Leading jets and energy loss

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In collaboration with

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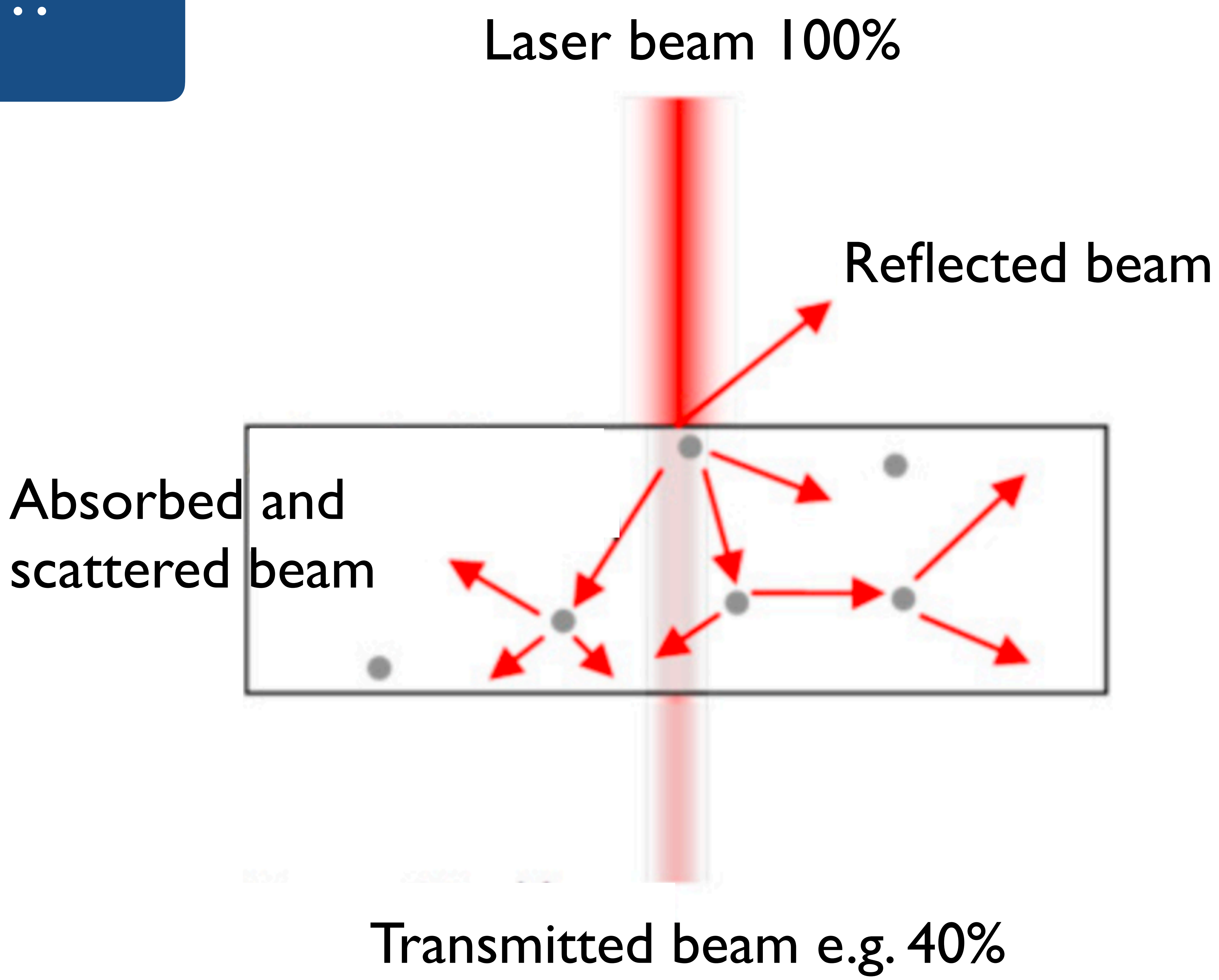
- Nobuo Sato, JLab

arXiv:2103.16573

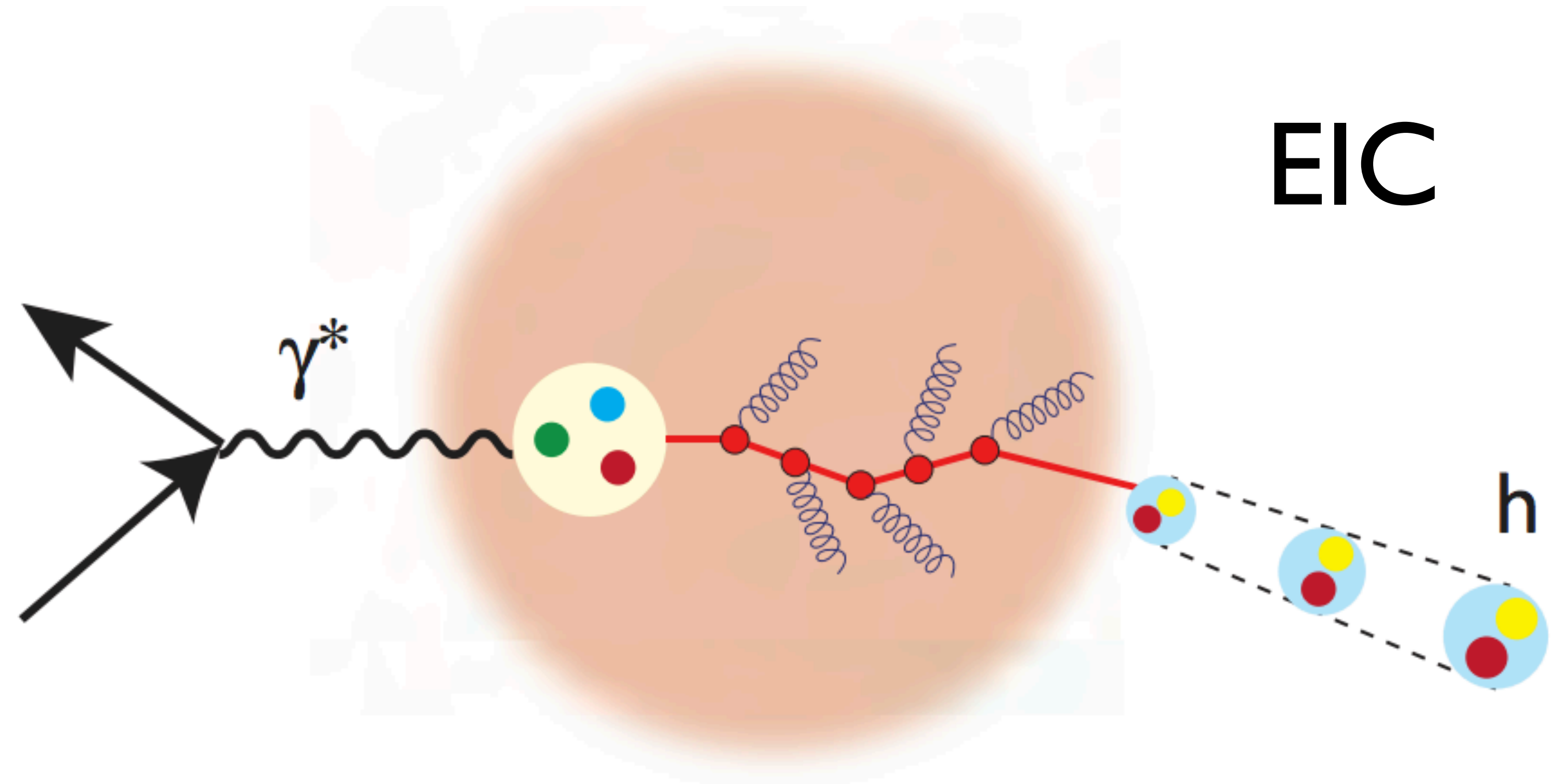
QCD Evolution, UCLA, 05/13/21

Probing nuclear matter

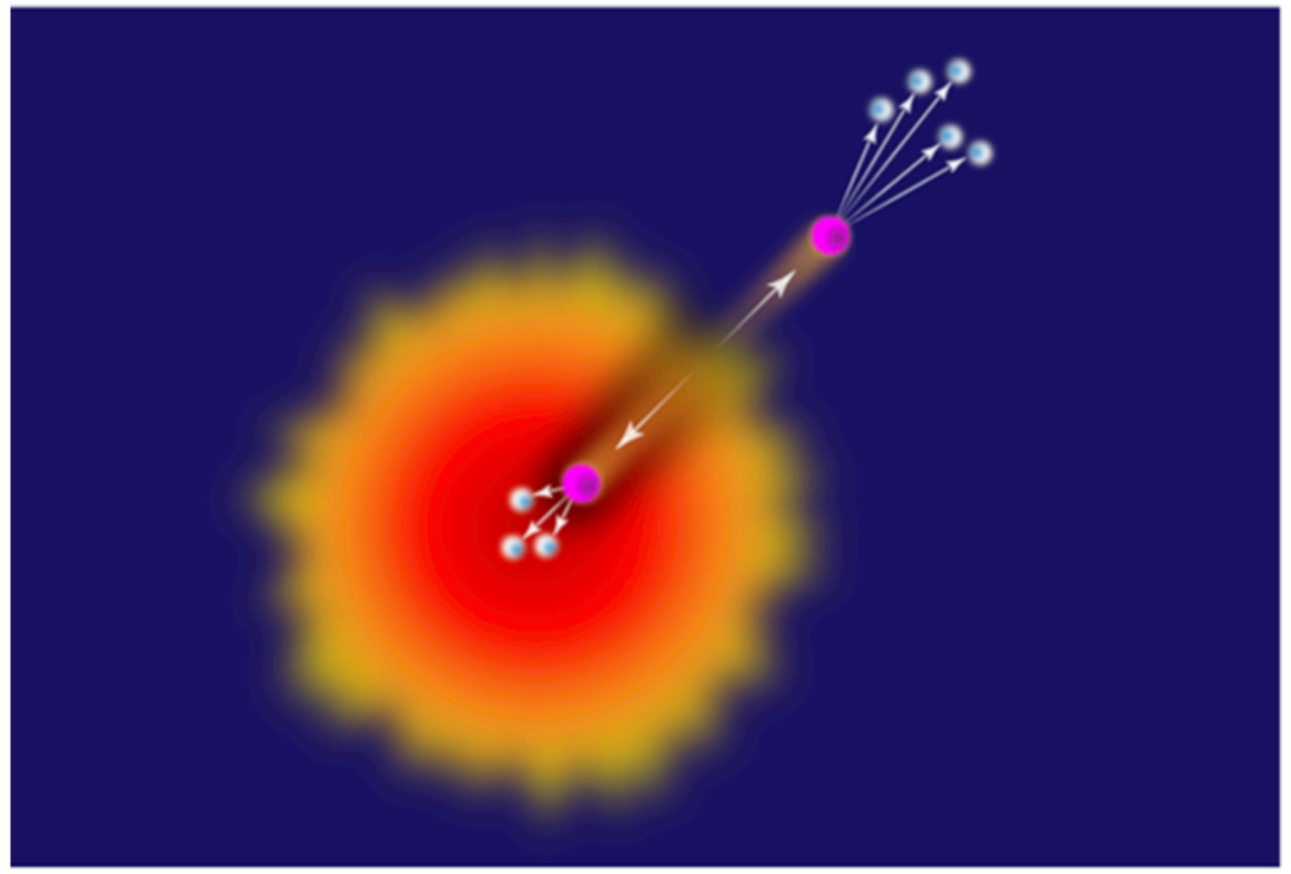
Ideally …



EIC



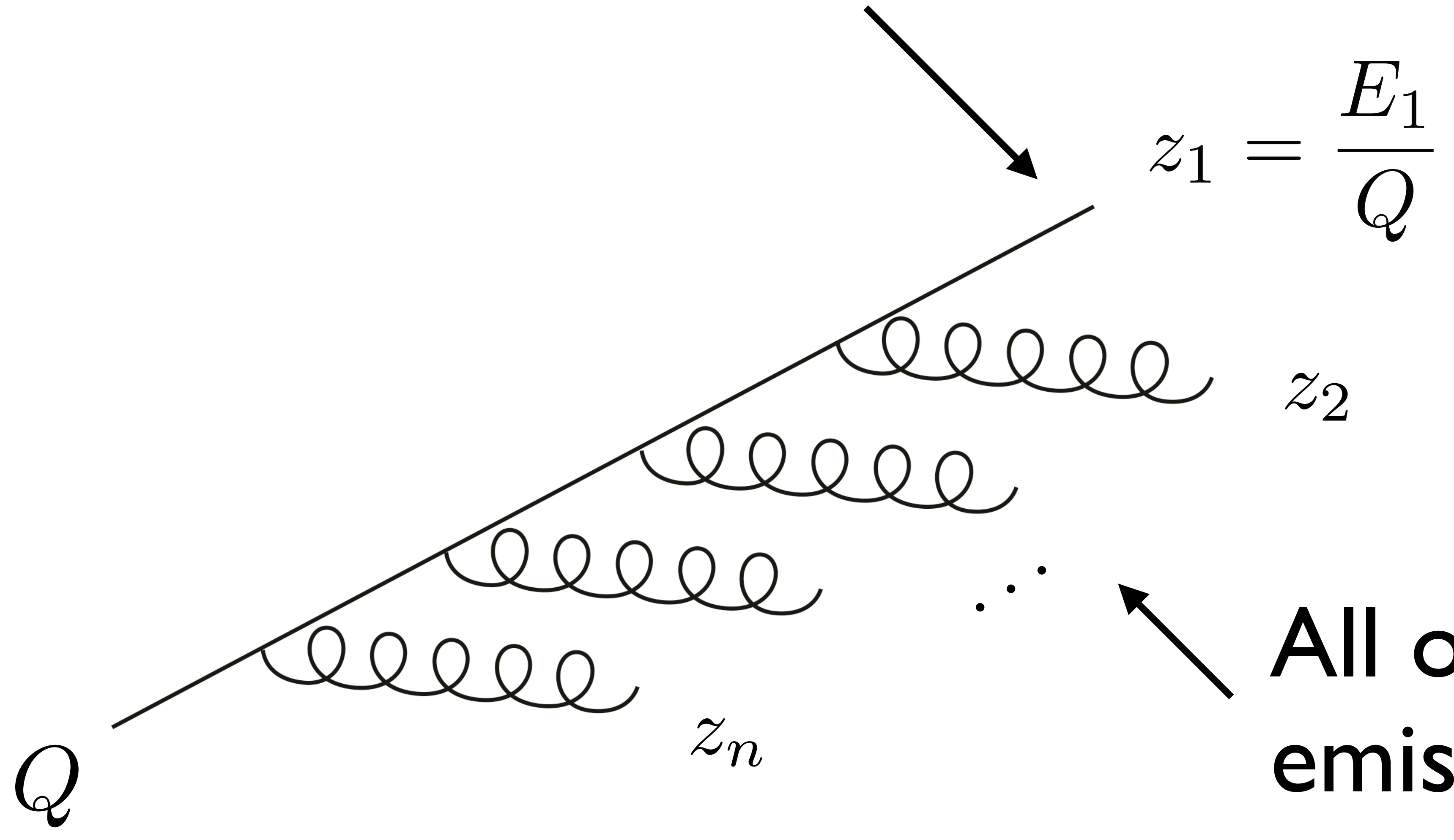
Heavy-ion



Jet quenching and energy loss

- Soft & collinear limit

Most energetic/leading parton



All other gluon emissions are soft $z_{i\geq 2} \ll 1$

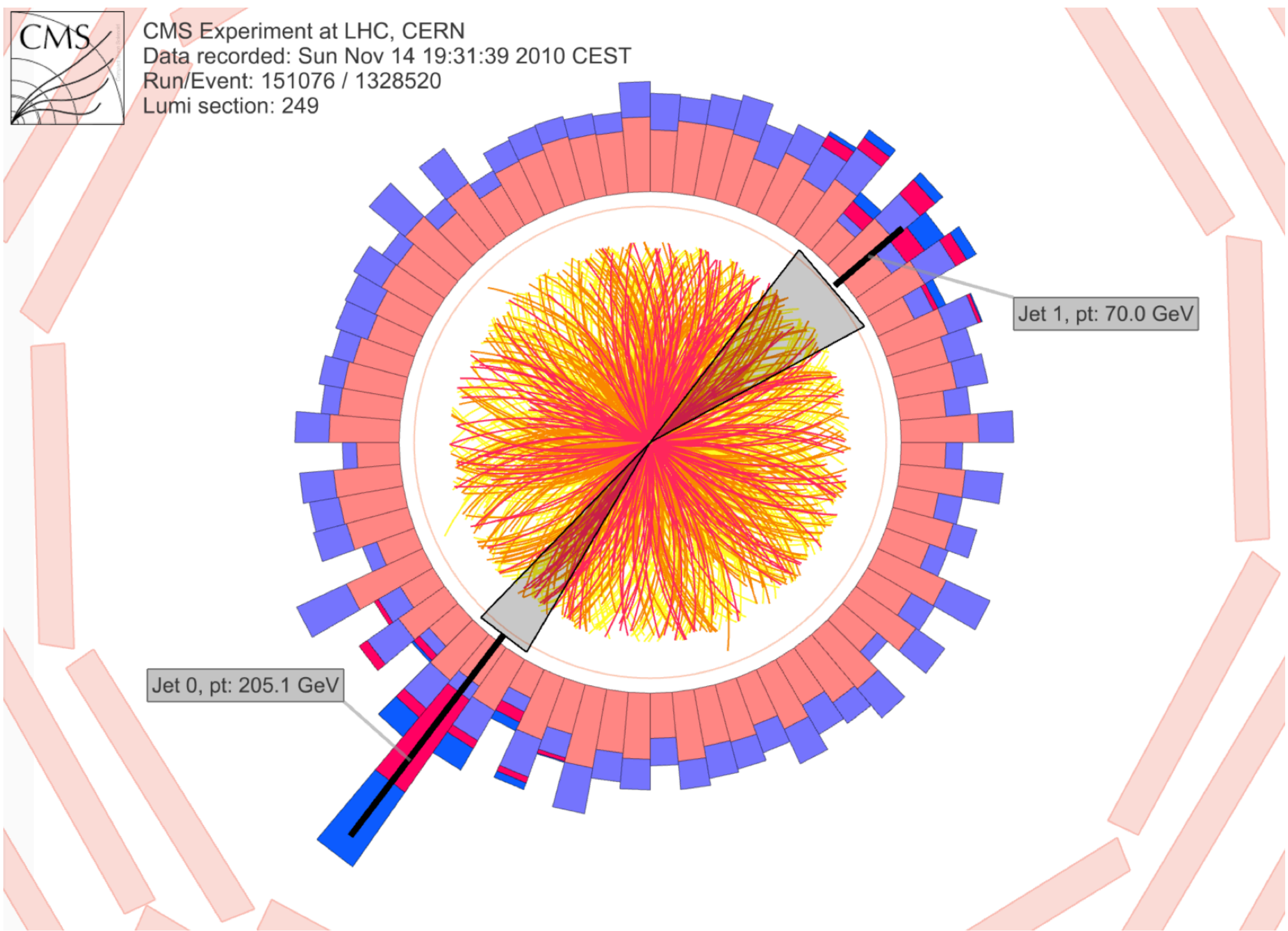
Energy loss

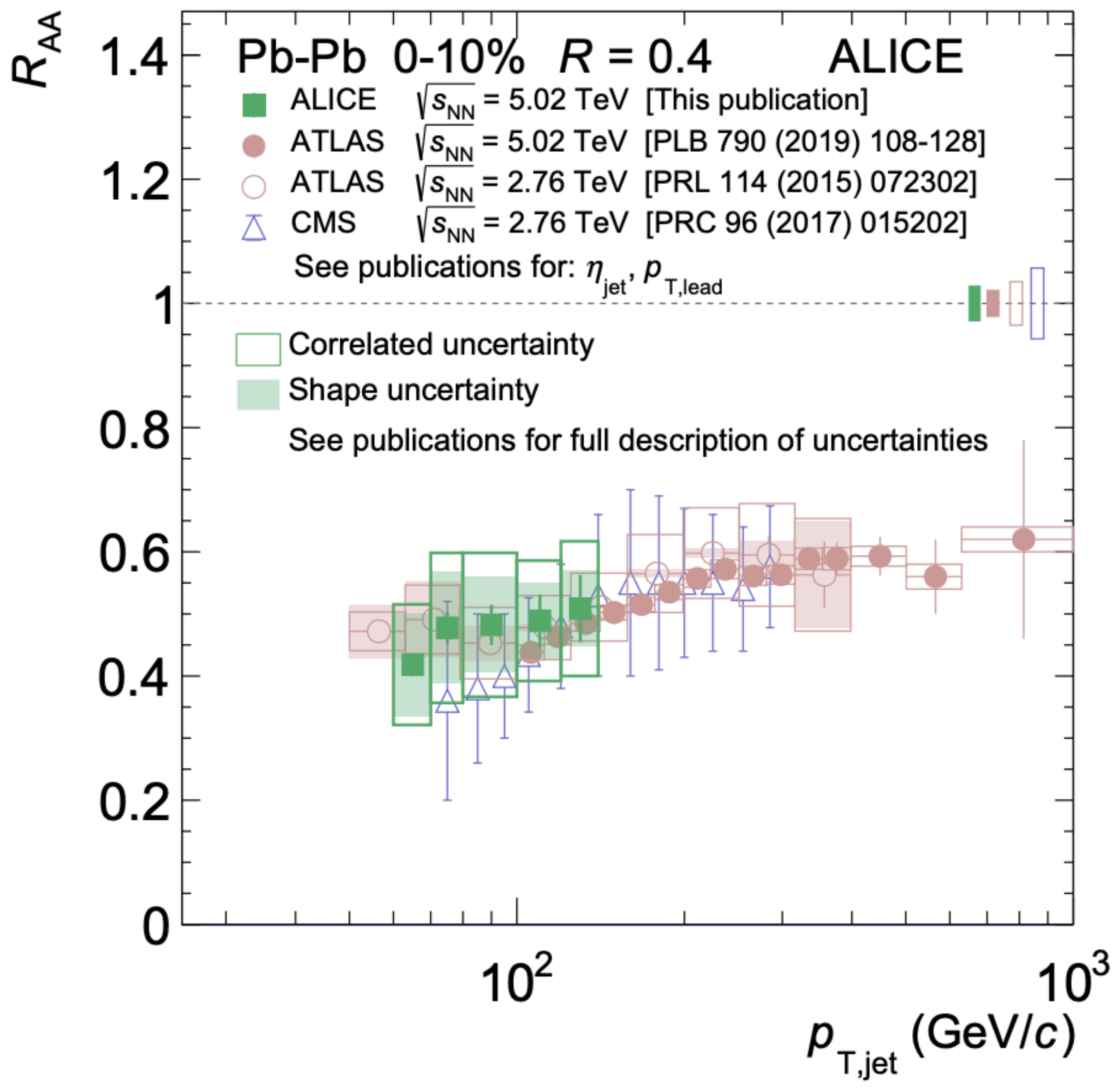
$$z_{\rm loss} = \sum_{i\geq 2} z_i$$
$$= 1 - z_1$$

- Medium induced effects *see e.g. Gyulassy, Wang `93, Baier, Dokshitzer, Mueller, Peigne, Schiff `96, Zakharov `96 Wiedemann `00, Gyulassy, Levai, Vitev `01, Arnold, Moore, Yaffe `02*

Jet quenching and energy loss

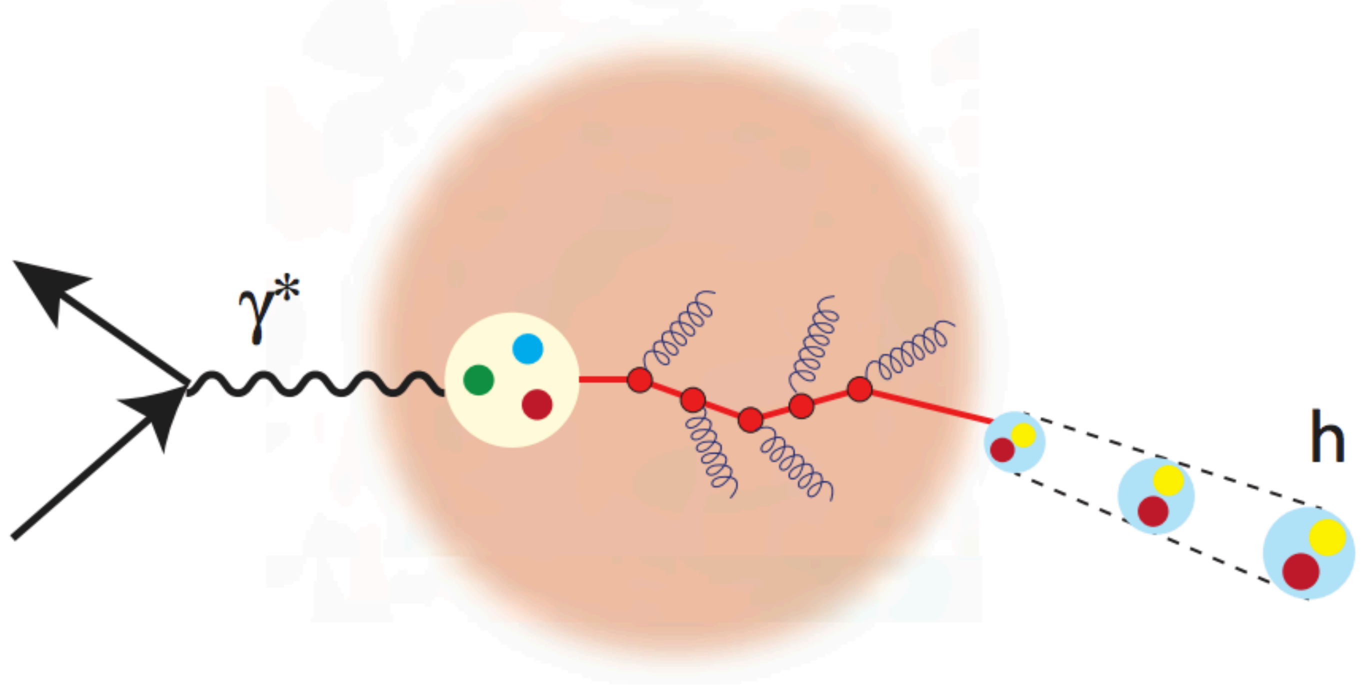
- Experimental results





ALICE, PRC 101 (2020) 034911

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



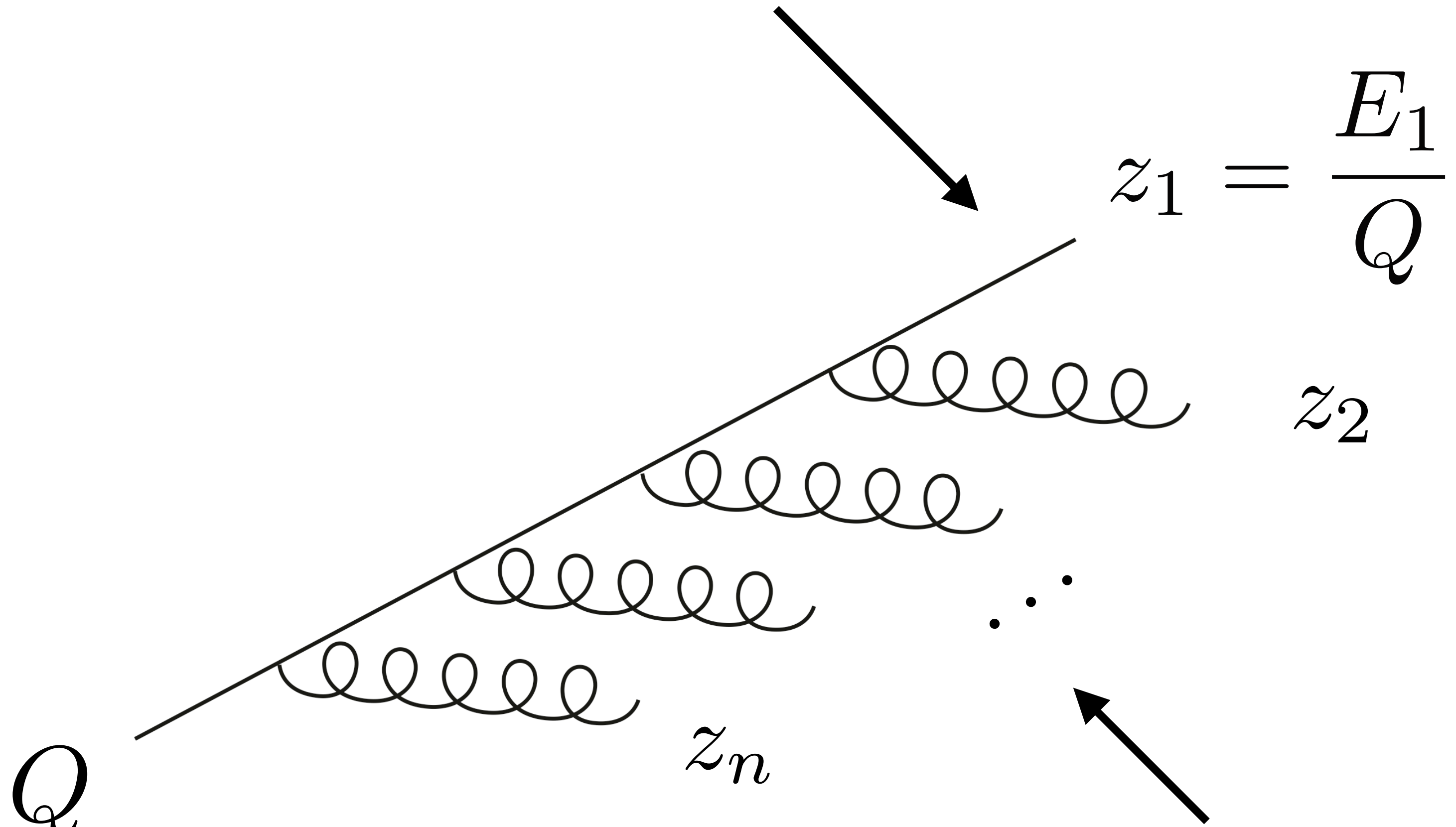
Similarly at the EIC

- Soft & collinear approximation not applicable
- Indirect measurements of energy loss

Can we measure energy loss more directly?

- Beyond the soft approximation

Most energetic/leading parton



- No requirement that gluons are soft $z_{i\geq 2}$
- Flavor changes

Energy loss

$$z_{\rm loss} = 1 - z_1$$

- Need a well defined probability density $\rho(z_1)$

$$\langle z_1 \rangle = \int_0^1 \mathrm{d}z_1 \, z_1 \rho(z_1)$$

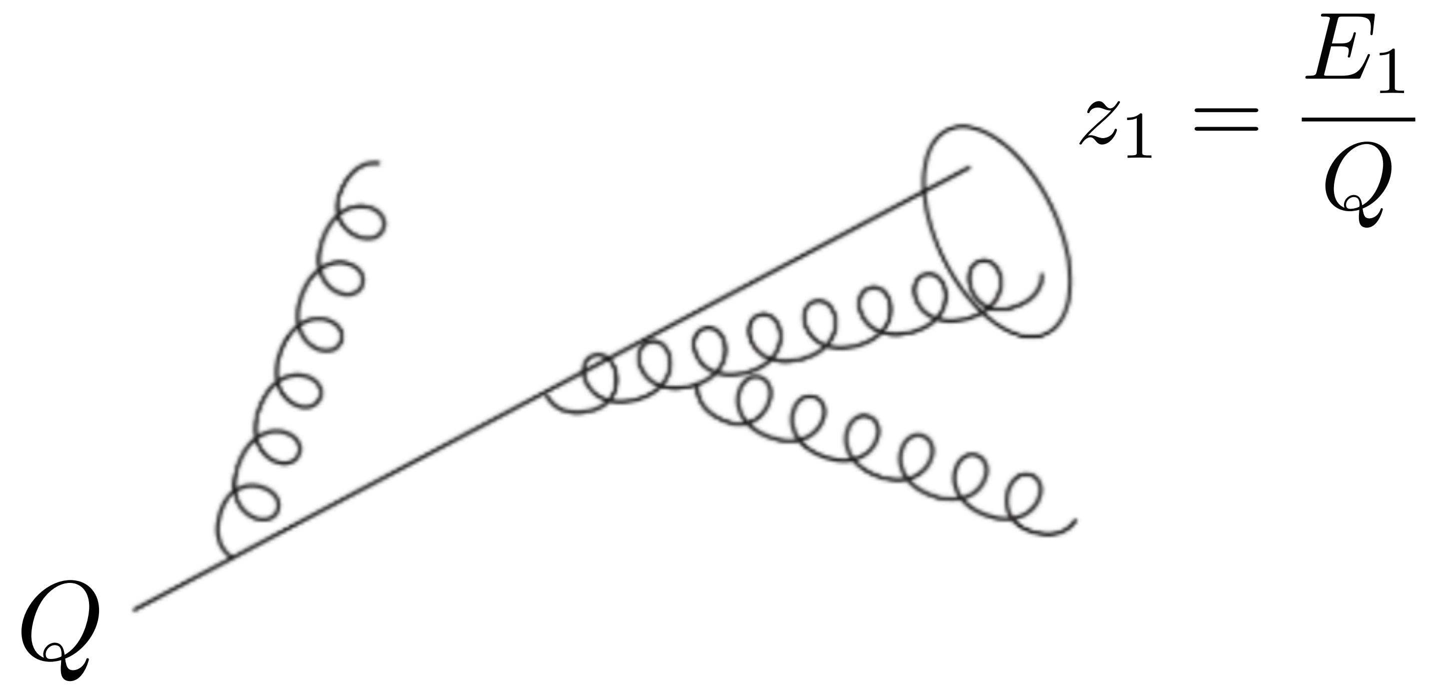
- This talk — vacuum energy loss

Requirements for energy loss measurements

1. Well defined object which has lost energy

Leading jet, not inclusive jets

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



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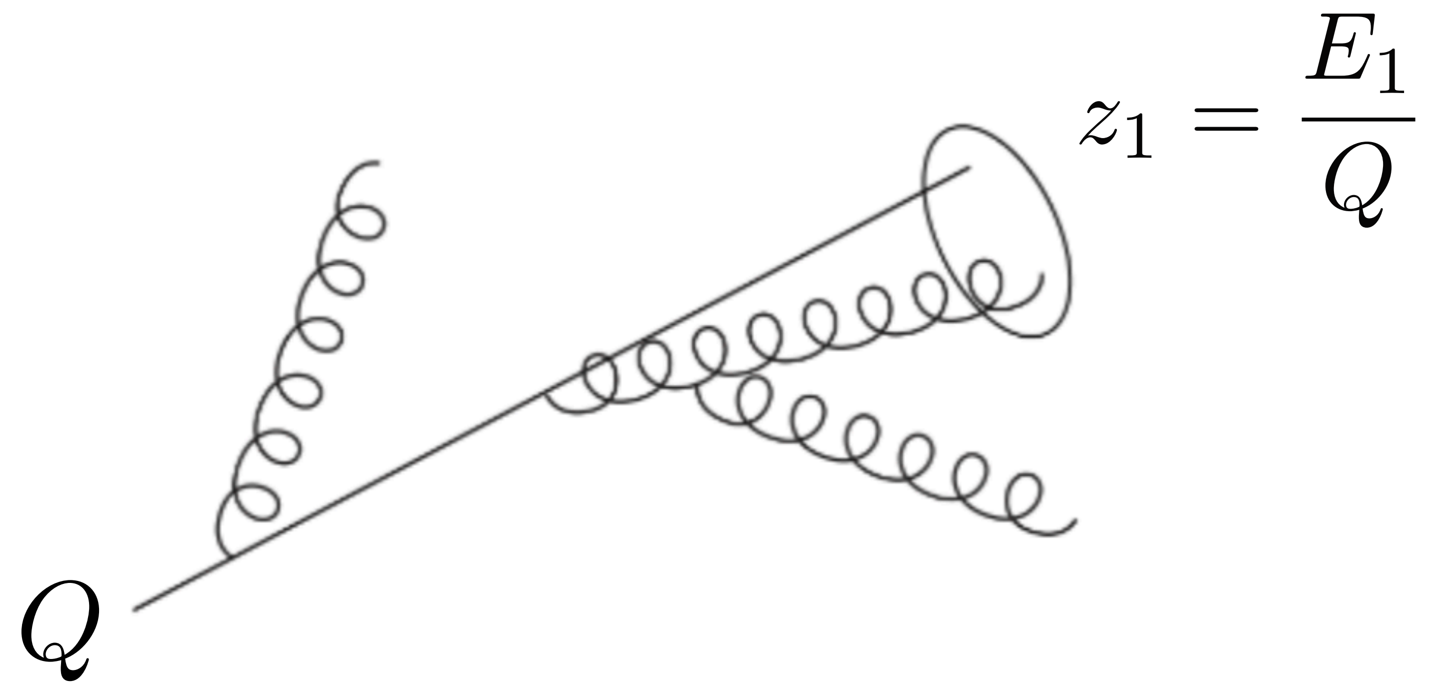
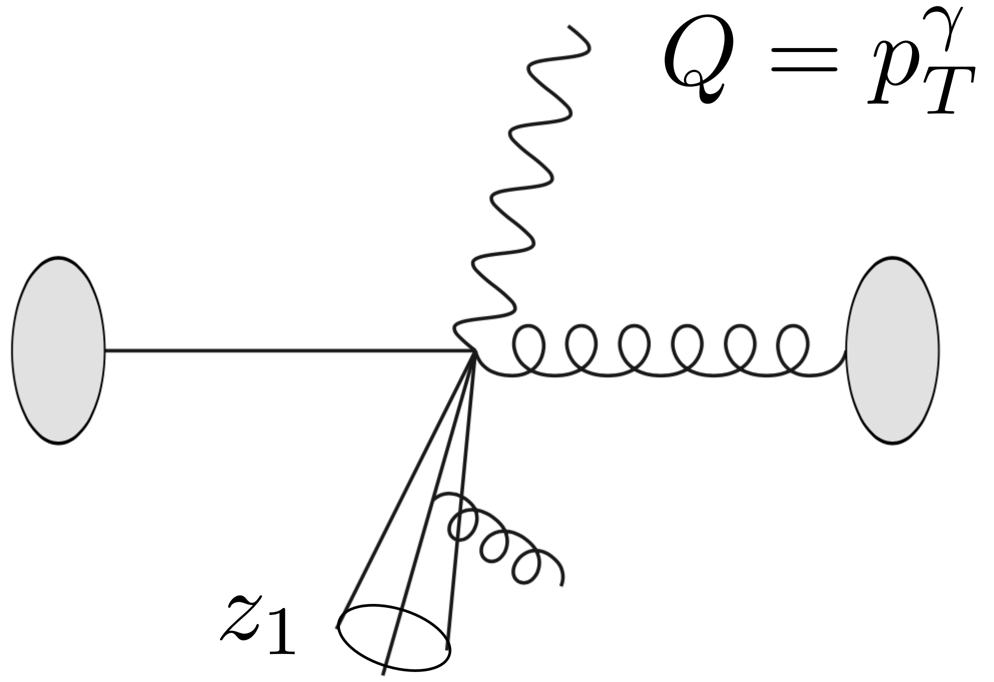


2. Reference scale to define lost energy

   Jet substructure, γ/Z-tagged jets, initial-state leptons



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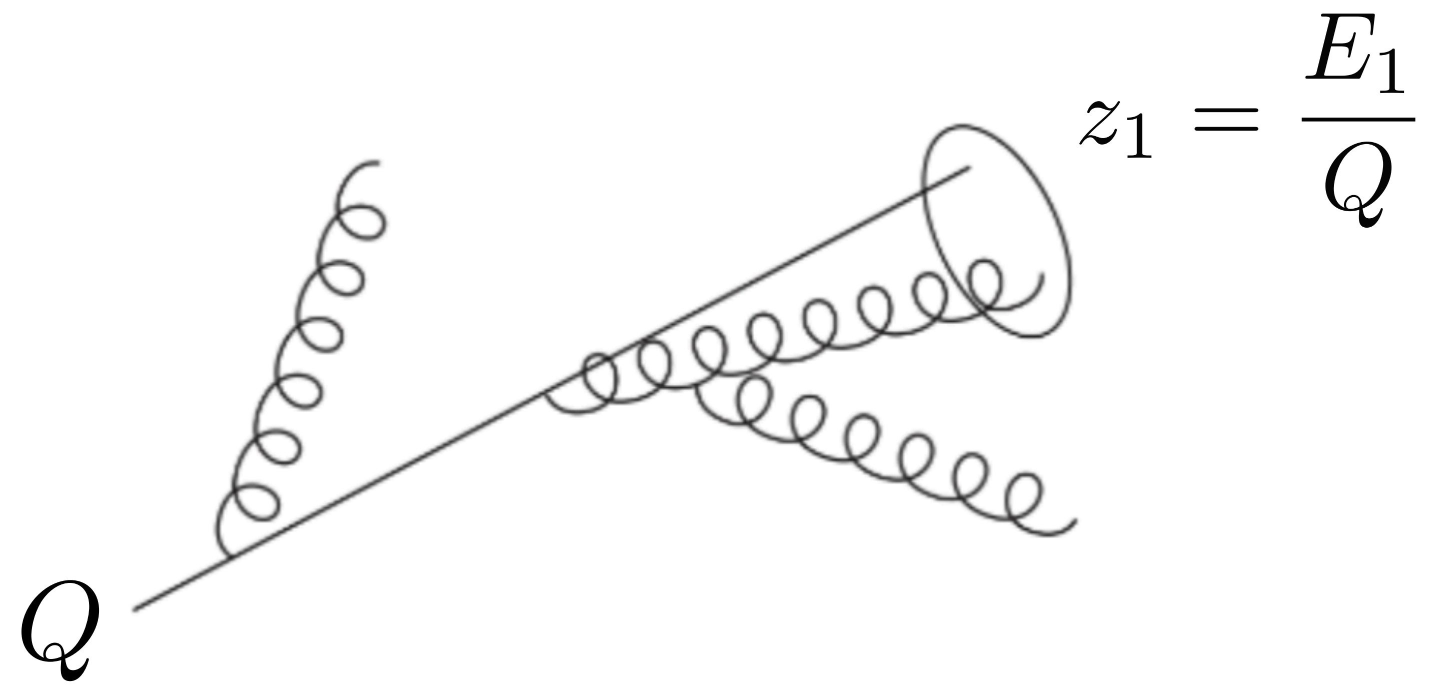

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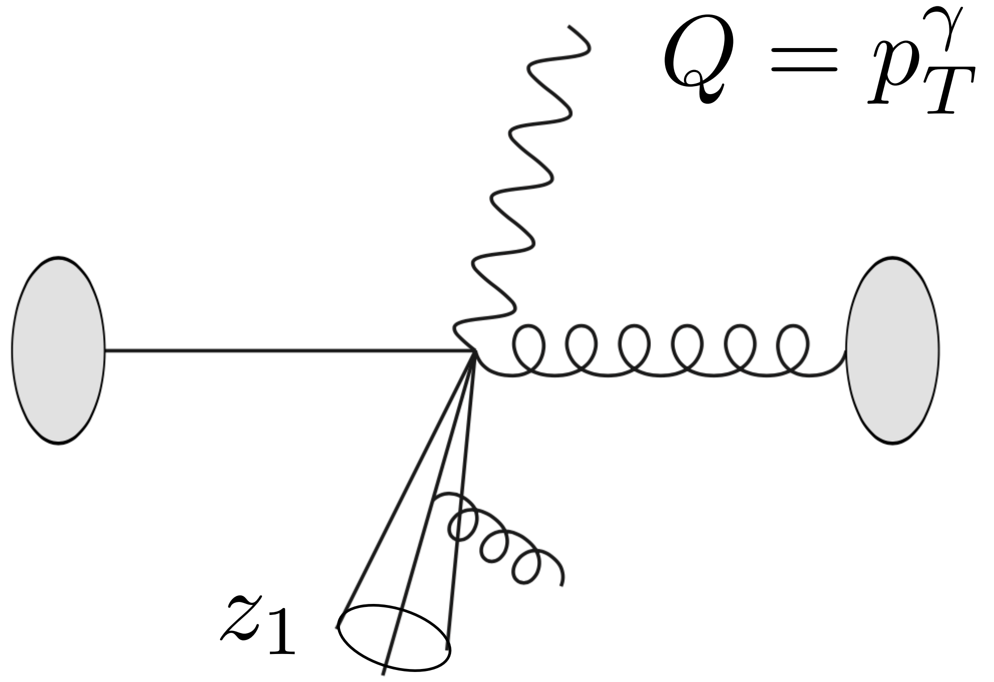


3. Identify at LL: parton $\longleftrightarrow$ jet energy loss

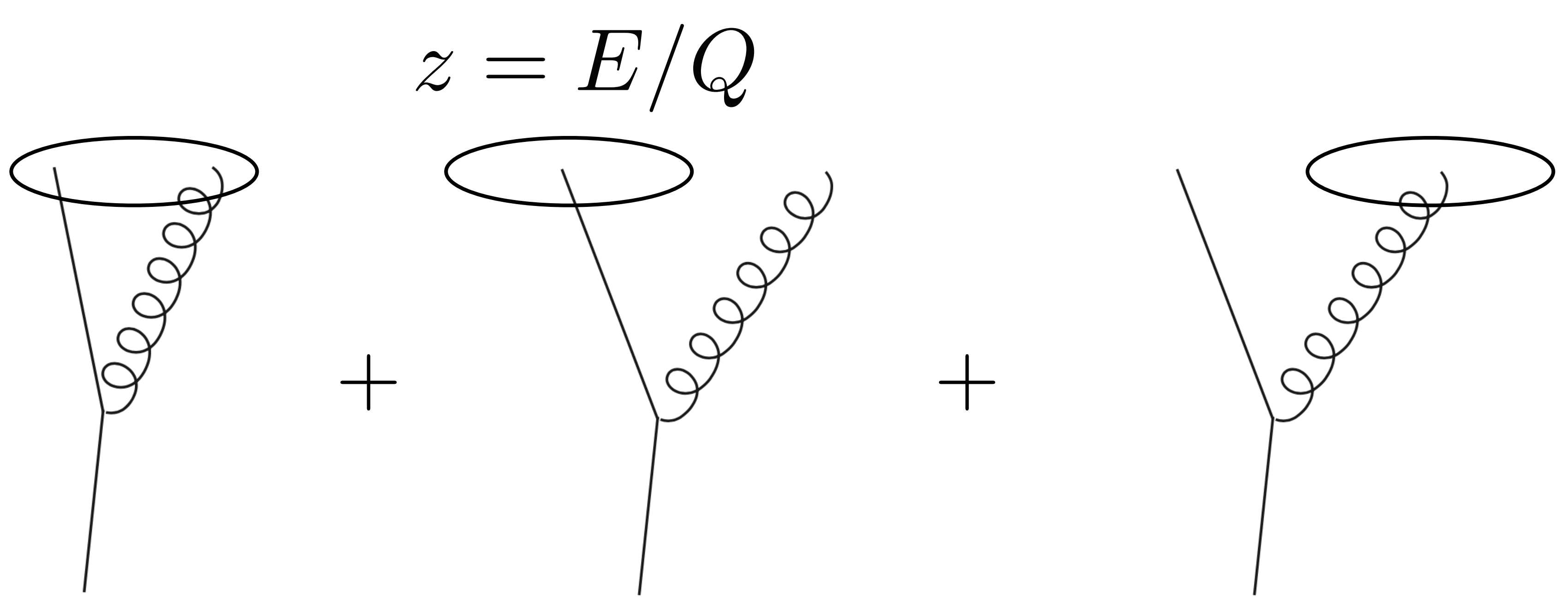
Similar to Bjorken x_B in DIS. As close to parton energy loss as allowed by QCD

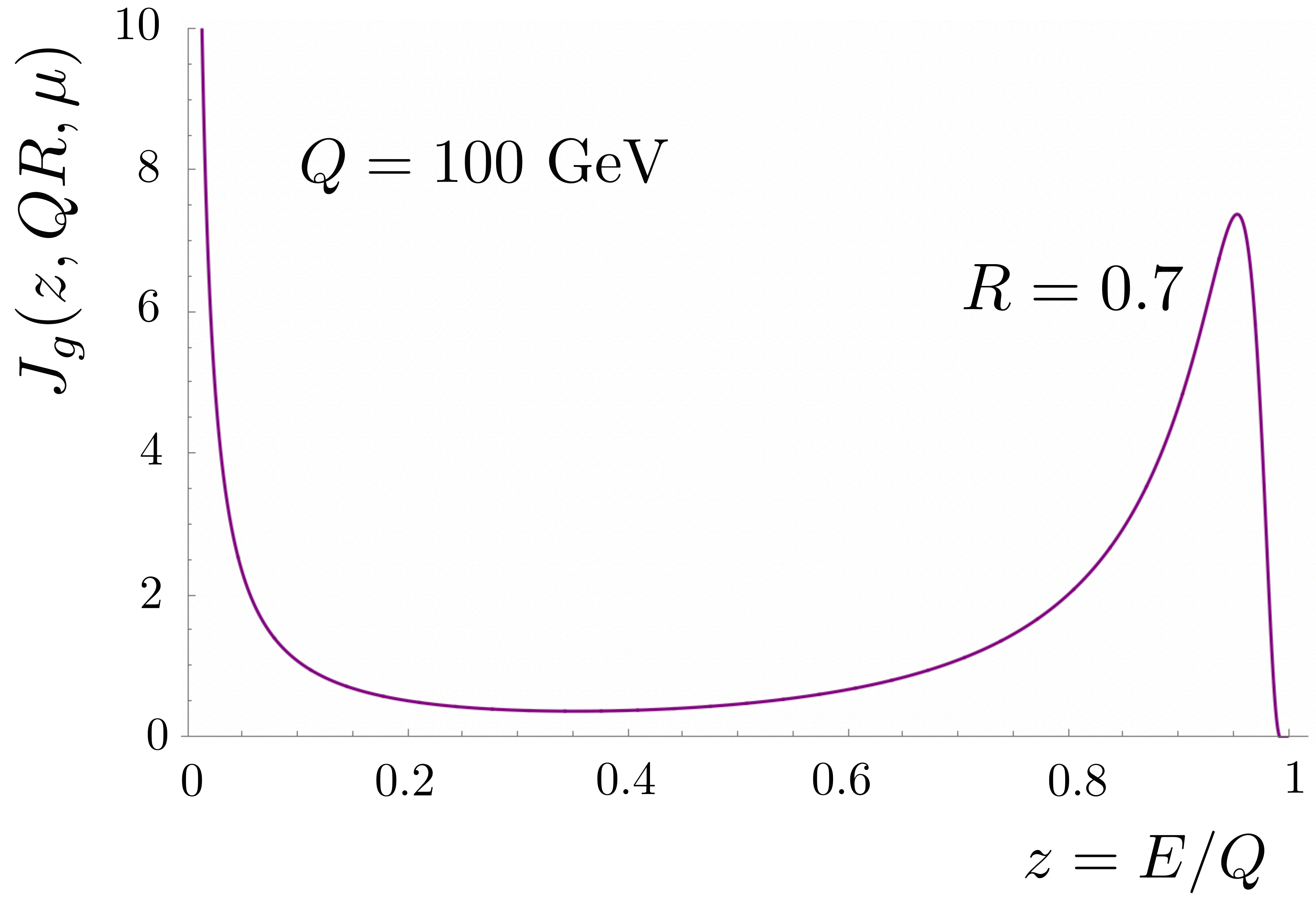
Outline

- Introduction
- Leading jet cross sections
- Energy loss
- Conclusions

Inclusive jet cross sections

- **NLO** $J_i(z, QR, \mu)$





$$J_q(z, QR, \mu) = \delta(1-z) + \frac{\alpha_s}{2\pi}\left(\ln\left(\frac{\mu^2}{Q^2R^2}\right) - 2\ln z\right)[P_{qq}(z) + P_{gq}(z)] \; + \; \ldots$$

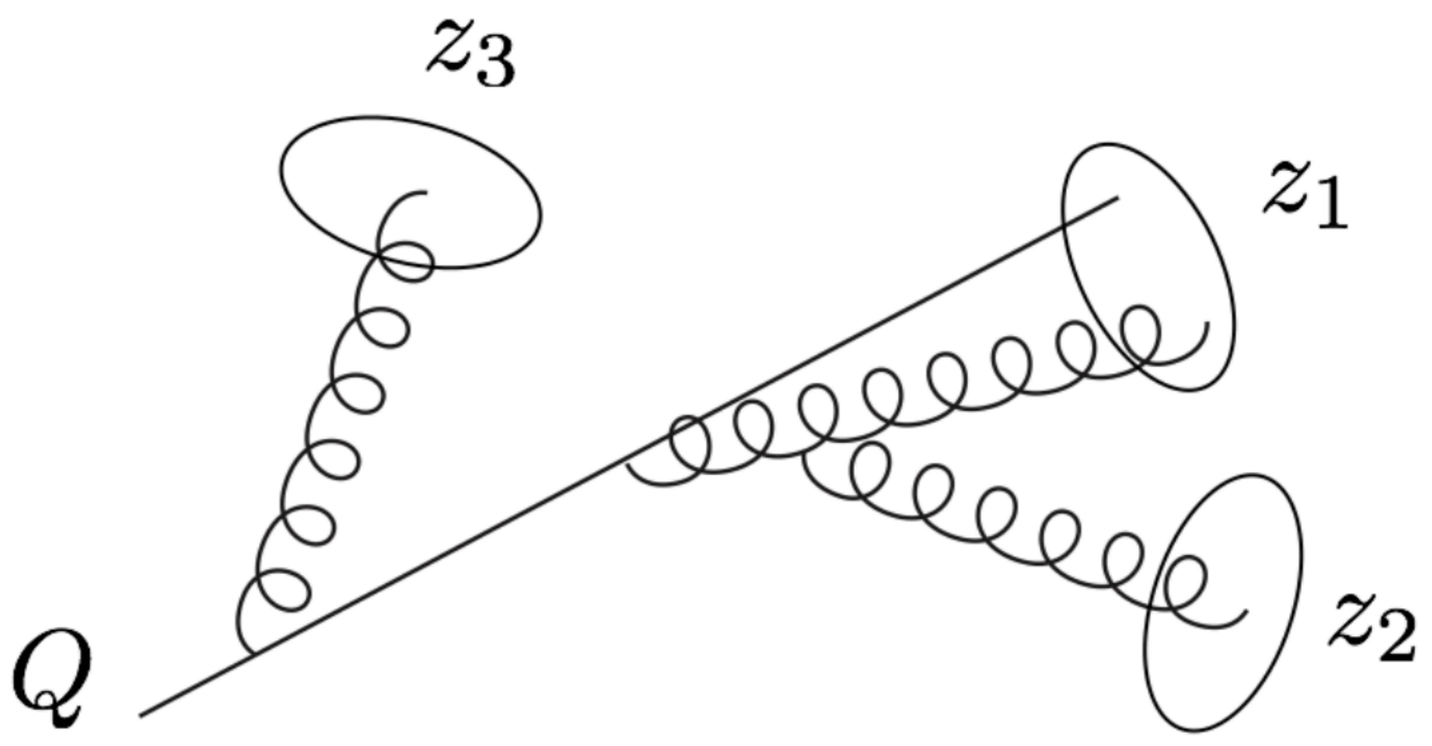
Dasgupta, Dreyer, Salam, Soyez `14
Kaufmann, Mukherjee, Vogelsang `15
Kang, Ringer, Vitev `16
Dai, Kim, Leibovich `16
Liu, Moch, Ringer `18, `19

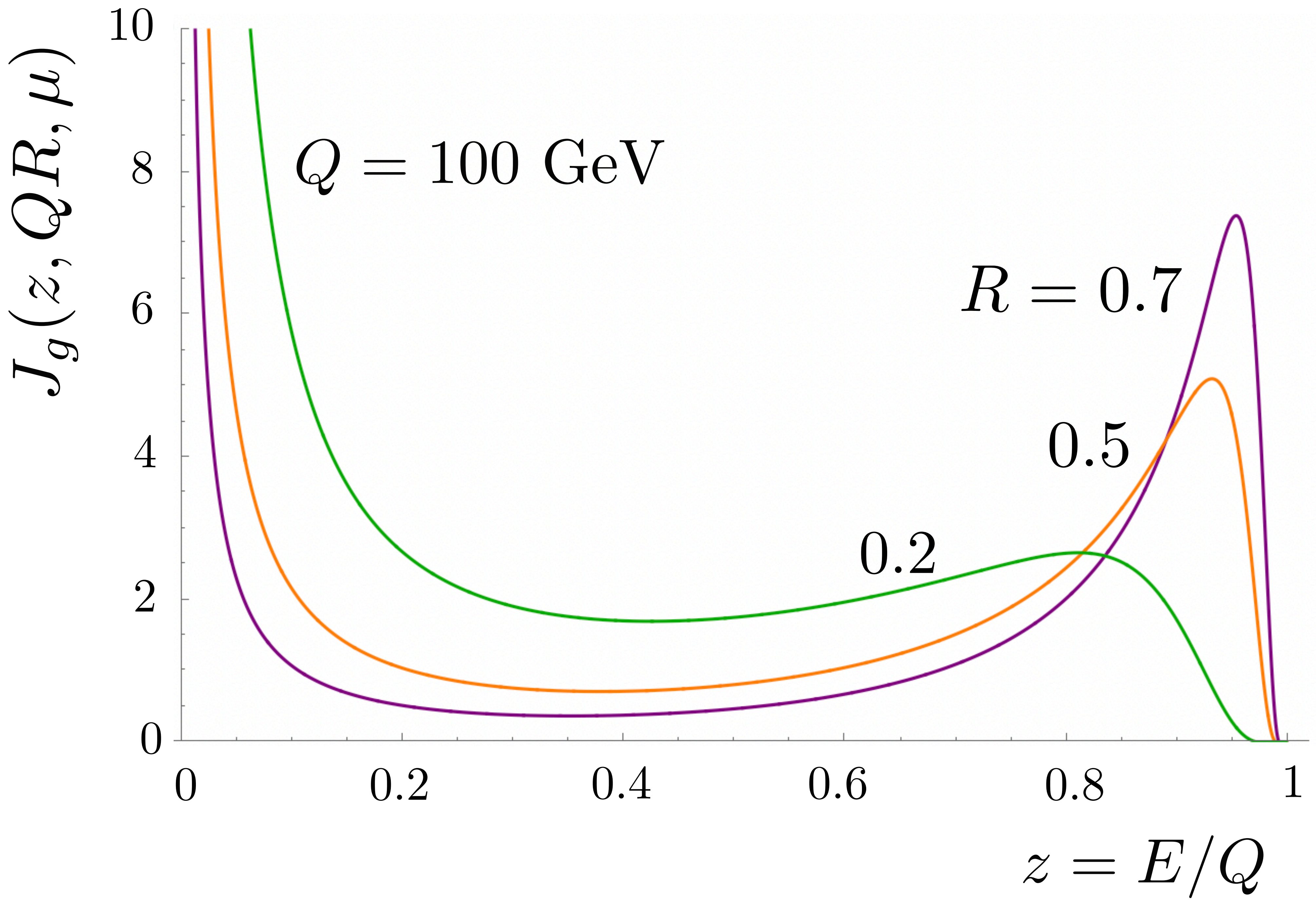
Inclusive jet cross sections

- **NLO** $J_i(z, QR, \mu)$

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

DGLAP like hadron fragmentation functions





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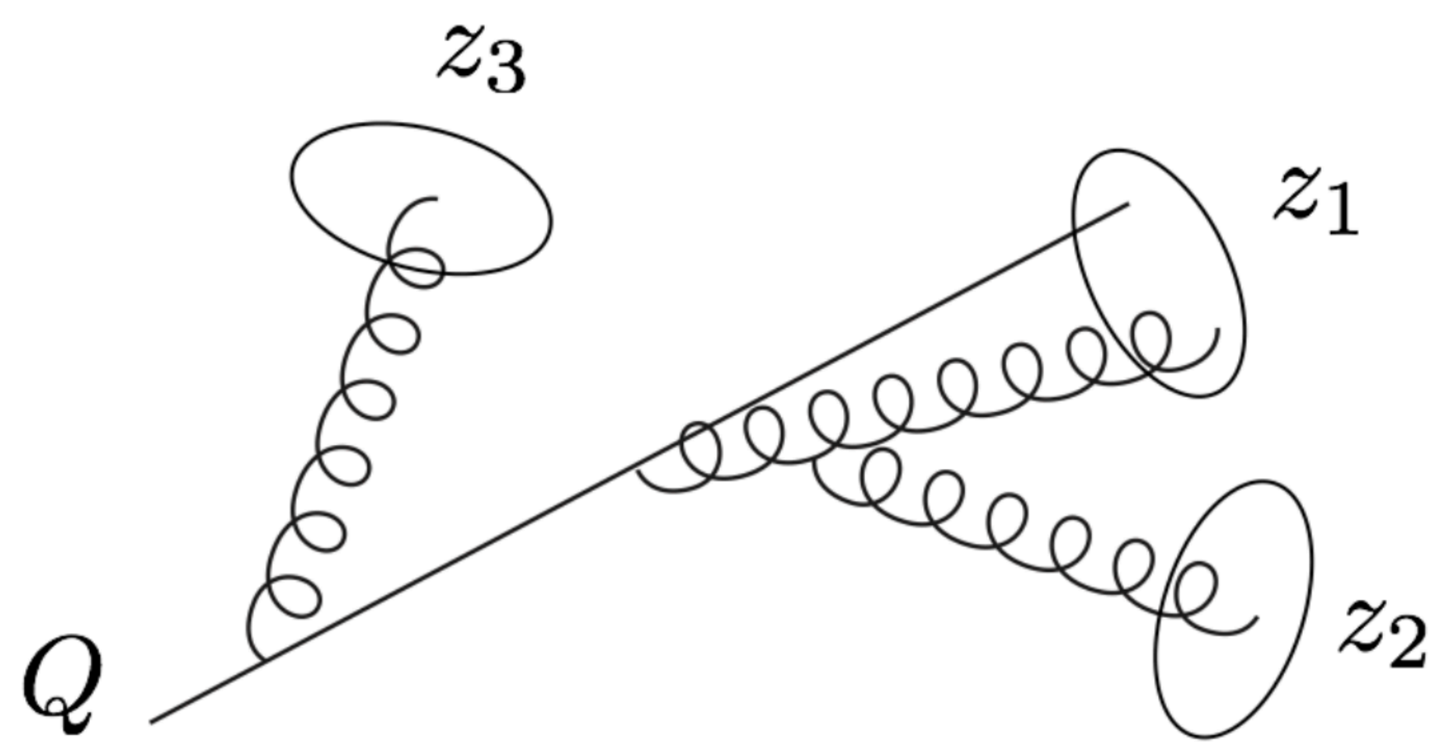
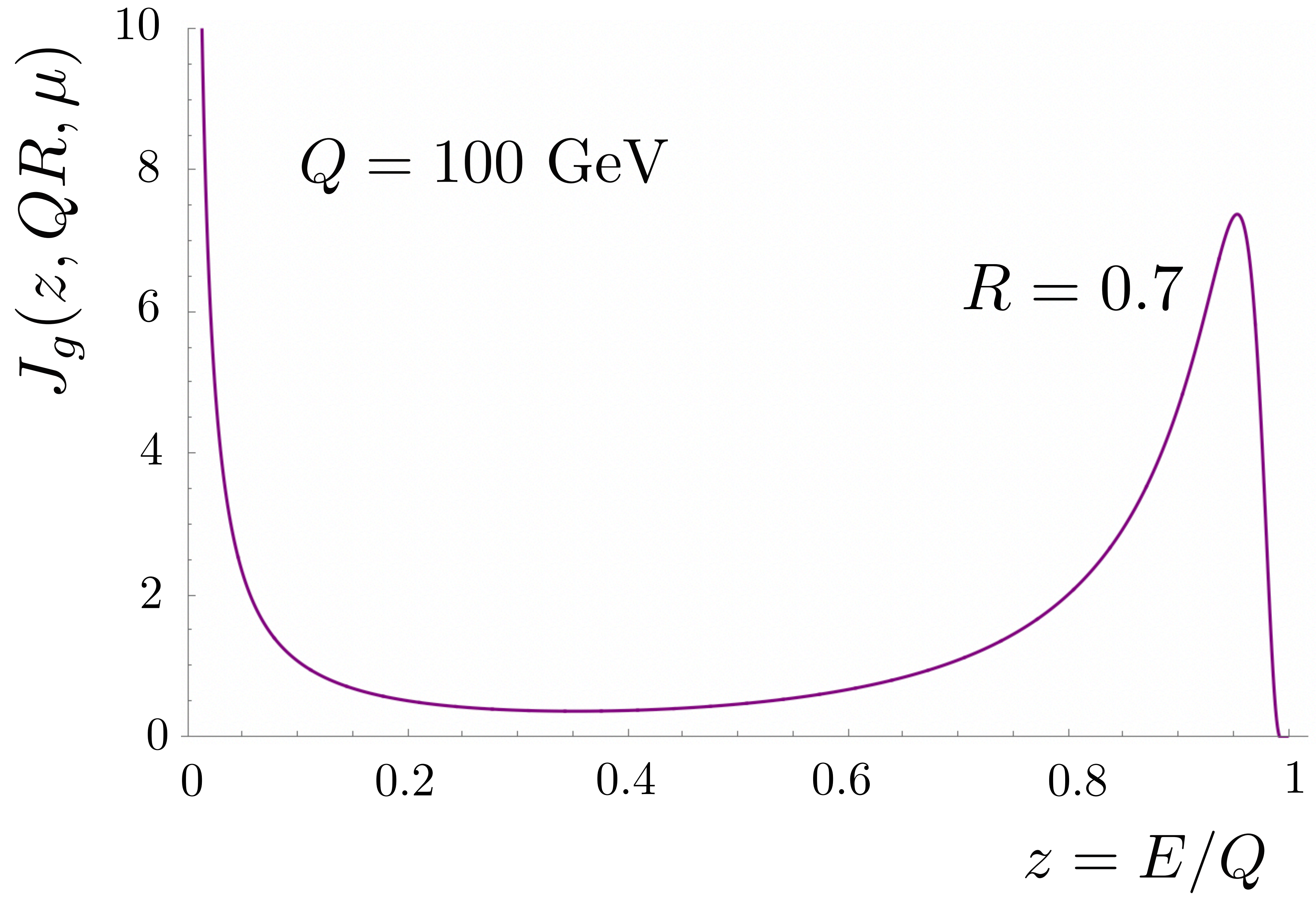
- **Factorization**

$$\frac{\mathrm{d}\sigma_{pp\to\text{jet}+X}}{\mathrm{d}\eta\mathrm{d}p_T} = \sum_{ijk} f_{i/p}\otimes f_{j/p}\otimes H_{ijk}\otimes J_k$$





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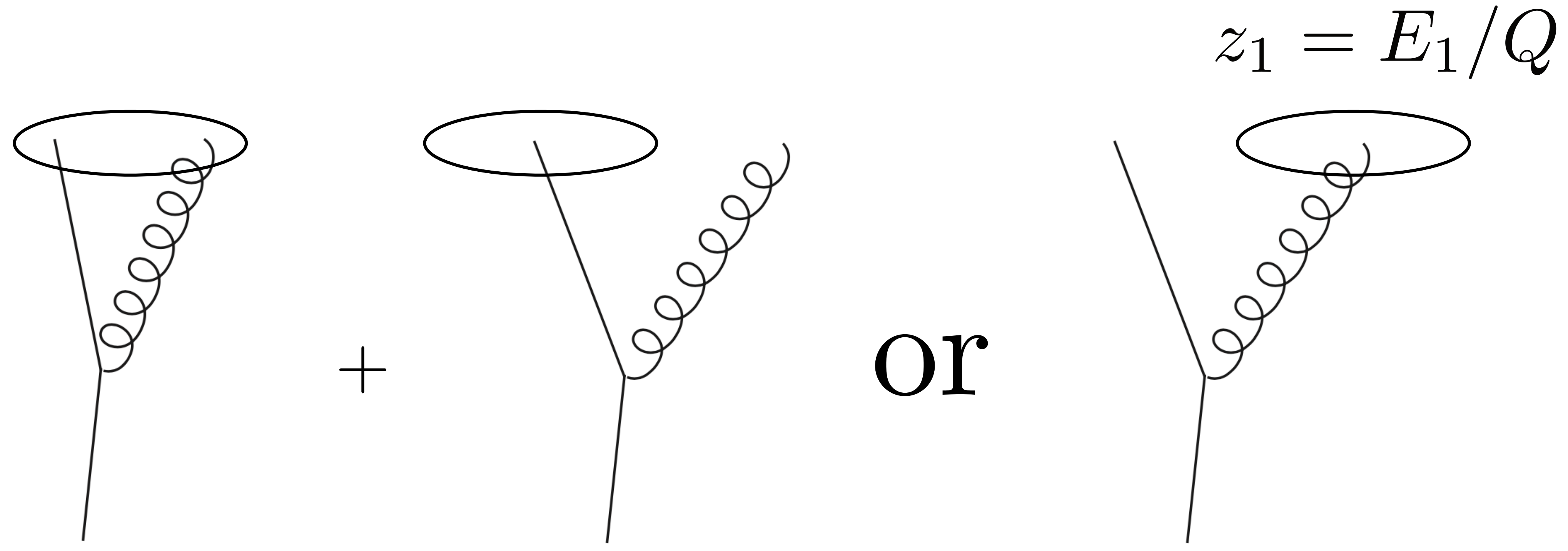
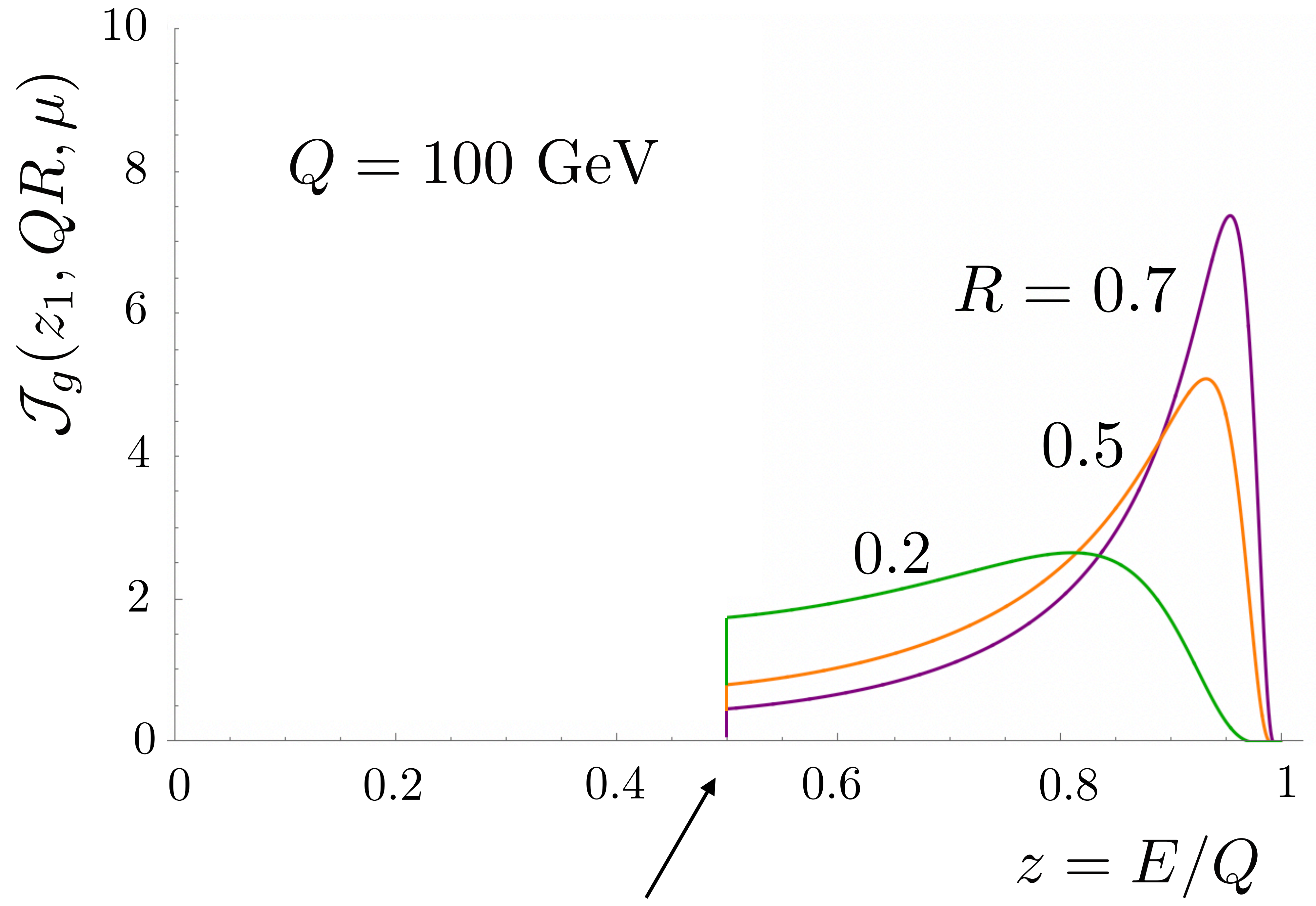
Leading jet cross sections

- **NLO**

Leading jet function

$$\mathcal{J}_i(z_1, QR, \mu) = \Theta(z_1 > 1/2)\, J_i(z_1, QR, \mu)$$





Fixed order $1/(n+1)$ at $\mathrm{N}^n\mathrm{LO}$

Consider only the leading parton if they are clustered into separate jets

Dasgupta, Dreyer, Salam, Soyez `14
Scott, Waalewijn `19
Neill, Ringer, Sato `21

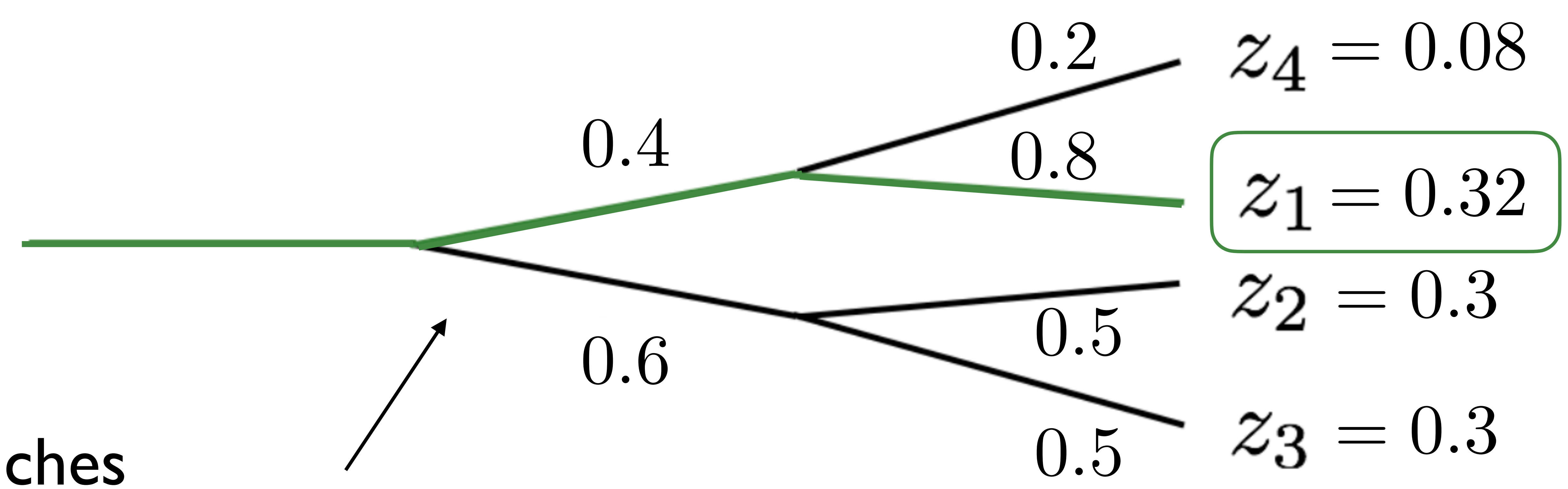
Leading jet cross sections

- **NLO** $\mathcal{J}_i(z_1, QR, \mu)$
- **QCD evolution**

Non-linear DGLAP-type evolution

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\mathcal{J}_i\left(z_{i1}, QR, \mu\right) = \frac{1}{2}\sum_{jk}\int \mathrm{d}z\,\mathrm{d}z_{j1}\mathrm{d}z_{k1}\frac{\alpha_s(\mu)}{\pi}P_{i\to jk}(z)\;\mathcal{J}_j\left(z_{j1}, QR, \mu\right)\;\mathcal{J}_k\left(z_{k1}, QR, \mu\right)$$

$$\times\,\delta\left(z_{i1} - \max\left\{z z_{j1}, (1-z)z_{k1}\right\}\right)$$



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

Dasgupta, Dreyer, Salam, Soyez `14
Scott, Waalewijn `19
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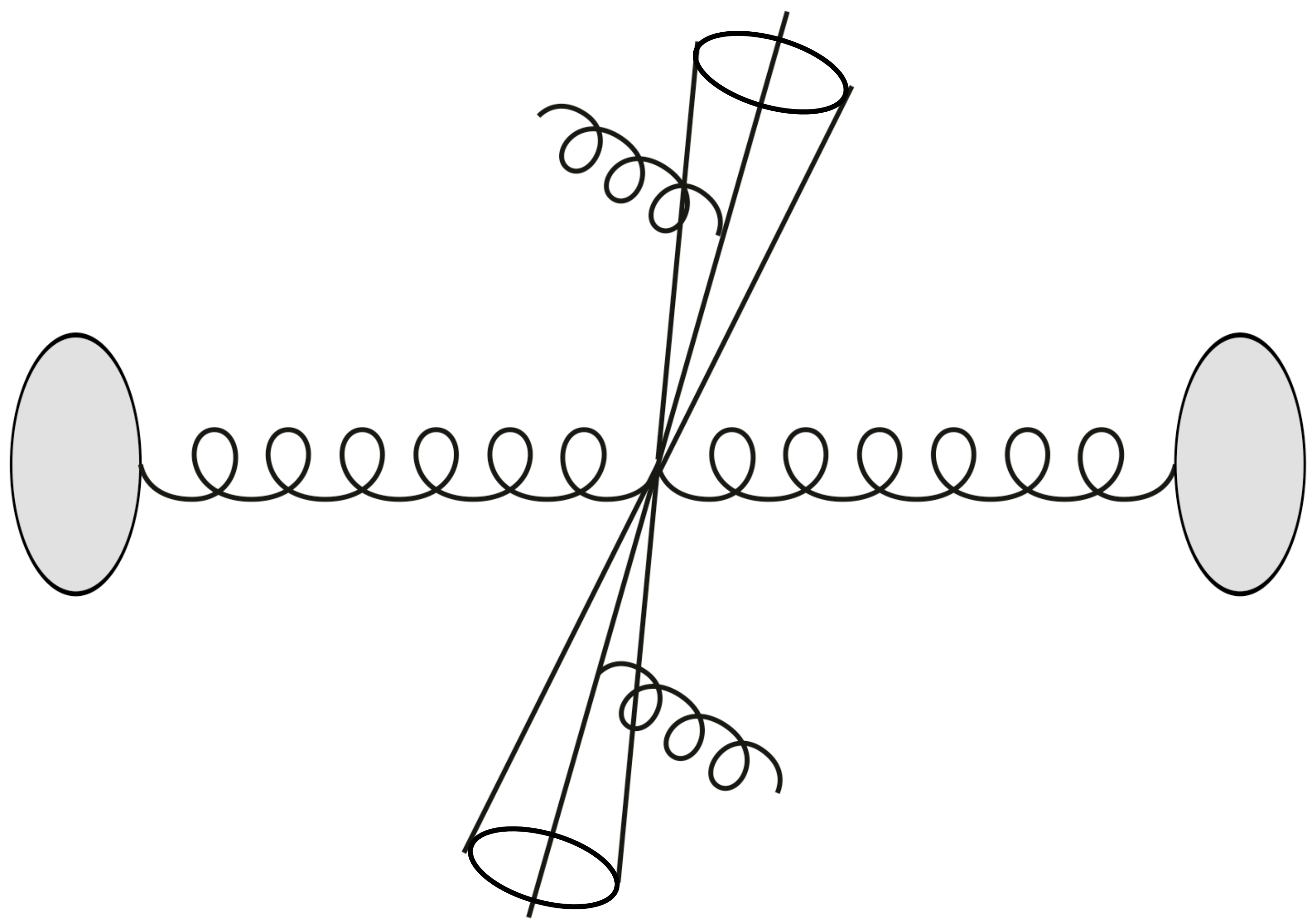
Leading jet cross sections

- **NLO** $\mathcal{J}_i(z_1, QR, \mu)$
- **QCD evolution**
- **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

Here LO + LL' accuracy

- Factorization structure depends on the perturbative accuracy
- Similar for subleading jets

Dasgupta, Dreyer, Salam, Soyez `14
Scott, Waalewijn `19
Neill, Ringer, Sato `21

Inclusive vs. leading jets

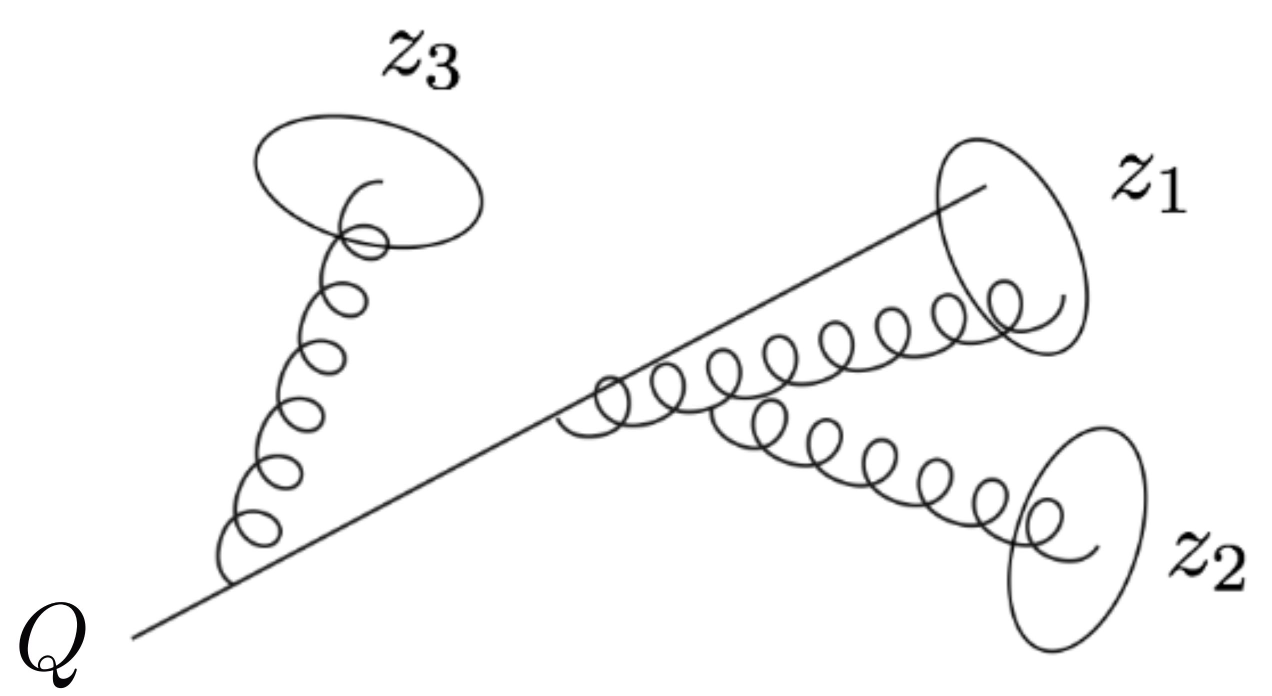
- Jet function - number densities

$$\int_0^1 \mathrm{d}z\, J_i(z, QR, \mu) = \langle N_{i,\mathrm{jets}} \rangle$$

- Momentum conservation

$$\int_0^1 \mathrm{d}z\, z\, J_i(z, QR, \mu) = 1$$

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



Inclusive vs. leading jets

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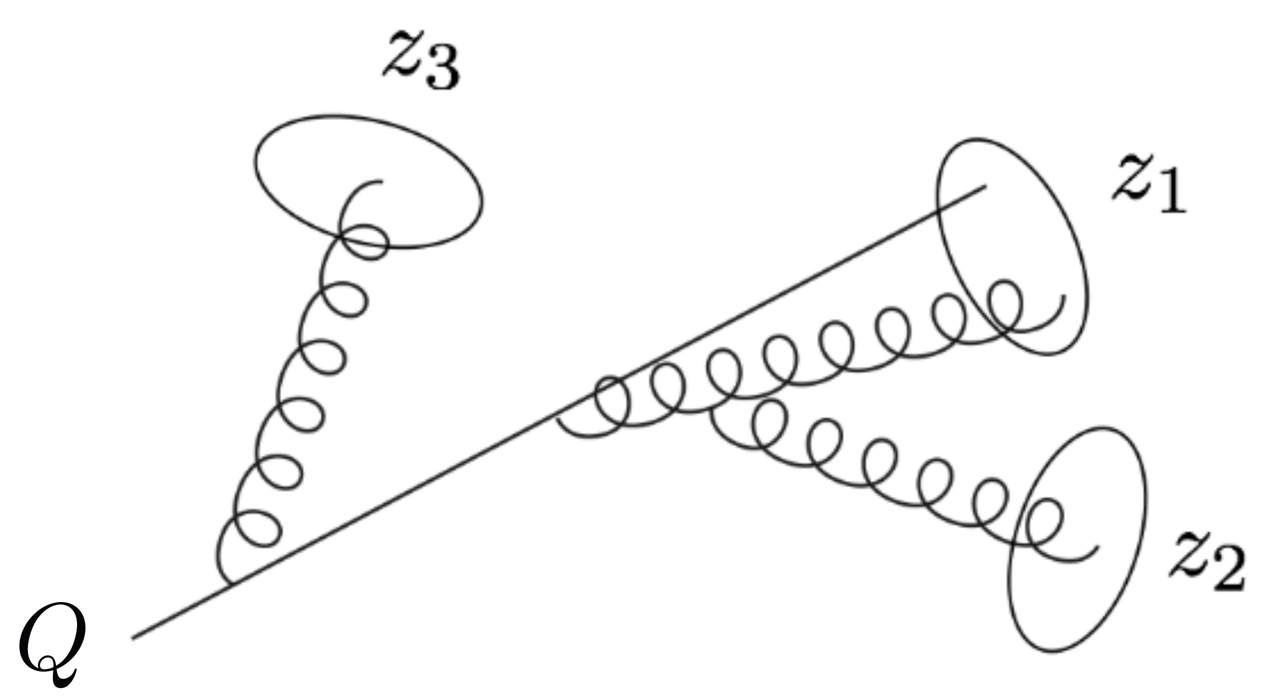

- Jet function - probability densities

1. Normalized $\int_0^1 \mathrm{d}z_1 \mathcal{J}_i\,(z_1, QR, \mu) = 1$
2. Positive $\mathcal{J}_i\,(z_1, QR, \mu) > 0$

requires threshold resummation

Inclusive vs. leading jets

- Jet function - number densities

$$\int_0^1 \mathrm{d}z\, J_i(z, QR, \mu) = \langle N_{i,\mathrm{jets}} \rangle$$

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$$\int_0^1 \mathrm{d}z\, z\, J_i(z, QR, \mu) = 1$$

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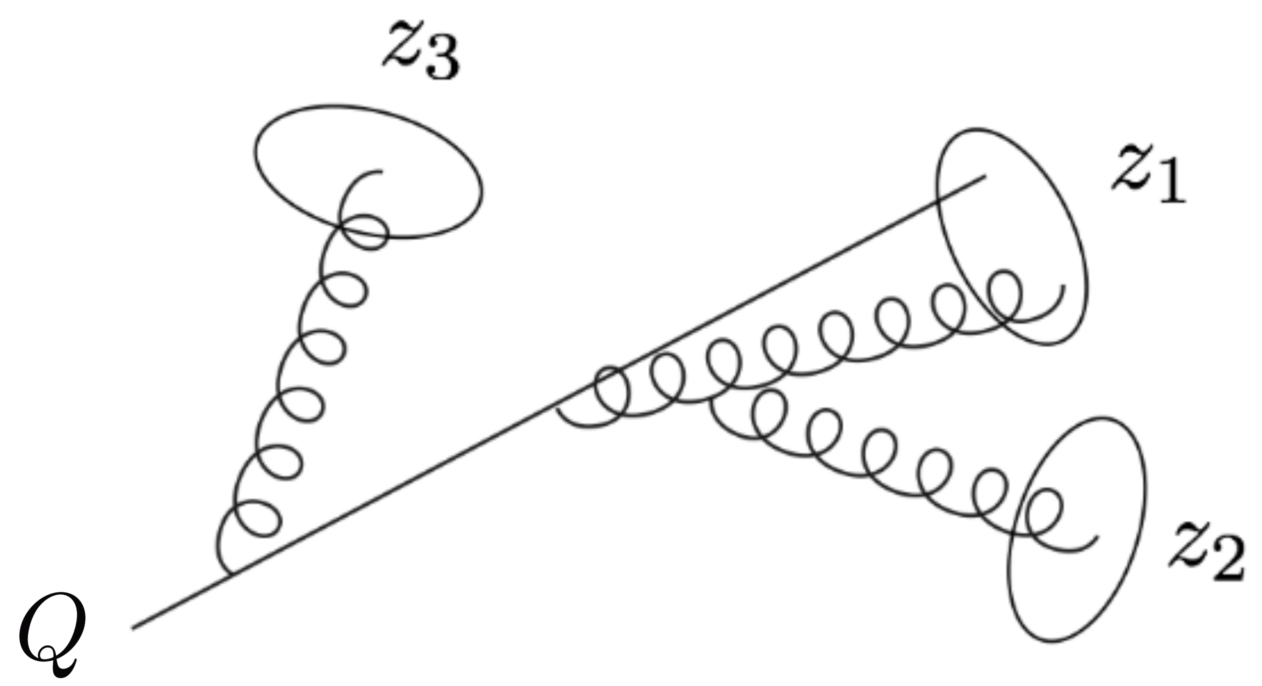

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requires threshold resummation

- Average energy loss

$$\int_0^1 \mathrm{d}z_1 z_1 \mathcal{J}_i\,(z_1, QR, \mu) = \langle z_1 \rangle$$

$$= 1 - \langle z_{\mathrm{loss}} \rangle$$

Threshold resummation

- Jet function

$$J_q(z,QR,\mu) = \delta(1-z) + \frac{\alpha_s}{2\pi}\left(\ln\left(\frac{\mu^2}{Q^2R^2}\right) - 2\ln z\right)[P_{qq}(z)+P_{gq}(z)]$$

$$-\frac{\alpha_s}{2\pi}4C_F\left(\frac{\ln(1-z)}{1-z}\right)_+ \quad + \ldots$$

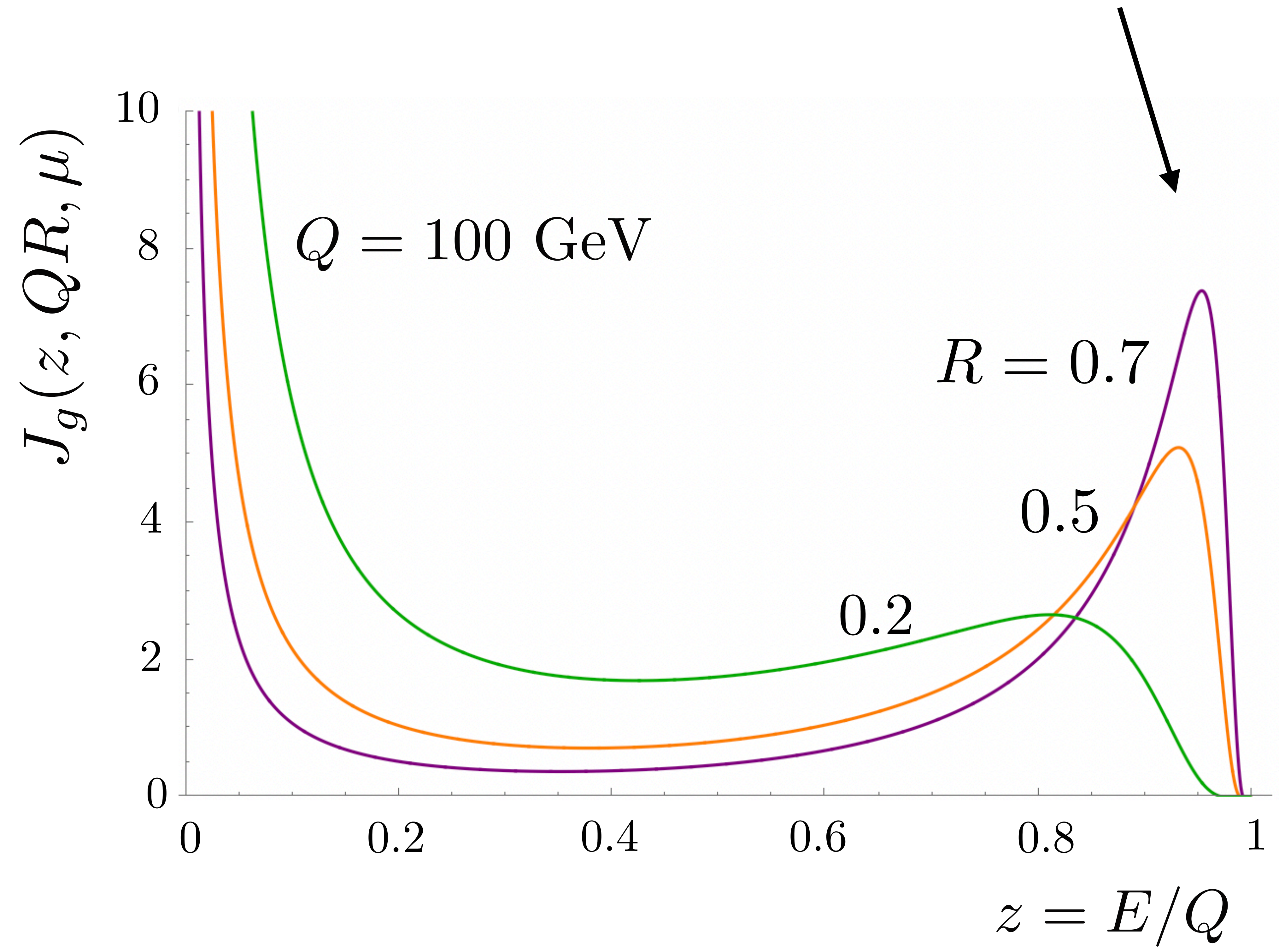
- Additional threshold logarithms in the hard function $H_i \otimes J_i$

- Requires joint resummation $\alpha_s^n \ln^n R,\ \ \alpha_s^n \ln^{2n}(1-z)$

Sterman `86, Catani,Trentadue `89
Dai, Kim, Leibovich `17
Liu, Moch, Ringer `17, `18
Neill, Ringer, Sato `21

- Without threshold resummation:

Divergent and can be negative depending on the value of R

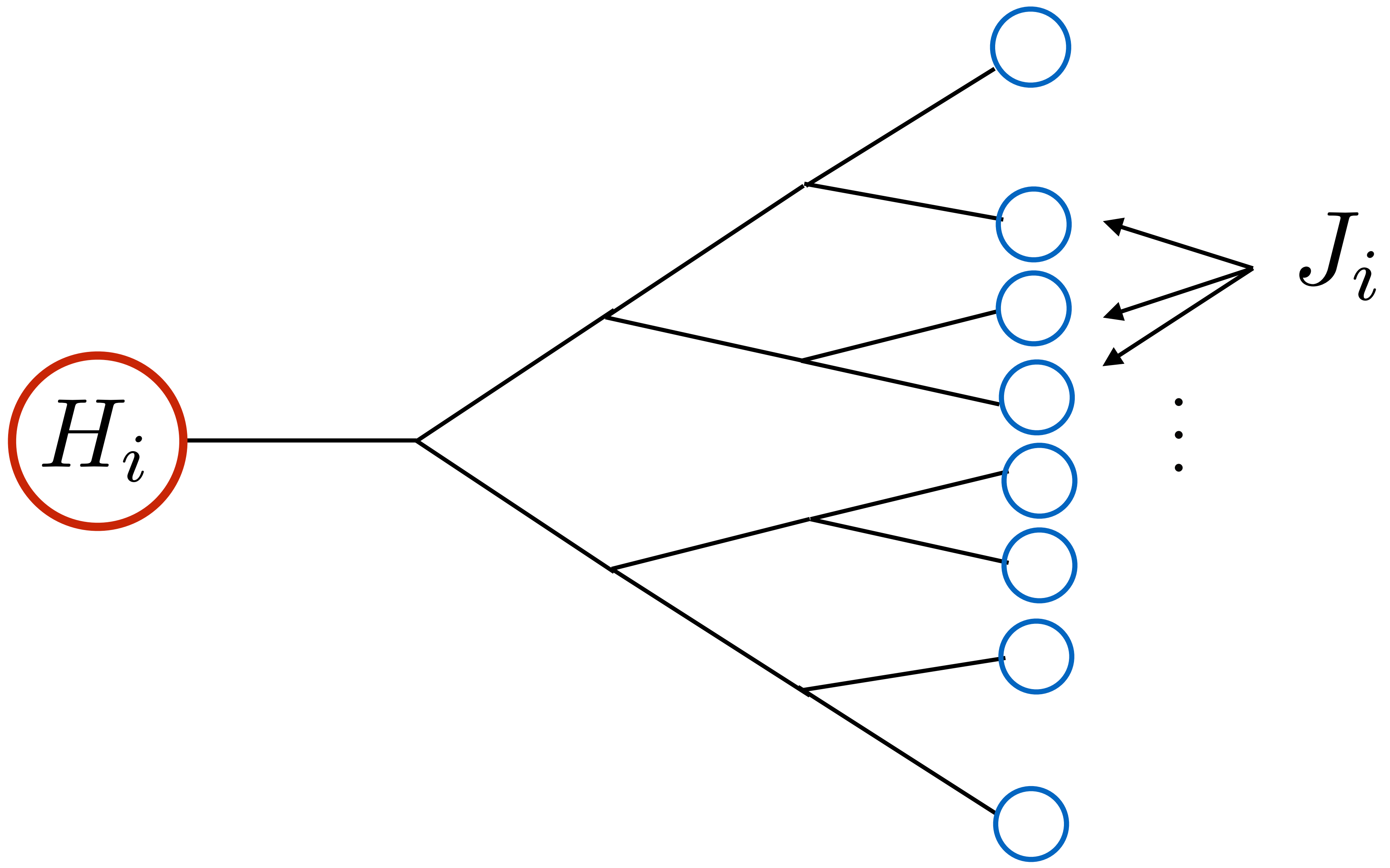


Parton shower

Neill, Ringer, Sato `21

- Use a parton shower to solve the non-linear evolution equations for leading jets

1. Set up a DGLAP parton shower
2. Include (threshold) resummed jet & hard functions
3. Measure leading jets at the end



- Not a multi-purpose parton shower <u>but</u> we can achieve full agreement with analytical calculations for inclusive jets

$\longrightarrow$ parton shower provides a systematic extension to leading jets

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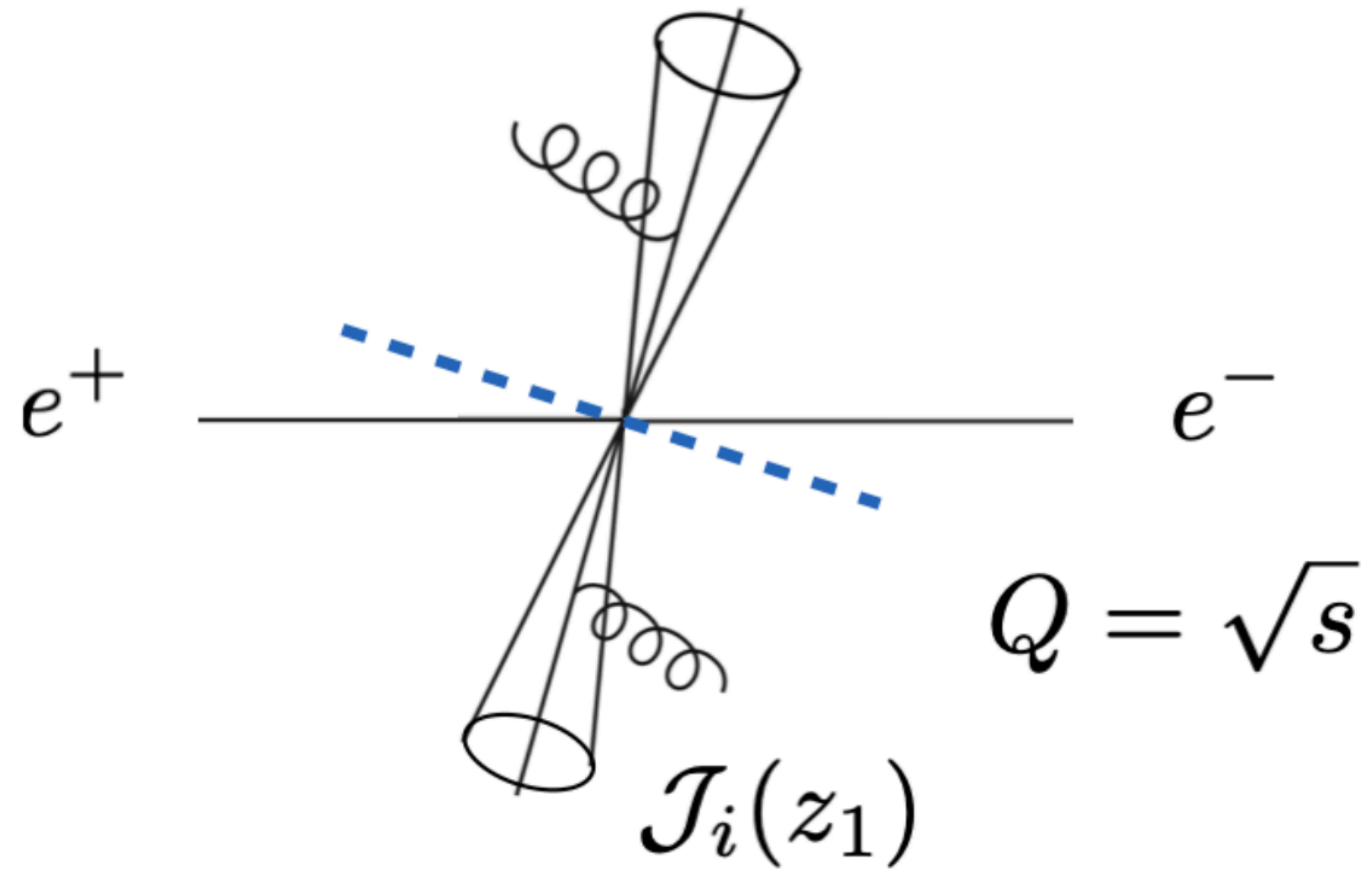
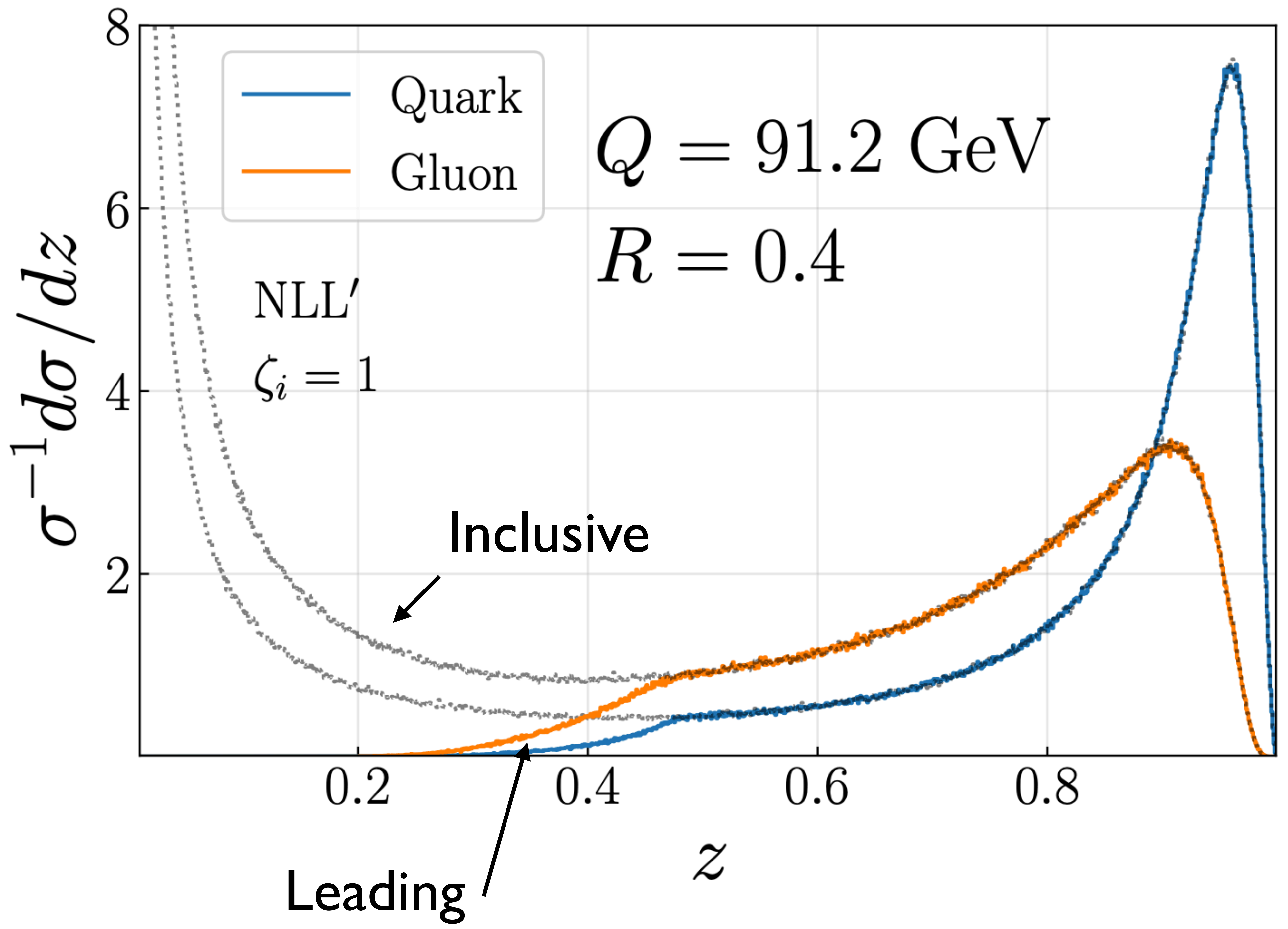
Leading jets in e⁺e⁻ collisions

- Hemisphere jets





Jet energy loss

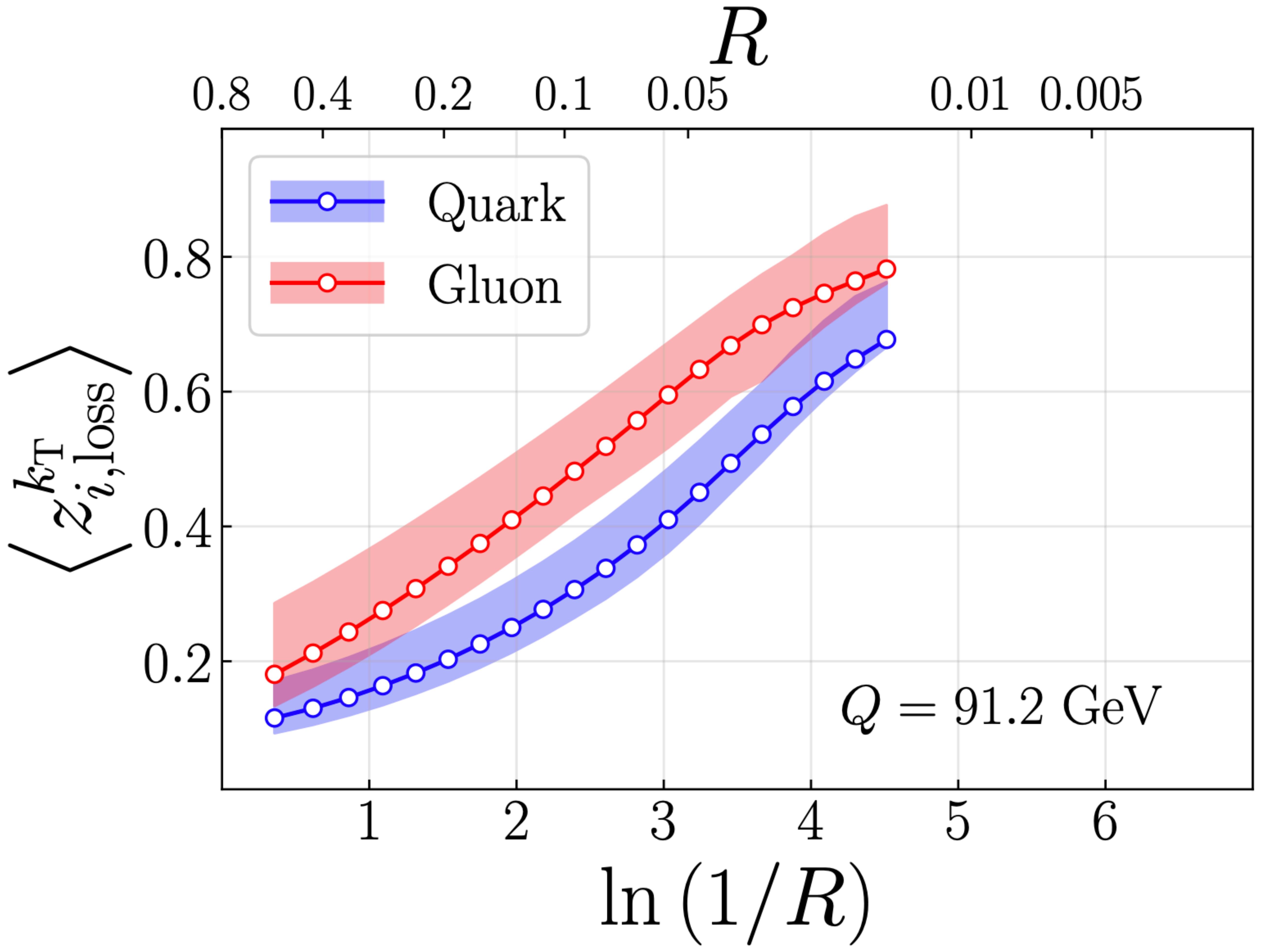
- Average leading jet energy

$$\int_0^1 \mathrm{d}z_1\, z_1 \frac{1}{\sigma_{\mathrm{tot}}} \frac{\mathrm{d}\sigma_{e^+e^-\to \mathrm{jet}_1+X}}{\mathrm{d}z_1} = \langle z_1 \rangle$$

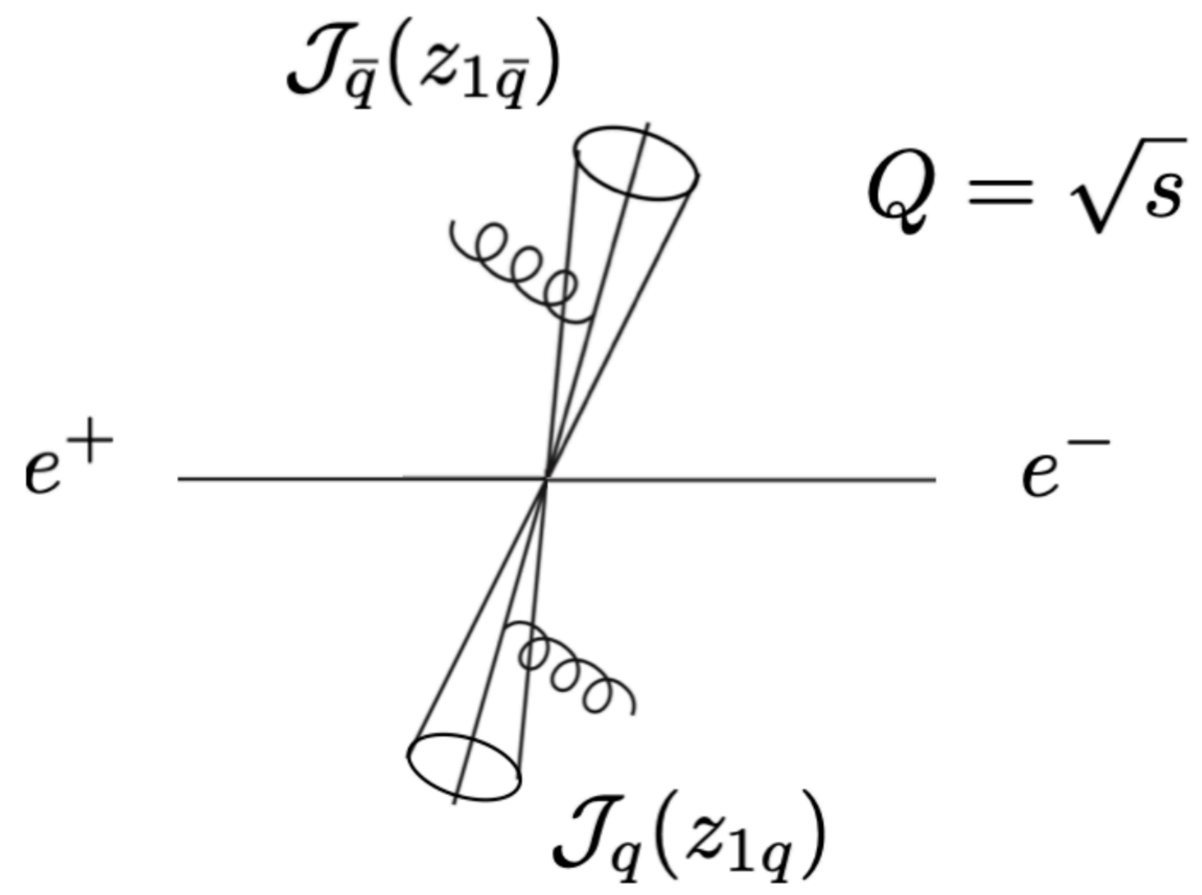
- Average energy loss

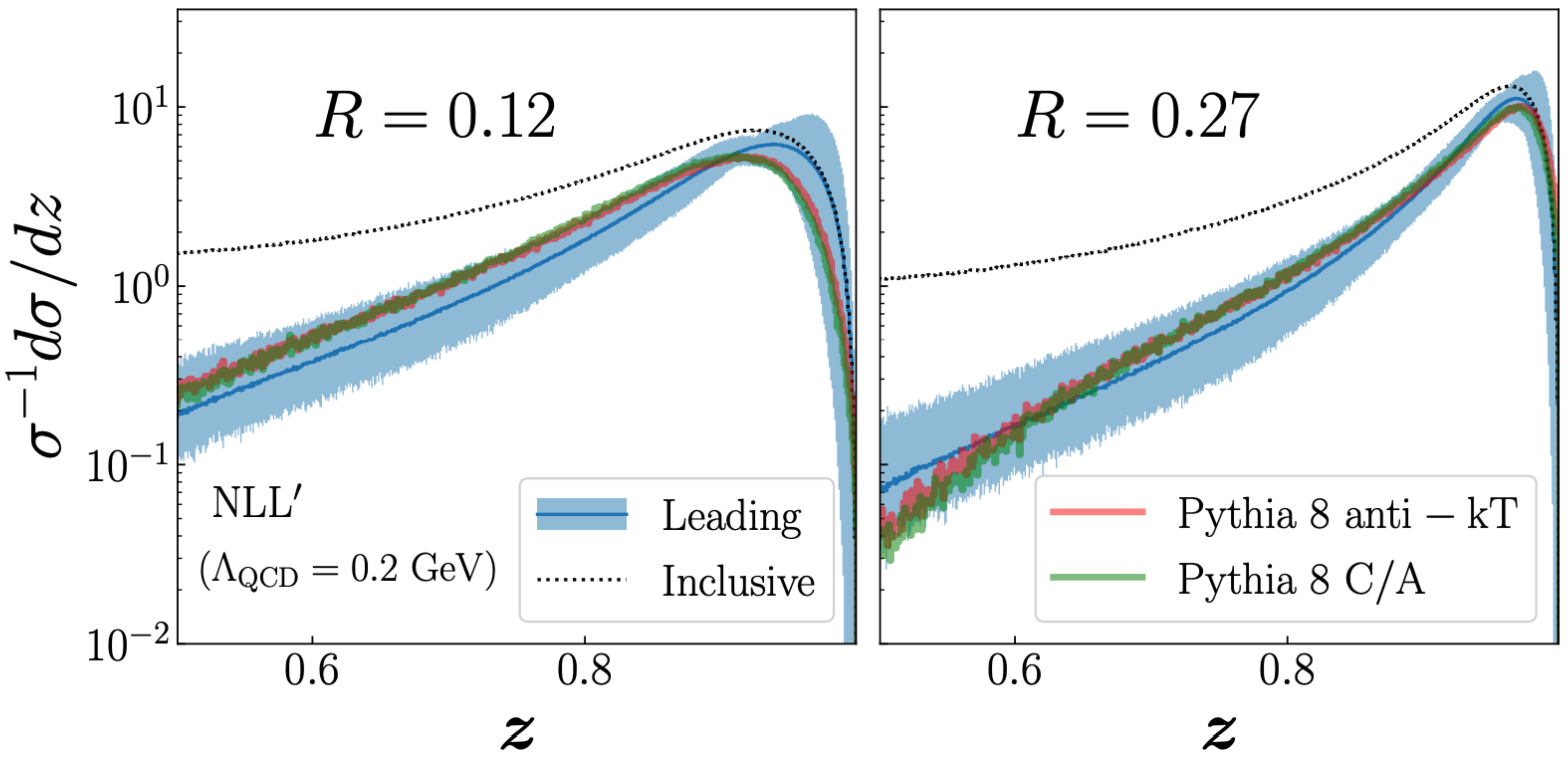
$$\langle z_{\mathrm{loss}} \rangle = 1 - \langle z_1 \rangle$$

- Mean, variance, KL divergence …



Event-wide leading jets in e⁺e⁻ collisions





- Existing measurements from OPAL

Outline

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Further applications

- Jet substructure observables
- Quark/gluon tagging
- Statistical quantities like the variance, KL divergence
- Di/tri-jet observables
- Leading and subleading hadrons
- Starting point for eA/AA energy loss
- First results will come out soon from ALICE
- EIC is ideally suited for energy loss measurements