QCD Jets in DIS

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Introduction

Jets and jet substructure at
- HERA
- LHC, RHIC
- the future EIC, LHeC

\[ Q^2 = 25030 \text{ GeV}^2, \quad y = 0.56, \quad x = 0.50 \]
A few of recent examples:

- Hadron-in-jet distributions
  Anderle, Kaufmann, Stratmann, FR, Vitev `17

- Measurement of the QCD splitting function
  Soft drop or subjets
  Larkoski, Marzani, Thaler `15; Kang, FR, Waalewijn `18

- Quark/ gluon tagging: e.g. jet angularities

- Jet charge  Waalewijn `12, Fraser, Schwartz `18
Jets at the EIC

• Jets are inherently interesting
Jets at the 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 the 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
- Semi-inclusive jet observables
- Lepton-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

\( p \rightarrow c \quad \text{jet} + X \)

\[ \begin{align*}
ATLAS, JHEP 1205 (2012) 128
\end{align*} \]
Factorization

- Hard-collinear factorization $R \ll 1$

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

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

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

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

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

$pp \rightarrow (\text{jet } m_J^2) X$

Diagram showing hard-collinear and soft-collinear processes.
$pp \to (\text{jet } m_J^2) X$

Perturbative result

**Single inclusive ungroomed jet**

$\sqrt{s} = 7 \text{ TeV}$, $\text{anti-}k_T$, $R = 1$, $|\eta| < 2$

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

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

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

$500 < p_T < 600 \text{ GeV}$

**ATLAS, JHEP 05 (2012) 128**

Kang, Lee, FR '18, Kang, Lee, Liu, FR '18
\[ pp \rightarrow (\text{jet } m_J^2) X \]

**Perturbative result**

Including \( d\sigma^{\text{pert}} \otimes F \)

**NP shape function**

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

\[ \text{Kang, Lee, FR `18, Kang, Lee, Liu, FR `18} \]

\[ \text{Stewart, Tackmann, Waalewijn `15} \]
For example: Photoproduction at the EIC

- Require high $p_T$ and $Q^2 < 0.1 \text{ GeV}^2$
- Access the parton content of (polarized) photons
- Measure final state jets instead of hadrons
- Jet mass allows for tagging quark/gluon jets

- How large are NP corrections associated with the jets?
- Can we disentangle the different NP contributions?

see also Xiaoxuan Chu’s talk

Jäger, Stratmann, Vogelsang  `03
de Florian, Pfeuffer, Schäfer, Vogelsang `13
Stewart, Tackmann, Waalewijn `15
Chu, Aschenauer, Lee, Zhang `17
Aschenauer, Kang, Lee, Page, FR,Vogelsang,Yuan
Photoproduction at the EIC

- Inclusive jets
  \[
  \frac{d\sigma}{dp_T d\eta} = \sum_{a,b,c} f_{a/\ell} \otimes f_{b/p} \otimes H_{ab}^c \otimes J_c
  \]
  Weizsäcker-Williams spectrum
  resolved: \( \otimes f_{a/\gamma} \)

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

Universality of the semi-inclusive jet functions
Kang, FR, Vitev `16

Chu, Aschenauer, Lee, Zhang `17

Aschenauer, Kang, Lee, Page, FR, Vogelsang, Yuan
Photoproduction at the EIC

\[ \sqrt{s} = 140 \text{ GeV} \]

\[ R = 0.8, \text{ anti-}k_T \]

Comparison to MC is work in progress

Here: Shift of the peak instead of convolution with shape function

CT14, GRS 99 PDFs
Photoproduction at the EIC

\[ \sqrt{s} = 140 \text{ GeV} \]
\[ R = 0.8, \text{ anti-}k_T \]
\[ 10 < p_T < 20 \text{ GeV} \]

CT14, GRS 99 PDFs
Outline

• Introduction
• Semi-inclusive jet observables
• Lepton-jet correlations
• Conclusions
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

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

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

Consider

Requires TMD resummation for \( q_\perp \ll k_{\ell\ell'} \)

for the back-to-back configuration, and jet radius resummation for \( R \ll 1 \)
Factorization

• Joint $q_\perp$ and jet radius resummation

$$\frac{d\sigma}{dy_{\ell'}d^2k_{\perp\ell'}d^2q_\perp} = H_q(k_{\ell'}\perp, \mu) \cdot J_q(k_{\ell'}\perp R, \mu)$$

$$\int d^2k_{\perp} d^2\lambda_1 \perp d^2\lambda_2 \perp x f_q(x, k_{\perp}, \mu, \nu) \cdot S_{gl}(\lambda_1 \perp, \mu, \nu) \cdot S_{sc}(\lambda_2 \perp R, \mu) \cdot \delta^{(2)}(q_{\perp} - k_{\perp} - \lambda_1 \perp - \lambda_2 \perp)$$

Global soft  Soft-collinear (in the jet direction)

Liu, FR, Yuan - in preparation
Factorization

• Joint $q_{\perp}$ and jet radius resummation

\[
\frac{d\sigma}{dy_\ell d^2k_{\perp\ell} d^2q_{\perp}} = H_q(k_{\perp\ell}, \mu) J_q(k_{\perp\ell} R, \mu)
\]

\[
\int d^2k_{\perp} d^2\lambda_1 d^2\lambda_2 x f_q(x, k_{\perp}, \mu, \nu) S_{gl}(\lambda_1, \mu, \nu) S_{sc}(\lambda_2 R, \mu) \delta^{(2)}(q_{\perp} - k_{\perp} - \lambda_1 - \lambda_2)
\]

Global soft  Soft-collinear (in the jet direction)

• Identified modes similar to the joint threshold and jet radius resummation

• Relation to lepton-hadron correlations

• Similar analogy: Fragmentation function $\longleftrightarrow$ semi-inclusive jet functions

for inclusive hadron/ jet production

\[
\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes D^h_c
\]

\[
\frac{d\sigma^{pp\to jetX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c
\]
Azimuthal lepton-jet correlation

Liu, FR, Yuan - in preparation

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

• currently \( \ln R \) not yet resummed
Outline

• Introduction
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Conclusions

- Jets can be a unique tool at the future EIC
- Extract collinear and TMD PDFs
- Jet substructure
- NP effects important
- Probe of nuclear matter
- LHeC

Dedicated workshop: “Probing quark-gluon matter with jets”
July 23-25, BNL