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QCD Measurements with the ATLAS Experiment

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The ATLAS experiment has performed a range of QCD measurements in final states with jets. Jet cross-section ratios between inclusive bins of jet multiplicity are measured differentially in variables that are sensitive to either the energy-scale or angular distribution of hadronic energy flow in the final state. Using charged particles inside jets, the Lund plane is reconstructed and measured in top quark pair production, separately for jets from hadronic decays of the W boson and for b-quark jets. A differential measurement of the subjet multiplicities in dijet events and a measurement of non-perturbative jet track functions are presented. Finally, properties of the underlying-event are studied in events with strange hadrons reconstructed in minimum-bias collisions data, and used to construct underlying-event observables in azimuthal regions computed relative to the leading charged-particle jet in the event.

1 Introduction

In these proceedings, a number of measurements related to Quantum ChromoDynamics (QCD) recently published by the ATLAS Collaboration [1] are presented. These include: a measurement of jet cross-section ratios [2], a measurement of strange hadron production aimed at characterising the underlying event [3], measurements of the Lund Jet Plane (LJP) in W and top jets [4] and of the Lund subjet multiplicity in inclusive jets [5], and lastly a measurement of jet track functions [6].

2 Jet cross section ratios

The ATLAS Collaboration has presented a differential measurement of jet production cross sections for various jet multiplicities and their respective ratios. The analysis focuses on inclusive multijet production, considering final states containing anti-k_t jets of radius R = 0.4 with $p_{\mathrm{T}} > 60$ GeV and rapidity $|y| < 4.5$. Events are also required to have $N_{\mathrm{jets}} \geq 2$, with scalar p_{T} sum of the leading jet pair $H_{\mathrm{T2}} \geq 250$ GeV. The cross sections are measured with respect to several observables: H_{T2} and the p_{T} of the first N jets $p_{\mathrm{T}}^{\mathrm{Ninc}}$, chosen for their sensitivity to fixed order effects. Additionally, observables which favour configurations with large logarithmic corrections, such as the rapidity difference of the two leading jets (y_{jj}) and the invariant mass of the leading jet pair (m_{jj}) are measured.

Figure 1 shows the 3-jet to 2-jet cross-section ratio obtained from data, as a function of H_{T2} for events containing at least 3 jets where the p_{T} of the third jet $p_{\mathrm{T3}} > 60$ GeV, and predictions obtained from various Monte Carlo (MC) generators and fixed-order next-to-leading order (NLO) and next-to-next-to leading order (NNLO) calculations. Predictions are obtained with Pythia 8.230 [7] with the A14 tune [8] and Lund string hadronisation model [9] (Pythia), Herwig 7.1.6 [10] with

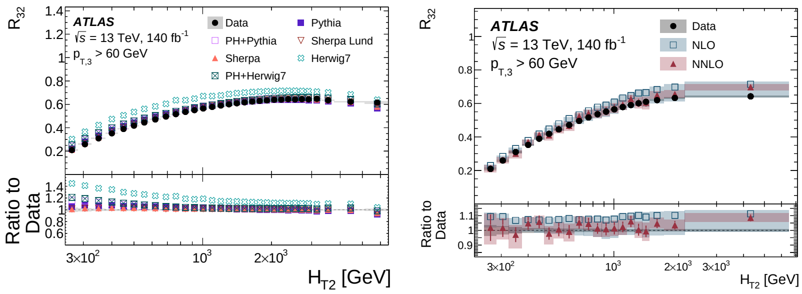

Figure 1 – The ratio R_{32} compared to predictions obtained with several different MC generators (left) and to fixed-order calculations (right). [2]

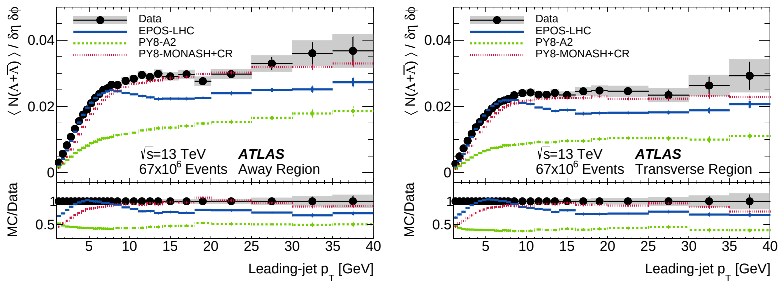

Figure 2 – Yields for $(\Lambda + \bar{\Lambda})$ production in the away region (left) and the transverse region (right) and relative MC predictions normalised per event. [3]

the cluster hadronisation model and angular-ordered parton shower (Herwig7), two Powheg v2 samples with either the Pythia dipole parton shower (PH+Pythia) or the Herwig angular-ordered parton shower [11] [12] (PH+Herwig7), and two different Sherpa 2.2.5 [13] samples with either the AHADIC cluster hadronisation model [14] (Sherpa) or the Lund string hadronisation model (Sherpa Lund). The two Sherpa samples are those which best agree with data. NNLO calculations also show better agreement to data with respect to NLO calculations.

3 Underlying-event studies with strange hadrons

To better understand non-perturbative processes such as multiparton interactions (MPI) and hadronisation, ATLAS has carried out a measurement of strange hadron production in minimum bias [15] and ultra-low pileup proton-proton data. Events are required to have at least one track with $p_{\mathrm{T}} > 1$ GeV, a reconstructed primary vertex with at lesat two tracks with $p_{\mathrm{T}} > 100$ MeV and at least one anti-k_t jet of radius R = 0.4 and pseudorapidity $|\eta| < 2.1$. Events are classified into three regions, defined based on the leading jet axis: a towards region with angle $2\pi/3$ around the jet axis, which includes most of the hard scattering, an away region of the same angle at π radians opposite the jet, containing most of the hadronic recoil, and lastly a transverse region in between, most sensitive to to hadronisation effects associated with MPI, as it is the region least contaminated by the hard scattering.

Strange hadrons $(K^0_S, \Lambda, \bar{\Lambda})$ are reconstructed through the identification of their decay vertex. Their multiplicity is measured in each of the three aforementioned regions, as a function of either the leading jet p_{T} or the number of charged particles in the transverse region $N_{\mathrm{ch,trans}}$. No distinction is made between Λ and $\bar{\Lambda}$. Multiplicity ratios are also constructed.

Figure 2 shows the measured $(\Lambda + \bar{\Lambda})$ multiplicities in the away and transverse regions and predictions for the same obtained with EPOS-LHC [16], Pythia8 with the A2 tune [17], and Pythia8 with Monash tune and an improved colour-reconnection (CR) model [18]. In the soft regime, for leading jets with $p_{\mathrm{T}} < 10$ GeV, EPOS-LHC provides predictions which best describe the data. At higher values of jet p_{T}, Pythia8 predictions with Monash+CR tune, better model the data, though these fail to describe the correct yield. When considering all yields in all regions, no generator can describe the data across the full p_{T} spectrum.

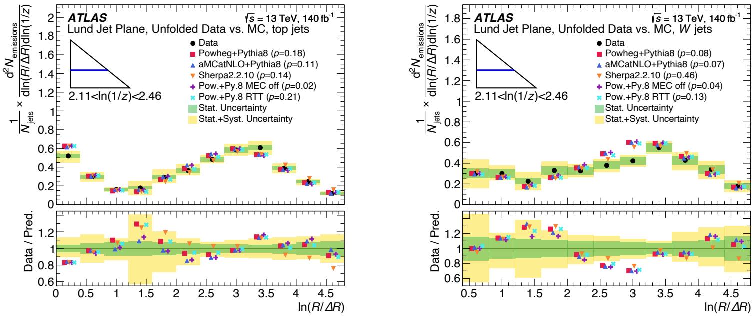

Figure 3 – Slices of the LJP for top jets (left) and W jets (right) as a function of $\ln(R/\Delta R)$ for values of $2.11 < \ln(1/z) < 2.46$. [4]

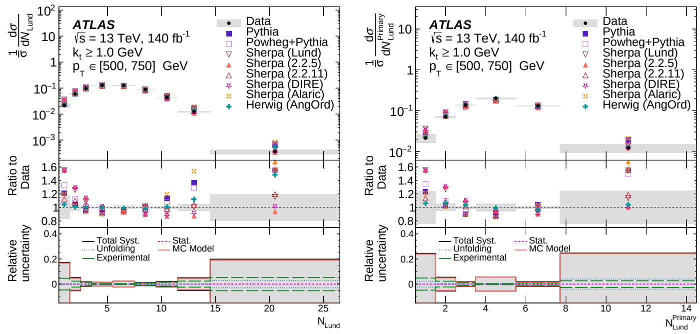

Figure 4 – Subjet multiplicity as measured in the full LJP (left) and restricted to just the primary LJP (right). [5]

4 Lund Jet Plane studies

The LJP is an interesting observable as it provides insight into the jet formation process [19]. The ATLAS Collaboration has presented three measurements involving this observable.

The first measurement focuses on the LJP measured in large-R jets of radius R = 1.0 in top and W jets in $t\bar{t}$ events. Appropriate selections to identify $t\bar{t}$ events are applied, such as requiring the presence of a lepton (ℓ) and a b-tagged jet of radius R = 0.4 within $\Delta R < 1.5$ from said lepton. Top jets are subsequently differentiated from W jets via selections on the jet mass and the presence of a second b-tagged jets of radius R = 0.4 within the large-R jet. The LJP is then constructed by matching tracks of $p_{\mathrm{T}} > 500$ MeV to the jet.

The data are compared to predictions made by MadGraph5_aMC@NLO [20] + Pythia8, a nominal Powheg + Pythia8 sample, alternative samples of the same generator in which matrix error corrections (MEC) are switched off and a third with an improved treatment of recoil from gluon emission (RTT) [21], and lastly a Sherpa 2.2.10 sample.The MC predictions agree well with the data in most regions of LJP, some tension in central regions, particularly for W jets, as shown in Figure 3.

ATLAS also presented a measurement of the LJP subjet multiplicities, for both the primary LJP ($N_{\mathrm{Lund}}^{\mathrm{Primary}}$), considering only emissions off of the core of the jet, and in the full clustering history (N_{Lund}). The measurement was carried out on dijet events, on jets with radius $R = 0.4$, $p_{\mathrm{T}} > 120$ GeV, and $|\eta| < 2.1$. To favour $2 \to 2$ scattering processes, jets in the events are required to be balanced, i.e. $p_{\mathrm{T}}^{\mathrm{leading}} < 1.5 \times p_{\mathrm{T}}^{\mathrm{subleading}}$. The LJP for each jet is once again constructed with tracks with $p_{\mathrm{T}} > 500$ MeV. The results of the measurement are binned in different ranges of jet p_{T} obtained by varying the k_t cut applied, where k_t indicates the relative p_{T} of an emitted subjet with respect to its emitter. Figure 4 shows the number of emissions in primary LJP and in the full jet tree and predictions for this observable for jets with $p_{\mathrm{T}} \in [500, 750]$ GeV and with $k_t > 1.0$. No MC generator is capable of fully describing the data, especially at low and high values of multiplicities.

The LJP measurements discussed above reconstruct the observable from charged tracks matched to the jet, due to the higher resolution of the ATLAS inner tracker compared to the hadronic

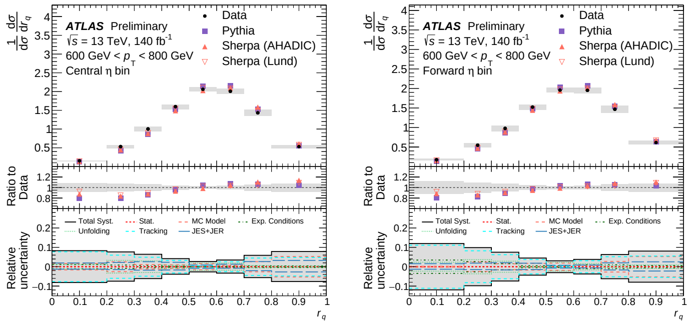

Figure 5 – The dijet production cross section as a function of r_q in the central (left) and forward (right) bins and predictions to the same cross section obtained from MC generators. [6]

calorimeter. For this reason, it is crucial to have precise knowledge of the fraction of momentum of a jet carried by charged particles r_q. It is known that the first moment $\langle r_q \rangle = 2/3$, but this constitutes the first measurement of higher moments.

ATLAS has measured the value of r_q in dijet events, where the jets must be balanced, of radius $\mathrm{R} = 0.4$, $|\eta| < 2.1$ and the leading jet must have $p_\mathrm{T} > 240$ GeV. The charged component of the jet is identified by matching tracks with $p_\mathrm{T} > 500$ MeV to the jets.

Figure 5 shows the differential dijet cross section as a function of r_q in central and forward regions. This is an event-based classification, where the two jets in each event are allotted into separate bins based on the most appropriate allocation. MC predictions are obtained with Pythia8 and Sherpa 2.2.5 with the AHADIC or Lund string hadronisation models. Predictions tend to underestimate the cross section at low values of r_q, though agree with data within uncertainties.

5 Conclusions

State-of-the-art results from the ATLAS Experiment describing recent QCD measurements are presented. Several discrepancies with theoretical predictions are present, especially pertaining to modelling of strange hadron production and features of the LJP. These measurements will thus aid in the improvement of MC generators and the further understanding of QCD processes.

References

1. ATLAS Collaboration. The ATLAS Experiment at the CERN Large Hadron Collider. *JINST*, 3:S08003, 2008.
2. ATLAS Collaboration. Measurements of jet cross-section ratios in 13 TeV proton-proton collisions with ATLAS. *Phys. Rev. D*, 110:072019, Oct 2024.
3. ATLAS Collaboration. Underlying-event studies with strange hadrons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. *arXiv:2405.05048*, 2024.
4. ATLAS Collaboration. Measurement of the Lund jet plane in hadronic decays of top quarks and w bosons with the ATLAS detector. *arXiv:2407.10879*, 2024.
5. ATLAS Collaboration. Measurements of Lund subjet multiplicities in 13 tev proton-proton collisions with the atlas detector. *Physics Letters B*, 859:139090, 2024.
6. ATLAS Collaboration. Measurement of Track Functions in ATLAS Run 2 Data. Technical Report ATLAS-CONF-2024-012, CERN, Geneva, 2024. https://cds.cern.ch/record/2905858.
7. T. Sjöstrand et al. An introduction to PYTHIA 8.2. *Comput. Phys. Commun.*, 191:159–177, 2015.
8. ATLAS Collaboration. ATLAS Pythia 8 tunes to 7 TeV data. Technical Report ATL-PHYS-PUB-2014-021, CERN, Geneva, 2014. https://cds.cern.ch/record/1966419.
9. B. Andersson et al. Parton fragmentation and string dynamics. *Physics Reports*, 97(2):31–145, 1983.
10. J. Bellm et al. Herwig 7.1 release note, 2017.
11. S. Alioli et al. Jet pair production in POWHEG. *JHEP*, 04:081, 2011.
12. S. Alioli et al. A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX. *JHEP*, 06:043, 2010.
13. D. J. Lange. The EvtGen particle decay simulation package. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 462(1):152–155, 2001. BEAUTY2000, Proceedings of the 7th Int. Conf. on B-Physics at Hadron Machines.
14. B.R. Webber. A QCD model for jet fragmentation including soft gluon interference. *Nuclear Physics B*, 238(3):492–528, 1984.
15. ATLAS Collaboration. Performance of the Minimum Bias Trigger in p-p Collisions at Sqrt(S) = 7 TeV. Technical Report ATLAS-CONF-2010-068, CERN, 7 2010. https://cds.cern.ch/record/1281343.
16. T. Pierog and K. Werner. EPOS model and ultra high energy cosmic rays. *Nuclear Physics B - Proceedings Supplements*, 196:102–105, 2009. Proceedings of the XV International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI 2008).
17. ATLAS Collaboration. Further ATLAS tunes of PYTHIA6 and Pythia 8. Technical Report ATL-PHYS-PUB-2011-014, CERN, Geneva, 2011. https://cds.cern.ch/record/1400677.
18. J.R. Christiansen and P.Z. Skands. String formation beyond leading colour. *Journal of High Energy Physics*, 2015:3, August 2015.
19. F.A. Dreyer, G.P. Salam, and G. Soyez. The Lund Jet Plane. *JHEP*, 12:064, 2018.
20. J. Alwall et al. The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. *JHEP*, 07:079, 2014.
21. H. Brooks and P. Skands. Coherent showers in decays of colored resonances. *Phys. Rev. D*, 100(7):076006, 2019.