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WG1 Summary: Structure Functions and Parton Densities

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Presentations on "Structure Functions and Parton Densities" working group are summarized. They include results from various global analyses for the parton distribution functions (PDFs) inside the proton and nucleus, and the impact of new experimental data and progress in theoretical calculations, on the extraction of PDFs. Various studies were also presented regarding the constraints on the proton and nuclear PDFs from some specific experimental data from the LHC, HERA, RHIC, and elsewhere.

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1. Introduction

The continued excellent performance of the CERN Large Hadron Collider (LHC) [1] has helped to usher in an era of unprecedented precision in particle physics. The efforts to extract of parton distribution functions (PDFs) have an extensive impact in high energy physics and nuclear physics. With an increasingly extensive collection of experimental data samples, improvements in the theoretical predictions are needed to match the current (and future) experimental precision. Consequently, it has now become standard practice in recent QCD analyses, for the PDFs of proton and neutron to be determined at the next-to-next-to-leading order (NNLO) in the QCD coupling. Such precision is required for the confrontation of the standard model of elementary particle physics with the experimental data, and in the search for new physics beyond the standard model at the LHC.

In this session, various talks were presented regarding recent developments in theoretical calculations and experimental analysis, from which various updated PDF global analyses were also presented, both for the proton (neutron) and various heavy nuclei.

2. Updates on global proton PDF fits

New QCD analyses of the proton PDF were presented from all the major PDF fitting groups, increasingly now including more of the LHC data.

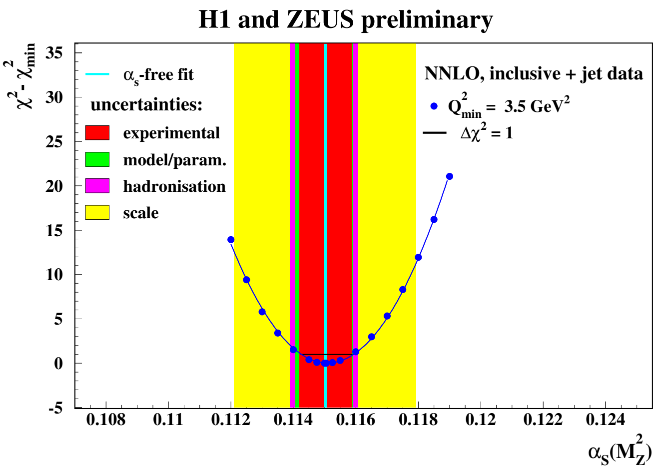

Figure 1: The determination of strong coupling constant from the new HERAPDF2.0 fit, with the inclusion of DIS jet data.

The new HERAPDF2.0 [2] fit includes the inclusive DIS data and now also DIS jet data from both ZEUS and H1 with the full NNLO prediction from NNLOJET [3]. The new NNLO fit favours lower $\alpha_s(M_Z)$ value with a central value at 0.1150 (see Figure 1) as compared to the NLO result centred at 0.1183. Consequently, two new HERA2PDF2.0Jets NNLO fits, with different α_s values have been made available.

The CTEQ-TEA group is ready to release the new CT18 and CT18Z PDF sets at the NNLO order. More than 700 data points from 12 new LHC data sets were included in the new fits. The CT18Z fit includes the ATLAS 7 TeV W and Z rapidity distribution data which are not included in the nominal CT18 fit, and additionally the factorisation and renormalisation scales are now x-dependent. Before performing the global fit, it is possible to use the PDFSense code [4] recently

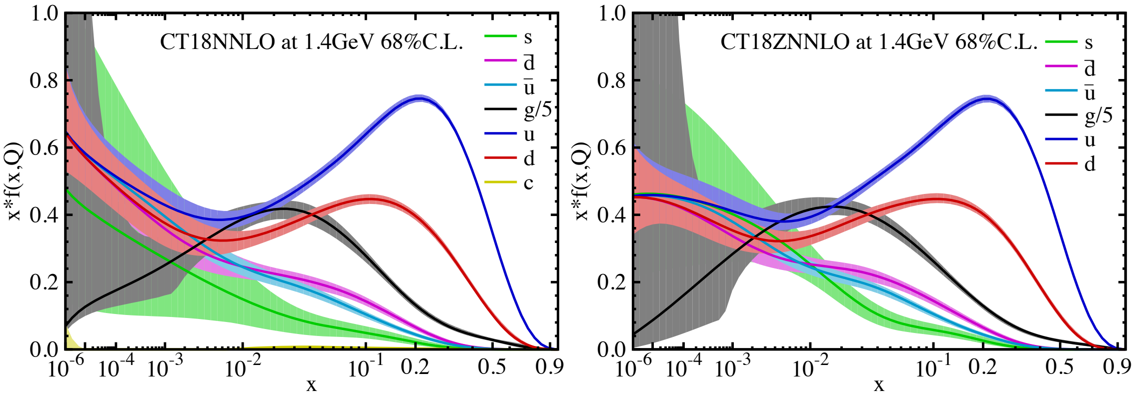

Figure 2: The CT18 and CT18Z parton distribution functions at $Q = 1.4$ GeV for $u, \overline{u}, d, \overline{d}, s = \overline{s}$, and g.

developed by the CTEQ-TEA group, to estimate the impact of each new experimental data set to the updated PDFs. The CT18 PDF uncertainties are mildly reduced as compared to CT14, while the best-fit PDFs are consistent with the CT14. The most important data sets that drive the changes in the quark and anti-quark flavor PDFs are the LHCb W and Z boson data. After including the LHCb W and Z boson data, very mild changes in the fitted PDFs were observed with the addition of the ATLAS 8 TeV and CMS 7 and 8 TeV W and Z boson data in the CT18 fits. The resulting parton distributions for the CT18 and CT18Z fits can be seen in Figure 2. The central gluon PDF has decreased in CT18 at $x \approx 0.3$, with a smaller error band at $x \sim 0.1$ and below. The decrease of g PDF for $0.1 < x < 0.4$ is caused by the inclusion of CMS and ATLAS jet data and ATLAS 8 TeV Z boson transverse momentum data. After the LHC jet data sets are included in the CT18 fits, little changes are found in the fitted PDFs with the addition of the ATLAS and CMS top quark pair data. Furthermore, the value of $(s+\bar{s})\,/\,(\bar{u}+\bar{d})$ increase in the small-x region as compared to CT14, due predominantly to the inclusion of the LHCb data in the CT18 fit, and also ATLAS 7 TeV W and Z rapidity distribution data in the CT18Z fit.

Figure 3 shows the comparison of the various parton luminosities at the 13 TeV LHC, predicted by CT18, MMHT2014 and NNPDF3.1 PDF sets.

The new fits from the MMHT group [5] include the new LHC data sets - notably the particularly precise ATLAS W and Z measurements from 7 TeV which may have implications for the strangeness contribution. The MMHT fit has been updated with an improved and extended parameterisation, and eigenvectors sets, using Chebyshev polynomials which is more accurate and more well behaved that the previous parameterisation. There remain issues with the correlated uncertainties from some of the jet and differential top data. Figure 4 shows the strangeness ratio. $r_s = (s+\bar{s})/(\bar{u}+\bar{d})$ and the light quark asymmetry, $x(\bar{d}-\bar{u})$, for the new MMHT fits. Here, the inclusion of the ATLAS inclusive W and Z data increases the strangeness ratio at low x, whilst still allowing a positive asymmetry, albeit with a maxima at slightly lower x. At the time of the workshop, the full release of the new MMHT PDFs, including QED corrections was expected soon.

The NNPDF Collaboration presented new QCD analyses for the proton densities where [6] it is observed that the difference between the NNLO and NLO fits is now of the order of, or larger than, the PDF uncertainties. As a consequence, significant efforts have been undertaken to better understand the theoretical uncertainties arising from missing higher orders and how these relate to

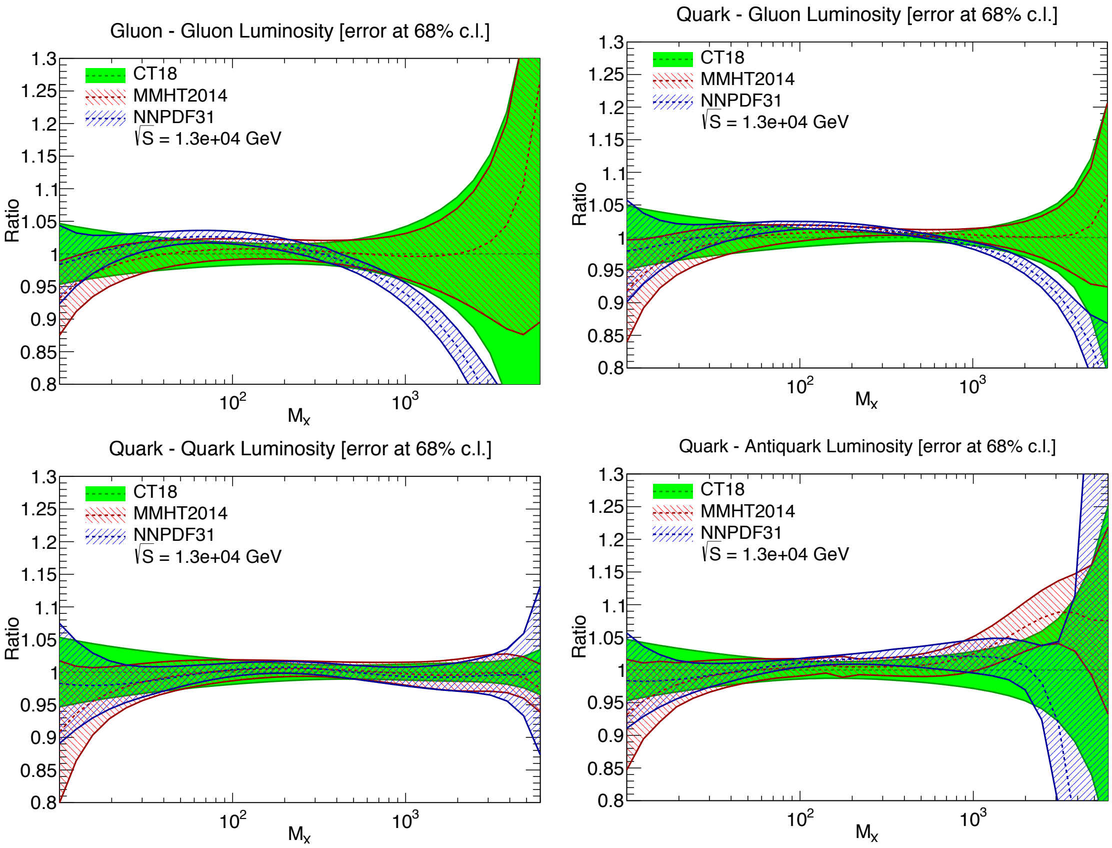

Figure 3: Comparisons of CT18, MMHT2014 and NNPDF3.1 PDF sets in various parton luminosities at the 13 TeV LHC.

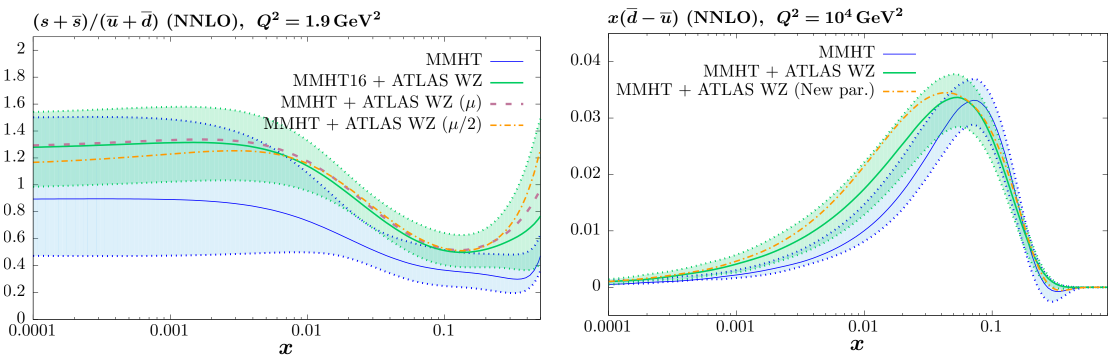

Figure 4: The strangeness ratio (left) and the light quark sea asymmetry (right) from the new fits from MMHT.

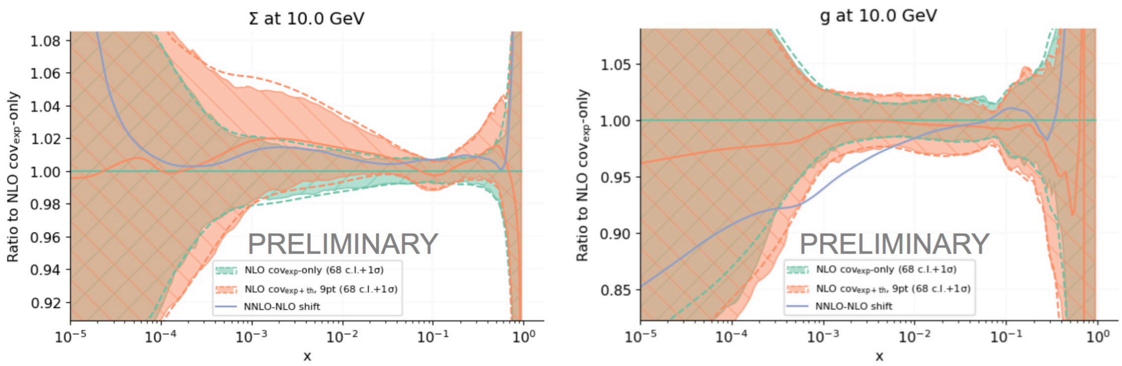

Figure 5: The quark non-singlet and the gluon contributions from the QCD analysis from the NNPDF group.

PDF fits obtained by varying the renormalisation or factorisation scales during the fit. The concept of a theoretical covariance matrix was introduced, which naturally introduced correlations between the predictions for cross sections from different experiments. The resulting uncertainties for the non-singlet and gluon distributions for the PDF at $\mu^2 = 10$ GeV^2, compared to the difference between the NLO and NNLO fits can be seen in Figure 5.

Additional studies on understanding the missing higher order corrections were also presented, notably on the consistent use of scale variation in a PDF fit and the subsequent predictions [7] and in using a statistical description of the behaviour of the theory uncertainty at higher orders assuming that the coefficients are bounded, and using Bayesian inference to obtain an improved estimate of the uncertainty [8, 7].

Figure 6 shows the update to the ABM PDF including higher twist effects, and including top pair production data, together with more stringent cuts. The resulting PDF has a lower strangeness ratio at low x, but still around unity, and higher gluon at low x. The more stringent cuts means that the impact of higher-twist terms is reduced. Some validation of the tools is still required, but steady progress has been made accommodating more of the DY data into the fit, notably the recent ATLAS data at 5 and 7 TeV and the double differential data on Z-boson production from both ATLAS and CMS.

3. Nuclear PDFs

In recent years, there have been many new developments in the extraction of the nuclear PDFs relevant to the nuclear physics community. For example, the CTEQ-based nuclear PDF fit, CTEQ-Jefferson Lab "CJ" PDF fits incorporate higher twist, target mass corrections to extract neutron PDFs from global DIS data at the NLO accuracy, after considering deuteron nuclear corrections for DIS data. The nNNPDF1.0 global PDF fit has been performed at the NNLO accuracy, and was obtained by analyzing all the available neutral current DIS data for A=2 to A=208. Another CTEQ-based nuclear PDF fit, called nCTEQ, was also recently updated using nCTEQ++ code with APPLgrid predictions in order to make it possible to include the $p-Pb$ scattering data from the LHC in nCTEQ fit.

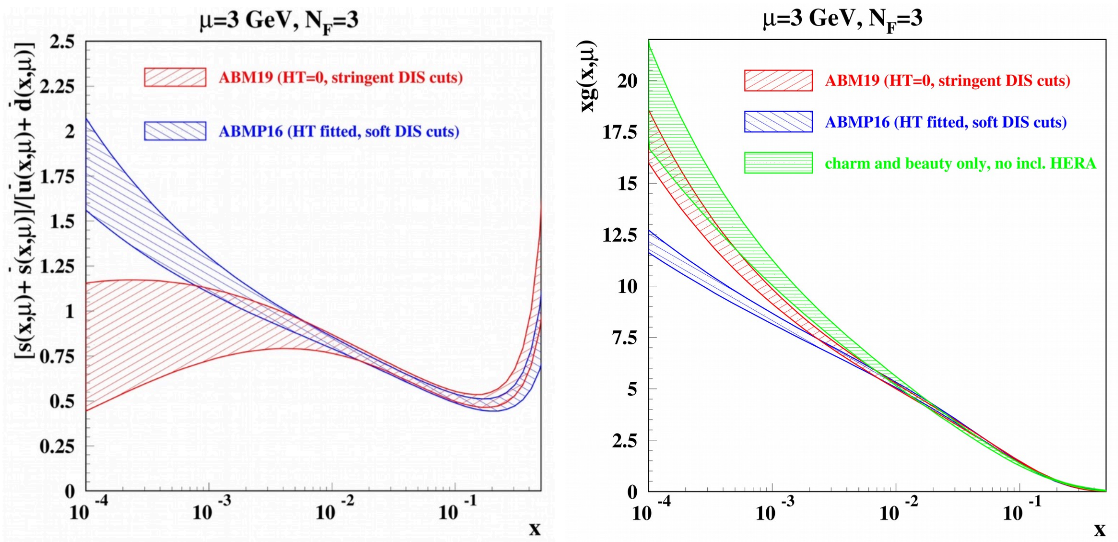

Figure 6: The strangeness ratio (left) and gluon contribution (right) from the new ABMP19 fit.

4. New data for PDF determination

Precision measurements of vector boson production cross sections at the LHC yield important information about the quark PDFs in the proton. New measurements of inclusive W and Z production at 5.02 and 8 TeV were presented by ATLAS [9, 10]. The data reach percent level precision and in particular, are the first presented measurement of this kind at 5.02 TeV. It is expected that the difference in beam energy with respect to existing measurements can be exploited to provide additional sensitivity to the quark distributions at different x values.

LHC data on top quark pair ($t\bar{t}$) production is already used in global PDF fits to constrain the gluon distribution – see for instance the ATLAS fits presented at this workshop [13]. With the increased statistics of Run 2 new measurements become possible. The first measurement of the triple-differential $t\bar{t}$ cross section was presented by CMS [14, 11]. Observables were chosen which are sensitive to different aspects of the production dynamics, enabling from this measurement, a simultaneous determination of the PDFs, α_s and top quark pole mass, m_t^{pole}. The α_s and m_t^{pole} values extracted using different PDF sets are shown in Figure 7 (left). The fit with the new $t\bar{t}$ data reveals a significant constraint on the gluon PDF at high x and provides a precise determination of both α_s and m_t^{pole} with a weak correlation between them. The latest ATLAS PDF fit to include top data was also presented [13], using recently available NNLO calculations. Furthermore, the impact of the $t\bar{t}$ data in the CTEQ-TEA analysis was discussed in detail using the `ePump` code [15], concluding that the $t\bar{t}$ data have a similar effect on the PDFs as the jet data, though with a larger uncertainty due to the significantly lower number of data points. However, when jet data is already included in the global fit, the top quark pair data does not have noticeable effect on further constraining the gluon PDF.

The NNLO corrections for jet production in ep [17] and pp [18, 19] collisions recently became available. Measurements of jet cross sections are a significant factor in the determination of the gluon PDF and α_s. The H1 and ZEUS collaborations presented the new fit of the inclusive DIS data,

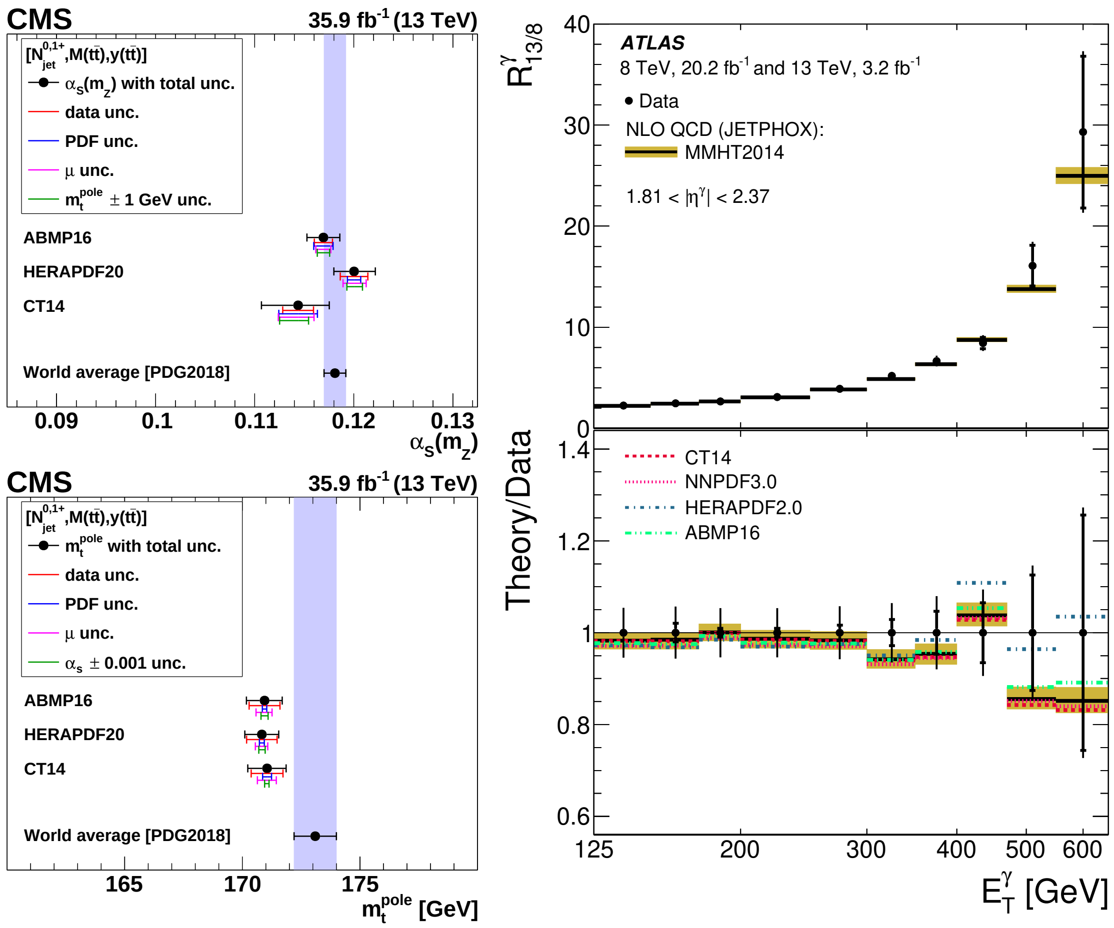

Figure 7: The α_s (top left) and m_t^{pole} (bottom left) values extracted from CMS triple-differential cross sections for $t\bar{t}$ production [11]. On the right, are shown the ratios of the cross sections for inclusive isolated-photon production at 13 and 8 TeV measured by ATLAS, compared to NLO QCD predictions using different PDF sets [12].

also including also the HERA jet data from both H1 and ZEUS at full NNLO using calculations from NNLOJET mentioned earlier and a new extraction of α_s from the inclusive DIS jet data that will be discussed later. It is rewarding to see the jet data starting to be used in QCD fits to DIS data at full NNLO, and it will be extremely interesting to see what effect this has when the LHC jet data can be included in a PDF fit at full NNLO. In this light, some of the LHC jet measurements [16] could still benefit from a more complete understanding of the systematic uncertainties and the correlations between the data points. These data are able to distinguish between modern PDF sets as shown in Figure 8 so being able to use these data in fits with NNLO calculations will be of great benefit. An impressive array of the correlated systematics which affect the ATLAS measurements of jet production has been studied [20], providing important information on how the uncertainties should be included in a fit to these data.

New measurements of prompt photon production [21], also in association with jets [12], was presented by ATLAS [22]. The measured ratios of cross sections for prompt photon production at 8 and 13 TeV afford a substantial reduction of many experimental and theoretical uncertainties,

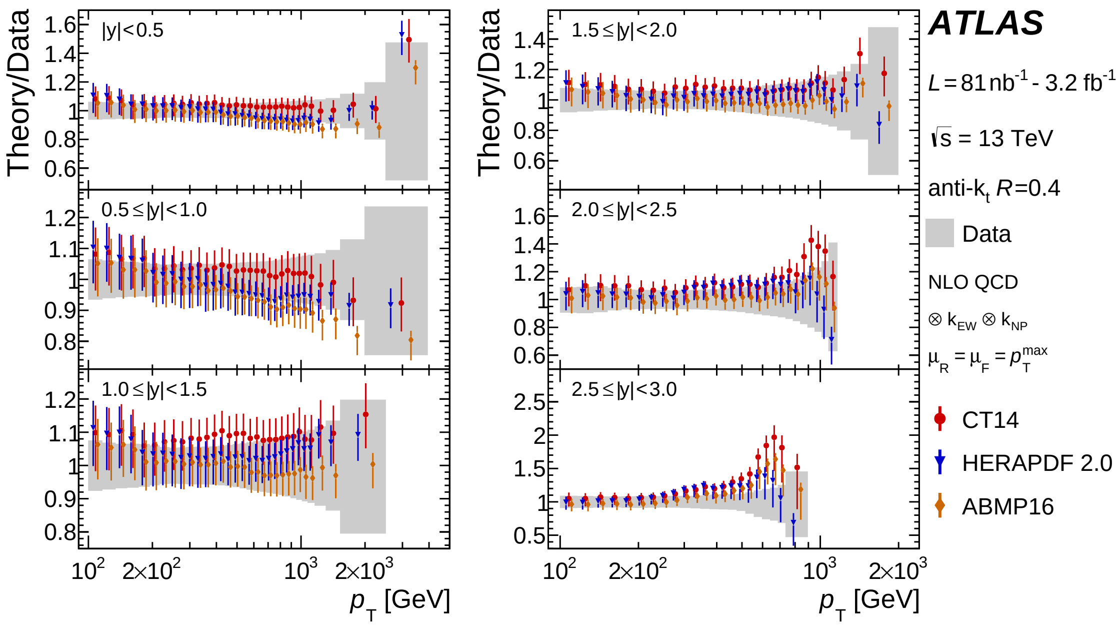

Figure 8: Comparison of the ATLAS inclusive jet cross-sections and the NLO QCD predictions obtained using different PDF sets [16].

providing a stringent test of perturbative QCD. The sensitivity of the new data to the PDFs is visualised in Figure 7 (right). New calculations of direct photon production at NNLO are starting to become available, so these data are starting to become more significant.

Additional new measurements from HERA continue to appear, such as the measurement of charm production in Charged Current [23, 24] DIS, and the investigation of the parton densities at very high Bjorken x [25].

New data from the SeaQuest experiment were presented [26], and the status of the analysis towards determining the $\bar{d}/\bar{u}$ ratio at high values of x was discussed. Another source of information for the $\bar{d}/\bar{u}$ ratio comes from the (W^+/W^-) cross section ratio from STAR, and preliminary results of the 2011–2013 cross section ratio measurements were presented [27].

Continuing with W data, the ATLAS Collaboration also presented a QCD analysis [28] using on the HERA inclusive data and the high precision ATLAS inclusive W And Z data, but also including the ATLAS $W + jet$ data at 8 TeV. The additional QCD emission allows a better constraint of the quark distributions at higher x, such that the strangeness ratio is reduced for x in the region of 0.1, due to a small increase in the d sea quark distribution. However, the enhanced strangeness at low-x is confirmed, this time with positive $\bar{d}-\bar{u}$, being more in line with the observation from the global fits.

In addition, studies of $W + c$ production were also presented [29] using the data on D meson production from the LHCb Collaboration, illustrating the potential of these data to constrain the strange quark and gluon densities, although some open questions remain. Using the high precision data from the High Luminosity LHC running, the $W + c$ data in the forward direction should greatly help to constrain the strange density [30], and the precision data from the higher energy electron-proton collisions from the proposed LHeC, should be able to greatly constrain the gluon distribution

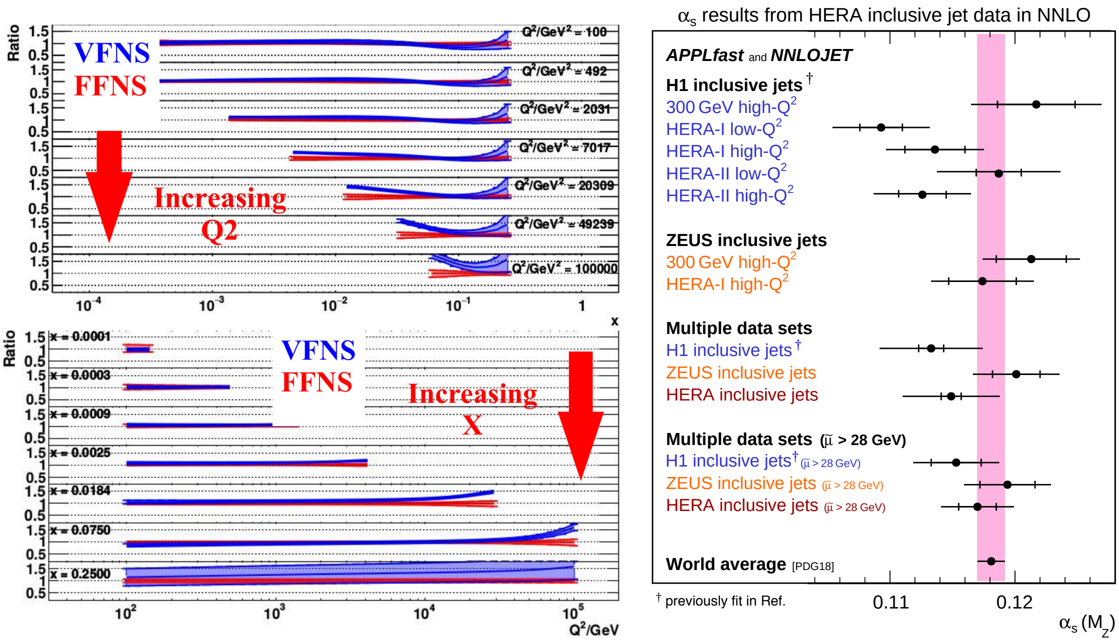

Figure 9: Predictions for charm production in Charged Current at the LHeC (left) obtained in different heavy-flavour schemes [32]. On the right, values of α_s extracted from measurements of jet production at HERA [33].

at very high x through correlations with the other parton densities which would become increasingly well constrained [31].

5. Updates on theoretical calculations and tools

The importance of heavy-flavour production processes as a tool for constraining the proton PDF was discussed [29], and recent theoretical developments for W boson production in association with heavy quarks, and heavy-quark pair hadroproduction were presented. In particular, theoretical predictions in the $\overline{\mathrm{MS}}$ scheme as an alternative to the on-shell scheme for renormalising the heavy-quark masses were advertised. Furthermore, the phenomenological relevance of different heavy-flavour schemes in the semi-inclusive DIS production of the charm and bottom quarks, and the impact of resummation of large logarithms, was discussed [34]. The theoretical understanding of heavy-quark hadroproduction is important for the interpretation of future data from neutrino telescopes such as IceCube and KM3NET, and state-of-the-art predictions for the ultra-high energy neutrino-nucleus cross sections in Charged Current and Neutral Current scattering were presented [35]. It was suggested that astroparticle experiments will play a role as the ultimate QCD microscopes and offer further opportunities to study the strong interaction at extremely high scales.

To fully exploit the potential of new experimental data and theoretical calculations, advanced fitting tools are required. One such tool is xFitter [36] which was the first open-source QCD fit framework. An increasingly large number of results have been obtained using xFitter recently [32], for example, a study of the heavy-flavour scheme in different kinematic regimes has been performed, and is shown in Figure 9 (left). A study examining the PDF constraints obtained from measurements of the Drell-Yan forward-backward asymmetry at the High Luminosity LHC using xFitter was also presented [37], demonstrating that such data will provide information mostly on the sum of u and d valence quark distributions, and thus will be complementary to the measurement of the W asymmetry which constrain the difference of u and d valence quark distributions. Another study using xFitter focusing on the fits to the HERA data was presented, and a new functional form for the PDF parameterisation at the starting scale was proposed [38]. The new parameterisation gives an improved description of the HERA data. Similar functionality to that from xFitter, provided by `ePump`, was also presented [15], and includes the effects of considering the potential tensions between various precision experimental data.

The usage of experimental data on hadronic interactions, particularly that from the LHC means that for fits to the PDF at NNLO fast computation techniques, such as APPLgrid [39, 40] or fastNLO [41, 42], are required. These provide a fast and flexible way to reproduce the results of the perturbative QCD cross section calculations with any PDF, renormalisation or factorisation scale, and α_s values. Recent developments in the generation and distribution of fast interpolation grids from the APPLfast group were presented for LHC processes [43] and for inclusive jet production in DIS [44]. The APPLfast project provides a standardised interface between the physics processes implemented at NNLO from the NNLOJET calculation code with the the fast interpolation grid code from APPLgrid and fastNLO. The grids for the inclusive DIS jets were presented and have been made available [33, 44], together with an exemplary application of a determination of α_s, shown in Figure 9 (right).

The latest developments concerning the APFEL++ program were also presented [45]. The APFEL++ project is a reimplementation in C++ of the original Fortran evolution code APFEL, and provides PDF evolution and structure function calculations. APFEL++ is based on a completely new code design and guarantees better performance along with more optimal memory management. An efficient numerical solution of the DGLAP equations for single and double PDFs, based on the Chebyshev interpolation of these functions was presented [46].

Finally, it should be noted that at this conference, there were also many theoretical works reported relating to other important aspects of theoretical developments with insufficient space here to do them justice. An incomplete list of some of these include, but is not limited to; developments in the resummation of large-logs in DIS processes; hadron mass corrections in DIS and semi-inclusive DIS processes; the estimation of the uncertainties from missing higher order contributions in PDF fits; the effect of nuclear uncertainties in the extraction of PDFs; the investigation of new parameterised forms for non-perturbative PDF at the starting scale; using the parton branching method to generate transverse momentum dependent PDFS; the extraction of photon PDFs; and the discussion of the fracture functions and their factorisations. The authors recommend that the reader study the proceedings for these, and the many other important developments.

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