Recent jet substructure calculations and comparison to LHC data

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LoopFest XX, 05/12/22

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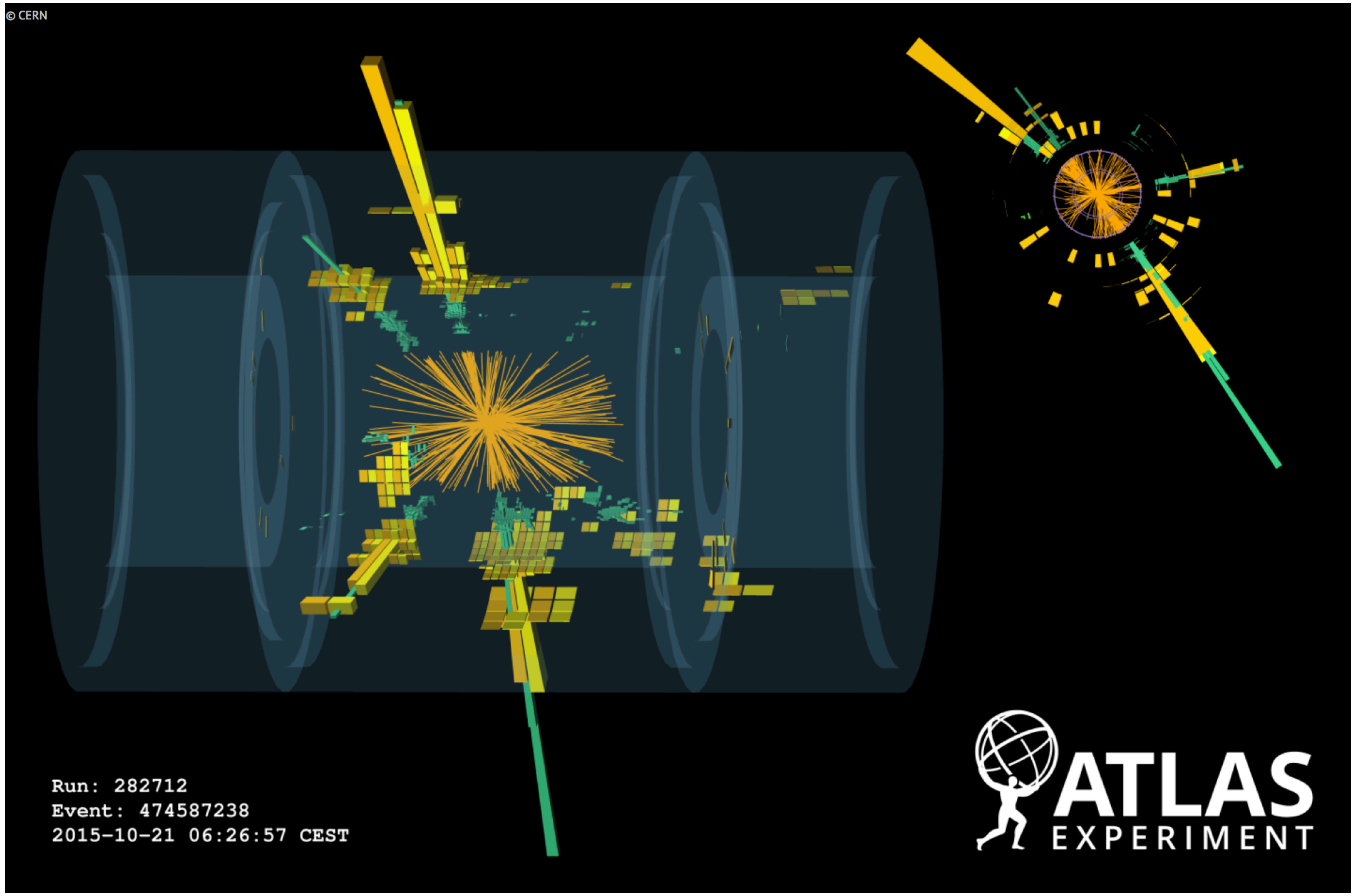
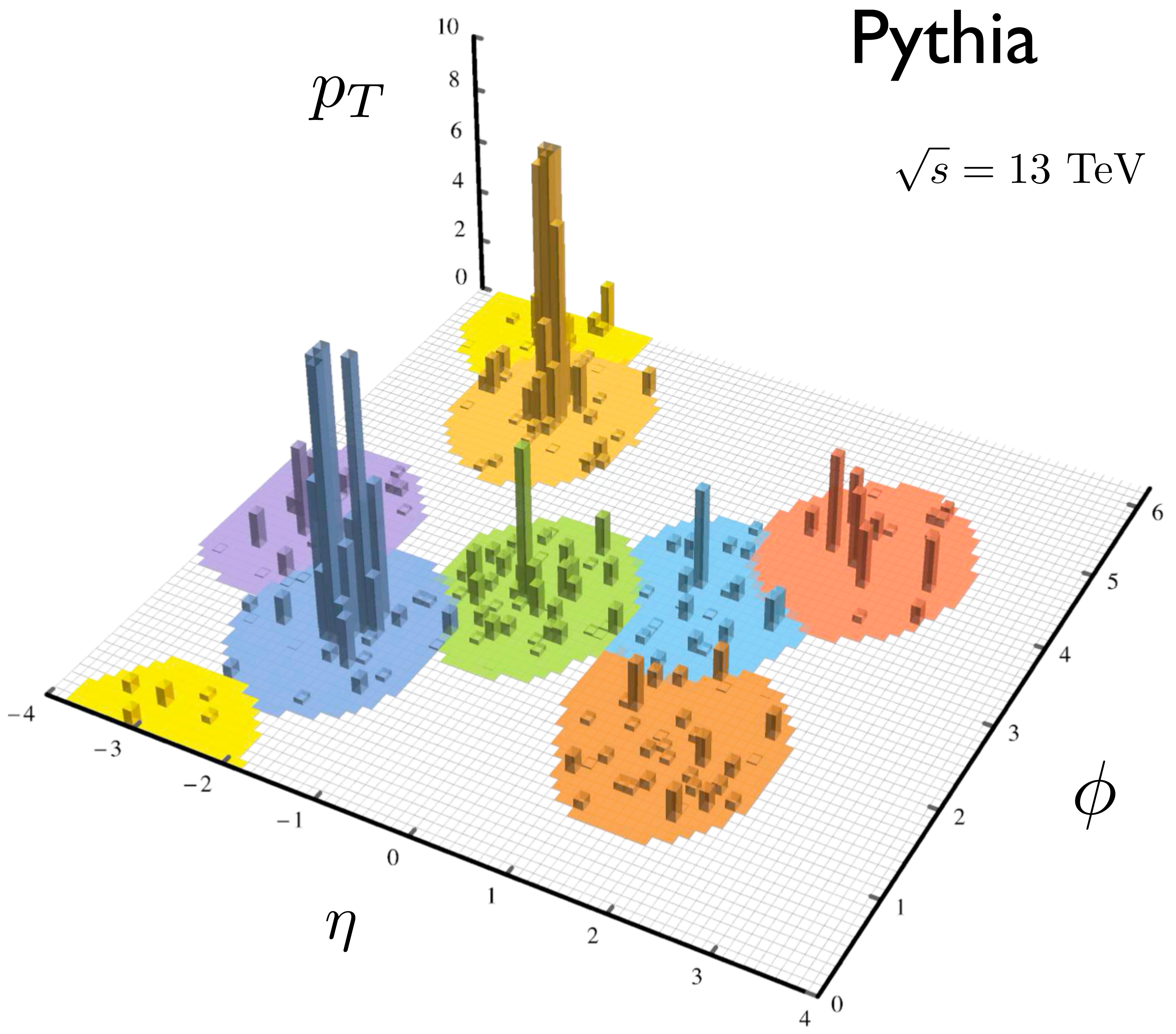
SIMONS FOUNDATION


© CERN
Run: 282712
Event: 474587238
2015-10-21 06:26:57 CEST
ATLAS
EXPERIMENT

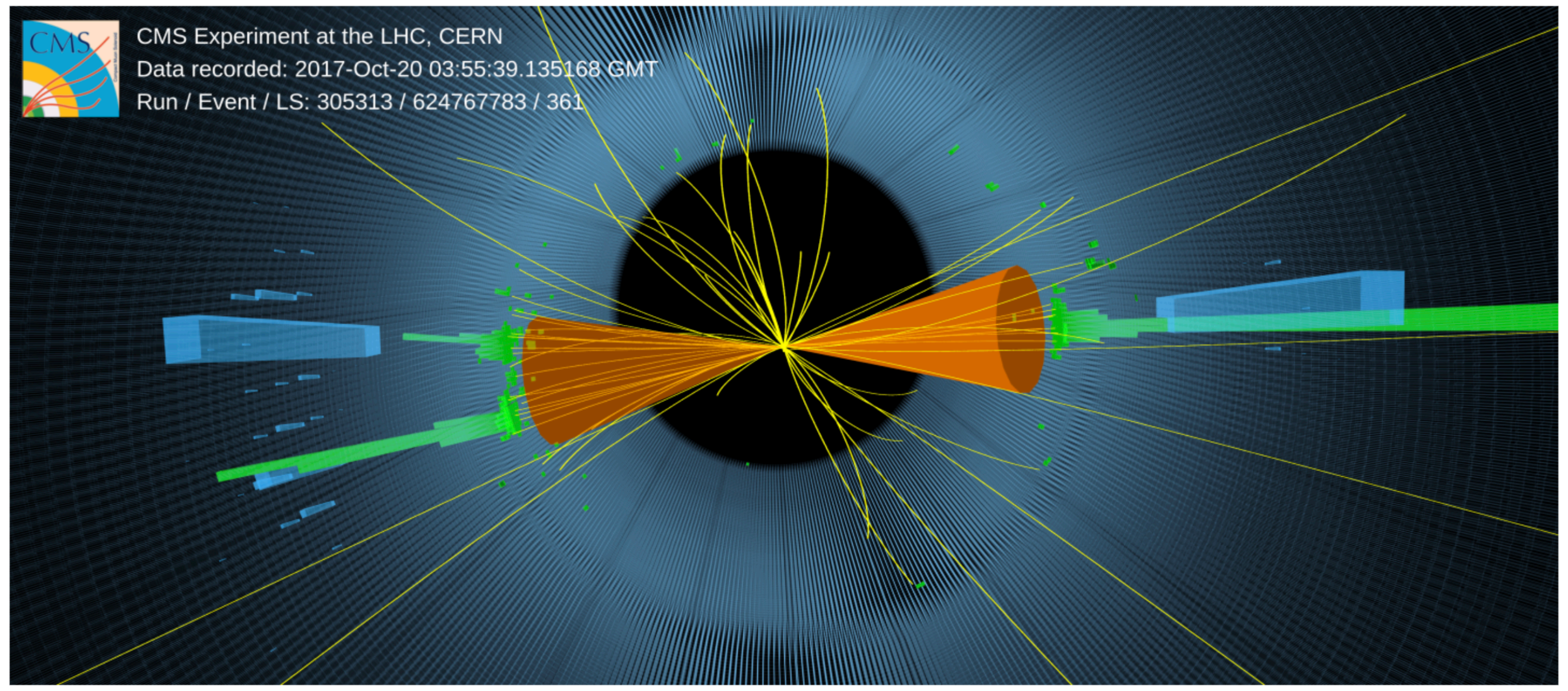

Pythia
$\sqrt{s} = 13$ TeV
p_T
η
ϕ

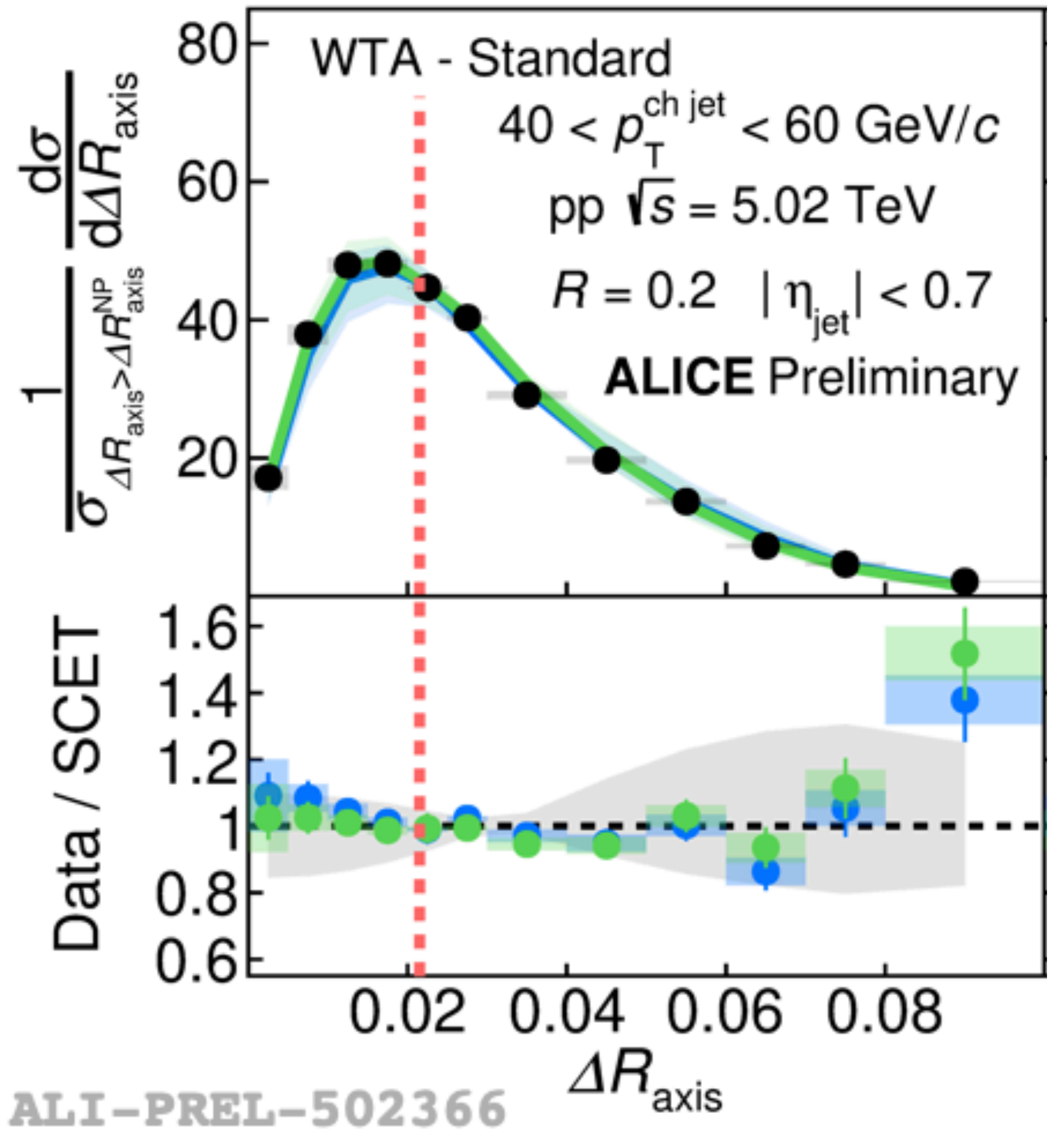
Jet substructure observables

- Probe the Standard Model & search for new physics
- Heavy-ion physics and Electron-Ion Collider
- Recent measurements of new observables
- Constraints on nonperturbative physics

  e.g. rapidity anomalous dimension

- Nonperturbative effects, UE make comparison challenging



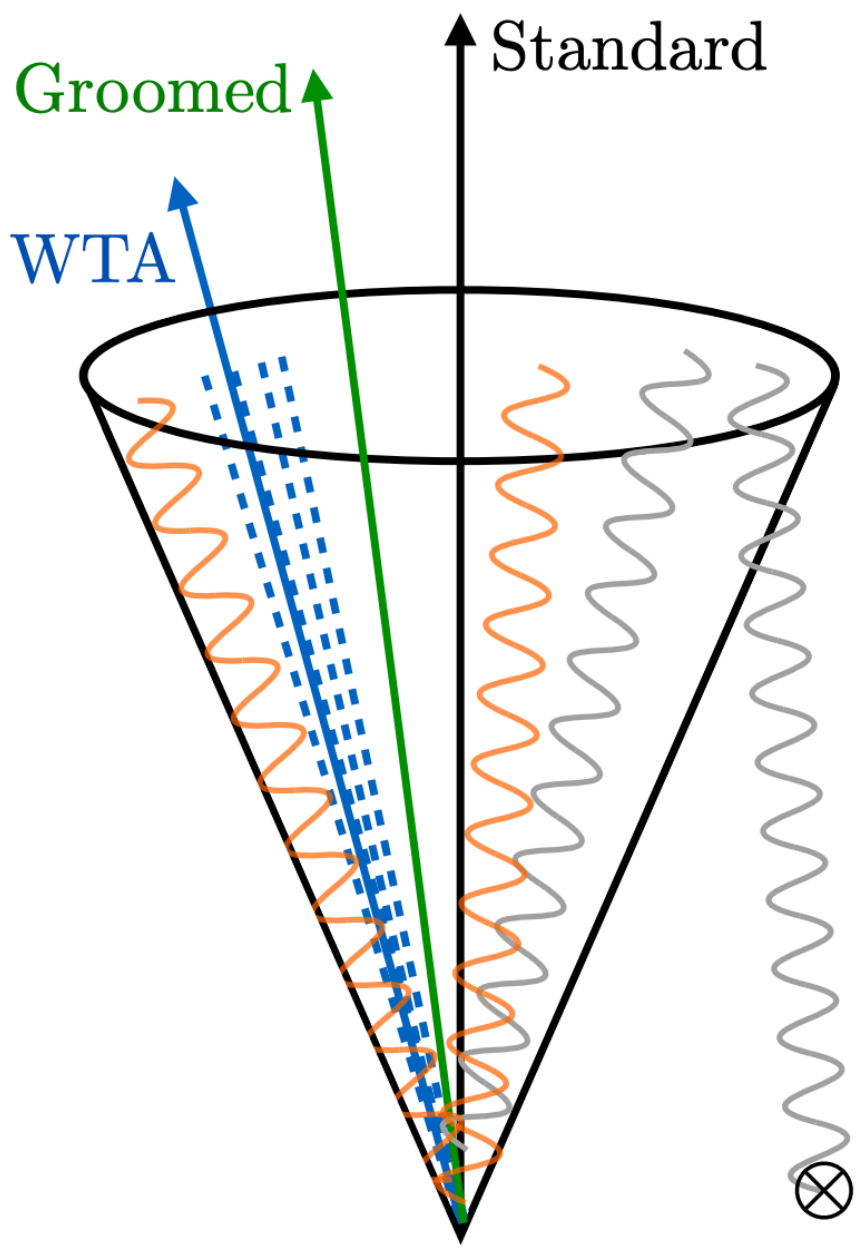


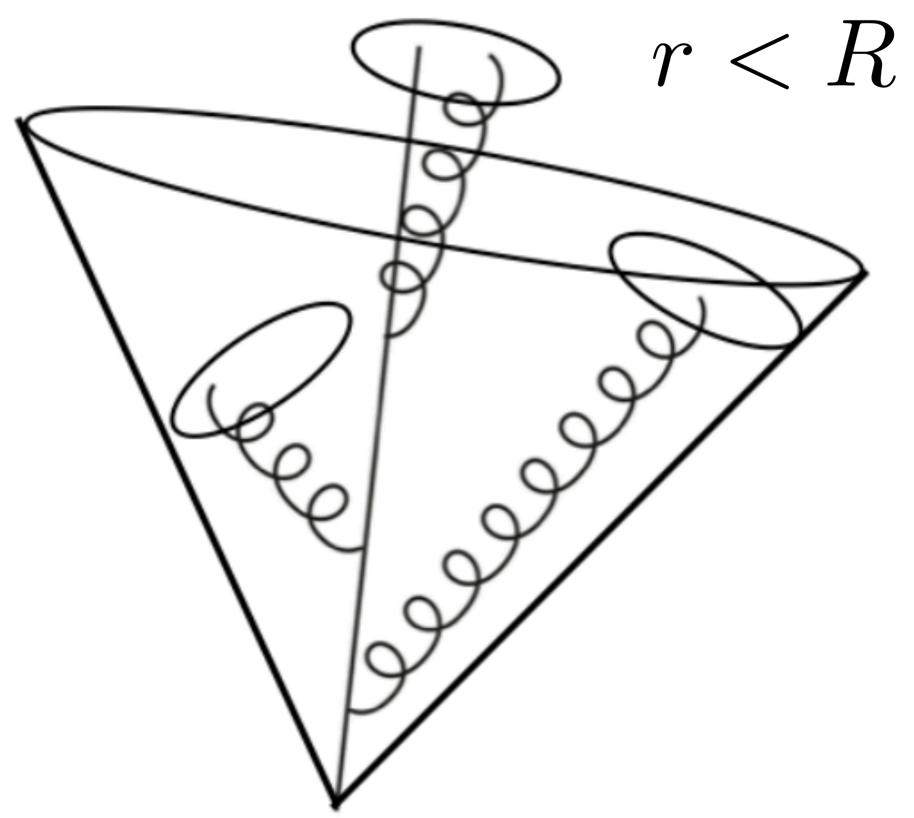
https://alice-figure.web.cern.ch/node/19522

Jet substructure observables

- Relative angles between different jet axes

Neill, FR, Sato `21





- Energy fraction carried by inclusive & leading subjets

Cal, Neill, FR, Waalewijn `20

- Comparison to recent ALICE & LEP data `22, `21

Outline

Angles between jet axes

Inclusive and leading subjets

Conclusions

Angles between jet axes

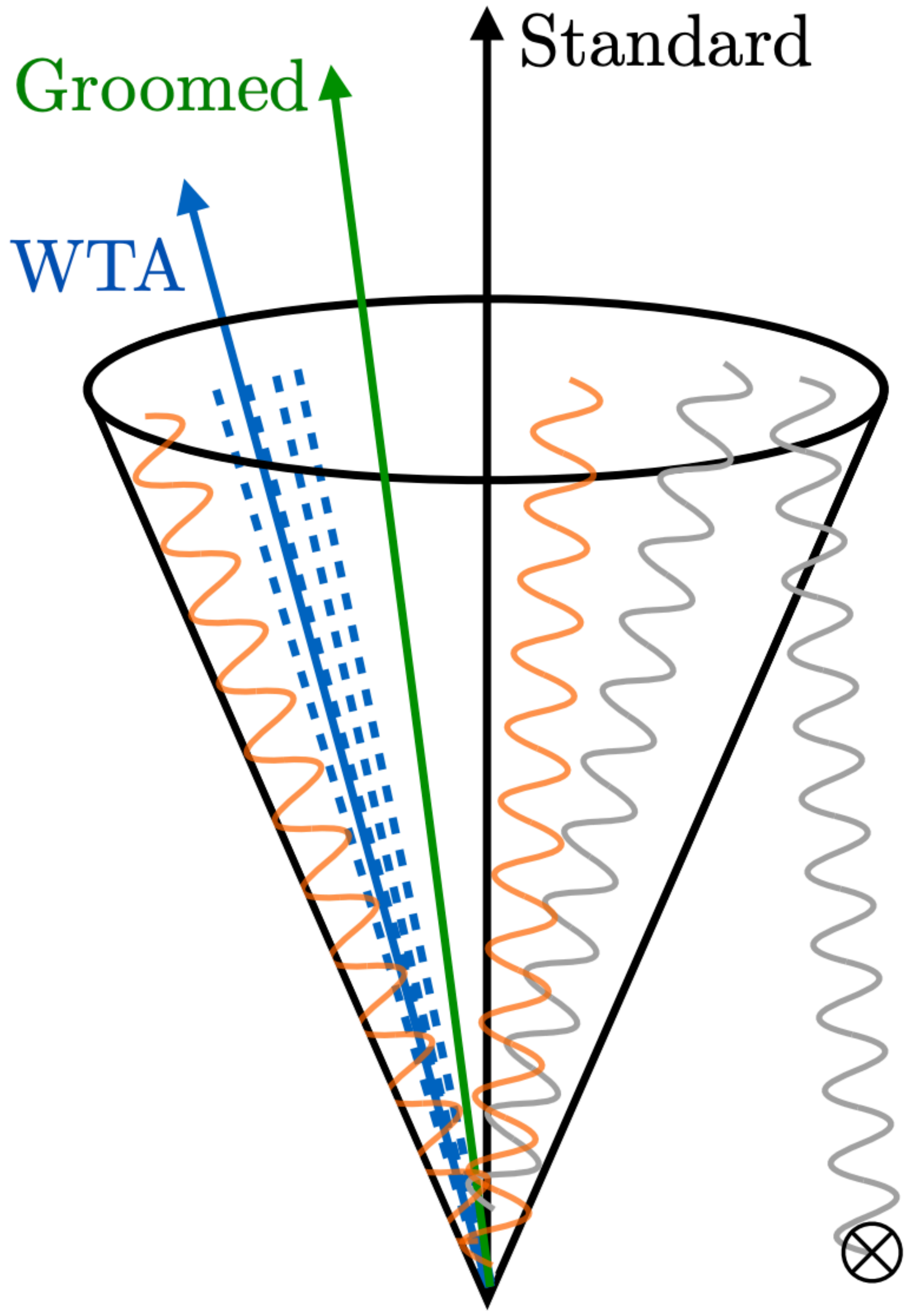
Cal, Neill, FR, Waalewijn `20

- Standard jet axis, E-scheme $p_{12}^\mu = p_1^\mu + p_2^\mu$
- Winner-Take-All (WTA)
  - Follow more energetic clustering
  - Insensitive to soft recoil
- Jet axis after removal of soft radiation, grooming

$$\frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R}\right)^\beta$$

Larkoski, Marzani, Soyez, Thaler `15

$\theta = |\vec{k}_\perp|/p_T$

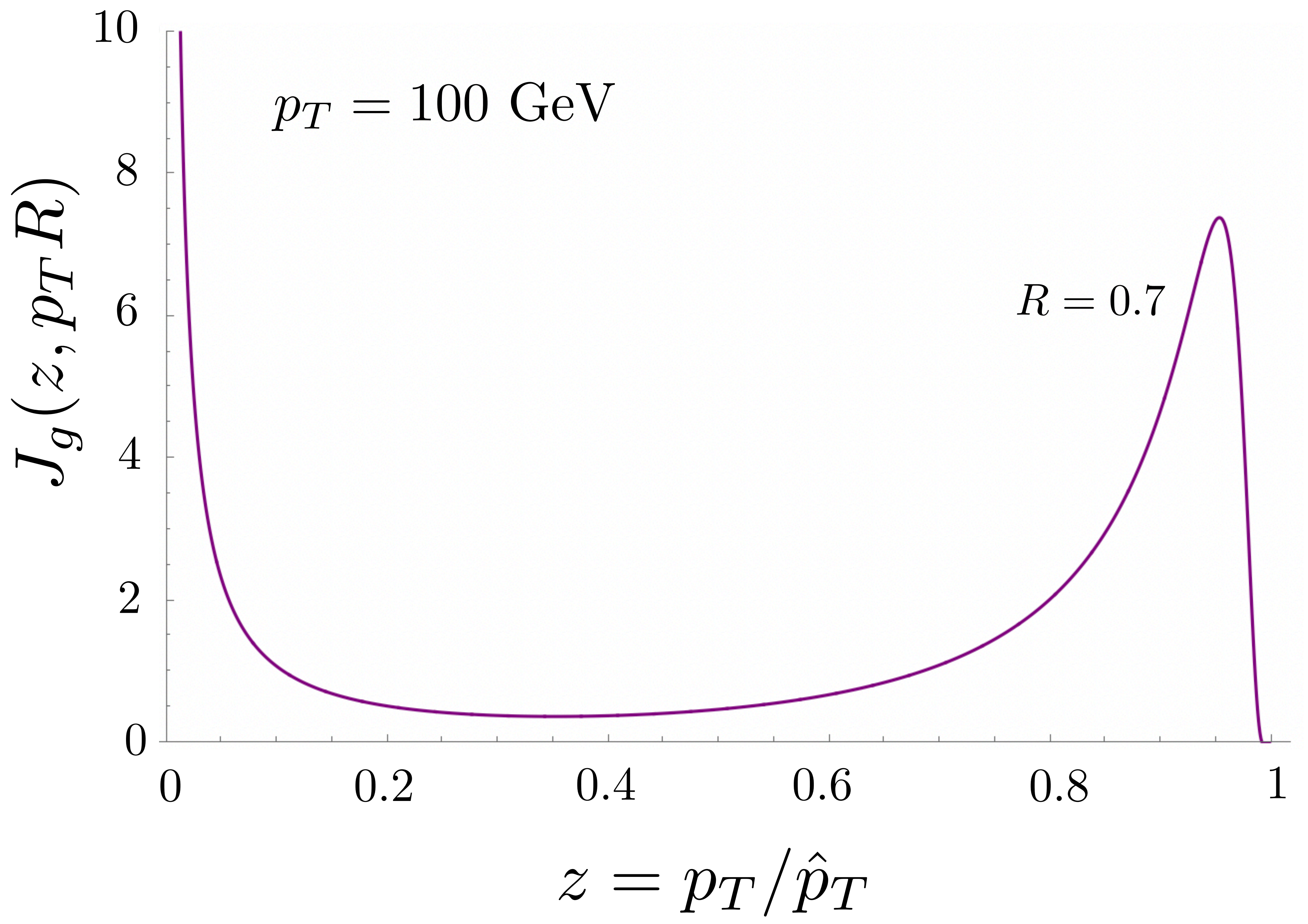


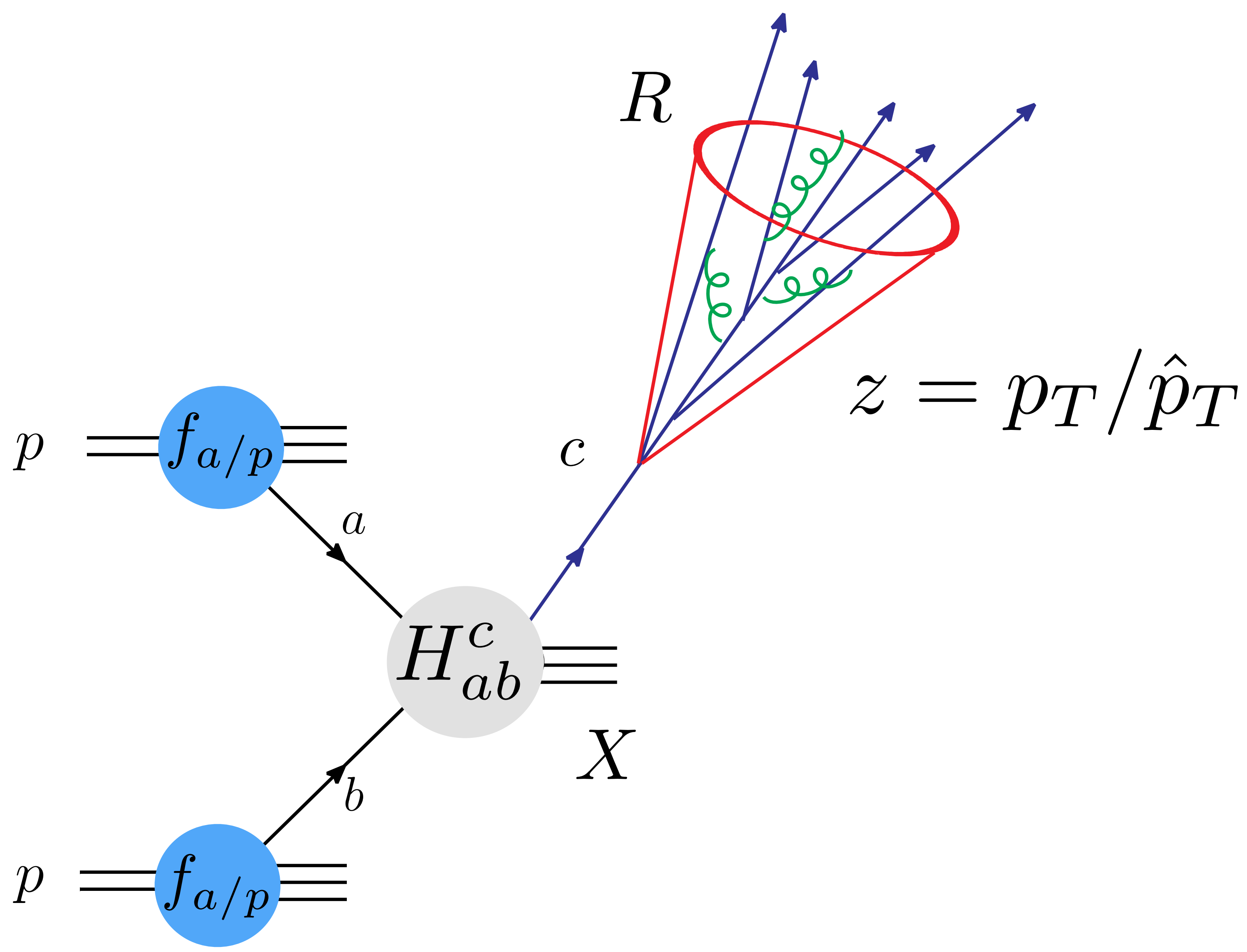
- Angles are measures of soft physics
- Hadronization correction relatively well under control

Collinear factorization for inclusive jets

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

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





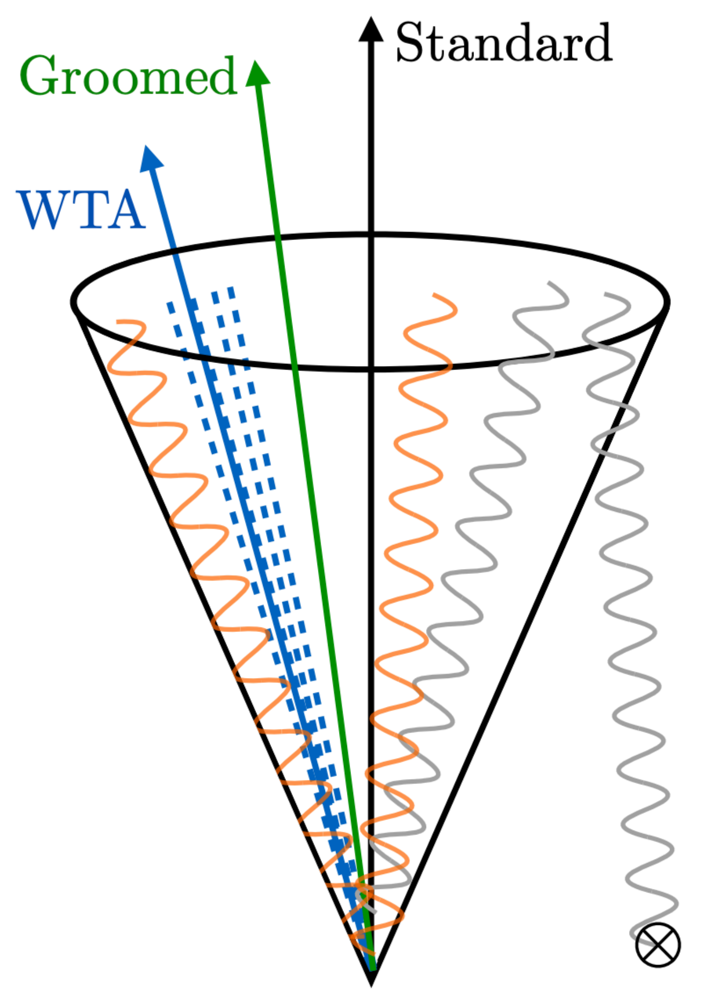
Dasgupta, Dreyer, Salam, Soyez `14
Mukherjee, Kaufmann, Vogelsang `15
Kang, FR, Vitev `16
Dai, Kim, Leibovich `16

Collinear factorization for inclusive jets

Cal, Neill, FR, Waalewijn `20

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

$$\frac{d\sigma^{pp\to \text{jet}\,X}}{d\eta\, dp_T\, dk_\perp} = f_{a/p} \otimes f_{b/p} \otimes H_{ab}^c \otimes_z \mathcal{G}_c(z, k_\perp) + \mathcal{O}(R^2)$$



- Angle between Standard & WTA axes

$$\Delta\mathcal{G}_q^{\text{ST,WTA}}(k_\perp, p_T R, \alpha_s(\mu)) = \frac{\alpha_s C_F}{\pi^2}\Theta\Big(k_\perp < \frac{p_T R}{2}\Big)\Big\{ -\frac{1}{2\mu^2}\mathcal{L}_1\Big(\frac{k_\perp^2}{\mu^2}\Big) + \frac{1}{\mu^2}\mathcal{L}_0\Big(\frac{k_\perp^2}{\mu^2}\Big)\Big[\ln\Big(\frac{p_T R}{\mu}\Big) + \ln\Big(1 - \frac{k_\perp}{p_T R}\Big) + \frac{3}{2}\frac{k_\perp}{p_T R} - \frac{3}{4}\Big] + \delta(k_\perp^2)\Big[-\ln^2\Big(\frac{p_T R}{\mu}\Big) + \frac{3}{2}\ln\Big(\frac{p_T R}{\mu}\Big) - \frac{3}{2}\ln 2 + \frac{\pi^2}{6} - \frac{3}{2}\Big]\Big\}$$

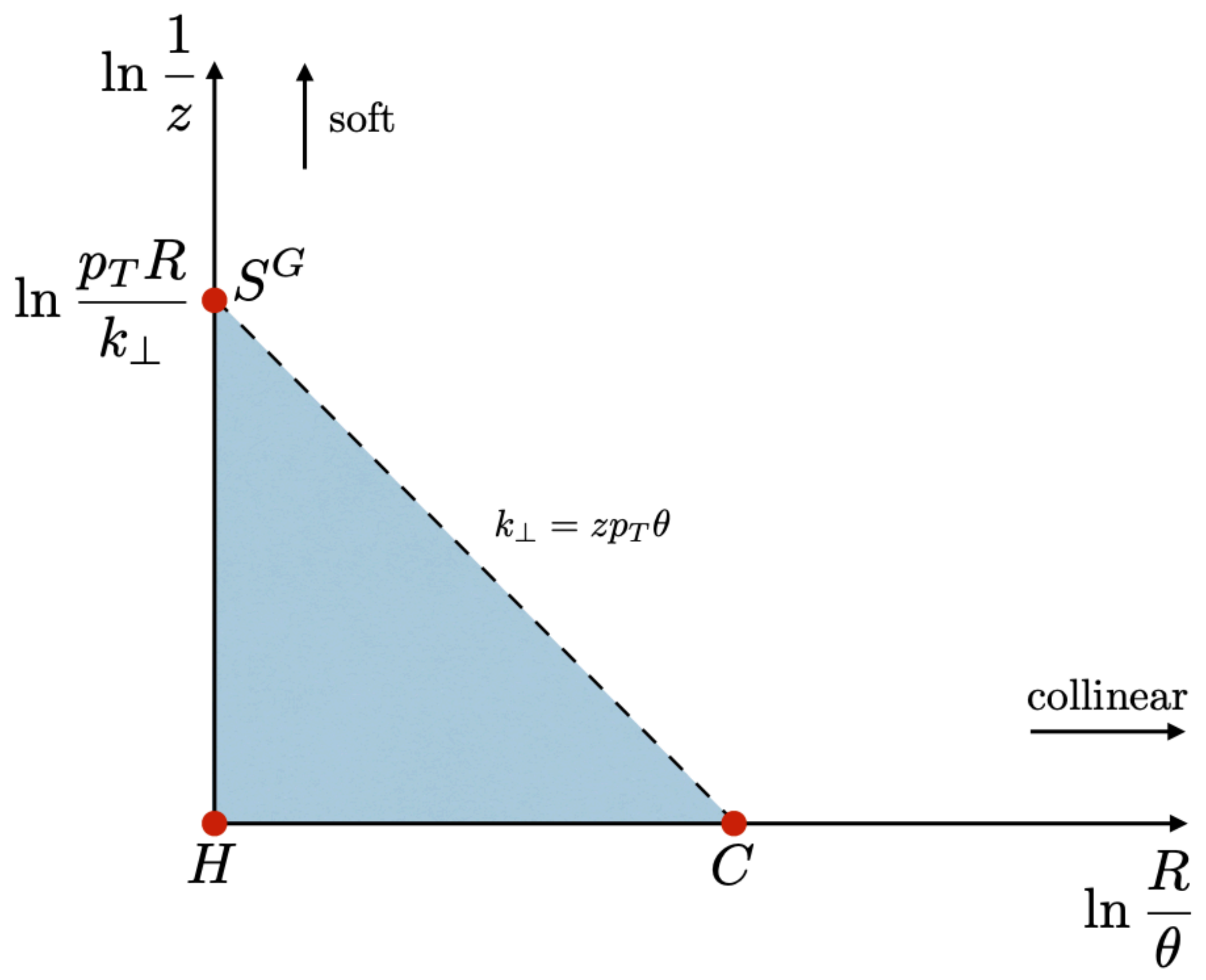
- Where $\mathcal{L}_n(x) = \Big[\frac{\ln^n x}{x}\Big]_+$
- 1-loop result
- Power corrections negligible

Collinear factorization for inclusive jets

Cal, Neill, FR, Waalewijn `20

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

$$\frac{d\sigma^{pp\to \text{jet}\, X}}{d\eta dp_T dk_\perp} = f_{a/p} \otimes f_{b/p} \otimes H_{ab}^c \otimes_z \mathcal{G}_c(z, k_\perp) + \mathcal{O}(R^2)$$



- Angle between Standard & WTA axes

$$\tilde{\mathcal{G}}_i^{\text{ST,WTA}}(k_\perp, p_T R, \alpha_s(\mu)) \overset{\text{NLL}'}{=} \tilde{H}_i(p_T R, \mu) \int d^2\vec{k}'_\perp C_i(k'_\perp, \mu, \nu) \int d^2\vec{k}''_\perp S_i^{\text{G}}(\vec{k}_\perp - \vec{k}'_\perp - \vec{k}''_\perp, \mu, \nu R) \times S_i^{\text{NG}}\left(\frac{k''_\perp}{p_T R}\right)$$

Collinear — Soft — Non-global

TMD factorization, SCET_{II}, but IRC safe; Solve numerically in b-space w/ b_* prescription

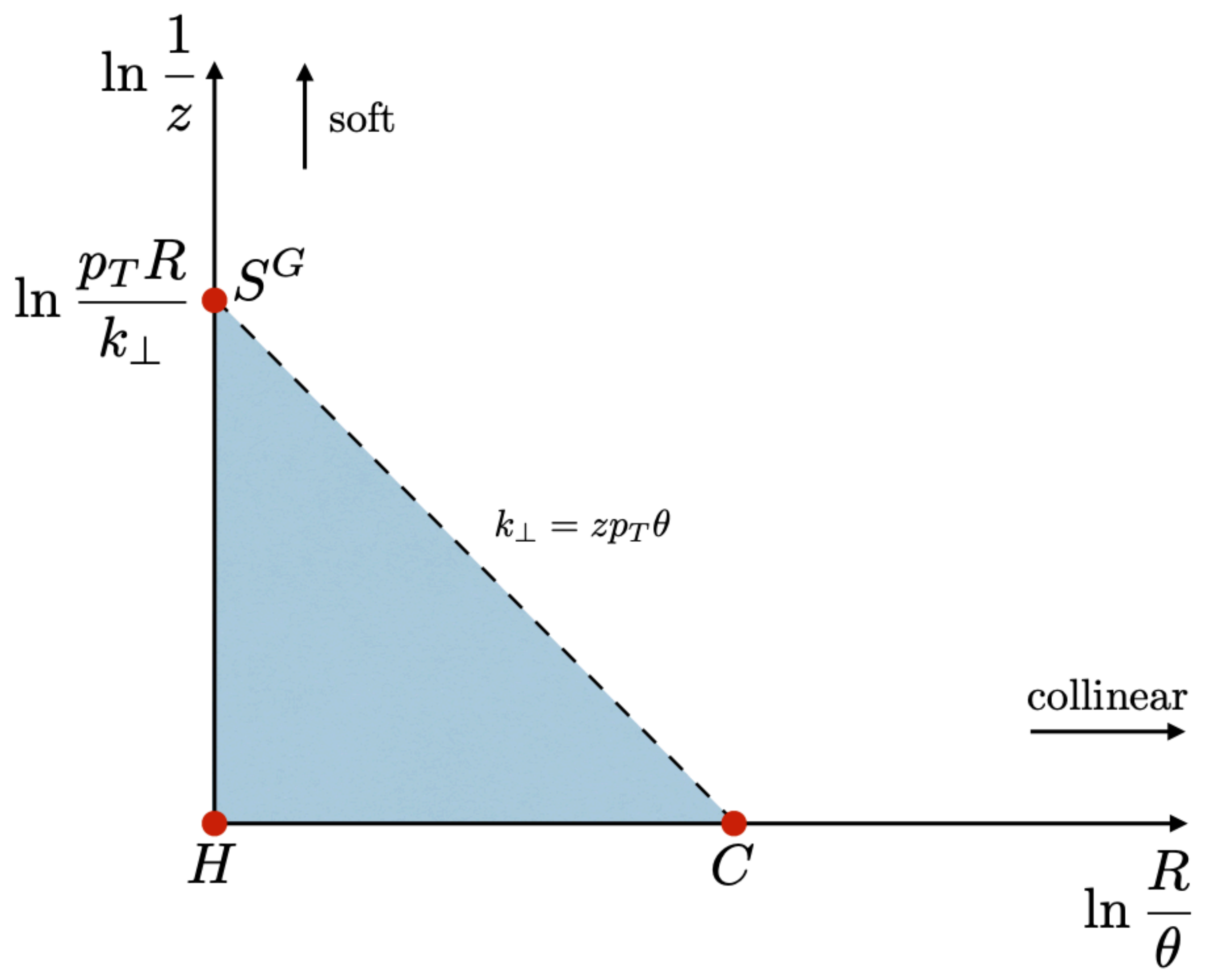
Collins, Soper, Sterman `85

Collinear factorization for inclusive jets

Cal, Neill, FR, Waalewijn `20

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

$$\frac{d\sigma^{pp\to\text{jet }X}}{d\eta dp_T dk_\perp} = f_{a/p} \otimes f_{b/p} \otimes H_{ab}^c \otimes_z \mathcal{G}_c(z, k_\perp) + \mathcal{O}(R^2)$$



- Angle between Standard & WTA axes

$$\tilde{\mathcal{G}}_i^{\text{ST,WTA}}(k_\perp, p_T R, \alpha_s(\mu)) \overset{\text{NLL}'}{=} \tilde{H}_i(p_T R, \mu) \int d^2\vec{k}'_\perp C_i(k'_\perp, \mu, \nu) \int d^2\vec{k}''_\perp S_i^{\text{G}}(\vec{k}_\perp - \vec{k}'_\perp - \vec{k}''_\perp, \mu, \nu R) \times S_i^{\text{NG}}\left(\frac{k''_\perp}{p_T R}\right)$$

Collinear Soft Non-global

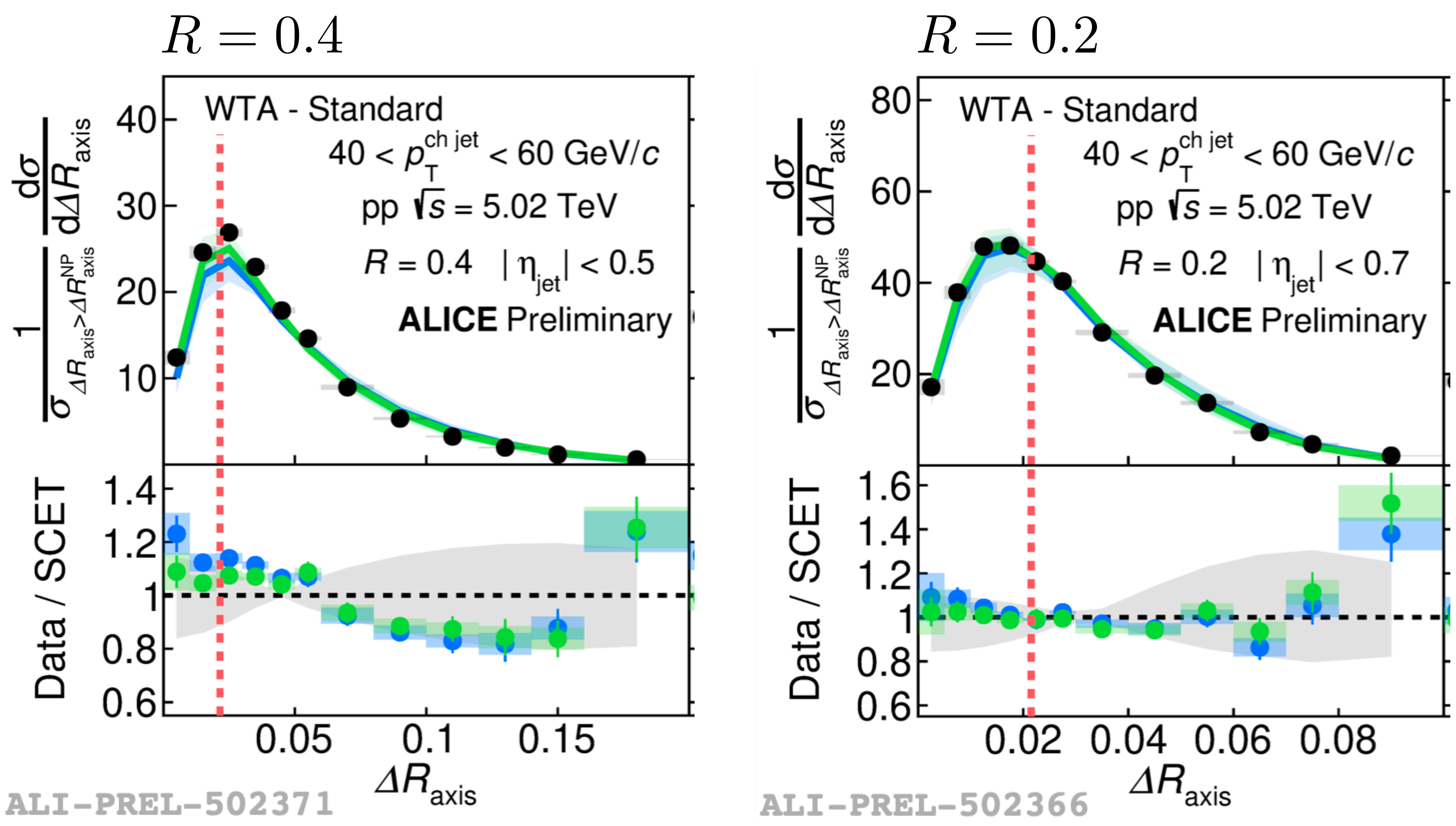
- Grooming requires additional resummation & multi-differential calculation in R_g

Comparison to ALICE data

Cal, Neill, FR, Waalewijn `20

- Theory corrected to charged-particle level ➝ underlying event and charged vs. full jets
- Avoids mathematical instabilities (ill-posed inverse problem)
- Model dependence on theory side, which may be easier updated later on

Angle between Standard & WTA axes



Comparison to ALICE data

Cal, Neill, FR, Waalewijn `20

Standard & WTA,
Groomed & WTA axes

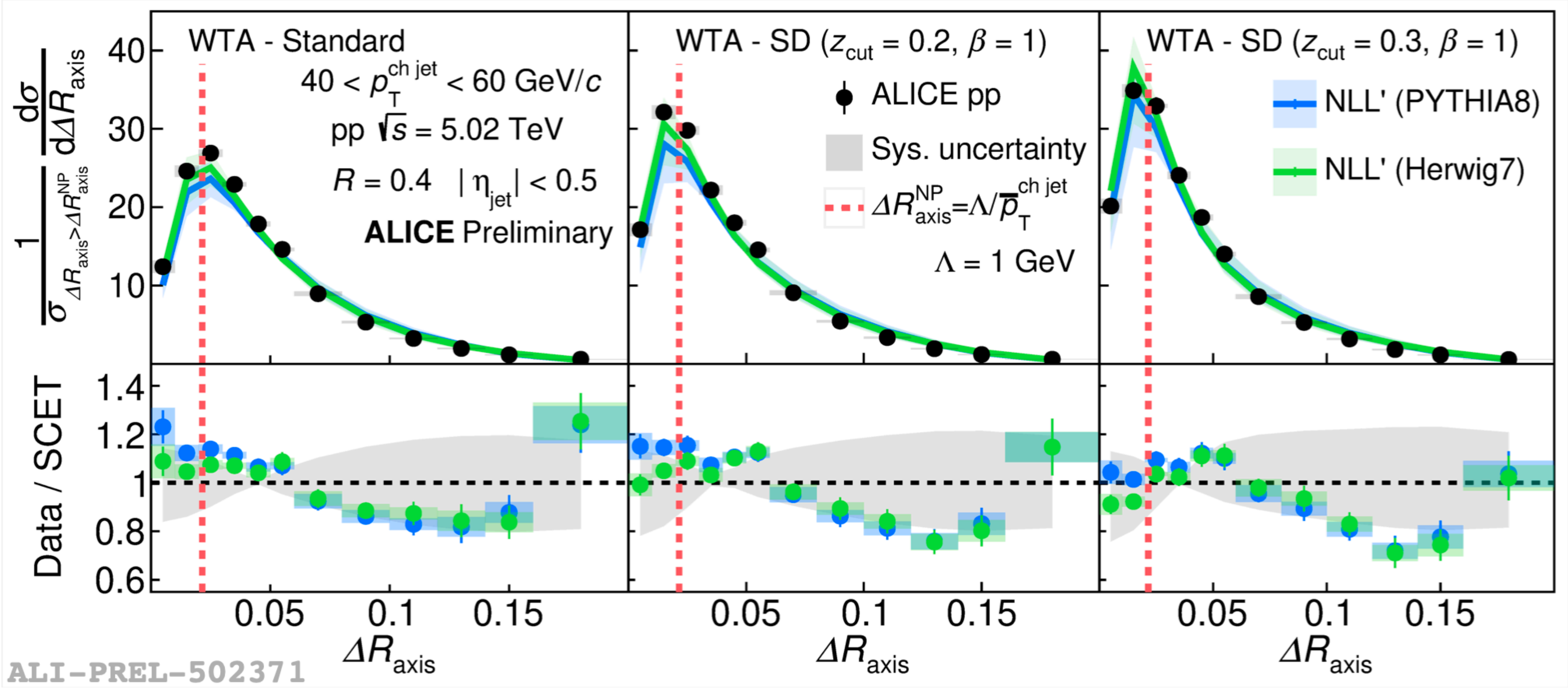
- Non-perturbative input

$$g_K(b_\perp, b_\perp^{\max}) = g_2(b_\perp^{\max}) b_\perp^2$$

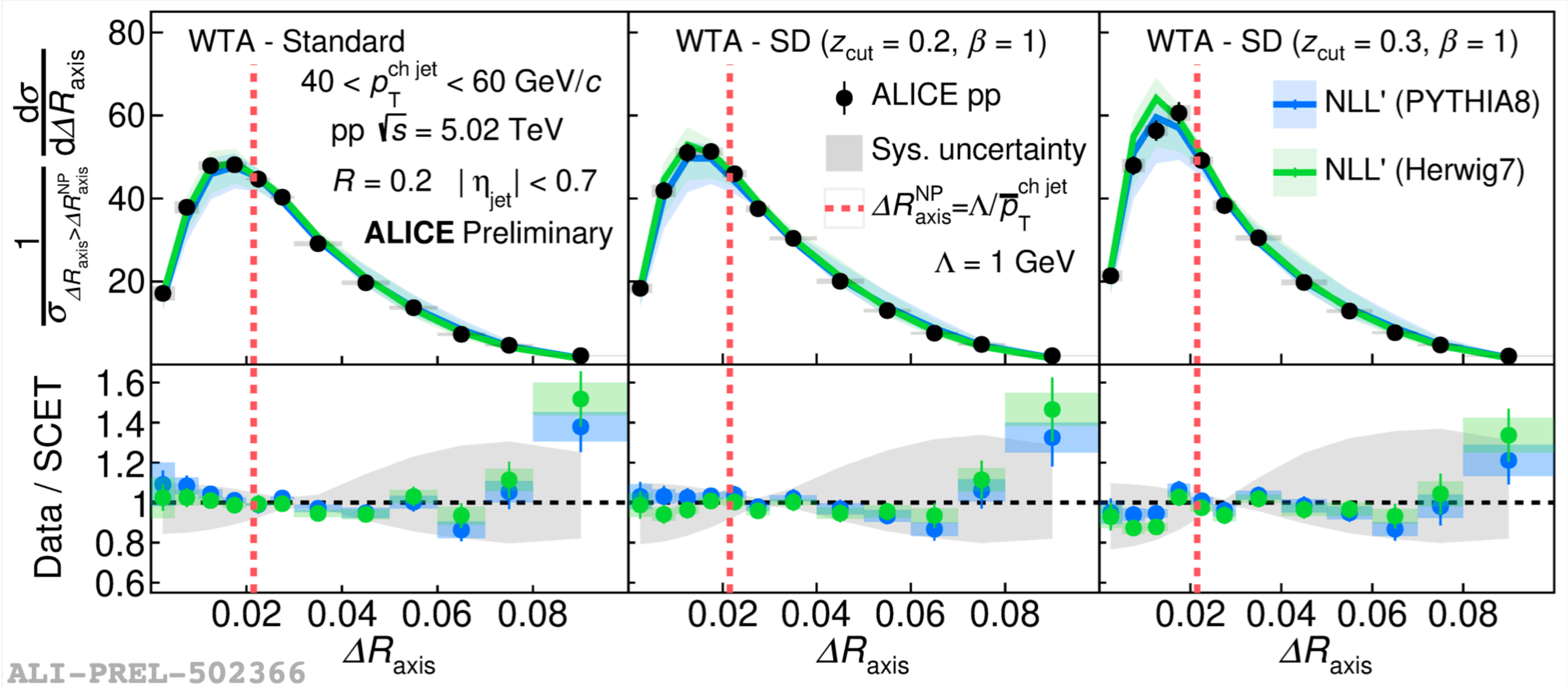
Konychev, Nadolsky `06

- Lattice QCD results *see Shanahan et al.*
- Best we can do w/o lattice results for real-time correlators
- Overall good agreement!

$R = 0.4$



$R = 0.2$



with grooming

Outline

Angles between jet axes

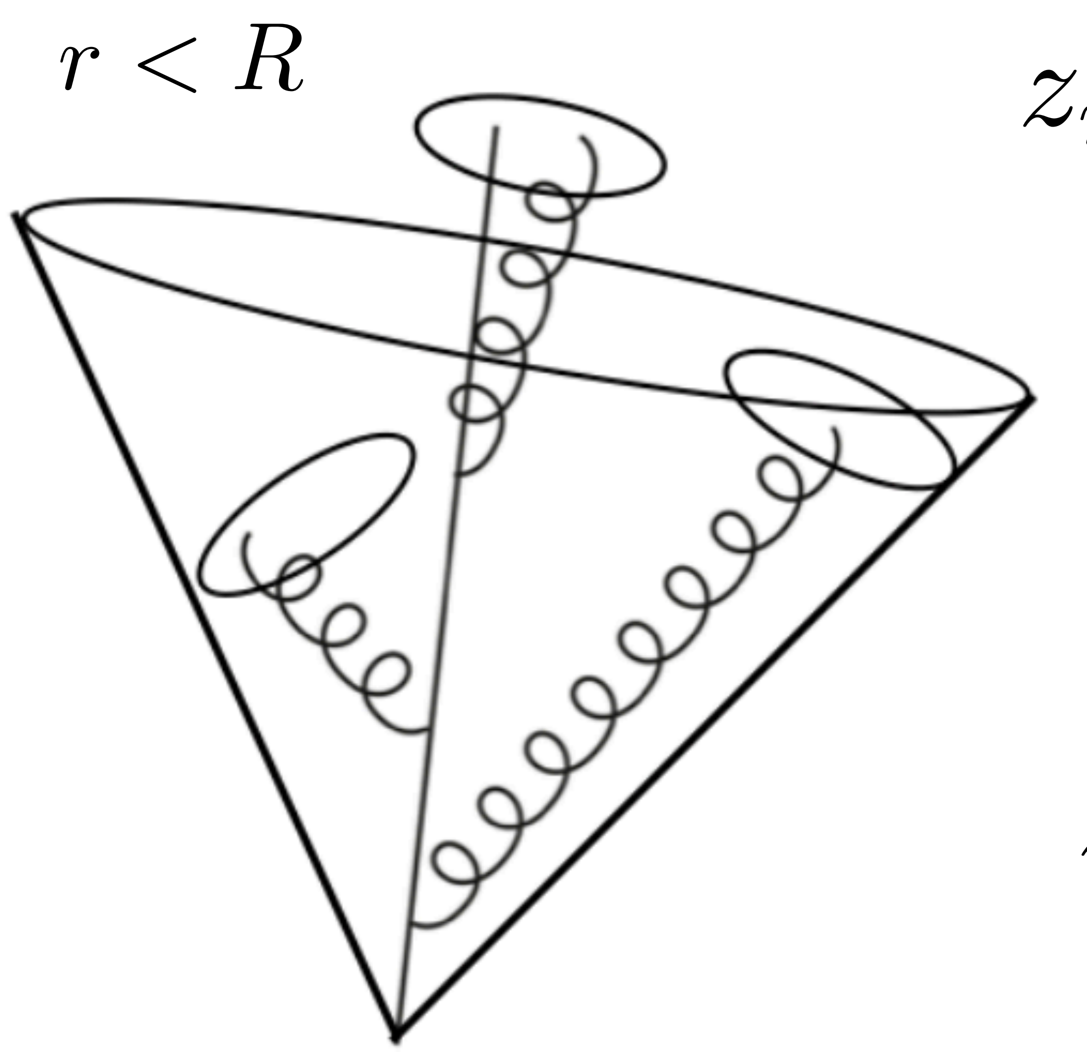
Inclusive and leading subjets

Conclusions

Inclusive and leading subjets

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

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



Longitudinal momentum of subjets

$$z_r = p_T^r / p_T$$

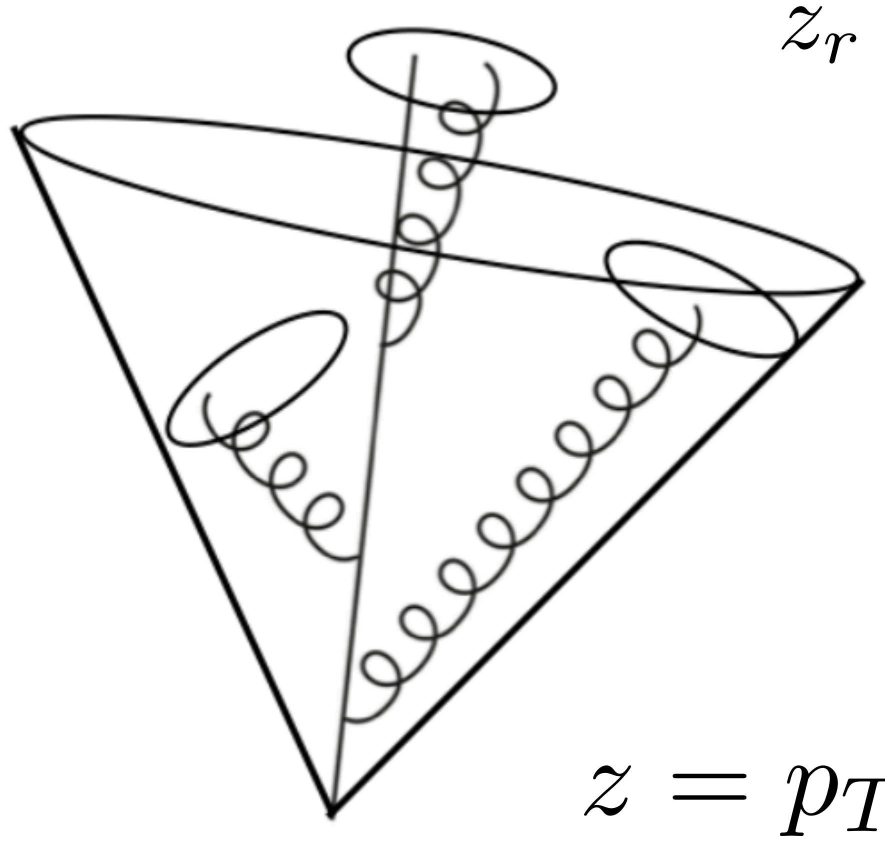
$$z = p_T / \hat{p}_T$$

Dasgupta, Dreyer, Salam, Soyez `14
Dai, Kim, Leibovich `16
Scott, Waalewijn `20
Neill, FR, Sato `21

Inclusive and leading subjets

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

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

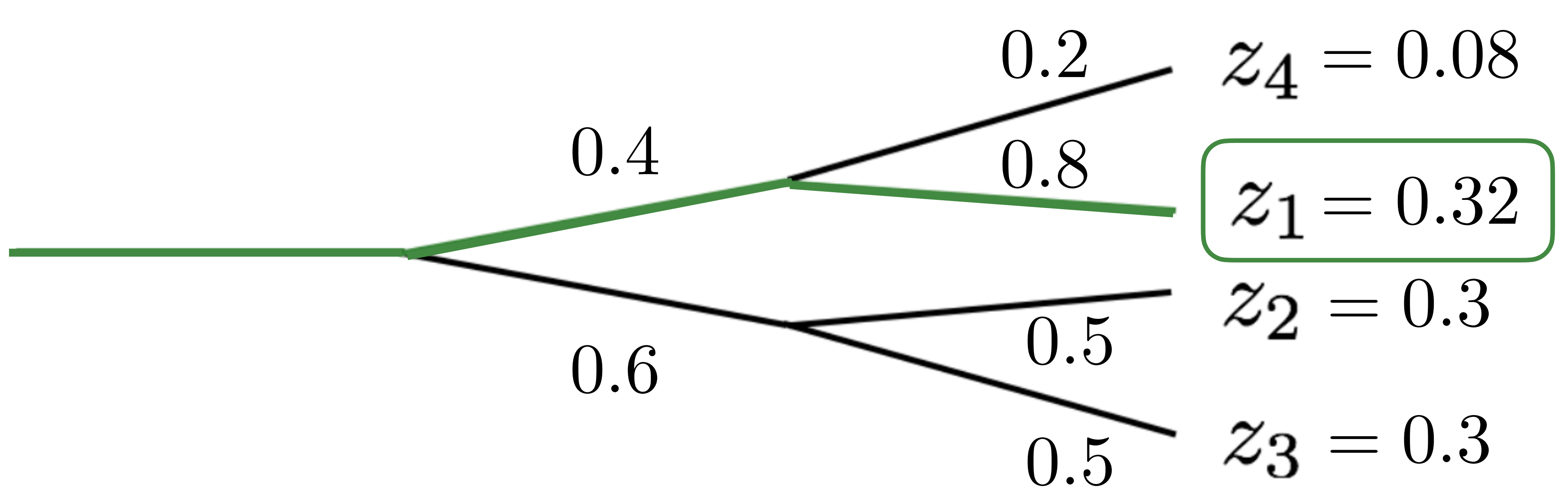


- Differences between inclusive and leading jets

  1. DGLAP vs. non-linear evolution

$$\mu\frac{d}{d\mu}\mathcal{J}_i(z_{i1}, QR, \mu) = \frac{1}{2}\sum_{jk}\int dz\, dz_{j1} dz_{k1} \frac{\alpha_s(\mu)}{\pi} P_{i\to jk}(z)\; \mathcal{J}_j(z_{j1}, QR, \mu)\; \mathcal{J}_k(z_{k1}, QR, \mu)$$
$$\times\, \delta(z_{i1} - \max\{z z_{j1}, (1-z) z_{k1}\})$$

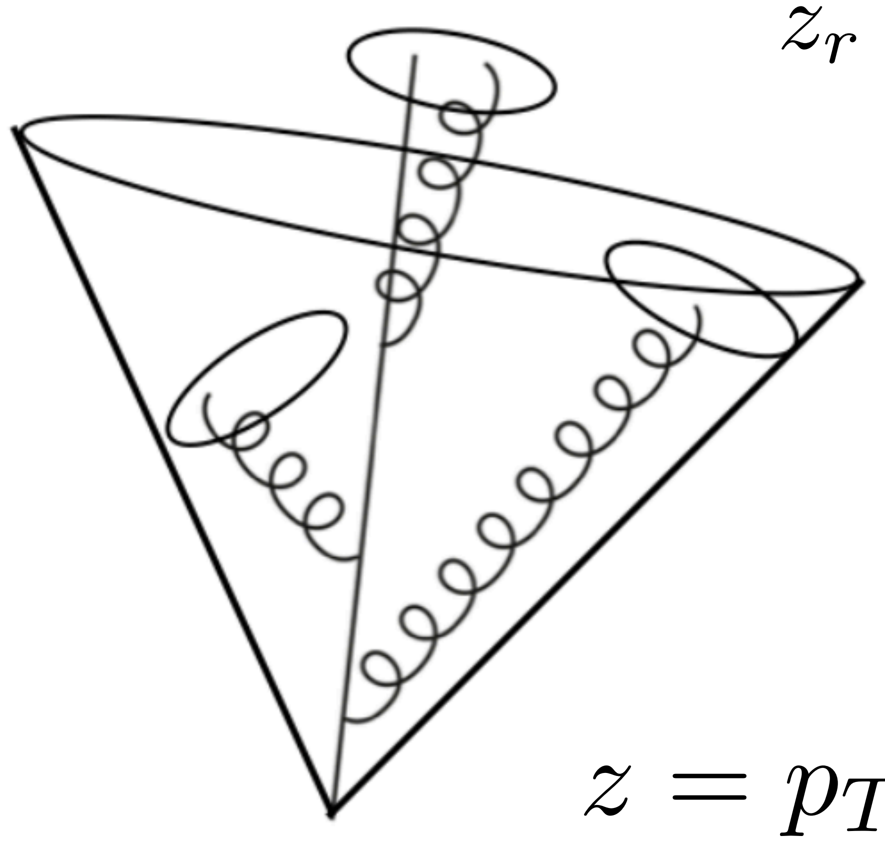
→ Solve with a parton shower



Inclusive and leading subjets

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

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



$z_r = p_T^r / p_T$

$z = p_T / \hat{p}_T$

- Differences between inclusive and leading jets

1. DGLAP vs. non-linear evolution

2. Factorization structure

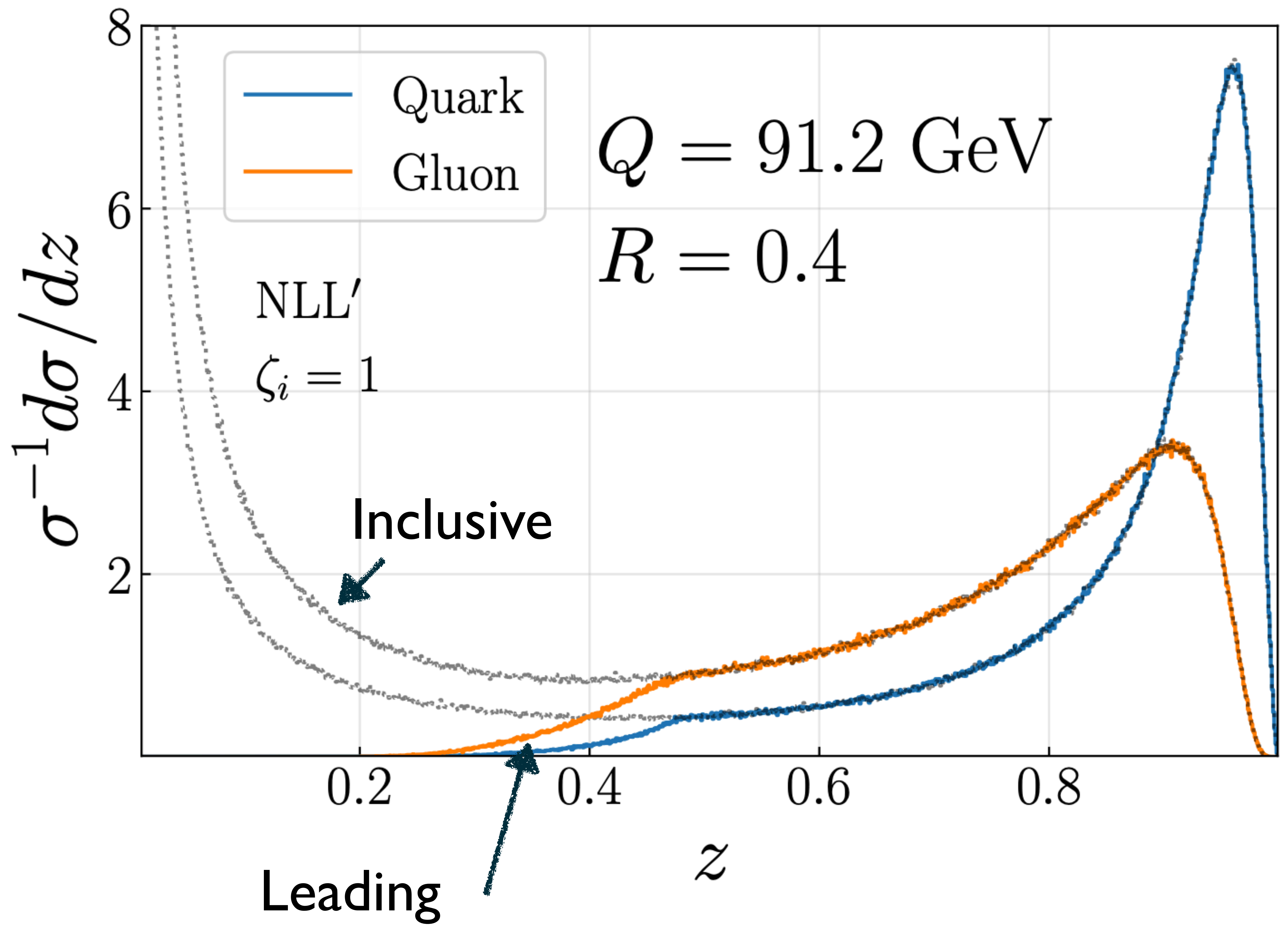
$$\frac{d\sigma^{(0)}_{pp\to\text{jet}_1+X}}{dp_{T1}} = \sum_{ij} \int d\hat{p}_{Ti}\, d\hat{p}_{Tj} \int dz_i\, dz_j\, \mathcal{H}_{ij}^{(0)}(\hat{p}_{Ti}, \hat{p}_{Tj}, \mu)$$

$$\times\ \mathcal{J}_i(z_i, \hat{p}_{Ti}R, \mu)\ \ \mathcal{J}_j(z_j, \hat{p}_{Tj}R, \mu)\ \times \delta(p_{T1} - \max\{z_i\hat{p}_{Ti}, z_j\hat{p}_{Tj}\})$$

Inclusive and leading subjets

Neill, FR, Sato `21

- Jet radius
- Threshold resummation



Inclusive and leading subjets

Neill, FR, Sato `21

- Jet radius
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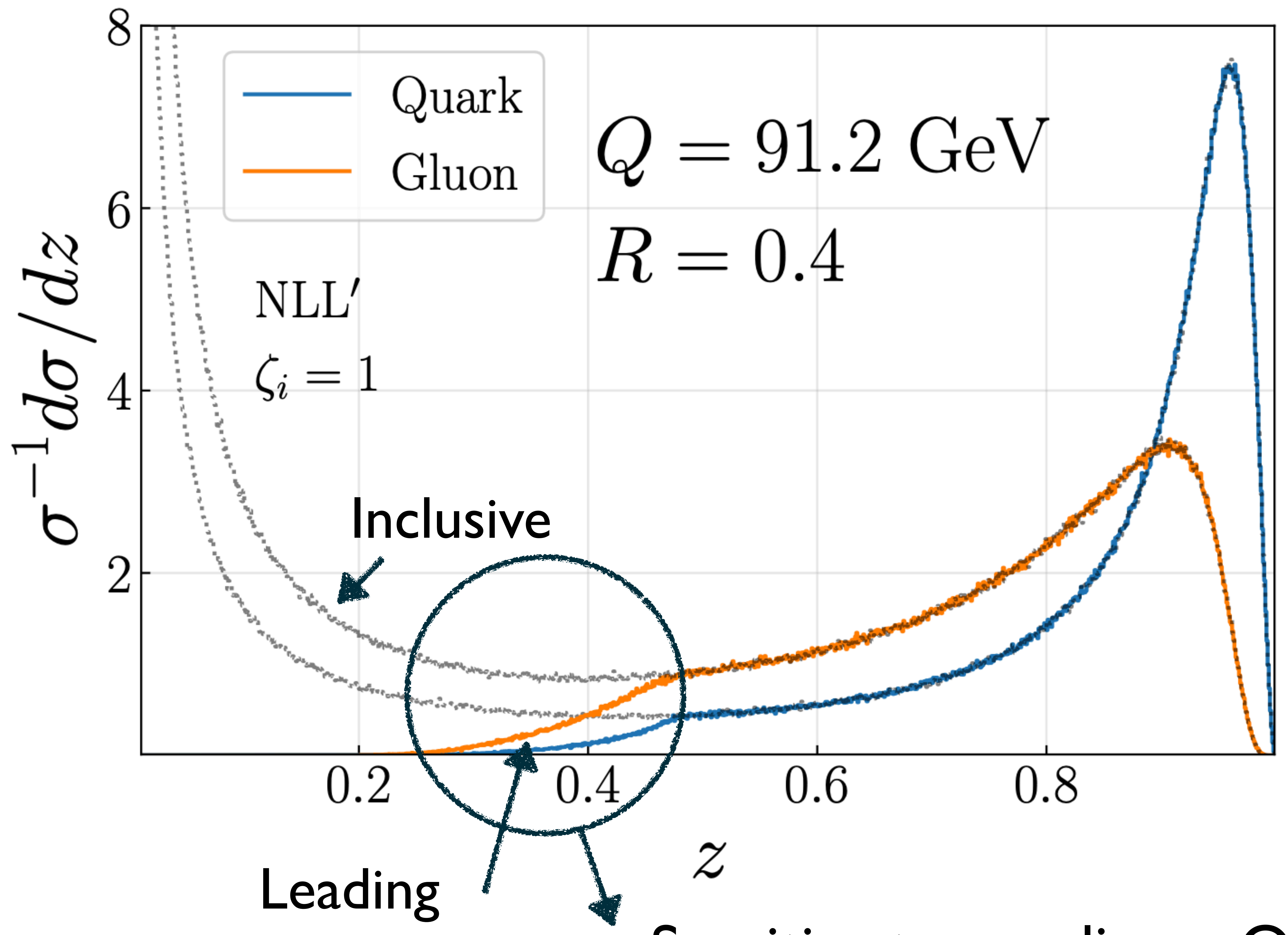
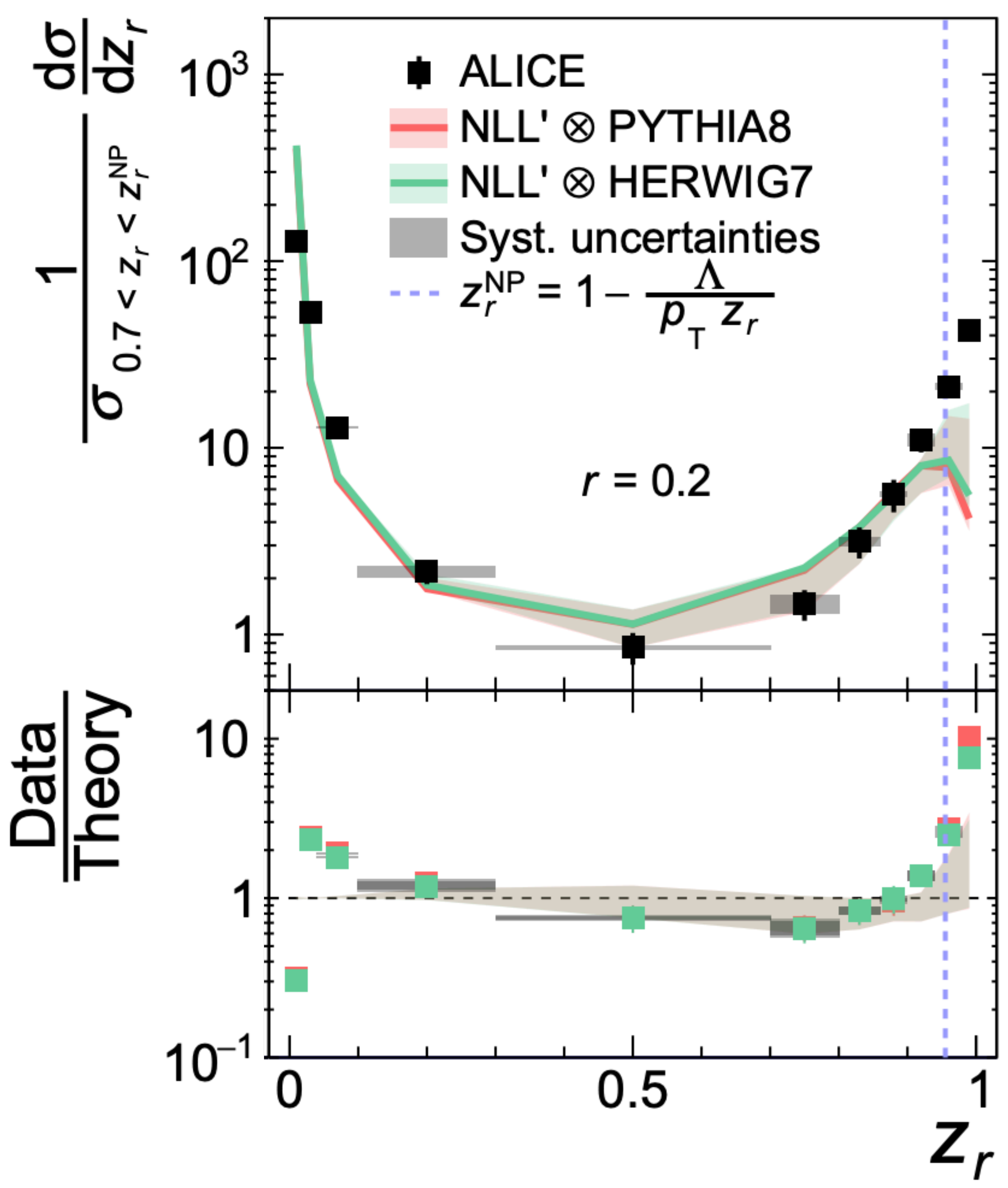
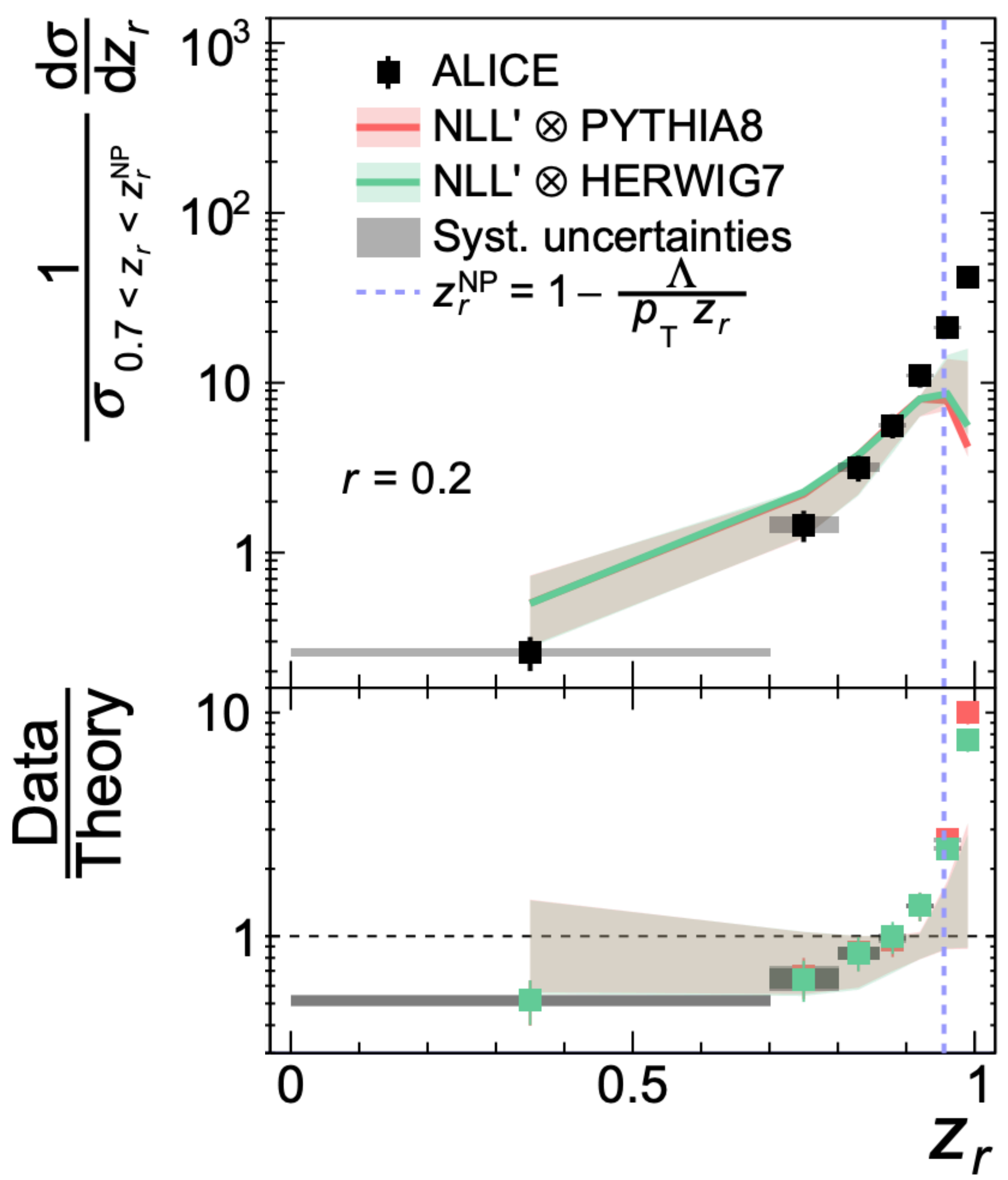


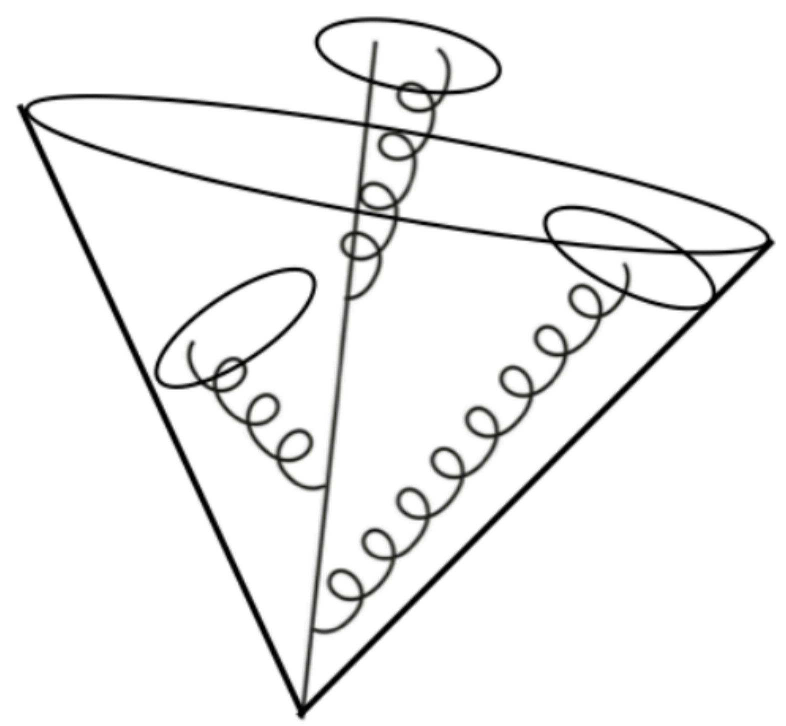
Sensitive to non-linear QCD dynamics

Comparison to ALICE data

ALICE, 2204.10270





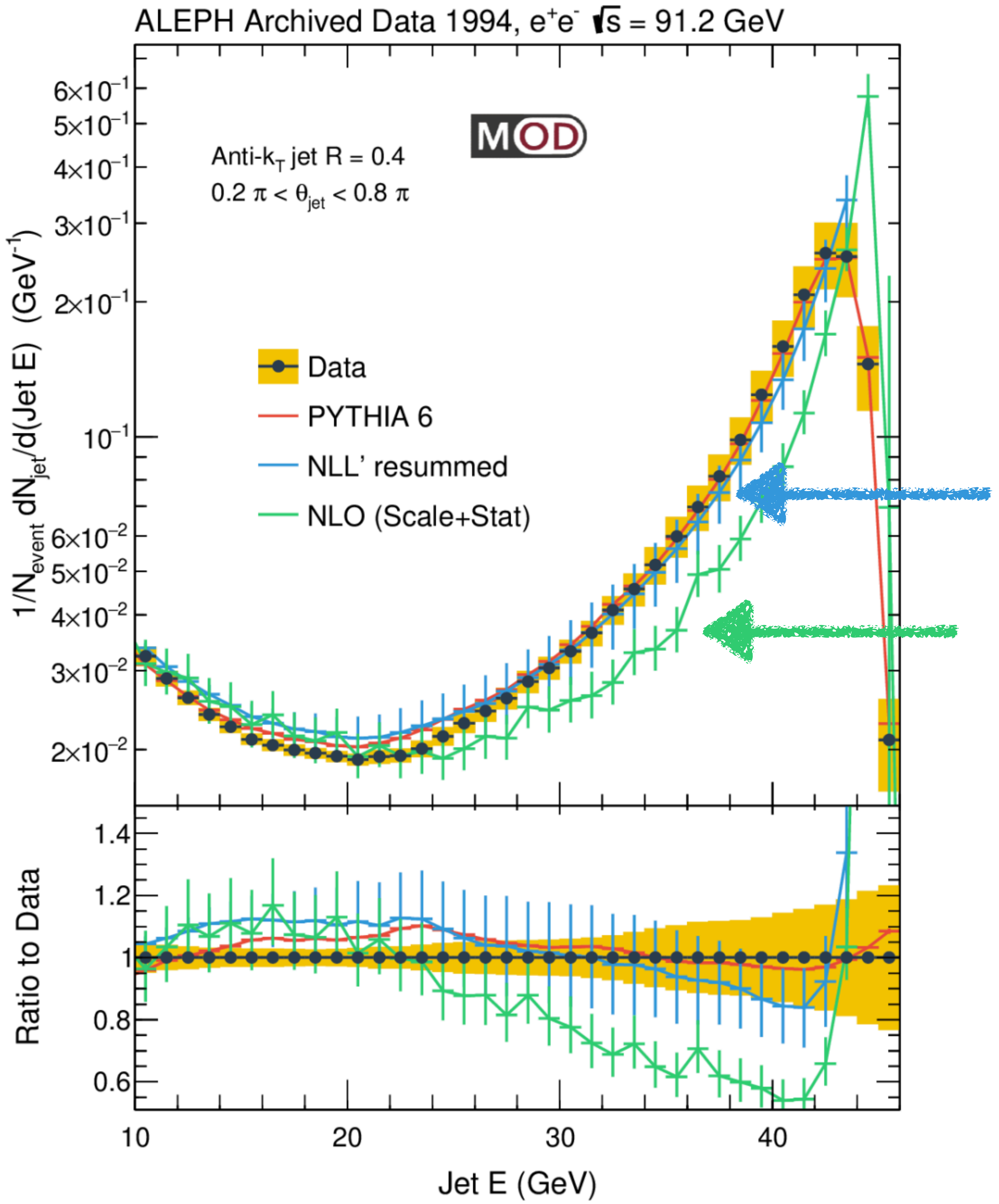


Inclusive subjets

Leading subjets

Comparison to LEP data

ALEPH, 2111.09914

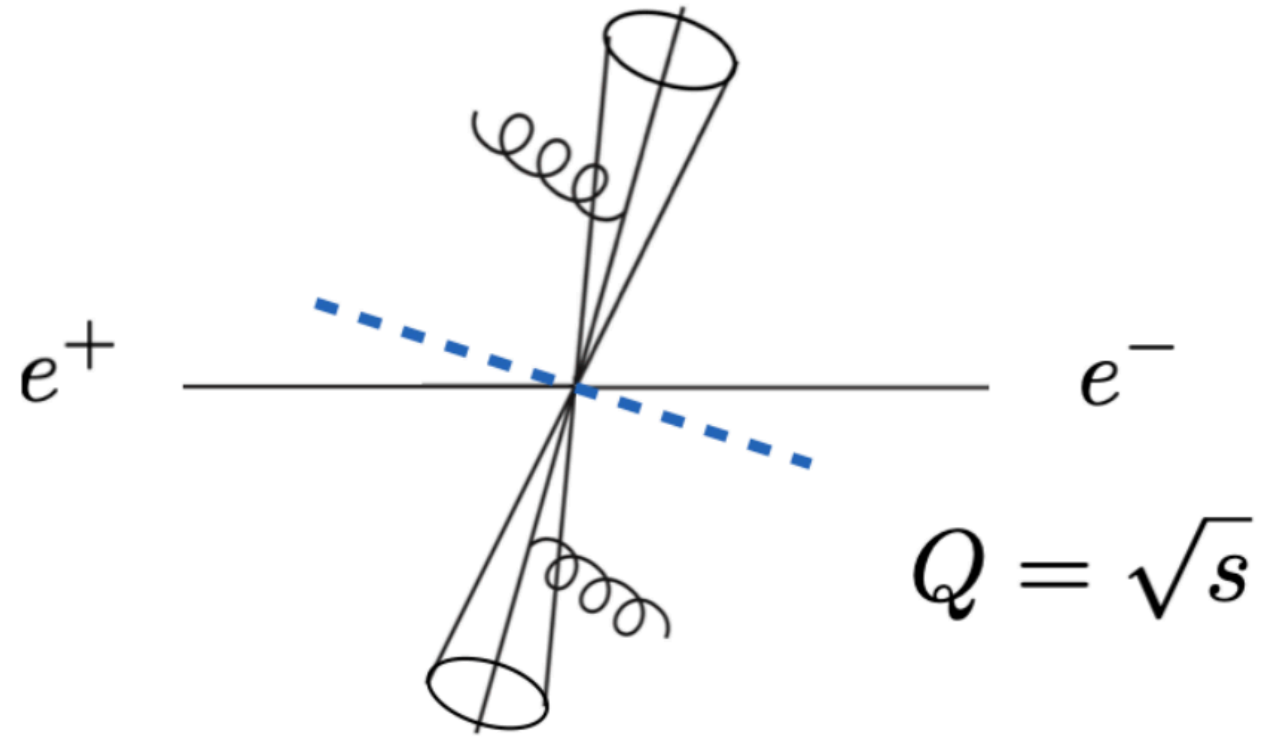


NLL' result

NLO

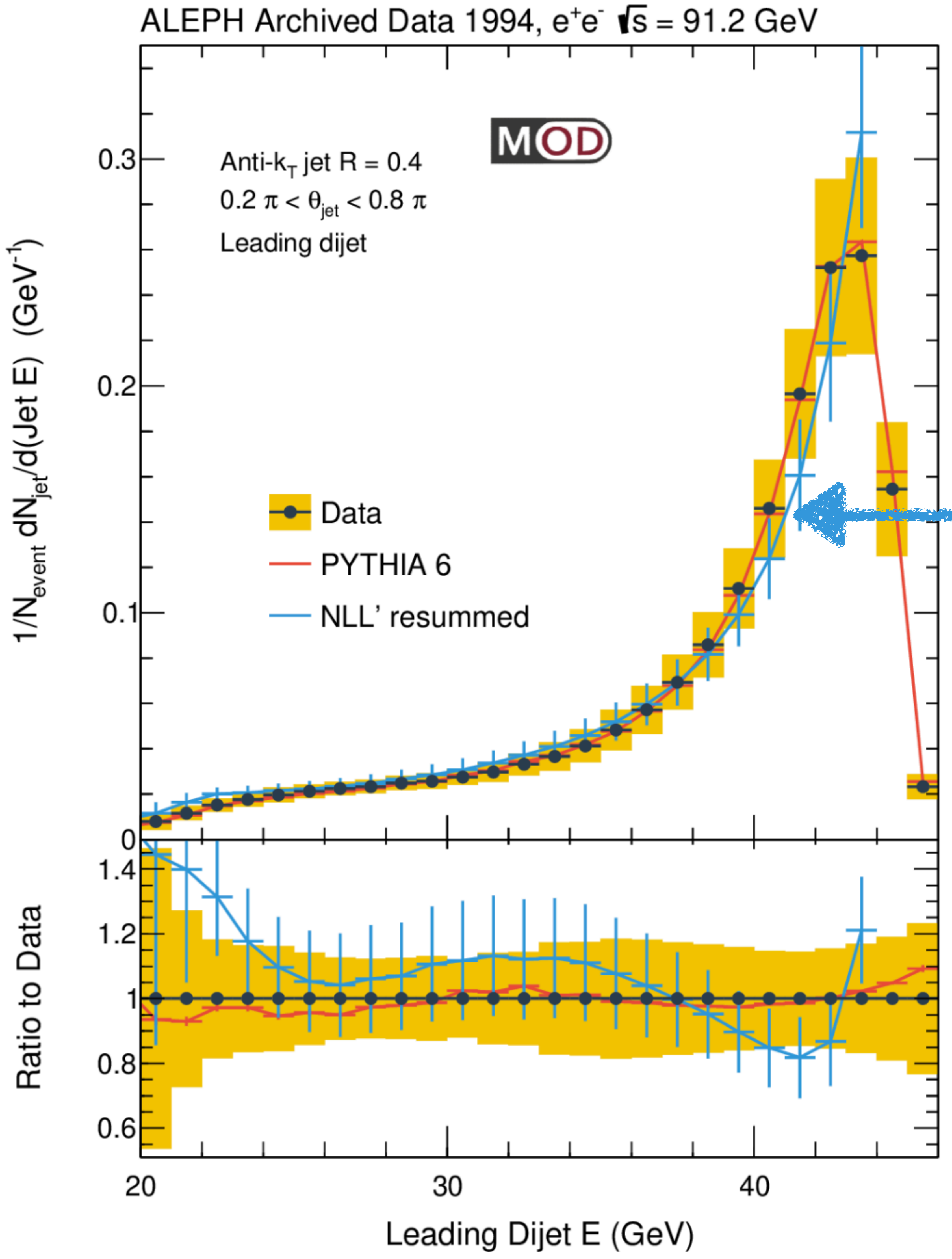
Inclusive jets

Jet energy E



Comparison to LEP data

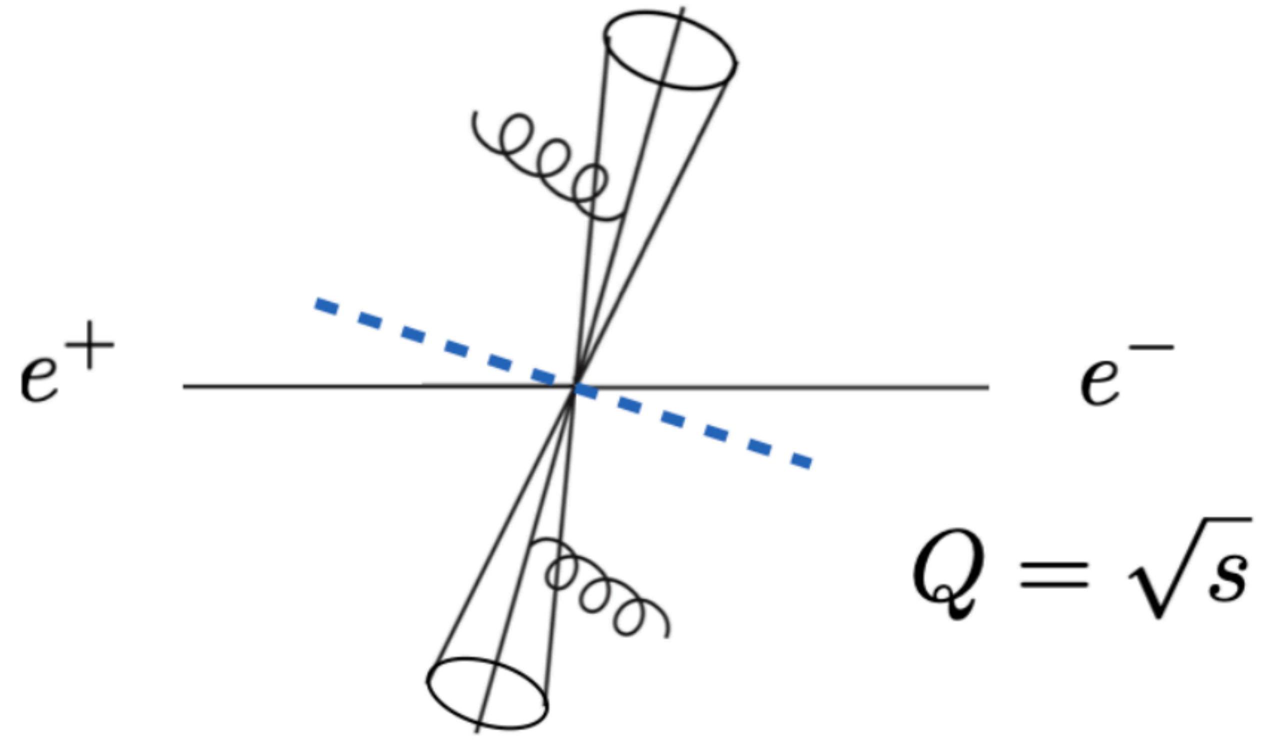
ALEPH, 2111.09914



NLL' result

Event-wide
leading di-jets

Jet energy E



Outline

Angles between jet axes

Inclusive and leading subjets

Conclusions

Conclusions

- New jet substructure observables
- Quantitative comparisons to experimental results
- Results can constrain nonperturbative quantities
- Higher precision can be achieved in the future