

Parton distributions and LHC data

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Summary. — In this contribution we briefly report on the progress and open problems in parton distribution functions (PDFs), with emphasis on their implications for LHC phenomenology. Then we study the impact of the recent ATLAS and CMS W lepton asymmetry data on the NNPDF2.1 parton distributions. We show that these data provide the first constraints on PDFs from LHC measurements.

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1. – Progress and open problems in parton distributions

The quantitative control of the Standard Model contribution to collider signal and background processes at the few percent level is a necessary ingredient not only for precision physics, but also for discovery at the LHC. The precision determination of parton distribution functions (PDFs) is essential in order to achieve this level of theoretical accuracy.

There has been substantial progress in PDF analysis in the last years, and it is thus impossible to review it in detail in this contribution. A recent concise report of the status of the field can be found in ref. [1], while more detailed reviews can be found in refs. [2-5]. In this contribution we restrict ourselves to highlight some important topics in PDF determinations. First of all, we will sketch the current status of PDF fits and discuss some of the open problems in the field. Then we will discuss how the ATLAS and CMS measurements of the W lepton asymmetry data provide the first constraints on PDFs from the LHC, thus paving the way for PDFs based on LHC data.

PDF analysis have entered the era in which they can be considered as a quantitative science. An ideal PDF determination should satisfy several important requirements [2]. These include being based on a dataset which is as wide as possible, in order to ensure that all relevant experimental information is retained, to use a sufficiently general and unbiased parton parametrization and to provide statistically consistent confidence levels for PDF uncertainties. Moreover, such ideal set should include heavy quark mass effects through a GM-VFN scheme [6] and be based on computations performed at the highest

TABLE I. – Summary of the features of the most updated PDF sets from each group. The CT10, MSTW08 and NNPDF2.1 sets include data from a wide variety of physical processes and are thus called global PDF sets. See text for more details.

	Ref	Dataset	Parametrization	PDF uncertainties
ABKM09	[14]	DIS+DY	Polynomial	Hessian, standard tol.
CT10	[15]	DIS+DY+W/Z+jet	Polynomial	Hessian, dyn. tol.
HERAPDF1.0	[16]	DIS	Polynomial	Hessian, standard tol.
JR08	[17]	DIS+DY+jet	Polynomial	Hessian, fixed tol.
MSTW08	[18]	DIS+DY+W/Z+jet	Polynomial	Hessian, dyn. tol.
NNPDF2.1	[12]	DIS+DY+W/Z+jet	Neural Nets	Monte Carlo

	PT order	Heavy Quarks	Strong coupling
ABKM09	NLO/NNLO	FFNS	Fitted
CT10	NLO	S-ACOT- χ	Fixed + range of values
HERAPDF1.0	NLO	TR	Fixed
JR08	NLO/NNLO	FFNS	Fitted
MSTW08	LO/NLO/NNLO	TR	Fitted + range of values
NNPDF2.1	NLO	FONLL-A	Fixed + range of values

available perturbative order. Finally, PDF sets should be provided for a variety of values of α_s , reasonably thinly spaced, similarly for the heavy quark masses, and should include an estimate of uncertainties related to the truncation of the perturbative expansion. While for each of these aspects there has been sizable progress in the recent years, still no PDF sets fulfill all these conditions.

One important development in PDFs in the recent years has been the NNPDF approach [7-11]. Thanks to a combination of Monte Carlo techniques and the use of artificial neural networks, the NNPDF approach avoids some of the drawbacks of the standard approach like the bias due to the arbitrary choice of input functional forms or the use of linear approximations for PDF uncertainty estimation. The most updated NNPDF set is NNPDF2.1 [12], an unbiased NLO global fit of all relevant hard scattering data based on the FONLL-A GM-VFN scheme [13].

Several groups provide regular updates of their PDF sets: in alphabetic order these are ABKM, CT, HERAPDF, JR, MSTW and NNPDF. In table I we summarize some of the features of the most updated PDF sets from each collaboration. We consider only those sets available in the LHAPDF library. We compare the dataset, parametrization, method to estimate PDF uncertainties, perturbative order at which PDFs are available, the theoretical schemes adopted to include heavy quark mass effects and the treatment of the strong coupling α_s . More details on each of these issues can be found in refs. [2, 4, 5], as well as in the original publications of each group.

The main difference arises from the data sets used in each of the various analysis. The CT10, MSTW08 and NNPDF2.1 sets include data from a wide variety of physical

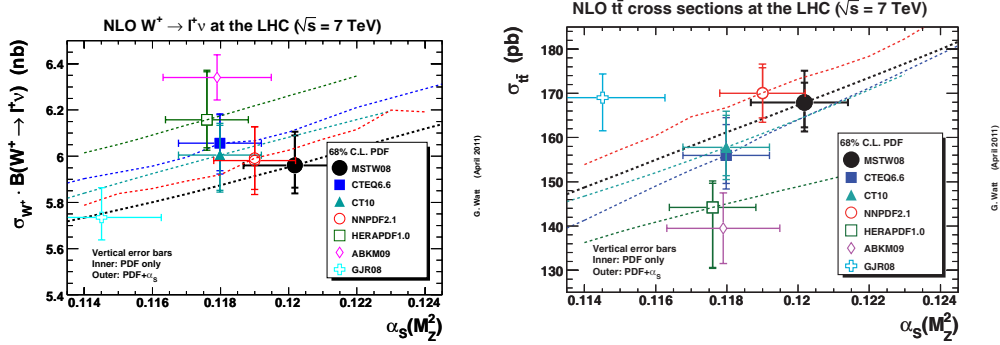


Fig. 1. – Comparison of the NLO total cross sections for W^+ and $t\bar{t}$ production and their combined PDF+ α_s uncertainties at the LHC 7 TeV between the most updated PDF sets of each group. Plots from G. Watt.

processes and are thus called *global* PDF sets. Other PDF sets use more restrictive subsets, like ABKM09, which excludes Tevatron jet and weak vector production data and HERAPDF1.0, that is based solely on HERA data.

PDFs are typically parametrized with relatively simple functional forms like $q(x, Q_0^2) \sim x^a(1-x)^b P(x, c, d, \dots)$ with P a polynomial that interpolates between the small- and large- x regions. These unjustified theoretical assumptions introduce a potentially large functional form bias in PDF determinations. The NNPDF approach bypasses this problem using neural networks as universal unbiased interpolants. Related techniques for general PDF parametrizations like Chebishev polynomials have also been discussed in the literature [19, 20].

PDF uncertainties are estimated by all groups (but NNPDF) using the Hessian method. However, different choices for the tolerance $T = \sqrt{\Delta\chi^2}$ adopted to define 1-sigma PDF uncertainties are used. For example, while HERAPDF1.0 and ABKM08 are based on a textbook tolerance $\Delta\chi^2 = 1$, MSTW08 and CT10 adopt a dynamical tolerance criterion that results in tolerances $\Delta\chi^2 \geq 1$, which are moreover different for each eigenvector direction. The need for large tolerances has been suggested to partly arise when restrictive input functional forms are used [20]. NNPDF, on the other hand, is based on the Monte Carlo approach, that is, a sampling in the space of experimental data, that allows an exact uncertainty propagation from data to PDFs and from these to physical observables.

Recently, a detailed benchmarking of the predictions for relevant LHC observables from modern NLO PDF sets was performed in the context of the PDF4LHC working group [5]. In fig. 1 we compare the NLO predictions for different PDF sets for two important LHC observables, the total W^+ and $t\bar{t}$ cross sections. One of the conclusions from that study is that the agreement between *global* PDF sets is reasonable for most LHC processes, much better than for sets based on restrictive datasets. However, it was also clear that even within global sets there are important discrepancies whose origin needs still to be understood, related for example to the large- x gluon and to strangeness. Another recent benchmark study, this time at NNLO, was presented in [21].

The PDF4LHC exercise allowed to elucidate differences and similarities between PDF sets. In particular it showed that the most important source of difference between sets is the choice of fitted data. This study was the basis of the PDF4LHC recommendation [22],

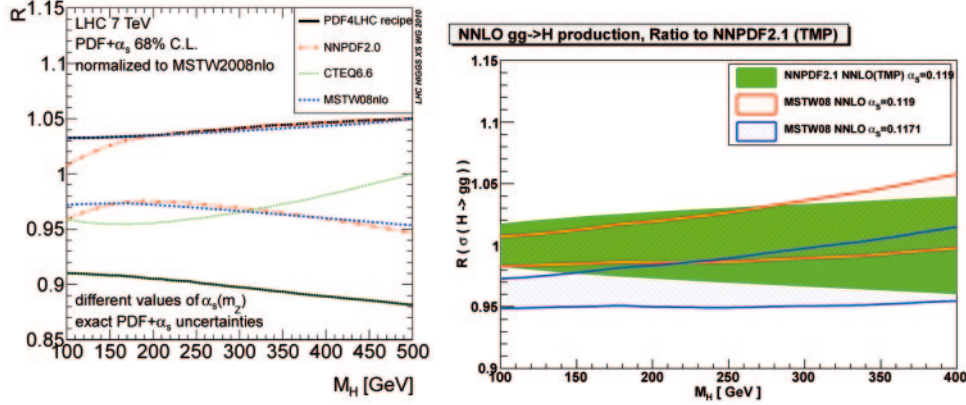


Fig. 2. – Left plot: Comparison of the NLO Higgs production cross section with the combined PDF+ α_s uncertainties from NNPDF2.0, MSTW08 and CTEQ6.6, and the resulting PDF4LHC recipe [22] envelope, from ref. [1]. Right plot: comparison of the MSTW08 and the preliminary NNPDF2.1 NNLO predictions for the NNLO Higgs production cross section. For the MSTW08 prediction two values of α_s have been used.

that suggests to take the envelope of the combined PDF+ α_s uncertainties from the three global PDF sets, CT10, MSTW08 and NNPDF2.1, to estimate the PDF+ α_s uncertainty on LHC processes. The PDF4LHC has been adopted by ATLAS and CMS in those analysis sensitive to PDFs, and in particular the LHC Higgs cross section working group [1] uses the PDF4LHC recipe to estimate the combined PDF+ α_s uncertainty in their theoretical predictions, see fig. 2. The same recipe has been used to derive the most updated Tevatron Higgs exclusion limits [23].

Let us now turn to discuss some open problems in PDF fits: the treatment of α_s , Higgs production at hadron colliders and deviations from DGLAP in HERA data. The treatment of the strong coupling in PDF fits is a source of differences between sets, as summarized in table I. Some groups, like MSTW or ABKM, determine α_s simultaneously with the PDFs, while others, like CT or NNPDF, take for α_s a fixed value close to the PDG average [24], $\alpha_s(M_Z) = 0.1184 \pm 0.0007$ in the latest update. Differences between PDF sets are reduced when a common value of α_s is used, as shown also in the comparison plots of fig. 1.

Let us emphasize that the choice of fixing α_s to the PDG value in the reference PDF set is not necessarily related to the sensitivity of a given PDF analysis to α_s . Rather, it reflects the idea than the average of α_s from a wide range of processes, including some like τ decays unrelated to the proton structure, is necessarily more accurate than the determination from a single PDF fit. For example, NNPDF [25] has recently performed a NLO determinations of the strong coupling, finding good consistency with the PDG value: $\alpha_s(M_Z) = 0.1191 \pm 0.0006$, where the uncertainty is purely statistical.

The treatment of α_s is closely related to one of the most important process at the LHC, the Higgs production cross section in its dominant production channel of gluon fusion. This process is very sensitive to α_s [26], since the partonic cross section depends as $\mathcal{O}(\alpha_s^2)$ already at leading order, and has received a lot of attention recently due to claims that theoretical uncertainties were being underestimated. Preliminary NNLO results from NNPDF, shown in fig. 2, suggest a reasonable agreement with the MSTW08

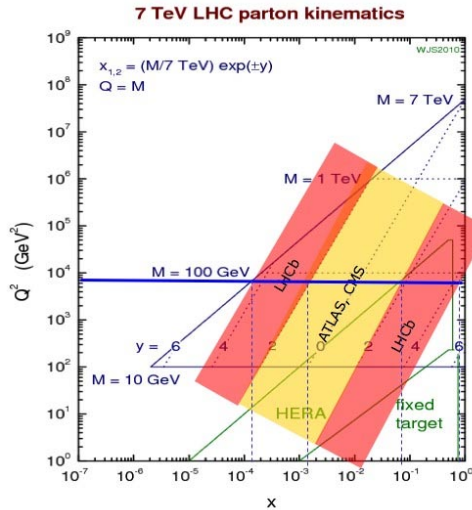


Fig. 3. – The kinematic coverage in the (x, Q^2) plane for W production at the LHC in the central (ATLAS and CMS) and forward (LHCb) regions.

NNLO prediction, as was already the case at NLO, thus confirming the PDF4LHC recipe estimates. It is also clear how the use of a common value of α_s improves further the agreement between the two sets.

Another open problem in PDF determinations are the potential departures from fixed-order DGLAP evolution in small- x and Q^2 HERA data. The analysis of refs. [27, 28] found evidence for deviations from NLO DGLAP in the small- x combined HERA-I data, consistent with small- x resummation and non-linear dynamics but not with NNLO corrections. This effect has been confirmed by the HERAPDF analysis, which also finds a worse fit quality at NNLO for the small- x data. A related CT10 [29] analysis found some hints as well but it was restricted to the use of few functional forms for the small- x PDFs. If deviations from DGLAP for low- x HERA data are confirmed, this suggests that small- x resummation [30] is a necessary ingredient in order to use all the potential of HERA data for precision LHC physics.

2. – Constraining PDFs with LHC W asymmetry data

We now turn to discuss the first constraints on PDFs from LHC data, provided by the ATLAS [31] and CMS [32] measurements of the leptonic W asymmetry⁽¹⁾. As is well known, W production at hadron colliders is sensitive to the light quark and antiquark PDFs at medium and small- x . The kinematic coverage of W production at the LHC is summarized in fig. 3. We have studied the impact of the W asymmetry data using the Bayesian reweighting method of ref. [33]. Bayesian reweighting is a powerful technique to efficiently determine the impact of new data into PDFs without the need of refitting. This method also allows to determine the internal consistency of the data sets and their compatibility with the global fit.

⁽¹⁾ There exist as well preliminary data from LHCb that will be sensitive to even smaller and larger values of x , see fig. 3.

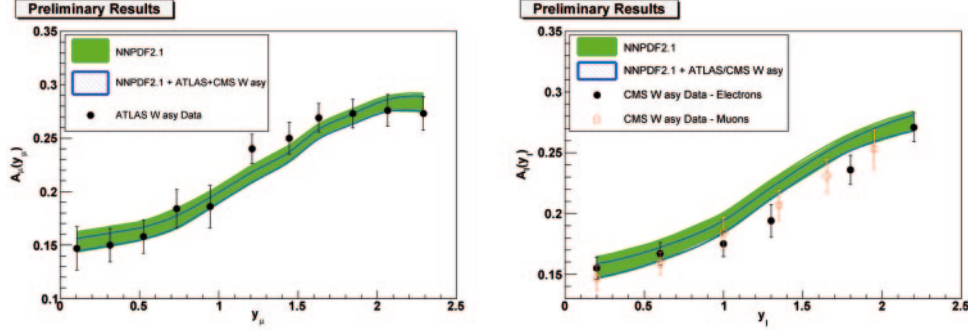


Fig. 4. – The ATLAS and CMS W lepton asymmetry data compared to the NNPDF2.1 predictions before and after reweighting.

A detailed discussion of the impact of LHC data on NNPDF will be presented elsewhere. In this contribution we restrict ourselves to some selected preliminary results. We will show results for the impact of the combined ATLAS and CMS data. In the case of CMS we consider the more inclusive dataset (with the cut in lepton transverse momentum of $p_t^l \geq 25$ GeV) and both electrons and muons. For ATLAS only the muon asymmetry has been presented. The theoretical predictions have been computed with the DYNLO generator [34] at NLO accuracy for NNPDF2.1. The kinematic cuts are the same as in the respective experimental analyses.

In fig. 4 we compare the ATLAS and CMS lepton asymmetry data with the NNPDF2.1 predictions before and after including the effect of these data sets. We notice that the data is already nicely consistent with the NNPDF2.1 prediction within the respective uncertainties. After including the LHC measurements, one finds that the W asymmetry data constraints the PDF uncertainties and leads to an even better agreement with the data. A more detailed statistical analysis confirms that the ATLAS and CMS data are consistent between them and with the experiments included in the global PDF analysis. After reweighting, the χ^2 per data point of the combined CMS and ATLAS data is ~ 1 .

Next, in fig. 5 we show the constraints on the PDFs provided by the combined ATLAS and CMS W asymmetry data. We find that the PDF uncertainties are reduced for

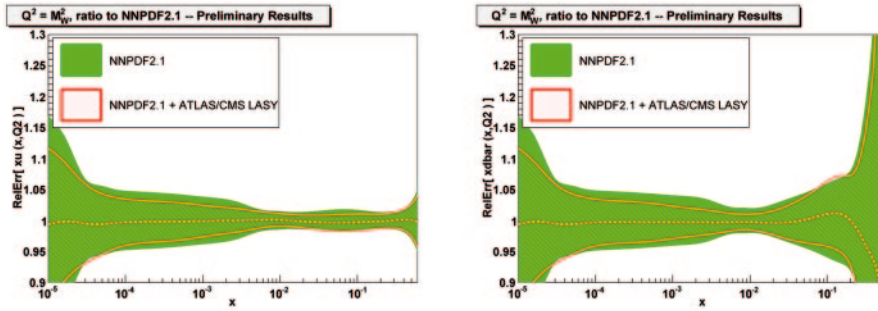


Fig. 5. – The impact of the ATLAS and CMS lepton asymmetry data on the relative uncertainty of the light quark and antiquark NNPDF2.1 PDFs.

medium- and small- x light quark and antiquarks, by a factor that can be as large as $\sim 30\text{--}40\%$. The impact on other PDFs is smaller. The central PDF prediction is almost unaffected by the LHC data, confirming further the consistency of the W asymmetry measurements with the global fit. At large- x the constraints are weaker, as expected from the kinematic coverage shown in fig. 3. Upcoming measurements of this asymmetry by LHCb might help in reducing PDF uncertainties in the large- x region.

Note that these preliminary results have been derived from a sample of only $N_{\text{rep}} = 100$ Monte Carlo replicas. This means that there can be non-negligible fluctuations and explains why PDF uncertainties are apparently reduced even at very small x , outside the kinematic coverage of the ATLAS and CMS data.

To summarize, we have shown that the W lepton asymmetry is the first dataset from the LHC that has the precision to constrain PDFs and thus improve the accuracy of Standard Model computations for LHC processes. We have quantified this impact on the light quark and antiquark PDFs, and found that PDF uncertainties can be reduced by factors up to $\sim 40\%$ at medium and small x . More constraints on PDFs should soon be available from upcoming LHC measurements.

3. – Outlook

In this contribution we have briefly reviewed recent developments and open problems related to PDFs, with emphasis on their implications for the LHC physics program. While our understanding of the proton structure has seen a huge progress in the recent years, there are still open questions that need to be answered, and that are important to improve even further the accuracy of theoretical predictions at the LHC. We have also presented preliminary results on the impact of the LHC W lepton asymmetry data on the NNPDF2.1 set. We have shown that these data provide the first constraints on PDFs from LHC measurements, in particular they help to pin down with better accuracy the medium- and small- x light quarks and antiquarks.

In the medium term, LHC measurements will provide very important constraints on most PDF combinations. This will allow parton distributions to be derived solely from collider data: HERA, Tevatron and the LHC. Collider data is more robust theoretically and experimentally than low-energy fixed target data, that now provide basic constraints in global PDF analysis. In order to achieve this program, several measurements will be provided by the LHC: Z -boson rapidity distributions, low mass Drell-Yan differential distributions, high- E_T jets and photons, and W/Z production in association with heavy quarks. The increased experimental and theoretical accuracy on PDFs determined this way will provide a solid ground for precision Standard Model predictions and searches for new physics at the LHC.

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