Parton Distribution Functions at present and future colliders

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Abstract

In this contribution we give a brief overview of the status of Parton Distribution Function (PDF) determinations as of September 2015, with particular emphasis on the impact of Run I LHC data already included in the fits. We then move to discuss which measurements could be performed during the LHC Run II and at future colliders that could provide relevant constraints for PDF determinations.

1 Introduction

Parton Distribution Functions (PDFs) encode the information on the longitudinal momentum carried by quarks and gluons inside a hadron when it undergoes an high energy collision. In this respect, they are one of the fundamental building blocks of theoretical predictions for observables at experiments carried out at hadron colliders.

In perturbative QCD the cross-section for inclusive production of a massive final state (X) in an hadron-hadron collision can be written, according to the Factorization Theorem [1], in a convolution form as

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1, \mu_F) f_b(x_2, \mu_F) \hat{\sigma}_{ab\to X} \left(x_1, x_2, \alpha_s(\mu_R), \frac{Q^2}{\mu_R}, \frac{Q^2}{\mu_F} \right) , \tag{1}$$

where the sum runs over the partonic content (quarks, antiquarks and gluon) of the hadrons, f_a and f_b are the Parton Distribution Functions of the incoming hadrons, $\hat{\sigma}$ denotes the partonic cross-section, μ_F and μ_R are the factorisation and renormalisation scales and Q is the typical hard scale of the process.

Parton densities are non-perturbative quantities, which cannot be determined from first principle computations in perturbative QCD. They are extracted from global fits to a wide variety of data from Deep Inelastic Scattering (ep) and hadron collider (pp) experiments.

2 Overview of Parton Distribution Function determinations

Different groups regularly produce PDF fits and recently released updated versions of their sets [2, 3, 4, 5, 6]. The most recent PDF determinations differ primarily because of the data sets on which they are based. On the one side there are the global fits (CT [3], MMHT [5] and NNPDF [6]), which aim to include a large number of different processes and observables in order to constrain most combinations of parton densities. On the other side there are those PDF determinations, like ABM [2] and especially HERAPDF [4], which are based on restricted, but more homogeneous data sets for which theoretical predictions are available at the highest perturbative order (NNLO). Aside from the data set, PDF determinations difffer in many aspects of the fits. For example the way heavy flavour mass effects are taken into account, the number of PDF combinations parametrized at the initial scale and the form of parametrisation (either fixed functional forms or neural networks). In Table 1 we collect relevant information about the ingredients entering the most recent updates of the mentioned PDF determinations.

Due to the assumptions made by the various groups the parton densities and their uncertainties determined by different collaborations show differences both in central values and uncertainties size which are suggestive of the fact

Table 1: *Parton Distribution Function fits routinely used in the experimental analyses at the LHC experiments and their characterisitics: the perturbative QCD order, the scheme in which the heavy flavour contibutions are treated (Fixed Flavour Number Scheme or General Mass Variable Flavour Number Scheme), whether the strong coupling constant is fitted along with the PDF parameters, how many independent PDF combinations are parametrised at the initial scale and whether polynominal functional forms or Neural Networks are used and the form of PDF uncertainties are represented, whether Hessian (with or without tolerance) or Monte Carlo.*

PDF set	**PT Order**	**HQ Treat.**	α_s	**Param.**	**Uncert.**
ABM12 [2]	NLO NNLO	FFN	Fit	6 indep. PDF Polynom.	Hessian
CT14 [3]	LO NLO NNLO	GM-VFNS	Input	6 indep. PDF Polynom.	Hessian Tolerance
HERAPDF2.0 [4]	NLO NNLO	GM-VFNS	Input	5 indep. PDF Polynom.	Hessian
MMHT14 [5]	LO NLO NNLO	GM-VFNS	Fit	7 indep. PDF Polynom.	Hessian Tolerance
NNPDF3.0 [6]	LO NLO NNLO	GM-VFNS	Input	7 indep. PDF Polynom.	Monte Carlo

that a single group might underestimate the uncertainties and a combination of individual PDF sets is required for a reliable estimation of uncertainties on LHC cross-sections. Such a combination has recently been performed in the context of the PDF4LHC working group [7] and PDFs made available through the LHAPDF interface [8].

3 Impact of LHC Run I data on PDF fits

The three global fits (CT, MMHT and NNPDF) already include in their fits a substantial number of data sets from the LHC experiments (ATLAS, CMS and LHCb). In particular, the NNPDF3.0 data set includes ATLAS and CMS inclusive jet data and top pair production total cross-section, W and Z rapitidy distributions from ATLAS and LHCb. W asymmetry and double differential Drell-Yan data from CMS and associated production of W boson with a charm quark.

These data provide moderate, but already noticeable, constrains on different PDF distributions. In Fig. 1 we illustrate the impact of LHC Run I data by comparing the outcome of two fits from the NNPDF3.0 series [6], one with and one without LHC data. It is clear how different data sets do provide constraints on different PDF combinations. In particular, the impact of inclusive jet data is seen in the reduction of the uncertainties on the gluon distribution and medium-/large-x, the light quark flavours are affected by the inclusion in the fit of the CMS W boson asymmetry and double-differential Drell-Yan data and, finally, the CMS associated production of a W boson with a charm quark data provide the best constraint on the strange quark distribution.

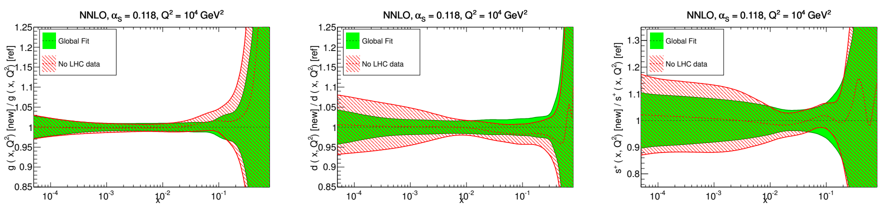

Figure 1: *Impact of the LHC data included in the NNPDF3.0 analysis on different PDF combinations: the gluon parton distribution (left), the d quark distribution (center) and the* $(s+\bar{s})$ *distribution (right).*

4 More constraints to come from LHC Run I and Run II data

A detailed study of PDF related issues at the LHC experiments has recently been completed [9]. This includes a thorough assessment of the impact of LHC Run I data on PDF fits and the identification of a number of measurements, both with Run I and Run II data, which could provide important constraints when included in PDF determinations.

Among the measurements performed by ATLAS, CMS and LHCb at the LHC Run I, which have the potential to substantilly constrain PDFs and have not yet been included in PDF fits we find the associated production of vector bosons (W, Z) with heavy quarks (c, b) which provide independent constraints on the charm and bottom distributions, allowing us to measure eventual intrinsic heavy quark components. The Z transverse momentum distribution measurements, either in the inclusive or the $Z + jet$ channel, give an independent constrain to the gluon distribution in the x range relevant for Higgs production in gluon-gluon fusion. Multi-jet (dijet and three-jets) distributions, when cross-correlations with inclusive jet production are properly accounted, strenghten the constraints on the gluon distribution at large x. Other measurments that have the potential to constrain the gluon distribution in the medium-/large-x region are direct photon production and top quark pair differential distributions. Finally, it is important to keep in mind that the LHCb experiment, with its unique coverage of the forward kinematic region, allows us to explore the small-x region [10]. In particular, the LHCb measurements of low-mass Drell-Yan are sensitive to quark distributions at x values as low as $8 \cdot 10^{-6}$ for $Q^2 = 25$ GeV^2 and the measurements of J/Ψ and Υ photo-production can put strong constraints on the low-x gluon.

During the Run II period the LHC will collide protons at 13 TeV center-of-mass energy, with an expected integrated luminosity up to 300 fb^1. The higher center-of-mass energy compared to Run I implies larger cross sections and extended kinematic reach for many processes which are of interest in PDF fits. The expected increase in the inclusive cross-section is by a factor of 2 for W and Z production an a factor of 4 for top pair production. At the same time the kinematic coverage for processes like inclusive jets and prompt photons will be substantially extended. This means that Run II data will not only strenghten the constraints from LHC data already included in PDF fits but will provide constraints in regions not probed by present data.

Finally, the possibility of using ratios of measurements at different center-of-mass energy, taking into account the full information on systematic cross-correlations, will prove to be a crucial tool to fully exploit the physics potential of the LHC data for constraining PDFs and, at the same time, looking for new physics. A study of the potential impact of LHC Run II data in PDF fits, based on a profiling analysis performed using the HERAFitter code [11], has been presented in the PDF4LHC report [9]. In Fig.2 we show as an example the expected impact on the up and down valence distributions of adding Run II W asymmetry pseudodata to each of the three global fits (CT10, MMHT14 and NNPDF3.0).

5 Outlook to future (possible) colliders

Looking down the road to possible future colliders it is clear that Parton Distribution Functions and their uncertainties will remain one of the fundamental

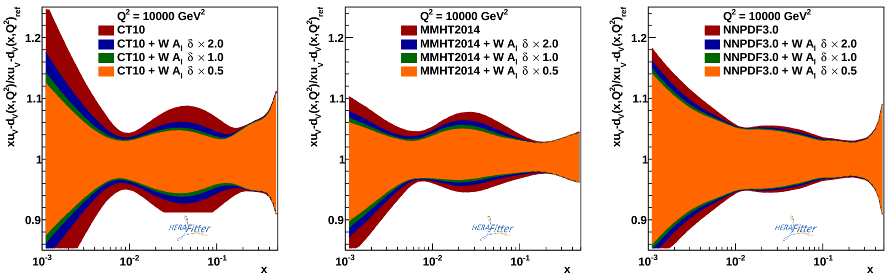

Figure 2: *Relative uncertainty of the* $u_V - d_V$ *distribution as a function of* x *for* $Q^2 = 10^4$ *GeV*^{2} *estimated based on CT10nnlo (left), MMHT14 (middle) and NNPDF3.0 (right) PDF sets, respectively. The outer uncertainty band corresponds to the original PDF uncertainty. The embedded bands represent results of the PDF profiling using the W asymmetry measurements pseudo-data at 13 TeV corresponding to (from outermost to innermost band) a conservative, a baseline and an aggressive model of the data uncertainties. (Figure taken from the PDF4LHC report* [9]*).*

ingredients of our theoretical predictions based on perturbative QCD, often being one of the limiting factors to fully exploit their potential for discovery of new physics. Conversly, a large number of measurements could be performed that would help us to better determine PDFs.

Primary examples are acurate measurements of high-mass tails of distributions, forseen in the preliminary studies for the High-Luminosity phase of the LHC (HL-LHC). These measurements, the precision of which is limited by statistics at the LHC Run I and II, will allow us to probe and constrain PDFs in the large-x region.

Further down the road, the LHeC machine [12], a Large Hadron Electron Collider at CERN, could offer unique possibilities to reach the ultimate precision in PDF determinations by probing kinematic regions which are far from the reach of current experiments. For example, exploring in detail the small-x region ($x \sim 10^{-6}$) to look for evidence of deviations from DGLAP evolution due to BFKL resummation or saturation effects.

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