EXPERIMENTAL TESTS OF QCD

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The first very successful LHC running period has been finished. At 7 TeV centre-of-mass energy about 5 fb$^{-1}$ of data have been collected and at 8 TeV even 20 fb$^{-1}$. Many detailed analyses of these data are still going on. The latest measurements on photon, weak boson plus jet, and jet production are compared against the most recent theory predictions. They are complemented by new results reported by the experiments at the Tevatron and HERA colliders. Finally, several new determinations of the strong coupling constant from jet data are presented.

1 Introduction

Through the abundant production of jets, i.e. collimated streams of particles, hadron colliders essentially become jet laboratories. QCD analyses of these data comprise a huge variety of phenomena and allow, amongst others, to learn about hard QCD or nonperturbative effects. As background the huge cross sections of jet, photon, and weak boson production pose a problem for many searches for new phenomena. Since hadrons are “made of QCD”, a precise understanding of their structure is indispensable as a linking piece between many collision types and processes. In particular at the LHC, which makes a huge new region of phase space accessible in energy scale $Q$ and fractional momentum of the proton $x$, new measurements by ATLAS and CMS$^{1,2}$ provide significant constraints on the parton distribution functions (PDFs) of the proton and the strong coupling constant $\alpha_S(M_Z)$.

2 Photon production

The analysis of direct photons is complicated by the fact that photons can also be produced in the transition phase from a parton shower to measurable particles. This so-called fragmentation component is much less understood than the perturbatively calculable QCD Compton, $qg \rightarrow \gamma q$, or annihilation processes, $q\bar{q} \rightarrow \gamma g$. Despite the possibility to probe and better determine the gluon PDF, observed discrepancies between measurement and theory for centre-of-mass energies of 20–40 GeV lead to the abandonment of photon data for PDF analyses.$^3$ With improved
techniques requiring photons to be isolated, the fragmentation component can be suppressed, in particular when accessing much higher photon transverse momenta at the LHC with more fine-grained detectors than previously possible. This suggests to re-address the comparison of photon data to perturbative QCD and their re-integration into global PDF fits.

In Fig. 1 left the ATLAS Collaboration extends the measured cross section of isolated photons versus transverse energy up to 1 TeV and observes agreement with NLO predictions by JETPHOX over five orders of magnitude in cross section. Some tension between data and theory remains with respect to the absolute photon rapidity as shown in Fig. 1 right. The limiting factor for more precise comparisons lies with the dominant scale uncertainty of the NLO calculations.

Within the context of Higgs boson searches (and now measurements) the isolated photon-pair production as irreducible background to $H \rightarrow \gamma\gamma$ is of special interest. The CDF and D0 Collaborations have published detailed studies including the full recorded luminosity and find a significantly improved description at NNLO compared to NLO.

Figure 1: Transverse energy and absolute rapidity of isolated prompt photons as measured by ATLAS in comparison to LO predictions from PYTHIA and HERWIG, and to NLO from JETPHOX.

Figure 2: Azimuthal angular difference between the photons of isolated photon-pair events. The differential cross sections, measured by CDF at 1.96 TeV (left) and by ATLAS at 7 TeV (right) are compared to predictions by theory up to NNLO.
This is confirmed by ATLAS\textsuperscript{11} although some discrepancies remain in particular in the distribution of the azimuthal difference between the two photons as presented in Fig. 2 for CDF (left) and ATLAS (right).

3 Weak boson+jet production

The D0 Collaboration also investigated the production of $W$ bosons in association with at least one jet,\textsuperscript{12} which is well described by NLO as given by BLACKHAT + SHERPA\textsuperscript{14,15,17}. As expected LO plus parton shower event generators fail progressively for higher jet multiplicities as demonstrated in Fig. 3 left. The ATLAS experiment measured inclusive $Z$+jet cross sections with up to seven or more jets.\textsuperscript{13} Again BLACKHAT + SHERPA\textsuperscript{14,16,17} provides NLO precision up to inclusive $Z$ + 4-jet production and agrees with the data, while MC@NLO\textsuperscript{20} exhibits large discrepancies for more than one jet, see Fig. 3 right.

Identifying charm jets produced in association with a $W$ boson, e.g. via decays of the charmed hadrons $D^{\pm}$ or $D^{*\pm}$, gives direct access to the strange quark and antiquark content of the proton. This can help to significantly reduce the uncertainties of and assess potential asymmetries between the strange quark and antiquark PDFs. The measurement by CMS\textsuperscript{18} as presented in Fig. 4 left agrees with theory computations at NLO from MCFM\textsuperscript{21} employing global PDF sets that include constraints on the strange content from low-energy deep-inelastic scattering (DIS) data. In contrast, a similar study from ATLAS\textsuperscript{19} shown in Fig. 4 right prefers PDFs excluding these DIS data. Since the phase space of the two analyses is different, their compatibility is hard to judge. It will be illuminating to see both data sets, when finalized, included into a common global PDF fit.
4 Jet production

ATLAS and CMS, both employ the anti-$k_T$ jet algorithm to define their jets, however with different jet size parameters $R$ of 0.4 or 0.6 for ATLAS and 0.5 or 0.7 for CMS, respectively. Profiting from the excellent performance of both detectors the dominant experimental uncertainty induced by the jet energy calibration could be limited to about 10–20%. The common normalization uncertainty caused by the luminosity determination could be reduced from initially more than 10% down to 2–4%. Contrasting jet measurements from CMS, or from ATLAS at 2.76 TeV in Fig. 5 right, with theory at NLO demonstrates agreement within uncertainties. This statement holds also when looking into higher order observables like the 3-jet mass cross section as studied by CMS in Fig. 6 left for predictions involving various PDF sets. The limiting factor, however, for even more accurate comparisons is the lack of NNLO predictions, which, at least for dijet production, will become available in the near future and allows to reduce the large scale dependence.

A possibility to partially cancel experimental as well as theoretical uncertainties in cross-section ratios is exploited by ATLAS through the division of their inclusive jet measurements at two different energy points. Profiting from data at 2.76 TeV, the baseline proton-proton centre-of-mass energy for heavy ion collisions, in addition to the 7 TeV data, the ATLAS Collaboration derives more significant constraints on PDFs in the accessible phase space than when considering each jet cross section alone.

Another possibility is, following a suggestion in Ref., the cross-section ratio for jets defined with different jet size parameters. Using this method, details of the parton showering and the nonperturbative hadronization phase are emphasized such that even NLO calculations are not able to describe the data as shown by CMS in Fig. 6 right, or previously by the ALICE experiment. Investigating the angular correlation in the emission of third jets around the second-leading jet in $p_T$, effects of colour coherence of the strong interaction can be compared to the modelling in parton shower event generators. Such an analysis has been performed recently by CMS emphasizing the need for better event generator tunings.

In contrast, observables like the multi-jet cross sections normalized to the neutral-current DIS cross section shown in Fig. 7, the average number of neighbouring jets within a given distance in an inclusive jet sample, $R_{\Delta R}$ or the inclusive 3-jet over 2-jet event, $R_{32}$ or jet cross-section ratios, $N_{32}$ are designed to be reliably comparable to perturbative QCD. Confronting theory
Figure 5: Double-differential inclusive jet cross sections as measured by CMS\textsuperscript{22,23} at 8\,TeV and by ATLAS\textsuperscript{24} at 2.76\,TeV. The measurements are compared to predictions at NLO times nonperturbative (NP) corrections.

Figure 6: The 3-jet mass cross section for central rapidity by CMS (left)\textsuperscript{25} at 7\,TeV as a ratio to theory at NLO times nonperturbative (NP) corrections for various PDF sets, and the jet cross-section ratio, also at 7\,TeV, for the two different jet size parameters of $R = 0.5$ and 0.7 by CMS (right)\textsuperscript{26}. The latter is compared to predictions at LO and NLO with or without NP corrections; the best description of the data is given by POWHEG\textsuperscript{27} NLO + PYTHIA (not shown).
Figure 7: Inclusive jet, dijet, and trijet cross sections as measured by H1 for momentum transfers squared $Q^2$ between 150 and 15000 GeV$^2$. The cross sections are normalized to the neutral-current cross section in deep-inelastic $ep$ scattering.

Figure 8: The strong coupling $\alpha_s(Q)$ (solid black line) and its total uncertainty (band) evolved from the CMS determination $\alpha_s(M_Z) = 0.1160^{+0.0072}_{-0.0031}$ as a function of the momentum transfer $Q = \langle p_T^1, p_T^2 \rangle$. The extractions of $\alpha_s(Q)$ from the 3-jet mass measurement are shown in eight separate ranges of $Q$ together with previous results from CMS and other hadron collider experiments.
predictions with measurements of these quantities the strong coupling constant \( \alpha_S(M_Z) \) can be determined from energy scales \( Q \) ranging from tenths of GeV up to 1 TeV. All fit results, 
\[
\alpha_S(M_Z) = 0.1163^{+0.0040}_{-0.0041} \text{ (H1)}, \quad \alpha_S(M_Z) = 0.1191^{+0.0046}_{-0.0047} \text{ (D0)}, \quad \alpha_S(M_Z) = 0.111^{+0.007}_{-0.0067} \text{ (ATLAS)},
\]
and 
\[
\alpha_S(M_Z) = 0.1148 \pm 0.0055 \text{ (CMS)},
\]
where the quadratically added total uncertainty is given, are compatible with the world average value of 
\[
\alpha_S(M_Z) = 0.1184 \pm 0.0007. \quad ^{45}\text{In all cases the total uncertainty is dominated by the scale uncertainties of the theory predictions at NLO. An overview of the } Q \text{ dependent determinations including the D0 and CMS results, the latter also comprising } \alpha_S(M_Z) \text{ extractions from 3-jet mass cross sections and } t\bar{t} \text{ production at threshold}^{25,35} \text{ is shown in Fig. 8. No deviation from the expected running behaviour of the strong coupling } \alpha_S(Q) \text{ is observed.}
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5 Summary

It is a great achievement that such a large amount of accurate data from multiple colliders are in general agreement with predictions of QCD over many orders of magnitude in cross section and in a wide region of phase space. Although a vast number of new theoretical tools and calculations, including multiplicities with up to five jets, have been developed at the same time, there are still cases, where theoretical uncertainties are the limiting factor. For even more precise comparisons NNLO is required. With all this progress in measurements and theory more insight can be gained into the workings of QCD with significant impact on the strong coupling constant, PDFs, and cross-section predictions e.g. for the Higgs boson and for searches for new physics.

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