Jets Measurements with ATLAS

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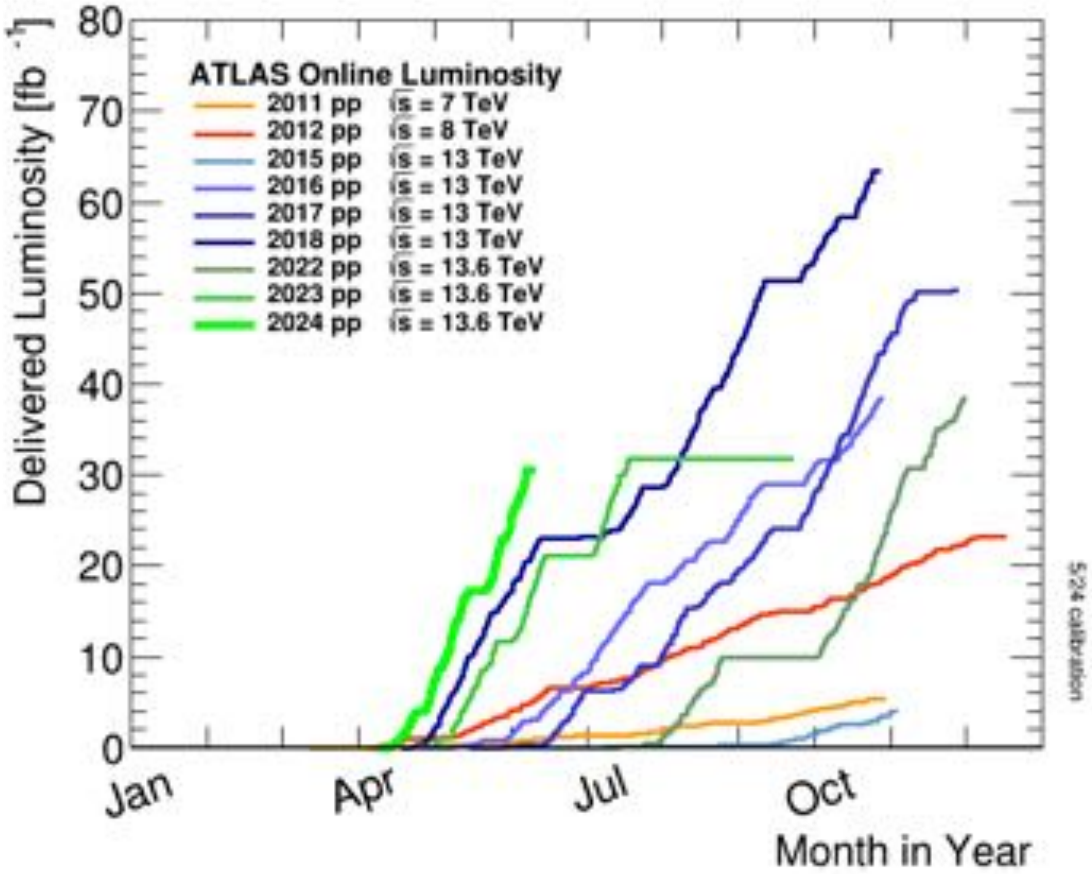
ATLAS experiment and QCD measurements

- proton - proton collider data at √s = 13 TeV

- middle of the Run 3 data collection

- all LHC observations rely
  on the modeling of QCD production :
  need precise theory with higher-order
  both QCD and EW calculations



- QCD measurements :
  - precise understanding of fundamental parameters of QCD
  - valuable inputs for theory development
  - improve future physics searches – better knowledge of backgrounds

Overview : recent QCD measurements in final states with jets using ATLAS experiment pp data at $\sqrt{s}$ = 13 TeV

- Correlation in multijet events and α_S measurement

  ➥ JHEP 07 (2023) 85

- Jet cross-section ratios between inclusive bins of jet multiplicity

  and impact of improvements of the overall ATLAS jet energy scale uncertainty on this measurement NEW NEW

  ➥ arXiv:2405.20206v1, Eur. Phys. J. C 81 (2021) 689, Eur. Phys. J. C 83 (2023) 761

- Interest on jet substructure measurements :
  - Lund jet plane using charged particles

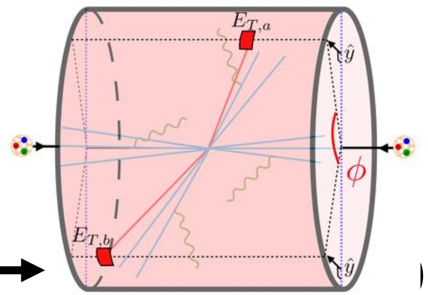
    ➥ Phys. Rev. Lett. 124 (2020) 222002

  - Differential cross section measurement of the subjet multiplicities in dijet events

    ➥ arXiv:2402.13052 NEW

Correlation in multijet events

- Transverse Energy-Energy Correlations or TEEC
  are a class of event shapes
  - Event shapes mesure how the (hadronic) energy flows in space in QCD events
    (= E_T weighted distribution of the azimuthal differences between jet pairs →



  - Stringent test of α_s at large scales (TeV)

- Full Run 2 13 TeV data (139 fb^{-1})

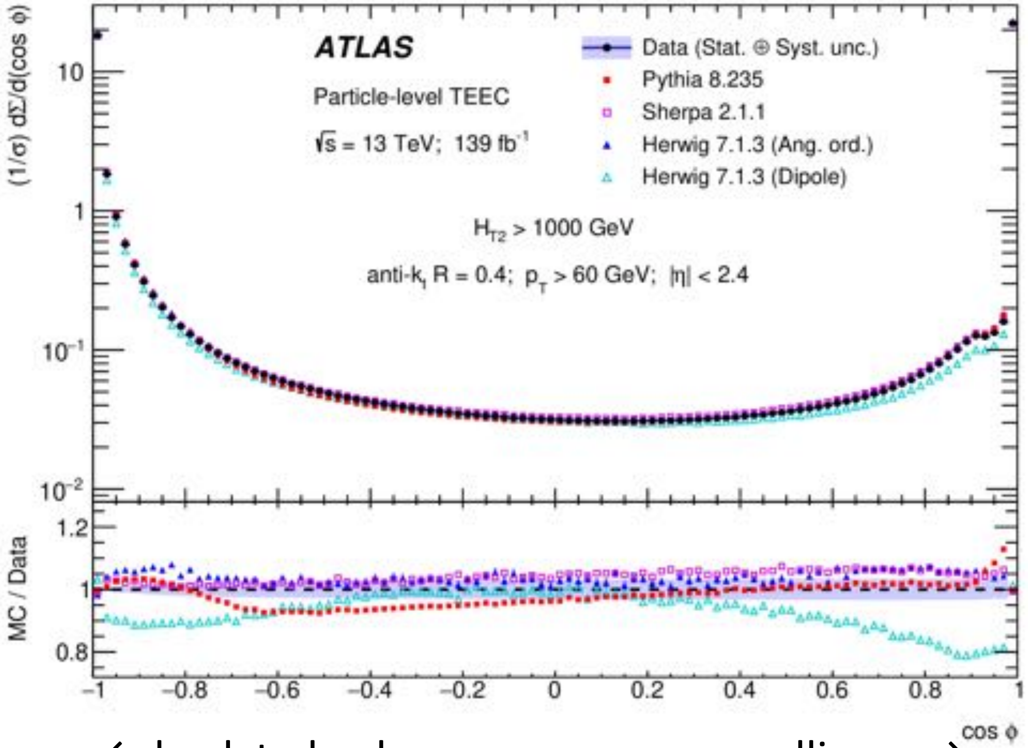
- Increased precision compared to measurement at 7 and 8 TeV

- Data unfolded to particle level
  and compared to NNLO theory prediction for the first time

- Experimental uncertainties ~ 3 %
  mainly from JES and MC Modeling

- No MC can model the data well on all range

- Significant difference between the 2 Herwig versions (dipole and angular-ordered)



← back to back
with $H_{T2} = p_{T,1} + p_{T,2}$

collinear →

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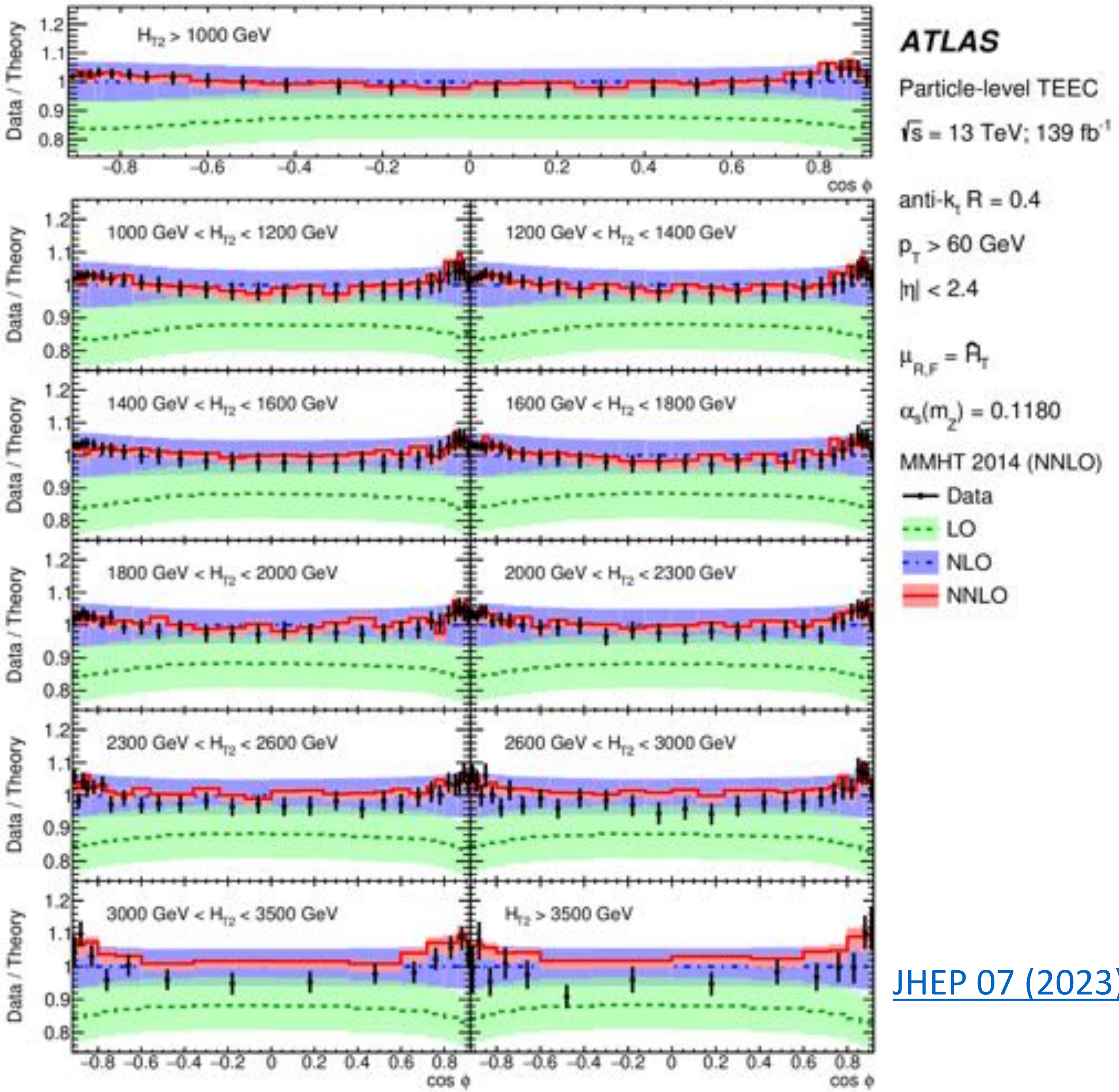
Correlation in multijet events

- Inclusive and in 10 H_T bins
- Reduction of uncertainties at NNLO to ⅓ of NLO and good agreement with data
- Highest theory uncertainty arises from scale variations
- and in α_s measurement

☞



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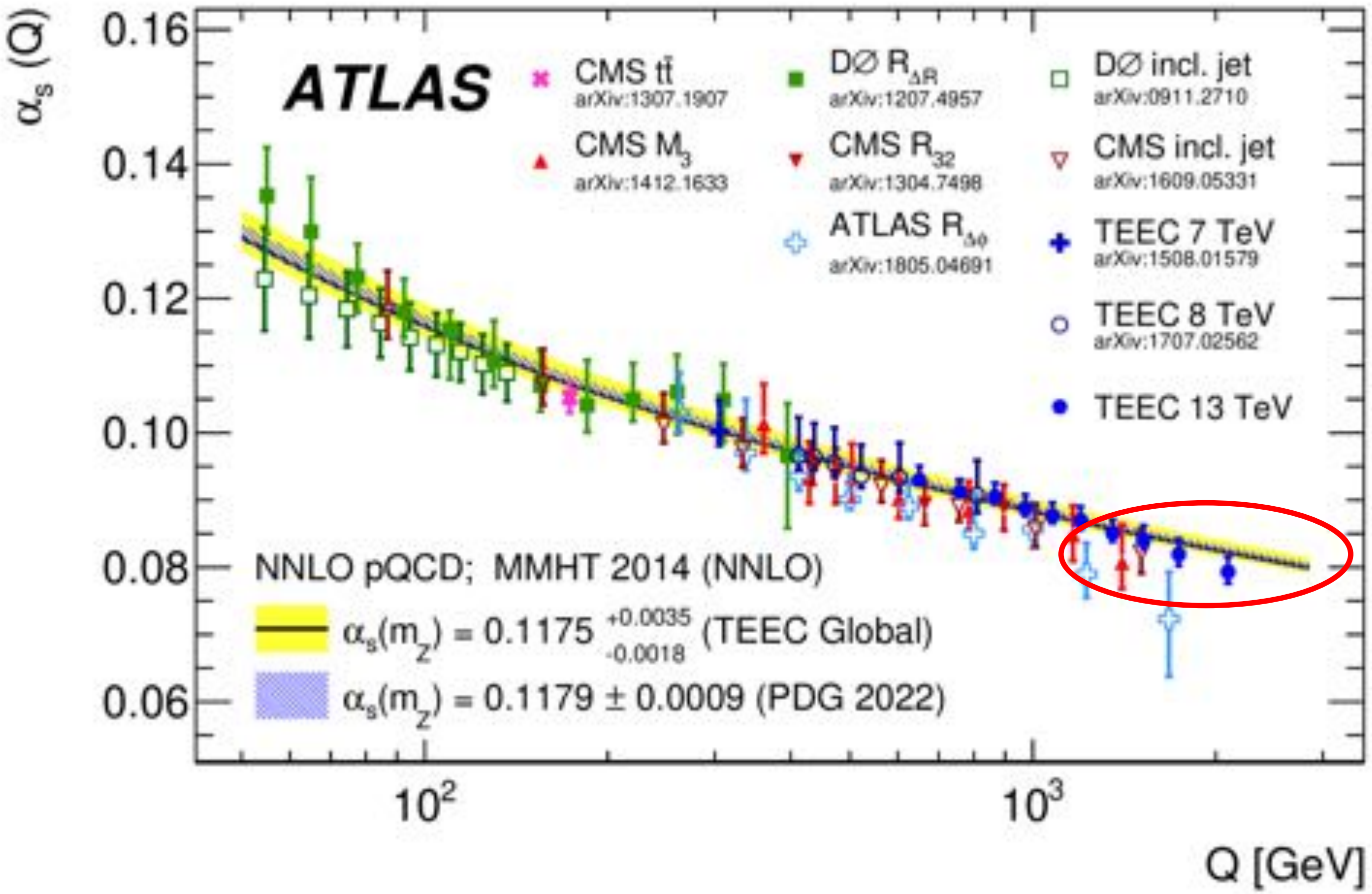
α_S measurement



- Least known fundamental forces of nature
- Large uncertainty in many LHC measurements e.g. Higgs couplings
- Single free parameter in massless QCD limit
- Asymptotic freedom
  decreasing with scale of the process ~ ln Q^2/Λ^2
  tested up to multi-TeV scale

S. Camarda, QCD@LHC

QQ̄ bound states	0.1181	0.0037	3.1%	4
DIS and PDF fits	0.1162	0.0020	1.7%	6
e+e- jets and shapes	0.1171	0.0031	2.6%	10
Hadron colliders	0.1165	0.0028	2.4%	5
Electroweak boson decays	0.1208	0.0028	2.4%	2
Lattice QCD (FLAG 21)	0.1184	0.0008	0.7%	11
PDG 22 World Average	0.1179	0.0009	0.8%	39

	$\alpha_s(m_Z)$	$\delta\alpha_s(m_Z)$	Rel. Unc.
ATLAS ATEEC	0.1185	0.0021	1.7%
CMS inclusive jets	0.1166	0.0016	1.4%
CMS dijets	0.1201	0.0020	1.7%
ATLAS Z pT	0.1183	0.0009	0.7%

Asymmetric TEEC

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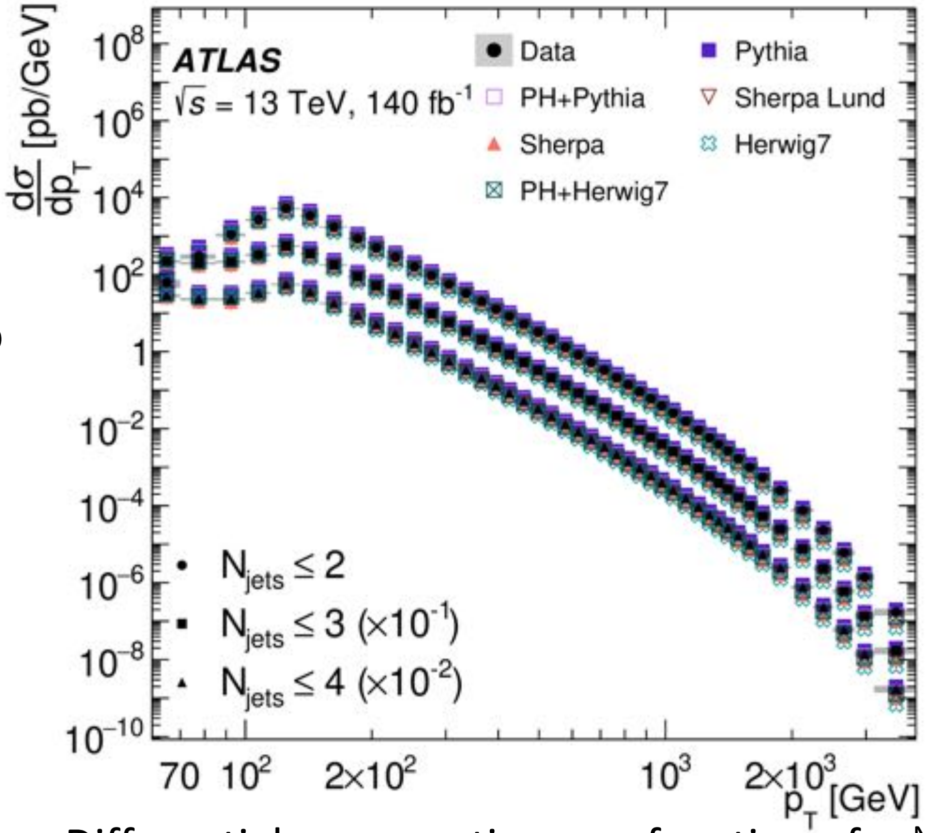
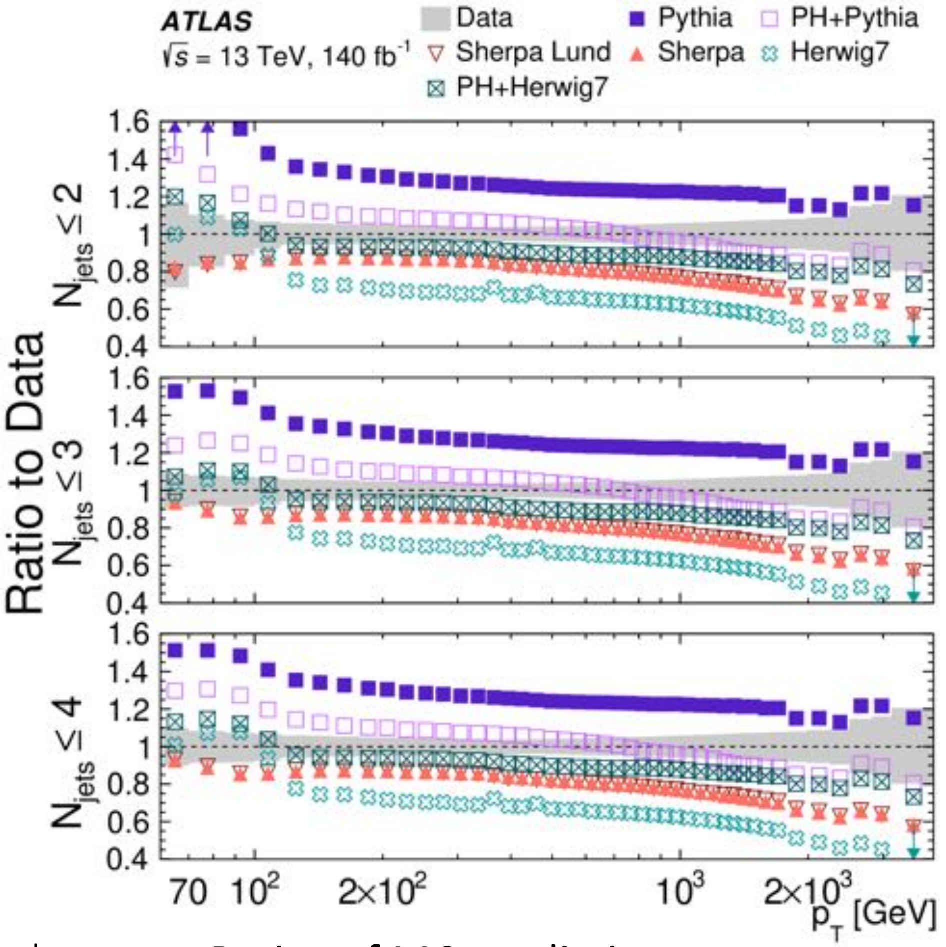
Jet cross-section ratios between inclusive bins of jet multiplicity

- 140 fb^{-1} Run 2 13 TeV data
- unfolded for acceptance and detector effects
- sensitive to α_s
  + less sensitive than other observables to systematic uncertainties, parton distribution functions
- data compared to NNLO predictions
- no single MC prediction is able to describe the data across all multiplicity bins



Differential cross-section as a function of p_T^{Nincl} in inclusive bins of N_{jets}



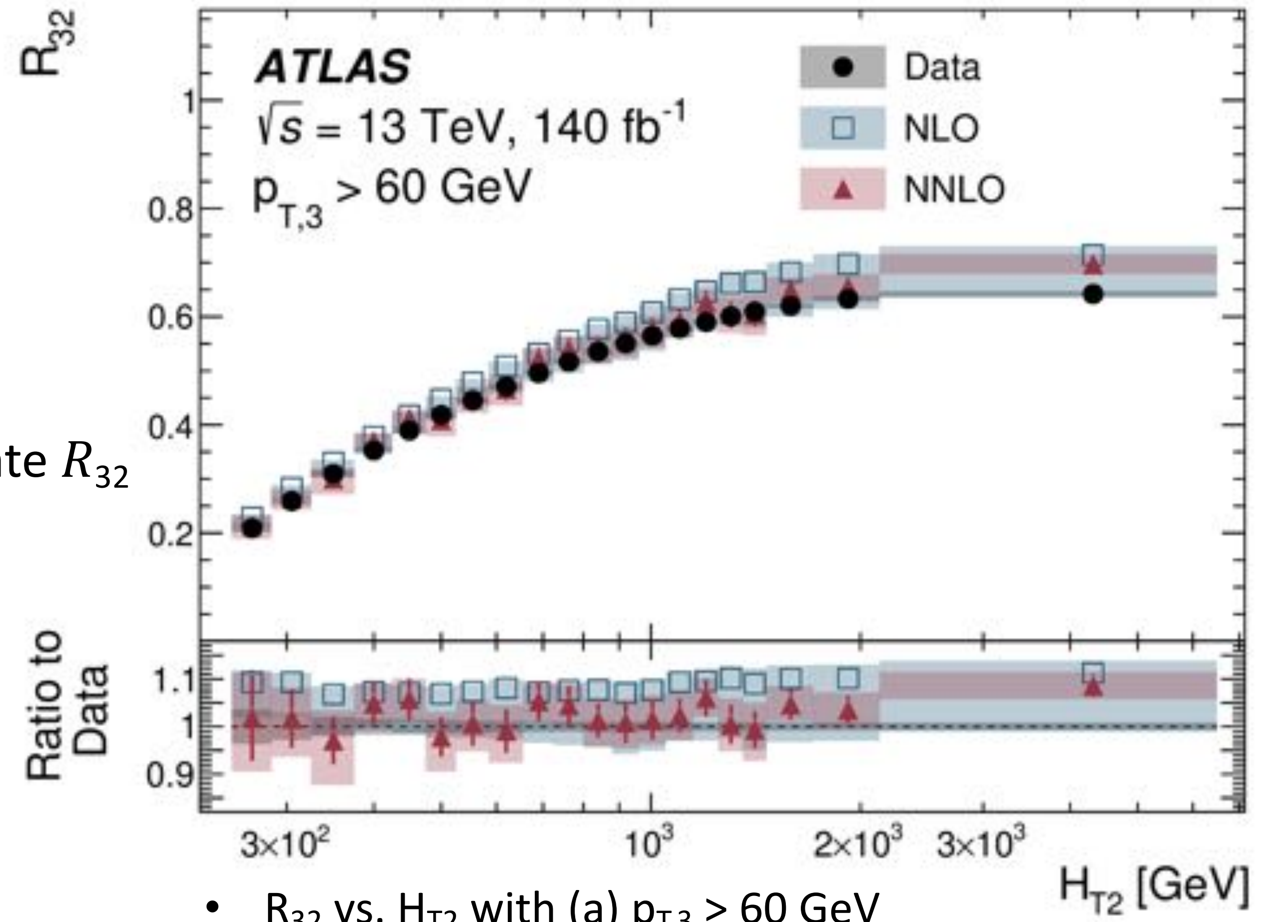
Ratios of MC predictions to the measured data distribution

arXiv:2405.20206v1

Jet cross-section ratios between inclusive bins of jet multiplicity

- ratios of the measured observables
- as expected, uncertainties are reduced because correlated systematic variations partially cancel out
- NNLO prediction ≈ accurate description of R_{32}
  compare to NLO prediction which tends to overestimate R_{32}

  $\Longrightarrow$ highlights the importance of the higher-order predictions in describing multijet production
- statistical fluctuations in the NNLO prediction due to the significant computational requirements



- R_{32} vs. H_{T2} with (a) $p_{T,3}$ > 60 GeV
- R_{32} = three-jet to two-jet cross-section ratio
- $H_{T2} = p_{T,1} + p_{T,2}$ + must satisfy $H_{T2} \geq 250$ GeV

arXiv:2405.20206v1

Significant improvements of the overall ATLAS jet energy scale uncertainty

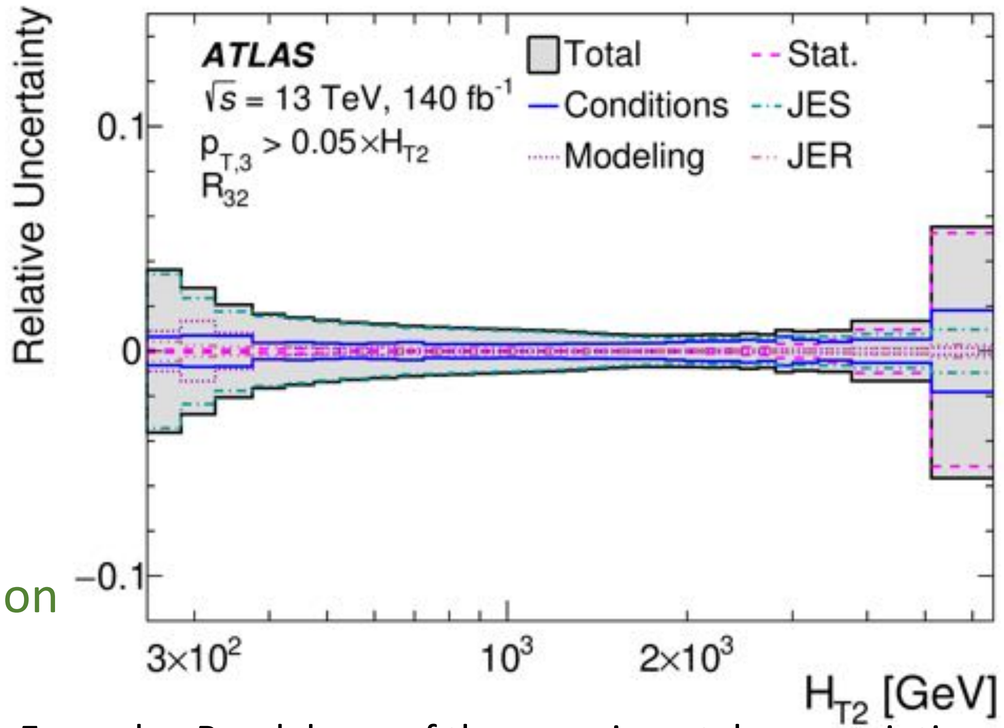
- Systematic uncertainties in the R = 0.4 jet energy scale (JES) and resolution (JER) is known with simulation-based techniques and in situ measurements

➡ the dominant sources of experimental uncertainty in jets measurements

but

➡ the impact of certain components of the JES uncertainty has been recently reduced for :

- the relative jet energy response for simulated quark- and gluon-initiated jets between different MC generators (= jet-flavor response)
- the component of the JES uncertainty related to the extrapolation of single-hadron response measurements to jets



Example : Breakdown of the experimental uncertainties for R_{32} measurement differential in H_{T2} (with R_{32} and H_{T2} defined as previously)

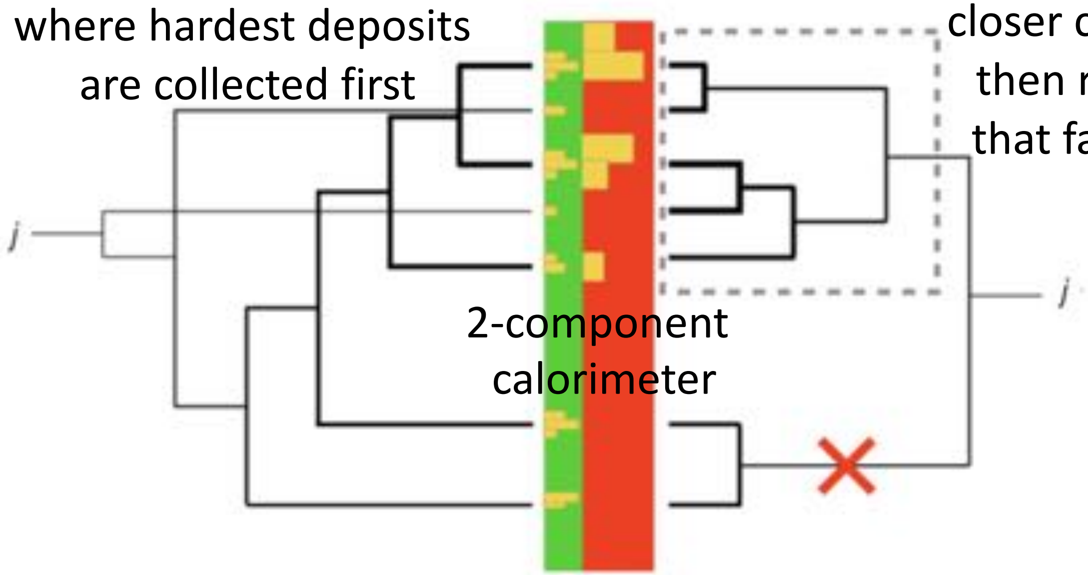
arXiv:2405.20206v1

Eur. Phys. J. C 81 (2021) 689 and Eur. Phys. J. C 83 (2023) 761 for jet calibration

Jet substructure : From grooming to lund jet plane

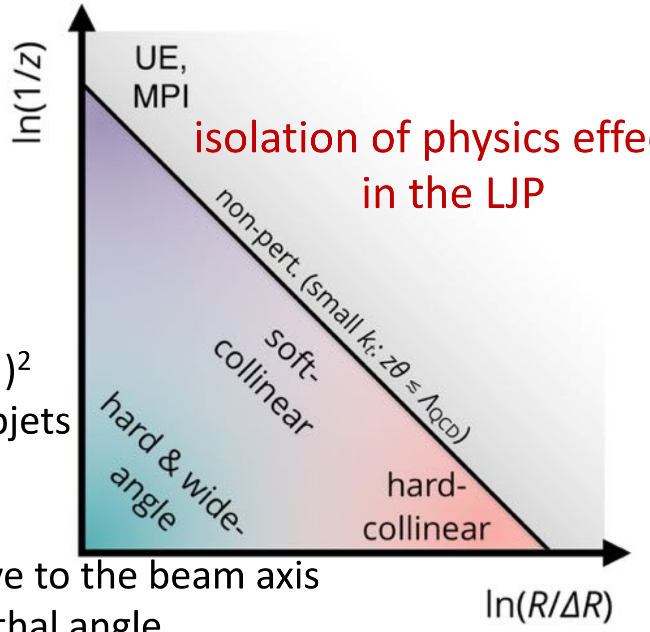
standard jet clustering where hardest deposits are collected first

grooming : closer constituents first then removing parts that fail some criteria



with $1/z = k_T = p^{j2}_T \Delta R$
and $\Delta R = \sqrt{(y^{j1} - y^{j2})^2 + (\varphi^{j1} - \varphi^{j2})^2}$
j1 and j2 : harder and softer subjets in the branching
p^{j2}_T : transverse momentum of the softer subjet relative to the beam axis
and y and φ rapidity and azimuthal angle

isolation of physics effects in the LJP



- Jet Substructure (JSS) at first emerged as a powerful framework
- But not easy to disentangle contributions of different modelling QCD tools (perturbative / non perturbative effects)
- Grooming is the first breakthrough in JSS physics thanks to possibility of isolated physical processes
- Charged-particle tracking very useful to precisely measure JSS observables (better angular distribution) and particle flow
- Lund Jet Plane (LJP) is the second breakthrough : can isolate physical effects too and in addition is multi-dimensional

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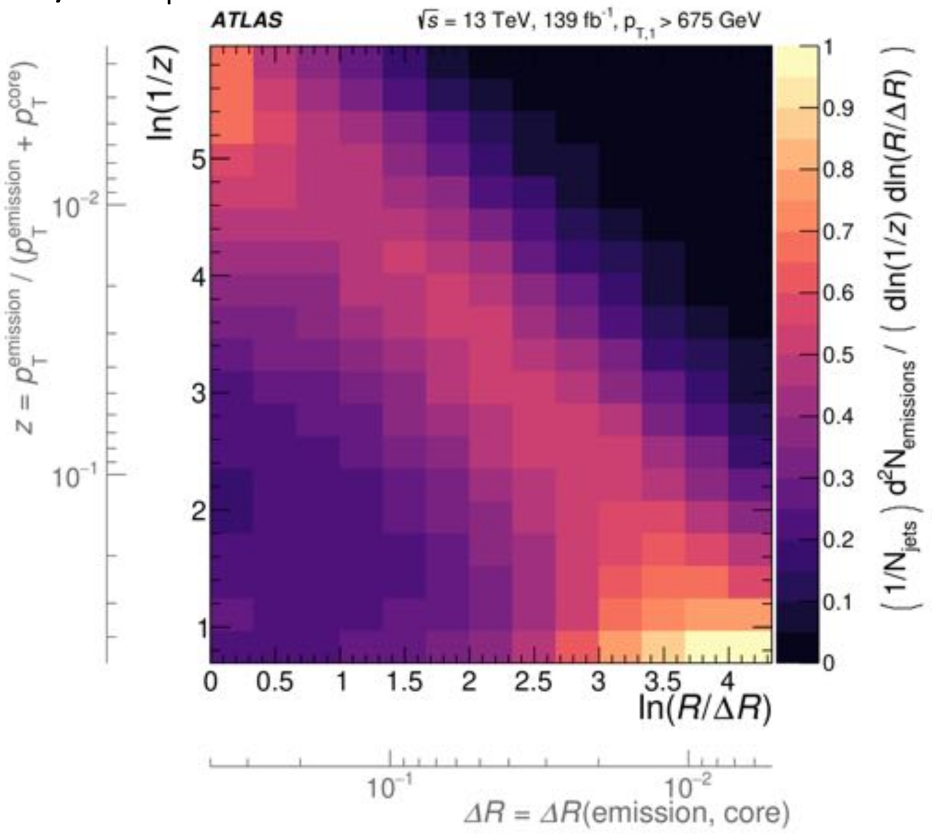
Lund jet plane using charged particles

$1/z = k_T$



LJP measured using jets in 13 TeV pp ATLAS data corrected to particle level

- a jet is approximated as soft emissions around a hard core which represents the original quark or gluon
- double-differential cross-section measurement of the Lund jet plane using 139 fb^{-1} for jets with p_T > 675 GeV
- selected jets are reconstructed from topological clusters using the anti-k_t algorithm with R = 0.4 + associated charged-particle tracks (= better angular resolution)

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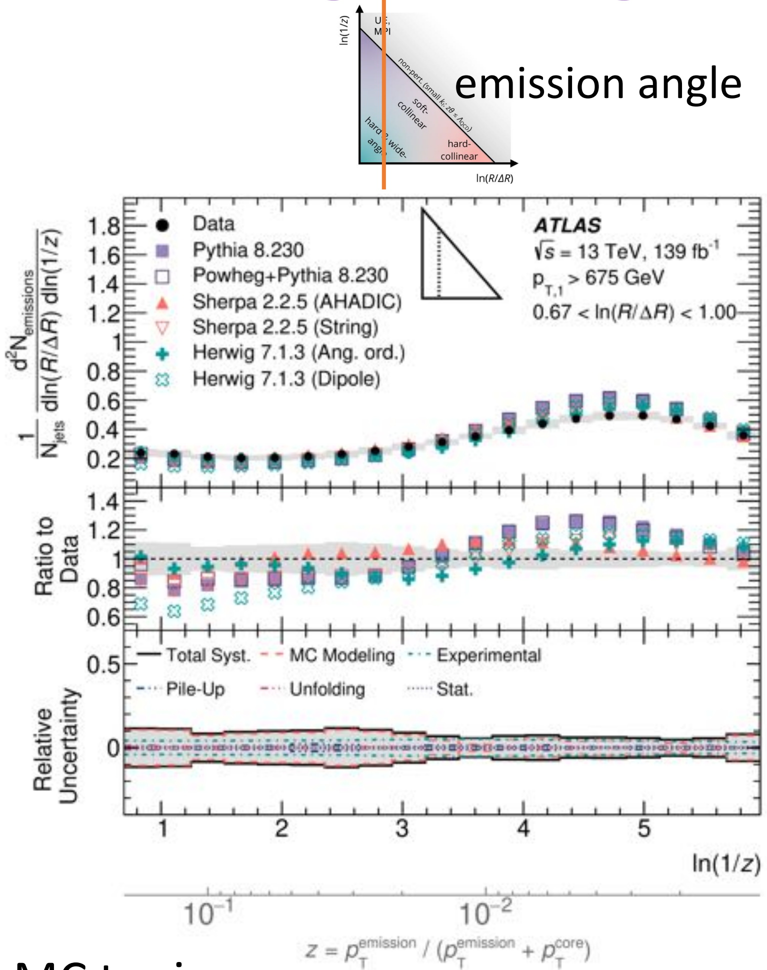
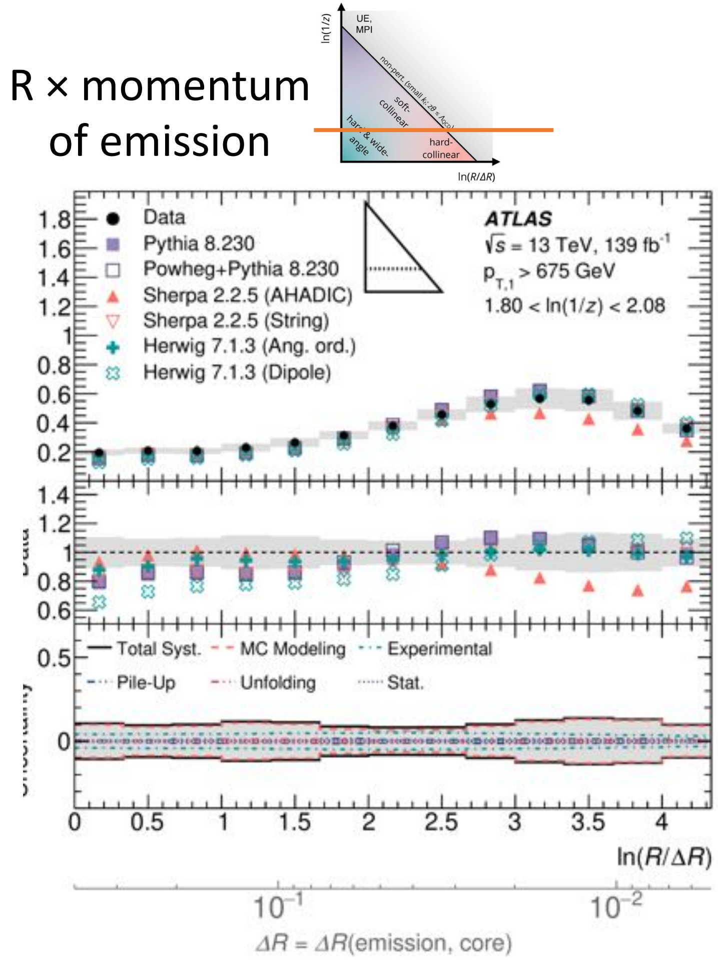
Lund jet plane using charged particles

Horizontal and vertical slices through the LJP :
- double-differential cross-section measurement
- unfolded data
  + particle-level simulation
  from several MC generators





- Crucial input from NLL parton shower and MC tuning
- No single model found to be in agreement with the measured data across the entire plane

⇨ useful input to perturbative and non perturbative model development and tuning

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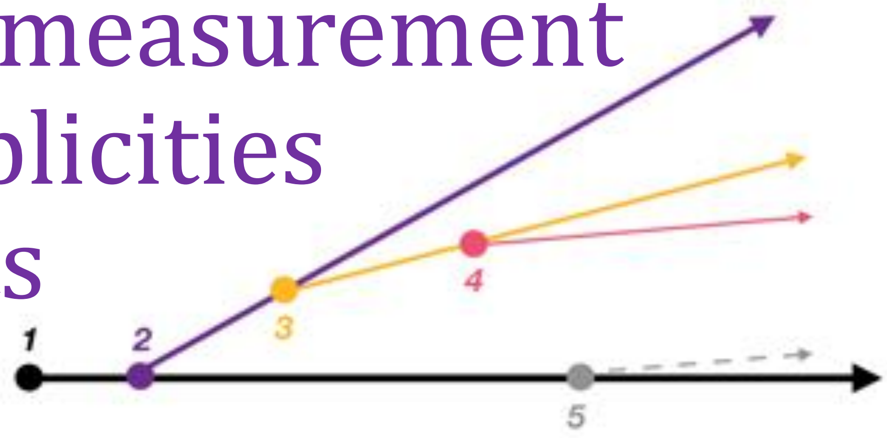
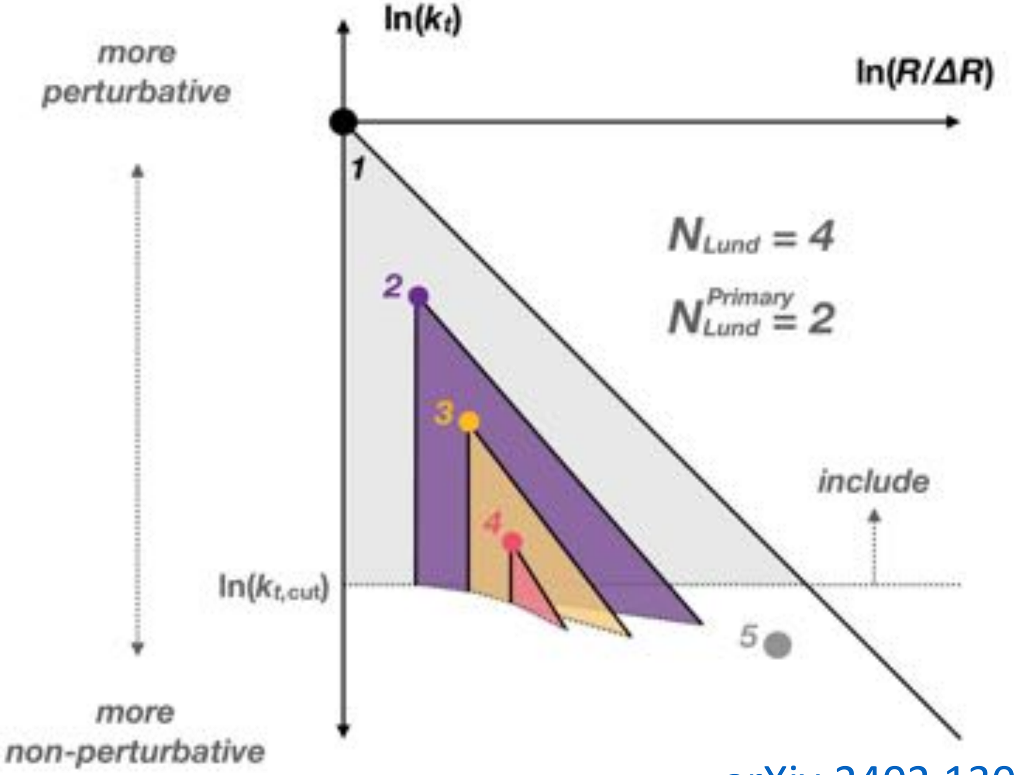
Differential cross section measurement of the subjet multiplicities in dijet events



- Lund multiplicity counts the number of subjets above a specified p_T requirement in a jet's angle-ordered clustering history

- Branches of the clustering history with relative p_T are the 'emission' (= lower) and 'core' (= highter)

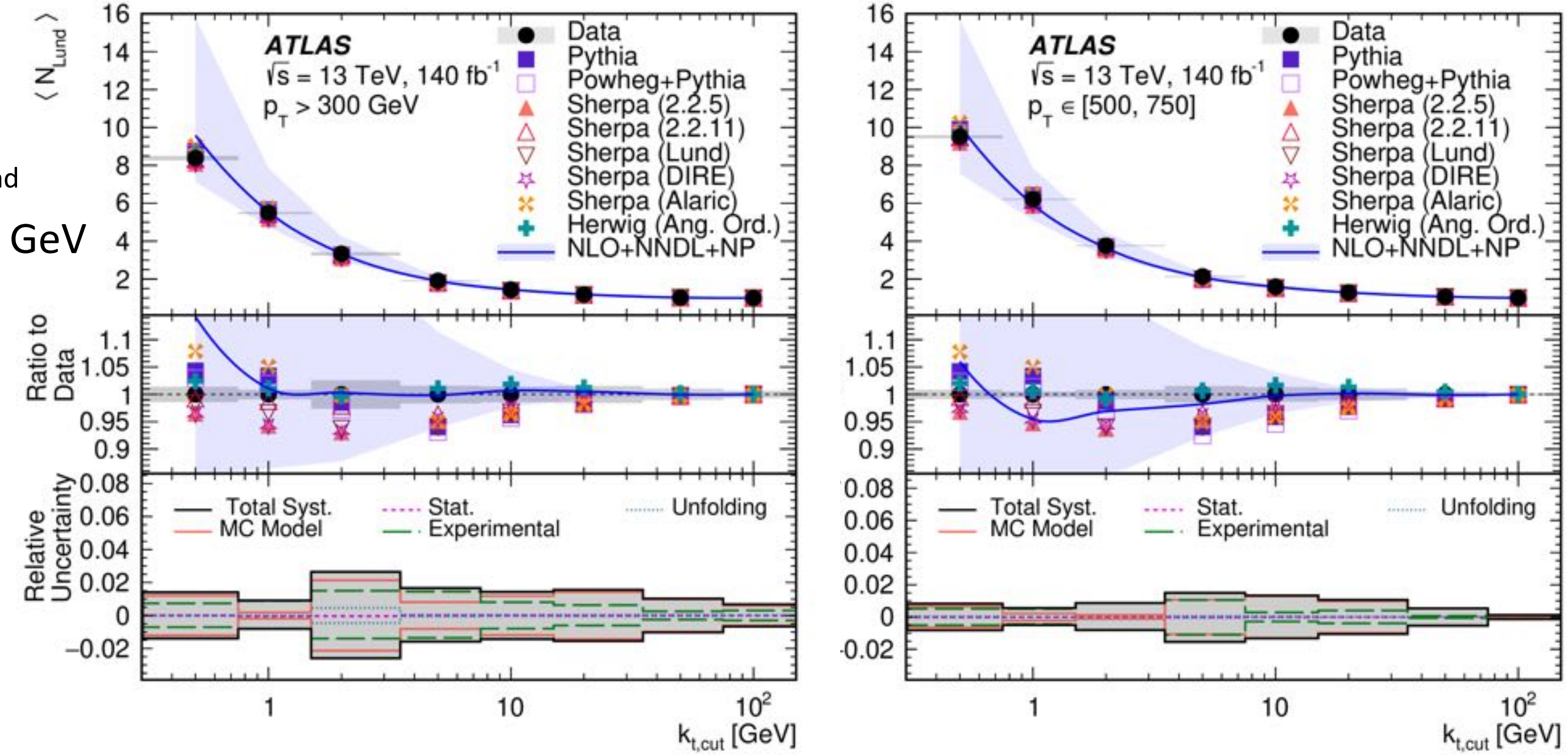
- $k_t = p_T^{\text{ emission}} \cdot \Delta R(p^{\text{ emission}}, p^{\text{ core}})$



arXiv:2402.13052

Differential cross section measurement of the subjet multiplicities in dijet events

measured differential cross-section of N^{Lund}
for an emission k_t requirement of 1 and 10 GeV
in an inclusive bin of jet rapidity
+ a bin of jet p_{T}



- di-jets using 140 fb^{-1} for 13 TeV pp data
- unfolded data compared to different MC models
- most of the studied MC models do not describe the shape of the measured data
- the Herwig sample generated with the default angular-ordered PS agrees best overall with the measured data

arXiv:2402.13052

Conclusion

- Wealth of precise measurements with multijet events
- QCD physics at the LHC has entered % precision era both in terms of theory and experimental measurements
- Beneficial for the improvement of MC generator modelling, perturbative and non-perturbative effects
- Accurate pQCD predictions are indispensable (NNLO computations available for many processes)
- Run 3 is on-going : many more results still to come