Jets at an EIC: An Experimental Perspective

Brian Page
Brookhaven National Laboratory
Santa Fe Jets and Heavy Flavor Workshop
Outline

• Brief Introduction to the Electron Ion Collider (EIC)
• Underlying Event Characteristics
• Accessing Photon Structure and Gluon Spin with Dijets
• Quark – Gluon Discrimination
• Detector Smearing
EIC Goals in a Nutshell

Gain a Better Understanding of QCD via Precision Measurements of the Bound States of the Theory

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

- Where does the saturation of gluon densities set in?

- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

Understanding the glue that binds us all
Potential EIC Realizations

- Two designs are in active development:
  - eRHIC (BNL)
  - JLEIC (JLab)

- eRHIC utilizes the existing RHIC hadron facility and adds an electron ring and injector

- JLEIC utilizes CEBAF as an electron accelerator and adds a hadron source / booster and collider rings

- Broad tradeoff: eRHIC will start with lower luminosities but have larger center of mass energies while JLEIC will prioritize luminosity but with smaller collision energies
Simulation Details / Particle Cuts

- Electron – Proton events generated at $\sqrt{s} = 141$ GeV using PYTHIA (Full energy eRHIC design 20x250 GeV electron x proton)

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

- Jet Algorithm: Anti-$k_T$ ($R = 1.0$)

- 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

[Graph showing data from PRD 96, 074035 (2017)]
Relevant Subprocesses

Resolved

QCD-Compton (QCDC)

Photon-Gluon Fusion (PGF)

DIS
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
Jets at an EIC: Points to Remember

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

- Jets contain relatively few particles overall

- Events should be relatively clean with moderate underlying event

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

- ep events are expected to be relatively clean, with moderate underlying event activity

- Want to systematically quantify the amount of underlying event present in a typical event

- Divide event into regions based on position of a trigger jet

- Transverse regions sensitive to underlying event contribution

- For this study: Dijet events from Resolved, QCDC, and PGF subprocesses; \( Q^2 < 1 \text{ GeV}^2 \); \( p_{T1} > 5, p_{T2} > 4.5 \text{ GeV/c} \)
Underlying Event Characteristics

- Plot average number of charged particles per event as a function of azimuthal angle from trigger jet.
- Also plot the average summed particle $p_T$.
- See little dependence on trigger jet $p_T$.
- The number of charged particles and $p_T$ sum in transverse region is small.

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Comparison with STAR

- Plot the average $p_T$ for charged tracks as a function of trigger jet $p_T$
- See that these quantities are independent of the trigger jet $p_T$ in transverse region as well as $Q^2$
- See similar behavior in 200 GeV pp events at STAR
- Can we use STAR data to study certain EIC jet observables?

arXiv:1107.4891
Jets as Parton Surrogates

- Jets should approximate the energy and momentum of the partons from which they arise allowing the reconstruction of event kinematics such as $x_\gamma$ (photon momentum fraction) and $x_p$ (parton momentum fraction) among many other applications.

- $x_\gamma$ will allow tagging of direct vs resolved subprocesses which will be important for studies of photon structure (Phys. Rev. D 96, 074035) as well as alternative methods for accessing $\Delta G$.

**Diagrams:**

- **QCD – Compton**
- **Photon-Gluon Fusion**
- **Resolved**
Subprocess Tagging and Kinematics

- Use dijet energy and momentum to reconstruct $x_\gamma$ and $x_p$
- Cutting on $x_\gamma$ can enhance or reduce resolved contribution (which becomes more prominent at low $Q^2$) depending on the analysis needs
- Both $x_\gamma$ and $x_p$ accurately reconstructed
Study the polarized and unpolarized hadronic structure of the photon

- In QCD, the photon can be considered a superposition of a bare photon state and a hadronic state
- Want to characterize the polarized and unpolarized structure of this hadronic state (photon PDFs)
- EIC cross section data will allow very precise extractions of these PDFs and give access to the polarized structure for the first time
Flavor Tagging

- Would also like to look more differentially and constrain photon PDFs for different parton flavors

- See that the jet associated with the photon preferentially goes to lower pseudorapidities

- Can tag the highest $p_T$ hadron inside the jet associated with the photon to enhance certain flavors

- See $\pi^+$ and $\pi^-$ enhance $u$ and $u$-bar fractions while kaons enhance $u/u$-bar and $s/s$-bar

- Take advantage of the excellent PID capabilities of the planned EIC detectors

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

$$\frac{dg_1(x, Q^2)}{dln(Q^2)} \approx -\Delta g(x, Q^2)$$

Can also get access to $\Delta G$ by using dijets to tag the photon-gluon fusion process, providing a cross-check and allowing studies of the evolution of $\Delta G$ with respect to $Q^2$

Reconstruction of $x_\gamma$ will facilitate rejection of resolved events $x_p$ will help isolate PGF from the quark-induced QCD-Compton process
\( A_{LL} \) Vs Di-jet Mass

- Weight simulated events by product of the partonic asymmetry and the ratios of the polarized over unpolarized photon and proton PDFs to obtain realistic estimate of \( A_{LL} \)

\[ \int \mathcal{L} dt = 10 \text{ fb}^{-1} \]

All Subprocesses

- 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

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

\[ w = a(s, t, \mu^2, Q^2) \cdot \frac{\Delta f_a^\ast (x_a, \mu^2)}{f_a^\ast (x_a, \mu^2)} \cdot \frac{\Delta f_b^N (x_b, \mu^2)}{f_b^N (x_b, \mu^2)} \]
$A_{LL}$ Vs Di-jet Mass: $x_p$ Cuts

Total $A_{LL}$ Vs Dijet Mass: $Q^2 = 10-100$ GeV$^2$

- QCDC and PGF asymmetries largely cancel out making overall asymmetry small
- Want to enhance PGF subprocess w.r.t. QCDC
- PGF events peaked to lower $x_p$ values
**A_{LL} Vs Di-jet Mass: x_p Cuts**

- Selecting events with $0.005 < x_p < 0.03$ enhances PGF asymmetry but restricts mass range.
- Intermediate $x_p$ values get more QCDC contribution.
- Largest $x_p$ values have roughly equal amounts of PGF and QCDC.
Quark – Gluon Discrimination

• Can we use the distribution of energy within a jet to determine if that jet arose from a quark or a gluon? Possibility to tag QCD-Compton process via detection of a gluon.

• This is a preliminary look at jet substructure at eRHIC; eventually want to explore the utility of substructure for studying how partons lose energy and hadronize in the cold nuclear medium.

• For this study, look at jets with $p_T \geq 10$ GeV as this is where separation between quark and gluon jets is seen. Only consider light quarks: u, d, and s.
Input Variables

\[ \text{Girth}^2 = \sum_i \frac{p_{Ti}}{p_{Tjet}} |r_i|^2 \]

\[ 2 \text{ Point} = \frac{1}{p_{Tjet}^2} \sum_{i \neq j} p_{Ti} \cdot p_{Tj} \cdot |r_{ij}|^\beta \]
• Characterize a number of multivariate methods by percentage of background (quarks) rejected vs signal (gluons) retained

• All methods performed roughly the same

• For the following, use MLPBNN which is a neural network implementation
After cut is applied, can plot quark and gluon jets vs any relevant variable.

Here we see that gluons dominate at higher rapidity.

Look at jets with rapidity > 1.8 to further enhance gluon fraction.

Dotted Red = All Quarks (11650)
Dotted Blue = All Gluons (4511)
Solid Red = Quarks After Cut (1964)
Solid Blue = Gluons After Cut (2568)

G/Q Before Cut = 0.39
G/Q After Cut = 1.31
G/(G+Q) Before = 28%
G/(G+Q) After = 57%
Simulating Detector Response

- Need to study the effect that detector smearing will have on jet observables and kinematic quantities reconstructed from jets
- Do this via a fast smearing program based on the BeAST detector design
- Electromagnetic calorimeter coverage spans range of +/- 4.5 in pseudorapidity with resolution between 7 and 15%/VE
  - EM clusters assumed to be massless
- Tracking coverage spans range of +/- 3.5 in pseudorapidity
  - Tracks assumed to have pion mass
  - Tracking inefficiencies of 5 and 10% also considered
- Hadronic calorimetry in forward / backward region (1 < |eta| < 4.5) with resolution of 1.5%/50%/VE
  - Optional mid-rapidity calorimeter with 7%/85%/VE also considered
Particle – Detector Comparison

Jet $p_T$: BeAST

Jet $p_T$: BeAST with Mid-Rapidity HCal

Dijet Mass: BeAST

Dijet Mass: BeAST with Mid-Rapidity HCal
Particle – Detector Comparison

• Have seen that the individual jet quantities are well reproduced after smearing

• What about quantities derived from jet properties such as $x_\gamma$ and $x_P$?

Both $x_\gamma$ and $x_P$ show good agreement between the generated and smeared values

Level of smearing is similar to that seen between particle level and generated values
• Characterization of the underlying event was made and the contribution was found to be rather small

• Methods for studying photon structure and gluon polarization using dijets were detailed

• Studies of jet substructure are beginning and a preliminary look at their utility for discriminating between quark and gluon initiated jets has been done

• Impacts of detector effects on jet observables are being investigated using a fast smearing package and BeAST detector parameters
Backup
Comparison with STAR
Underlying Event Characteristics

- Plot the average number of charged particles and average summed $p_T$ for the three regions as a function of trigger jet $p_T$.

- See that these quantities are independent of the trigger jet $p_T$ in transverse region.

- Underlying event activity similar to that seen in pp collisions at STAR at $\sqrt{s} = 200$ GeV.
UE Method Comparison

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Gluons can be also 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.
Gluons can be also 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.

At lower Q2, resolved processes in which the photon assumes a hadronic structure begin to dominate.

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

Would like to suppress the resolved component.
Direct Vs Resolved Processes

\[ X_\gamma = \frac{1}{2E_{ey}} (m_{T1} e^{-\gamma_1} + m_{T2} e^{-\gamma_2}) \]

- 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 \( Q^2 \)
$X_\gamma$: 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

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

$X_P = \frac{1}{2E_P} (m_{T1} e^{y_1} + m_{T2} e^{y_2})$

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Proton Partonic Kinematics

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

\[ Q^2 = s y x_B \]

\[ X_P = x_B + \frac{M^2}{s y} \]

\[ \approx \frac{100}{(20000 \times 0.95)} \approx 0.005 \]

- To measure \( \Delta G \), need to probe the parton coming from the proton
- Momentum fraction of the parton from proton is well reconstructed
- \( X_P \) is related to Bjorken-\( x \) and \( Q^2 \) at leading order
- \( Q^2 \) 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
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 ∆G

Yield

Q^2 = 10-100
\[ \int L = 0.25 \text{ fb}^{-1} \]

Yield

Q^2 = 0.01-0.1
\[ \int L = 0.002 \text{ fb}^{-1} \]
Weighting PYTHIA

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

- 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

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

- 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
Weighting PYTHIA

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

- 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

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

- Last term is the ratio of the polarized to unpolarized proton PDFs
- Use DSSV14 for polarized and CTEQ5M for unpolarized
Dijet Phase Space

\[ \sqrt{s} = 141 \text{ GeV} \]
\[ \sqrt{s} = 63 \text{ GeV} \]
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/c$^2$

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

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

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

\[ \sigma = \sqrt{\frac{1}{N} - \frac{A^2}{N}} \]
For current study, place cut where signal purity = signal efficiency

• TMVA evaluates all input and maps them to a single variable with more signal-like events having a higher value

• Plot signal & background efficiency, signal purity, significance, etc as a function of this cut value

• This plot shows where to place cut in order to maximize purity, efficiency, or whatever an analysis requires
MLPBNN Response

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Jet $p_T$ Spectra With Rapidity Cut

- Plot jet $p_T$ after all cuts
- See reasonable enhancement of gluon jets over $p_T$ range
- Should be able to get relatively pure quark sample and enhanced gluon sample for applications which require identification

Red = Quark After MV & Rap Cut (1207)
Blue = Gluon After MV & Rap Cut (1941)

$G/Q = 1.61$
$G/(G+Q) = 62\%$

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Particle – Detector Jet $p_T$
Particle – Detector Jet Rapidity

Jet Rapidity: BeAST

Jet Rapidity: BeAST 5% Track Inefficiency

Jet Rapidity: BeAST 10% Track Inefficiency

Jet Rapidity: BeAST with Mid-Rapidity HCal
Particle – Detector Dijet Mass

- Dijet Mass: BeAST
- Dijet Mass: BeAST 5% Track Inefficiency
- Dijet Mass: BeAST 10% Track Inefficiency
- Dijet Mass: BeAST with Mid-Rapidity HCal

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Particle – Detector X_Gamma

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Particle – Detector X_Proton

X_p: BeAST

X_p: BeAST 5% Track Inefficiency

X_p: BeAST 10% Track Inefficiency

X_p: BeAST with Mid-Rapidity HCal