The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

04 April 2018 (v3, 11 April 2018)

Hard QCD Measurements at LHC

Gabriella Pasztor on behalf of the ATLAS, CMS and LHCb collaborations

Abstract

The rich proton-proton collision data of the LHC allow to study QCD processes in a previously unexplored region with ever improving precision. This paper summarises recent results of the ATLAS, CMS and LHCb Collaborations using primarily multi-jet and vector boson plus jet data collected at $\sqrt{s} = 8$ and 13 TeV. Comparisons to higher-order theoretical calculations and sophisticated Monte Carlo predictions are presented, as well as the impact of the data on the determination of the parton distribution functions and the measurement of the strong coupling constant, α_s .

Presented at *LP2017 The 28th International Symposium on Lepton Photon Interactions at High Energies*

Hard QCD measurements at the LHC

Gabriella Pásztor

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group

Eötvös Loránd University, Budapest, Hungary

E-mail: gabriella.pasztor@cern.ch

<http://pasztor.web.cern.ch/gpasztor/>

on behalf of the ATLAS, CMS and LHCb Collaborations

The rich proton-proton collision data of the LHC allow the study of QCD processes in a previously unexplored region with ever improving precision. This paper summarises recent results of the ATLAS, CMS and LHCb Collaborations using primarily multi-jet and vector boson plus jet data collected at $\sqrt{s} = 8$ and 13 TeV. Comparisons to higher-order theoretical calculations and sophisticated Monte Carlo predictions are presented, as well as the impact of the data on the determination of the parton distribution functions and the measurement of the strong coupling constant, α_s .

Keywords: LHC, ATLAS, CMS, LHCb, QCD, pQCD, jet, photon, Drell-Yan, parton distribution function, pdf, strong coupling constant

1. Introduction

Processes governed by the strong interaction are dominant in the high-energy proton-proton collisions at the LHC, making the machine a jet factory. The rich jet data allows us to study perturbative QCD (pQCD) in a previously unexplored region.

Cross-sections at LHC — including the coveted New Physics processes such as supersymmetric partner, dark matter or other exotic particle production — are affected by QCD processes. The cross-sections can be written as the convolution of three terms. The initial state is described by universal parton distribution functions (PDFs) that are fitted from data using Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) evolution. The hard scattering matrix element (ME) is typically calculated to (next-to-)next-to-leading-order ((N)NLO) in perturbative QCD α_s expansion with the resummation of large logarithms due to soft and collinear gluon corrections up to (next-to-)next-to-leading-log ((N)NLL). Final-state partons then form hadrons, the process is described by universal fragmentation functions (FFs) fitted from data using DGLAP evolution.

The extraction of the strong coupling constant, the proton PDFs and the FFs are important thus not only from a QCD perspective but for the whole physics program of the LHC. PDF uncertainty is dominant systematics for Higgs boson and top production, and it limits the precision measurements of the strong coupling constant and the top mass as well as the search for new heavy particles. The running of α_s is affected if new colored particles exist, and thus its measurement constrains

New Physics.

QCD processes also give significant background to new particle searches, thus the test of their higher-order calculations, the validation of sophisticated Monte Carlo (MC) tools^a, including parton shower (PS) modelling and ME-PS matching, also contribute to the success of the New Physics program of the LHC.

The impressive agreement between LHC data and theoretical predictions over many orders of magnitude in cross-section (from inclusive jet production to the rare electroweak production of two bosons accompanied by two jets as shown in Fig. 1) is a feat. It is thanks to the advances in experimental methods (such as improved object reconstruction and calibration that are robust against the number of proton-proton collisions per bunch crossing, high-performance triggers, sophisticated data-driven background predictions, boosted techniques) and in theoretical predictions (including NNLO and N³LO pQCD calculations, resummation of large logs, improved treatment of parton showers and their matching to matrix element calculations, electroweak corrections, versatile MC tools).

Fig. 1. Total and fiducial production cross-section measurements of Standard Model processes corrected for leptonic branching fractions and compared to the corresponding theoretical expectations calculated at NLO or higher order¹.

^aFor references of the Monte Carlo tools, the parton distribution functions and tunes used in the analyses, see the references in the quoted experimental papers.

The LHC delivered about 23 fb^{-1} data at a proton-proton center-of-mass energy of $\sqrt{s} = 8 \text{ TeV}$ in 2012, as well as about 4 fb^{-1} and 40 fb^{-1} data at $\sqrt{s} = 13 \text{ TeV}$ in 2015 and 2016 respectively. In the following, selected results are shown from the ATLAS, CMS and LHCb Collaborations concentrating on multi-jet and vector boson plus jet final states based on these datasets. The emphasis is on detailed data comparisons to theoretical calculations and Monte Carlo predictions validating the recent advances, as well as on the extraction of α_s and the proton PDFs.

The LHC can reach down to the low- x and up to the high- Q^2 region in parton kinematics extending the phase space previously explored by fixed target experiments and the HERA electron-proton collider, as shown in Fig. 2. We have many handles that provide complementary information. Studies of jet, top-quark pair and prompt photon production test the gluon and valence quark PDFs and are sensitive to α_s . W and Z production cross-sections and cross-section ratios help to differentiate light-flavour quark PDFs. Off-peak Drell-Yan production reaches low- and high- x regions for u- and d-quark PDFs. While Z/W+jets measurements are especially sensitive to the gluon PDF, the Z/W + heavy flavour processes constrain the strange, charm and bottom quark distributions.

Fig. 2. Parton kinematics at the LHC at $\sqrt{s} = 13 \text{ TeV}$ in the $x - Q^2$ plane². The coverage of previous fixed target experiments and HERA is also shown.

2. Multi-jet results

2.1. Jet reconstruction at LHC

Jets are typically formed from reconstructed particles, so called particle-flow³ objects that result from the combined information of charged particle tracks in the inner tracking detectors and muon spectrometers and of energy deposits in the electromagnetic and hadronic calorimeters. They aim to precisely reconstruct the physics objects (photons, electrons, muons, tau leptons, charged and neutral hadrons) and their interactions as they traverse the detector. To reconstruct the jets, the infrared- and collinear-safe anti-kt clustering algorithm⁴ is used with size parameter typically in the $R = 0.4 - 0.8$ range.

The reconstructed hadronic jets are corrected for detector effects and are frequently unfolded to estimate the kinematic distributions of the original "true" particle jets to facilitate comparisons with theoretical predictions and with other experimental results.

In most measurements the dominant experimental systematics arise from jet energy calibration. As an example, the size of the jet energy correction is around 10% at a jet transverse momentum (p_T) of 100 GeV in the CMS measurements at $\sqrt{s} = 8$ TeV⁵. The resolution improves from about 15% at $p_T = 10$ GeV to about 4% at $p_T = 1$ TeV. These induce a systematic uncertainty on the jet cross-section of 2-4% at sub-TeV and 20% at the highest transverse momenta from the energy scale, as well as about 30% at low and 1-5% at high p_T from the energy resolution.

2.2. Inclusive jet cross-section

The LHC data covers more than 12 orders of magnitude in jet cross-section measured differentially in jet transverse momenta and absolute jet rapidity ($|y|$) as illustrated in Fig. 3(left). The experimental uncertainties being smaller than the theoretical ones, these measurements are powerful in constraining the proton PDFs in particular for gluons and valence quarks. Measurements of cross-section ratios at different center-of-mass energies profit from partial cancellation of systematic uncertainties. The CMS results⁵ comparing jet production at 2.76 TeV and 8 TeV clearly disfavour ABM11 PDF set as shown in Fig. 3(right).

The measured data shows a reasonable agreement with next-to-leading order (NLO) theoretical predictions when studied in individual p_T bins but show some tension when fitting all bins together for all tested PDF sets as illustrated by the ATLAS measurement⁶ at $\sqrt{s} = 8$ TeV on Fig. 4 for four PDF sets. When considering all jets above 70 GeV for all rapidity bins, the χ^2 ranges from 340 to 424 for 171 degrees of freedom, depending on the PDF set tested, the value of R in the anti-kt clustering ($R=0.4$ or 0.6) and the choice of central renormalisation and factorisation scales.

The gluon density at high Bjorken x is poorly constrained. While quark-gluon (qg) interactions dominate the dijet cross-section for almost the full kine-

Fig. 3. (left) Double-differential inclusive jet cross-sections as function of jet p_T in bins of rapidity for anti-kt jets with $R=0.7$. The data are compared to NLO predictions corrected for non-perturbative (NP) and electroweak (EWK) effects. (right) Ratio of the inclusive jet production cross-sections at $\sqrt{s} = 2.76$ TeV and 8 TeV as function of jet p_T for jet rapidities of $|y| < 0.5$.

Fig. 4. Ratio of the inclusive jet cross-section predicted by NLO QCD corrected for non-perturbative and electroweak effects to the cross-section observed in data as a function of the jet p_T in each jet rapidity bin for anti-kt jets with $R=0.4$. Various PDF sets are compared with the data. The central renormalisation and factorisation scales are set to the maximum jet p_T in the event. The points are slightly offset along the jet p_T axis for better visibility.

matic range, at high p_T quark-quark (qq) processes take over. The impact of the 8 TeV CMS data on the gluon and light quark PDFs is shown on Fig. 5⁵. The improvement is most notable for the gluon densities. If the strong coupling constant is left free in the fit, the derived value of $\alpha_s(M_Z) = 0.1184^{+0.0019}_{-0.0021}$ (exp) $^{+0.0002}_{-0.0015}$ (model) $^{+0.0000}_{-0.0004}$ (param) $^{+0.0022}_{-0.0018}$ (scale) = $0.1184^{+0.0019}_{-0.0021}$

is compatible with the world average⁷ of $\alpha_s(M_Z) = 0.1181 \pm 0.0011$.

Fig. 5. Gluon (left), u valence quark (middle), and d valence quark (right) distributions as functions of Bjorken x at the starting scale $Q^2 = 1.9 \text{ GeV}^2$ (top) and at high $Q^2 = 10^5 \text{ GeV}^2$ (bottom)⁵. The results of the fit to the HERA data and inclusive jet measurements at 8 TeV by CMS (shaded band), and to HERA data only (hatched band) are compared with their total uncertainties as determined by using the HERAPDF method. In the bottom panels the fractional uncertainties are shown.

The inclusive jet cross-section is also measured at the highest available energy of 13 TeV with jet transverse momentum up to 2 TeV and rapidity up to $|y| = 4.7$. Comparisons with various LO and NLO Monte Carlo generators, complemented with electroweak and non-perturbative corrections, using the anti-kt algorithm with $R=0.4$ (see Fig. 6) and 0.7 show that data reconstructed with a larger jet size are better described by the fixed order NLO prediction⁸. When NLO is matched to parton shower (Powheg interfaced to Pythia8) the description for reconstruction with a lower jet size value is also improved.

Recent next-to-next-to-leading order (NNLO) calculations are also compared to the LHC data. In Fig. 7 the ATLAS 13 TeV results⁹ show that while scale uncertainties decrease in general for NNLO, the central scale choice (either the jet p_T or the maximum jet p_T in the event) has a large impact on the prediction. At NNLO using $\mu_R = \mu_F = p_T$ for the central scale describes the data better, especially at low jet transverse momenta.

Fig. 6. Ratio of measured values of the inclusive jet cross-section to theoretical predictions⁸.

Fig. 7. Ratios of pQCD predictions corrected for non-perturbative and electroweak effects to the measured inclusive jet cross-sections as a function of the jet p_T in $|y|$ bins for anti- k_t jets with $R=0.4$. The NLO predictions are calculated using NLOJET++, while the NNLO predictions are provided by NNLOJET, both using MMHT 2014 PDF sets and p_T^{jet} (upper panel) or p_T^{max} (lower panel) as the central QCD scale⁹.

2.3. Dijet cross-section

The double differential dijet cross-section⁹ manifests in Fig. 8(top right) a reasonable agreement as function of the dijet mass in rapidity bins with NLO pQCD calculations, with the tested proton PDF sets showing similar behaviour. Measurements¹⁰ are also performed triple differentially by CMS as a function of the average jet transverse momentum $p_{T,avg}$, the average jet rapidity y_b and the rapidity difference $y^* = 0.5|y_1 - y_2|$, as presented in Fig. 8(top left). AMB11, due to its soft gluon PDF and low α_s , underestimates the data in most of the phase space. At high $p_{T,avg}$ and high y_b (i.e. in the previously less studied high-x region) the theoretical prediction overestimates the data by up to a factor of two (see Fig. 8(bottom)). As the experimental precision is better than the theoretical one, the proton PDFs can

Fig. 8. (top left) Double differential dijet cross-section as a function of the dijet mass m_{jj} and rapidity difference $y^* = |y_1 - y_2|/2$, for anti-kt jets with $R=0.4$ ⁹. The data are compared to NLO pQCD predictions calculated using NLOJET++ with $p_T^{\max} e^{0.3y^*}$ as the QCD scale and the CT14 NLO PDF set, to which non-perturbative and electroweak corrections are applied. In most bins the experimental systematic uncertainty is smaller than the theory uncertainties and is not visible. (top right) Triple differential dijet cross-section for anti-kt jets with $R=0.7$ as a function of the average jet transverse momentum $p_{T,avg}$, average jet rapidity y_b and rapidity difference y^* compared to the NLOJET++ prediction using the NNPDF3.0 PDF set¹⁰. (bottom) Ratio of the triple-differential dijet cross-section to the NLOJET++ prediction in a selected (y^*, y_b) bin¹⁰. The ratios calculated with the predictions for different PDF sets are also shown.

be constrained, in particular the uncertainty on the gluon PDF is decreased. The constraints are similar to those obtained from the inclusive jet data.

The jet mass is sensitive to parton shower modelling. It is used to reconstruct the mass of heavy particles in analyses of boosted topologies, such as searches for new heavy states or studies of Higgs boson or top quark production. The double differential cross-section is presented in Fig. 9 unfolded in jet p_T and jet mass¹¹ in dijet events, for anti-kt jets with $R=0.8$, with and without soft drop jet grooming¹². With grooming the Sudakov peak is suppressed and a better agreement is seen at moderate values of jet mass and p_T as the soft radiation contribution is removed. Pythia8 agrees best with the data. Semi-analytical NNLL calculations¹³ predict the data well except at high mass and p_T as illustrated in Fig. 10.

Fig. 9. Differential cross-sections in the jet mass unfolded for (left) ungroomed and (right) groomed jets in p_T bins¹¹. The data with total uncertainties are compared to Pythia8 predictions.

Fig. 10. Unfolded jet mass distribution for (left) ungroomed and (right) groomed jets for $650 \text{ GeV} < p_T < 760 \text{ GeV}$ compared to various Monte Carlo predictions and for groomed jets also to semi-analytical calculations¹¹.

The observed azimuthal correlations in two-, three-, four-jet topologies¹⁴, such as the azimuthal difference of the two leading jets $\Delta\phi_{1,2}$ shown in Fig. 11 or the minimal azimuthal difference in the event $\Delta\phi_{2j}^{\min}$, are generally not well described by MC simulations. LO Pythia8 and Herwig++ show large deviations. The tree-

Fig. 11. (top) Normalised inclusive 2-jet cross-section differential in $\Delta\phi_{1,2}$ in different regions in the maximum jet $p_T^{\max}$ ¹⁴. The size of the data symbol includes the total uncertainties. (bottom) Ratios of various Monte Carlo predictions to the normalised inclusive 2-jet cross-section¹⁴.

level multijet event generator MadGraph in combination with Pythia8 for showering, hadronisation, and multiparton interactions provides a good overall description (except for $\Delta\phi_{2j}^{\min}$ in four-jet topologies). The NLO dijet and three-jet simulations with Powheg fail to describe the measured correlations. The NLO dijet sample by Herwig7 matched to parton shower contributions with the MC@NLO method provides a very good description of $\Delta\phi_{1,2}$. The results prove that the azimuthal correlations are sensitive to details of the modelling of the non-perturbative effects and emphasize the need to improve predictions for multijet production.

All Monte Carlo generators have difficulty reproducing the $b\bar{b}$ dijet data. The ATLAS measurement¹⁵ shown in Fig. 12 requires a jet with $p_T > 270$ GeV which enhances the sample with events of three-jet topology thus raising the contribution of processes of gluon-splitting and flavor excitation. The NLO Powheg interfaced to Pythia6 provides a better description than MC@NLO, but significant differences are visible in regions dominated by flavour creation (low transverse momentum, high mass, large angular separation of the $b\bar{b}$ system). The rapidity distribution is sensitive to the PDF and is well described by Powheg. LO Pythia6 dijet simulation (scaled by 0.61 to correct the overall normalisation) describes the shapes somewhat better than LO Sherpa including matrix elements up to $2 \rightarrow 3$ processes.

Fig. 12. Differential cross-section for $b\bar{b}$ production as a function of (left) the mass, (middle) the transverse momentum, (right) the average boost of the $b\bar{b}$ system compared to various MC predictions¹⁵.

2.4. Determination of the strong coupling constant

The strong coupling constant can be determined in a variety of ways at the LHC.

The inclusive jet cross-section $d^2\sigma/dp_T d\eta$ is proportional to α_s^2 . Various experimental and theoretical errors cancel in inclusive cross-section ratios $R_{mn} = \sigma(pp \rightarrow m \text{ jets})/\sigma(pp \rightarrow n \text{ jets})$ that are proportional to α_s^{m-n} . CMS has measured the strong coupling constant at NLO with both methods (see Fig. 13) and arrived to

$$\alpha_s(M_Z) = 0.1162^{+0.0014}_{-0.0015} (\text{exp}) \quad {}^{+0.0053}_{-0.0028} (\text{scale}) \quad {}^{+0.0025}_{-0.0029} (\text{PDF}) \pm 0.0001 (\text{NP})$$

from the inclusive cross-section⁵ and to

$$\alpha_s(M_Z) = 0.1142 \pm 0.0010 \text{ (exp)} \stackrel{+0.0049}{-0.0006} \text{ (scale)} \pm 0.0013 \text{ (PDF)} \pm 0.0014 \text{ (NP)}$$

from the R_{32} ratio measurements¹⁶. These are compatible with the world average $\alpha_s(M_Z) = 0.1181 \pm 0.0011$ ⁷.

Fig. 13. (left) Ratio of the observed inclusive jet cross-section over theory prediction using the CT10 NLO PDF set as a function of the jet p_T for anti-kt jets with $R = 0.7$ with the default $\alpha_s(M_Z) = 0.118$ value⁵. Ratios of the predictions obtained with the CT10 PDF set evaluated with different values of $\alpha_s(M_Z)$ indicate the sensitivity of data to the strong coupling constant. (middle) Cross-section ratio R_{32} as a function of average jet transverse momentum¹⁶. (right) Ratio of measured R_{32} over NLO theory with non-perturbative corrections¹⁶.

The running of α_s from the R_{32} measurement is shown in Fig. 14 using the MSTW2008 NLO PDF set evolving the extracted $\alpha_s(M_Z)$ values using the 2-loop 5-flavour renormalisation group equations. The result agrees well with previous measurements and the world average.

Fig. 14. The running $\alpha_s(Q)$ as a function of the scale Q as obtained by using the MSTW2008 NLO PDF set¹⁶. The dashed line represents the evolution of the world average.

ATLAS uses transverse energy – energy correlation (TEEC), the energy weighted angular distribution of jet pairs to measure the strong coupling constant¹⁷. TEEC, shown in Fig. 15(top left) gets only moderate NLO corrections and is also robust with respect to experimental uncertainties, thus well-suited for precision tests of pQCD. One can also use the asymmetry (ATEEC) between the forward and backward contributions of TEEC (see Fig. 15(top right) for data - MC comparisons). Both TEEC and ATEEC are proportional to α_s^2 at NLO. Both distributions are well described by NLO pQCD predictions within the uncertainties. The extracted α_s values from the TEEC and ATEEC distribution respectively are

$$\begin{aligned}\alpha_s(M_Z) &= 0.1162 \pm 0.0011 \text{ (exp)} \begin{matrix} +0.0076 \\ -0.0061 \end{matrix} \text{ (scale)} \pm 0.0018 \text{ (PDF)} \pm 0.0003 \text{ (NP)} \\ \alpha_s(M_Z) &= 0.1196 \pm 0.0013 \text{ (exp)} \begin{matrix} +0.0061 \\ -0.0013 \end{matrix} \text{ (scale)} \pm 0.0017 \text{ (PDF)} \pm 0.0004 \text{ (NP)}\end{aligned}$$

The running of α_s is shown in Fig. 15 for the slightly more precise ATEEC measurement. Both results agree with the world average⁷.

Fig. 15. Particle-level distributions for (top left) the TEEC and (top right) the ATEEC functions for the 900 GeV to 1000 GeV bin in the average jet transverse momentum of the two leading jets $H_{T,2}/2$, compared to various MC predictions¹⁷. (bottom) Comparison of the values of $\alpha_s(Q)$ obtained from fits to the TEEC functions at the energy scales given by $< H_{T,2} > /2$ with the uncertainty band from the global fit and the world average¹⁷.

3. Probing QCD with photons

Photonic final states allow the test of pQCD with a hard, colorless probe.

Prompt photon production ($qg \rightarrow q\gamma, q\bar{q} \rightarrow g\gamma$) is sensitive to the gluon PDF at leading order. NLO predictions by JETPHOX provide a reasonable description of the inclusive photon data¹⁸ of the ATLAS experiment as illustrated in Fig. 16(left, middle). It, however, can not describe the angular difference between the photon and the closest jet ($\Delta\phi^{\gamma\text{-jet}}$)¹⁹ due to limitations in the number of final state partons. Sherpa with up to $2 \rightarrow 5$ matrix elements calculated at NLO agrees well with data for $\Delta\phi^{\gamma\text{-jet}}$, but has difficulty describing the leading jet transverse momentum distribution which is well reproduced by JETPHOX as shown in Fig. 16(right)¹⁹. The experimental uncertainties are lower than the theoretical ones, thus NNLO calculations are desirable to decrease the scale uncertainties.

Fig. 16. (left) Measured cross-sections for isolated-photon production as functions of the photon transverse energy in different photon pseudorapidity ranges¹⁸. (middle) Ratio of the NLO pQCD predictions from JETPHOX based on the MMHT2014 PDFs to the measured cross-sections¹⁸. (right) Measured cross-sections for isolated-photon plus one-jet production as a function of the leading jet transverse momentum¹⁹.

The ATLAS Collaboration in its $\sqrt{s} = 8$ TeV measurement²⁰ observed for the first time the difference in QCD radiation pattern around the leading jet and the photon, in agreement with theoretical predictions.

The diphoton production cross-section is sensitive to pQCD corrections. Fixed order calculations are lower than the observed data²¹, though NNLO brings significant improvement as shown in Fig. 17. However, especially in regions sensitive to infrared emission, soft-gluon resummation is needed at NNLL. The best description of the data is provided by SHERPA with NLO matrix element calculation up to $2 \rightarrow 5$ processes and parton shower simulation.

Fig. 17. (top) Measured fiducial cross-section of diphoton production compared to theoretical predictions²¹. (bottom) Differential cross-sections as functions of the diphoton transverse momentum and the angle between the two photons compared to NLO and NNLO predictions²¹.

4. Drell-Yan production

A large number of studies are carried out for Drell-Yan lepton-pair production. The LHCb data^{22,23} reaching large rapidities complements the ATLAS and CMS kinematic coverage.

The cross-section is measured differentially in the dilepton mass from 15 GeV to more than 2 TeV over nine orders of magnitude in cross-section at the highest energy of $\sqrt{s} = 13$ TeV by CMS and described well by theoretical predictions²⁴. These final states offer clean signatures and large statistics. Together with precise detector calibrations, they allow reaching an experimental systematics of about 1%. The uncertainty on the luminosity (2-3%) as well as other contributions can be cancelled out in cross-section ratio measurements.

The Drell-Yan data samples thus help understanding the proton structure, probe higher-order pQCD calculations, allow the study of non-perturbative effects like soft gluon resummation and parton shower modelling, test the available Monte Carlo tools. All these are essential both for precision physics and searches at the LHC.

Electroweak vector boson production was reviewed by Q. Lee on the conference. It is, however, important to comment on the huge impact of the precision W and Z data on our knowledge of the proton PDFs. This is illustrated in Fig. 18.

Fig. 18. (top) Constraints from the CMS $\sqrt{s} = 8$ TeV W boson charge asymmetry measurement on the valence quark PDFs²⁵. (middle) Constraints from the ATLAS $t\bar{t}$ and Z measurements on the sea quark and gluon PDFs²⁶. (bottom) Constraints from the ATLAS $\sqrt{s} = 7$ TeV Z and W boson precision cross-section measurements on the strange quark distribution²⁹. The left plot shows the results before, while the right one after the inclusion of the precision W and Z data.

The W charge asymmetry is measured as a function of the lepton pseudorapidity. It is sensitive to the $u(x)/d(x)$ ratio as the main production mechanisms are $u\bar{d} \rightarrow W^+$ and $d\bar{u} \rightarrow W^-$. The additional constraints on the valence quark PDFs from the $\sqrt{s} = 8$ TeV CMS measurement²⁵, when added to the HERA deep inelastic scattering data, are shown in the top plots of Fig. 18.

The measurement of the $t\bar{t}$ to Z production cross-section ratio allows the cancellation of the luminosity uncertainty. The largest challenge is to take correlations between the $t\bar{t}$ and Z measurements precisely into account. Double ratios like $[\sigma_{t\bar{t}}(\sqrt{s_1})/\sigma_Z(\sqrt{s_1})]/[\sigma_{t\bar{t}}(\sqrt{s_2})/\sigma_Z(\sqrt{s_2})]$ allow most uncertainties to cancel out. The $\sqrt{s} = 7$ TeV $t\bar{t}$ ATLAS data causes a tension in these measurements²⁶. The constraints on the sea quark and gluon distributions are presented in the middle row plots of Fig. 18.

The strange quark distributions can be measured studying W+charm production. While the $\sqrt{s} = 7$ TeV Wc results^{27,28} do not show enhanced s-quark content, the global fit to the ATLAS precision W and Z data²⁹ does, as illustrated on the bottom plots of Fig. 18.

Z boson production in association with jets (Z+jets) is used to study kt-splitting for anti-kt jet reconstruction algorithm with distance parameters $R=0.4$ and $R=1$ ³⁰. The distributions of $\sqrt{d_0}$ quantifying the p_T of the leading jet and the distances $\sqrt{d_N}$ ($N > 0$), where the N-jet event resolves to N+1 jets, are studied. At high values of $\sqrt{d}$ the perturbative model is tested, while in the low $\sqrt{d}$ region non-perturbative effects like hadronisation and parton shower modelling, multi-parton interactions also play a role. Fig. 19 shows that at high $\sqrt{d}$, the SHERPA generator (NLO for up to 2 jets and LO for up to 4 jets) performs better using the improved CKKW method for ME-PS matching. At low values, DYNLO interfaced to Powheg and Pythia8 underestimates the data less, though neither Monte Carlo tool gives a good description. These data can be used to tune the non-perturbative stages of the Monte Carlo models.

Fig. 19. Charged-only distributions for the splitting scales (left) $\sqrt{d_0}$, (middle) $\sqrt{d_2}$ and (right) $\sqrt{d_5}$ in the $(Z \rightarrow e^+e^-)$ +jets analysis using the anti-kt jet-radius parameter $R=0.4$ compared to theoretical predictions from Sherpa (MEPS@NLO) and DYNLO (NNLOPS)³⁰.

5. Jet properties

Jet properties, such as particle multiplicities and charge, depend on the type of the fragmenting parton.

Gluon jets are expected to have higher particle multiplicities due to the gluons' higher colour charge. Moreover the particle multiplicity also grows faster for gluon jets with the jet transverse momentum. These properties can be measured on dijet events, as more forward jets typically belong to the partons with higher longitudinal momentum and thus less likely to come from a gluon. ATLAS has measured the charged multiplicity for central and forward jets and extracted the gluon and quark jets' average charged multiplicities as a function of the jet transverse momentum³¹ shown in Fig. 20(top). The N³LO pQCD calculation can not give absolute predictions but describes well the p_T dependence.

Fig. 20. Jet properties in dijet events. (top) Charged multiplicity of quark and gluon jets as a function of the jet transverse momentum³¹. (bottom left) Jet charge distribution of the leading jet³². (bottom right) Average jet charge for up and down quarks as a function of the jet transverse momentum³³.

The jet charge is defined as the momentum-weighted sum of particle charges above a transverse momentum threshold: $Q_J = (p_{T,J})^{-\kappa} \sum_{i:\text{tracks}} q_i \cdot (p_{T,i})^\kappa$, where κ is a free regularisation parameter (typically chosen between 0.2 and 1.0). The jet charge is expected to be correlated with the charge of the parton thus could be used to identify the origin of a jet. The average jet charge in inclusive dijet events should increase with the parton center-of-mass energy due to the increasing u valence quark fraction. The jet charge is sensitive to the proton PDFs and the fragmentation modelling, both of these contributing to its p_T dependence.

CMS extracted the jet charge distribution of the leading jet in dijet events (an example is shown in Fig. 20(bottom left)) and compared it to theoretical models³² using various definitions of the jet charge. ATLAS studied the average jet charge and the jet charge distribution's standard deviation for the more central and more forward jets³³. Using PDF information, the average jet charge for up and down quarks are extracted as a function of p_T , shown in Fig. 20(bottom right). The data shows that the jet charge slowly decreases with p_T and this decrease increases with κ , as predicted.

6. Summary

As demonstrated in this paper, the ATLAS, CMS and LHCb proton-proton collision data provide a wealth of precise information about the strong interaction, accessing new regions in the phase space. The LHC entered its precision era. In general, good agreement is observed with pQCD theoretical predictions but deviations are present in certain kinematic regions. (N)NLO predictions provide an improved description of the measurements but non-perturbative effects play also a major role and their careful modelling is necessary to understand the observations.

The experimental precision for certain processes (jet, photon+jet, diphoton production) exceeds the theoretical one. Improved (NNLO+NNLL, N³LO) theoretical calculations are desirable for these processes. Certain calculations (like that of the dijet cross-section) show a strong dependence on the choice of the central renormalisation and factorisation scales at NNLO, exceeding the size of the uncertainty bands.

The jet and Drell-Yan data allow placing significant constraints on the proton PDFs. New measurements of the strong coupling constant at high Q are available and give good agreement with the world average.

Acknowledgements

The author wishes to thank for their support the National Research, Development and Innovation Fund, NKFI of Hungary (research grant no. 124845) and the Lendület (Momentum) Programme of the Hungarian Academy of Sciences (contract no. LP 2015-7/2015).

References

1. ATLAS Collaboration, <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults> (July 2017 version).
2. W.J. Stirling, <http://www.hep.ph.ic.ac.uk/~wstirling/plots/plots.html>.
3. CMS Collaboration, JINST 12 (2017) P10003.
4. M. Cacciari, G. P. Salam, and G. Soyez, JHEP 04 (2008) 063
5. CMS Collaboration, *JHEP* **03** (2017) 156.
6. ATLAS Collaboration, *JHEP* **09** (2017) 020.
7. C. Patrignani and others (Particle Data Group), Review of Particle Physics, *Chin. Phys. C* **40** (2016) 100001.
8. CMS Collaboration, *Eur. Phys. J. C* **76** (2016) 451
9. ATLAS Collaboration, ATLAS-CONF-2017-048 (July 2017), <https://cds.cern.ch/record/2273864/>.
10. CMS Collaboration, *Eur. Phys. J. C* **77** (2017) 746.
11. CMS Collaboration, CMS PAS SMP-16-010 (July 2017), <https://cds.cern.ch/record/2273393>.
12. A. J. Larkoski, S. Marzani, G. Soyez, and J. Thale, JHEP 05 (2014) 146.
13. C. Frye, A. J. Larkoski, M. D. Schwartz, and K. Yan, JHEP 07 (2016) 064; S. Marzani, L. Schunk, and G. Soyez, JHEP 07 (2017) 132.
14. CMS Collaboration, CMS-PAS-SMP-16-014 (March 2017), <http://cds.cern.ch/record/2257685>.
15. ATLAS Collaboration, *Eur. Phys. J. C* **76** (2016) 670.
16. CMS Collaboration, CMS-PAS-SMP-16-008 (February 2017), <https://cds.cern.ch/record/2253091>.
17. ATLAS Collaboration, *Eur. Phys. J. C* **77** (2017) 872.
18. ATLAS Collaboration, *Phys. Lett. B* **770** (2017) 473.
19. ATLAS Collaboration, ATLAS-CONF-2017-059 (July 2017), <https://cds.cern.ch/record/2273875>.
20. ATLAS Collaboration, *Nucl. Phys. B* **918** (2017) 257.
21. ATLAS Collaboration, *Phys. Rev. D* **95** (2017) 112005.
22. LHCb Collaboration, *JHEP* **5** (2016) 001.
23. LHCb Collaboration, *JHEP* **01** (2016) 155, *JHEP* **10** (2016) 030.
24. CMS Collaboration, CMS-PAS-SMP-16-009 (August 2016), <https://cds.cern.ch/record/2205152>.
25. CMS Collaboration, *Eur. Phys. J. C* **76** (2016) 469.
26. ATLAS Collaboration, *JHEP* **02** (2017) 117.
27. ATLAS Collaboration, *JHEP* **02** (2014) 013.
28. CMS Collaboration, *JHEP* **05** (2014) 068.
29. ATLAS Collaboration, *Eur. Phys. J. C* **77** (2017) 367.
30. ATLAS Collaboration, *JHEP* **08** (2017) 026.
31. ATLAS Collaboration, *Eur. Phys. J. C* **76** (2016) 1.
32. CMS Collaboration, *JHEP* **10** (2017) 131.
33. ATLAS Collaboration, *Phys. Rev. D* **93** (2016) 052003.