SPIN PHYSICS PROGRAM AT RHIC

Goals:

- Using spin as a unique probe to unravel the internal structure of nucleon
- Understanding the role of spin in QCD

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 proton and properties of QCD?
RHIC – POLARIZED PROTON COLLIDER

• Polarized protons $\sqrt{s} = 62, 200, 500$ GeV
• Transverse and longitudinal polarization
• Alternating spin configurations bunch by bunch and fill by fill
• The only polarized high-energy proton-proton collider

Hard scattering processes with control of systematic effects
RHIC – POLARIZED PROTON COLLIDER
SOLENOIDAL TRACKER AT RHIC

Electromagnetic Calorimeter
- $\Delta \phi = 2\pi$, $-1 < \eta < 2$
- Barrel ($|\eta| < 1$) and Endcap ($1 < \eta < 2$)
- Energy measurement, trigger

Time Projection Chamber
- $\Delta \phi = 2\pi$, $|\eta| < 1$, 0.5 T
- PID, tracking, vertex reconstruction

Time of Flight Barrel
- $\Delta \phi = 2\pi$, $|\eta| < 1$
- PID

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

Beam-Beam Counter
Vertex Position Detector
- Relative luminosity and MB trigger

Zero Degree Calorimeter
- Relative luminosity and local polarimetry

Roman Pots

Forward Upgrade (discussed later)

Characteristics
- Large acceptance (PID and calorimetry)
- Good for jets and correlations
- Upgrades: iTPC, EPD, ETOF
PHENIX DETECTOR

Central Arm
- $|\eta| < 0.35$, $\Delta \phi = 2 \times \pi/2$, 0.78 T
- VTX detector
- Electromagnetic Calorimeter
- Tracking: Drift chambers, Pad chambers
- PID: RICH, ToF

Muon Arm
- $1.2 < |\eta| < 2.4$, $\Delta \phi = 2\pi$, 0.72 T
- Muon PID and Tracking
- PID, tracking, vertex reconstruction

Muon Piston Calorimeter
- $\Delta \phi = 2\pi$, $3.1 < |\eta| < 3.9$

Beam-Beam Counter
Zero Degree Calorimeter
- Relative luminosity

Characteristics
- High rate capabilities + good resolution
- Central arms: $\pi^0$ and $\eta$
- Muon arms

I do not discuss BRAHMS, $A_N$DY, pp2pp here

Took data up to 2016
Being replaced by sPHENIX
HOW TO ACCESS GLUON HELICITY?
HOW TO ACCESS $\Delta G$?

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

LO for illustration

Which processes dominate at RHIC?

What are $a_{LL}$ for these processes?

Sensitive to $qg$ and $gg$ – Access to $\Delta G/G$
• Cross-section measurement to support the NLO pQCD interpretation of asymmetries
• Theoretical error includes the PDF uncertainty and sensitivity to the variation of the factorization and renormalization scales (altered simultaneously by factors of 0.5 and 2.0)
CROSS-SECTIONS

di-jet production and photon

Phys. Rev. D 95 (2017) 71103

STAR 2009 Di-jet Cross Section
- Data
- NLO pQCD CT10 + UEH
- UEH Systematic Uncertainty

pp @ \sqrt{s} = 200 GeV
- Anti-k_T, R = 0.6, |η_1, η_2| < 0.8
- \int \mathcal{L} dt = 18.5 \text{ pb}^3 \pm 8.8\%


\begin{itemize}
  \item Cross-section measurement to support the NLO pQCD interpretation of asymmetries of correlations and rare probes
\end{itemize}
STATUS OF $\Delta G$

Precision $A_{LL}$

1. $A_{LL}$ positive for large $p_T$ - positive gluon polarization

2. Included in DSSV and the NNPDF PDF fits (NLO)
   - These data drive the constraints on $\Delta G$ in both fits
   - Initial sensitivity to different $x_g$ from rapidities
   - In the PDF fit also PHENIX $\pi^0$ $A_{LL}$ included
     PRD 90, 012007 (2014)

Evidence for positive gluon polarization in the $x$ range $0.05 < x < 0.2$ and at $Q^2 = 10$ GeV$^2$

Run 2009 - 25 pb$^{-1}$
Further precision: Run 2015 – 50 pb$^{-1}$
STATUS OF $\Delta G$

Impact of ALL from 2009 data on $\Delta G$

$\Delta g(x, Q^2=10 \text{ GeV}^2)$

DSSV: $0.20^{+0.06}_{-0.05}$, at 90% C.L. $x > 0.05$

NPDF: $0.23 \pm 0.07$, $0.05 < x < 0.5$
STATUS OF $\Delta G$

Impact of $A_{LL}$ from 2009 data on $\Delta G$

Low-x range

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

High-x range

Further precision from:
- Jet and neutral pion probes
- Complementary probes

\[ \Delta G = \int_0^1 \Delta g(x) \, dx \]
CENTRAL $\pi^0$ AND JETS AT 510 GEV
Towards smaller $x_g$

- Consistent result from both energies and both experiments
- **Higher $\sqrt{s}$ pushes sensitivity to lower $x > 0.02$**
- More to come:
  - 2013 data: High luminosity (300 pb$^{-1}$) 510 GeV STAR
  - 2015 data: Double 2009 statistics 200 GeV: STAR

**STAR:** $A_{LL}$ of $\pi^0$ at 510 GeV with FMS ($2.6 < \eta < 4$), $x > 0.001$, run 2012 (82 pb$^{-1}$) and 2013 (300 pb$^{-1}$)

**PRD 98 (2018), 032013**
DI-JET MEASUREMENT
Towards smaller $x_g$ and complementary probes

Di-jets give stricter constraints to underlying partonic kinematics
- May place better constraints on functional form of $\Delta g(x)$
- More-forward production - lower $x$ down to 0.01, $x_2$ – likely gluon, $x_1$ – likely quark
- Narrow ranges of initial state partonic momentum tested
DI-JET MEASUREMENT
Towards smaller $x_g$ and complementary probes

- Central di-jet measurement Run 2009 $\sqrt{s} = 200$ GeV (25 pb$^{-1}$): PRD 95 (2017), 071103
- Central di-jet measurement Run 2012 $\sqrt{s} = 510$ GeV (82 pb$^{-1}$): PRD 100 (2019), 052005
- Further precision: Run 2015 $\sqrt{s} = 200$ GeV – x 1.5 statistics, Run 2013 $\sqrt{s} = 510$ GeV – x 3.2 statistics

11/14/2019
DI-JET MEASUREMENT
Impact on $\Delta g(x)$

$\Delta g(x, Q^2=10 \text{ GeV}^2)$

- Influence of central and forward di-jets from 2009 data (25 pb$^{-1}$) $\sqrt{s} = 200 \text{ GeV}$ on DSSV calculations

D. de Florian, G. A. Lucero, R. Sassot, M. Stratmann, W. Vogelsang,
FUTURE OPPORTUNITIES

Deep insight with EIC
- Scaling violation in inclusive DIS: $g_1(x, Q^2)$

Predictions for:
- Luminosity: 10 fb$^{-1}$
- Polarization: 70%, Efficiency: 50%

Potential future with forward upgrade
- Di-jet asymmetries with $x$ up to $10^{-3}$
- Luminosity: 1 fb$^{-1}$, Polarization: 60%, Efficiency: 66%
HOW TO ACCESS QUARK-SEA?
**QUARK HELICITIES**

Single spin asymmetry and cross sections for W production

**Goal: Constrain the sea-quark helicity**

**Separation of quark flavour**
- $W^+(W^-)$: 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

**Experiment Signature:**
- Large $p_T$ lepton, missing $E_T$

**Experiment Challenges:**
- Charge-ID at large $|\eta|$  
- Electron-hadron discrimination  
- High luminosity needed
QUARK HELICITIES

Cross sections for W production

• Agreement between theory and experiment for different bosons, for different collision systems, and over a wide energy range

• Support for the NLO pQCD interpretation of asymmetry measurements

• Ratio measurements may provide insights in unpolarized light quark distributions

• PHENIX:
  \[ W \to \mu A_L, \sigma, 1.2 < |\eta| < 2.4, \]
  PRD98, 032007 (2018)
  \[ W \to e A_L, |\eta| < 0.35, PRD93, 051103 (2016) \]
  \[ W \to e \sigma, PRL106 062001 (2011) \]

• STAR:
  \[ W \to e \sigma, PRD85 092010 (2011) \]
  \[ W \to e A_L, |\eta| < 1, PRL113, 072301 (2014) \]
  \[ W \to e A_L, PRL116, 132301 (2016) \]
  \[ W \to e A_L, PRD 99, 051102 (2019) \]
QUARK HELICITIES
Single spin asymmetry for W production at STAR

For covered lepton $\eta$: $0.05 < x_1 < 0.25$

- 2013 data (300 pb$^{-1}$) – Most precise data to date
- Combined precision (full available data set) – **important constraint on sea asymmetry**
- Predictions from DSSV and NNPDF agree with data
- Data agrees with DIS results in the valence region

- Significant preference for $\Delta\bar{u}$ over $\Delta\bar{d}$
- Opposite to the spin-averaged quark-sea distributions
- Verification of different nucleon structure models

PRD 99 (2019), 051102
QUARK HELICITIES
Single spin asymmetry for W production at STAR

PRD 99 (2019), 051102

Motivation to investigate further the sea asymmetry
Opportunities at EIC
• Accurate determination of $\Delta \bar{u}$ and $\Delta \bar{d}$ through CC DIS and SIDIS with pions
• Access to strangeness: SIDIS with kaons and CC mediated charm production in DIS: $W^+s \rightarrow c$

• Significant preference for $\Delta \bar{u}$ over $\Delta \bar{d}$
• Opposite to the spin-averaged quark-sea distributions
• Verification of different nucleon structure models
UNPOLARIZED SEA-QUARK DISTRIBUTIONS
Probing the $\overline{d}(x)/\overline{u}(x)$ ratio

Drell–Yan cross sections
NA51, E866, SeaQuest
Ratio of cross-sections with proton and deuteron target gives access to $\overline{d}(x)/\overline{u}(x)$

\[
\frac{\sigma_{dp}}{2\sigma_{pp}} \sim \frac{1}{2} \left( 1 + \frac{\overline{d}(x)}{\overline{u}(x)} \right)
\]

$W^+/W^-$ cross section ratio at STAR
- Complementary to NA51, E866, and SeaQuest
- STAR data cover $\sim 0.1 < x < \sim 0.3$, $|\eta_e| < 1$
- Higher $Q^2 = M_W^2$

W. Lorenzon (SeaQuest), Hadron-China (2019)
UNPOLARIZED SEA-QUARK DISTRIBUTIONS

Cross sections for W production

- W-boson kinematics determined by reconstructing its recoil
- Rapidity determined from data combined with simulations
- Constraints on global PDF fitting for $\bar{u}$ and $\bar{d}$ quarks through W production at higher $Q^2$ than SeaQuest and NuSea and overlapping x region: 0.1 – 0.3.

Publication in preparation

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

(LO)
SIVERS FUNCTION – SIGN CHANGE
TMD FACTORIZATION AT WORK

TMD factorization formalism used to extract universal **TMDPDFs** and **non-perturbative evolution kernel** from DY/Z boson production

State-of-the-art implementation of TMD factorization
- Analysis performed at NNLO in pQCD
- Scale fixation within the $\zeta$-prescription approach
  $\rightarrow$ non-perturbative evolution values can be used in, e.g., the analysis of polarized TMDPDFs

- 457 data points with restrictive cut on kinematics
  $\rightarrow$ well within TMD factorization range
SIVERS FUNCTION – SIGN CHANGE

Transverse spin structure
- Most observables in pp only related through Twist-3 formalism: collinear quark-gluon-quark correlations (1 hard scale needed, e.g., $p_T$ of hadron or jet)
- TMD parton distributions: e.g. Collins or Sivers functions (require 2 scales, e.g., $p_T$ and $M$ of $W$)

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

Not universal in hard scattering
Rescattering of the stuck parton in the color field of the remnant of polarized proton

$$Sivers_{DIS} = - Sivers_{DY/W/Z}$$

Fundamental prediction about the nature of QCD
SIVERS FUNCTION – SIGN CHANGE

$A_N$ for $W^+$ and $W^-$ at STAR

Nonuniversality of Sivers function in QCD: $Sivers_{DIS} = - Sivers_{DY/W/Z}$

→ Critical test of $k_T$ factorization

PRL 116 (2016), 132301

- STAR: $A_N$ for $W$ production with 25 pb$^{-1}$ of data – $W$ kinematics fully reconstructed
- 2017 results will be based on 350 pb$^{-1}$ data – more definite test
- Other opportunities, e.g. photons (sign change in the Twist-3 formalism), Drell-Yan
- Gradual upgrades to existing STAR forward instrumentation

Fit based on Kang-Qiu (KQ) model Z. Kang and J. Qiu, PRL 103 (2009), 172001
Results favor sign change if evolution effects are not large
SIVERS FUNCTION – SIGN CHANGE

A_N for W^+ and W^- at STAR

Nonuniversality of Sivers function in QCD: Sivers_{DIS} = - Sivers_{DY/W/Z}

→ Critical test of k_T factorization

\[ \begin{align*}
A_N(y^W) & \quad \text{STAR projections} \\
L(\text{det.}) = 400 \text{ pb}^{-1} \\
W^+ & \rightarrow \ell^+ \nu \\
W^- & \rightarrow \ell^- \nu \\
\end{align*} \]

- Uncertainties on sea quarks from DIS and SIDIS measurements large
- Precision data on from DIS from EIC
- Kang-Qiu (KQ) model Z. Kang and J. Qiu, PRL 103 (2009), 172001 → No TMD evolution

• STAR: A_N for W production with 25 pb^{-1} of data – W kinematics fully reconstructed

• **2017 results** will be based on 350 pb^{-1} data – more definite test

• **Other opportunities**, e.g. photons (sign change in the Twist-3 formalism), Drell-Yan

• Gradual **upgrades** to existing STAR forward instrumentation

arXiv:1602.03922
Fixed-target DIS, RHIC-spin, and EIC are truly complementary
RHIC-spin has a unique role in hadro-production with kinematics from high to low $x$ at high $Q^2$
Precision tests of universality when EIC data become available
TRANSVERSITY
TRANSVERSITY

Methods to access it at RHIC: Single spin asymmetries of the azimuthal distributions $A_{UT}$
- Spin-dependent modulation of hadrons in jets → Collins function (TMD FF)
- Di-hadron correlation measurements → “interference FF” (collinear framework)

- Well described by recent IFF asymmetry calculations incorporating SIDIS and Belle $e^+e^-$ data
- 200 GeV data included in global analysis: M. Radici and A. Bacchetta, PRL 120, (2018) 192001

More from STAR on IFF and Collins
- Collins results from 2012 200 GeV (22 pb$^{-1}$) being finalized
- 200 GeV data from 2015 (x 2 more then 2012) & 500 GeV data from 2017 (x 12 more)
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Connection to BSM physics

Tensor charge for a quark type q: first moment of the transversity distribution for valence quarks

\[ \int_0^1 dx \left( h_1^q(x, Q^2) - h_1^{ar{q}}(x, Q^2) \right) \]

Intensity frontier: search for low-energy footprint of BSM physics at higher scales

Neutron EDM \( d_n \): estimate CP violation induced by quark chromo-EDM \( d_q \)

\[ \delta \mathcal{L}_{\text{CPV}} \supset -\frac{ie}{2} \sum_{f=u,d,s,e} d_f \bar{f} \sigma_{\mu\nu} \gamma_5 F^{\mu\nu} f \]

\[ d_n = g_T^u d_u + g_T^d d_d + g_T^s d_s \]

Bounds on CPV sources encoded in quark EDM

Gobal analysis including 200 GeV IFF STAR data:
\[ g_T^T = 0.53(25) \text{ at } Q^2 = 4 \text{ GeV}^2 \]
M. Radici and A. Bacchetta, PRL 120, (2018) 192001
ORIGIN OF LARGE FORWARD $A_N$
ORIGIN OF LARGE FORWARD $A_N$

Puzzle since E704

- Large asymmetries nearly independent on $\sqrt{s}$ (especially $\pi^0$)

- Interpretations within Twist-3 formalism:
  - K. Kanazawa, Y. Koike, A. Metz, and D. Pitonyak, PRD 89 (2014), 111501(R) – 3-parton collinear FF fit to RHIC data + soft-gluon pole term fixed – good description of $\pi A_N$

arXiv:1602.03922
ORIGIN OF LARGE FORWARD $A_N$

- Description of $A_N$ beyond pQCD $2 \rightarrow 2$ process
- Low-multiplicity observation suggests diffraction mechanism
- STAR Roman Pots + FMS ($2.6 < \eta < 4$) – direct access to diffractive $A_N$
OUTLOOK

STAR Forward Upgrade

- Ensure jet ($\sqrt{s} = 500$ GeV) and Drell-Yan capability, and charge-sign discrimination
- Access to the charged hadron asymmetries and flavor-enhanced jets up to the highest $\sqrt{s}$ at RHIC
- Drell-Yan and direct photon – initial state and hadronization in nuclear collisions, Sivers sign change
- Full jets in forward direction – TMDs at low and high $x$ and $\Delta g(x)$ at small $x$

- **Tracking:** Si disks + small Thin Gap Chambers
- **Calorimetry:** hadronic and electromagnetic

Experts at the workshop: E.-C. Aschenauer, Z. Ye

### PLANS WITH FORWARD UPGRADE


<table>
<thead>
<tr>
<th>Year</th>
<th>√s (GeV)</th>
<th>Delivered Luminosity</th>
<th>Scientific Goals</th>
<th>Observable</th>
<th>Required Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>2023</td>
<td>p+p @ 200</td>
<td>300 pb(^{-1}) 8 weeks</td>
<td>Subprocess driving the large (A_N) at high (x_F) and (\eta)</td>
<td>(A_N) for charged hadrons and flavor enhanced jets</td>
<td>Forward instrum. ECal+HCal+Tracking</td>
</tr>
<tr>
<td>2023</td>
<td>p+Au @ 200</td>
<td>1.8 pb(^{-1}) 8 weeks</td>
<td>What is the nature of the initial state and hadronization in nuclear collisions</td>
<td>(R_{pAu}) direct photons and DY</td>
<td>Forward instrum. ECal+HCal+Tracking</td>
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<td></td>
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<td></td>
<td>Clear signatures for Saturation</td>
<td>Dihadrons, γ-jet, h-jet, diffraction</td>
<td></td>
</tr>
<tr>
<td>2023</td>
<td>p+Al @ 200</td>
<td>12.6 pb(^{-1}) 8 weeks</td>
<td>A-dependence of nPDF, A-dependence for Saturation</td>
<td>(R_{pAl}) direct photons and DY</td>
<td>Forward instrum. ECal+HCal+Tracking</td>
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<td>Dihadrons, γ-jet, h-jet, diffraction</td>
<td></td>
</tr>
<tr>
<td>2021</td>
<td>p+p @ 510</td>
<td>1.1 fb(^{-1}) 10 weeks</td>
<td>TMDs at low and high (x)</td>
<td>(A_{LL}) for Collins observables, i.e. hadron in jet modulations at (\eta &gt; 1)</td>
<td>Forward instrum. ECal+HCal+Tracking</td>
</tr>
<tr>
<td>2021</td>
<td>p+p @ 510</td>
<td>1.1 fb(^{-1}) 10 weeks</td>
<td>(\Delta g(x)) at small (x)</td>
<td>(A_{LL}) for jets, di-jets, h/γ-jets at (\eta &gt; 1)</td>
<td>Forward instrum. ECal+HCal</td>
</tr>
</tbody>
</table>

- **2023**: Concurrent with sPHENIX run: opportunities with and without forward instrumentation
- **2021/22 (potential)**: More high-impact science with unique forward capabilities of STAR following the completion of the ongoing BES-II campaign and before RHIC running with sPHENIX
PROTON-NUCLEUS COLLISIONS
Probing initial state in AA collisions

Adapted from arXiv:1602.03922

- Understanding of initial state: critical for LHC and RHIC program
- Our knowledge about nPDFs still limited

Opportunities at RHIC:
- pAl, pAu
  → A-dependence of nPDFs
  → Test saturation models predictions of A-dependence
- moderate $Q^2$ and medium and low $x$ → nuclear effects large

\[ R_{pA} \text{ for Drell-Yan } \rightarrow \text{nuclear modification of sea-quarks} \]
\[ R_{pA} \text{ for direct forward photon } \rightarrow \text{gluons} \]
Free of final state effects

Armesto, N. et al. EPJC (2016) 76, 218
PROTON-NUCLEUS COLLISIONS
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$R_{pA}$ for direct forward photon → gluons
Free of final state effects

Armesto, N. et al. EPJC (2016) 76, 218
SUMMARY

RHIC-spin program has provided unique insight into:

- The **polarized sea quark** distributions via W/Z production
- Constraints on the **polarized gluon distribution**
  - Towards lower x: high luminosity 2013 data at \(\sqrt{s} = 510\) GeV
  - Towards precision in current x region: 2015 data at \(\sqrt{s} = 200\) GeV
- **Sivers’ sign-change** from W-boson data
  - Sivers’ measurements with W-bosons, Drell-Yan, and photons in 2017 (x 12 more data)
- **Transversity** through the **Collins and IFF asymmetry** and **gluon linear polarization** through the the **Collins-like asymmetry**
  - More data from 2015 run (x 1.5 for \(\sqrt{s} = 200\) GeV and x 12 for 510 GeV)

Ongoing forward 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**
- Accessing **gluon helicities** at lower x
- Understanding nature of **initial state** and **hadronization** in pA collisions

Precision measurements at RHIC important for meaningful comparisons and interpretation with future EIC data to test the **factorization** and **universality**.

**Polarized proton program at RHIC is an important precursor to EIC**
THANK YOU

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PROTON-NUCLEUS COLLISIONS

Saturation

- Evidence seen at HERA, RHIC, and LHC alternative explanations remain
- Key observable at RHIC: **di-hadron correlations**
- CGC predicts suppression
- Study the evolution of $Q_s^2$ in $x$ and $A$-dependence
- Resolve ambiguity what causes the suppression in dAu

Increased luminosity with **forward upgrade**
Additional probes: photon, photon-jet, photon-hadron and di-jet correlations
PROTON-NUCLEUS COLLISIONS

Saturation

Increased luminosity with **forward upgrade**
Additional probes: photon, photon-jet, photon-hadron and di-jet correlations

- Sensitive to gluon dipole
- Expected 1M forward γ+jet events in 2023 pAu and pAl
  - 0.001 < x < 0.005
  - arXiv:1602.03922

- Correlation in minimum bias pp and pAu

**Nuclear modification factor**

Error estimation: variation of $Q_s^2$ from studies of DIS structure functions and particle production in min-bias pp, pA and AA collisions in the CGC formalism
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For a complete picture of nucleon spin structure at leading twist: transversity

Methods to access it at RHIC
Single spin asymmetries of the azimuthal distributions $A_{UT}$

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 and momentum cross-product of di-hadron pair
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Interference Fragmentation Function (IFF)

- The angle $\phi_{RS} = \phi_R - \phi_S$ modulates the asymmetry due to the product of transversity and the IFF by $\sin(\phi_{RS})$

- First significant transversity signal measured in the central detector in pp collisions
- Well described by recent IFF asymmetry calculations incorporating SIDIS and Belle $e^+e^-$ data

- Global analysis including the IFF results from 200 GeV pp collisions
  M. Radici and A. Bacchetta, PRL 120, (2018) 192001
  → Reduction of the uncertainty for $h_1^u$
  → uncertainty for $h_1^d$: dominated by $g \rightarrow \pi^+\pi^-$ FF

PLB 780 (2018), 332
TRANSVERSITY

Interference Fragmentation Function (IFF)

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  - Reduction of the uncertainty for \( h_1^u \)
  - Uncertainty for \( h_1^d \): dominated by \( g \rightarrow \pi^+\pi^- \) FF
TRANSVERSITY
Collins asymmetry

Transversity $\times$ Collins

$$d\sigma_{UT} \sim d\sigma_{UU}[1 + A'_{UT} \sin(\phi_S - \phi_H) + A''_{UT} \sin(\phi_S - 2\phi_H)]$$

The angle $\phi_{SH} = \phi_S - \phi_H$ modulates the asymmetry due to the product of transversity and the Collins function by $\sin(\varphi_{RS})$

D’Alesio, Murgia & Pisano
PLB 773 (2017), 300

Kang, Prokudin, Ringer & Yuan,
PLB 774 (2017), 635
without and with evolution

- Theory predistions using transversity and Collins FF extracted from SIDIS and $e^+e^-$
- TMD Evolution effects appear to be small
TRANSVERSITY

Collins-like Asymmetry

- First ever measured Collins-like Asymmetry
- First limit on linearly polarized gluons in a polarized proton
- Best sensitivity at low $p_T$
- First input to constrain models

More from STAR on IFF and Collins
- Collins results from 2012 200 GeV being finalized
- 200 GeV data from 2015 (x 2 more then 2012)
- 500 GeV data from 2017 (x 12 more)
Opportunities with a future 500 GeV Run
• Statistical uncertainties based on an accumulated luminosity of 268 pb$^{-1}$
Current understanding of nPDFs still limited

- LHC: p+Pb, very high $Q^2$, nuclear effects reduced by evolution

- RHIC: p+Al, p+Au (A-dependence), moderate $Q^2$, medium and low $x$

Golden channels:
- $R_{pA}$ for Drell-Yan $\rightarrow$ nuclear modification of sea-quarks
- $R_{pA}$ for direct forward photon $\rightarrow$ gluons

Impact of the LHC Run-I data on the nPDFs
ORIGIN OF LARGE FORWARD $A_N$

Small forward jet $A_N$ from $A_N$DY Collaboration, PLB 750 (2015), 660

- L. Gamberg, Z.-B. Kang, and A. Prokudin, PRL 110 (2013), 232301 – Twist-3 parton correlation function for u and d valence quarks cancel
- Pursue charged-pion enhanced jets, and possible Twist-3 origin of forward $A_N$ with improved photon $A_N$ measurements
- Diffractive origin: Roman-Pot data (exist on tape) + full forward jet-capability and tracking are needed to pursue cancellation scenarios
NUCLEAR DEPENDENCE OF $A_N$

Very forward neutron

In the **perturbative** region:

- color-glass-condensate models: hadronic $A_N$ should decrease with increasing $A$
  
  e.g. Y. V. Kovchegov and M. D. Sievert, PRD 86, 034028 (2012)

- Some approaches based on pQCD factorization: $A_N$ would stay approximately the same
  

No studies in **nonperturbative** region or diffractive scattering

Possible explanation:

- EM processes important at large $Z$
- nonresonant photo-$\pi^+$ production and $n$ from photonucleon excitation - $\Delta$ resonance
ΔG AT EIC

Constrain Δg through scaling violations of $g_1$
full NNLO [NPB 417 (1994) 61; NPB 889 (2014) 351]
map Δg with an accuracy of 10% (or better) at $x > 10^{-4}$
may be advantageous to measure $Δσ$ instead of $A_1^P$ or $g_1^P$.

Study possible deviations from DGLAP evolution
not clear if EIC kinematic range is large enough
the shape of Δg at small x may change significantly.
DI-JET MEASUREMENT
Towards smaller $x_g$ and complementary probes

- Di-jets give stricter constraints to underlying partonic kinematics
- May place better constraints on functional form of $\Delta g(x)$
- More-forward production - lower $x$ down to 0.01, 2 – likely gluon, 1 – likely quark
- Narrow ranges of initial state partonic momentum tested

\[ M = \sqrt{x_1 x_2 s} \]
\[ \eta_3 + \eta_4 = \ln \frac{x_1}{x_2} \]
\[ x_1 = \frac{1}{\sqrt{s}} (p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}) \]
\[ x_2 = \frac{1}{\sqrt{s}} (p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4}) \]

Unlike-sign topology

\[
\begin{align*}
\eta^3, p_T^3 \\
\eta^4, p_T^4
\end{align*}
\]

Same-sign topology

\[
\begin{align*}
\eta^3, p_T^3 \\
\eta^4, p_T^4
\end{align*}
\]

Forward jets probe lower values of $x_g$
DI-JETS MEASUREMENT

Towards smaller $x_g$ and complementary probes

- Di-jets give stricter constraints to underlying partonic kinematics
- May place better constraints on functional form of $\Delta g(x)$
- Much narrower ranges of initial state partonic momentum tested
- Different di-jet topologies enhances sensitivity of the data to selected $x$

2015 data at 200 GeV (2x statistics)
DI-JET MEASUREMENT
Towards smaller $x_g$ and complementary probes: $\sqrt{s} = 510$ GeV

PRD 100 (2019), 052005
DI-JET MEASUREMENT
Impact on $\Delta g(x)$

- Influence of central and forward di-jets from 2009 data $\sqrt{s} = 200$ GeV on DSSV calculations
FORWARD PION PRODUCTION
Towards smaller $x_g$ and complementary probes

- $A_{LL}$ of neutral pions at 510 GeV
- Measured with FMS (2.6 < $\eta$ < 4)
- Access to gluons $x > 0.001$

1 – likely quark, 2 – likely gluon

- All available 510 GeV analyzed: run 2012 (82 pb$^{-1}$) and 2013 (300 pb$^{-1}$)
- Run 2015 at 200 GeV (50 pb$^{-1}$) – analysis underway. Can probe $x > 0.0025$. 

PRD 98, (2018) 032013
HELICITY OUTLOOK

Helicity structure of proton from STAR

1. Non-perturbative sea-quark polarization at W-mass scale, free of fragmentation uncertainties

2. Insight into gluon polarization:

   **Low-x range**
   - Inclusive jets at 510 GeV
   - Di-jets at 510 GeV in mid-rapidity region
   - Forward pion measurements with FMS

   **High-x range**
   Run 2015 at 200 GeV (50 pb⁻¹)
   Further precision:
   - Central inclusive jet measurement
   - Central di-jet measurement
QUARK HELICITIES

Single spin asymmetry and cross sections for W production

- Cross sections well-described by NLO pQCD theory (FEWZ + MSTW08),
- Support NLO pQCD interpretation of the asymmetry measurements

- PHENIX:
  \( W \to \mu A_L, \sigma, 1.2 < |\eta| < 2.4, \) PRD98, 032007 (2018)
  \( W \to e A_L, |\eta| < 0.35, \) PRD93, 051103 (2016)
  \( W \to e \sigma, \) PRL106 062001 (2011)

- STAR:
  \( W \to e A_L, |\eta| < 1, \) PRL113, 072301 (2014)
  \( W \to e \sigma, \) PRD85 092010 (2011)
## TRANSVERSE SPIN MEASUREMENTS

### TMD formalism

<table>
<thead>
<tr>
<th><strong>Sivers function</strong> – correlation between parton transverse momentum and nucleon transverse spin</th>
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<tbody>
<tr>
<td>[ T_{q,F}(x, x) = - \int d^2 k_\perp \frac{</td>
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<table>
<thead>
<tr>
<th><strong>Collins function</strong> – correlation of the transverse spin of a fragmenting quark and the transverse momentum of a hadron</th>
</tr>
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<tbody>
<tr>
<td>Requires 2 scales: hard scale ( Q^2 ) and soft scale ( p_T )</td>
</tr>
<tr>
<td>Where: ( \lambda_{QCD} &lt; p_T &lt;&lt; Q )</td>
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</table>

### Twist-3 formalism

<table>
<thead>
<tr>
<th><strong>ETQS function</strong> – transverse momentum integrated distribution Twist-3 analog</th>
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<tbody>
<tr>
<td>Twist-3 analog fragmentation function</td>
</tr>
<tr>
<td>Requires 1 scale: ( Q^2 ) or ( p_T )</td>
</tr>
<tr>
<td>Where: ( \lambda_{QCD} &lt;&lt; p_T, Q )</td>
</tr>
</tbody>
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### Observables

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<th><strong>Observables</strong>: azimuthal dependences of hadrons within a jet, Drell-Yan, W/Z</th>
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<tbody>
<tr>
<td><strong>Observables</strong>: Inclusive ( A_N ) (( \pi^0, \gamma, \text{jet, charmed mesons} ))</td>
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TRANSVERSITY

For a complete picture of nucleon spin structure at leading twist: transversity

Transversity: $\delta q(x)$
Net density of quarks with spin aligned with the transversely polarized nucleon

- Difficult to access - **chiral-odd nature**
- Couples to chiral-odd fragmentation functions
- Much less data than for helicity
- Before observed in SIDIS combined with $e^+e^-$
- First **global analyses**: simultaneously the transversity and polarized FF
- All show large uncertainties
STAR: KINEMATIC COVERAGE
IFF and Collins asymmetry

PRD 97 (2018), 032004
TRANSVERSITY

Collins asymmetry

- 500 GeV pp results hinted the $A_{UT}$ peak shifts to higher $j_T$ as $z$ increases
- Preliminary 200 GeV pp results show similar behavior
- Hadron $j_T$ is independent of initial state transverse momentum
- Additional statistics for both 200 ($x \approx 2.5$) and 500 GeV ($x \approx 12$) available

Collins asymmetry

\[
\sin(\theta_S - \phi_T) = A_{UT} \sin(2\theta_S)
\]
TWIST-3

Heavy flavor $A_N$

- PHENIX: $A_N$ $\mu$ asymmetries from open heavy-flavor decays at $\sqrt{s} = 200$ GeV.
- Heavy flavor asymmetries sensitive to twist-3 tri-gluon correlator

Asymmetries were found to be small and in agreement with model calculations for twist-3 ($D \rightarrow \mu$)
UNPOLARIZED PDFs
HELICITY DEPENDENT PDFs