Recent STAR Cold QCD Results and Forward Upgrade

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Outline:
• Results on longitudinally polarized program
• Results and Forward Upgrade on
  • Transversely polarized program
  • Unpolarized program
The STAR detector

**Time Projection Chamber**: $|\eta| < 1$, $\Delta \phi = 2\pi$
- Tracking, PID, vertex reconstruction

**Electromagnetic Calorimeter**: $-1 < \eta < 2$, $\Delta \phi = 2\pi$
- Energy measurement

**Time-of-Flight**: $|\eta| < 1$, $\Delta \phi = 2\pi$
- Particle identification

**Forward Meson Spectrometer**: $2.6 < \eta < 4$, $\Delta \phi = 2\pi$
- Energy measurement

Complemented by many ancillary subsystems:
- Beam-Beam Counter
- Vertex Position Detector
- Zero Degree Calorimeter
- Roman Pots
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:
- $h^{\pm}$, $e^{\pm}$ (with good $e/h$ discrimination)
- Photons, $\pi^0$
- Jets, $h$ in jets
- Lambda’s
- Drell-Yan and $J/\Psi$ di-electrons
- Mid-forward and forward-forward correlations

Run period:
- STAR alone (NOW): 2022 → 510 GeV polarized p+p
- STAR in parallel with sPHENIX:
  - 2023 and 2025 → 200 GeV Au+Au
  - 2024 → 200 GeV polarized p+p and p+Au
Longitudinally polarized program

Longitudinally polarized $p+p \rightarrow \Delta f(x, Q^2)$

Polarized gluon distribution $\Delta g$
- $\vec{p}+p \rightarrow \text{jet/dijet/hadron} + X$: $A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \propto \frac{\Delta f_a \otimes \Delta f_b}{f_a \otimes f_b}$

Polarized sea quark distributions
- $\Delta \bar{u}$ and $\Delta \bar{d}$
  - $\vec{p}+p \rightarrow W + X$: $A_L = \frac{\sigma_{++} - \sigma_{--}}{\sigma_{++} + \sigma_{--}}$
  - $W^{+/−} \rightarrow$ natural flavor separation
- $\Delta s$
  - $\Lambda (\bar{\Lambda})$ production: $D_{LL} = \frac{\sigma_{p+p \rightarrow \Lambda^+X} - \sigma_{p+p \rightarrow \Lambda^-X}}{\sigma_{p+p \rightarrow \Lambda^+X} + \sigma_{p+p \rightarrow \Lambda^-X}}$
  - Sensitive to polarized fragmentation functions (FF) and the helicity distributions of $s$ ($\bar{s}$)
STAR inclusive jets $A_{LL}$ at 200 and 510 GeV from 2009 to 2015:

- Consistent results from both energies
- 200 GeV data constrain $\Delta g(x)$ for $x > 0.05$; 510 GeV data push sensitivity to lower $x \to 0.02$
Dijets provide stricter constraints to underlying partonic kinematics:

- Narrow ranges of initial state partonic momentum fraction probed
- More-forward production: lower $x \to 0.01$ (PRD 98 (2018), 032011)
Helicity PDFs: $\Delta \bar{u}$ and $\Delta \bar{d}$

\[
\bar{p} + p \rightarrow W^\pm + X \rightarrow e^\pm + X \\
\sqrt{s} = 510 \text{ GeV} \\
25 < E_T^e < 50 \text{ GeV}
\]

Impact of STAR data

Sea Asymmetry

$\chi(\Delta \bar{u} - \Delta \bar{d})$

- Polarized flavor asymmetry:
  - $\Delta \bar{u} > \Delta \bar{d}$ for $0.05 < x < 0.25$
  - Opposite to the unpolarized flavor asymmetry: $\bar{u} < \bar{d}$
Helicity PDFs: $\Delta s$

- Results show consistency between $\Lambda$ and $\bar{\Lambda}$
- Data agree with various models within uncertainties
- Most precise measurements to date with twice the statistics of the 2009 dataset (STAR, PRD 98 (2018) 112009)

STAR has concluded the collection of longitudinally polarized data


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

Transversely polarized $p+p \rightarrow f(x, k_T, S_T)$

- Transverse Momentum Dependent parton distribution functions (TMDs):
  - Sivers effect
  - Collins fragmentation functions (FF)
- What measurements will Forward Upgrade enable?

arXiv:1212.1701
One of the 8 TMDs known as **Sivers function:**

- **Observables:** transverse single spin asymmetry (TSSA) for jets, $W^{+/−}$, $Z^0$, Drell-Yan

$$A_N = \frac{d\sigma(\phi) - d\sigma(\phi + \pi)}{d\sigma(\phi) + d\sigma(\phi + \pi)}$$
Transversity and Collins fragmentation functions

Transversity

Proton momentum

Parton spin
Nucleon spin

Quark polarization along the spin of a transversely polarized proton

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

• Observables: \( A_{UT}^{\sin(\phi)} \) for pions
• Collins function predicted to be universal
$A_N$ for $W^{+/−}$ and $Z^0$

**Mid-rapidity $W^{+/−}$ and $Z^0$ $A_N$:**
- Statistics much improved with run 2017 (350 pb$^{-1}$) compared to run 2011 (25 pb$^{-1}$)
- Predictions from PRL 126, 112002 (2021)
  - Extraction includes SIDIS, DY and STAR run 2011 results
  - $N^3$LO accuracy of the TMD evolution assuming sign-change

Expect $\sim 350$ pb$^{-1}$ more data from run 2022 with Forward Upgrade and $\eta$ coverage extended by STAR iTPC
**Forward $\pi^0 A_N$:**

- Weak dependence on the center-of-mass energy
- Larger $A_N$ for isolated $\pi^0$: additional mechanism needed to explain asymmetries $\rightarrow$ diffractive processes?
- Suppression of $A_N$ in p+A to $A_N$ in p+p collisions is observed $\rightarrow$ nuclear dependence of TMDs?
$A_N$ for EM-jet

EM-jet reconstructed only using photons

**Forward EM-jet $A_N$:**
- Decreases with increasing photon multiplicity
- Provides substantial constraints on the Sivers effect at high $x$

M.Boglione et al, PLB 815 (2021), 136135

STAR, PRD 103 (2021) 92009

Impact of EM-jet $A_N$
Collins asymmetry for $\pi^\pm$ in jets

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
Transverse physics with Forward Upgrade

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

- Study forward Sivers, Collins and diffractive processes → charge-tagged jets and 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 with Forward Upgrade: low to high x at moderate and high Q^2 → TMD evolution:
  - x up to ~0.5 → sensitive to valence quark
How well Forward Upgrade will do?

Sivers

Forward Upgrade enables full jet reconstruction with charge-sign tagging (no PID) of a hadron fragment:

- **Sivers**: projected statistical uncertainties drawn on twist-3 predictions from Gamberg et al; up to 10 σ separation between plus-tagged and minus-tagged jet $A_N$
- **Transversity**: precise measurements at high $x$ with uncertainties $\sim 10^{-3}$

All Plots: STAR Beam Use Request for Run 2022

Projected uncertainty of the data from 2022

CPHI-2022, Xiaoxuan Chu
Unpolarized program

Unpolarized $p+p$ and $p+A \rightarrow f(x, Q^2)$

- Sea quark distributions and nuclear parton distributions
- What measurements will Forward Upgrade enable?

SeaQuest, Nature 590, 561–565 (2021)

K.J.E at el, EPJC (2017) 77:163
W and Z⁰ cross section

• Sensitive to the region 0.1 < x < 0.3 in STAR mid-rapidity (|η| < 1) at $Q^2 = M_W^2$
• Clean theoretical and experimental observable

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

Expect ~350 pb⁻¹ more data from run 2022 with Forward Upgrade
Nonlinear gluon dynamics in QCD

- Forward rapidities $\rightarrow$ high gluon densities
- STAR $\pi^0 - \pi^0$ correlations: $p_T$, E.A. and A dependence
- This measurement is essential to explore the universality of nonlinear effects along with the future EIC

STAR $\sqrt{s_{NN}} = 200$ GeV, $NN \rightarrow \pi^0\pi^0X$
- $2.6 < \eta < 4$, $\Delta\phi \in [\frac{\pi}{2}, \frac{3\pi}{2}]$
- $p_T^{\text{trig}} = 1.5-2$ GeV/c
- $p_T^{\text{asso}} = 1-1.5$ GeV/c
- $p_{\text{Au/pp}}$, $p_{\text{Al/pp}}$

Relative area

E.A. ($\Sigma E_{\text{BBC}}$)

$A^{1/3}$

$\pm$ $P = -0.09 \pm 0.01$

\[ \sqrt{s_{NN}} = 200 \text{ GeV}, \, NN \rightarrow \pi^0\pi^0X \]

2.6 < $\eta$ < 4, $\Delta\phi \in [\frac{\pi}{2}, \frac{3\pi}{2}]$

$p_T^{\text{trig}} = 1.5-2$ GeV/c

$p_T^{\text{asso}} = 1-1.5$ GeV/c

$p_{\text{Au/pp}}$, $p_{\text{Al/pp}}$
Future measurements with Forward Upgrade

Expanded observables by Forward Upgrade: di-hadron, di-jet, $\gamma$-hadron/jet, inclusive $\gamma$...

- $R_{pAu}^\gamma$ of direct photon: free from the final state effects; precise measurements of nuclear gluon distribution

arxiv:1602.03922
Summary

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

Transversely polarized:
• $A_N$ for W and Z boson $\rightarrow$ precise measurement to investigate Sivers effect
• Non-zero Collins asymmetry for $\pi^\pm$

Unpolarized:
• $W^+/W^-$ ratio $\rightarrow$ constrain sea quark distributions
• Forward $\pi^0 - \pi^0$ correlation $\rightarrow$ evidence of nonlinear gluon dynamics

STAR is taking data with the Forward Upgrade. The upgrade will provide insights in:
• 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 nucleon and nucleus