EXPERIMENTAL COLD QCD AT RHIC

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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
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\[ \bar{p} + \bar{p} \rightarrow \text{jet/dijet/hadrons} + X \]

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

\[ A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum \Delta f_a \otimes \Delta f_b \otimes \Delta a_{LL} \otimes D}{\sum f_a \otimes f_b \otimes \hat{\sigma} \otimes D} \]

LO for illustration

STAR inclusive jet \( A_{\perp L} \) from 2009 data at \( \sqrt{s} = 200 \text{ GeV} \)
PRL 115 (2015) 9, 092002
Included in global pQCD analysis provided evidence for positive gluon polarization for \( x > 0.05 \) at \( Q^2 = 10 \text{ GeV}^2 \)

**Low-x range**
- Extend sensitivity to smaller \( x \):
  - Forward rapidity \( x_g \propto \exp(-y) \)
  - \( \sqrt{s} = 510 \text{ GeV} \) 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

- Consistent with 2009 data, which provided first evidence for **positive gluon polarization for $x > 0.05$**
- Twice larger figure-of-merit ($L^4$) with improved systematics
- Will significantly reduce uncertainty on $\Delta g(x)$ 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

Dijets give stricter constraints to underlying partonic kinematics
- Better constraints on functional form of $\Delta g(x)$ - 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 $\pi$, JETS, AND PHOTONS AT 510 GEV
Towards smaller $x$ and complementary probes

Higher $\sqrt{s}$ 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 $A_{\text{LL}}$ ordering connected to the gluon polarization sign
- Direct photon sensitive to $gq \rightarrow \gamma q$ LO process; clean access to $\Delta g(x)$ (no hadronization)

- Further precision with jet $A_{\text{LL}}$ from Run 2013 data at $\sqrt{s} = 510$ 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 $\Delta g(x)$ well into the future
QUARK-SEA DISTRIBUTIONS
SEA-QUARK HELICITIES

Single spin asymmetry and cross sections for W production

\[ A_{L}^{W^+}(y_W) \propto \frac{\Delta d(x_1) u(x_2) - \Delta u(x_1) \bar{d}(x_2)}{d(x_1) u(x_2) + u(x_1) \bar{d}(x_2)} \]

\[ A_{L}^{W^-}(y_W) \propto \frac{\Delta \bar{u}(x_1) d(x_2) - \Delta d(x_1) \bar{u}(x_2)}{\bar{u}(x_1) d(x_2) + d(x_1) \bar{u}(x_2)} \]

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

\( W^{+/-} \) and Z cross section
- Agreement between theory and experiment
- Support for the NLO pQCD interpretation of asymmetry measurements

Phys. Rev. D 103, 012001
QUARK HELICITIES

Single spin asymmetry for W production at STAR

- 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 $\Delta u$ over $\Delta d$
  → 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

**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 $\eta$ 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)

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

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

- Improved uncertainties from run 2017 preliminary results
- Bury, Prokudin, and Vladimirov PRL 126, 112002 (2021) – extraction includes SIDIS, DY and 2011 STAR data with $N^3\text{LO}$ 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)

\[
\langle \boldsymbol{S}_{\text{proton}} \cdot (\boldsymbol{p}_{\text{proton}} \times \boldsymbol{k}_{T}) \rangle \neq 0
\]

- 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 (\( Q^2 > 160 \text{ GeV}^2 \))
ASYMMETRY FOR DIRECT PHOTONS AND HEAVY FLAVOR ELECTRONS

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

- sPHENIX capabilities in mid-rapidity: direct photons and D⁰ meson asymmetries
- STAR capabilities with forward upgrade: jet, π⁰, charged hadrons, photons Aₐ: 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

Di-hadron correlation measurements

“interference FF” (collinear framework)
Correlation of transverse spin of fragmenting quark and momentum cross-product of di-hadron pair
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 $\sqrt{s} = 200$ 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 transversity 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 $A_N$

- Measured small $A_N$ for EM-jets and Collins asymmetry for $\pi^0$ within EM jets
- Weak dependence on the center-of-mass energy
- $A_N$ for non-isolated $\pi^0$ 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

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Theory curves: J. Cammarota et al. PRD 102, 054002 (2020)
ORIGIN OF LARGE FORWARD $A_N$

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

Forward EM jets $A_N$

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NUCLEAR DEPENDENCE OF $A_N$

**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 $\pi^0$ $A_N$**  
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 $x$

**Forward jet, photon, and charged hadron capabilities with STAR forward upgrade:**
- Opportunity for di-$h^\pm$, photon-jet, photon-hadron and dijet correlation measurements in pp and pA

Forward jet, photon, and charged hadron capabilities with **STAR forward upgrade**:
- Opportunity for di-$h^\pm$, photon-jet, photon-hadron and dijet correlation measurements in pp and pA
**RUN 2022**

**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

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

Project supported by National Science Foundation and Chinese Funds

(see T. Lin’s talk, 06/08/21, 11:20)
COLD QCD WITH sPHENIX AND STAR

Program with $p^+p^+$, $p^+Au$ 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 $350 \text{ pb}^{-1}$)
  - 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-rapidity, 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 ($x \times 12$ 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