Recent Results of the STAR Cold QCD Physics Program

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Note: Due to time constraints I will only focus on \textit{p+p} collisions
Proton Structure

- Unpolarized
  - Parton distributions
  - Fragmentation Functions (FF)
- Longitudinal Spin
  - Parton helicity distributions
  - Polarized FF
- Transverse Spin
  - Transverse momentum distributions (TMDs)
  - Exhibit correlations arising from spin-orbit effects
  - Close connection to twist-3 correlations
  - Polarized FF
- STAR has provided insight into all three areas of proton structure.
RhIC at
Brookhaven National Laboratory
Long Island, NY

- World’s only polarized synchrotron collider
- Spin states known for every proton bunch
- Can collide longitudinally or transversely polarized protons.
Solenoid Tracker at RHIC (STAR)

- **Calorimetry** system with $2\pi$ coverage: **BEMC** ($|\eta| < 1$) and **EEMC** ($1 < \eta < 2$)
- **TPC**: tracking and particle ID
- **ZDC**: Relative luminosity and local polarimetry
- **BBC**: Relative luminosity and minimum biased trigger.
- **Forward Meson Spectrometer**
  (not shown) extending $2.6 < \eta < 4$
- **Spin structure** is measured via single and double spin asymmetries (spin-dependent cross section differences).
  \[
  A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}, \quad A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}
  \]
- **Unpolarized structure** is measured using cross sections and cross section ratios.
Gluon Polarization (Central Rapidity)

- STAR data has already had a significant impact on understanding the gluon polarization.

  - Included in DSSV and NNPDF global analyses
  - DSSV $\int_{0.05}^{1} \Delta g(x) \, dx = 0.20^{+0.06}_{-0.07} \ (90\% \ C.L.)$
  - NNPDF $\int_{0.05}^{0.2} \Delta g(x) \, dx = 0.17 \pm 0.06$

- STAR will further constrain the gluon polarization with additional central rapidity data
  - Di-Jets at 200 GeV in 2009
  - Jets and di-jets at 200 GeV in 2015
  - Jets and di-jets at 510 GeV in 2012 and 2013

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Higher center of mass energy accesses lower x
Gluon Polarization (Intermediate Rapidity)

- Requiring more forward jets gives access to even lower $x$, down to 0.01.

- Recently released and upcoming STAR results from 2012 and 2013 at $\sqrt{s} = 510$ GeV will further constrain the gluon helicity and begin to determine its shape.
Gluon Polarization (Forward Rapidity)

- STAR Forward Meson Spectrometer provides calorimetry out to a pseudo-rapidity of 2.6 - 4
- $A_{LL}$ of $\pi^0$ in FMS at $\sqrt{s} = 510 \text{ GeV}$ provides access to gluons down to $x \sim 10^{-3}$
- Analysis of 200 GeV is underway
Quark Helicity Distributions

- Sensitive to sea quark helicity distributions.
- STAR (2011+2012+2013) data provides the most precise $W A_L$ measurement.
- Provides clear evidence of flavor asymmetry in the polarized sea $\Delta \bar{u} > \Delta \bar{d}$.
- Will provide significant constraint on sea quark helicity distributions, in particular $\Delta \bar{u}$ and $\Delta \bar{d}$. 
Quark Helicity Distributions

- Longitudinal spin transfer $D_{LL}$ is sensitive to helicity distributions and polarized fragmentation function.
- In naïve quark model $D_{LL}$ of $\Lambda$ is connected to $\Delta S$.
- New results improve on STAR 2009 results.
- $D_{LL}$ of $\Lambda$ ($\Lambda$) consistent with zero.
- More precision is needed to rule out various models.
Transverse Momentum PDFs (TMDs)

- STAR provides unique kinematic coverage
  - broad range at high $Q^2$
  - low to high $x$
  - Provides excellent opportunity to study TMD evolution

- TMD can be further studied by including other experimental data

STAR unique kinematics: from high to low $x$ at high $Q^2$
Sivers Function: Inclusive Jet $A_N$

- Sivers mechanism correlates proton spin to quark $k_T$, and is an initial state effect.
- Sivers function can be related to twist-3 correlation functions and couples to parton orbital angular momentum.
- Inclusive jet $A_N$ measurements are sensitive to the gluon Sivers function.
- Asymmetries should help constrain twist-3 PDFs for gluonic interactions, which are connected to the gluon Sivers function.
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- New preliminary results at 200 GeV
  - Provide better precision than 500 GeV data

Preliminary

$\sqrt{s} = 200$ GeV
Sivers Function: $W A_N$

- $W A_N$ is sensitive to the anti-quark Sivers functions.
- When compared to SIDIS results can provide a test of the sign change predicted from QCD factorization: $Sivers_{SDIS} = -Sivers_{DY, W/Z}$
- **Run 2011**: Exploratory $A_N(W)$, 25 $pb^{-1}$
  - $W$ kinematics fully reconstructed
  - Favors **sign change**, assuming evolution effects are small
Run 2017: Definitive $A_N(W, Z)$, $A_N(DY)$, $A_N(\gamma)$ 350 pb$^{-1}$

- See sign change if evolution effects are less than a factor of 5
- Probe anti-quark Sivers function for the first time.
- Directly measure evolution effects using $W/Z$ and Drell-Yan
  - Both have similar $x$, but different $Q^2$
  - $W/Z$ central and Drell-Yan forward rapidity
- Currently under analysis
Transversity: Spin Transfer

- Measurements of **transversity** convoluted with
  - Spin transfer
  - Di-hadron interference fragmentation functions (IFF)
  - Collins fragmentation function
- Transverse spin transfer of hyperons provide access to **transversity** and transversely polarized **fragmentation function**.
- First transverse spin transfer measurement in p+p collisions at RHIC.
- $D_{TT}$ of $\Lambda$ ($\bar{\Lambda}$) are consistent with model prediction.
- Asymmetries are small and consistent with zero

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Transversity: IFF

- **IFF Asymmetry** correlates quark polarization to azimuthal distribution of final state hadron pairs
- STAR measurements provide first observations at large $Q^2$
- **Significant** IFF asymmetries at both $\sqrt{s} = 200$ and 500 GeV
  - Provides basis to investigate $Q^2$ evolution of transversity.
- STAR measurements are well described by recent IFF calculations (from $e^+e^-$ and SIDIS fits) hints at universality.
Transversity: Collins

- Collins asymmetry sensitive to **quark transversity**
  - best sensitivity at higher $p_T$

- First observation in polarized proton collisions by STAR
- Data agrees well with theory predictions extracted from SIDIS and $e^+e^-$
  - Suggests universality of Collins function and small factorization breaking.

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Collins asymmetry sensitive to quark transversity
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$Q^2$ evolution can be looked at when 200 GeV data is included
Constraining Gluon Linear Polarization

- First ever measured **Collins-like asymmetry**
  - Gluon analog to Collins FF
  - Sensitive to **gluon linear polarization**
  - Best sensitivity at low $p_T$
  - Provide **first ever** input on linearly polarized gluons in a polarized proton to constrain models.

- **Preliminary** results from **200 GeV** will provide **stronger** constraints.

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**PRD 97 (2018) 032004: 500 GeV**

![Graph showing Collins-like asymmetry results](image.png)
Unpolarized Sea Quarks

- The sea quark distributions need to be better understood, in particular $\bar{d}/\bar{u}$.
- It is evident from global PDF extraction and experiment that more data is needed.
- $W$ cross section ratio at LO is sensitive to $\bar{d}/\bar{u}$:

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

- STAR can provide data in the kinematic range of $0.06 \leq x \leq 0.4$ corresponding to $-2 \leq \eta_e \leq 2$
- Provide constraints on $\bar{d}/\bar{u}$
- 2017 $W$ data will double preliminary statistics.
- STAR differential $W/Z$ cross sections can also be used to help constrain TMDs in global fits (under analysis).
STAR Beyond 2020

- STAR has an opportunity to extend its cold QCD program **beyond 2020** and continue to answer some **fundamental questions** in QCD via a **forward upgrade**.
- This instrumentation upgrade includes **forward calorimeter** and **tracking detectors** that will allow STAR to reach study in more details the forward rapidity range \((2.5 < \eta < 4)\).
  - Ability to probe **higher-x valence region** and **lower x** where gluons and sea quarks are prominent.
- Serve as a **bridge** to EIC physics and an in-situ **testing ground** for EIC R&D technology.
- **Strongly** endorsed by BNL PAC over the last few years.
Summary

- **STAR** has played and will continue to play a **critical** and **complementary** role in resolving the structure of the proton.

- **Longitudinally** polarized p+p collisions have provided insight into
  - **Sea quark** distributions via W/Z production.
  - **Polarized gluon** distribution through jet, di-jet, and π A_{LL}.

- **Transversely** polarized p+p collisions have accessed the transverse spin structure of the proton such as
  - the **Silvers** function through W/Z production.
  - **twist-3** quark/gluon correlators via inclusive Jet asymmetries.
  - **Transversity** sensitive quantities have been probed through the Collins asymmetry and IFF.

- **Unpolarized** p+p collisions have provided and will provide constraints for global analyses
  - Sea quark distributions
  - TMDs

- **STAR forward upgrade** will allow measurements in the rapidity range of \(2.5 \leq \eta \leq 4.0\) and continue to investigate the structure of the proton.