Probing perturbative QCD at the ATLAS experiment

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Abstract

ATLAS recent results obtained at the LHC on inclusive jet and dijet production at $\sqrt{s} = 13$ TeV, on transverse energy-energy correlations and on azimuthal decorrelations at $\sqrt{s} = 8$ TeV are discussed. The latter two are used to determine the strong coupling constant and to probe its running up to scales of order 2 TeV.

Keywords: Jets, LHC, ATLAS, QCD, TEEC, ATEEC, azimuthal decorrelations, running strong coupling constant

1. Inclusive jet and dijet production

At the LHC, ATLAS [1] has recently measured inclusive jet and dijet production at 13 TeV [2]. Jets in the hadronic final states have been reconstructed with the anti- k_T algorithm with $R = 0.4$.

Figure 1: Illustrative example for transfer matrices used in unfolding of dijet cross-sections [2].

The production cross sections for inclusive jets in the kinematic region $100 \text{ GeV} < p_T < 3.5 \text{ TeV}$ and $|y| < 3.0$ have been obtained using single jet triggers with varying thresholds between 55 GeV and 360 GeV. The production cross sections for dijets in the kinematic domain

$300 \text{ GeV} < m_{ij} < 9 \text{ TeV}$, $y^* < 3.0$ and $H_{T2} > 200 \text{ GeV}$ have been obtained using pairing of jet triggers. Here m_{ij} denotes the mass of jets i and j , y^* is defined as usual as $y^* = |y_1 - y_2|/2$ and H_{T2} denotes the scalar sum of the transverse momenta of the two leading jets. Both data sets are unfolded for detector effects using transfer matrices as shown in Fig. 1. Electroweak and non perturbative corrections are also applied. The dominant experimental systematic effects are those due to jet the energy scale (JES) [3]. They are moderate, 5 – 10%, except for the p_T or m_{ij} tails. The dominant theoretical systematic uncertainties are due to the choice of the renormalization and factorization scale. They are also found to be at the few percent level unless you approach the high end kinematical limits in transverse momentum or dijet mass. The unfolded data are shown in Fig. 2.

Fair agreement between data for inclusive jet production and NLO pQCD predictions is found in individual bins with p-values in the percent range. Some tension appears when considering all data points across p_T and rapidity. This calls for a good understanding of the correlations between experimental and theoretical systematic uncertainties. This is thoroughly discussed in [4]. The p-values are now smaller than 10^{-3} . No significant differences between the inclusive jet cross-sections and the NNLO calculations [5] are observed when using p_T^{jet} as the renormalization scale. When using p_T^{max} the NNLO calculations tend to overestimate the data.

Figure 2: Unfolded data for inclusive jet and dijet production along with comparisons to NLO predictions [2].

For the dijet production, fair agreement is observed between data and NLO pQCD predictions. The p-values for individual bins are typically larger than 50% and 5 – 10% for a global fit.

2. Measurement of transverse energy-energy correlations

Transverse energy-energy correlation (TEEC) are defined as the weighted average of azimuthal differences between jet pairs [6] i.e.:

$$\frac{1}{\sigma'} \frac{d\Sigma'}{d\phi} = \frac{\int_{E_T^{\min}}^{\sqrt{s}} dE_T d^2\Sigma(E_T, \eta)/dE_T d\phi}{\int_{E_T^{\min}}^{\sqrt{s}} dE_T d^2\sigma(E_T, \eta)/dE_T d\phi} \quad (1)$$

In practical terms, for a sample of N multijet events:

$$\frac{1}{\sigma'} \frac{d\Sigma'}{d\phi} = \frac{1}{N} \sum_{A=1}^N \frac{1}{\Delta\phi} \sum_{\text{pairs} \sin\Delta\phi} \frac{2E_{T_a}^A E_{T_b}^A}{(E_T^A)^2} \quad (2)$$

NLO corrections have been recently calculated [7] using the NLOJET++ code [8]. They have been found to be moderate, with PDF uncertainties also well under control, thus making this observable suitable for a precise test of pQCD and for a determination of the strong coupling constant. Recent measurements of transverse energy energy correlations (TEEC) have been published by the ATLAS Collaboration at 8 TeV [9]. The analysis represents an extension of previous measurements at 7 TeV [10]. The selection criteria require at least two anti- k_T jets ($R=0.4$) such that $H_{T2} = p_{T1} + p_{T2} \geq 800$ GeV with the transverse momenta of any additional jet above 100 GeV. To ensure that jet reconstruction is optimal, jets are required to be central with $|\eta_{jet}| \leq 2.5$. In the 2012 data sample used in this analysis the total number of selected events is 6.2×10^6 . The data is further binned in six intervals in H_{T2} , the first one between 800-850 GeV and the last one above 1400 GeV.

The data are corrected for detector effects using either a bin-by-bin correction or a Bayesian unfolding. For the latter, the transfer matrices for the last bin in H_{T2} are shown in Fig. 3

Figure 3: Illustrative example for transfer matrices used in unfolding of the TEEC [9].

The systematic uncertainties are dominated by the choice of the MC model used in the unfolding, modelling, and by the JES which include 67 independent sources. The total systematic uncertainty for the TEEC measurements are always below the 4 – 5% level.

The unfolded data is fitted to NLOJET++ predictions which are dependent on $\alpha_s(M_Z)$. The choice of renormalization and factorization scales is $\mu_R = H_{T2}/2$ with $\mu_F = \mu_R/2$. The theoretical uncertainties are dominated by the scale uncertainties, while those due to the PDF eigenvectors are subdominant.

The comparison between unfolded data for the TEEC and its associated forward-backward asymmetry (ATEEC) and theoretical predictions is fair as illustrated in Fig. 4 for the highest bin in H_{T2} namely $H_{T2} \geq 1400$ GeV.

Figure 4: Results of fitting the unfolded data on the TEEC (up) and its asymmetry (down) to NLOJET++ predictions [9].

The values for α_s obtained at scales $H_T/2$ from the TEEC and its asymmetry are shown in Fig. 5

Figure 5: The scale dependence of α_s values obtained from TEEC (up) and ATEEC (down) measurements [9].

They are in very good agreement with the renormalization group equation (RGE) dependence predicted in QCD. In fact, the goodness of this agreement has been used recently to put limits on new coloured fermions in a way which is independent of assumptions about their decay modes [11]. From a global fit to the complete data sample the following values for the strong coupling constant at the Z boson mass are obtained:

- $\alpha_s^{TEEC}(M_Z) = 0.1162 \pm 0.0011(exp)_{-0.0061}^{+0.0076}(scale) \pm 0.0018(PDF) \pm (0.0003)(NP)$
- $\alpha_s^{ATEEC}(M_Z) = 0.1196 \pm 0.0013(exp)_{-0.0013}^{+0.0061}(scale) \pm 0.0017(PDF) \pm (0.0004)(NP)$

3. Measurement of azimuthal decorrelations

The azimuthal decorrelations are defined [12]:

$$R_{\Delta\phi}(H_T, y^*, \Delta\phi_{max}) = \frac{\frac{d^2\sigma_{dijet}(\Delta\phi_{dijet} < \Delta\phi_{max})}{dH_T dy^*}}{\frac{d^2\sigma_{dijet}(inclusive)}{dH_T dy^*}} \quad (3)$$

as the fraction of the inclusive dijet cross-section for which the azimuthal difference between the two leading jets is smaller than a given value, $\Delta\phi_{\max}$.

ATLAS has recently presented measurements on azimuthal decorrelations [13] as an alternative method to determine the strong coupling constant and to probe pQCD at high scales. The analysis is based on the 2012 sample with a luminosity of 20.2 fb^{-1} . Anti- k_T jets ($R=0.6$) are selected with $p_{T\min} = 100 \text{ GeV}$ and $|y| \leq 2.5$. The selection criteria require $H_T = \sum_i p_{Ti} \geq 450 \text{ GeV}$, $p_{T1} > H_T/3$, $y^* = |y_1 - y_2|/2 < 2$ and $|y_i - y_{\text{boost}}| < 0.5$ with $y_{\text{boost}} = |y_1 + y_2|/2$. The data are presented as a function of H_T in three y^* bins and four values of $\Delta\phi_{\max}$.

The data are further corrected for detector effects using a bin-by-bin reweighting procedure. The systematic uncertainties are very well under control, typically around the few percent level. The theoretical calculations have been performed as in the previous section using NLOJET++. The renormalization and factorization scales are set at $\mu_R = \mu_F = H_T/2$. The corrected data are shown in Fig. 6 along with a comparison to the NLO predictions.

Figure 6: The azimuthal decorrelations compared to NLO pQCD predictions [13].

The agreement is fair. A closer look at the data/theory ratios indicate that the predictions do best for $\Delta\phi_{\max} = 7\pi/8$ as expected. Therefore for a determination of α_s the data for this particular value of $\Delta\phi_{\max}$ is integrated over y^* and its H_T dependence fitted to pQCD predictions at NLO accuracy. The results of this fit are shown in Fig. 8.

They yield the following value for the strong coupling constant at the Z mass:

$$\bullet \alpha_s^{\text{decorr}}(M_Z) = 0.1127^{+0.0063}_{-0.0027}(\text{total})$$

The error is dominated again by the theoretical scale uncertainties.

Figure 7: The azimuthal decorrelations compared to NLO pQCD predictions [13].

Figure 8: Summary of the dependence of the strong coupling constant with the scale, from fits to azimuthal decorrelations [13].

4. Summary and conclusions

To summarize, three recent results on jet physics from the ATLAS Collaboration at the LHC have been discussed as ways to probe pQCD at high scales. The main quantitative results is that the coupling constant has been measured with good precision as illustrated in Fig. 9 and its running tested to unprecedented scales of the order of 2 TeV. In fact the level of experimental precision is similar to that of the LEP experiments. This calls for improved calculations beyond the NLO accu-

racy for jet cross sections in $p - p$ collisions.

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Figure 9: Summary of $\alpha_s(M_Z)$ values obtained at colliders. In blue those based on NNLO calculations.

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