Jet properties and substructure

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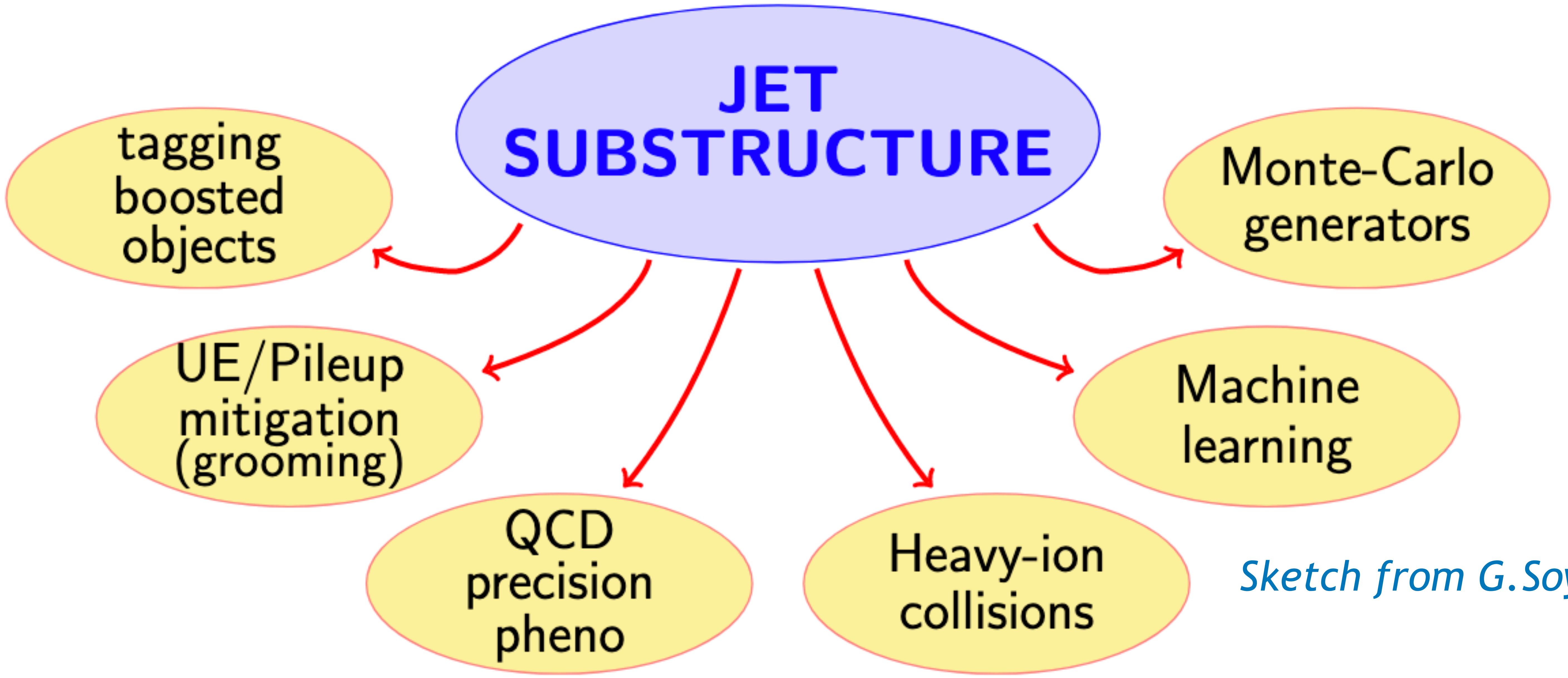
on behalf of ALICE/ATLAS/CMS/LHCb Collaborations

9th edition of the Large Hadron Collider Physics Conference
11th June, 2021

Jet substructure

Jets play a central role at the LHC

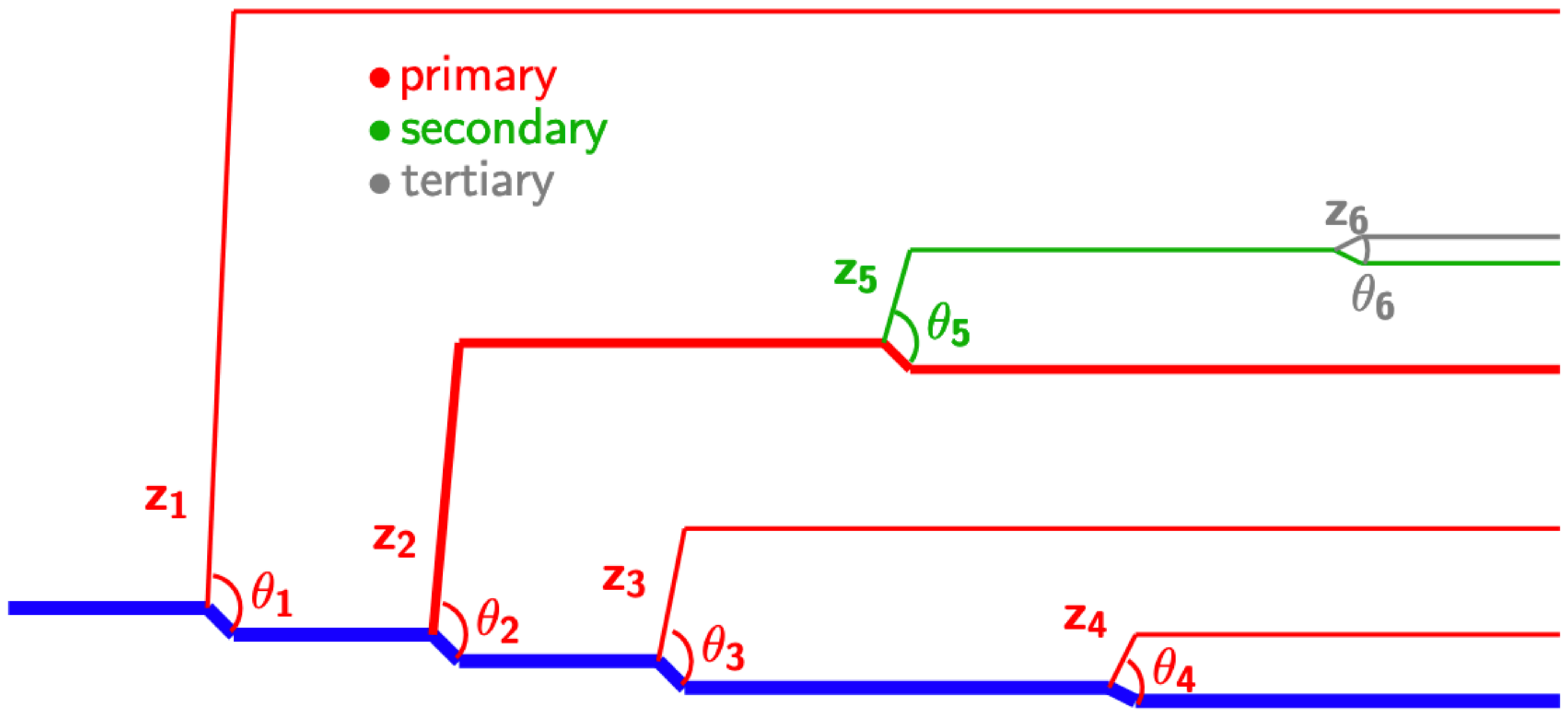
Jet substructure exploits info on internal radiation pattern, many scopes:



Sketch from G.Soyez

In this talk
- Recent results that constrain the parton shower modelling and fixed-order calculations
- Few examples where quantum properties are exposed in new ways

Jet substructure using the clustering history



Another sketch from G.Soyez

The Cambridge/Aachen algorithm sequentially combines the closest pairs

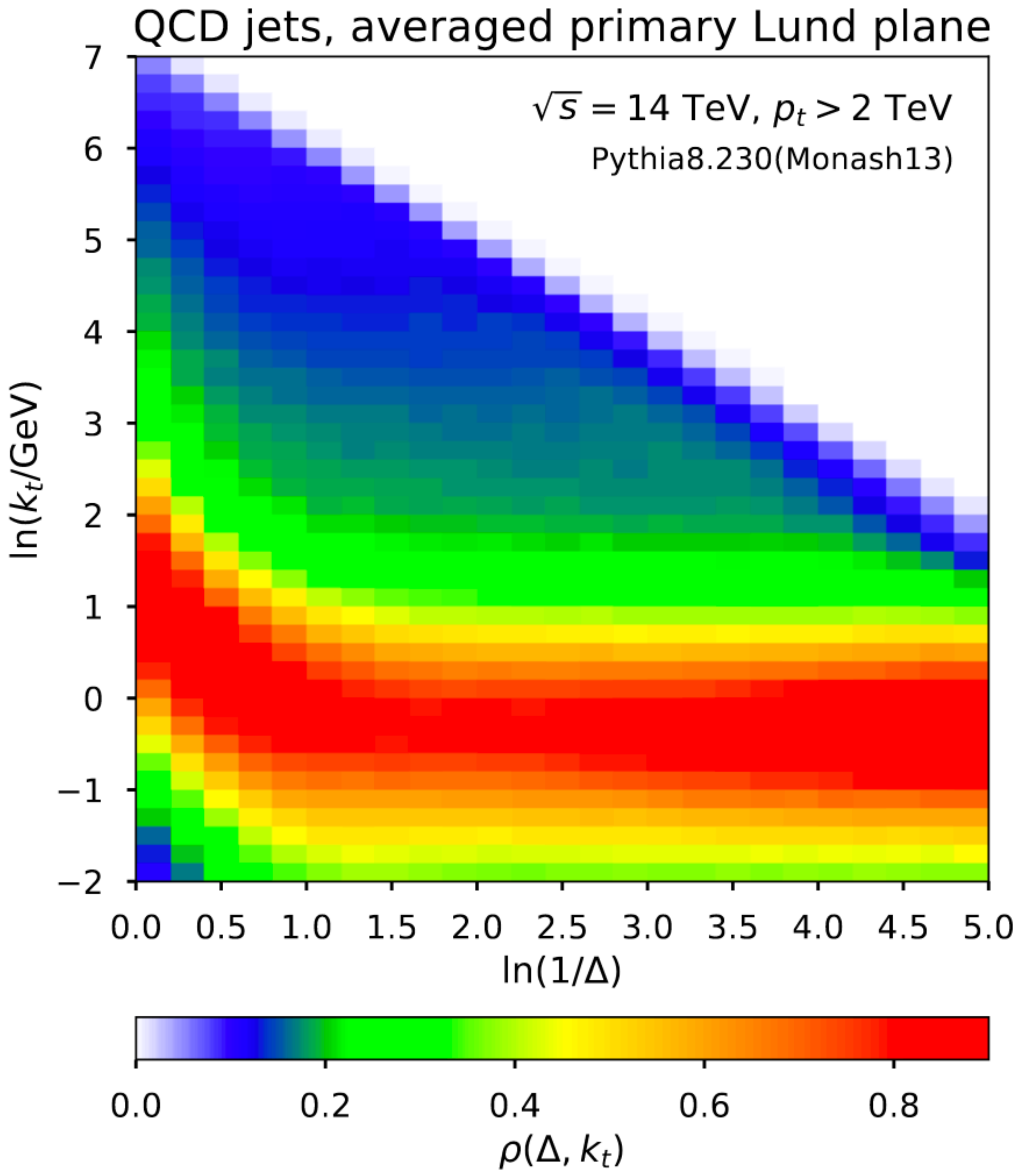
The clustering history can be undone iteratively, following always the hardest branch

At each step, two subjet prongs are obtained, **j1** and j2 , with $p_{T,1} > p_{T.2}$

where θ is the angle between the prongs,
$k_T = \theta p_{T,2}$
and $z = p_{T,2}/(p_{T,1} + p_{T,2})$

The iterative declustering proceeds until substructure is found (grooming)
or the jet can be fully declustered to study the kinematics of all the emissions (Lund jet plane)

The primary Lund plane: visualizing the parton shower



At leading order, emissions populate the plane uniformly and the running of the coupling sculpts the plane

QCD Splitting probability

$$d^2P = 2\frac{\alpha_s(k_\perp)C_R}{\pi}dln(z\theta)dln(\frac{1}{\theta})$$

An all-order calculation is available: *Lifson et al, JHEP 10 (2020) 170*

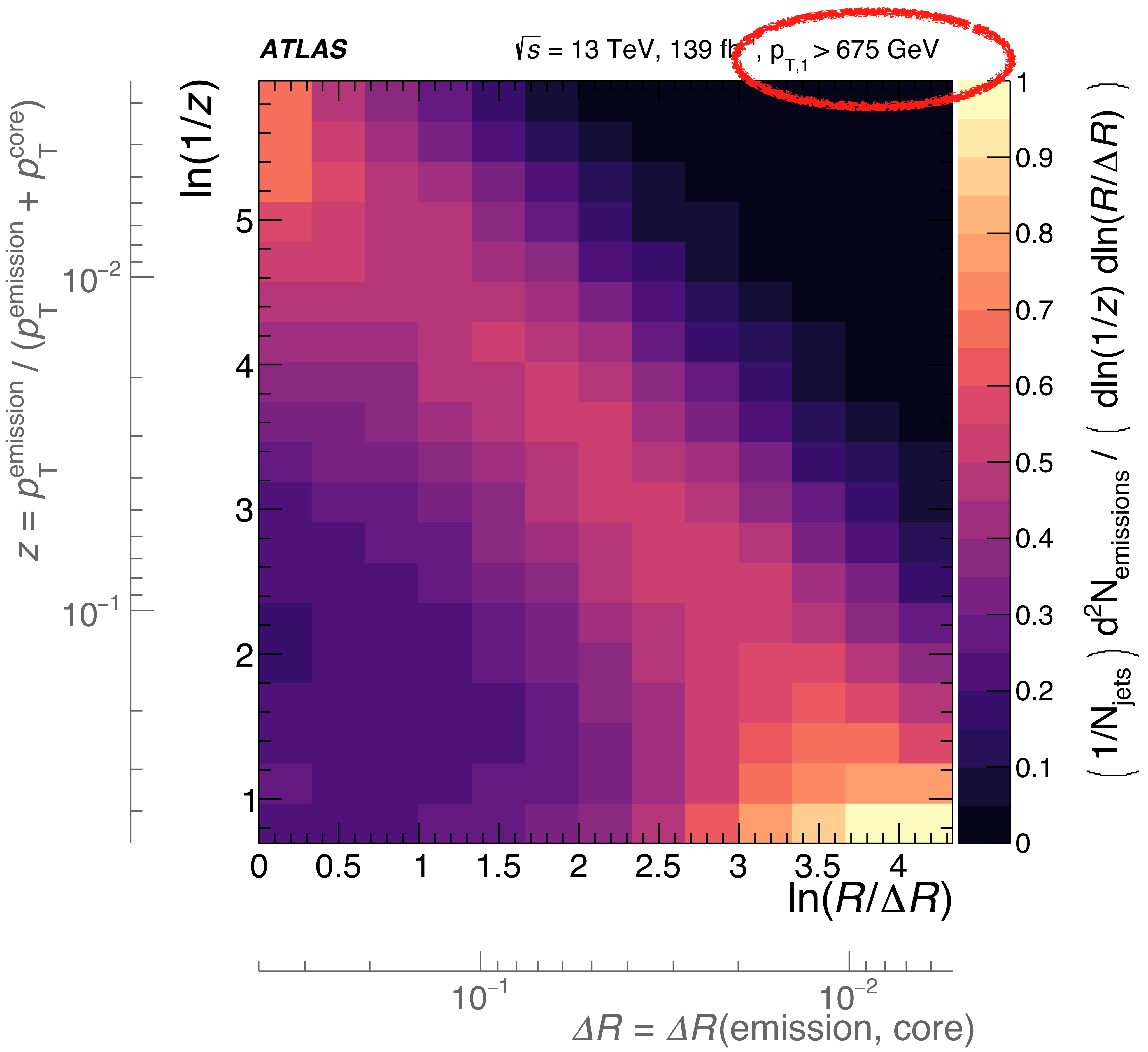
Vast applications, as a tagger and as an observable!

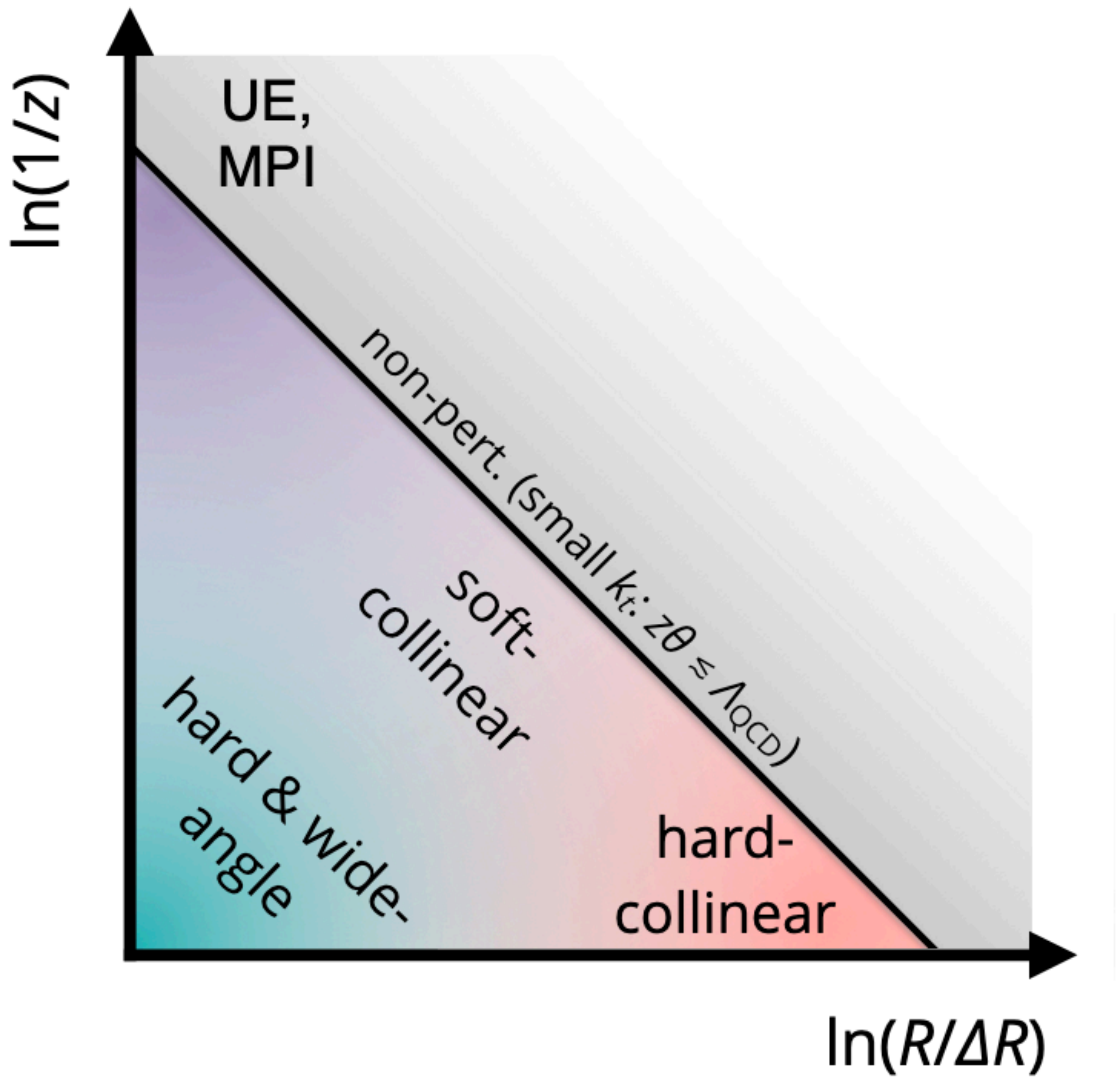
Dreyer et al, JHEP 12 (2018) 064

The primary Lund plane with ATLAS

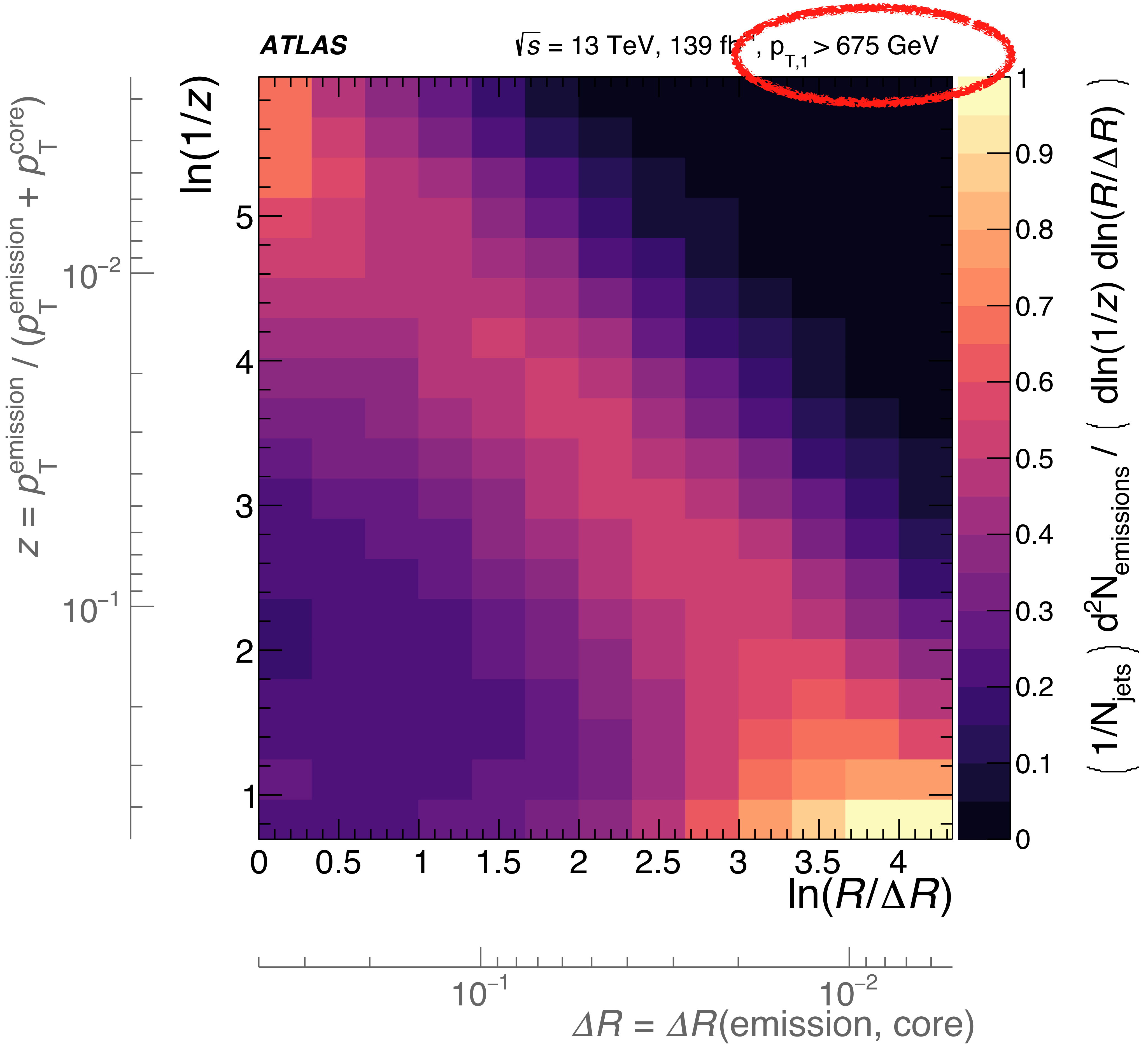
See talk by Robin Newhouse

ATLAS, Phys.Rev.Lett. 124 (2020) 22, 222002

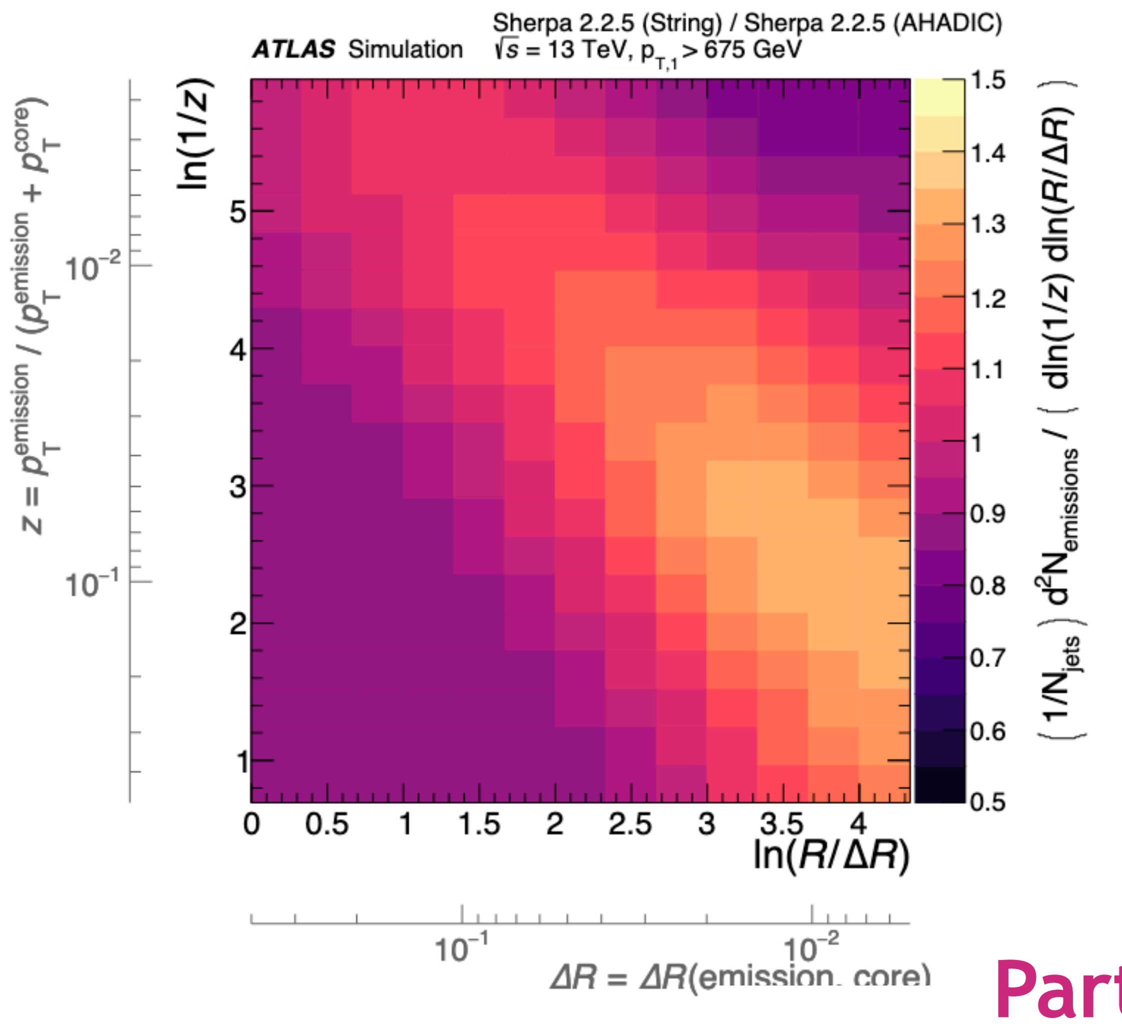




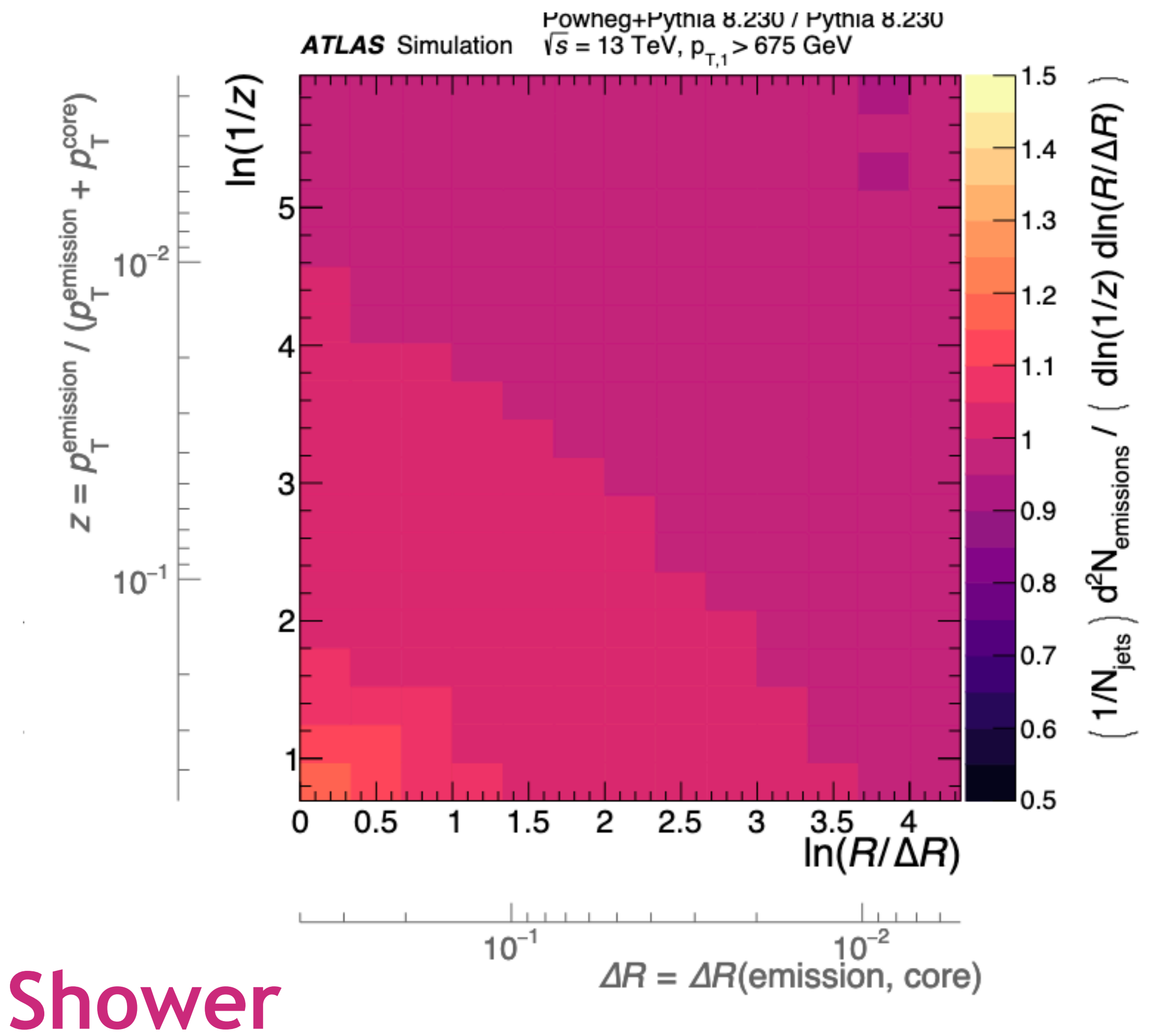
The primary Lund plane with ATLAS



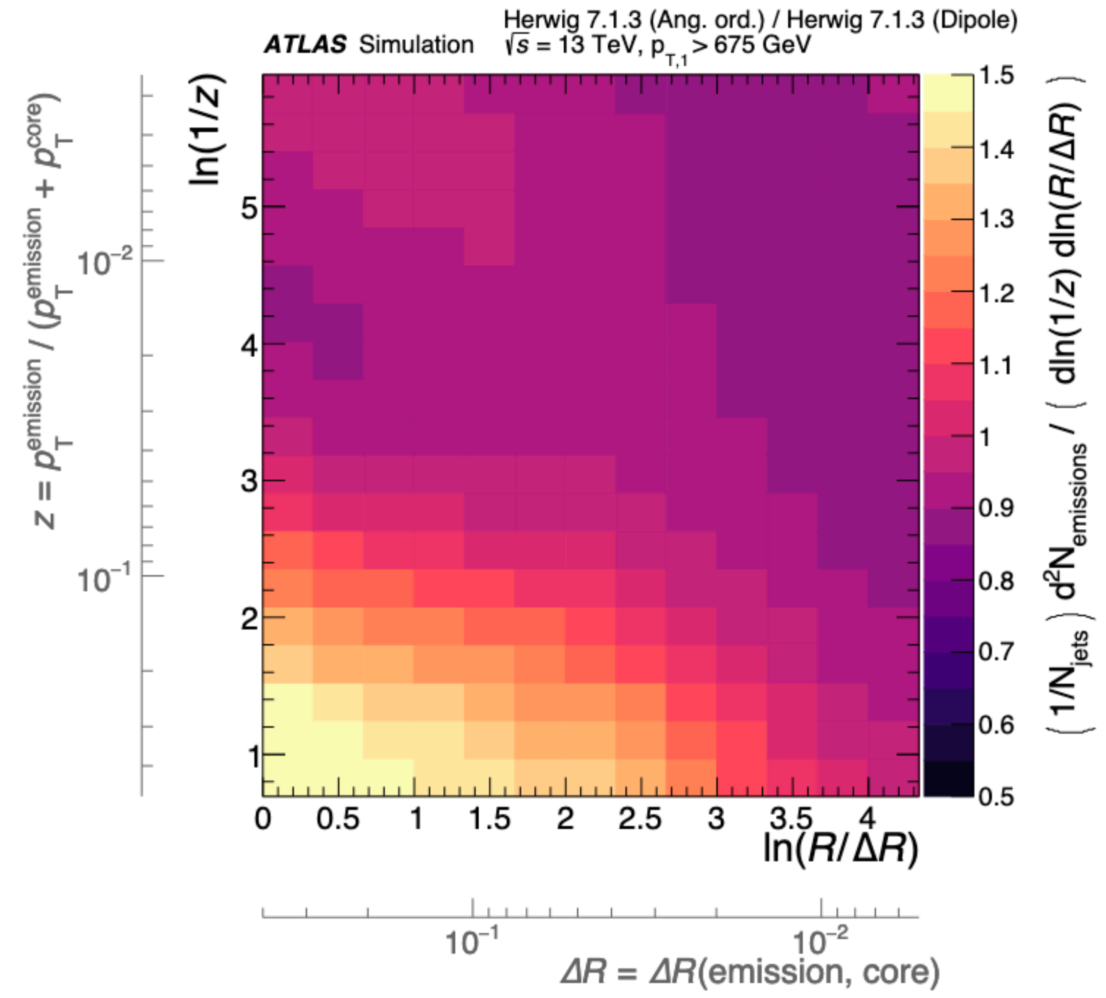
Hadronization



Matrix elements



Parton Shower



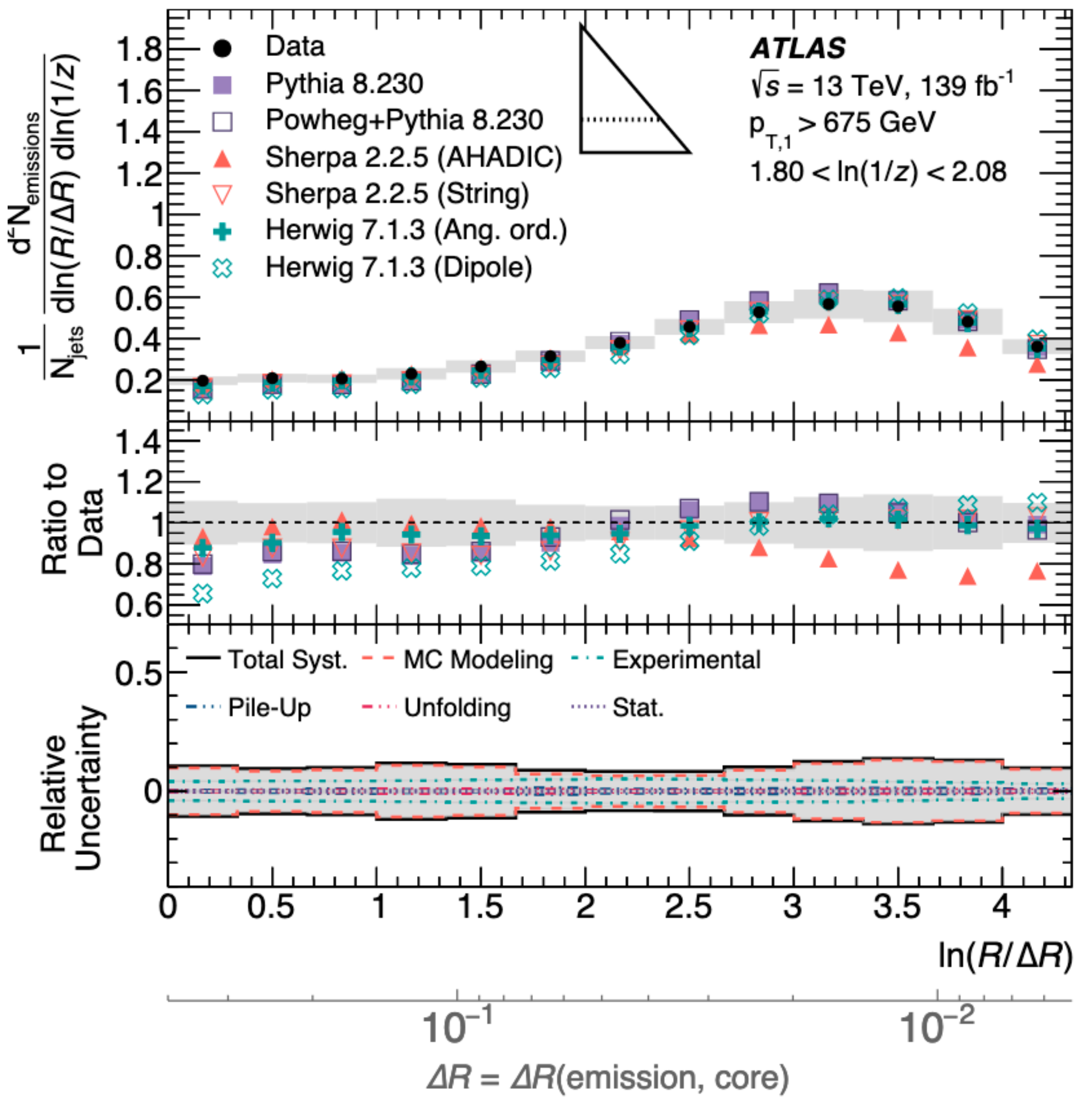
- Multiple physics effects contribute beyond the LO uniformly-filled plane
- However the measurement captures salient features of the q/g parton shower: the running of the coupling sculpts the plane

[ATLAS, Phys.Rev.Lett. 124 (2020) 22, 222002]

The primary Lund plane with ATLAS

Comparisons to MC generators

Parton shower ⟷ Hadronisation

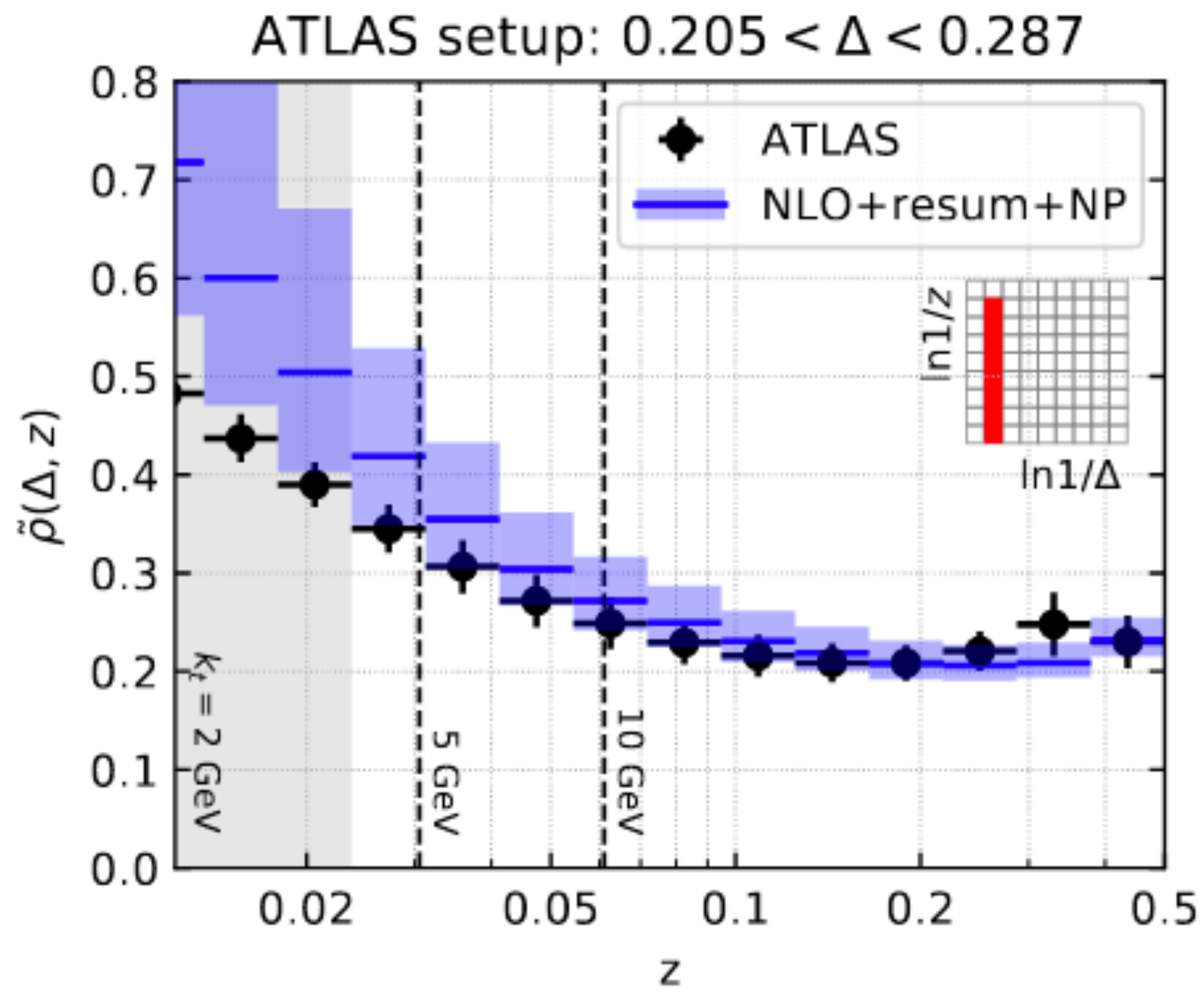


Ability of the Lund Plane to isolate physics effects:

- PS effects (wide angles)
- hadronisation (collinear splits).

Input to (non)perturbative model development and tuning

Comparison to analytical calculations



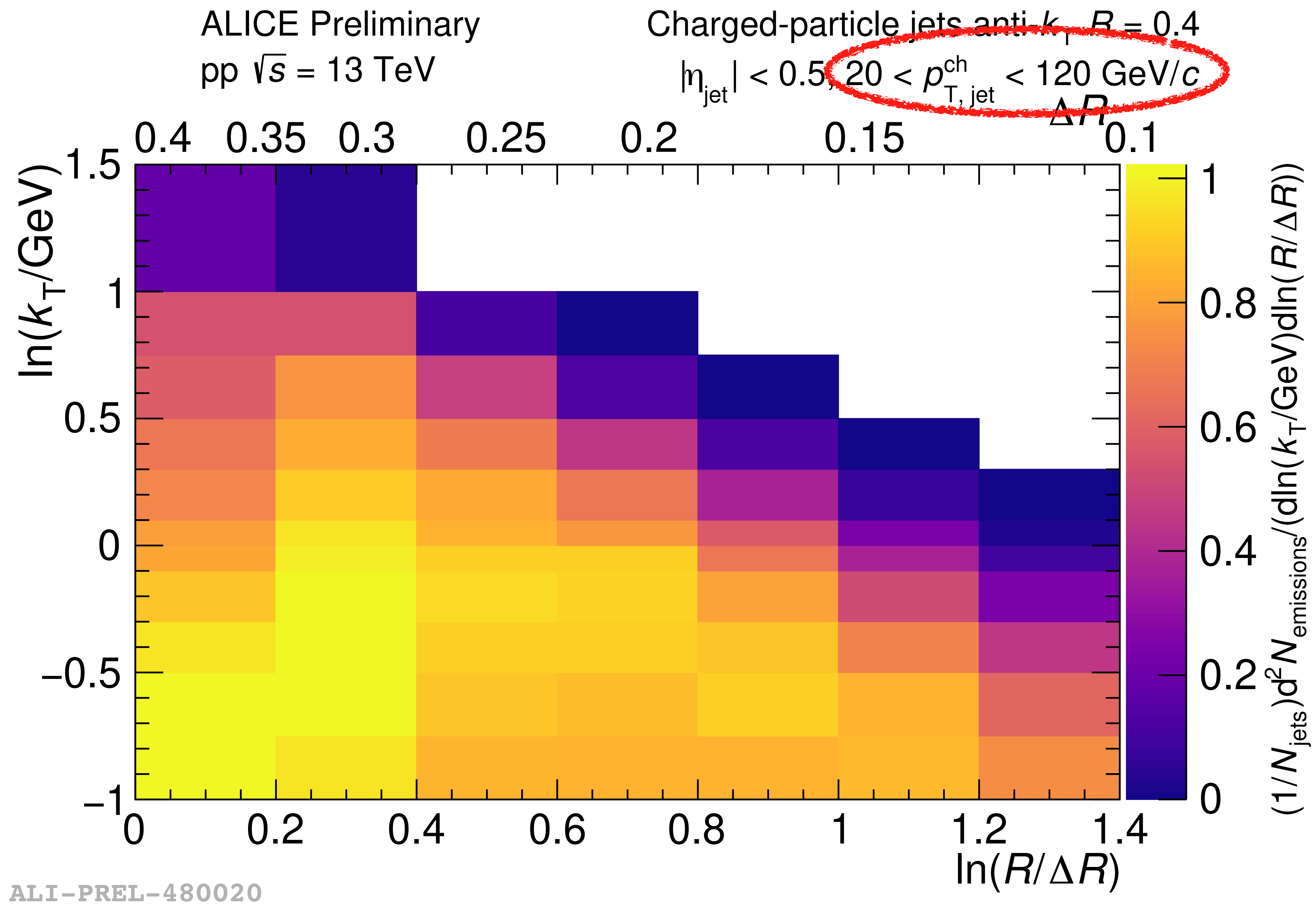
New all-order single log calculation of the Lund plane density including [Lifson et al, JHEP 10 (2020) 170]

Precision of the Lund plane density 5-7% at high k_T while ~20% at the edge of the perturbative region (k_T~5 GeV)

New at LHCP

The primary Lund plane with ALICE

New at LHCP



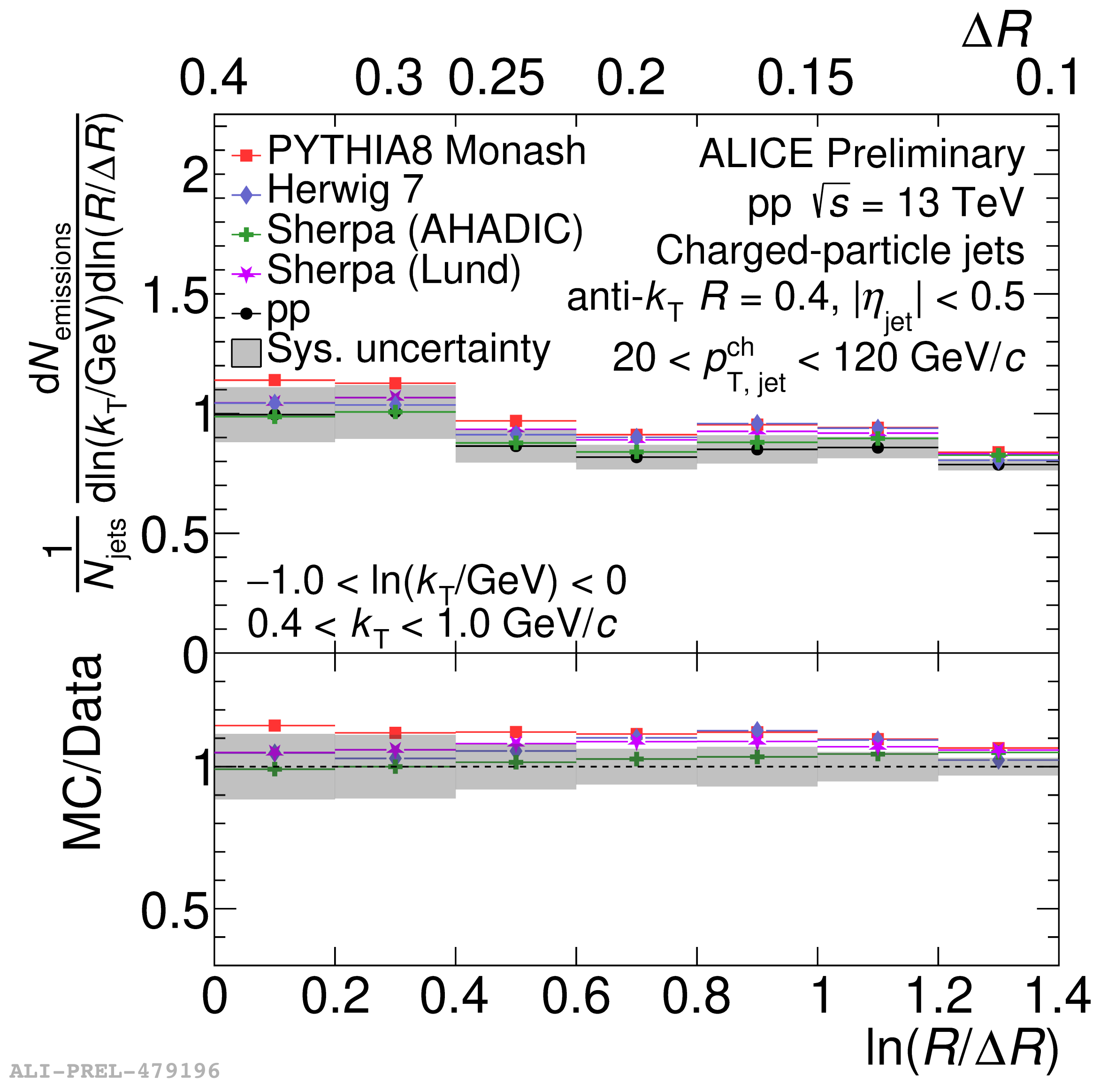
	ALICE	ATLAS
$p_{T,jet}$ (GeV)	20-120	>675
max k_T (GeV)	5	>135
ΔR (rad)	0.1-R	0.005 - R

ALICE-PUBLIC-2021-002.

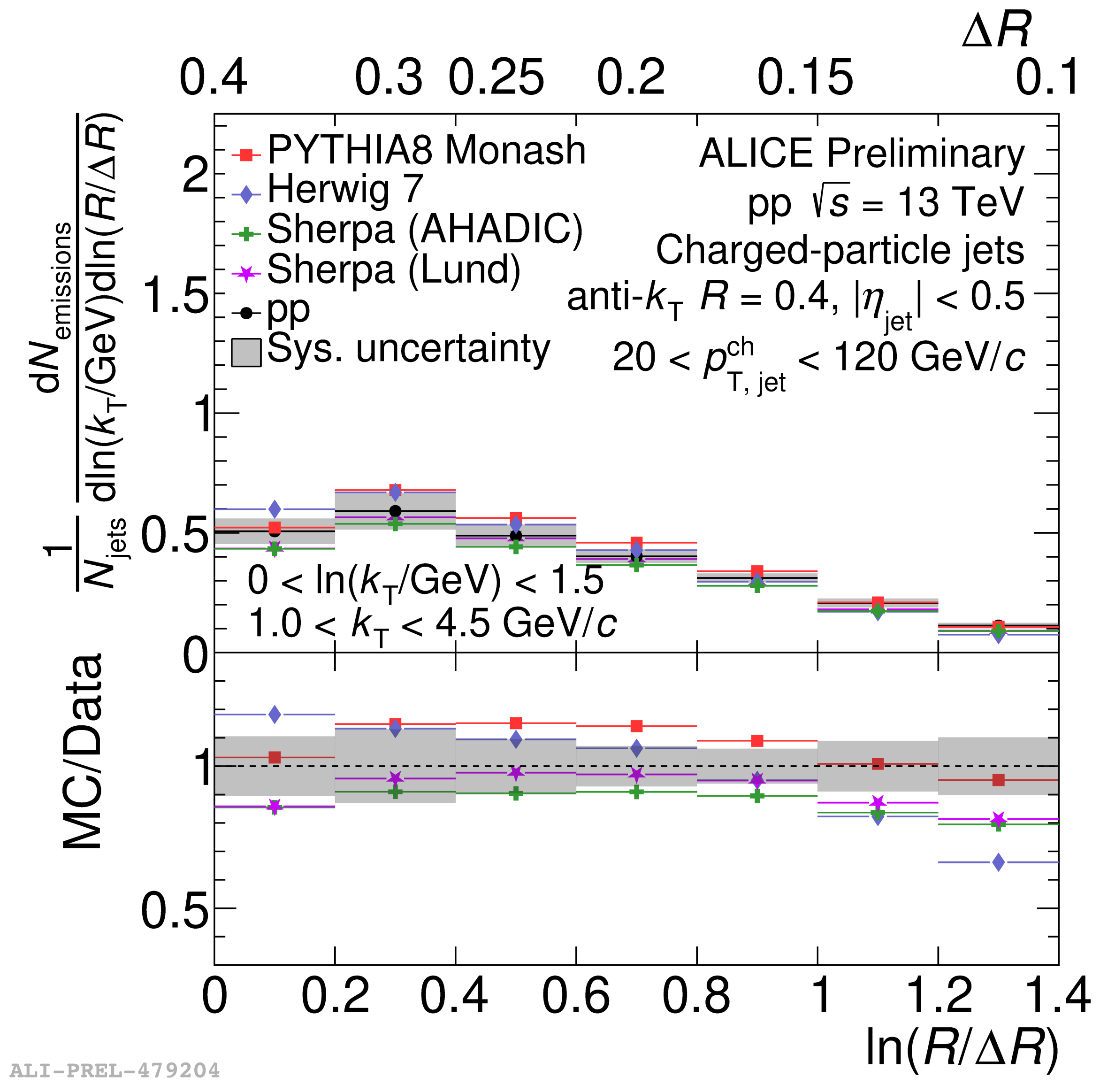
The primary Lund plane with ALICE

New at LHCP

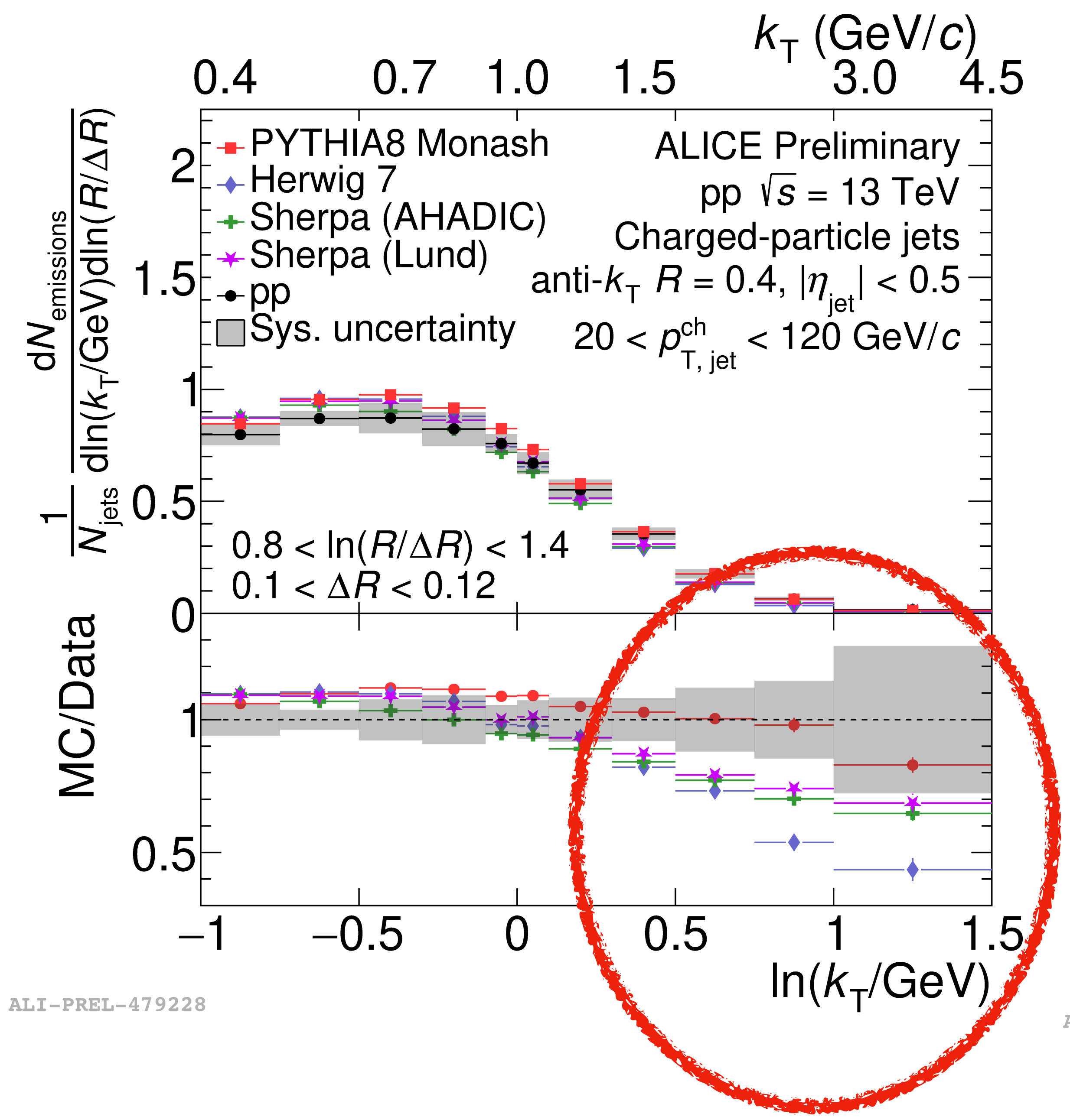
Soft



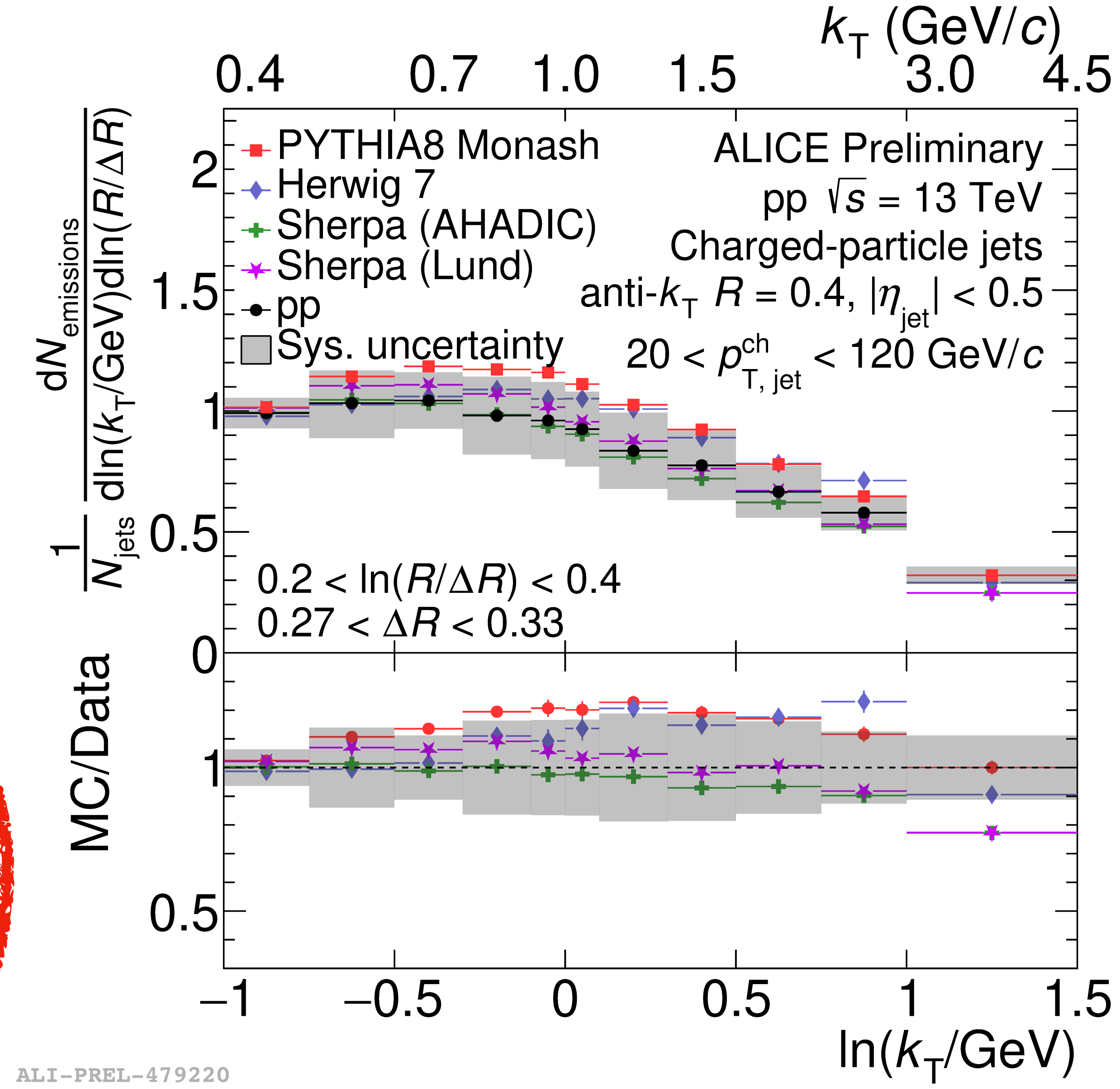
Harder



Small-angle



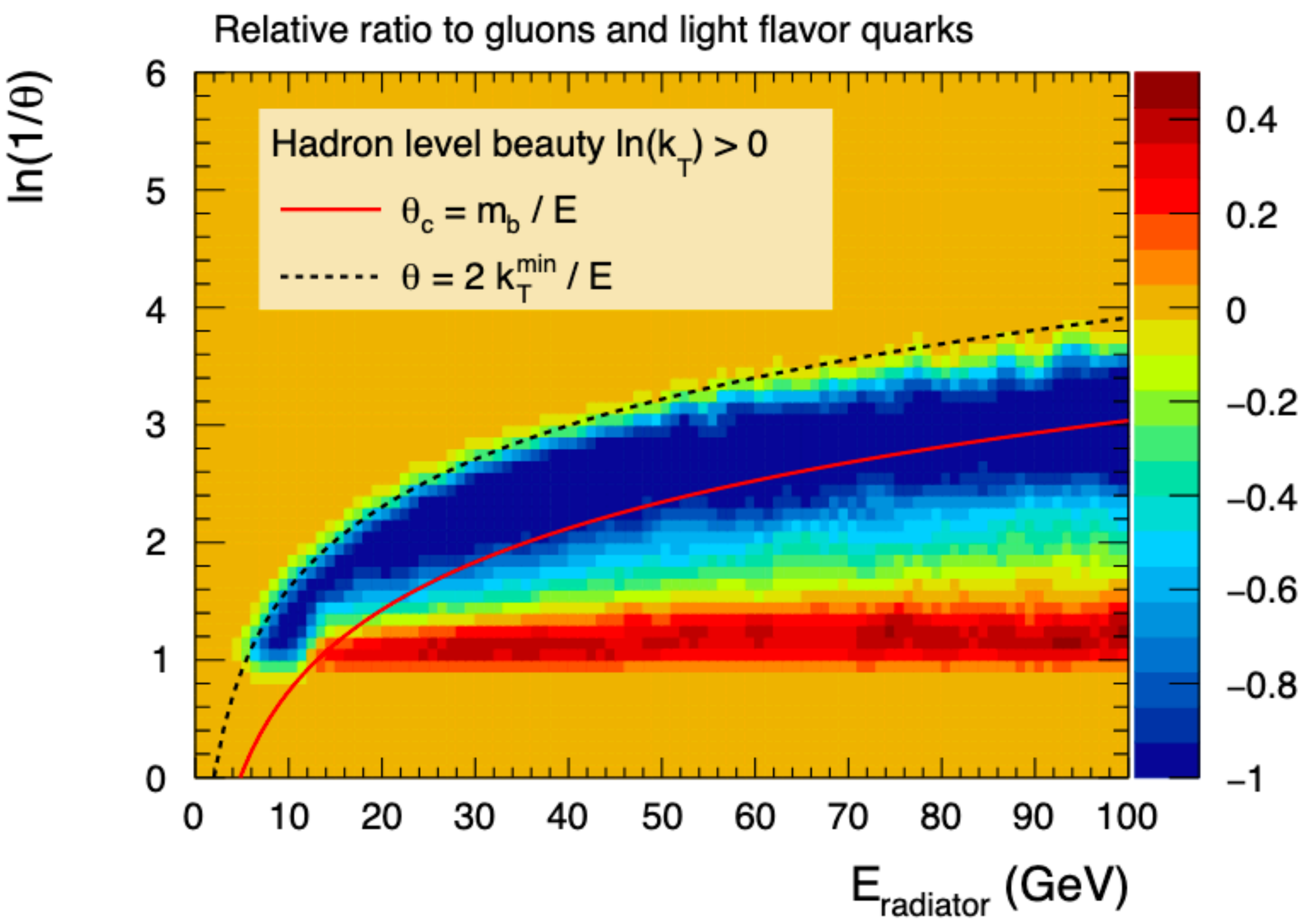
Wide-angle



- Similarly to ATLAS measurement, model uncertainties (Herwig vs PYTHIA in the response and matching purity/efficiency corrections) are dominant
- Some tensions in the moderately hard, moderately low angles (0.1-0.2 rad)
- Perturbative reach to be extended with triggered samples

ALICE-PUBLIC-2021-002.

The Lund plane of heavy-quark jets: exposing the dead cone



- Iteratively decluster jets with a fully reconstructed D^0 among its constituents
- Follow always the prong containing the D^0
- Register the splitting energy E_{radiator} and the splitting k_T at each step

Define:

$$R(\theta) = \frac{1}{N^{D^0\,\text{jets}}}\frac{dn^{D^0\,\text{jets}}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{\text{inclusive jets}}}\frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)}\Bigg|_{k_T,\,E_{\text{Radiator}}}$$

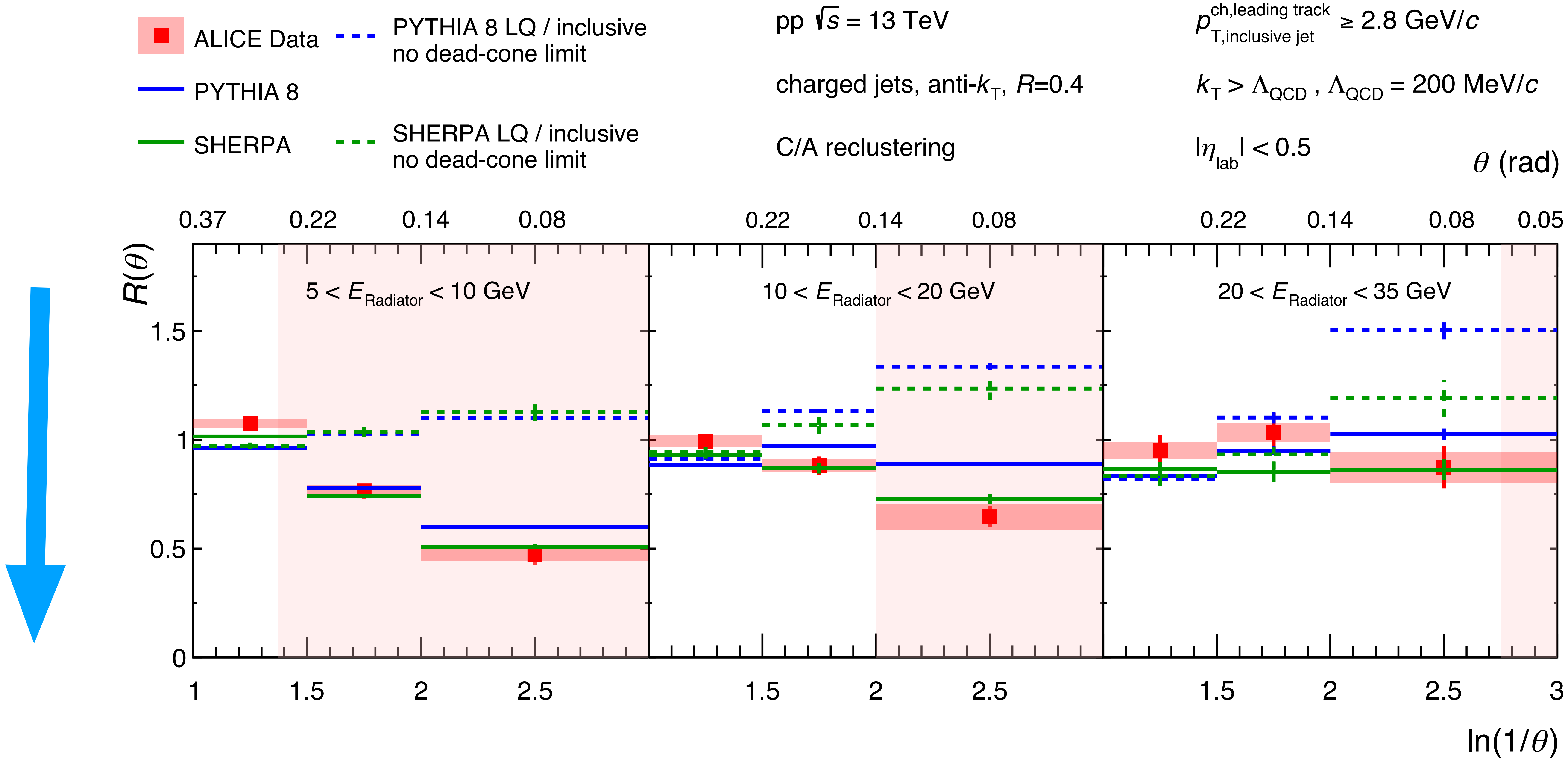
E_{radiator}=energy of the splitting prong at each declustering step

The deepest levels of the jet tree are splittings at small angles/lower energies ->most sensitive to mass and the dead cone effect

Cunqueiro, Ploskon, Phys.Rev.D 99 (2019) 7, 074027

The Lund plane of heavy-quark jets: exposing the dead cone

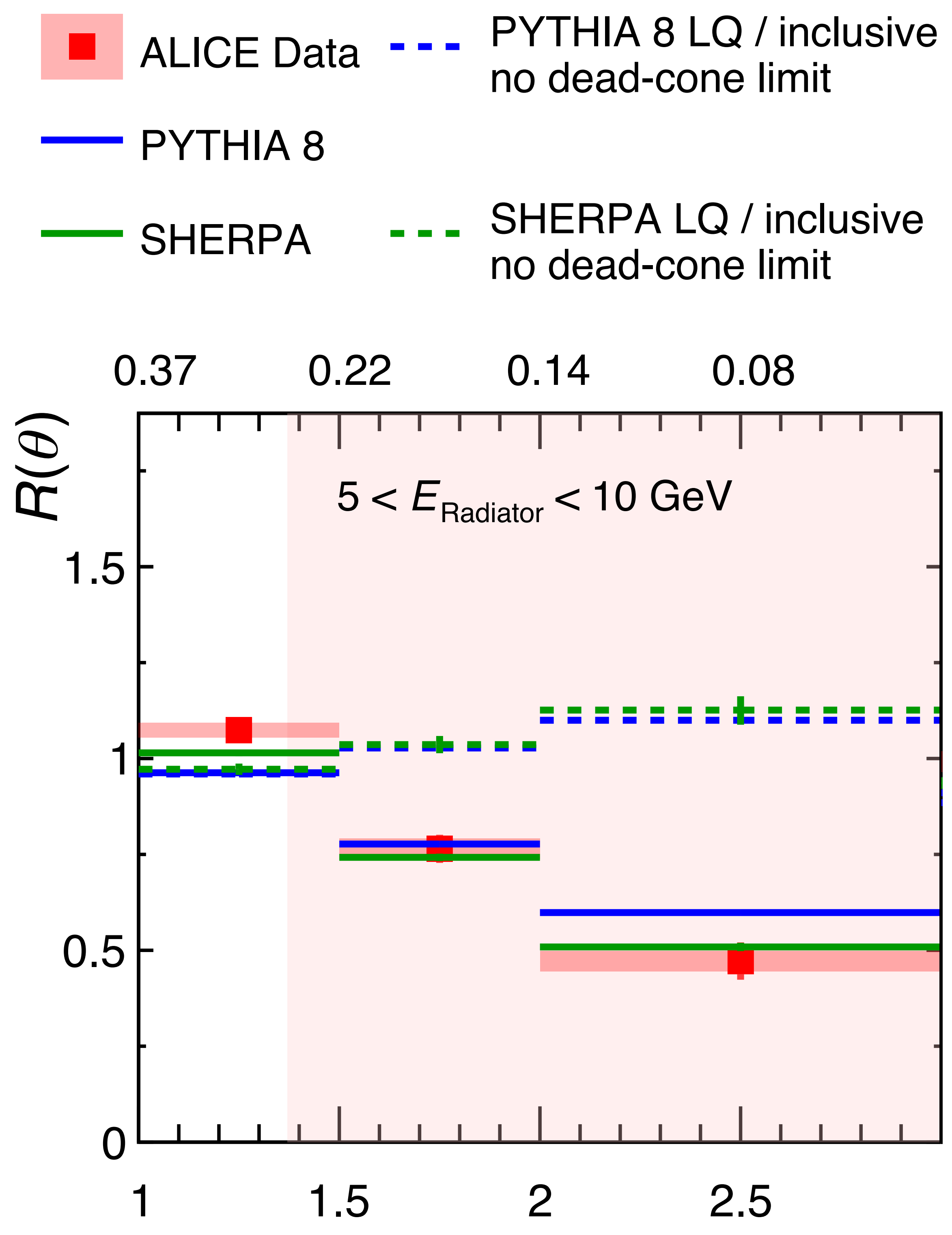
ALICE, arXiv:2106.05713

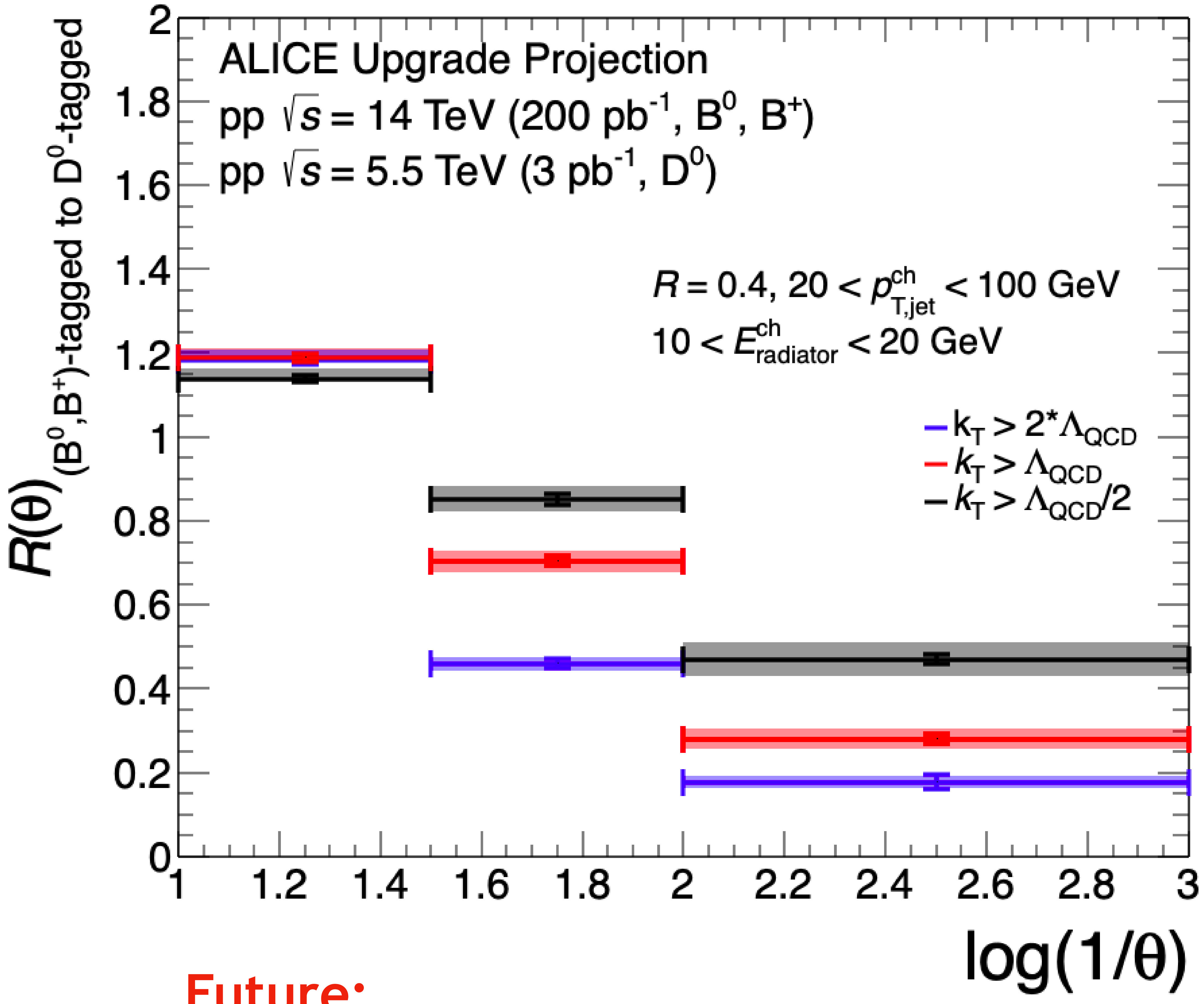


- Suppression of emissions at low angles for D^0 jets as compared to inclusive jets
- Smaller effects for higher splitting energy

The Lund plane of heavy-quark jets: exposing the dead cone

ALICE, arXiv:2106.05713





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- Suppression of emissions at low ang
- Smaller effects for higher splitting energy

Future:
mass scan of the effect: B jets, top quark

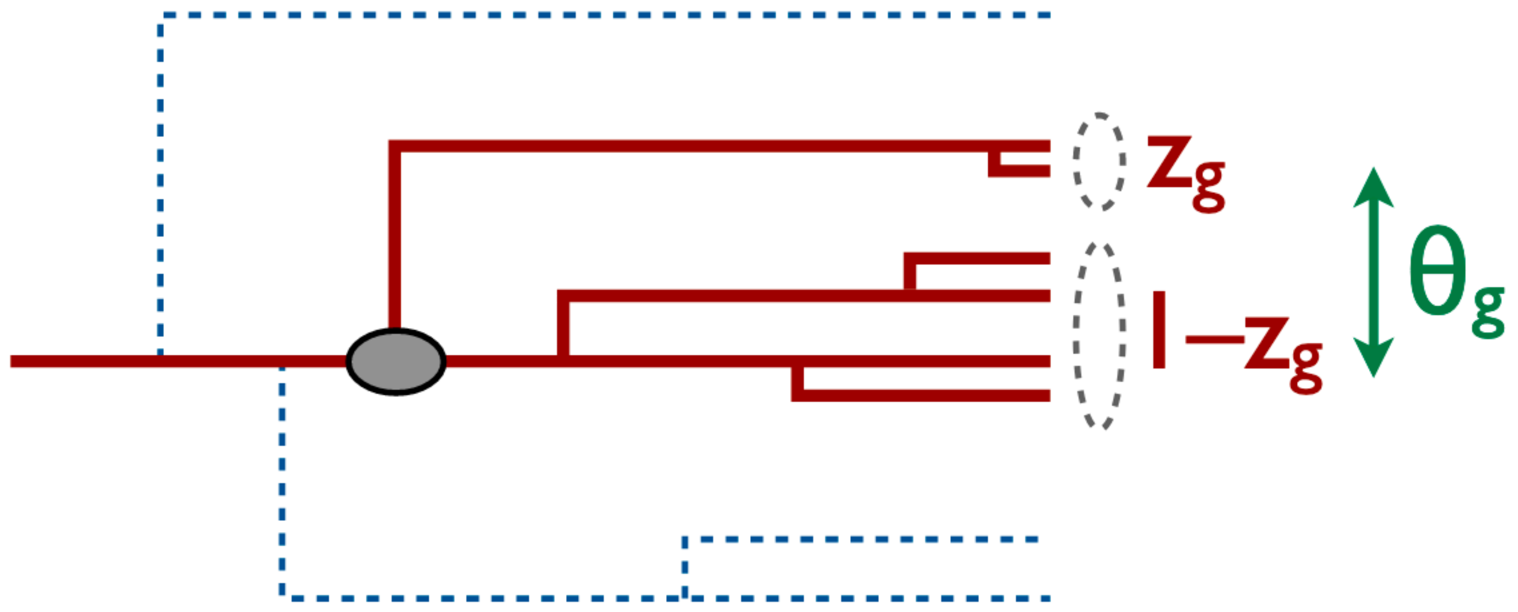
Grooming

Groom away branches in order to **access hard parts of the jet that are under better theoretical control**

- **mMDT/SofDrop grooming**

Remove branches of an angular-ordered clustering tree until you find a splitting that satisfies:

$$z_g = \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$



Larkoski et al, JHEP 05 (2014) 146
(Recursive SD) Dreyer et al, JHEP 06 (2018) 093
Butterworth et al,Phys.Rev.Lett. 100 (2008) 242001

- **New: Dynamical Grooming**

1. Select the hardest branch in the C/A sequence
2. Drop all branches at larger angles

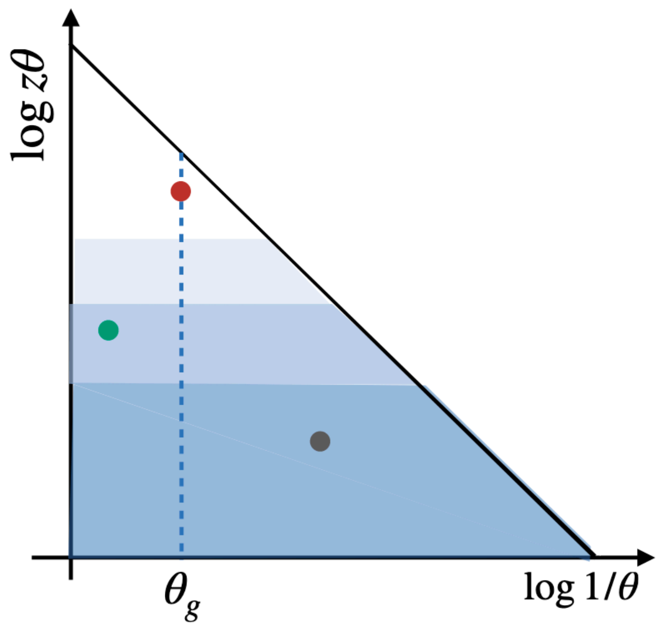
$$\kappa^{(a)} = \frac{1}{p_T} \max_{i \in \mathrm{C/A}} z_i(1 - z_i) p_{T,i} (\theta_i / R)^a$$

New at LHCP

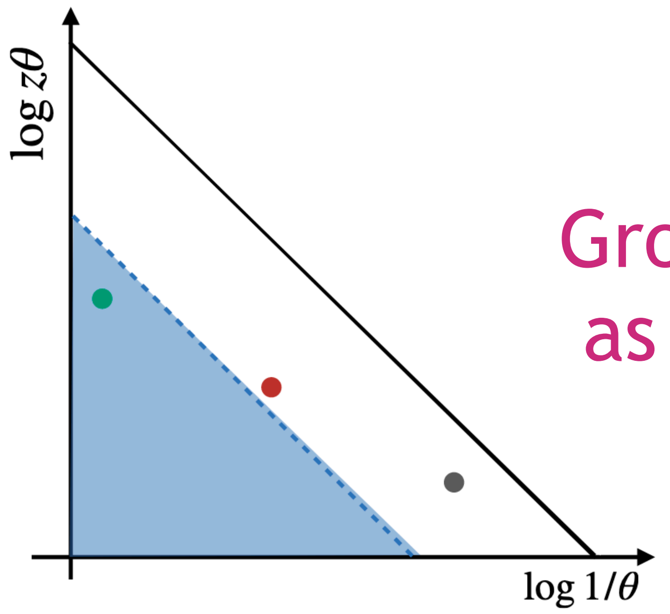
More aggressive grooming with decreasing parameter a

Mehtar-Tani et al, Phys.Rev.D 101 (2020) 3, 034004

DyG:



SD:

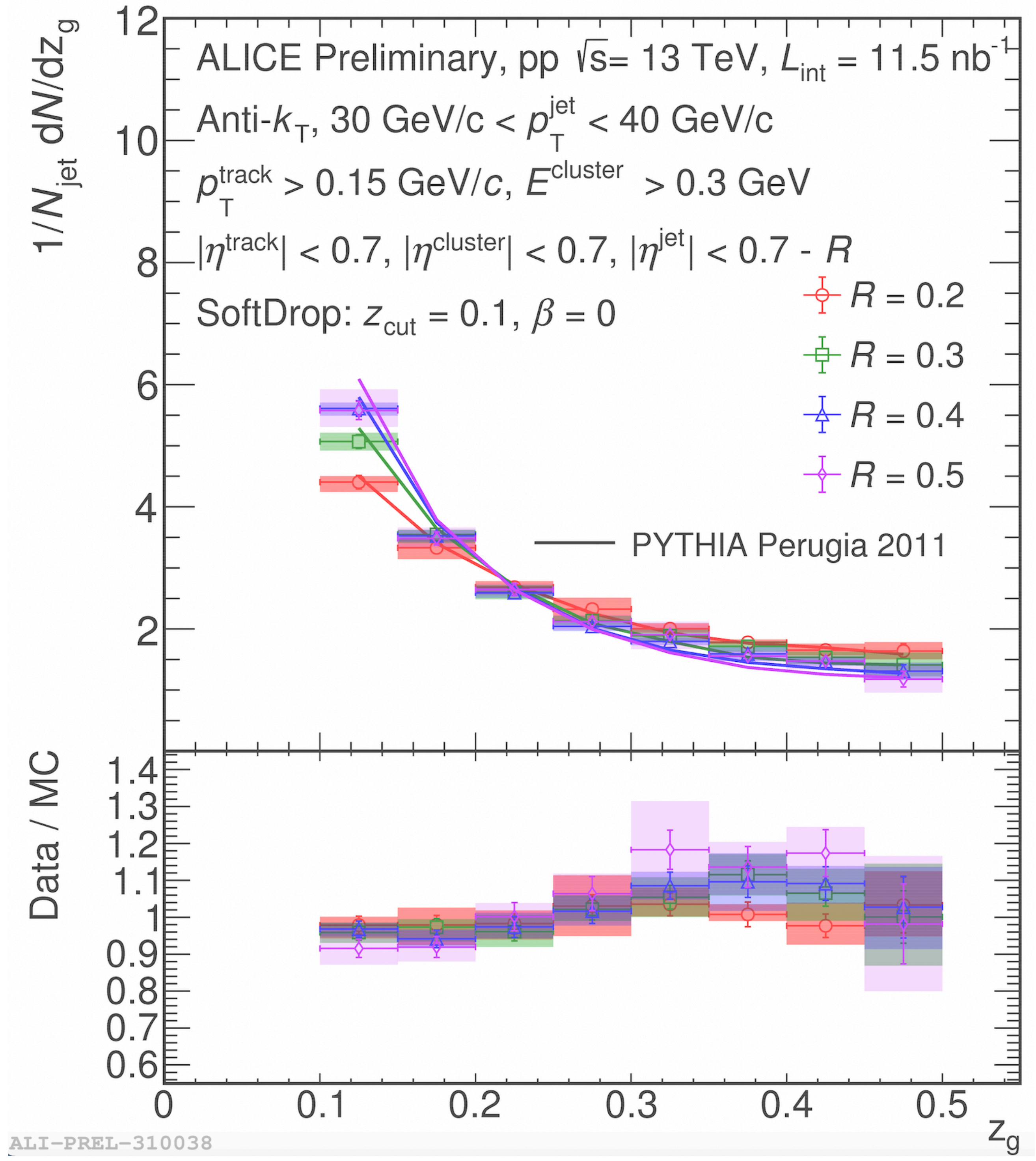


Groomed-away areas can we drawn as exclusion regions in the Lund Jet Plane

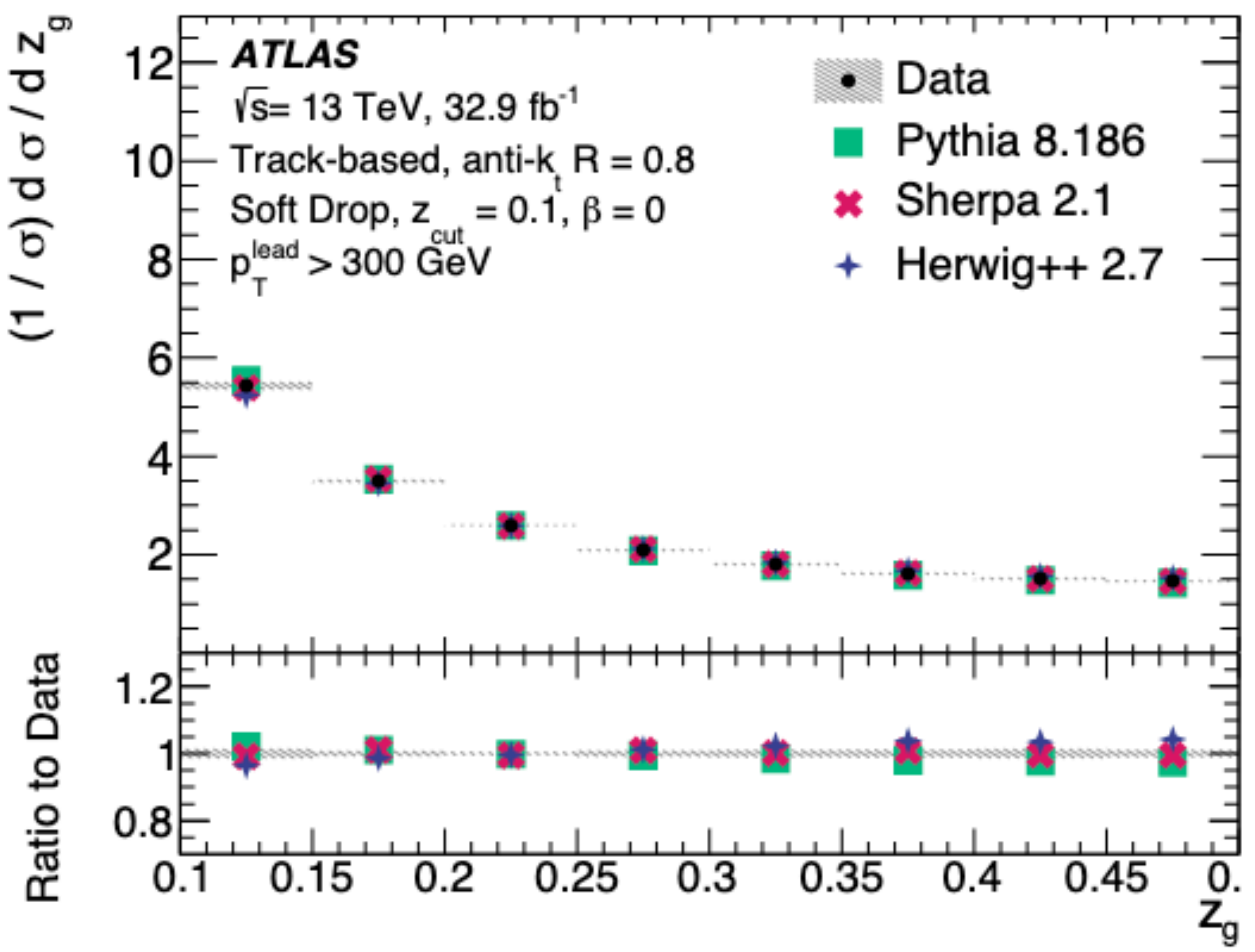
The groomed momentum balance

$$z_g = \frac{p_{T2}}{p_{T1} + p_{T2}}$$

Low p_T, R dependence



High p_T, large R=0.8, more grooming



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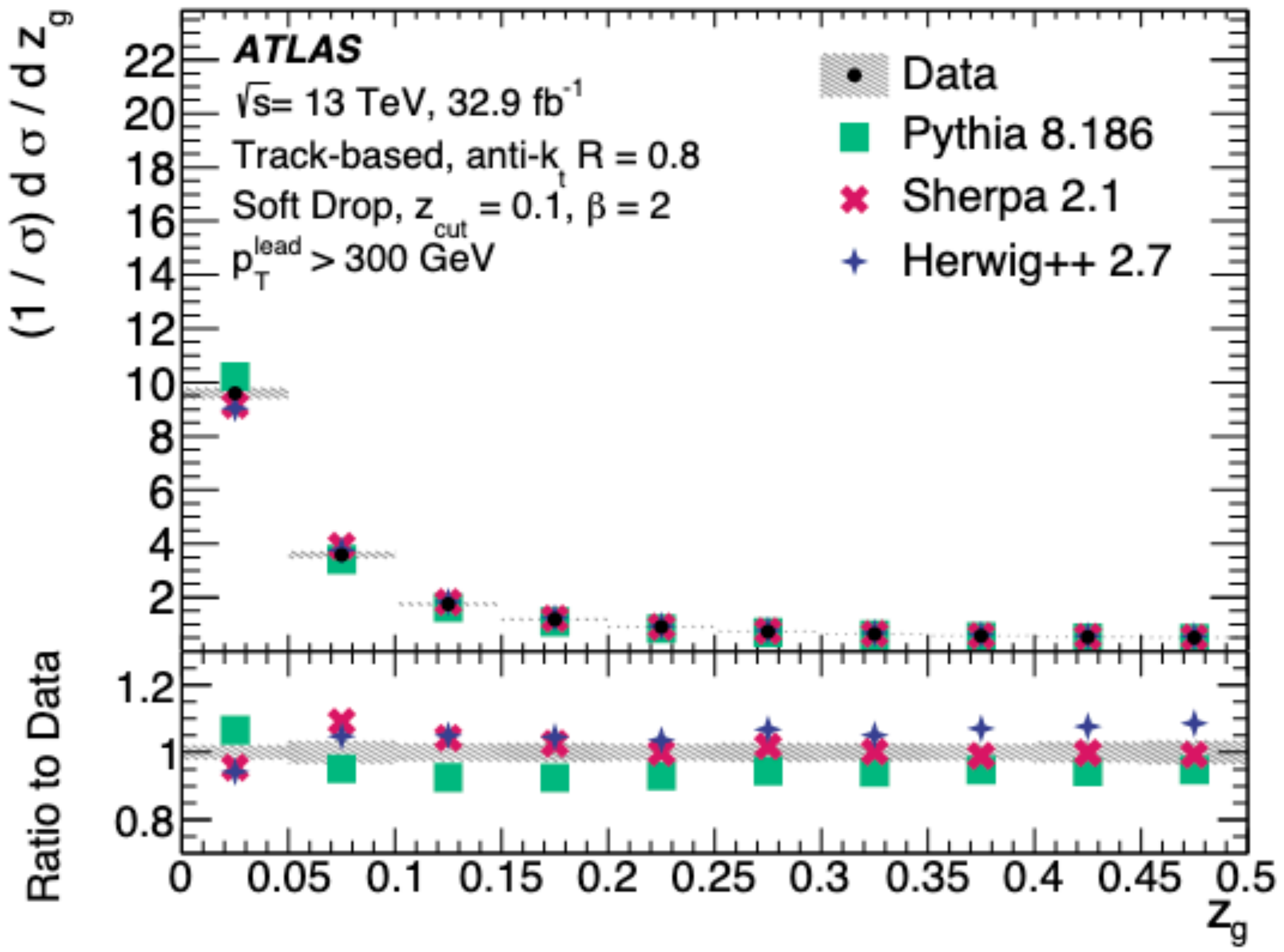


Phys. Rev. D 101, 052007 (2020)

Low z_g affected by non pert. effects (UE)
More soft subleading prongs at large R

Good description by MC generators
Largest discrepancies in the regions most affected by non pert. effects (higher β, low z_g)

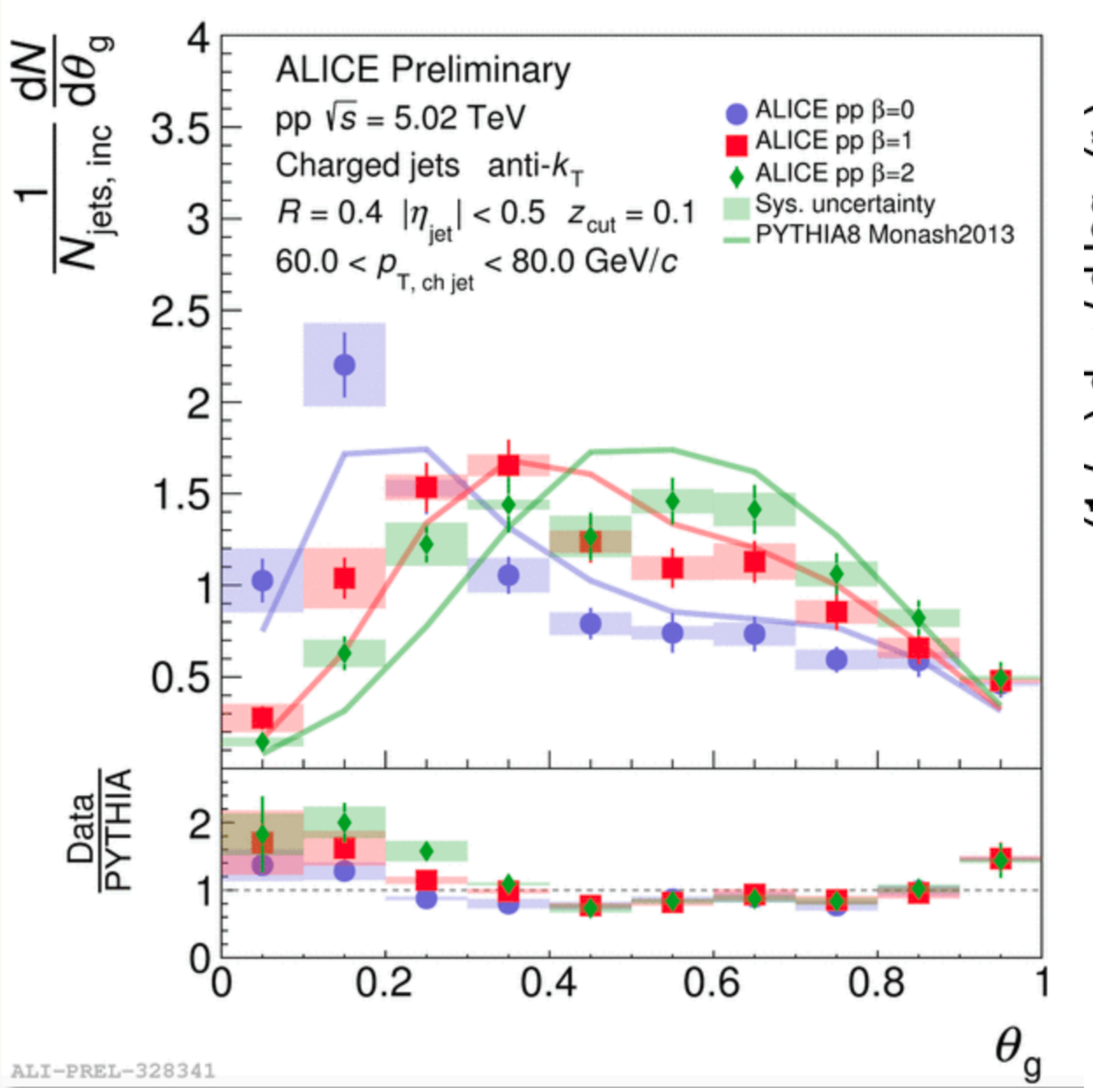
z_g exposes the QCD splitting function

Larkoski et al, Phys. Rev. Lett. 119, 132003 (2017)

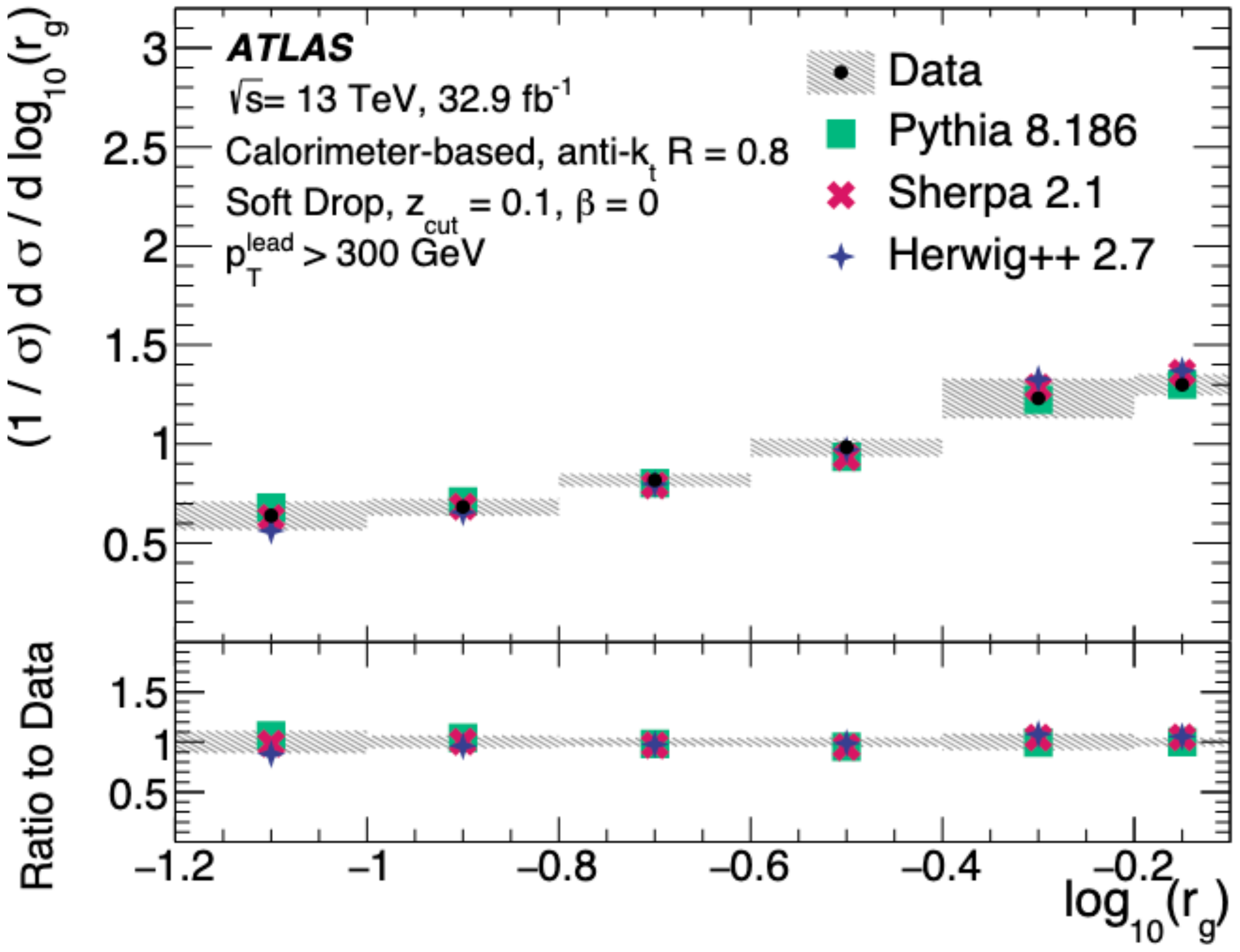
The groomed jet radius

$$\theta_g = \frac{\Delta R(j_1, j_2)}{R_0}$$

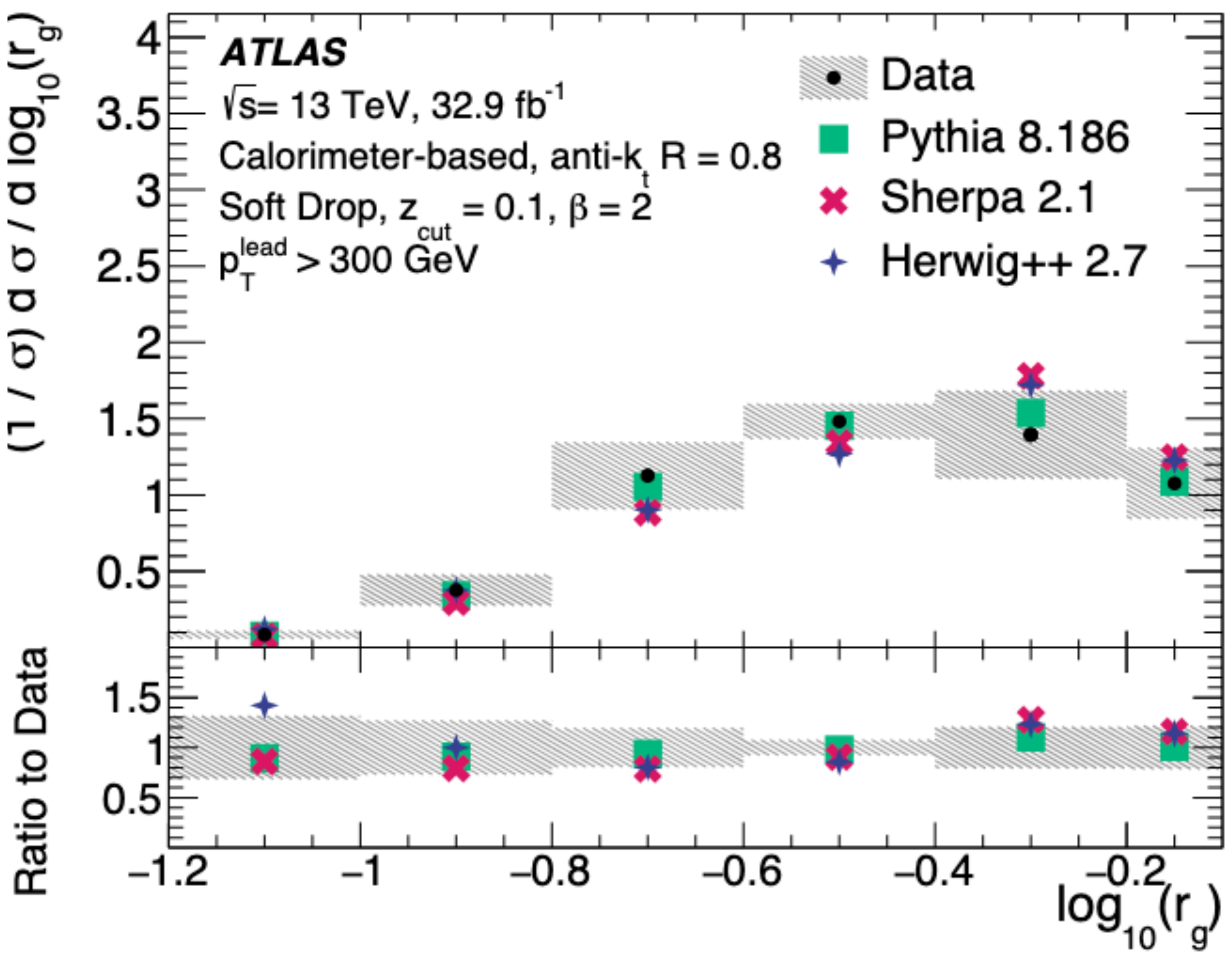
Low p_T, R=0.4



High p_T, large R=0.8, more grooming



High p_T, large R=0.8, less grooming



Phys. Rev. D 101, 052007 (2020)

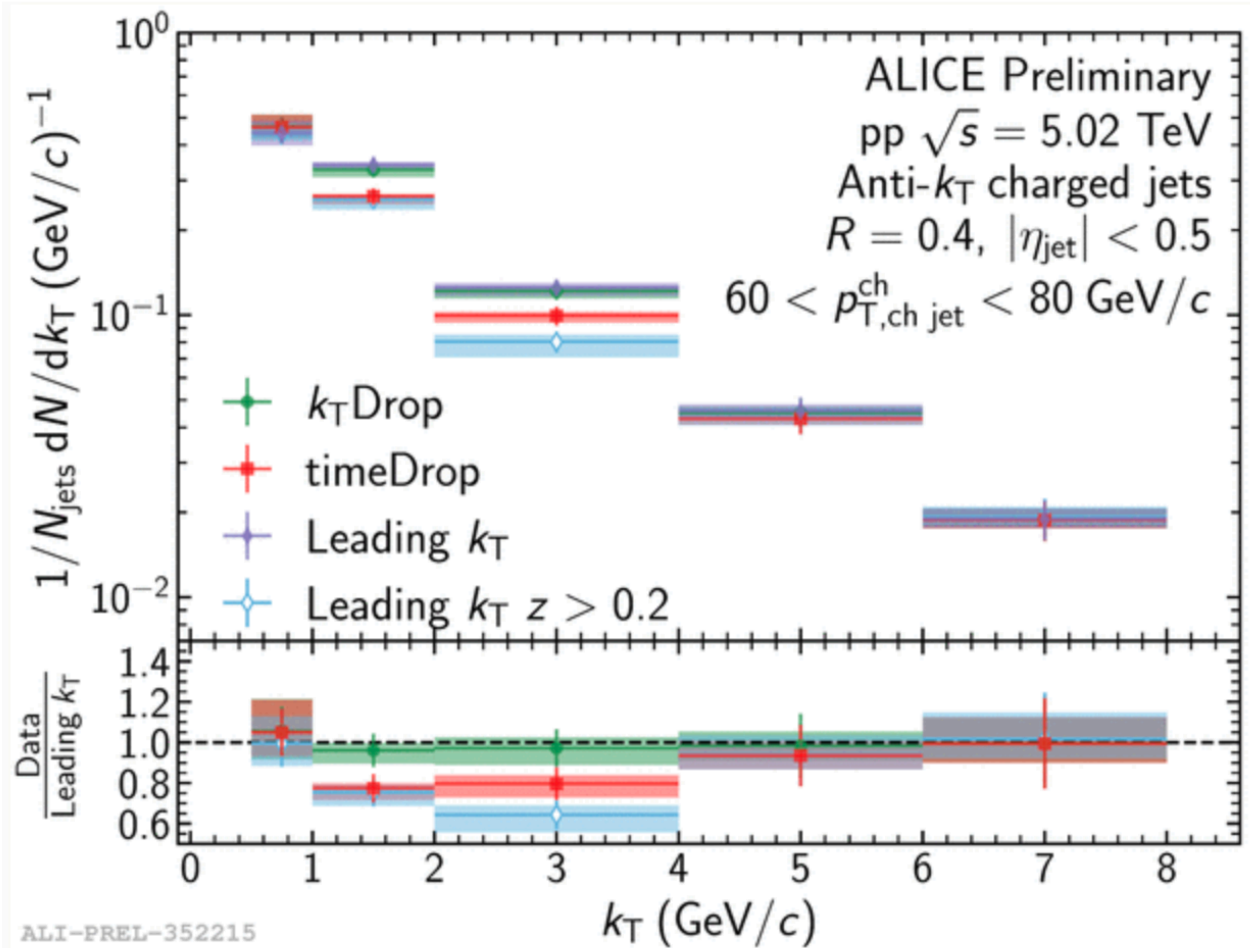
Good description by MC generators

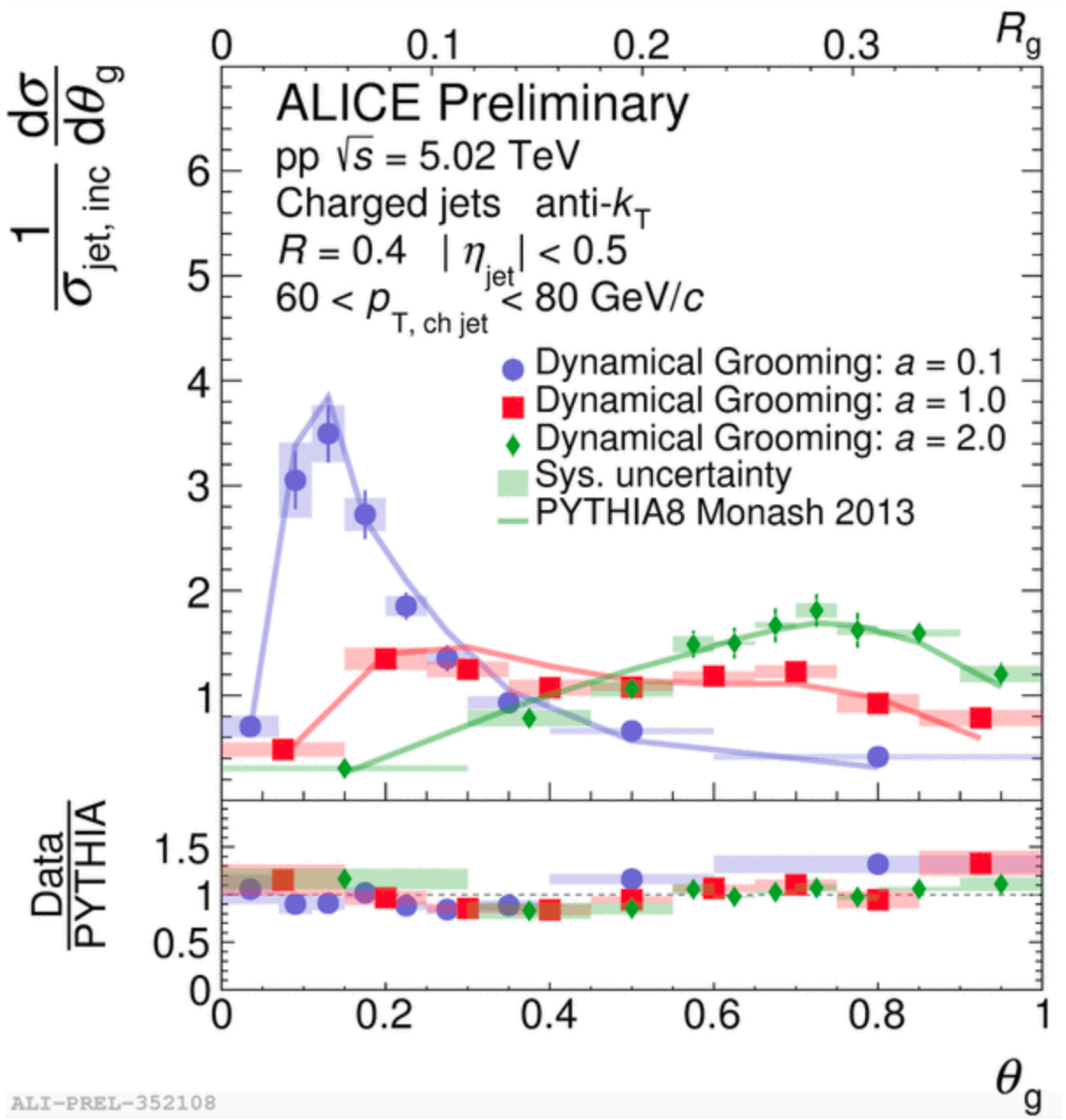
Largest discrepancies with less grooming in the regions most affected by non-perturbative effects (collinear splits)

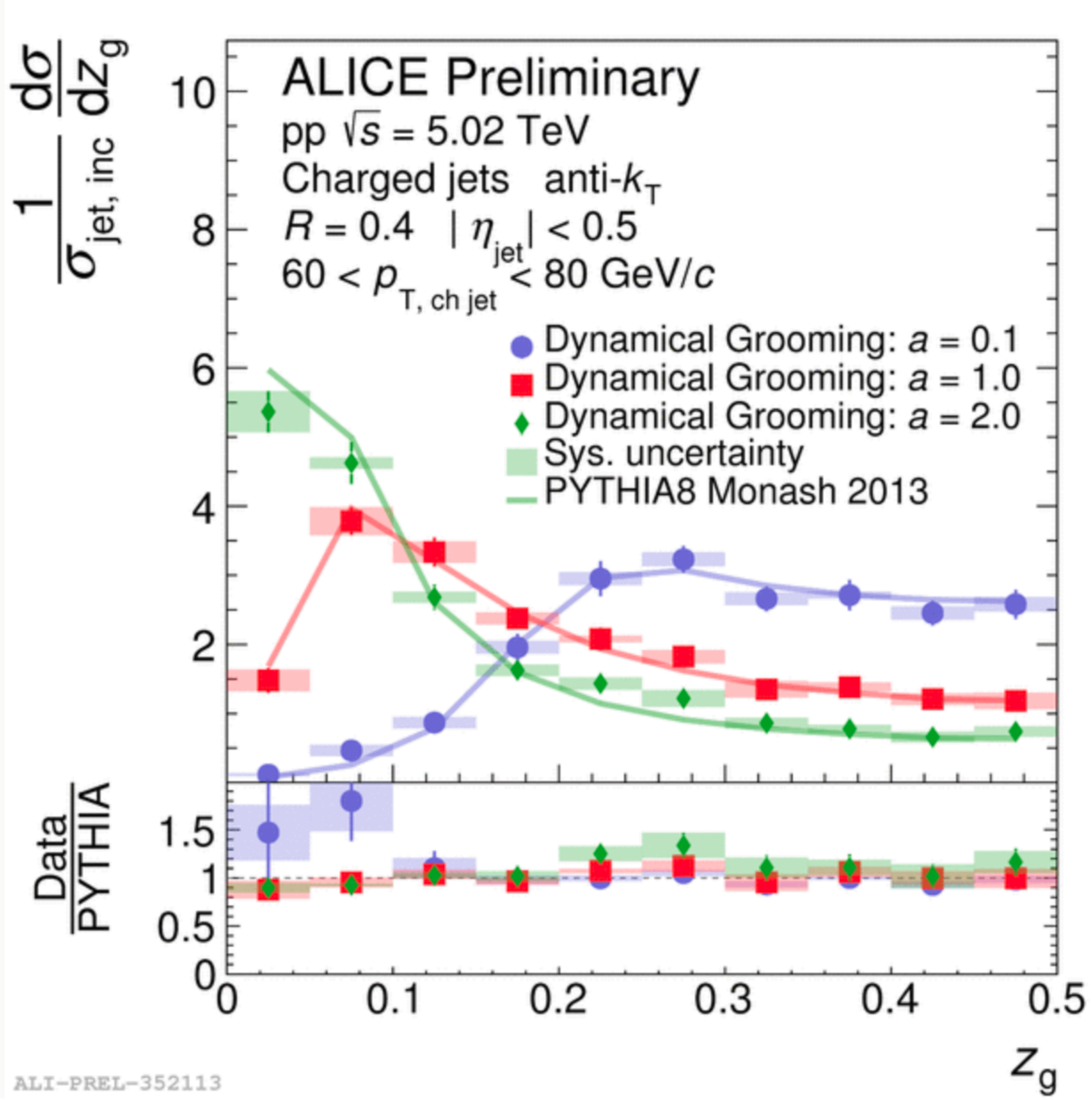
See talk of James Mulligan for observables that measure the angle between jet axes found with different recombination schemes (see also backup)

Dynamical grooming

New at LHCP





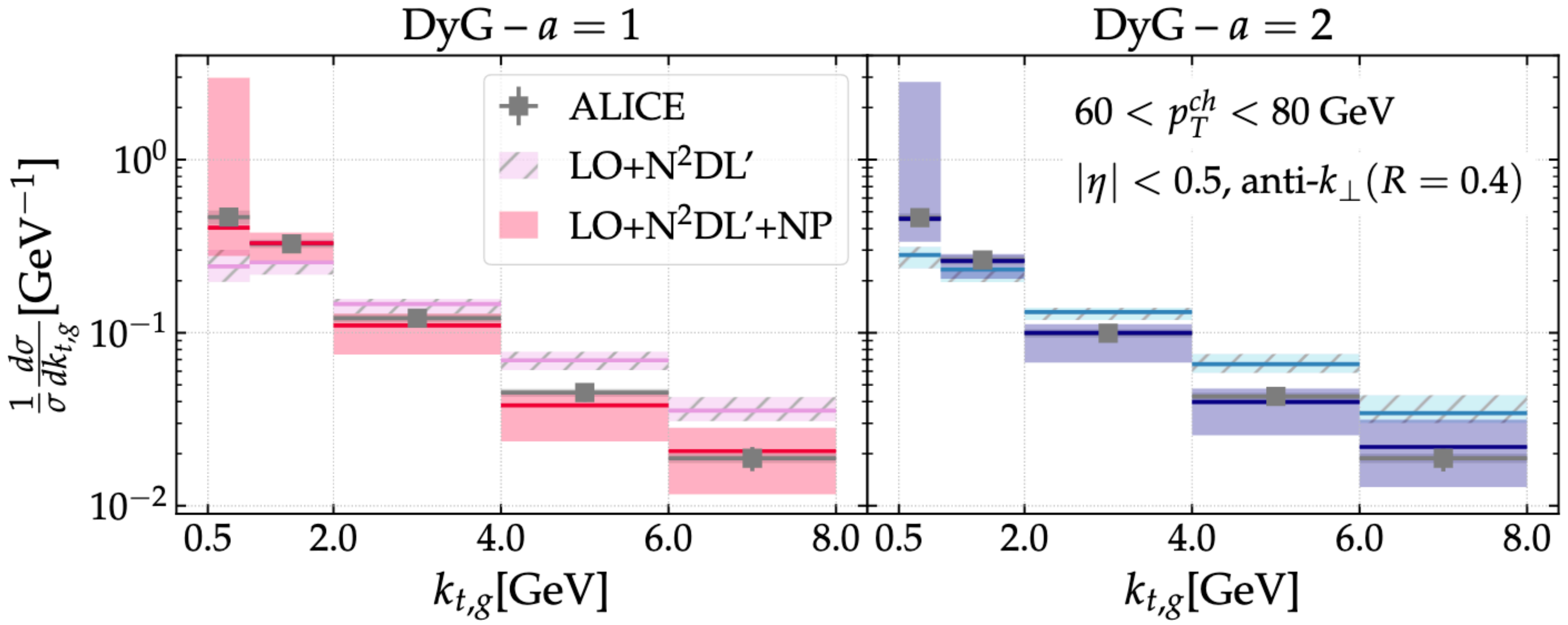


- First measurement of dynamical grooming
- Good agreement between PYTHIA and data
- At high k_T, different dyn grooming settings seem to select the same splitting
- First comparisons to analytical calculations at LO+N2DL accuracy *Caucal et al, arXiv:2103.06566*

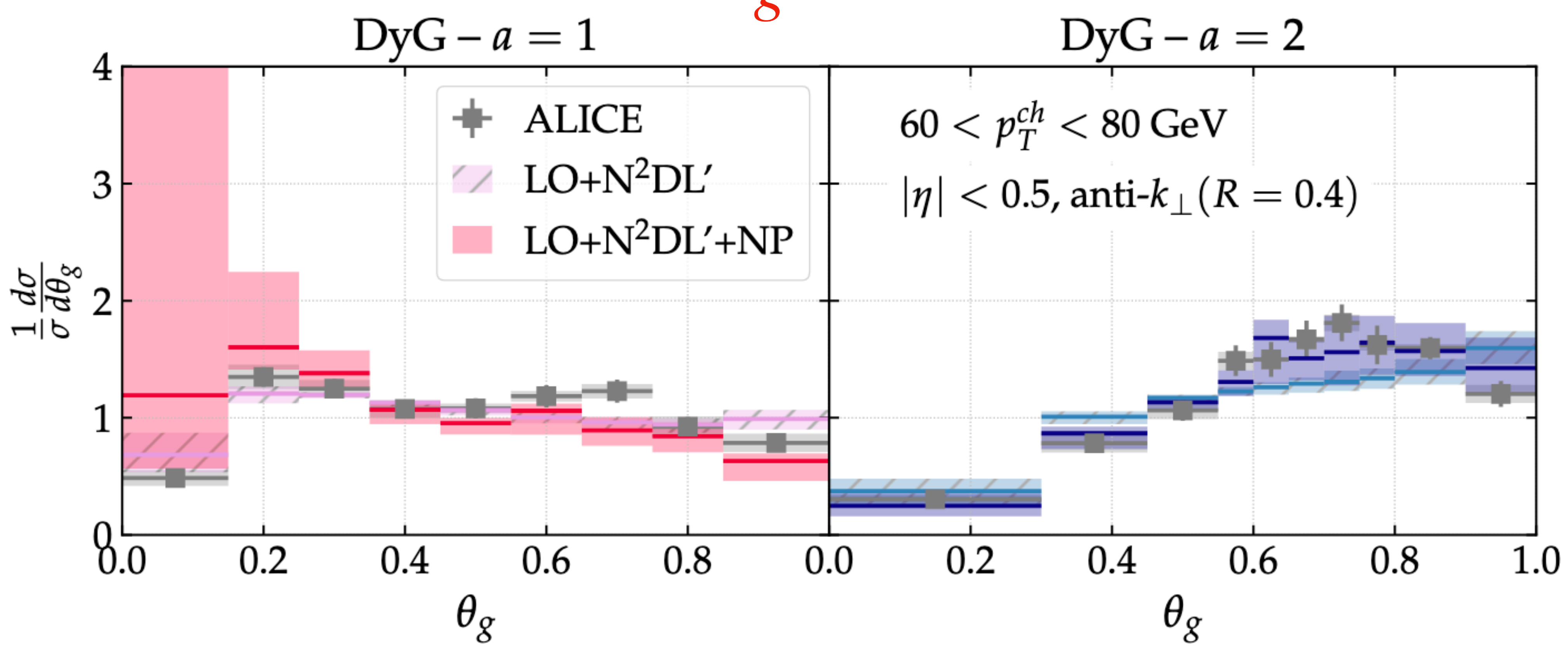
Dynamical grooming

New at LHCP

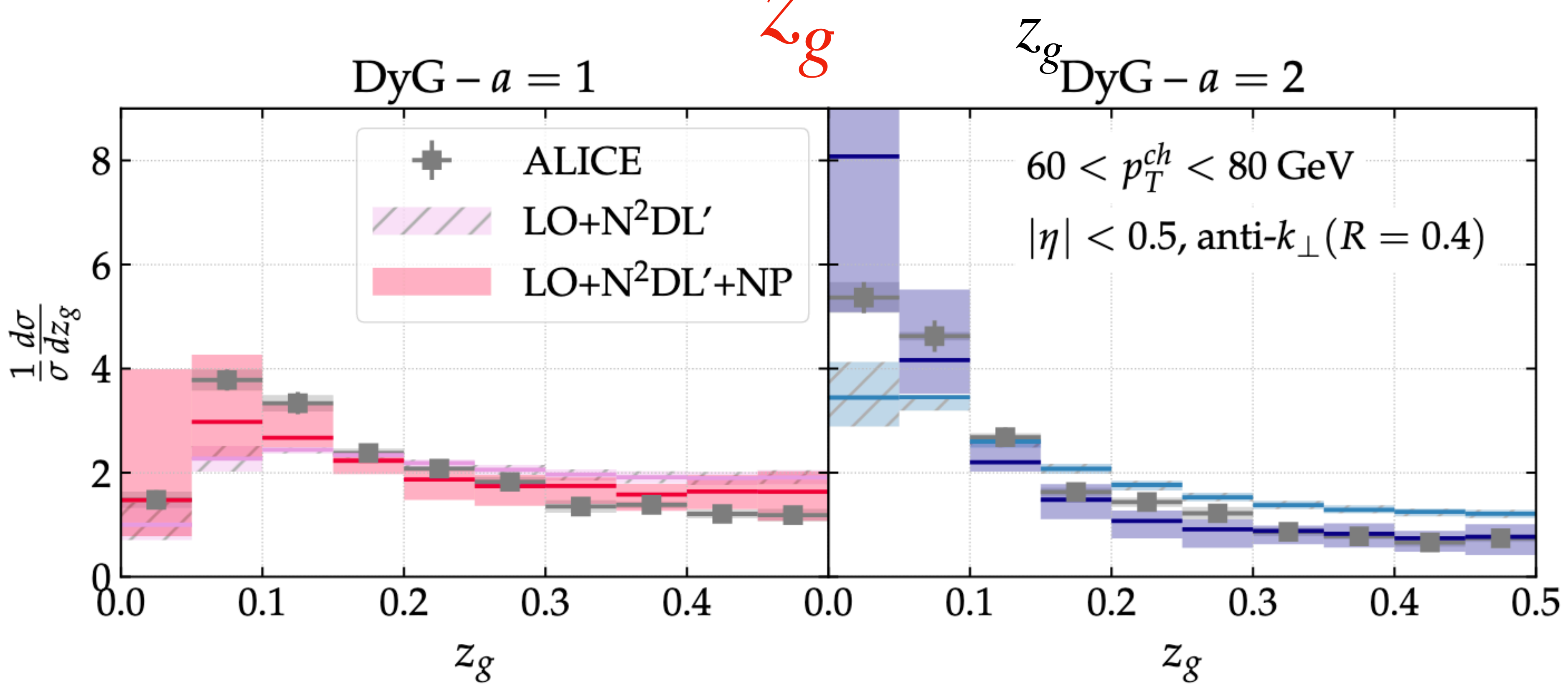
$k_{T,g}$



θ_g



z_g



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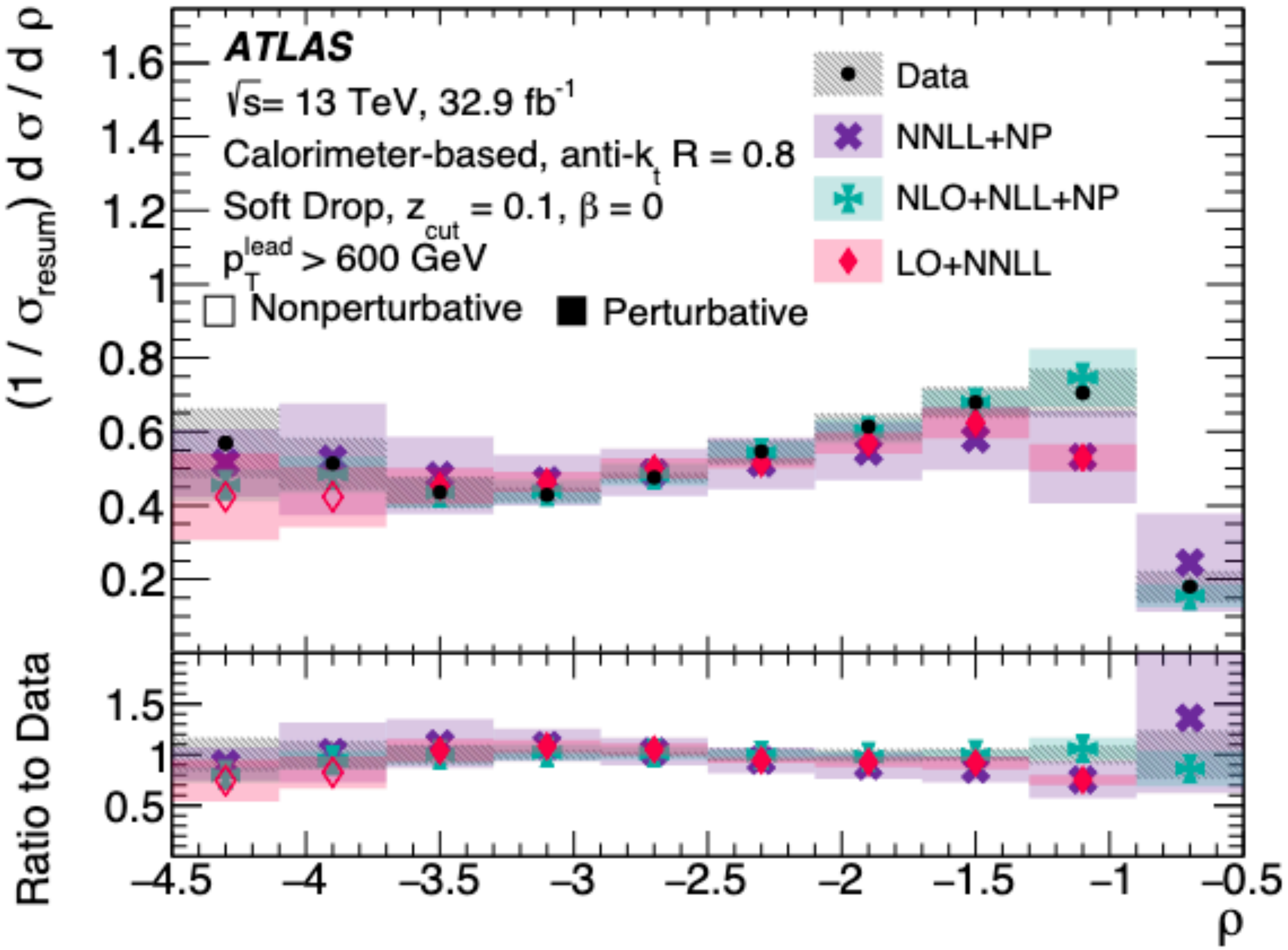
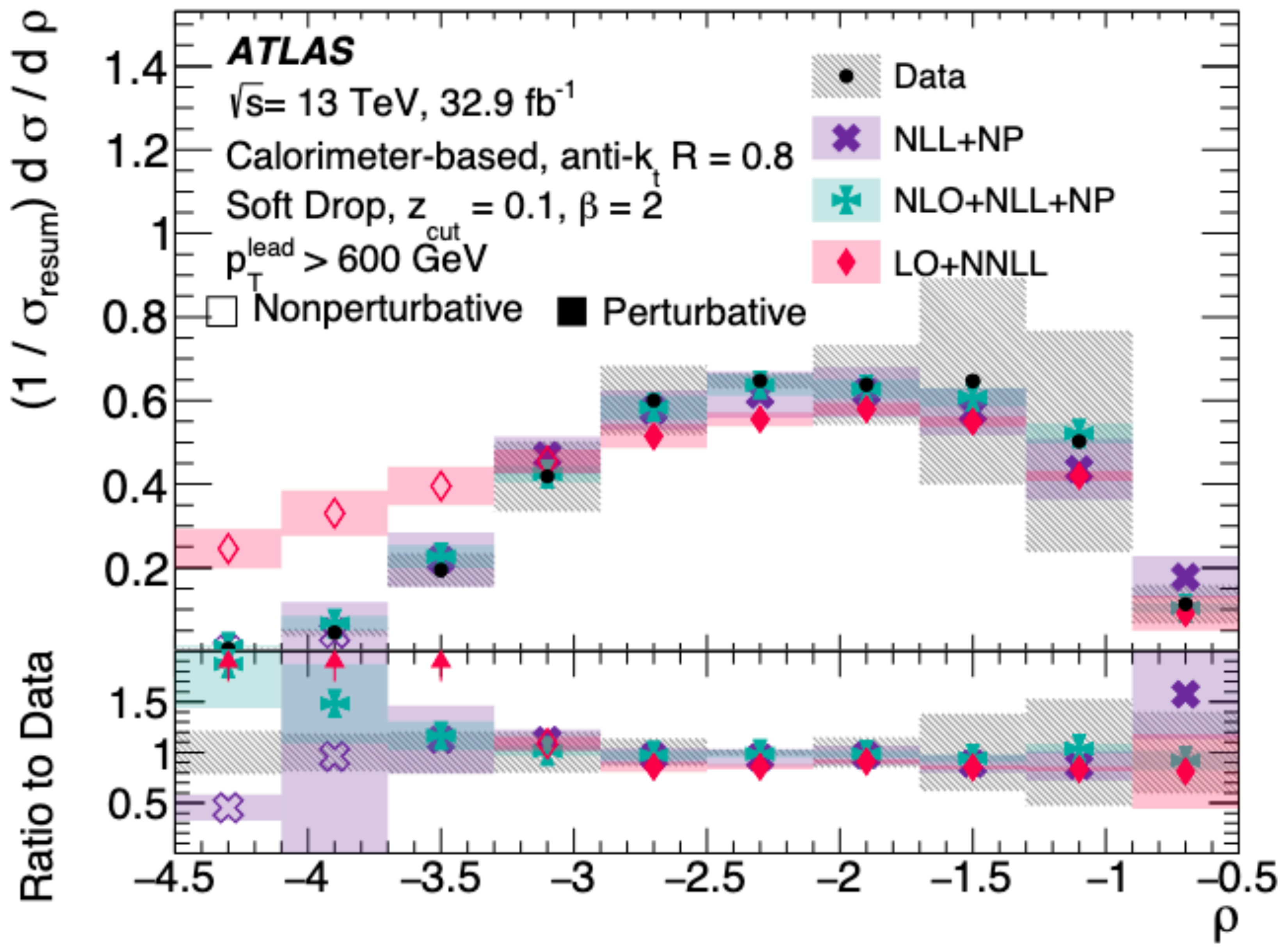
The groomed jet mass: precision QCD

$$\rho = 2log_{10}(\frac{m_j}{p_{T,j}R})$$

Phys. Rev. D 101, 052007 (2020)



less aggressive grooming



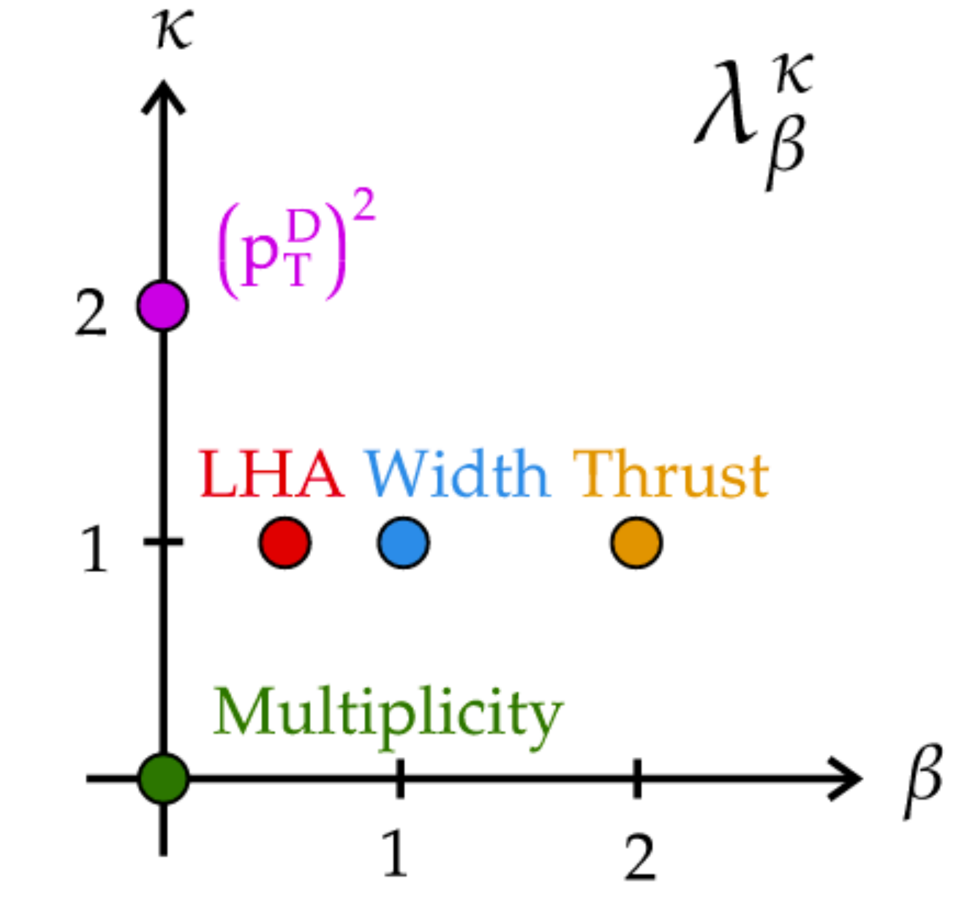
NP regime Resummation regime Fixed-order regime

- The calculations are able to describe the data in the resummation regime at the level of 10%
- See also CMS comparisons of groomed and ungroomed mass *CMS,JHEP 11 (2018) 113*
- *R*g comparison to NLL calculations also available (see backup)

Quark and gluon fragmentation

New at LHCP

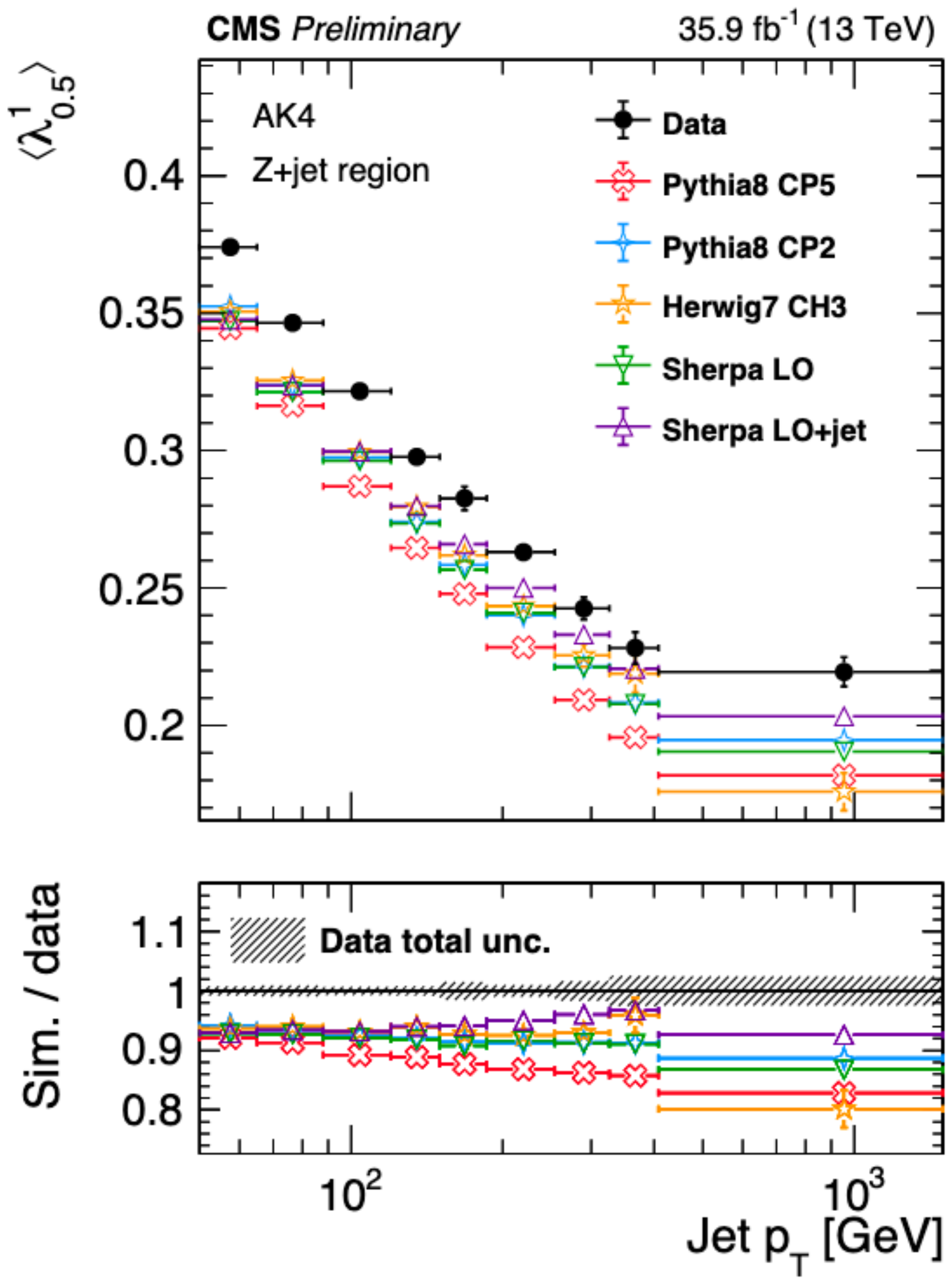
See talk by Markus Seidel



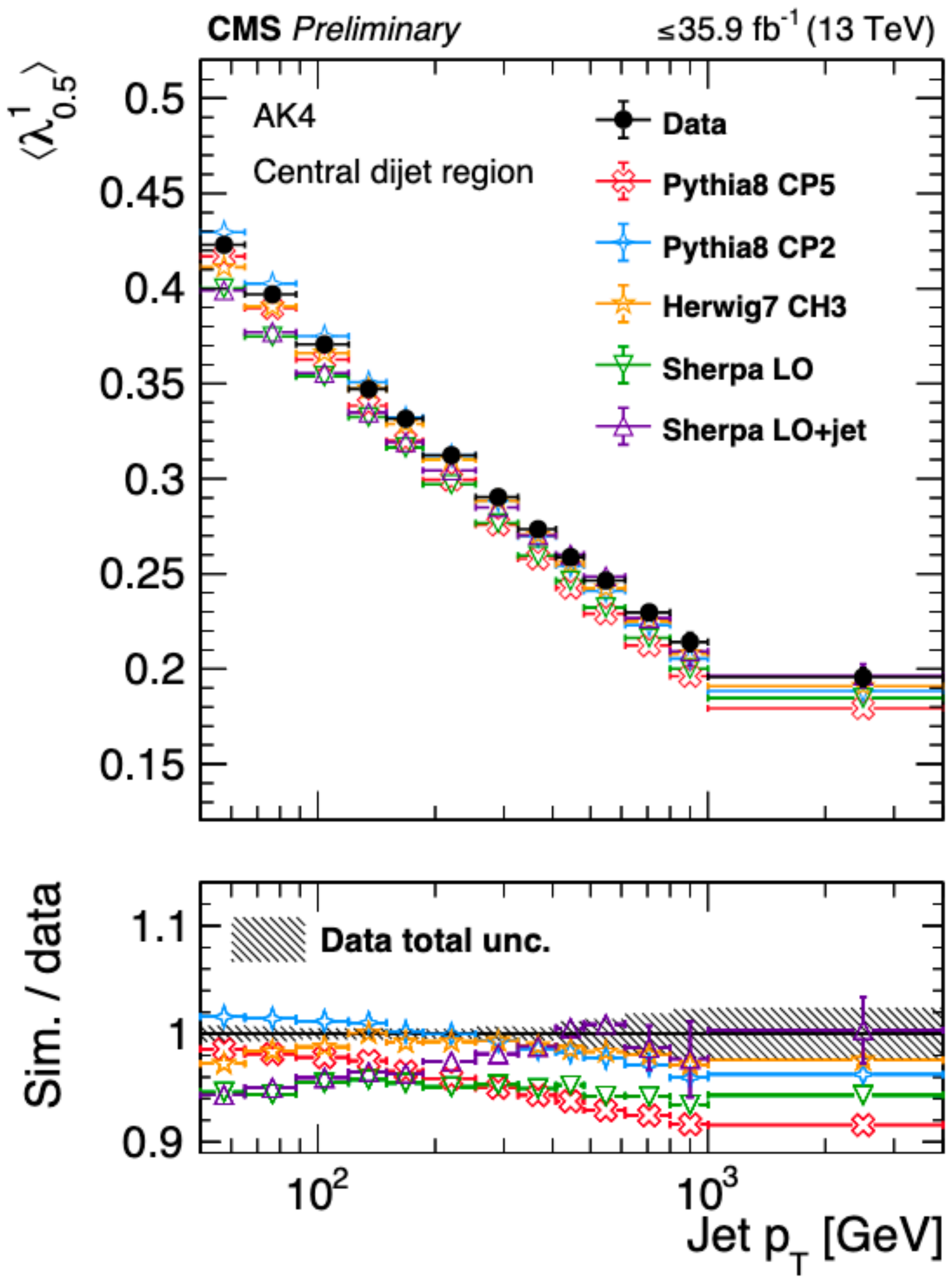
$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R} \right)^\beta$$

CMS PAS SMP-20-010

Z+jet, quark-enriched



dijets, gluon-enriched



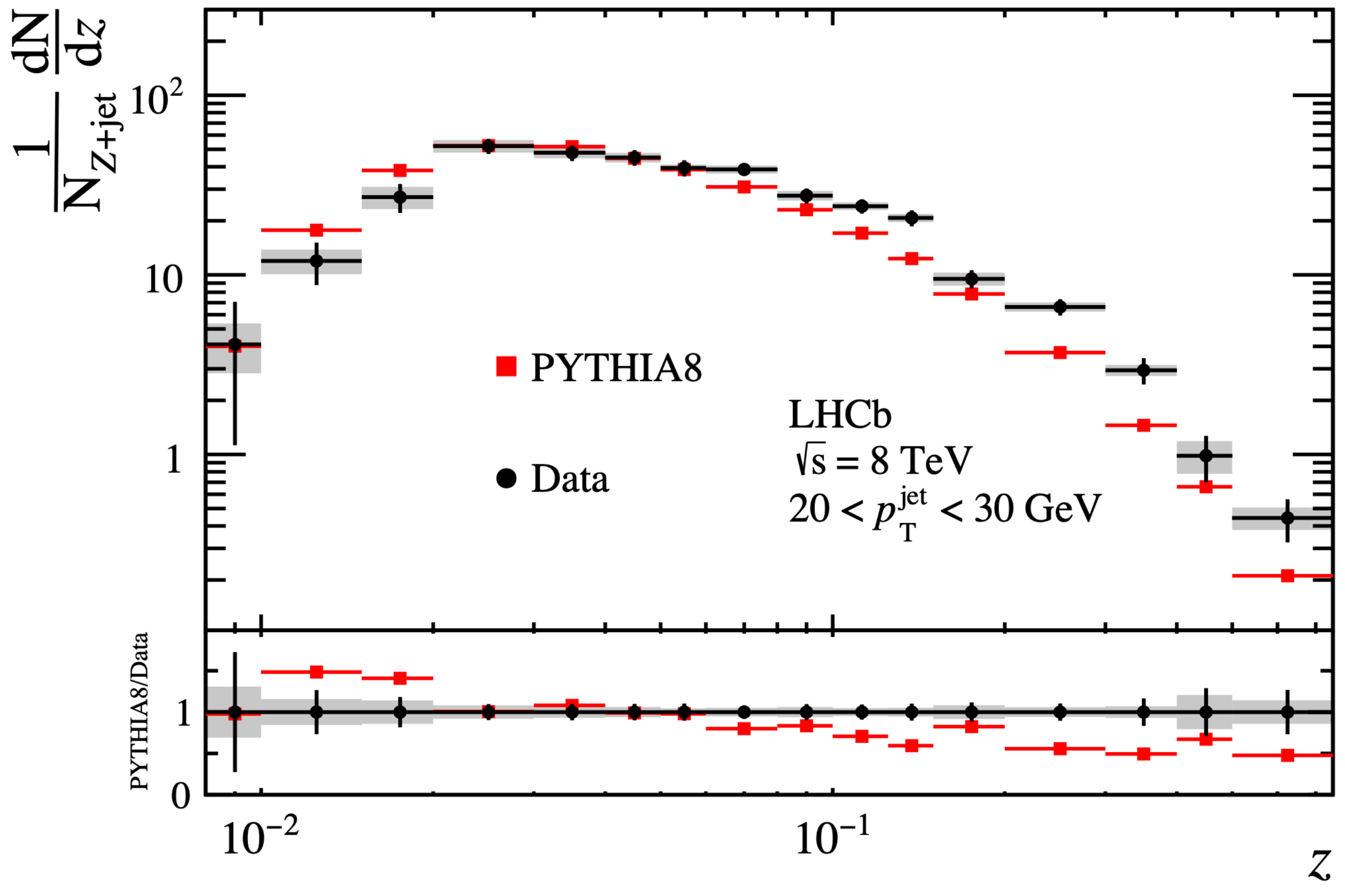
- At LO, LHA, Width, Thrust, Multiplicity, are expected to be higher in gluon-enriched samples
- Quark and gluon initiated jet showers not well described by generators, important consequences for taggers

Quark fragmentation with LHCb

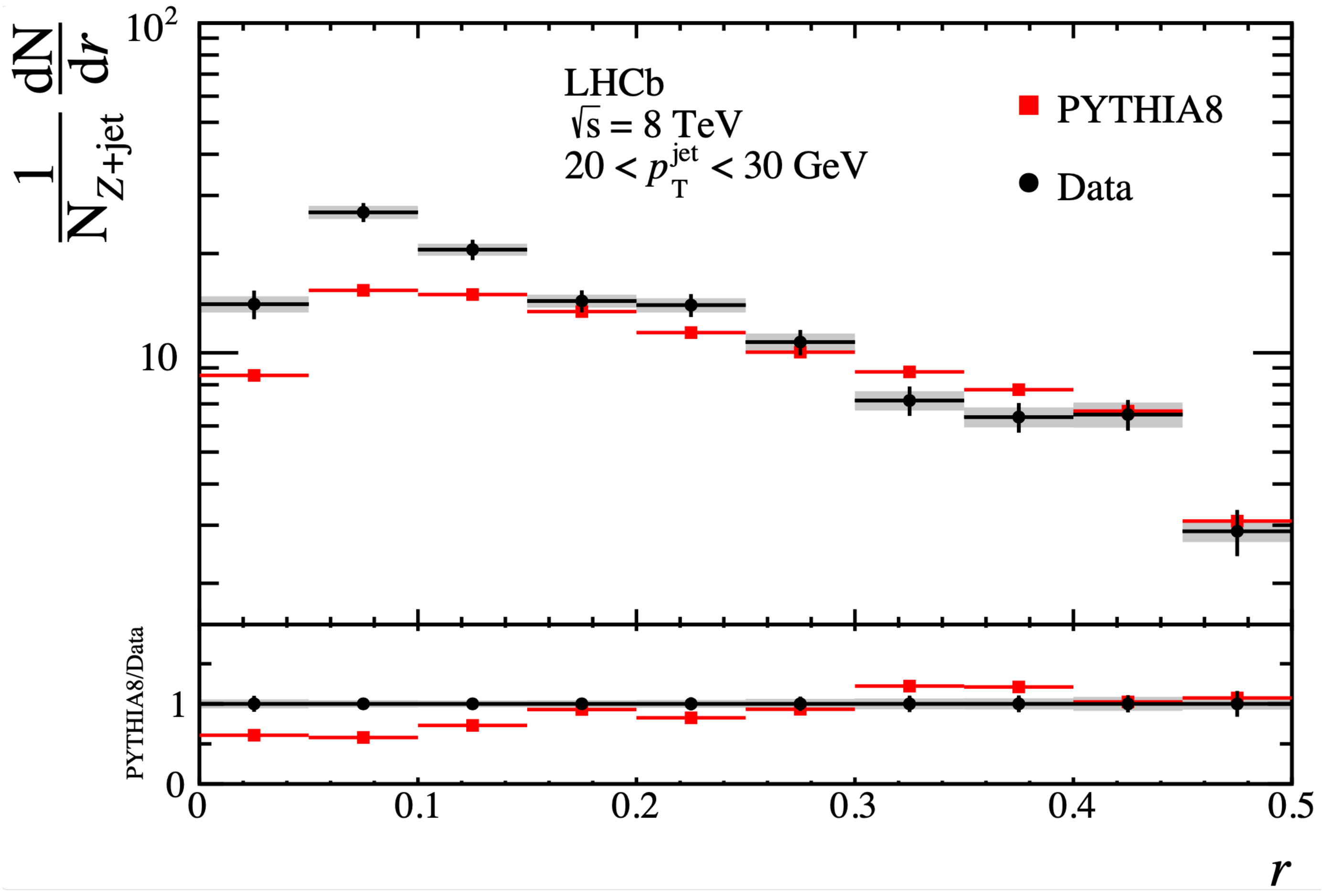
New at LHCP

See talk by Martin Kucharczyk

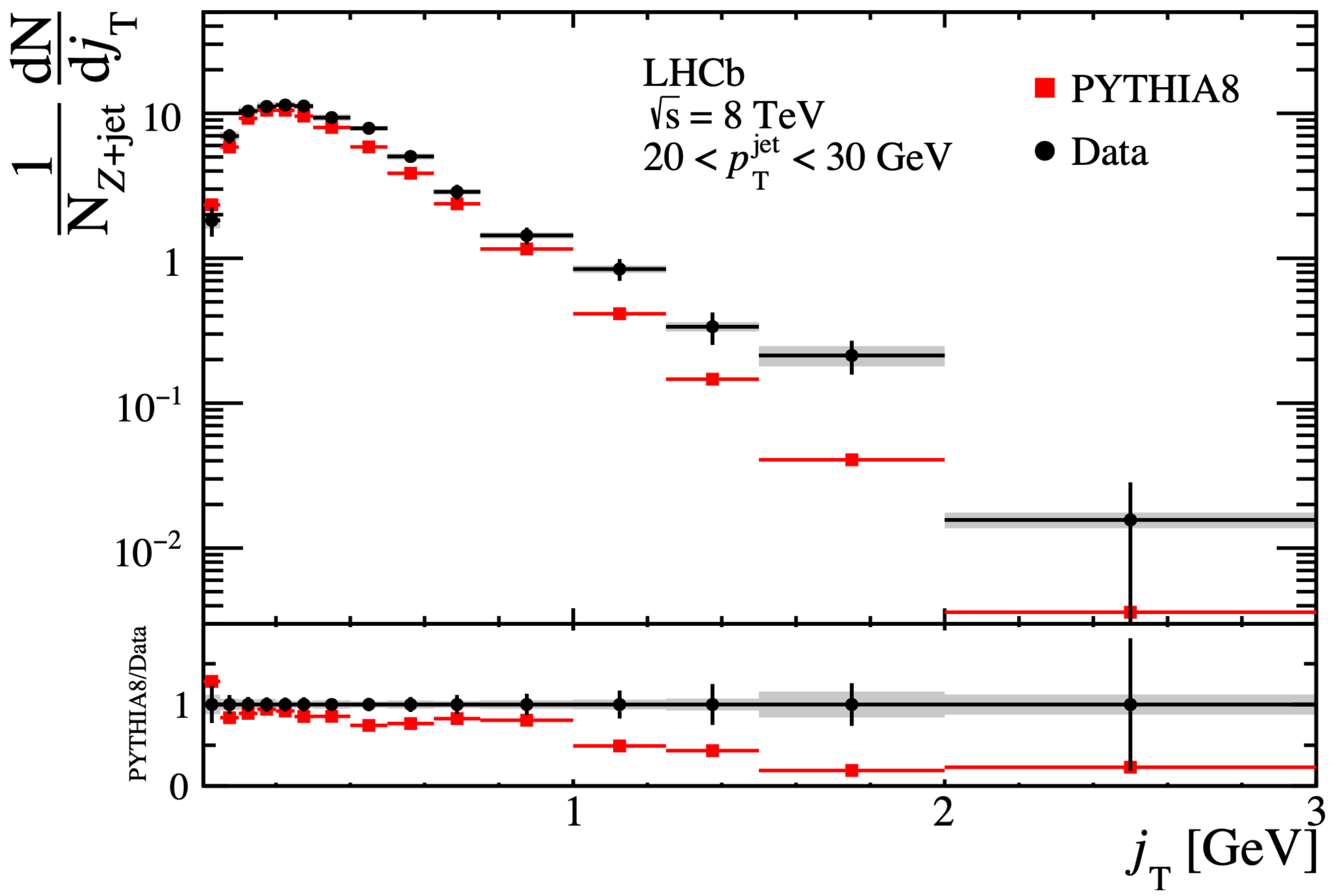
Longitudinal momentum fraction

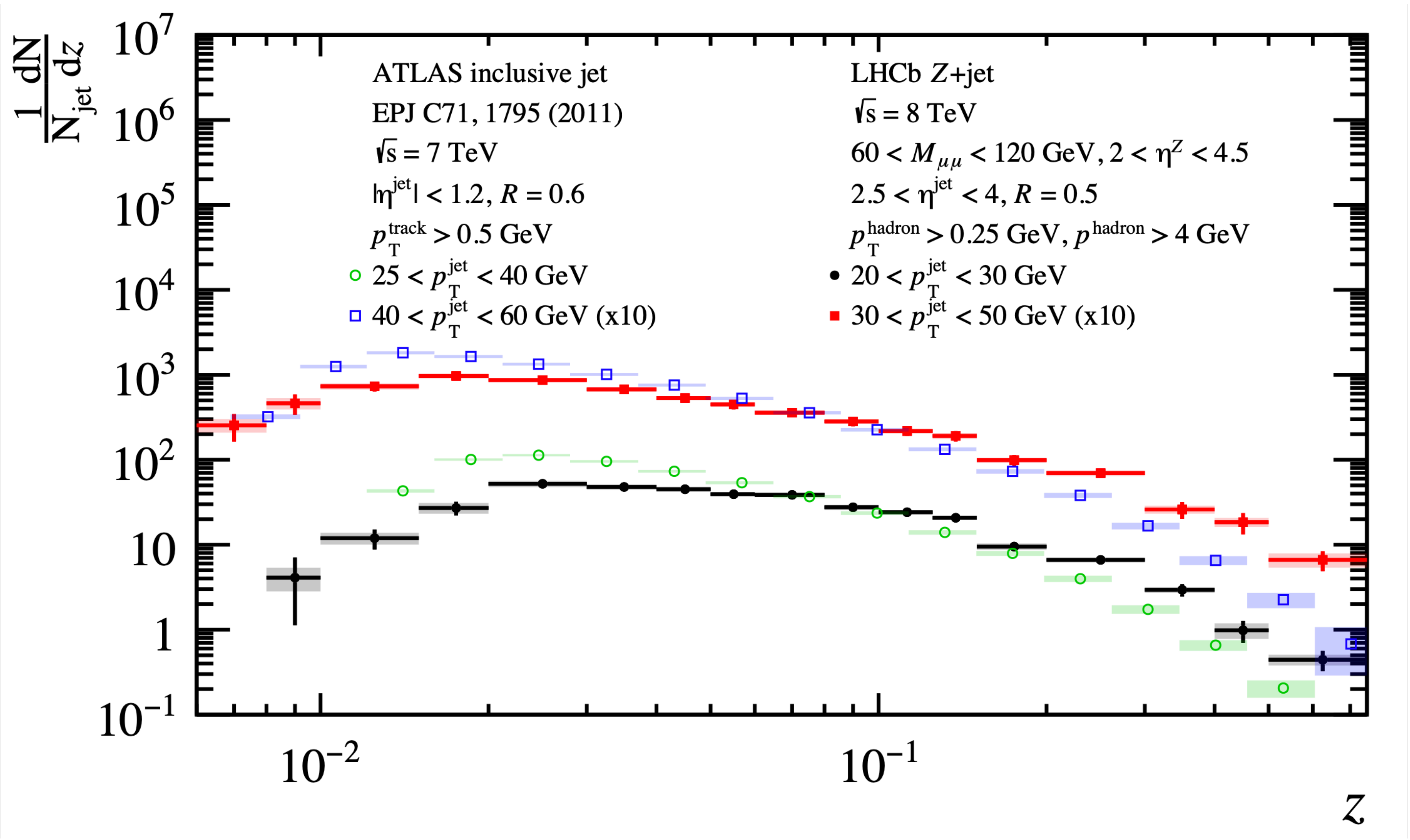


Distance to the jet axis



Transverse momentum fraction





Jet shapes of jets recoiling from Z boson in the forward region, quark enriched

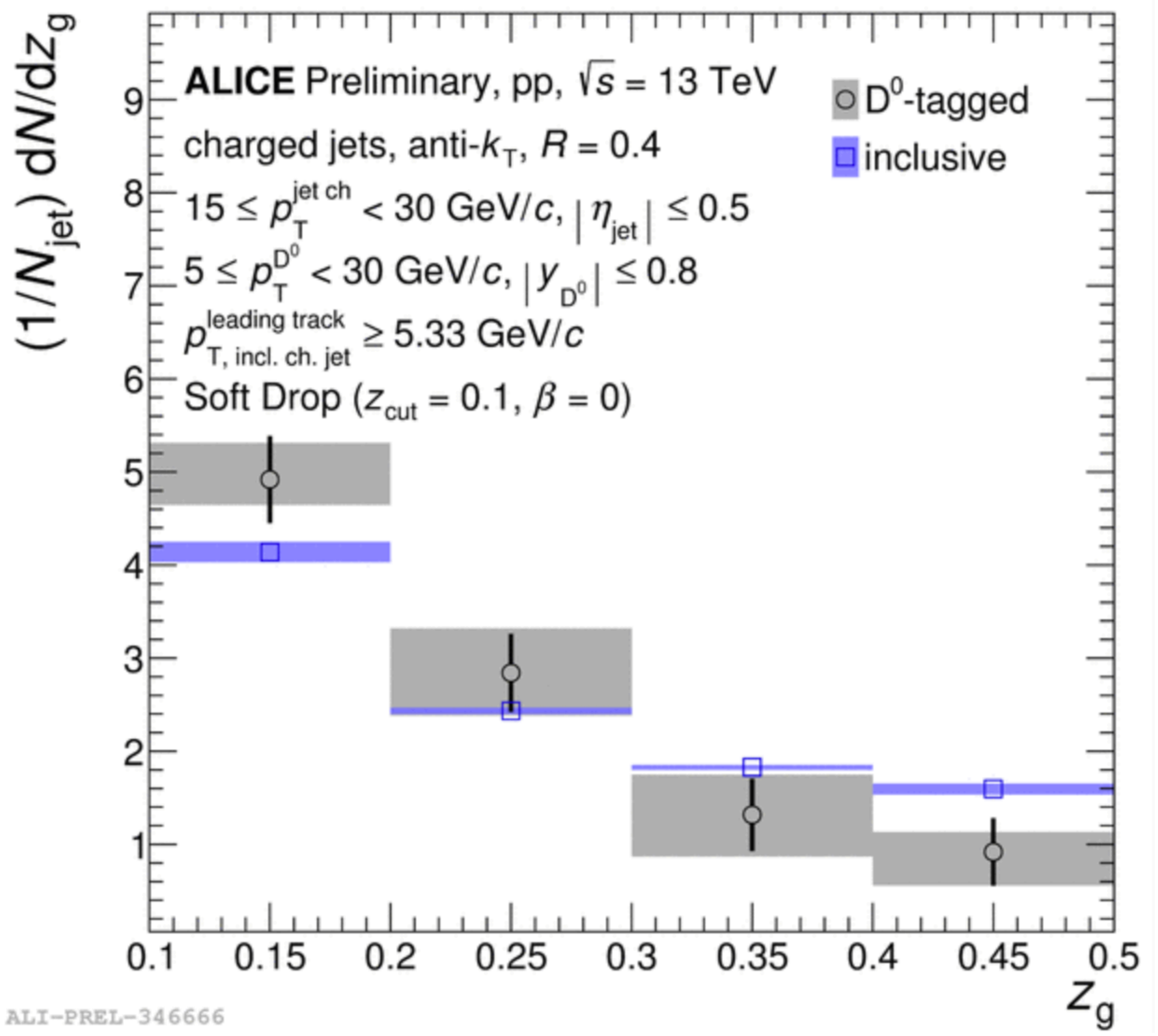
$2.5 < \eta_{jet} < 4$

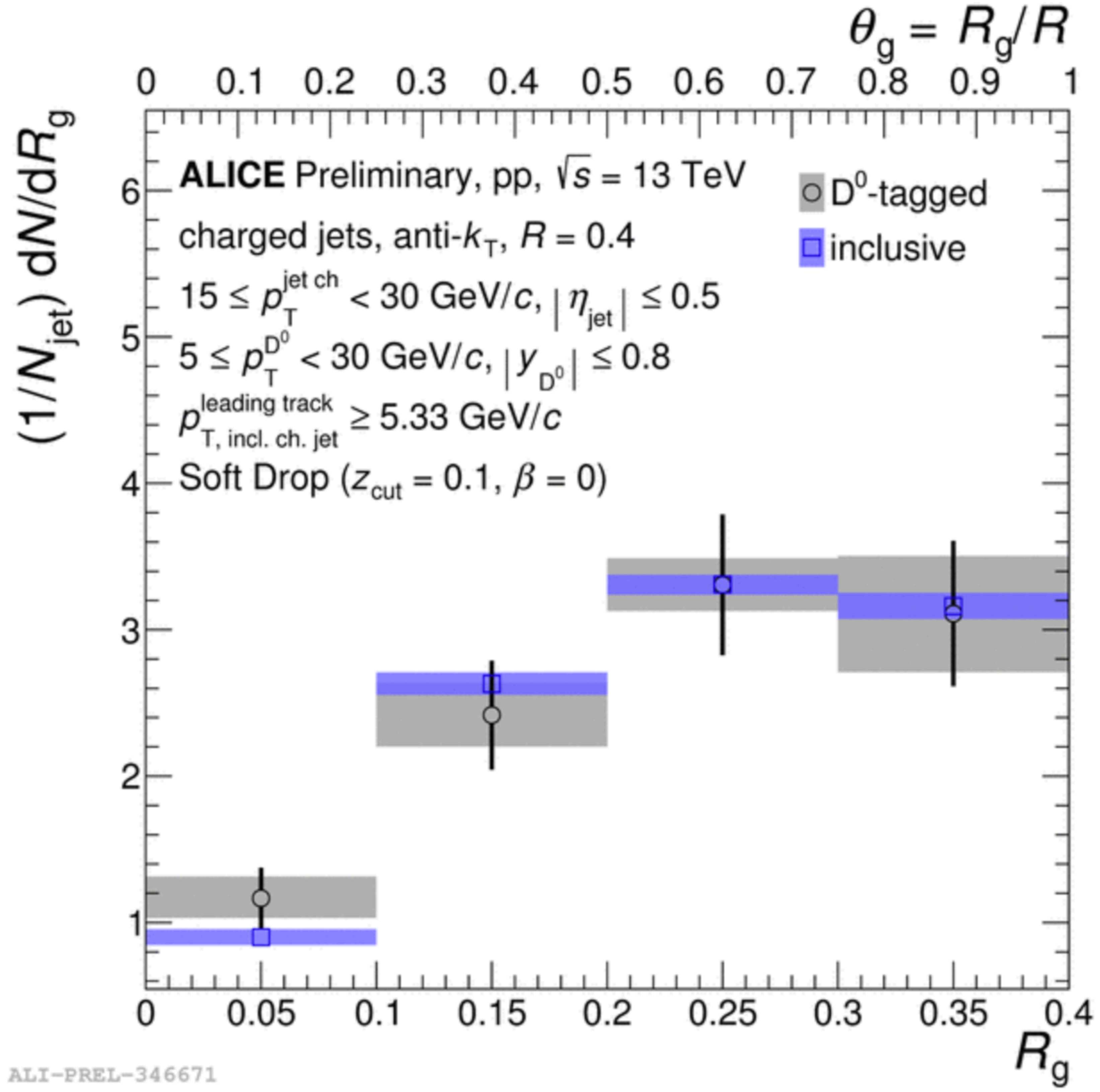
- PYTHIA underestimates number of high-z/low-r hadrons
- PYTHIA underestimates the charged hadron multiplicity
- Qualitative comparisons to ATLAS central measurements point to harder and more collimated fragmentation in the forward region

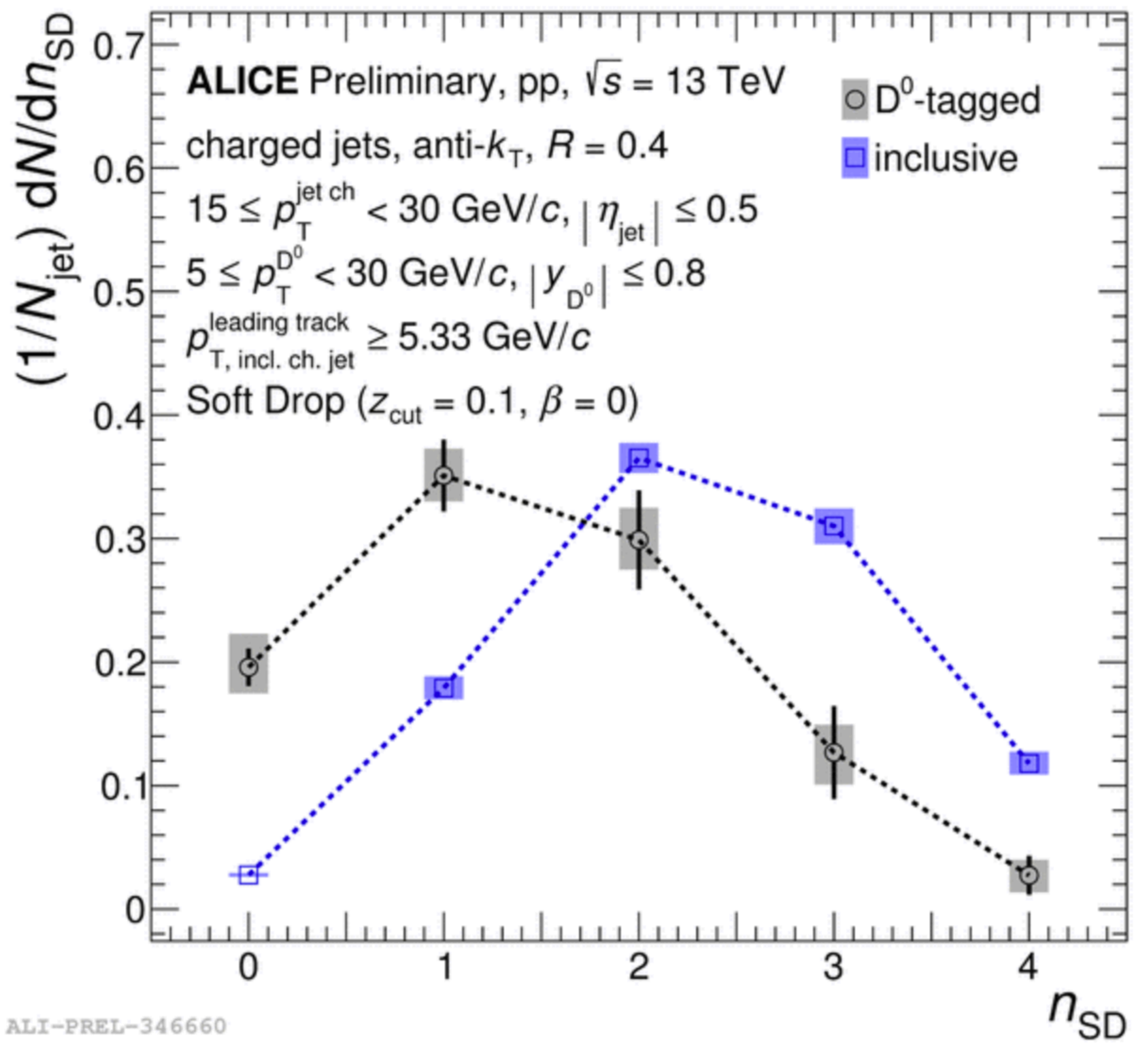
LHCb Phys. Rev. Lett. 123, 232001 (2019)

Heavy flavour jet substructure

ALICE-PUBLIC-2020-002

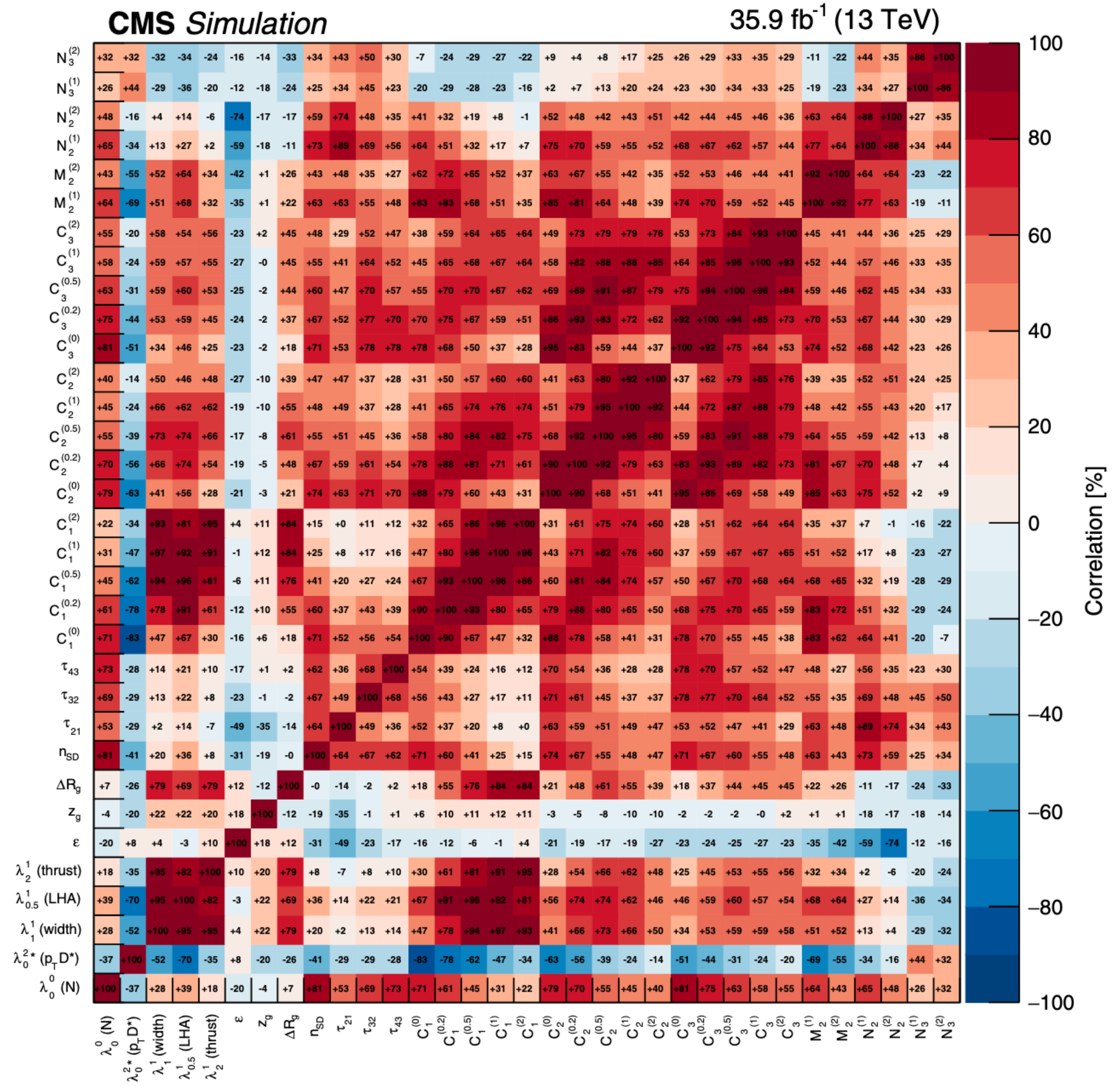






- Groomed momentum imbalance more asymmetric for D^0-tagged jets, consistent with a harder fragmentation than inclusive jets
- R_g consistent with inclusive jets: less sensitivity to small angles compared to full declustering
- Fewer (SD) emissions in the D^0-tagged jets measured via the n_{SD} (or n_{LH}), consequence of both color factors and mass effects

Correlation of substructure observables



[See talk by Markus Seidel]

Most of the considered substructure observables are strongly correlated

Useful to select a set of minimally correlated variables:

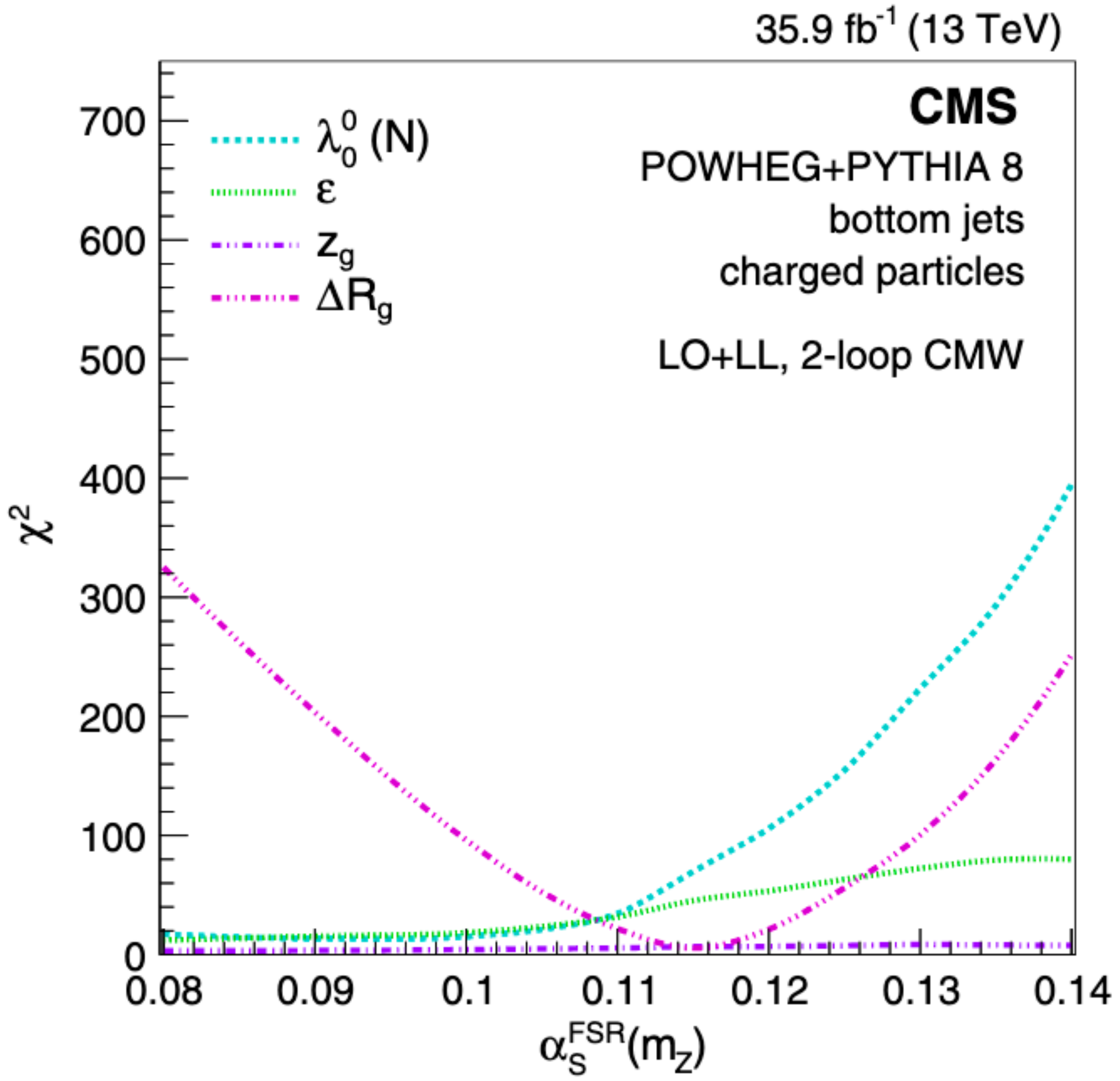
R_g, z_g, multiplicity, ϵ

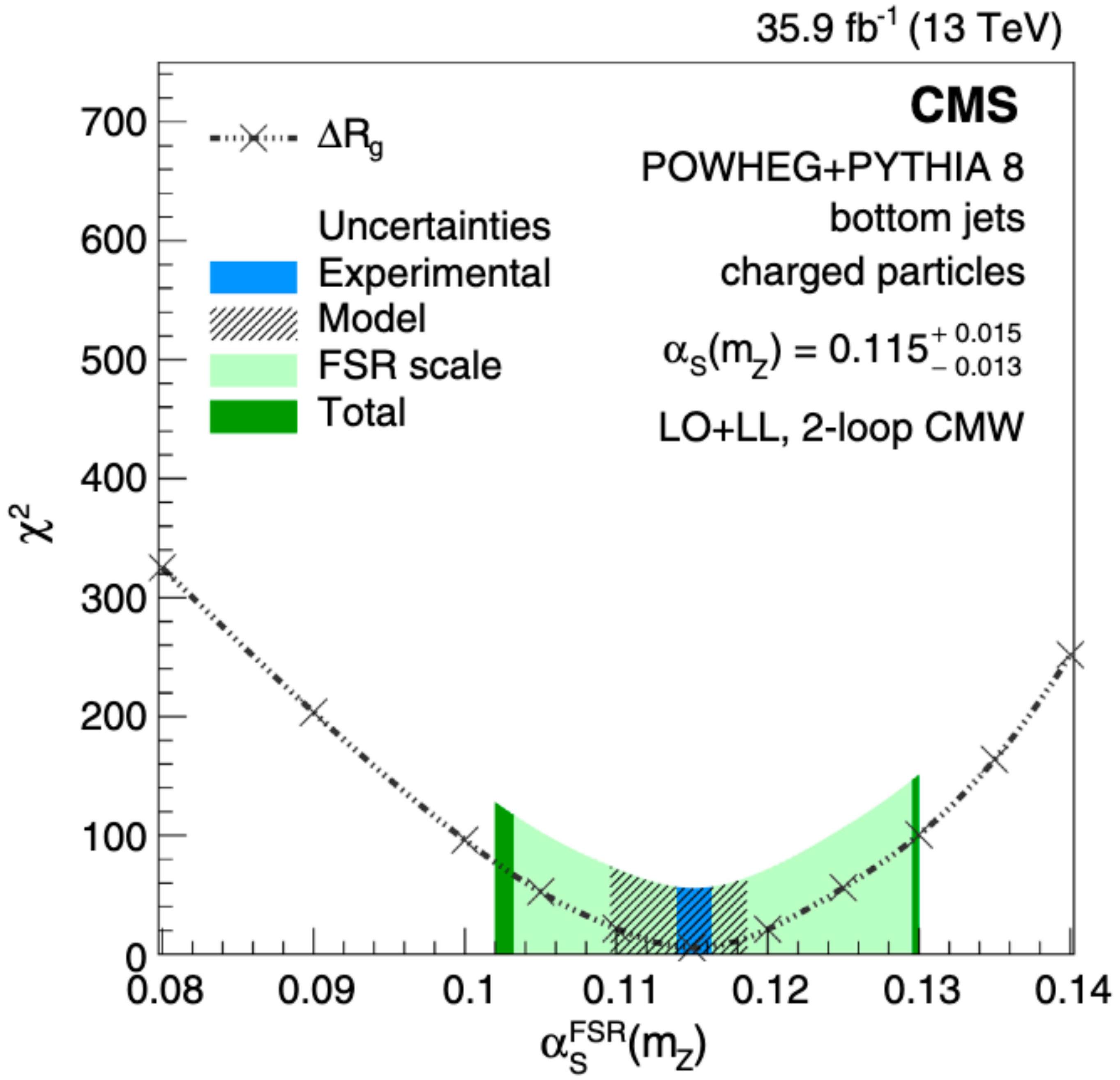
And study the best $\alpha_S(m_Z)$ that describes the data

This kind of consideration has broad scope!

[CMS, Phys.Rev.D 98 (2018) 9, 092014]

Correlation of substructure observables





Most of the considered substructure observables are strongly correlated

Useful to select a set of minimally correlated variables:

R_g, z_g, multiplicity, ϵ

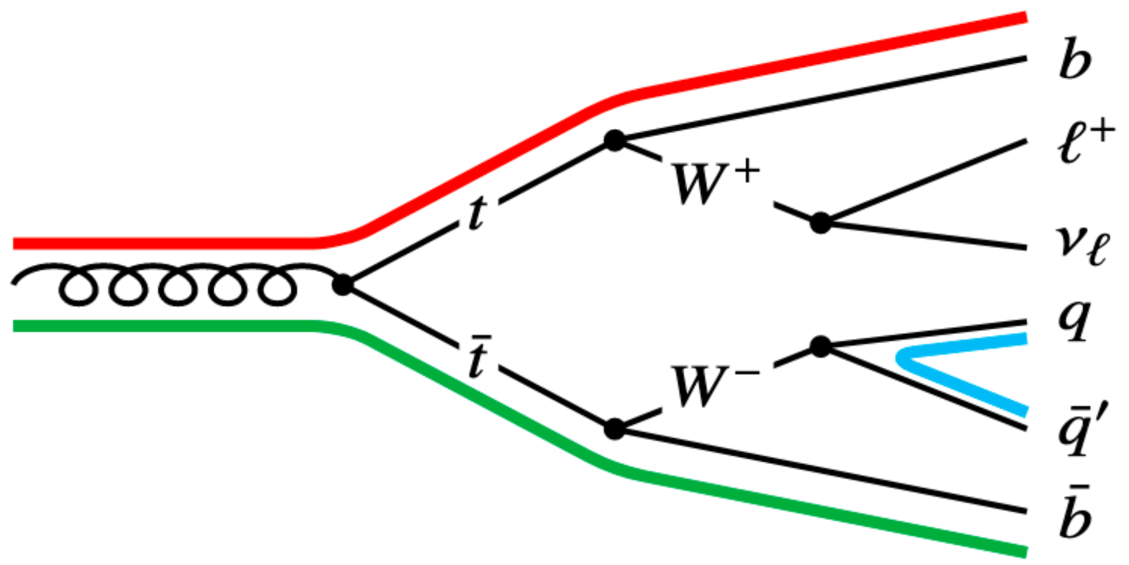
And study the best $\alpha_S(m_Z)$ that describes the data

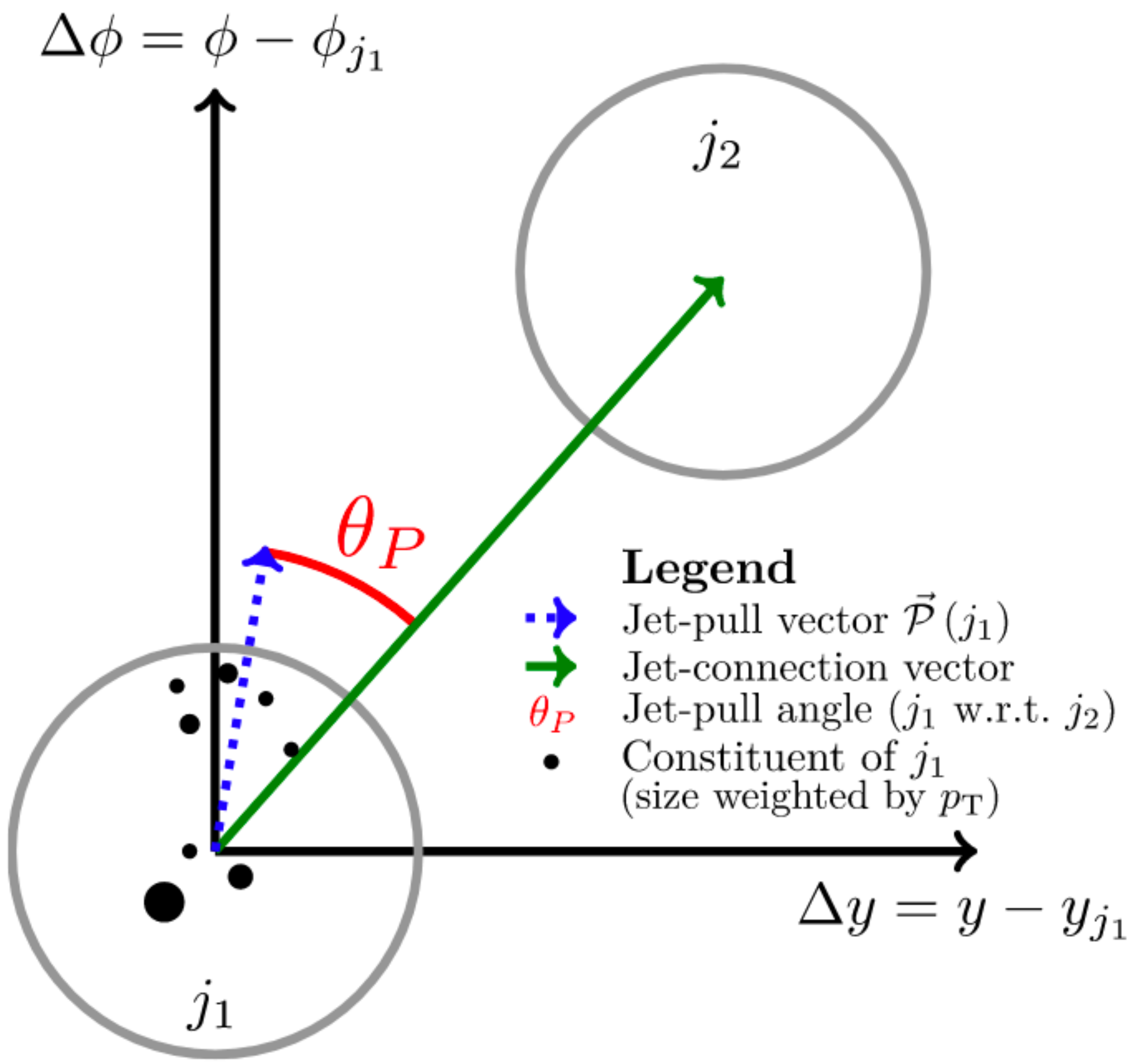
- z_g independent on $\alpha_S(m_Z)$ (LO expectation)
- Multiplicity expected to be highly affected by non pert. effects
- $R_{g;}$ lower impact of non pert. radiation, sensitivity to $\alpha_S(m_Z)$

CMS, Phys.Rev.D 98 (2018) 9, 092014

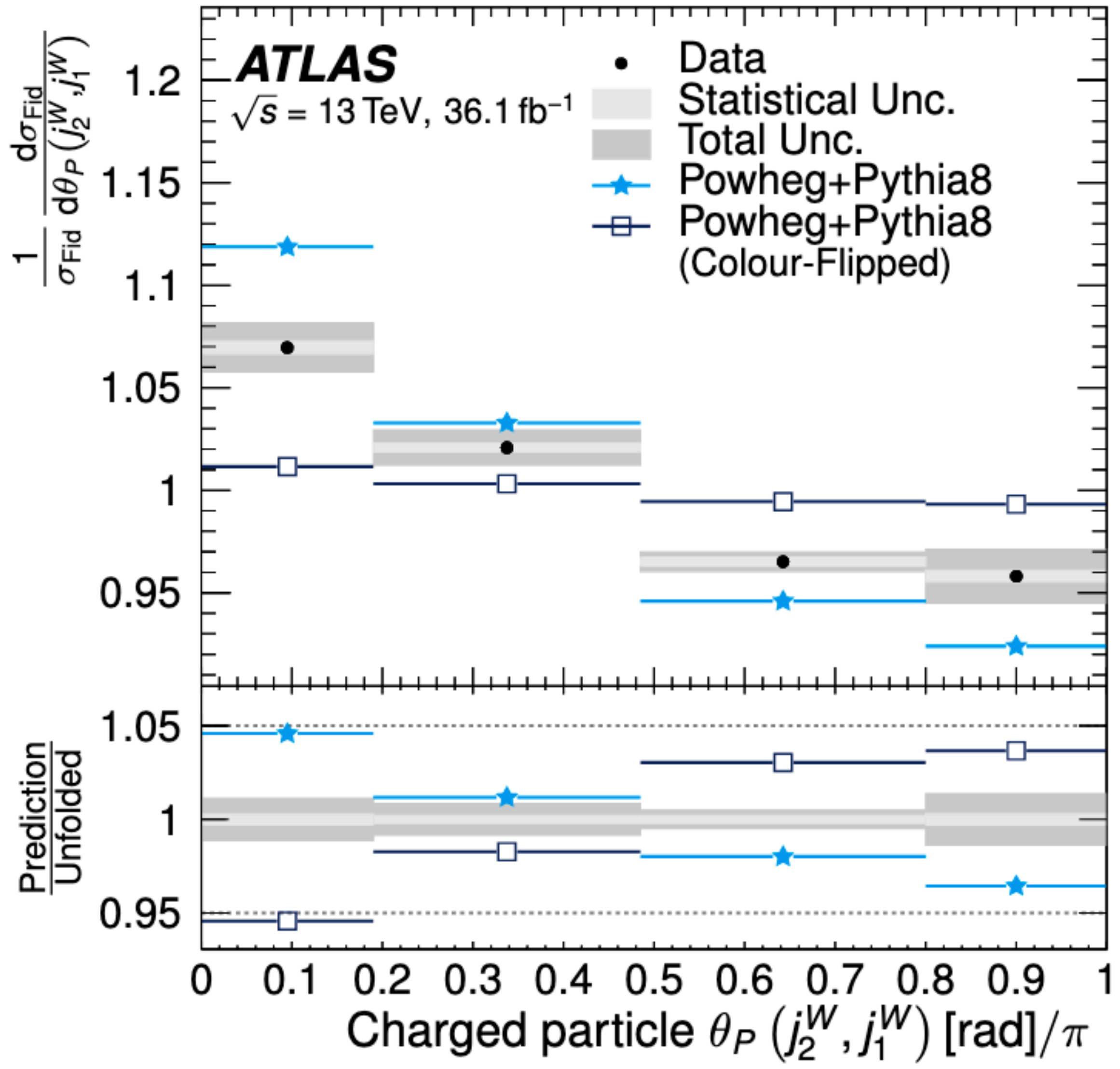
What about colour flow?

Color singlet vs octet decays

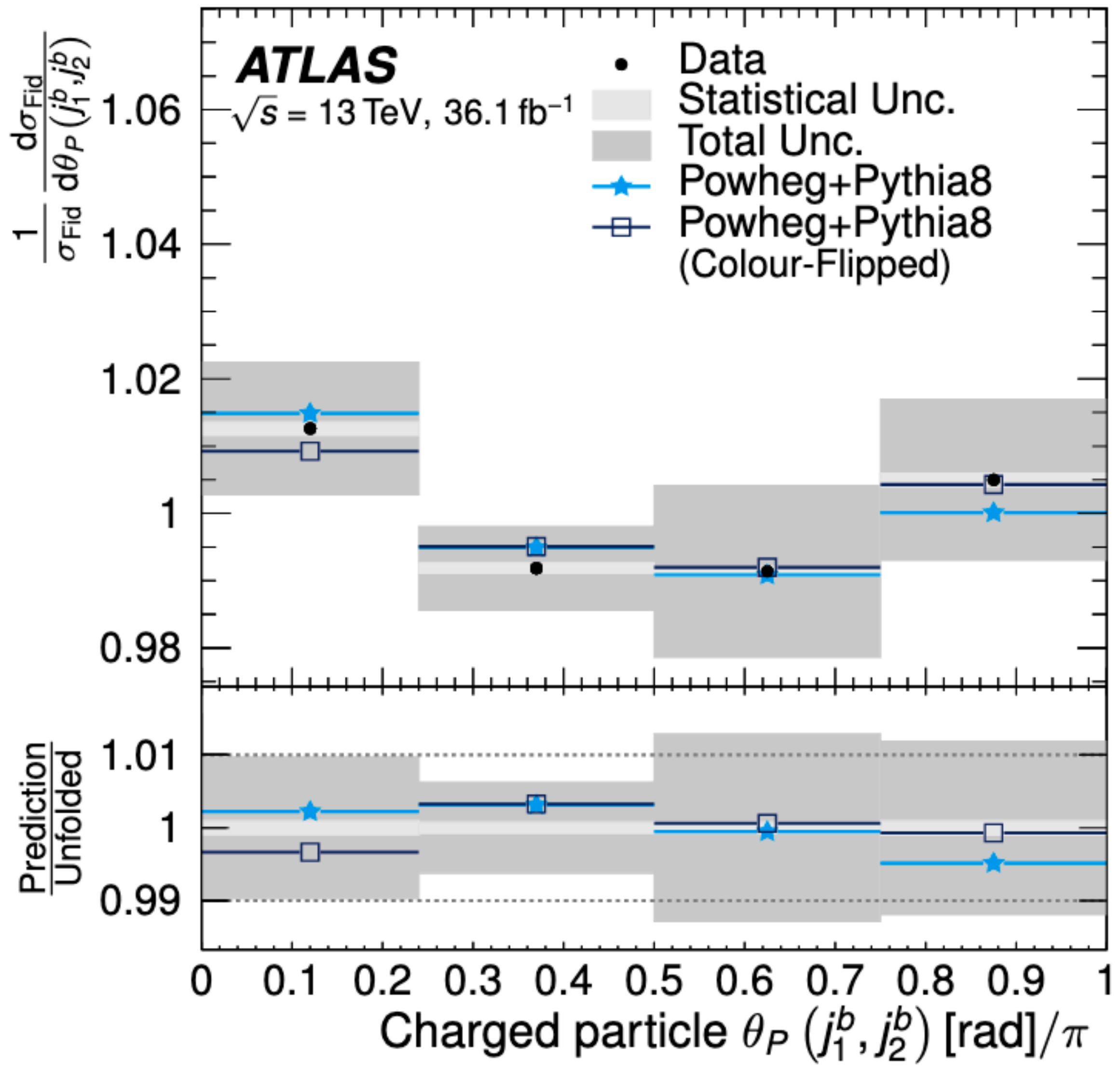




ATLAS, Eur. Phys. J. C 78 (2018) 847



(b) $\theta_{\mathcal{P}}\,(j_2^W, j_1^W)$



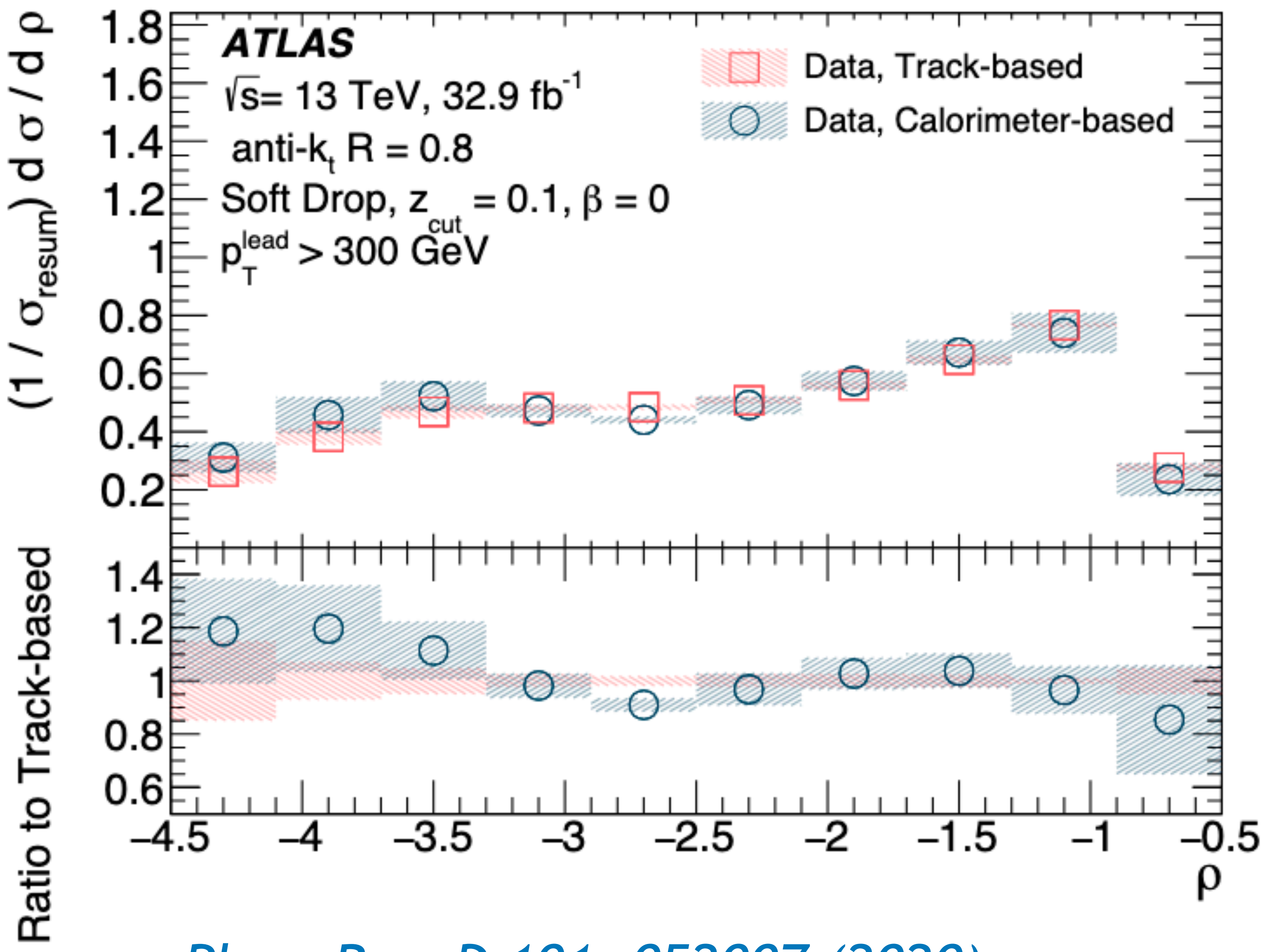
Pull angle: measurement of how much the radiation pattern from one jet leans towards another

Color flow not well constrained in QCD

Color info could complement kinematic properties to select specific topologies

New IRC-safe version (pull magnitude and projections)
Larkoski et al, JHEP 01 (2020) 104

A note on calorimetric vs track-based results



[Phys. Rev. D 101, 052007 (2020)](https://doi.org/10.1103/PhysRevD.101.052007)

Track-based measurements are more precise due to the angular resolution of tracks

Relevant question with substructure entering precision regime: can jet substructure be formulated in a manner that facilitates more precise calculations?

- Track functions: *Chan et al Phys.Rev.Lett. 111 (2013) 102002*
- Interesting proposal that incorporates non-perturbative info from tracks or charges into pert. calculation and connects to formal developments in QFT
  Chen et al, Phys. Rev. D 102, 054012 (2020)

Conclusions and prospects

New techniques like grooming or the iterative declustering allow to isolate different physics effects and constrain the parton shower ->prominent example is the Lund Jet Plane

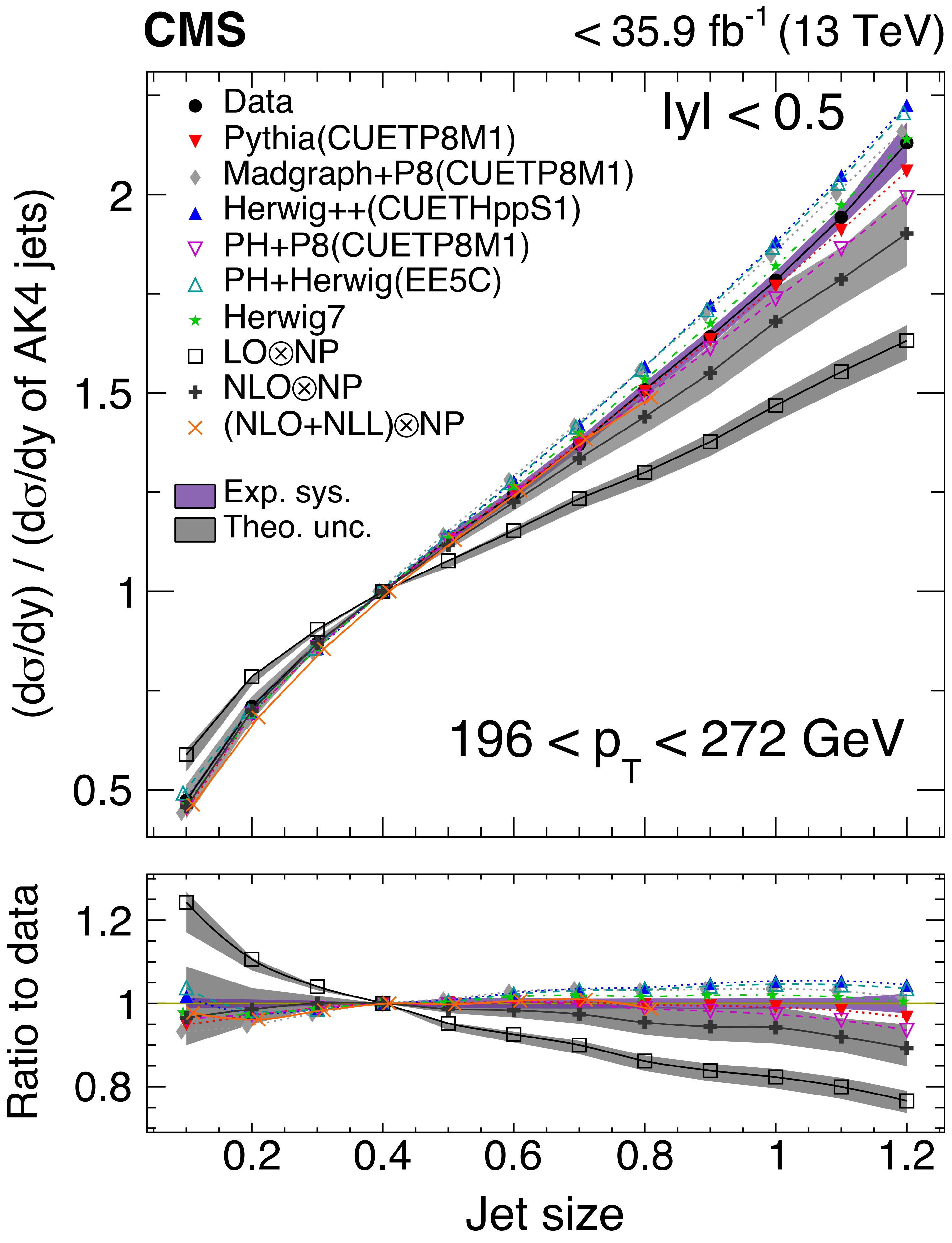
Beyond utility for searches and constraining SM calculations, new techniques expose building blocks of QCD like the splitting function, or quantum properties like the dead cone effect or the color flow

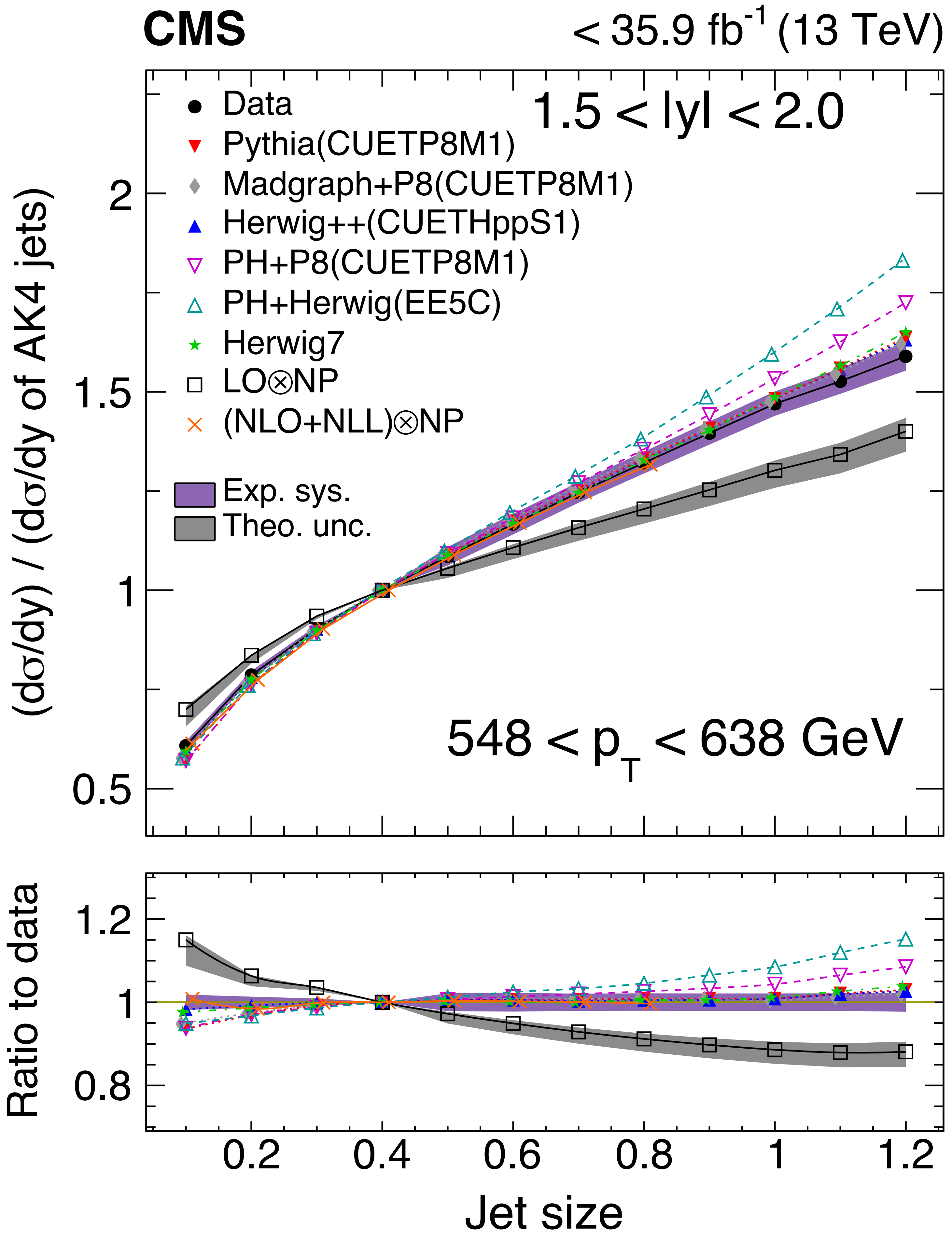
Interesting developments for using track-based measurements as precision tests of the SM

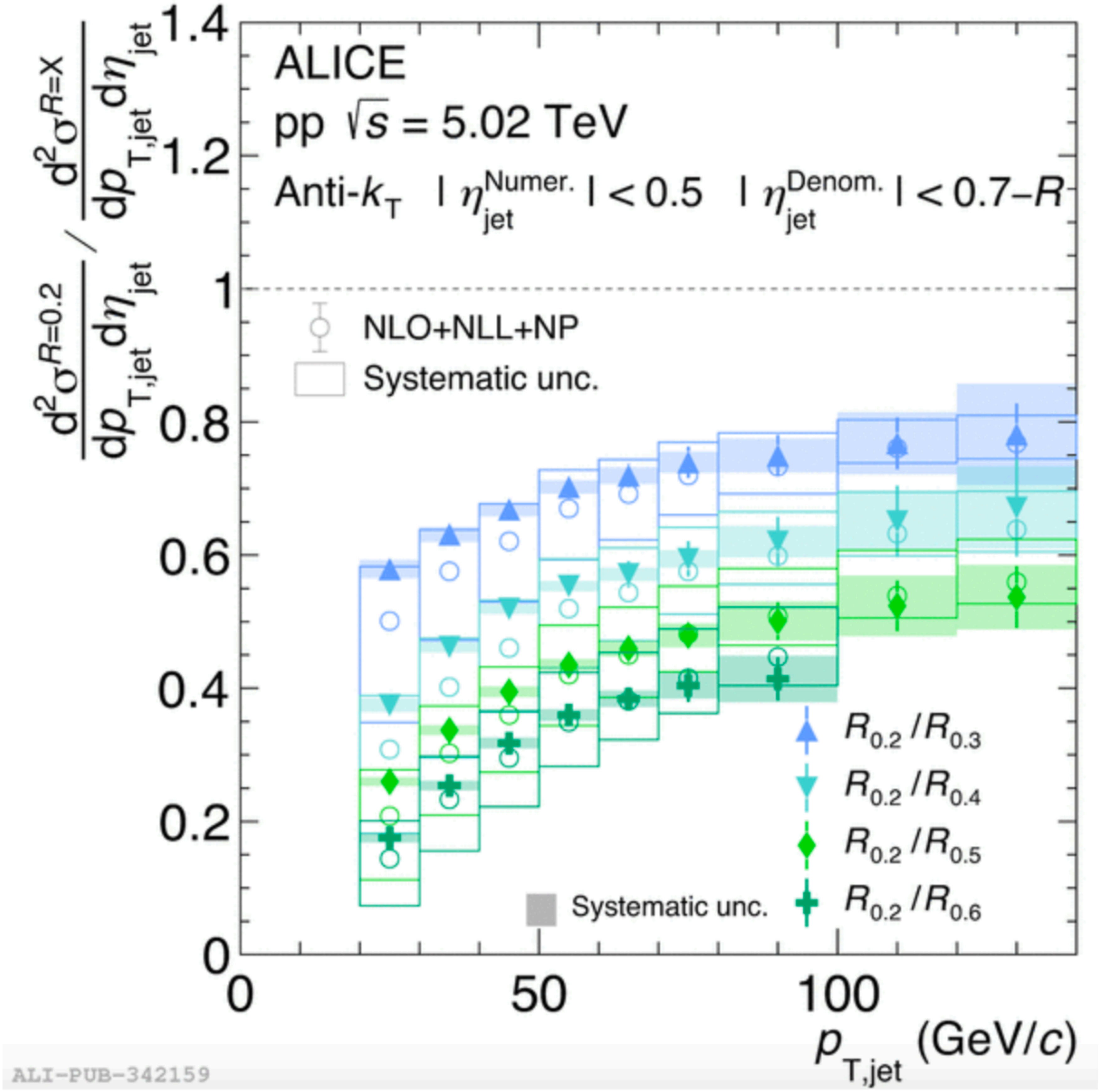
Not discussed here, check out recent results on jet substructure in heavy-ion collisions in talks by *Laura Havener*, *Robin Newhouse*, *James Mulligan*, *Helena Pintos* and many other interesting results on event shapes, inclusive/multi-jet production and correlations, Z boson and jets and more in talks by *Salim Cerci*, *Tibor Zenis*, *Martin Kucharczyk*

BACKUP

Other relevant recent results







[CMS,HEP 12 (2020) 082](#)

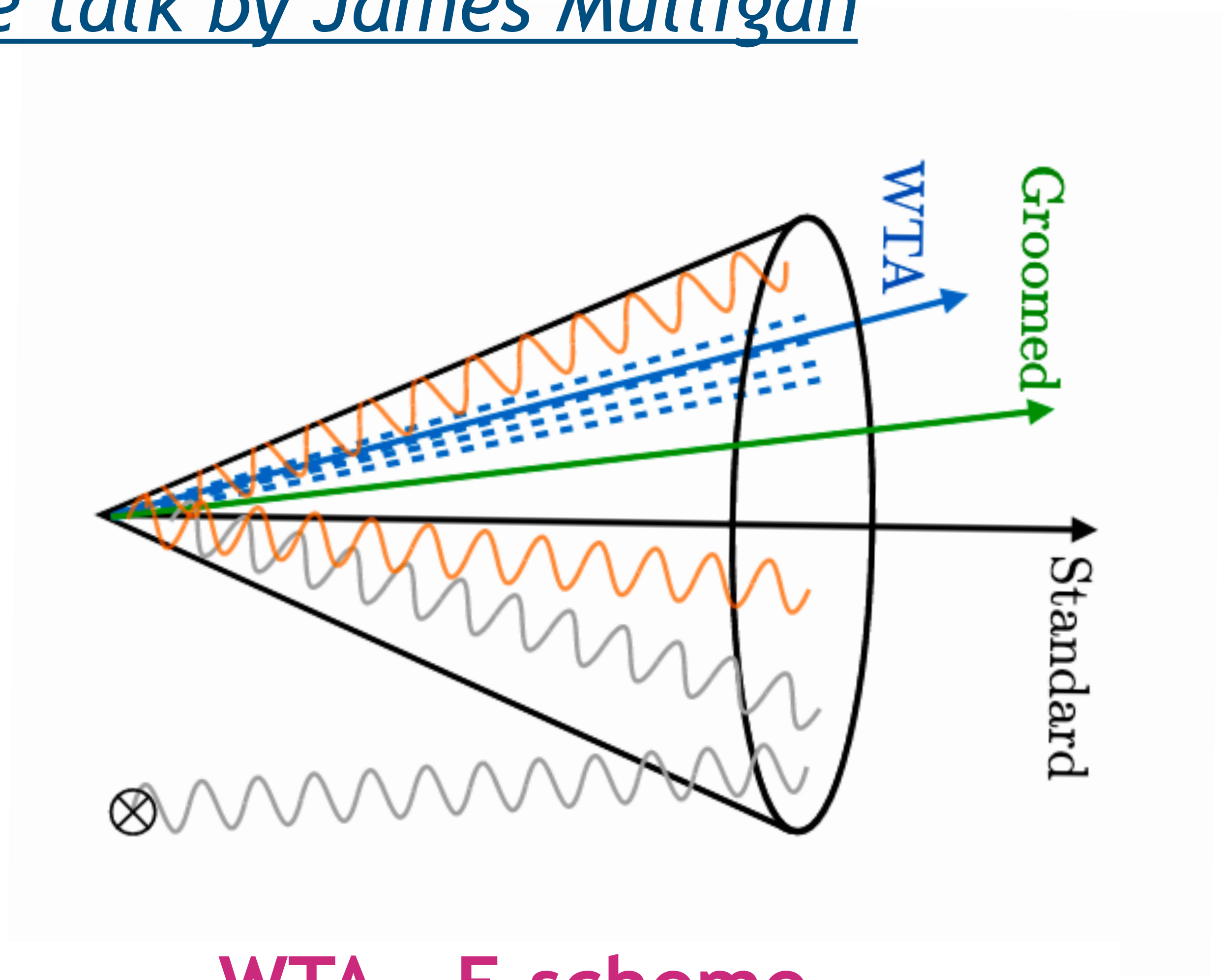
[ALICE, Phys. Rev. C 101, 034911 (2020)](#)

IRC-safe ratios of jet cross sections for different resolution R

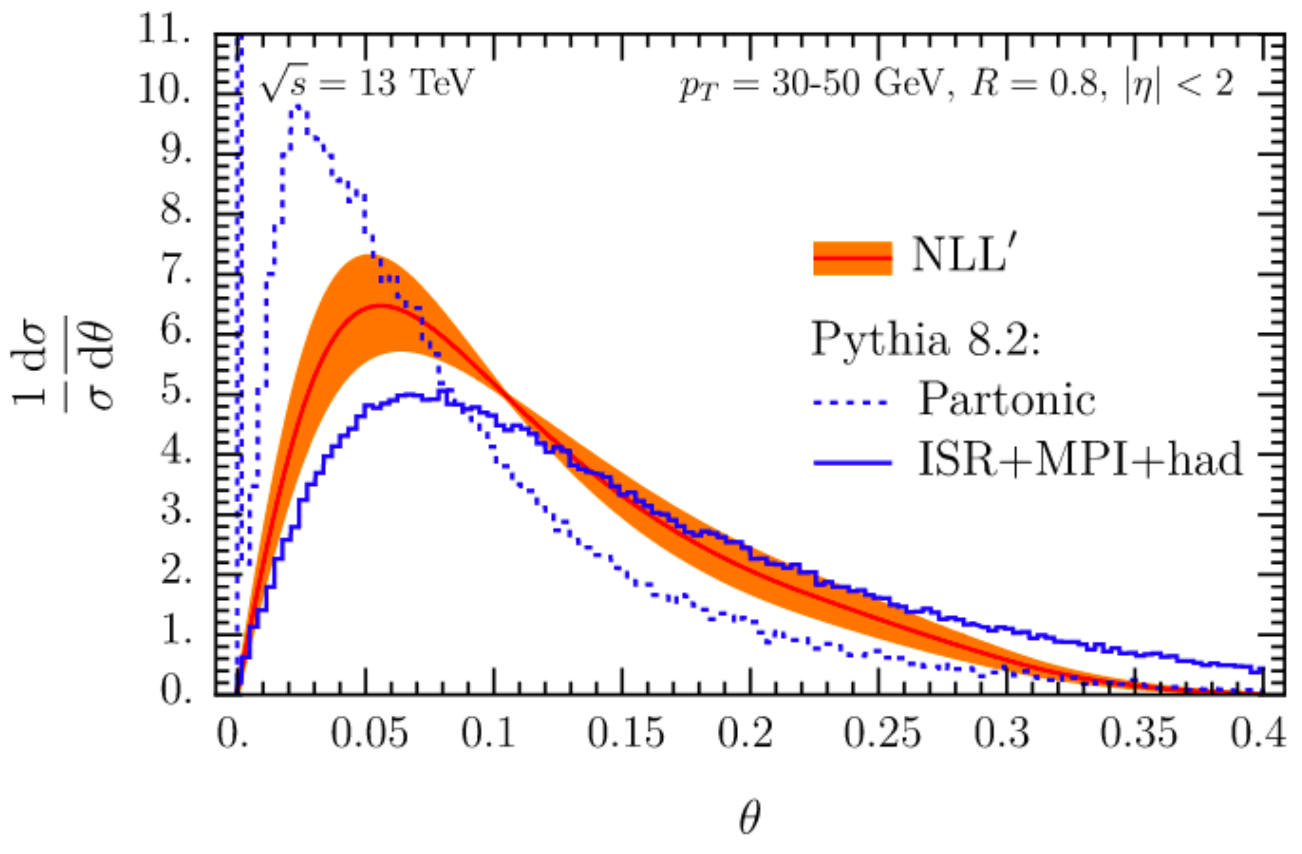
Measuring the angle between different jet axes

New at LHCP

See talk by James Mulligan

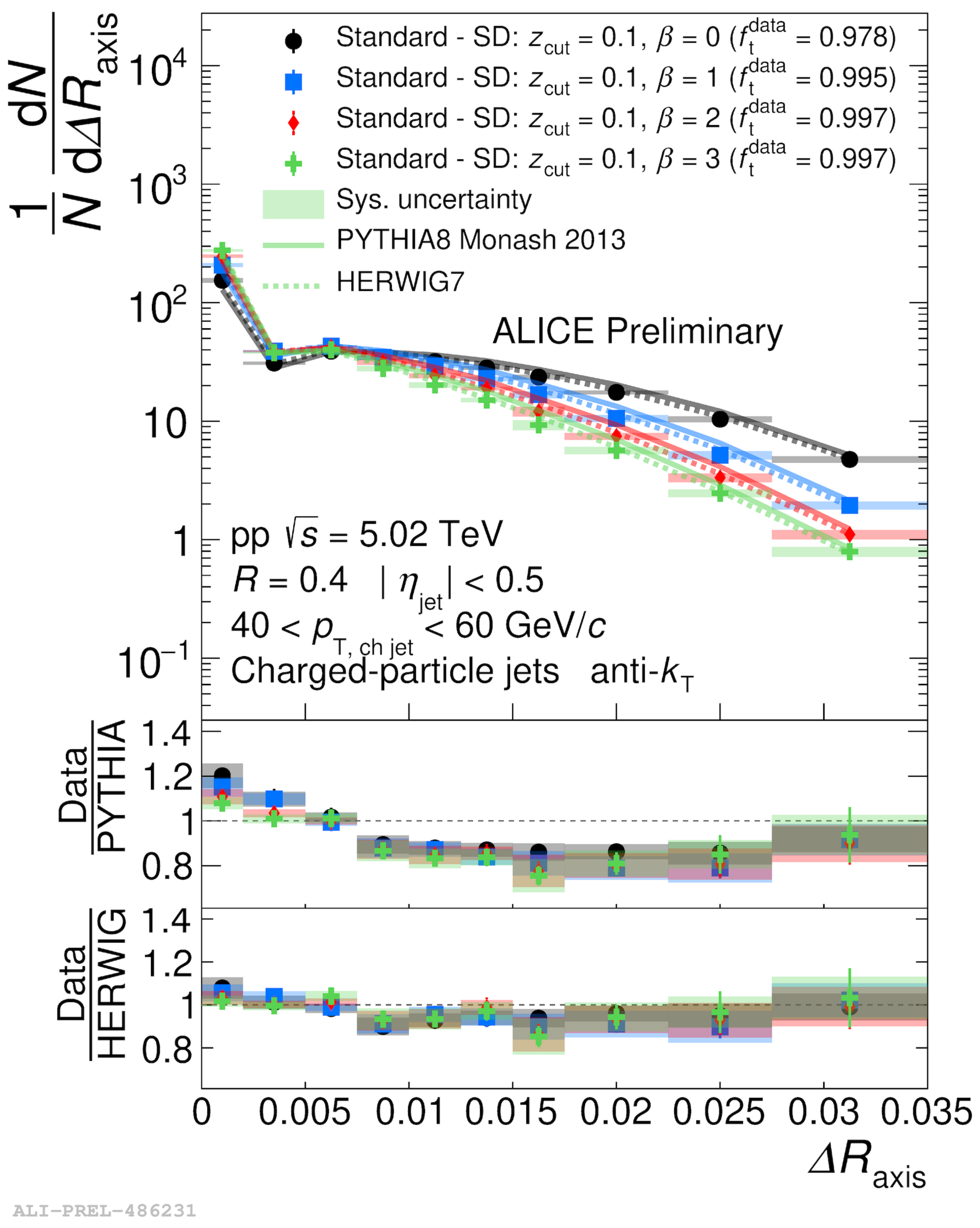


WTA —E-scheme

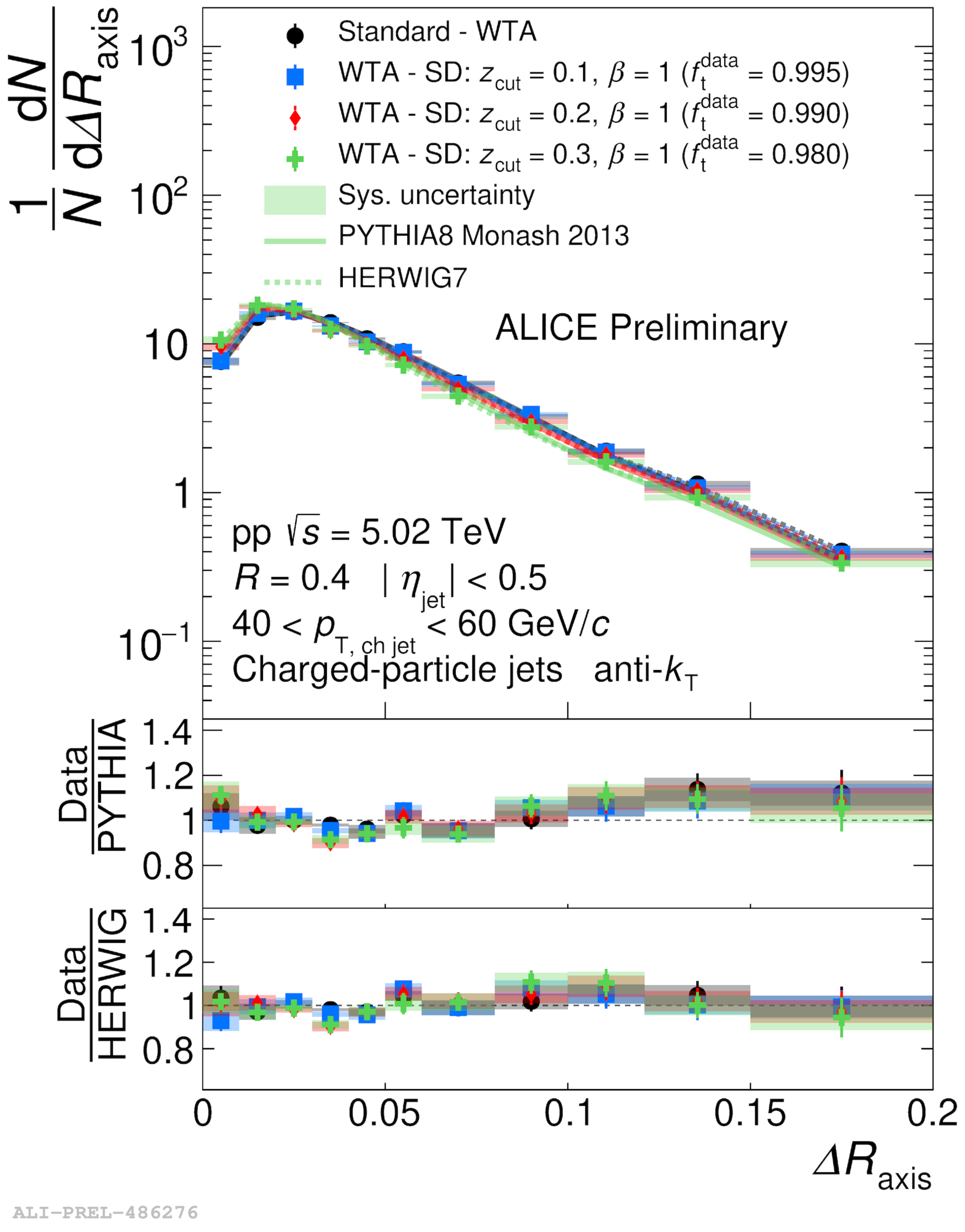


Cal et al, JHEP 04 (2020) 211

E-scheme — SD

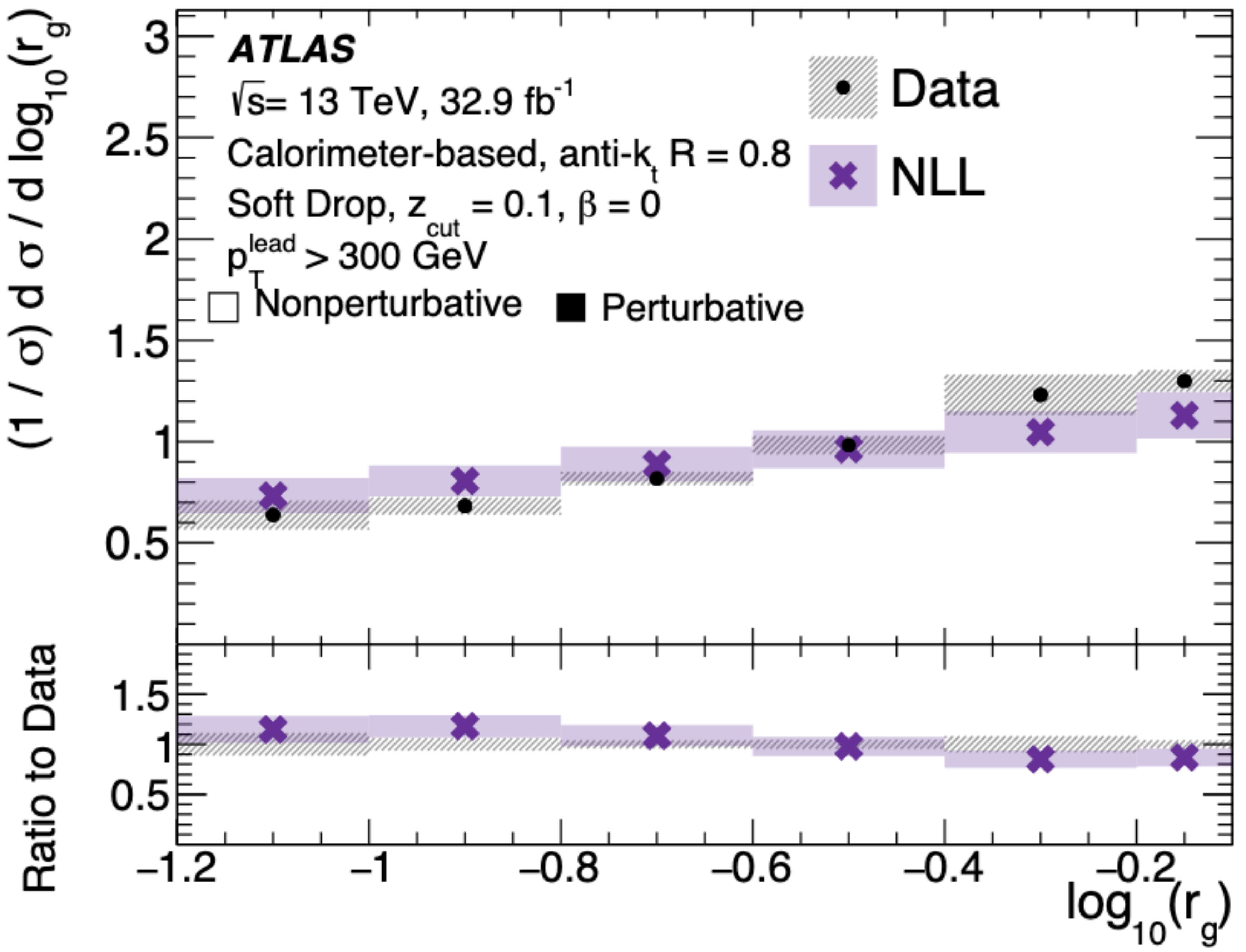


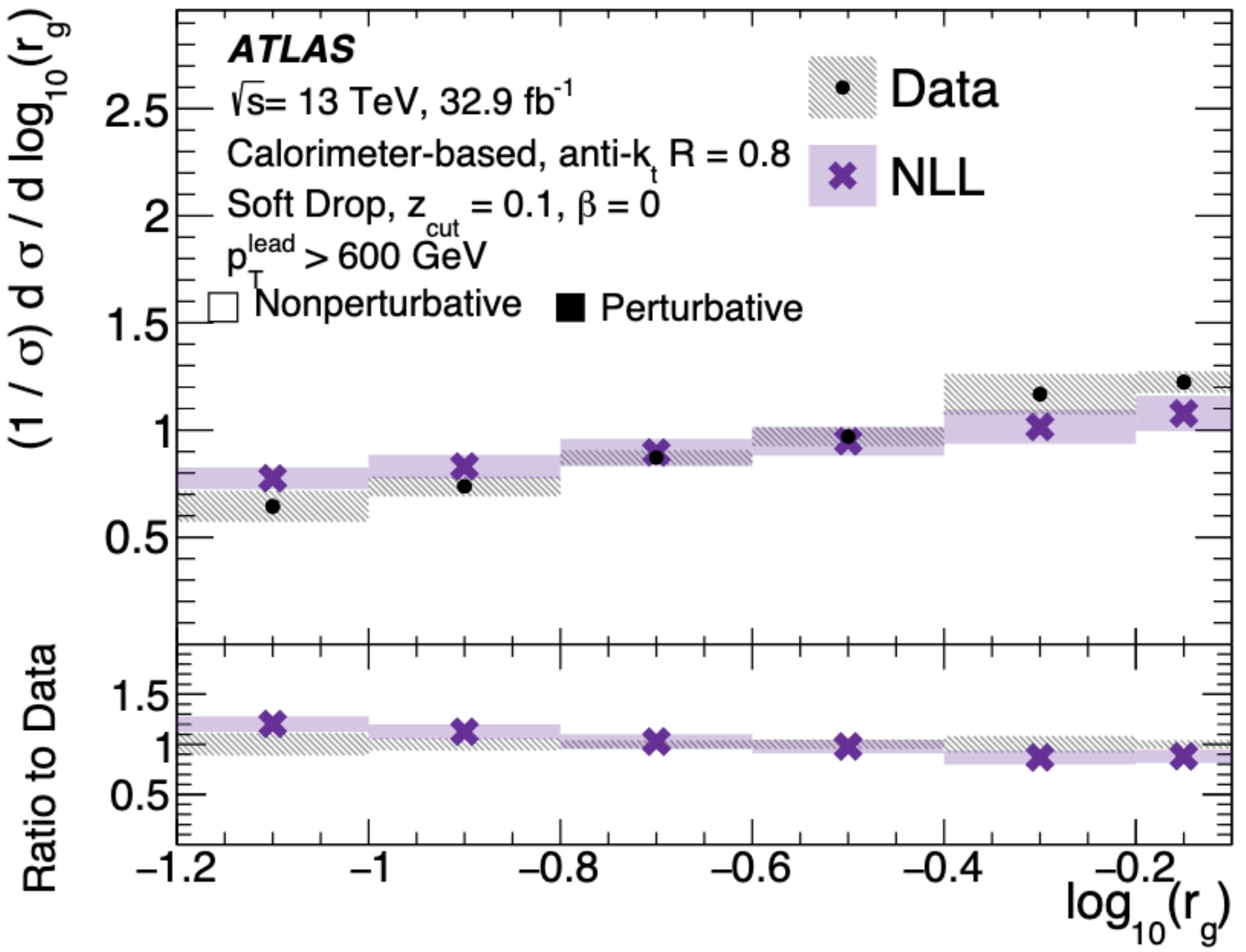
WTA —E-scheme



- Strong correlation between SD and E-scheme axes
- More aggressive grooming (β=0) ->larger ΔR_{axis} for SD and E-scheme
- Negligible dependence on grooming condition for WTA—E-scheme
- Differences sensitive to soft radiation pattern

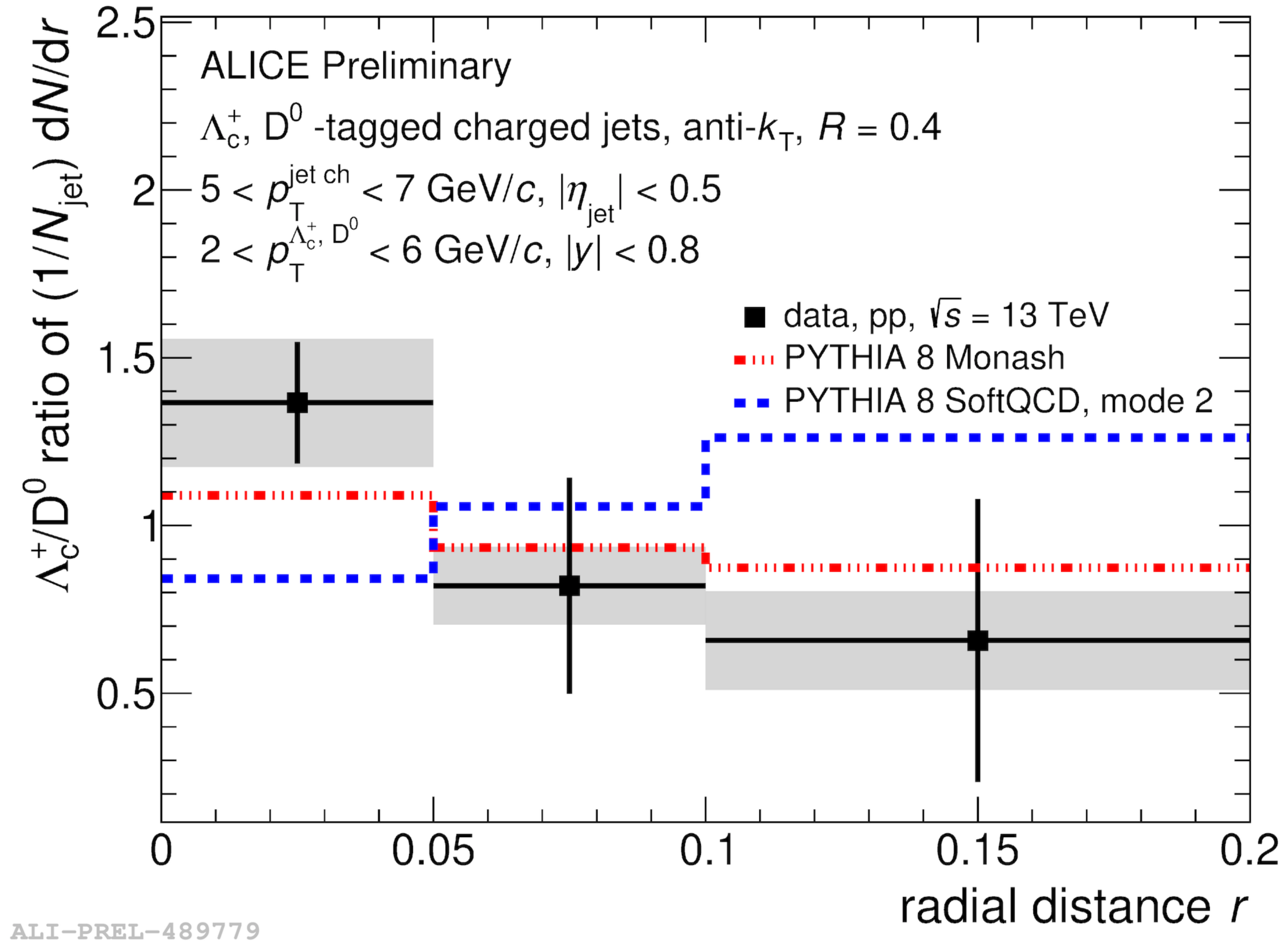
R_g compared to analytical calculations

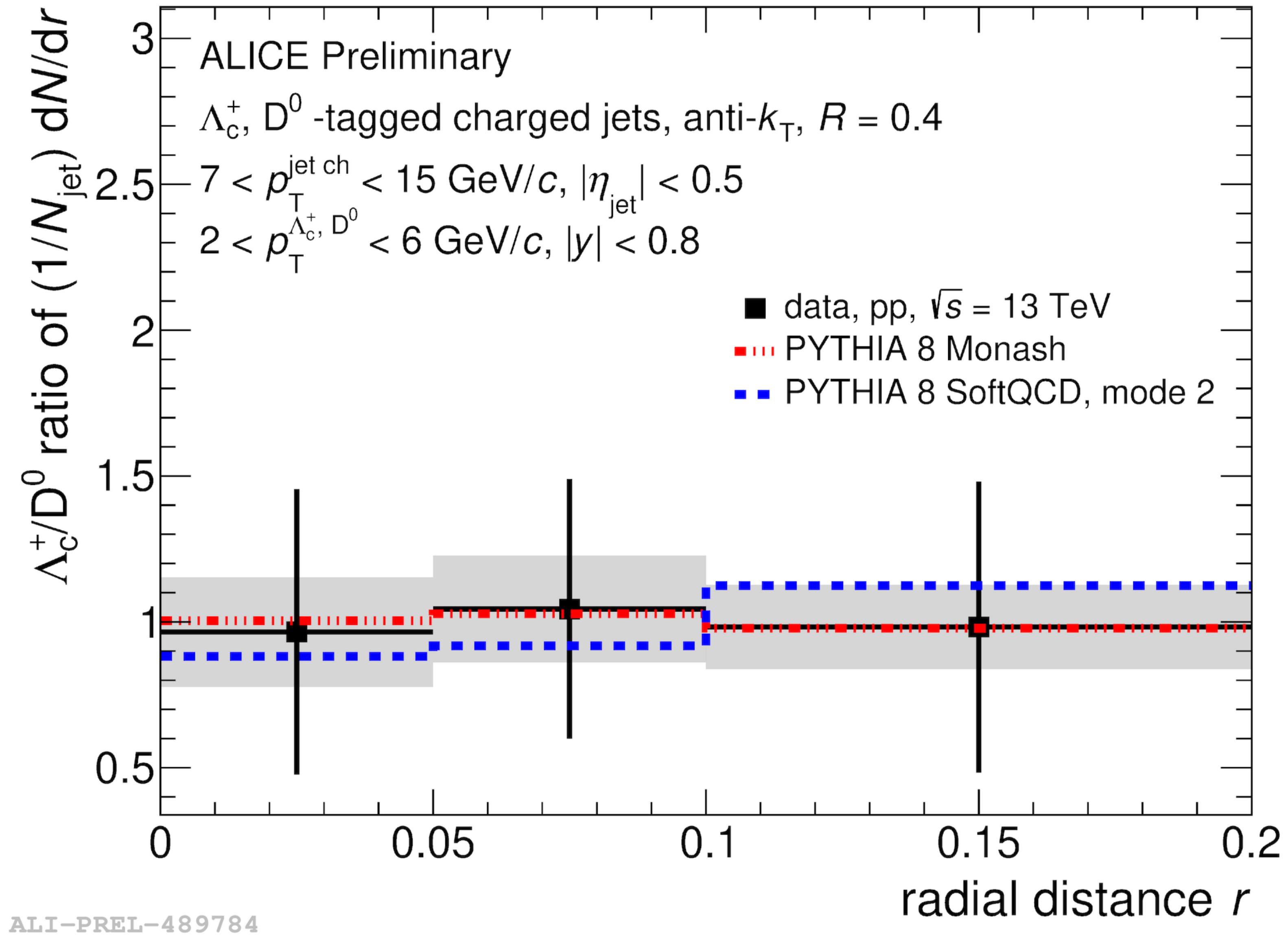


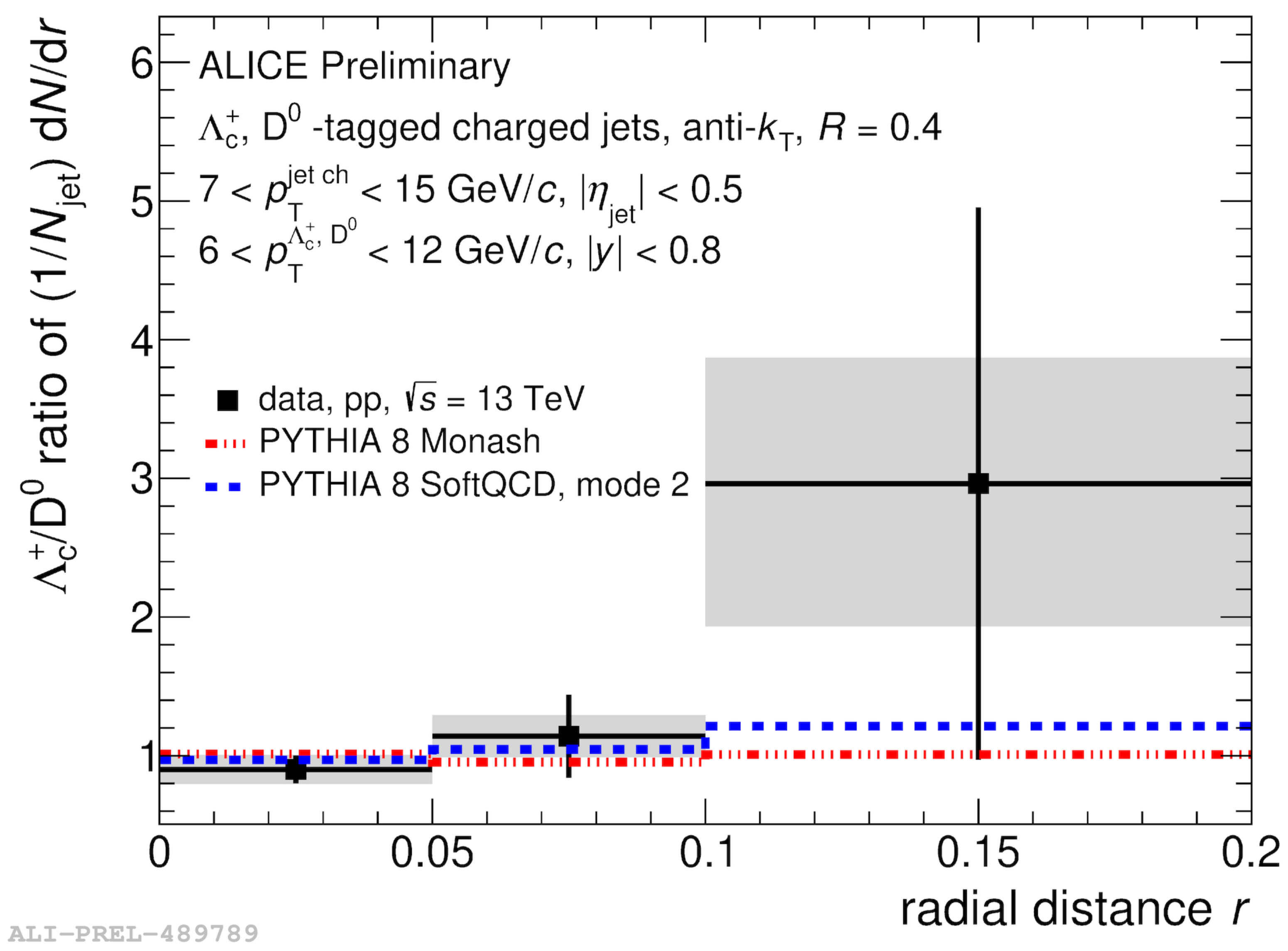


NLL calculation by Kang et al JHEP 02, 054 (2020)

Hadronisation







The Lund plane, ALICE