Leading jet cross sections and comparison to experimental data

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Jet physics: From RHIC/LHC to EIC
CFNS, Stony Brook University, 06/30/21

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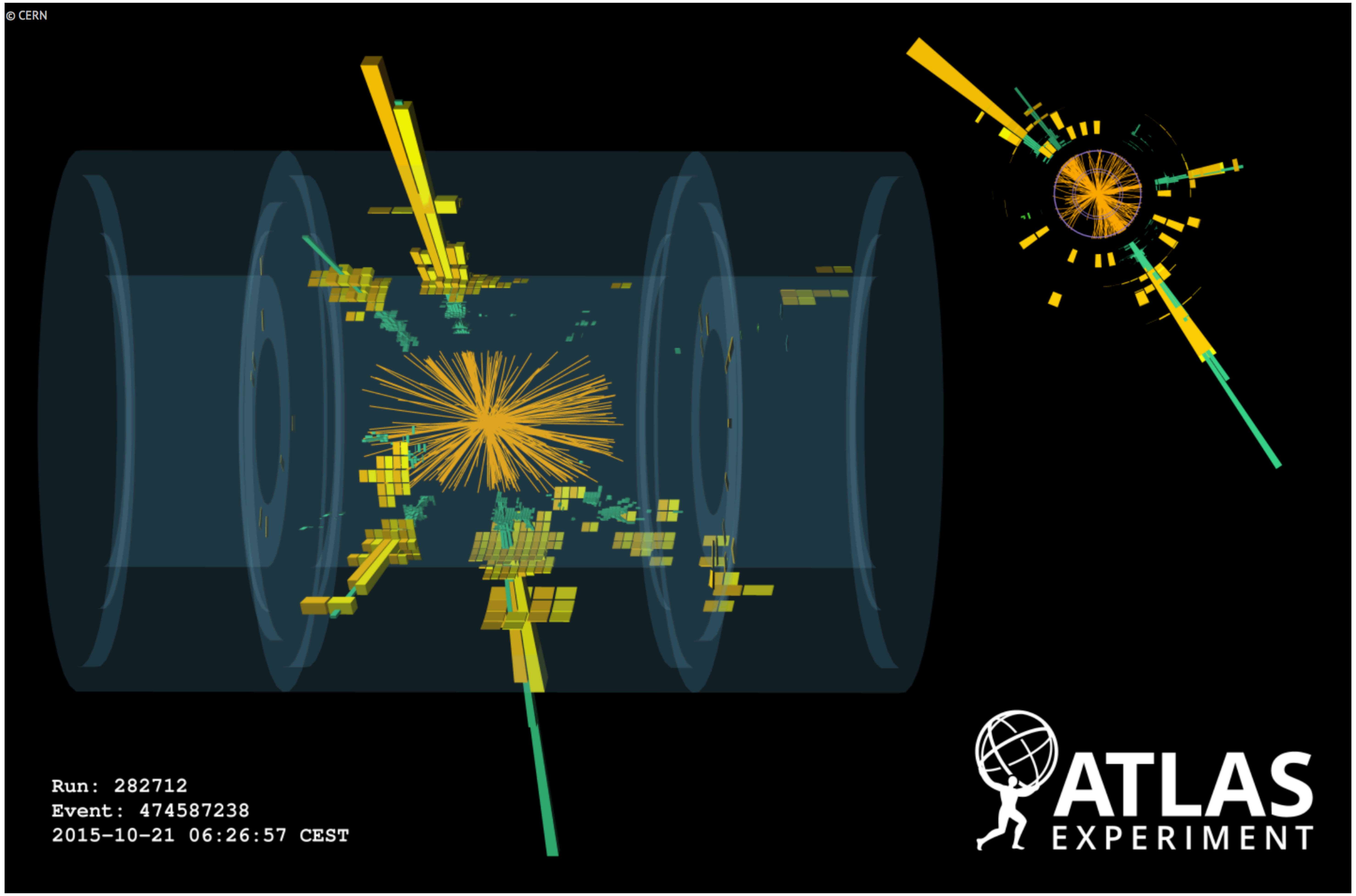
Jefferson Lab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Run: 282712
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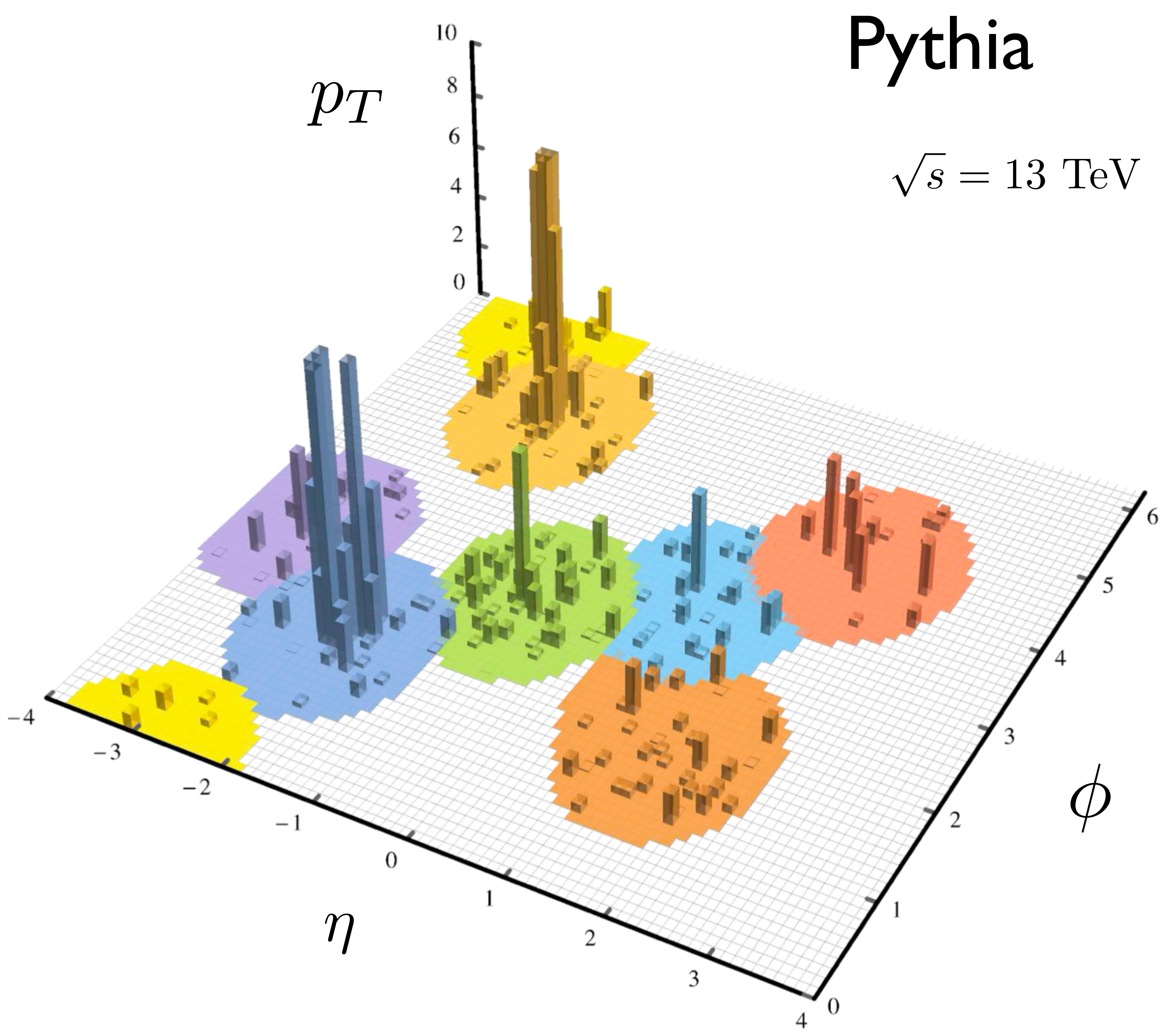
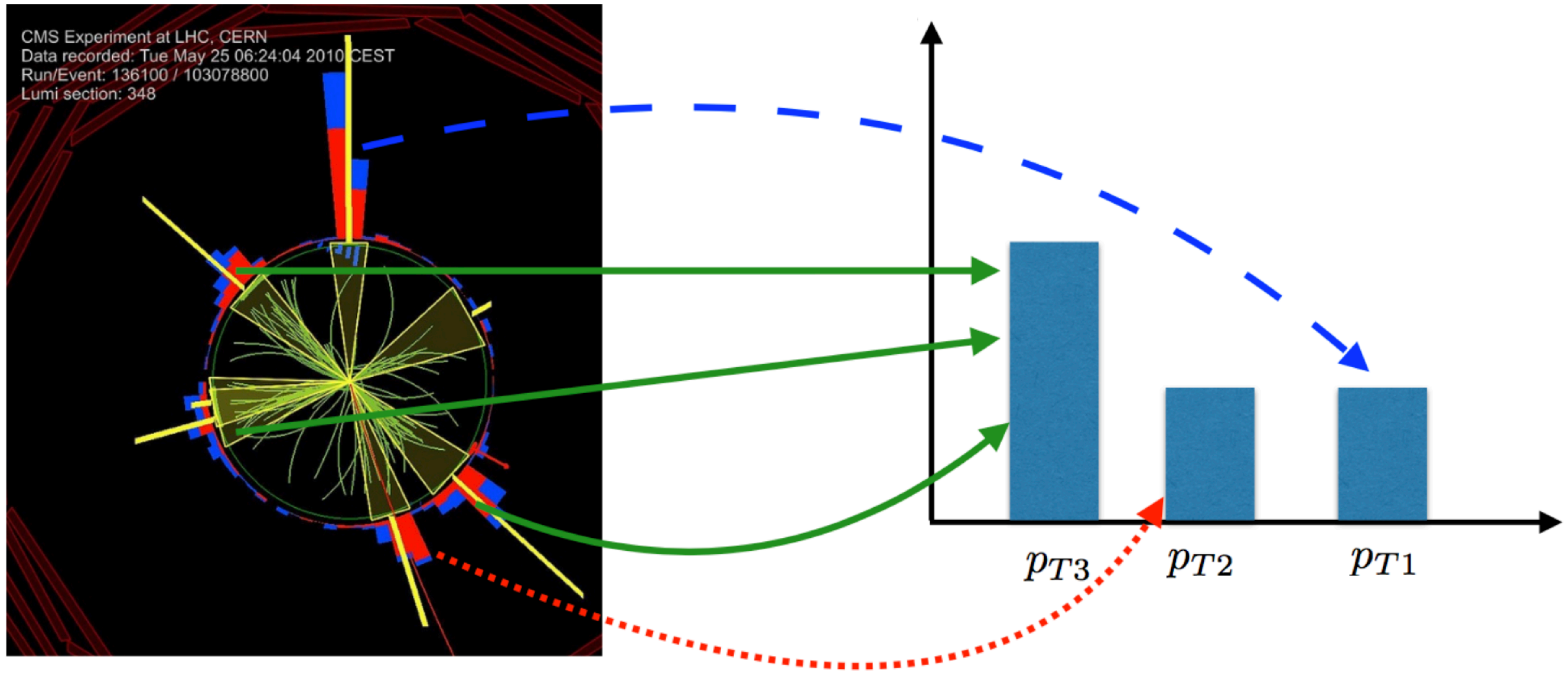
2015-10-21 06:26:57 CEST
ATLAS
EXPERIMENT


Pythia
p_T
$\sqrt{s} = 13$ TeV
η
ϕ

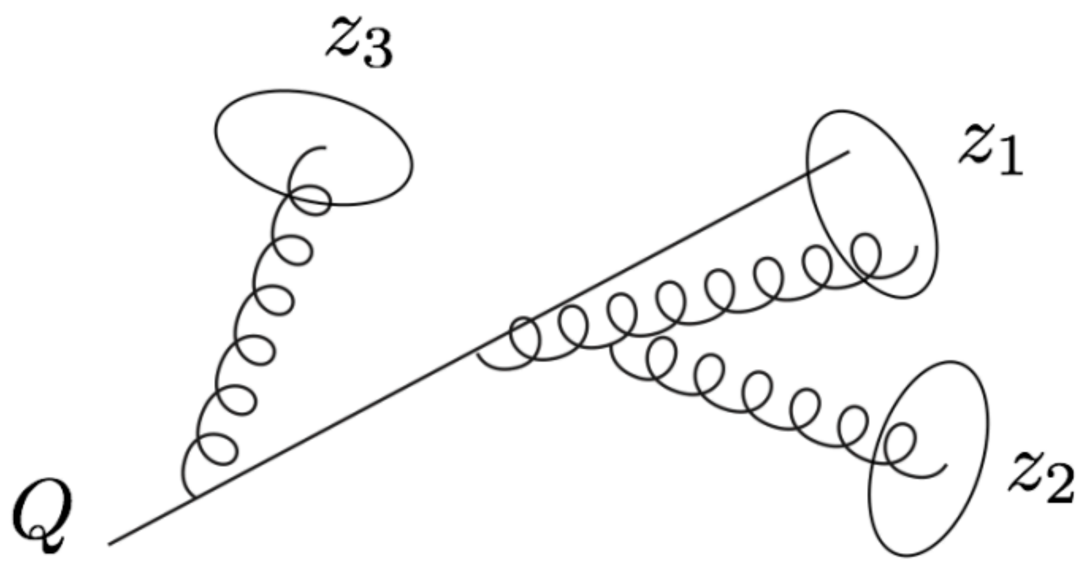
Inclusive vs. leading jets

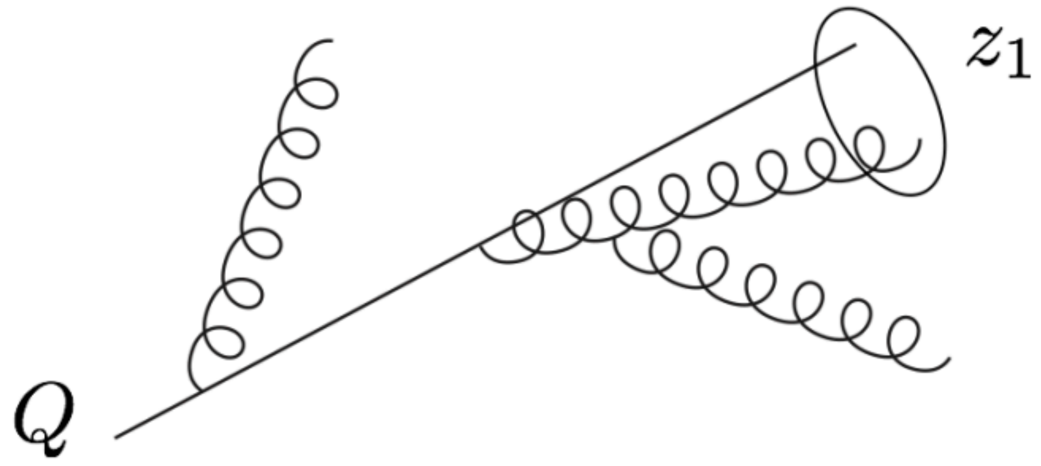
- Inclusive jets



- Leading jets - only one per event

  (in a given η bin)



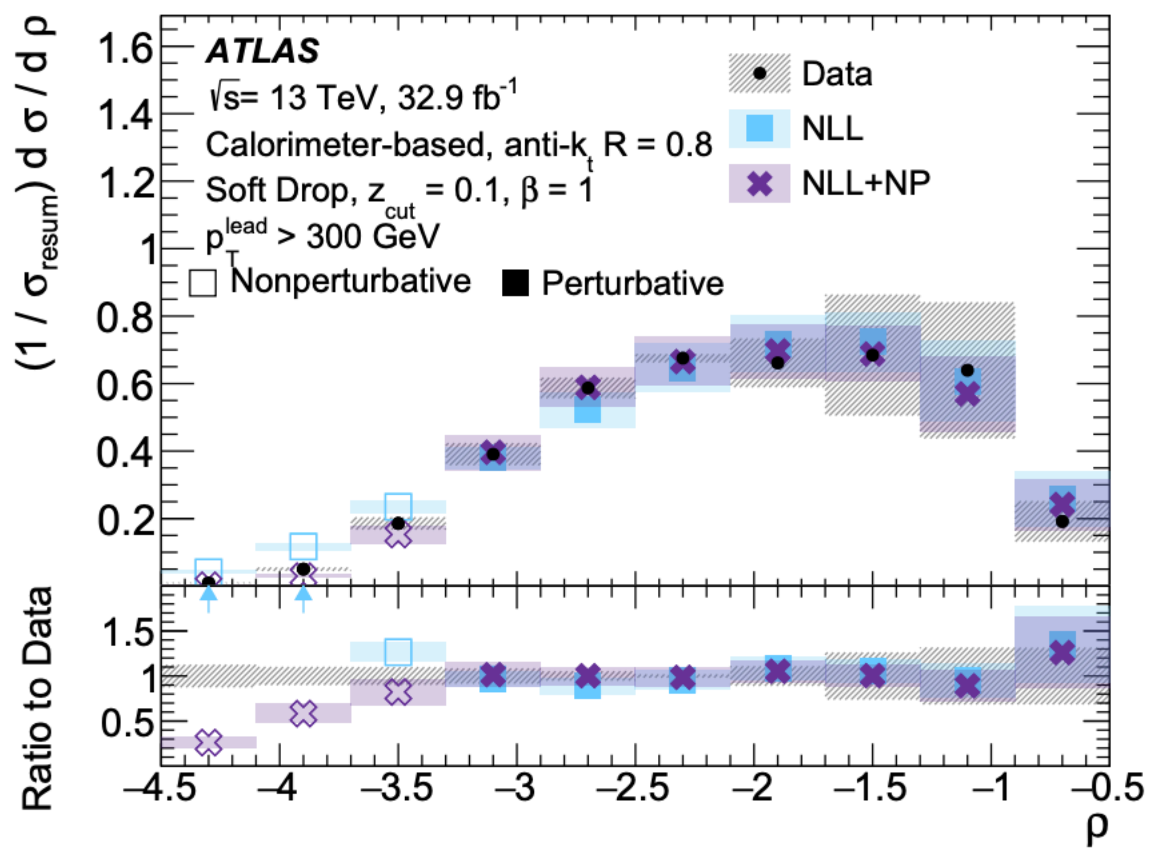


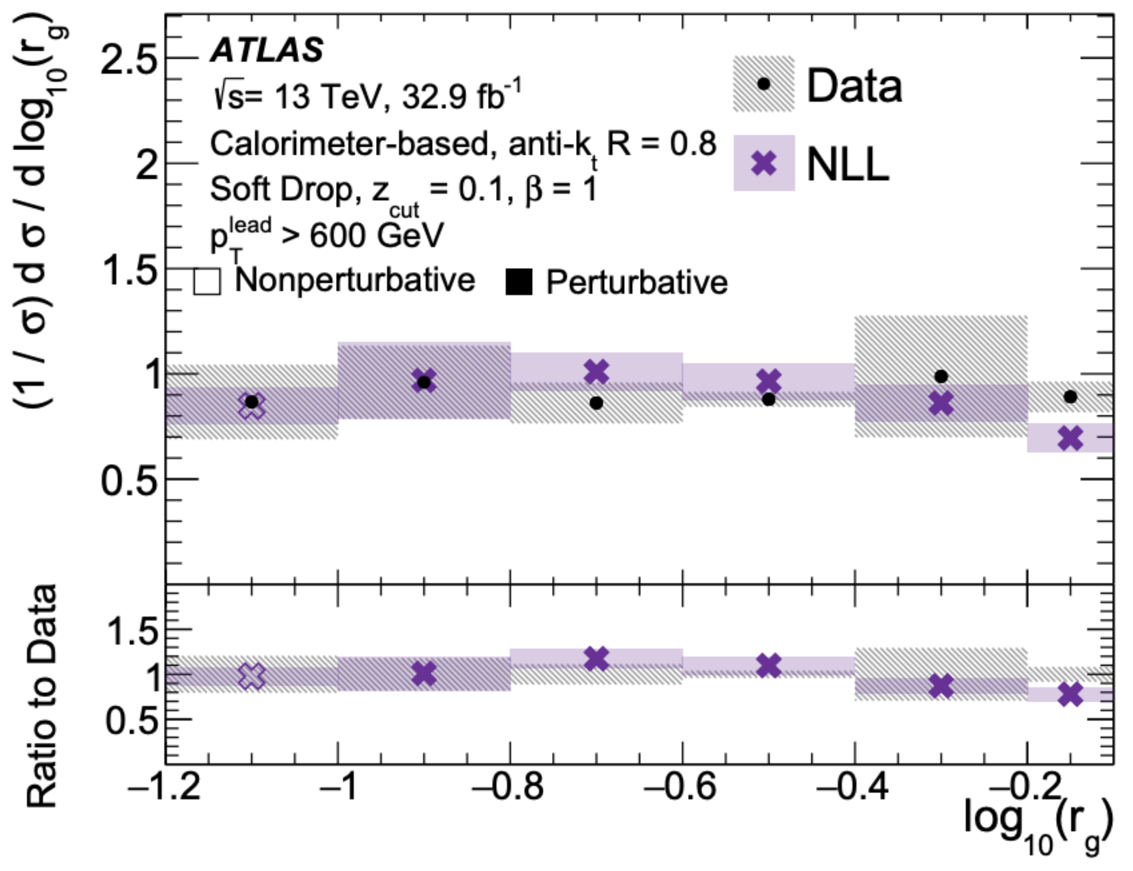
Leading jets

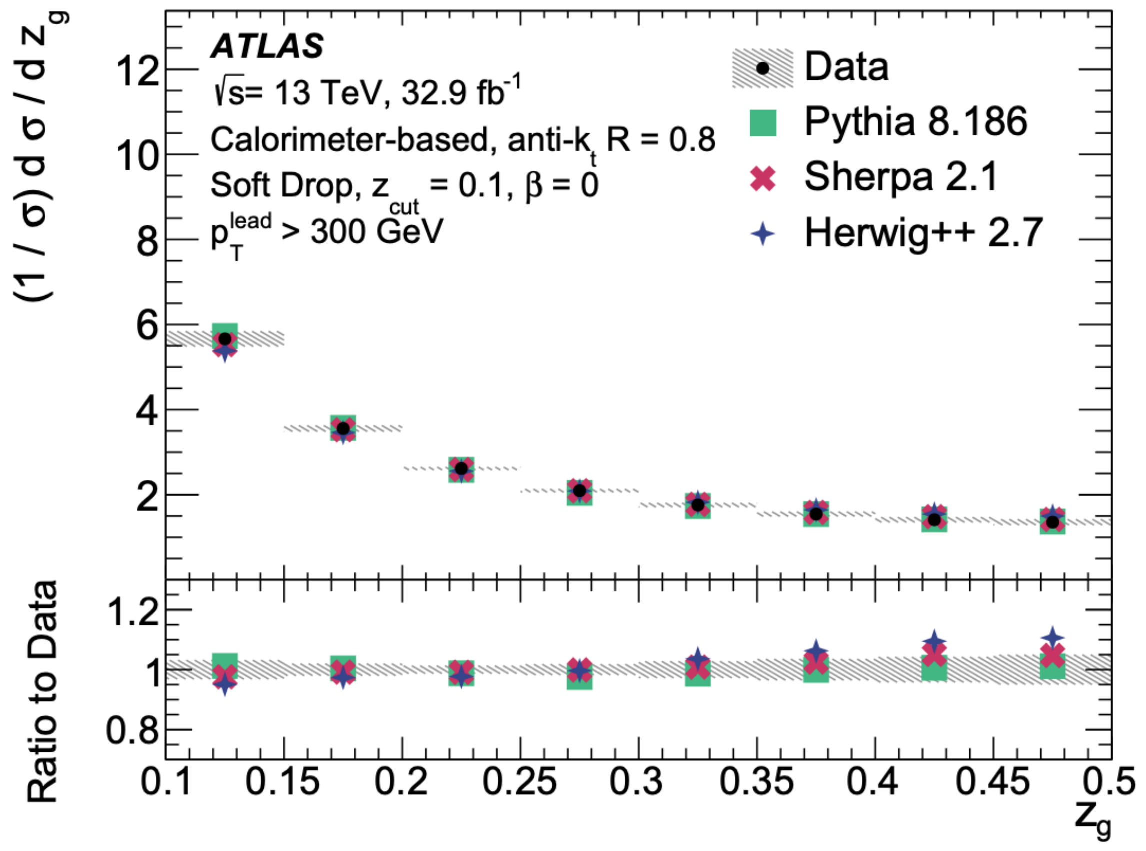
- Jet substructure measurements - pp

  Precision calculation of quark/gluon fractions

ATLAS, PRD 101 (2020) 052007







Leading jets

- Jet substructure measurements - pp

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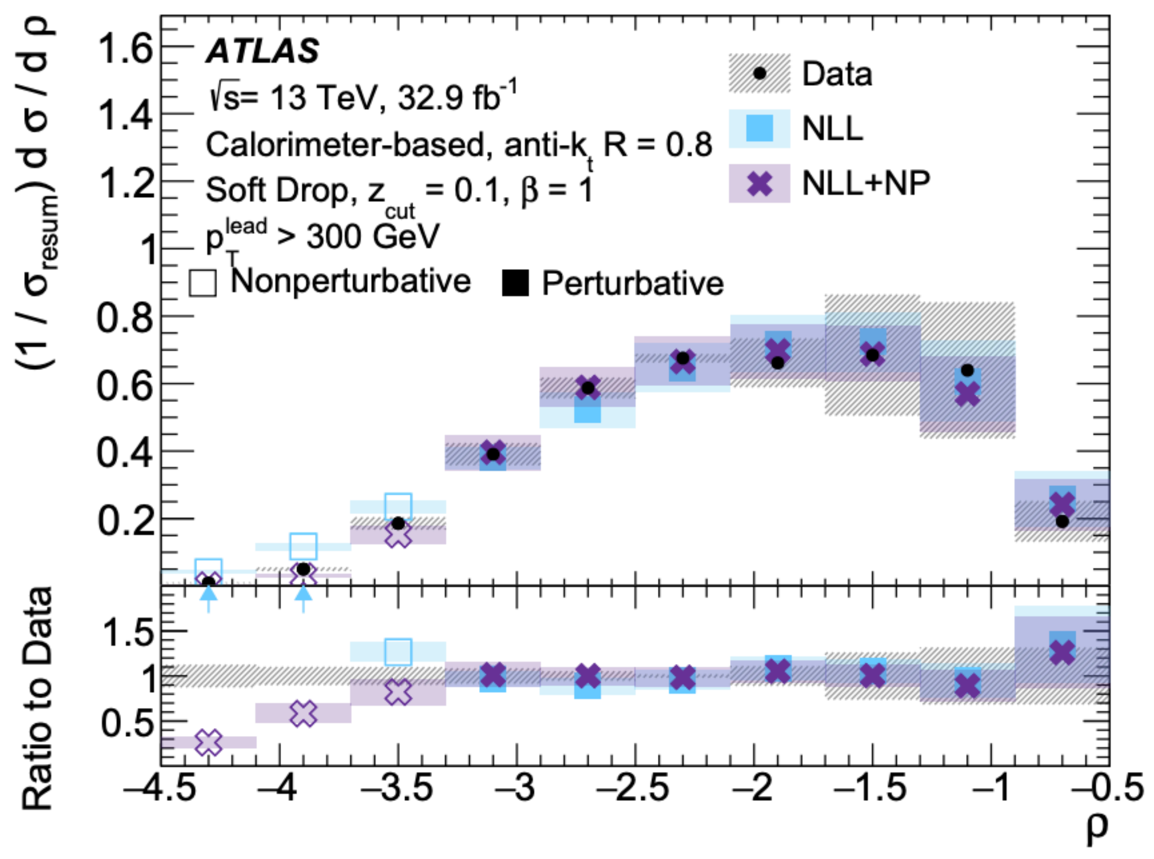
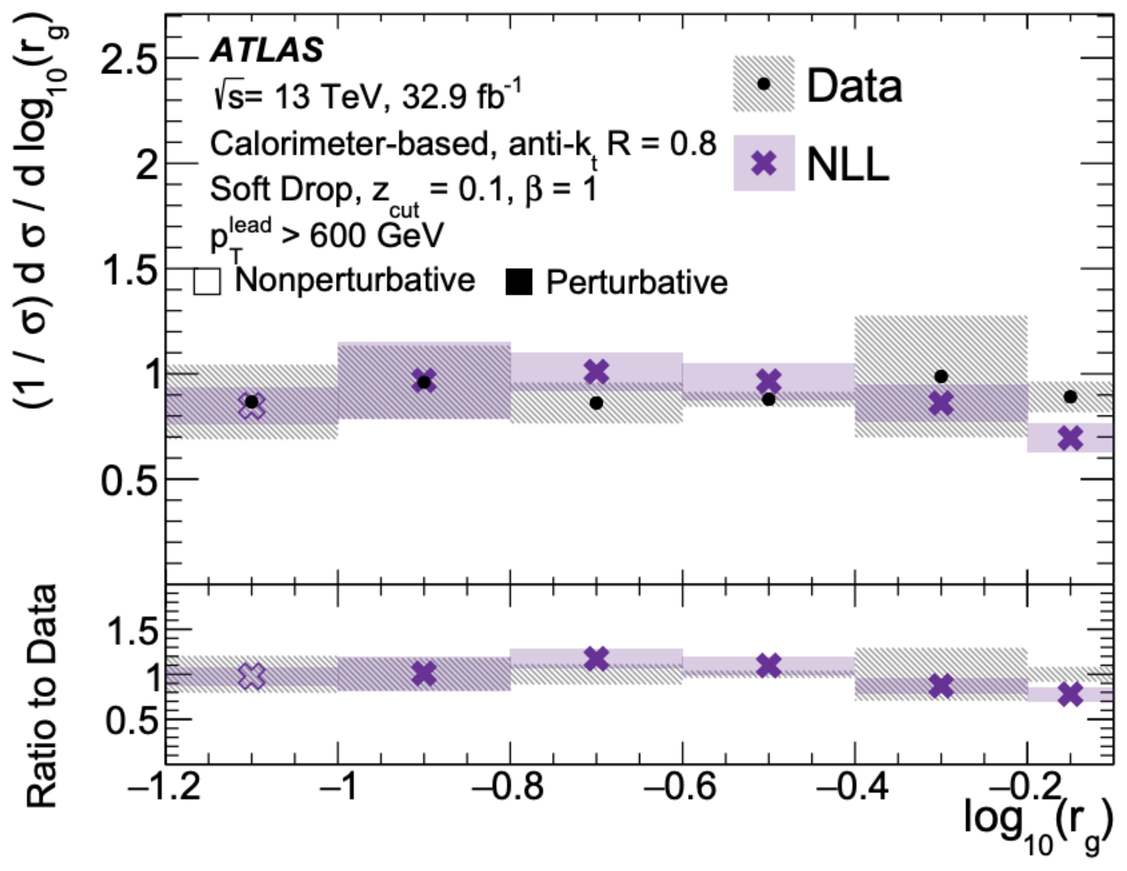
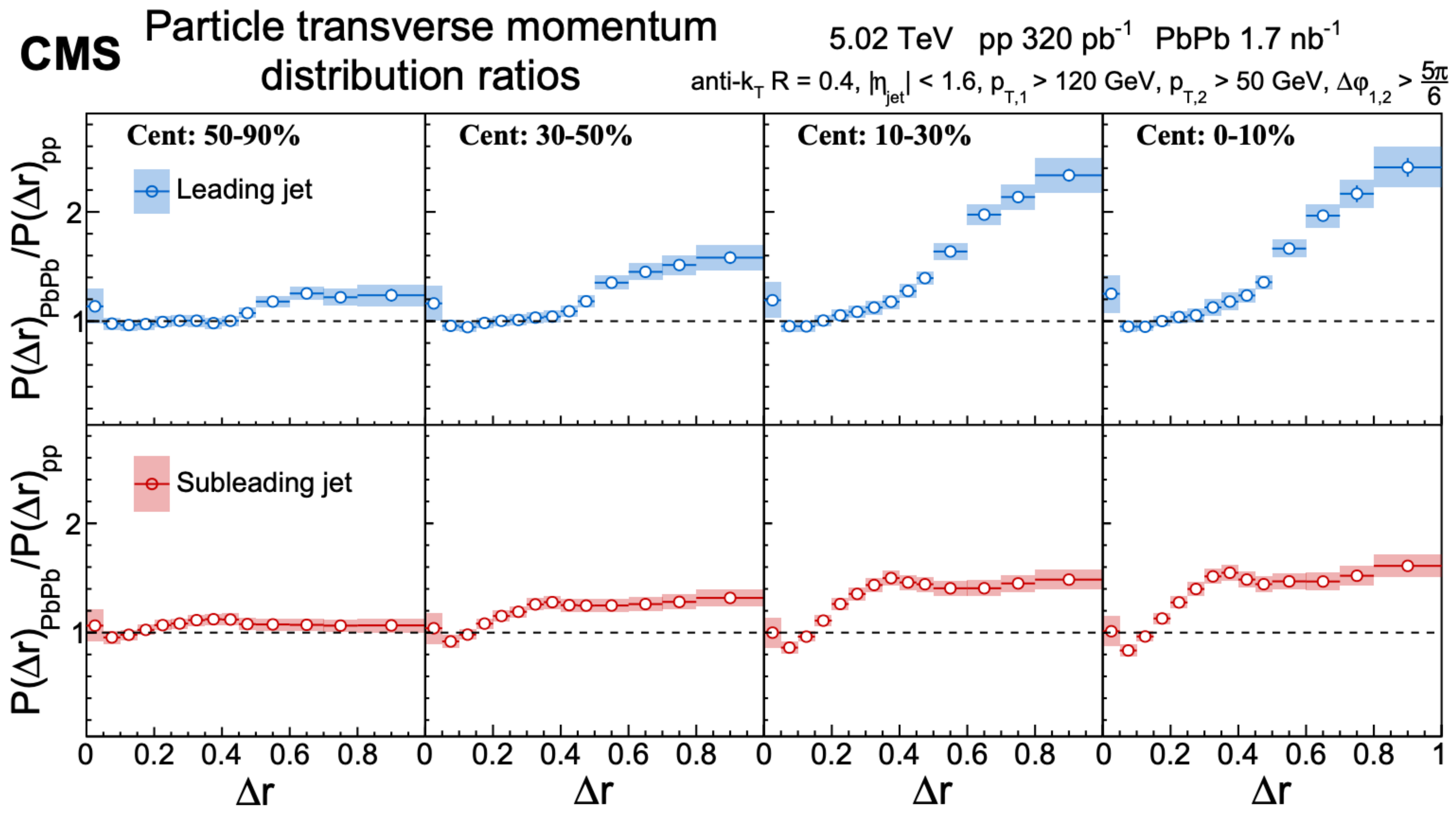
  ATLAS, PRD 101 (2020) 052007





- Jet substructure measurements - AA

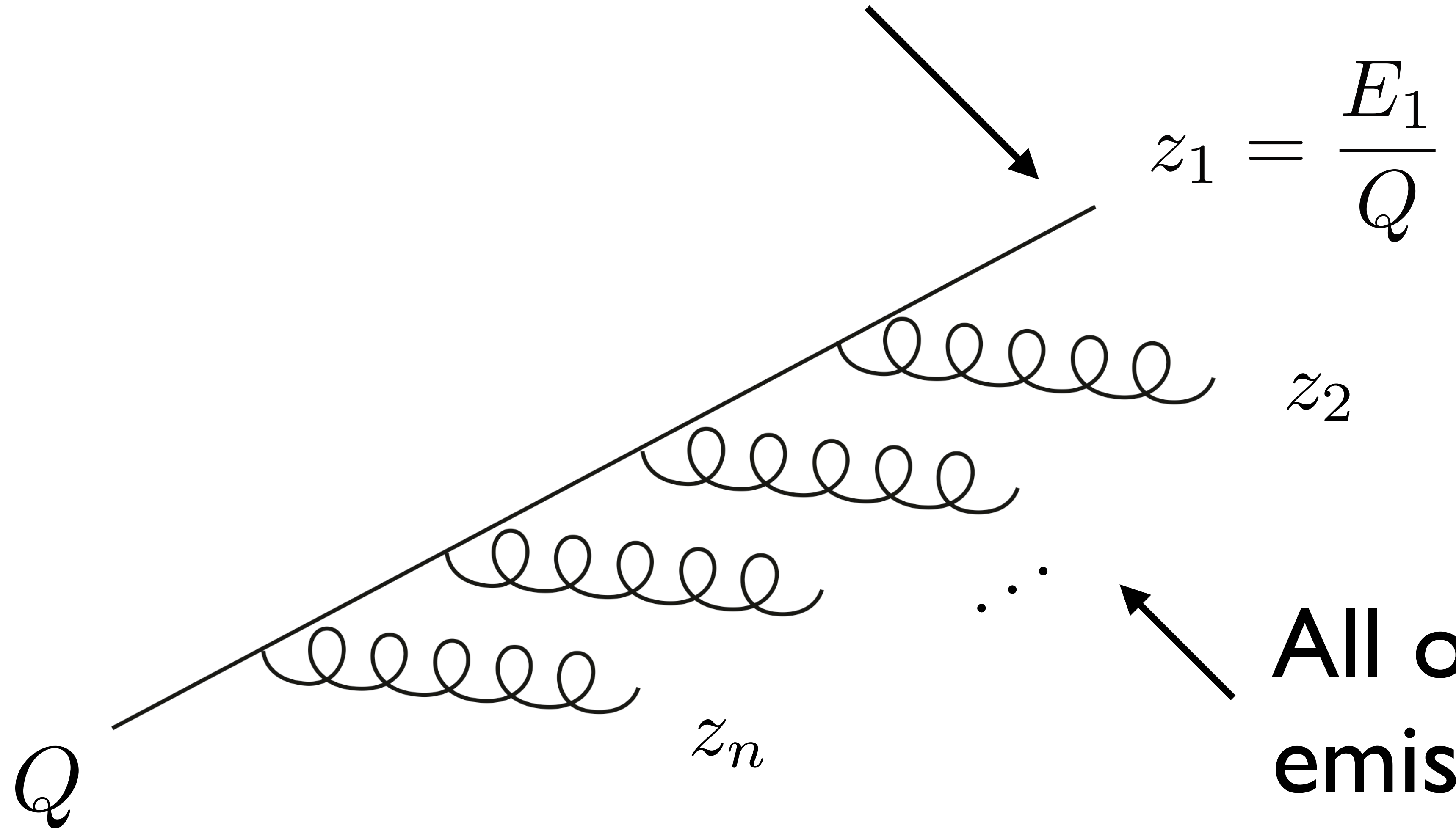
  CMS, 2101.04720



Leading jets & energy loss

- Soft & collinear limit

Most energetic/leading parton



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

Energy loss

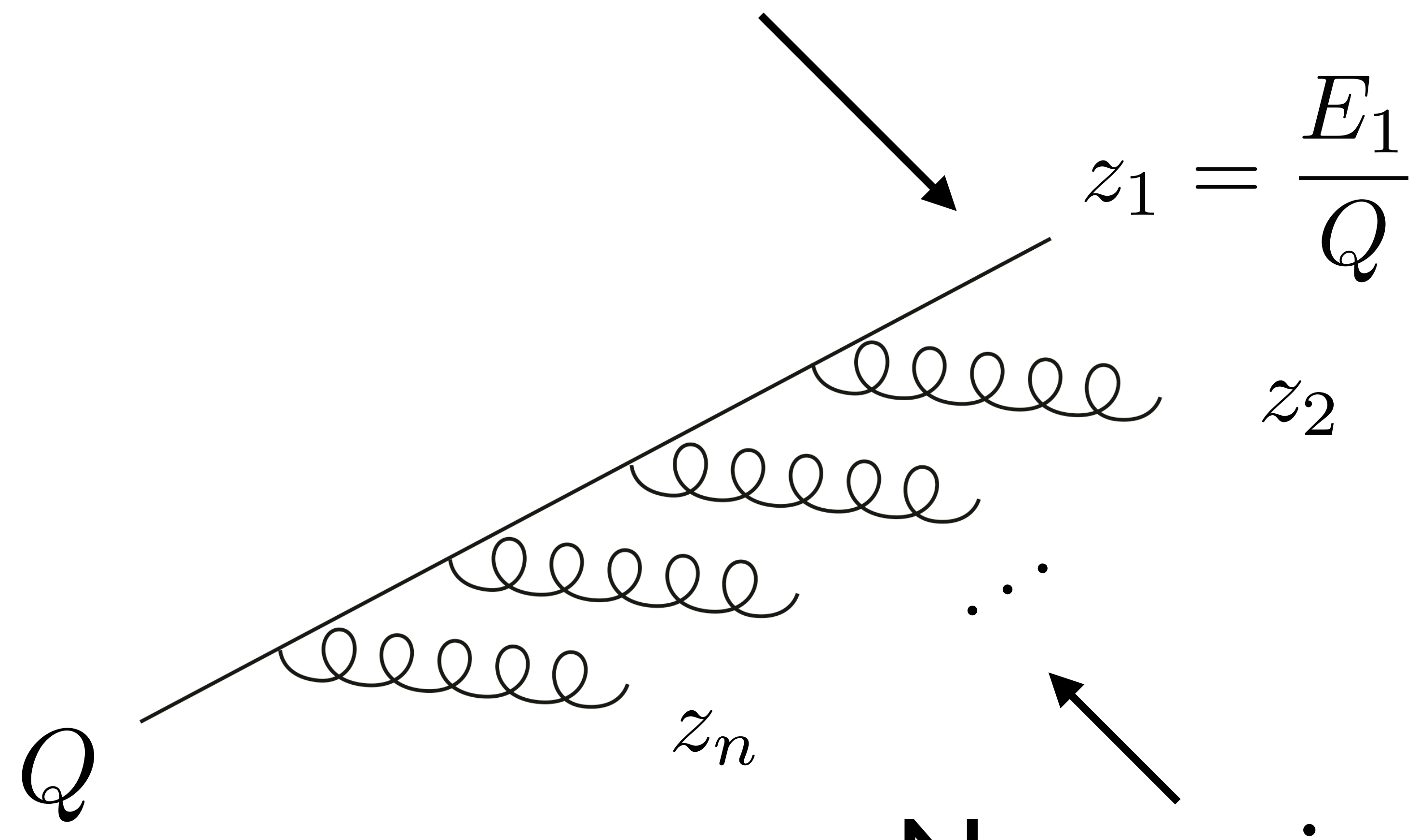
$$z_{\rm loss} = \sum_{i\geq 2} z_i$$
$$= 1 - z_1$$

- 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*

Leading jets & energy loss

- 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

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

- This talk — vacuum energy loss

Outline

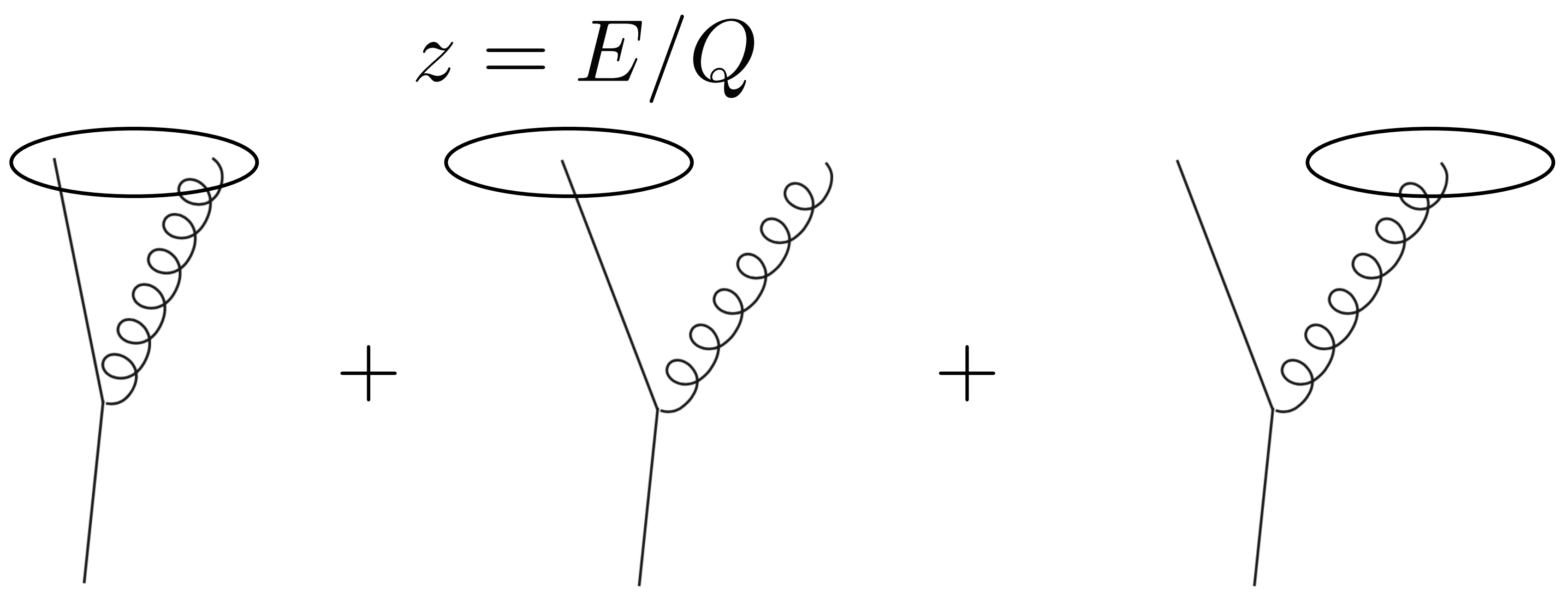
Introduction

Inclusive and leading jets

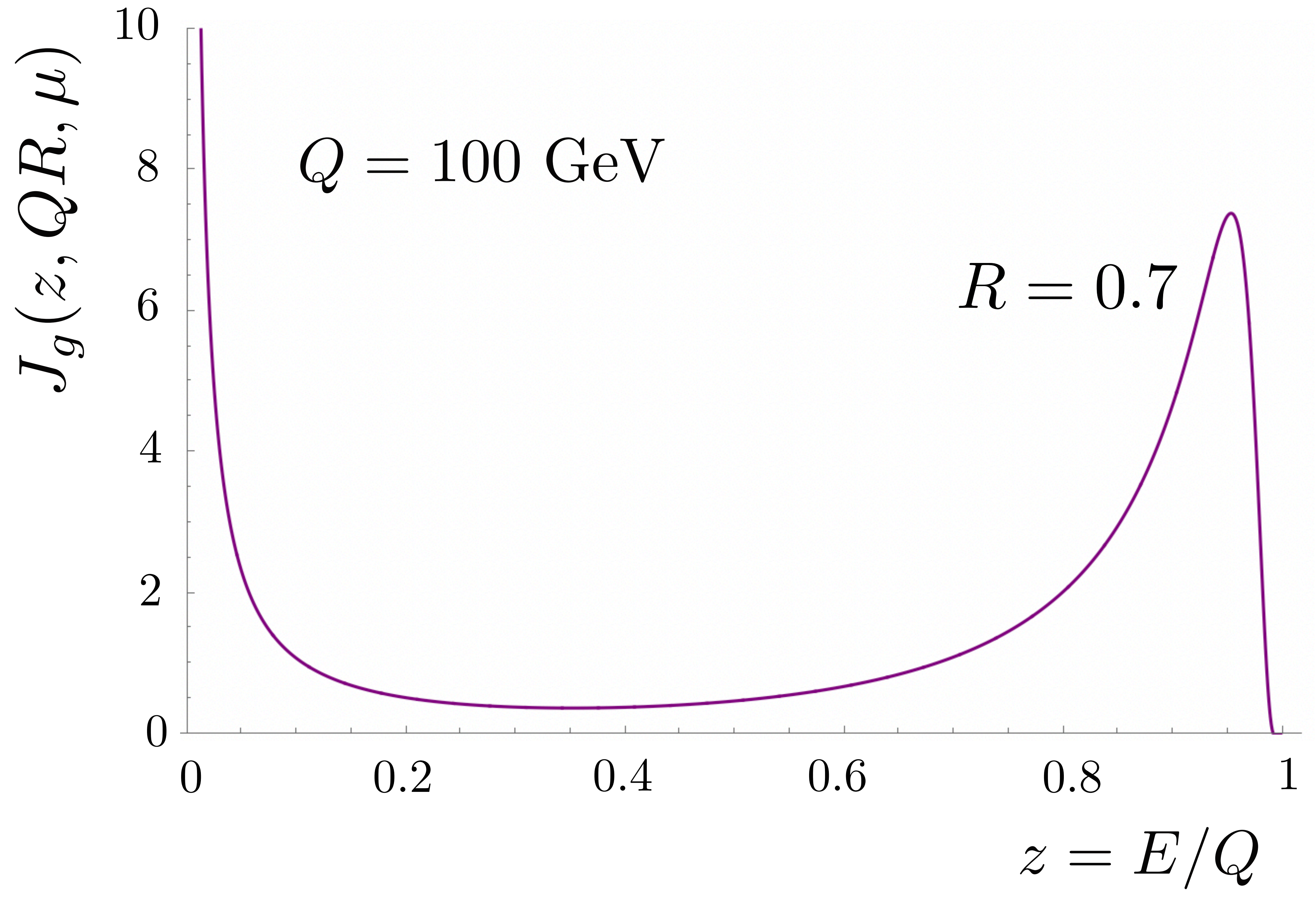
Comparison to ALICE & LEP data

Inclusive jet cross sections

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



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



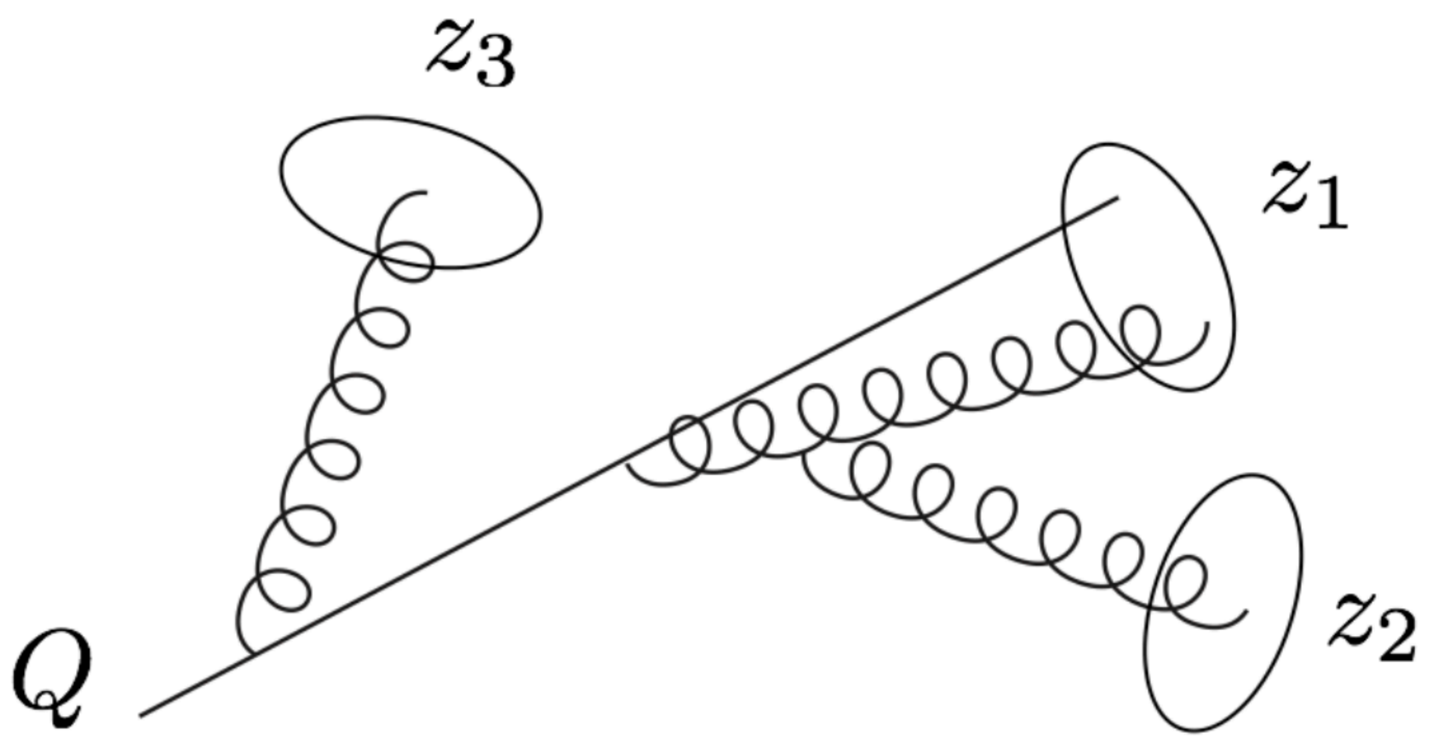
Dasgupta, Dreyer, Salam, Soyez `14
Kaufmann, Mukherjee, Vogelsang `15
Kang, Ringer, Vitev `16
Dai, Kim, Leibovich `16
Liu, Moch, Ringer `18, `19

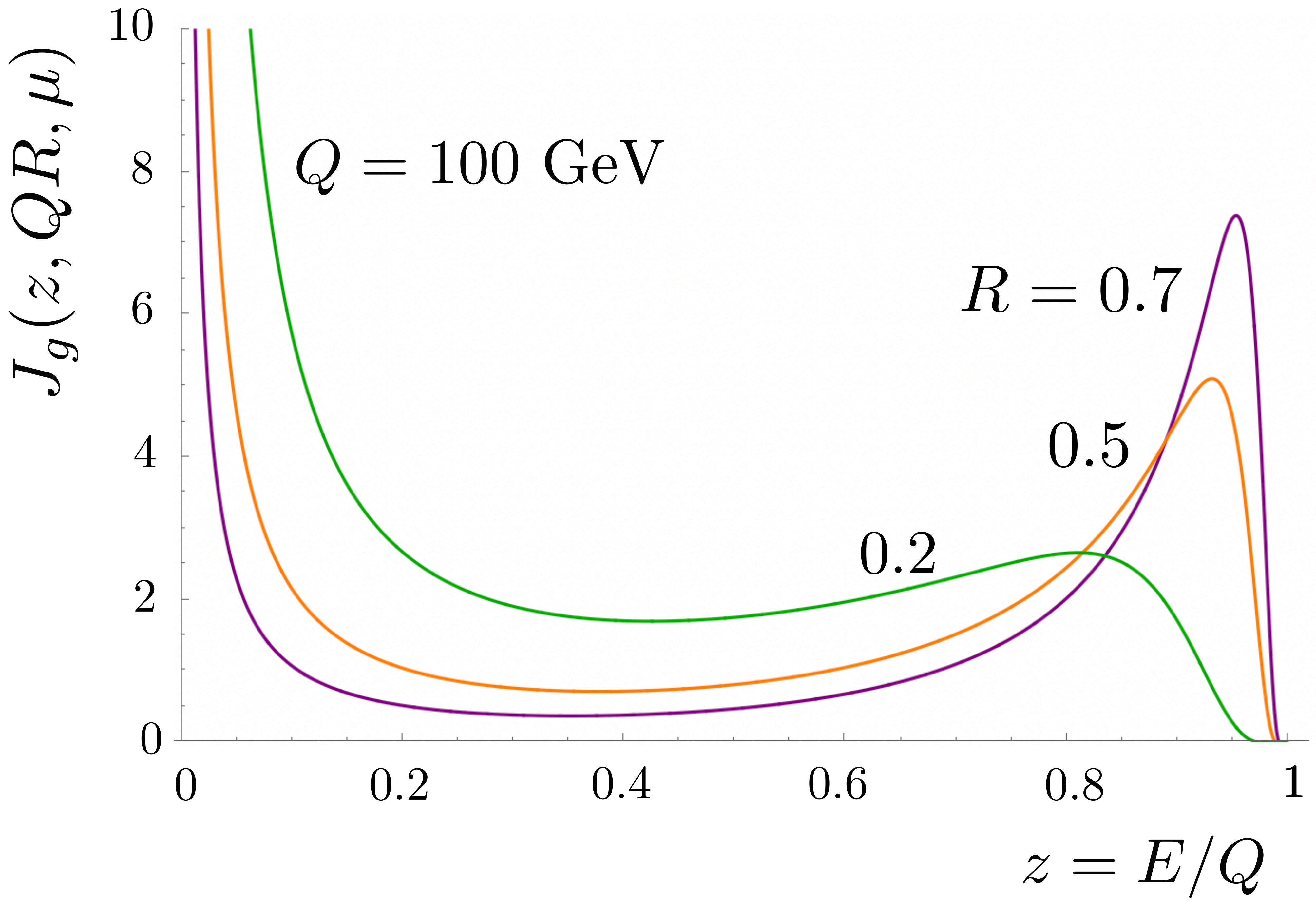
Inclusive jet cross sections

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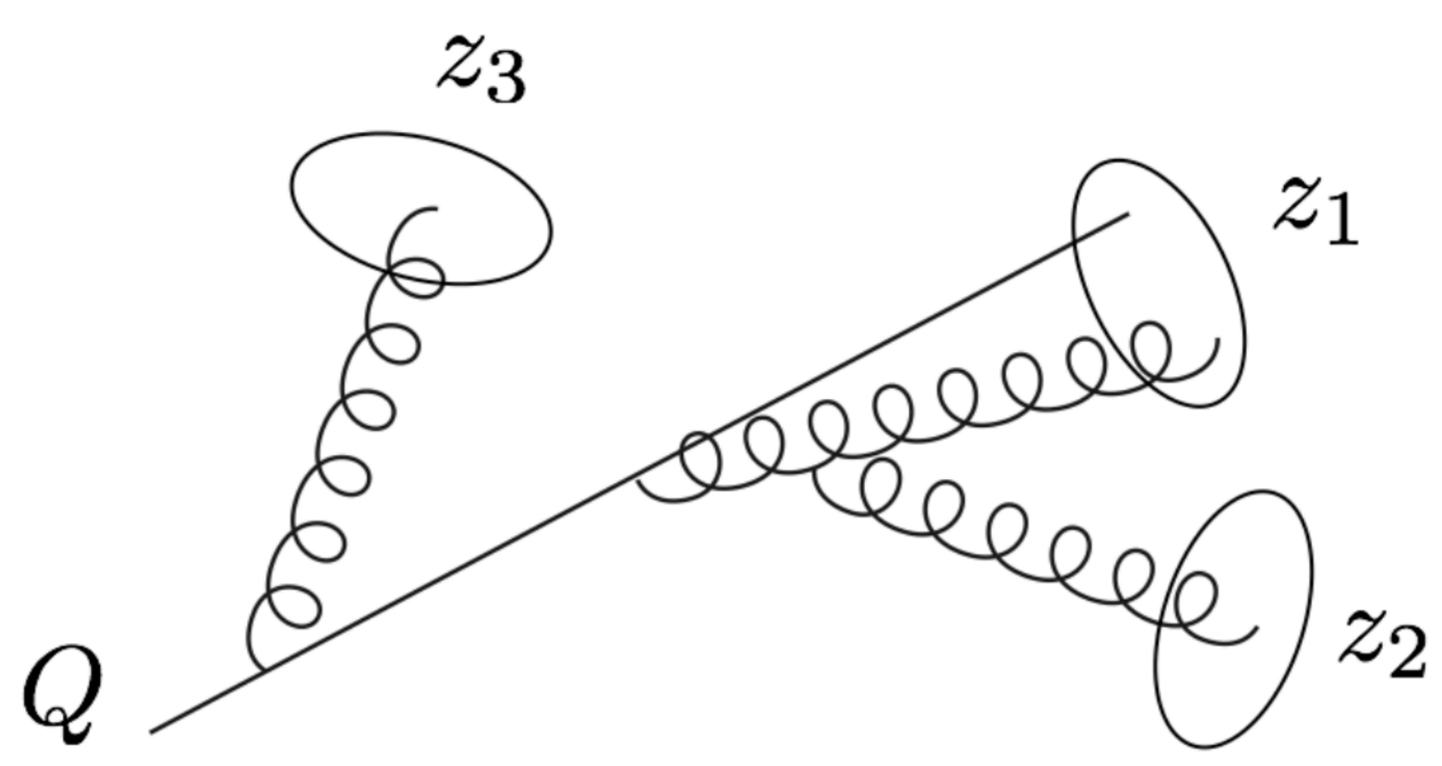
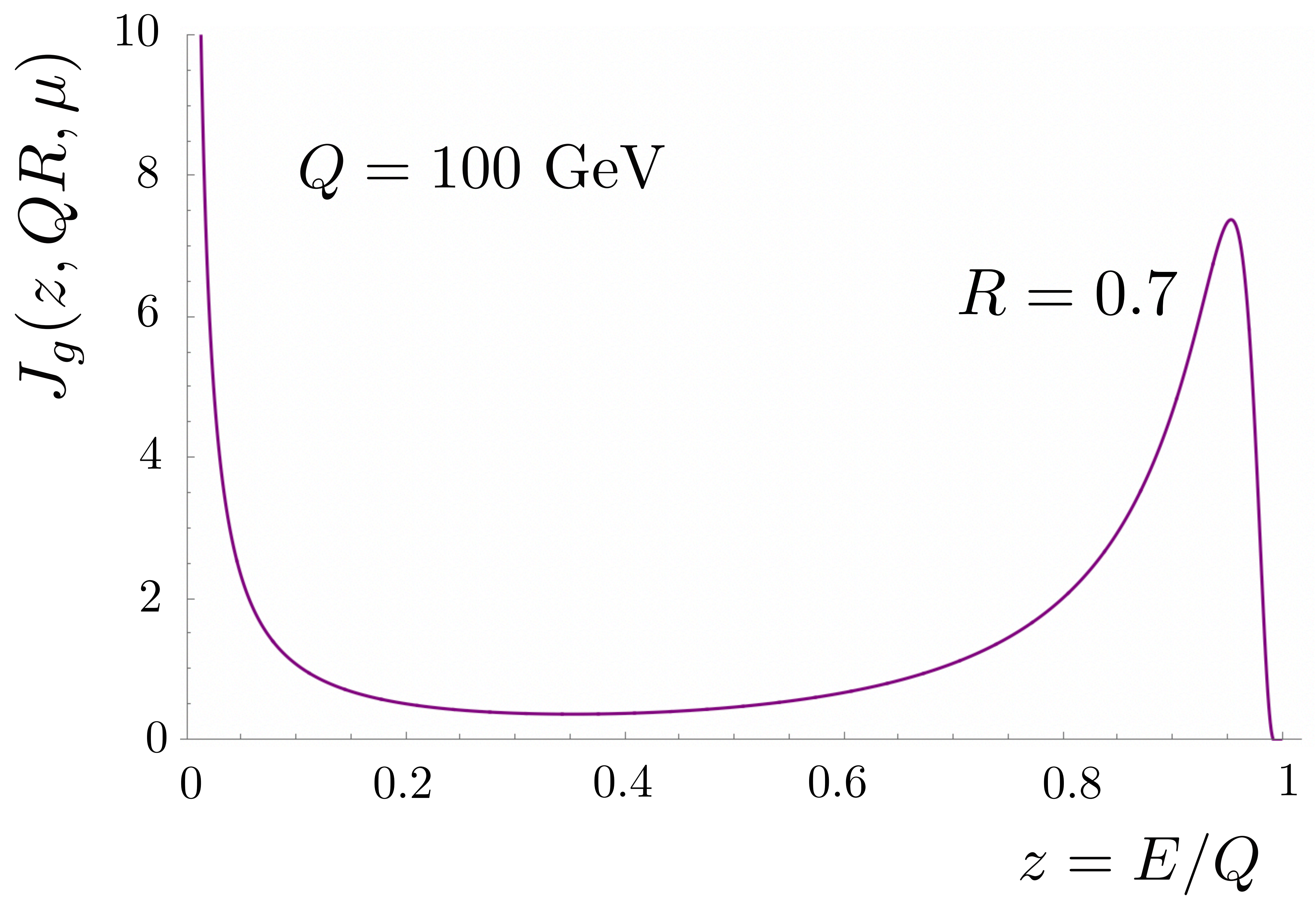
- **QCD evolution** $$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}J_i = \frac{\alpha_s}{2\pi}\sum_j P_{ji}\otimes J_j$$

- **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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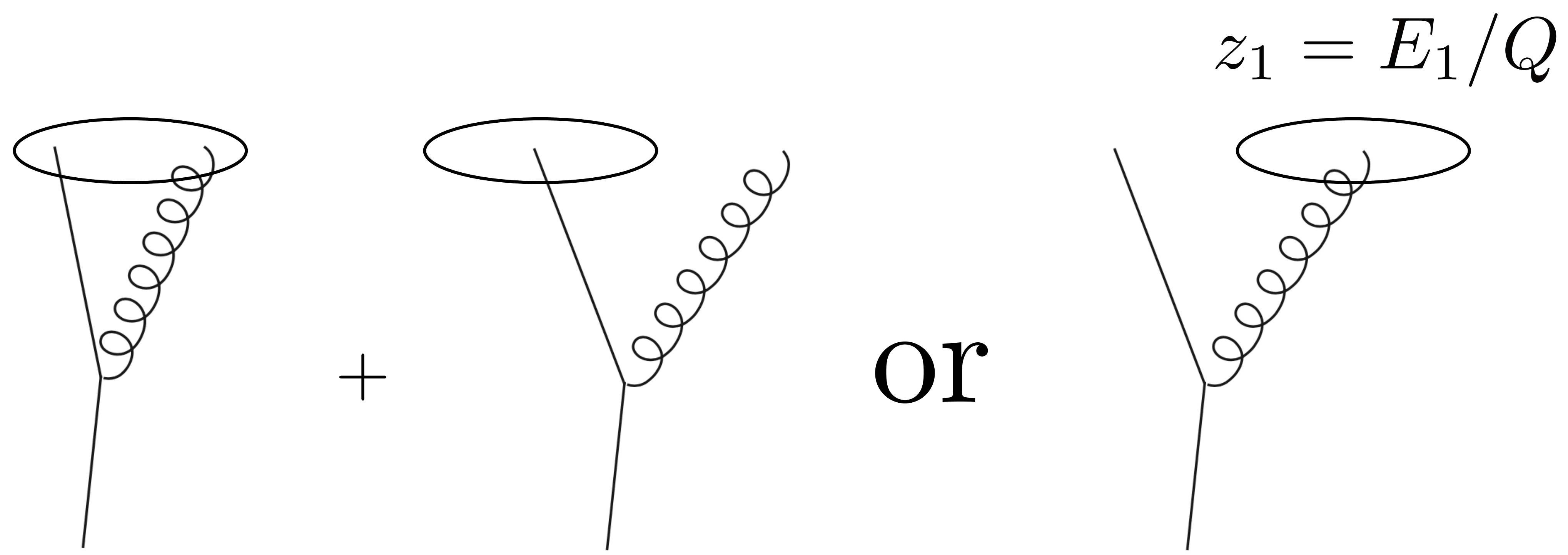
Leading jet cross sections

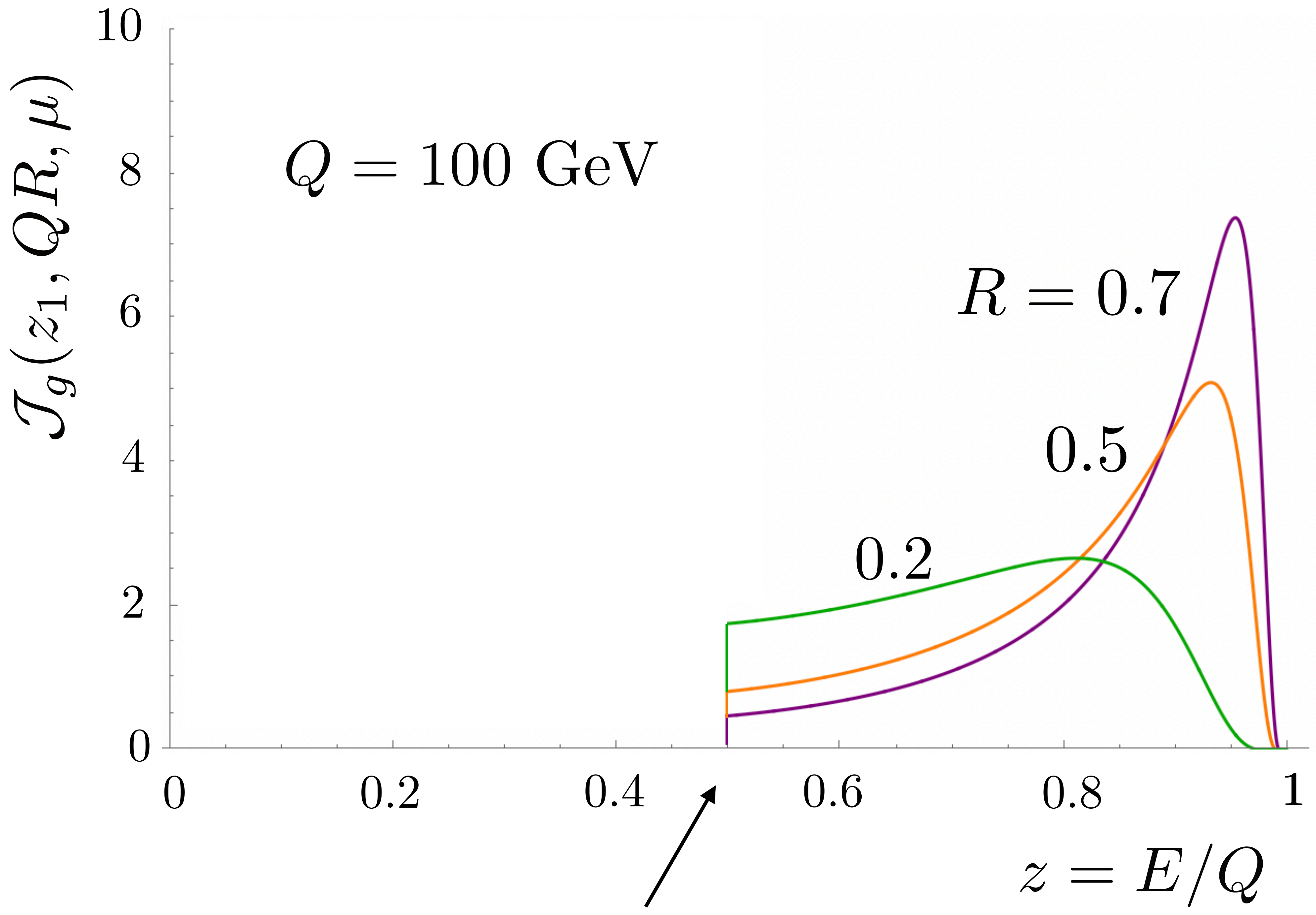
- **NLO**

Leading jet function

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



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



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

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Scott, Waalewijn `19
Neill, Ringer, Sato `21

Leading jet cross sections

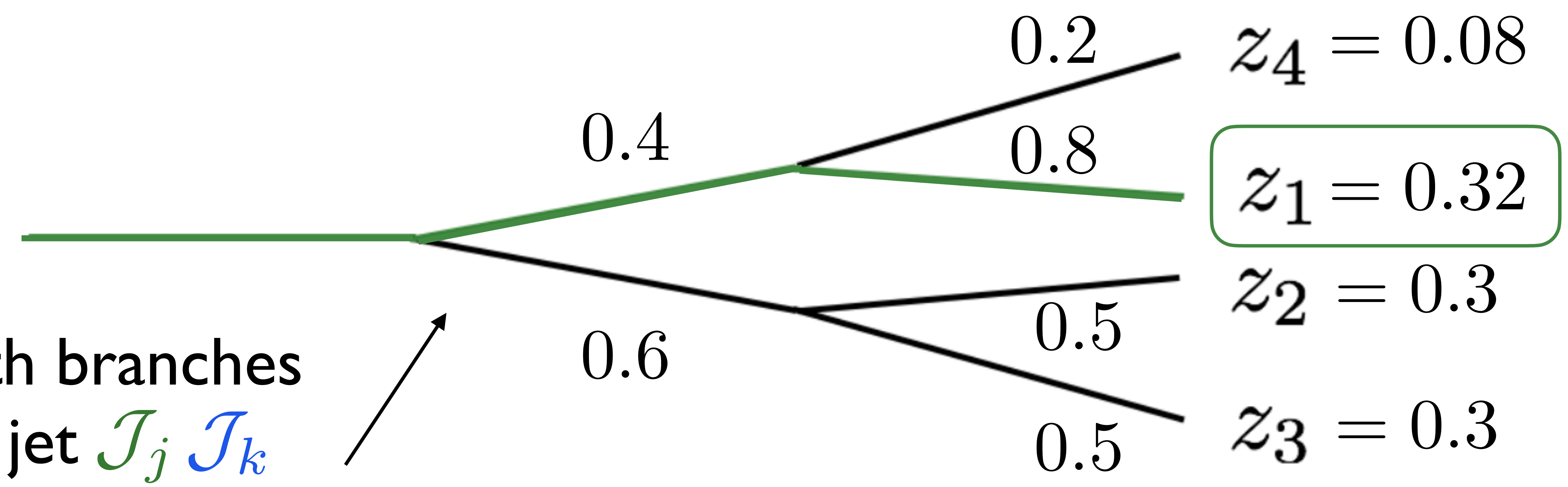
- **NLO** $\mathcal{J}_i(z_1, QR, \mu)$

- **QCD evolution**

Non-linear DGLAP-type evolution

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

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



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

- Solve with a parton shower

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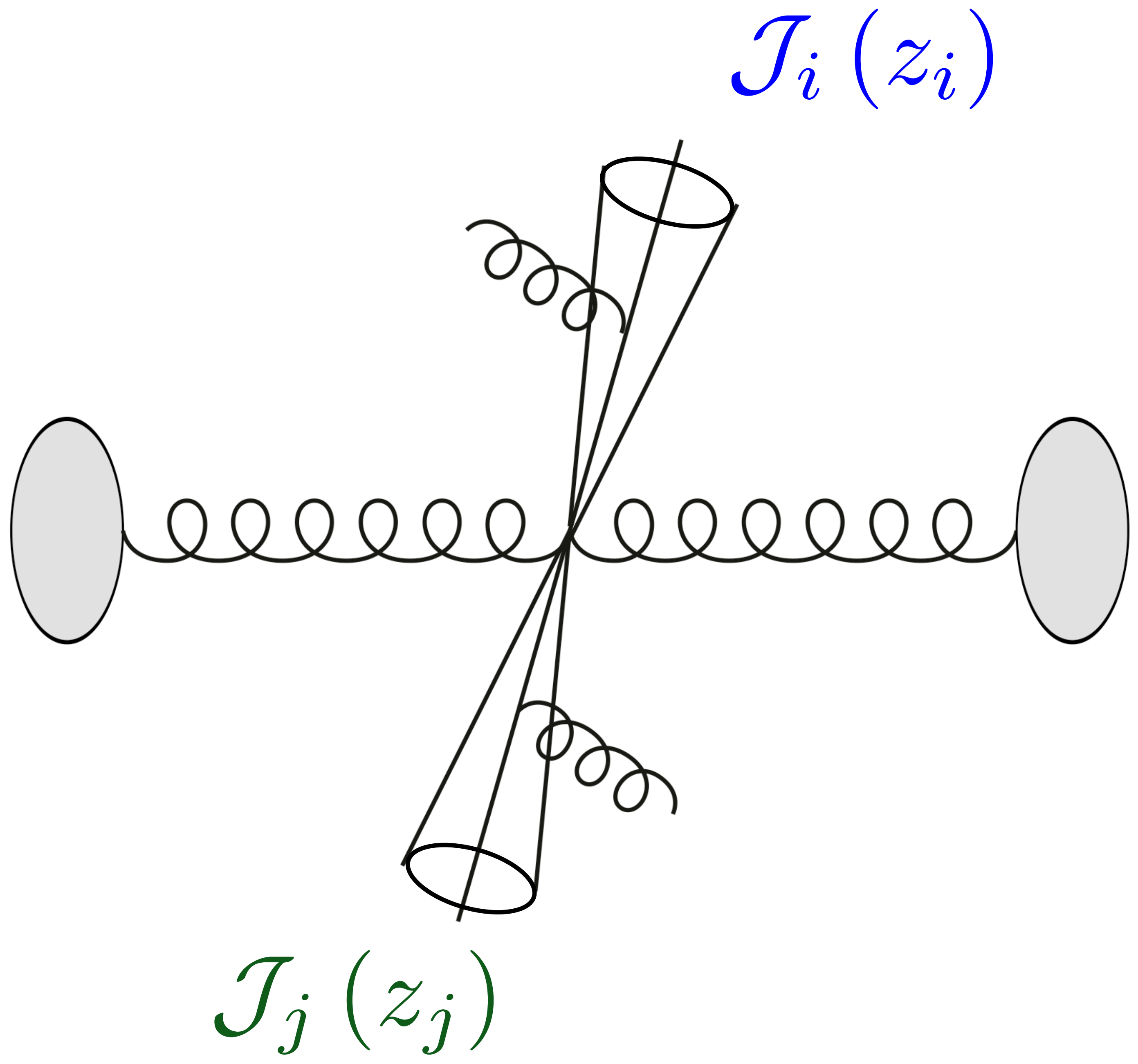
Neill, Ringer, Sato `21

Leading jet cross sections

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

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



Measurement at the end

Here LO + LL' accuracy

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

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Inclusive vs. leading jets

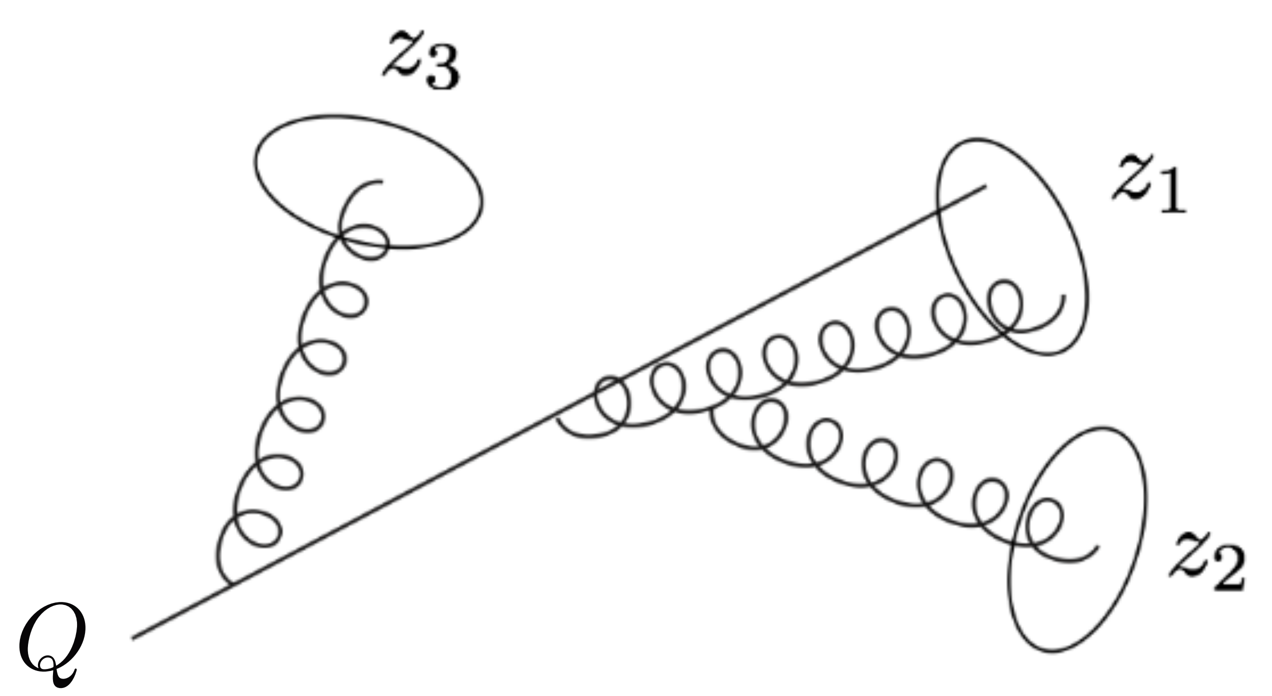
- Jet function - number densities

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

- Momentum conservation

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

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



- Jet function - probability densities

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

requires threshold resummation

Inclusive vs. leading jets

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

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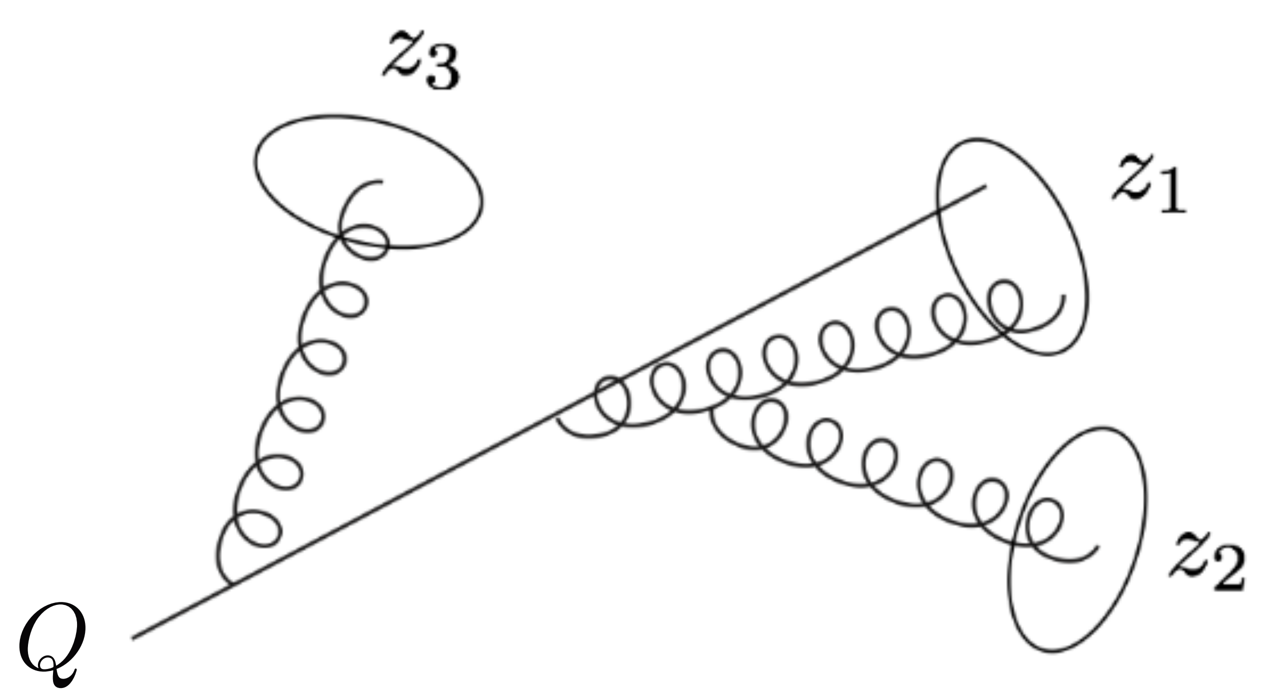

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2. Positive $\mathcal{J}_i\left(z_1, QR, \mu\right) > 0$

requires threshold resummation

- Average energy loss

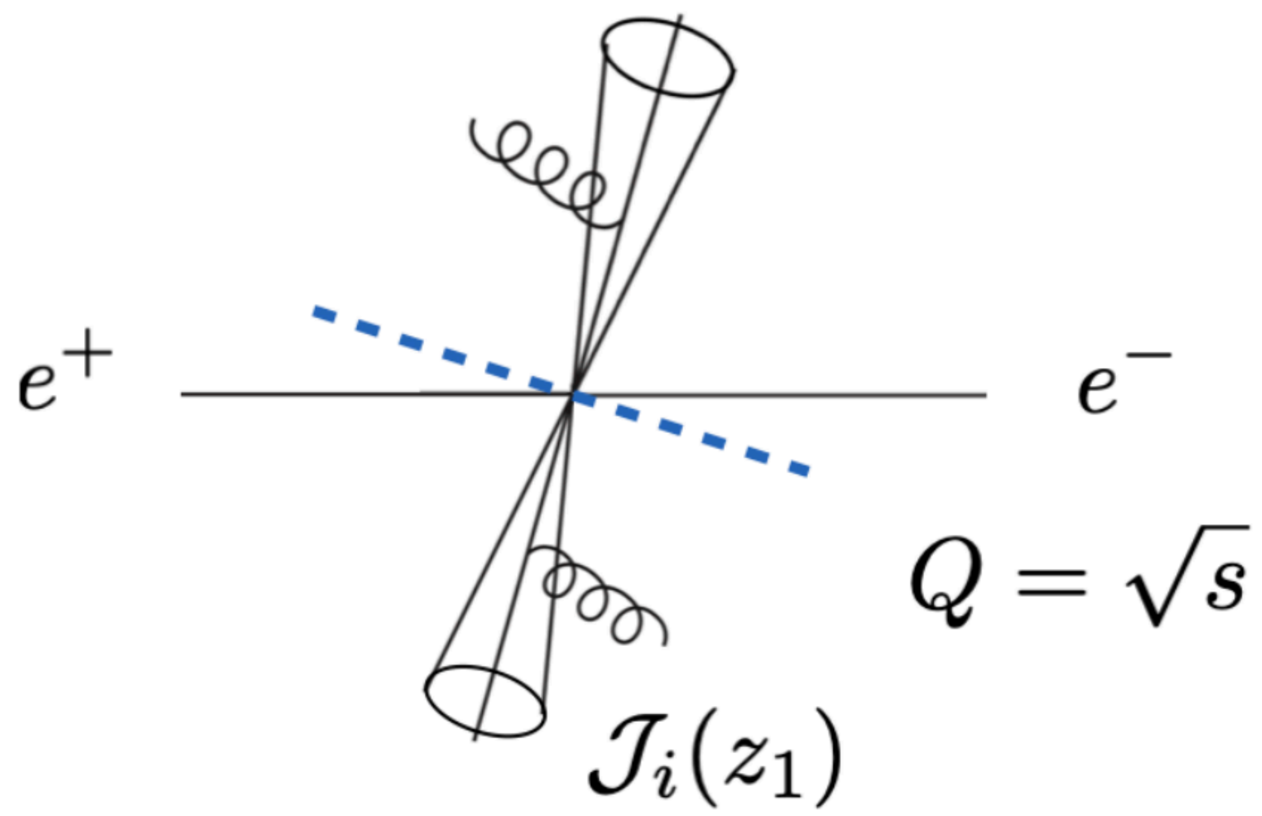
$$\int_0^1 \mathrm{d}z_1 z_1 \mathcal{J}_i\left(z_1, QR, \mu\right) = \langle z_1 \rangle$$

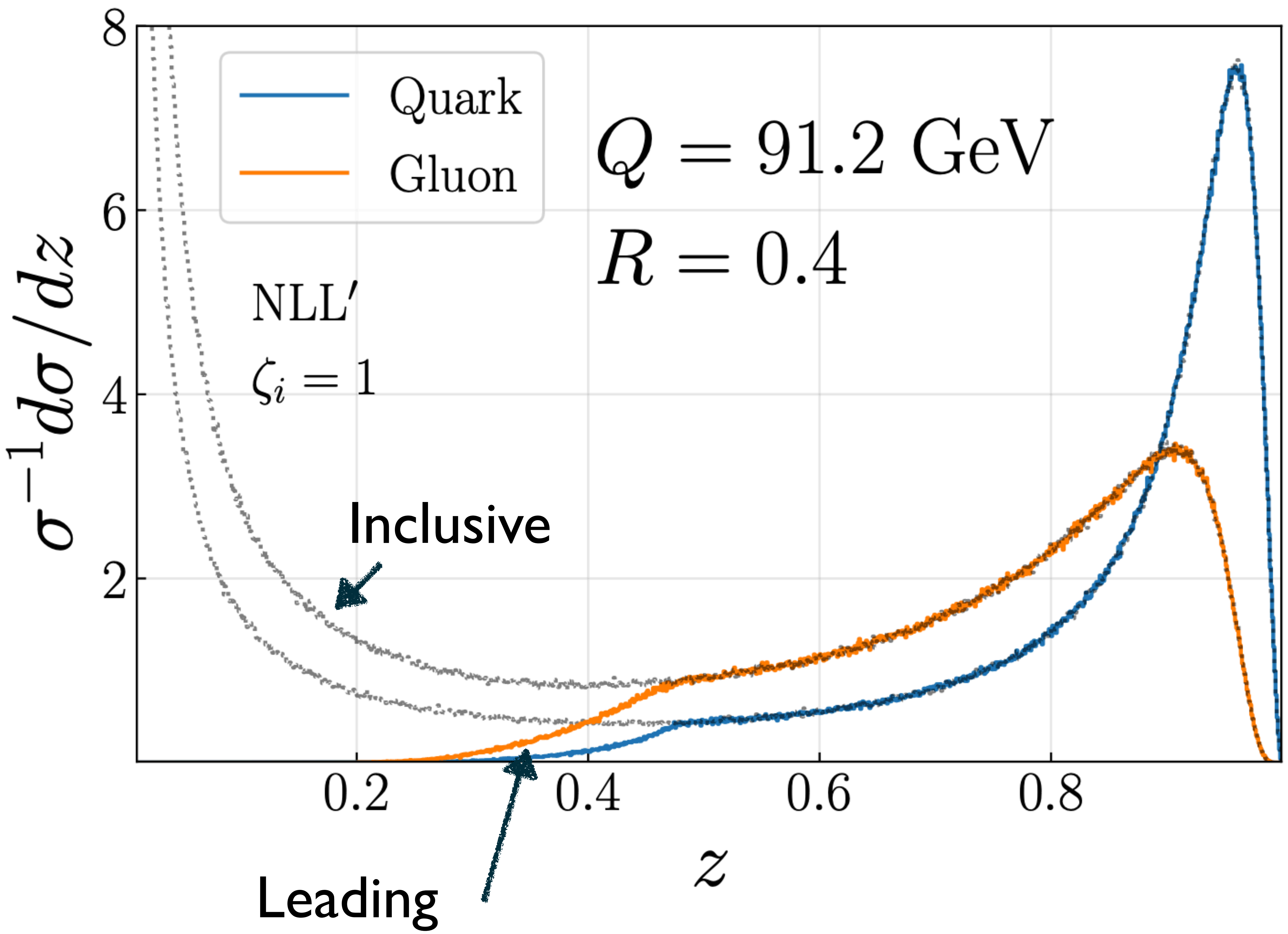
$$= 1 - \langle z_{\mathrm{loss}} \rangle$$

Inclusive and leading subjets

Neill, FR, Sato `21

- Jet radius
- Threshold resummation





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Neill, FR, Sato `21

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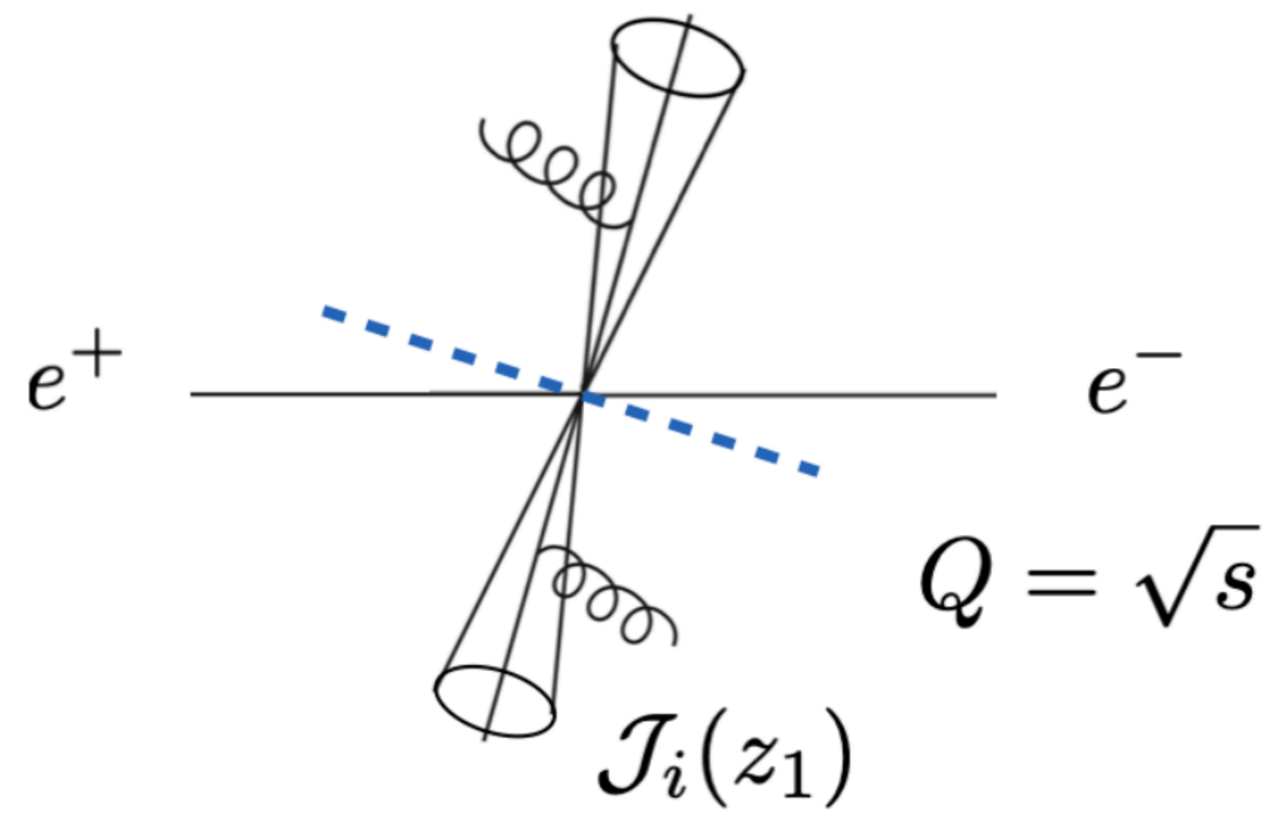
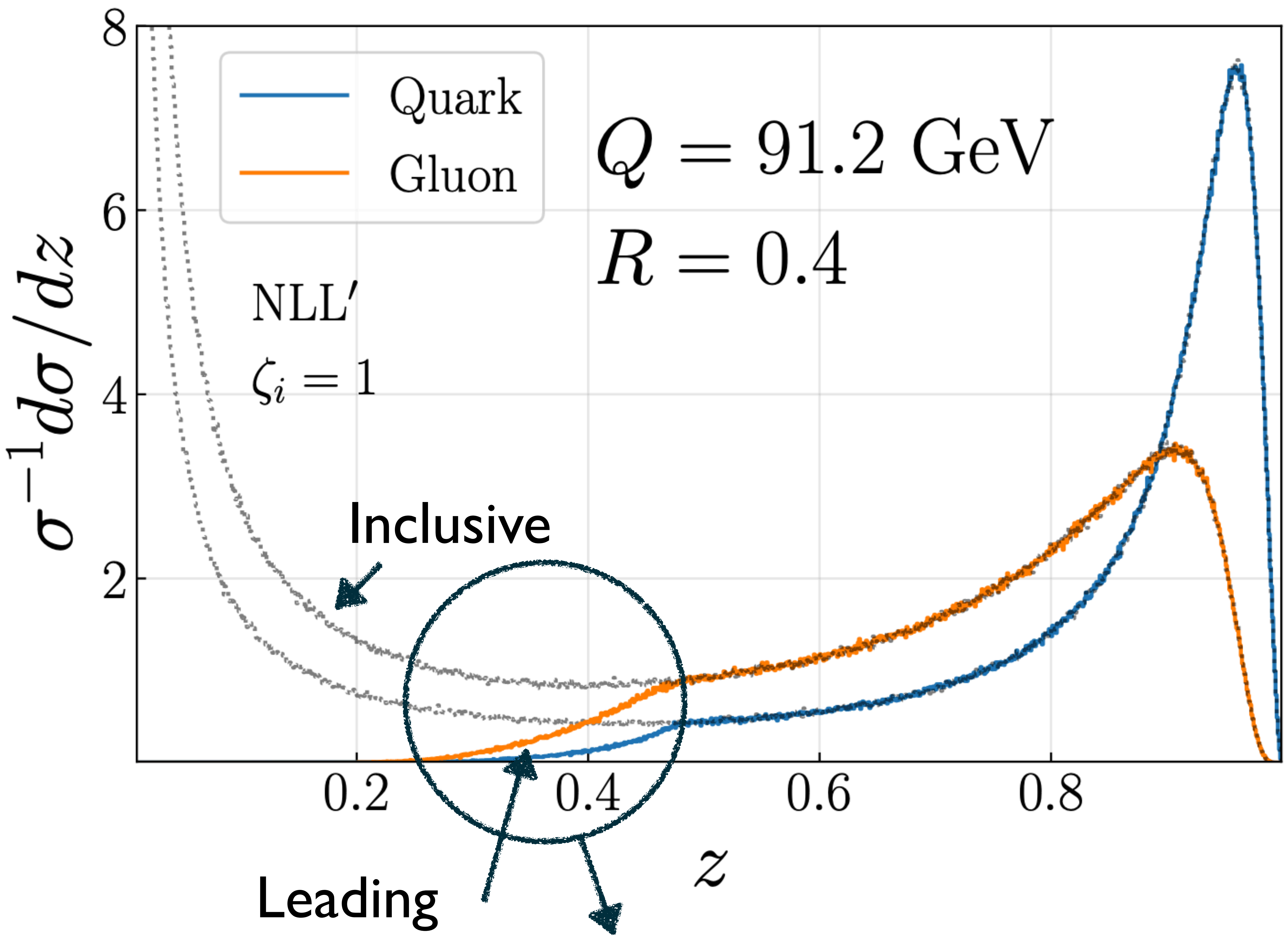




Sensitive to non-linear QCD dynamics

Outline

Introduction

Inclusive and leading jets

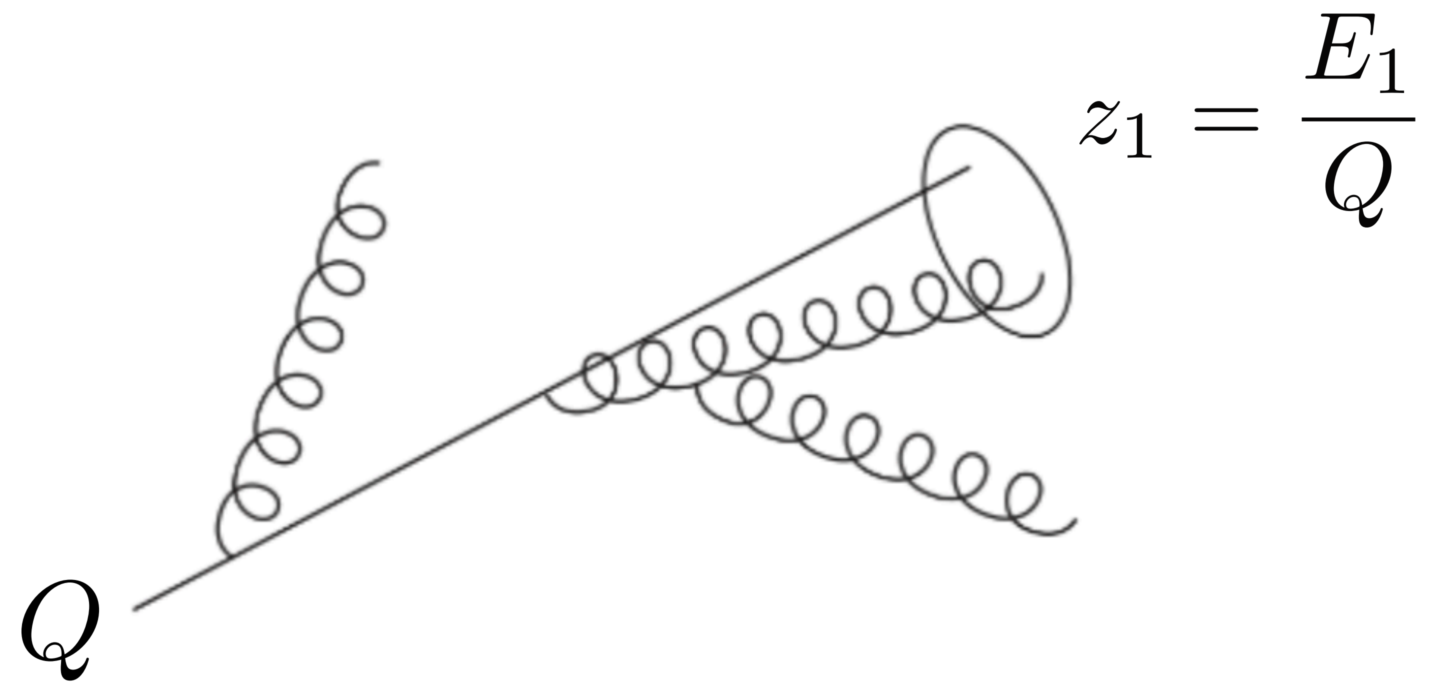
Comparison to ALICE & LEP data

Requirements for energy loss measurements

1. Well defined object which has lost energy

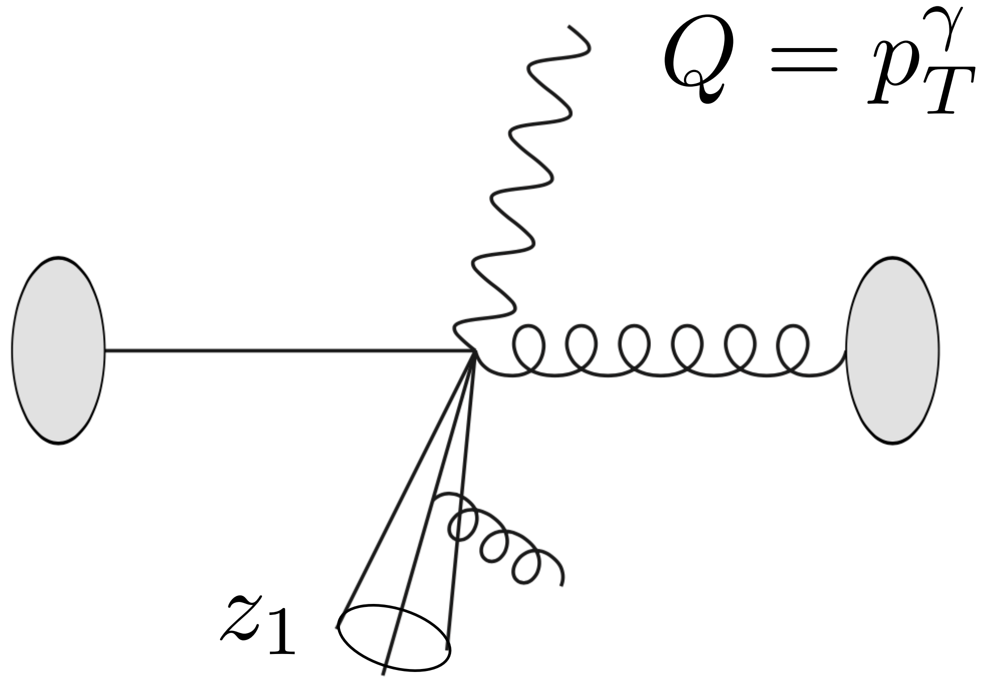
Leading jet, not inclusive jets

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



2. Reference scale to define lost energy

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



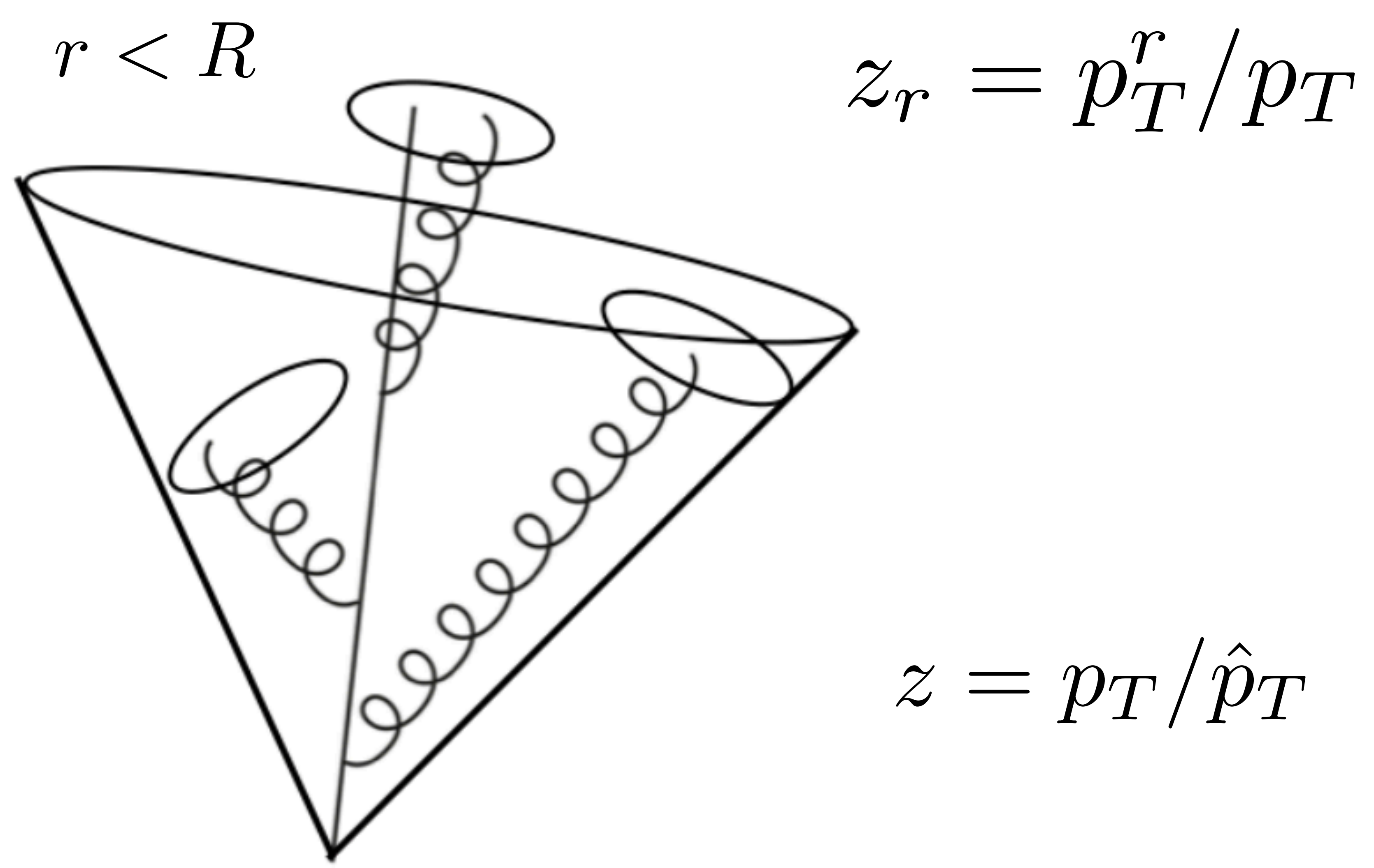
3. Identify at LL: parton ⟷ jet energy loss

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

Inclusive and leading subjets

- **Jet production** $pp \to \text{jet} + X$

$$\frac{d\sigma^{pp\to\text{ jet }X}}{d\eta dp_T dz_r} = f_{a/p} \otimes f_{b/p} \otimes H^c_{ab} \otimes_z \mathcal{G}_c(z, z_r) + \mathcal{O}\left(R^2\right)$$



Longitudinal momentum of subjets

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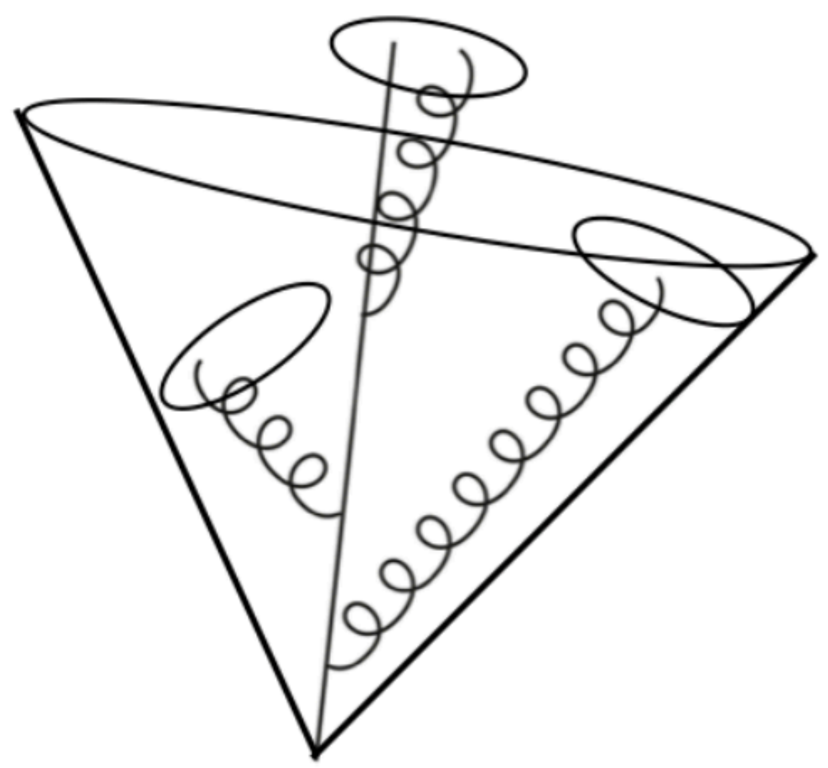
Comparison to ALICE data

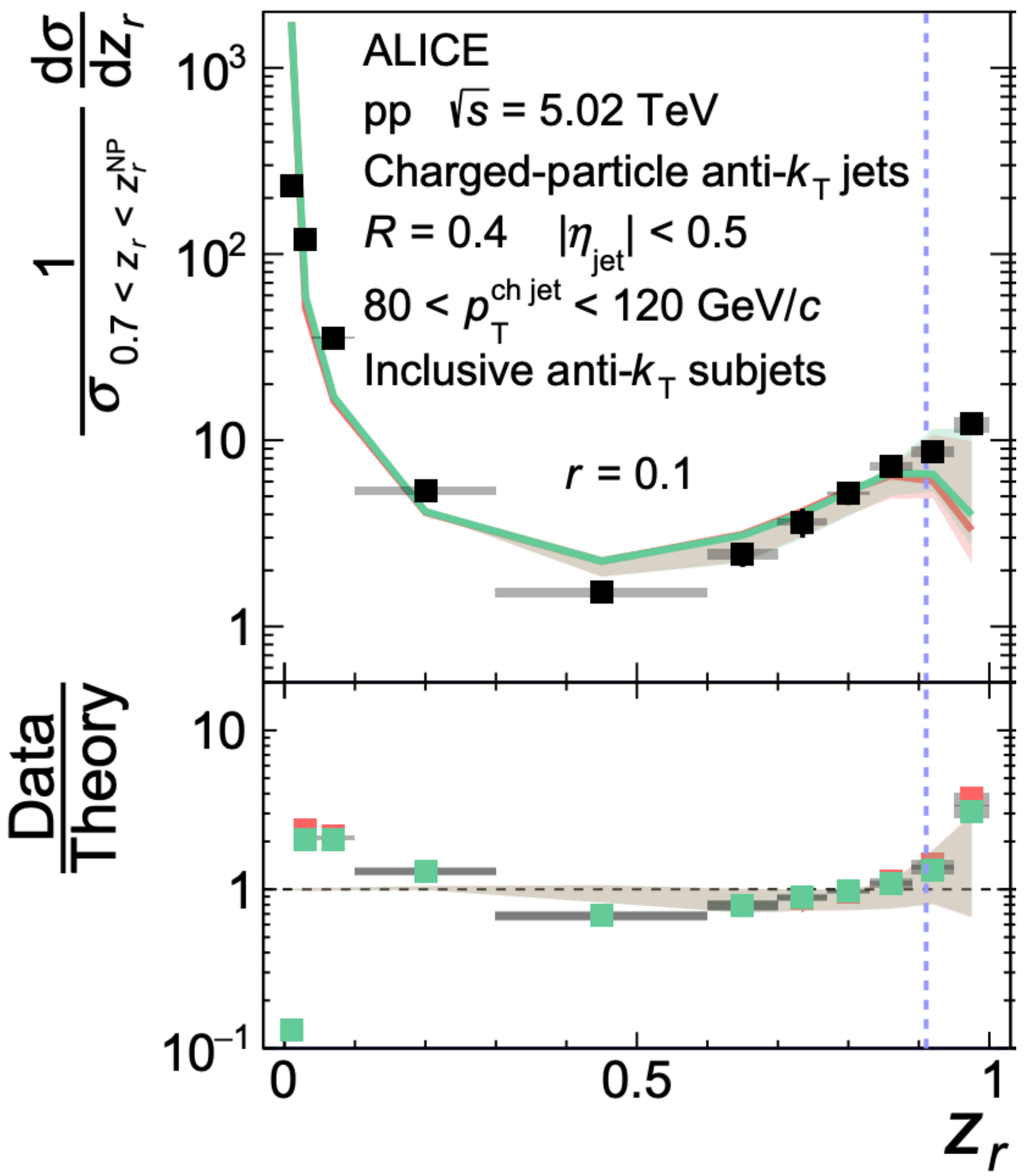
ALICE, 2204.10270

- Inclusive subjets



- Theory corrected to charged-particle level → underlying event and charged vs. full jets

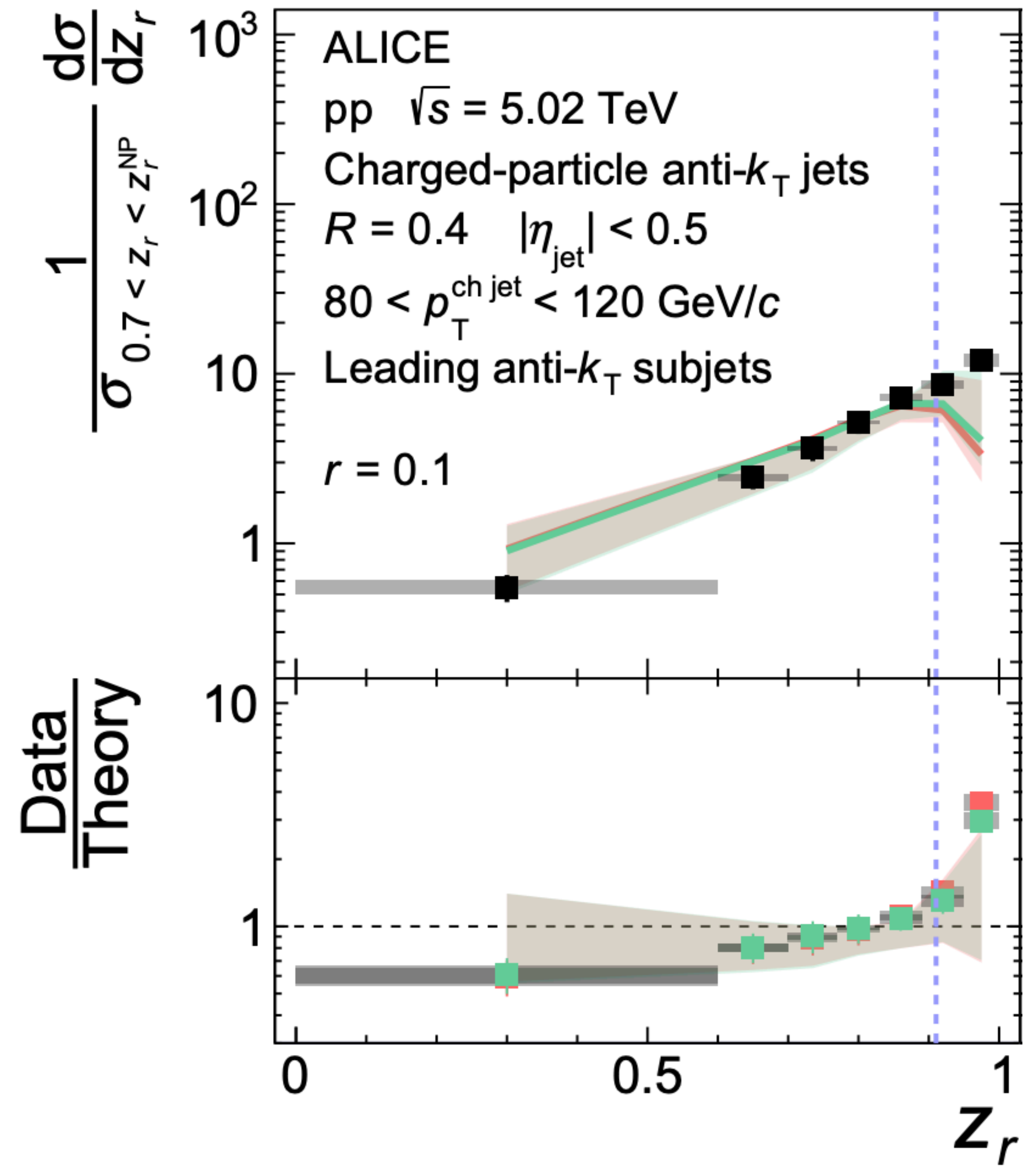
- Measurements also in PbPb



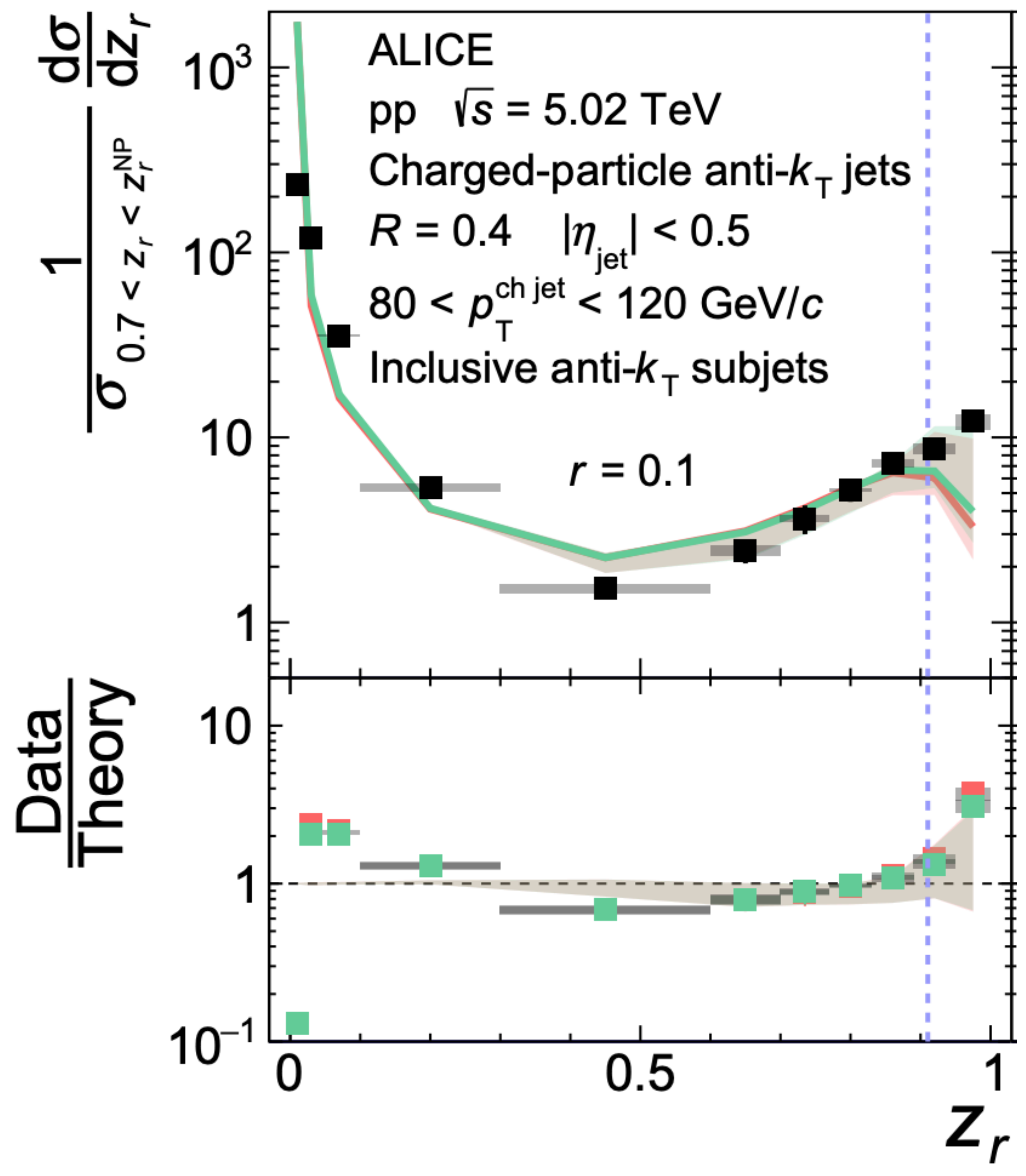
Inclusive subjets

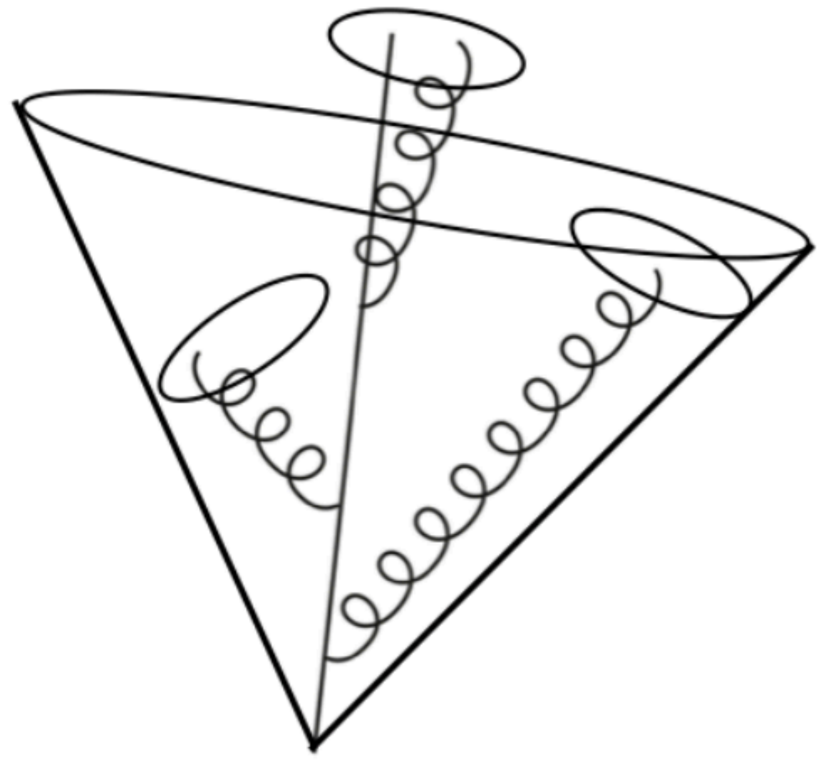
Comparison to ALICE data

ALICE, 2204.10270



Leading subjets

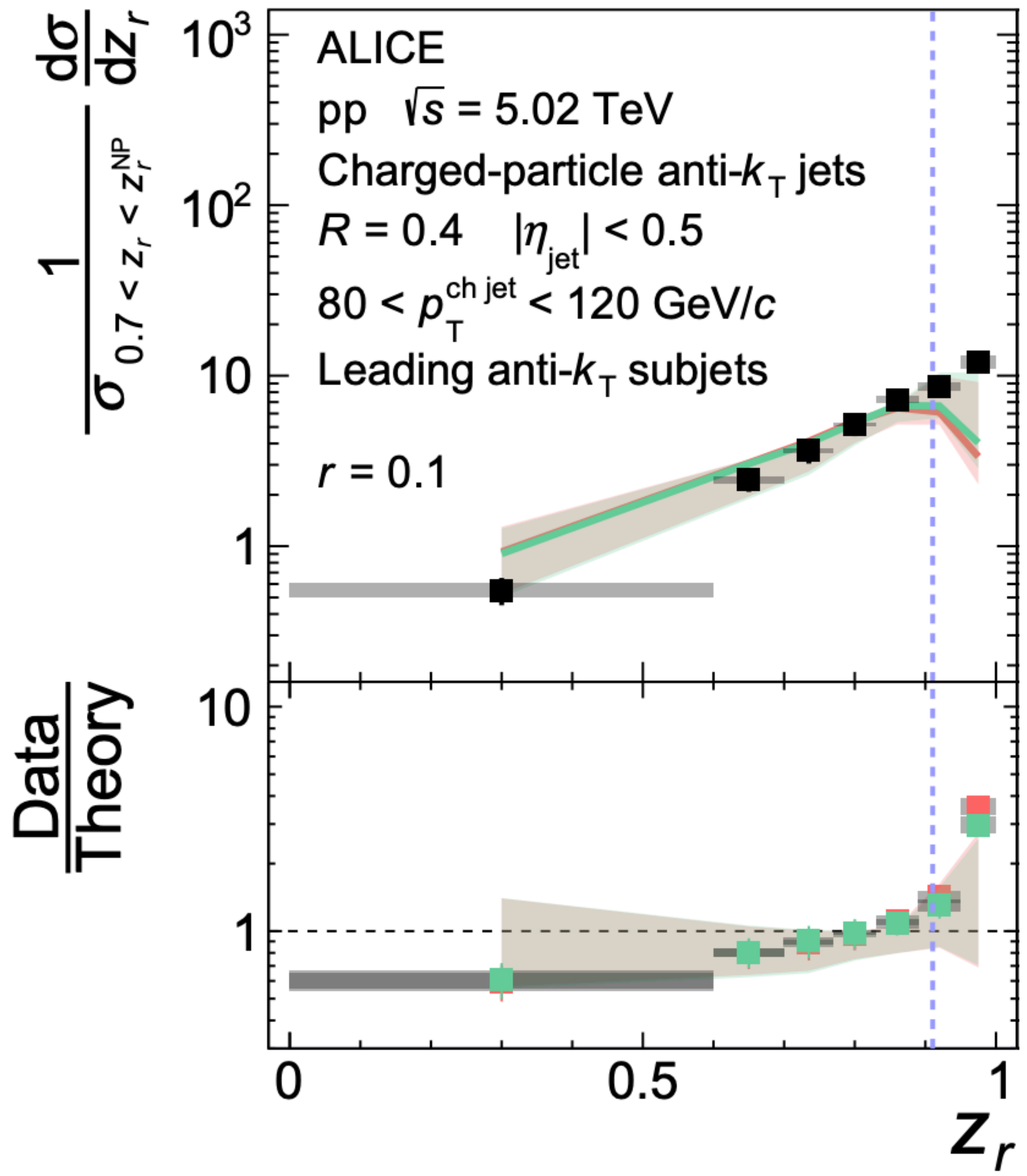




Inclusive subjets

Comparison to ALICE data

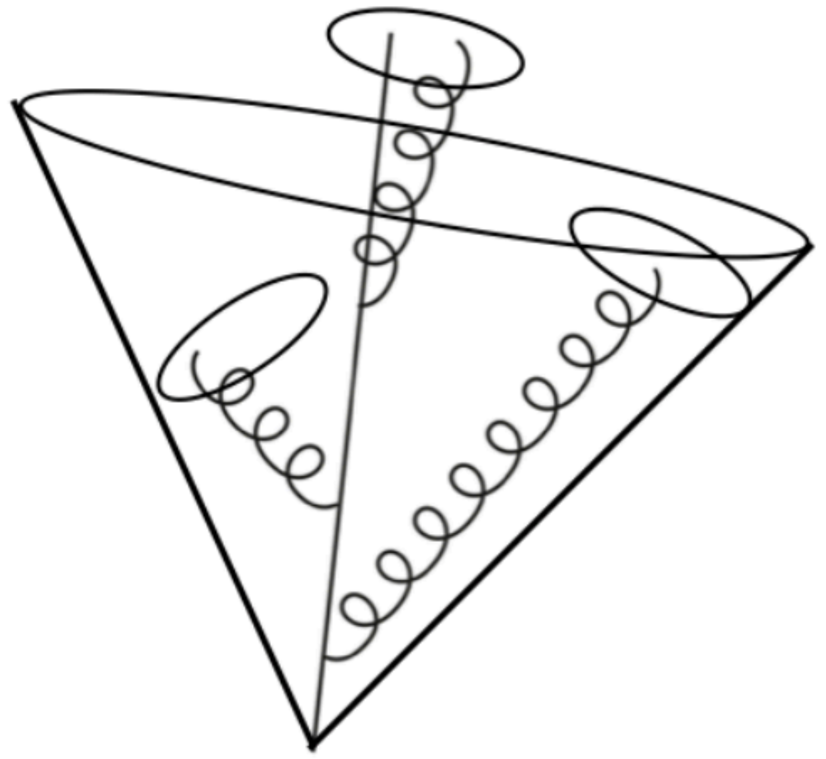
ALICE, 2204.10270



Leading subjets

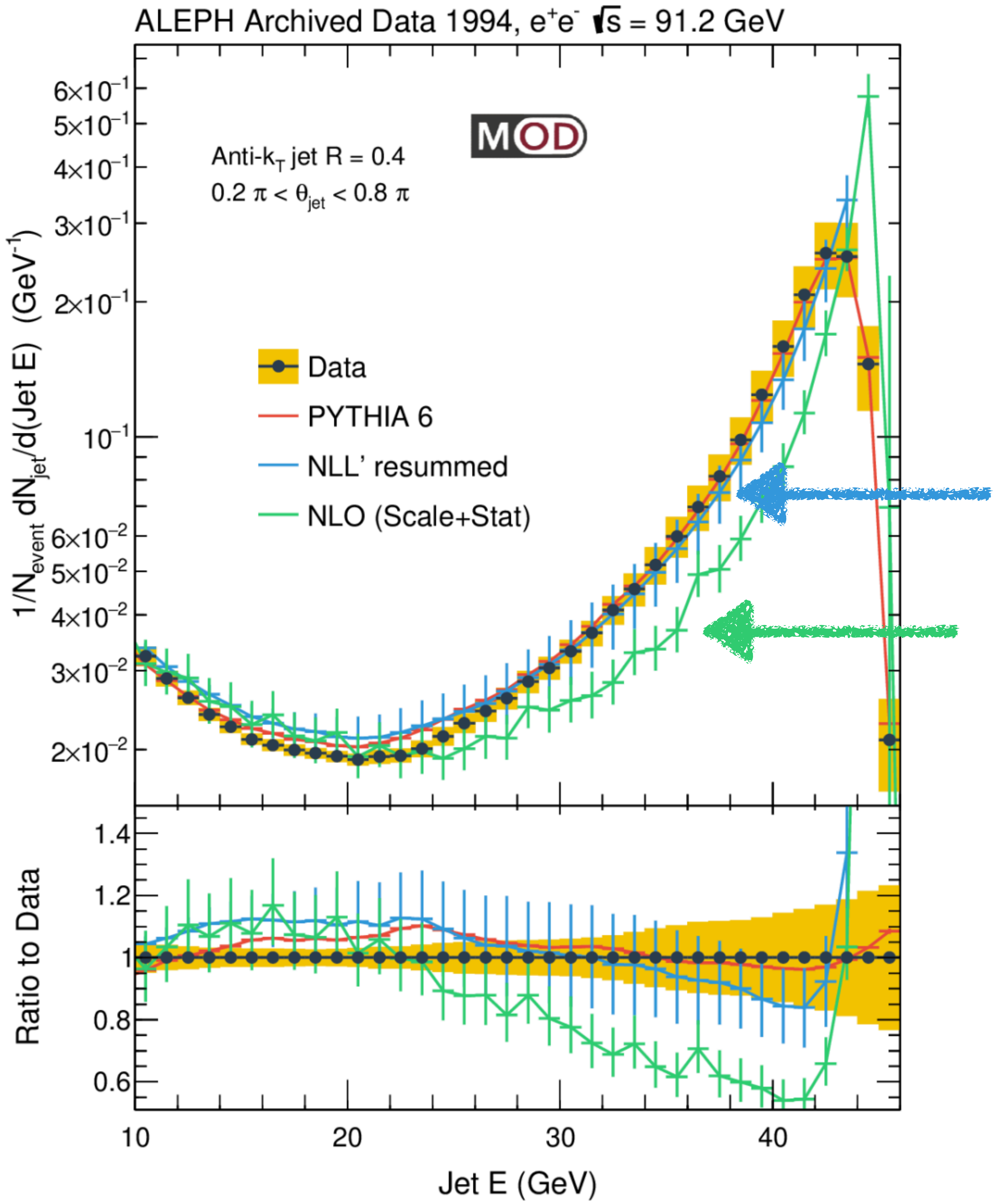
- Average leading subjet energy loss (vacuum)

$$\langle z^{loss}_{r=0.1} \rangle = 0.21$$
$$\langle z^{loss}_{r=0.2} \rangle = 0.10$$



Comparison to LEP data

ALEPH, 2111.09914

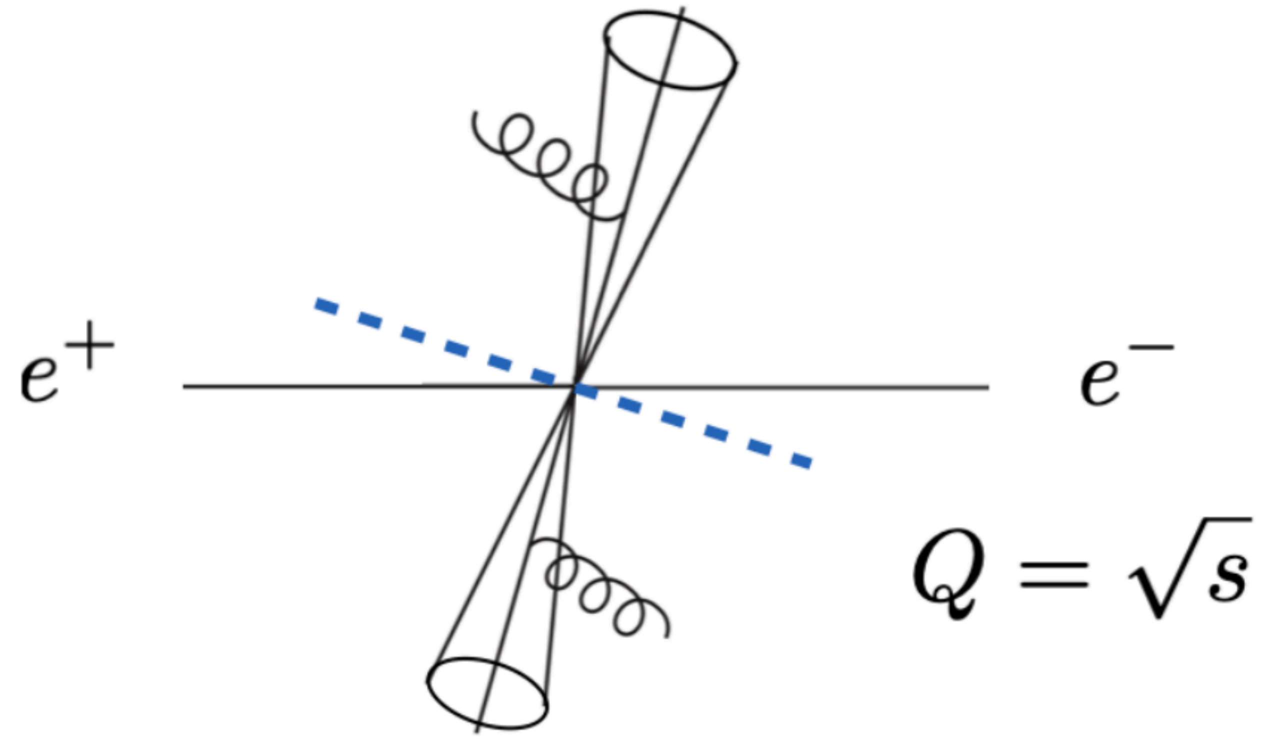


NLL' result

NLO

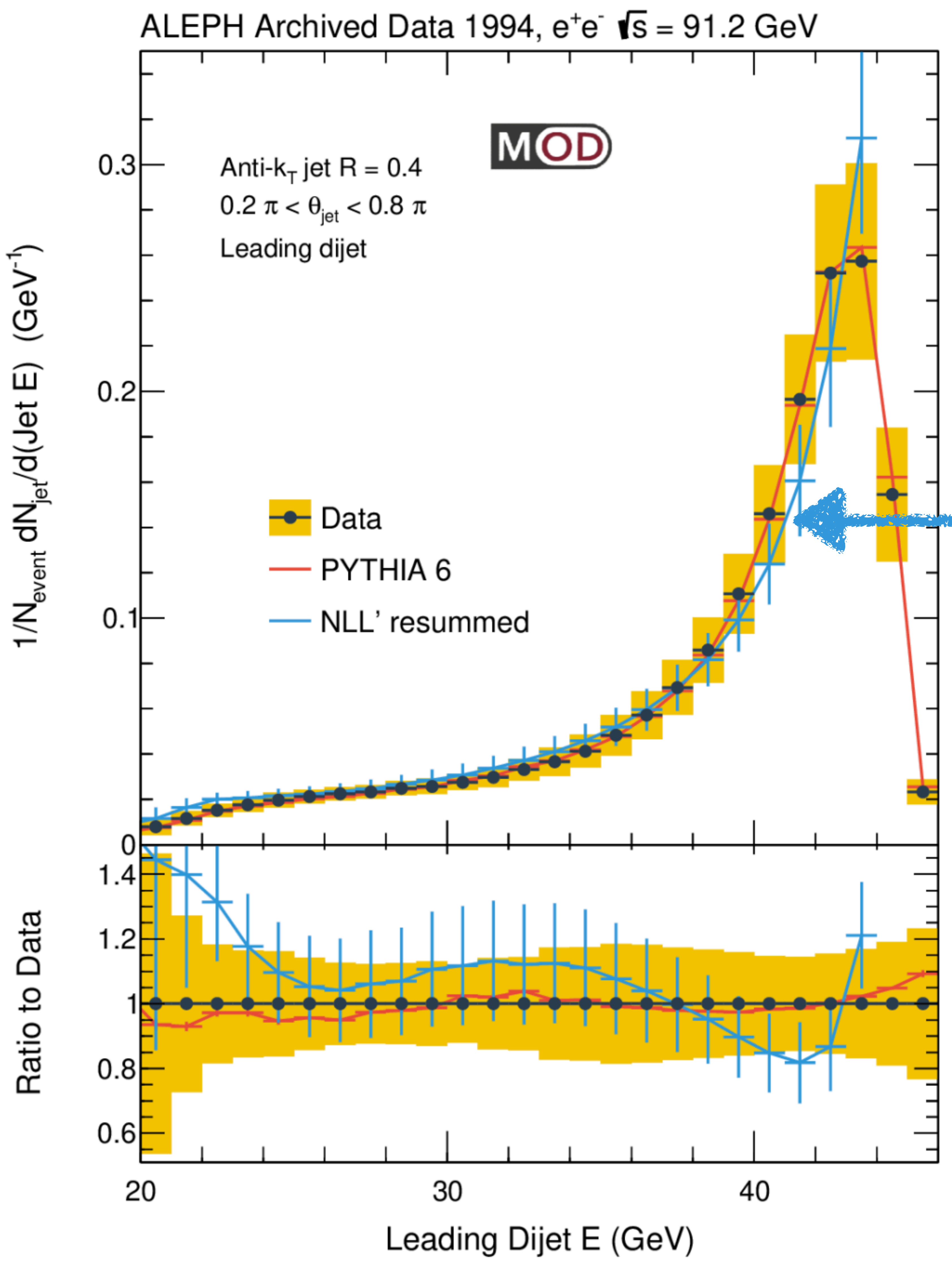
Inclusive jets

Jet energy E



Comparison to LEP data

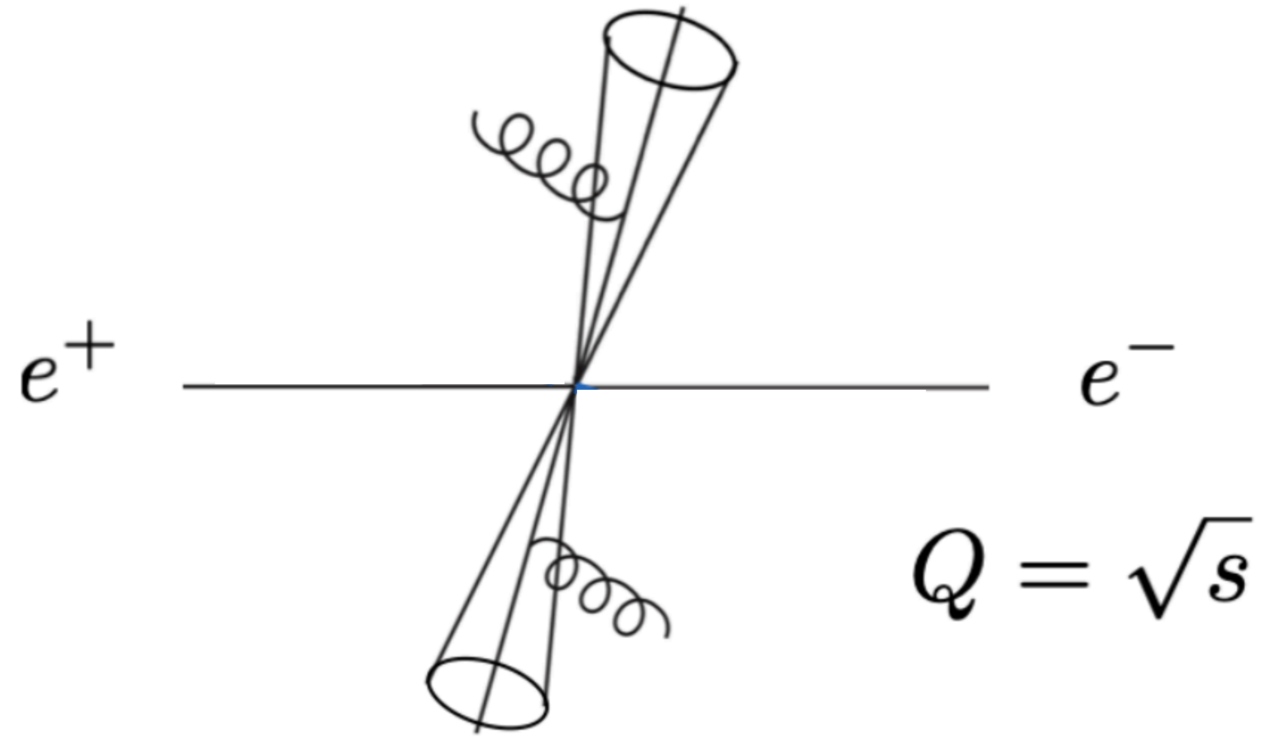
ALEPH, 2111.09914



NLL' result

Event-wide
leading di-jets

Jet energy E



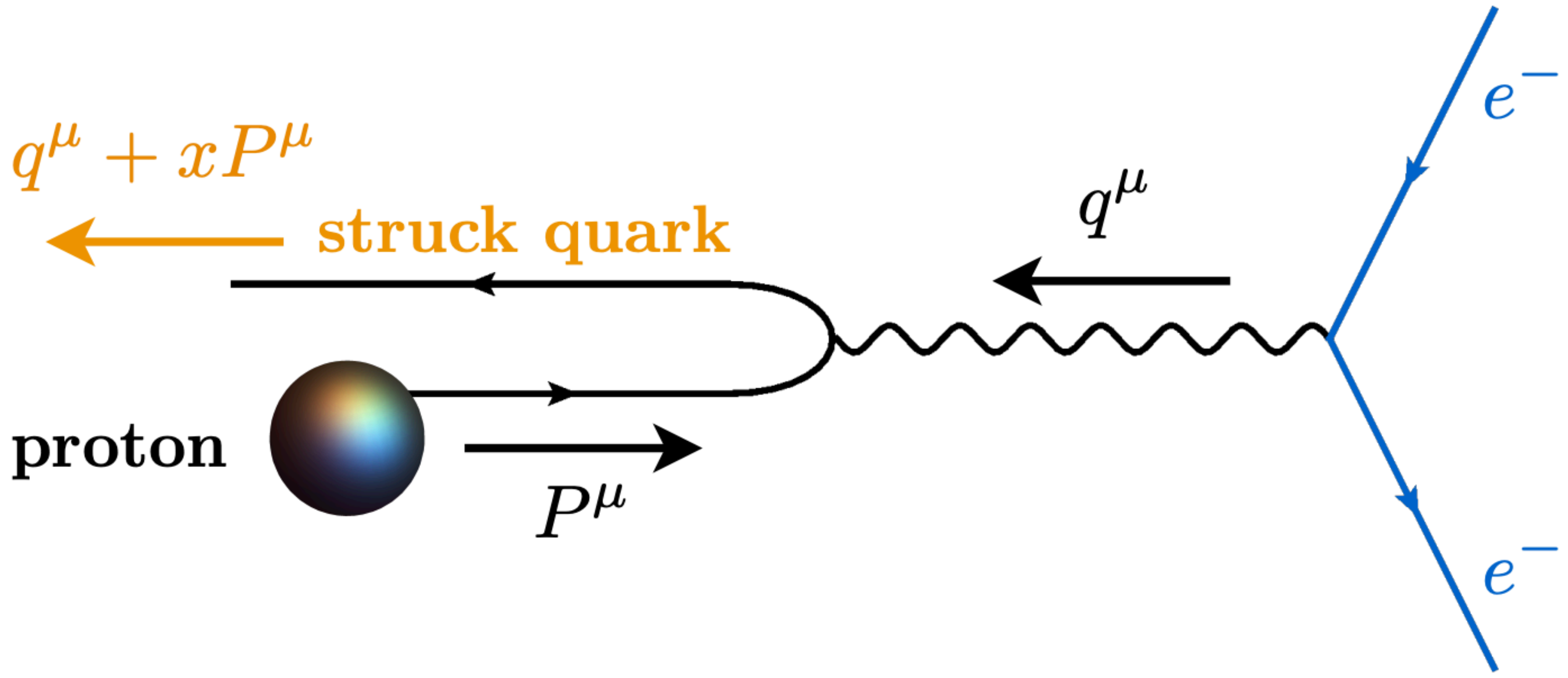
$Q = \sqrt{s}$

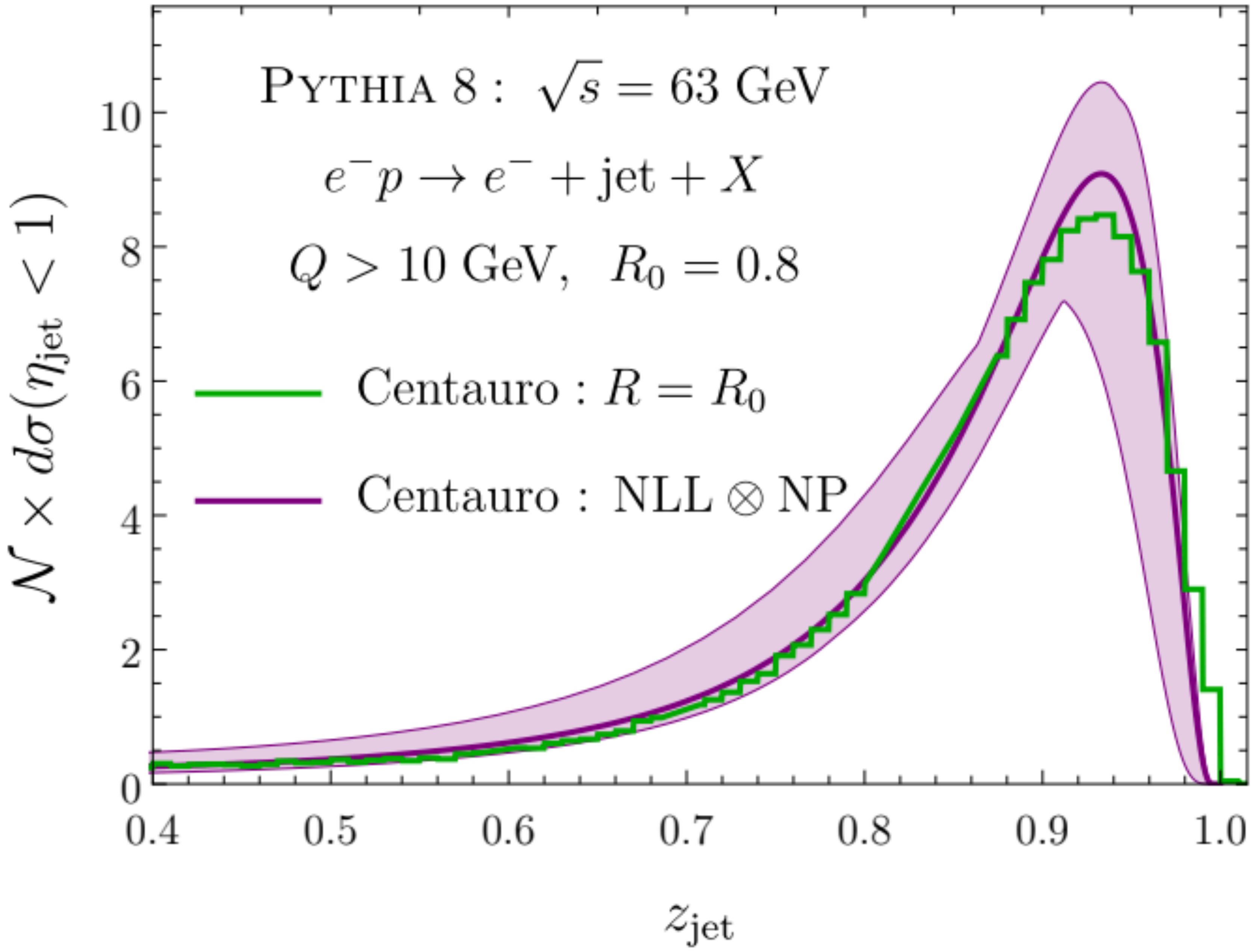
Leading jets at the future EIC

Arratia, Makris, Neill, Ringer, Sato `21

- Can naturally measure leading jets in electron-proton/nucleus collisions

- Use a spherically invariant jet clustering algorithm (Breit frame) using particle energies as in e^+e^-



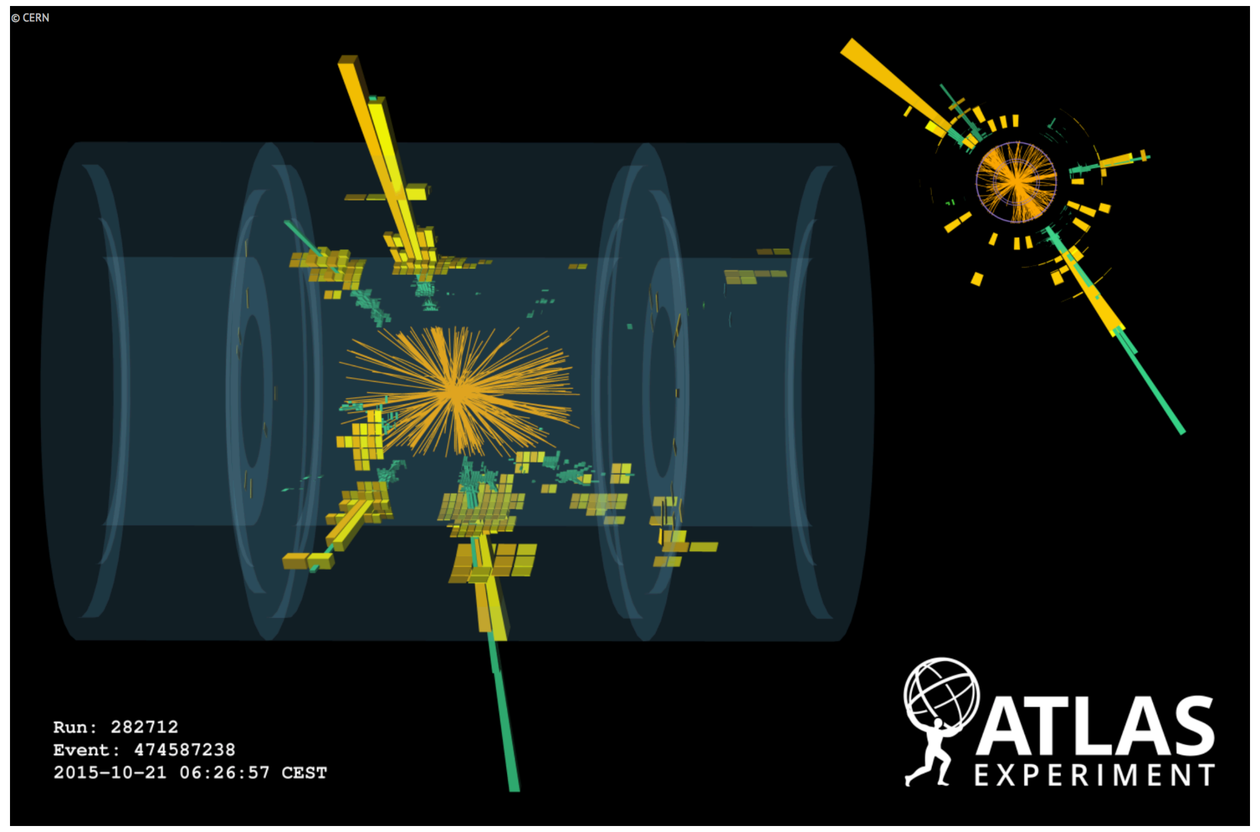


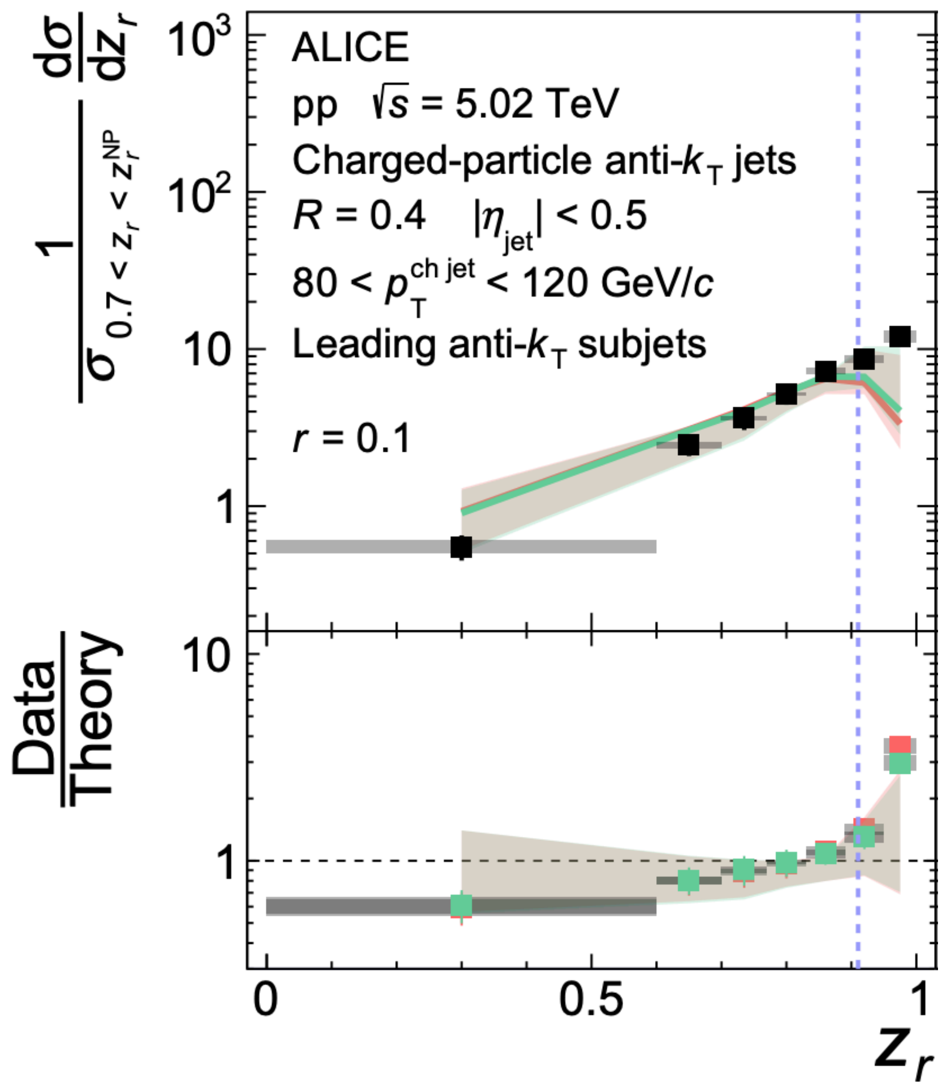
Outline

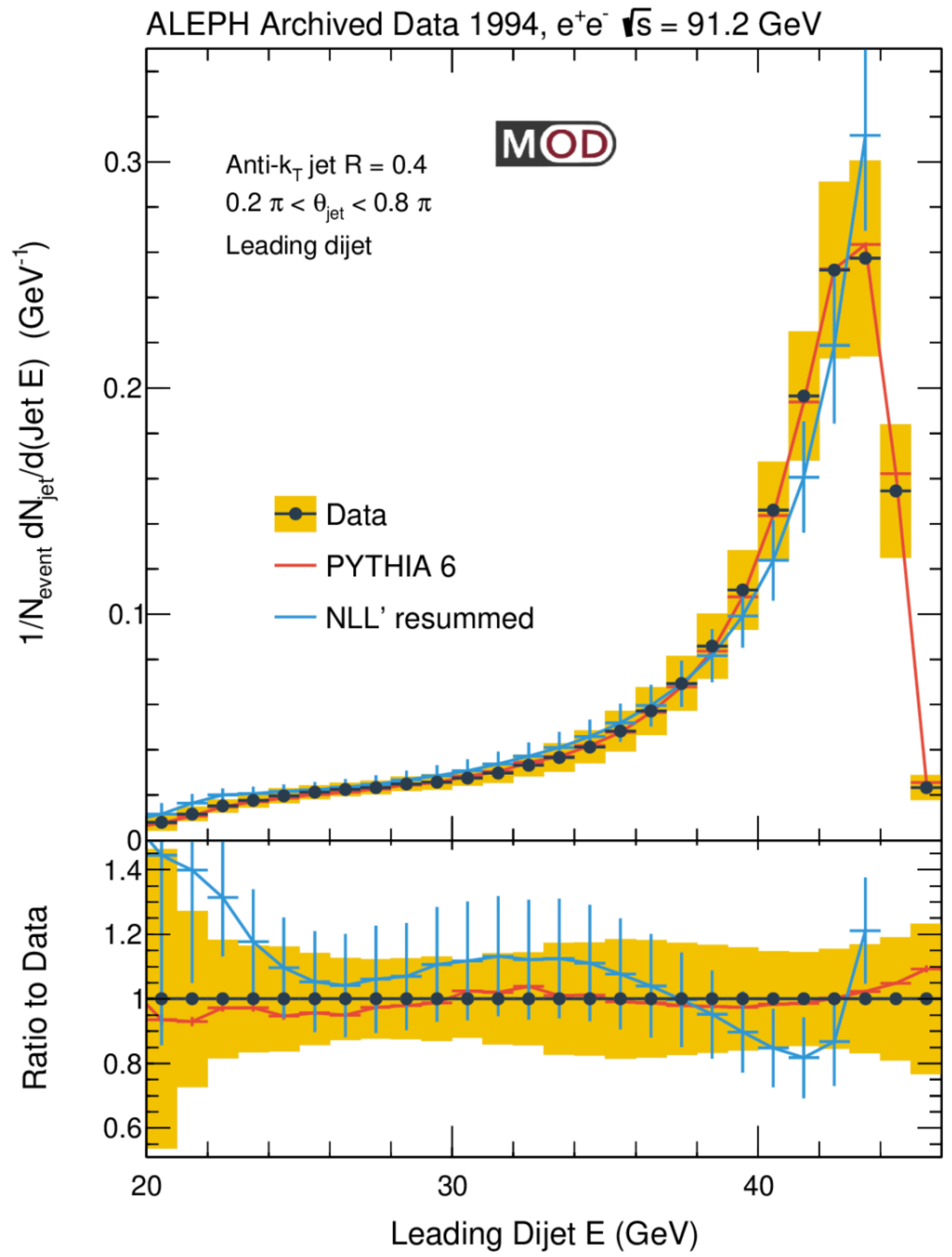
- Introduction
- Inclusive and leading jets
- Comparison to ALICE & LEP data

Conclusions

- Leading & subleading jets
- Related to a "direct" measurement of energy loss
- Quantitative comparisons to experimental results
- Higher precision can be achieved in the future







$$\langle z^{loss}_{r\,=\,0.1} \rangle = 0.21$$

$$\langle z^{loss}_{r\,=\,0.2} \rangle = 0.10$$