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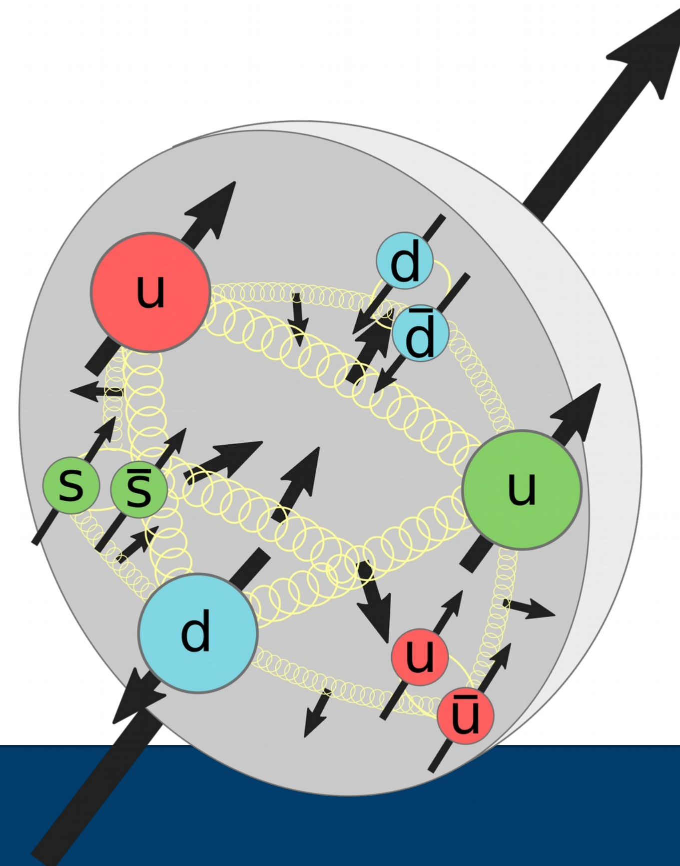


EXPERIMENTAL COLD QCD AT RHIC

11 JUNE 2021 | MARIA ŻUREK | ARGONNE NATIONAL LABORATORY

RHIC & AGS ANNUAL USERS' MEETING 2021

SPIN PHYSICS PROGRAM AT RHIC

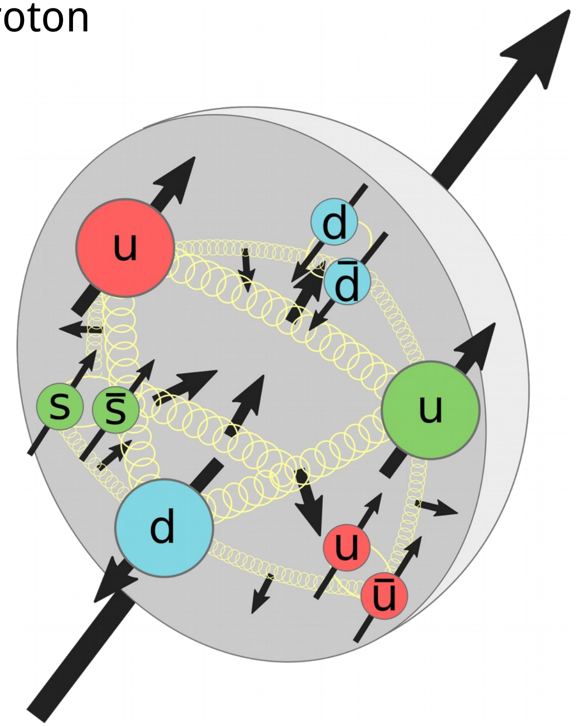
Goals:

- Using spin as a unique probe to unravel the internal structure of the proton
- Understanding QCD processes in cold nuclear matter

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 nucleon and nucleus and properties of QCD?
- What is the **initial state in nuclear collisions**?



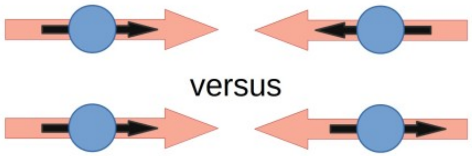
Probing the **cold nuclear matter** via **strong interactions** in pA and pp collisions

Cold-QCD Highlights: See talks on 06/08 by B. Mulilo (9:00 AM), H. Menjo (9:25), X. Chu (9:50 AM)
Future Cold-QCD prospects with pp and pA: See talks on 06/08 by J. Huang (10:55), T. Lin (11:20)

GLUON HELICITY

GLUON HELICITY

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

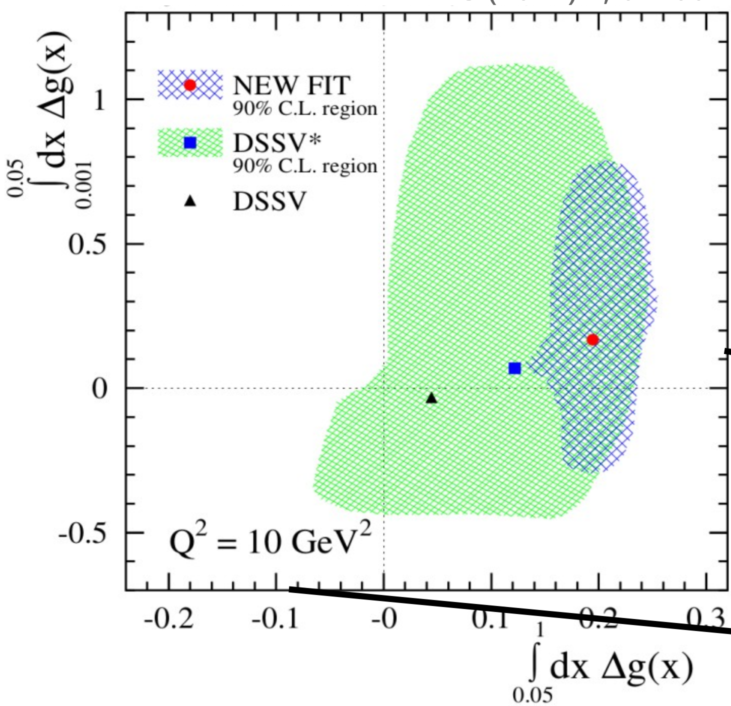


$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma}\hat{a}_{LL} \otimes D}{\Sigma f_a \otimes f_b \otimes \hat{\sigma} \otimes D}$$

LO for illustration

- At RHIC energies: sensitivity to qg and gg – Access to **Δg(x)/g(x)**
- Cross-section measurement to support the NLO pQCD interpretation of asymmetries

PRL 113 (2014) 1, 012001



STAR inclusive jet A_{LL} from 2009 data at √s = 200 GeV

PRL 115 (2015) 9, 092002

Included in global pQCD analysis provided evidence for **positive gluon polarization for x > 0.05 at Q^2 = 10 GeV**

Low-x range

Extend sensitivity to smaller x:
- Forward rapidity $x_g \propto \exp(-\eta)$
- √s = 510 GeV data $x_g \propto 1/\sqrt{(s)}$

High-x range

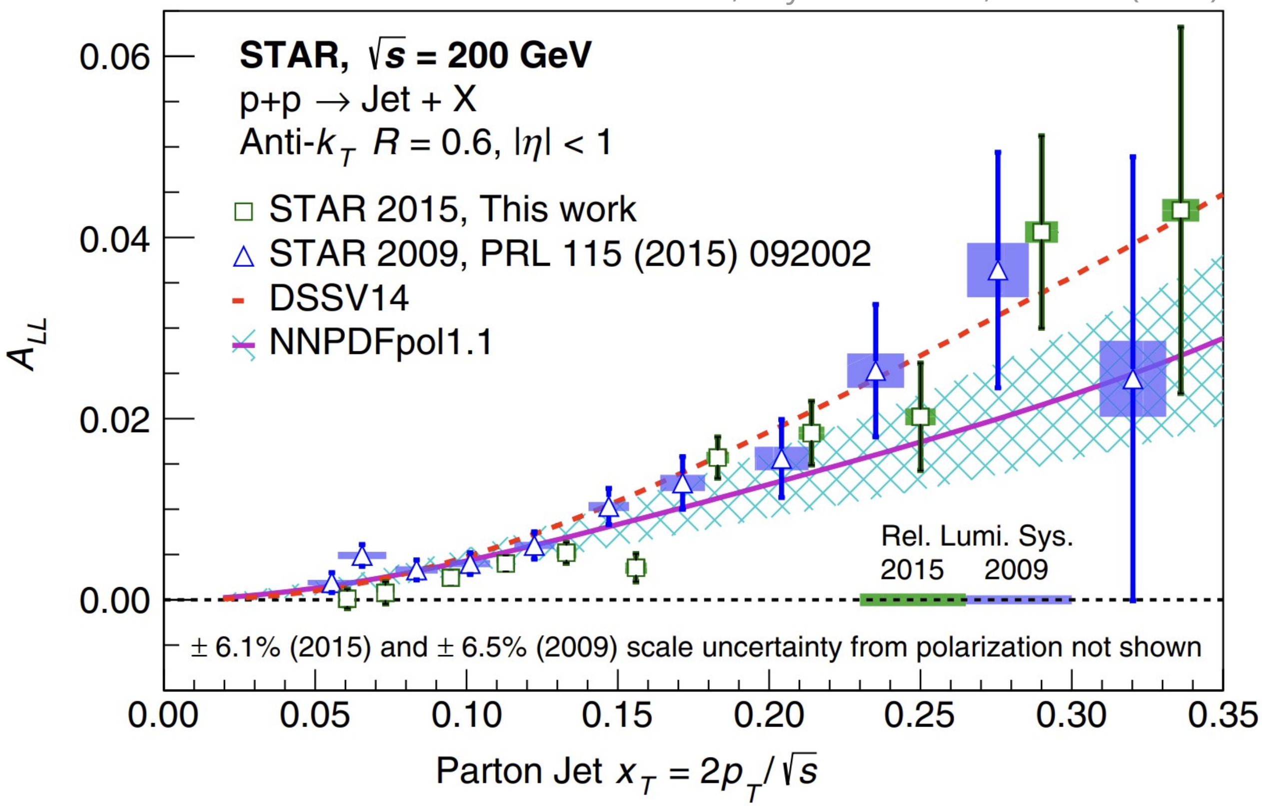
Further precision from:
- Jet and neutral pion probes
- Complementary probes (dijets)

INCLUSIVE JETS AT 200 GEV

Towards higher precision at x > 0.05

New result on jet and dijet A_{LL} from STAR from 2015 data

STAR, Phys. Rev. D 103, L091103 (2021)



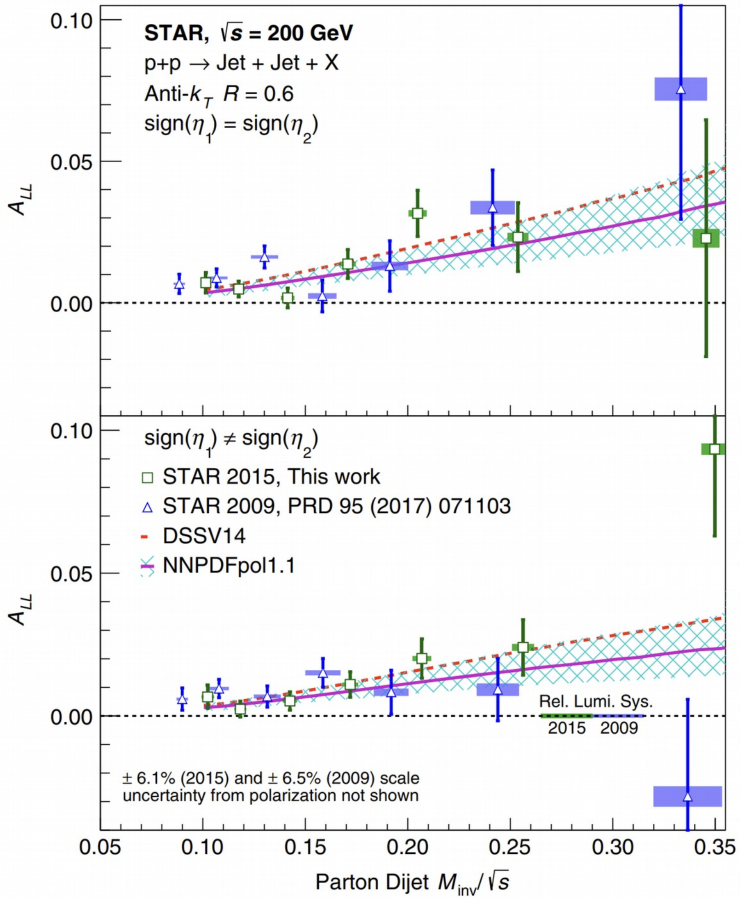
- Consistent with 2009 data, which provided first evidence for **positive gluon polarization for x > 0.05**
- Twice larger figure-of-merit ($\mathcal{L}P^4$) with improved systematics
- Will significantly reduce uncertainty on **Δg(x) for x > 0.05** once included in global fits

The most precise dataset likely to conclude the 200 GeV longitudinal spin program with jets

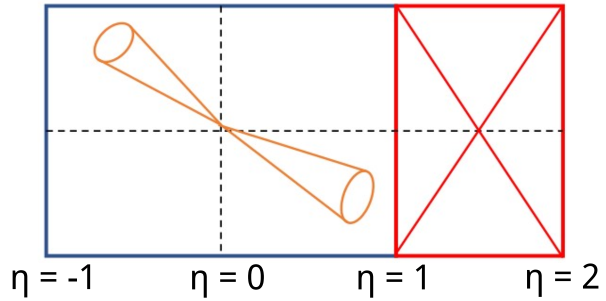
DIJETS AT 200 GEV

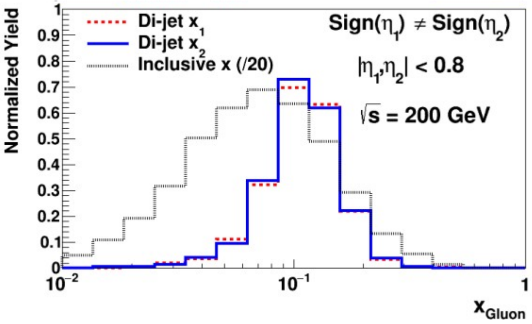
Towards higher precision at x > 0.05

STAR, Phys. Rev. D 103, L091103 (2021)

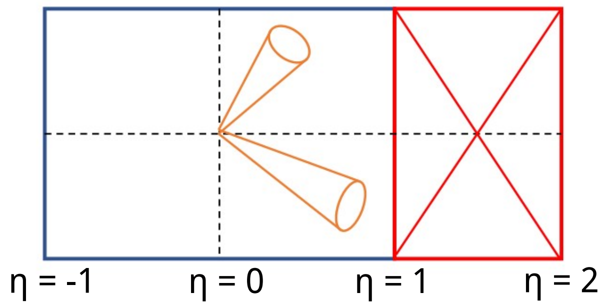


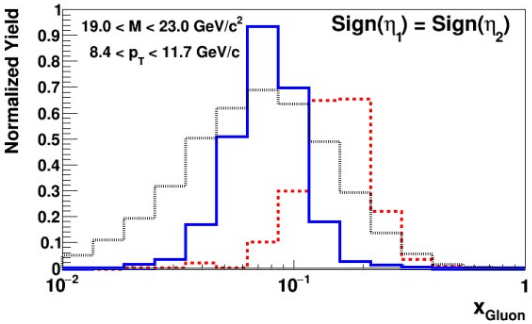
sign(η_1) ≠ sign(η_2)





sign(η_1) = sign(η_2)





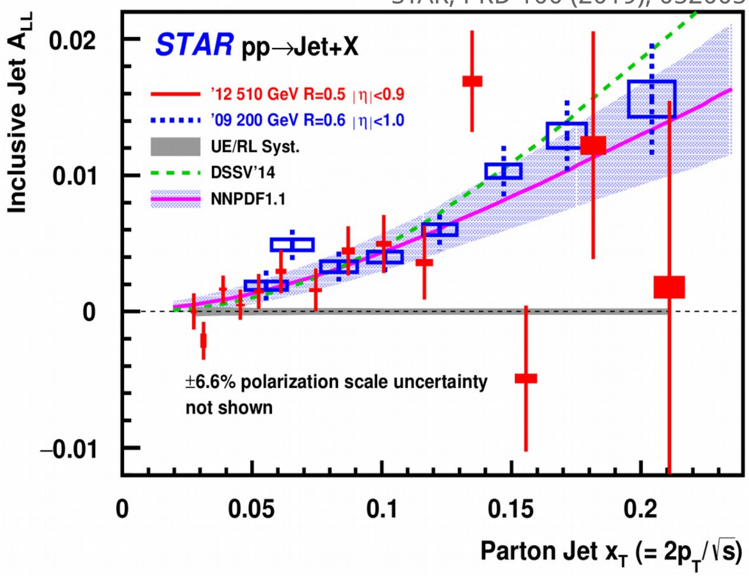
Dijets give stricter constraints to underlying **partonic kinematics**

- Better constraints on **functional form of Δg(x) - narrow ranges** of initial state partonic momentum tested
- More-forward production - **lower x** (down to 0.01 with STAR Endcap PRD 98 (2018), 032011)
  x_2 – likely gluon, x_1 – likely quark

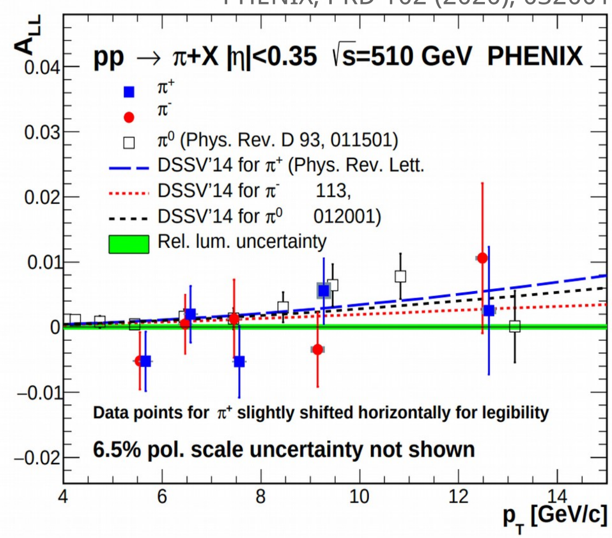
CENTRAL π, JETS, AND PHOTONS AT 510 GEV

Towards smaller x and complementary probes

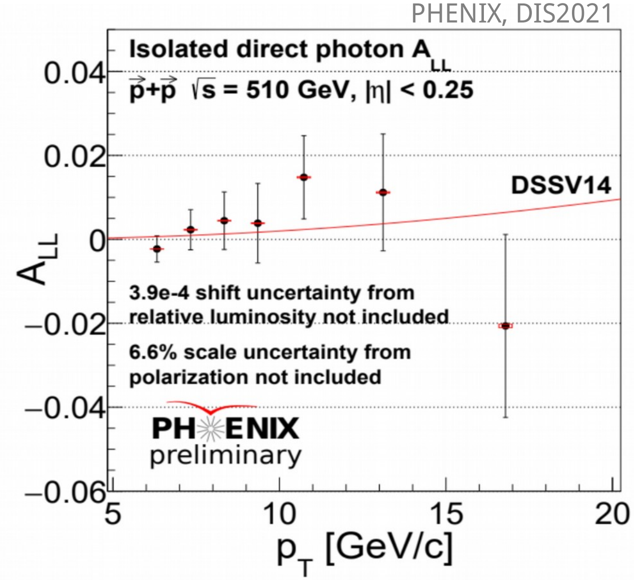
STAR, PRD 100 (2019), 052005



PHENIX, PRD 102 (2020), 032001



PHENIX, DIS2021



Higher √s pushes sensitivity to lower x (down to ~ 0.004 with STAR Endcap dijets at 510 GeV)

- Consistent results from both energies and both experiments
- Pion A_{LL} ordering connected to the gluon polarization sign
- Direct photon sensitive to gq → γq LO process; clean access to Δg(x) (no hadronization)

- Further precision with jet A_{LL} from Run 2013 data at √s = 510 GeV – x 3.5 statistics w.r.t. Run 2012 and dijets with Endcap from Run 2015 – x 2 statistics w.r.t Run 2009

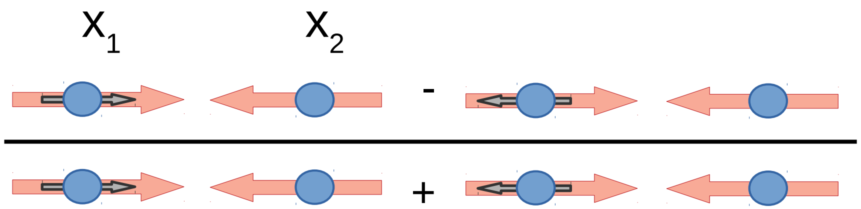
RHIC concluded the data taking with longitudinally polarized protons in 2015

The data are anticipated to provide the most precise insights in Δg(x) well into the future

QUARK-SEA DISTRIBUTIONS

SEA-QUARK HELICITIES

Single spin asymmetry and cross sections for W production



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

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

LO for illustration

Separation of quark flavor

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

Maximal parity violation

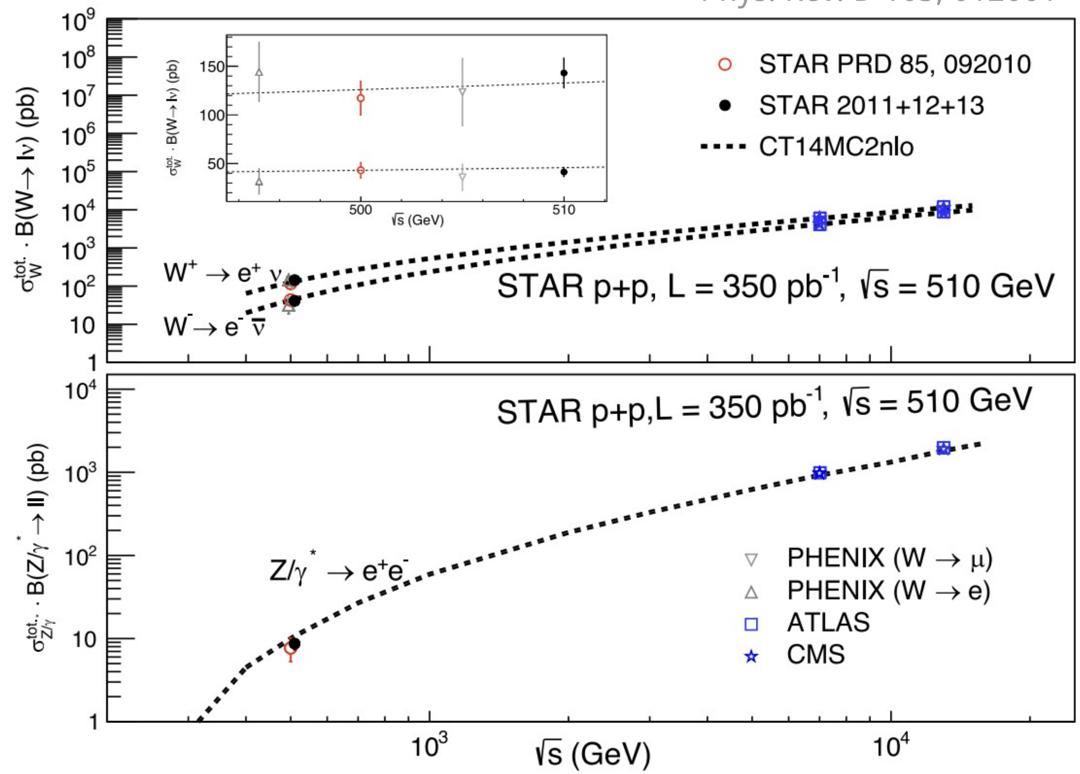
- W couples to left-handed particles or right-handed antiparticles

The decay process is calculable

- Free from fragmentation function

Access both to sea and valence quarks

Phys. Rev. D 103, 012001



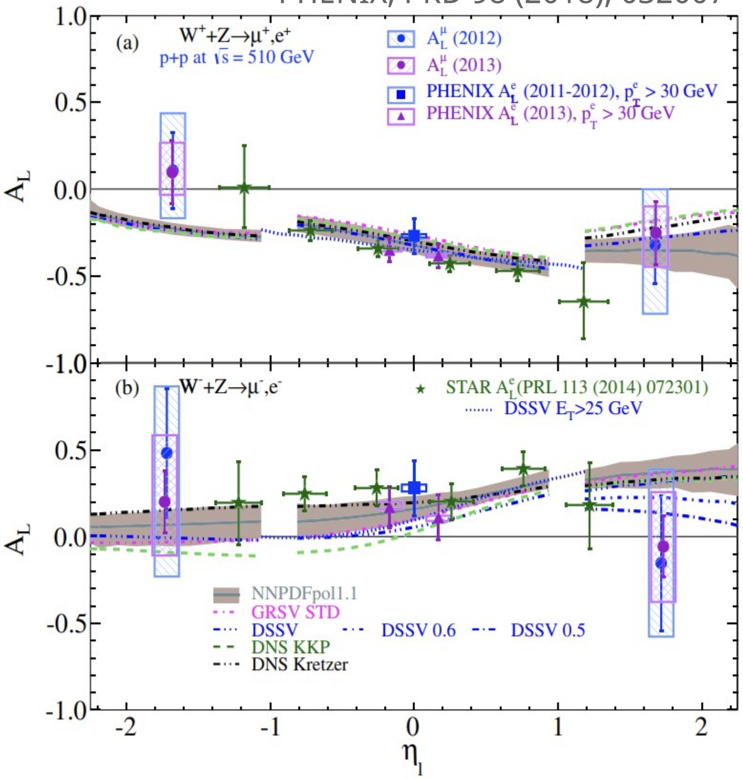
$W^{+/-}$ and Z cross section

- Agreement between theory and experiment
- Support for the NLO pQCD interpretation of asymmetry measurements

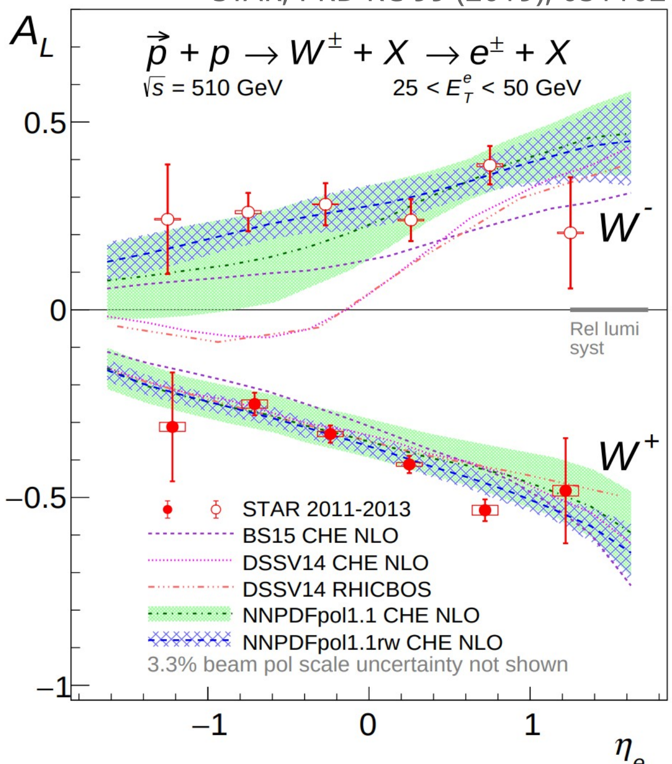
QUARK HELICITIES

Single spin asymmetry for W production at STAR

PHENIX, PRD 98 (2018), 032007

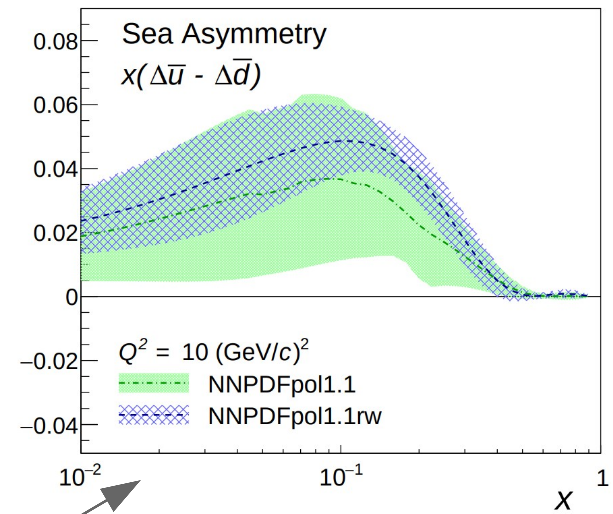


STAR, PRD RC 99 (2019), 051102



Covered lepton η: $0.05 < x_1 < 0.25$

Flavor asymmetry for quark sea



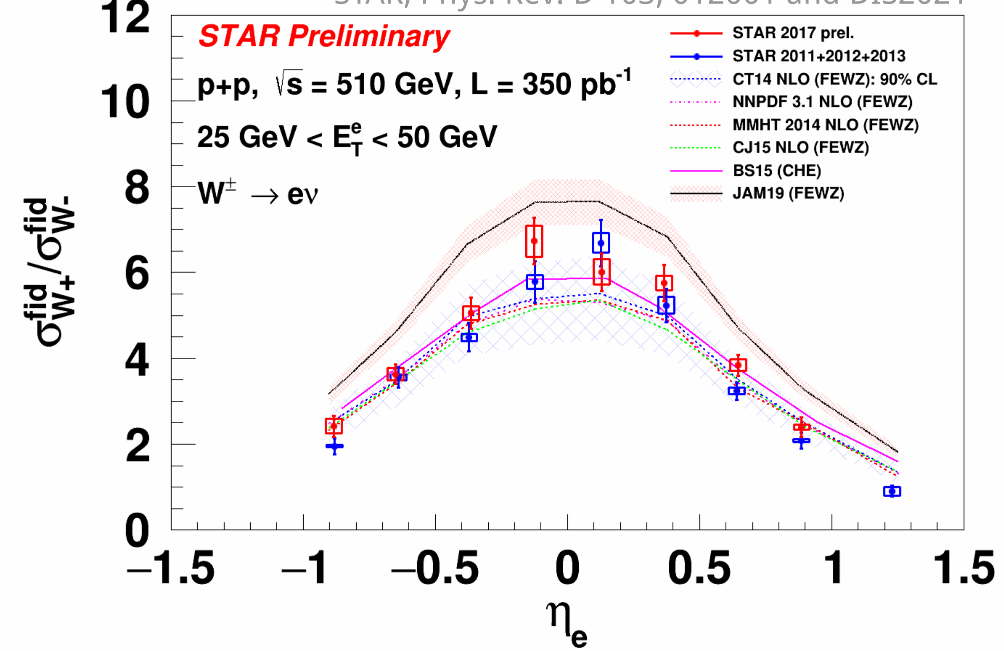
- Full available data set analyzed 2011- 2013 data (300 pb^{-1}) – most precise data to date
- **First evidence for a polarized flavor asymmetry**
- **Significant preference for $\Delta\bar{u}$ over $\Delta\bar{d}$**
  → Opposite to the spin-averaged quark-sea distributions
- Evaluations from DSSV and NNPDF agree with data in sea and valence quark region

UNPOLARIZED SEA-QUARK DISTRIBUTIONS

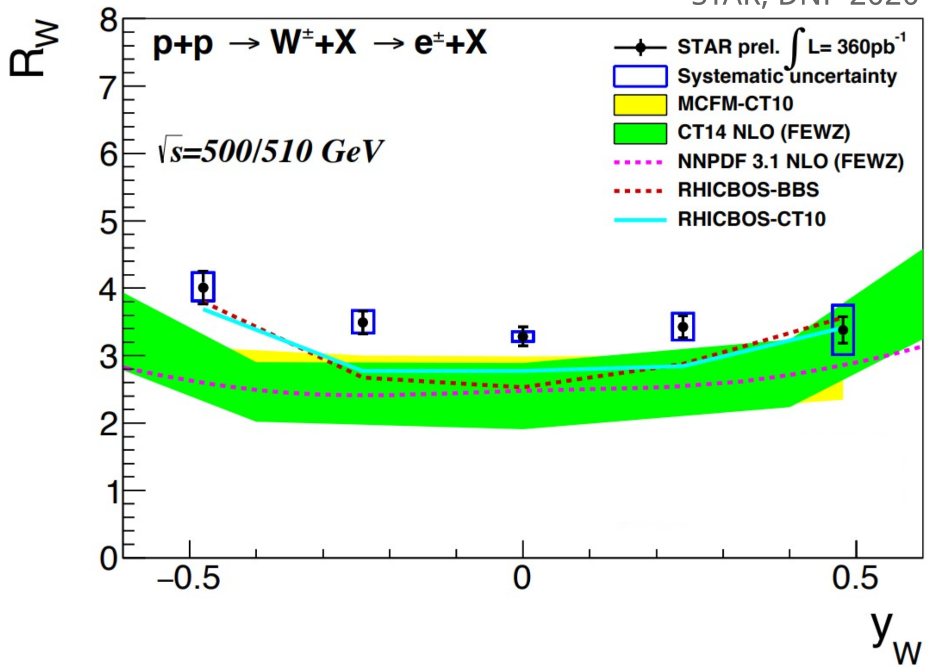
Cross-section ratio for W production

Sensitivity to the **unpolarized $\bar{d}(x)/\bar{u}(x)$** quark distribution

STAR, Phys. Rev. D 103, 012001 and DIS2021



STAR, DNP 2020



W^+/W^- cross section ratio at STAR complementary to the Drell-Yan data

- Data cover overlapping region of ~0.1 < x < ~0.3, $|\eta_e| < 1$ at higher $Q^2 = M_W^2$
- Cross sections ratio measured vs the decay lepton η and the W rapidity (from recoil)

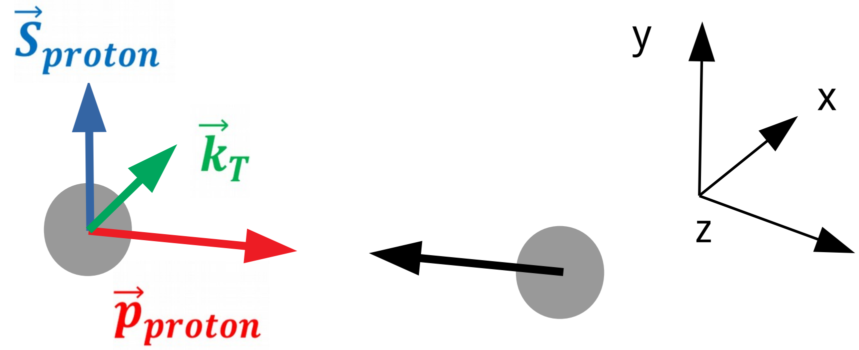
Will provide insights into unpolarized light quark distributions **$\bar{d}(x)$ and $\bar{u}(x)$ at x > 0.05**
Further opportunities with run 2022 at 510 GeV: x 2 statistics

SIVERS FUNCTION

ASYMMETRY FOR $W^{+/-}$ AND Z PRODUCTION

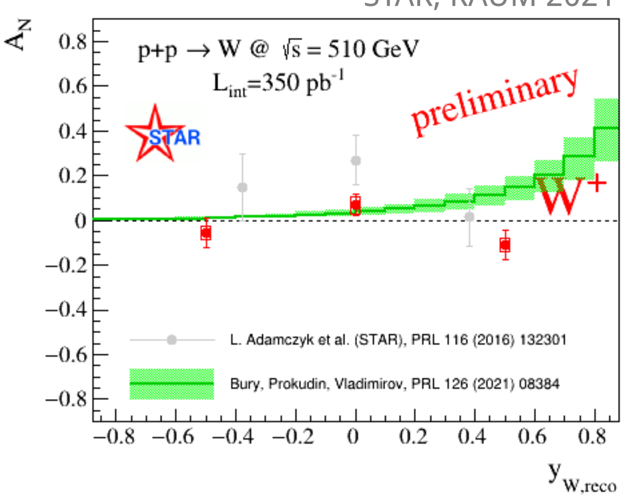
Sivers function - describes correlation between parton's **transverse momentum** inside the proton with proton **transverse spin** (initial state TMD)

$$\langle \vec{S}_{proton} \cdot (\vec{p}_{proton} \times \vec{k}_T) \rangle \neq 0$$

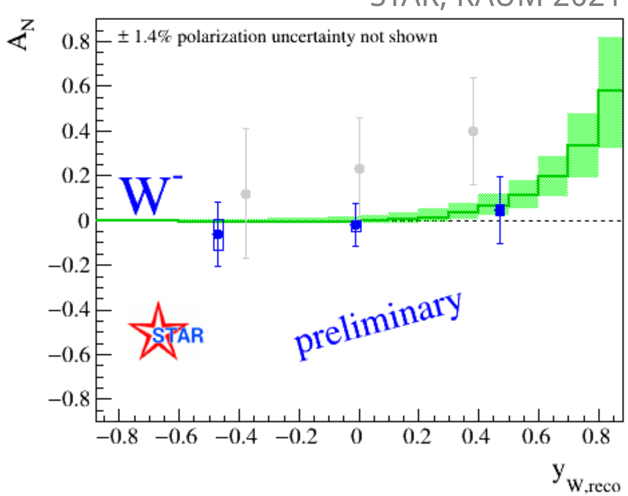


Test of nonuniversality of Sivers function: Sivers_{DIS} = - $\text{Sivers}_{DY/W/Z}$ and TMD evolution effects

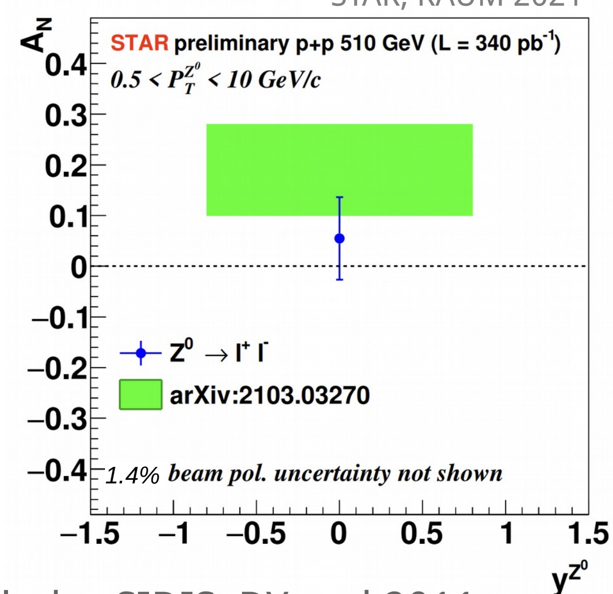
STAR, RAUM 2021



STAR, RAUM 2021



STAR, RAUM 2021

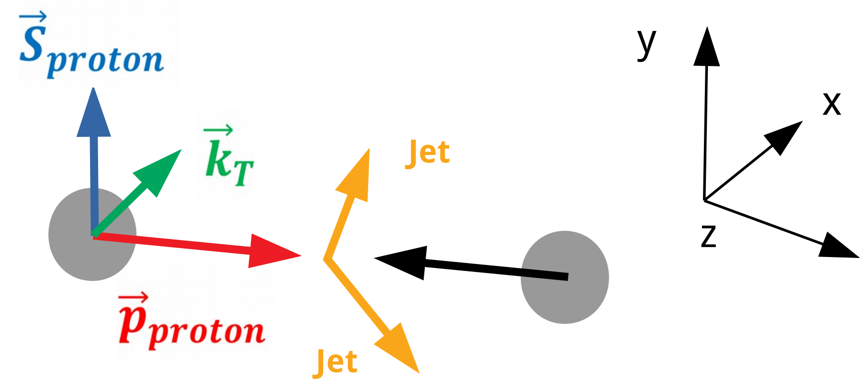


- **Improved uncertainties from run 2017 preliminary results**
- Bury, Prokudin, and Vladimirov PRL 126, 112002 (2021) – extraction includes SIDIS, DY and 2011 STAR data with N^3LO and NNLO accuracy of the TMD evolution assuming sign-change
- 2x more statistics from run 2022 at 510 GeV with STAR iTPC (expec. ~350 pb^{-1})

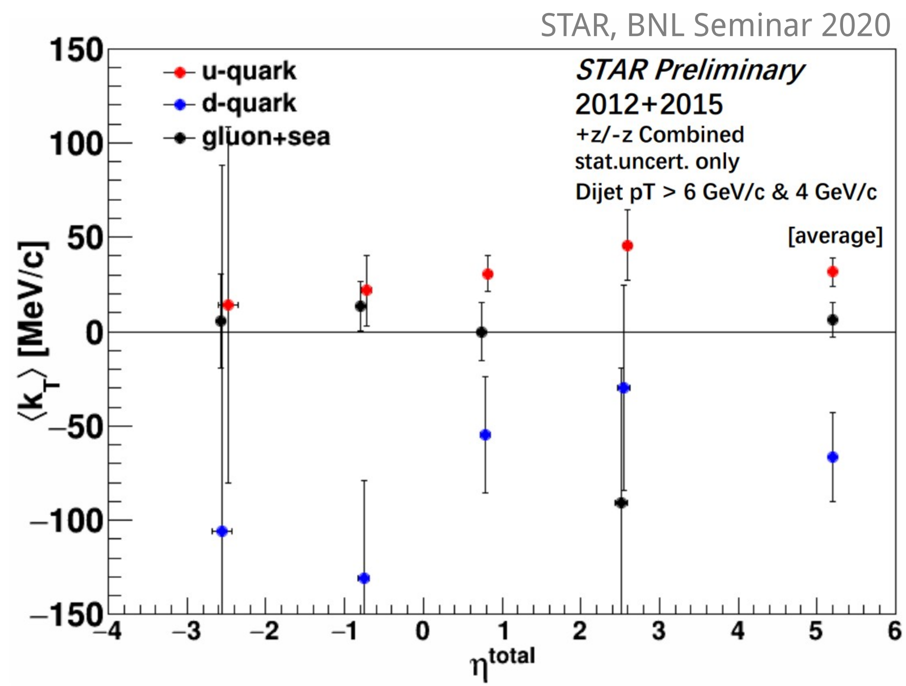
ASYMMETRY FOR THE DIJET OPENING-ANGLE

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

$$\langle \vec{S}_{proton} \cdot (\vec{p}_{proton} \times \vec{k}_T) \rangle \neq 0$$



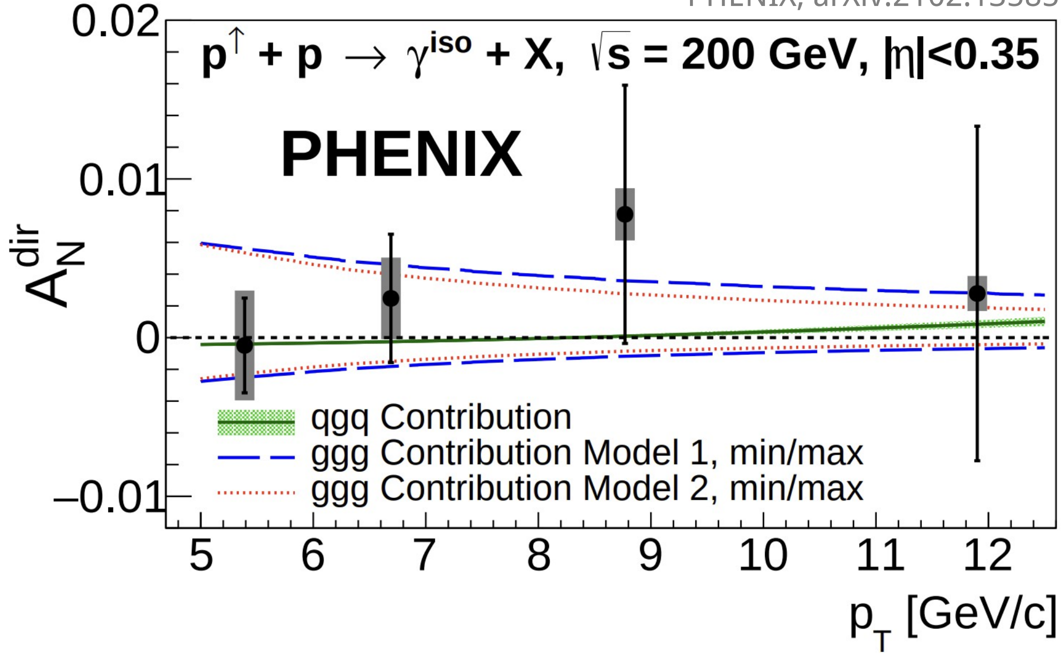
- Non-zero k_T leads to spin-dependent **tilt of dijet opening angle** in transverse plate
- Expect no effect on average: enhancing contribution of u or d quarks by **sorting jets by their net charge**
- Tilt unfolded for the k_T of individual partons
- k_T for d opposite in sign, twice as large as average k_T for u quarks
- Constraints for the Sivers function at a high Q^2 scale (Q^2 > 160 GeV^2)



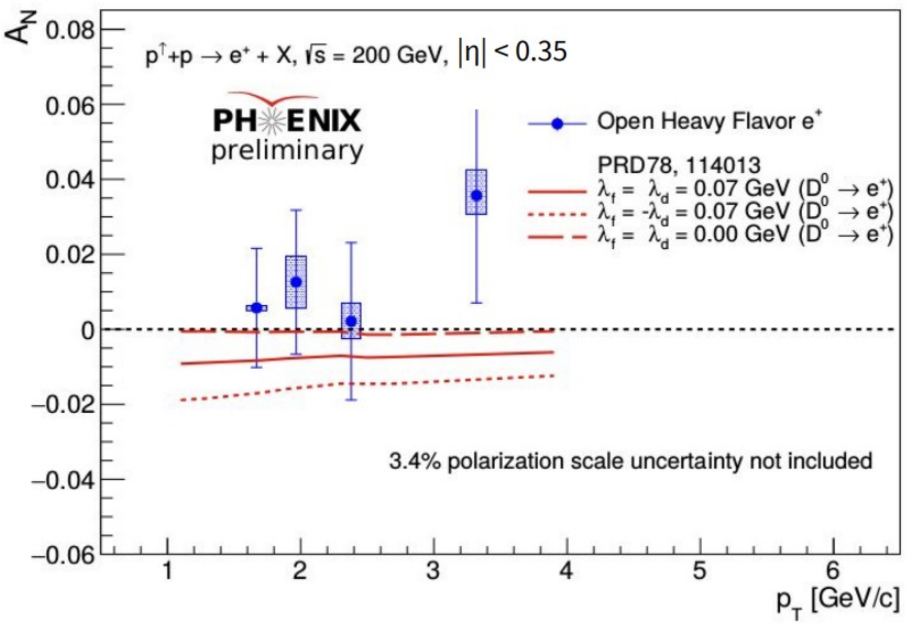
ASYMMETRY FOR DIRECT PHOTONS AND HEAVY FLAVOR ELECTRONS

Indirect constraint on the **Sivers function** via integral relationship with the **Twist-3 trigluon correlator**

PHENIX, arXiv:2102.13585



PHENIX, DIS2021

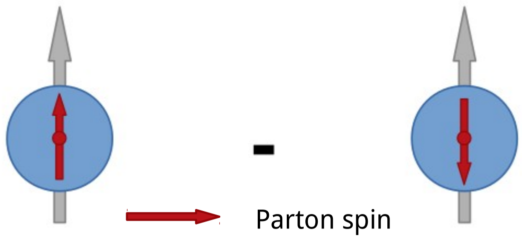


- sPHENIX capabilities in mid-rapidity: direct photons and D^0 meson asymmetries
- STAR capabilities with forward upgrade: jet, π^0, charged hadrons, photons A_N:
  → constraint on the evolution and flavor dependence of the Twist-3 ETQS function

TRANSVERSITY

TRANSVERSITY

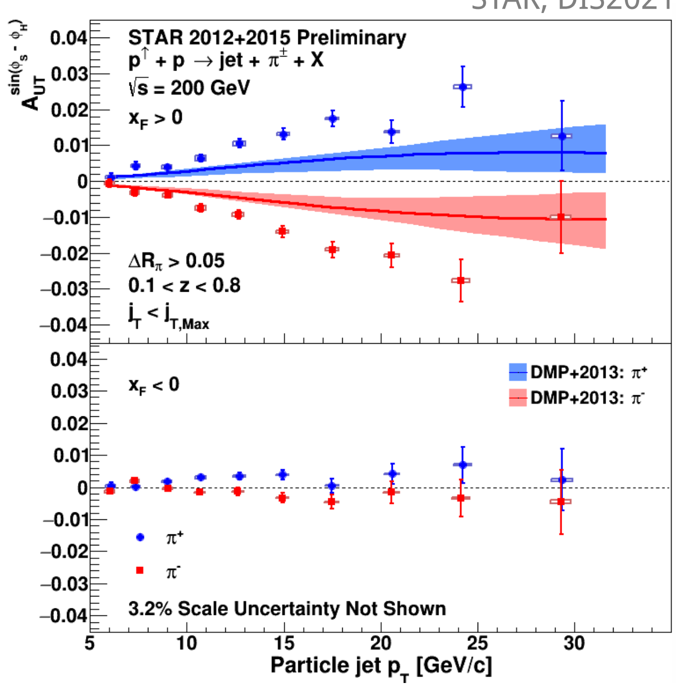
- Net density of quarks with spin aligned with the transversely polarized nucleon (leading twist)
- Two asymmetries A_{UT} provide sensitivity at RHIC



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

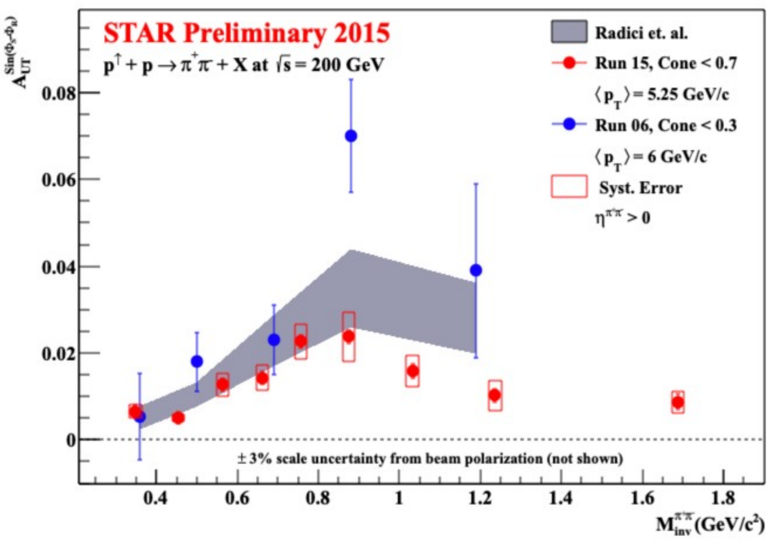
STAR, DIS2021



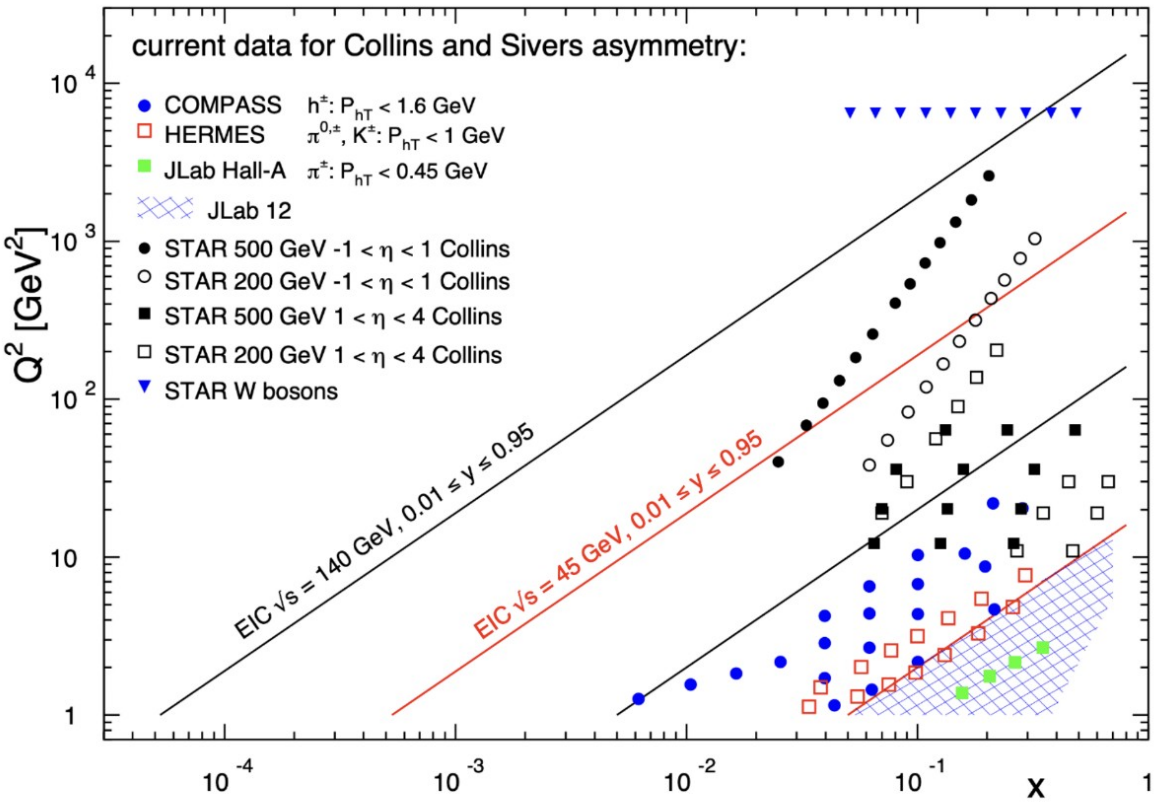
Di-hadron correlation measurements

"interference FF" (collinear framework)
Correlation of transverse spin of fragmenting quark and momentum cross-product of di-hadron pair

STAR, DIS2021 and PRL 115 (2015) 242501



OVERLAP WITH KINEMATIC REACH OF EIC



Fixed-target DIS, RHIC-spin, and EIC are truly complementary

Transversity from the Collins and IFF
→ Study factorization breaking effects for TMD observables in hadronic collisions
Sivers and Collins effect at √s = 200 and 500 GeV
→ Important input to study evolution of TMDs and essential kinematic overlap in x-Q^2 with future EIC

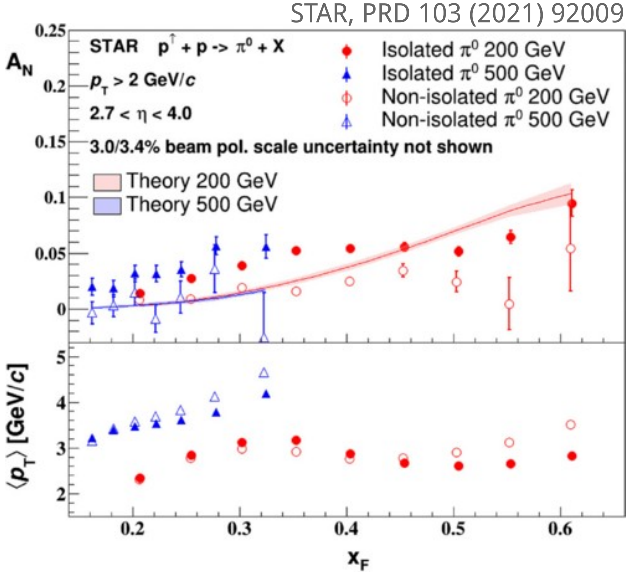
- Forward jet and charged hadron capabilities at STAR in Run 22 → Probing transvesity in valence region
- Increased statistics in mid-rapidity → STAR and sPHENIX in pp and pA runs in Run 24

GOING FORWARD

ORIGIN OF LARGE FORWARD A_N

π^0 A_N

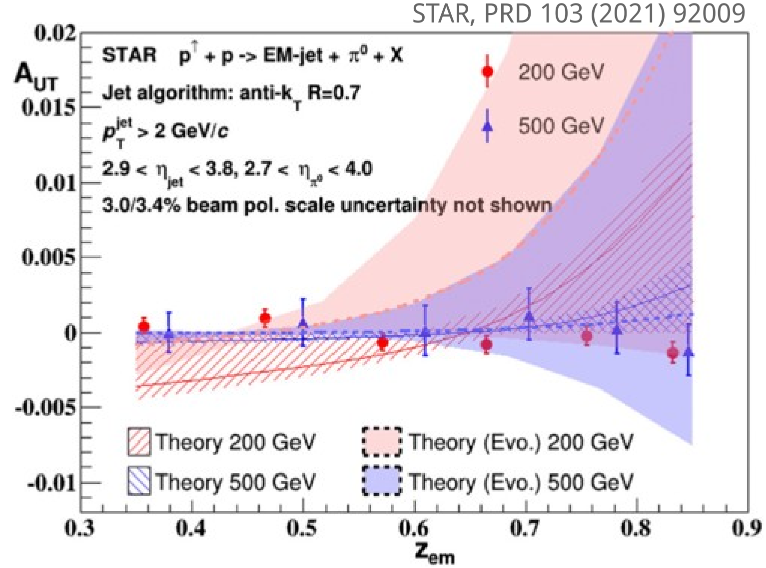
STAR, PRD 103 (2021) 92009



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

π^0 in EM jets A_{UT}

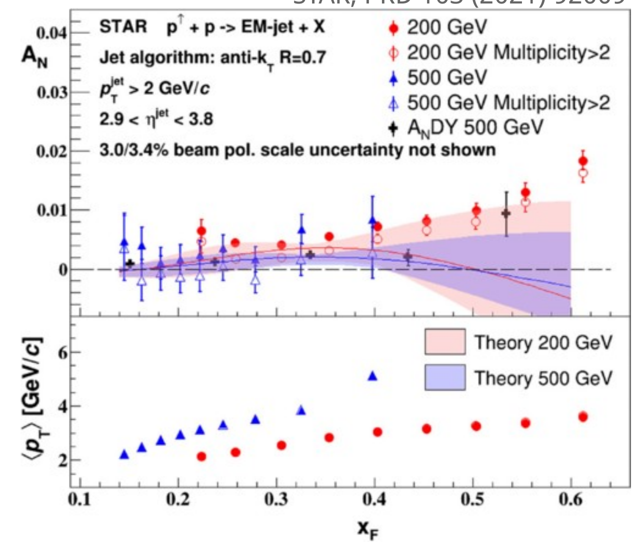
STAR, PRD 103 (2021) 92009



Theory curves : Z. Kang, et al. PLB 774, 635 (2017)

Forward EM jets A_N

STAR, PRD 103 (2021) 92009



Theory curves : L. Gamberg, Z. Kang, A. Prokudin, PRL 110 23, 232301 (2013)

- Measured **small** A_N for EM-jets and Collins asymmetry for π^0 within EM jets
- Weak dependence on the center-of-mass energy
- A_N for non-isolated π^0 and higher-multiplicity EM jets lower

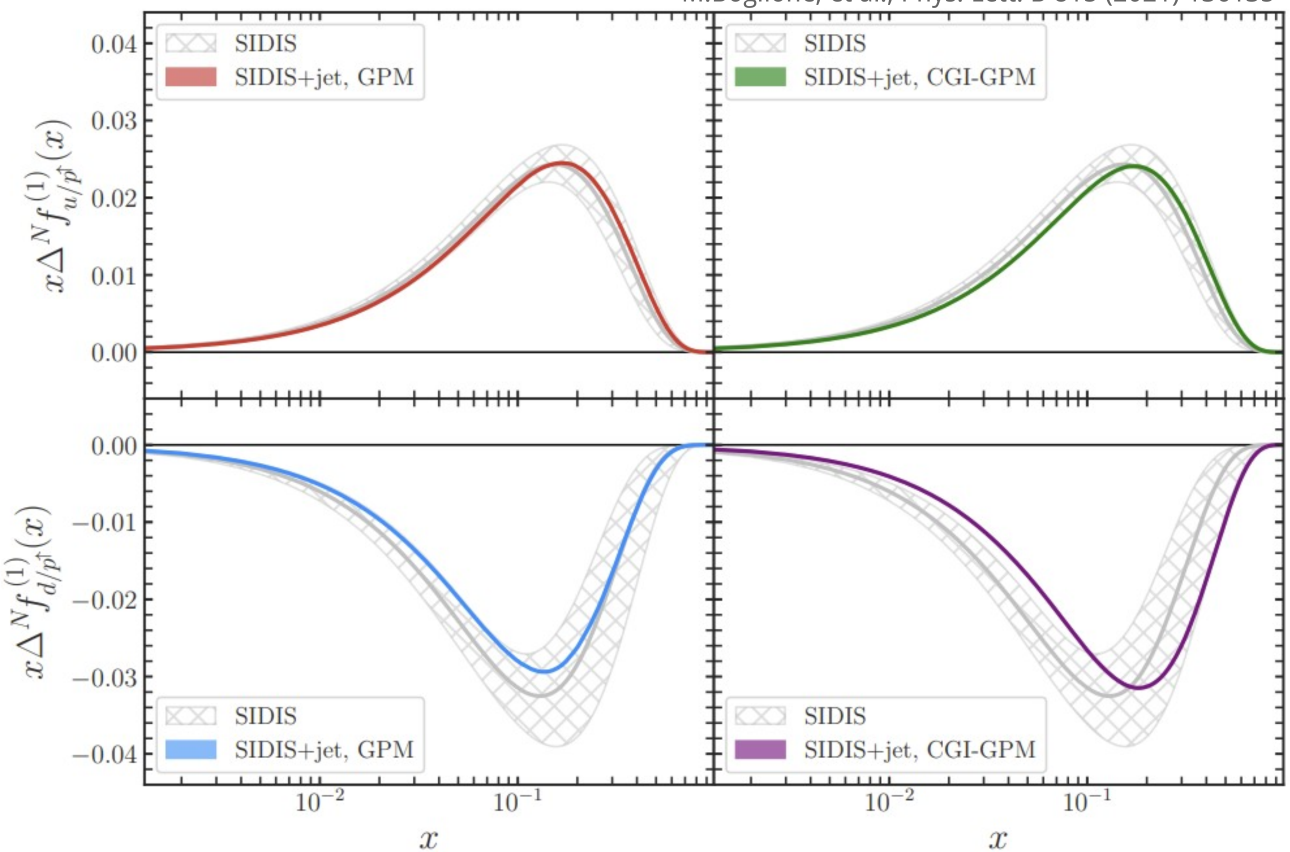
STAR forward upgrade capabilities with jets and charged hadrons

- Study forward Sivers, Collins and Diffractive processes:
  → charged-hadron enhanced jets (prediction from Twist-3 formalism), hadron in jet Collins asymmetry, diffractive processes with rapidity gaps

ORIGIN OF LARGE FORWARD A_N

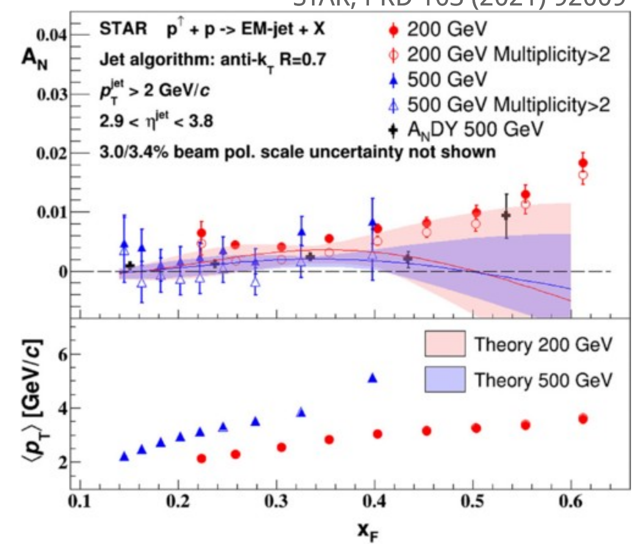
Impact of forward EM jets A_N on u and d Sivers function

M.Boglione, et al., Phys. Lett. B 815 (2021) 136135



Forward EM jets A_N

STAR, PRD 103 (2021) 92009



Theory curves : L. Gamberg, Z. Kang, A. Prokudin, PRL 110 23, 232301 (2013)

STAR forward upgrade capabilities with jets and charged hadrons

- Study forward Sivers, Collins and Diffractive processes:
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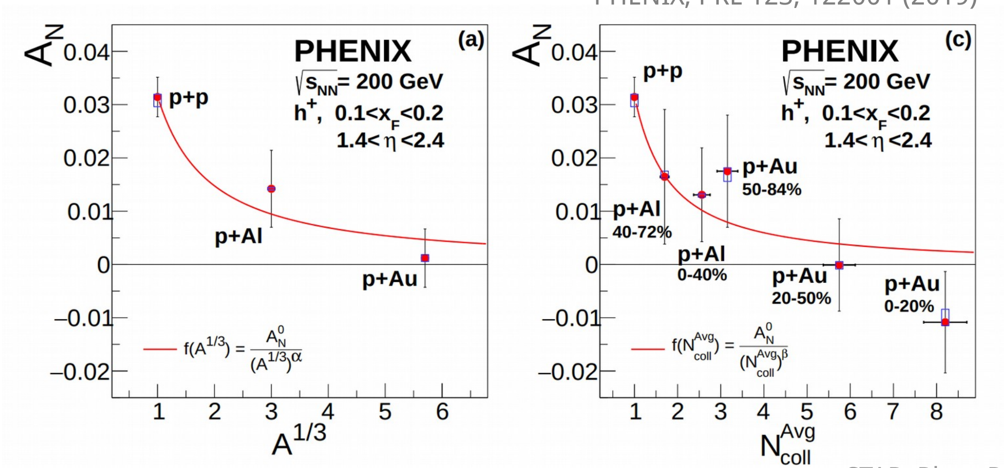
NUCLEAR DEPENDENCE OF A_N

PHENIX, PRL 123, 122001 (2019)



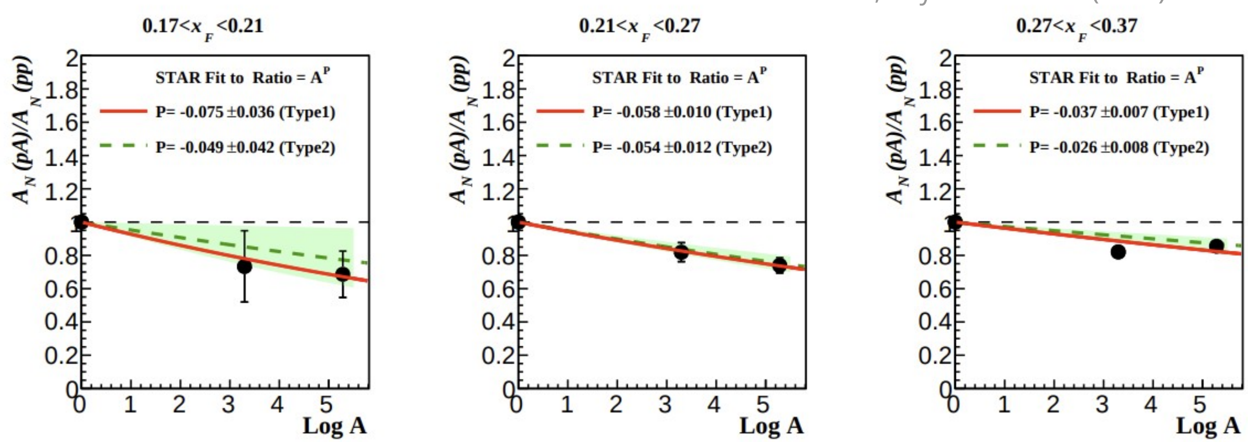
PHENIX charged hadron A_N

$1.4 < \eta < 2.4$

$0.1 < x_F < 0.2$, $1.8 < p_T < 7$

- Noticeable A_N suppression in pA collisions

STAR, Phys. Rev. D 103 (2021) 72005



STAR π^0 A_N $2.6 < \eta < 4.0$

$0.2 < x_F < 0.7$, $1.5 < p_T < 7$

- No strong A dependence

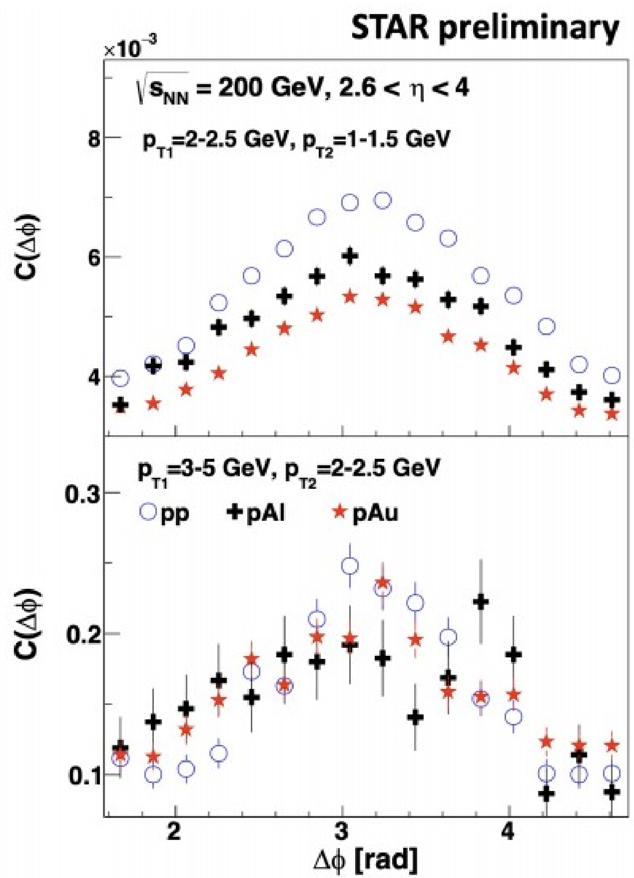
- **Future data taking with** STAR with forward upgrade
  → Capability to measure A_N in the complementary region $2.5 < \eta < 4.0$ for h^+ and h^-
- sPHENIX to improve statistics in the region of $0.1 < x_F < 0.2$

See also new results from PHENIX on very forward neutron A_N PRD103, 032007 (2021)

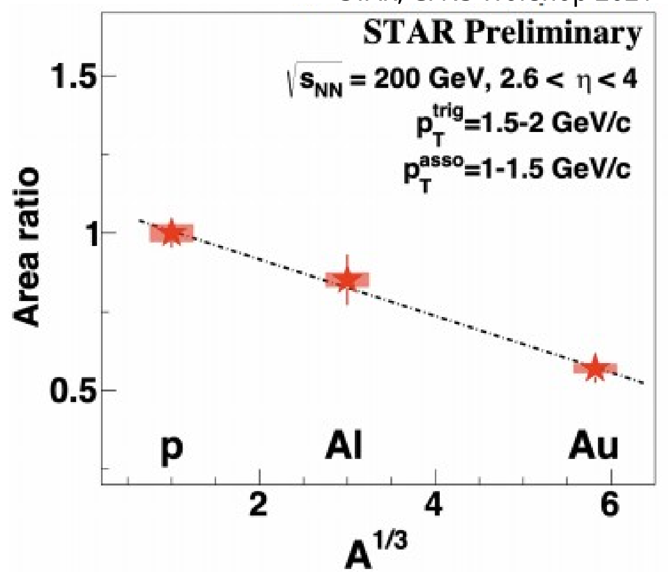
DI-HADRON CORRELATIONS

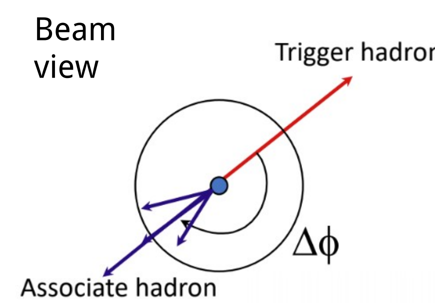
Motivation: Access to **non-linear gluon dynamics** at small x (gluon saturation)

- Saturation scale Q_S: grows with A and decreases with x



STAR, CFNS Worshop 2021





$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig}}$$

- **A dependence**: at low p_T more suppression in pAu than pAl in comparison to the pp
- **x dependence**: at high p_T range (large x) no suppression in pA

Forward jet, photon, and charged hardon capabilities with **STAR forward upgrade**:

- Opportunity for di-h$^{\pm}$, photon-jet, photon-hadron and dijet correlation measurements in pp and pA

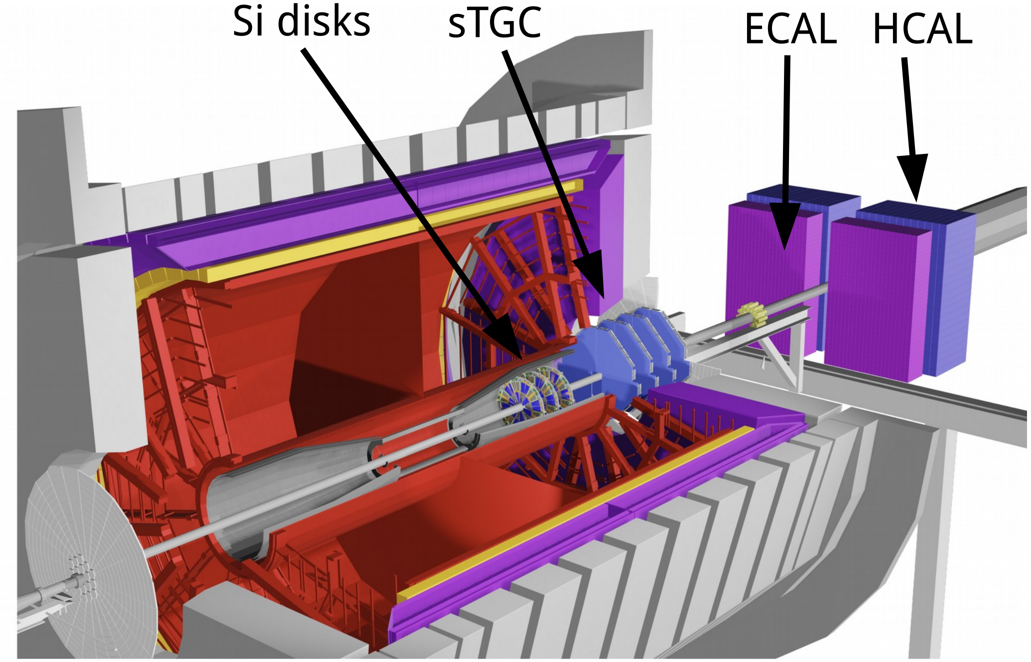
RUN 2022

(see T. Lin's talk, 06/08/21, 11:20)

Program with p↑p↑ at 510 GeV with STAR forward upgrade and enhanced PID at mid-η

Forward jet capability and **charge-sign discrimination**: charged-particle tracking (p_T and sign)

- **Tracking:** Si disks + small Thin Gap Chambers
- **Calorimetry:** hadronic and electromagnetic
- Access to **highly asymmetric partonic collisions**: high x-quark and low-x gluon interactions



Forward rapidity 2.5 < η < 4
TMD measurements at high x › Sivers through tagged jets, direct photon › Transversity at high x + Collins/IFF › Diffractive processes
Midrapidity -1.5 < η < 1.5
Improved statistical precision and the extended acceptance with iTPC › Sivers measurements with W/Z and dijet › Transversity + Collins/IFF › Unpolarized W/Z cross section

Large group of STAR collaborators actively engaged in all aspects of the project:
ACU, BNL, UCLA, UCR, UIC, Indiana University CEEM, UKU, OSU, Rutgers U., Temple U., Texas A&M U., Valparaiso U., Shandong U., NCKU, USTC

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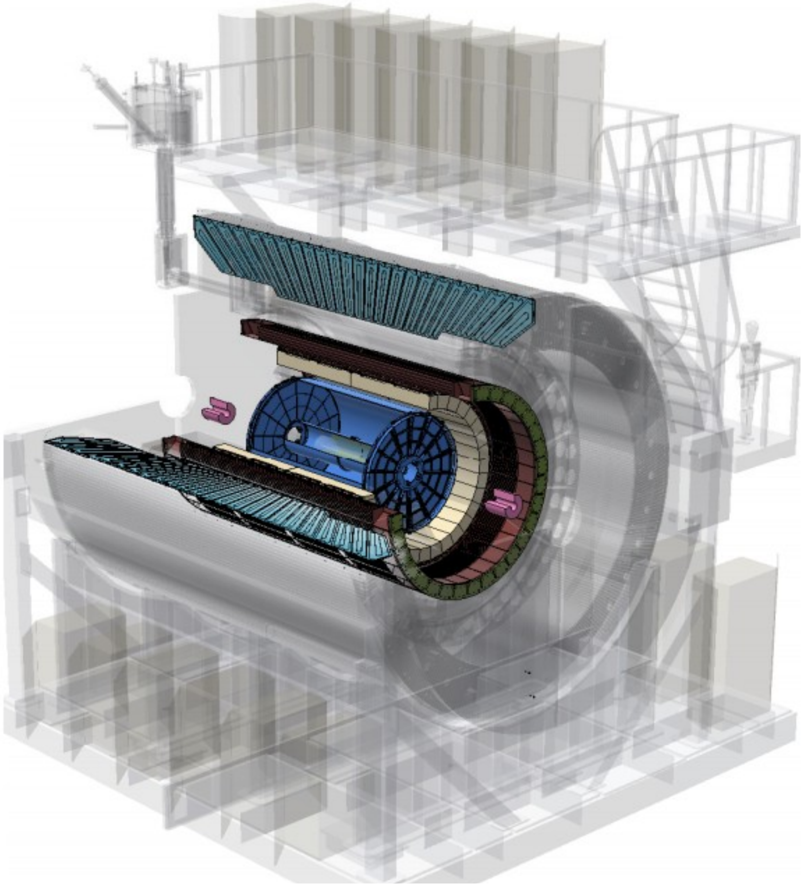
COLD QCD WITH sPHENIX AND STAR

Program with $p^{\uparrow}p^{\uparrow}$, $p^{\uparrow}Au$ at 200 GeV (sPHENIX + STAR) in 2024

- Complementary to each other in the future RHIC measurements

Together with Run 2022 important to **realize the scientific promise of future EIC**:

- Overlap in kinematic coverage with EIC
- Establishing the validity and limits of factorization and universality



Cold QCD opportunities with **sPHENIX**
(see J. Huang 's talk, 06/08/21, 10:55)

→ Utilizing the **jet, heavy flavor** and **direct photon** strengths of the sPHENIX **barrel** to probe

- Sivers and Collins effect and
- Nuclear PDFs and FF in **midrapidity**

Capabilities of **STAR** with forward upgrade
(see T. Lin's talk, 06/08/21, 11:20)

- Allows exploration of **low-x** → gluon saturation
- Nuclear effects in the initial and final state
- Combination of Run 22 results with similar data taken at 200 GeV

SUMMARY

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

RHIC-spin program has provided unique insight into:
- Constraints on the **polarized gluon distribution**
  Evidence for the positive gluon polarization for $x > 0.05$
- The **polarized and unpolarized sea quark** distributions via W/Z production
  Polarized sea quark shows significant preference for $\Delta\bar{u}$ over $\Delta\bar{d}$

- **Sivers' function**
  Initial transverse W-boson data that are consistent with the Sivers' sign-change
  - 2022 with iTPC (STAR) (expected 350 pb^{-1})

  Observation of non-zero Sivers effect in dijets
  - 2017 with higher $\sqrt{s}$ and forward and mid-rapidity regions from 2022/2024

  Twist-3 gluon dynamics with direct photon and HF
  - 2024 sPHENX in mid-rapidiy, 2022/2024 STAR forward rapidities for ETQS function
- **Transversity** through the **Collins and IFF asymmetry**
  Non-zero asymmetries at mid-rapidity that are sensitive to quark-transversity at hard scales
  - 2017 (x 12 more data) and higher statistics and better PID in fwd and mid-rapidity in runs 2022/2024

Ongoing 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**
- Understanding nature of **initial state** and **hadronization** in pA collisions