Recent STAR Jet results of the high-energy spin physics program at RHIC at BNL

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(On behalf of the STAR Collaboration)
Outline

- Experimental aspects:
  RHIC / STAR

- Theoretical foundation

- Results / Status: Jet production
  - Gluon related studies
    - Cross-section measurements: $g$
    - Asymmetry measurements: $\Delta g$

- Summary and Outlook

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**Theoretical foundation**

- **Probing gluons in ep vs. pp scattering**

\[
d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x)
\]

\[
d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h
\]

- **Momentum contribution**

\[
f(x) = f^+(x) + f^-(x)
\]

- **Spin contribution**

\[
\Delta f(x) = f^+(x) - f^-(x)
\]

**Universality**

**Factorization**
Theoretical foundation

- Proton spin structure using high-energy polarized p+p collisions: Helicity
  - Observable: Gluon polarization (Jet/Hadron production)
  - Double longitudinal single-spin asymmetry $A_{LL}$

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

Colliding beam helicities!

$$= \frac{\Delta f_1 \otimes \Delta f_2 \otimes \sigma_h \cdot a_{LL} \otimes D_h^h}{f_1 \otimes f_2 \otimes \sigma_h \otimes D^h_f}$$

$\Delta f_1$ $\Delta f_2$ $a_{LL} = \frac{\Delta \sigma_h}{\sigma_h}$ Input

- Double longitudinal single-spin asymmetry $A_{LL}$

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Experimental aspects - RHIC

- The world’s first polarized proton+proton collider

Diagram showing the experimental setup, including:
- Siberian Snakes
- RHIC pC Polarimeter
- Absolute Polarimeter (H jet)
- PHENIX
- STAR
- Spin Rotators
- Pol. Proton Source
- 200 MeV Polarimeter
- Rf Dipole
- Strong AGS snake
- Helical Partial Siberian Snake
- AGS polarimeters
Polarized p+p collisions

- Production runs at √s=200 / 500 / 510 GeV (long. polarization) in 2009, 2012, 2013 and 2015: Jet and Hadron production (Gluon related studies!)
- Jet results will be shown from Run 9 and Run 12
Experimental aspects - STAR

- Overview
  - Calorimetry system with $2\pi$ coverage:
    - BEMC (-1<\(\eta\)<1) and EEMC (1<\(\eta\)<2)
  - TPC: Tracking and particle ID
    (\(|\eta|<1.3\))
  - FGT: Forward GEM Tracker (Run 13)
    (1<\(\eta\)<2)
  - ZDC: Relative
    luminosity and local polarimetry
  - BBC: Relative
    luminosity and Minimum bias trigger

\[ \eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right) \]
Results / Status - $g / \Delta g(x)$ related studies

- RHIC Gluon studies: Jet-type measurements

Jet

$\pi^*$ $\pi^0$

$\Delta g$

$\Delta q$

$\Delta q$

$\Delta q$

Inclusive Jet production (200GeV: Solid line / 500GeV: Dashed line)

$$x_T = \frac{2p_T}{\sqrt{s}} \quad (x \text{ value at } \eta = 0)$$
Results / Status - $g / \Delta g(x)$ related studies

**STAR: Mid-rapidity Inclusive Jet cross-section measurement (Run 9) at 200GeV**

- Unfolded inclusive jet cross-section using anti-$k_T$ algorithm ($R=0.6$) (Smaller dependence on underlying event (UE) and Pile-up)
  
  \[
  D_{ij} = \min \left( \frac{1}{k_{T,i}^2}, \frac{1}{k_{T,j}^2} \right) \frac{\Delta R_{ij}^2}{R}
  \]
  
  \[
  \Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2
  \]
  
  \[
  D_i = \frac{1}{k_{T,i}^2}
  \]
  
  \[
  d = \min (\{D_{ij}, D_i\})
  \]
  
  If $d = D_{ij}$: Combine jet $i$ and jet $j$
  
  If $d = D_i$: Define jet $i$ as final jet

- Corrected to particle level for three different pseudo-rapidity regions of $|\eta|<1$, $|\eta|<0.5$ and $0.5<|\eta|<1.0$

- Hadronization and UE corrections evaluated using PYTHIA applied to NLO calculations applied to pure NLO calculations for data comparison

- Comparison to NLO calculations for CT10, NNPDF3.0 and MRST-W2008 with a preference for CT10

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X. Li et al. (STAR Collaboration), DIS 2015.
STAR: Mid-rapidity Inclusive Jet $A_{LL}$ measurement (Run 9) at 200GeV


- Run 9 $A_{LL}$ measurement between BB10 and DSSV / Clearly above zero at low $p_T$
- Larger asymmetry at low $p_T$ suggests larger gluon polarization compared to DSSV
- With global analysis, $A_{LL}$ jet result provides evidence for positive gluon polarization for $x > 0.05$
Results / Status - $g / \Delta g(x)$ related studies

- **Impact on $\Delta g$ from RHIC data (RHIC Run 9)**
  - Wide spread at low $x$ ($x < 0.05$) of alternative fits consistent within 90% of C.L.

- **DSSV**: Original global analysis incl. first RHIC results (Run 5/6)
- **DSSV\*: New COMPASS inclusive and semi-inclusive results in addition to Run 5/6 RHIC updates
- **DSSV - NEW FIT**: Strong impact on $\Delta g(x)$ with RHIC run 9 results: $0.20^{+0.06}_{-0.07}$ 90% C.L. for $0.05 < x$
- **Similar conclusion by independent global analysis of NNPDF**: $0.23^{+0.07}_{-0.07}$ for $0.05 < x < 0.5$

"...better small-x probes are badly needed."


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Results / Status - $g / \Delta g(x)$ related studies

- **STAR: Mid-rapidity Inclusive Jet $A_{LL}$ measurement (Run 12) at 510GeV**

  **Graph**

  - $A_{LL}$ vs $p_T$ for $|\eta| < 0.9$ and $|\eta| < 1.0$
  - Relative luminosity uncertainty
  - LSS10p, DSSV'14, NNPDF1.1

  **Equation**

  $$A_{LL} \left( \frac{2p_T}{\sqrt{s}} \right)$$

  **Results**

  - Probing smaller $x$-values going from 200GeV to 510GeV in Run 12 and Run 13
  - Preliminary results of $A_{LL}$ at 510GeV (Run 12) well described by global fit results including Run 9 constraint
  - Additional large data sample in Run 13 at 510GeV will reduce $A_{LL}$ uncertainties further

  **Notes**

  - Additional data set at 200GeV taken in Run 15
  - Projected statistical uncertainties of Run 9 and Run 15 combined at 200GeV in comparison to Run 9 uncertainties

  **References**

  Z. Chang et al. (STAR Collaboration), SPIN 2014. (Run 12 / 510GeV)

  - More details and comparisons to earlier measurements.

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**Results / Status - $g / \Delta g(x)$ related studies**

- **RHIC Gluon polarization - Correlation Measurements**
  - Correlation measurements provide access to LO partonic kinematics through Di-Jet/Hadron production and Photon-Jet production:
    
    \[
    x_1 (2) = \frac{1}{\sqrt{s}} \left( p_T^3 e^{\eta_3(-\eta_3)} + p_T^4 e^{\eta_4(-\eta_4)} \right)
    \]
  - Bjorken $x$-coverage:

![Di-Jet production diagram](diagram.png)

- Current STAR acceptance
- Released STAR results

Di-Jet production

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

\[
M = \sqrt{s} \sqrt{x_1 x_2}
\]

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Results / Status - $g / \Delta g(x)$ related studies

- **STAR: Mid-rapidity Di-Jet cross-section and $A_{LL}$ measurement (Run 9) at 200GeV**

- **STAR 2009 Di-Jet Cross Section**

  - Data
  - NLO pQCD CT10 + UEH
  - UEH Systematic Uncertainty

  $\int \mathcal{L} dt = 18.6 \text{ pb}^{-1} \pm 8.8\%$

- **Data are well described by NLO pQCD plus hadronization and underlying event corrections**

- **$A_{LL}$ measurements consistent with DSSV2014 and NNPDF1.1 constrained by Run 9 data**

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

L. Adamczyk et al. (STAR Collaboration), arXiv:1610.06616.
(Submitted for publication, PRD)

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STAR: Mid-rapidity Di-Jet $A_{LL}$ measurement (Run 12) at 510GeV

$A_{LL}$ measurements consistent with DSSV2014 and NNPDF1.1 constrained by Run 9 data and consistent with Run 9 di-jet results

S. Ramachandran et al. (STAR Collaboration), DIS 2016. (Run 12 / 510GeV)
Results / Status - g / Δg(x) related studies

- STAR: Forward rapidity Di-Jet $A_{LL}$ measurement (Run 9) at 200GeV

T. Lin et al. (STAR Collaboration), DNP 2016.

- Forward rapidity STAR Di-Jet $A_{LL}$ measurement based on three topological combinations in $\eta$:
  - Barrel East (-0.8<$\eta$<0) - EEMC (-0.8<$\eta$<0)
  - Barrel West (0<$\eta$<0.8) - EEMC (-0.8<$\eta$<0)
  - EEMC (-0.8<$\eta$<0) - EEMC (-0.8<$\eta$<0)

- 2009 forward $A_{LL}$ measurement consistent with global fit results constrained by Run 9 $A_{LL}$ data
Results / Status - g / Δg(x) related studies

- Status of Run 13 jet analysis: Inclusive Jet and Di-Jet $A_{LL}$ analysis at 510GeV

  - Run 13 data sample: $\sim 250 \text{pb}^{-1}$ (Run 12: $\sim 80 \text{pb}^{-1}$)
  
  - Run 13 average beam polarization: $\sim 55\%$ (Run 12: $\sim 55\%$)
  
  - Run 13 FOM relevant for double-spin asymmetry $A_{LL}$: $P^4L = 23 \text{pb}^{-1}$ (Run 12: $7.3 \text{pb}^{-1}$)
    
    $\Rightarrow$ FOM Factor $\sim 3$ improvement compared to Run 12!

- STAR TPC and BEMC calibration (W Run 13 analyses released!): Completed

- Extensive test of both tracking software and jet triggers: Completed

- QA of jet analyses: Finalizing

- MC / Embedding samples Run 13: Initial testing
Future - $g / \Delta g(x)$ related studies

- Impact of new RHIC data and future EIC facility
  - Integral of $\Delta g (Q^2=10\text{GeV}^2)$ (Running integral) from $x_{\text{min}}$ to 1 as a function of $x_{\text{min}}$
    \[
    \Delta G(Q^2 = 10 \text{ GeV}^2) = \int_{x_{\text{min}}}^{1} \Delta g(x, Q^2 = 10 \text{ GeV}^2) \, dx
    \]
  - Uncertainties shown on running integral!
  - Important constraint from high-statistics 200GeV data (Run 9 / Published and Run 15) together with 500GeV data (Run 12 and Run 13) and forward rapidity measurements at RHIC prior to EIC - critical for low-x coverage (Di-Jet results not included!)
Future - \( g / \Delta g(x) \) related studies

- Probing smaller \( x \)-values 'badly needed' (DSSV 2014) - Extend di-jet measurements at forward rapidity
- Forward di-jet measurements allow to probe \( \Delta g \) at very low \( x \) values \( \sim 10^{-3} \)
- Forward hadronic calorimeter upgrade required - Upgrade plans at STAR and sPHENIX
Recently published / preliminary results: $g / \Delta g$

- Precise Run 9 $A_{LL}$ inclusive jet measurement: Non-zero $\Delta g$ of similar magnitude as quark polarization (Published!)
- Run 9 $A_{LL}$ Di-jet measurements open path to constrain the shape of $\Delta g$
- Run 12 Inclusive jet and di-jet Run 12 preliminary $A_{LL}$ measurement at 510GeV probe $\Delta g$ at lower $x$
- Run 9 Inclusive jet cross-section measurement: Important constraint for unpol. gluon distribution at high $x$

Upcoming results: $g / \Delta g$

- Large Run 13 data sample: Measurement of Inclusive jet and di-jet $A_{LL}$ at 510GeV probing $\Delta g$ lower $x$
- Additional data sample at 200GeV from Run 15 combined with Run 9

Future

- Long 510GeV run in 2017 (Run 17) at transverse spin polarization of about 400pb$^{-1}$: $W A_N /$ Unpol. QCD sea
- Exciting long-term prospects beyond 2020 requiring forward detector upgrade (Cold QCD plan) / Potential of probing gluons at low-$x$ $\sim 10^{-3}$ using forward di-jet measurements!

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