Theory review of jets at the EIC

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Introduction

Inclusive Jets                     Jet Substructure                   Correlations                      Conclusions

Jets and jet substructure at
• LEP, HERA
• Tevatron, RHIC, LHC
• EIC

Q^2 = 25030 GeV^2, y = 0.56, x = 0.50

Electron Ion Collider: The Next QCD Frontier

Understanding the glue that binds us all

H1 Run 122145 Event 69506
Date 19/09/1995
A few of recent examples:

- Quark/ gluon tagging using for example jet angularities
- Jet charge
- Hadron-in-jet distributions
- Possible extraction of $\alpha_s$  [Les Houches `17]
- Measurement of the QCD splitting function using Soft drop or subjets
Jets at an EIC

• Jets are inherently interesting
• Constrain non-perturbative quantities
e.g. collinear and TMD (un)polarized PDFs

For recent work see for example: Schlegel, Hinderer, Vogelsang `15, Abelov, Boughezal, Liu, Petriello `16,
Klasen, Kovarik `18, Currie, Gehrmann, Glover, Huss, Niehus, Vogt `18,
Chu, Aschenauer, Lee, Zhang `17 …
Jets at an EIC

- Jets are inherently interesting
- Constrain non-perturbative quantities e.g. collinear and TMD (un)polarized PDFs
- No fragmentation functions required
- Complimentary to observables with identified hadrons
- Probe of nuclear matter effects in eA
- Can make use of new methods developed for the LHC and RHIC like jet substructure and tagging

Challenge: We have to understand the NP physics of jets
1. Validate with RHIC, HERA measurements or
2. Compare to MC simulations
Outline

• Introduction
• Inclusive jets at the EIC
• Jet substructure
• Jet correlations
• Conclusions
Single inclusive jets at the EIC

- $pp \rightarrow \text{jet} + X$

Lepton unobserved, high $p_T$

$\frac{d\sigma}{dp_T d\eta}$

EIC $\sqrt{s} = 100$ GeV, $P_{jet} = 10$ GeV

Schlegel, Hinderer, Vogelsang `15, `17,
Abelov, Boughezal, Liu, Petriello `16,
Boughezal, Petriello, Xing `18
**Single inclusive jets at the EIC**

- $pp \to \text{jet} + X$

Lepton unobserved, high $p_T$

\[
\frac{d\sigma}{dp_T d\eta} \quad \sqrt{s} = 100 \text{ GeV}
\]

$Q^2 > 10$ GeV, $|\eta_{\text{jet}}| < 2$

$\mu_R = \mu_F = p_T^{\text{jet}}$

$R = 0.5$

CT14 pdf

Schlegel, Hinderer, Vogelsang '15, '17,
Abelov, Boughezal, Liu, Petriello '16,
Boughezal, Petriello, Xing '18
Single inclusive jets at the EIC

- $pp \rightarrow \text{jet} + X$
  
  Lepton unobserved, high $p_T$

$$\frac{d\sigma}{dp_T d\eta}$$

$\sqrt{s} = 100$ GeV

Schlegel, Hinderer, Vogelsang ’15, ’17,
Abelov, Boughezal, Liu, Petriello ’16,
Boughezal, Petriello, Xing ’18
Single inclusive jets at the EIC

- $pp \rightarrow \text{jet} + X$  
  Lepton unobserved, high $p_T$

\[
\frac{d\sigma}{dp_T d\eta}
\]

- $pp \rightarrow \ell + \text{jet} + X$  
  DIS, high $p_T, Q^2$

\[
\frac{d\sigma}{dp_T d\eta dQ^2}
\]

- $pp \rightarrow \ell + \text{jet} + X$  
  Photoproduction, high $p_T, Q^2 < 0.1 \text{ GeV}^2$

\[
\frac{d\sigma}{dp_T d\eta dQ^2}
\]
Inclusive jet production \( pp \rightarrow \text{jet} + X \)

\[
\frac{d\sigma_{pp\rightarrow\text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c + O(R^2)
\]

perturbatively calculable

RG evolution of jet functions

\[
\mu \frac{d}{d\mu} J_i = \sum_j P_{ji} \otimes J_j
\]

Dasgupta, Dreyer, Salam, Soyez \`15
Kaufmann, Mukherjee, Vogelsang \`15
Kang, FR, Vitev \`16
Dai, Kim, Leibovich \`16
QCD factorization

- Inclusive jet production \( pp \rightarrow \text{jet} + X \)

\[
\frac{d\sigma_{pp \rightarrow \text{jet} X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c + \mathcal{O}(R^2)
\]

- Jet substructure \( \tau \)

\[
\frac{d\sigma_{pp \rightarrow (\text{jet} \tau) X}}{dp_T d\eta d\tau} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes \Gamma_c(\tau) + \mathcal{O}(R^2)
\]

Dasgupta, Dreyer, Salam, Soyez '15
Kaufmann, Mukherjee, Vogelsang '15
Kang, FR, Vitev '16
Dai, Kim, Leibovich '16
QCD factorization

• Inclusive jet production $pp \to \text{jet} + X$

$$\frac{d\sigma_{pp\to\text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes J_c + O(R^2)$$

• Jet substructure $\tau$

$$\frac{d\sigma_{pp\to(\text{jet } \tau)X}}{dp_T d\eta d\tau} = \sum_{abc} f_a \otimes f_b \otimes H^c_{ab} \otimes G_c(\tau) + O(R^2)$$

• Hard functions for lepton-proton scattering, e.g.

$$\frac{d\sigma_{\ell p\to\ell' \text{ jet}+X}}{dp_T d\eta dQ^2 d\tau}$$

• Photoproduction
  
  Jäger, Stratmann, Vogelsang `03

  (unpolarized and polarized)

• DIS

  Daleo, de Florian, Sassot `04,
  Gonzalez-Hernandez, Rogers, Sato, Wang `18
Photoproduction at the EIC

- Require high $p_T$ and $Q^2 < 0.1 \text{ GeV}^2$
- 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

• Inclusive jets

\[
\frac{d\sigma}{d p_T d\eta d Q^2} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H_{ab}^c \otimes J_c
\]

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

• Jet mass

\[
\frac{d\sigma}{d p_T d\eta d Q^2 d m_J} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H_{ab}^c \otimes G_c(m_J)
\]

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

Jäger, Stratmann, Vogelsang `03
Chu, Aschenauer, Lee, Zhang `17
\( \sqrt{s} = 141 \text{ GeV} \)
\( R = 0.8 \)
\( p_T > 10 \text{ GeV} \)
\( Q^2 < 0.1 \text{ GeV}^2 \)
\( E_e = 20 \text{ GeV} \)
\( E_p = 250 \text{ GeV} \)
\( \sqrt{s} = 141 \text{ GeV} \)

\( R = 0.8 \)

\( p_T > 10 \text{ GeV} \)

\( Q^2 < 0.1 \text{ GeV}^2 \)

\( E_e = 20 \text{ GeV} \)

\( E_p = 250 \text{ GeV} \)
Cold nuclear matter effects in eA

- Hadron multiplicity ratios $d\sigma/dz_h$
- SIDIS

$eA \rightarrow e h X$

$Q^2 > 1 \text{ GeV}^2$  \quad $\nu < 23 \text{ GeV}$

$W^2 > 10 \text{ GeV}^2$

Constrain medium input and extrapolate to jets at the EIC

HERMES, 2003

$D_i^h(z_h) \rightarrow D_i^{\text{med},h}(z_h)$
Outline

• Introduction
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• Jet correlations
• Conclusions
The jet mass at the LHC

- Jet mass $m_J^2 = \left( \sum_{i \in J} p_i \right)^2$ for inclusive jet production $pp \rightarrow (\text{jet } m_J^2)X$

- Quark-gluon discrimination

- NP contribution:
  - Multi parton interactions (MPI)
  - Hadronization
  - Pileup

- Including soft drop: $\alpha_s$ extraction possible

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Kang, Lee, FR '18
Kang, Lee, Liu, FR '18

see also: Li, Li, Yuan '11,
Dasgupta, Khelifa-Kerfa, Marzani, Spannowsky '12, …

ATLAS, JHEP 1205 (2012) 128
Factorization

- Hard-collinear factorization $R \ll 1$

\[
\frac{d\sigma}{d\eta dp_T d\tau} = \sum_{abc} f_a(x_a, \mu) \otimes f_b(x_b, \mu) \otimes H_{ab}^c(x_a, x_b, \eta, p_T/\eta, \mu) \otimes G_c(\tau, p_T, R, \tau, \mu)
\]

- Hard-collinear-soft factorization $\tau \ll R^2$

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

Kang, Lee, FR `18, Kang, Lee, Liu, FR `18

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

$pp \to (\text{jet } m_J^2) X$
$p p \rightarrow (\text{jet } m^2_J)X$

Perturbative result

\begin{align*}
\sqrt{s} = 7 \text{ TeV, anti-} k_T, R = 1, |\eta| < 2
\end{align*}

$200 < p_T < 300 \text{ GeV}$

$300 < p_T < 400 \text{ GeV}$

$400 < p_T < 500 \text{ GeV}$

$500 < p_T < 600 \text{ GeV}$
pp → (jet $m_J^2$)X

Perturbative result

Including $d\sigma^{\text{pert}} \otimes F$

NP shape function

$F_1(k) = \frac{4k}{\Omega^2} \exp(-2k/\Omega)$

Stewart, Tackmann, Waalewijn `15

Kang, Lee, FR `18,
Kang, Lee, Liu, FR `18
Jet angularities

- Family of observables with a continuous parameter $\alpha$
- Jet mass ($\alpha = 0$), jet broadening ($\alpha = 1$)
- Dependence on jet axis: standard, recoil free
- Event shape type of observables

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

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

\[ G_c(z, p_T, R, \tau_\alpha, \mu) = \sum_i \mathcal{H}_{c\to i}(z, p_T R, \mu) C_i(\tau_\alpha, p_T, \mu) \otimes S_i(\tau_\alpha, p_T, R, \mu) \]
Jet angularities

\[ F(\tau_a; \eta, p_T, R) = \frac{d\sigma^{pp \to (\text{jet } \tau_a)X}}{d\eta dp_T d\tau_a} / \frac{d\sigma^{pp \to \text{jet } X}}{d\eta dp_T} \]

Kang, Lee, FR `18
Quark-gluon discrimination

Kang, Lee, FR `18
Quark-gluon discrimination

Kang, Lee, FR `18

ROC curve

200 GeV < p_T < 250 GeV, |η| < 1.2
\( a = 0.5, R = 0.4, \sqrt{s} = 7 \text{ TeV} \)
Photoproduction at the EIC

\[ \int \frac{d\sigma}{d\log_{10}(|a|)} \]
Photoproduction at the EIC

Log Angularity: $R = 0.8$: $p_T > 10.0$: $a = 0.0$

Log Angularity: $R = 0.4$: $p_T > 10.0$: $a = 0.0$

$\sqrt{s} = 141$ GeV, anti-$k_T$

$p_T > 10$ GeV, $|\eta| < 2.5$

NLL ($R = 0.4$)
NLL ($R = 0.8$)

in collaboration with Aschenauer, Page
Power corrections

- e.g. \( m_J^2 = \left( \sum_{i \in J} p_i \right)^2 \) vs. \( \tau_0 = \frac{1}{p_T} \sum_{i \in J} p_{T_i} \Delta R_{i,J}^2 \)

\[ R = 0.4 \]
\[ a = -2.0 \]
\[ \text{red} \quad a = 0.0 \]
\[ \text{green} \quad a = 1.0 \]

\[ R = 0.8 \]

in collaboration with Aschenauer, Page
The jet energy profile

\[ \psi(r) = \frac{\sum \Delta R_{i,J} < r \ p_{T,i}}{\sum \Delta R_{i,J} < R \ p_{T,i}} \]

\[ \rho(r) = \frac{d\psi(r)}{dr} \]

- Most frequently studied jet substructure observable
- LEP, HERA, Tevatron, LHC, …
- Inclusive jets, Z+jet, Higgs+jet, …
The jet energy profile

The jet energy profile

\[ \psi(r) = \frac{\sum_{\Delta R_{i,j} < r} p_{Ti}}{\sum_{\Delta R_{i,j} < R} p_{Ti}} \]

\[ \rho(r) = \frac{d\psi(r)}{dr} \]

- Factorization beyond leading-log

\[ G_i(z, p_T R, r/R, \mu) = \sum_j H_{i \to j}(z, p_T R, \mu) \times \int d^2k_\perp C_j(p_T r, k_\perp, \mu, \nu) S^G_j(k_\perp, \mu, \nu R) S_j^{NG}(r/R) \]

- NLL' resummation of \( \ln(r/R) \)
- Rapidity RG evolution, SCET_{II}
- Soft recoil
- Non-global logarithms

ATLAS, PRD 83 (2011) 052003

Earlier work see:
- Ellis, Kunszt, Soper '92
- Seymour '98
- Li, Li, Yuan '11
- Chien, Vitev '14
Identified hadrons inside jets

- Constrain fragmentation functions
- Tagging

\[
\frac{d\sigma_{pp \rightarrow (\text{jet } h)} }{dp_T d\eta dz_h} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes G_c(z_h)
\]

Arleo, Fontannaz, Guillet, Nguyen ´14
Kaufmann, Mukherjee, Vogelsang ´15
Kang, FR, Vitev ´16
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Lepton-jet correlations

- Measure imbalance between lepton and jet
- Spin asymmetries and eA collisions
- Analogous to e.g. $pp \rightarrow \text{di-jets} + X$ (Sun, Yuan, Yuan '15)
- cms or laboratory frame; close analogy to $pp$ collisions

\[
\ell' (k_{\ell'}) \\
\ell \\
A \\
\text{Jet} (p_J) \\
\text{Transverse plane}
\]

\[
q_{\perp} = |k_{\ell'} + \vec{p}_J| \\
\vec{k}_{\ell'_{\perp}} \\
\vec{p}_J_{\perp}
\]

- Consider
\[
\frac{d\sigma}{dy_{\ell'} d^2k_{\perp \ell'} d^2q_{\perp}}
\]
Requires TMD resummation for $q_{\perp} \ll k_{\ell'}$

for the back-to-back configuration, and jet radius resummation for $R \ll 1$

Liu, FR, Vogelsang, Yuan
- in preparation
**Introduction**

- **Inclusive Jets**

**Jet Substructure**

**Correlations**

**Conclusions**

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**Factorization**

- Joint $q_\perp$ and jet radius resummation

\[
\frac{d\sigma}{d y_{c} d^2 k_{\perp} R} = H_{q}(k_{\perp} R, \mu) J_{q}(k_{\perp} R, \mu)
\]

\[
\int d^2 k_{\perp} \lambda_{1\perp} d^2 k_{\perp} \lambda_{2\perp} x f_q(x, k_{\perp}, \mu, \nu) S_{gl}(\lambda_{1\perp}, \mu, \nu) S_{sc}(\lambda_{2\perp} R, \mu) \delta^{(2)}(q_{\perp} - k_{\perp} - \lambda_{1\perp} - \lambda_{2\perp})
\]

Global soft  Soft-collinear (in the jet direction)

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*Liu, FR, Vogelsang, Yuan*  
*in preparation*
Azimuthal lepton-jet correlation

- Sample EIC kinematics
  \( \sqrt{s} = 80 \text{ GeV} \)
  \( k_{T} = 5 \text{ GeV} \)
  \( 5 < p_{T} < 10 \text{ GeV} \)

- Currently \( \ln R \) not yet resummed
Outline

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Conclusions

• Jets can be a unique tool at the future EIC
• Requires further theoretical efforts
• Extract collinear and TMD PDFs
• Jet substructure
• NP effects important
• Probe of nuclear matter