SPIN PHYSICS PROGRAM AT RHIC

Goal:

Using spin as a unique probe to unravel the internal structure and the QCD dynamics of nucleons with unprecedented precision

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 polarized quark-sea in the nucleon?
- What do transverse-spin phenomena teach us about the structure of proton?
RHIC – POLARIZED PROTON COLLIDER

- Polarized proton √s = 62, 200, 500 GeV
- Transverse and longitudinal polarization
- Alternating spin configurations bunch by bunch and fill by fill

Hard scattering processes with control of systematic effects
## RHIC – POLARIZED PROTON COLLIDER

<table>
<thead>
<tr>
<th>Year and $\sqrt{s}$</th>
<th>STAR $L$ [pb$^{-1}$]</th>
<th>PHENIX $L$ [pb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal runs</strong></td>
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<tr>
<td>$\sqrt{s} = 200$ GeV</td>
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<td>2009</td>
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<td>2015</td>
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<tr>
<td>$\sqrt{s} = 500/510$ GeV</td>
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<td>2009</td>
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<td>2011</td>
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<td>2012</td>
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<tr>
<td>2013</td>
<td>300</td>
<td>155</td>
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<td><strong>Transverse runs</strong></td>
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<tr>
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<td>320</td>
<td>-</td>
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</tbody>
</table>
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

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

Took data up to 2016
**HELCITY STRUCTURE OF PROTON**

Density of partons with spin aligned with a longitudinally polarized proton that carry a fraction $x$ of proton momentum

**Helicity $\Delta f(x)$**

How do gluons contribute to the proton spin?

**Double polarization**

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

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

What is the landscape of the polarized sea in the proton?

**Single polarization + weak interaction**

$$\bar{p} + p \rightarrow W^{+/-} \rightarrow e^{+/-} + \nu$$

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$
HOW TO ACCESS $\Delta G$?
**HOW TO ACCESS \( \Delta G \)?**

\[
A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Delta G}{G} - \frac{\Delta q}{q} + \frac{\Delta G}{G}
\]

Which processes dominate at RHIC?

What are \( a_{LL} \) for these processes?

Sensitive to \( qg \) and \( gg \) – Access to \( \Delta G/G \)

**ArXiv:1501.01220**

Subprocess fraction in central jet production

**HOW TO ACCESS $\Delta G$?**

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

LO for illustration

**Which processes dominate at RHIC?**

Sensitive to $qg$ and $gg$ – Access to $\Delta G / G$

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

Subprocess fraction in central jet production

arXiv:1501.01220

1. Significant advance in respect to old data:
   • About an order in precision
   • Extended kinematic range
   • Initial sensitivity to different $x_g$ from rapidities

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

3. Included in DSSV and the NNPDF PDF fits (NLO)
   • These data drive the constraints on $\Delta G$ in both fits

   **DSSV:** $0.20^{+0.06}_{-0.05}$, at 90% C.L., $x > 0.05$
   **NNPDF:** $0.23 \pm 0.07$, $0.05 < x < 0.5$

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

Low-x range

- Improving constrain for $x < 0.05$
- Extend sensitivity to smaller $x_g$:
  - forward rapidity
  $$x_g \propto \exp(-\eta)$$
  - $\sqrt{s} = 510\text{ GeV}$ data
  $$x_g \propto \frac{1}{\sqrt{s}}$$

High-x range

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

$$\Delta G = \int_0^1 \Delta g(x) \, dx$$

$Q^2 = 10\text{ GeV}^2$
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 510 GeV: STAR and PHENIX
  - 2015 data: Double 2009 statistics 200 GeV: STAR

STAR: $A_{LL}$ of $\pi^0$ at 510 GeV with FMS ($2.6 < \eta < 4, x > 0.001$) PRD 98 (2018), 032013

STAR: $A_{LL}$ of $\pi^0$ at 200 GeV at midrapidity PRD 80 (2009), 111108
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

\[
M = \sqrt{x_1 x_2 s} \\
\eta_3 + \eta_4 = \ln \frac{x_1}{x_2}
\]

**Unlike-sign topology**

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

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

**Same-sign topology**

**Forward jets probe lower values of $x_g$**
DI-JET MEASUREMENT
Towards smaller $x_g$ and complementary probes

- Central di-jet measurement Run 2009 $\sqrt{s} = 200$ GeV: PRD 95 (2017), 071103
- Central di-jet measurement Run 2012 $\sqrt{s} = 510$ GeV: arXiv:1906.02740, Accepted for publication in PRD
- Further precision: Run 2015 $\sqrt{s} = 200$ GeV – x 1.5 statistics
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
QUARK-SEA HELICITIES
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

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

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

(LO)

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 with NLO pQCD theory and with other experiments
- Support for the NLO pQCD interpretation of asymmetry measurements

- W+/W-: Probing the $\overline{d}(x)/\overline{u}(x)$ ratio
- Complementary to NA51, E866, and SeaQuest
- STAR data cover $~0.1 < x < ~0.3$, $|\eta_e| < 1$
- Run 17: 350 pb$^{-1}$ of polarized data
QUARK HELICITIES
Single spin asymmetry for W production at STAR

PRD 99 (2019), 051102; PRL 116 (2016), 132301

\[ \vec{p} + p \rightarrow W^\pm + X \rightarrow e^\pm + X \]

\( s = 510 \text{ GeV} \)
\( 25 < E_T < 50 \text{ GeV} \)

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

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
TRANSVERSITY
TRANSVERSITY

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
TRANSVERSITY

Interference Fragmentation Function (IFF)

- The angle $\varphi_{RS} = \varphi_R - \varphi_S$ modulates the asymmetry due to the product of transversity and the IFF by $\sin(\varphi_{RS})$

- 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

![Diagram](image-url)
TRANSVERSITY

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**TRANSVERSITY**

Collins asymmetry

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

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

- Theory predictions 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 than 2012)
- 500 GeV data from 2017 (x 12 more)

Precision data at fixed $x$ and different $\sqrt{s}$ → ideal to constrain TMD evolution
SIVERS FUNCTION – SIGN CHANGE
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

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

---

**Notation:**
- **DIS**: Final-state interaction
  - Opposite colors attract
- **Drell-Yan, W or Z**: Initial-state interaction
  - Like colors repel

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

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

→ Critical test of $k_T$ factorization

- 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

• 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

08/24/2019 M. Żurek – RHIC Spin Results
SIVERS FUNCTION – SIGN CHANGE

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

- Critical test of \( k_T \) factorization

- Kang-Qiu (KQ) model Z. Kang and J. Qiu, PRL 103 (2009), 172001
  - No TMD evolution
  - TMD evolved

- 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
ORIGIN OF LARGE FORWARD $A_N$
ORIGIN OF LARGE FORWARD $A_N$

Puzzle since E704

08/24/2019  M. Żurek – RHIC Spin Results  Page 32

- 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 $A_N$
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
OUTLOOK

STAR Forward Upgrade

- Access to the charged hadron asymmetries up to the highest $\sqrt{s}$ at RHIC
- Full jets in forward direction at $\sqrt{s} = 200$ and 500 GeV - TMDs at low and high $x$ and $\Delta g(x)$ at small $x$
- Precision $A_N$ (Drell-Yan) to complete the Sivers measurements

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

SUMMARY

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

From **longitudinal** polarized p+p collisions RHIC has provided unique insight into:

- The **polarized sea quark** distributions via W/Z production.
- Constraints on the **polarized gluon distribution** through jet and di-jet $A_{LL}$
  - 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

**Transverse** polarized p+p collisions at RHIC have accessed the transverse spin processes:

- **Sivers’ sign-change** from W-boson data
  - Sivers’ measurements with W-bosons, Drell-Yan, and photons in 2017 (x 12 more data)
- **Transverity** sensitive quantities through the Collins asymmetry and IFF
- **Gluon linear polarization** through the first measurement of 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 to STAR**
- Aiming for complete upgrade for potential polarized pp run at 500 GeV in 2022 and future data taking periods
THANK YOU

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@mariakzurek
### PLANS

**RHIC cold-QCD plan for 2017-2023 (arXiv:1602.03922):**

<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>
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<tbody>
<tr>
<td>2017</td>
<td>p⁺p @ 510</td>
<td>400 pb⁻¹ 12 weeks</td>
<td>Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{g,F}(x,x)$&lt;br&gt;Sensitive to sea quark Sivers or ETQS function&lt;br&gt;Evolution in TMD and Twist-3 formalism&lt;br&gt;Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3&lt;br&gt;First look at GPD $E_g$</td>
<td>$A_N$ for $\gamma$, $W^\pm$, $Z^0$, DY&lt;br&gt;$A_{UT}^{\sin(\phi_x-2\phi_h)}A_{UT}^{\sin(\phi_x-\phi_h)}$ modulations of $h^\pm$ in jets, $A_{UT}^{\sin(\phi_3)}$ for jets&lt;br&gt;$A_{UT}$ for $J/\Psi$ in UPC</td>
<td>$A_N^{DY}$: Postshower to FMS@STAR&lt;br&gt;None</td>
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<td>p⁺p @ 200</td>
<td>300 pb⁻¹ 8 weeks</td>
<td>subprocess driving the large $A_N$ at high $x_F$ and $\eta$&lt;br&gt;evolution of ETQS fct.&lt;br&gt;properties and nature of the diffractive exchange in p⁺p collisions.</td>
<td>$A_N$ for charged hadrons and flavor enhanced jets&lt;br&gt;$A_N$ for $\gamma$&lt;br&gt;$A_N$ for diffractive events</td>
<td>Yes Forward instrum.&lt;br&gt;None&lt;br&gt;None</td>
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<td>What is the nature of the initial state and hadronization in nuclear collisions&lt;br&gt;Nuclear dependence of TMDs and nFF&lt;br&gt;Clear signatures for Saturation</td>
<td>$R_{pAu}$ direct photons and DY&lt;br&gt;$A_{UT}^{\sin(\phi_x-\phi_h)}$ modulations of $h^\pm$ in jets, nuclear FF&lt;br&gt;Dihadrons, $\gamma$-jet, h-jet, diffraction</td>
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<td>1.1 fb⁻¹ 10 weeks</td>
<td>TMDs at low and high $x$</td>
<td>$A_{UT}$ for Collins observables, i.e. hadron in jet modulations at $\eta &gt; 1$</td>
<td>Forward instrum. ECal+HCal+Tracking</td>
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<td>p+@ 510</td>
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<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>
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**Scheduled RHIC running**

**Potential future running**
UNPOLARIZED PDFs
HELICITY DEPENDENT PDFs
STATUS OF $\Delta G$

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


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

PRL 113 (2014) 1, 012001

$Q^2 = 10 \text{ GeV}^2$

RHIC x-range

NNPDFpol1.0

NNPDFpol1.1

positivity bound
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

ArXiv:1906.02740, Accepted to publication in PRD

- Analysis with 2013 data - high luminosity 510 GeV: ongoing
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 $x > 0.001$

$1 \rightarrow$ likely quark, $2 \rightarrow$ 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 $x > 0.0025$. 
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:
  \( W \rightarrow \mu A_L, \sigma, 1.2 < |\eta| < 2.4, \) PRD98, 032007 (2018)
  \( W \rightarrow e A_L, |\eta| < 0.35, \) PRD93, 051103 (2016)
  \( W \rightarrow e \sigma, \) PRL106 062001 (2011)

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

TMD formalism

**Sivers function** – correlation between parton transverse momentum and nucleon transverse spin

\[ T_{q,F}(x, x) = - \int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x, k_\perp^2) \big|_{SIDIS} \]

**Collins function** – correlation of the transverse spin of a fragmenting quark and the transverse momentum of a hadron

Requires **2 scales**: hard scale \( Q^2 \) and soft scale \( p_T \)
Where: \( \lambda_{QCD} < p_T < Q \)

**Observables**: azimuthal dependences of hadrons within a jet, Drell-Yan, W/Z

Twist-3 formalism

**ETQS function** – transverse momentum integrated distribution Twist-3 analog

**Twist-3 formalism**

**Observedas**: Inclusive \( A_N \) \( (\pi^0, \gamma, \text{jet, charmed mesons}) \)

**Requires 1 scale**: \( Q^2 \) or \( p_T \)
Where: \( \lambda_{QCD} \ll p_T, Q \)

**Observables**: Inclusive \( A_N \) \( (\pi^0, \gamma, \text{jet, charmed mesons}) \)
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

STAR values span broad and overlapping regions

Q^2 [GeV^2/c^2]

10^4
10^3
10^2
10^1
10
1

10^{-2} 10^{-1} x

COMPASS
HERMES
JLab Hall-A
STAR \sqrt{s}=500 GeV
STAR \sqrt{s}=200 GeV

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 ($\times 2.5$) and 500 GeV ($\times 12$) available
RHIC KINEMATIC
Collins and Sivers asymmetry

arXiv:1602.03922
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 ($D \to \mu$)