Jets and fragmentation at the EIC

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Jets and jet substructure at

• LEP, HERA
• LHC, RHIC, Tevatron
• EIC
Jets at the EIC

• Constrain non-perturbative quantities
  Collinear and TMD (un)polarized PDFs

Double spin asymmetries in $ep \rightarrow jet + X$

$\sqrt{s} = 100$ GeV, $|\eta| < 2$

• Potentially enhance gluon contribution by tagging the final state jet

*Hinderer, Schlegel, Vogelsang `17
Boughezal, Petriello, Xing `18*
Introduction

Jet Production
Jet Substructure
Lepton-Jet Correlations
Conclusions

Jets at the EIC

• Constrain non-perturbative quantities
  Collinear and TMD (un)polarized PDFs

Liu, FR, Vogelsang, Yuan `18
Jets at the EIC

- Constrain non-perturbative quantities
  Collinear and TMD (un)polarized PDFs
- Probe of nuclear matter effects in eA
  Parton energy loss in cold nuclear matter

Determine $\hat{q}$ for example  
*Liu, FR, Vogelsang, Yuan '18*
Jets at the EIC

• Constrain non-perturbative quantities
  Collinear and TMD (un)polarized PDFs

• Probe of nuclear matter effects in eA

• Tune parton showers, tag quark/gluon jets + quark flavor
  The jet shape

  see Christine Aidala’s talk


New NLL’ \rightarrow \text{parton shower}
Jets at the EIC

- Constrain non-perturbative quantities
  Collinear and TMD (un)polarized PDFs
- Probe of nuclear matter effects in eA
- Tune parton showers, tag quark/gluon jets
  The jet shape
- Determine the strong coupling constant $\alpha_s$

High luminosity

Most precise results from event shapes

\[ \frac{1}{\sigma} \frac{d\sigma}{d\tau} \]

N$^3$LL' results

$Q = m_Z$

Thrust

$\alpha_s(M_Z^2) = 0.1181 \pm 0.0011$

Abbate, Fickinger, Hoang, Mateu, Stewart '10
Jets at the EIC

- Constrain non-perturbative quantities
  Collinear and TMD (un)polarized PDFs

- Probe of nuclear matter effects in eA

- Tune parton showers, tag quark/gluon jets
  The jet shape

- Determine the strong coupling constant $\alpha_s$
  Jet mass of narrow jets or DIS event shapes like thrust

- Jet fragmentation functions and hadronization

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Jet pull to probe the color flow in the event

Sudakov safety

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Gallicchio, Schwartz `10
Jets at the EIC

- Constrain non-perturbative quantities
  - Collinear and TMD (un)polarized PDFs
- Probe of nuclear matter effects in eA
- Tune parton showers, tag quark/gluon jets
  - The jet shape
- Determine the strong coupling constant $\alpha_s$
  - Jet mass of narrow jets or DIS event shapes like thrust
- Jet fragmentation functions and hadronization
- Need to understand non-perturbative aspects and power corrections at low particle multiplicities and low jet $p_T$
Jets at the EIC

- Constrain non-perturbative quantities
  Collinear and TMD (un)polarized PDFs
- Probe of nuclear matter effects in eA
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- Jet fragmentation functions and hadronization

- Need to understand non-perturbative aspects and power corrections at low particle multiplicities and low jet $p_T$

- Validate with low $p_T$ jet data from HERA, RHIC
- Compare to MC simulations and pQCD results
Outline

- Introduction
- Jet production at the EIC
- Jet substructure
- Lepton-jet correlations
- Conclusions
Monte Carlo simulations

- Pythia6 based eRHIC tune
- Comparison to HERA jet shape data
- SAS 1D-LO photon PDF Schuler, Sjoestrand '95
- Hadronization, ISR, no MPI

Jets at the EIC

Scattered lepton

\[ 0.1 < y < 0.85, 10 < p_T^{\text{electron}} < 30 \text{ GeV/c}, \quad Q^2 > 100 \text{ GeV}^2 \]

Struck quark

\[ 0.1 < y < 0.85, 10 < p_T^{\text{electron}} < 30 \text{ GeV/c}, \quad |\phi^{\text{jet}} - \phi^e - \pi| < 0.4, Q^2 > 100 \text{ GeV}^2 \]

Jets

\[ 0.1 < y < 0.85, 10 < p_T^{\text{electron}} < 30 \text{ GeV/c}, \quad |\phi^h - \phi^e - \pi| < 0.4, Q^2 > 100 \text{ GeV}^2 \]

Hadrons

\[ \sqrt{s} = 89 \text{ GeV} \]

Rapidity and momentum
Jet transverse momentum spectra

Photoproduction

- $-2 < \eta_{lab} < 4$, anti-$k_T$, $0.2 < y < 0.8$
- $\sqrt{s} = 141 \text{ GeV}$, $Q^2_{\text{max}} < 1 \text{ GeV}^2$

Deep Inelastic Scattering

- $\sqrt{s} = 89 \text{ GeV}$
- $0.1 < y < 0.85$
- $Q^2 > 25 \text{ GeV}^2$
- $|\phi^\text{jet} - \phi^e - \pi| < 0.4$

Aschenauer, Lee, Page, FR `19

Arratia, Jacak, FR, Song `19
Number of particles inside jets

Deep Inelastic Scattering

Arratia, Jacak, FR, Song '19

$\sqrt{s} = 89$ GeV, $0.1 < y < 0.85$

$p_T^{\text{particle}} > 250$ MeV/c
Jet production at the EIC

- $\ell p \to \text{jet} + X$ \text{Lepton unobserved, high } p_T$
  \[ \frac{d\sigma}{dp_T d\eta} \]

- $\ell p \to \ell' + \text{jet} + X$ \text{DIS, high } p_T, Q^2$
  \[ \frac{d\sigma}{dp_T d\eta dQ^2} \]

- $\ell p \to \ell' + \text{jet} + X$ \text{Photoproduction, high } p_T, Q^2 < 0.1 \text{ GeV}^2$
  \[ \frac{d\sigma}{dp_T d\eta dQ^2} \]

Analytical control for these processes
Other observables are possible and will “only” need to adjust q/g fractions

\[ Hinderer, Schlegel, Vogelsang '17 \]
\[ Boughezal, Petriello, Xing '18 \]
\[ Daleo, de Florian, Sassot '04, Gonzalez-Hernandez, Rogers, Sato, Wang '18 \]
\[ Jäger, Stratmann, Vogelsang '03 \]
Photoproduction at the EIC

- Require high $p_T$ and $Q^2 < 0.1$ GeV$^2$
- Access the parton content of (polarized) photons

Jäger, Stratmann, Vogelsang `03
de Florian, Pfeuffer, Schäfer, Vogelsang `13
Chu, Aschenauer, Lee, Zhang `17
Photoproduction at the EIC

Leading power factorization

- Inclusive jets
  \[
  \frac{d\sigma}{dp_T d\eta dQ^2} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H_{ab}^c \otimes J_c
  \]

- Jet mass
  \[
  \frac{d\sigma}{dp_T d\eta dQ^2 dm_J} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H_{ab}^c \otimes G_c(m_J)
  \]

Weizsäcker-Williams spectrum
resolved: \( \otimes f_{a/\gamma} \)

\( \mu_H \sim p_T \)
\( \mu_J \sim p_T R \)

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Dasgupta, Dreyer, Salam, Soyez `15
Kaufmann, Mukherjee, Vogelsang `15
Kang, FR, Vitev `16
Dai, Kim, Leibovich `16
Photoproduction of jets at the EIC

\[ \ell p \to \ell' + \text{jet} + X \]

\[ \eta_{\text{lab}} = \eta + \frac{1}{2} \ln \frac{E_p}{E_e} \]

\[ E_e = 20 \text{ GeV} \]
\[ E_p = 250 \text{ GeV} \]

- Theory uncertainties need to be studied more carefully
Outline

• Introduction
• Jet production at the EIC
• Jet substructure
• Lepton-jet correlations
• Conclusions
Jet substructure at the EIC

• Which observables are useful?
  • Sensitivity to soft physics and scales
  • Control of nonperturbative physics

IRC safe + control of hadronization corrections

$$\exp(-g_K \ln(\mu/\mu_0))$$

see Alessandro’s talk

• Study hadronization
• Spin dependence
• Modification in eA

Cal, Neill, FR, Waalewijn ’19
Jet substructure at the EIC

• Which observables are useful?
  • Sensitivity to soft physics and scales
  • Control of nonperturbative physics

Hadrons inside jets

• Study collinear and TMD fragmentation functions
Jet substructure at the EIC

- Which observables are useful?
  - Sensitivity to soft physics and scales
  - Control of nonperturbative physics

Hadrons inside jets

Jet shapes

Angles between jet axes
Jet substructure at the EIC

- Which observables are useful?
  - Sensitivity to soft physics and scales
  - Control of nonperturbative physics

Hadrons inside jets

Jet shapes

Soft drop grooming $z_g, R_g$

Angles between jet axes

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Jet substructure at the EIC

• Which observables are useful?
  • Sensitivity to soft physics and scales
  • Control of nonperturbative physics

Hadrons inside jets

Jet shapes

Soft drop grooming $z_g, R_g$

Angles between jet axes

Very soft sensitive e.g. $\Delta E$
Jet angularities

- Family of observables with a continuous parameter $a$
- Jet mass ($a = 0$), jet broadening ($a = 1$)
- Event shape type of observables

\[
\tau_a = \frac{1}{p_T} \sum_{i \in J} p_{Ti} \Delta R_{ij}^{2-a}
\]

- Factorization $\tau_a^{1/(2-a)} \ll R$

\[
G_c(z, p_T, R, \tau, \mu) = \sum_i \mathcal{H}_{c\rightarrow i}(z, p_T R, \mu) C_i(\tau, p_T, \mu) \otimes S_i(\tau, p_T, R, \mu)
\]

- Each function has its own evolution equation e.g.

\[
\mu \frac{d}{d\mu} C_i(\tau_a, p_T, \mu) = \int d\tau'_a C_i(\tau_a - \tau'_a, p_T, \mu) C_i(\tau'_a, p_T, \mu)
\]
Jet angularities at the EIC

Aschenauer, Lee, Page, FR `19

Nonperturbative shape function \( F(k) = \frac{4k}{\Omega^2} \exp\left(-2k/\Omega_\alpha\right) \)

CT14, GRS 99 PDFs
Jet angularities at the EIC

- Power corrections

- e.g. \( m_J^2 = \left( \sum_{i \in J} p_i \right)^2 \) vs. \( \tau_0 = \frac{1}{p_T} \sum_{i \in J} p_T i \Delta R_{i,J}^2 \) vs. \( \tau'_a = \frac{1}{2E_J} \sum_{i \in J} |\vec{p}_T^{iJ}| \exp(-|\eta_{i,J}|(1 - a)) \)

CT14, GRS 99 PDFs
Soft drop grooming

- Systematically remove soft wide-angle radiation in the jet
- Recluster jet with the C/A algorithm

\[ d_{ij} = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \]

Angular ordered clustering tree

See also: Krohn, Thaler, Wang `10, Ellis, Vermilion, Walsh `10
Soft drop grooming

- Systematically remove soft wide-angle radiation in the jet

- Recluster jet with the C/A algorithm
  \[ d_{ij} = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \]

- Recursively decluster jet and check the criterion

\[
\min\left[\frac{p_{T1} + p_{T2}}{p_{T1} + p_{T2}}\right] > z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^\beta
\]

\[ \Delta R_{12}^2 = \Delta \eta^2 + \Delta \phi^2 \]

See also: Krohn, Thaler, Wang '10, Ellis, Vermilion, Walsh '10
Soft drop grooming

- Systematically remove soft wide-angle radiation in the jet

- Reclasser jet with the C/A algorithm

\[ d_{ij} = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \]

- Recursively decluster jet and check the criterion

\[ \frac{\text{min}[p_T_1, p_T_2]}{p_T_1 + p_T_2} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)^\beta \]

\[ \Delta R_{12}^2 = \Delta \eta^2 + \Delta \phi^2 \]

Particles in the groomed jet

See also: Krohn, Thaler, Wang '10, Ellis, Vermilion, Walsh '10

Dasgupta, Fregoso, Marzani, Salam '13
Larkoski, Marzani, Soyez, Thaler '14
Groomed jet substructure at the EIC?

- Groomed jet mass: Sensitivity to NP physics

\[
\mu_S \sim \frac{p_T \tau}{R}
\]

Ungroomed:
\[
\mu_S \sim \frac{p_T \tau}{R} \left( \frac{z_{\text{cut}} R^2}{\tau^2} \right)^{\frac{1}{2+\beta}}
\]

SD groomed:
\[
\mu_S = \Lambda_{\text{QCD}} \sim 1 \text{ GeV}
\]

Onset of NP physics

\[
\tau_{\text{gr}} = \tau_{\text{ungr}} \left( \frac{\Lambda_{\text{QCD}}}{p_T R z_{\text{cut}}} \right)^{\frac{1}{1+\beta}}
\]

Potentially 2 orders of magnitude difference for a 1 TeV jet and \( z_{\text{cut}} = 0.1 \)

\[ \tau = \frac{m^2}{p_T^2} \]

Frye, Larkoski, Schwartz, Yan `16

Les Houches `17
Groomed jet substructure at the EIC?

• Groomed jet mass: Sensitivity to NP physics

\[ \mu_S \sim \frac{p_T \tau}{R} \]

Ungroomed: \[ \mu_S \sim \frac{p_T \tau}{R} \]  
SD groomed: \[ \mu_S \sim \frac{p_T \tau}{R} \left( \frac{z_{cut} R^2}{\tau^2} \right)^{\frac{1}{2+\beta}} \]

with \[ \mu_S = \Lambda_{QCD} \sim 1 \text{ GeV} \]

→ Onset of NP physics

\[ \tau_{gr} = \tau_{ungr} \left( \frac{\Lambda_{QCD}}{p_T R z_{cut}} \right)^{\frac{1}{1+\beta}} \]

Potentially 2 orders of magnitude difference for a 1 TeV jet and \( z_{cut} = 0.1 \)!

Les Houches `17

• EIC this factor is \( o(1) \) …

Frye, Larkoski, Schwartz, Yan `16

\[ \tau = \frac{m^2}{p_T^2} \]
Can ask different questions about the groomed jet such as

- Groomed radius \( R_g = \Delta R_{12} = \theta_g R \)
- Momentum sharing fraction \( z_g = \frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} \)
- Displacement of the jet axis \( \theta_{st,gr} \)
- The jet energy drop due to grooming \( \Delta E \)

- Soft drop jet mass
- Angularities or energy-energy correlation functions

These observables have interesting properties and turn out to be calculable in pQCD
Recent results from ATLAS

- The groomed jet mass

\[ \beta = 0 \]

\[ \rho = \frac{m^2}{p_T^2} \]

\[ \beta = 2 \]
Recent results from ATLAS

• The groomed jet radius $R_g$

\[ \beta = 0 \]

\[ \beta = 2 \]

Kang, Lee, Liu, Neill, FR `19
Recent results from ATLAS

• The groomed momentum sharing fraction $z_g$

\[
\beta = 0 \hspace{2cm} \beta = 2
\]

\[
p(z_g) = \frac{1}{\sigma} \frac{d\sigma}{dz_g} = \int d\theta_g p(\theta_g) p(z_g | \theta_g)
\]

\[
p(z_g | \theta_g) = \frac{\alpha_s(z_g \theta_g p_T R) \bar{P}_i(z_g)}{\int_{z_{cut}}^{1/2} dz \alpha_s(z \theta_g p_T R) \bar{P}_i(z)} \Theta(z_g - z_{cut})
\]

Track functions  
Krohn, Schwartz, Lin, Waalewijn `12

Larkoski, Marzani, Thaler `15
Groomed jet substructure at the EIC

Arratia, Jacak, FR, Song '19
Groomed jet substructure at the EIC


\[
\begin{align*}
\sqrt{s} &= 89 \text{ GeV} \\
0.1 < y < 0.85 \\
p_T^{\text{jet}} > 4 \text{ GeV/c} \\
|\phi^{\text{jet}} - \phi^e - \pi| < 0.4, \ z_{\text{min}} = 0.1 \\
\langle x \rangle &= 0.13, \langle \nu \rangle = 1.18 \text{ TeV} \\
\langle x \rangle &= 0.35, \langle \nu \rangle = 1.47 \text{ TeV}
\end{align*}
\]
Groomed jet substructure at the EIC

Arratia, Jacak, FR, Song '19
FR, Xiao, Yuan '19

Broadening effect

- $\hat{q}L = 0 \text{ GeV}^2$
- $\hat{q}L = 0.2 \text{ GeV}^2$
- $\hat{q}L = 0.8 \text{ GeV}^2$

Pythia: $\sqrt{s} = 89 \text{ GeV}$
$20 < p_T^{\text{electron}} < 35 \text{ GeV/c}$
Outline

- Introduction
- Jet production at the EIC
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- Lepton-jet correlations
- Conclusions
Measurement of TMD PDFs at the EIC

- Semi-Inclusive Deep-Inelastic Scattering (SIDIS)
- Measure hadrons with low transverse momentum

\[
\frac{d\sigma}{dx dy d\psi dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \right\} + \ldots
\]

See Alessandro Bacchetta and Marco Radici’s talks

\[ \rightarrow \text{Sensitivity to (polarized) TMD PDFs} \]

- Complementary process using jets? Universality?
Lepton-Jet Correlations

- Require high $p_T$ jet
- Measure imbalance $q_\perp$ between lepton and jet in the lab frame

\[
\frac{d\sigma}{dy_\ell' d^2k_\perp \ell' d^2q_\perp}
\]

Transverse plane

- Spin asymmetries and eA collisions
- Analogous to e.g. $pp \rightarrow \text{di-jets} + X$
- CM or laboratory frame; close analogy to $pp$ collisions at RHIC & the LHC

Boer, Vogelsang `04
Vogelsang, Yuan `07
Sun, Yuan, Yuan `15

Liu, FR, Vogelsang, Yuan `18
Lepton-Jet Correlations

• TMD factorization for small $q_\perp$

$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2k_\perp d^2q_\perp} = H_{TMD}(Q, \mu_F) \int d^2k_\perp d^2\lambda_\perp x f_q(x, k_\perp, \zeta_c, \mu_F) S_J(\lambda_\perp, \mu_F) \delta^{(2)}(q_\perp - k_\perp - \lambda_\perp)$$

Hard \hspace{1cm} \text{Quark TMD} \hspace{1cm} \text{Soft}

• Small $q_\perp$ resummation achieved in $b$-space

$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2k_\perp d^2q_\perp} = H(Q, R, \mu_F) \int \frac{d^2b_\perp}{(2\pi)^2} \frac{e^{ik_\perp \cdot b_\perp}}{i} e^{-S_{pert}(b_\perp)-S_{NP}(b_\perp)+\Gamma_s(b_\perp)} \sum_i C_{q/i}(x, \mu_b/\mu) \otimes f_i(x, \mu_b)$$

with Sudakov exponent

$$S_{pert}(b_\perp) = \frac{1}{2} \int_{\mu_h^2}^{k_\perp^2} \frac{d\mu^2}{\mu^2} \left[ A_q(\alpha_s(\mu)) \ln \frac{s}{\mu^2} + B_q(\alpha_s(\mu)) \right]$$

+ non-global logarithms

see also: Gutierrez-Reyes, Makris, Vaidya, Scimemi, Zoppi `19
Azimuthal lepton-jet correlation

Liu, FR, Vogelsang, Yuan `18

$\ell(k) + A(P) \rightarrow \ell'(k_\ell) + \text{Jet}(P_J) + X$

- Use azimuthal angle $\phi$ instead of $q_\perp$

- Sample EIC kinematics

\[
\sqrt{s} = 80 \text{ GeV} \\
\not{k}_\ell \perp = 5 \text{ GeV} \\
5 < p_\perp < 10 \text{ GeV}
\]

\[ q_\perp = |\not{k}_\ell \perp + \not{P}_J \perp | \]

\[
\frac{1}{\sigma} \frac{d\sigma}{d\phi}
\]
Transverse spin dependent case

Liu, FR, Vogelsang, Yuan `18

\[ \ell(k) + A(P) \rightarrow \ell'(k_\ell) + \text{Jet}(P_J) + X \]

- TMD factorization for small \( q_\perp \)

- Sensitivity to Sivers TMD PDF  
  Sun, Yuan `13

- Test of universality and factorization breaking effects, see RHIC measurements  
  STAR, PRL 99 (2007) 142003
Transverse spin dependent case

- TMD factorization for small $q_{\perp}$

\[
\ell(k) + A(P) \rightarrow \ell'(k_{\ell}) + \text{Jet}(P_J) + X
\]

Liu, FR, Vogelsang, Yuan \`18

\[
A_N(\Delta \phi) = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}
\]

Asymmetry

- Sensitivity to Sivers TMD PDF Sun, Yuan \`13
- Test of universality and factorization breaking effects, see RHIC measurements STAR, PRL 99 (2007) 142003
Transverse momentum broadening in eA collisions

- Comparison to Pythia8
- $p_T$ broadening due to multiple scatterings $\hat{q}L$

$\hat{q}L = 0 \text{ GeV}^2$
$\hat{q}L = 0.2 \text{ GeV}^2$
$\hat{q}L = 0.8 \text{ GeV}^2$

Pythia: $\sqrt{s} = 89 \text{ GeV}$
$9 < p_T^{\text{electron}} < 11 \text{ GeV}/c$

$\langle x \rangle = 0.13, \langle \nu \rangle = 0.91 \text{ TeV}$

Liu, FR, Vogelsang, Yuan `18
Arratia, Jacak, FR, Song `19
Transverse momentum balance

Arratia, Jacak, FR, Song '19

$\sqrt{s} = 89$ GeV
$10 < p_T^{\text{electron}} < 15$ GeV/c
$\langle x \rangle = 0.11, \langle u \rangle = 1.17$ TeV
Outline

• Introduction
• Jet production at the EIC
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Conclusions

• Jets are unique tools at the future EIC
• Extract collinear and TMD PDFs
• Jet substructure and jet correlations
• Tune parton showers
• Probe of cold nuclear matter in eA
• Precision studies and NP effects
• Studies of fragmentation and hadronization
• Detector requirements
• Further studies needed