An overview of nucleon spin and 3D structure at STAR

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Brookhaven National Laboratory

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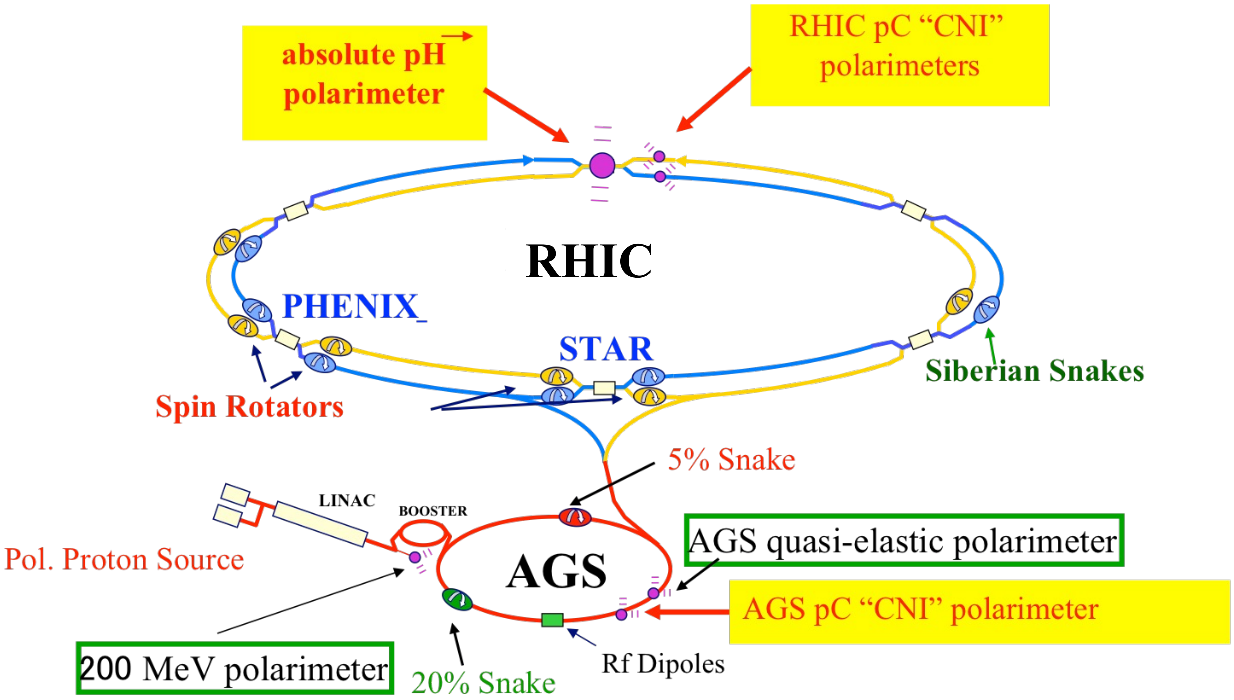
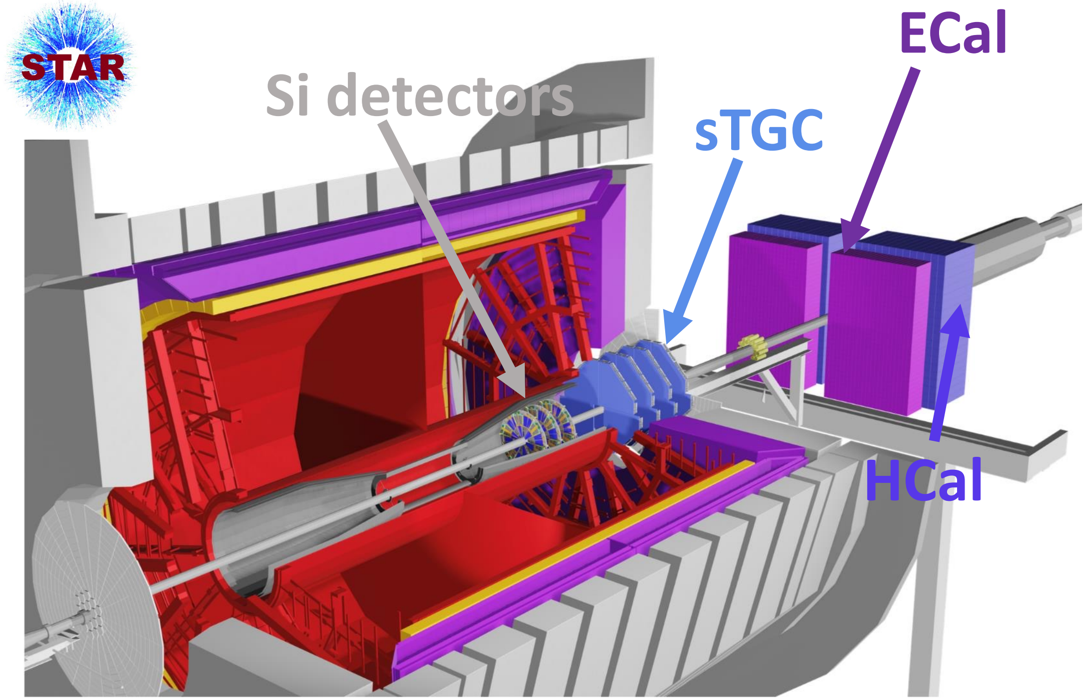
Supported by

The Cold QCD Program at STAR





STAR Forward Upgrade: $2.5 < \eta < 4$

- RHIC: first and only **(longitudinally and transversely) polarized** pp collider, also capable of colliding AA.
- STAR: has been collecting data with its **forward-upgraded detectors** and will continue data collection until 2025.
- RHIC **Run24: starts soon on April 15th**, includes **19 weeks of 200 GeV trans. polarized** pp and 6 weeks of $AuAu$.

The Cold QCD Program at STAR

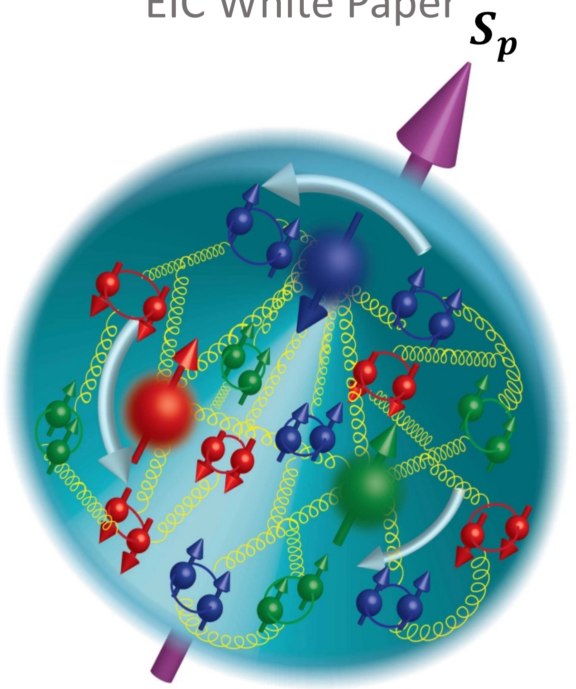
The **physics goals** of Cold QCD program at STAR:

1. understand the decomposition of **proton spin**:

- (anti)quark helicity: $W\ A_L$; $\Lambda\ D_{LL}$
- gluon helicity: jet and dijet A_{LL}; $\pi^0\ A_{LL}$

Long. polarized program

EIC White Paper



Inner building blocks of a proton, quarks and gluons, and their possible orbital motion, contribute to proton spin.

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

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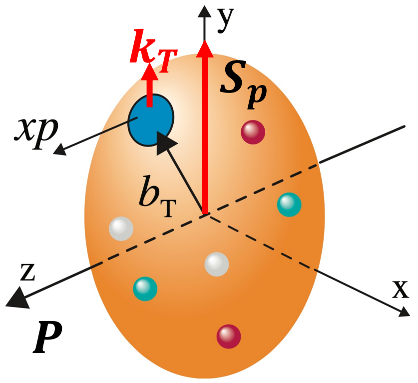
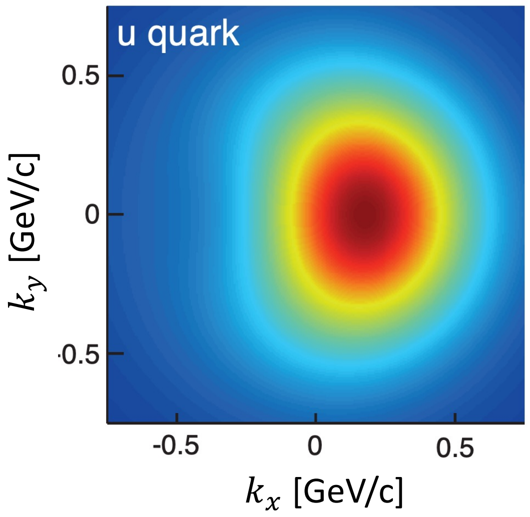
Long. polarized program

2. explore the **multidimensional landscape in coordinate and momentum space** of nucleons and nuclei:
- initial and final state TMD* effects
- single-spin asymmetry of weak boson
- single-spin asymmetry in forward region
- di-hadron interference fragmentation function

Tran. polarized program

EIC White Paper





3-denmentional image of the structure of a proton:
$k_\perp$ is the transverse momentum of a parton

*Transverse momentum dependent parton distribution function
TMD: $f(x, k_\perp, Q^2)$

The Cold QCD Program at STAR

The **physics goals** of Cold QCD program at STAR:

Courtesy: BNL

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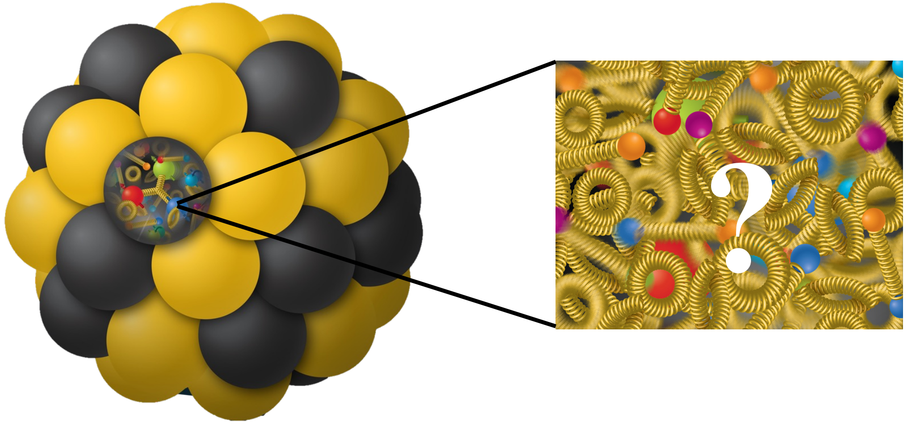
Long. polarized program



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- initial and final state TMD* effects
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- di-hadron interference fragmentation function

Small x gluon dynamics

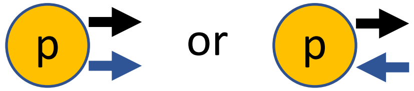
Tran. polarized program

3. study the collinear parton distributions
- high-x quark and low-x gluon distributions
- Λ polarization

*Transverse momentum dependent parton distribution function
TMD: $f(x, k_\perp, Q^2)$

Unpolarized program

Longitudinally polarized program at STAR

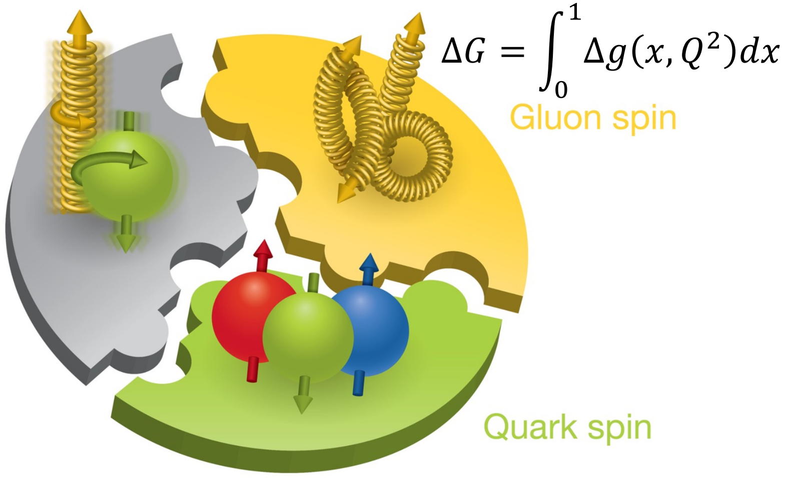


Proton beam spin direction

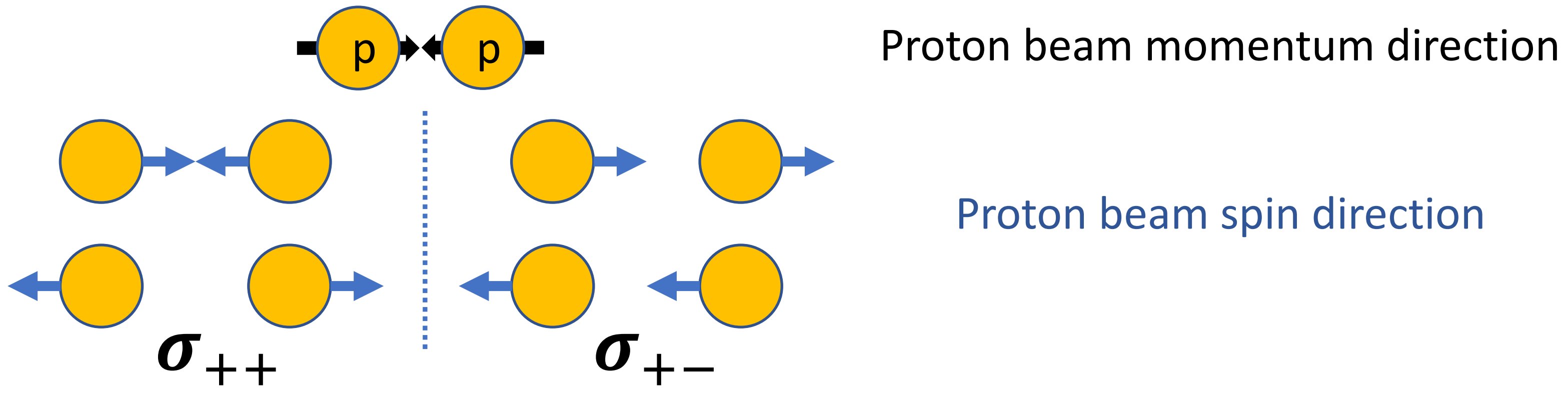
Proton beam momentum direction

Measuring quark and gluon helicity at STAR

Proton Spin S:



Description of A_{LL} measurement:



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} \hat{a_{LL}} \otimes D}{\Sigma f_a \otimes f_b \otimes \hat{\sigma} \otimes D} \xrightarrow{\text{Global fit}} \Delta f(x, Q^2)$$

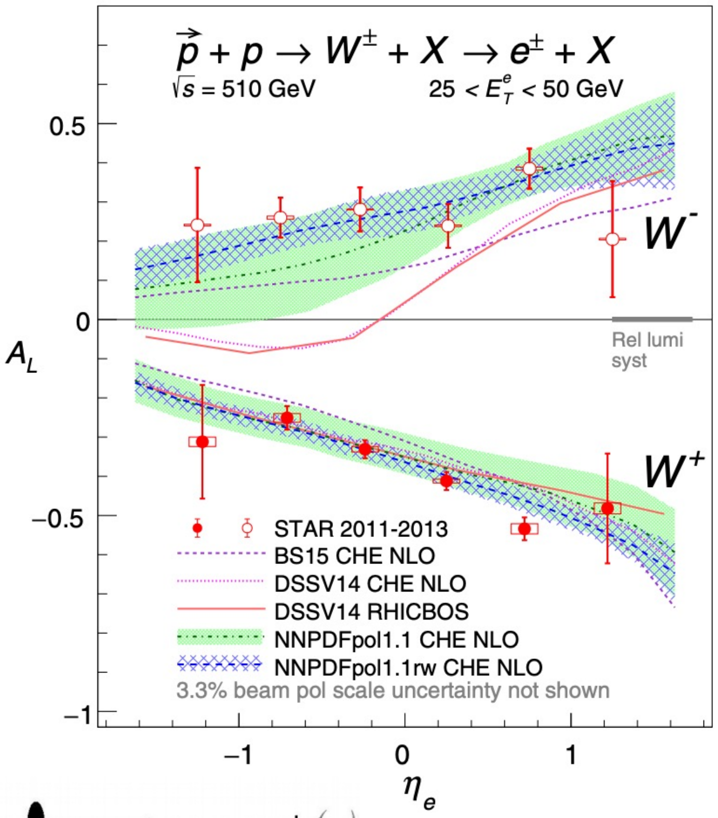
Measurements at RHIC use **longitudinally polarized p+p data to extract**:

- Polarized sea quark helicity distribution $\Delta \boldsymbol{q}$
  - $\Delta \bar{\boldsymbol{u}}$ **and** $\Delta \bar{\boldsymbol{d}}$: $\vec{p}p \rightarrow$ W + X, $A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$, W$^{+/-}$→ natural flavor separation
  - $\Delta \boldsymbol{s}(\bar{\boldsymbol{s}})$: Λ ($\bar{\Lambda}$) production, $D_{LL} = \frac{\sigma_{p^+p \to \Lambda^+ X} - \sigma_{p^+p \to \Lambda^- X}}{\sigma_{p^+p \to \Lambda^+ X} + \sigma_{p^+p \to \Lambda^- X}}$, sensitive to polarized fragmentation functions (FF) and Δs ($\bar{s}$)
- Polarized gluon helicity distribution $\Delta \boldsymbol{g}$: jet/dijet/hadron, $A_{LL} \propto \Delta f$, sensitive to Δg at RHIC energy

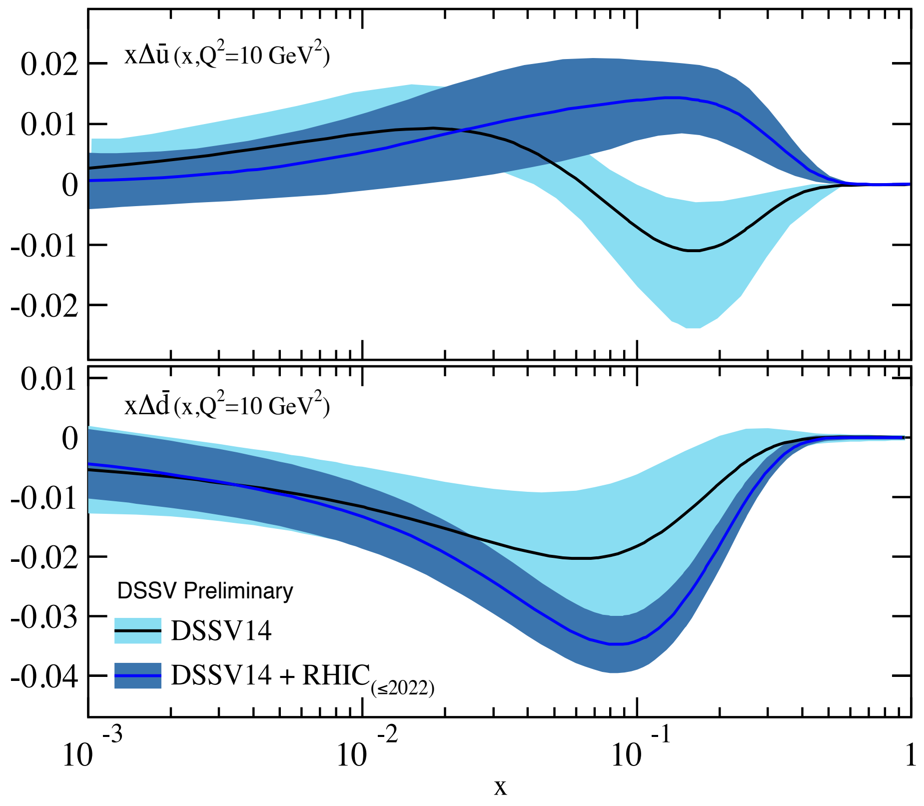
$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

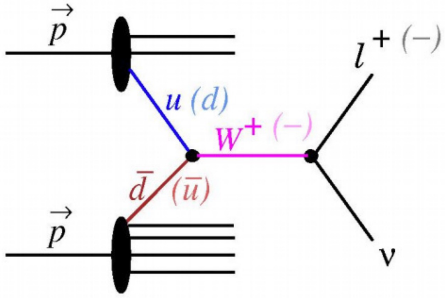
Sea quark helicity from STAR: $\Delta\bar{u}, \Delta\bar{d}$

STAR, PRD 99, 051102 (2019)



arXiv:2302.00605





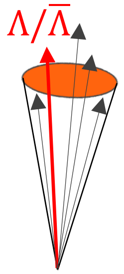
- Measured parity-violating single-spin asymmetry of $W^{+(-)} \propto \Delta\bar{d}(\Delta\bar{u})$
- For the first time, we can conclude an asymmetry between $\bar{u}$ and $\bar{d}$ polarization: **$\Delta\bar{u} - \Delta\bar{d} > 0$ with STAR 2013 $W^{+/-}$ data**

Strange quark helicity: Δs

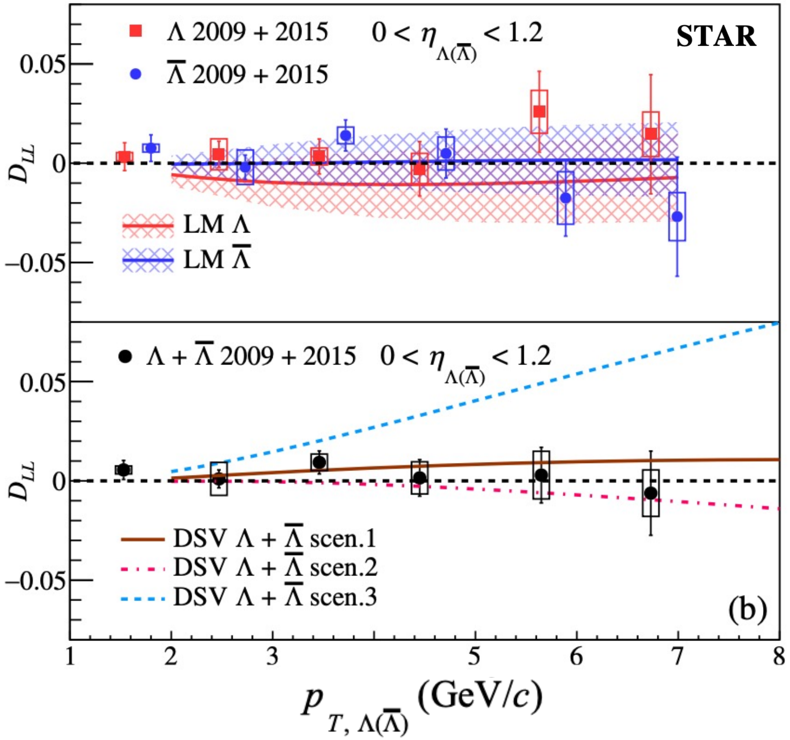
$$D_{LL} = \frac{\sigma_{p^+p\to\Lambda^+X} - \sigma_{p^+p\to\Lambda^-X}}{\sigma_{p^+p\to\Lambda^+X} + \sigma_{p^+p\to\Lambda^-X}}$$

See Yi Yu's talk, WG5, next talk

Recently published by STAR

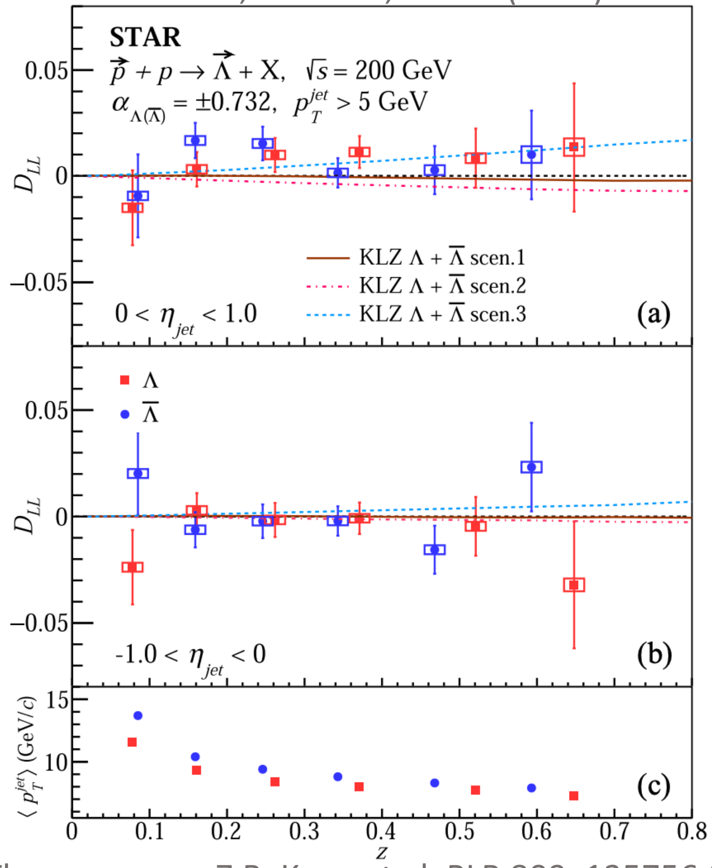


STAR, PRD 109, 12004 (2024)



Theory curves: D. de Florian et al, PRL 81, 530 (1998)

STAR, PRD 109, 12004 (2024)



$$z = \frac{\vec{p}_\Lambda \cdot \vec{p}_{jet}}{\vec{p}_{jet} \cdot \vec{p}_{jet}}$$

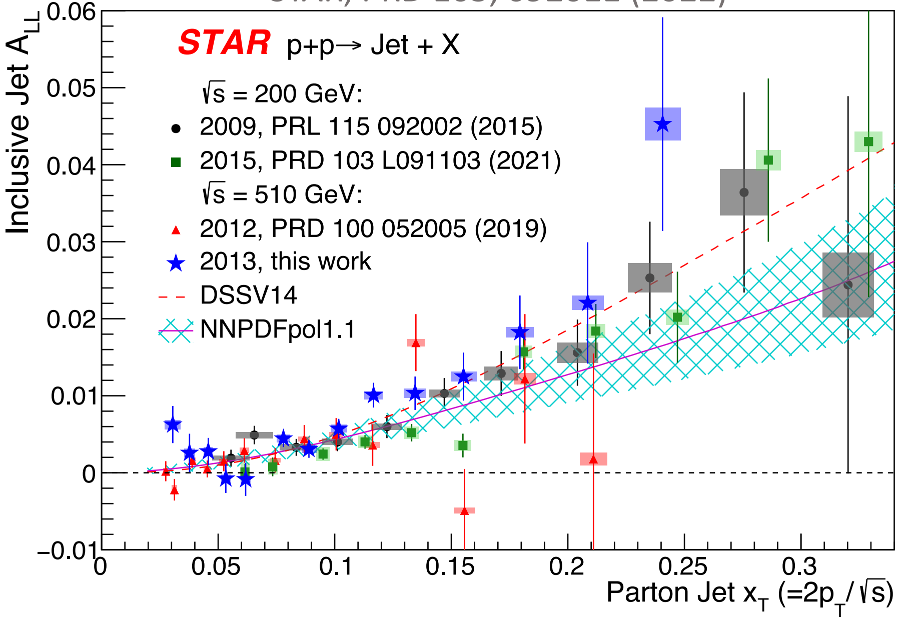
Theory curves: Z.B. Kang et al, PLB 809, 135756 (2020)

- Longitudinal spin transfer coefficient D_{LL} of Λ and $\bar{\Lambda}$ within jets constrains polarized fragmentation functions and $\Delta s(\bar{s})$
- Results show consistency between Λ and $\bar{\Lambda}$; data agree with various models within uncertainties
- 2015 data: most precise measurements to date with twice the statistics of the 2009 dataset STAR, PRD 98 (2018) 112009

Gluon helicity Δg measurement at STAR

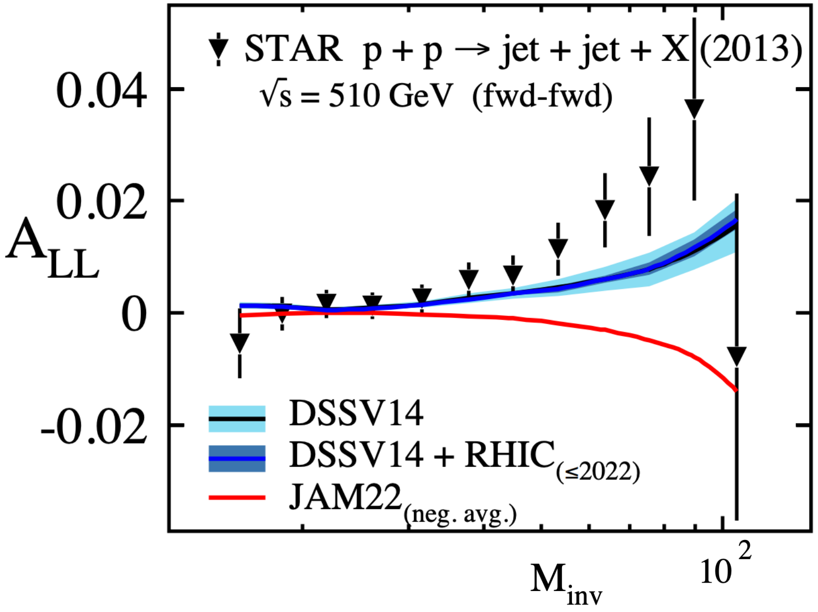
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

STAR, PRD 105, 092011 (2022)



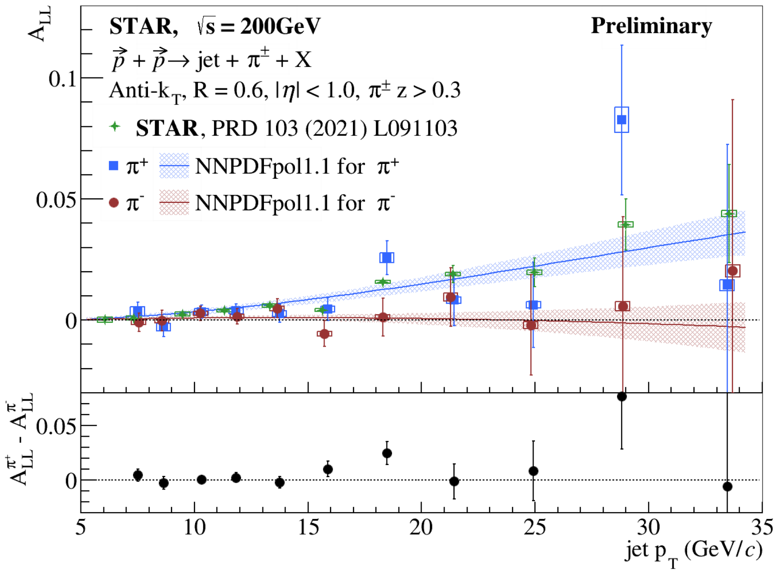
inclusive jet A_{LL}

STAR, PRD 105, 092011 (2022)



dijet A_{LL}

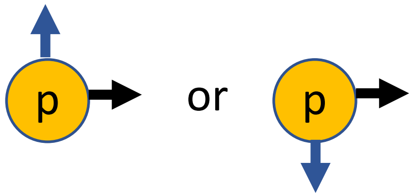
See Yi Yu's talk, WG5, next talk



π tagged jet A_{LL}

- STAR inclusive jet A_{LL} using 2009 data provided first evidence of positive gluon polarization at $0.05 < x < 0.2$
- STAR inclusive and dijets A_{LL} at 200 and 510 GeV using 2009 to 2015 data:
  - Consistent results from both energies
  - 200 GeV data constrain $\Delta g(x)$ for $x > 0.05$
  - Forward detection and higher collision energy at 510 GeV data push the sensitivity to lower $x \to 0.02$
- STAR inclusive jets tagged with $\pi^{\pm}$ carrying high z can provide further constraints on $\Delta g(x)$

Transversely polarized program at STAR

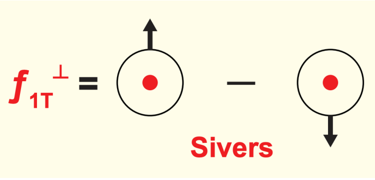


Proton beam spin direction

Proton beam momentum direction

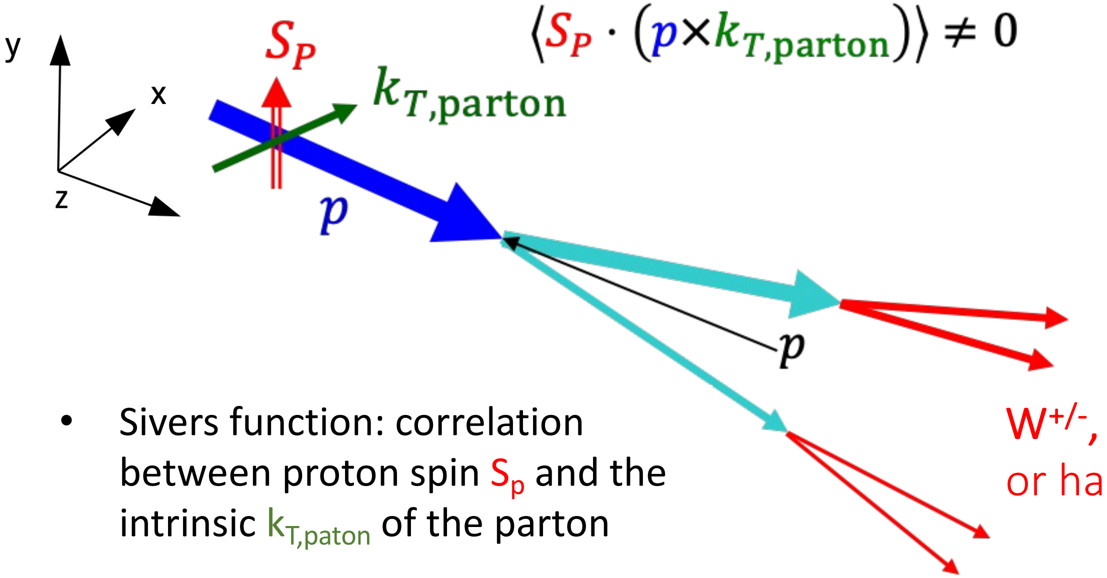
How to extract Sivers function

- Transverse single-spin asymmetry (TSSA, A_N) in 200 GeV and 500/510 GeV pp collisions
  - Sensitive to one of the polarized TMDs, Sivers Function



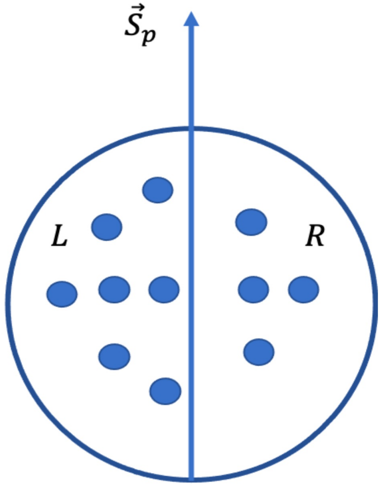
Initial state TMD

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



- Sivers function: correlation between proton spin S_p and the intrinsic $k_{T,paton}$ of the parton

- A_N: left-right asymmetry in the final state

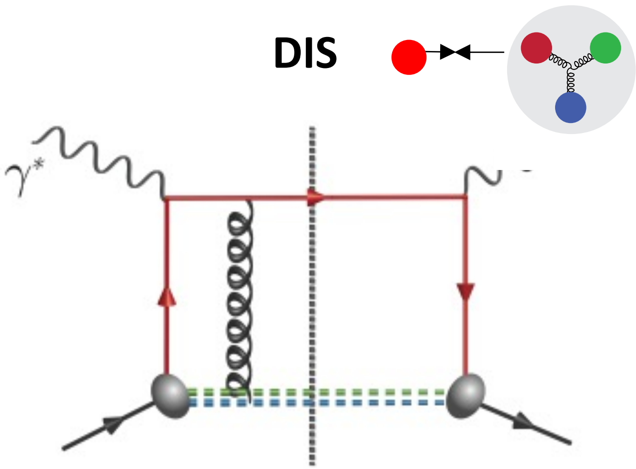


↑↓: spin up or down
P: polarization fraction
L,R: left or right respect to spin direction

$$A_N \cdot cos(\phi) = \frac{1}{\langle P \rangle} \cdot \frac{\sqrt{N_\uparrow(\phi) N_\downarrow(\phi+\pi)} - \sqrt{N_\uparrow(\phi+\pi) N_\downarrow(\phi)}}{\sqrt{N_\uparrow(\phi) N_\downarrow(\phi+\pi)} + \sqrt{N_\uparrow(\phi+\pi) N_\downarrow(\phi)}}$$

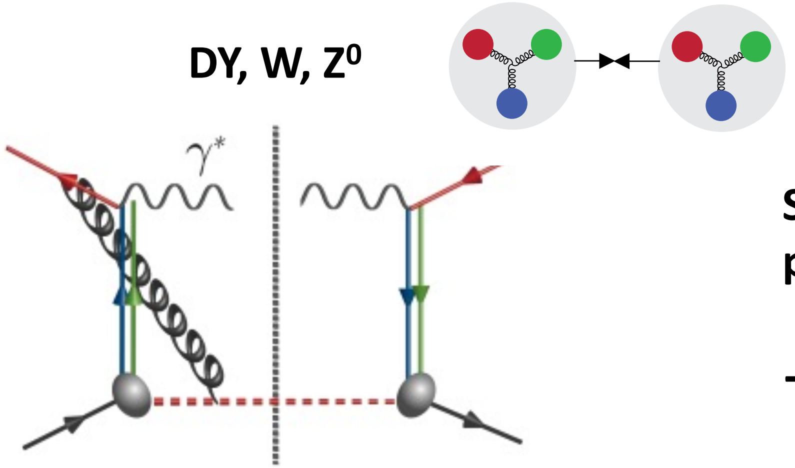
Sivers function for $W^{+/-}$ and Z^0

DIS



Final-state interaction

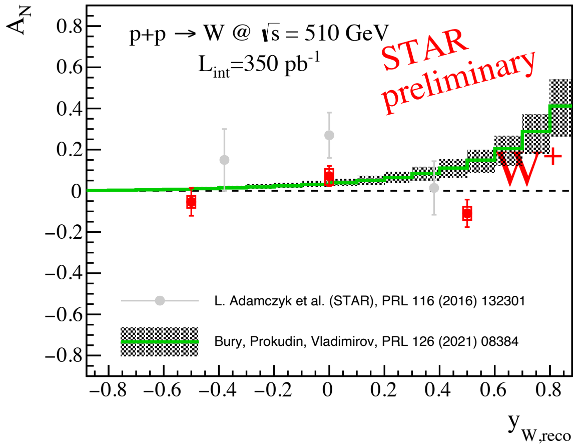
DY, W, Z^0

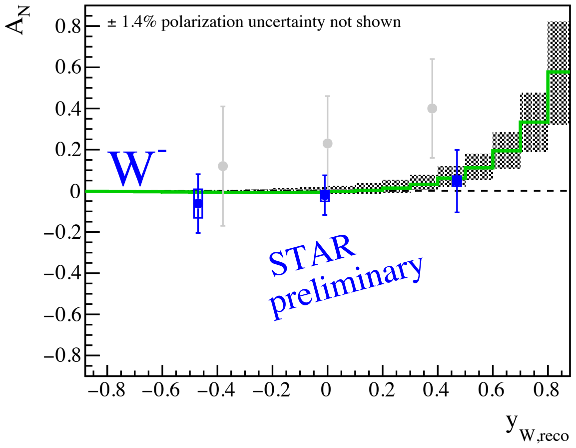


Initial-state interaction

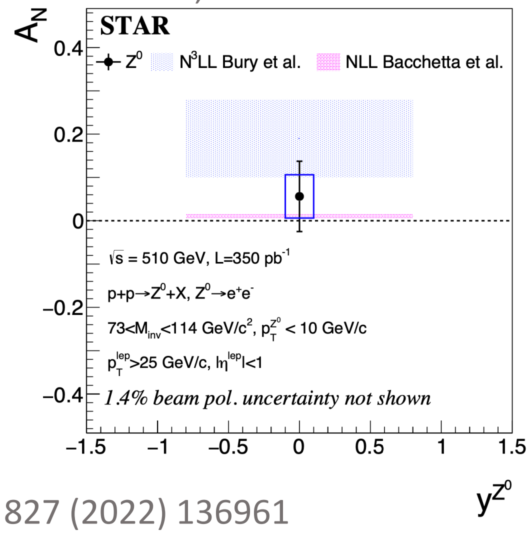
Sivers effect is NOT universal; it is a process-dependent effect:

→ Sivers_{DIS} = − (Sivers_{DY} or $\text{Sivers}_{W,Z0}$)





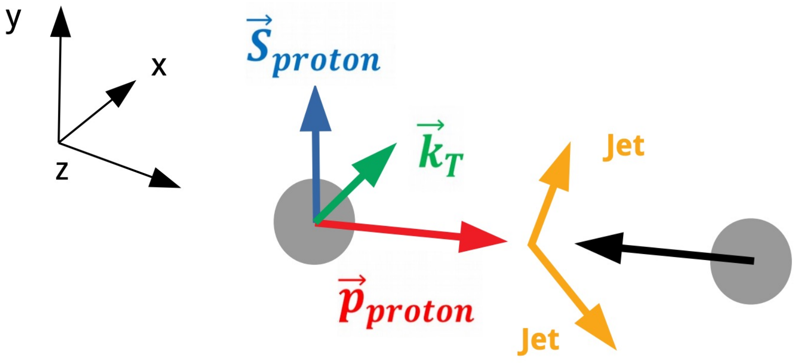
STAR, arXiv:2023.15496



Bury et al., PRL 126 (11) (2021) 112002; Bacchetta et al.,PLB 827 (2022) 136961

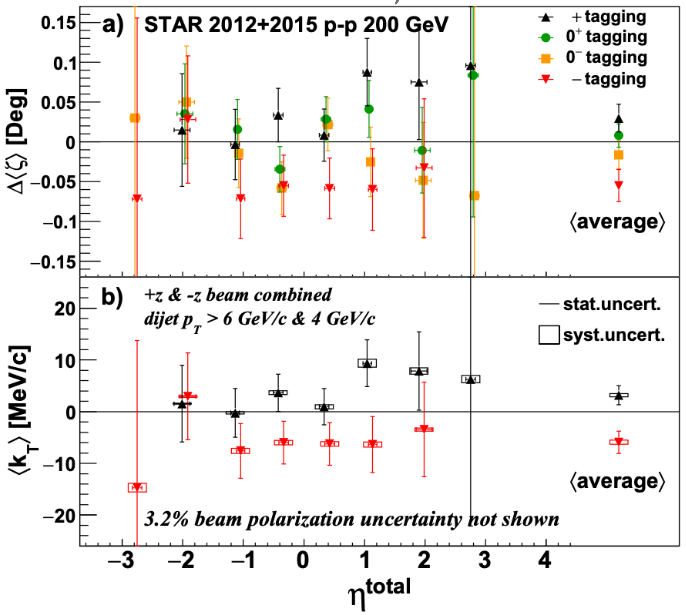
- Mid-rapidity $W^{+/-}$ and Z^0 A_N: statistics much improved with run 2017 compared to run 2011 (25 pb^{-1})
- Additional 400 pb^{-1} data from Run 2022 with Forward Upgrade and η coverage extended by STAR iTPC

Asymmetry for dijet opening angle

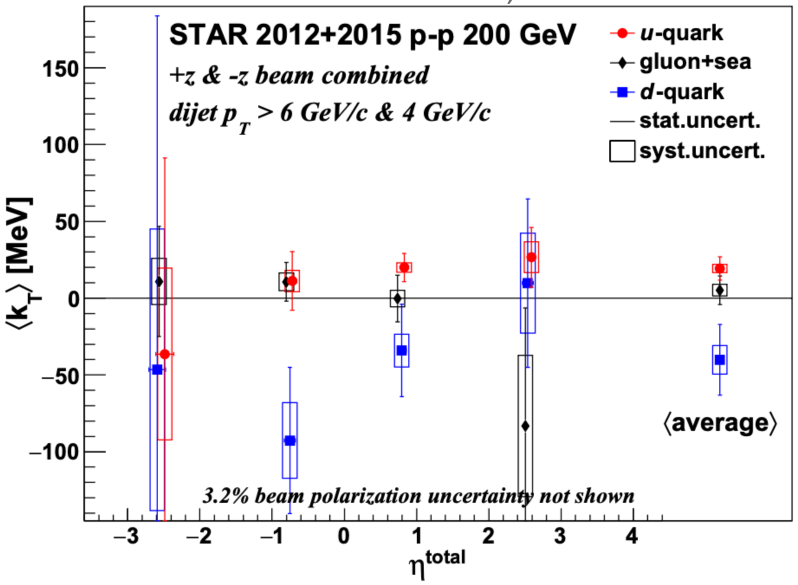


Spin-dependent dijet opening angle
→ sensitive to the Sivers TMD

STAR, arXiv:2305.10359



STAR, arXiv:2305.10359



- What's observed: the first non-zero Sivers effect

$$\langle k_T^u \rangle = 19.3 \pm 7.6 \pm 2.6 \frac{MeV}{c}, \langle k_T^d \rangle = -40.2 \pm 23.0 \pm 9.3 \frac{MeV}{c}, \langle k_T^{g+sea} \rangle = 5.2 \pm 9.3 \pm 3.8 \frac{MeV}{c}$$

with jet flavor tagged by jet charge $Q = \sum_{p>0.8\ GeV/c} \frac{p^{trk}}{p^{jet}} \cdot q$.

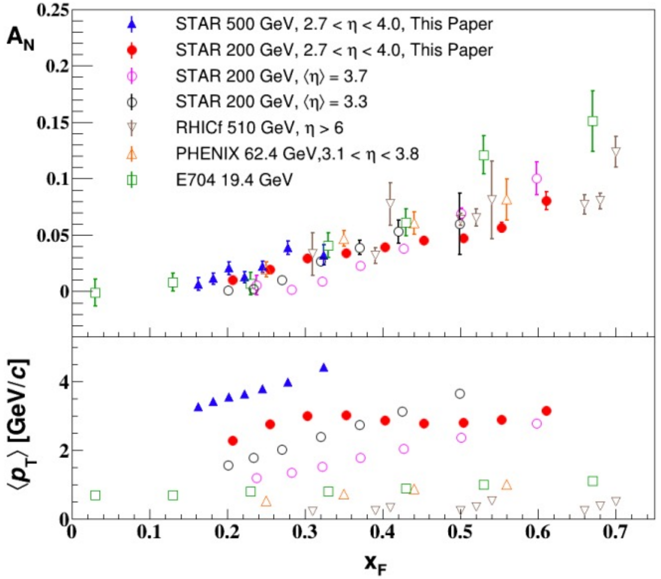
e.g., $Q > 0.25$ means + tagging, u quark signal enhanced

- What's next: x dependence probed by combining this result with 510/508 GeV data from 2017 and 2022, improved statistic with extended η coverage by STAR iTPC and Forward Upgrade for 2024 data-taking

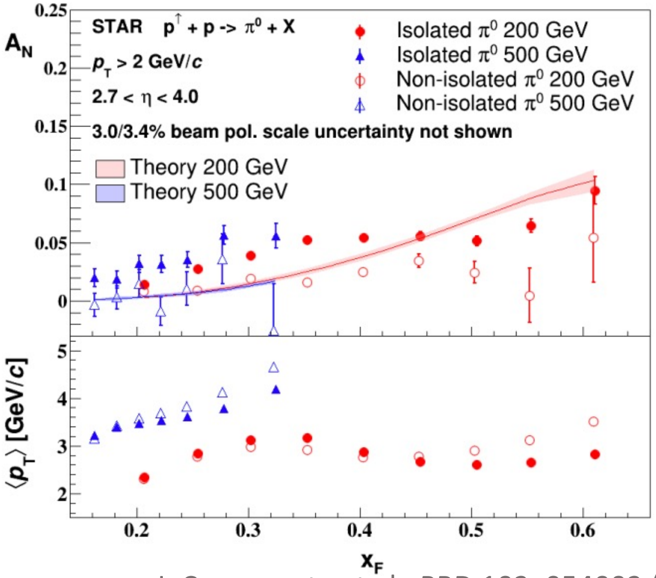
Asymmetry in the forward region

STAR, PRD 103, 92009 (2021)

A_N for inclusive π^0

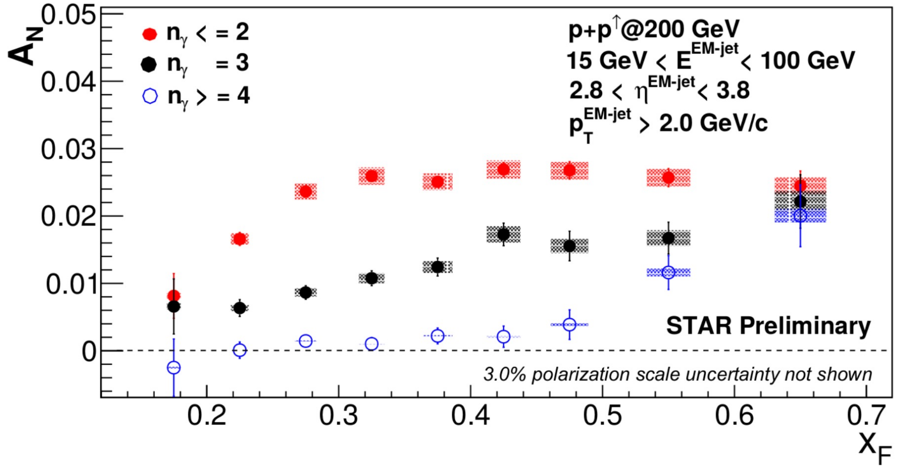


A_N for (non-)isolated π^0

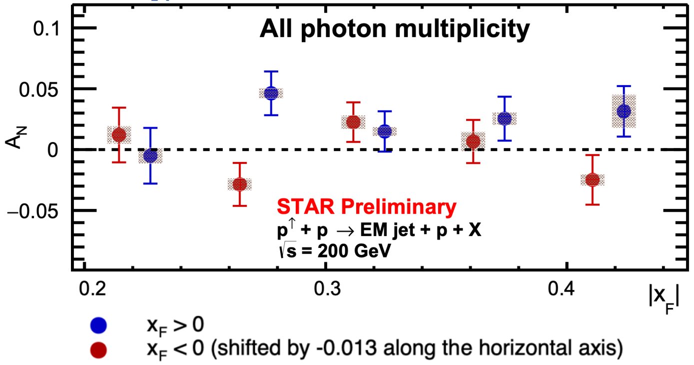


Theory curve: J. Cammarota et al., PRD 102, 054002 (2020)

A_N for EM jet



A_N for diffractive EM jet

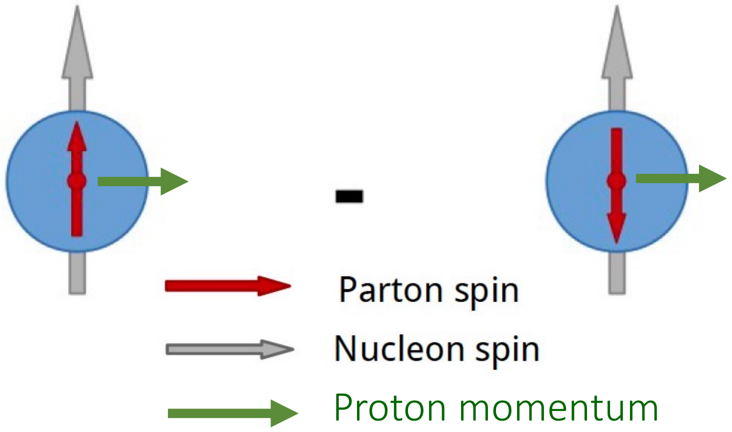


See Xilin Liang's talk, WG5, Wed 4pm

- **Sizeable A_N asymmetries for forward π^0 observed:** contributed from higher twist, Sivers, Collins (final state), and/or possibly from diffraction
- **Very weak collision energy dependence** of π^0/EM jet A_N
- **Topological dependence of π^0 A_N**: isolated π^0 > non-isolated π^0
- **γ multiplicity dependence** of EM jet A_N: decreases with higher multiplicity
- **Diffraction:** single diffractive EM jet A_N is >2σ from 0 when integrating over x_F
- **Run2022 and 2024:** improved statistic for various objects using Forward Upgrades

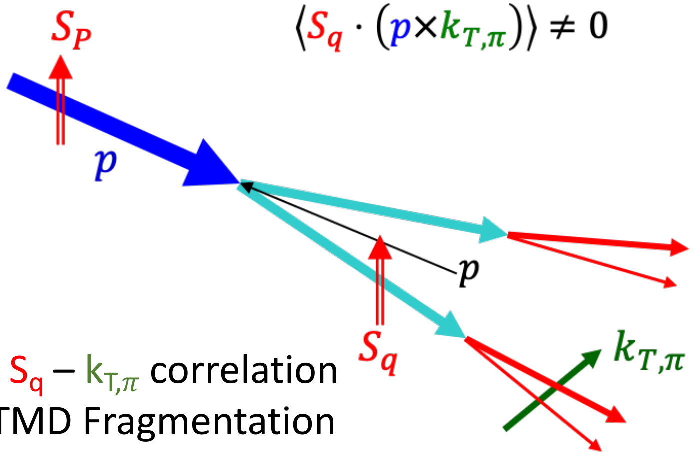
Transversity and Collins fragmentation functions

Transversity

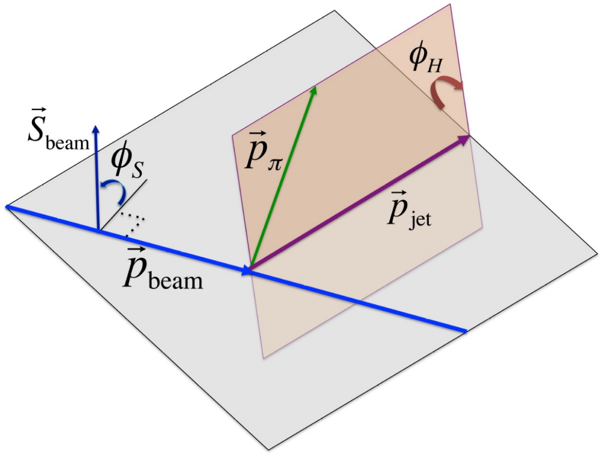


Final state: Collins

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



Sensitive to $S_q - k_{T,\pi}$ correlation
Transversity, TMD Fragmentation



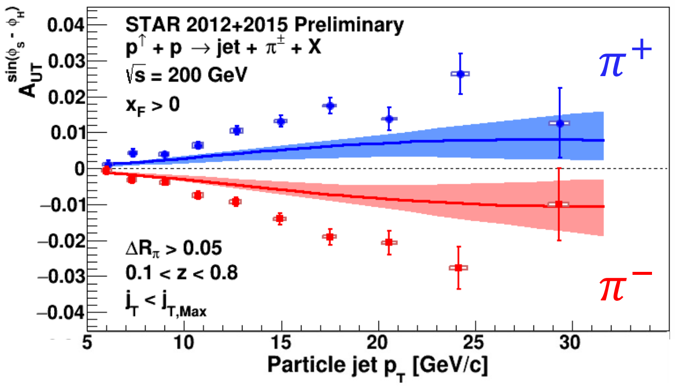
$\phi = \phi^S - \phi^H$

Quark polarization along the spin of a transversely polarized proton

- Observables: $A_{UT}^{\sin(\phi)}$ for hadrons
- Collins function is predicted to be universal

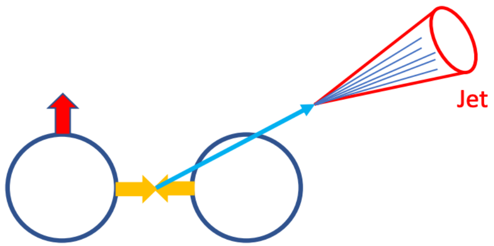
Collins asymmetry for $\pi^{\pm}$ in jets

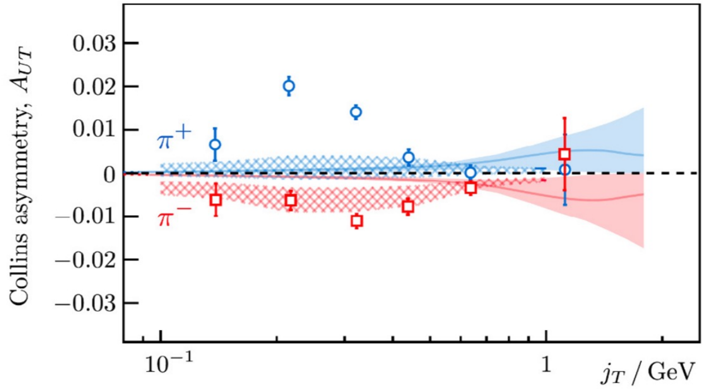
STAR, PRD 106, 072010 (2022)

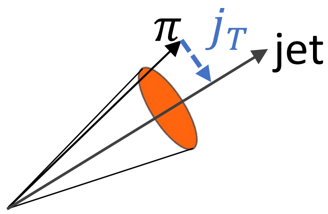


Highlight in 2023 LRP for NP

$\rightarrow x^F > 0$

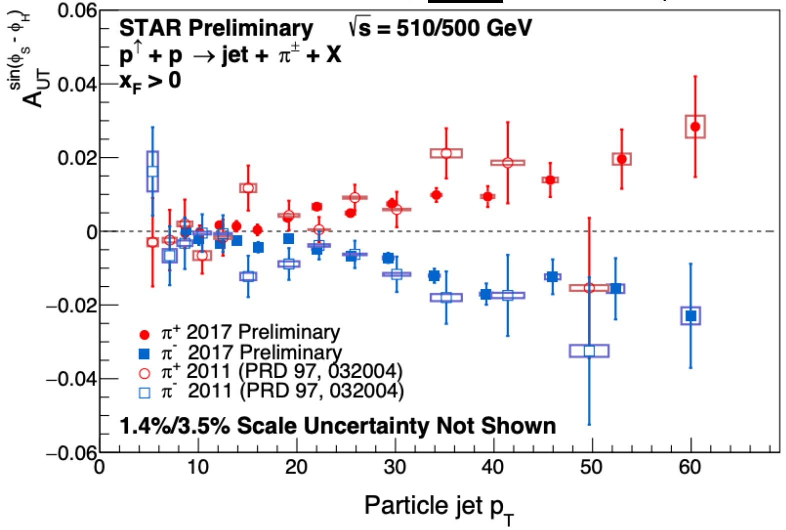


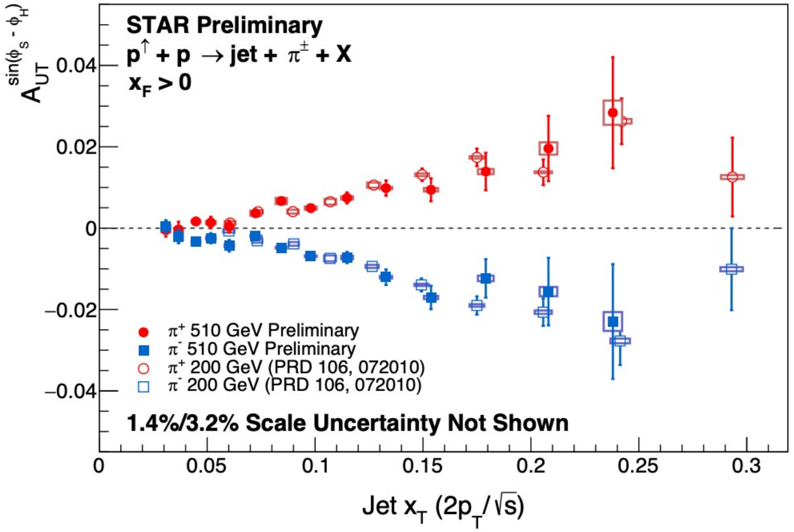




j_T: pion's momentum transverse to the jet axis

See Yike Xu's talk, WG5, Wed 4:20pm



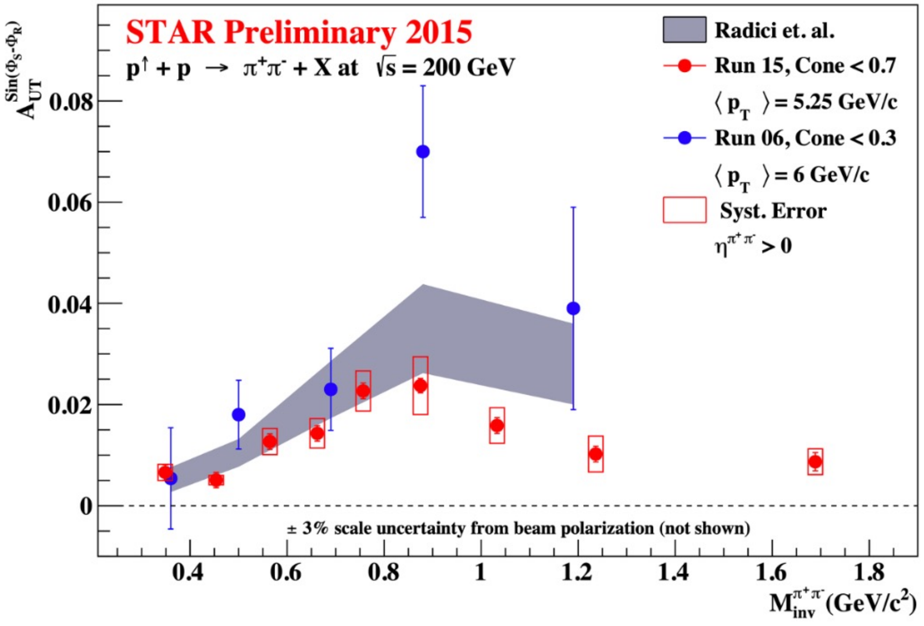


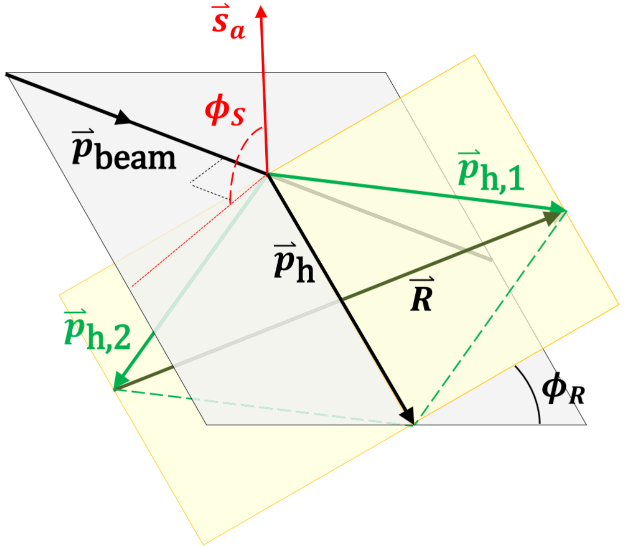
Spin-dependent modulation of $\pi^{\pm}$ in jets at mid-rapidity ($|\eta_{jet}| < 1$):

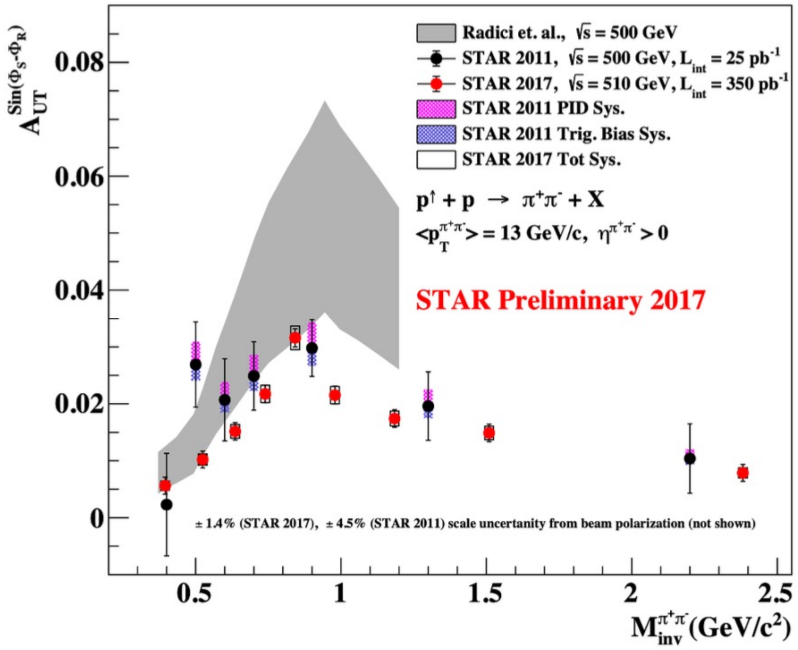
- Significant Collins asymmetries for $\pi^{\pm}$ measured with high precision
- Stringent constraints on theoretical calculations of transversity and Collins FF
- New results show weak energy dependence and provide important constraints on the scale evolution for Collins asymmetry

Interference FF from di-hadron measurement

See Bernd Surrow's talk, WG5, Wed 3:10pm



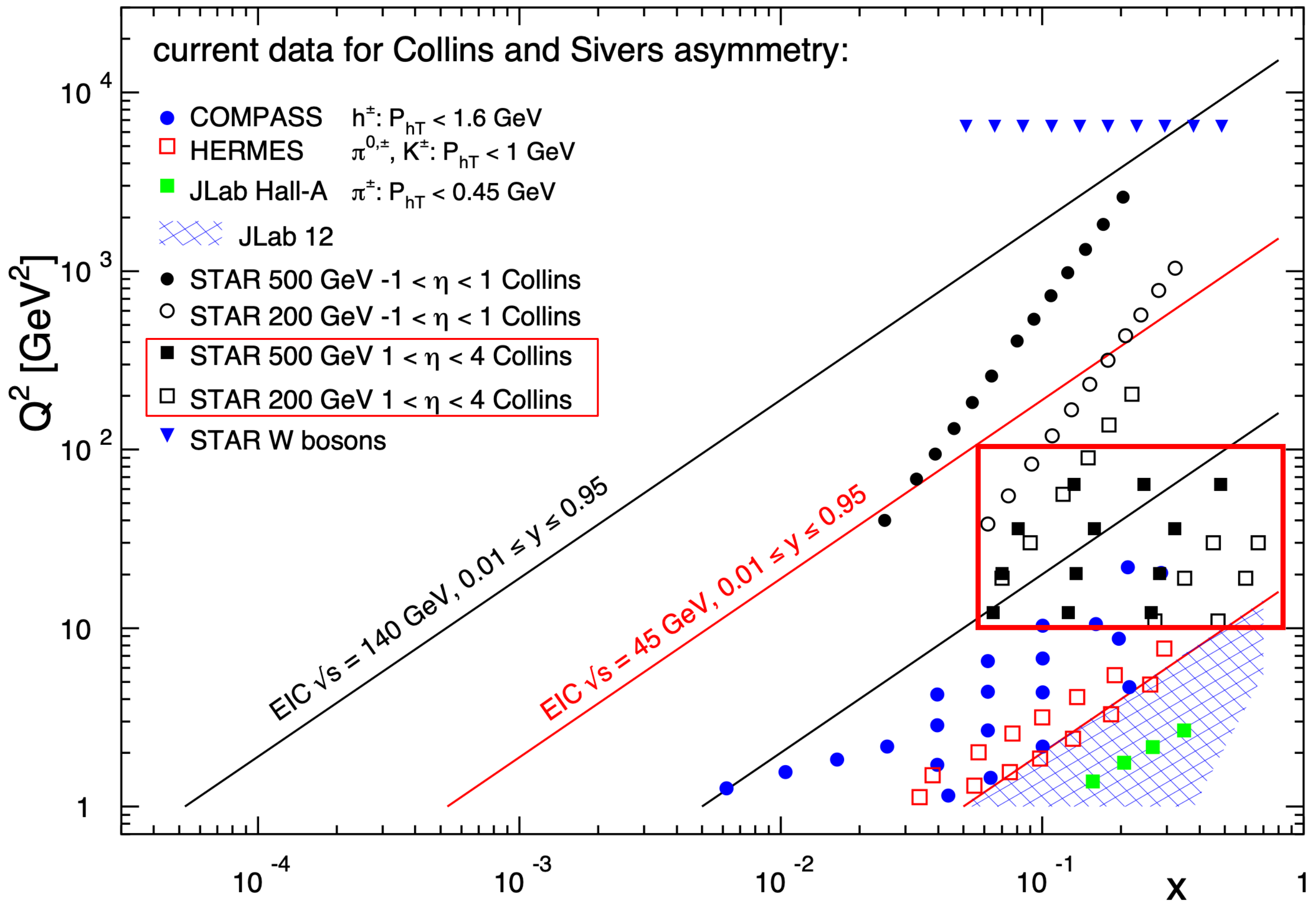




$$d\sigma_{UT} \propto \int dx_a dx_b h_1(x_a) f_1(x_b) \frac{d\Delta\hat{\sigma}}{d\hat{t}} H_1^{\sphericalangle}(z, M)$$

- Spin dependent di-hadron correlations probe collinear quark transversity coupled to the interference fragmentation function (IFF) at higher Q^2 region compared to SIDIS
- The results can test the universality property of IFF from e^+e^-, SIDIS and p+p data
- Planning for precision measurement of IFF asymmetries for pion/kaon from 2022+2024 dataset

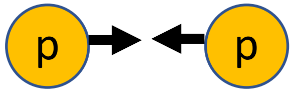
Where are we going?

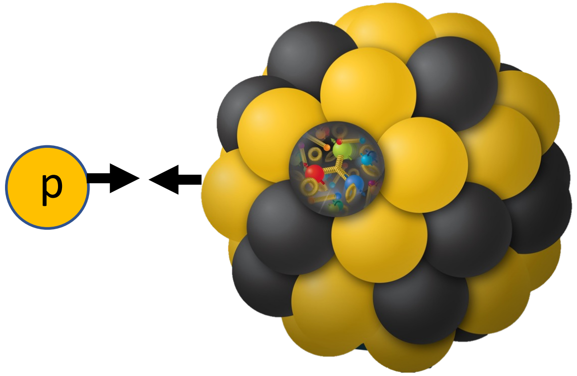


STAR Forward Upgrade capabilities with jets and hadrons for transverse asymmetries:

- Study forward Sivers, Collins, and diffractive processes → charge-tagged jets, di-jets, hadron-in-jets, and diffractive processes with rapidity gaps
- Before STAR: TMDs only came from fixed target e+p data with low Q^2
- STAR's unique kinematics coverage with the Forward Upgrade: low to high x at moderate and high Q^2 → TMD evolution:
  - x up to ~ 0.5 → sensitive to valence quark

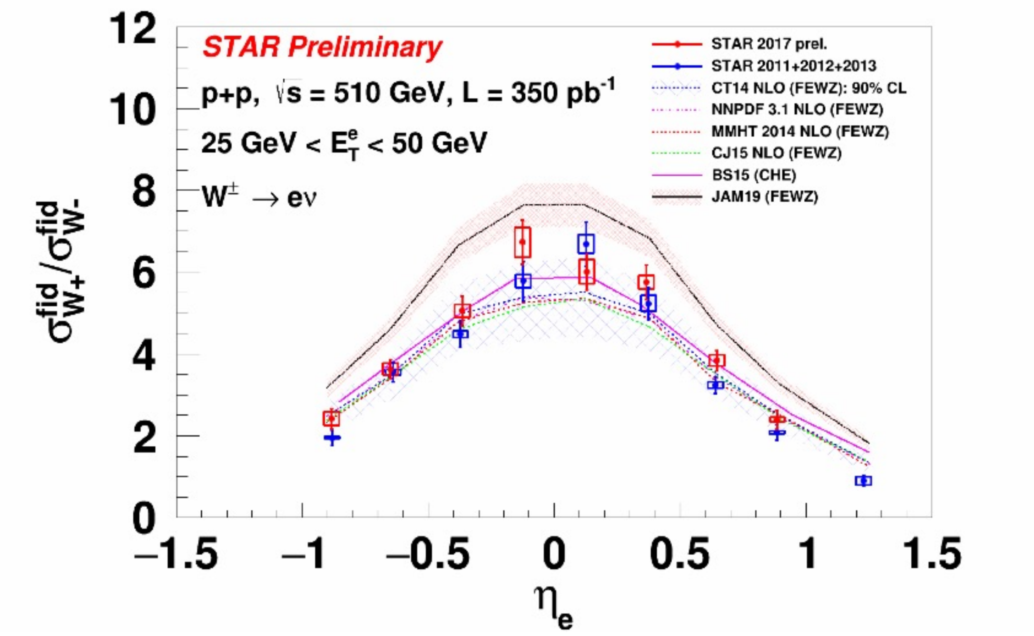
Unpolarized program at STAR



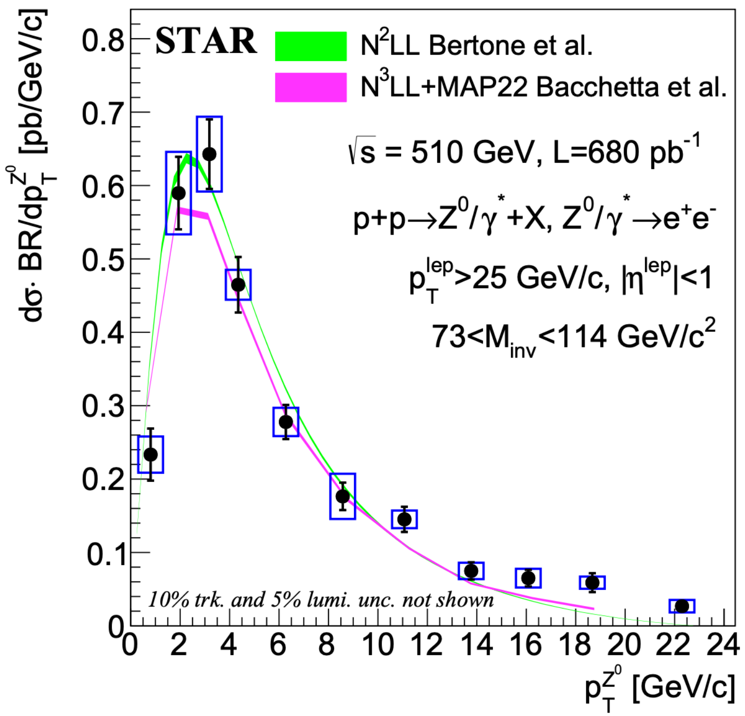


W and Z^0 cross section

Run11-13: STAR, PRD 103, 012001 (2021)



STAR, arXiv:2023.15496



Cross section ratio of W^+/ W^- constrains high x quark distributions $\bar{d}/\bar{u}$:

- Sensitive to the region $0.1 < x < 0.3$ in STAR mid-rapidity ($|\eta| < 1$) at $Q \sim M_W$
- Clean theoretical and experimental observable

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

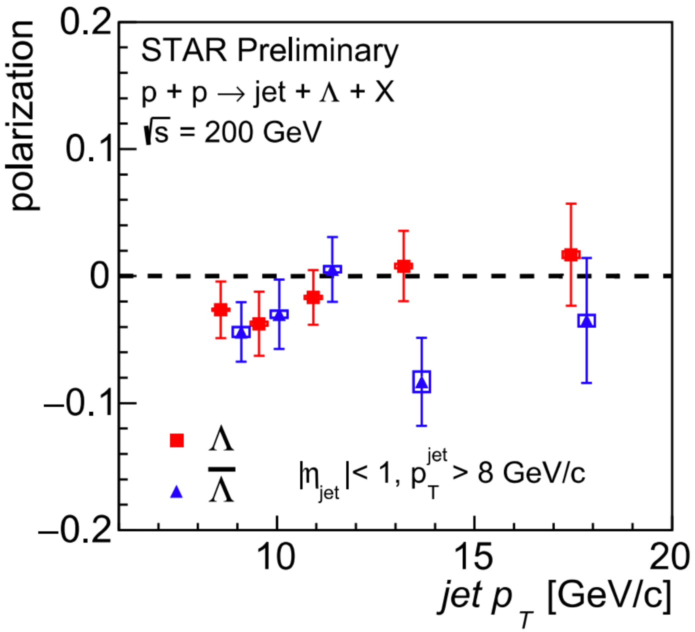
Differential Z^0 cross section vs. p_T:

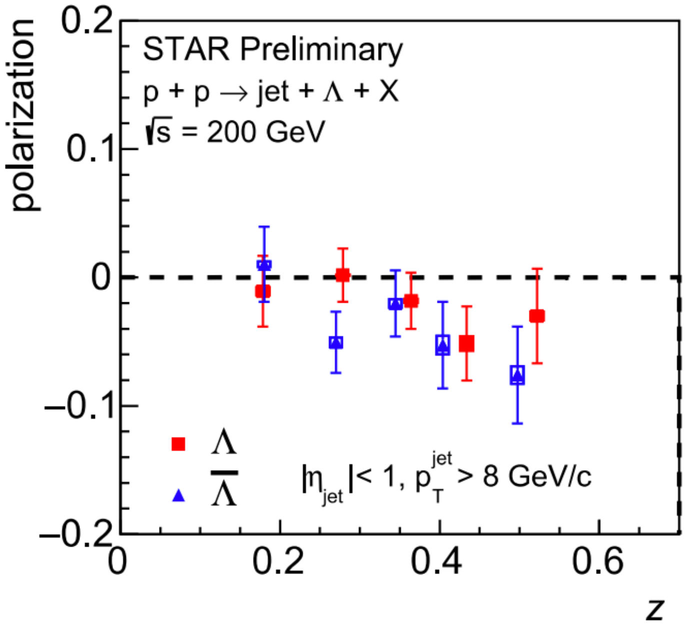
- Constrains on the energy scale dependence of TMDs
- Sensitive to the region $0.1 < x$ in STAR mid-rapidity ($|\eta| < 1$) at $Q = M_Z \gg p_T$

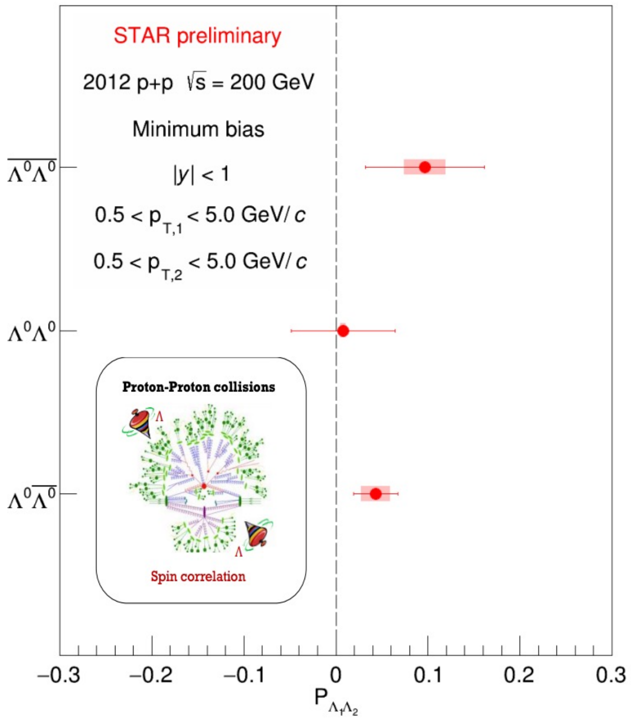
Bertone et al., JHEP 06(2019)028
Bacchetta et al., JHEP 10(2022)127

Λ polarization

See Jan Vanek's talk, WG5, Tue 3:10pm







Access polarizing Fragmentation Functions(pFFs) **by measuring transverse polarization of Λ-in-jet at STAR:**

- cover a wide range of jet p_T for measurement of energy scale dependence
- test universality of pFFs with results from e^+e^- and SIDIS

$$\frac{dN}{d\cos\theta^*} \propto (1 + \alpha P \cos\theta^*)$$

θ^*: angle between proton and spin direction in Λ rest frame

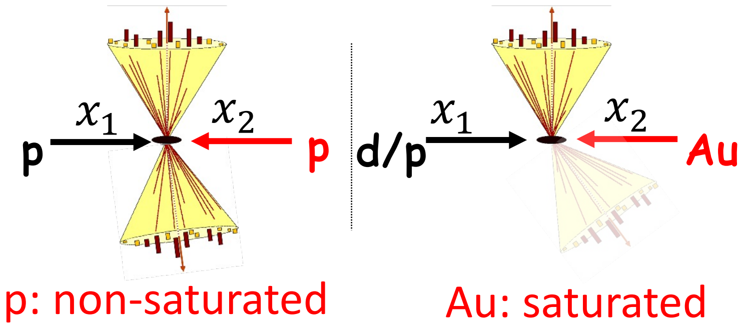
More investigation of Λ polarization from measuring spin correlation of two Λs:

- first experimental search
- consistent with 0 within uncertainty

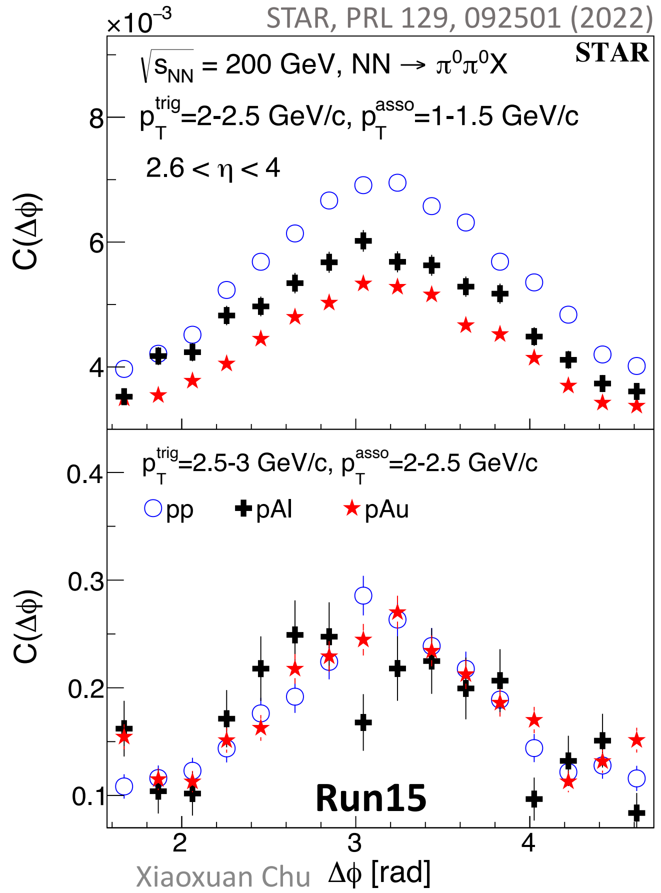
$$\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)} \sim 1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*)$$

θ^*: angle between two protons in the rest frame of their mother Λs

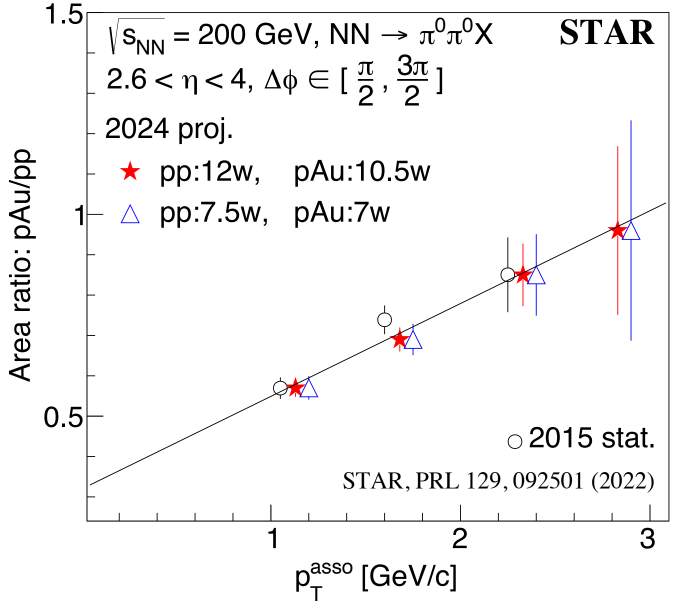
Nonlinear gluon dynamics in QCD



STAR, PRL 129, 092501 (2022)

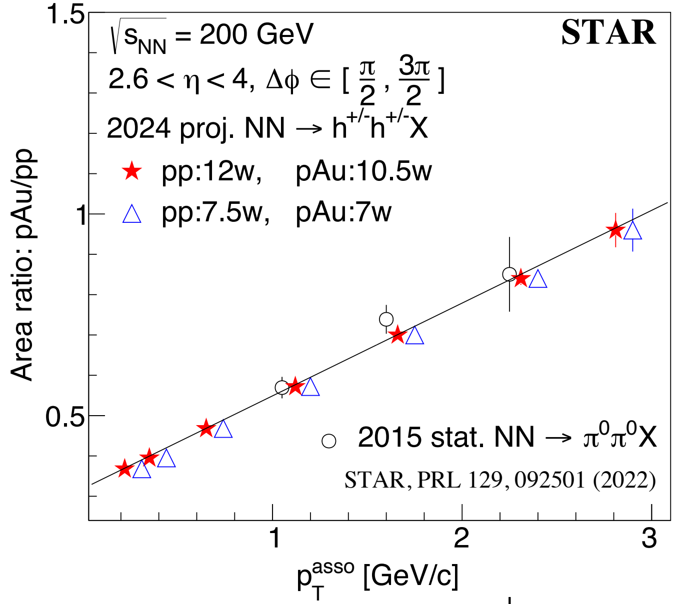


STAR, Beam User Request 24-25



Run24+25 di-π^0

STAR, Beam User Request 24-25



Run24+25 di-$h^{\pm}$

- Run15: di-π^0 correlations at forward rapidities from low p_T to high p_T → probe gluon dynamics from low $x(Q^2)$ to high $x(Q^2)$
- **di-$h^{\pm}$** measurement is crucial with Run24 (pp) + possibly pAu in the last 2 years of RHIC Run, for lowest p_T → 0.2 GeV/c where the strongest suppression is expected
- STAR data are essential to explore the universality of nonlinear effects along with the future EIC

Summary and outlook

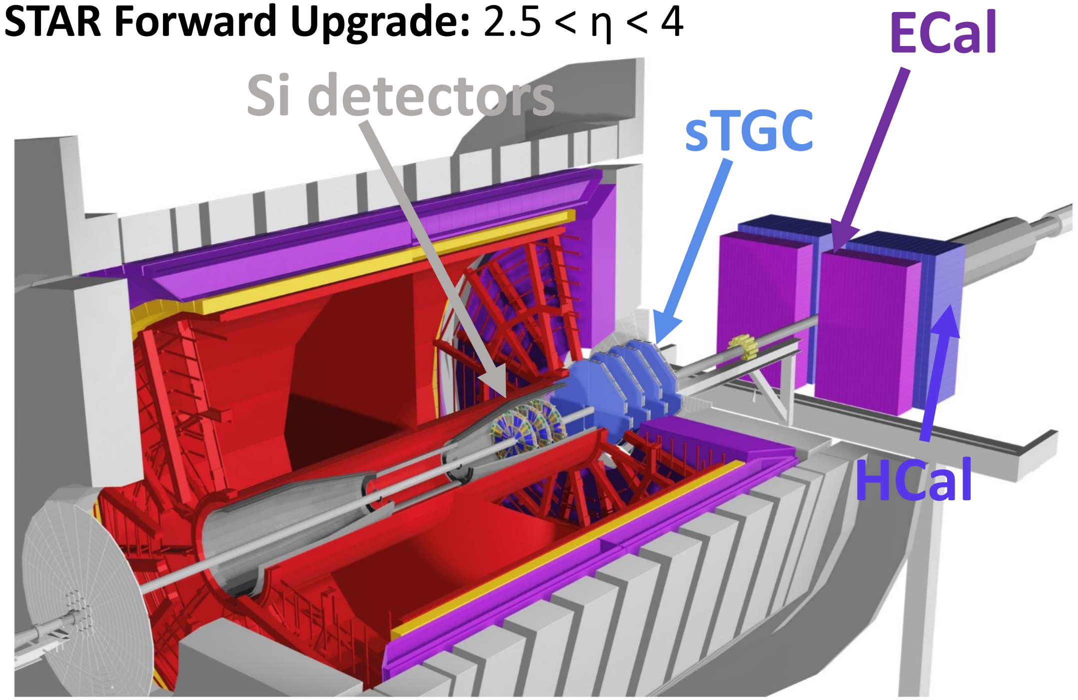
High impact of STAR Cold QCD program:
Longitudinally polarized: insights into Δg; $\Delta\bar{u} > \Delta\bar{d}$ and $\Delta s \sim 0$

Transversely polarized:
- Sivers asymmetry for W/Z boson ~ 0
- Nonzero Collins asymmetry for hadron-in-jet and IFF
- Investigation of large forward A_N, small contribution from diffraction

Unpolarized:
- W/Z boson cross section → high x quark distribution/TMD
- Forward di-π^0 corr. → nonlinear gluon dynamics
- Investigation of Λ polarization from various aspects

STAR will continue taking data with the Forward Upgrade through 2025: high-statistics tran. pol. pp data is coming soon!
- Understanding the origin of large forward A_N
- Testing TMD evolution and universality
- Constraining transversity at high x
- Understanding the nature of the initial state in nucleons and nuclei

STAR Forward Upgrade: 2.5 < η < 4



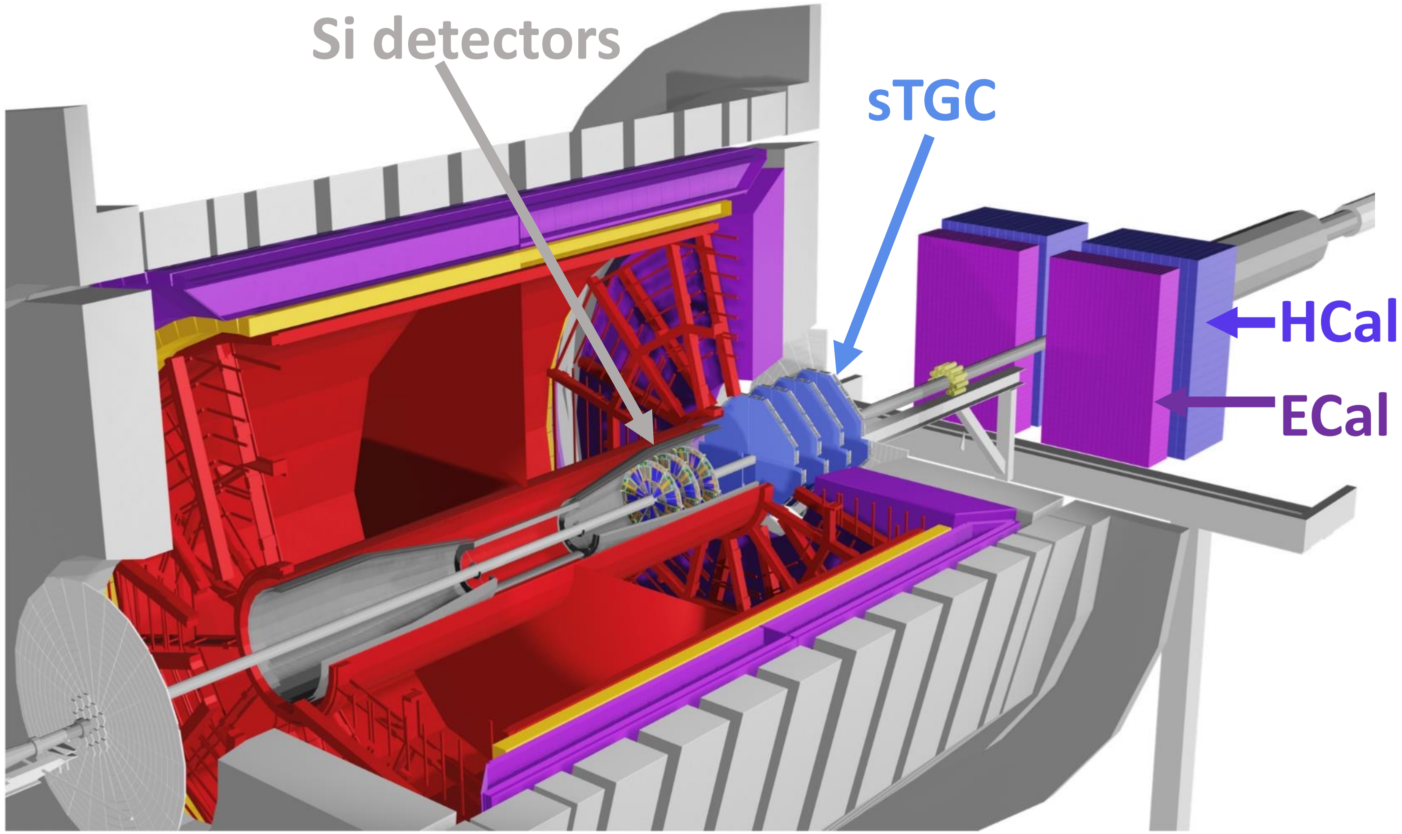
Run period for STAR:

2024 (from Apr 15th)	**19 weeks of pp** 6 weeks of AuAu	Transversely polarized pp
2025	AuAu	

It's possible to take **pAu** in the last 2 years of RHIC Run!

Back up

STAR Forward Upgrade



Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

STAR Forward Upgrade: $2.5 < \eta < 4$

Four new systems:

- Electromagnetic and Hadronic Calorimetry
- Tracking: Si detectors and small-strip Thin Gap Chambers (sTGC)

What we can measure:

- $h^{+/-}$, $e^{+/-}$ (with good *e*/*h* discrimination)
- Photons, π^0
- Jets, *h* in jets
- Lambda's
- Drell-Yan and J/Ψ di-electrons
- Mid-forward and forward-forward correlations

Run period:

- STAR in parallel with sPHENIX:
  - 2024 → 200 GeV polarized p+p and Au+Au
  - 2025 → 200 GeV Au+Au w/o p+Au

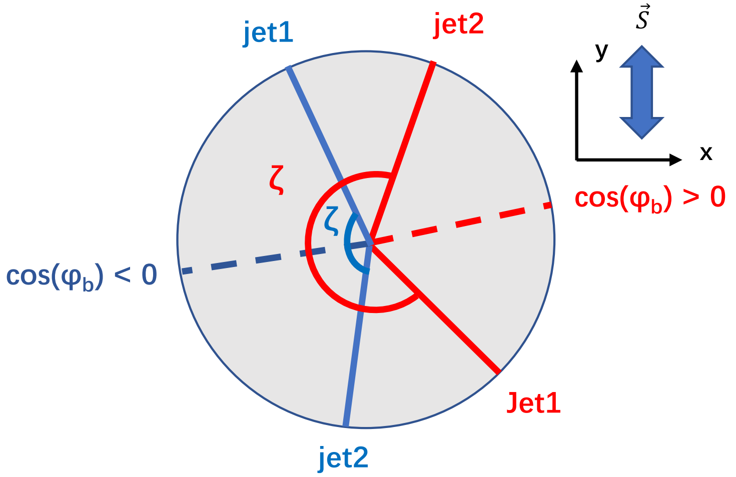
Dijet Sivers effects: kinematics

Observable for Probing the Sivers Effect in Dijet Event

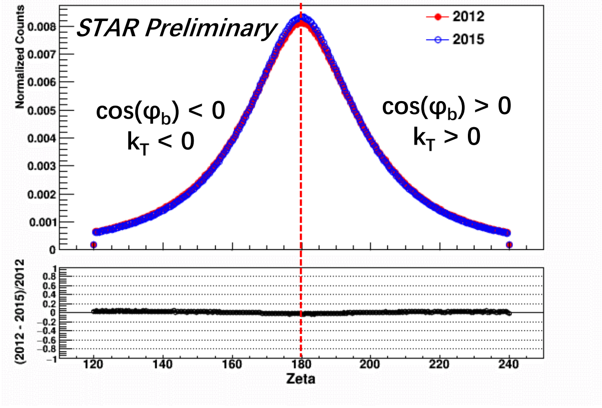
The Sivers asymmetry can be probed via the signed opening angle ζ .

Definition of ζ

ζ > π when cos(**φ_b**) > 0
ζ < π when cos(**φ_b**) < 0
where **φ_b** is dijet bisector angle



Distribution of ζ



Extraction of asymmetry

The Sivers effect leads to a spin-dependent centroid shift of **ζ**, so we define the asymmetry as:

$$\Delta\zeta = \frac{\langle\zeta\rangle^{+} - \langle\zeta\rangle^{-}}{P}$$

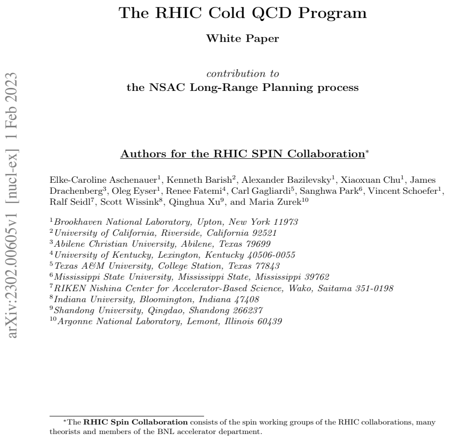
where $\langle\zeta\rangle^{+/-}$ is the centroid of **ζ** for spin-up and spin-down states, and **P** is the beam polarization.

DNP2020 - Dijet Sivers - Huanzhao Liu 4

Complementarity and Universality

Where are we?

2023



arXiv:2302.00605v1 [nucl-ex] 1 Feb 2023

The RHIC Cold QCD Program

White Paper

contribution to

the NSAC Long-Range Planning process

Authors for the RHIC SPIN Collaboration*

Elke-Caroline Aschenauer[1], Kenneth Barish[2], Alexander Bazilevsky[1], Xiaoxuan Chu[1], James Drachenberg[3], Oleg Eyser[1], Renee Fatemi[4], Carl Gagliardi[5], Sanghwa Park[6], Vincent Schoefer[1], Ralf Seidl[7], Scott Wissink[8], Qinghua Xu[9], and Maria Zurek[10]

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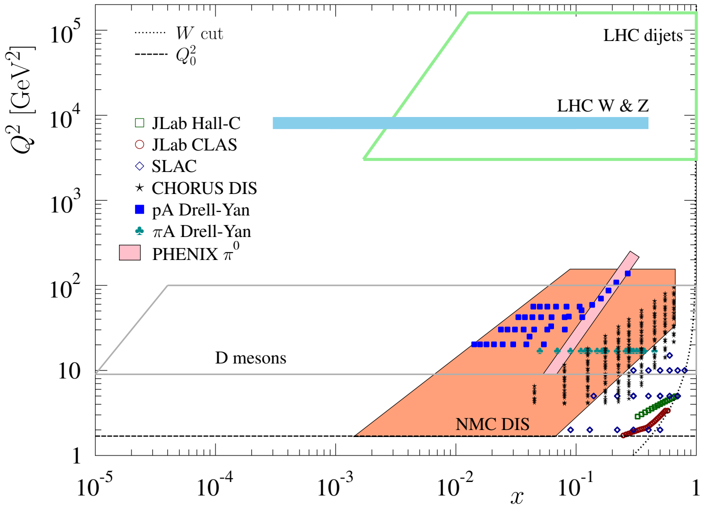
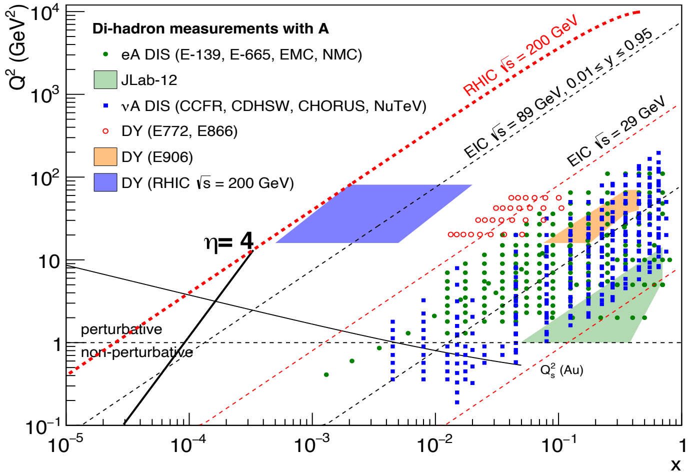
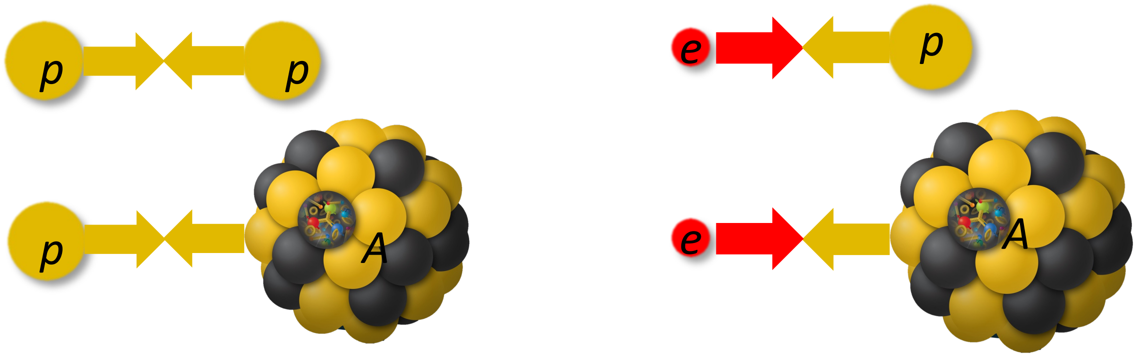
*The **RHIC Spin Collaboration** consists of the spin working groups of the RHIC collaborations, many theorists and members of the BNL accelerator department.

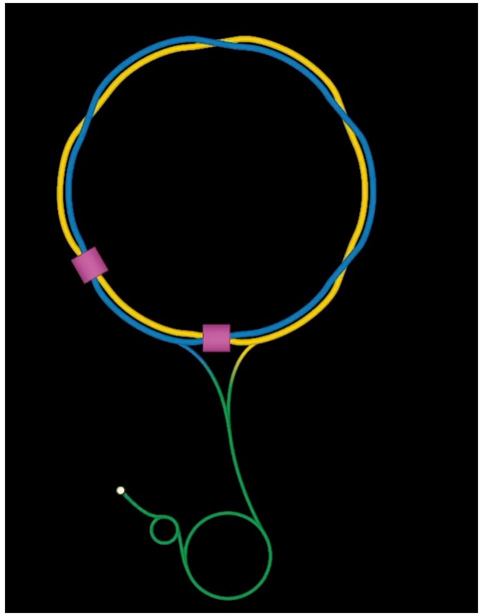
arXiv:2302.00605

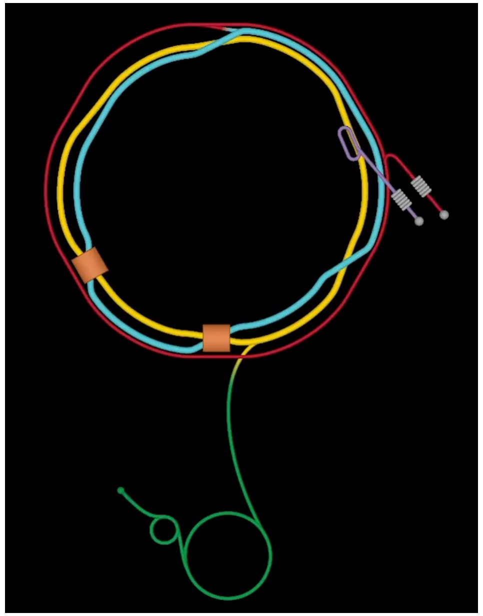




Where are we going?







RHIC ——— Path to ———→ **EIC**