QCD Measurements with ATLAS

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Rencontres de Blois - 22.10.2024

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ATLAS EXPERIMENT

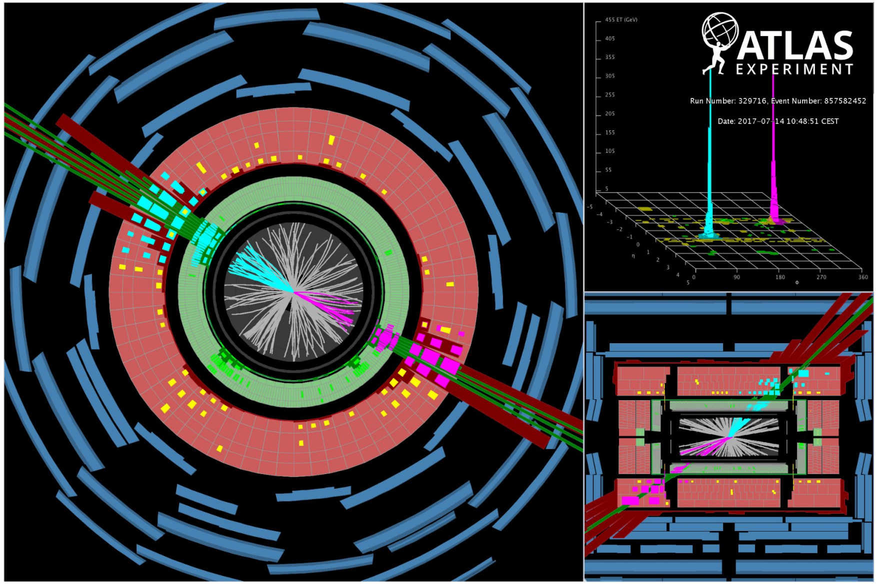
DESY.

Introduction

ATLAS: general purpose LHC experiment capable of measuring a broad range of physics processes

Many open questions in QCD!

- Jet formation
- Hadronisation
- Colour confinement
- Non-perturbative effects
- etc.



Outline

Many recent, interesting measurement released by ATLAS!

1. Measurement of jet cross-section ratios in 13 TeV pp collisions
2. Measurement of jet track functions
3. Lund jet plane in hadronic decays of top quarks and *W* bosons
4. Lund subjet multiplicities
5. Underlying-event studies with strange hadrons in pp collisions

Jet cross section ratios

arXiv:2405.20206 $\sqrt{s}$ = 13 TeV, 140 fb^{-1}

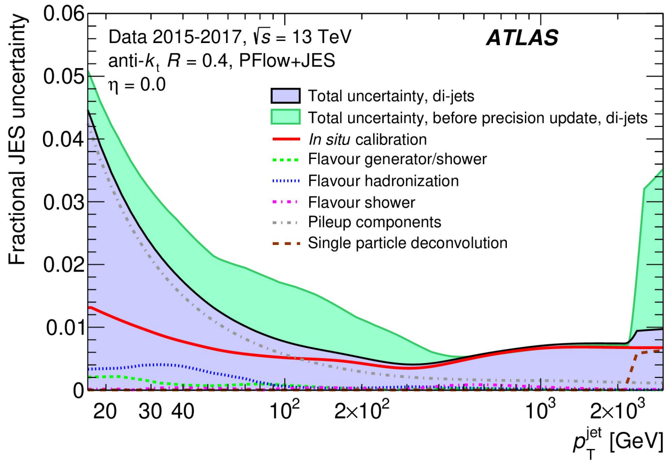
- ➔ Measure observables sensitive to energy-scale and angular distribution of QCD final-state radiation
- ➔ Aim to gather data to improve modelling of QCD processes

Select multijet events with:

- Anti-k_t jet w/ p_T > 60 GeV
- $|y|$ < 4.5
- $N_{jets} \geq 2$
- H_{T2} > 250 GeV

Measure cross sections and ratios vs:

- $H_{T2} = p_{T,1} + p_{T,2}$
- p_T^{Nincl}
- Δy_{jj} & $\Delta y_{jj,max}$ (not shown)
- Δm_{jj} & $\Delta m_{jj,max}$ (not shown)



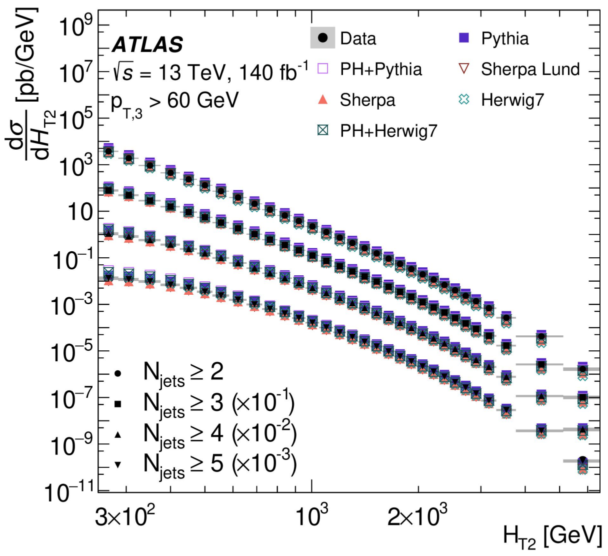
Analysis benefits from improved jet energy scale uncertainty due to flavor-specific treatment

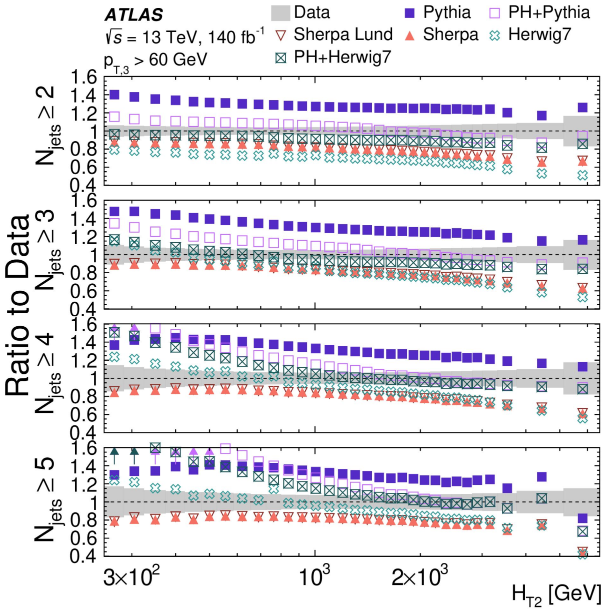
Eur. Phys. J. C (2023) 83:761

Results - H_{T2}

MC Predictions:

- Pythia 8.230 & A14 tune and Lund string hadronisation model
- Sherpa 2.2.5 with either AHADIC cluster hadronisation model or Lund string model
- Herwig 7.1.6 w/ default hadronisation model and either angular-ordered or dipole parton shower
- Powheg v2 and either Pythia8 or angular-ordered Herwig7 shower





No MC prediction is able to fully describe the data

Results - p_T^{Nincl}

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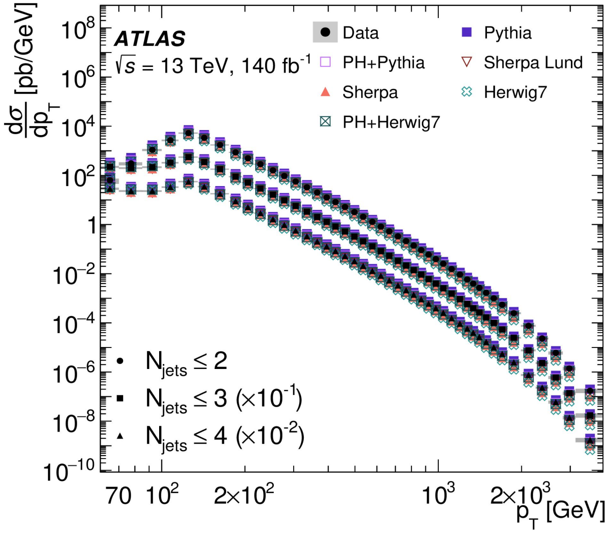
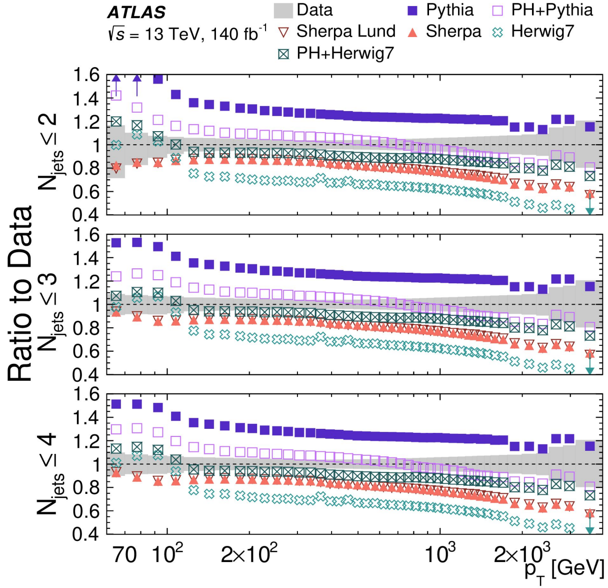




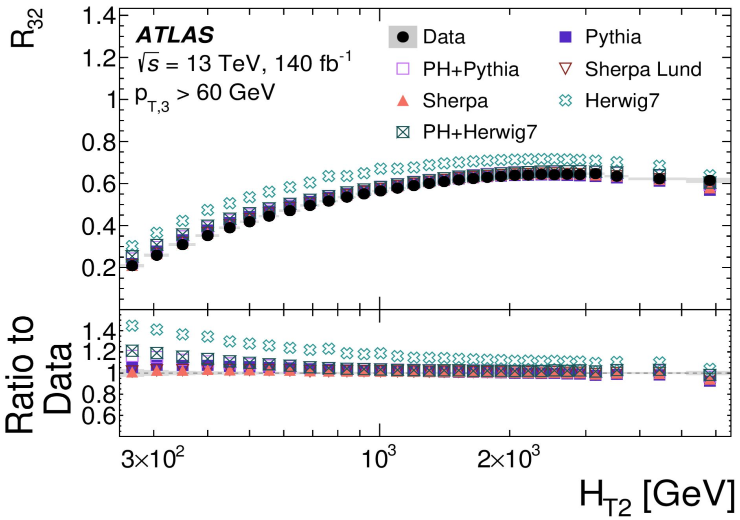
No MC prediction is able to fully describe the data

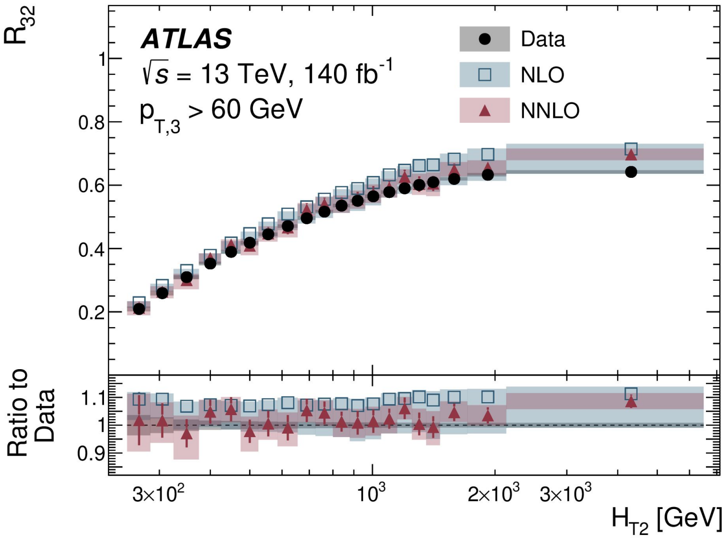
Results - R_{32}

Fixed Order Predictions:

- NLO – NLOJet++
- NNLO – AVHLIB, OpenLoops2, FivePointAmplitudes, PentagonFunctions++

$R_{32} = \sigma_{3jets} / \sigma_{2jets}$





Sherpa predictions agree with data, Herwig underestimates 2 jet cross section
NNLO prediction agrees with data, NLO prediction overestimates data

Jet track functions

ATLAS-CONF-2024-012 $\sqrt{s}$ = 13 TeV, 140 fb^{-1}

➔ Many jet substructure measurements rely on tracks due to finer resolution

➔ Measure r_q, p_T fraction carried by charged hadrons in jet to improve theoretical predictions of these track functions

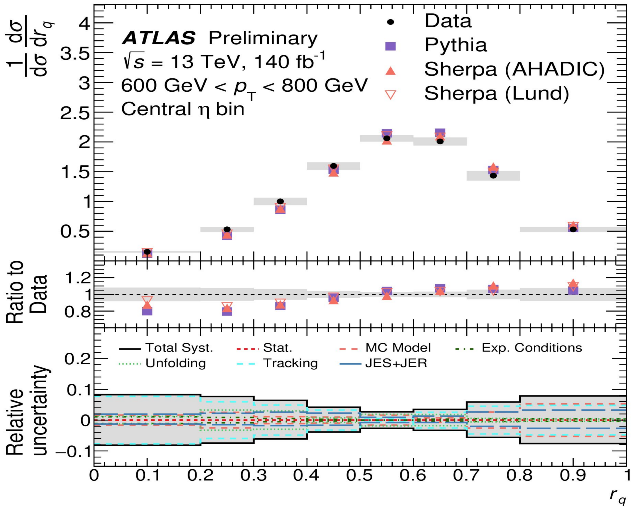
Selections:

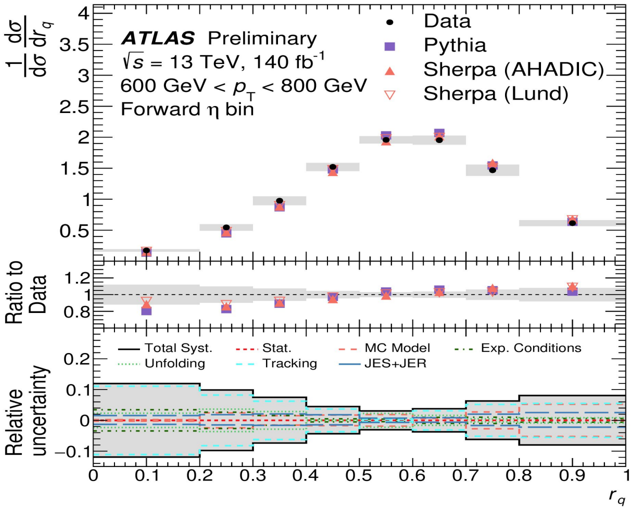
- Analyse two highest p_T anti-k_t jets with radius R = 0.4 in multijet events
- Jets must satisfy $|\eta| < 2.1$ and $p_T^{leading} > 240$ GeV
- Jets must be balanced $p_T^{leading} < 1.5 \times p_T^{subleading}$
- Select tracks associated to jets with $p_T > 500$ MeV
- Measure r_q in forward and central regions

Jet track functions – Results

Uncertainties:

- Theory uncertainty dominated by jet fragmentation modelling (2-5%)
- Experimental JES uncertainty benefits from improved treatment of jet flavour response





Predictions tend to underestimate cross section at low values of r_q and overestimate it at high values of r_q

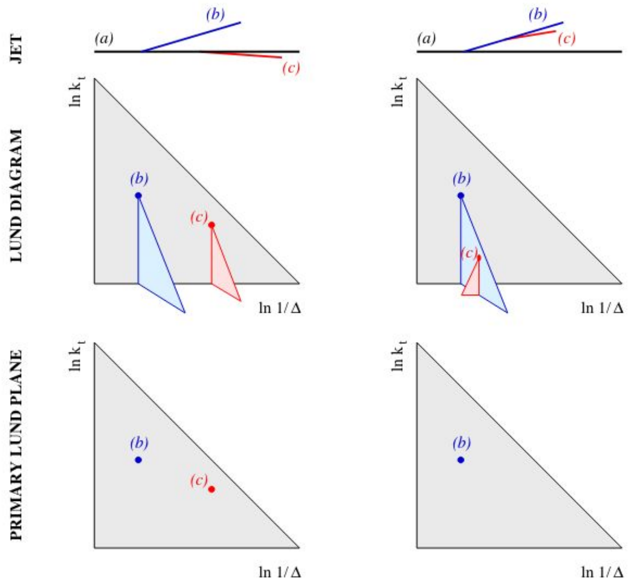
The Lund Jet Plane

- Re-cluster constituents of an anti-k_t jet with Cambridge-Aachen algorithm
- "De-cluster" the C/A jet following the hardest branch in each splitting
- Plot the coordinates ln(1/Δ) and ln(1/z) of the split branches on the coordinate plane

$$\Delta^2 = (y_a - y_b)^2 + (\phi_a - \phi_b)^2$$

$$z = p_T^j / (p_T^i + p_T^j)$$

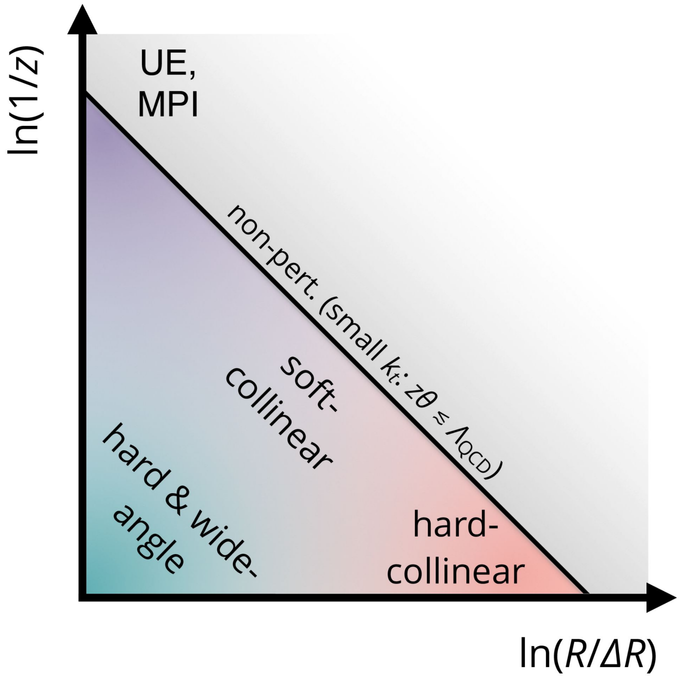
- Follow subsequent splittings to obtain secondary planes, tertiary planes, etc.



arXiv:1807.04758v2

Lund jet plane (cont.)

- Theoretical interest: Lund plane can be calculated **analytically!**
- Different kinematic regions easily identifiable
- Features of interest (jet mass, angle, momentum) readily available
- Allows characterisation of radiation pattern within jet
  - **Substructure**!



Phys. Rev. Lett. 124, 222002

Lund Jet Plane in top and *W* jets

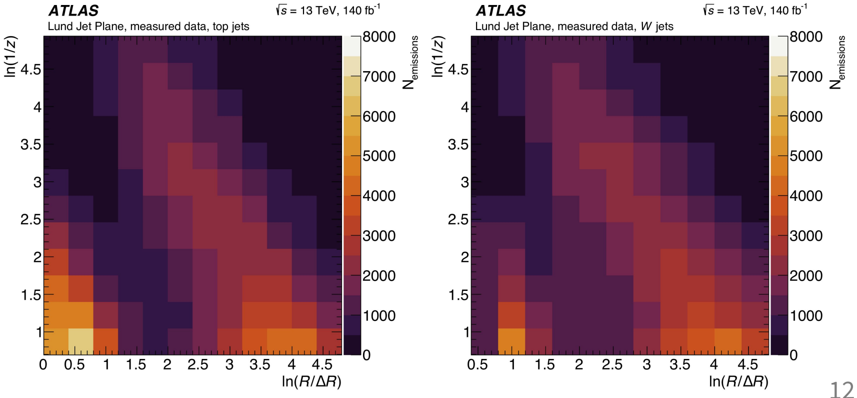
arXiv:2407.10879 $\sqrt{s}$ = 13 TeV, 140 fb^{-1}

➔ Study substructure of jets from hadronic decays of heavy flavour particles

Top jets:
- leading large-R jet mass m_J > 140 GeV
- presence of second b-tagged jet $j_{b,2}$ with $\Delta R(J, j_{b,1}) < 1.0$

***W* jets:**
- 60 GeV < m_J < 100 GeV

Selections:
- Exactly 1 electron or muon (ℓ)
- ≥1 anti-k_t b-tagged jets with radius R = 0.4 and $\Delta R(\ell, j_{b,1}) < 1.5$
- E_T^{miss} > 20 GeV & $E_T^{miss} + m^W_T$ > 60 GeV
- ≥1 anti-k_t jet with radius R = 1.0 (J) with $p_{T,J}$ > 350 GeV
- Distance between large-R jet and lepton $\Delta R(\ell, J) > 2.3$
- Leading large-R jet used to reconstruct Lund Plane
- Lund plane reconstructed with charged particles in jet with p_T > 500 MeV



Top W

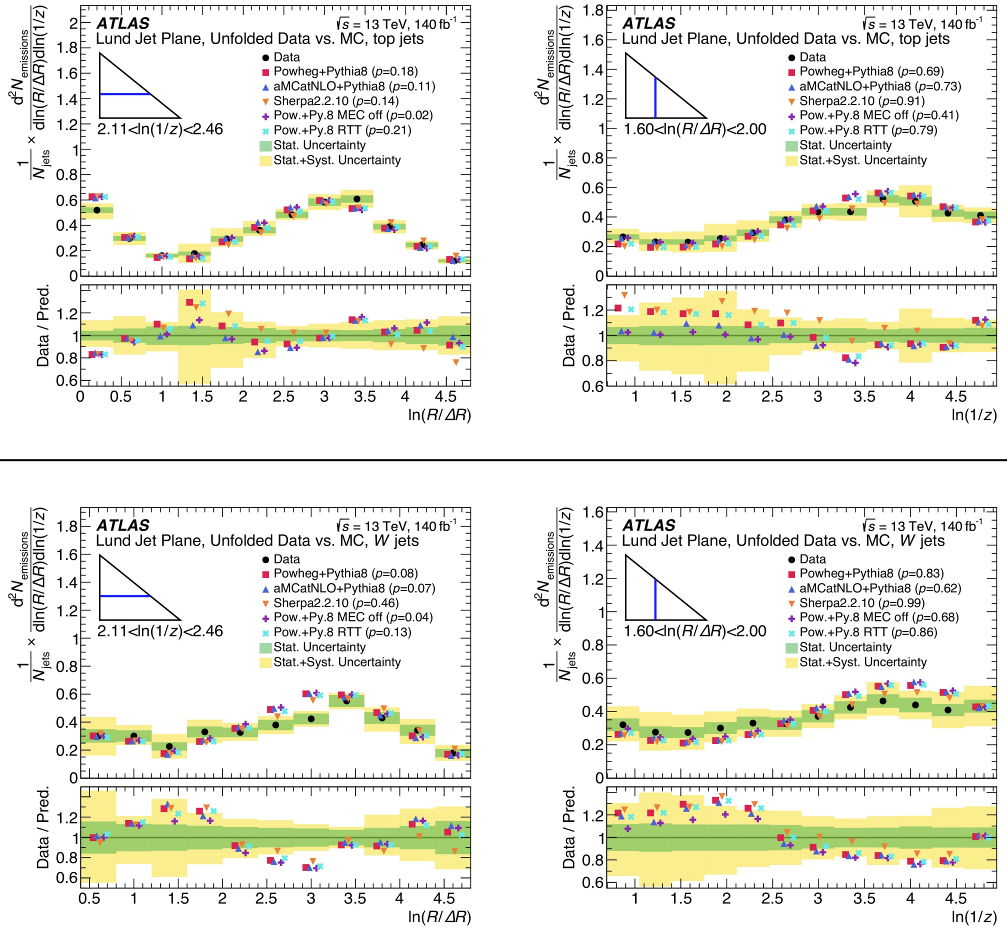
Results

Good agreement with MC predictions in most regions of Lund Plane

Some tension in central regions, particularly for *W* jets

MC predictions:

- Powheg + Pythia8
- MadGraph + Pythia8
- Sherpa 2.2.10
- Powheg + Pythia8 w/ ME corrections off
- Powheg + Pythia8 RTT w/ improved treatment of recoil from gluon emission



Top

W

Subjet multiplicities in dijet events

arXiv:2402.13052 $\sqrt{s}$ = 13 TeV, 140 fb^{-1}

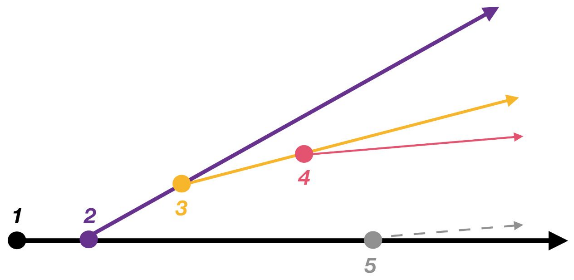
➔ Study subject multiplicity using Lund Plane formalism in dijet events

➔ Measure N_{Lund} (total no. of emissions) and $N_{\mathrm{Lund,\,primary}}$ (total no. of emissions in core of jet) as a function of k_t

Selections:

- Require R = 0.4 anti-k_t jets with p_T > 120 GeV and $|y| < 2.1$
- Jets must be balanced $p_T^{\mathrm{leading}} < 1.5 \times p_T^{\mathrm{subleading}}$
- Construct Lund plane from tracks with p_T > 500 MeV
- Account for neutral component by scaling k_t

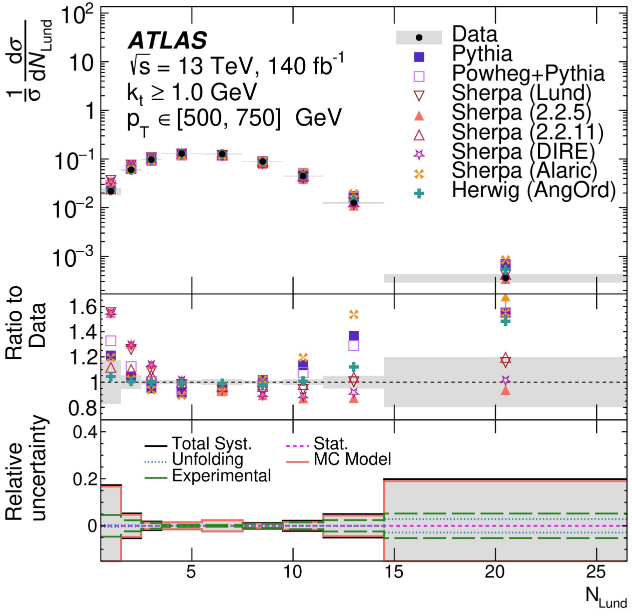
$$k_t = (p_T^{\mathrm{all}}/p_T^{\mathrm{charged}})k_t^{\mathrm{charged}}$$

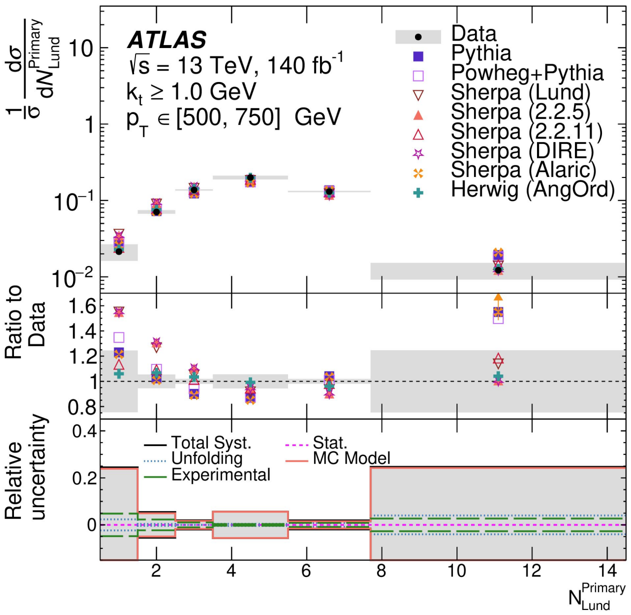


1: Core of jet
2: Primary Emission
3: Secondary emission off of 2
4: Tertiary emission off of 3
5: Primary emission

Subjet multiplicities - Results

Jet p_T 500-750 GeV
$k_t > 1.0$ GeV

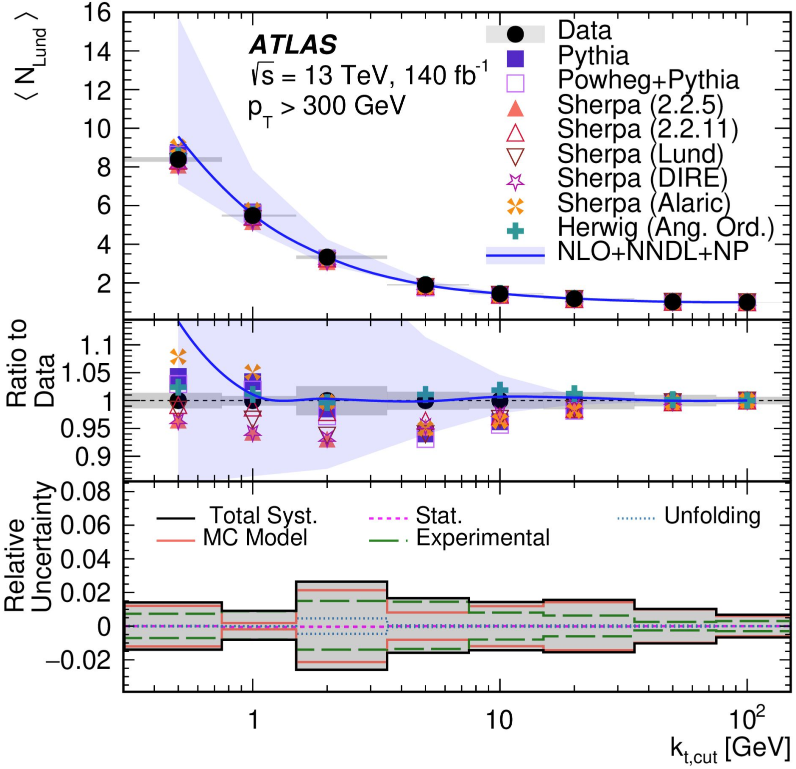




Most MC predictions fail to describe the data, especially at low and high values of multiplicities

Subjet multiplicities – Results

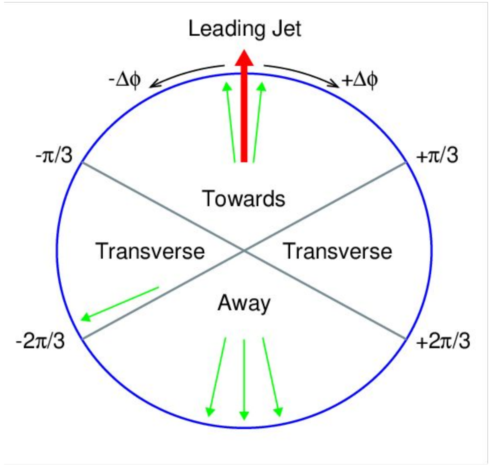
- Herwig angular shower gives best description of data
- Resummed analytic prediction agrees with data in perturbative ($k_t > 2$ GeV) regime
- Sherpa agreement improves when accounting for non-perturbative emissions



Strange hadron production

arXiv:2405.05048 $\sqrt{s}$ = 13 TeV, June 2015

- ➔ Phenomena such as hadronisation and multi-parton interactions (MPI) not well-modelled nor understood
- ➔ Data is needed to tune MC predictions



highest p_T anti-k_t jet with R = 0.4 and |η| < 2.1

Measure K^0_S and $(\Lambda + \bar{\Lambda})$ production and ratios in **towards**, **transverse** and **away** regions

Consider decays:

$$\Lambda \rightarrow \pi^{\mp} p^{\pm}$$

$$K^0_S \rightarrow \pi^+ \pi^-$$

Measurement carried out in **minimum bias** conditions with **ultra-low pileup** pp data

Towards: region sensitive to hard scattering

Transverse: region sensitive to MPI and hadronisation effects

Away: region containing most hadronic recoil

Strange hadron production

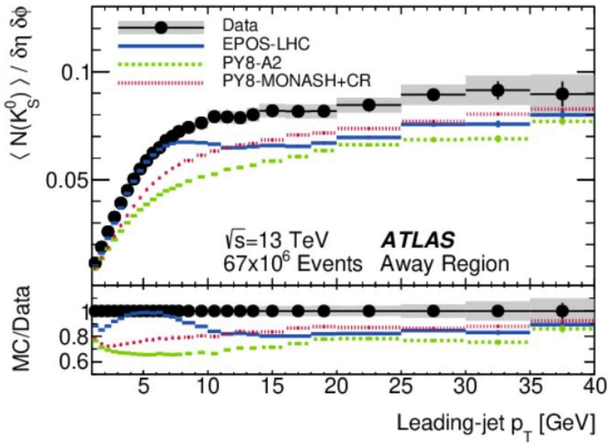
- ➔ Plot multiplicity of hadrons as function of leading jet p_T and no. of charged particles in the transverse region $N_{ch,trans}$
- ➔ Results show **two distinct regimes**
  - *Soft regime* — Jet p_T < 10 GeV
    - Characterised by monotonic rise of distribution
  - *Hard regime* — Jet p_T > 10 GeV
    - Characterised by constant slope or smaller slope
- ➔ Transition is evident only when multiplicities are plotted as function of jet p_T

MC predictions:

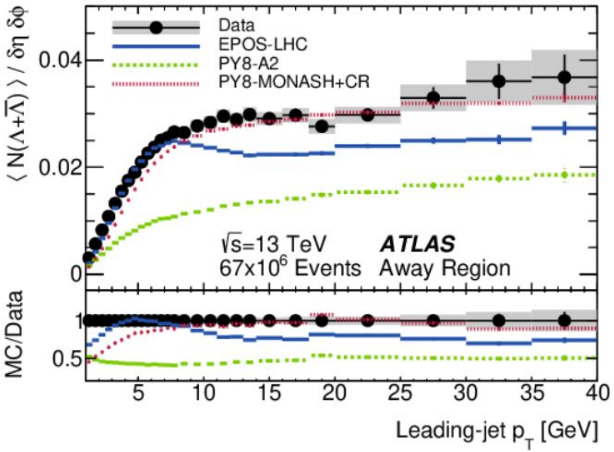
- EPOS-LHC — designed for minimum bias heavy-ion collisions and cosmic ray showers
  - Features hydrondynamic collective-flow approach to hadronisation
- Pythia8 A2 – Standard Pythia with ATLAS tune
- Pythia8 Monash + CR (colour reconnection)

Strange hadron production

per event normalisation

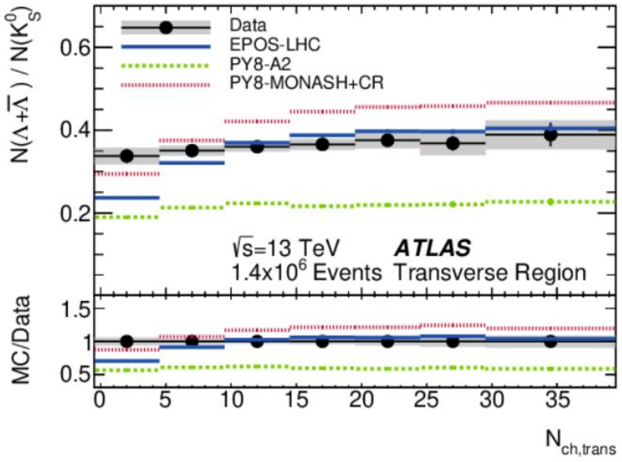


per event normalisation



Relative yield of Λ/K

Leading jet p_T range 10-40 GeV



- **No model can successfully describe the data over full kinematic range**
- **EPOS modelling better in soft regime**
- **Pythia8 modelling better in hard regime, but yields underestimated by up to 50%**

Conclusions

- **Many interesting QCD results from ATLAS**
- **Measurements can improve MC modelling of fundamental processes such as underlying events and hadronisation**
- **Improved treatment of jet energy scale leads to reduced uncertainties**
- **Much more data on the way!**

Backup