 GeV (2x statistics)

DI-JET MEASUREMENT

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

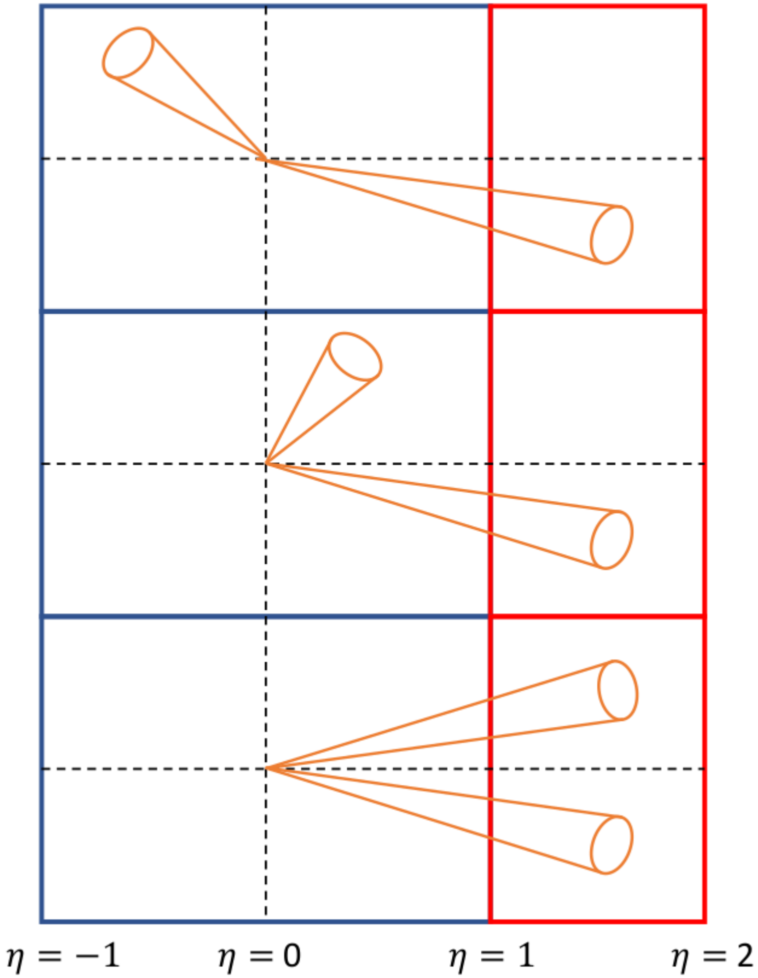
PRD 100 (2019), 052005

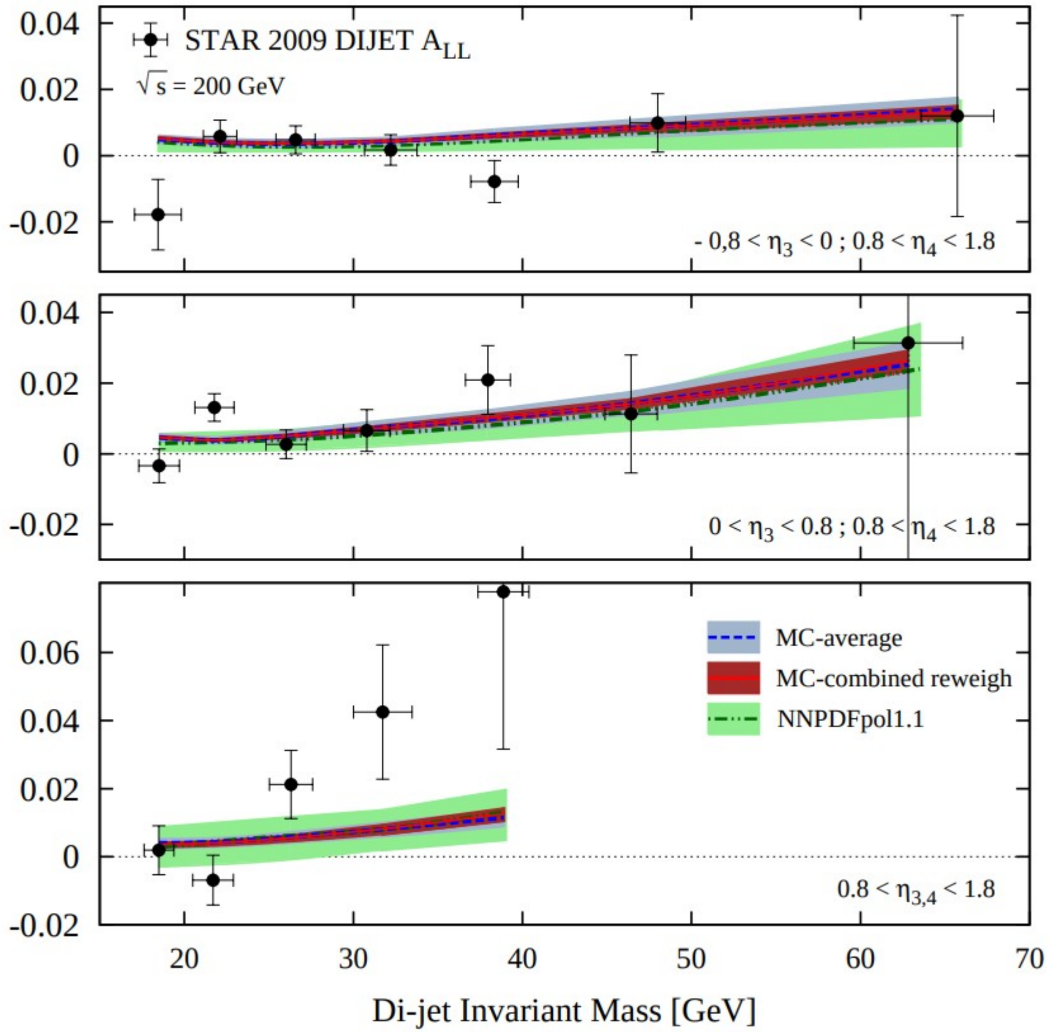


DI-JET MEASUREMENT

Impact on Δg(x)

arXiv 1902.10548



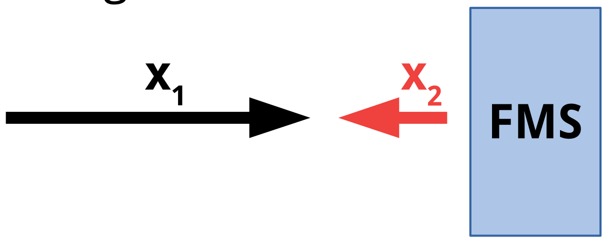


- Influence of central and forward di-jets from 2009 data √s = 200 GeV on DSSV calculations

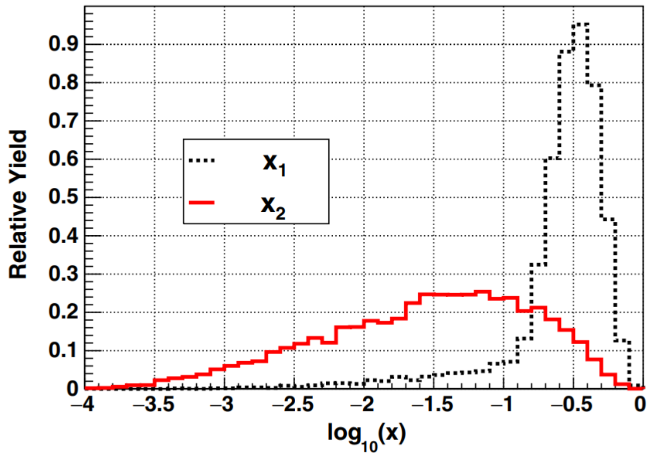
FORWARD PION PRODUCTION

Towards smaller x_g and complementary probes

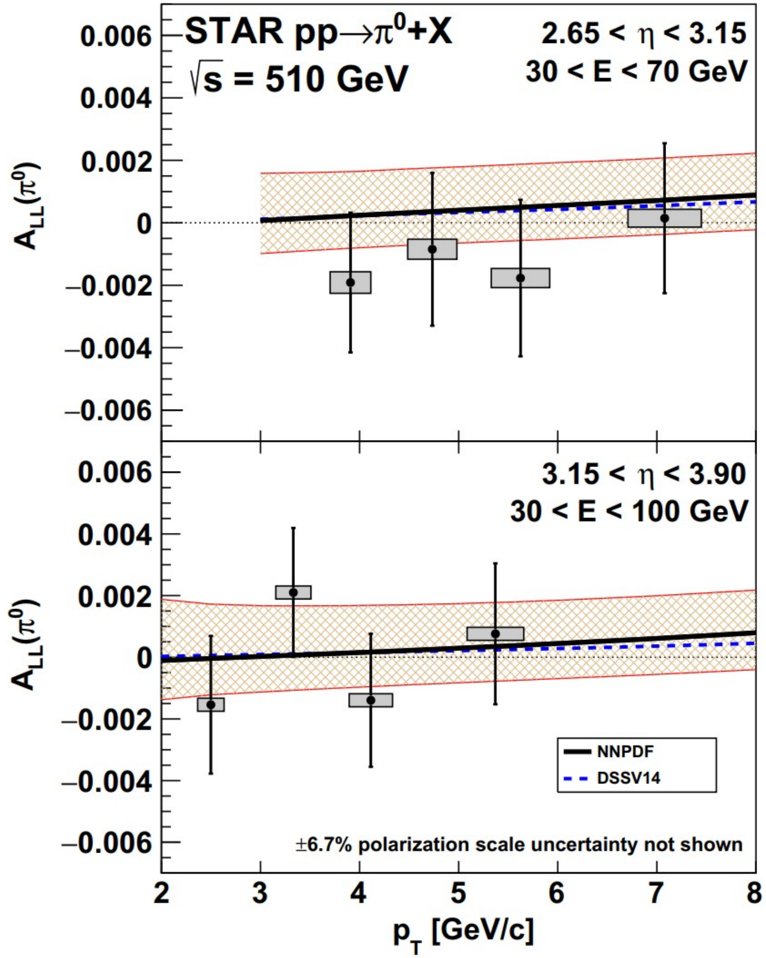
- A_{LL} of neutral pions at 510 GeV
- Measured with FMS ($2.6 < \eta < 4$)
- Access to gluons **x > 0.001**



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 $x > 0.0025$.

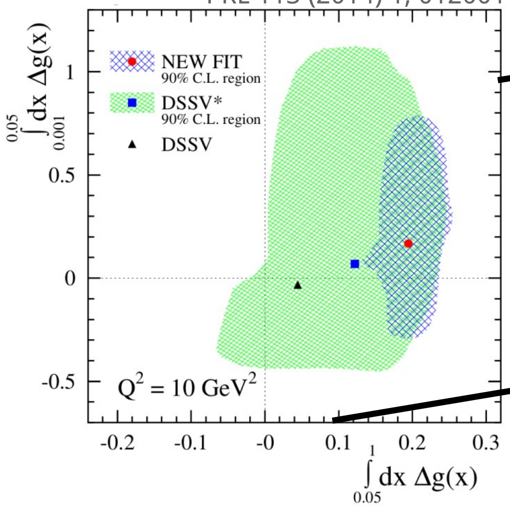
HELICITY OUTLOOK

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



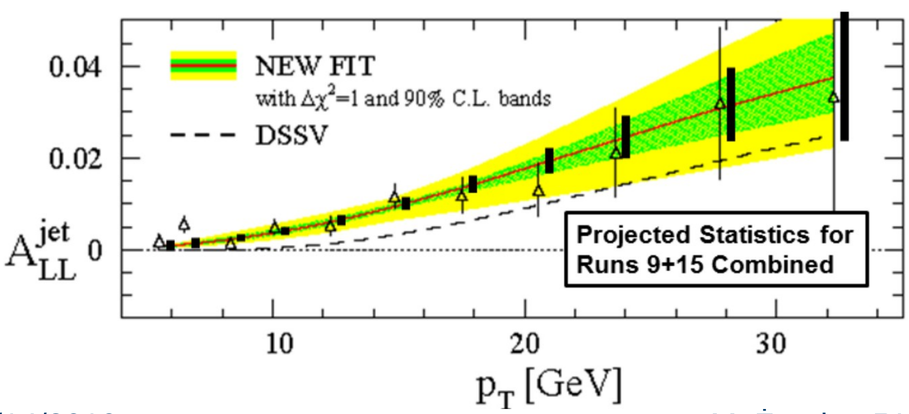
Low-x range

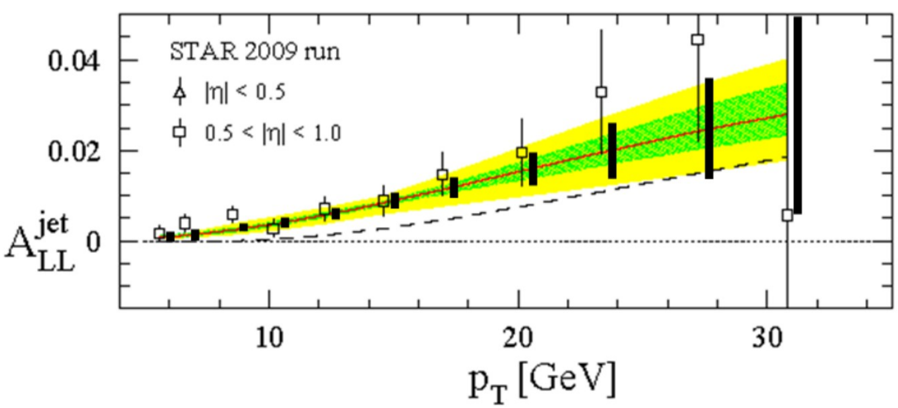
- Iclusive jets at 510 GeV
- Di-jets at 510 GeV in mid-rapidity region
- Forward pion measurements with FMS

High-x range

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

- Central inclusive jet measurement
- Central di-jet measurement

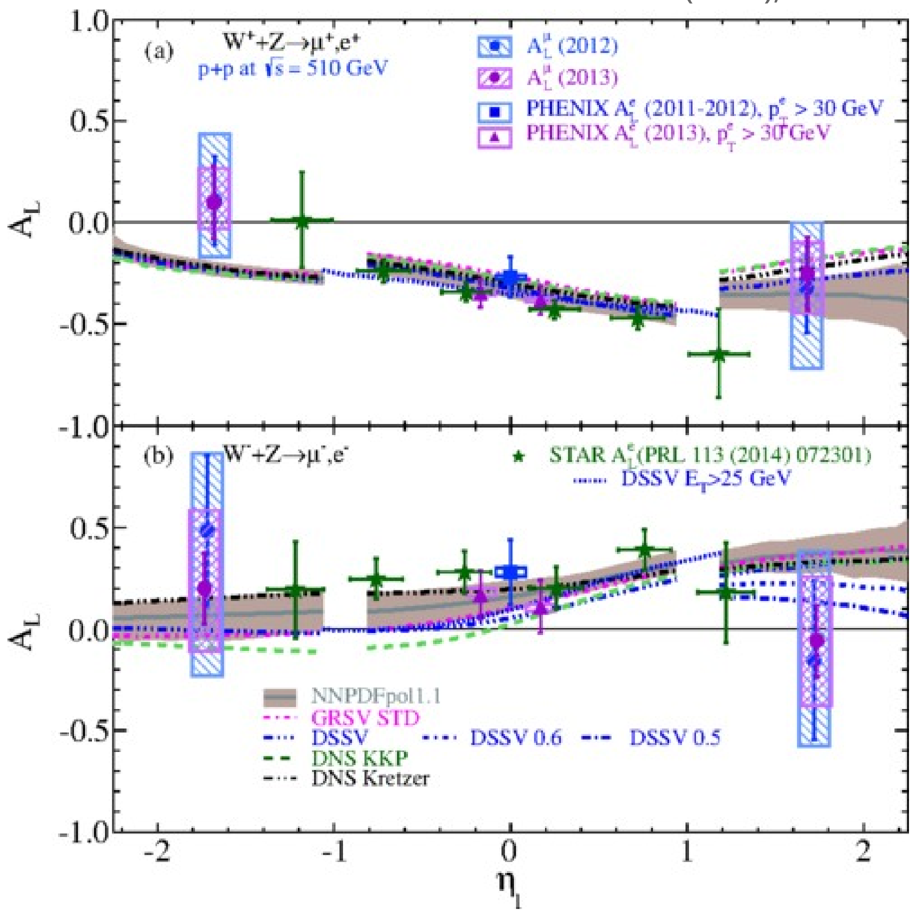




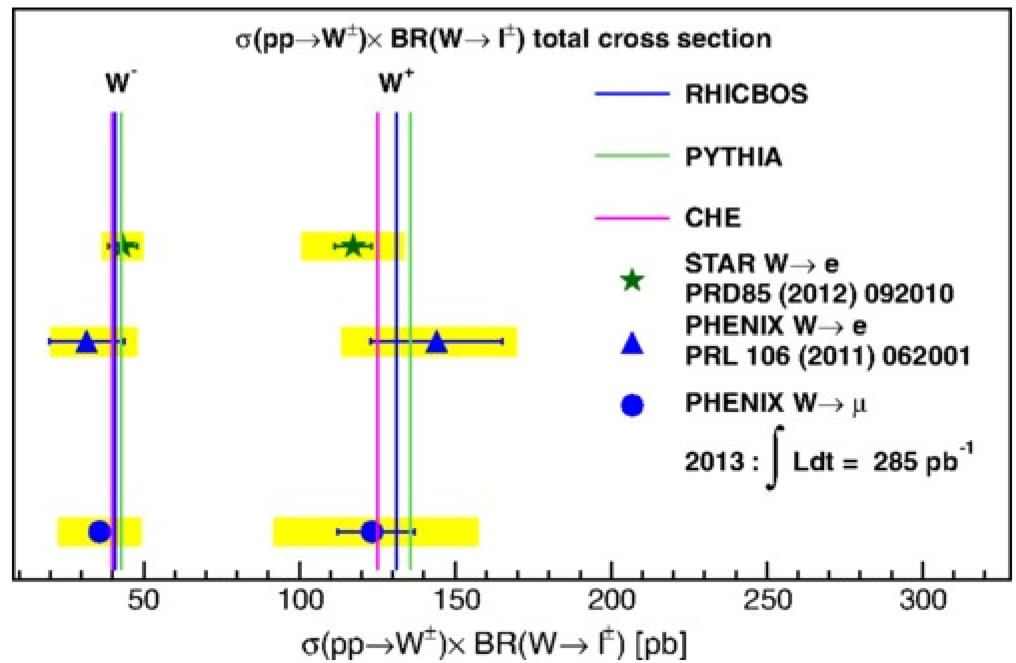
QUARK HELICITIES

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

TRANSVERSE SPIN MEASUREMENTS

TMD formalism

Twist-3 formalism

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

ETQS function – transverse momentum integrated distribution Twist-3 analog

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

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

Twist-3 analog fragmentation function

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

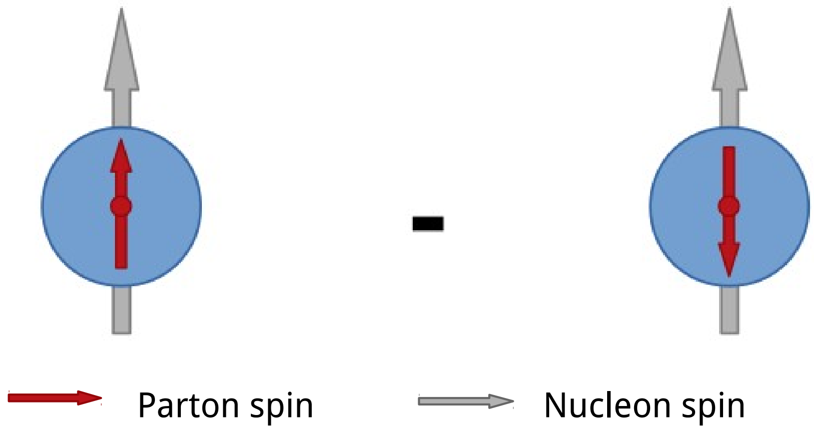
Requires **1 scale**: Q^2 or p_T
Where: $\lambda_{QCD} << p_T, Q$

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

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

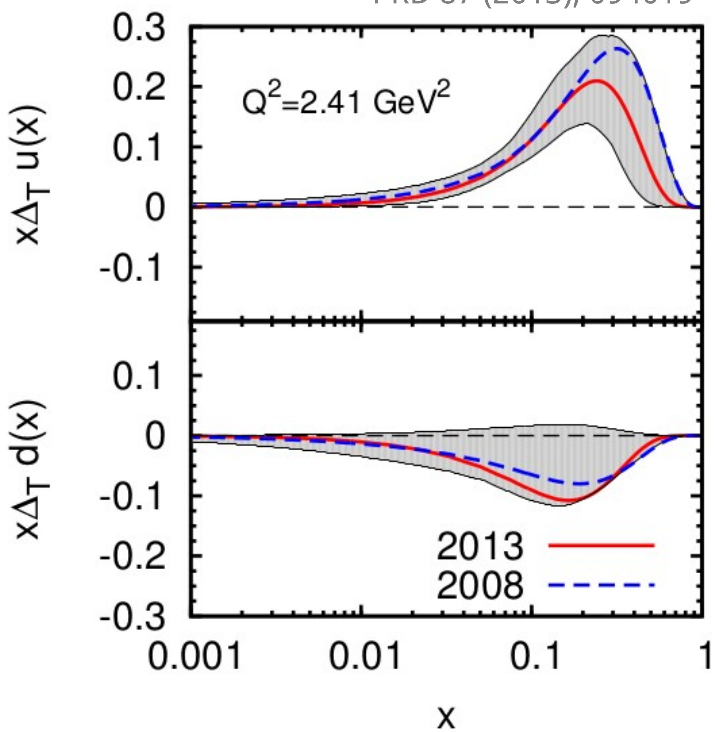
TRANSVERSITY

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

PRD 87 (2013), 094019



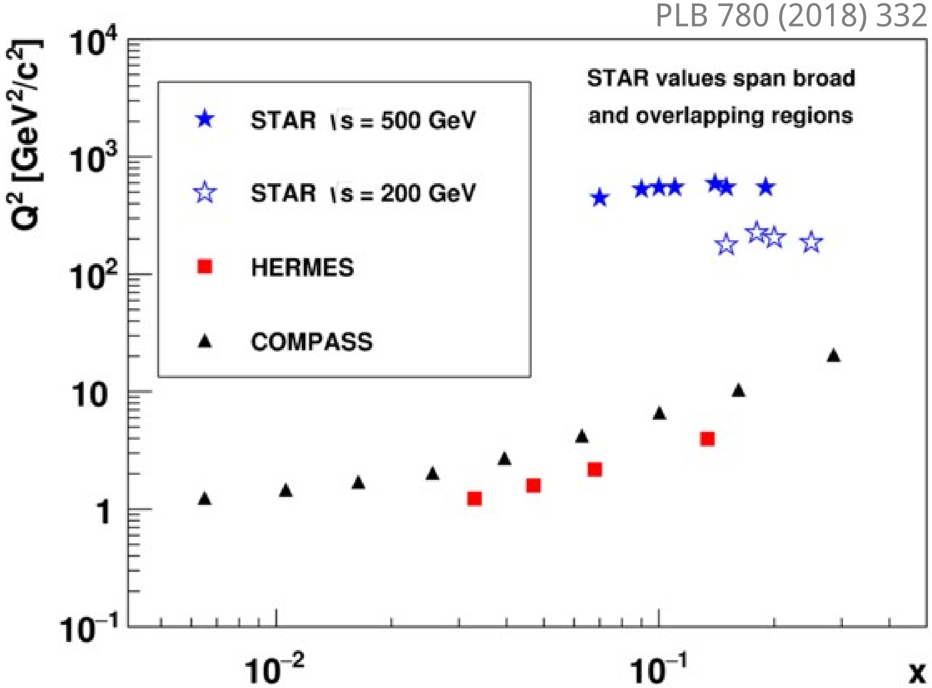
- Difficult to access - **chiral-odd nature**
- Couples to chiral-odd fragmentation functions

- 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

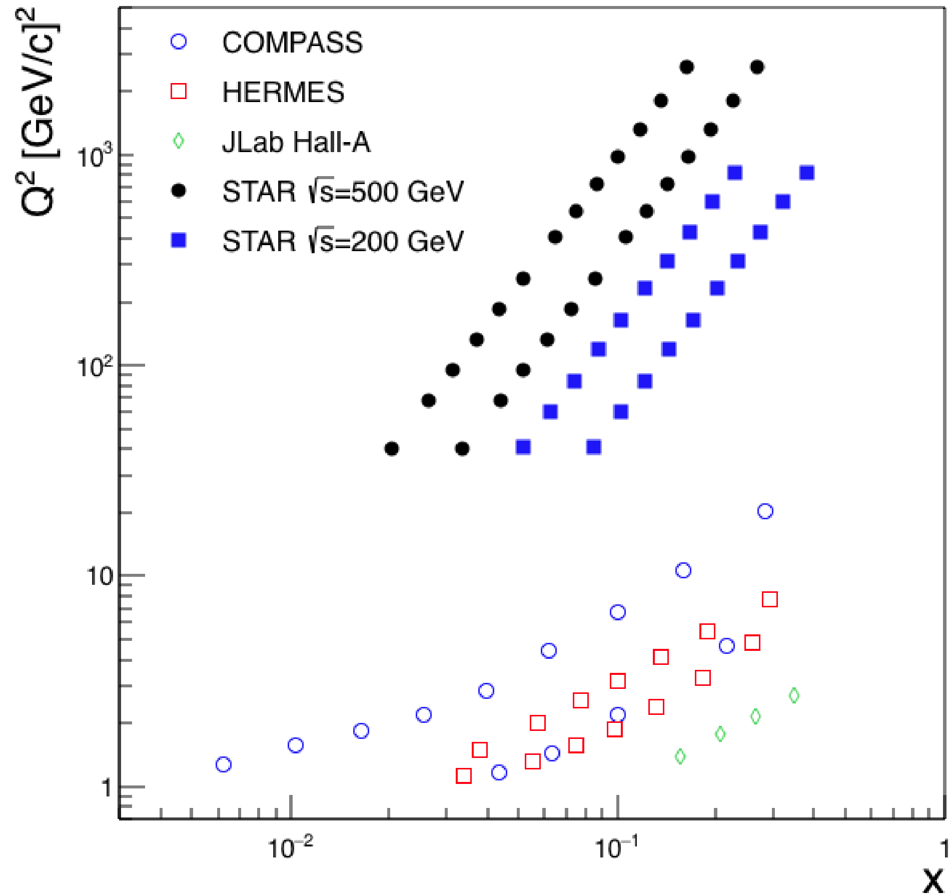
STAR: KINEMATIC COVERAGE

IFF and Collins asymmetry

PLB 780 (2018) 332



PRD 97 (2018), 032004

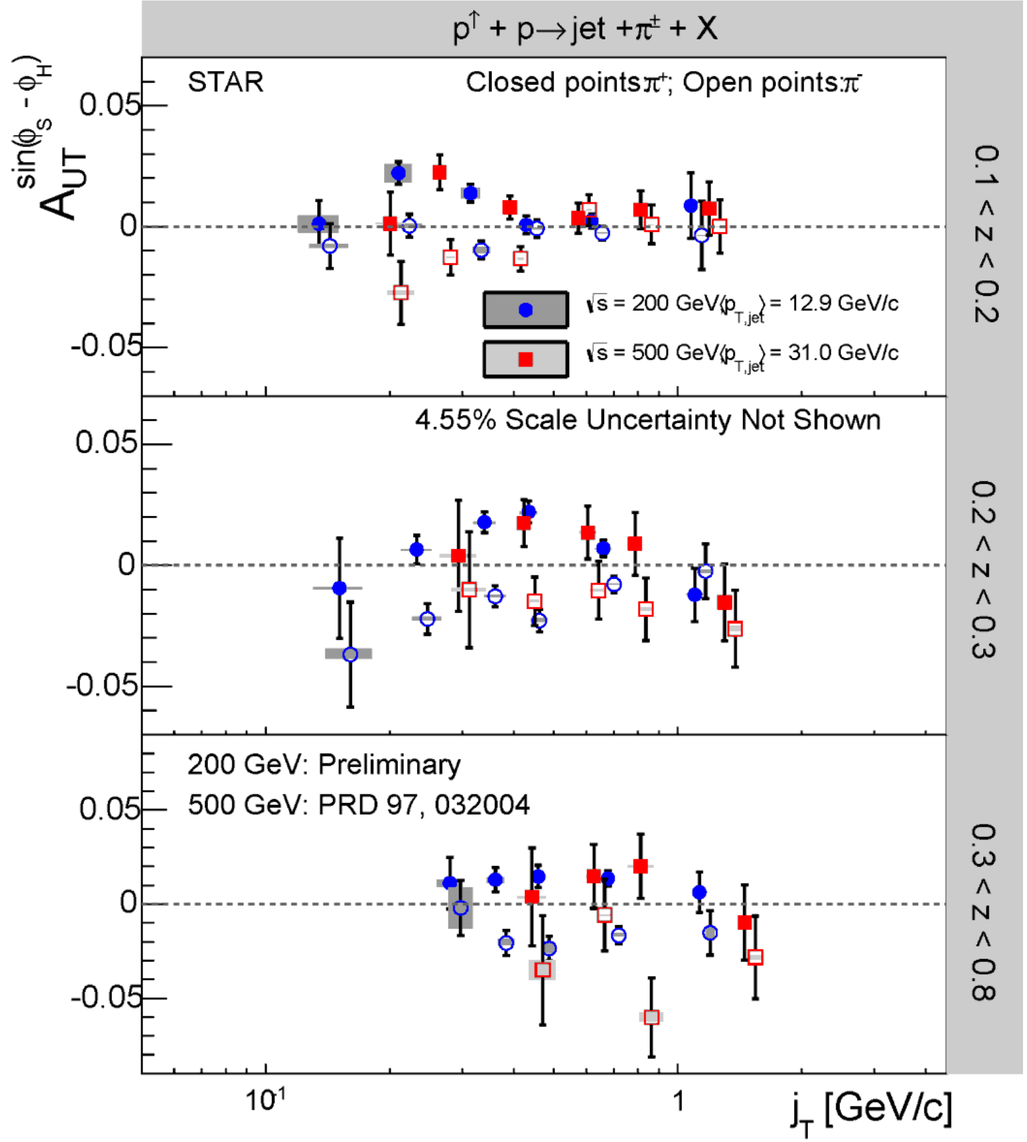


TRANSVERSITY

Collins asymmetry

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

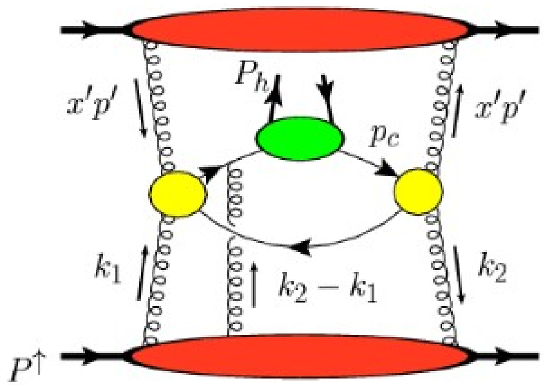
- 500 GeV pp results hinted the A_{UT} peak shifts to higher j_T as z increases
- Preliminary 200 GeV pp results show similar behavior
- Hadron j_T is independent of initial state transverse momentum
- Additional statistics for both 200 (x 2.5) and 500 GeV (x 12) available

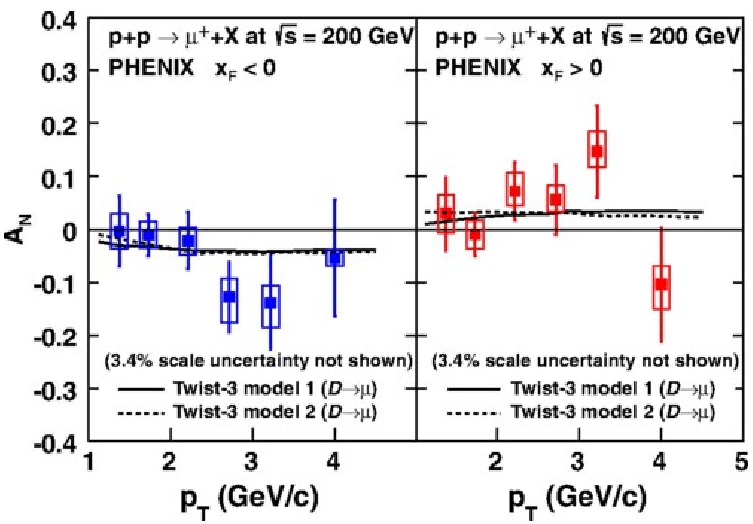


TWIST-3

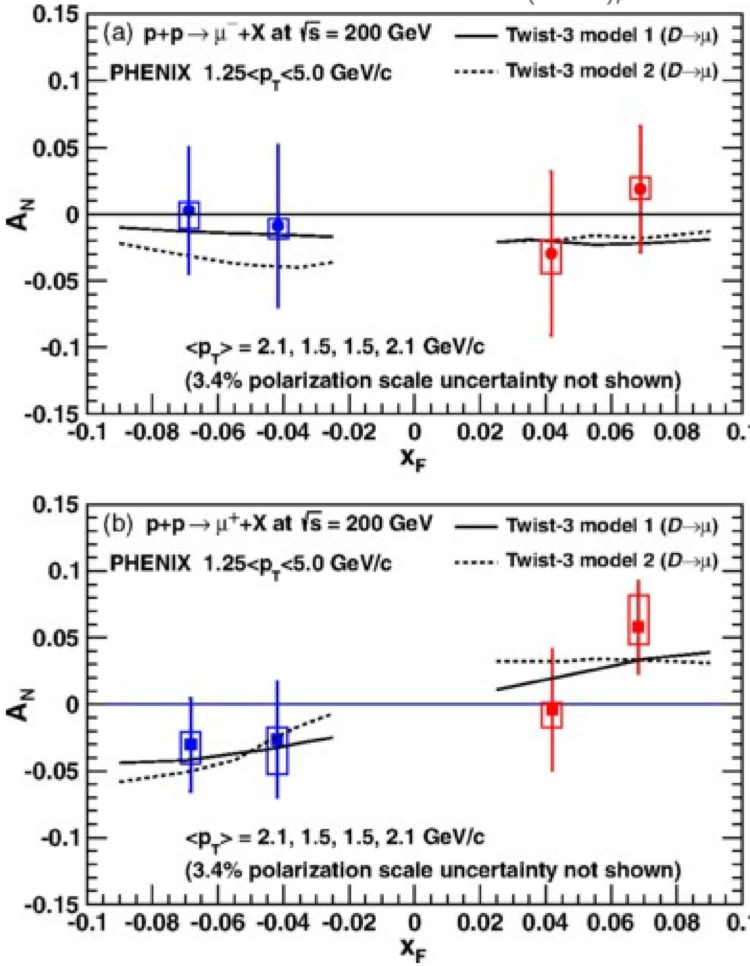
Heavy flavor A_N

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



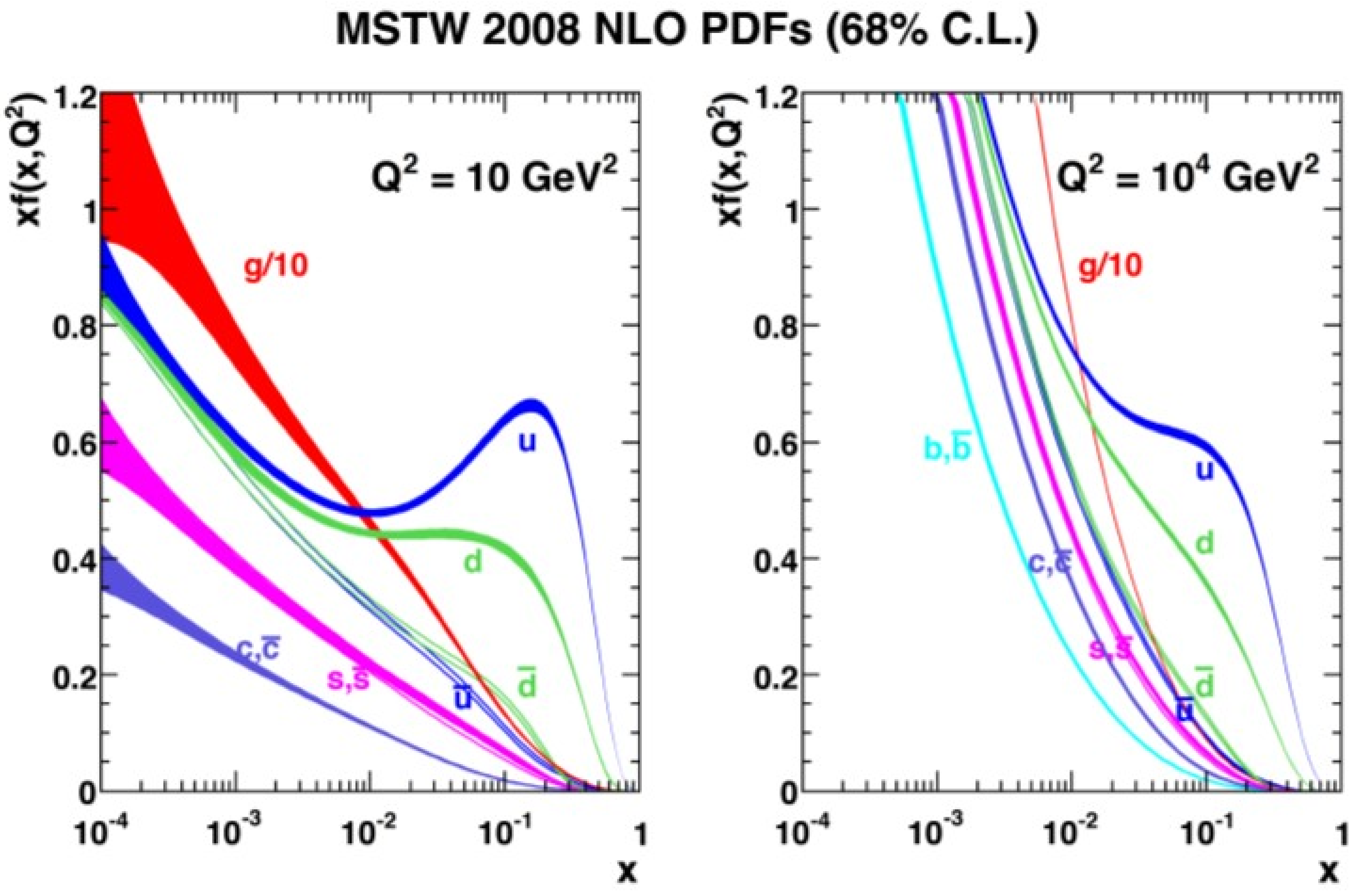


PRD 95 (2017), 112001



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

UNPOLARIZED PDFs



HELICITY DEPENDENT PDFs

DE FLORIAN, SASSOT, STRATMANN, AND VOGELSANG