

# LATEST JETS RESULTS FROM THE LHC

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A fundamental characteristic of hadron colliders is the abundant production of jets, which then are studied to learn about hard QCD, the proton structure, or nonperturbative effects. In the following the latest results and developments from the LHC experiments on jet cross sections, event shapes, flavour and rapidity dependence, and cross section ratios are presented. The ratio of the inclusive 3-jet to the inclusive 2-jet event cross section is used for a first determination of the strong coupling constant at the TeV scale.

## 1 Jet Cross Sections

Yields of collimated streams of particles, i.e. jets, are among the most fundamental observables at hadron colliders. Through their high production rates at low jet transverse momenta,  $p_T$ , they serve to benchmark detector performance and to perform first cross section measurements that are compared to theory predictions. As more data are accumulated, ever higher jet  $p_T$ 's become accessible providing significant constraints on the parton distribution functions (PDFs) of the proton and important input to searches for new physics.

ATLAS and CMS,<sup>1,2</sup> both employ the anti- $k_T$  jet algorithm<sup>3</sup> to define their jets, but with different jet size parameters  $R$  of 0.4 or 0.6 for ATLAS and 0.5 or 0.7 for CMS respectively. The dominant source of experimental uncertainty for jet measurements is the jet energy calibration, because the steeply falling jet  $p_T$  spectrum induces an approximately 5–6 times larger uncertainty on the jet cross sections than on the jet energies. Profiting from the excellent performance of both detectors, jet energy calibration uncertainties could be limited to about 1–3% already during the initial three-years running period, a feat that could be achieved previously only after many years. Apart from jets with less than  $\approx 50$  GeV of transverse momentum this good performance could be kept up despite the deteriorating influence of more pile-up collisions, i.e. additional proton-proton collisions in the same or neighbouring bunch crossings. At the next LHC start-up with even higher instantaneous luminosities pile-up will again pose a challenge.

The common normalization uncertainty caused by the luminosity determination could be reduced from initially more than 10% down to 2–4%. Including other systematic effects the

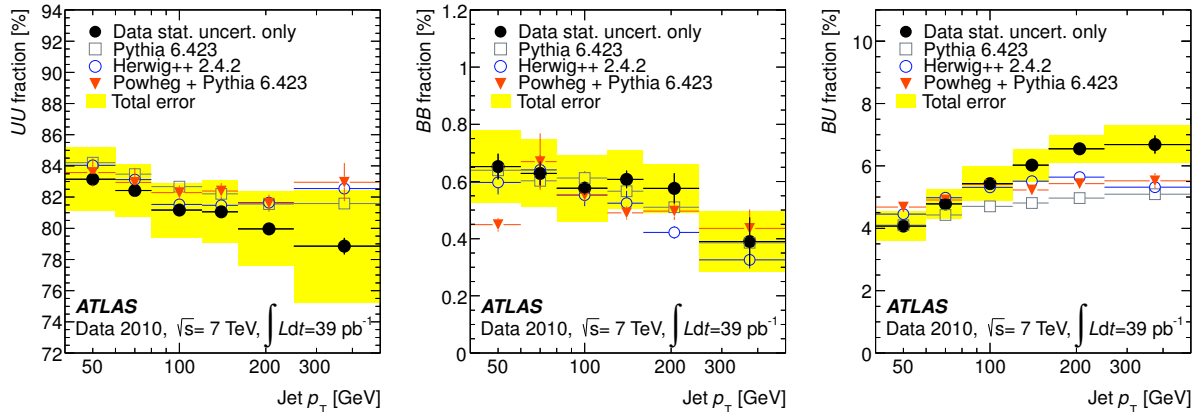


Figure 1: Relative frequency of jet flavours  $B$ ,  $C$ , and light ( $U$ ) in dijet events for the combinations  $BB$  (left),  $UU$  (middle), and  $BU$  (right plot).

inclusive jet  $p_T$  or the dijet mass cross sections could be measured by ATLAS and CMS to roughly 10 to 20% accuracy with less precision at the low end and also less data at the high end of the jet  $p_T$  and dijet mass ranges.<sup>4,5,6</sup>

It is a great achievement that these data are in general agreement with predictions of QCD over many orders of magnitude in cross section. With theoretical uncertainties of a similar order or larger these jet measurements help constrain PDFs. Recent progress in theory towards next-to-next-to-leading order (NNLO) predictions are reported elsewhere in these proceedings.<sup>7</sup>

## 2 Event Shapes

Alternatively to jet counting continuous dimensionless quantities that are not sensitive to the details of soft nonperturbative effects of QCD can be defined to characterize events. They are called *event shapes* and have been in use since the early days of QCD in the 70s. Several collinear and infrared-safe event shapes, e.g. *transverse thrust*, have been investigated by ATLAS and CMS, where the emphasis was on hard proton-proton scatterings and the phase space is subdivided into bins of  $p_T$  of the leading jet or the sum of all jet  $p_T$ 's.<sup>8,9</sup> In a new study ATLAS uses charged particles measured in their tracking system to investigate event shapes down to very small transverse momenta of 0.5 GeV.<sup>10</sup> In accordance with previous results it is found that better tunings of the MC event generators are needed in order to describe all available data.

## 3 Flavour and Rapidity Results

In Ref.<sup>11</sup> ATLAS compares the relative frequency of jet flavours in dijet events. Using template fits to kinematic properties of secondary vertices inside jets, ATLAS differentiates between the heavy,  $b$  and  $c$  quark initiated jets and *light* jets, which are labelled as  $B$ ,  $C$ , and  $U$  respectively. Figure 1 shows exemplarily the measurements for the  $UU$ ,  $BB$ , and  $BU$  dijet combinations, which demonstrate that light dijets compose about 80% of the total cross section while the heavy  $BB$  combination appears only in half a percent of the events. The results are described well within uncertainties by MC predictions except for the  $BU$  case, where some discrepancies can be observed.

Other analyses by ATLAS and CMS look into the dependence of the most forward and backward dijets or the ratio of all possible dijet pair distances over the leading dijet pair distance versus their separation in absolute rapidity,  $|\Delta y|$ .<sup>12,13</sup> It is expected that deviations from the usual evolution of the PDFs could show up in these quantities, where small parton momentum fractions are accessed. The comparisons of different models to the data are, however, inconclusive so far.

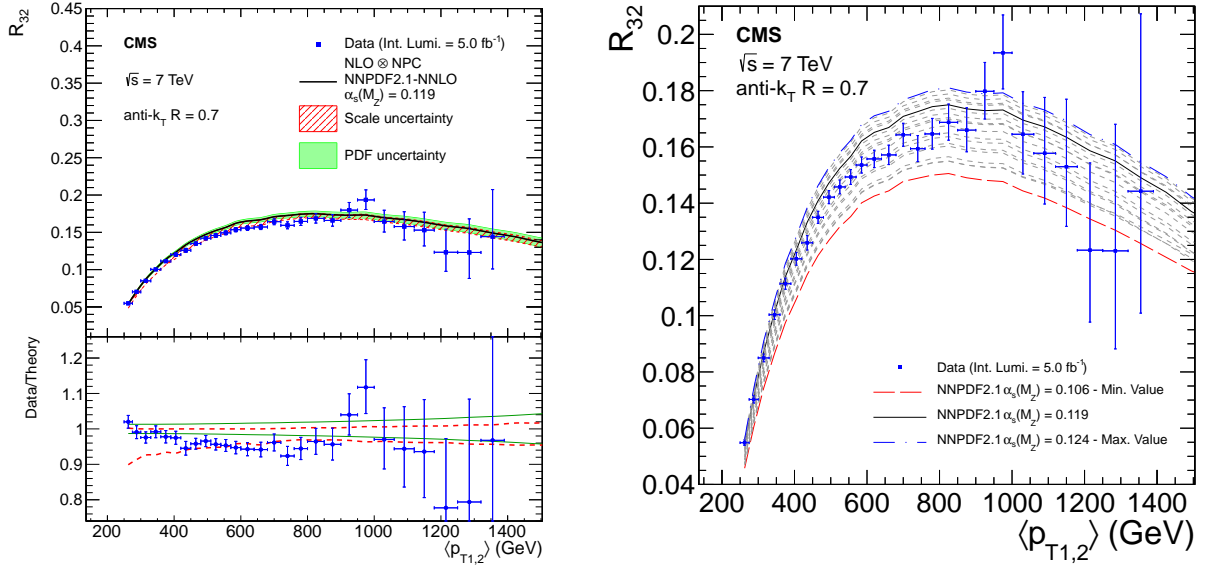


Figure 2: Left: Measured ratio  $R_{32}$  versus  $\langle p_{T1,2} \rangle$  (solid circles) together with the NLO prediction (solid line) corrected for nonperturbative effects (NPC), the scale uncertainty, and the PDF uncertainty. The bottom panel shows the ratio of data to the theoretical predictions, together with bands representing the scale (dotted lines) and PDF (solid lines) uncertainties while the error bars correspond to the total uncertainty. Right: The same comparison with theory but for a series of values of  $\alpha_S(M_Z)$ . The  $\alpha_S(M_Z)$  value is varied in the range of 0.106-0.124 in steps of 0.001. In both cases the NNPDF2.1 PDF set at NNLO evolution order has been employed.

#### 4 Ratios of Jet Cross Sections and Determination of the Strong Coupling Constant

In order to reduce experimental as well as theoretical uncertainties, jet cross section ratios are considered. Disposing of data at 2.76 TeV, the baseline proton-proton centre-of-mass energy for heavy ion collisions, in addition to the 7 TeV data, ATLAS analyzed the ratio of the inclusive jet cross section at these two energy points.<sup>14</sup> This provides more significant constraints on PDFs in the accessible phase space than considering each jet cross section separately.

The ALICE Collaboration followed a suggestion in Ref. <sup>15</sup> and examined the cross section ratio for jets defined with different jet size parameters, which in their case are  $R = 0.2$  and  $0.4$  because of their primary focus on heavy ion physics.<sup>16</sup> Using this method, details of the parton showering and the nonperturbative hadronization phase are emphasized in this ratio such that even NLO calculations are not able to describe the data as shown by ALICE.<sup>17</sup>

In contrast, the ratio of the inclusive 3-jet to the inclusive 2-jet event cross section,  $R_{32}$ , has been demonstrated by CMS to be reliably comparable to perturbative QCD, if sufficiently high thresholds, CMS requires  $p_{T,\text{jet}} > 150$  GeV, are imposed on all jets including the third leading one.<sup>18</sup> Figure 2 presents a comparison of the data, differential in the average transverse momentum of the two leading jets,  $\langle p_{T1,2} \rangle$ , to the theory predictions at NLO on the left and the sensitivity to a variation of the strong coupling constant  $\alpha_S(M_Z)$  on the right for the NNPDF2.1 PDF set at NNLO evolution order.<sup>19</sup> Fits of  $R_{32}$  in the range of  $420 < \langle p_{T1,2} \rangle < 1390$  GeV have been used to determine the strong coupling constant  $\alpha_S$  at the scale of the Z boson mass to be:

$$\alpha_S(M_Z) = 0.1148 \pm 0.0014 (\text{exp.}) \pm 0.0018 (\text{PDF})_{-0.0000}^{+0.0050} (\text{scale}) = 0.1148_{-0.0023}^{+0.0055}, \quad (1)$$

compatible with the world average value of  $\alpha_S(M_Z) = 0.1184 \pm 0.0007$ .<sup>20</sup> Here, the total uncertainty is derived from the experimental, PDF, and scale uncertainties by quadratic addition. This is the first determination of the strong coupling constant from measurements at scales  $Q$  of the order of 1 TeV. A comparison to other determinations at hadron colliders accessing different scales  $Q$  is shown in Fig. 3. No deviation from the expected running behaviour of the strong coupling constant is observed.

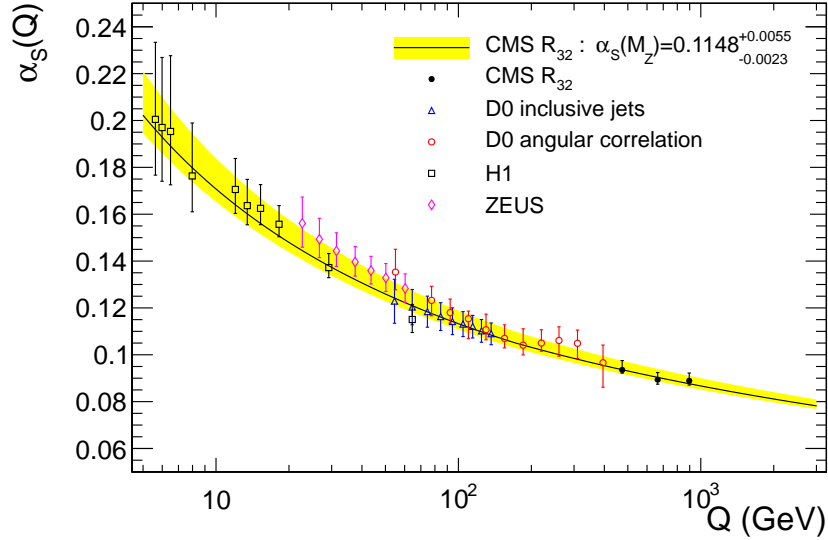


Figure 3: The strong coupling  $\alpha_S(Q)$  (solid line) and its total uncertainty (band) evolved from the CMS determination  $\alpha_S(M_Z) = 0.1148^{+0.0055}_{-0.0023}$  as a function of the momentum transfer  $Q = \langle p_{T1,2} \rangle$ . The extractions of  $\alpha_S(Q)$  in three separate ranges of  $Q$  are shown together with results from other hadron collider experiments.

## 5 Summary

In summary, hadron colliders, which are usually conceived of as *discovery machines*, are also great *jet laboratories*, which provide many opportunities for precise measurements as demonstrated. Further results from the Tevatron are discussed elsewhere.<sup>21</sup> Through these measurements more insight can be gained into the workings of QCD, our theory of the strong interaction, with significant impact on e.g. other cross section predictions and searches for new physics.

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