Exploring the Proton Spin with Di-jets at a Future EIC

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Simulation Details / Particle Cuts

- Electron – Proton events generated using PYTHIA

- Cut on inelasticity: $0.01 \leq y \leq 0.95$

- Jet Algorithm: Anti_\text{k}_T (R = 1.0)

- Jets found in Breit frame

- Particles used in jet finding:
  - Stable
  - $p_T \geq 250$ MeV
  - $\eta \leq 4.5$
  - Parent cannot originate from scattered electron
Jets at an EIC: Points to Remember

- Lower center of mass energies will lead to lower jet / di-jet yields and more limited $p_T$/mass reach

- Will need largest available energies and high luminosity to accumulate reasonable statistics at high $p_T$/mass – use $\sqrt{s} = 141$ GeV for all that follows
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• Jets contain relatively few particles overall

• Events are quite clean with little underlying event activity

• Typical particle $p_T$ is small -> precision tracking important for reducing jet energy scale uncertainties

Q$^2 = 10 - 100$ GeV$^2$
Jet / Di-jet Applications

- **Electron – Nucleus Collisions**
  - Nuclear PDFs
  - Medium Modification / Energy Loss
  - Hadronization and Confinement

- **Electron – Proton Collisions**
  - High – x Proton PDFs
  - Proton Orbital Angular Momentum / Gluon Wigner Distribution at Low x (Diffractive Di-jets)
  - Saturation (Diffractive Di-jets)
  - (Un)polarized Photon PDFs
  - PGF Tagging for Proton ΔG
Current fits to polarized DIS data give $\Delta \Sigma = 0.366^{+0.042}_{-0.062}$ for $10^{-3} < x < 1$.

This leaves over half of the proton spin budget unaccounted for – is any spin carried by the gluons?

Polarized p+p collision data from RHIC have placed strong constraints on $\Delta G$ for $x > 0.05$ and given evidence of non-zero gluon contribution, but large uncertainties at low $x$ will remain.

Need high precision and wide kinematic reach to solve spin puzzle.

Uncertainties on low-$x$ region will still be sizable with RHIC data.
Accessing $\Delta G$ in DIS

- Several observables are sensitive to $\Delta G$ in DIS but golden measurement at an EIC would be scaling violation of $g_1(x, Q^2)$

\[ \frac{dg_1(x, Q^2)}{d\ln(Q^2)} \approx -\Delta g(x, Q^2) \]

- Current DIS constraints on $\Delta G$ hampered by limited $x$ & $Q^2$ coverage

- EIC would greatly expand kinematic reach and precision of $g_1(x, Q^2)$ measurements!

arXiv:1206.6014
Gluons can be probed in DIS via the higher-order photon gluon fusion process.

Also have the QCD–Compton process which probes quarks at the same order.

Both processes produce 2 angularly separated hard partons—Di-jet.

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Asymmetry is a convolution of polarized PDF from the proton and polarized photon structure—which is completely unconstrained.

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Direct Vs Resolved Processes

\[ X_\gamma = \frac{1}{2Ee^y} \left( m_{T1}e^{-y_1} + m_{T2}e^{-y_2} \right) \]

- Plot reconstructed \( X_\gamma \) for direct and resolved processes
- Direct processes should concentrate toward 1 while resolved processes are at lower values
- Direct processes dominate at higher \( Q^2 \) while resolved are more prevalent at low \( Q^2 \)
- Cut of \( X_\gamma > 0.8 \) enhances the direct fraction at all \( Q^2 \)
Proton Partonic Kinematics

- To measure $\Delta G$, need to probe the parton coming from the proton
- Momentum fraction of the parton from proton is well reconstructed

$$X_p = \frac{1}{2E_P} \left( m_{T1} e^{y_1} + m_{T2} e^{y_2} \right)$$
Proton Partonic Kinematics

\[ X_P = x_B \left(1 + \frac{M^2}{Q^2}\right) \]

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\[ Q^2 = s y x_B \]

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- \( Q^2 \) and Bjorken-x are also related via the collision energy and inelasticity
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- Accessible \( X_P \) range basically determined by beam energies
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\[ Q^2 = syx_B \]

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- \( Q^2 \) and Bjorken-\( x \) are also related via the collision energy and inelasticity
- Accessible \( X_P \) range basically determined by beam energies
- Lowest \( X_P \) we can probe is about 0.005

\[ \approx \frac{100}{(20000 \times 0.95)} \approx 0.005 \]
X_p For Different Q^2

- At lower Q^2, contribution from resolved process increases while QCD Compton contribution decreases.

- For a given di-jet mass range (10 – 20 GeV in this case), same X_p can be reconstructed event-by-event and probed over large range of Q^2.

- This will allow for robust tests of the evolution of ΔG.
Complementary Coverage

Experimentally possible to extend these measurements to $Q^2 < 1$

$Q^2$ and $x$ range covered by di-jet asymmetry measurements
Weighting PYTHIA

\[ w = \hat{a}(s, t, \mu^2, Q^2) \cdot \frac{\Delta f_a^{\gamma^*}(x_a, \mu^2)}{f_a^{\gamma^*}(x_a, \mu^2)} \cdot \frac{\Delta f_b^N(x_b, \mu^2)}{f_b^N(x_b, \mu^2)} \]

- PYTHIA does not include parton polarization effects, but an asymmetry can be formed by assigning each event a weight depending on the hard-scattering asymmetry and (un)polarized photon and proton PDFs.

- Expected asymmetry is then the average over weights.

- Weights are sharply spiked near zero -> expect small asymmetries.
Weighting PYTHIA

\[ w = a(s, t, \mu^2, Q^2) \cdot \frac{\Delta f_a^{\gamma^*}(x_a, \mu^2)}{f_a^{\gamma^*}(x_a, \mu^2)} \cdot \frac{\Delta f_b^N(x_b, \mu^2)}{f_b^N(x_b, \mu^2)} \]

- Process-dependent hard scattering asymmetry is a function of Mandelstam variables (\(\cos(\theta^*)\))

- The direct process distributions will be smeared by the additional depolarization term

- Note that the asymmetry for PGF is negative

Resolved

\[ a(s, t, \mu^2) = \Delta \sigma / (2 \Delta \sigma) \]

Direct

\[ \Delta \sigma \]

\(\hat{a}\)

\(\cos(\theta^*)\)

\(\cos(\theta^*)\)

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Weighting PYTHIA

\[ w = \Delta f_{a}^{\gamma} (x_a, \mu^2) \cdot \frac{\Delta f_{b}^{N} (x_b, \mu^2)}{f_{a}^{\gamma} (x_a, \mu^2) \cdot f_{b}^{N} (x_b, \mu^2)} \]

- Second term is the ratio of the polarized to unpolarized photon PDFs.
- Use maximal scheme for polarized and GRV-G for unpolarized.
- For direct processes such as Photon-Gluon Fusion, this term is identically unity.
Weighting PYTHIA

\[ w = a(s, t, \mu^2, Q^2) \left( \frac{\Delta f_a^{\gamma^*}(x_a, \mu^2)}{f_a^{\gamma^*}(x_a, \mu^2)} \right) \frac{\Delta f_b^{N}(x_b, \mu^2)}{f_b^{N}(x_b, \mu^2)} \]
\[ A_{LL} \text{ Vs Di-jet Mass} \]

- Plot the expected \( A_{LL} \) as a function of di-jet invariant mass for each sub-process separately as well as the combined sample

- PGF asymmetry is nearly canceled out by QCDC asymmetry with opposite sign – would like to reduce QCDC contribution

- Need high integrated luminosity and high energy to probe the high-mass region where asymmetries can be sizable

- Control of systematics will be essential

\[ Q^2 = 10 - 100 \text{ GeV}^2 \]

\[ \sigma = \sqrt{\frac{1}{N} - \frac{A^2}{N}} \]
Asymmetry is plotted as a function of the momentum fraction of the parton from the proton.

Asymmetry shown for di-jet invariant masses between 10 and 20 GeV/c².

Error bars are statistical and scaled to the given integrated luminosity.

Different mass ranges will emphasize different momentum fraction ranges and subprocess mixes.

\[
Q^2 = 10 - 100 \text{ GeV}^2
\]

\[
\sigma = \sqrt{\frac{1}{N} - \frac{A^2}{N}}
\]
Summary

• Jets at an EIC will contain relatively few total particles and those particles will have low transverse momenta, making tracking essential for reducing jet energy scale uncertainties

• Di-jet measurements can be used to tag photon-gluon fusion events to access $\Delta G$ and investigate its evolution

• Combination of QCD-Compton and PGF subprocess asymmetries lead to small overall asymmetries

• Need large integrated luminosity and center-of-mass energy to explore asymmetries at high di-jet mass and good control on systematic effects
Backup
Jet Basics: Frames

• Can define several useful frames:

  • **Lab**: Detector-based frame

  • **Hadron-Boson**: Beam hadron is at rest, z-direction chosen along virtual photon momentum vector

  • **Breit**: Virtual photon moves in -z direction and boost such that it has zero energy. Separation into target and remnant regions

  • **Center of Mass**: Virtual photon and struck parton have equal and opposite momenta. Can define Feynman-x
Jet Basics: Radius

- For anti-$k_T$ algorithm the radius parameter determines the distance at which particles can be grouped together
- Sets the effective size of the jet

- Parameters: Min $p_T = 1.0$ GeV, Resolved processes
- Larger radii result in more found jets as well as more particles in jet
Jet Multiplicity: $Q^2 = 0.01 - 0.1$ GeV\(^2\)

### # Jets: Resolved Processes

- **# Jets: PGF**

### # Jets: QCDC

- Percentage of events with a certain number of found jets for different minimum allowed jet $p_T$.
- See a decrease in number of jets with increasing minimum jet $p_T$.
- Jet $p_T$ of 1 GeV may not be well described theoretically.
- Each curve normalized to unity.
Jet Multiplicity: $Q^2 = 10 - 100 \text{ GeV}^2$

- **# Jets: Resolved Processes**

- **# Jets: QCDC**

- **# Jets: PGF**

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Jet Particle Multiplicity

- Look at the average number of particles in jet as a function of jet $p_T$
- All stable particles (charged and neutral) are counted

Q$^2 = 10 - 100$ GeV$^2$

- No dependence on Q$^2$ or subprocess
- How few particles can be in jet before it doesn’t make sense to call the object a jet?

Q$^2 = 0.01 - 0.1$ GeV$^2$
Di-jet Yields

Photon-Gluon Fusion: $Q^2 = 1-10 \text{ GeV}^2$

- \( \bar{s} = 141 \text{ GeV} \)
- \( \bar{s} = 63 \text{ GeV} \)

Photon-Gluon Fusion: $Q^2 = 10-100 \text{ GeV}^2$

- \( \bar{s} = 90 \text{ GeV} \)
- \( \bar{s} = 40 \text{ GeV} \)
$X_\gamma$ Reproduction: $Q^2 = 10 - 100$ GeV$^2$

- How does the reproduction of $X_\gamma$ depend on jet $p_T$?
- As expected unmatched events do not reproduce $X_\gamma$ well
- See that high $p_T$ range is more peaked toward 1 even for matched events
Accessing $\Delta G$ at RHIC: $A_{LL}$

$$A_{LL} = \frac{\sigma^{++} - \sigma^{-+}}{\sigma^{++} + \sigma^{-+}} = \frac{\sum \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma} \delta_{f_a f_b \rightarrow f_c X} \cdot \hat{a}_{LL} \rightarrow f_c X \otimes D^h_{f_c}}{\sum f_a \otimes f_b \otimes d\hat{\sigma} \delta_{f_a f_b \rightarrow f_c X} \otimes D^h_{f_c}}$$

Partonic fractions in jet production at 200 GeV

For most RHIC kinematics, $gg$ and $qg$ dominate, making $A_{LL}$ for jets and hadrons sensitive to gluon polarization.
Accessing $\Delta G$ at RHIC: $A_{LL}$

- In polarized pp collisions, access $\Delta G$ via the longitudinal double helicity asymmetry $A_{LL}$ which is sensitive to the polarized gluon distribution at leading order.

- STAR and PHENIX measure $A_{LL}$ using inclusive jet and $\pi^0$ final states, respectively.
New DSSV Results

Integral of $\Delta g(x)$ in range $0.05 < x < 1.0$ increases from roughly $0.05$ to $0.20^{+0.06}_{-0.07}$. First indication of non-zero gluon polarization!
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- Uncertainty shrinks substantially from DSSV* to new DSSV fit

- Uncertainty on integral over low x region is still sizable (only $\sqrt{s} = 200$ GeV RHIC data)
Di-jet $A_{LL} (pp)$

- Coincidence measurements capture more information about hard scatter and better constrain initial kinematics.
Di-jet $A_{LL}$(pp)

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- Di-jet $A_{LL}$ plotted vs $M_{\text{inv}}/\sqrt{s}$ ($\sim \sqrt{x_1 x_2}$ at L.O.) for data taken at $\sqrt{s} = 200$ and 510 GeV.

- 510 GeV data extend to lower $M_{\text{inv}}/\sqrt{s}$ (lower $x$) where $\Delta G$ not as well constrained while 200 GeV data give better precision at mid to high $M_{\text{inv}}/\sqrt{s}$. 

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EIC: eRHIC or JLEIC
EIC: Impact on Quark Polarizations

$$\Delta \Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta \bar{u} + \Delta \bar{d} + \Delta \bar{s} + \cdots) dx$$

- $g_1$ is sensitive to the sum of all quark and anti-quark polarized PDFs meaning an EIC will place strong constraints on $\Delta \Sigma$

- An EIC will also be able to constrain the individual quark and anti-quark polarized PDFs via semi-inclusive DIS (SIDIS) measurements

- The polarized anti-quark distributions are of particular interest as they provide information on non-perturbative aspects of proton structure
EIC: Impact on Quark Polarizations

\[ \Delta \Sigma = \int \left( \Delta u + \Delta d + \Delta s + \Delta \bar{u} + \Delta \bar{d} + \Delta \bar{s} + \cdots \right) dx \]

- The above plots show the expected reduction in uncertainty for the polarized anti-quark distributions from EIC SIDIS data.
- Individual quark and anti-quark distributions can also be measured at an EIC via charged current DIS which access different combinations of PDFs.
EIC: Solving the Spin Puzzle

Gluon

- Above plot shows the running integral of $\Delta g(x,Q^2)$ from $x_{min}$ to 1 as a function of $x_{min}$

- Large reduction in uncertainty on $\Delta G$ from EIC can be seen

arXiv:1409.1633
EIC: Solving the Spin Puzzle

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Quarks

- EIC will also reduce the uncertainty on the quark contribution to the proton spin
- No assumptions about hyperon beta decay in EIC uncertainty

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EIC: Solving the Spin Puzzle

\[ \frac{1}{2} - \text{Gluon} - \text{Quarks} = \text{orbital angular momentum} \]

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- Large reduction in uncertainty on \( \Delta G \) from EIC can be seen
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- No assumptions about hyperon beta decay in EIC uncertainty

Constraints on gluon and quark contributions will provide information on the orbital angular momentum component of proton spin

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ \int_{x_{\text{min}}}^{1} dx \Delta g(x,Q^2) \]

\[ \int_{x_{\text{min}}}^{1} dx \text{DSSV 2014 with 90\% C.L. band} \]

\[ \text{eRHIC data:} \]
\[ 15 \times 100 \text{ GeV} \]
\[ +15 \times 250 \text{ GeV} \]
\[ +20 \times 250 \text{ GeV} \]

all bands 90\% C.L.

\[ \frac{1}{2} - \int_{x_{\text{min}}}^{1} dx [\frac{1}{2} Dg + Dg] \]

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ 10^{-1} \]

arXiv:1409.1633
**$X_\gamma$: Reconstructed Vs True**

- Will use virtual photon momentum fraction to discriminate between resolved and direct processes.
- See good agreement between reconstructed and true $X_\gamma$ for all $Q^2$ ranges.
- Di-jets found in Breit frame and required one jet with $p_T \geq 5$ GeV and the other with $p_T \geq 4$ GeV.

$$X_\gamma = \frac{1}{2E_{e\gamma}} \left( m_{T1}e^{-\gamma_1} + m_{T2}e^{-\gamma_2} \right)$$
Asymmetry