Jet physics at the EIC and medium modifications

Kyle Lee
Stony Brook University

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Jets at the LHC

- Jets are produced copiously at the LHC
- At the LHC, 60 - 70 % of ATLAS & CMS papers use jets in their analysis!
Jets at the EIC

• $\sqrt{S_{EIC}} \ll \sqrt{S_{LHC}} \Rightarrow \sqrt{p_{T,J,EIC}} \ll \sqrt{p_{T,J,LHC}}$
  Lower $p_{T,J}$ for EIC

• $N_{J,EIC} \ll N_{J,LHC}$
  Smaller jet multiplicity for EIC

• Less contamination from underlying events and pileups

• Different circumstances compared with the LHC and New opportunities
Jets at the EIC

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Role of higher power corrections?

- Different circumstances compared with the LHC and New opportunities
Application of jet studies at the LHC

• Precision probe of QCD

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Inclusive jets - perturbative probe
Application of jet studies at the LHC

• Precision probe of QCD

What is the role of jet as a perturbative probe at the EIC?

Inclusive jets - perturbative probe
Application of jet studies at the LHC

• Precision probe of QCD

What is the role of jet as a perturbative probe at the EIC?

• Constrain BSM Models

Fat jet from BSM signal

• Probe of quark gluon plasma
Application of jet studies at the LHC

- Precision probe of QCD
- Constrain BSM Models
- Probe of quark gluon plasma

What is the role of jet as a perturbative probe at the EIC?

Classification of different type of jets?

Cold Nuclear Modification in e+A
Application of jet studies at the LHC

• Typical event at the LHC and HERA
Application of jet studies at the LHC

• Typical event at the LHC and HERA

What is the role of NP physics at the EIC?
Plans of this talk

• Inclusive jets
• Jet substructure measurements at the LHC
• Subtracted moments
• Conclusions
Inclusive Jets

• $ep \rightarrow \text{jet} + X$, final lepton unobserved, high $p_T$  
  Boughezal, Petriello, Xing ´18,  
  Hinderer, Schlegel, Vogelsang ´18,  
  Uebler, Schfer, Vogelsang ´17,  
  Abelof, Boughezal, Liu, Petriello, ´16

• $ep \rightarrow e + \text{jet} + X$, DIS, high $p_T$ and $Q^2$

• $ep \rightarrow e + \text{jet} + X$, photoproduction, high $p_T$ and $Q^2 < 1$ GeV$^2$
Inclusive Jets

- $ep \rightarrow \text{jet} + X$, final lepton unobserved, high $p_T$

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- $ep \rightarrow e + \text{jet} + X$, DIS, high $p_T$ and $Q^2$

- $ep \rightarrow e + \text{jet} + X$, photoproduction, high $p_T$ and $Q^2 < 1 \text{ GeV}^2$

We focus on the photoproduction
Relevant Subprocesses

LO DIS

Resolved

Direct
Relevant Subprocesses

LO DIS does not contribute to high pT jet production for the photoproduction.
Photoproduction at the EIC

\[
\frac{d\sigma^{ep\to eHH}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H_{ab}^c \otimes D_h^c
\]

Weizsäcker-Williams spectrum

\[
f_{a/l} = P_{\gamma l} \otimes f_{a/\gamma}
\]

- For the direct process, \( f_{a/\gamma} = \delta(1 - x_{\gamma}) \).
- Observe outgoing lepton to tag \( Q^2 \)
- Require high \( p_T \) and \( Q^2 < 1 \text{ GeV}^2 \) (near on-shell photon)

See Jäger, Stratmann, Vogelsang `03
Polarized Gluon and Photon PDF

Study in 2003, Jäger, Stratmann, Vogelsang '03

\[ \frac{d\Delta \sigma^{ep \to e\pi^0 X}}{dp_T d\eta} = \sum_{a,b,c} \Delta f_{a/l} \otimes \Delta f_{b/p} \otimes \Delta H_{ab}^{c} \otimes D_{c}^{\pi^0} \]

• Sensitivity to polarized gluon pdf at low \( \eta_{lab} \)
• Sensitivity to polarized photon pdf at high \( \eta_{lab} \)

Assumptions: \( D_{c}^{\pi^0} \) has been well-determined.

Use inclusive jets as a perturbative probe!
HERA PDF fit with and without jets

- Important for constraining gluon PDF

Without jets

With jets

Role as a perturbative probe
Photoproduction at the EIC

Inclusive Jets

For polarized case,

\[
\frac{d\sigma_{ep\rightarrow ehX}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H_{ab}^c \otimes D_h^c
\]

\[
\frac{d\Delta\sigma_{ep\rightarrow ehX}}{dp_T d\eta} = \sum_{a,b,c} \Delta f_{a/l} \otimes \Delta f_{b/p} \otimes \Delta H_{ab}^c \otimes D_h^c
\]

Power corrections relevant for EIC

- Replacement of the fragmentation function with the perturbative jet function.
- Sensitivity to the photon pdfs. Can be done for polarized and unpolarized case.
- Role of power corrections?

Role as a perturbative probe

Jäger, Stratmann, Vogelsang ´03
Chu, Aschenauer, Lee, Zheng ´17

In collaboration with Elke Aschenauer and Brian Page
Unpolarized inclusive jets for photoproduction

- At $p_T > 10$ GeV, we see a good agreement.

- $O(\frac{\Lambda_{QCD}}{p_TR})$ power corrections must be studied.

\[ p_T^{\text{jet}} > 10 \text{ GeV} \]
\[ \sqrt{s} = 141 \text{ GeV}, \quad E_p = 250 \text{ GeV}, \quad E_e = 20 \text{ GeV} \]
\[ 0.2 < y < 0.8, \quad Q^2_{\text{max}} < 1 \text{ GeV}^2 \]
Jet angularity

- A generalized class of IR safe observables, angularity (applied to jet):

\[ \tau_a^{e^+ e^-} = \frac{1}{E_J} \sum_{i \in J} E_i \theta_{iJ}^{2-a} \]

\[ \tau_{pp} = \frac{1}{p_T} \sum_{i \in J} p_{T,i} (\Delta R_{iJ})^{2-a} = \left( \frac{2E_J}{p_T} \right)^{2-a} \tau_a^{e^+ e^-} + \mathcal{O}((\tau_{pp}^p)^2) \]

\[ \tau_{0}^{pp} = \frac{m_J^2}{p_T^2} + \mathcal{O}((\tau_{0}^{pp})^2) \]

More relevant for the EIC

Power corrections

Medium modifications

\[ g(\text{girth}) = \frac{1}{p_T} \sum_{i \in J} p_{T,i} (\Delta R_{iJ}) \]

Sterman et al. `03, `08, Hornig, C. Lee, Ovanesyan `09, Ellis, Vermilion, Walsh, Hornig, C. Lee `10, Chien, Hornig, C. Lee `15, Hornig, Makris, Mehen `16, Kang, KL, Ringer `18
Factorization for jet angularity

- Replace $J_c(z, p_T R, \mu) \rightarrow G_c(z, p_T R, \tau_a, \mu)$
- When $\tau_a \ll R^2$, Refactorize $G_c$ as

$$G_c(z, p_T R, \tau_a, \mu) = \sum_i H_{c \rightarrow i}(z, p_T R, \mu)$$

$$\times \int d\tau_a^C \int d\tau_a^S \delta(\tau_a - \tau_a^C - \tau_a^S) C_i(\tau_a^C, p_T \tau_a^{2-a}, \mu) S_i(\tau_a^S, \frac{p_T \tau_a}{R^{1-a}}, \mu) + O\left(\frac{m^2}{p_T^2 R^2}\right)$$

- Each pieces describe physics at different scales.
- Resums $(\alpha_s \ln R)^n$ and $(\alpha_s \ln^2 \frac{R}{\tau_a^{1/(2-a)}})^n$
Non-perturbative Effects

• Non-perturbative effects:

• Multi-Parton Interactions (MPI) (Underlying Events (UE))
Multiple secondary scatterings of partons within the protons may enter and contaminate jet.
Non-perturbative Effects

- Non-perturbative effects:

- Multi-Parton Interactions (MPI) (Underlying Events (UE))
  Multiple secondary scatterings of partons within the protons may enter and contaminate jet.

- Pileups
  Secondary proton collisions in a bunch may enter and contaminate jet.
Non-perturbative Effects

• Non-perturbative effects:

• Hadronization
  Partons forming the jet eventually hadronizes.
Non-perturbative Effects

Non-perturbative Model

• As $\tau$ gets smaller, $\mu_S \sim \frac{p_T \tau}{R}$ (smallest scale) can approach a non-perturbative scale.

We shift our perturbative results by convolving with non-perturbative shape function to smear

$$\frac{d\sigma}{d\eta dp_T d\tau} = \int dk F_\kappa(k) \frac{d\sigma^{\text{pert}}}{d\eta dp_T d\tau} \left( \tau - \frac{R}{p_T} k \right)$$

• Single parameter NP soft function:

$$F_\kappa(k) = \left( \frac{4k}{\Omega^2_\kappa} \right) \exp \left( -\frac{2k}{\Omega_\kappa} \right)$$  \[Stewart, Tackmann, Waalewijn `15\]

• Both hadronization and MPI effects in jet mass is well-represented by just shifting first-moments.

• The parameter $\Omega_\kappa$ is related to shift in the distribution:

$$\tau = \tau_{\text{pert}} + \tau_{\text{NP}} = \tau_{\text{pert}} + \frac{R \Omega_\kappa}{p_T} = \tau_{\text{pert}} + \frac{R (\Lambda_{\text{hadro.}} + \Lambda_{\text{MPI}})}{p_T}$$

$\Omega_\kappa \sim \Lambda_{\text{had}} \sim 1 \text{ GeV}$ corresponds to non-perturbative effects coming primarily from the hadronization alone.
Phenomenology

![Graph showing differential cross sections for single inclusive ungroomed jet production in ATLAS with NLL predictions.

The graphs illustrate the differential cross sections for the following p_T ranges:
- 200 < p_T < 300 GeV
- 300 < p_T < 400 GeV
- 400 < p_T < 500 GeV
- 500 < p_T < 600 GeV

The data points are compared to the NLL predictions, with the ATLAS results shown as black points.

The energy scale is√s = 7 TeV, using anti-k_T, R = 1, |η| < 2.
Phenomenology

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

\( 200 < p_T < 300 \text{ GeV} \)

\( 300 < p_T < 400 \text{ GeV} \)

\( 400 < p_T < 500 \text{ GeV} \)

\( 500 < p_T < \)
Phenomenology

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

single inclusive ungroomed jet

200 < p_T < 300 GeV

300 < p_T < 400 GeV

400 < p_T < 500 GeV

500 < p_T < 600 GeV

Kang, KL, Liu, Ringer `18
Phenomenology

- NLL
- NLL + NP (Ω = 8)
- ATLAS

Single inclusive ungroomed jet

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

- \( 200 < p_T < 300 \text{ GeV} \)
- \( 300 < p_T < 400 \text{ GeV} \)
- \( 400 < p_T < 500 \text{ GeV} \)
- \( 500 < p_T < 600 \text{ GeV} \)

\( \frac{1}{\sigma} \frac{d\sigma}{dm_J} \)

Perturbative result

\( \otimes \) NP shape function

Kang, KL, Liu, Ringer `18
Soft Drop Grooming

• Underlying Events (UE) are difficult to understand.

  How do we get a better hold of these soft uncorrelated contaminations (SUEs) in the jet?

• Hint: contamination generally from soft radiations.

  **Groom** jets to reduce sensitivity to wide-angle soft radiation.
• Developed the formalism for single inclusive groomed jet mass cross-section.

• Shows very good agreement with the data.

• $\Omega_k = 1$ GeV $\implies$ Reduced contamination as expected. NP effects mostly from hadronization.

See also
ATLAS, arXiv:1711.08341
Larkoski, Marzani, Soyez, Thaler `14
Frye, Larkoski, Schwartz, Yan `16
EIC results

- Perturbative results show good agreement without a need for a large shift.
  Small contamination from UE compared to the LHC.

Non-perturbative effects

In collaboration with Elke Aschenauer and Brian Page
Shift from hadronization effects

- Even without grooming, EIC results only require a small shift to agree with the Pythia result. ($\Omega \approx \Lambda_{QCD}$)
- NP effects mostly from hadronization.

\[
\frac{1}{\sigma} \frac{d\sigma}{d \log_{10}(\tau)}
\]

- $\sqrt{s} = 141$ GeV, anti-$k_T$
- $p_T > 10$ GeV, $|\eta| < 2.5$
- $R = 0.8$

NLL
NLL + NP($\Omega = 0.5$ GeV)
Pythia

In collaboration with Elke Aschenauer and Brian Page
Power corrections

- Smaller power corrections for smaller R due to soft scales.

In collaboration with Elke Aschenauer and Brian Page
Moments

Subtracted moments

- Heavy ion collisions produce large number of uncorrelated soft particles in the background contaminating the jet.

1. Develop a background subtraction techniques to identify true compositions of the jets.

   or

2. Define an observable insensitive to the uncorrelated background.

   a. Grooming (recursive algorithm)
   b. Subtracted moments

Kang, Makris, Mehen `17
Chien, Kang, KL, Makris, In Preparation
Subtracted moments

- An observable that studies the correlation between $p_T$ and a linearly additive substructure $U$.

- Linear additivity:

  \[ v = \sum_{i \in \text{signal}} v^i_{\text{signal}} + \sum_{j \in \text{SUEs}} v^j_{\text{SUEs}} \]

  \text{i.e. jet mass } (\sim \tau_0) \quad p^{-}_{J,\text{signal}} + p^{-}_{J,\text{SUEs}} \approx p^{-}_J \approx 2p_T \text{ (only signal is correlated with the } p_T \text{ of the jet)}

  \[
  \tau_0 = \frac{m^2_J}{p_T^2} = \frac{p^-_J p^+_J}{p_T^2} = 2 \frac{1}{p_T} (p^+_J,_{\text{signal}} + p^+_J,_{\text{SUEs}}) = \frac{m^2_{J,\text{signal}}}{p_T^2} + \frac{2}{p_T} p^+_J,_{\text{SUEs}}
  \]

  such separation gives the form of

  \[ \frac{d\sigma}{dp_T d\tau_0} = \int dp^+_J,_{\text{SUEs}} f(p^+_J,_{\text{SUEs}}) \frac{d\sigma^\text{signal}}{dp_T d\tau_0} \left( \tau_0 - \frac{2}{p_T} p^+_J,_{\text{SUEs}} \right) \]
Subtracted moments

\[
\frac{d\sigma}{dp_T d\tau_0} = \int dp_{J,SUEs}^+ f(p_{J,SUEs}^+) \frac{d\sigma^\text{signal}}{dp_T d\tau_0} (\tau_0 - \frac{2}{p_T} p_{J,SUEs}^+)
\]

Moments of the distribution can be separated into contribution from signal and background:

\[
\langle \tau_0 \rangle = \frac{1}{\sigma} \int d\tau_0 \tau_0 \frac{d\sigma}{d\tau dp_T} = \langle \tau_{0,\text{signal}} \rangle + \frac{2}{p_T} \Omega_f
\]

- Experiments often done with several bins of \( p_T \) range.
- The binned version would give:

\[
\langle \tau_0 \rangle [n] = \langle \tau_{0,\text{signal}} \rangle [n] + 2\Omega_f \langle p_T^{-1} \rangle [n]
\]

Subtracted moments (independent of contribution from SUEs):

\[
\Delta^{jk}_{\tau_0} = \langle \tau_0 \rangle [j] - \langle \tau_0 \rangle [k] \frac{\langle p_T^{-1} \rangle [j]}{\langle p_T^{-1} \rangle [k]} = \langle \tau_{0,\text{signal}} \rangle [j] - \langle \tau_{0,\text{signal}} \rangle [k] \frac{\langle p_T^{-1} \rangle [j]}{\langle p_T^{-1} \rangle [k]}
\]
• Independent of model, i.e. shape function.
• Useful to test modifications by medium with reduced sensitivity to uncorrelated radiations.
Even at 50 pile ups, the subtracted moments of $\tau_0$ gives same subtracted moments!
Testing limit of SUE independence

- At higher PU events, additivity starts failing since change in $p_T$ due to SUEs starts to become significant.

$$p_{J,\text{signal}} + p_{J,\text{SUEs}} \approx p_{J,\text{signal}} \approx p_J = 2p_T$$
Moments

200 PU events

\[ \hat{\tau} = \frac{m_J^2}{p_T} = \frac{p_J^- p_J^+}{p_T} = 2(p_{J,\text{signal}}^+ + p_{J,\text{SUEs}}^+) \]

\[ R = 0.4, \ \sqrt{s} = 5.02 \text{ TeV}, \ |\eta| < 2.1 \]

- Subtracted moments of $\hat{\tau}$ is insensitive to 200 PU events.
- Useful for studying jets in high-luminosity LHC (HL-LHC) and in the heavy ion collisions!
Quark and gluon fraction changes

\[ \langle \tau \rangle^{[n]} = \int_{g} f_{g}^{[n]} \langle \tau \rangle_{g}^{[n]} + (1 - f_{g}^{[n]}) \langle \tau \rangle_{q}^{[n]} \]

- Subtracted moments have discriminating power on models that predict changes in quark and gluon jet fractions due to the interaction with the medium.

Medium modifications
Conclusions

• Formalisms for studying semi-inclusive jet production with and without a substructure measurement were introduced.

• Discussed phenomenology of angularities, which are useful substructure observables to test medium modifications.

• Going from pp to ep, contamination from non-perturbative soft radiations was shown to be reduced. (can expect similar reduction from pA to eA?)

• Going from pp to ep, size of power corrections for inclusive and substructure observables for the EIC were discussed. (can expect similar effects from pA to eA?)

• Subtracted moments are shown to be independent of soft uncorrelated emissions and can be useful to study jets in HL-LHC and heavy ion collisions.