Future prospects of di-jet production at forward rapidity constraining $\Delta g(x)$ at low $x$ in polarized $p+p$ collisions at RHIC
Outline

- Gluon polarization program
  - Current results / status
  - Future prospects based on forward di-jet production

- Experimental aspects:
  RHIC / STAR

- Theoretical foundation

- Summary and Outlook
How do we probe the structure and dynamics of matter in ep vs. pp scattering?

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

Universality

\[ W^2 \approx Q^2/x \]

Momentum contribution

\[
\begin{align*}
  f(x) &= f^+(x) + f^-(x) \\
  \Delta f(x) &= f^+(x) - f^-(x)
\end{align*}
\]

Spin contribution

Factorization

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Theoretical foundation

- Explore proton spin structure using high-energy polarized p+p collisions

Observable: Gluon polarization (Jet/Hadron production)

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

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Delta f_1 \otimes \Delta f_2 \otimes \sigma_h \cdot a_{LL} \otimes D^h_f}{f_1 \otimes f_2 \otimes \sigma_h \otimes D^h_f}$$

$$A_{LL} = \frac{\Delta \sigma_h}{\sigma_h}$$
Experimental aspects - RHIC

- The world's first polarized proton-proton collider
Polarized p-p collisions

- Production runs at $\sqrt{s}=200\text{GeV}$ (long. polarization) in 2005, 2006, 2009: Jet and Hadron production (Gluon polarization)

- Production runs at $\sqrt{s}=500\text{GeV}$ (long. polarization) in 2009, 2011, 2012 and 2013: W production (Quark polarization) / Jet and Hadron production (Gluon polarization)
Experimental aspects - STAR

- **Overview**
  - Calorimetry system with
    - $2\pi$ coverage: BEMC ($-1<\eta<1$) and EEMC ($1.09<\eta<2$)
  - TPC: Tracking and particle ID ($-1.3<\eta<1.3$)
  - FGT: Tracking ($1<\eta<2$)
  - ZDC: Relative luminosity and local polarimetry (500GeV)
  - BBC: Relative luminosity and Minimum bias trigger

\[
\eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right)
\]
Mid-rapidity Inclusive Jet $A_{LL}$ measurement (Run 9)

- Run 9 $A_{LL}$ measurement between GRSV-STD and DSSV / Clearly above zero at low $p_T$
- Larger asymmetry at low $p_T$ suggests larger gluon polarization compared to DSSV
Results / Status - Gluon polarization program

- Impact on $\Delta g$ from RHIC data
  - Wide spread at low $x$ ($x<0.05$) of alternative fits consistent within 90% of C.L.
  - $Q^2 = 10 \text{ GeV}^2$
  - $\int_{0.05} dx \Delta g(x)$

- 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 $\Rightarrow$ Positive for $x > 0.05!$

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

D. deFlorian et al., arXiv:1404.4293

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Results / Status - Gluon polarization program

- RHIC Gluon polarization - Correlation Measurements
  - Correlation measurements provide access to partonic kinematics through Di-Jet/Hadron production and Photon-Jet production:
    \[
    x_1 (2) = \frac{1}{\sqrt{s}} \left( p_T^3 e^{\eta_3 (-\eta_3)} + p_T^4 e^{\eta_4 (-\eta_4)} \right)
    \]
  - Di-Jet production / Photon-Jet production
    - Di-Jets: All three (LO) QCD-type processes contribute: gg, qg and qq
    - Photon-Jet: One dominant underlying (LO) process
    - Larger cross-section for di-jet production compared to photon related measurements
    - Photon reconstruction more challenging than jet reconstruction
    - Full NLO framework exists → Input to Global QCD analysis
Results / Status - Gluon polarization program

- Mid-rapidity STAR Di-Jet cross-section (Run 9) and $A_{LL}$ measurement (Run 9)

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

- $A_{LL}$ measurements fall in-between GRSV-STD and DSSV

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

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Results / Status - Gluon polarization program

- **Mid-rapidity STAR Di-Jet $A_{LL}$ measurement in bins of $\eta$ (Run 9)**

  - **East - East and West - West Barrel**
  - **East Barrel - West Barrel**
  - **Full Acceptance**

- **Run 9 data**: First rapidity dependent di-jet measurement
  - Constrain x dependence!

  \[ M = \sqrt{s} \sqrt{x_1 x_2} \quad \eta_3 + \eta_4 = \ln \frac{x_1}{x_2} \]
Future prospects - Gluon polarization program

**Kinematic coverage - STAR (4-Vector Kinematics): \( x_1 \)**

\( x_1 \) vs. \((\eta_3, \eta_4)\) \( M_{\text{inv}} = 20 \text{ GeV} \ \sqrt{s}=500 \text{ GeV} \)

\( x_1 \) vs. \((\eta_3, \eta_4)\) \( M_{\text{inv}} = 40 \text{ GeV} \ \sqrt{s}=500 \text{ GeV} \)

\( x_1 \) vs. \((\eta_3, \eta_4)\) \( M_{\text{inv}} = 60 \text{ GeV} \ \sqrt{s}=500 \text{ GeV} \)

\( x_1 \) vs. \((\eta_3, \eta_4)\) \( M_{\text{inv}} = 80 \text{ GeV} \ \sqrt{s}=500 \text{ GeV} \)

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

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

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Future prospects - Gluon polarization program

- Kinematic coverage - STAR (4-Vector Kinematics): $x_2$

$\eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$

$M = \sqrt{s} \sqrt{x_1 x_2}$

$x_2$ vs. $(\eta_3, \eta_4)$ $M_{\text{inv}} = 20$ GeV $\sqrt{s}=500$ GeV

$x_2$ vs. $(\eta_3, \eta_4)$ $M_{\text{inv}} = 40$ GeV $\sqrt{s}=500$ GeV

$x_2$ vs. $(\eta_3, \eta_4)$ $M_{\text{inv}} = 60$ GeV $\sqrt{s}=500$ GeV

$x_2$ vs. $(\eta_3, \eta_4)$ $M_{\text{inv}} = 80$ GeV $\sqrt{s}=500$ GeV

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Future prospects - Gluon polarization program

- **Individual Partonic asymmetries**

Jet measurements do not distinguish between $gg$ / $qg$ and $qq$ jets

Size and thus weight of partonic asymmetries (Here LO) different for different topological configurations
Future prospects - Gluon polarization program

- Forward detector concept / Assumptions on projections
  - Efficiencies for EAST / WEST / EEMC all defined using STAR jet efficiencies. For new forward system FCS, assume hadronic calorimetry with 0.9
  - All jet calculations at NLO (Code: D. deFlorian and W. Vogelsang) / simulations with 5GeV/8GeV cuts
  - Systematics: Relative luminosity use $\delta R = 5 \cdot 10^{-4}$ (Run 9 Inclusive Jet value)
  - P/L numbers: $P = 60\%$ and $L_{\text{delivered}} = 1000\text{pb}^{-1}$ with 2/3 for $L_{\text{recorded}} / L_{\text{delivered}}$ (~1 long RHIC run!)

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<th>$\eta$</th>
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<td>+4.0</td>
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</table>
DSSV (2008) and GRSV-STD have been used for all projections in $A_{UL}$

- **NOTE**: GRSV-STD is much smaller than 90% C.L. envelope for $x < 0.05$ AND DSSV (2008) is smaller in magnitude for $x<0.05$ compared to 90% C.L. envelope

- Therefore: Uncertainties for $x < 0.05$ are larger than by the range of DSSV (2008) and GRSV-STD!
Future prospects - Gluon polarization program

**Kinematic coverage - Simulations / Central**

- **(EAST / EAST)**
  - $-0.8 < \eta_3 (4) < 0 / -0.8 < \eta_4 (3) < 0$
  - $d\sigma/dx_1 (d\sigma/dx_2)$ (pb)
  - $x_1 (x_2)$

- **(EAST / WEST)**
  - $-0.8 < \eta_3 (4) < 0 / 0 < \eta_4 (3) < +0.8$
  - $d\sigma/dx_1 (d\sigma/dx_2)$ (pb)
  - $x_1 (x_2)$

- **(EAST / EEMC)**
  - $-0.8 < \eta_3 (4) < 0 / 1.2 < \eta_4 (3) < 1.8$
  - $d\sigma/dx_1 (d\sigma/dx_2)$ (pb)
  - $x_1 (x_2)$

- **(WEST / WEST)**
  - $0 < \eta_3 (4) < 0.8 / 0 < \eta_4 (3) < 0.8$
  - $d\sigma/dx_1 (d\sigma/dx_2)$ (pb)
  - $x_1 (x_2)$

- **(WEST / EEMC)**
  - $0 < \eta_3 (4) < 0.8 / 1.2 < \eta_4 (3) < 1.8$
  - $d\sigma/dx_1 (d\sigma/dx_2)$ (pb)
  - $x_1 (x_2)$

- **(EEMC / EEMC)**
  - $1.2 < \eta_3 (4) < 1.8 / 1.2 < \eta_4 (3) < 1.8$
  - $d\sigma/dx_1 (d\sigma/dx_2)$ (pb)
  - $x_1 (x_2)$

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Future prospects - Gluon polarization program

$A_{LL}$ projections / Central

Cone alg. (R=0.7) / $E_{T3} > 5$GeV $E_{T4} > 8$GeV

Delivered Luminosity = 1000pb$^{-1}$
Polarization = 60%

$\delta R = 5 \times 10^{-4}$
Future prospects - Gluon polarization program

- Kinematic coverage - Simulations / Forward

Cone alg. (R=0.7) / $E_{T3} > 5$GeV $E_{T4} > 8$GeV

- Kinematic coverage - Simulations / Forward

Cone alg. (R=0.7) / $E_{T3} > 5$GeV $E_{T4} > 8$GeV
Future prospects - Gluon polarization program

- Cross-sections / Forward

- Cone alg. (R=0.7) / $E_{T3} > 5\text{GeV}$ $E_{T4} > 8\text{GeV}$

- $(EAST / FCS)$
  - $d\sigma/dM (\text{pb}/\text{GeV})$
  - $E_{T3} > 5\text{GeV}$ $E_{T4} > 8\text{GeV}$
  - $1029020\text{ pb}$ $1079120\text{ pb}$
  - CTEQ6M $\text{MRST2004}$
  - $(\text{EAST / FCS})$

- $(EEMC / FCS)$
  - $d\sigma/dM (\text{pb}/\text{GeV})$
  - $E_{T3} > 5\text{GeV}$ $E_{T4} > 8\text{GeV}$
  - $1155110\text{ pb}$ $1158740\text{ pb}$
  - CTEQ6M $\text{MRST2004}$

- $(\text{WEST / FCS})$
  - $d\sigma/dM (\text{pb}/\text{GeV})$
  - $E_{T3} > 5\text{GeV}$ $E_{T4} > 8\text{GeV}$
  - $1554990\text{ pb}$ $1581900\text{ pb}$
  - CTEQ6M $\text{MRST2004}$

- $(\text{FCS / FCS})$
  - $d\sigma/dM (\text{pb}/\text{GeV})$
  - $E_{T3} > 5\text{GeV}$ $E_{T4} > 8\text{GeV}$
  - $49898\text{ pb}$ $47818\text{ pb}$
  - CTEQ6M $\text{MRST2004}$

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Future prospects - Gluon polarization program

- $A_{LL}$ projections / Forward

\[ \delta R = 5 \cdot 10^{-4} \]

Delivered Luminosity = 1000 pb$^{-1}$
Polarization = 60%

Cone alg. (R=0.7) / $E_{T3} > 5\text{GeV}$, $E_{T4} > 8\text{GeV}$

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Future prospects - Gluon polarization program

- PYTHIA simulations incl. detector effects

- Invariant mass distribution based on PYTHIA simulations incl. detector effects (Only calorimetry!)

- Next: Specify resolution of forward detector system / UE events studies / Jet reconstruction studies
Status: Gluon polarization program:

- First Di-Jet measurement opens the path to constrain the shape of $\Delta g$
- Run 9 results: Precise $A_{LL}$ measurement suggesting non-zero $\Delta G$

New global analysis by DSSV:

- Non-zero $\Delta g(x)$ for $x > 0.05$
- Larger uncertainties for $x < 0.05$, i.e. below current RHIC kinematic region!

Run 14 STAR BUR request:

- 6 weeks with $L_{\text{delivered}} = 75 \text{pb}^{-1}$ and 60%

Forward jet production:

- Extend jet measurements at forward rapidity probing $\Delta g(x)$ as low as $10^{-3}$ in $x$
- Challenging measurement with good control of sys. uncertainties important (Assume ~ 1 long RHIC run!)
- Additional probes to be studied: $\pi^0$-jet correlations!
- Important step prior to a future Electron-Ion Collider (EIC) ~2025!
Outlook - Run 14 (200GeV)

**Kinematic coverage - Simulations / Central**

- **EAST / EAST**
  - $0.8 < \eta_3^{(4)} < 0 / -0.8 < \eta_4^{(3)} < 0$

- **EAST / WEST**
  - $0 < \eta_3^{(4)} < 0.8 / 0 < \eta_4^{(3)} < 0.8$

- **WEST / WEST**
  - $1.2 < \eta_3^{(4)} < 1.8 / 1.2 < \eta_4^{(3)} < 1.8$

- **EAST / EEMC**
  - $-0.8 < \eta_3^{(4)} < 0 / 0.8 < \eta_4^{(3)} < 1.8$

- **WEST / EEMC**
  - $0 < \eta_3^{(4)} < 0.8 / 0 < \eta_4^{(3)} < 0.8$

- **EEMC / EEMC**
  - $1.2 < \eta_3^{(4)} < 1.8 / 1.2 < \eta_4^{(3)} < 1.8$
Outlook - Run 14 (200GeV)

\[ A_{LL} \] projections / Central

...graphs showing projections for different kinematic ranges and CMS settings...