The energy loss of leading jets

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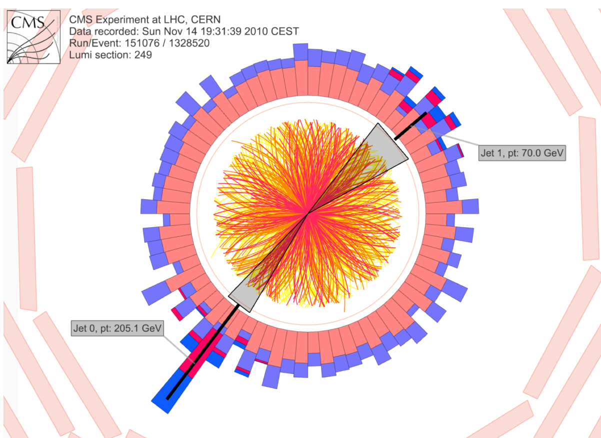
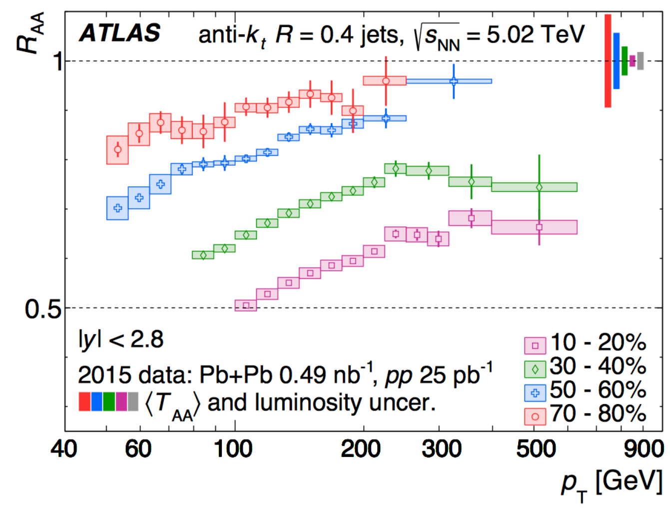
Jet quenching and jet energy loss

- Experimental results





$$R_{\mathrm{AA}}^{\mathrm{jet}} = \frac{\mathrm{d}\sigma^{\mathrm{PbPb}\to\mathrm{jet}+X}}{\langle T_{\mathrm{AA}}\rangle\, \mathrm{d}\sigma^{pp\to\mathrm{jet}+X}}$$

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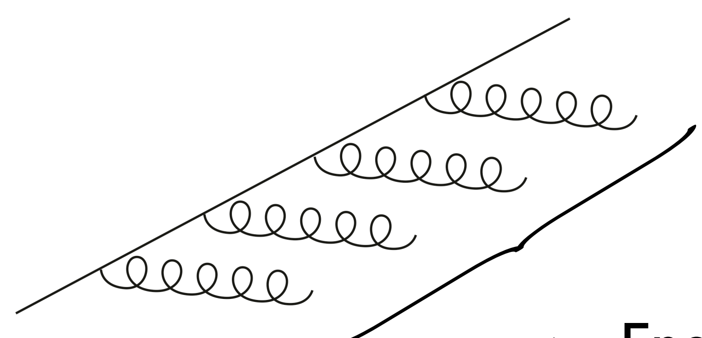
- Theory calculations often consider $\dfrac{\mathrm{d}I}{\mathrm{d}z}$

$z_1 = \dfrac{p_{T1}}{Q}$ Leading parton

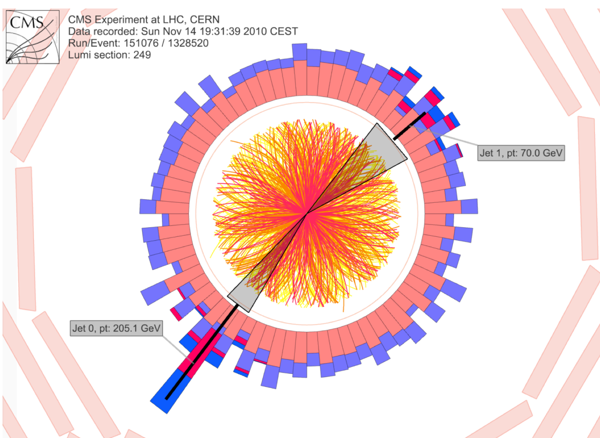


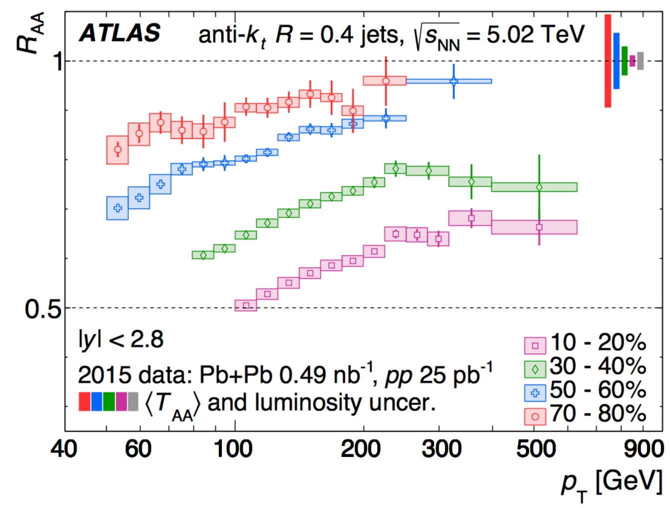
Soft gluon emissions

Q → Energy loss $z_{\mathrm{loss}} = 1 - z_1$

Jet quenching and jet energy loss

- Experimental results





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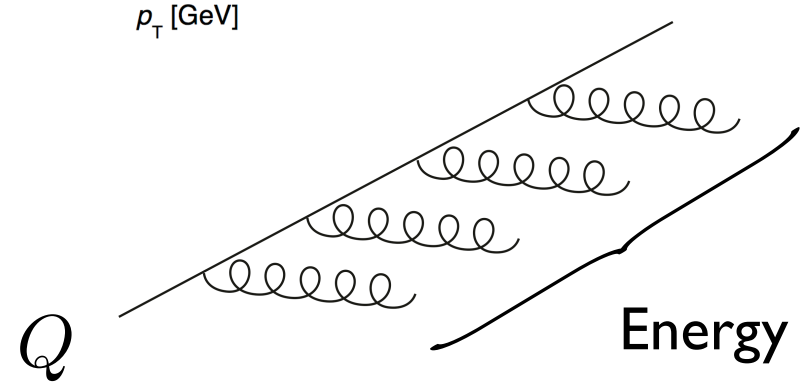


$z_1 = \dfrac{p_{T1}}{Q}$ Leading parton

Soft gluon emissions

Energy loss $z_{\mathrm{loss}} = 1 - z_1$

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

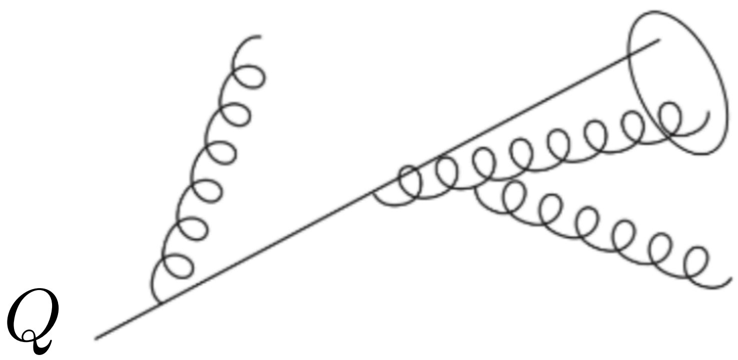
$$\langle z\rangle = \int_0^1 \mathrm{d}z\, z\, \rho(z)$$

- This talk — vacuum energy loss

Measuring the jet energy loss

- **Requirements**

1. Well defined object which has lost energy



$$z_1 = \frac{p_{T1}}{Q}$$

Leading jet, not inclusive jets

Energy not contained in the leading jet is lost $z_{\text{loss}} = 1 - z_1$

Measuring the jet energy loss

- **Requirements**

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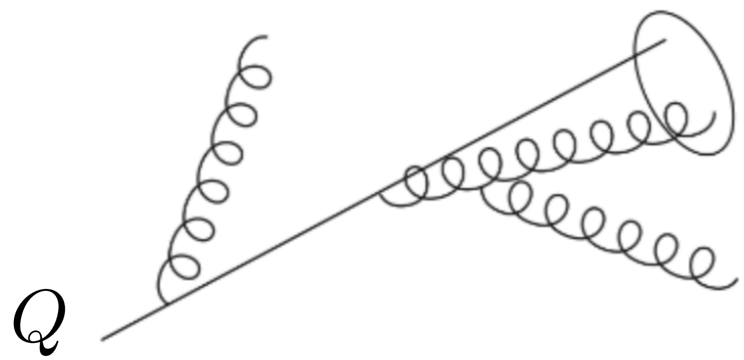


1. Well defined object which has lost energy

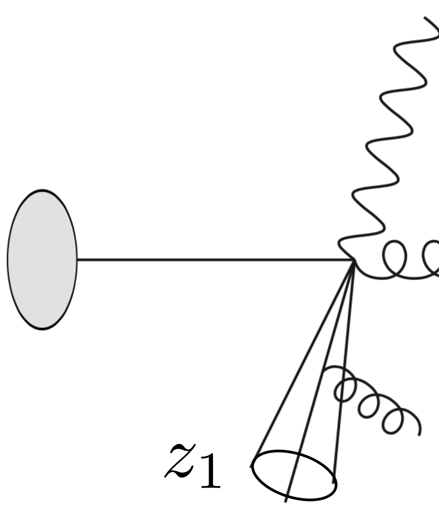
   Leading jet, not inclusive jets

   Energy not contained in the leading jet is lost $z_{\mathrm{loss}} = 1 - z_1$

$$Q = p_T^{\gamma}$$

2. Reference scale to define lost energy

   Jet substructure or γ/Z-tagged jets



Measuring the jet energy loss

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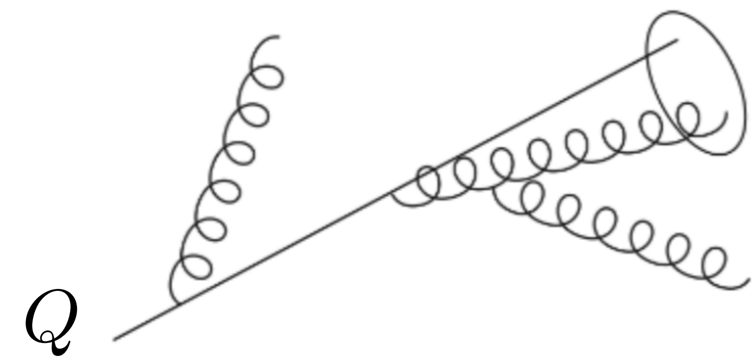

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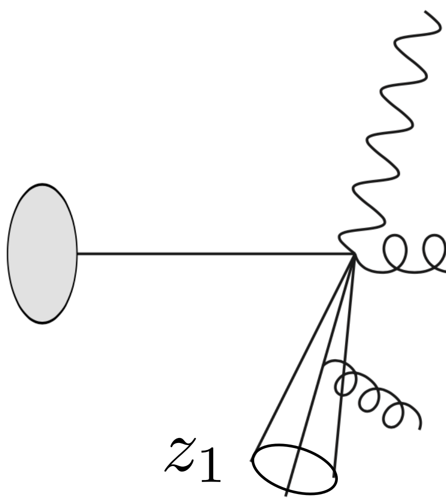


$$Q = p_T^\gamma$$

2. Reference scale to define lost energy

   Jet substructure or γ/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

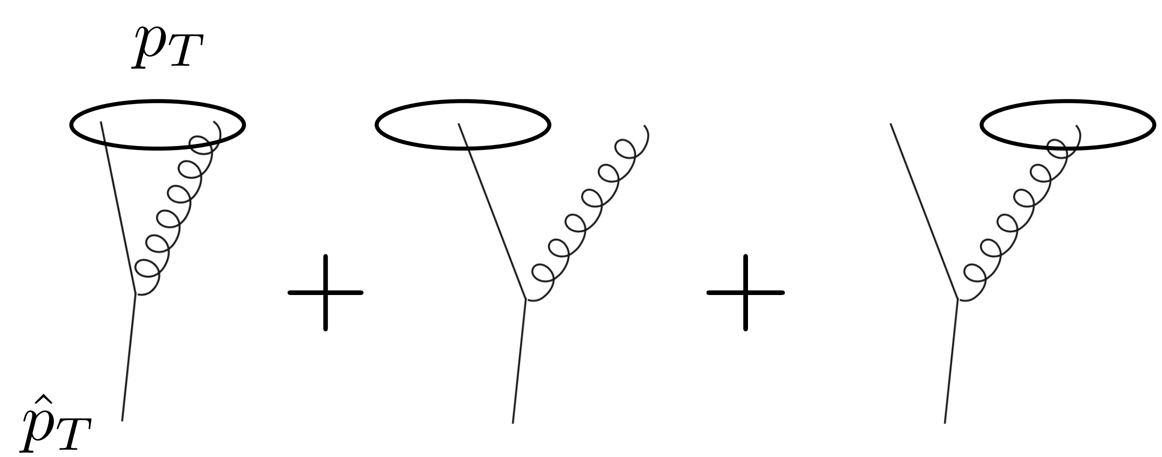
Outline

- Introduction
- Leading jets
- Jet energy loss
- Conclusions

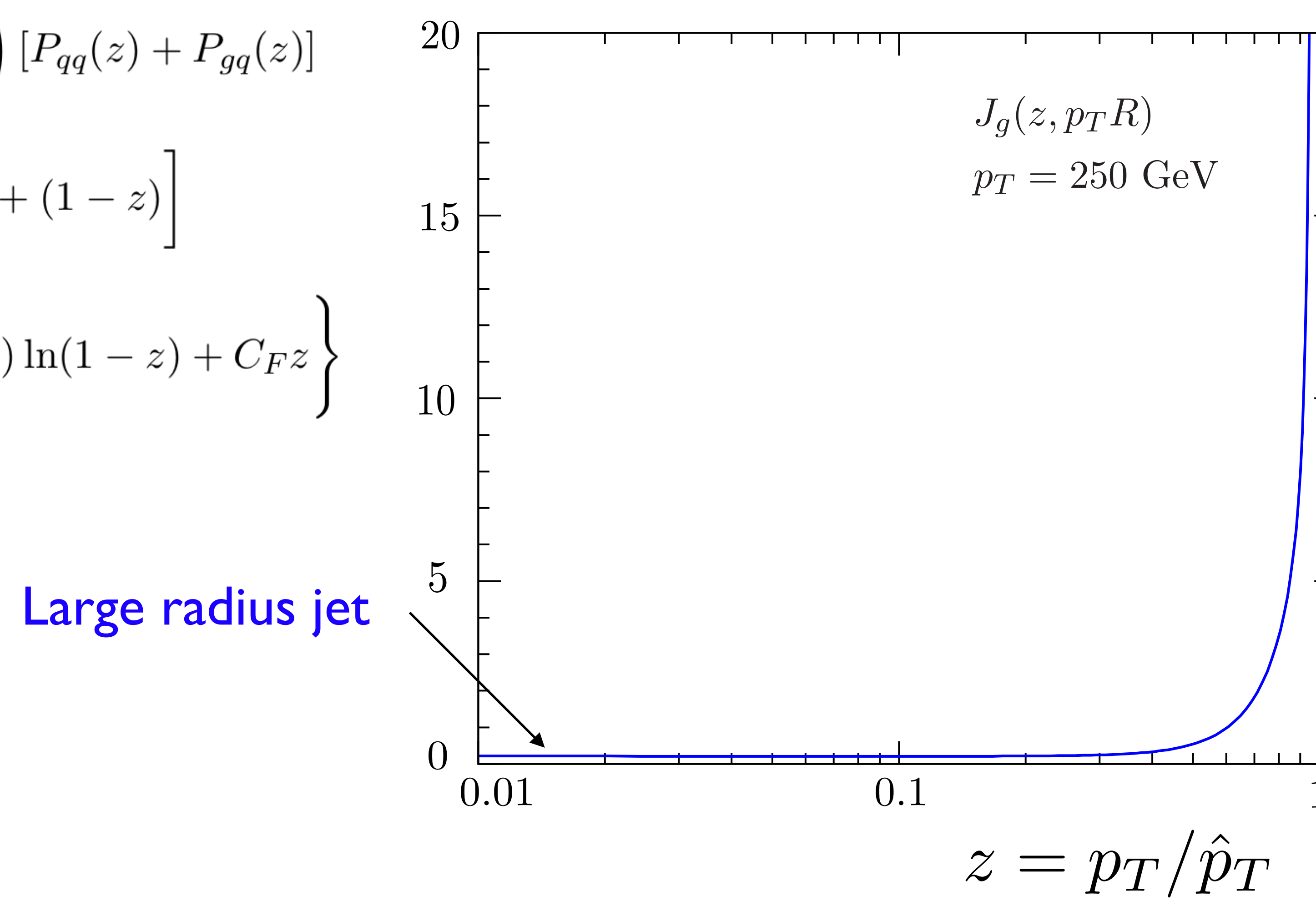
Inclusive jets

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

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



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



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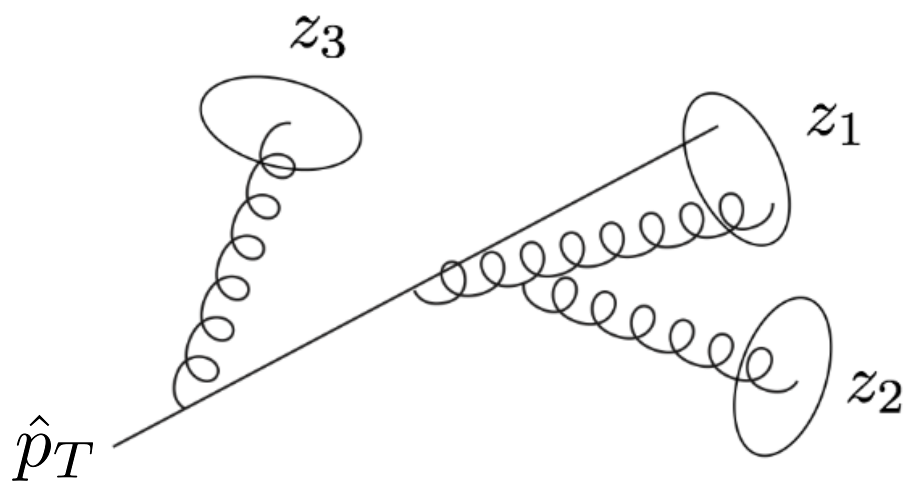
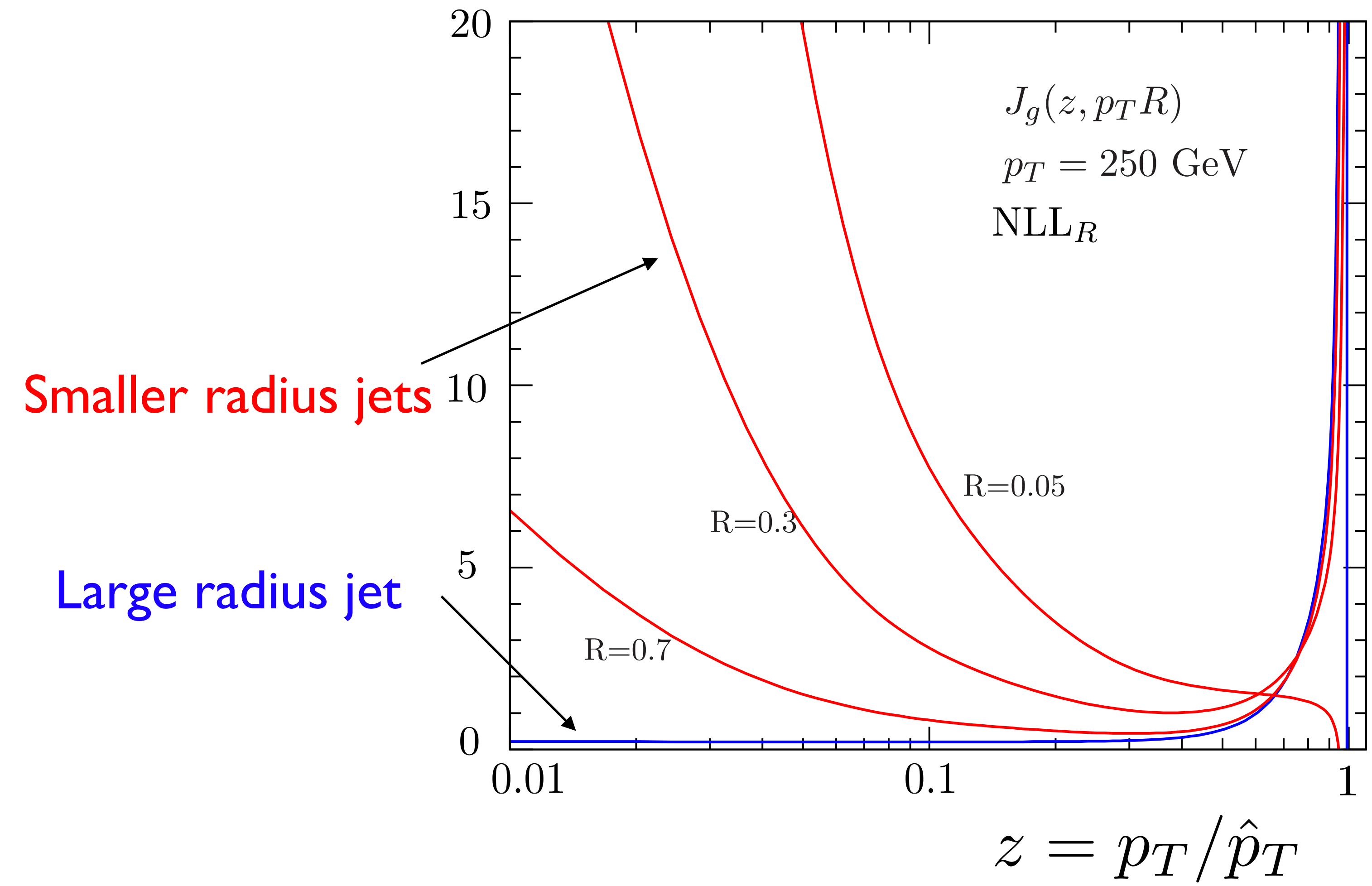
- **NLO** $J_i\left(z, \hat{p}_T R, \mu\right)$

- **DGLAP evolution equation** $\mu \frac{\mathrm{d}}{\mathrm{d}\mu} J_i = \frac{\alpha_s}{2\pi} \sum_j P_{ji} \otimes J_i$





Approximates the traditional fragmentation function for $R \to 0$

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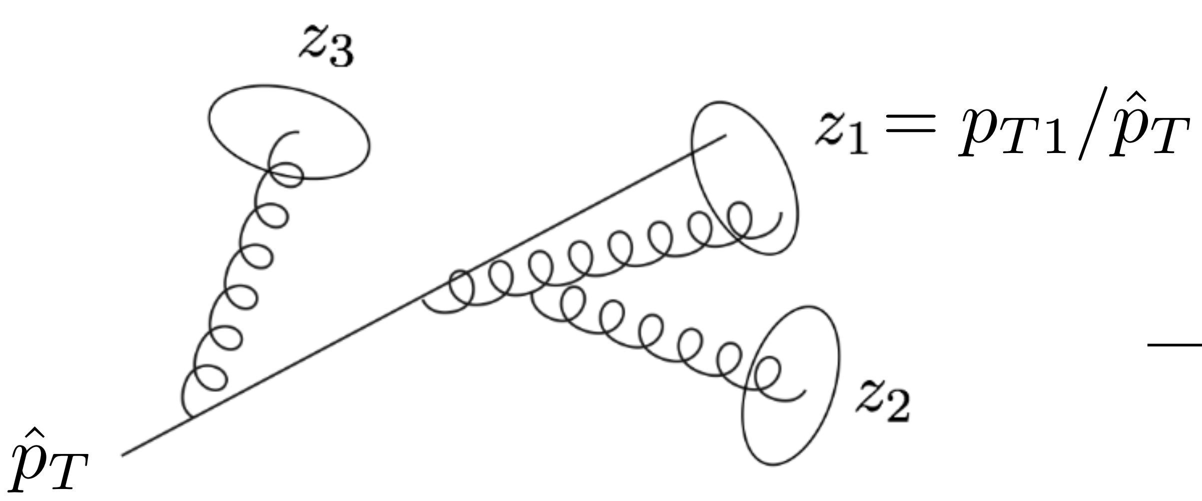
- **NLO** $J_i\left(z, \hat{p}_T R, \mu\right)$
- **DGLAP evolution equation** $\mu \frac{\mathrm{d}}{\mathrm{d}\mu} J_i = \frac{\alpha_s}{2\pi} \sum_j P_{ji} \otimes J_i$
- **Factorization** $\frac{\mathrm{d}\sigma_{pp\to \mathrm{jet}+X}}{\mathrm{d}\eta \mathrm{d}p_T} = \sum_{ijk} f_{i/p} \otimes f_{j/p} \otimes H_{ijk} \otimes J_k$



→ Successful phenomenology, see e.g.

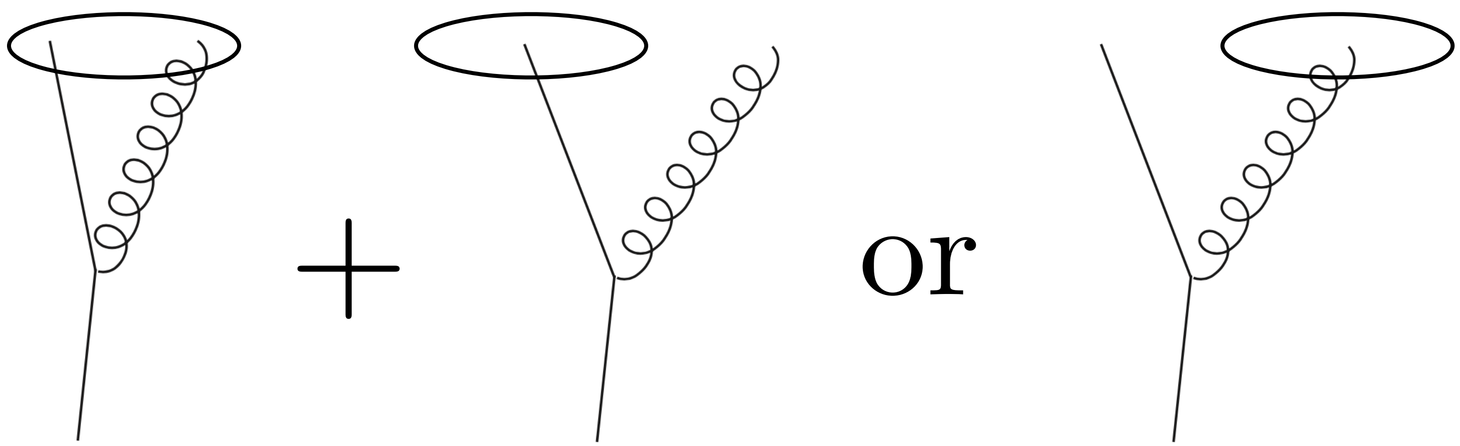
CMS, 2005.05159
ALICE, PRC 101 (2020) 034911

Leading jets

Dasgupta, Dreyer, Salam, Soyez `14
Scott, Waalewijn `19
Neill, Ringer, Sato - in preparation

- **NLO**

Leading jet function $\mathcal{J}_i\left(z, \hat{p}_T R, \mu\right) = \Theta(z > 1/2)\, J_i\left(z, \hat{p}_T R, \mu\right)$



Now pick only the leading parton if clustered into separate jets

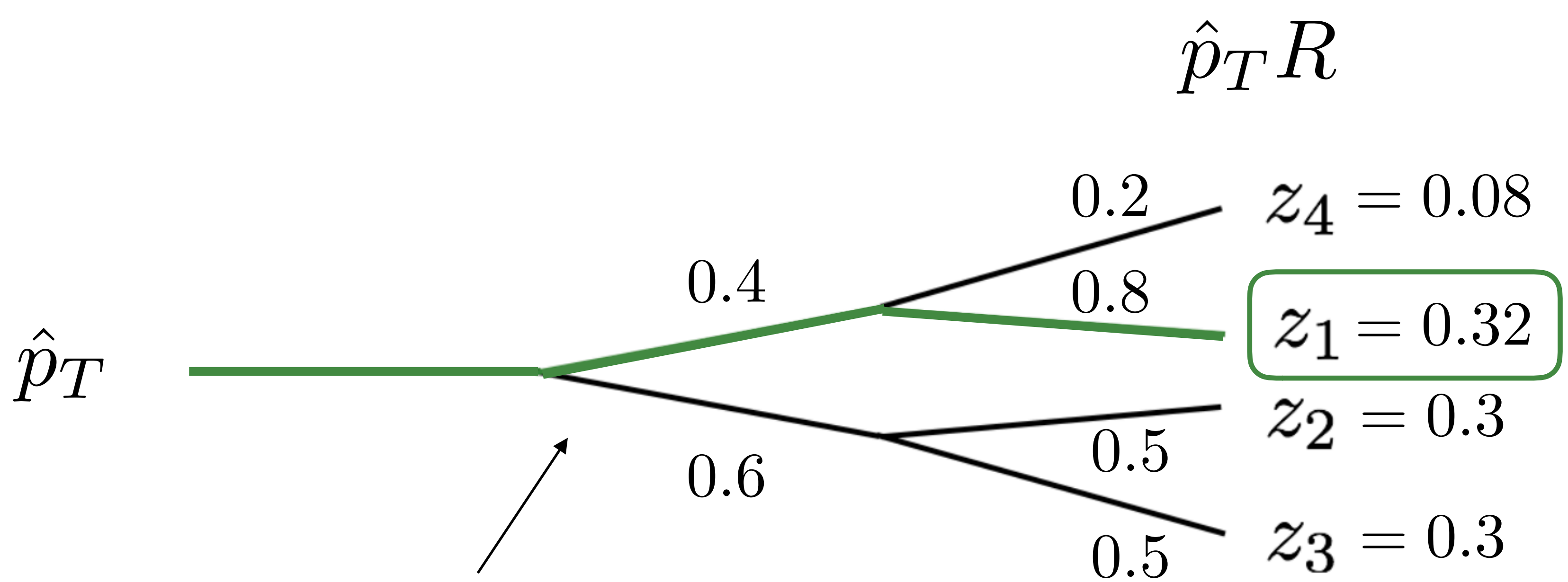
Leading jets

Dasgupta, Dreyer, Salam, Soyez `14
Scott, Waalewijn `19
Neill, Ringer, Sato - in preparation

- **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**

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\mathcal{J}_i(z,\hat{p}_T R,\mu) = \frac{1}{2}\sum_{jk}\int \mathrm{d}z'\mathrm{d}z_j\mathrm{d}z_k\frac{\alpha_s(\mu)}{\pi}P_{i\to jk}(z')\;\mathcal{J}_j\,(z_j,\hat{p}_T R,\mu)\;\mathcal{J}_k\,(z_k,\hat{p}_T R,\mu)$$
$$\times\,\delta(z-\max\left\{z' z_j,(1-z')z_k\right\})$$



Need to know about both branches to determine the leading jet $\mathcal{J}_j\;\mathcal{J}_k$

Leading jets

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

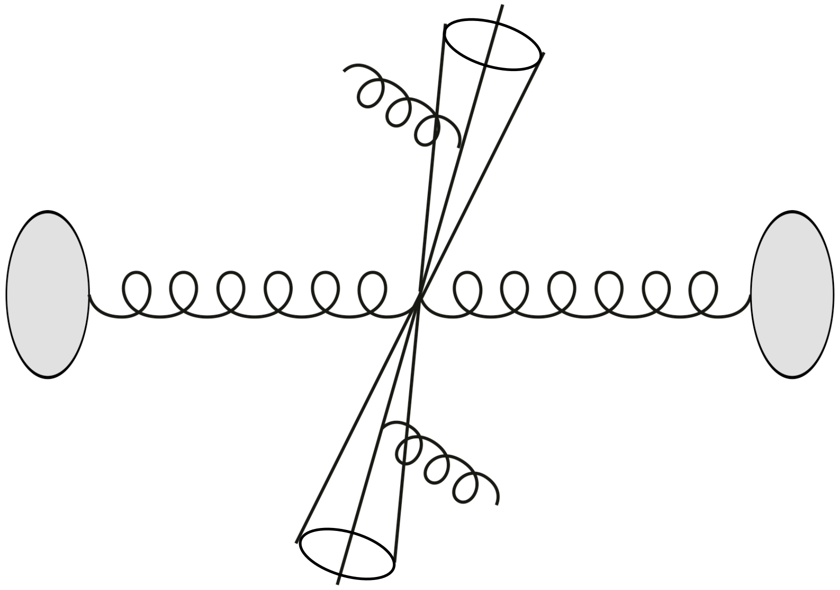
- **Non-linear evolution equation**

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} \mathcal{J}_i(z, \hat{p}_T R, \mu) = \frac{1}{2} \sum_{jk} \int \mathrm{d}z' \mathrm{d}z_j \mathrm{d}z_k \frac{\alpha_s(\mu)}{\pi} P_{i\to jk}(z')\ \mathcal{J}_j\left(z_j, \hat{p}_T R, \mu\right)\ \mathcal{J}_k\left(z_k, \hat{p}_T R, \mu\right)$$
$$\times\ \delta(z - \max\left\{z' z_j, (1-z') z_k\right\})$$

- **LL factorization**

$$\frac{\mathrm{d}\sigma^{(0)}_{pp\to \mathrm{jet}_1+X}}{\mathrm{d}p_{T1}} = \sum_{ij} \int \mathrm{d}\hat{p}_{Ti}\, \mathrm{d}\hat{p}_{Tj} \int \mathrm{d}z_i\, \mathrm{d}z_j\ \mathcal{H}^{(0)}_{ij}(\hat{p}_{Ti}, \hat{p}_{Tj}, \mu)$$
$$\times\ \mathcal{J}_i\left(z_i, \hat{p}_{Ti} R, \mu\right)\ \ \mathcal{J}_j\left(z_j, \hat{p}_{Tj} R, \mu\right)$$
$$\times\ \delta(p_{T1} - \max\{z_i \hat{p}_{Ti}, z_j \hat{p}_{Tj}\})$$

Measurement at the end



Inclusive vs. leading jets

Neill, Ringer, Sato - in preparation

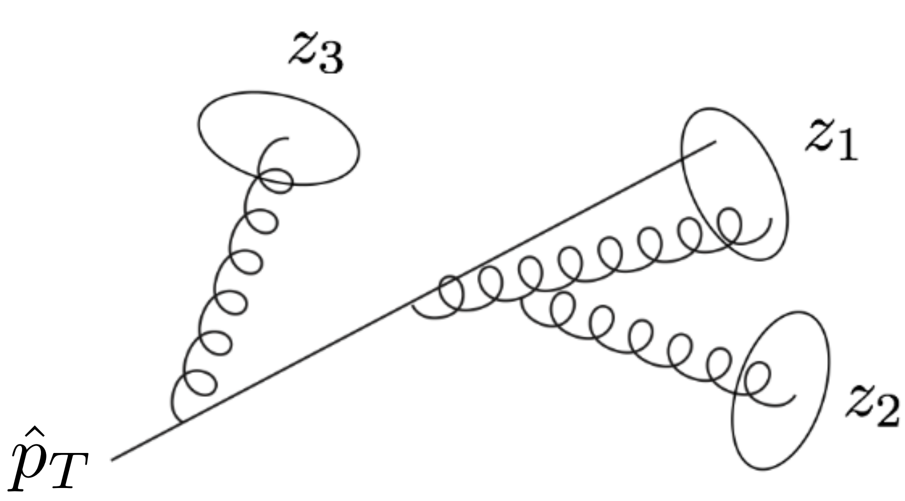
- Jet function - number densities

$$\int_0^1 \mathrm{d}z \, J_i(z, \hat{p}_T R, \mu) = \langle N_{\text{jets}} \rangle$$

- Momentum conservation

$$\int_0^1 \mathrm{d}z \, z \, J_i(z, \hat{p}_T R, \mu) = 1$$

$$\overset{\text{e.g.}}{=} z_1 + z_2 + z_3$$



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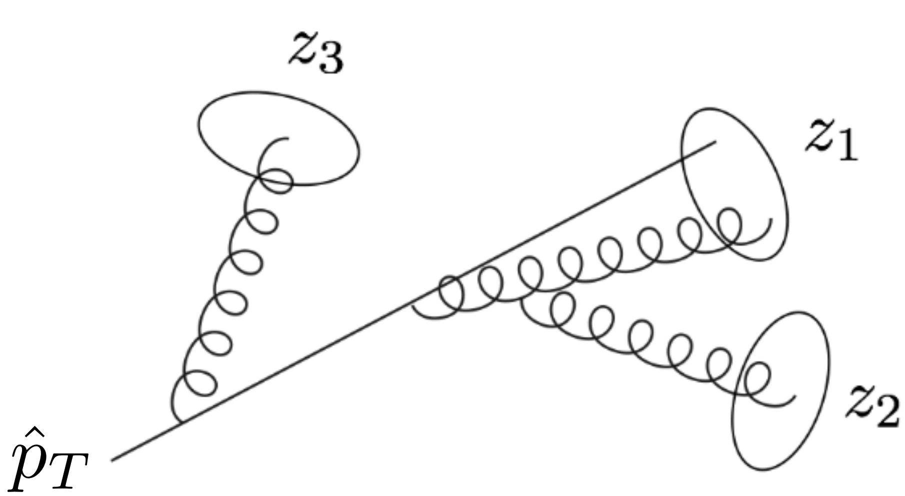
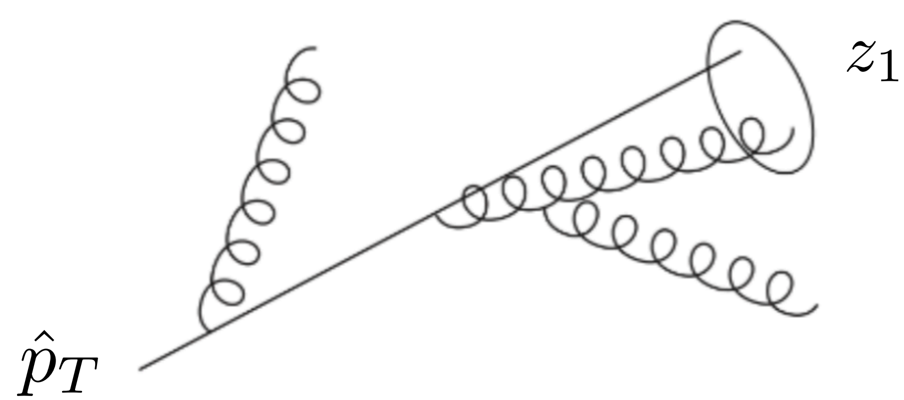


- Jet function - probability densities $\rho_i(z)$

$$\int_0^1 \mathrm{d}z\, \mathcal{J}_i(z, \hat{p}_T R, \mu) = 1$$



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- Jet function - number densities

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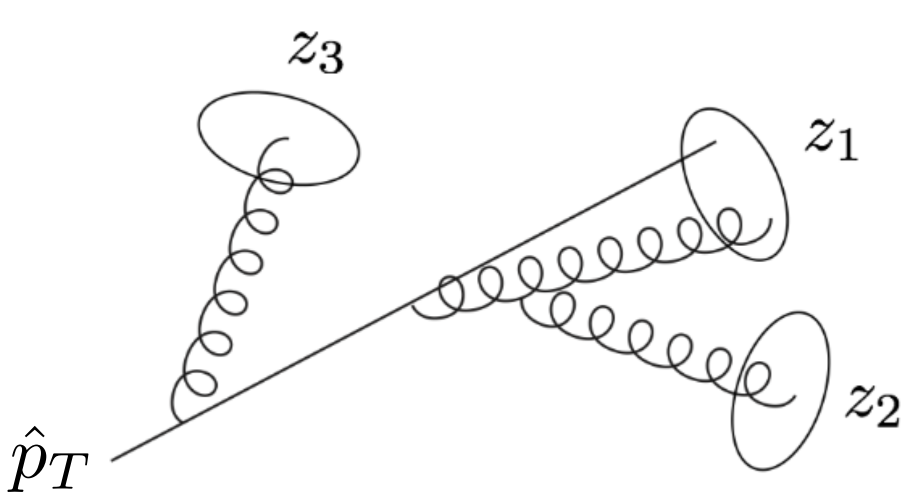
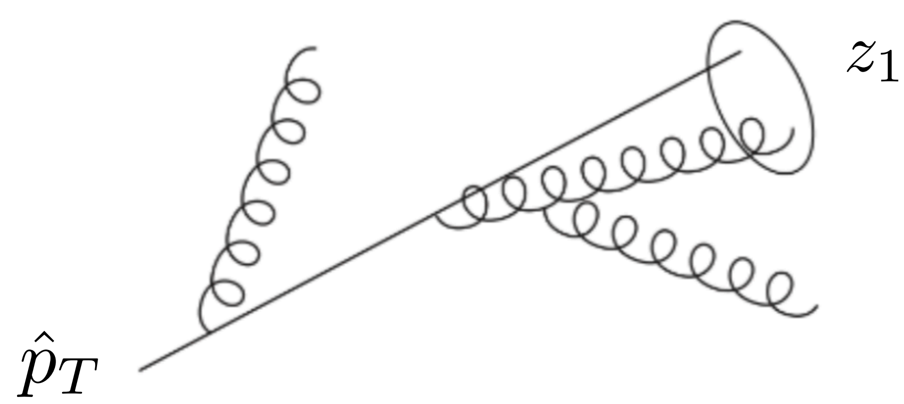


- Jet function - probability densities $\rho_i(z)$

$$\int_0^1 \mathrm{d}z\, \mathcal{J}_i(z, \hat{p}_T R, \mu) = 1$$

- Average parton energy loss

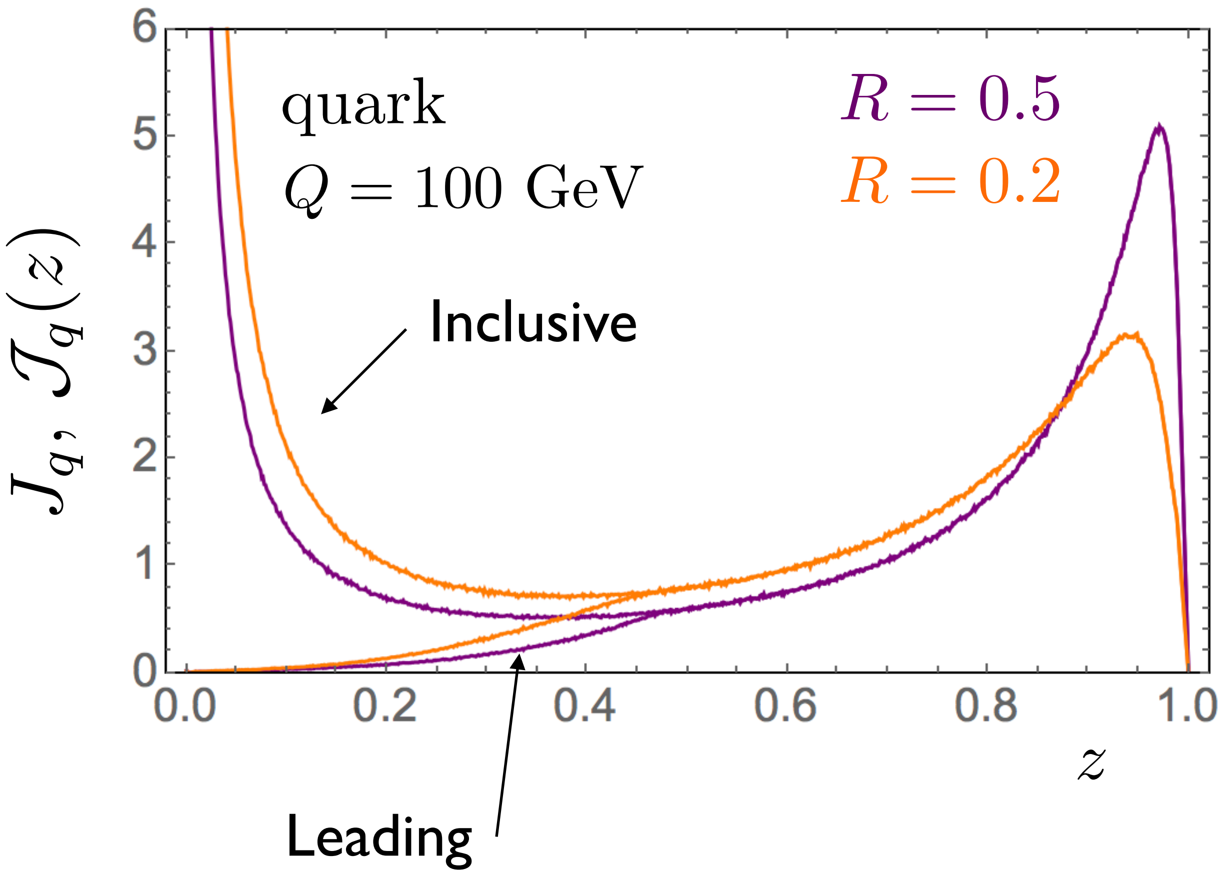
$$\int_0^1 \mathrm{d}z\, z\, \mathcal{J}_i(z, \hat{p}_T R, \mu) = \langle z_i \rangle$$



Leading jet functions and energy loss

Neill, Ringer, Sato - in preparation

- **Leading jet function**



NLO + radius + threshold resummation at NLL'

see also Dai, Kim, Leibovich `17

Leading jet functions and energy loss

Neill, Ringer, Sato - in preparation

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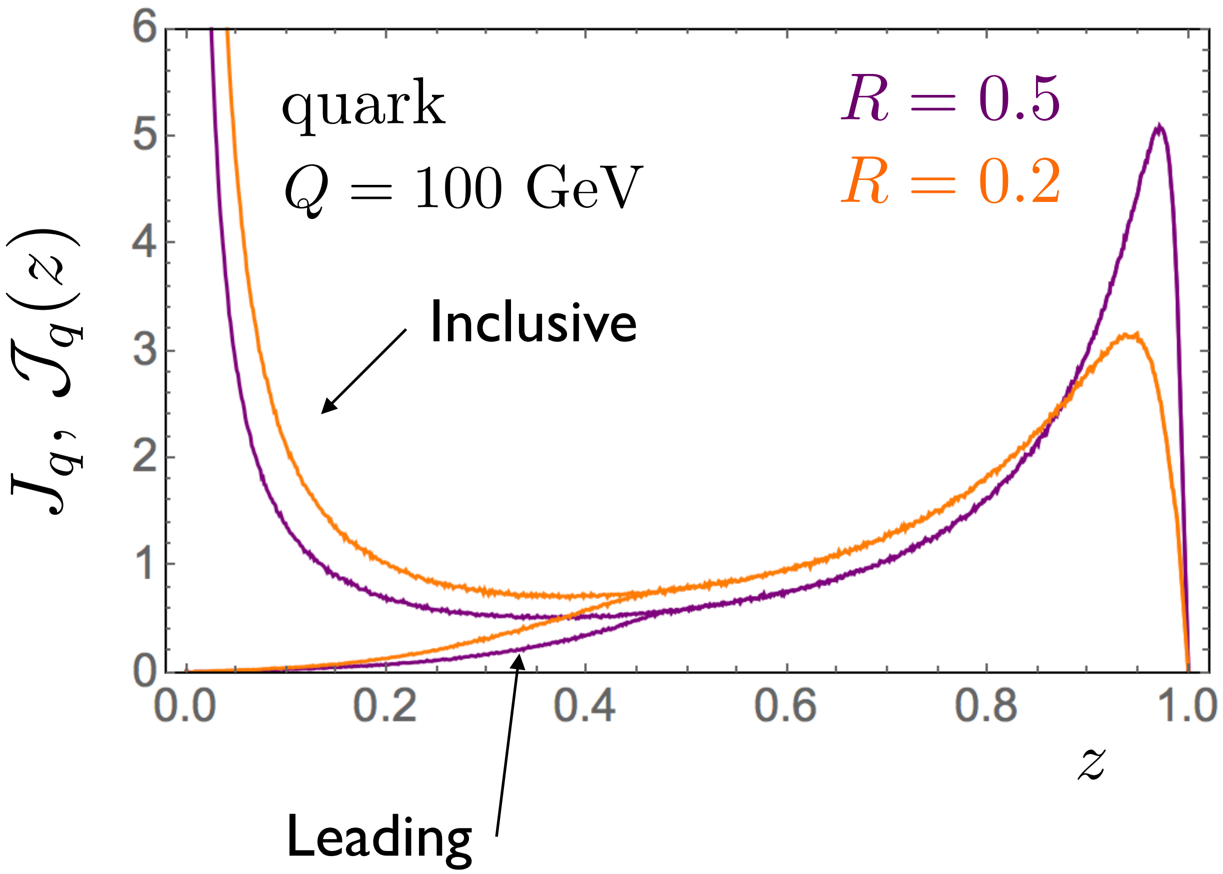

NLO + radius + threshold resummation at NLL'

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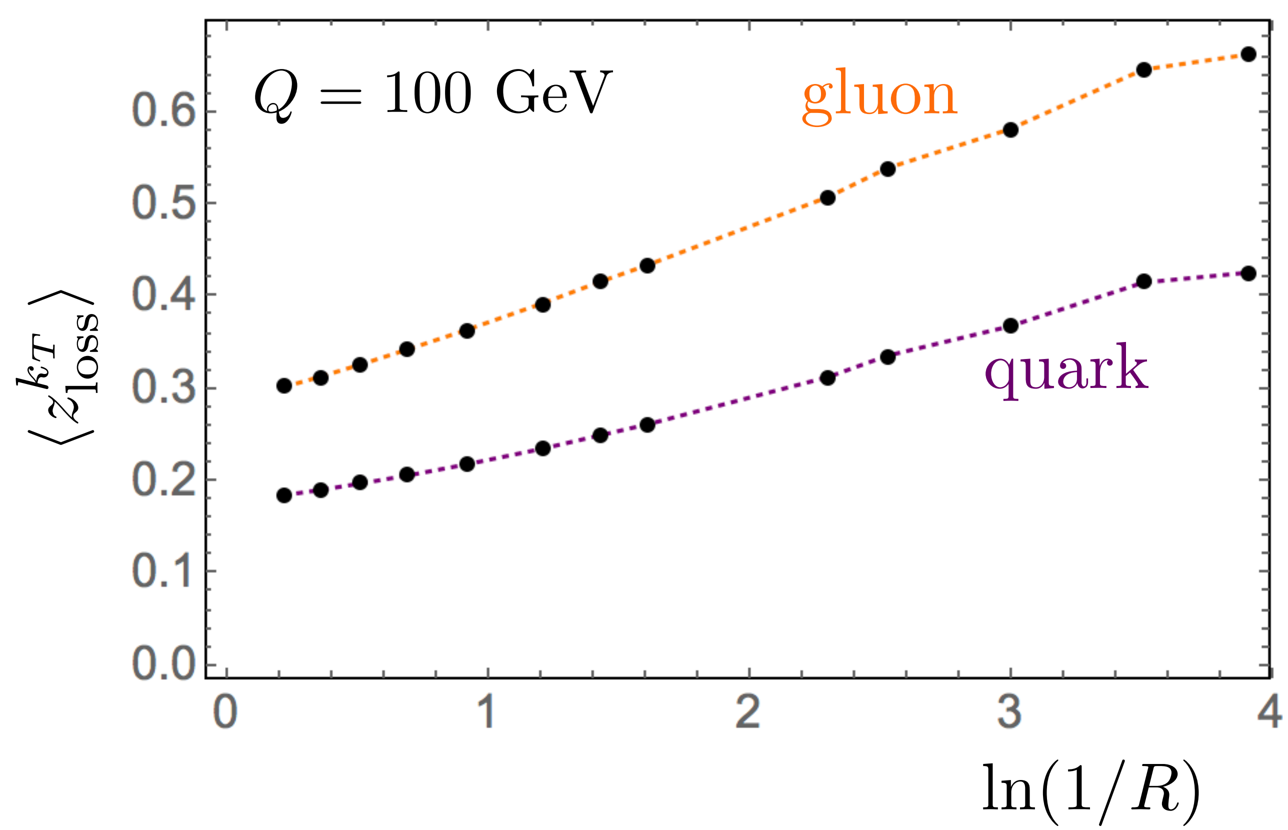
- **Average energy loss** $\int_0^1 \mathrm{d}z\, z\, \mathcal{J}_i(z, \hat{p}_T R, \mu) = \langle z_i \rangle$



- **NLO** $$\langle z_{q,\rm loss}^{k_T} \rangle = -\frac{\alpha_s}{2\pi} C_F \ln\left(1/R^2\right)\left(\frac{3}{8} - 2\ln 2\right) - \frac{\alpha_s}{2\pi} C_F \left(\frac{19}{8} - \frac{3}{2}\ln 2 - 4\ln^2 2 - \frac{\pi^2}{3}\right)$$

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- Jet energy loss
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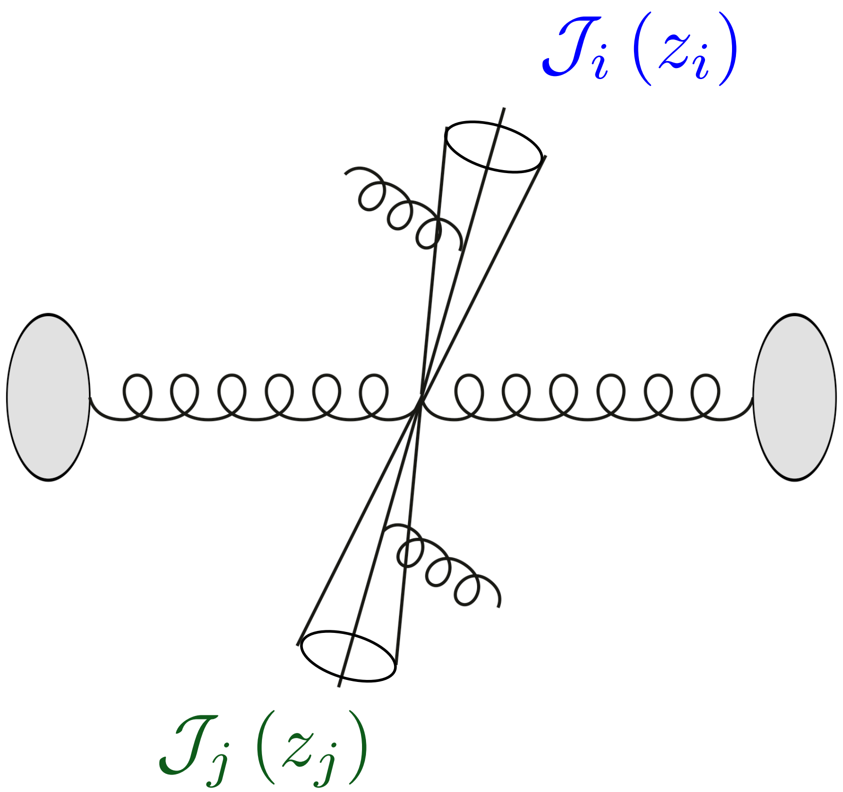
Leading jets

Neill, Ringer, Sato - in preparation

$$\frac{\mathrm{d}\sigma^{(0)}_{pp\to\mathrm{jet}_1+X}}{\mathrm{d}p_{T1}} = \sum_{ij} \int \mathrm{d}\hat{p}_{Ti}\,\mathrm{d}\hat{p}_{Tj} \int \mathrm{d}z_i\,\mathrm{d}z_j\, \mathcal{H}^{(0)}_{ij}(\hat{p}_{Ti},\hat{p}_{Tj},\mu)$$
$$\times\ \mathcal{J}_i\,(z_i,\hat{p}_{Ti}R,\mu)\ \ \mathcal{J}_j\,(z_j,\hat{p}_{Tj}R,\mu)$$
$$\times\ \delta(p_{T1}-\max\{z_i\hat{p}_{Ti},z_j\hat{p}_{Tj}\})$$



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

Leading subjets

Neill, Ringer, Sato - in preparation

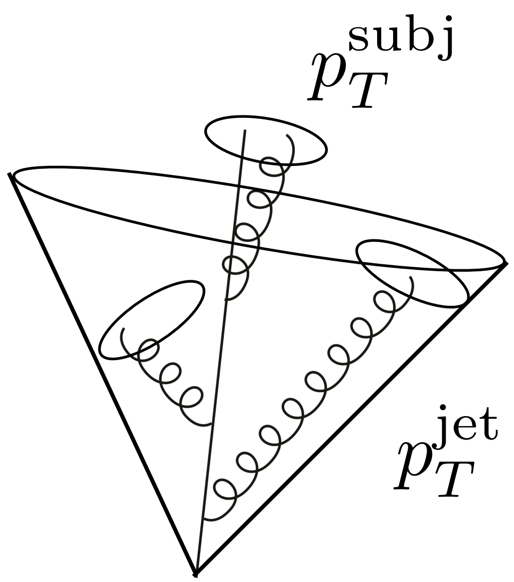
- Initial R sized jet sets the reference scale $Q = p_T^{\rm jet}$
- Measure small r reclustered leading subjets $z_1 = p_T^{\rm subj} / p_T^{\rm jet}$
- LL factorization

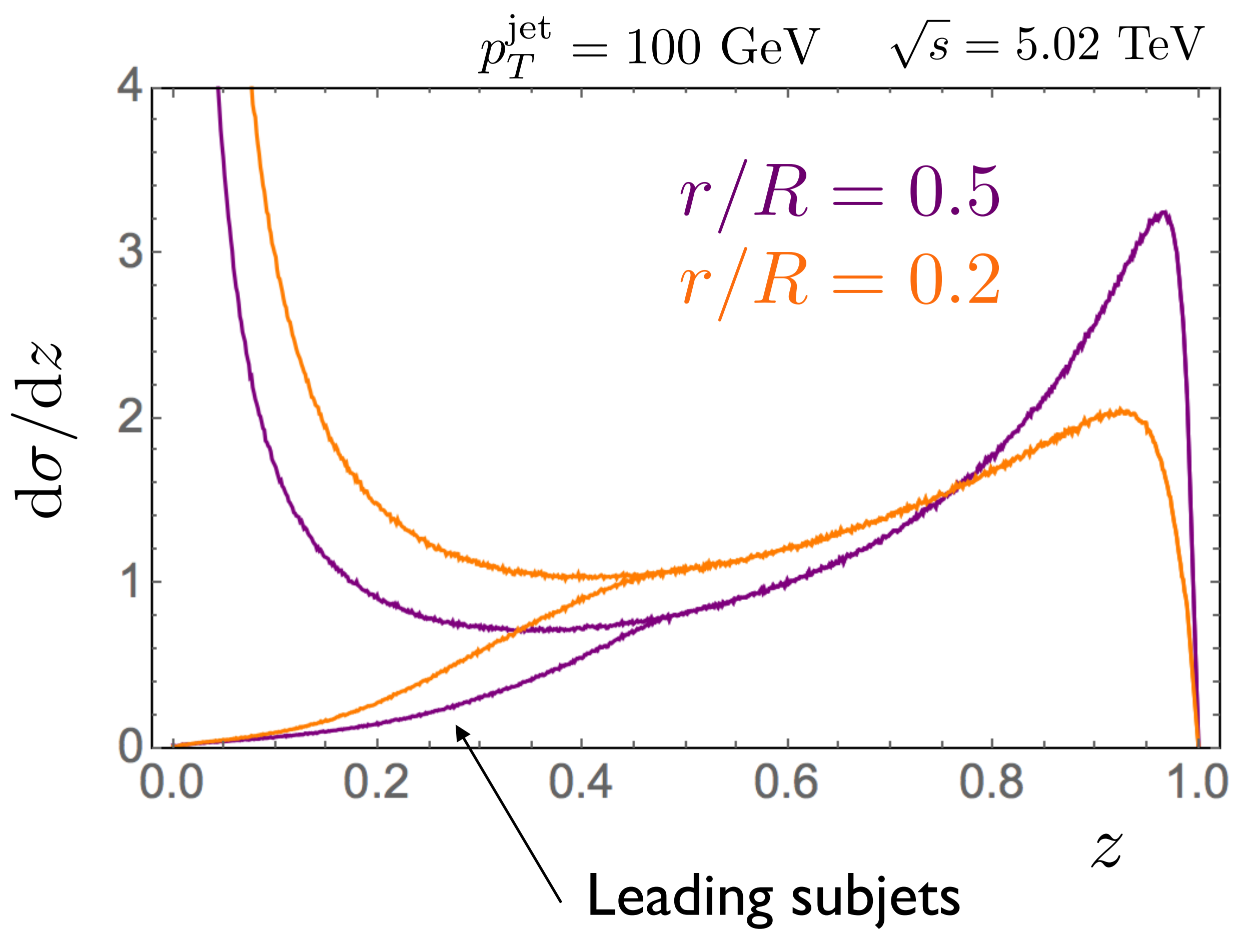
$$\frac{{\rm d}\sigma^{(0)}_{pp\to {\rm j}({\rm sj}_1)+X}}{{\rm d}p_T^{\rm jet}\,{\rm d}\eta\,{\rm d}z_1} = \sum_i \mathcal{H}_i^{(0)}(p_T^{\rm jet},\eta)\,\mathcal{J}_i(z_1, p_T^{\rm jet}R,\mu)$$

- Average energy loss

$$\langle z_1\rangle = \int_0^1 {\rm d}z_1\, z_1 \frac{1}{\sigma_{\rm tot}} \frac{{\rm d}\sigma^{(0)}_{pp\to {\rm j}({\rm sj}_1)+X}}{{\rm d}z_1}$$

$$= f_q\,\langle z_{1,q}\rangle + f_g\,\langle z_{1,g}\rangle$$





γ/Z-tagged leading jets

Neill, Ringer, Sato - in preparation

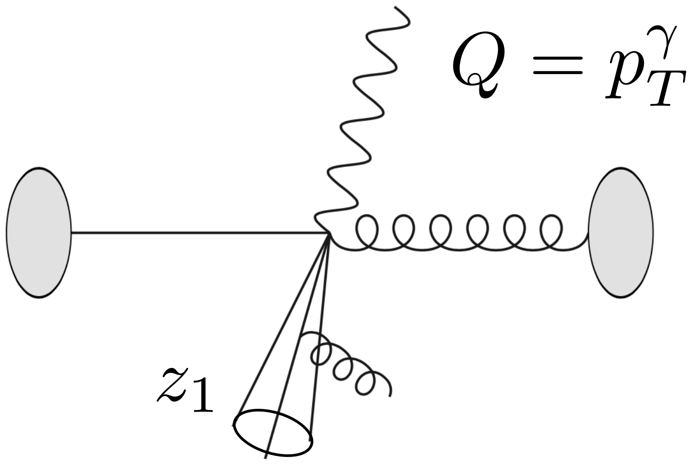
- γ/Z provides reference scale $Q = p_T^\gamma$
- Measure leading jet $z_1 = p_{T1}/p_T^\gamma$
- LL factorization

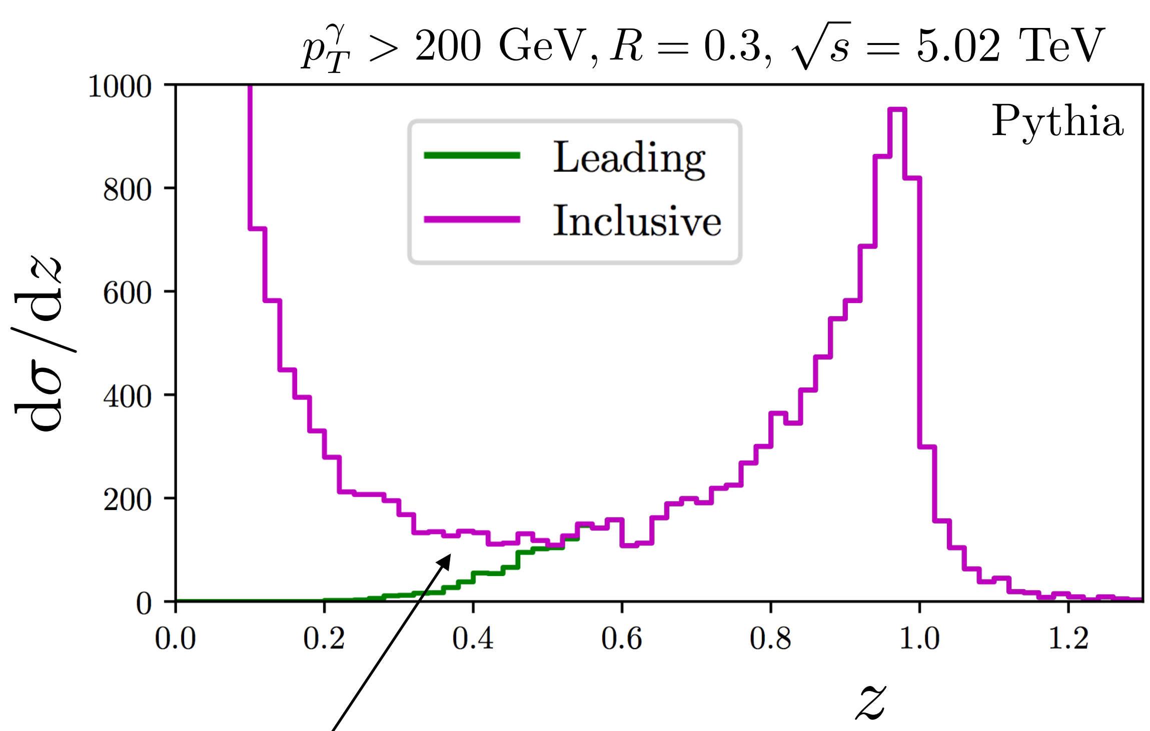
$$\frac{d\sigma^{(0)}_{pp\to\gamma+\text{jet}+X}}{dp_T^\gamma\, d\eta^\gamma\, dz_1} = \sum_i \mathcal{H}_i^{(0)}(p_T^\gamma, \eta)\, \mathcal{J}_i(z_1, p_T^\gamma R, \mu)$$

- Average energy loss

$$\langle z_1\rangle = \int_0^1 dz_1\, z_1 \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma^{(0)}_{pp\to\gamma+\text{j1}+X}}{dz_1}$$

$$= f_q \langle z_{1,q}\rangle + f_g \langle z_{1,g}\rangle$$





Energy loss is the difference between the leading and inclusive spectrum

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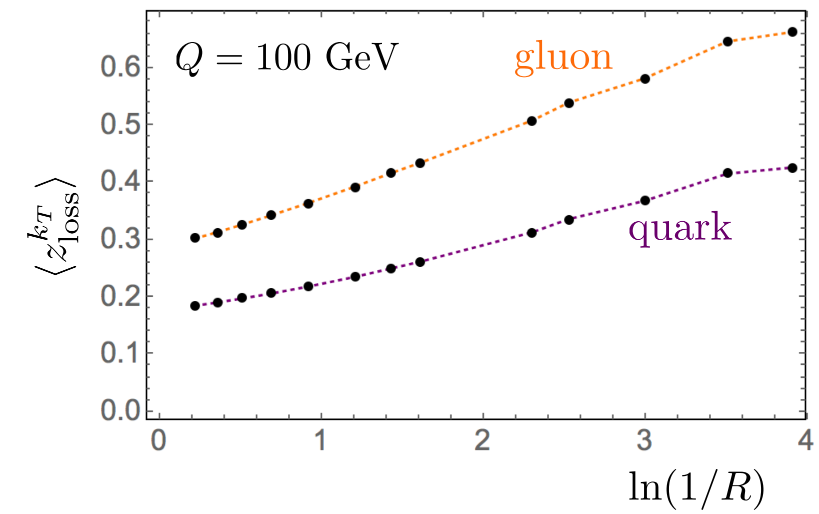
Conclusions



- **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 γ/Z-tagged jets
  3. Identify at LL: parton $=$ jet energy loss

- **Heavy-ion collisions**
  - Quantify jet-medium interaction in AA
  - How opaque is the QGP?