Measurements of jet substructure in quark & gluon jets

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on behalf of the CMS & ATLAS collaborations

QCD & Jet Substructure

Jet substructure fundamental tool in many SM & BSM analyses

→ "Tagging" decays of W/Z/H/t

Understanding of quark/gluon jet substructure vital

→ QCD often large background

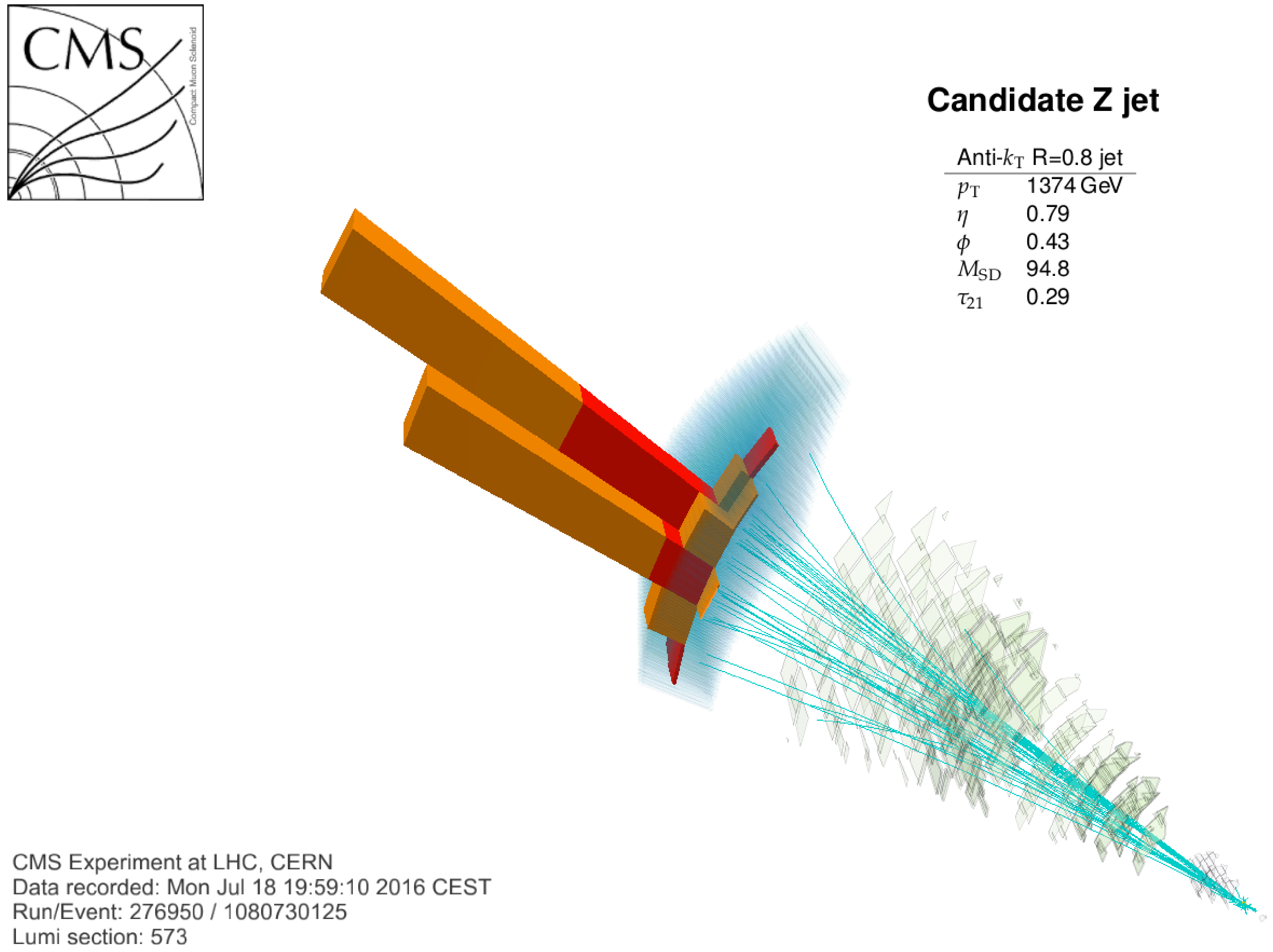
Wide variety of predictions available; data not always well-modelled

→ Often large source of uncertainty when evaluating taggers

→ Gluon jets less well-modelled, fewer constraining measurement

Jet substructure measurements offer insight into various contributions & scales

→ Feedback into better understanding, better modelling, better tagging



Phys. Rev. D 97 (2018) 072006

http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-17-001/index.html

Overview of measurements

Jet production vs distance parameter
2005.05159

Jet mass
JHEP 11 (2018) 113

Jet substructure observables in $t\bar{t}$
Phys. Rev. D 98 (2018) 092014

Soft drop jet observables
Phys. Rev. D 101 (2020) 052007

Lund Jet Plane
Phys. Rev. Lett. 124 (2020) 222002

Jet production vs distance parameter

Anti-k_T jet clustering characterised by distance parameter R

- Approx. size in η-ϕ plane

How much energy is cluster by jet depends on:

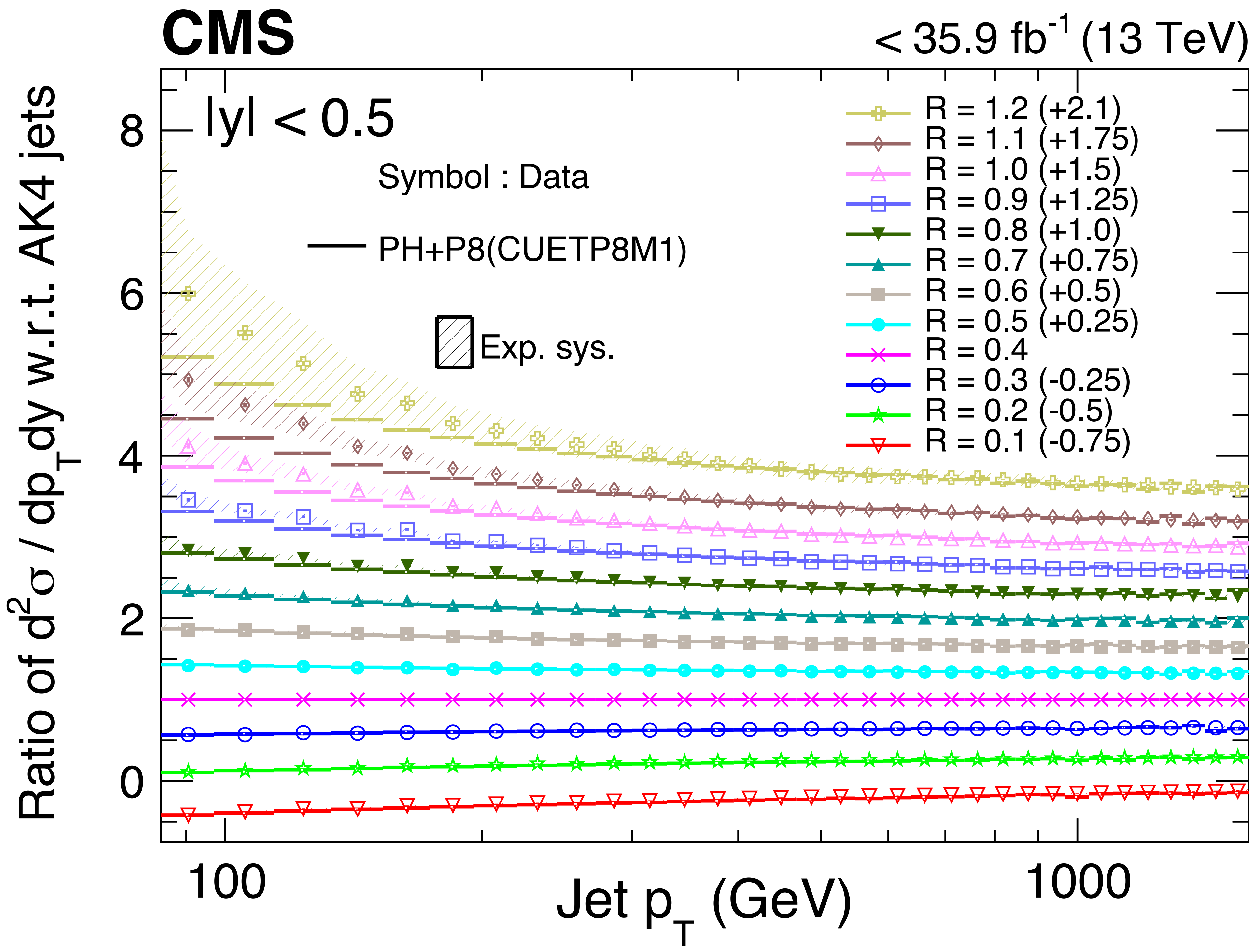
- Emission of secondary quarks/gluons that can fall outside R
- Non-perturbative hadronisation

Amounts depend on whether jet initiated by quark or gluon

- Additional particles from the underlying event (= multiple interactions between the proton remnants)

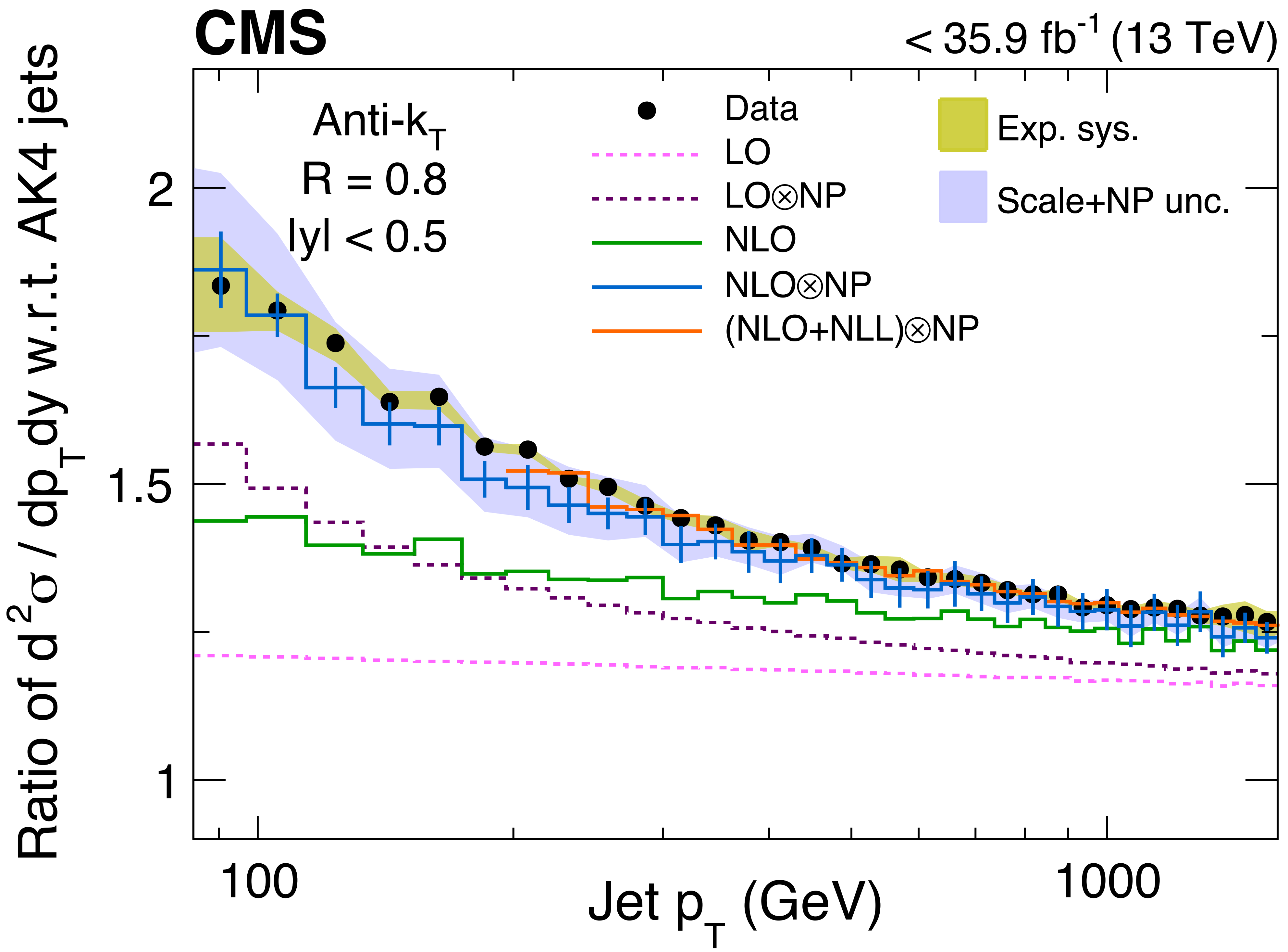
Measure jet p_T spectrum relative to R = 0.4 jets in dijet events, unfolding result

Jet production vs distance parameter



Reasonable agreement with Powheg+Pythia8

Large R with lower p_T less well-modelled



Comparison with NLOJET++ calculations:
→ clear that NLO and NP corrections required

Resummed calculations even better

Soft Drop

JHEP 1405 (2014) 146

Jet grooming technique: remove soft, wide-angle radiation from jet

- Correlations amongst out-of-jet soft gluon emissions & wide-angle radiation from other jets → causes non-global logarithms for non-global observables, hard to handle beyond leading-log → grooming removes these
- Reduces effects of initial-state radiation (ISR), underlying event (UE), & pileup
- Accesses more of the core parton information

Recluster jet with Cambridge-Aachen (C/A), then work backwards along clustering history:

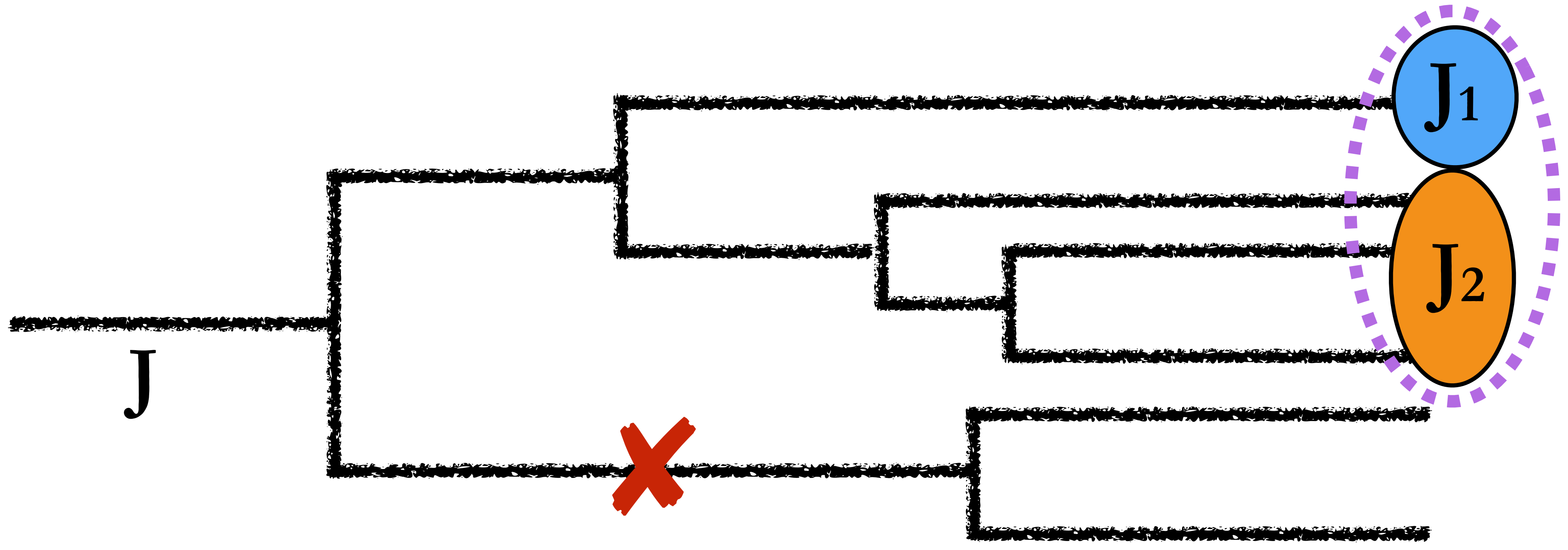
If subjets satisfy condition: $$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

z_{cut}, β tuneable parameters

then stop → this is the groomed jet

Otherwise, redefine the jet as the larger-p_T subjet, and iterate

- z_{cut}: controls soft/hard-ness of groomed-away radiation
- β: controls whether collinear/wide-angle radiation groomed away



C/A performs angular-ordered clustering

Soft Drop Observables

Measure several observables after applying soft drop, and varying soft drop parameters:

- Dimensionless jet mass, $\rho = \log(m^2/p_T^2)$ $\rightarrow$ less dependence on p_T
- p_T balance, $z_g = \dfrac{\min(p_{T,j1}, p_{T,j2})}{p_{T,j1} + p_{T,j2}}$
- Splitting opening angle, $r_g = \Delta R_{12}$
- $z_{cut} = 0.1$, $\beta = 0, 1, 2$

All related: $\rho \sim \log(z_g r_g^2)$

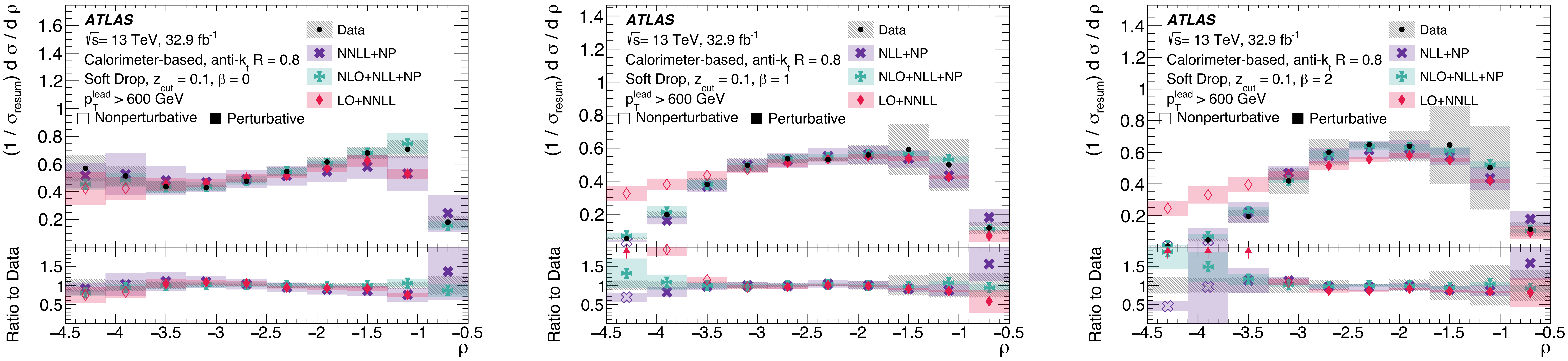
Measure in dijet events: 2 anti-k_T R=0.8 jets, $p_T^{\text{leading jet}} > 300$ GeV, $p_T^{\text{leading jet}} < 1.5 \times p_T^{\text{subleading jet}}$

Unfold back to particle-level

Soft Drop Observables

Compare data with analytical calculations at varying orders in α_S: (1704.02210, 1712.05105, 1603.09338, 1603.06375)

Increasing β = less grooming = more soft radiation in jet



Nonperturbative region

Resummation region

Fixed-order region

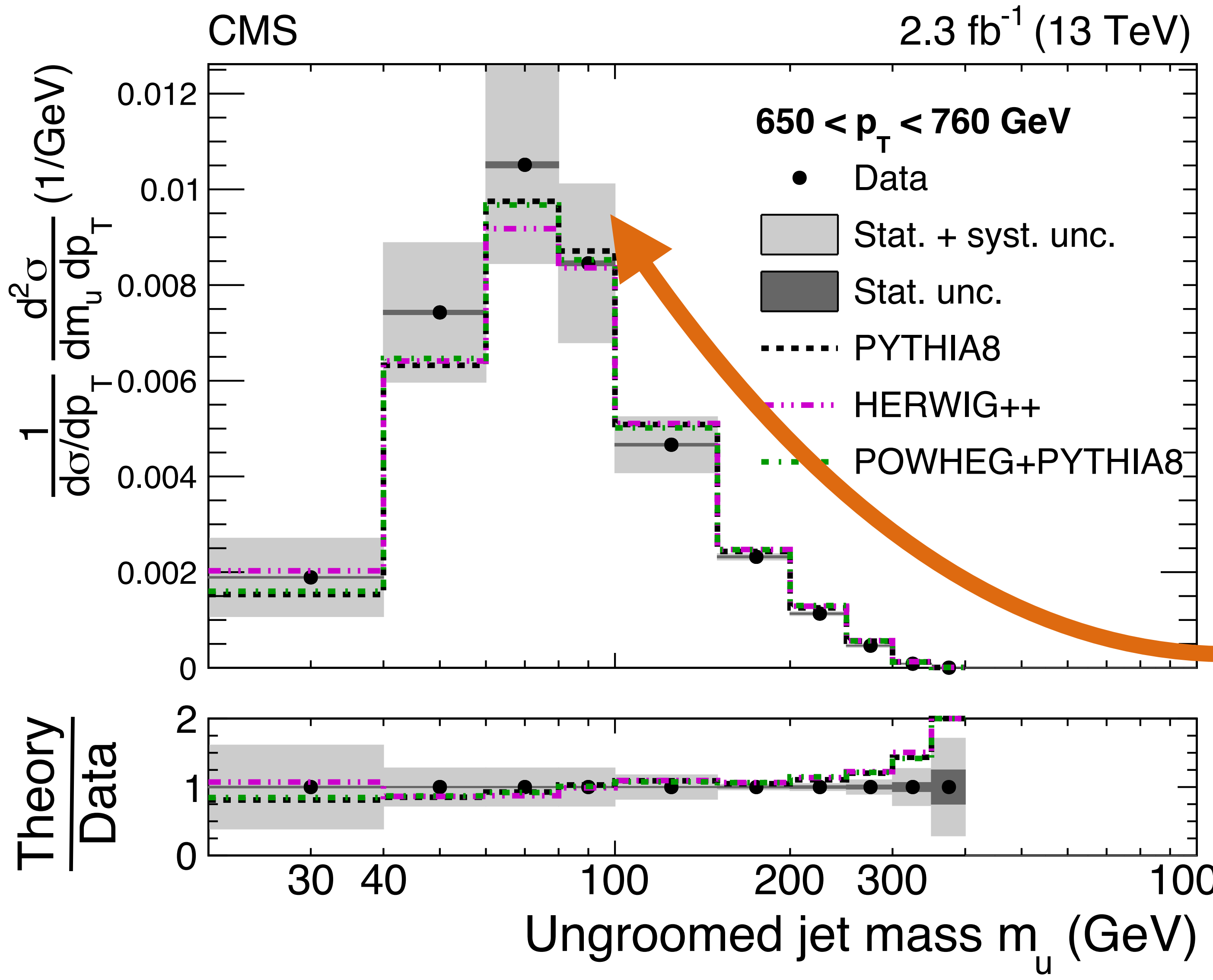
→ Nonperturbative region shows importance of NP corrections, especially with larger β

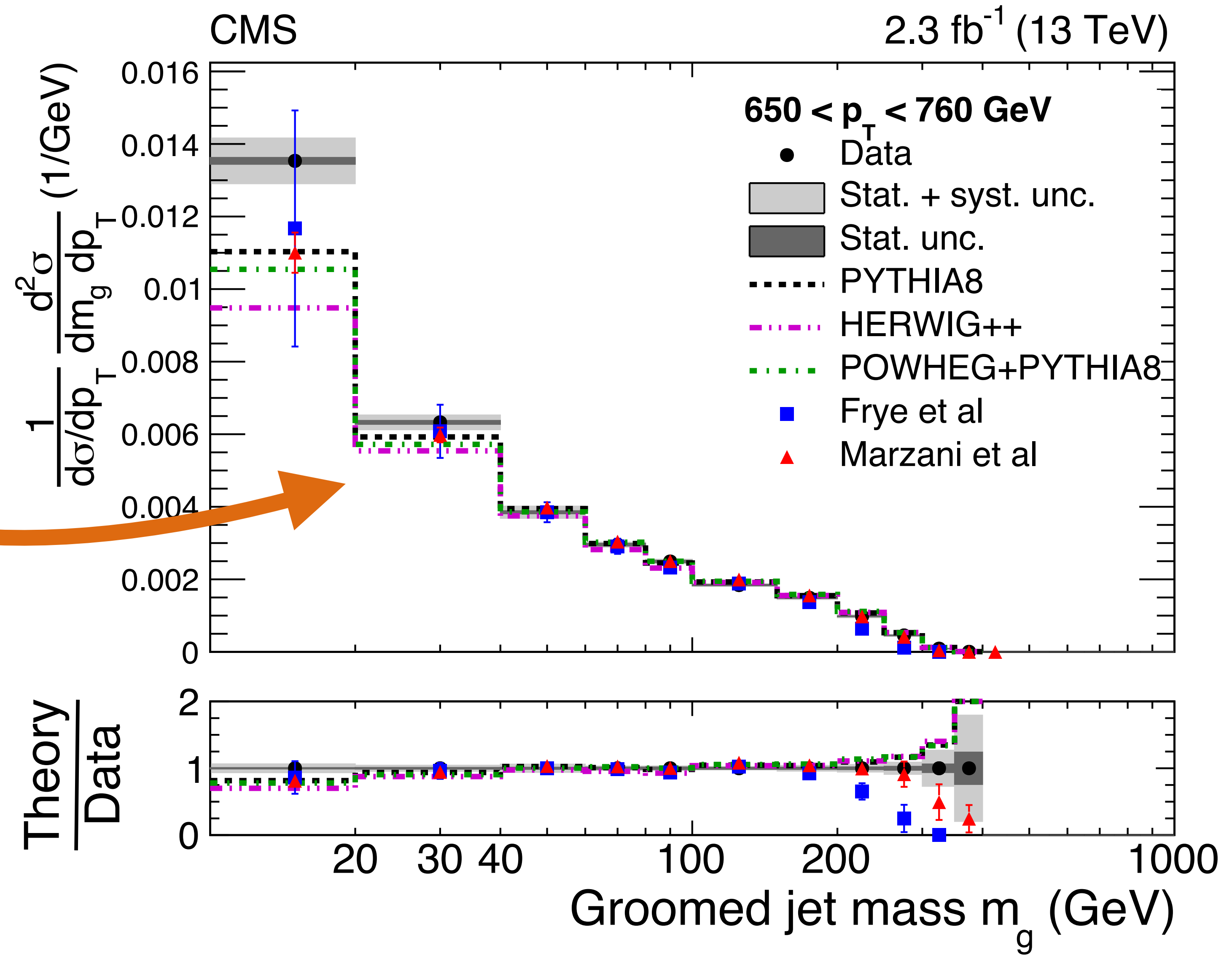
→ Excellent agreement in resummation region

→ Improvements in fixed-order region from using NLO+NLL instead of LO+NNLL

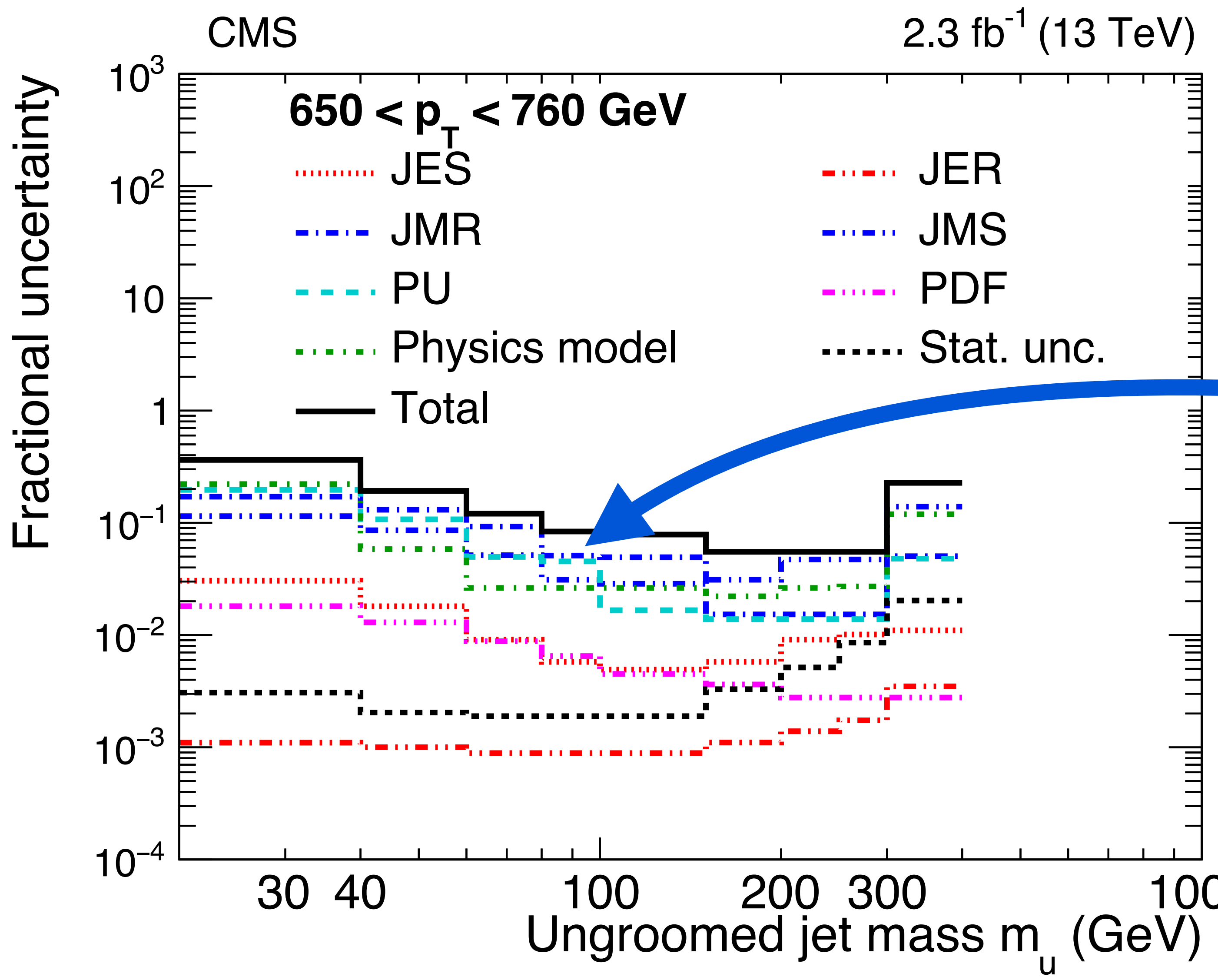
Soft Drop Observables

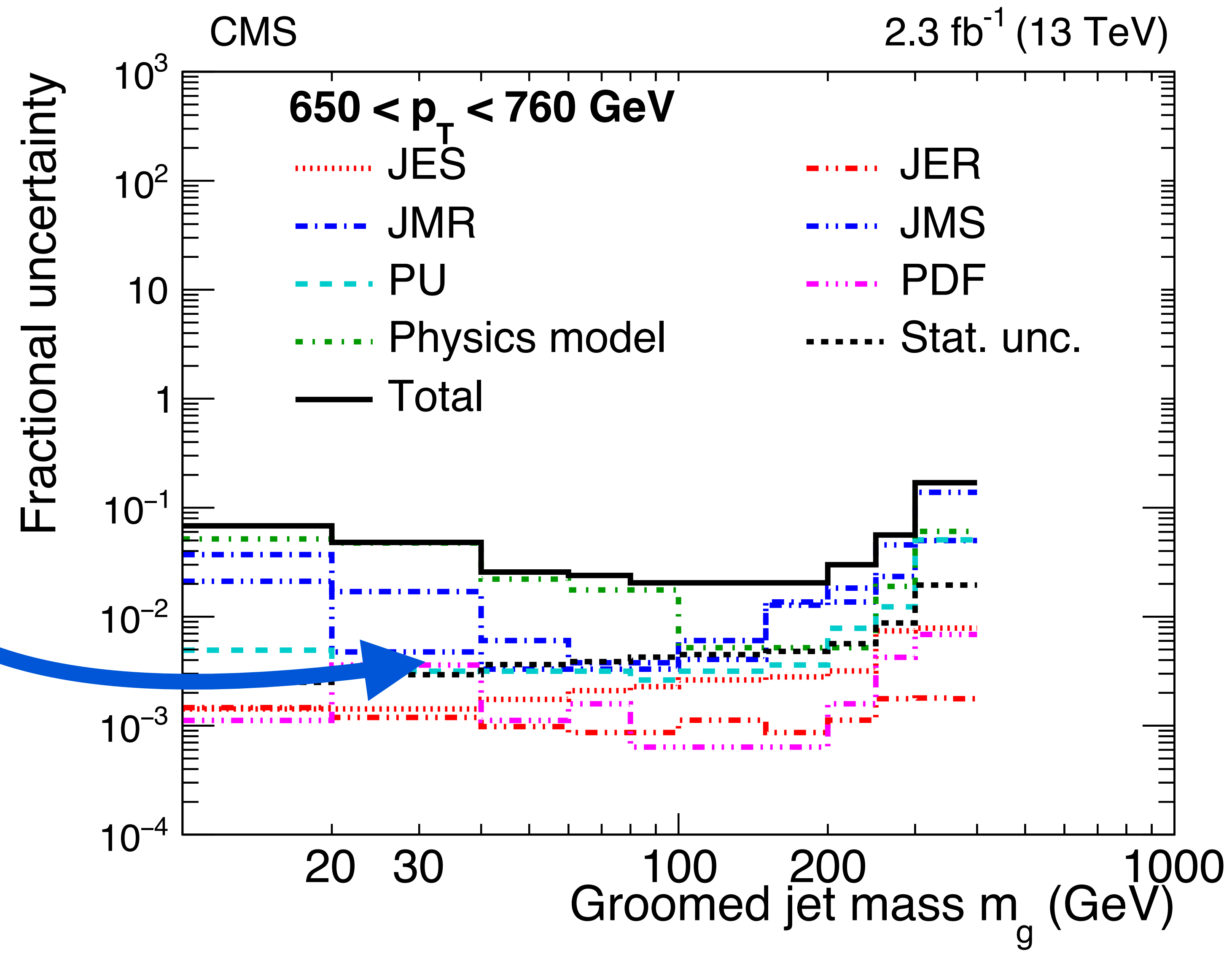
Similar results from CMS using 2015 data looking at ungroomed & groomed jet mass in dijet events:





Grooming lowers jet mass & removes "Sudakov" peak



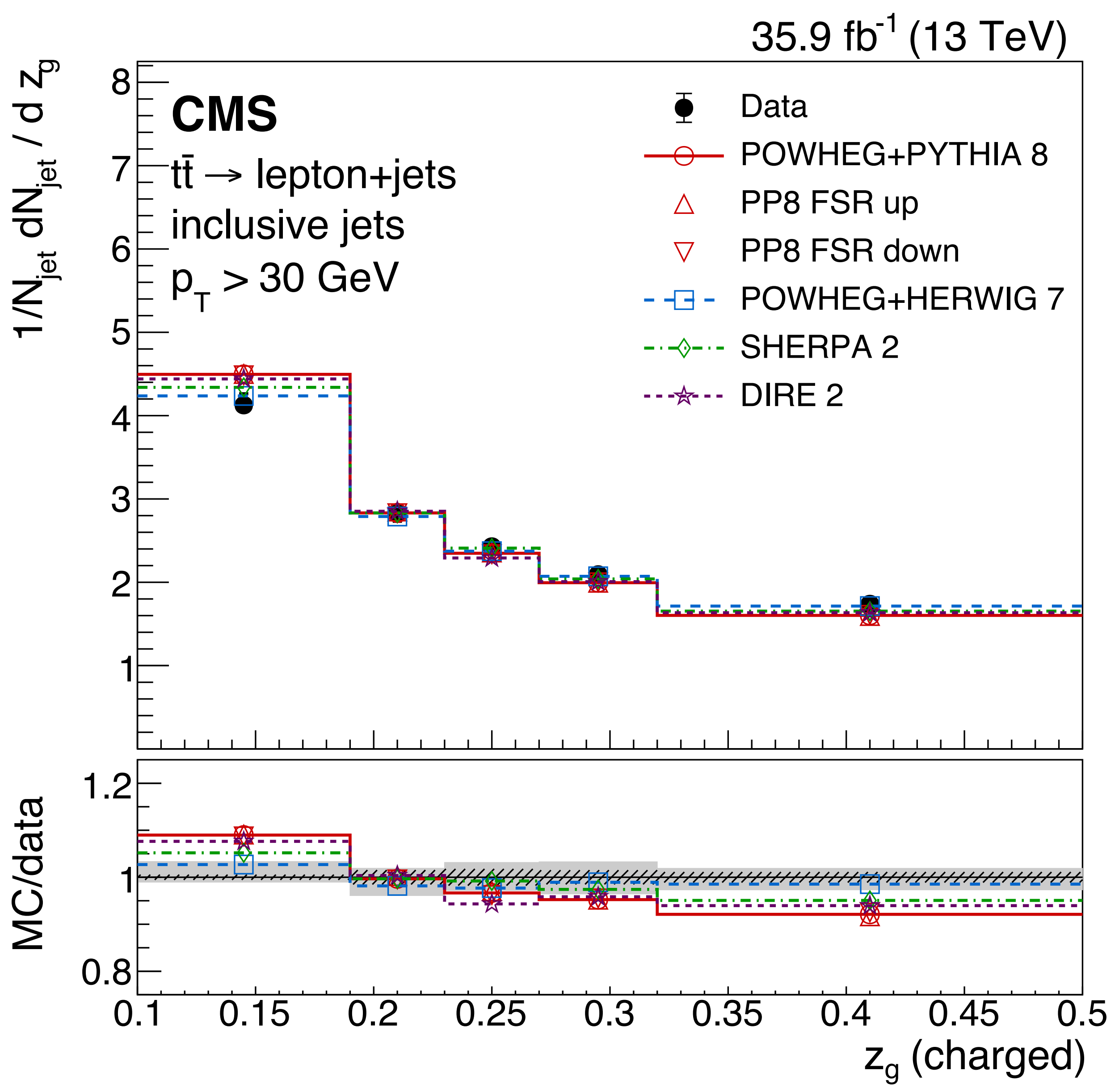


Systematic uncertainties significantly reduced by grooming: esp. pileup, and jet mass energy scale & resolution

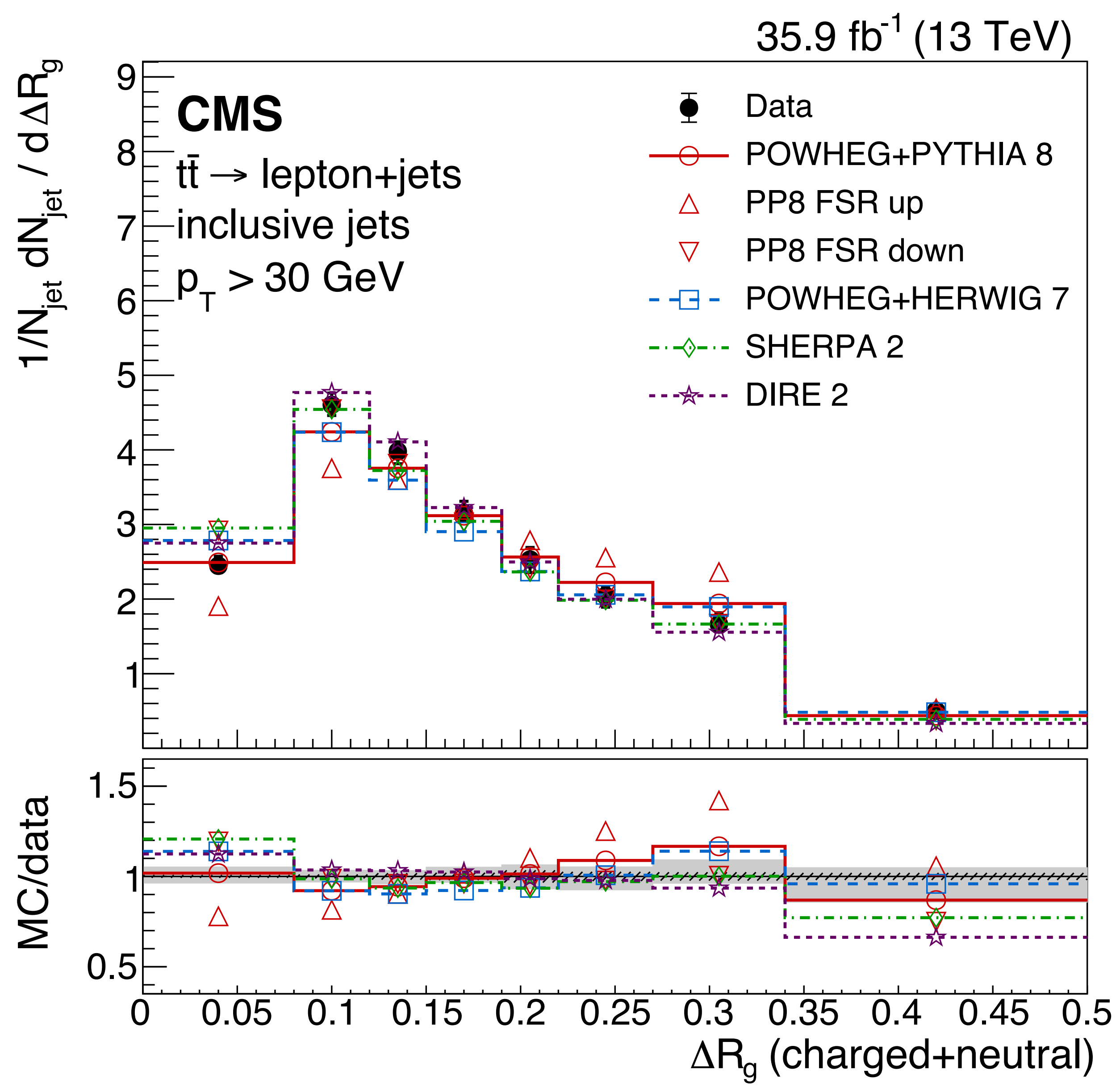
Jet Substructure Observables in $t\bar{t}$

Use $W \rightarrow qq'$ in semileptonic resolved $t\bar{t}$ decays → samples of light flavour & b jets, and gluon jets from ISR

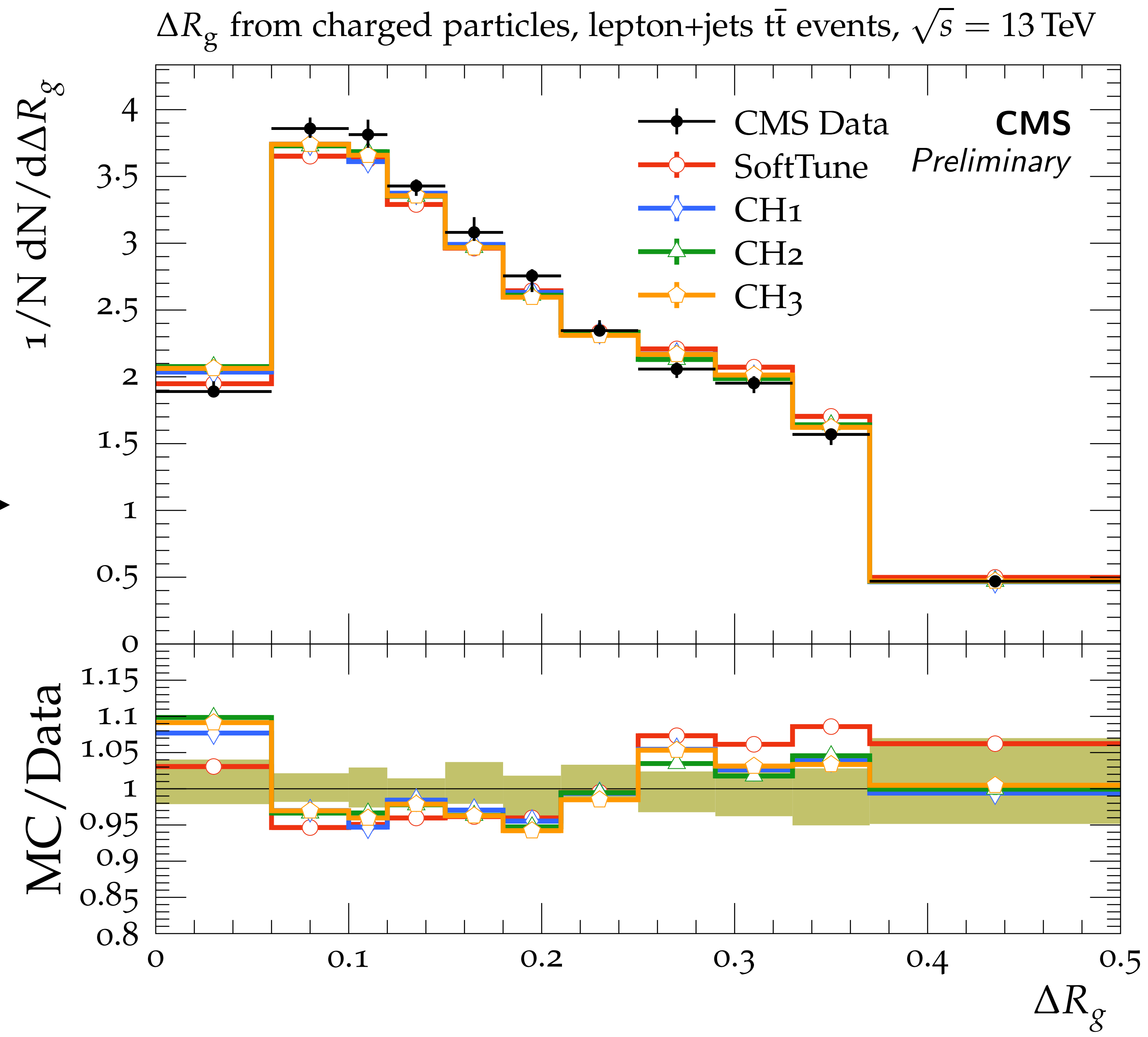
Measure variety of substructure variables in anti-k_T R=0.4 jets, unfolded to particle-level



Well-described by Powheg + Herwig7, less so by other generators



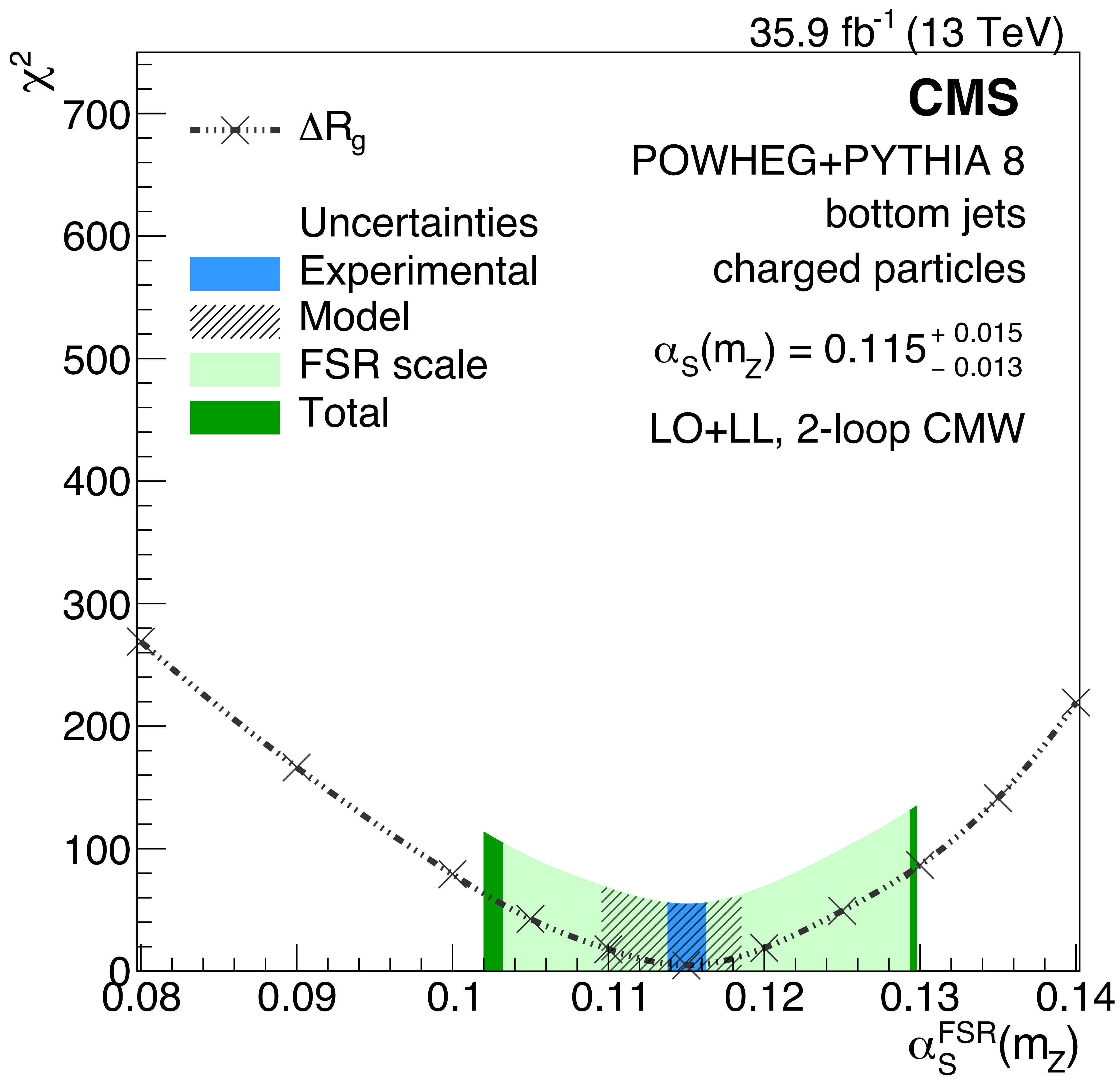
Powheg+Herwig7 not clear winner
Significant dependence on FSR



Results used in new CMS Herwig7 tuning
CMS-PAS-GEN-19-001
Impact of different α_S :
SoftTune (0.1292) vs CH1/2/3 (0.118)

Jet Substructure Observables in $t\bar{t}$

Strong dependence of ΔR_g on α_S^{FSR} → can use to extract most-compatible value:



Lund Jet Plane

A different way to represent a jet: start with a hard quark/gluon core, with a soft emission

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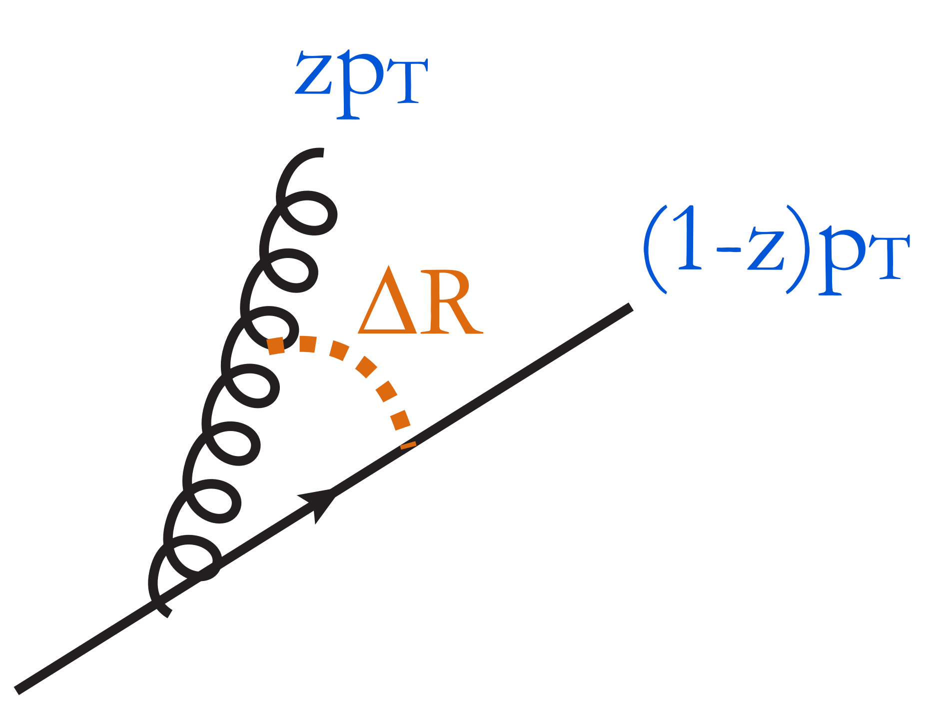
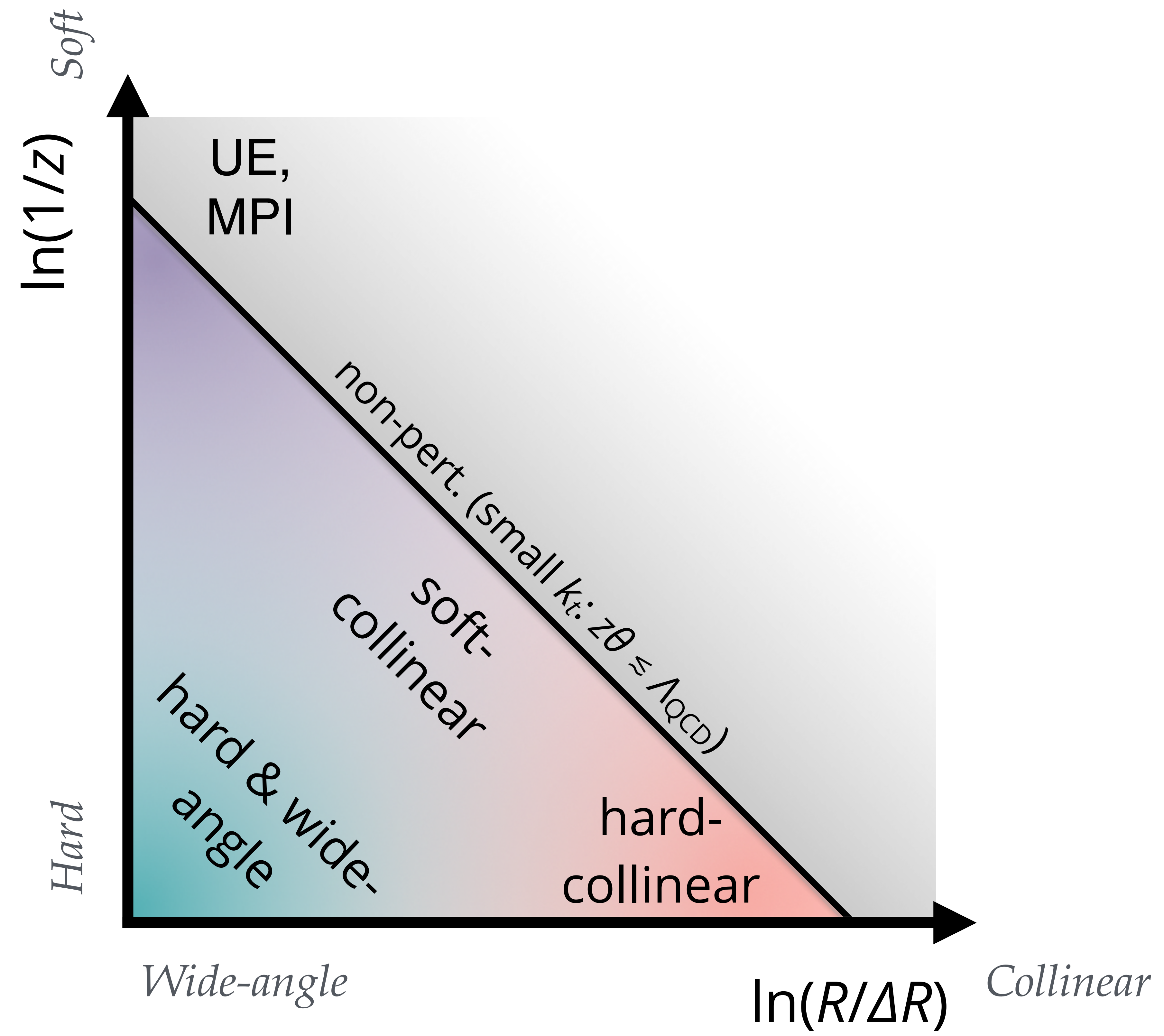


z = relative momentum fraction of emission vs core

ΔR = separation between emission & core

Phase space of possible (z, ΔR): **the Lund Plane**

Maps regions of soft/hard, wide/collinear, MPI, etc



Lund Jet Plane

- Use high-p_T dijet events:

$p_T^{\text{leading jet}} > 675$ GeV, $p_T^{\text{leading}} < 1.5 \times p_T^{\text{subleading}}$

- Cluster anti-k_T R= 0.4 jets

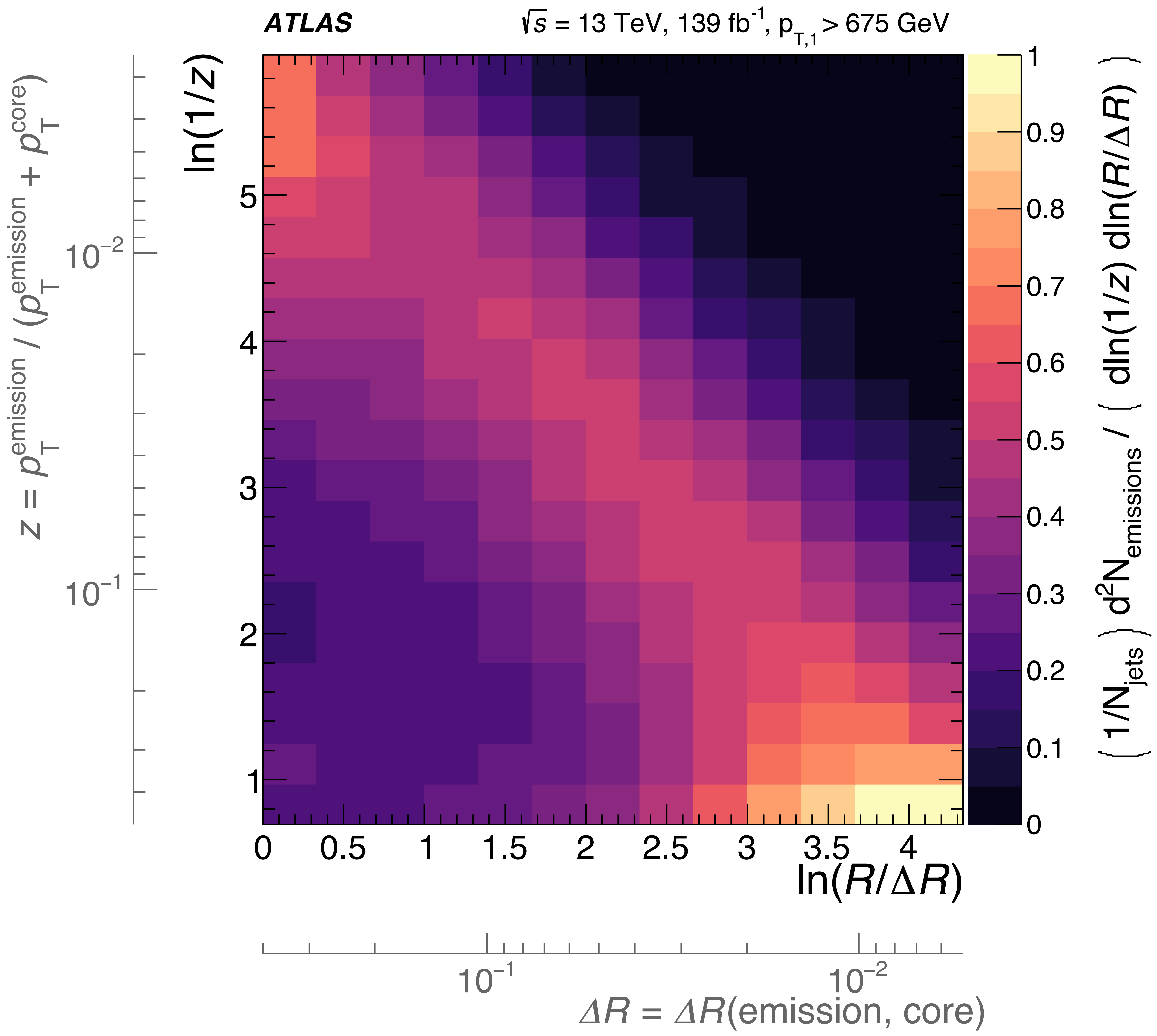
- Identify reconstructed tracks (charged hadrons) with $p_T > 500$ MeV within $\Delta R < 0.4$ of jets

  - Uses fine granularity of tracker

- Cluster tracks (charged hadrons) with C/A

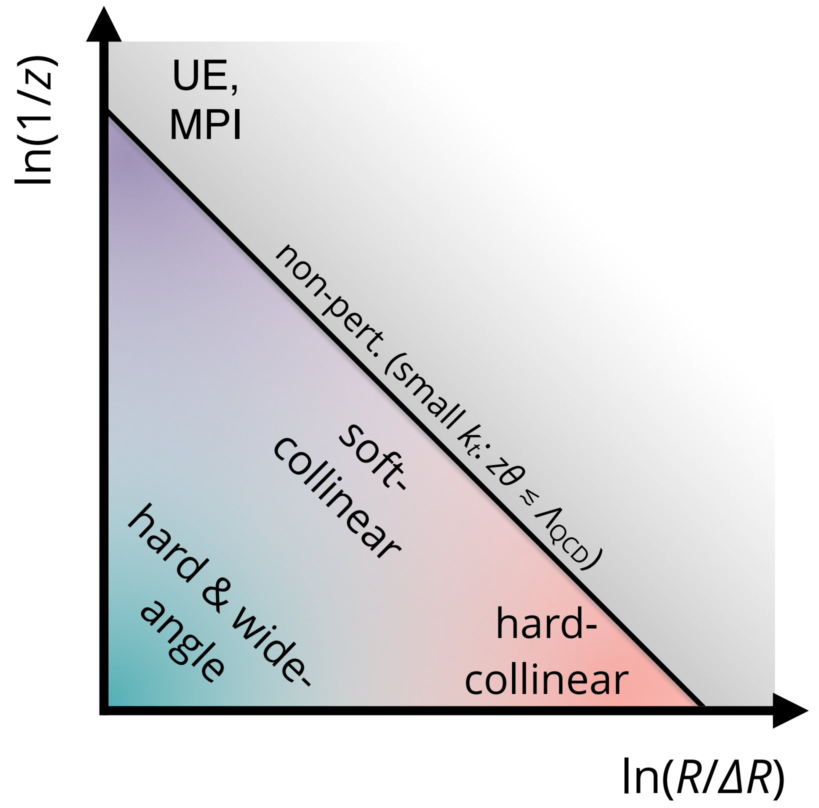
- Iteratively de-cluster: treat each step as an emission → add a point to Lund plane

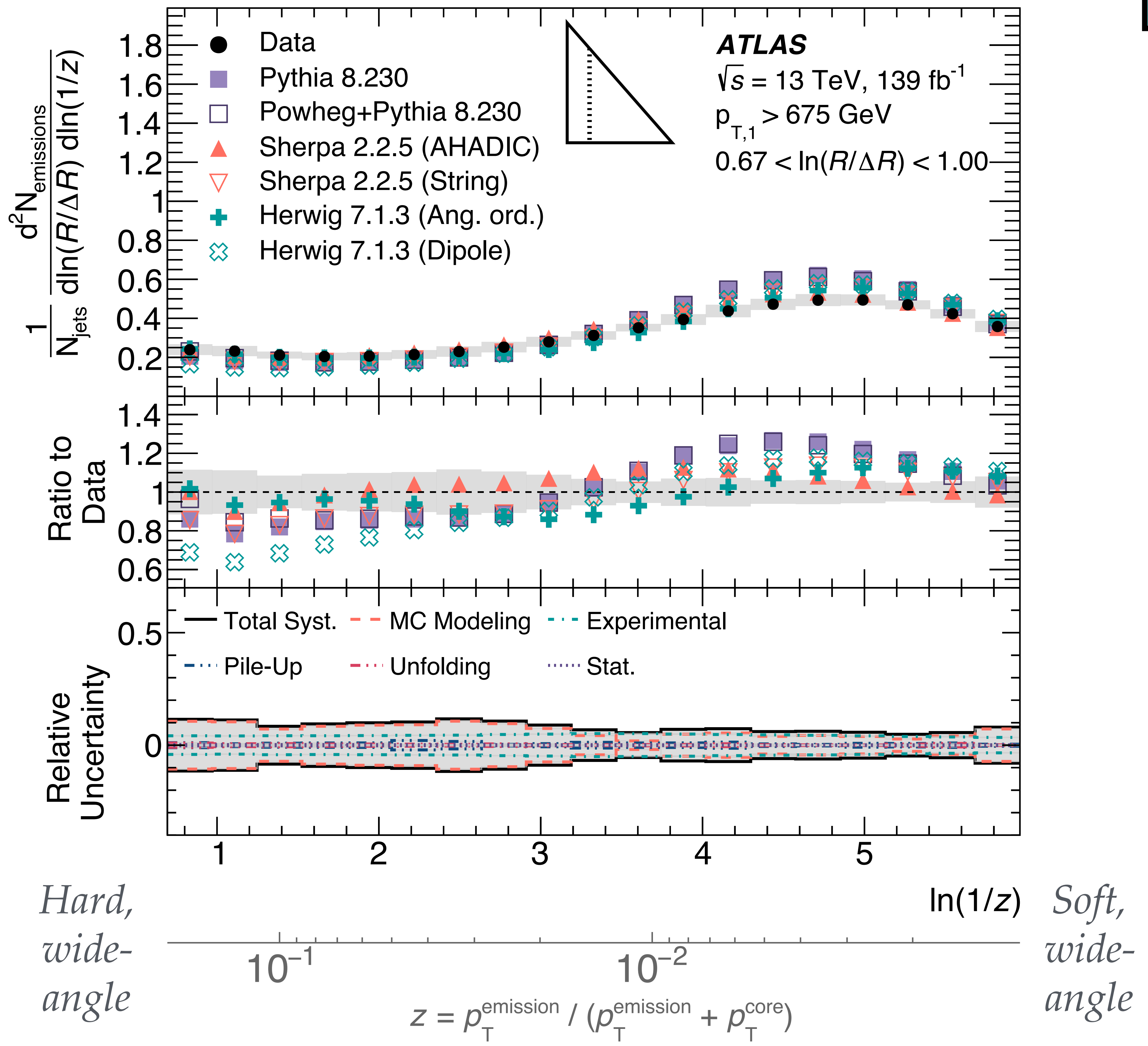
- Unfold reconstructed to charged-particle level

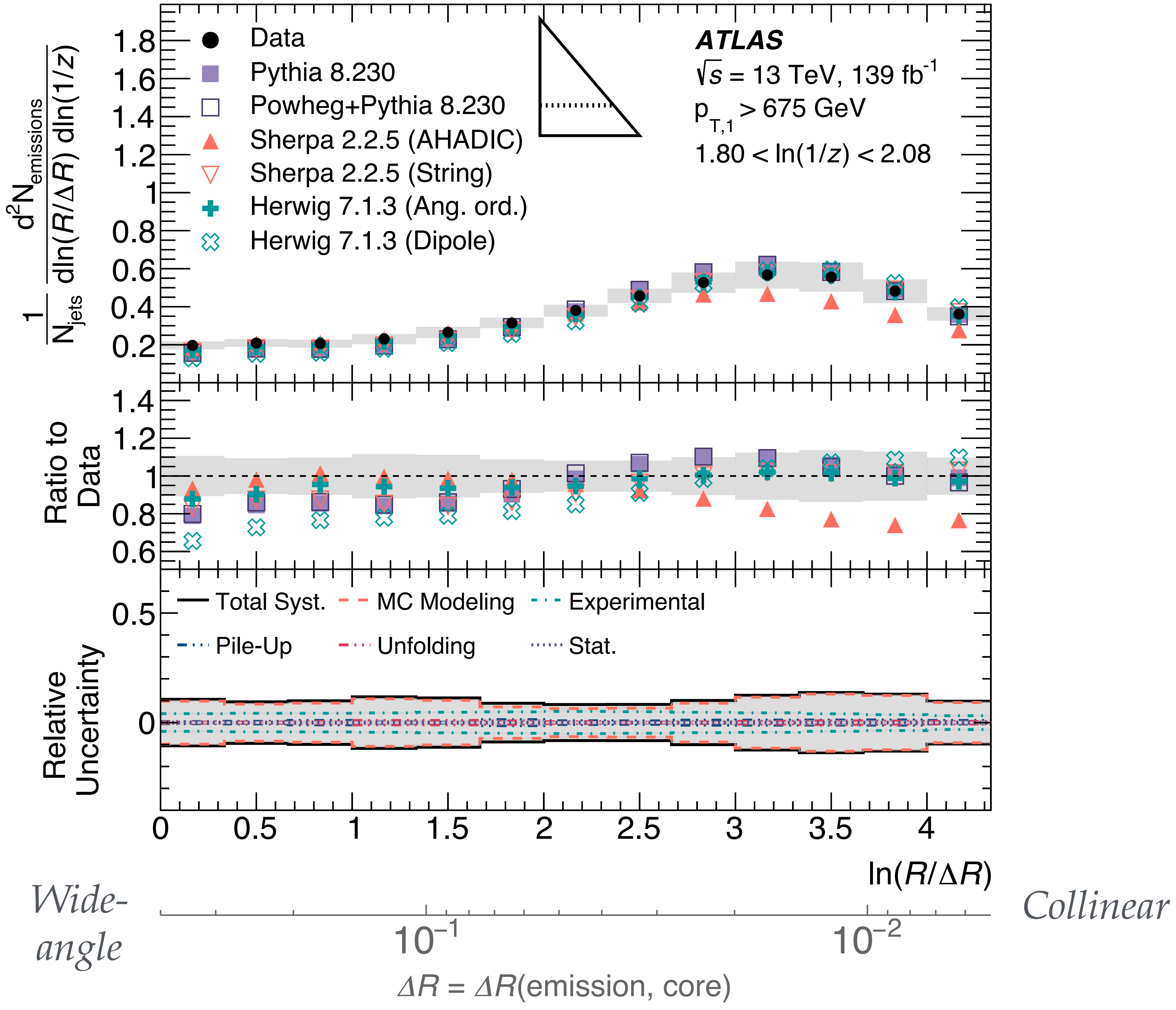


Lund Jet Plane

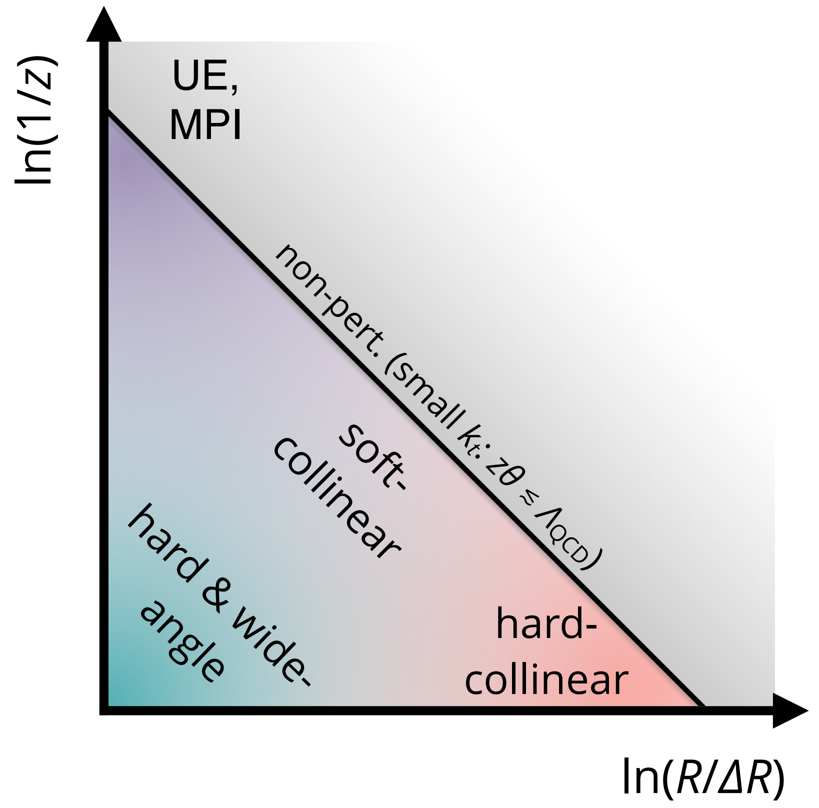
Take "slices" through phase space:

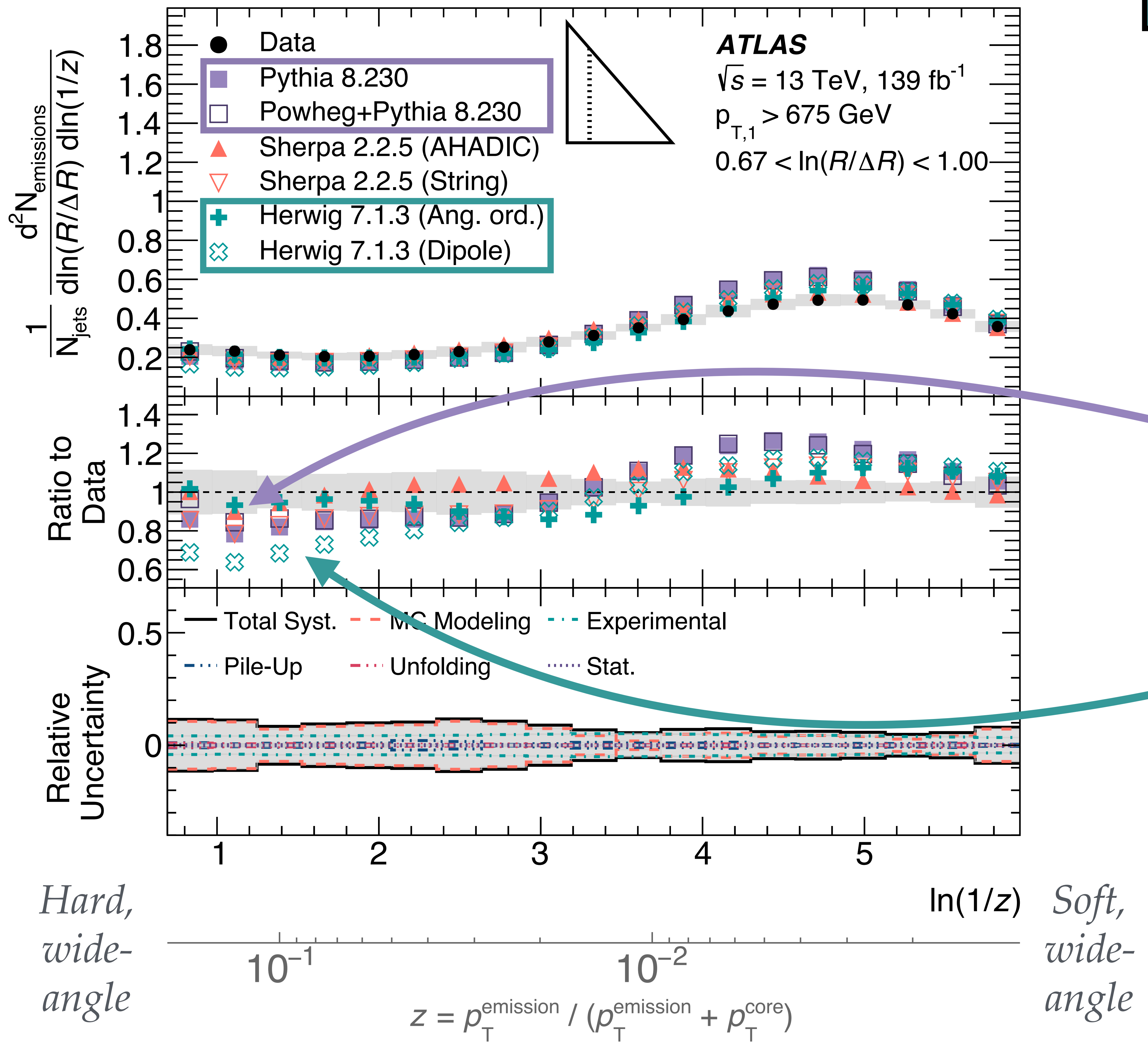






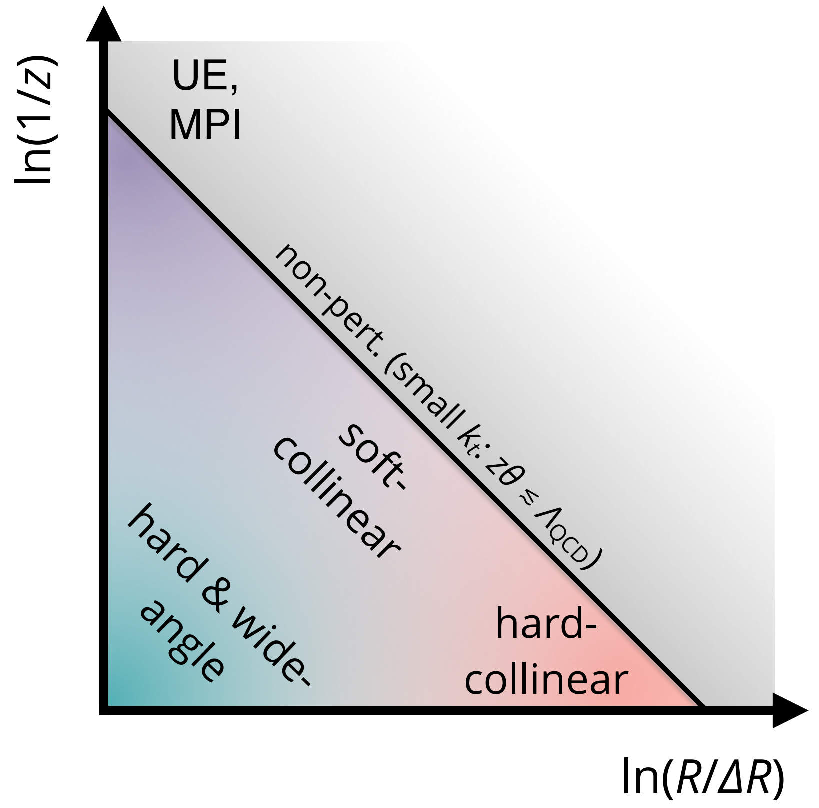
Lund Jet Plane



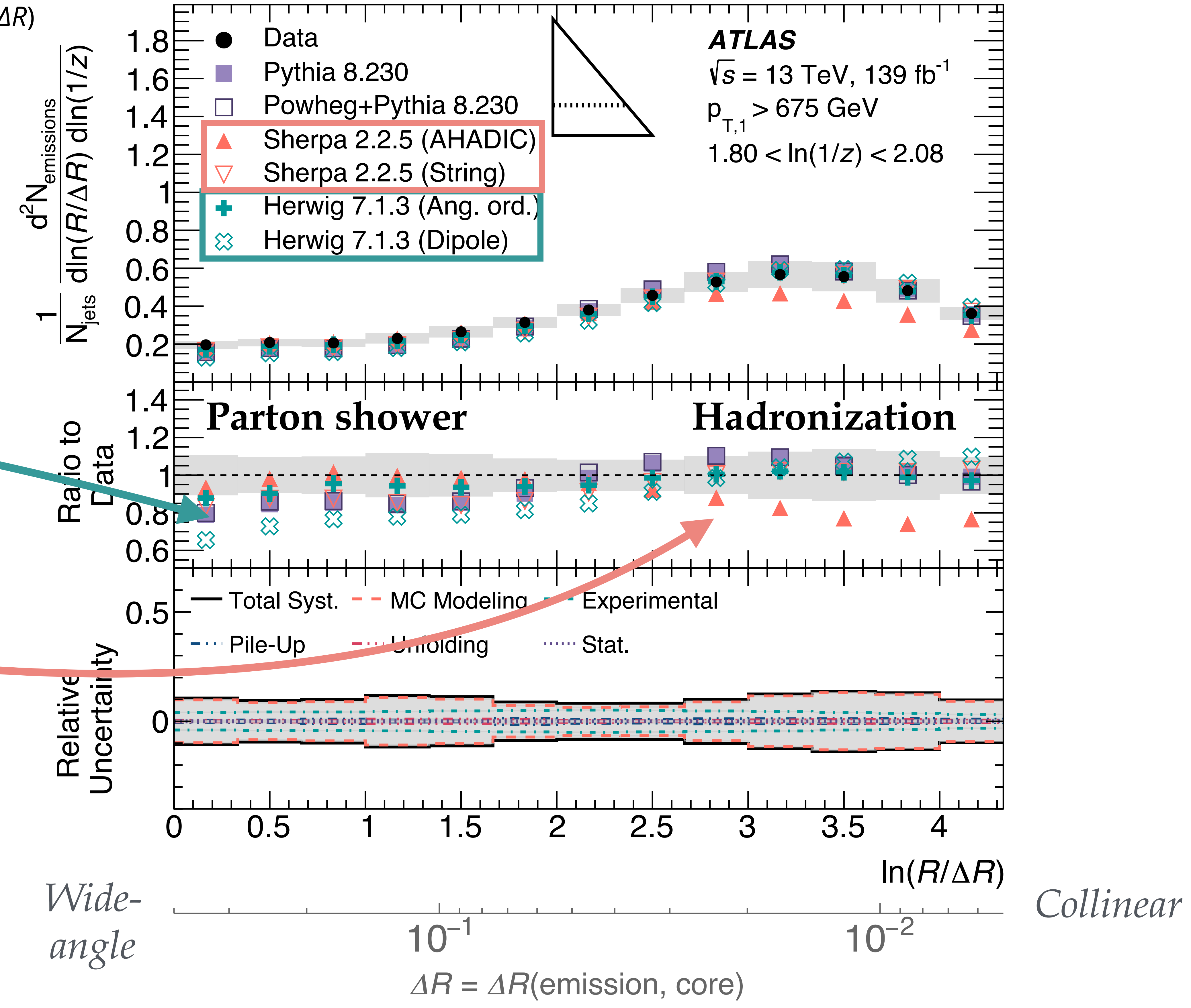


- None of the MC are perfect:
  - Herwig7 (angular-ordered) best across most of phase space
- Matrix Element corrections (Pythia vs Powheg+Pythia) only visible for widest-angle emissions
- Difference in Herwig7 parton showering clearly evident for hard, wide-angle emissions

Lund Jet Plane



- Lund Plane can isolate physical effects
- Difference in Herwig7 parton showering clearly evident for hard, wide-angle emissions
- Collinear region more sensitive to hadronization model (Sherpa AHADIC vs Lund string model)

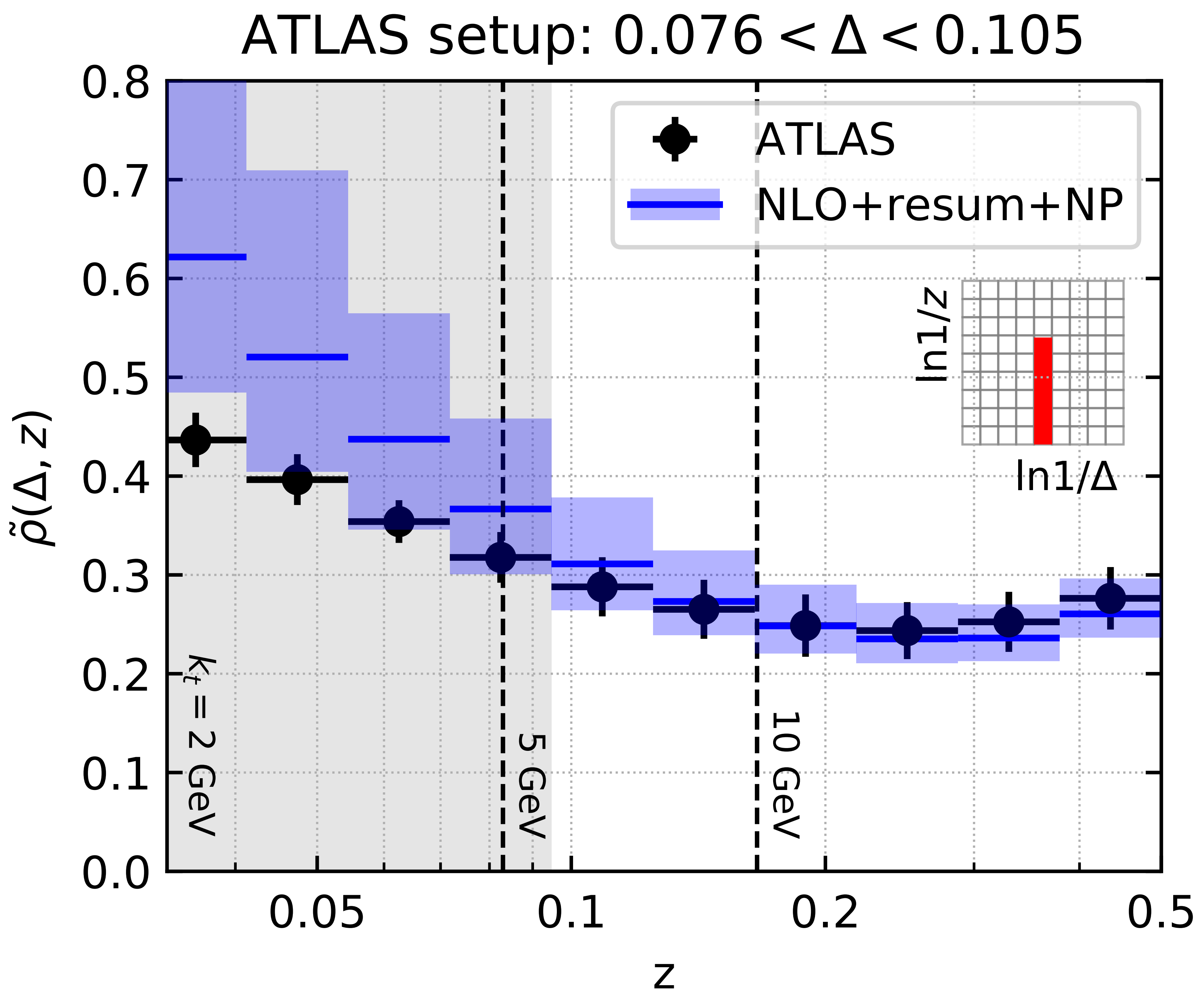


Lund Jet Plane

Compare with calculation of Lund Jet Plane:

- Valid down to $k_T \simeq 5$ GeV
- Combined with non-perturbative corrections from MC

Good agreement with data in well-understood region



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Summary

Wide variety of measurements probing nature of QCD

- Across parton showering, hadronisation, etc

Pushing our understanding through new techniques & observables

- Grooming now a standard tool, not just for highly-boosted W/Z/H/t; Lund Jet Plane can help decouple the various effects

Precision comparison between LHC data & pQCD predictions

- Soft Drop key tool to improve understanding of substructure & at high p_T

Clearly identify regions in which existing MCs perform strongly... and not so strongly

- Exciting to see feedback of results into simulation

New generation of taggers exploit even more information about individual jet constituents

- Modelling under even more scrutiny

Backup

Herwig7 tunes

Table 2: Values of the parameters for SoftTune [3, 12], CH1, CH2, and CH3.

		SoftTune	CH1	CH2	CH3
	$\alpha_S(m_Z)$	0.1262	0.118	0.118	0.118
PS	PDF set	MMHT2014 LO	NNPDF3.1 NNLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO
	$\alpha_S^{\mathrm{PDF}}(m_Z)$	0.135	0.118	0.118	0.118
MPI	PDF set	MMHT2014 LO	NNPDF3.1 NNLO	NNPDF3.1 LO	NNPDF3.1 LO
	$\alpha_S^{\mathrm{PDF}}(m_Z)$	0.135	0.118	0.118	0.130
	$p_{\perp,0}^{\mathrm{min}}$	3.502	2.322	3.138	3.040
	b	0.416	0.157	0.120	0.136
	μ^2	1.402	1.532	1.174	1.284
	p_{reco}	0.5	0.4002	0.479	0.471
	χ^2/N_{dof} (fit)	-	4.15	1.54	1.71
	χ^2/N_{bins}	12.5	5.11	1.50	1.67