The energy loss of leading jets

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Jet quenching and jet energy loss

• Experimental results

\[ R_{\text{jet}}^{\text{AA}} = \frac{d\sigma^{\text{PbPb} \rightarrow \text{jet} + X}}{\langle T_{\text{AA}} \rangle d\sigma^{\text{pp} \rightarrow \text{jet} + X}} \]

\[ z_1 = \frac{p_{T1}}{Q} \quad \text{Leading parton} \]

\[ z_{\text{loss}} = 1 - z_1 \quad \text{Energy loss} \]

• Theory calculations often consider

\[ \frac{dI}{dz} \]
Jet quenching and jet energy loss

- Experimental results

- Theory calculations often consider $\frac{dI}{dz}$

- Can we directly measure the (average) parton/jet energy loss?
- Need a well defined probability density $\rho(z)$
- This talk — vacuum energy loss

\[
R_{AA}^{jet} = \frac{d\sigma^{PbPb\rightarrow jet+X}}{\langle T_{AA} \rangle d\sigma^{pp\rightarrow jet+X}}
\]

ATLAS, PLB 790 (2019) 108

\[
z_1 = \frac{pT1}{Q}
\]

Leading parton

Soft gluon emissions

Energy loss $z_{loss} = 1 - z_1$
Measuring the jet energy loss

• **Requirements**

  1. Well defined object which has lost energy

     Leading jet, not inclusive jets

     Energy not contained in the leading jet is lost

\[
z_1 = \frac{pT_1}{Q}
\]

\[
z_{loss} = 1 - z_1
\]
Measuring the jet energy loss

**Requirements**

1. Well defined object which has lost energy
   - Leading jet, not inclusive jets
   - Energy not contained in the leading jet is lost

2. Reference scale to define lost energy
   - Jet substructure or $\gamma/Z$-tagged jets

\[ z_{1} = \frac{p_{T1}}{Q} \]

\[ z_{\text{loss}} = 1 - z_{1} \]

\[ Q = p_{T}^{\gamma} \]
Measuring the jet energy loss

**Requirements**

1. **Well defined object which has lost energy**
   - Leading jet, not inclusive jets
   - Energy not contained in the leading jet is lost

2. **Reference scale to define lost energy**
   - Jet substructure or $\gamma/Z$-tagged jets

3. **Identify at LL:** parton = jet energy loss
   - Similar to Bjorken $x_B$ in DIS. As close to parton energy loss as allowed by QCD

\[
\frac{z}{1} = \frac{p_T^1}{Q}
\]

\[
Q = p_T^\gamma
\]
Outline

• Introduction

• Leading jets

• Jet energy loss

• Conclusions
Inclusive jets

- **NLO** \( J_i(z, \hat{p}_T R, \mu) \)

\[
J_i(z, \hat{p}_T R, \mu) = \delta(1 - z) + \frac{\alpha_s}{2\pi} \left( \ln \left( \frac{\mu^2}{\hat{p}_T R^2} \right) - 2 \ln z \right) [P_{qq}(z) + P_{gq}(z)] \\
- \frac{\alpha_s}{2\pi} \left\{ C_F \left[ 2(1 + z^2) \left( \frac{\ln(1 - z)}{1 - z} \right)_+ + (1 - z) \right] \\
- \delta(1 - z) C_F \left( \frac{13}{2} - \frac{2\pi^2}{3} \right) + 2P_{gq}(z) \ln(1 - z) + C_F z \right\}
\]

Large radius jet

\[
J_g(z, \hat{p}_T R, \mu) = \delta(1 - z) + \frac{\alpha_s}{2\pi} \left( \ln \left( \frac{\mu^2}{\hat{p}_T R^2} \right) - 2 \ln z \right) [P_{gq}(z)]
\]

\[
p_T = 250 \text{ GeV}
\]

\[
z = \frac{p_T}{\hat{p}_T}
\]
Inclusive jets

- **NLO** \( J_i(z, \hat{p}_T R, \mu) \)

- **DGLAP evolution equation**

\[
\frac{\mu}{d\mu} J_i = \frac{\alpha_s}{2\pi} \sum_j P_{ji} \otimes J_i
\]

Approximates the traditional fragmentation function for \( R \to 0 \)

\( \hat{p}_T \)

- Smaller radius jets
- Large radius jet

\( z = \frac{p_T}{\hat{p}_T} \)
Inclusive jets

- **NLO** \( J_i(z, \hat{p}_T R, \mu) \)

- **DGLAP evolution equation**

\[
\mu \frac{d}{d\mu} J_i = \frac{\alpha_s}{2\pi} \sum_j P_{ji} \otimes J_j
\]

- **Factorization**

\[
\frac{d\sigma_{pp \rightarrow \text{jet} + X}}{d\eta d\hat{p}_T} = \sum_{ijk} f_{i/p} \otimes f_{j/p} \otimes H_{ijk} \otimes J_k
\]

\( z_1 = pT_1 / \hat{p}_T \)

Successful phenomenology, see e.g.

Dasgupta, Dreyer, Salam, Soyez ’14
Kaufmann, Mukherjee, Vogelsang ’15
Kang, Ringer, Vitev ’16
Dai, Kim, Leibovich ’16
Liu, Moch, Ringer ’18, ’19

CMS, 2005.05159
ALICE, PRC 101 (2020) 034911
Leading jets

\[ \mathcal{J}_i(z, \hat{p}_T R, \mu) = \Theta(z > 1/2) \ J_i(z, \hat{p}_T R, \mu) \]

**NLO**

Now pick only the leading parton if clustered into separate jets
**Leading jets**

**NLO**

\[ \mathcal{J}_i (z, \hat{p}_T R, \mu) = \Theta(z > 1/2) J_i (z, \hat{p}_T R, \mu) \]

**Non-linear evolution equation**

\[
\mu \frac{d}{d\mu} \mathcal{J}_i (z, \hat{p}_T R, \mu) = \frac{1}{2} \sum_{jk} \int dz' dz_j dz_k \frac{\alpha_s(\mu)}{\pi} P_{i \rightarrow jk}(z') \mathcal{J}_j (z_j, \hat{p}_T R, \mu) \mathcal{J}_k (z_k, \hat{p}_T R, \mu) \times \delta(z - \max \{z'z_j, (1 - z')z_k\})
\]

\[ \hat{p}_T R \]

Need to know about both branches to determine the leading jet \( \mathcal{J}_j \mathcal{J}_k \)
Leading jets

- **NLO**
  \[ \mathcal{J}_i (z, \hat{p}_T R, \mu) = \Theta(z > 1/2) \mathcal{J}_i (z, \hat{p}_T R, \mu) \]

- **Non-linear evolution equation**
  \[
  \mu \frac{d}{d\mu} \mathcal{J}_i (z, \hat{p}_T R, \mu) = \frac{1}{2} \sum_{jk} \int dz' dz_j dz_k \frac{\alpha_s(\mu)}{\pi} P_{i \to jk} (z') \mathcal{J}_j (z_j, \hat{p}_T R, \mu) \mathcal{J}_k (z_k, \hat{p}_T R, \mu)
  \]
  \[\times \delta(z - \max \{z' z_j, (1 - z') z_k\})\]

- **LL factorization**
  \[
  \frac{d\sigma^{(0)}_{pp \to \text{jet}_1 + X}}{dp_{T1}} = \sum_{ij} \int d\hat{p}_{Ti} d\hat{p}_{Tj} \int dz_i dz_j \mathcal{H}_{ij}^{(0)} (\hat{p}_{Ti}, \hat{p}_{Tj}, \mu)
  \]
  \[\times \mathcal{J}_i (z_i, \hat{p}_T R, \mu) \mathcal{J}_j (z_j, \hat{p}_T R, \mu)
  \]
  \[\times \delta(p_{T1} - \max\{z_i \hat{p}_{Ti}, z_j \hat{p}_{Tj}\})\]

/ Measurement at the end

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Dasgupta, Dreyer, Salam, Soyez '14
Scott, Waalewijn '19
Neill, Ringer, Sato - in preparation
Inclusive vs. leading jets

- Jet function - number densities

\[ \int_{0}^{1} dz \, J_i(z, \hat{p}_T R, \mu) = \langle N_{\text{jets}} \rangle \]

- Momentum conservation

\[ \int_{0}^{1} dz \, z \, J_i(z, \hat{p}_T R, \mu) = 1 \]

\[ = z_1 + z_2 + z_3 \]

Neill, Ringer, Sato - in preparation
Inclusive vs. leading jets

Neill, Ringer, Sato - in preparation

- Jet function - number densities

\[
\int_0^1 dz J_i(z, \hat{p}_T R, \mu) = \langle N_{\text{jets}} \rangle
\]

- Jet function - probability densities \( \rho_i(z) \)

\[
\int_0^1 dz J_i(z, \hat{p}_T R, \mu) = 1
\]

- Momentum conservation

\[
\int_0^1 dz z J_i(z, \hat{p}_T R, \mu) = 1
\]

e.g.

\[
= z_1 + z_2 + z_3
\]
Inclusive vs. leading jets

Neill, Ringer, Sato - in preparation

• Jet function - number densities

\[ \int_0^1 dz \, J_i(z, \hat{p}_T R, \mu) = \langle N_{jets} \rangle \]

• Jet function - probability densities \( \rho_i(z) \)

\[ \int_0^1 dz \, J_i(z, \hat{p}_T R, \mu) = 1 \]

• Momentum conservation

\[ \int_0^1 dz \, z \, J_i(z, \hat{p}_T R, \mu) = 1 \]

e.g. \[ z_1 + z_2 + z_3 \]

• Average parton energy loss

\[ \int_0^1 dz \, z \, J_i(z, \hat{p}_T R, \mu) = \langle z_i \rangle \]
Leading jet functions and energy loss

Neill, Ringer, Sato - in preparation

• Leading jet function

\[ J_q, J_g(z) \]

- quark: \( Q = 100 \text{ GeV} \), \( R = 0.5 \)
- quark: \( Q = 100 \text{ GeV} \), \( R = 0.2 \)

Inclusive

Leading

NLO + radius + threshold resummation at NLL'

see also Dai, Kim, Leibovich '17
Leading jet functions and energy loss

- **Leading jet function**

  \[ J_q(z), J_g(z) \]

  - Quark
    - \( R = 0.5 \)
    - \( Q = 100 \text{ GeV} \)
  - Gluon
    - \( R = 0.2 \)

  - Inclusive

- **Average energy loss**

  \[
  \int_0^1 dz \, J_i(z, \hat{p}_T R, \mu) = \langle z_i \rangle
  \]

  - Quark
    - \( Q = 100 \text{ GeV} \)
  - Gluon

- **NLO**

  \[
  \langle z^{k_T}_{q, \text{loss}} \rangle = -\frac{\alpha_s}{2\pi} C_F \ln \left(\frac{1}{R^2}\right) \left(\frac{3}{8} - 2 \ln 2\right) - \frac{\alpha_s}{2\pi} C_F \left(\frac{19}{8} - \frac{3}{2} \ln 2 - 4 \ln^2 2 - \frac{\pi^2}{3}\right)
  \]

NLO + radius + threshold resummation at NLL'

see also Dai, Kim, Leibovich `17

Neill, Ringer, Sato - in preparation
Outline

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- Conclusions
Leading jets

\[
\frac{d\sigma^{(0)}_{pp \to \text{jet}_1+X}}{dp_{T1}} = \sum_{ij} \int d\hat{p}_{T_i} d\hat{p}_{T_j} \int dz_i dz_j \mathcal{H}^{(0)}_{ij}(\hat{p}_{T_i}, \hat{p}_{T_j}, \mu) \\
\times \mathcal{J}_i(z_i, \hat{p}_{T_i} R, \mu) \mathcal{J}_j(z_j, \hat{p}_{T_j} R, \mu) \\
\times \delta(p_{T1} - \max\{z_i \hat{p}_{T_i}, z_j \hat{p}_{T_j}\})
\]

- Well defined object which has lost energy
- Reference scale to define lost energy
- Identify at LL: parton = jet energy loss

Neill, Ringer, Sato - in preparation
Leading subjets

- Initial $R$ sized jet sets the reference scale $Q = p_T^{\text{jet}}$

- Measure small $r$ reclustered leading subjets $z_1 = p_T^{\text{subj}} / p_T^{\text{jet}}$

- LL factorization

$$\frac{d\sigma^{(0)}_{pp\rightarrow j(sj_1)+X}}{dp_T^{\text{jet}}\,d\eta\,dz_1} = \sum_i \mathcal{H}_i^{(0)}(p_T^{\text{jet}}, \eta) \mathcal{J}_i(z_1, p_T^{\text{jet}}, R, \mu)$$

- Average energy loss

$$\langle z_1 \rangle = \int_0^1 dz_1 \, z_1 \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma^{(0)}_{pp\rightarrow j(sj_1)+X}}{dz_1}$$

$$= f_q \langle z_{1,q} \rangle + f_g \langle z_{1,g} \rangle$$
\( \gamma/Z\)-tagged leading jets

- \( \gamma/Z \) provides reference scale \( Q = p_T^{\gamma} \)
- Measure leading jet \( z_1 = p_{T1}/p_T^{\gamma} \)
- LL factorization

\[
\frac{d\sigma_{pp \to \gamma+\text{jet}+X}^{(0)}}{dp_T^{\gamma} d\eta^{\gamma} dz_1} = \sum_i \mathcal{H}_i^{(0)}(p_T^{\gamma}, \eta) \mathcal{J}_i(z_1, p_T^{\gamma}, R, \mu)
\]

- Average energy loss

\[
\langle z_1 \rangle = \int_0^1 dz_1 z_1 \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma_{pp \to \gamma+1+X}^{(0)}}{dz_1} = f_q \langle z_{1,q} \rangle + f_g \langle z_{1,g} \rangle
\]

\( p_T^{\gamma} > 200 \text{ GeV}, R = 0.3, \sqrt{s} = 5.02 \text{ TeV} \)

Energy loss is the difference between the leading and inclusive spectrum
Outline

- Introduction
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- Conclusions
Conclusions

- **Direct measurement of energy loss**

  1. Well defined object which has lost energy — Leading jet, $\rho(z)$
  2. Reference scale to define lost energy — Jet substructure or $\gamma/Z$-tagged jets
  3. Identify at LL: parton $\Rightarrow$ jet energy loss

- **Heavy-ion collisions**

  - Quantify jet-medium interaction in AA
  - How opaque is the QGP?