Recent Spin Results at RHIC

Heavy Ion Meeting 2023-08

Bok, Jeongsu (PNU)

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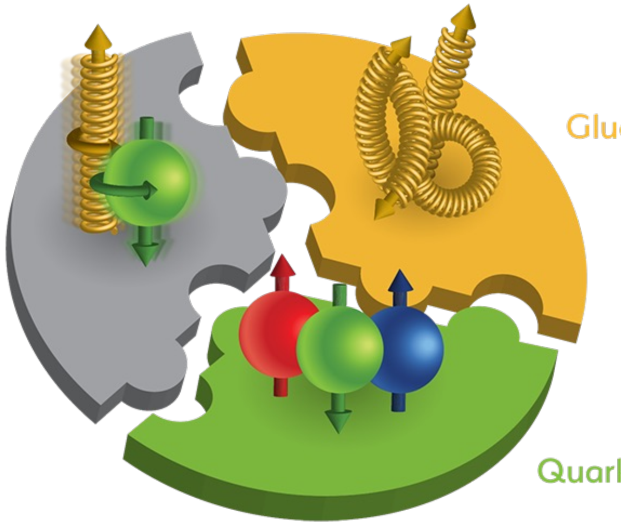
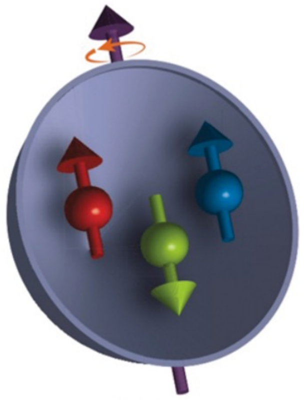


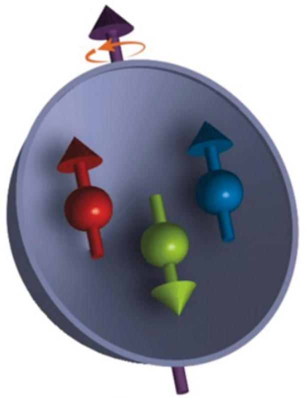
Introduction to spin physics

Origin of proton's spin



- Protons and Neutrons are spin 1/2 particles
- Quarks that constitute them are also spin 1/2 particles
- Historically taken seriously

Proton spin crisis



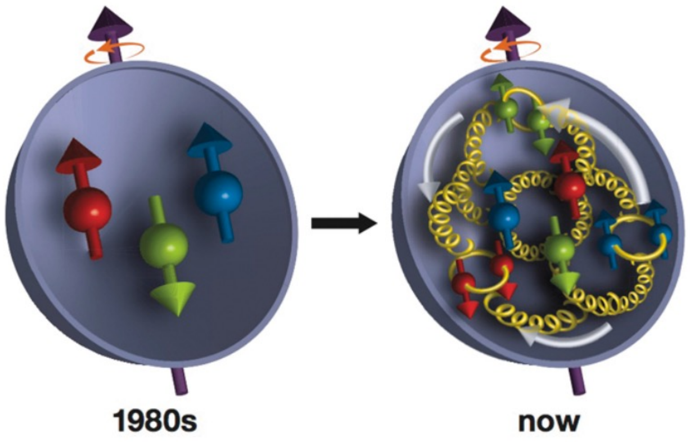
1980s

> In conclusion, measurements have been presented of the spin asymmetries in deep inelastic scattering of polarised muons on polarised protons. The spin dependent structure function g_1 of the the proton has also been determined. The integral $\int_0^1 g_1^p(x)dx = 0.114 \pm 0.012 \pm 0.026$ is significantly lower than the value expected from the Ellis-Jaffe sum rule. Assuming the validity of the Bjorken sum rule this

EMC, Phys. Lett. B 206 (1988) 364-370

- Protons and Neutrons are spin 1/2 particles
- Quarks that constitute them are also spin 1/2 particles
- European Muon Collaboration (EMC) reported that most of the proton's spin is not carried by quarks

Proton spin puzzle

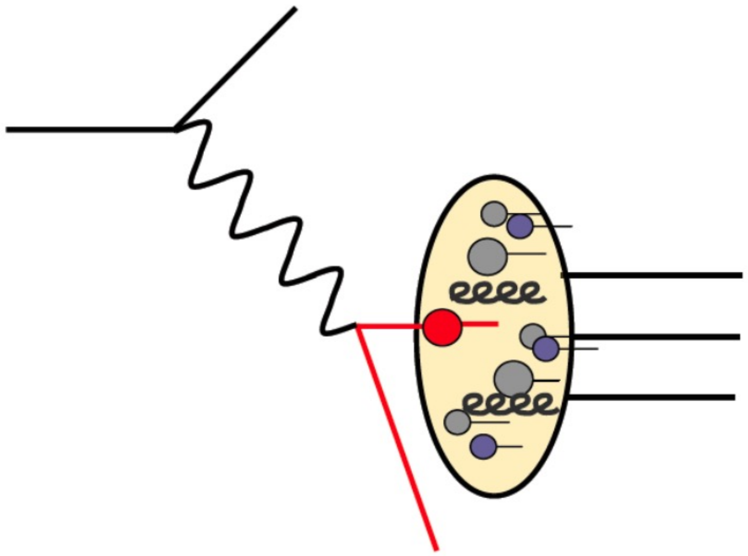


$$S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

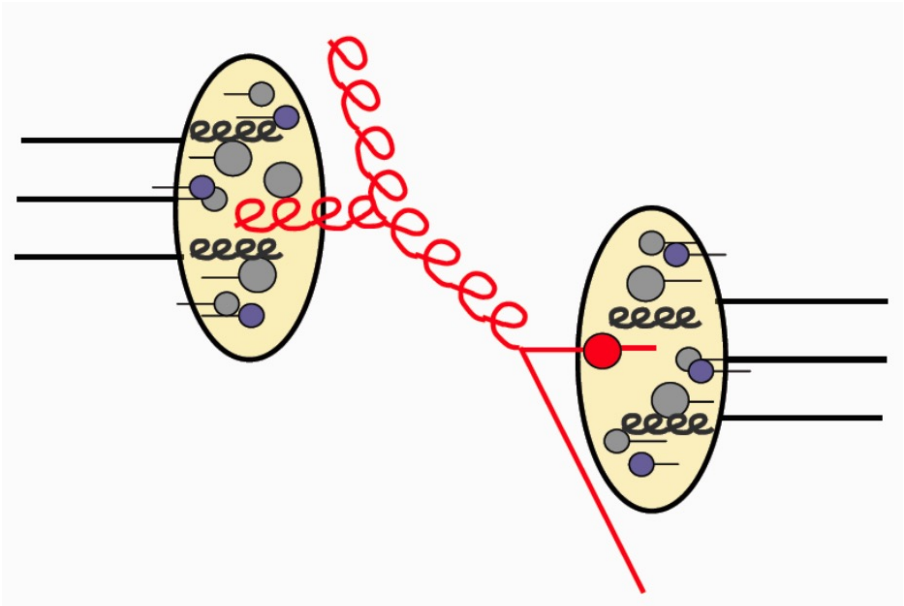
- Current understanding on proton's spin 1/2.
  - Quark-antiquark : $\Delta\Sigma$ ~ 0.3
  - Gluon
  - Angular momentum
- Direct measurement of gluon spin with other probes warranted.
  - Seeded the RHIC Spin program

RHIC spin program

Why polarized proton collider?



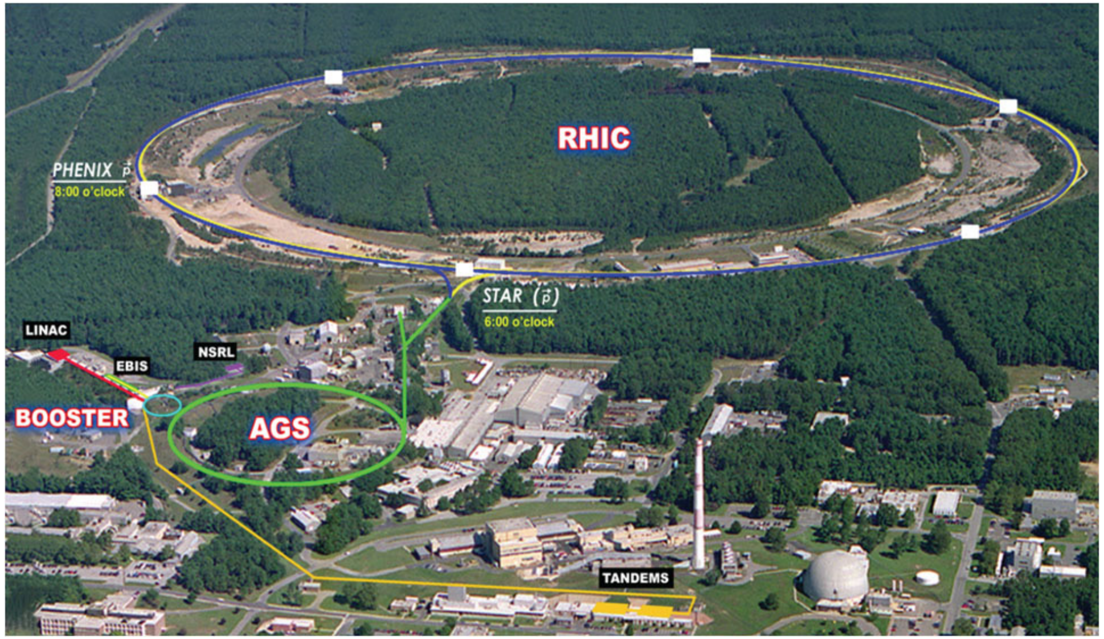
Lepton- proton collision
Photons colorless. Forced to interact at NLO with gluons
Cannot distinguish between quarks and anti-quarks either

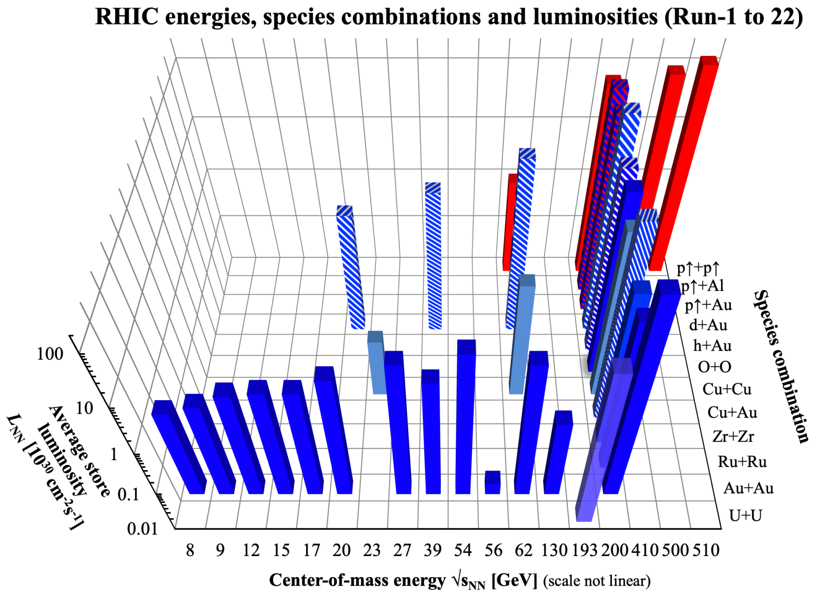


Polarized proton-proton collision
polarized quarks and **gluons** abundantly available

- Searching for the origin of proton’s spin was started from DIS experiments.
- Complementary techniques : polarized proton-proton collision

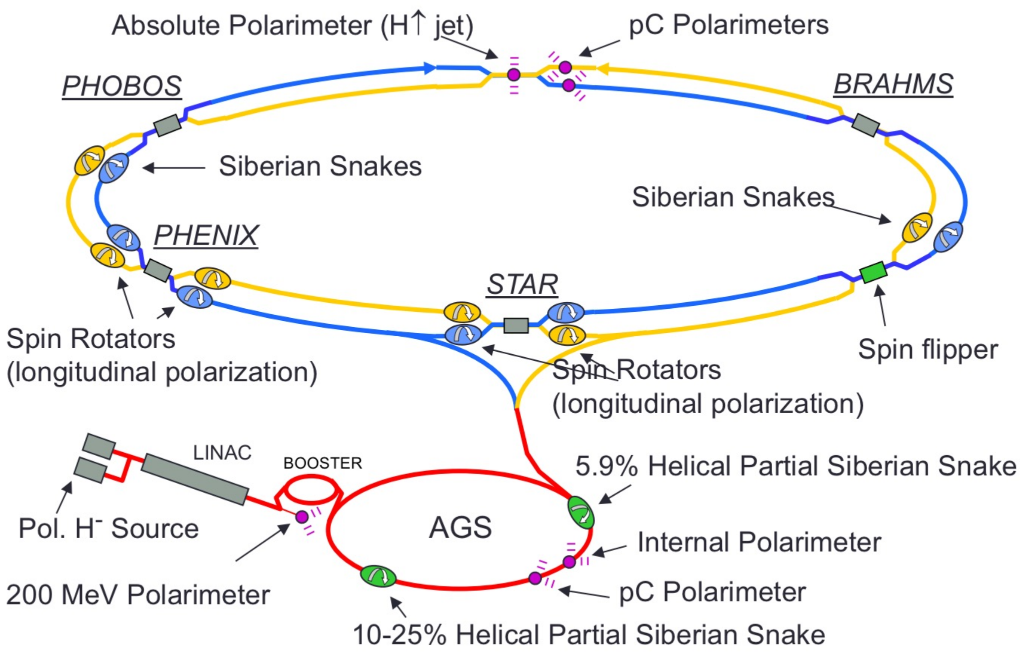
Relativistic Heavy Ion Collider

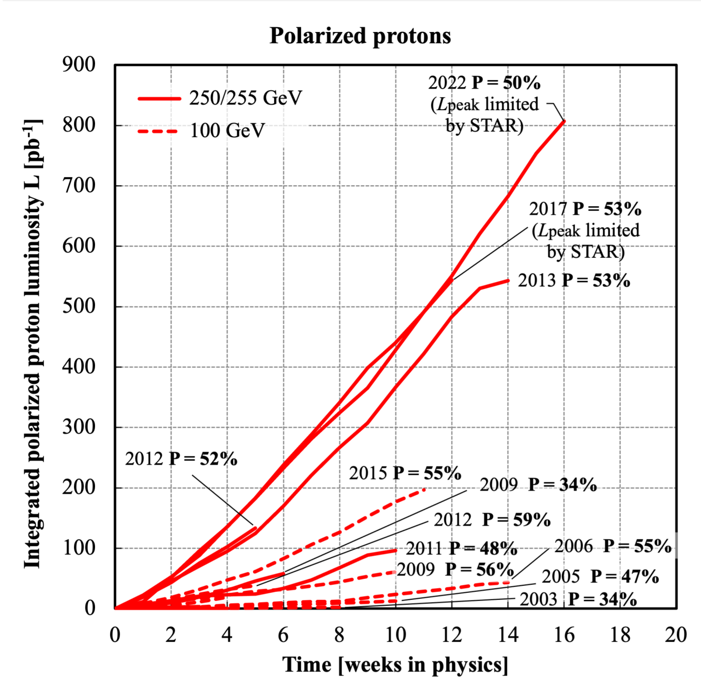


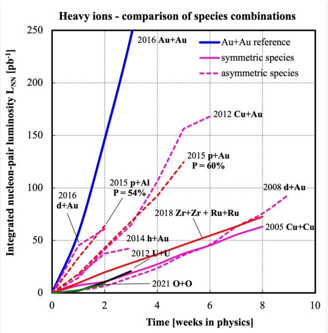


- RHIC can collide various ions in wide range of energies.
  - Up to 100 GeV for ions, 255 GeV for protons
- The only facility: polarized proton collider
  - Polarization orientations: longitudinal or transverse
  - First and only polarized proton-ion collisions in RUN 2015

RHIC spin program

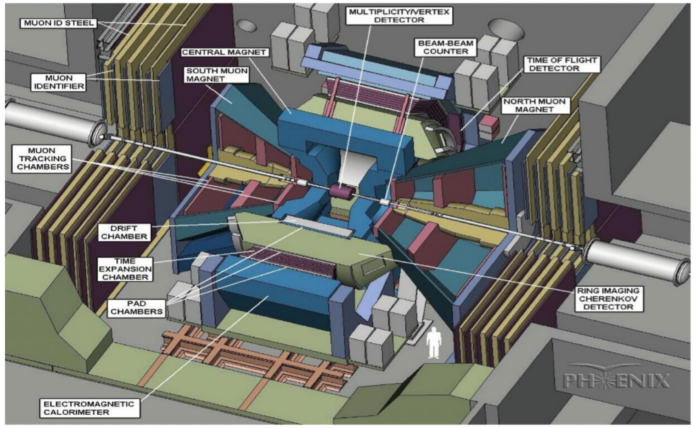


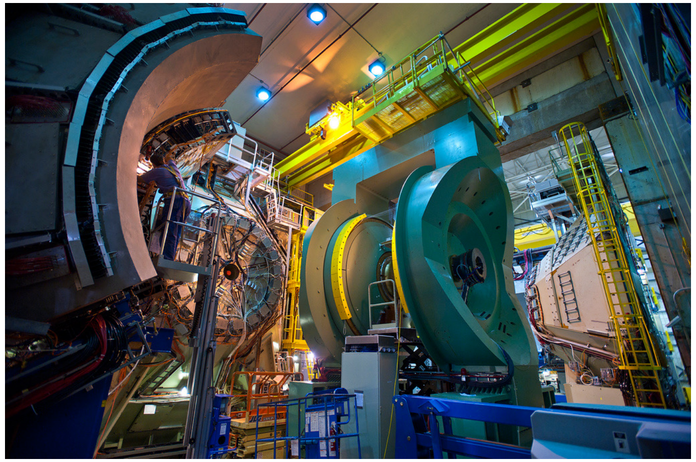


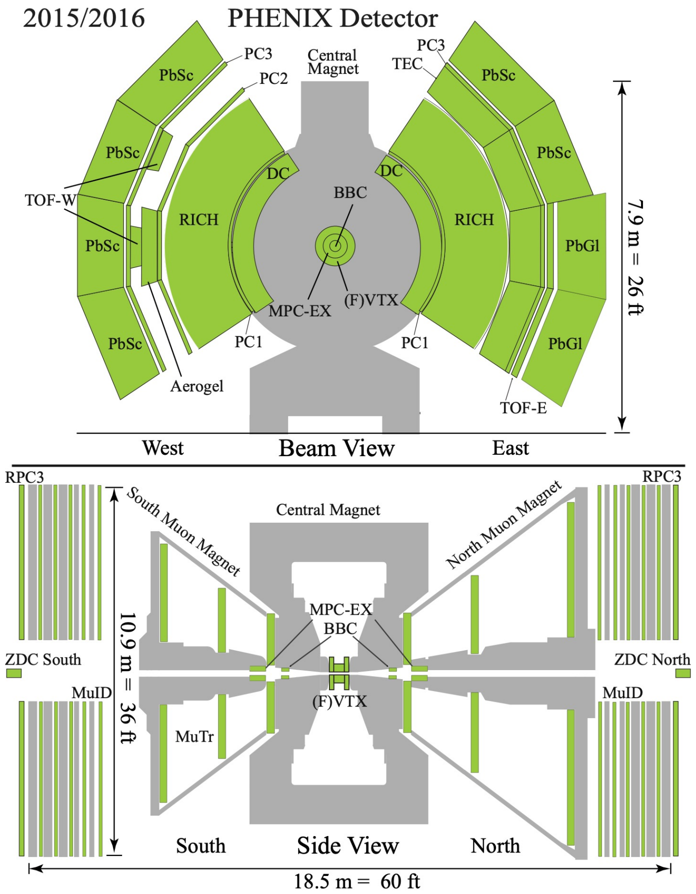


- How do gluons contribute to the proton spin?
- What is the landscape of the polarized sea in the nucleon?
- What do transverse spin phenomena teach us about proton structure?

PHENIX detector

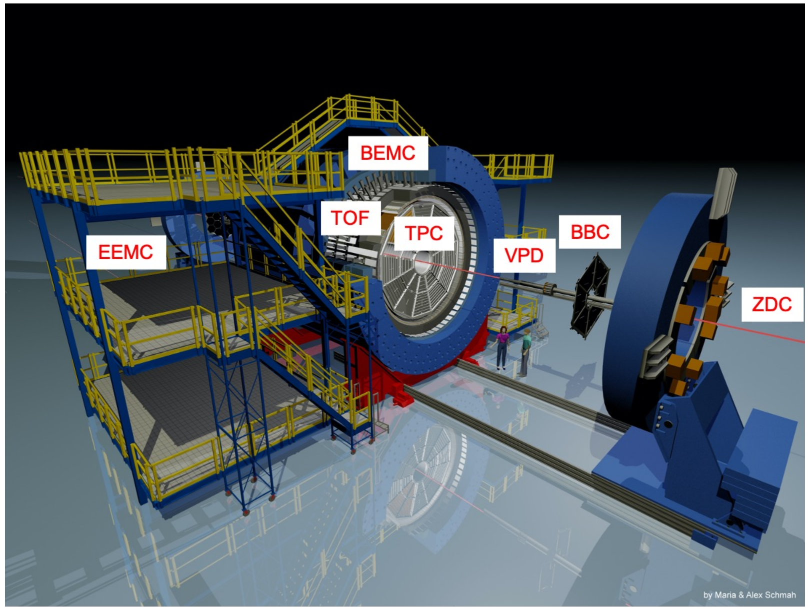


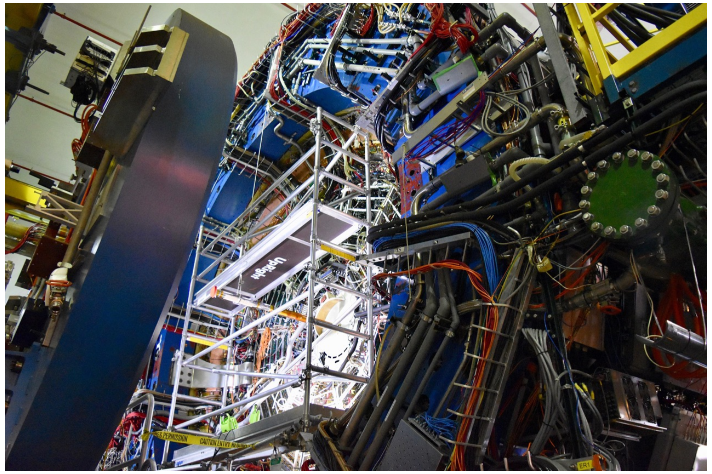




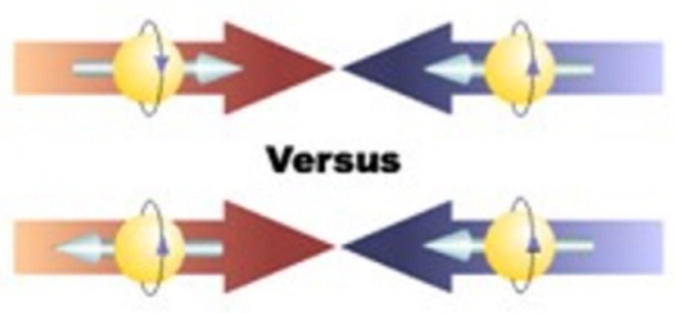
- Central Arms
  - π, K, η, γ …
  - $\Delta\phi = 0.5\pi$/arm, $|\eta| < 0.35$
- Muon Arms
  - D→μ, $h^{\pm}(\pi$,K)
  - $1.2<|\eta|<2.4$
- More
  - Forward π^0, η $3.1<|\eta|<3.9$
  - Neutrion (ZDC)
  - (F)VTX, BBC

Star Detector



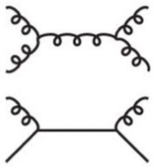
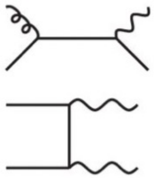


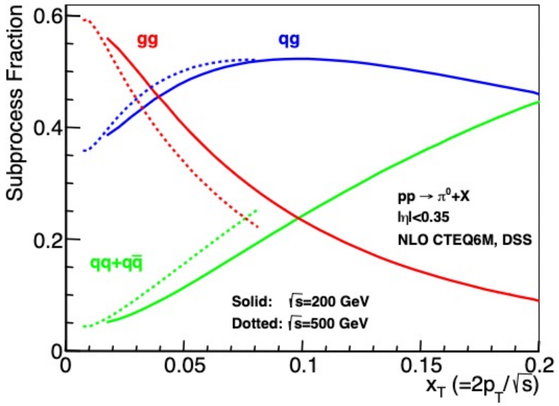
- Full 2π coverage in azimuthal
- Tracking with TPC: |η| < 1.3
- π^0 at forward rapidity

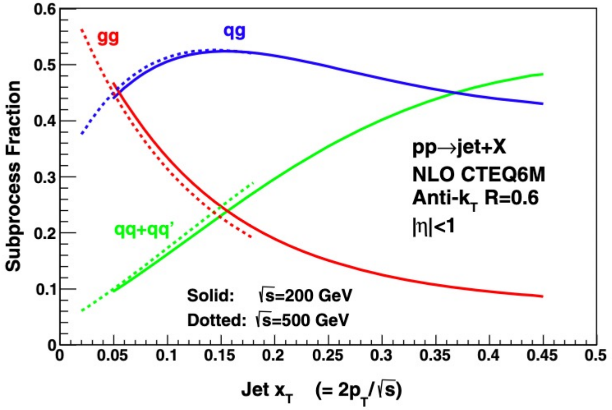


Recent RHIC spin results
1. Longitudinal spin

ΔG at RHIC

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	

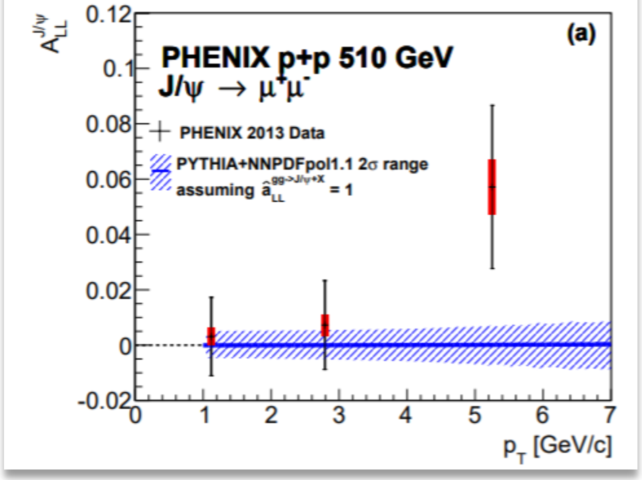




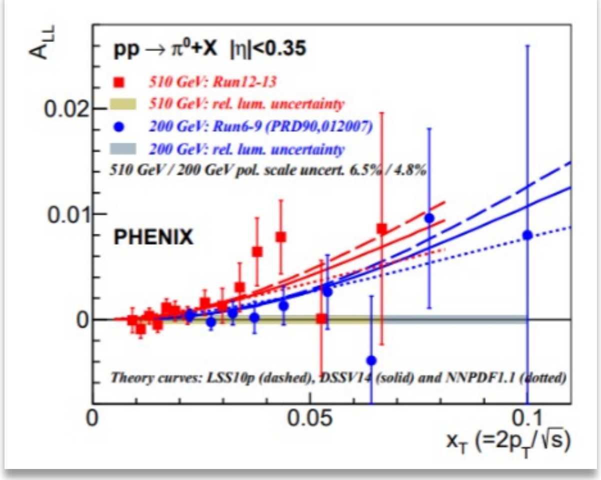
- Access gluons at LO
- *gg* and *qg* dominant at RHIC kenematics

Δg through Inclusive Meson Production

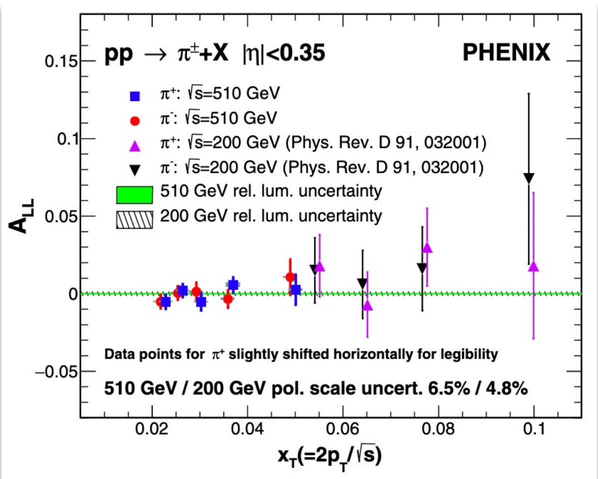
PRD 94 (2016) 112008



PRD 93 (2016) 011501

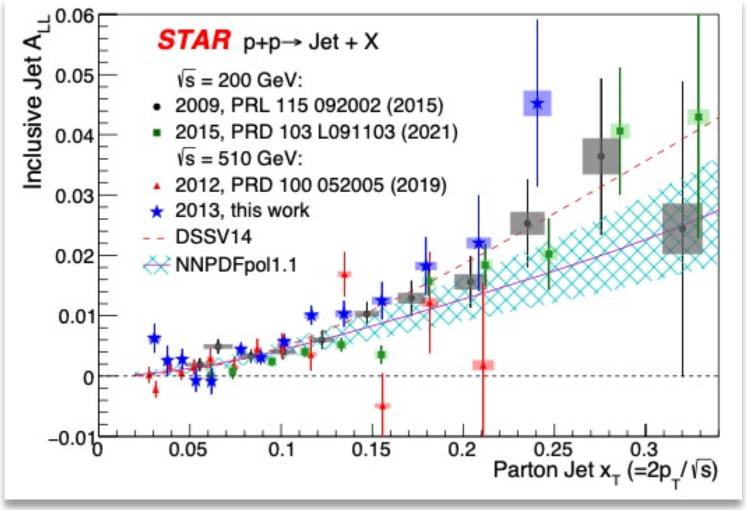


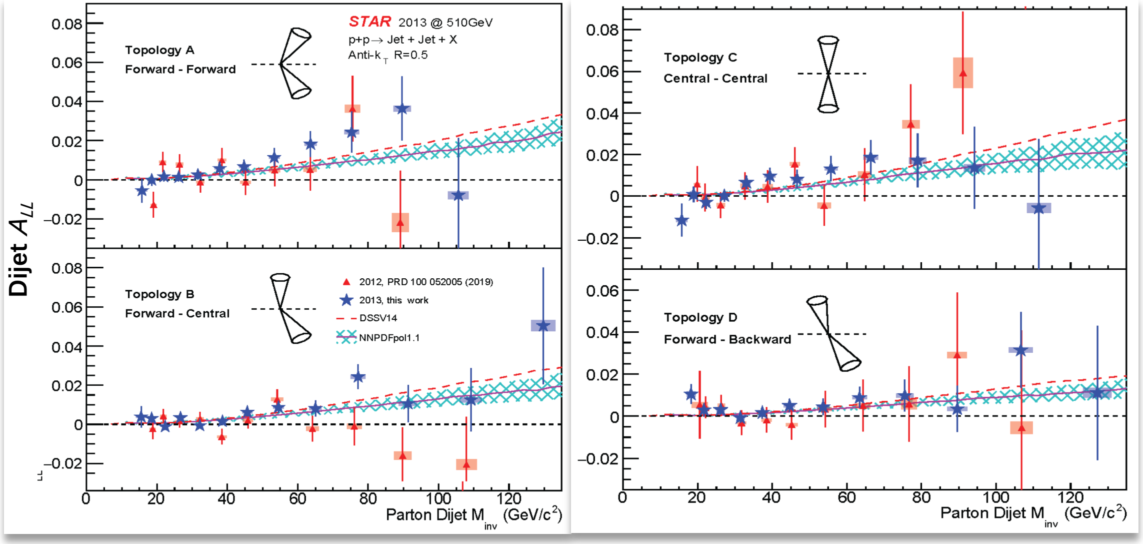
PRD 102 (2020) 032001



- PHENIX has measured a wide variety of probes at 200 & 510 GeV
- Very precise data, asymmetries are small
- Limited sensitivity to non-zero gluon polarization

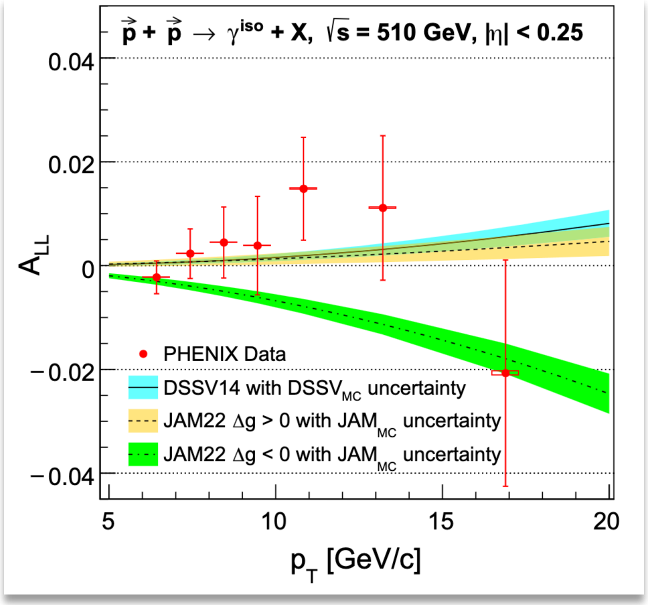
Δg through Jet A_{LL}

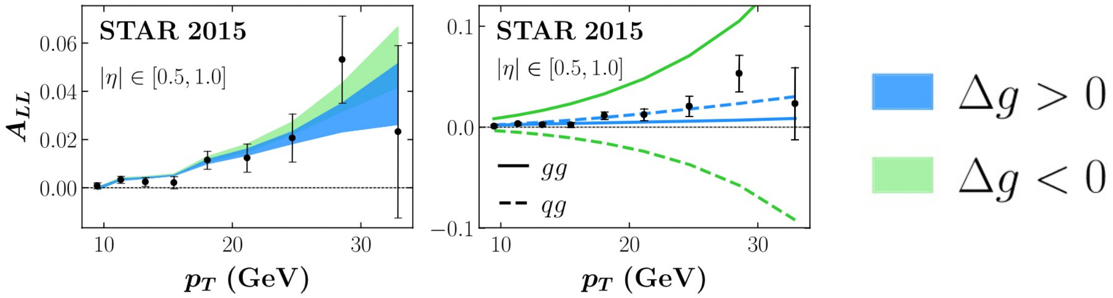




- *Phys. Rev. D 105 092011 (2022) (STAR)*
- Golden probes for Δg
  - A_{LL} for jets, di-jets and meson-production
- Dijet: constrain the shape of the $\Delta g(x,Q^2)$

Δg through Direct photon A_{LL}

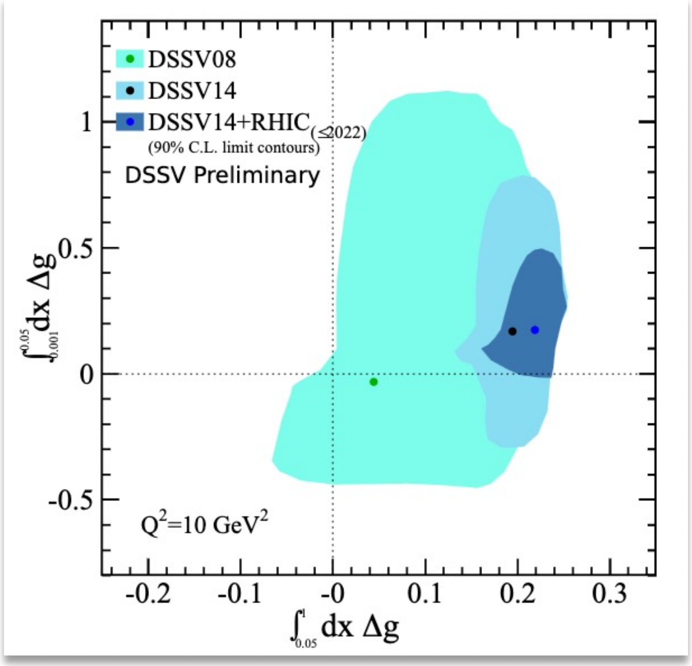


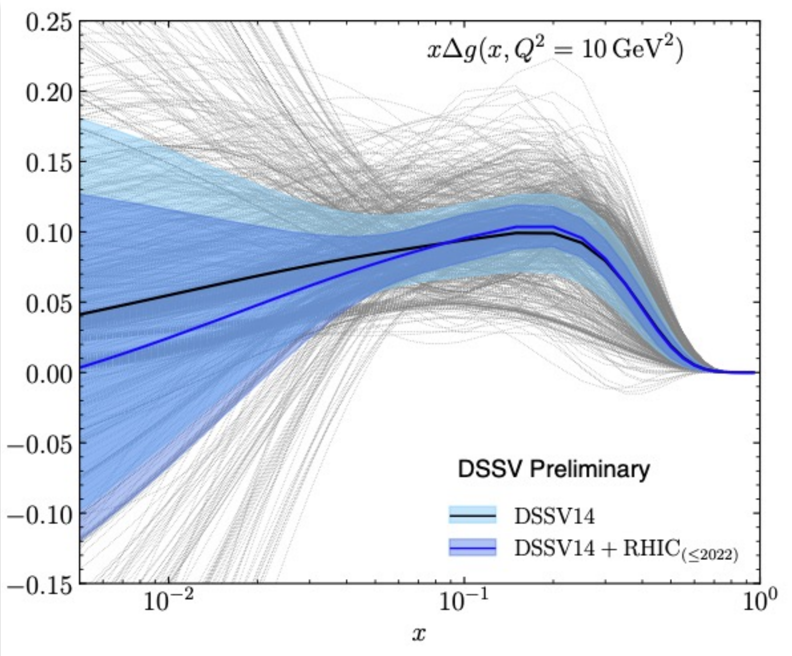


JAM global QCD analysis: A_{LL} vs Jet p_T
Phys. Rev. D. 105.074022 (2022)

- *Phys. Rev. Lett. 130, 251901 (2023) (PHENIX)*
- First published measurement of direct photon A_{LL}
- Dominated by quark-gluon Compton process $qg \rightarrow q\gamma$
- Compared with Δg>0, Δg<0 scenarios for gluon spin
  - Data consistent with the positive gluon spin contributions and disfavor the negative Δg scenario

Conclusion of Δg from RHIC≤ 2022





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

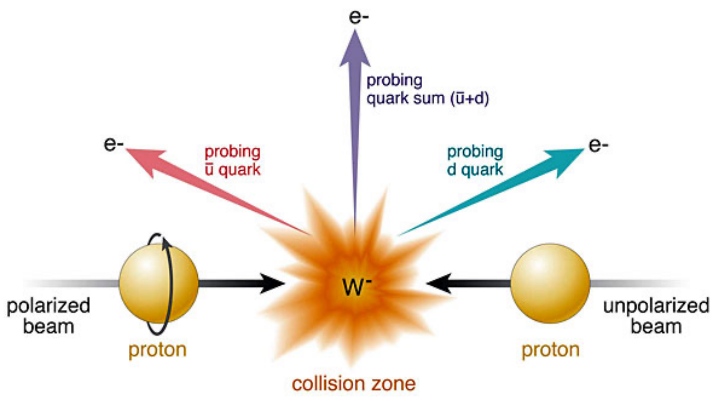
quarks gluons orbital angular momentum

DSSV preliminary (DSSV14 + RHIC≤2022)

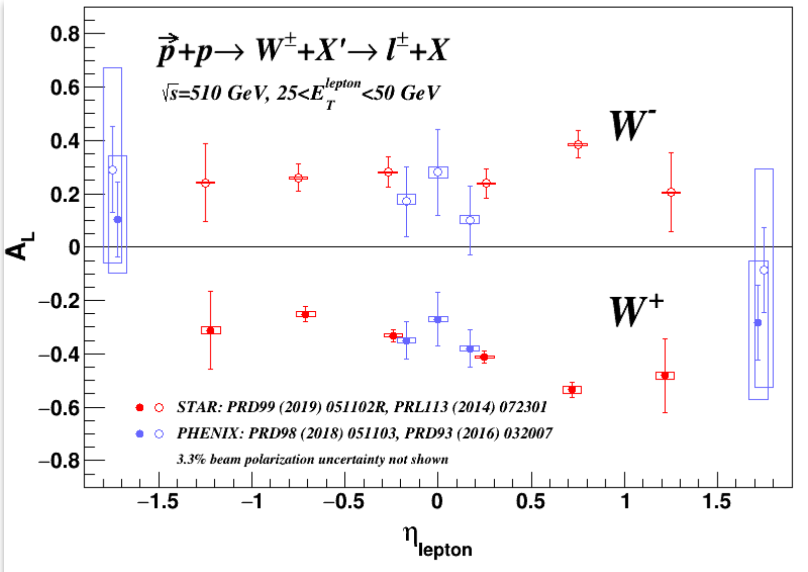
- DSSV global fit including RHIC ≤2022 data: jet, dijet, π, W

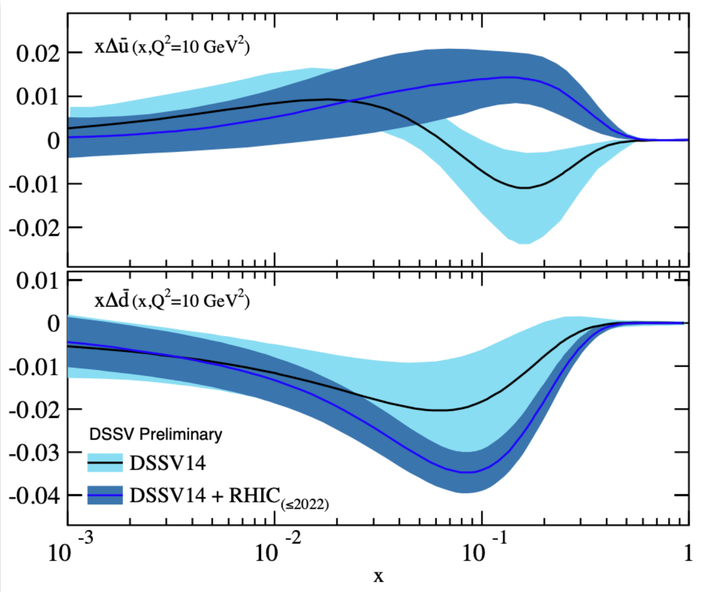
$$\int_{0.05}^{1} dx\Delta g = 0.218 \pm 0.027$$

$\Delta\bar{q}$ (sea quark polarization) through W production



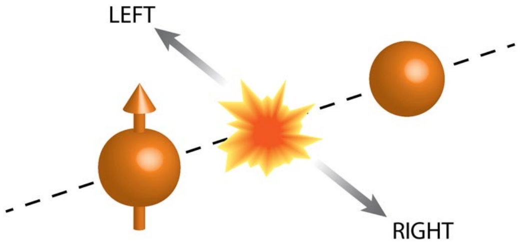
$$u\bar{d} \rightarrow W^+$$
$$d\bar{u} \rightarrow W^-$$





DSSV global fit including RHIC W data

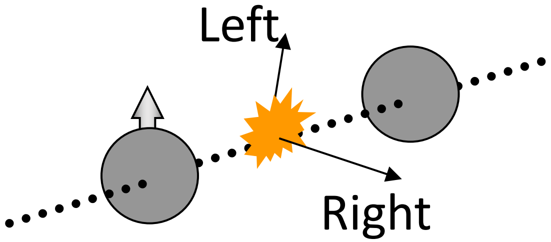
- From RHIC W-program
  - Ws naturally separate quark flavors → rapidity: sea vs. valence quarks
  - STAR: *PRD 99 (2019) 051102, PRL 113 (2014) 072301*
  - PHENIX: *PRD 98 (2018) 032007, PRD 93 (2016) 032007*
- Result: $\Delta\bar{u} - \Delta\bar{d} > 0$

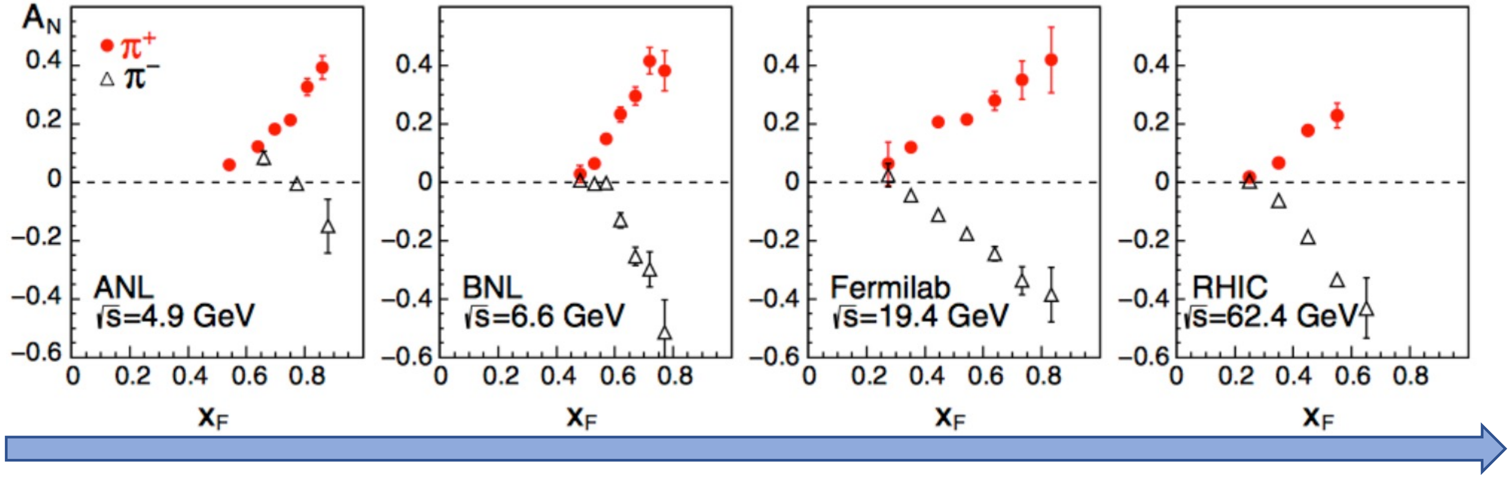


Recent RHIC spin results
Transverse spin

Transverse Single-Spin Asymmetry (A_N)

$$A_N = \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}}$$

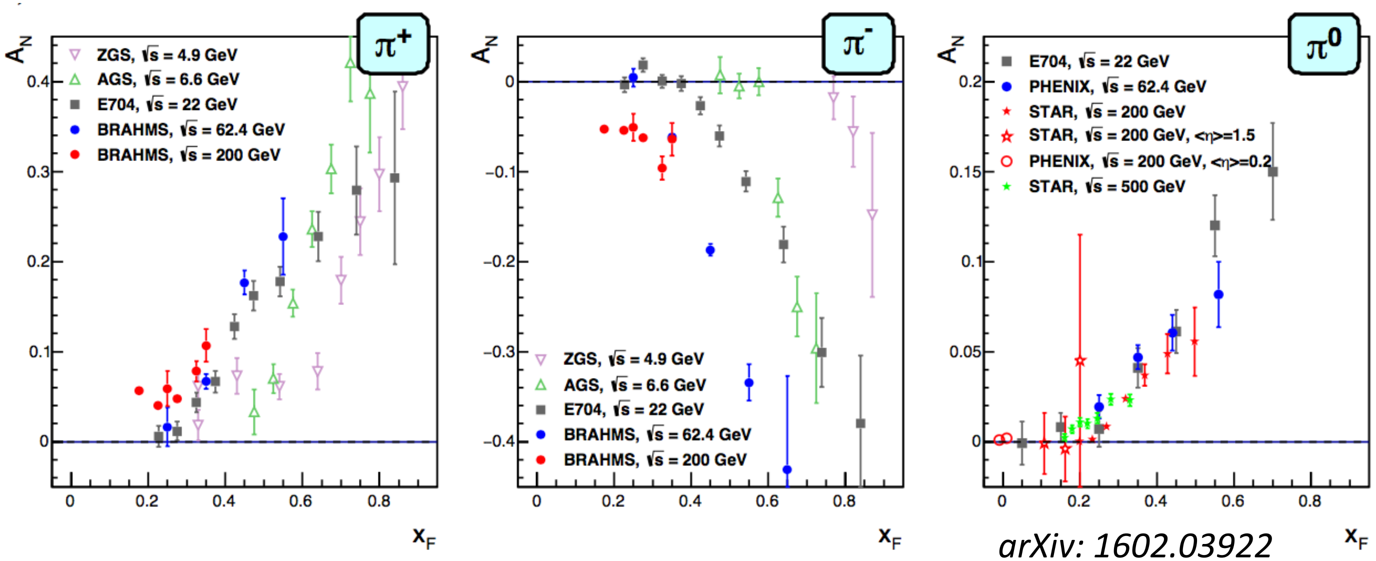




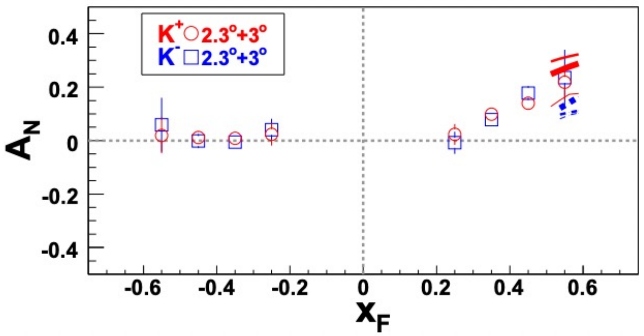
$$x_F = \frac{2p_L}{\sqrt{s}}$$

- Large A_N in single hadron production consistently observed up to RHIC energies, over 40 years.
- Transverse spin can be used as a probe, as it can correlate with parton's transverse momentum
- Transverse spin is related to the angular momentum contribution for proton's spin puzzle

A_N at RHIC energies



arXiv: 1602.03922

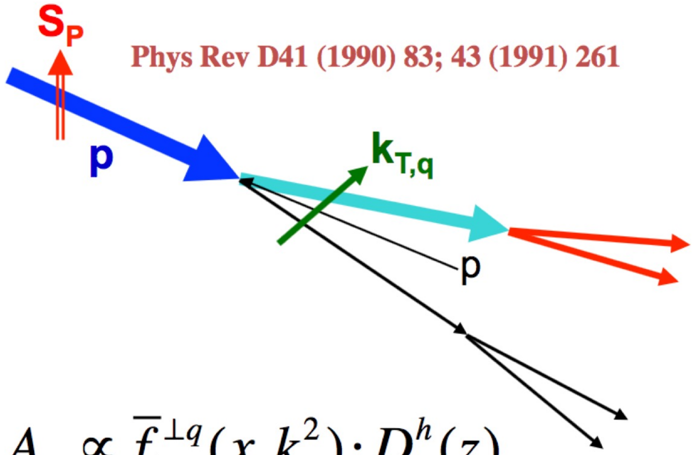


BRAHMS, PRL 101 042001 (2008)

- General features at forward rapidity
  - Striking effects at large x_F
  - A_N survives at large energies
  - $A_N(\pi^+)$ and $A_N(\pi^-)$ have roughly same magnitude, opposite sign
  - $A_N(K^+)$ and $A_N(K^-)$ same sign
  - $A_N(\pi^0)$ is positive, smaller than $A_N(\pi^+)$

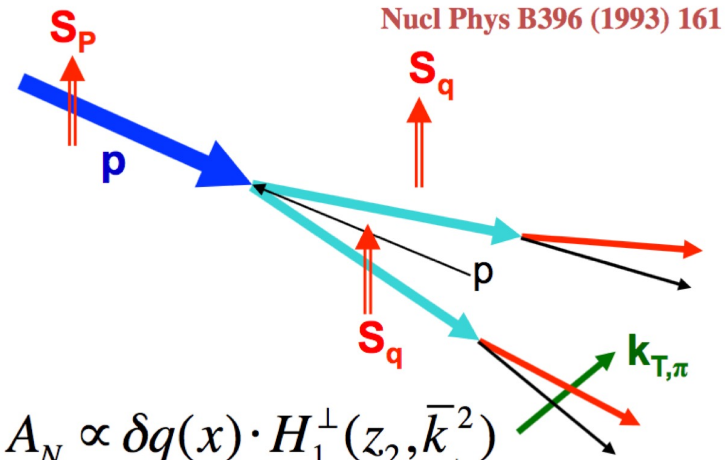
Possible origin of A_N

Sivers Mechanism
Correlation between proton spin & parton k_T



$$A_N \propto \bar{f}_{1T}^{\perp q}(x,k_\perp^2)\cdot D_q^h(z)$$

Collins Mechanism
Transversity x spin-dependent fragmentation

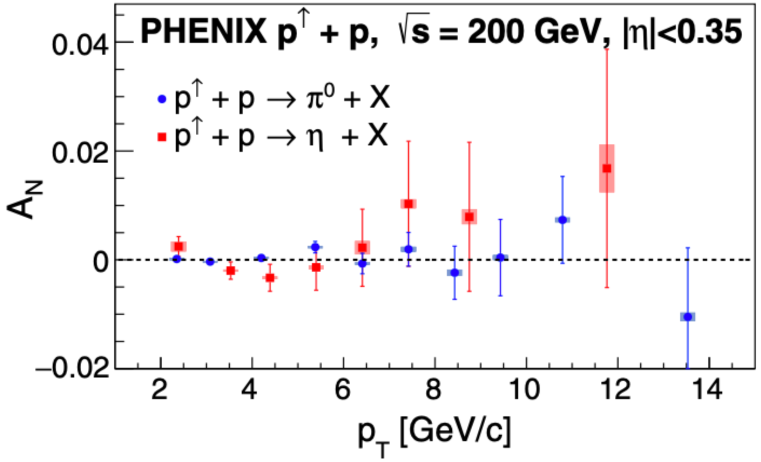


$$A_N \propto \delta q(x)\cdot H_1^\perp(z_2,\bar{k}_\perp^2)$$

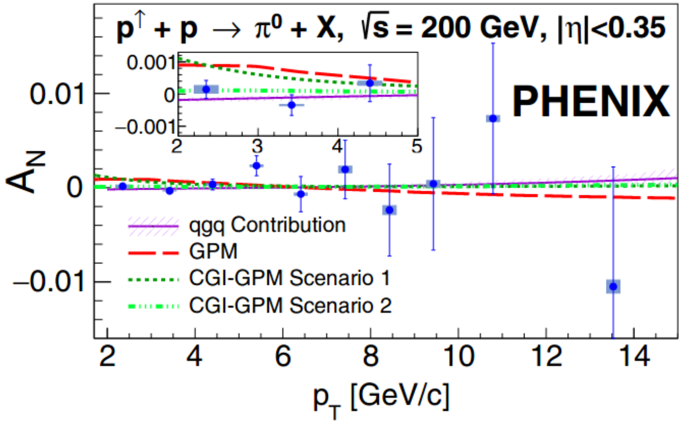
- Transverse Momentum Dependent Functions
  - Requires two scales: hard-scattering energy scale Q and a soft scale k_T, where $k_T \ll Q$
- $p^\uparrow + p \rightarrow h + X$: Collinear factorization approach
  - Twist-3 Multiparton(*qgq*, *ggg*) correlations and twist-3 fragmentation functions

π, η A_N at midrapidity

PRD 103, 052009 (2021)

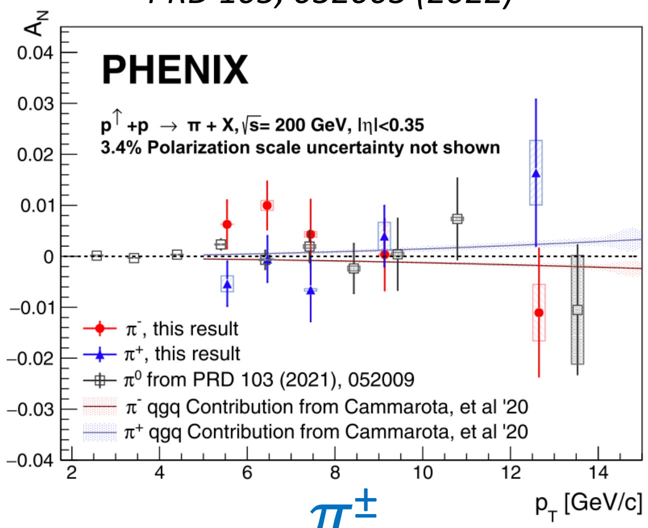


π^0, η



π^0

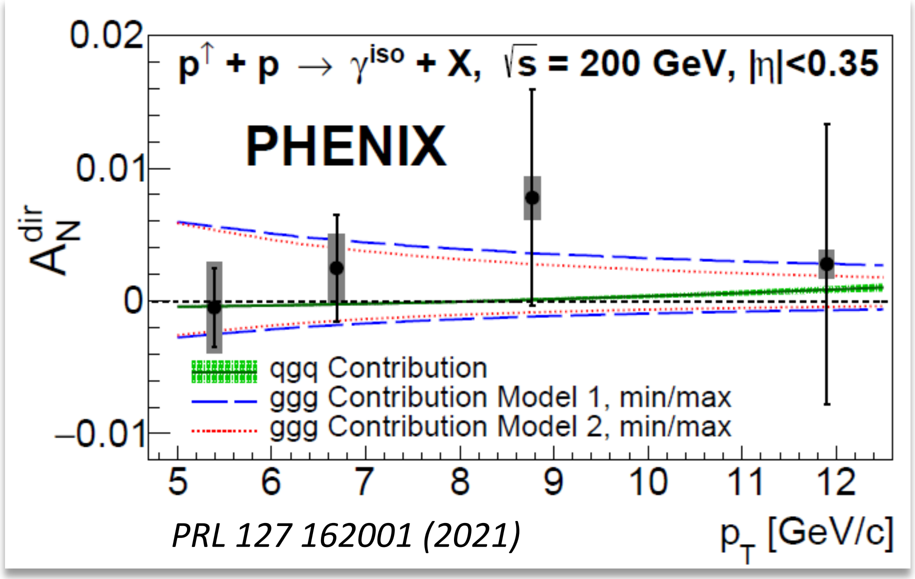
PRD 105, 032003 (2022)



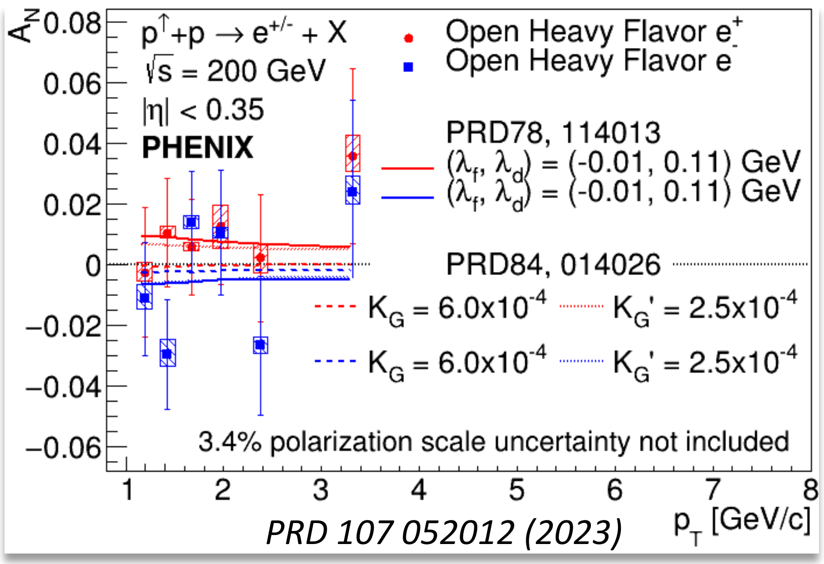
$\pi^\pm$

- π^0, η : sensitive to both initial- and final-state effects
- $\pi^\pm$: provide different flavor sensitivity via the fragmentation functions and could test whether cancellations happen
- Small asymmetry expected.

γ, HF A_N at midrapidity



Direct γ

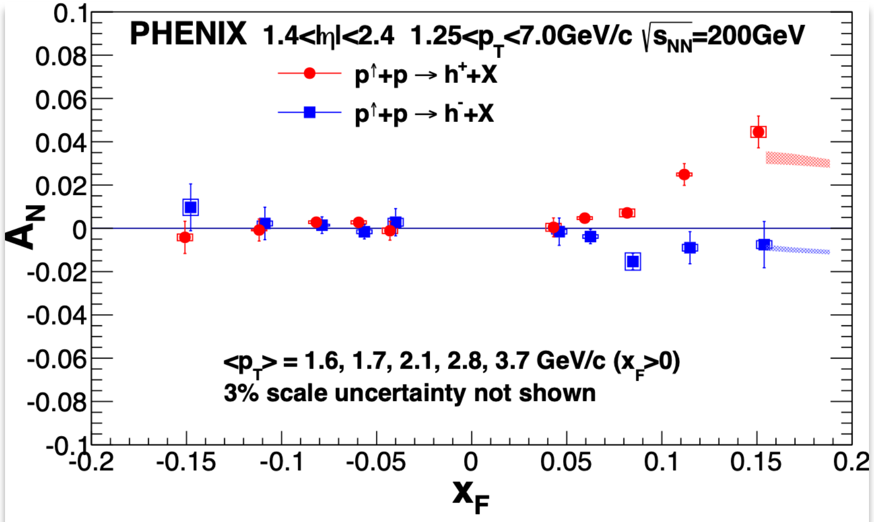


Open HF→$e^{\pm}$

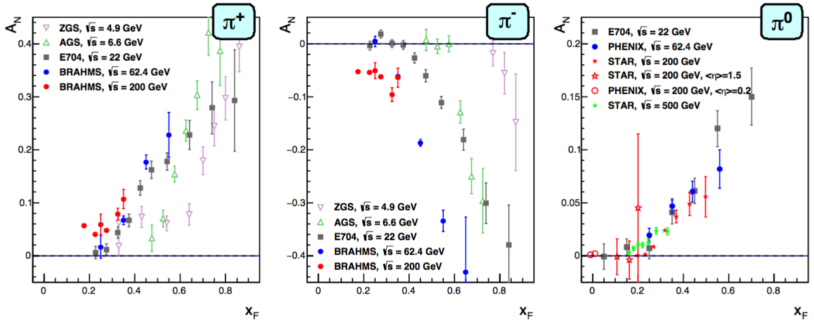
- First direct photon A_N from PHENIX
- Constrains twist-3 correlation function
  - Dominated by ggg correlator, small contribution from qgq correlators
- Larger asymmetries expected at forward rapidity

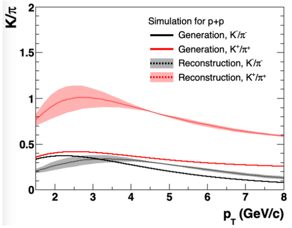
- Almost only gluon related, no final state effects → tri-gluon correlation
- Potential to constrain parameter ranges in D meson A_N theory calculations
- Comparison of charges provides further sensitivity

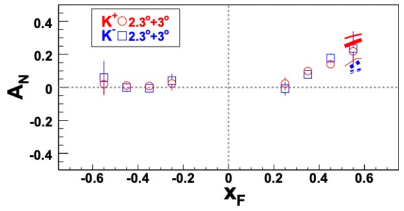
h±, Heavy Flavor A_N at forward/backward rapidity

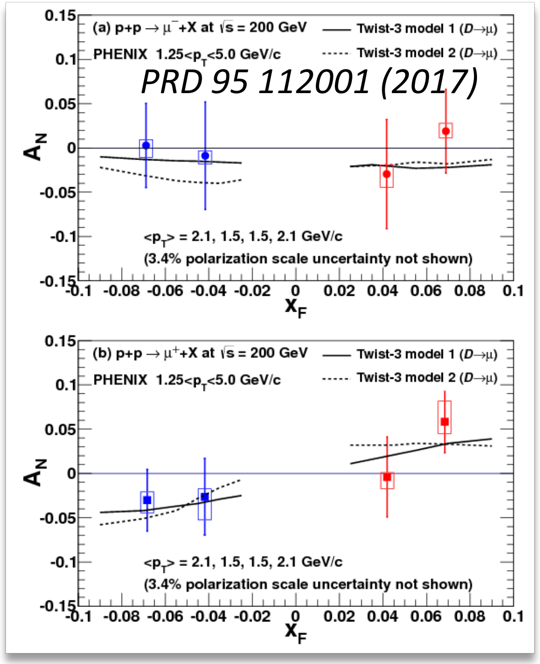


arXiv: 2303.07191





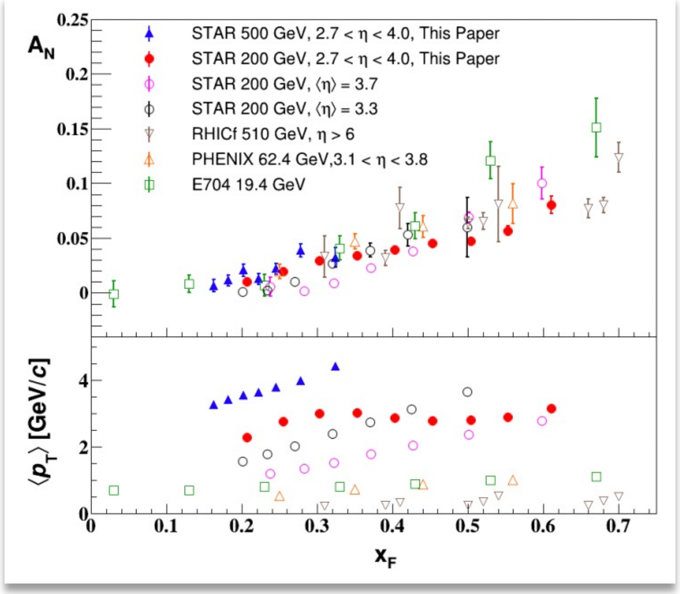


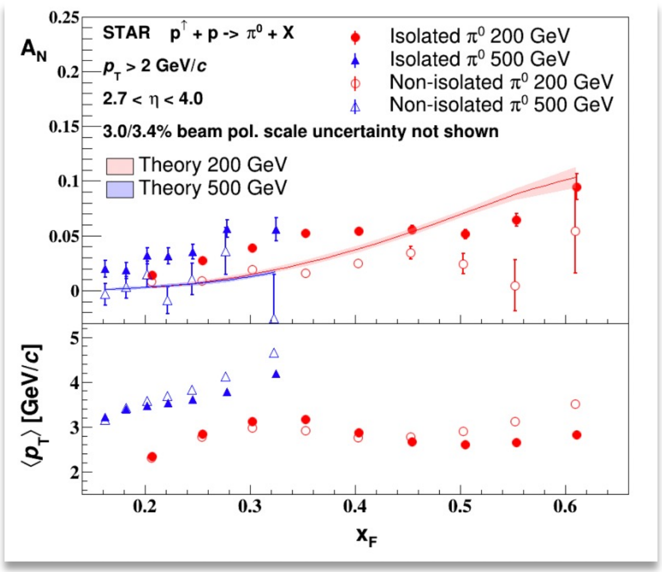


- Charged hadron A_N ($\pi^{\pm}$,$K^{\pm}$)
  - $A_N(h^+)$ increases as x_F increases at x_F>0
  - $A_N(h^+)$ small to zero: Opposite sign of A_N for π^-,K^- canceled partially at x_F>0
  - Model at x_F>0.15 : *PLB 770, 242 (2017)*
- Open Heavy Flavor A_N (D→$\mu^{\pm}$)
  - Dominated by gluon-gluon interaction
  - Clean probe for gluon Sivers effect
    - Sensitive to twist-3 ggg function
    - Twist-3 model: PRD 84 014026 (2011)
  - Working on Run-15 data, uncertainty will be greately reduced.

Forward neutral pions A_N

Phys. Rev. D 103, 092009 (2021)

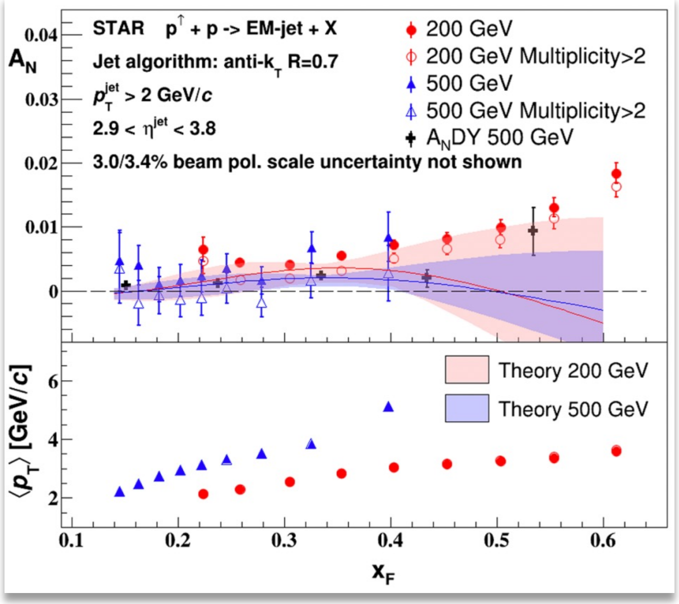




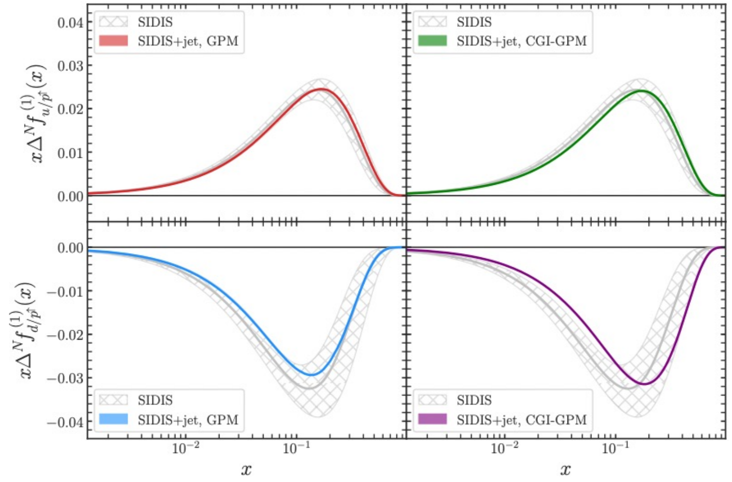
- Weak energy dependence of $A_N(\pi^0)$
- Very forward $A_N(\pi^0)$ at $\eta>6$, $p_T<1$ GeV/c at RHICf *(PRL 124 252501 (2020))*
- Isolated π^0 has larger A_N than nonisolated
  - There could be different mechanisms in play to explain the large asymmetries

EM jet AN

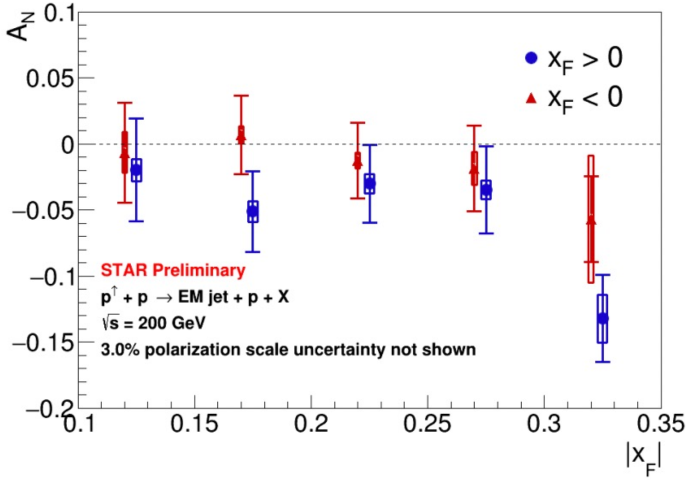
Phys. Rev. D 103, 092009 (2021)



PLB 815, 136135 (2021)



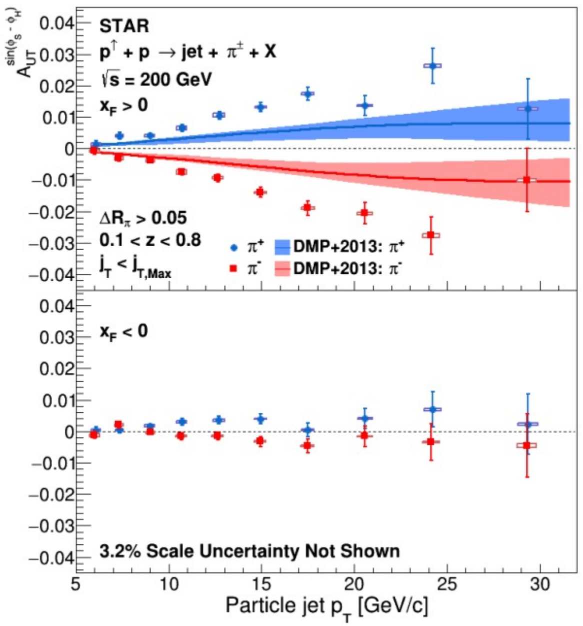
Diffractive EM jet

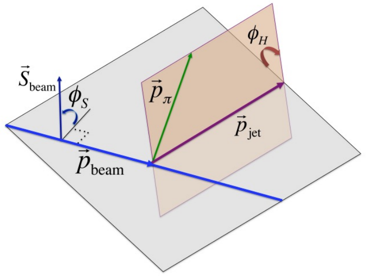


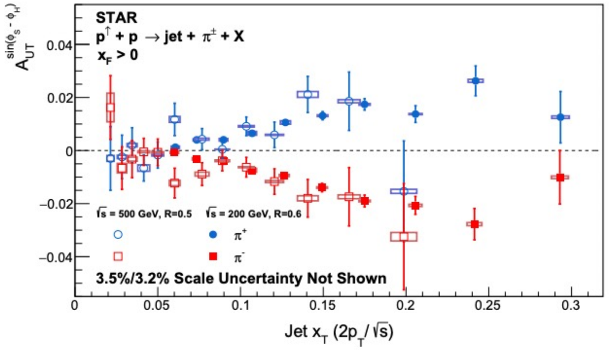
- EM-jet: increase with x_F , but A_N is much smaller than π^0
- Significant constraint to global fit of the Sivers function
- Diffractive EM jet: most probably not the source of the large positive $A_N(\pi^0)$

Transversity, Collins Asymmetry

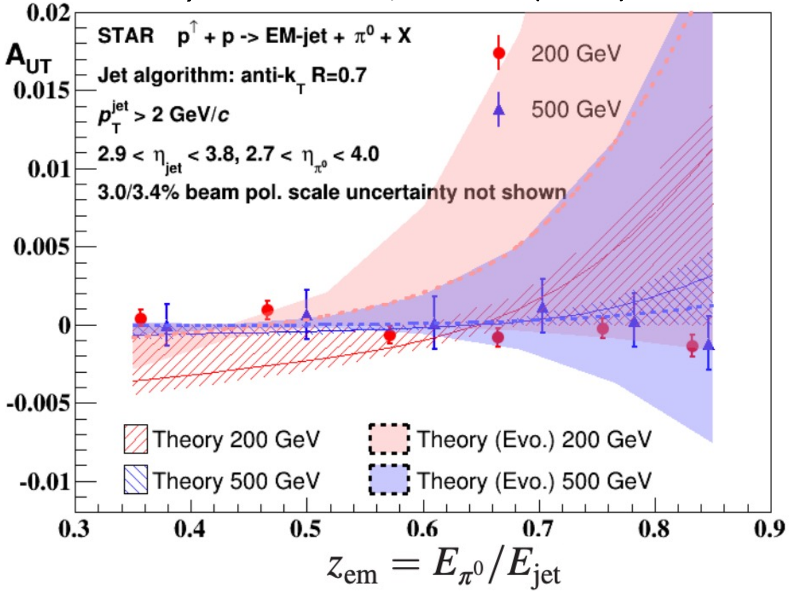
Phys. Rev. D 106, 072010 (2022)





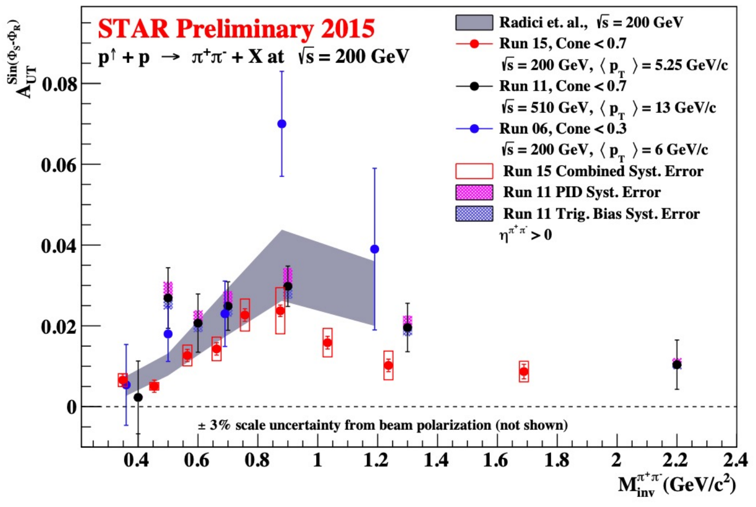


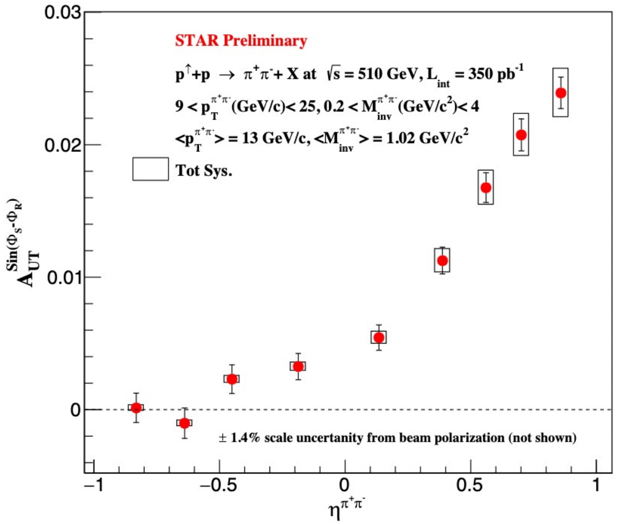
Phys. Rev. D 103, 092009 (2021)



- Collins asymmetry in pp collision: ideal tool to explore the fundamental QCD questions of TMD factorization, universality, and evolution
- $\pi^{\pm}$ within jet : sensitive to quark transversity.
  - larger asymmetry than model based on SIDIS(Transversity), e^+e^-(Collins Fragmentation Function)
- π^0 within EM jet : small Collins asymmetry
  - small contribution from Collins to $A_N(\pi^0)$

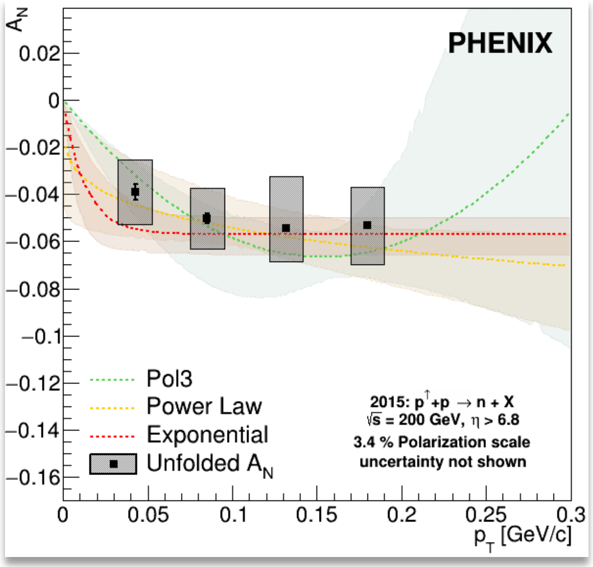
Transversity via IFF



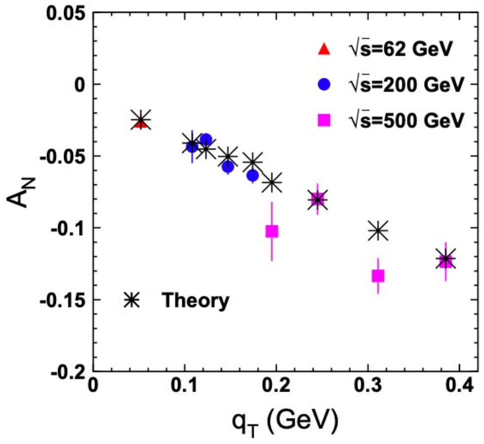


- Interference Fragmentation Functions (IFF)
  - $\pi^+\pi^-$ azimuthal asymmetry
  - (collinear) complementary probe of transversity relative to the Collins asymmetry, provide significant additional constraints on the u- and d-quark transversities
  - Large asymmetry at high η
    - significant quark transversity at large x – Small asymmetry at negative η due to small transversity at low x

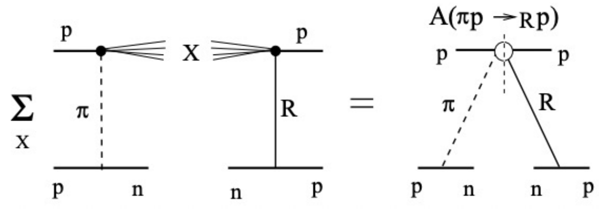
A_N at very forward region



PRD 103, 032007 (2021)

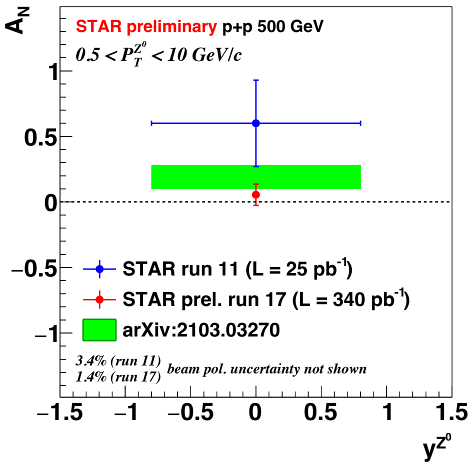


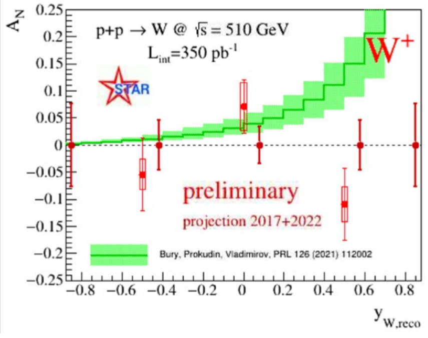
PRD 84, 114012 (2011)

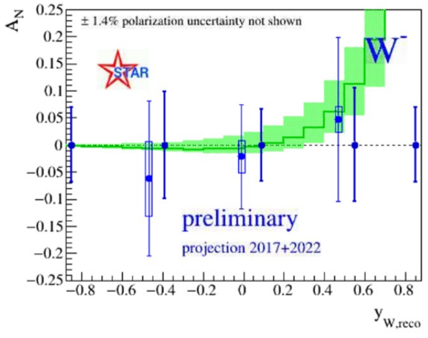


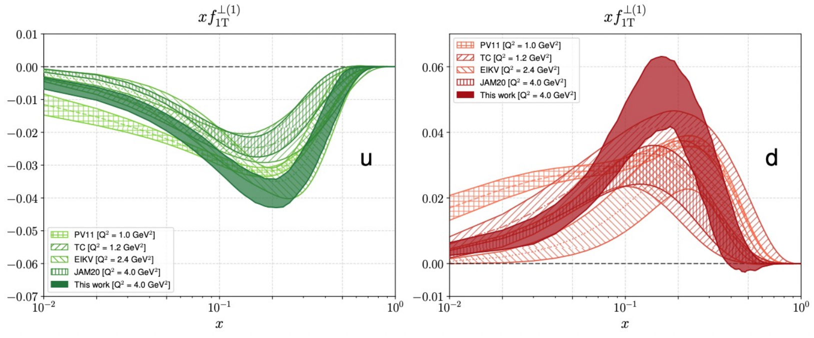
- Neutron A_N
  - π-R interference in hadronic interactions.
  - Negative A_N with linear p_T dependence.

Weak boson A_N



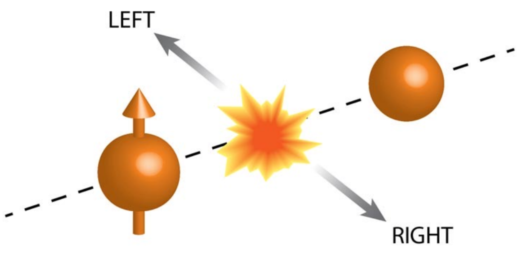


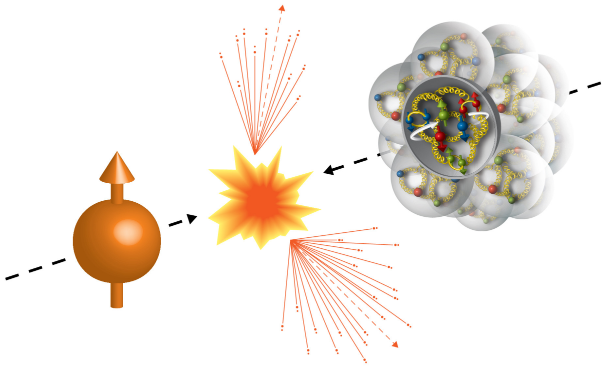




PLB 827, 136961 (2022)

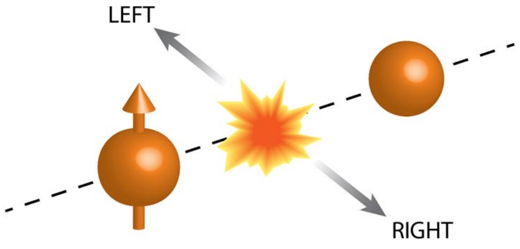
- Transverse partonic motion must be in the initial state
- predicted sign change in A_N relative to final-state interactions
- global QCD extraction of the Sivers function included 2011 W,Z

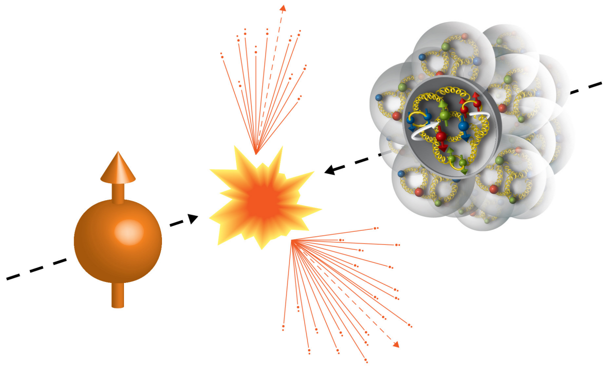




Transverse spin in p+A

A_N in polarized p+A





- The first and only (transversely) polarized p+A collision at RHIC 2015 run
- Nuclear effects in various A_N measurements
  - Inclusive hadron production $p^{\uparrow}$+A → h+X
    - Nonzero A_N in inclusive hadron in transversely polarized p+p: puzzle over 40 years
    - Help to disentangle differing mechanisms and clarify the origin of the A_N.
    - A-dependence of A_N can be a probe for the saturation scale in the nucleus.

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 \ll Q_s^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{\frac{P_{h\perp}^2 \delta^2}{Q_{sp}^4}} \quad \left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 \gg Q_s^2} \approx 1$$

PRD 84 034019 (2011)

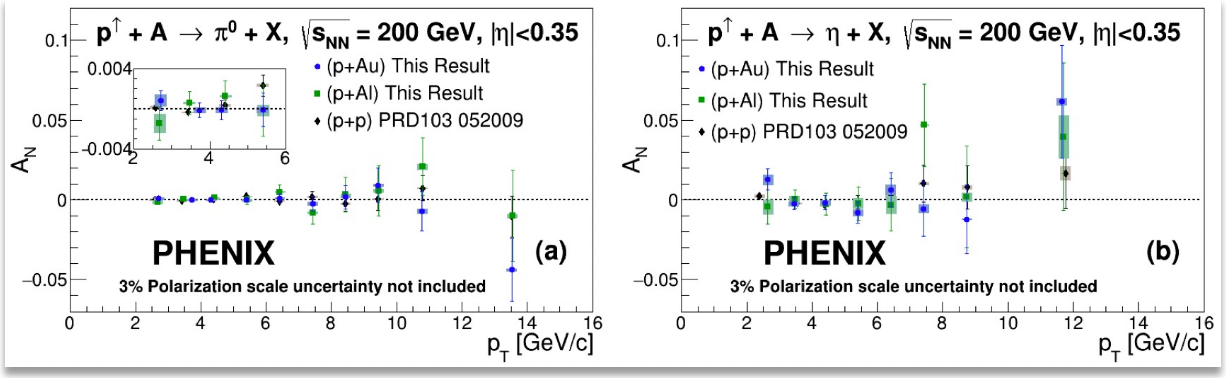
$$A_N^{(q)}(k_T \approx Q_s) \sim \frac{1}{Q_s^7} \sim A^{-7/6}$$

PRD 86 034028 (2012)

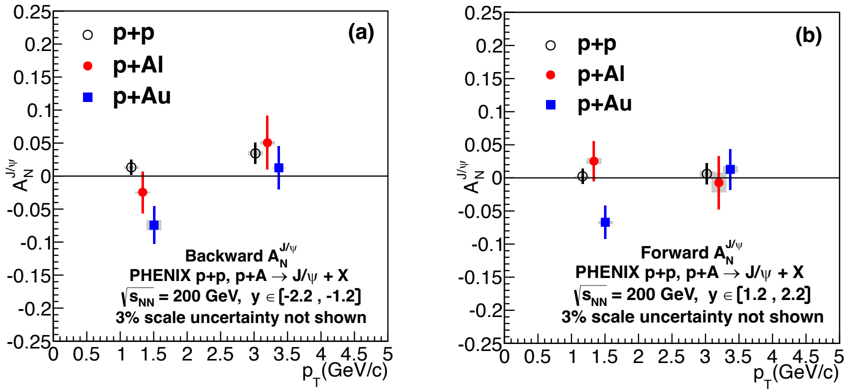
$$\frac{A_N^{pA}}{A_N^{pp}} \sim \frac{Q_{sp}^2}{Q_{sA}^2} \sim \frac{1}{A^{1/3}} < 1 . \quad (P_{hT} \lesssim Q_s)$$

PRD 94 054013 (2016) PRD 95 014008 (2017)

π^0, η, J/ψ, neutron in transversely polarized p+A

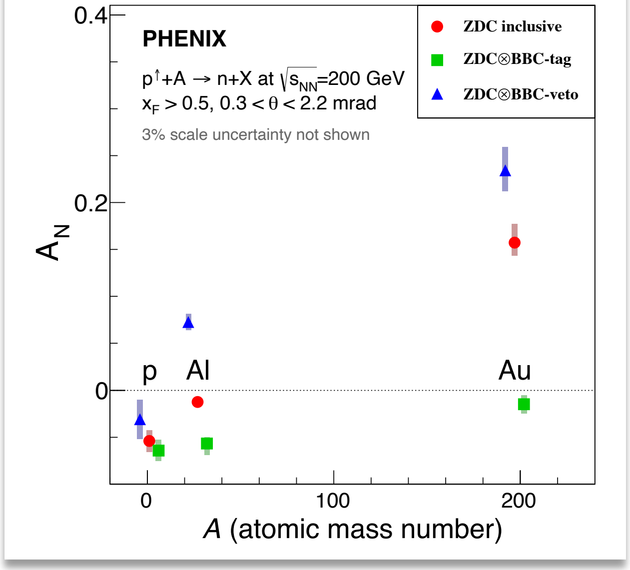


PRD 107 112004 (2023)



PRD 98 012006 (2018)

PRL 120 (2018) 022001

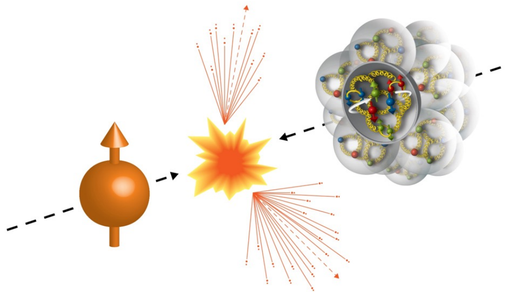


- Midrapidity π^0,η A_N
  - similar to p+p. no evidence of additional effect from complex invironment
- Forward rapidity J/ψ A_N
  - negative asymmetry in p+Au collisions in both forward and backward
- Very forward neutron A_N
  - Sign changed.
  - UPC can generate A_N (PRC 95 044908(2017))
  - p_T and x_F dependence: PRD 105 032004 (2022)

Nuclear Dependence of A_N : $h^{\pm}$, π^0

In 2015 RHIC run transversely polarized

$p^{\uparrow} + p$, $p^{\uparrow} + \mathrm{Al}$ and $p^{\uparrow} + \mathrm{Au}$



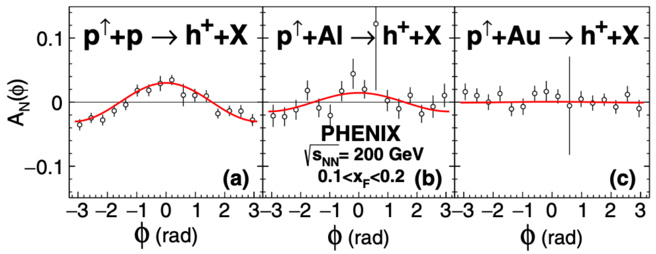
PHENIX charged hadron A_N

$1.4 < \eta < 2.4$

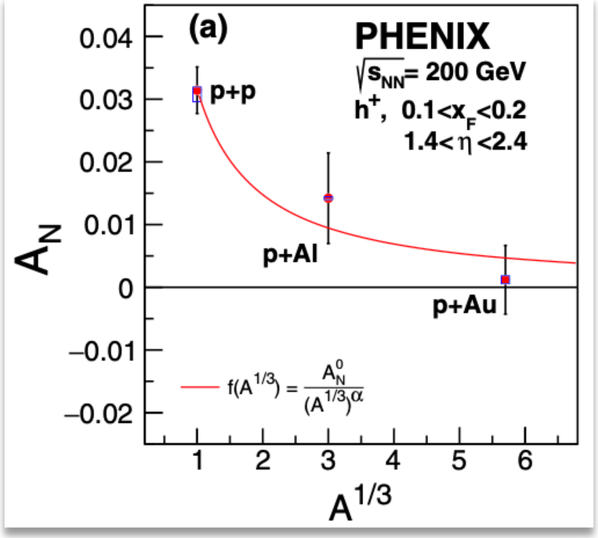
$0.1 < x_F < 0.2$

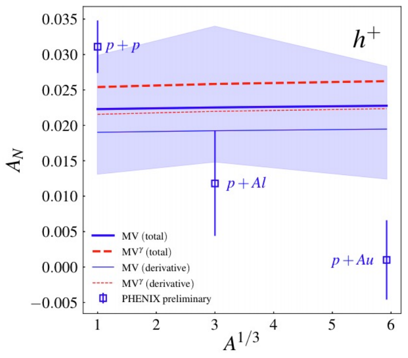
$1.8 < p_T < 7\ \mathrm{GeV}/c$

Strong A_N suppression in p+Au



PHENIX, PRL 123, 122001 (2019)





PRD 99, 094012 (2019)

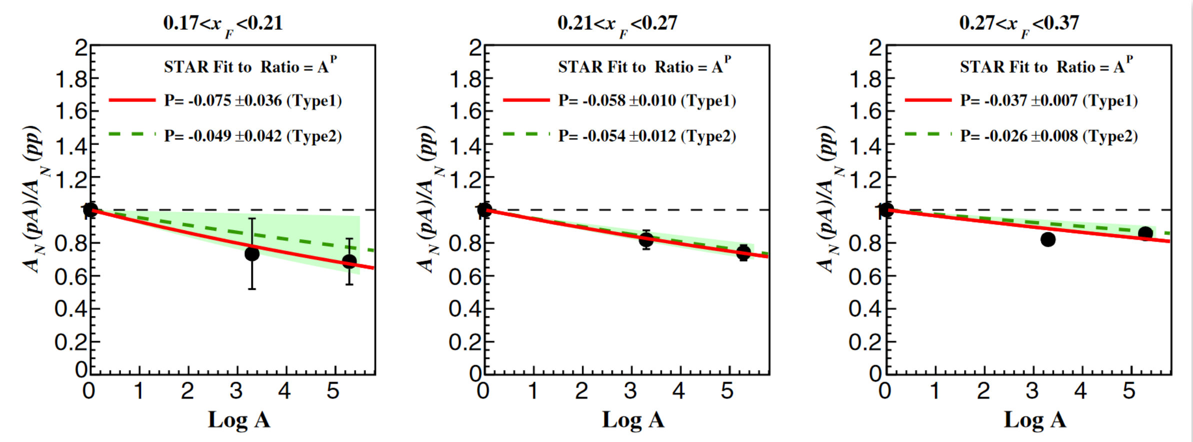
STAR forward π^0 A_N

$2.6 < \eta < 4.0$

$0.2 < x_F < 0.7$

$1.5 < p_T < 7\ \mathrm{GeV}/c$

Moderate A dependence

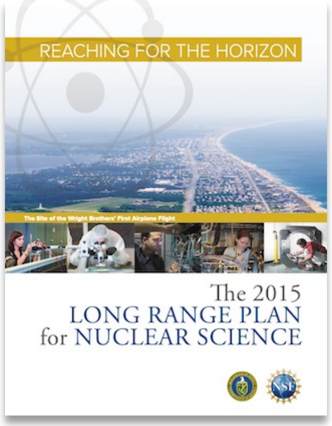


STAR, PRD 103, 072005 (2021)

- Installed, Au+Au running in 2023, pp & pA running in 2024
- The sPHENIX barrel will be able to measure jets, heavy flavor, direct photons, $h^{\pm}$ to probe
- Cold QCD topic
  - Sivers effect with γ-jet, di-jet
  - Transversity with Collins and IFF through h in jet and di-hadron
  - Trigluon correlation function with direct photons and heavy flavor
  - Hadron A_N in pp vs pA

Future Perspectives: RHIC Cold QCD Plan Electron-Ion Collider

Bridge between present and future: sPHENIX and STAR upgrade



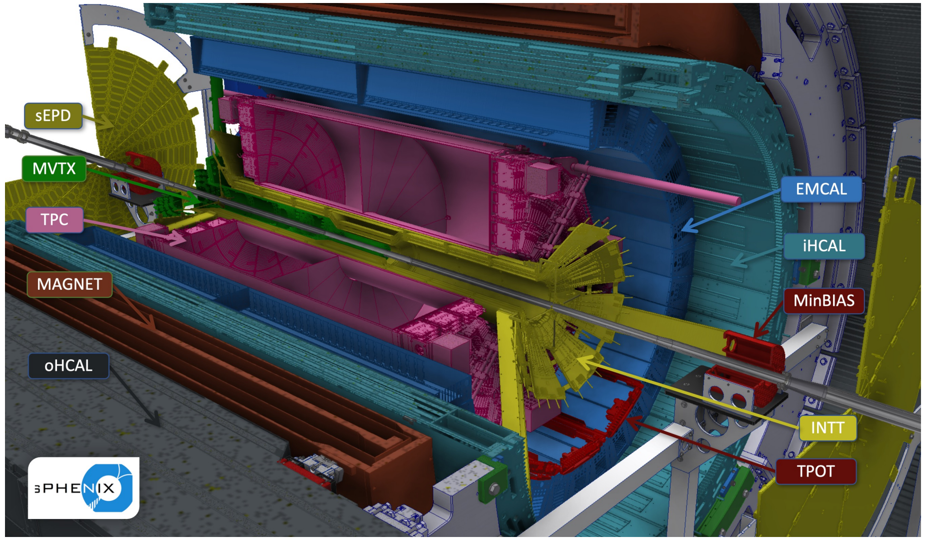
There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

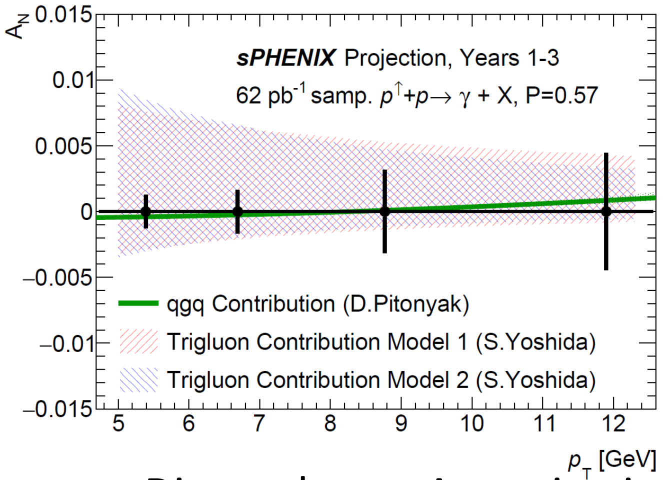
The Present and Future of QCD

QCD Town Meeting White Paper – An Input to the 2023 NSAC Long Range Plan

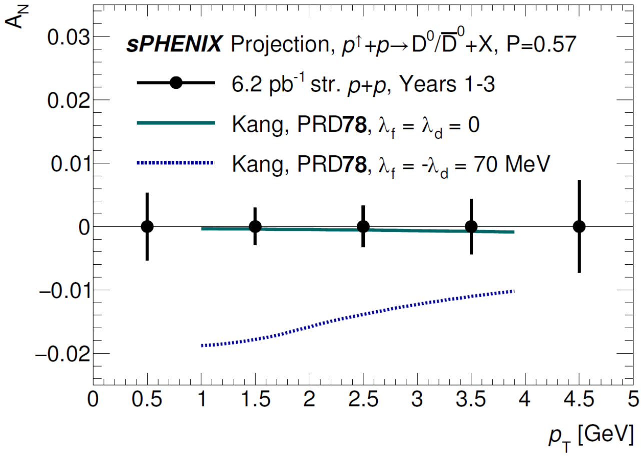
- The RHIC facility revolutionized our understanding of QCD, as well as the spin structure of the nucleon. To successfully conclude the RHIC science mission, it is essential to complete the sPHENIX science program as highlighted in the 2015 LRP, the concurrent STAR data taking with forward upgrade, and the full data analysis from all RHIC experiments.

sPHENIX – Cold QCD Program



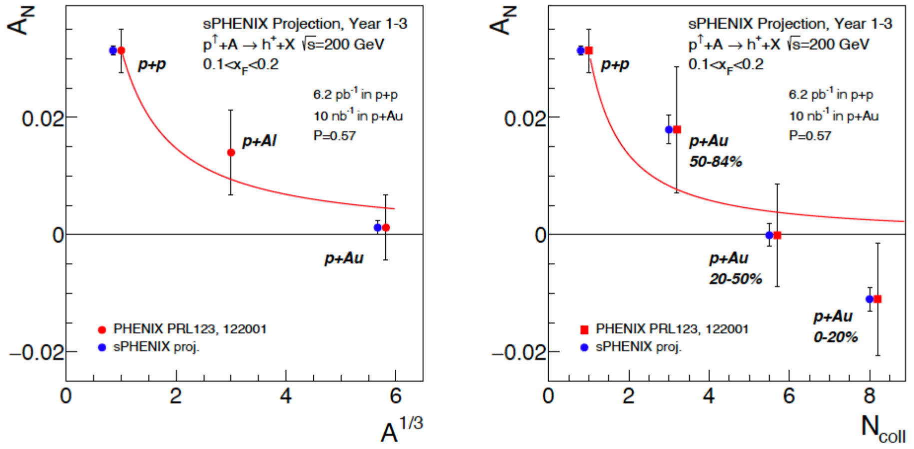


Direct photon A_N projection



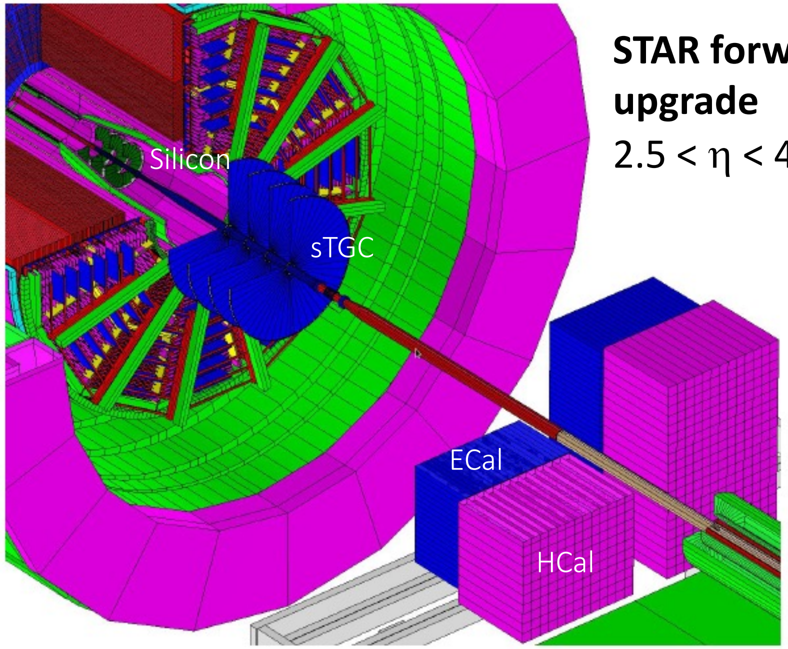
D meson A_N projection

- Installed, Au+Au running in 2023, pp & pA running in 2024
- The sPHENIX barrel will be able to measure jets, heavy flavor, direct photons, $h^{\pm}$ to probe
- Cold QCD topics
  - Sivers effect with γ-jet, di-jet
  - Transversity with Collins and IFF through h in jet and di-hadron
  - Trigluon correlation function with direct photons and heavy flavor
  - Hadron A_N in pp vs pA



Hadron A_N in pp vs pA projection

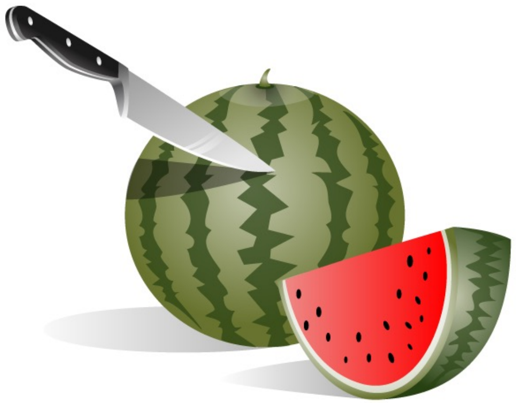
The STAR Forward Upgrade

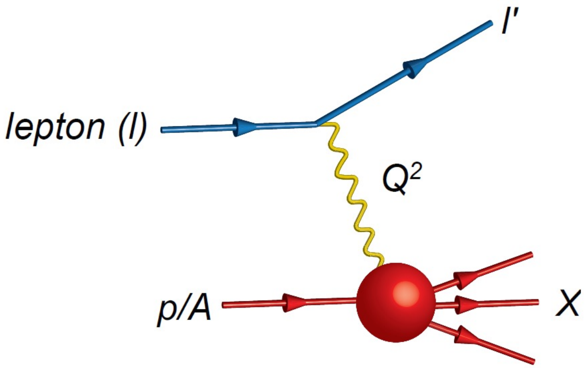


STAR forward upgrade
$2.5 < \eta < 4$

- Electromagnetic and Hadronic Calorimetry with SiPM readout & new ADC + trigger modules, with Tracking Silicon detectors and small-strip Thin Gap Chambers
- STAR forward upgrade was fully operation for 2022 transversely polarized pp 510 GeV
- Topics
  - A_N(W,Z) : Sivers sign change
  - A_N for $h^{+/-}$ and π^0 : Unravel the mystery what is the underlying process of A_N
  - $h^{+/-}$ with z > 0.5 in jet : flavor tagging of the Twist-3 equivalent of the Sivers function
  - high precision data to test universality of CGC, evolution/universality of Q_s^2 with A and x

Smash? Or cut open?

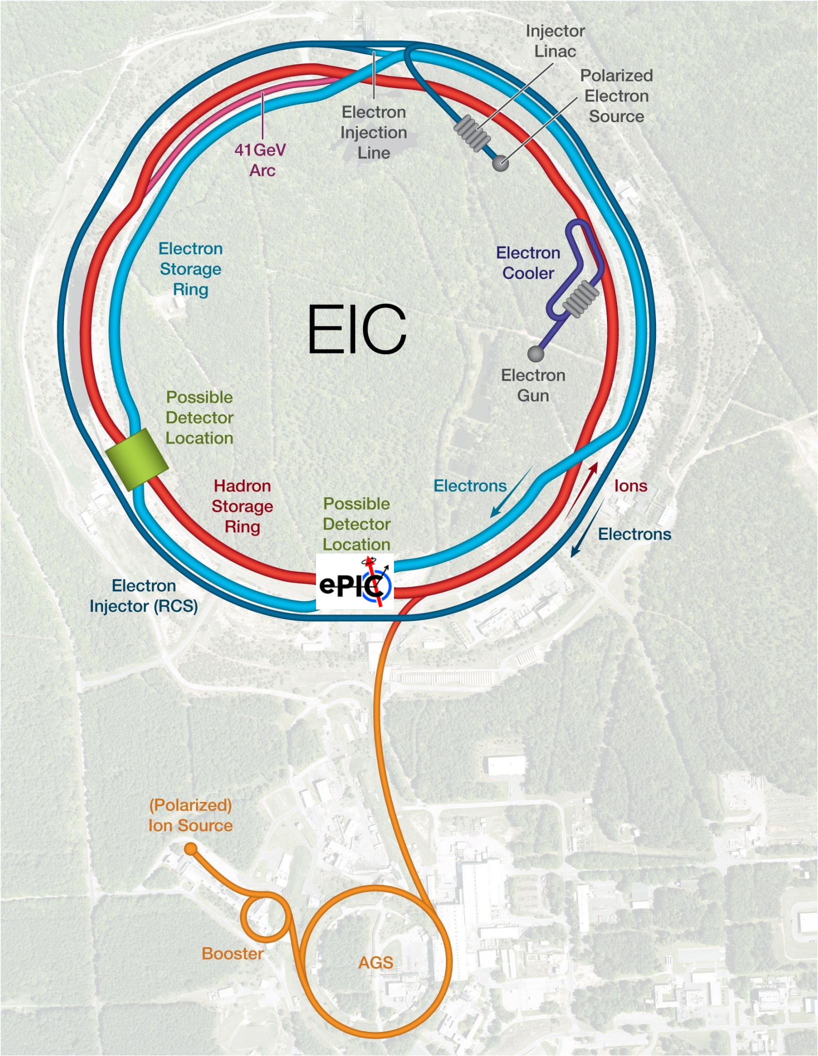




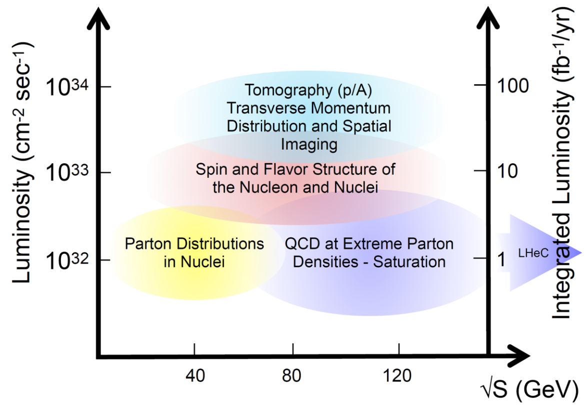
- "cut open" the nucleon/nucleus with DIS
  - Discovered quarks inside the nucleus
  - Discovered proton spin crisis
  - Discovered the quarks inside a proton in nucleus behave differently

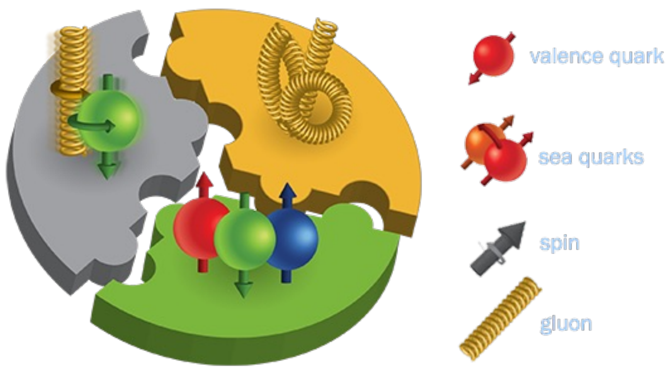
- DIS enables us to look into
  - Gluon momentum distribution in nuclei
  - Energy loss in cold nuclear matter and emergence of hadrons
  - Parton spin in nucleons/nuclei
  - Dynamics of a bound QCD system

Electron-Ion Collider



- the ONLY world-wide new collider in foreseeable future
- A high luminosity (10^{33} – 10^{34} $cm^{-2}s^{-1}$) polarized electron proton / ion collider with $\sqrt{s_{ep}}$ = 28 – 140 GeV
- factor 100 to 1000 higher luminosity as HERA
- both e, p / light nuclei polarized,
- nuclear beams: d to U
- ePIC at 6o'clock



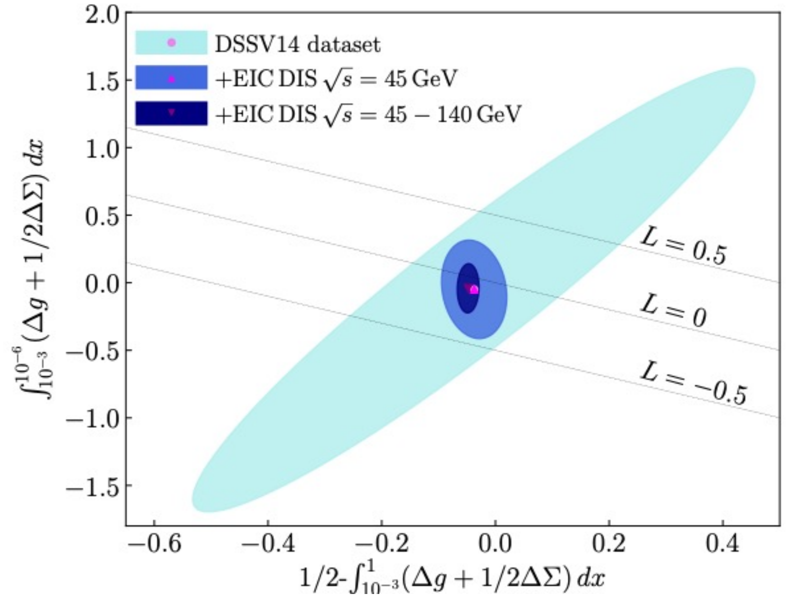


EIC physics

- How do the nucleonic properties such as mass and spin emerge from partons and their underlying interactions?
- How are partons inside the nucleon distributed in both momentum and position space?
- How do color-charged quarks and gluons, and jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?

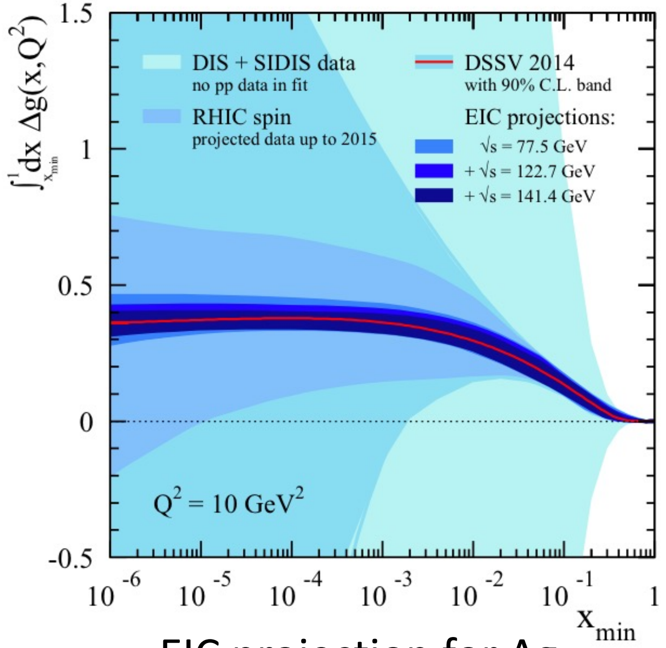
Proton spin decomposition at EIC

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



PRD 102 (2020) 094018

Room left for potential orbital angular momentum contributions



EIC projection for Δg

- Key Observables: Structure function $g_1(x,Q^2)$ for proton and He^3/D → ΔΣ, ΔG
- SIDIS double spin asymmetries for p, K → flavor separated Δq

3-Dimensional Imaging Quarks and Gluons

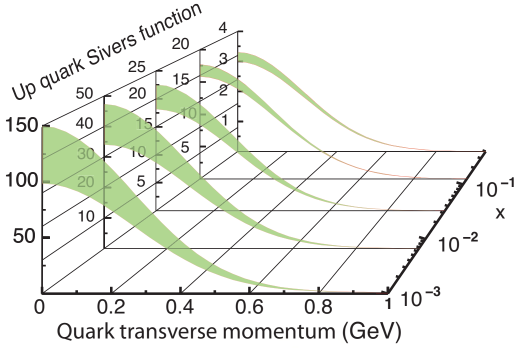
Wigner functions $W(x,b_T,k_T)$

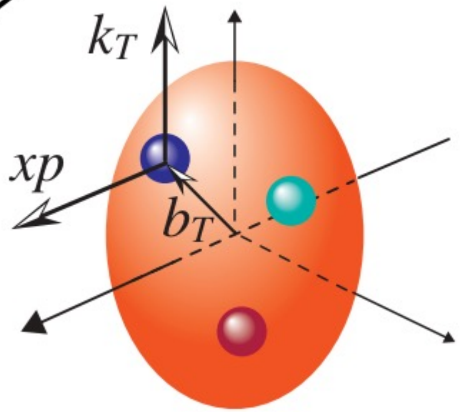
offer unprecedented insight into confinement and chiral symmetry breaking.

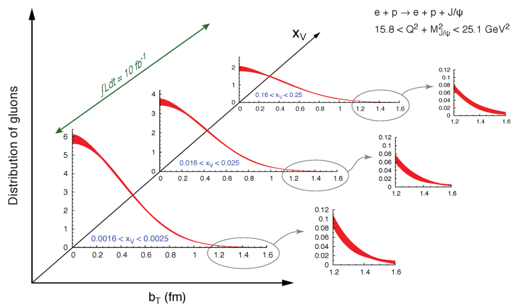
$$W(x,b_T,k_T)$$

$\int d^2b_T$ → *Momentum space* → $f(x,k_T)$

$\int d^2k_T$ → *Coordinate space* → $f(x,b_T)$







Spin-dependent 3D momentum space images from semi-inclusive scattering → **TMDs**

Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering → **GPDs**

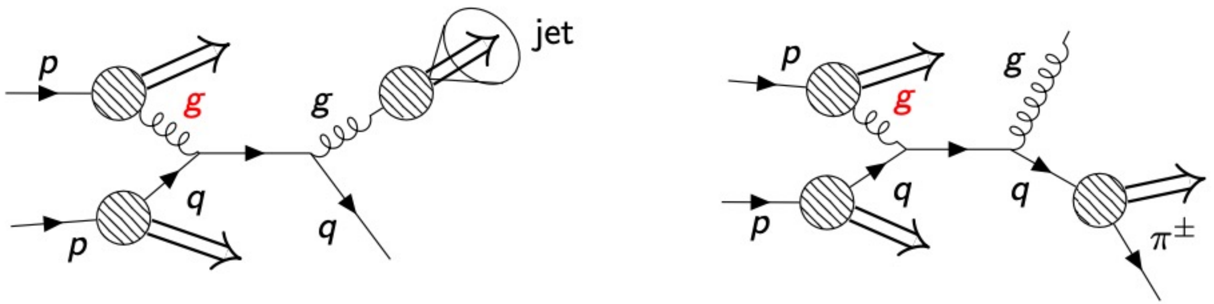
- EIC – 3D imaging of partons
  - TMDs – confined motion in a nucleon (semi-inclusive DIS)
  - GPDs – Spatial imaging of quarks and gluons (exclusive DIS)

Conclusion

- Proton spin puzzle, proton 3D momentum structure has been explored from DIS to RHIC pp collision
- The RHIC Spin program was an enormous success to deepen understanding of the proton spin structure and dynamics
  - Longitudinally polarized proton collision: gluon, sea quark contribution in proton spin puzzle
  - Transversely polarized proton collision: 3D momentum structure of proton using spin-momentum correlation
- EIC will explore the details of nucleon/nuclei precisely
- sPHENIX, STAR upgrade will be a bridge to EIC

backup

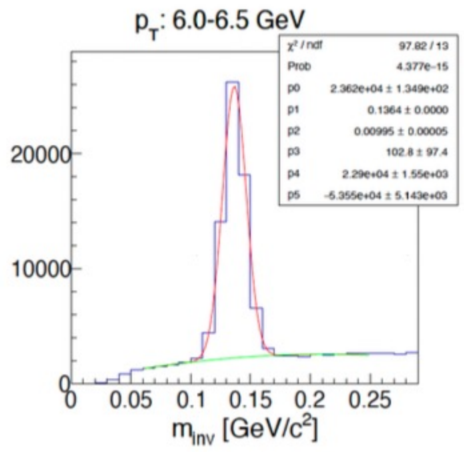
Jet and charged pion production at RHIC

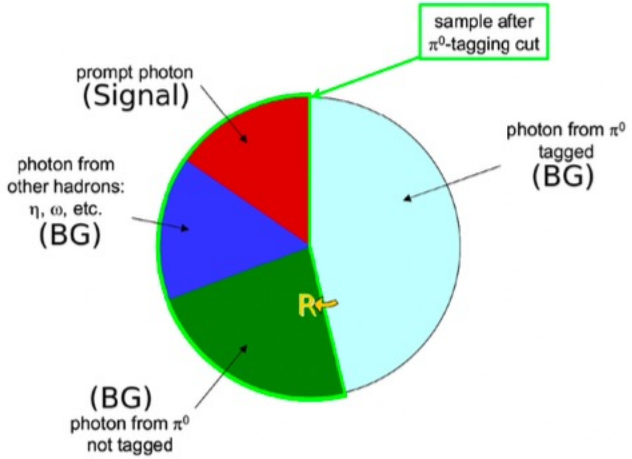


- Larger statistics: not suppressed by small QED coupling.
- RHIC 200 GeV data probe $0.05 < x < 0.2$.
- RHIC 510 GeV data probe $0.02 < x < 0.08$.

Direct photon identification (PHENIX)

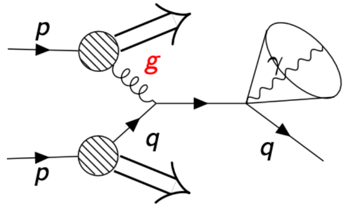
- Photons detected by EMCal
- Effectively reduced BGs by π^0decay tagging





Yield of direct photon:

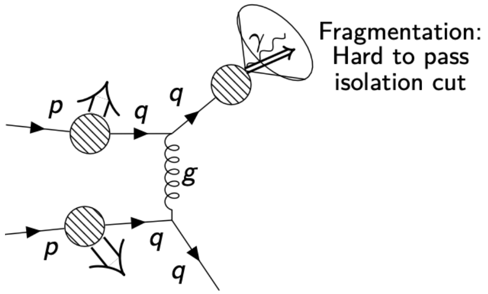
- $N_{dir} = N_{total} - (1 + A)(1 + R)N_{\pi^0}$
  - R: π^0 one photon missing ratio.
  - A: Other hadrons' to π^0's photon ratio.

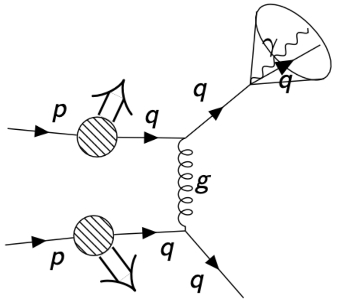


$r_{cone} = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} = 0.5$

Isolation cut requirement:

$\sum E_{in\ cone} < 0.1E_\gamma$



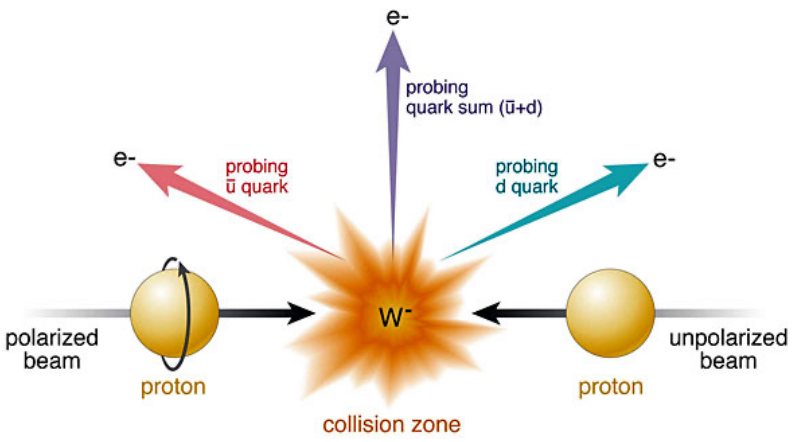


- Isolation cut: reduced the BG contributions from patron fragmentation and hadron decays

$$r_{cone} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.5\ rad$$

$$E_{cone} < E_\gamma \cdot 10\,\%$$

W-Production



- Ws naturally separate quark flavors

→ rapidity: sea vs. valence quarks

- Ws are maximally parity violating

→ Ws couple only to one parton helicity

longitudinal polarized protons:

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

unpolarized protons:

$$A\left(W^+/W^-\right) = \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

- Complementary to SIDIS:
  - very high Q^2-scale 6400 GeV^2
  - extremely clean theoretically
  - No Fragmentation function

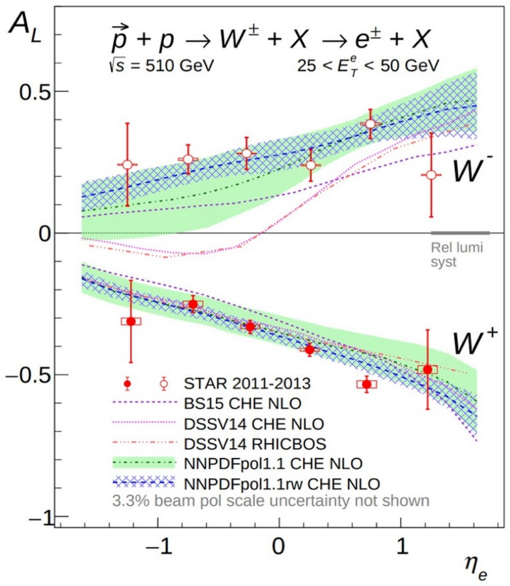
→ stringent test on theory approach for SIDIS UNIVERSALITY of PDFs

Sea quark helicity

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

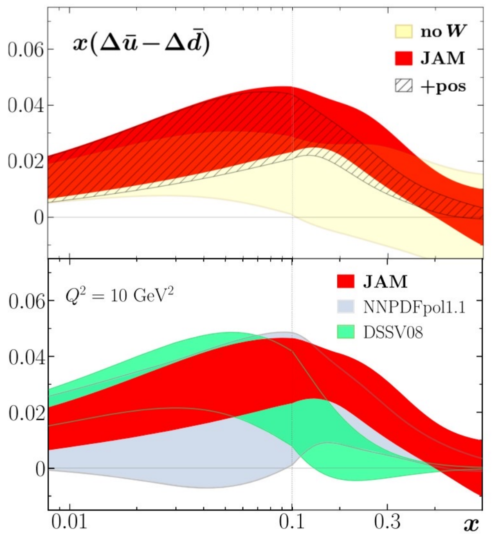
$$A_L^{W^-}(y_W) \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$



STAR, PRD99 (2019), 051102

Lepton η covers $0.05<x_1<0.25$



JAM, PRD 106, (2022) L031502

- Separation of quark flavor
  - W+(W-): predominantly u(d) and d(u)
- Maximal parity violation
  - W couples to left-handed particles or right-handed antiparticles
- The decay process is calculable
  - Free from fragmentation function

Dijet A_{LL}

Phys. Rev. D 105 (2022), 092011

- Golden probes for Δg:
  - Double spin asymmetry A_{LL} for jets, di-jets and meson-production
- increase x-range covered: go to higher √s (200 GeV → 500 GeV)
  - or go to higher rapidity: -1<η<1 → -1 <η<1.8) or both
- Di-jets: constrain the shape of the Δg(x,Q2)

Inclusive jet

$$x \approx \frac{2p_T}{\sqrt{s}} e^{\pm\eta}$$

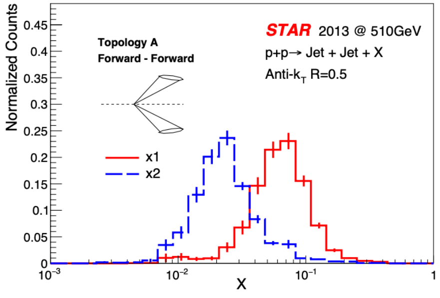
Dijet

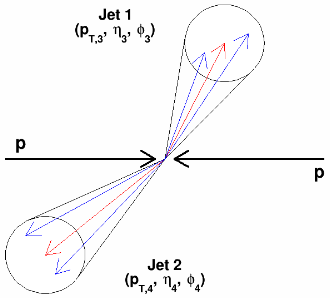
$$x_1 = \frac{1}{\sqrt{s}}(p_{T,3}e^{\eta_3} + p_{T,4}e^{\eta_4})$$

$$x_2 = \frac{1}{\sqrt{s}}(p_{T,3}e^{-\eta_3} + p_{T,4}e^{-\eta_4})$$

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

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





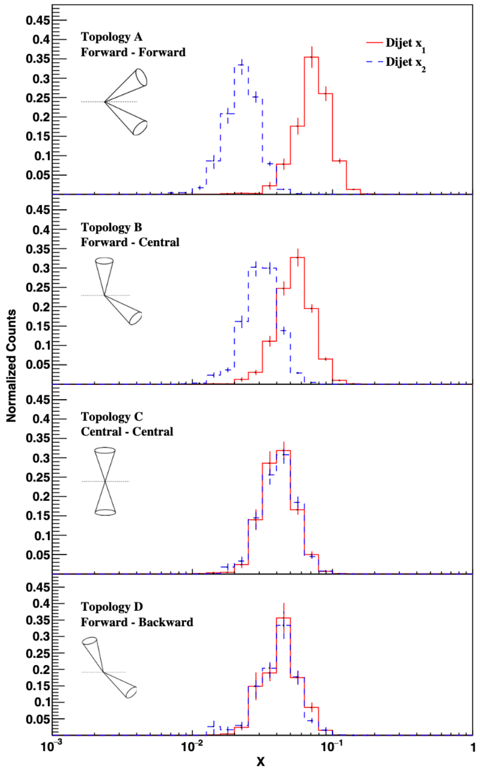
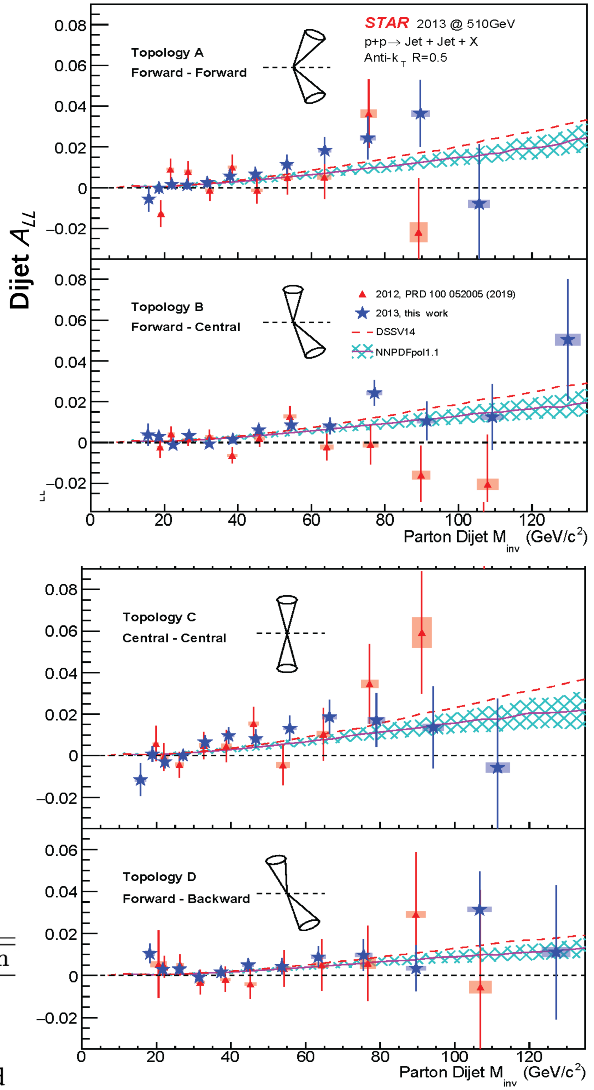
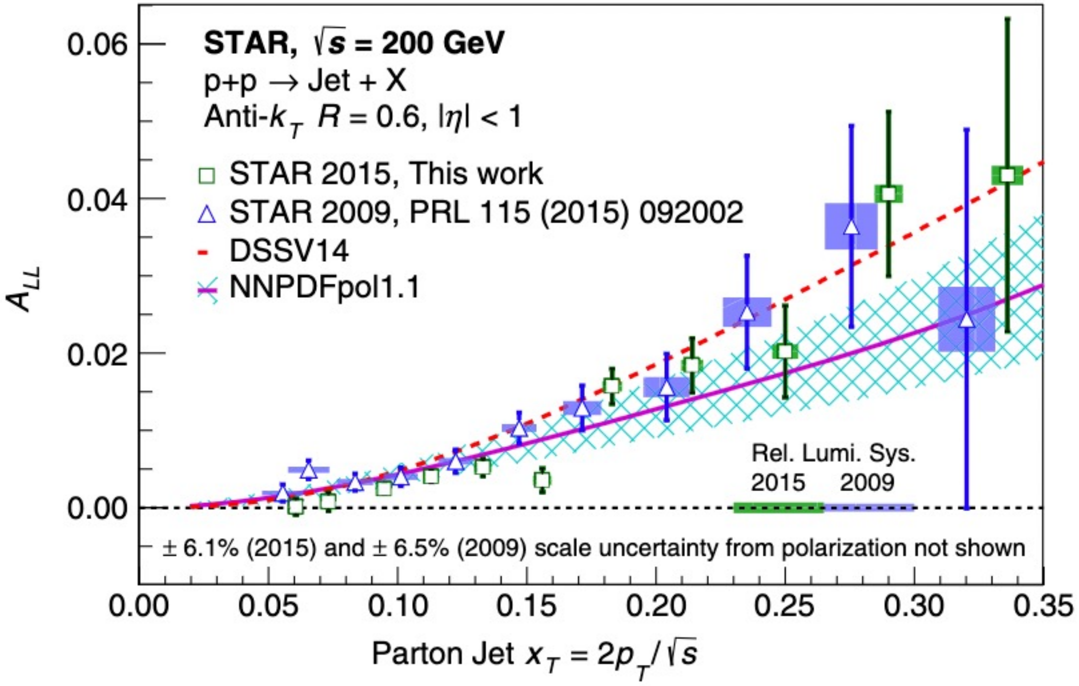


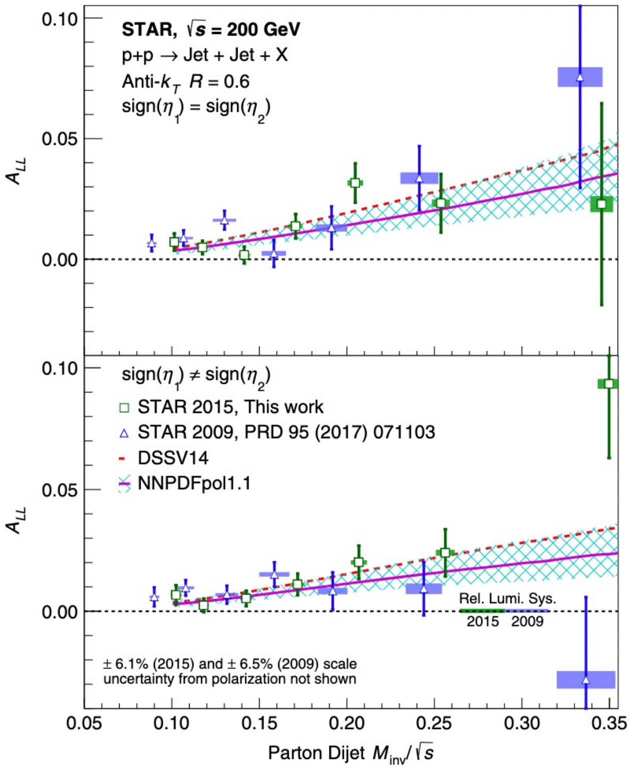
TABLE I. The four dijet topology bins A-D.

Bin	η_3 and η_4 regions	Physics description
A	$0.3 < \|\eta_{3,4}\| < 0.9;\ \eta_3 \cdot \eta_4 > 0$	Forward-forward
B	$\|\eta_{3,4}\| < 0.3;\ 0.3 < \|\eta_{4,3}\| < 0.9$	Forward-central
C	$\|\eta_{3,4}\| < 0.3$	Central-central
D	$0.3 < \|\eta_{3,4}\| < 0.9;\ \eta_3 \cdot \eta_4 < 0$	Forward-backward



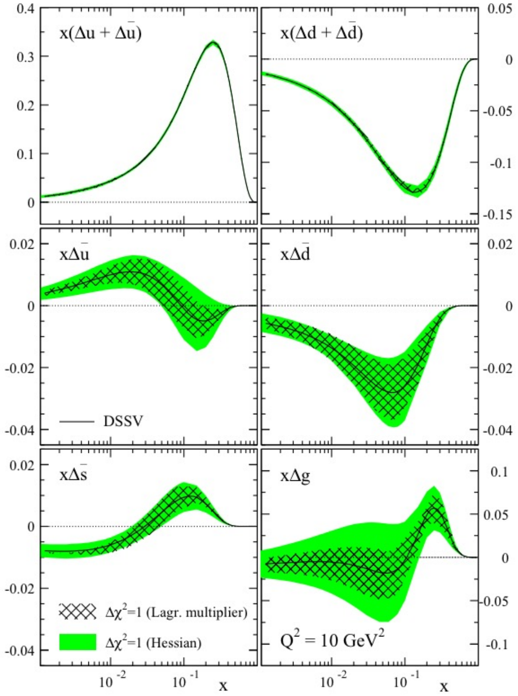
Jet A_{LL} 200GeV

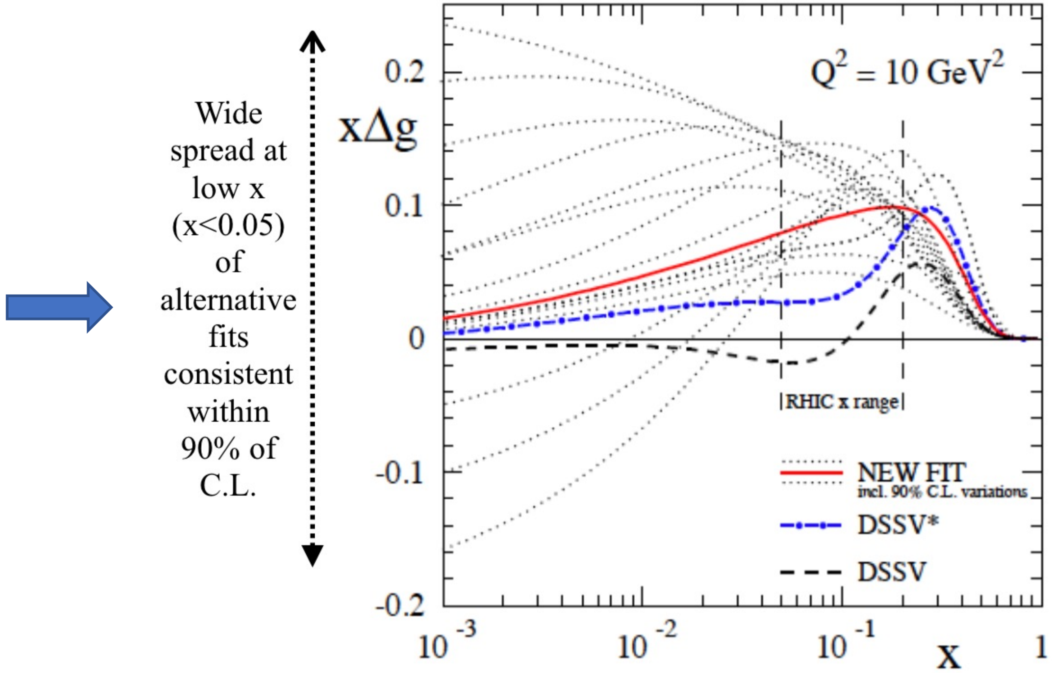


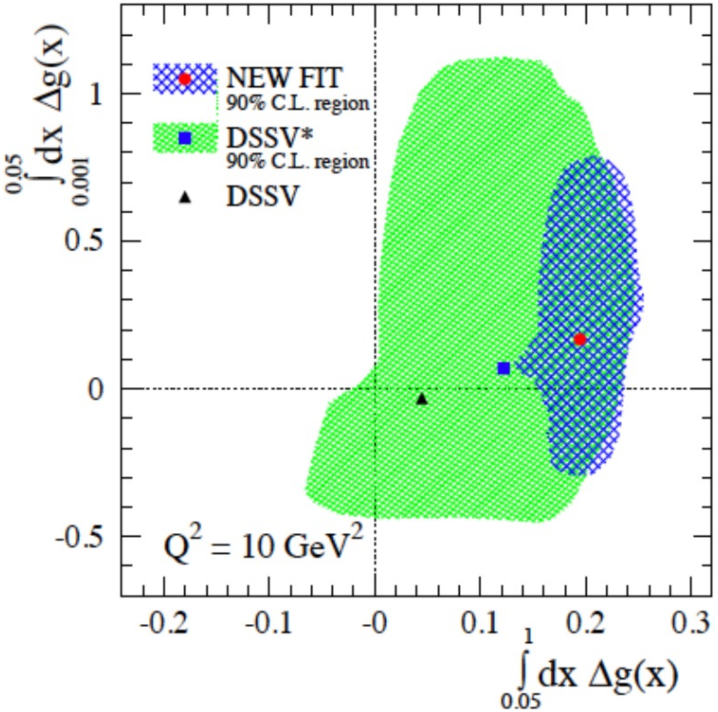


- PRD 103, L091103 (2021)
- ALL inclusive and di-jet measurements for Run 15 in good agreement with Run 9 measurements - Further evidence for positive Δg(x, Q2) for x > 0.05
- Good agreement with NLO calculations based on DSSV14 and NNPDFpol1.1 PDF set

Global analysis including RHIC results: DSSV







- D. deFlorian et al. Phys.Rev.D 80 (2009) 034030 →, Phys.Rev.Lett. 113(2014)1, 012001
- polarized PDFs of the proton, Gluon helicity distribution
- We are improving ΔG contributions only in a limited x-region, allowing large uncertainties to remain in the low-x unmeasured
- $\int_{0.05}^{1} dx\Delta g(x, Q^2 = 10\text{GeV}/c) = 0.20^{+0.06}_{-0.07}$, 90% C.L. Indicate large and non-zero gluon spin contribution: The RHIC cold QCD Plan, arXiv:1602.03922

DSSV14 (1404.4293)

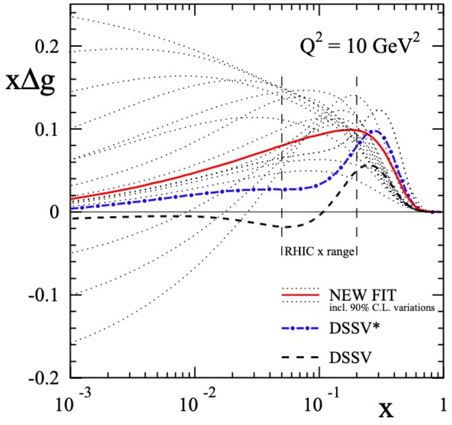
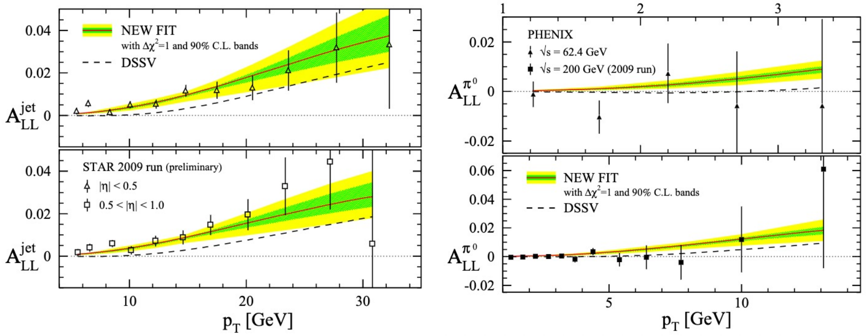
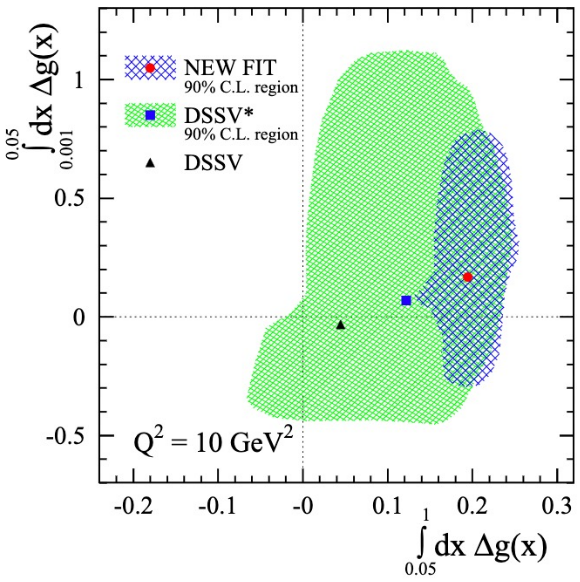


FIG. 1: Gluon helicity distribution at $Q^2 = 10\,\mathrm{GeV}^2$ for the new fit, the original DSSV analysis of [3], and for an updated analysis without using the new 2009 RHIC data sets (DSSV*, see text). The dotted lines present the gluon densities for alternative fits that are within the 90% C.L. limit. The x-range primarily probed by the RHIC data is indicated by the two vertical dashed lines.



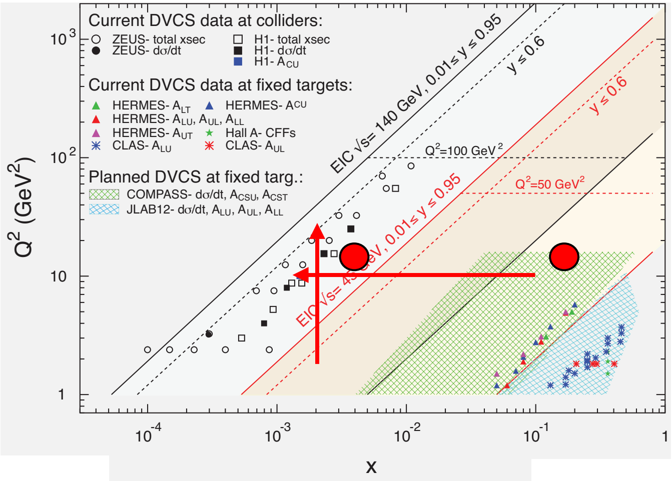


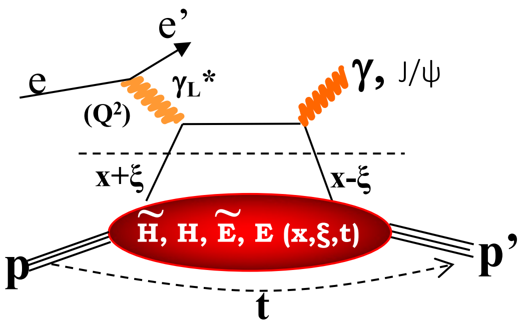
- Inclusion of STAR, PHENIX jet,pion data
  - arXiv:1303.0543, arXiv:1402.6296
- Previously $0.05 \leq x \leq 0.2$ at RHIC
- Very little contribution to ΔG is expected to come from x > 0.2
- $\int_{0.001}^{1} dx \Delta g(x, Q^2)$ accounts for over 90% of the full ΔG at Q^2=10 GeV^2

2+1d-Imaging in coordinate space

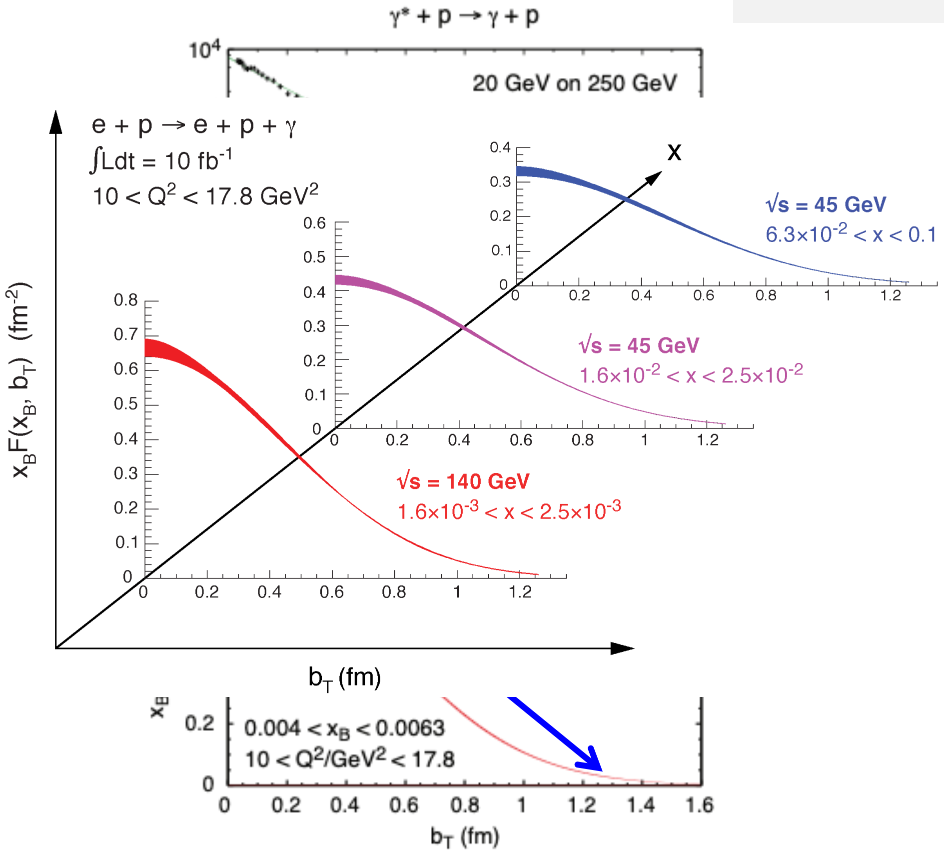
High precision imaging at EIC at low and high x Golden channels:

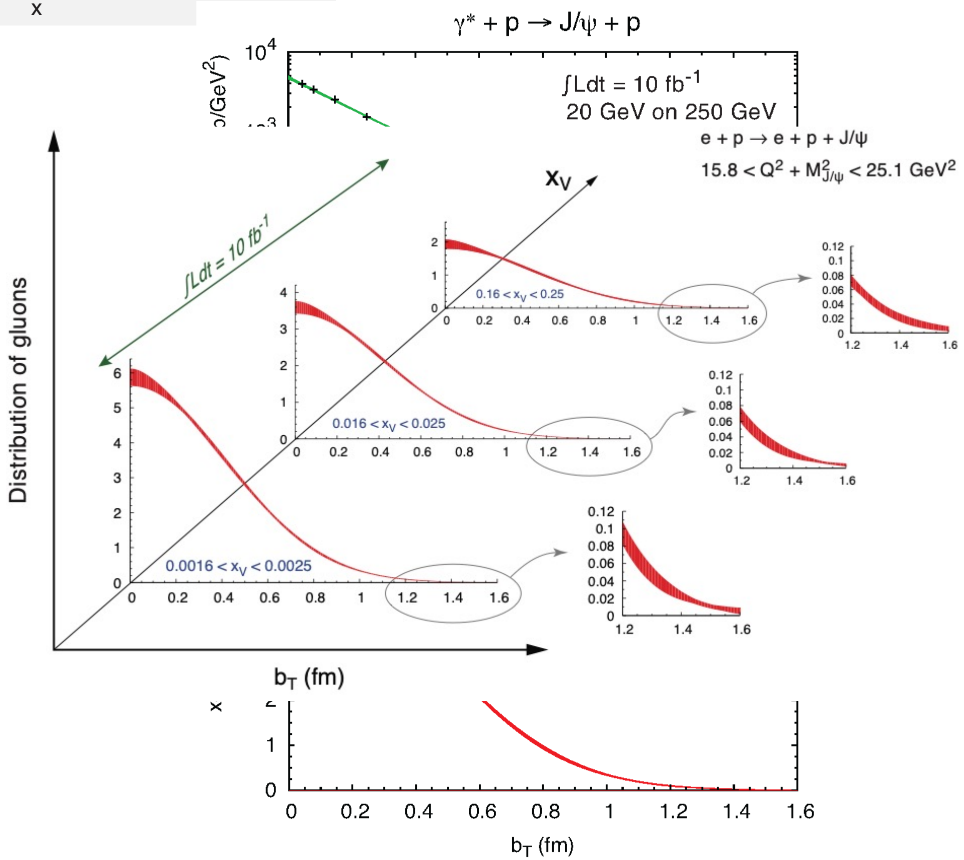
DVCS



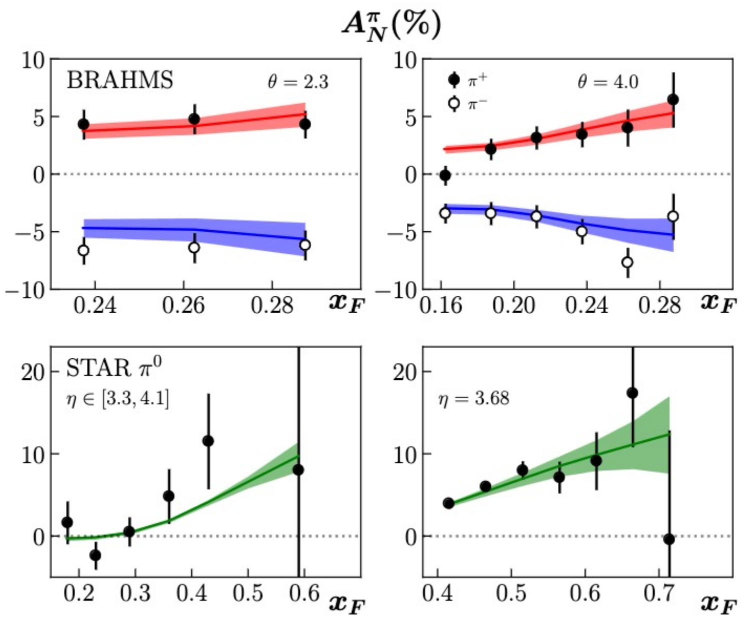


J/ψ





Global analysis of nonzero A_N at forward rapidity



- Global analysis using TMD, twist-3 (qgq) observables
- PRD 106 (2022) 3, 034014 (2022)

Collinear Twist-3 functions

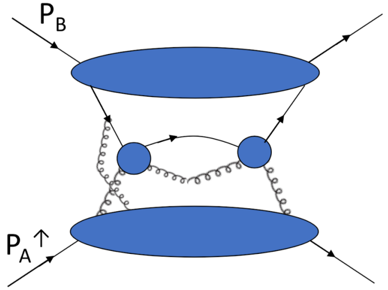
$$A_N \propto \sum_{abc} \phi^{(3)}_{a/A}(x_1, x_2, \vec{s}_\perp) \otimes \phi_{b/B}(x') \otimes \hat{\sigma} \otimes D_{c\to C}(z)$$
$$+ \sum_{abc} \delta q_{a/A}(x, \vec{s}_\perp) \otimes \phi^{(3)}_{b/B}(x'_1, x'_2) \otimes \hat{\sigma}' \otimes D_{c\to C}(z)$$
$$+ \sum_{abc} \delta q_{a/A}(x, \vec{s}_\perp) \otimes \phi_{b/B}(x') \otimes \hat{\sigma}'' \otimes D^{(3)}_{c\to C}(z_1, z_2).$$

- Terms with A, B in subscript : initial state effects
  - a=A means the distribution of parton a in hadron A
- Terms with C in subscript : final state effects
  - c → C means the fragmentation of parton c into hadron C.
- Terms with (3) in superscript: twist 3 correlators
  - z is the fraction of the outgoing partonic momentum carried by the detected hadron
- Measuring A_N for different final state particles gives access to specific terms in the sum

Higher Twist Functions

Formal definition of twist: "mass dimension minus spin" of the operator in a matrix element within the Operator Product Expansion

Twist 2: traditional PDFs and FFs only consider interactions between one parton in the proton at a time



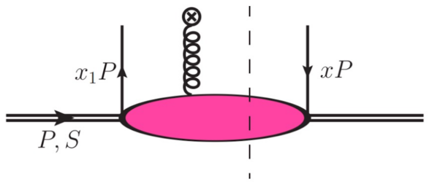
Twist 3: Quantum mechanical interference between one parton versus interacting with two partons at the same relative x

- Can describe spin-momentum correlations in the proton and in hadronization

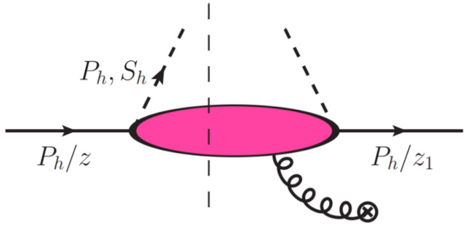
Twist 3 Functions

Multiparton correlations: quantum mechanical interference between scattering off of one versus two partons at the same x

- Quark-Gluon-Quark (qgq) Correlation Function: scattering off of quark and a gluon versus a single quark of the same flavor
- Three-gluon Correlation Function (ggg): two gluons versus one gluon



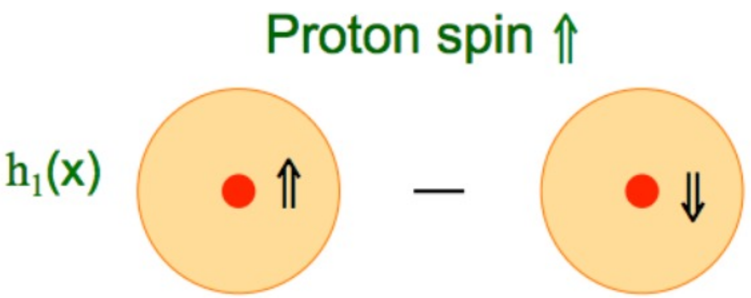
qgq Twist-3 Initial State



qgq Twist-3 Final State

Daniel Pitonyak *International Journal of Modern Physics A* **31**, No. 32, 1630049 (2016)

Transversity



- Quark polarization along the spin of a transversely polarized proton
- No gluon transversity
- May be a collinear or a transverse-momentum-dependent function.

Twist-2 observable

Not covered in this presentation

- Unpolarized pdf related topic
- Accessing dbar/ubar with W production
- Lambda polarization
- etc