Measurement of jet substructure with the ATLAS detector

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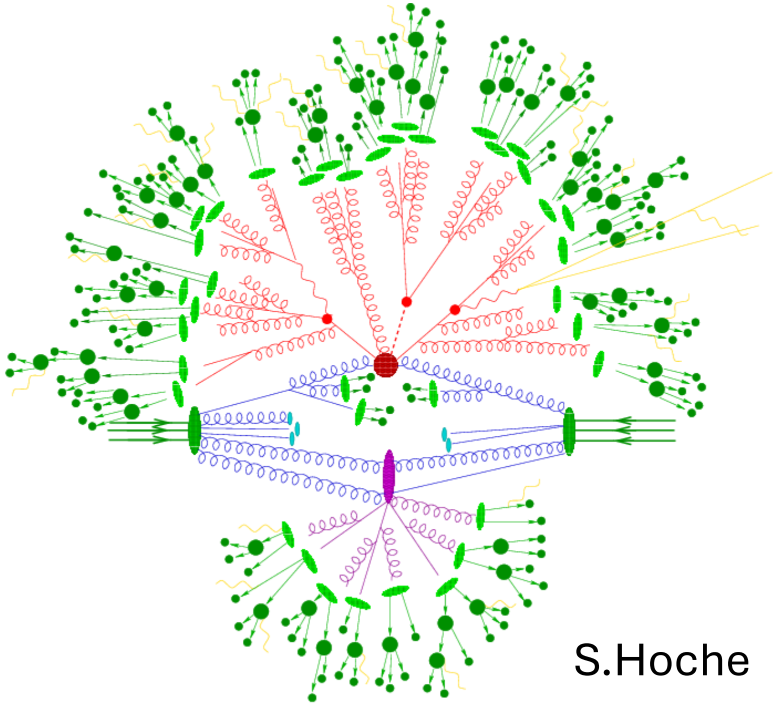
On behalf of the ATLAS collaboration

Why jet substructure?

- Hadronic jets are complex objects
- The relationship between primary partons and the jets observed in an event require sophisticated QCD parton shower descriptions and phenomenological hadronization models
- There is a wide range of Monte Carlos (MCs) with different PS descriptions and hadronization models, which often results in significant systematic errors on measurements
- Jet substructure measurements seek to characterize parton showers and hadronization and improve their descriptions
- ATLAS has made several measurements of the Lund Jet Plane to characterize jet substructure in light/gluon-jets, W-jets and t-jets
  - ***Measurement of the Lund Jet Plane for Jets Initiated by Top Quarks and W Bosons, https://arxiv.org/abs/2407.10879***
  - ***Measurements of Lund subjet multiplicities in 13 TeV proton-proton collisions with the ATLAS detector, https://arxiv.org/abs/2402.13052, submitted to PLB***
  - ***Measurement of the Lund jet plane using charged particles in 13 TeV proton–proton collisions with the ATLAS detector, Phys. Rev. Lett. 124 (2020) 222002***



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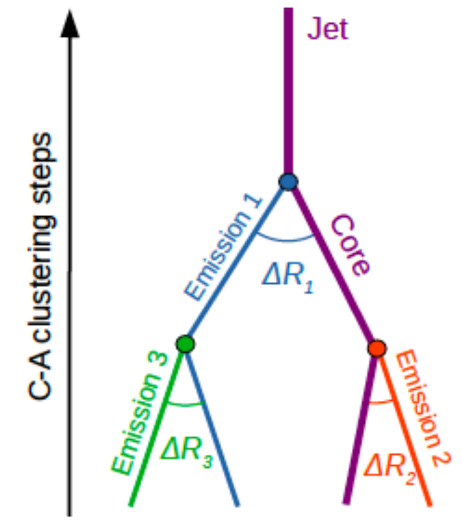
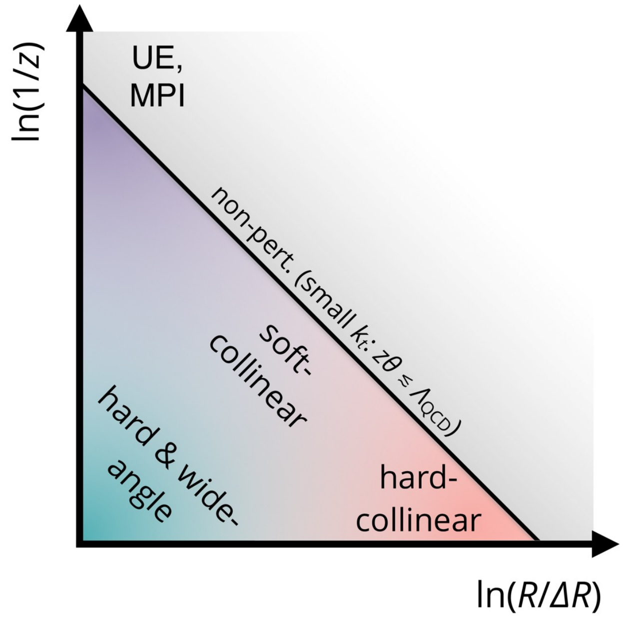
Measurement of the Lund Jet Plane in light quark/gluon, W and top jets





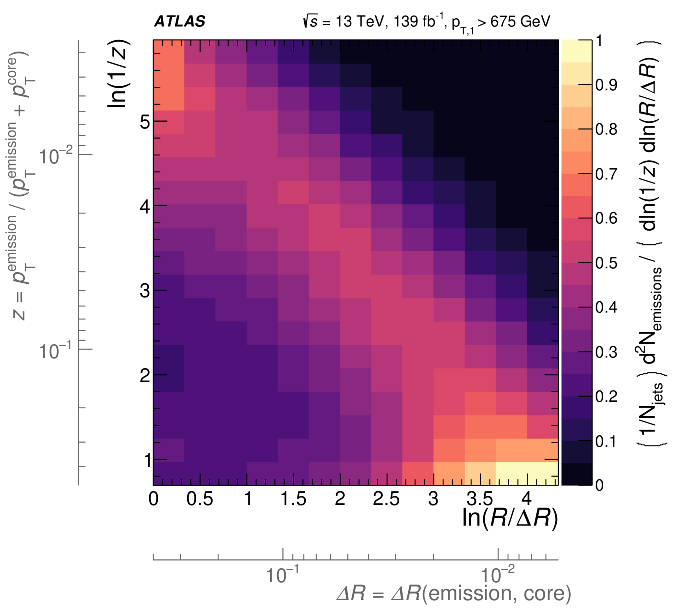
The Lund Jet Plane plots the emissions through the shower, each point represents the phase space of the emission.

$z=p_t^{emission}/(p_t^{core}+ p_t^{emission})$
$\Delta R=(y^{core}- y^{emission})^2+ =(\phi^{core}-\phi^{emission})^2$

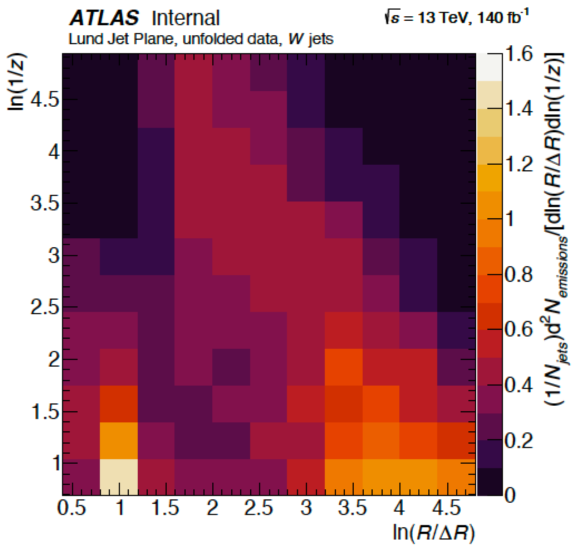
The primary Lund Jet Plane follows the emissions of the core

- Inclusive light quark/gluon di-jets, $139fb^{-1}$ at 13TeV
  - R=0.4 anti-kt jets reconstructed using particle flow objects
- Top events (semi-leptonic channel),$140fb^{-1}$ at 13TeV
  - R=1.0 anti-kt jets using topoclusters
  - R=0.4 anti-kt jets using particle flow object
- Recluster tracks in jets using C/A to produce track-based jets
  - R=0.4 for jets, R=1.0 for t-jets
  - t-jets: $M_{jet} > 140GeV$, $dR_{jb} < 1.0$
  - W-jets: M_{jet} 60-100GeV, b-tagged jet
- Decluster jets using C/A algorithm by reversing the clustering to identify emissions – measure density of emissions in Lund Jet Plane
- The total uncertainty on the LJP density is dominated by the modelling of the ttbar signal
- Use tracks to reconstruct charged particle jets
  - Improved resolution – better granularity than calorimeters
  - Reduce impact of pile-up by associating tracks to primary vertex

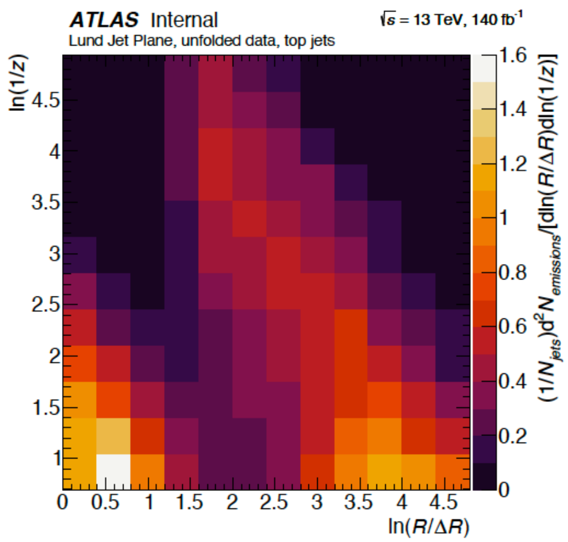
Lund Jet Plane in light quark/gluon, W and top jets



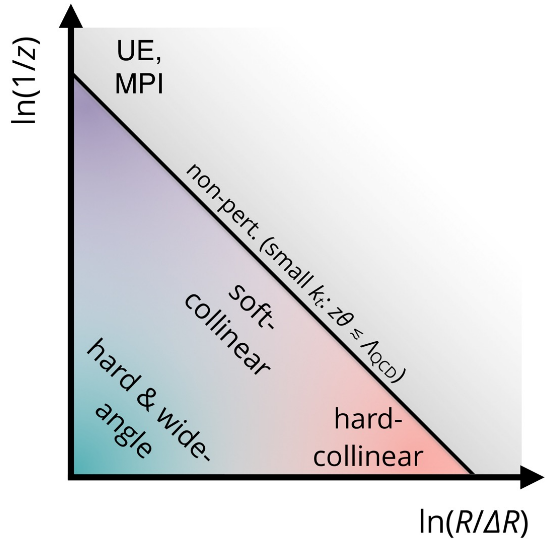
Light quark/gluon Jets p_t>675GeV



W-jets p_t>350GeV



t-jets p_t>350GeV



Lund jet plane structure clearly seen:

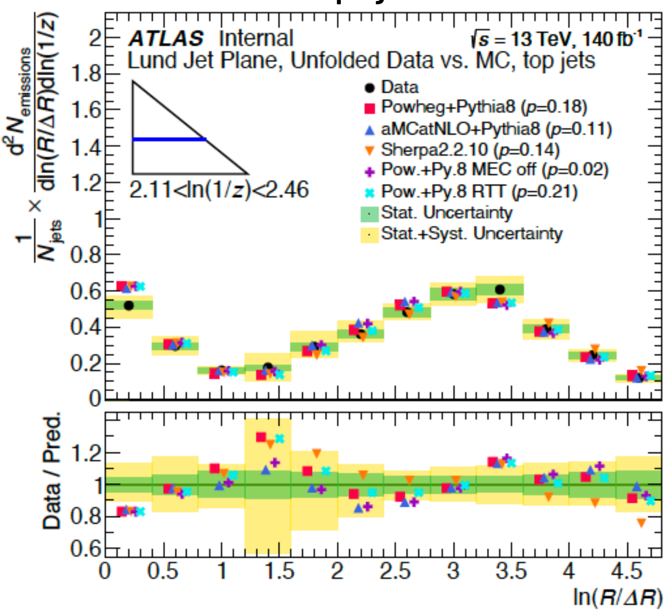
Soft collinear and hard colinear in light quark/gluon jets, W-jets and t-jets

Hard wide-angle jets observed in W-jets and t-jets

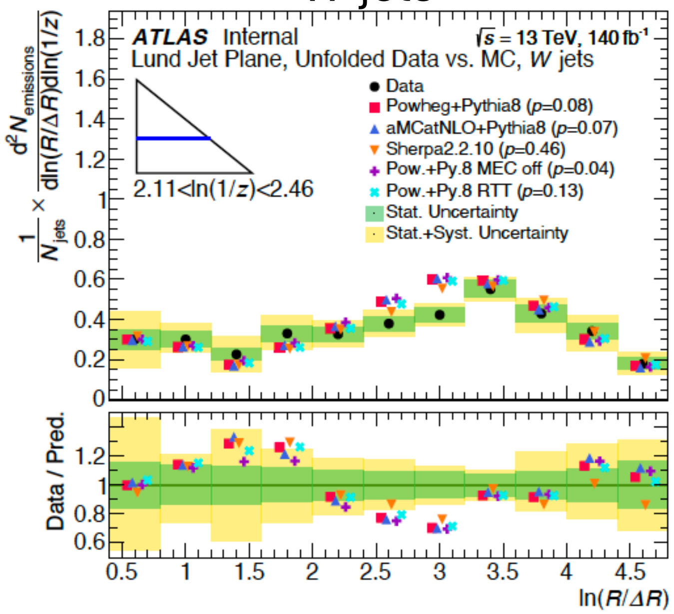
$\langle N_{Lund}^{Primary} \rangle$ W-jets= 6.02±0.04 (stat.)±0.22 (syst.); top-jets=6.74±0.02 (stat.)±0.13 (syst.)

Lund Jet Plane in light quark/gluon, W and top jets

Top-jets

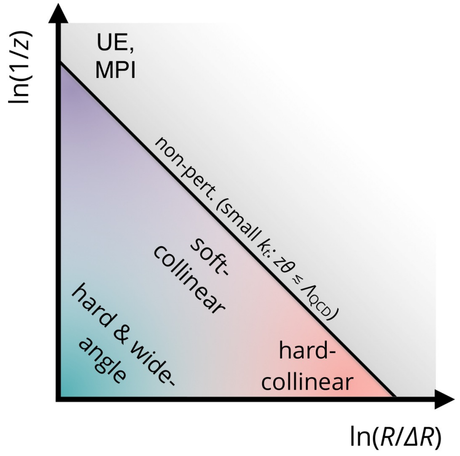


W-jets



Sample name	χ^2	χ^2/NDF (NDF=132)	p-value [%]
Powheg + Pythia 8	149	1.13	15
aMCatNLO + Pythia 8	149	1.13	14
Sherpa 2.2.10	139	1.05	33
Powheg + Herwig 7.0	169	1.28	2
Powheg + Herwig 7.2	165	1.25	3
Powheg + Herwig 7.1	150	1.14	14
Powheg + Pythia 8 MEC Off	176	1.34	1
Powheg + Pythia 8 RTT	145	1.10	20
Powheg + Pythia 8 FSR UP	148	1.12	17
Powheg + Pythia 8 FSR DOWN	162	1.23	4

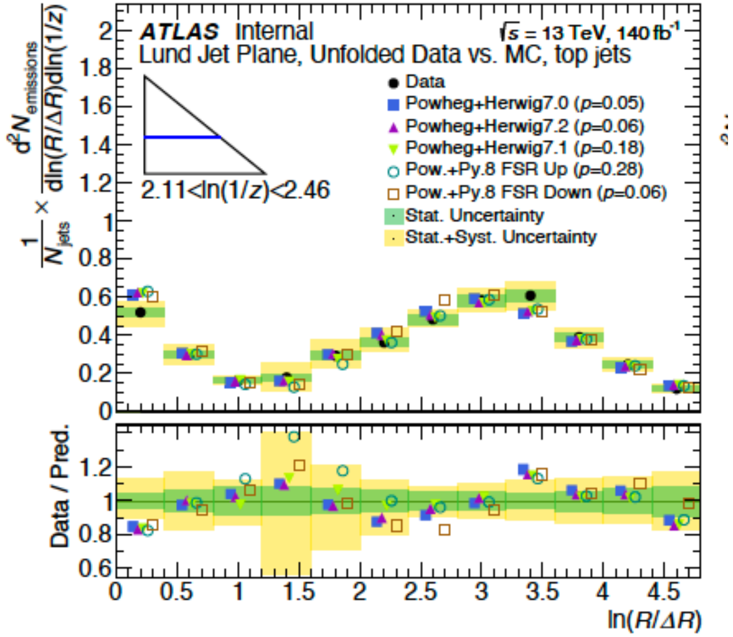
Global p-values for top-jets
W-jets all have p-values < 1



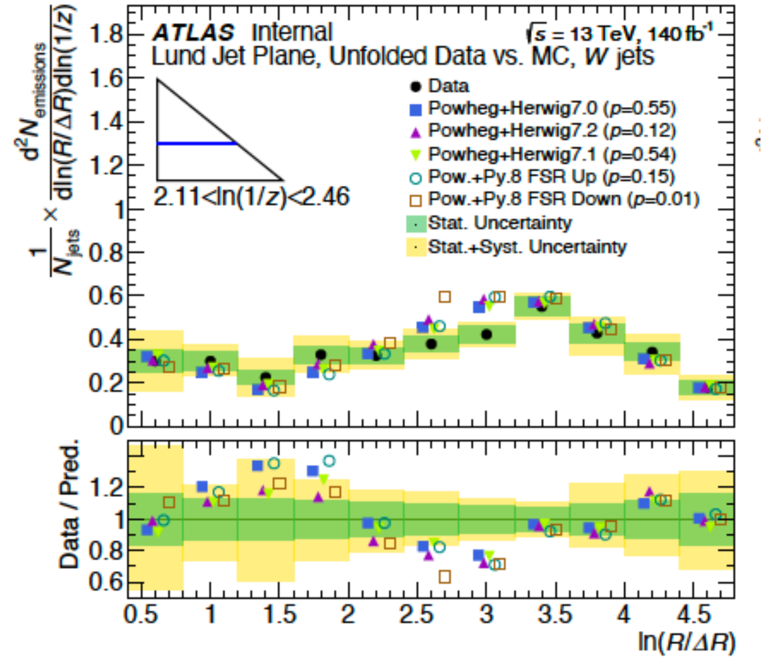
- Measurement shows good discrimination between different MCs
- Globally: Good agreement between data and some MCs for t-jets
- Globally: W-jets are not well described by any generator (p-values <1%), better agreement in sub-regions
- Best agreement between data and Sherpa 2.1.10

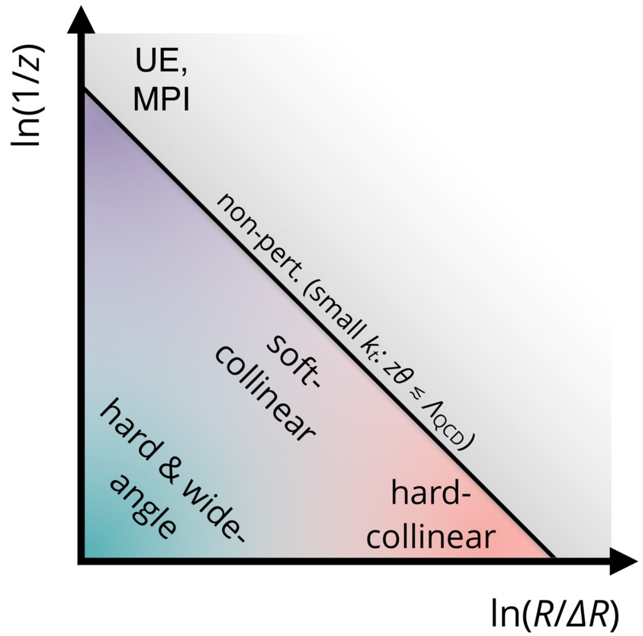
Lund Jet Plane in light quark/gluon, W and top jets

Top-jets



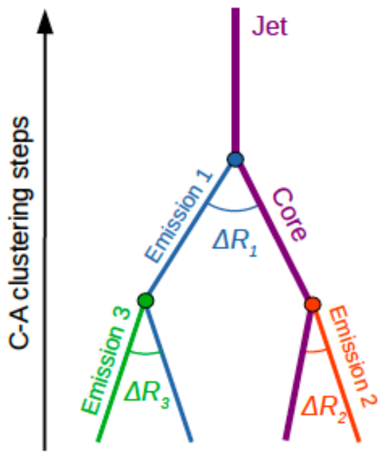
W-jets

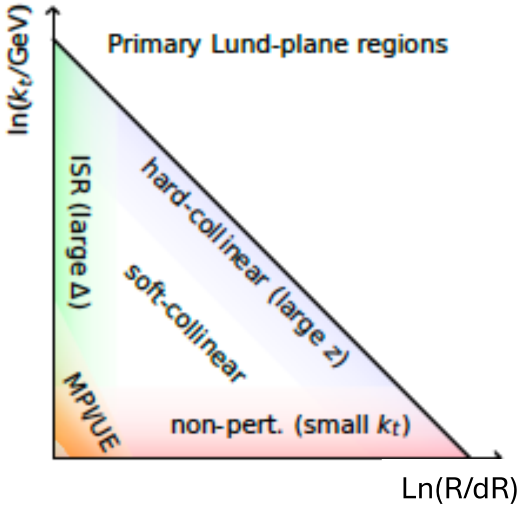




- Focus on Powheg and Herwig and Powheg and Pythia
- Discrimination between different versions of Herwig
- Powheg+Pythia8 (FSR down) shows the most significant disagreement with data, both globally and in both ln(1/z) and ln(R/dR) slices

Lund subjet multiplicities

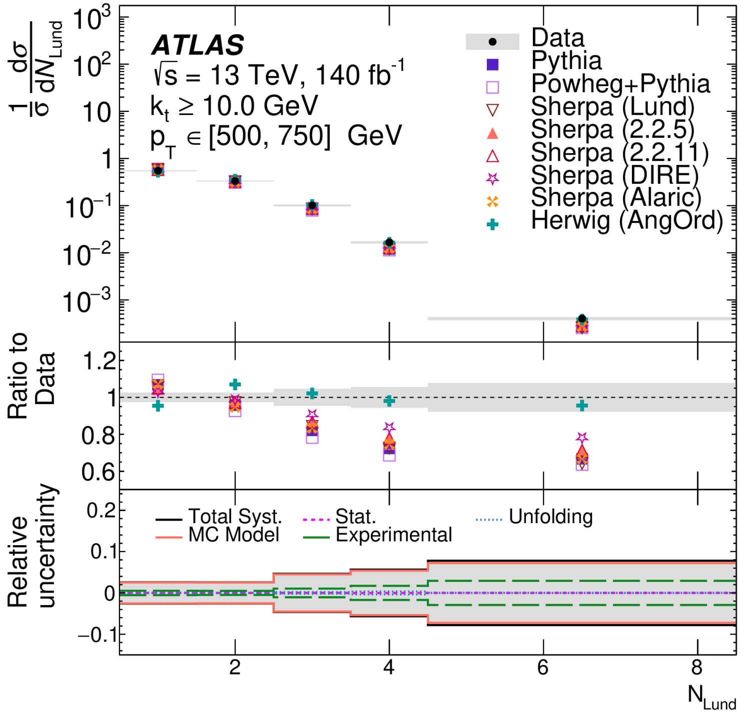


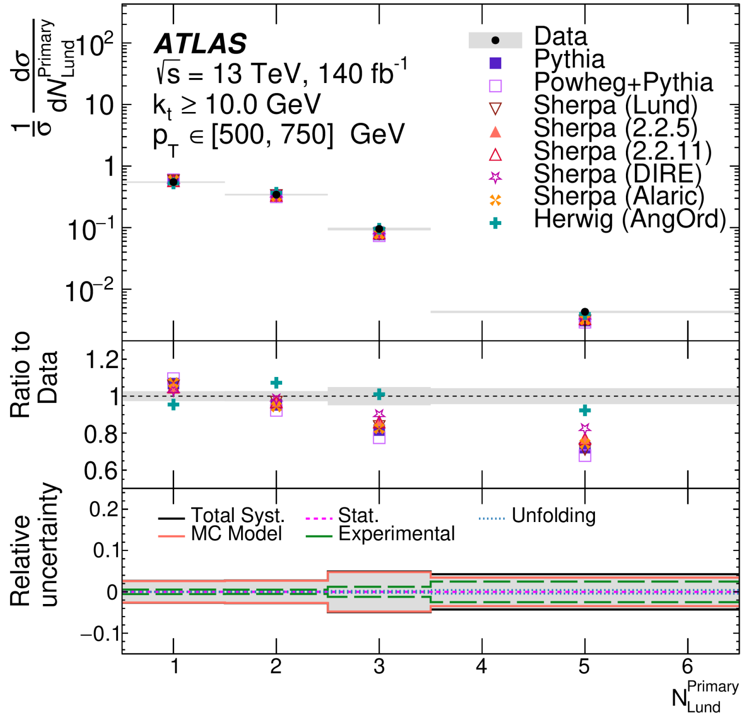


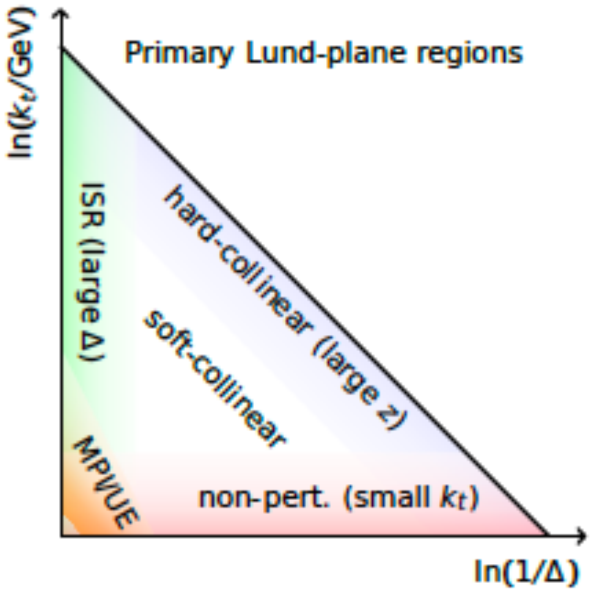
- Plane defined by k_t and ΔR
- $k_t = p_t^{emission} \Delta R(p_t^{core}, p_t^{emission})$
- Subjet multiplicity = number emissions with $k_t > k_t$-cut
- Subjet multiplicity has been measured for both primary and full Lund Jet Planes

- Light quark/gluon di-jets
  - $140 fb^{-1}$ at 13TeV
  - R=0.4 anti-kt jets reconstructed using particle flow objects
- Recluster tracks in R=0.4 jets using C/A to produce track-based jets
- Decluster jets using C/A algorithm by reversing the clustering to identify emissions – apply cut in k_t

Lund subjet multiplicities

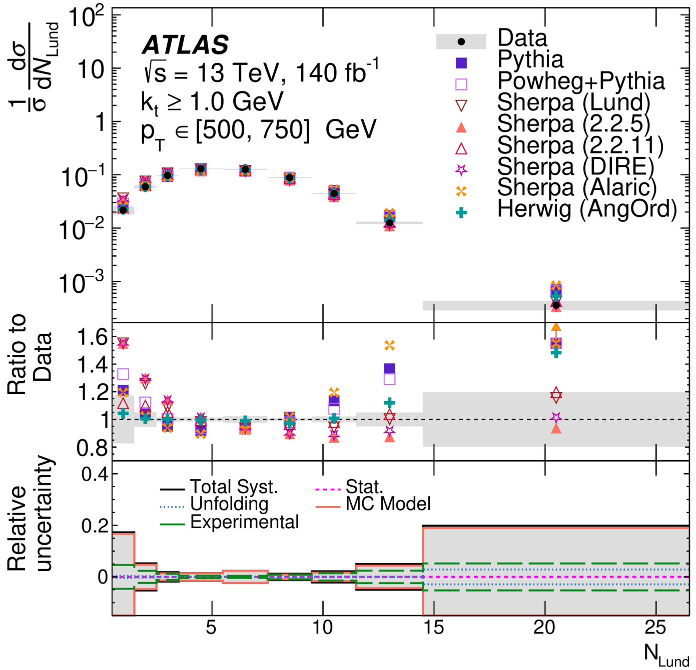


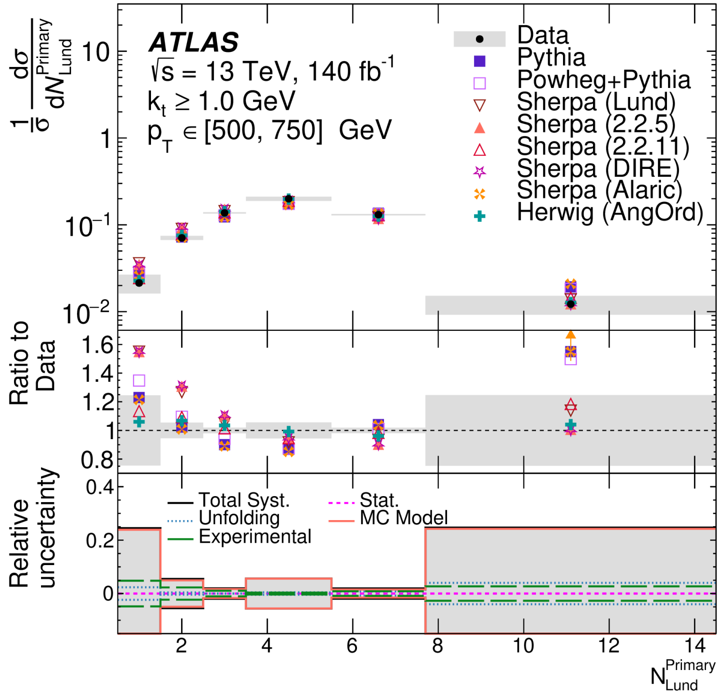


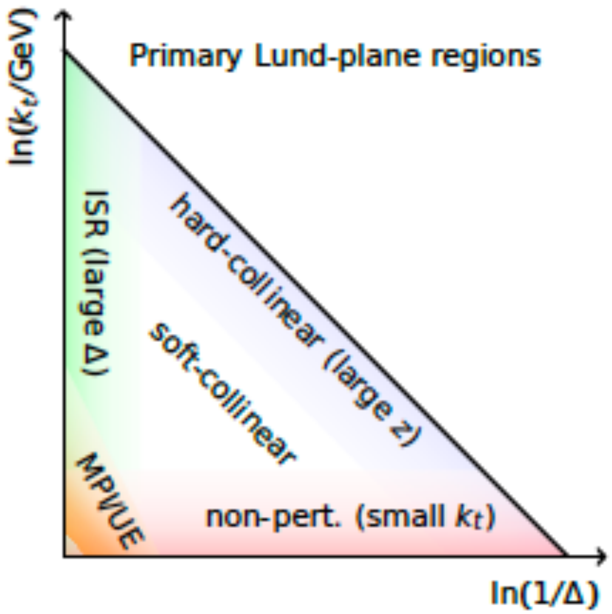


- For perturbative region k_t>10.0GeV the different PS show similar levels of agreement/disagreement for both the full Lund jet plane and the primary Lund jet plane
- Herwig with angular ordering gives the best agreement. Sherpa and Powheg+Pythia show increasing disagreement with increasing multiplicity for both the full LJP and primary LJP

Lund subjet multiplicities

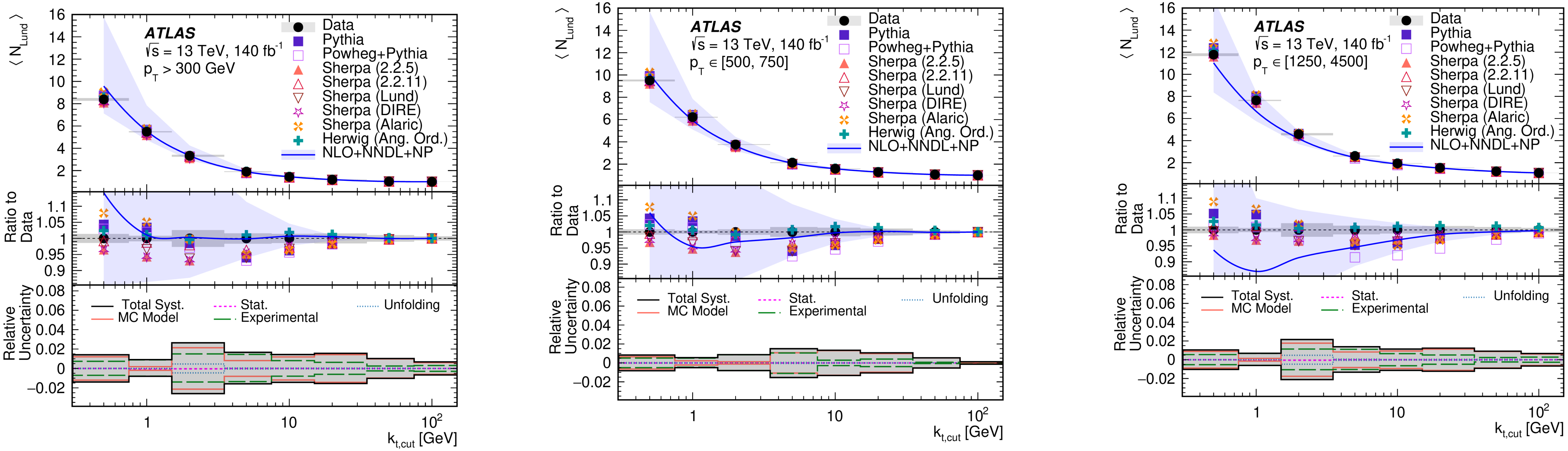






- k_t>1GeV sensitive to non-perturbative effects
- Overall Herwig angular ordered agrees well with data except for high multiplicity region in full LJP. Agrees well over the full multiplicity range for primary LJP
- Sherpa (2.2.5 & DIRE) agrees better at high multiplicity in the full LJP and primary LJP

Lund subjet multiplicities



- Comparison to NLO matched to NNLL resummation (R. Medves, A. Soto-Ontoso and G. Soyez)
- Non-perturbative added using (hadron level+MPI)/(PS without MPI), introduces a large error at low k_t
- Agreement of central value with data is good in the low multiplicity region for low pt jets, comparable to MCs
- Agreement is less good for higher pt jets but within uncertainties, and competitive with MCs.
- For small k_t agreement is poor but it is within theoretical error.

Conclusions

- Measurements of jet substructure using the Lund Jet Plane can discriminate between different ME-matching, parton shower and hadronization models in MCs

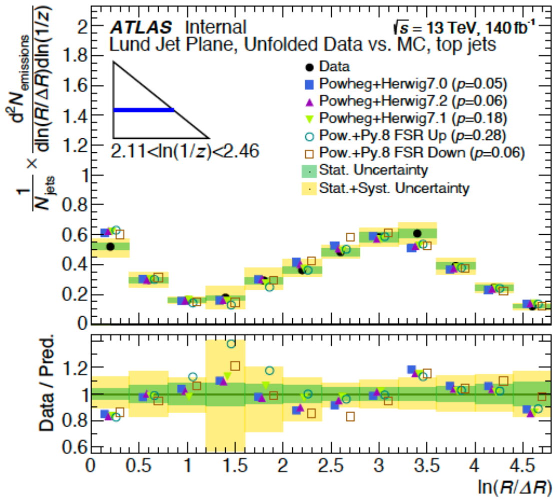
- Measurements of Primary Lund Jet Plane in light quark/gluon, W and t-jets show the expected structure of parton showers and heavy particle decays
- Level of agreement and disagreement between data and different MCs varies both globally and in different regions of the Lund Jet plane

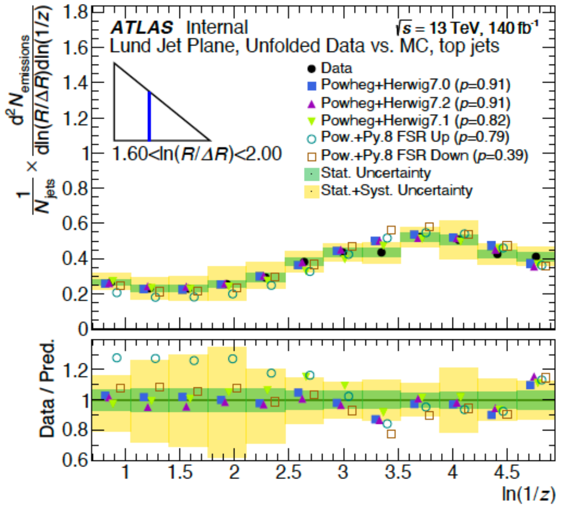
- Measurements of Lund subjet multiplicities show similar levels of agreement/disagreement between data and different MCs in both the full and primary Lund Jet Planes
- Lund subjet multiplicities can be described by NLO matched to NNLL resummation in perturbative regions

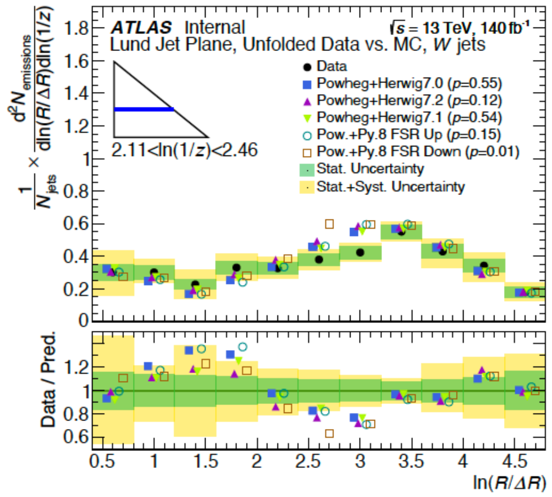
- Lund jet plane analysis has been used with graph neural networks to develop new taggers for W/top or q/g jet tagging PHYS-PUB-2023-017.

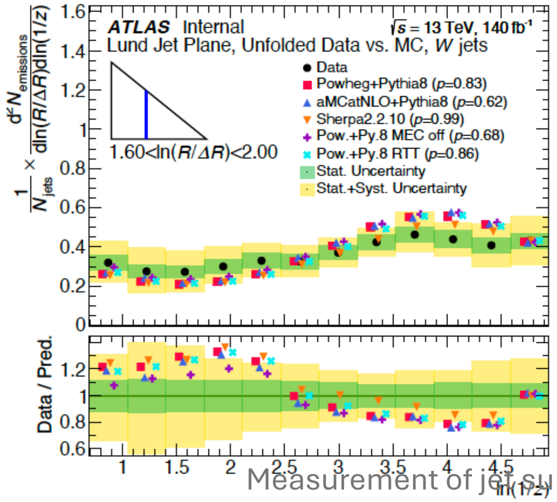
Backup/notes

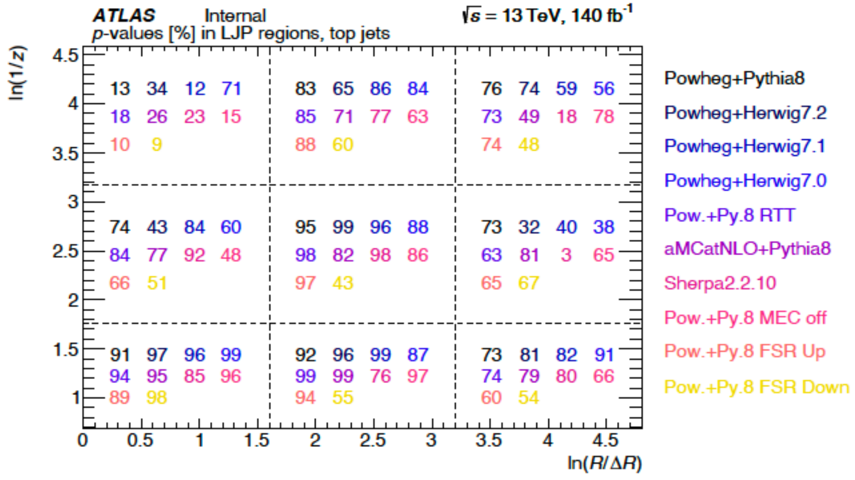
Lund Jet Plane in light quark/gluon, W and top jets











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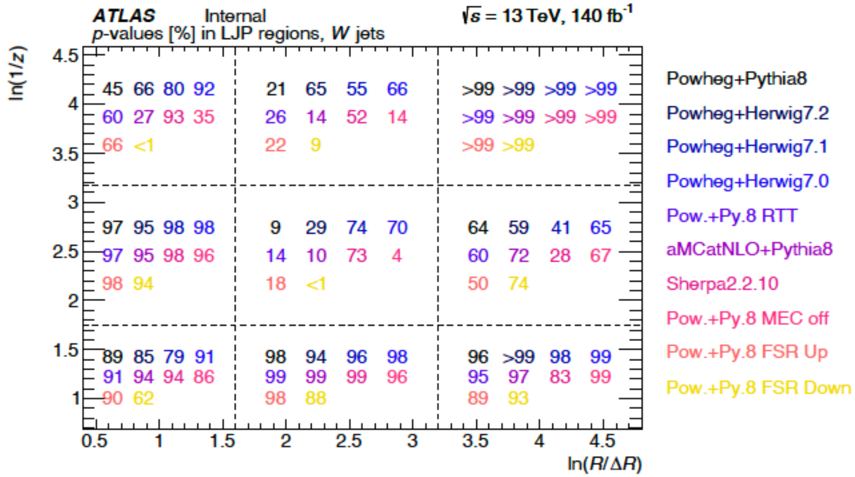

(b)