LHC precision EW working group

PDF issues related to precision Drell-Yan measurements at the LHC

ABSTRACT

Over the past few years, a number of very precise measurements from the LHC experiments have been produced concerning inclusive Drell-Yan production of W/Z bosons. In parallel, the global fits to parton distribution functions have improved their accuracy through the use of the wealth of available LHC data, through the inclusion of the full HERA-2 data and of legacy precision measurements from the Tevatron, and through further developments of the underlying theory. Because of the intrinsic uncertainties related to the proton parton distribution functions, the precision of recent measurements of some of the fundamental parameters of the theory, such as the W-boson mass and the weak mixing angle, is limited in large part by the uncertainties in the parton distribution functions themselves. In addition, clear limitations have appeared in the use of purely perturbative QCD to describe the inclusive production of vector bosons at the LHC when performing global fits of the parton distribution functions.

This short note is a proposal to open a detailed discussion with the PDF4LHC forum to assess how best to deal with PDF uncertainties and their profiling in precision Drell-Yan measurements such as the weak mixing angle (used as the main example in this note) or the mass of the W boson, and also hopefully on how to improve the underlying theoretical tools used for Drell-Yan production. Some concrete requests are made and two dedicated meetings are proposed to be held jointly before the end of 2018.

Proposal for discussion: **October 24, 2018**.

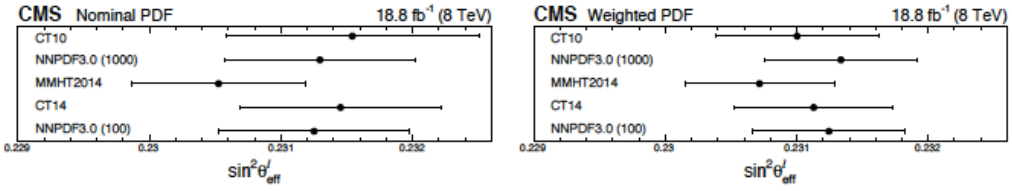

Figure 1: Spread of values obtained for $\sin^2\theta^{\ell}_{\text{eff}}$ by CMS using different PDF sets as quoted in Ref. [14] for the dimuon channel.

1 Introduction

The effective leptonic weak mixing angle, $\sin^2\theta^{\ell}_{\text{eff}}$, has been measured precisely at the LEP and SLC electron-positron colliders [1, 2], and more recently at the Tevatron [3, 4, 5, 6, 7, 8, 9, 10] and LHC [11, 12, 13, 14, 15] hadron colliders. The combined average of the most precise six measurements from the LEP and SLC colliders yields a value of 0.23149 ± 0.00016 for $\sin^2\theta^{\ell}_{\text{eff}}$ [2], displaying however a 3.2 standard-deviation difference between the two most precise individual measurements, namely the combined LEP/SLD measurement of the b-quark forward-backward asymmetry, $A^{0,b}_{\text{FB}}$ and the SLD left-right polarisation asymmetry, $\mathcal{A}_{\ell}$, measurement. Recently, the legacy combination of all the Tevatron measurements has been published in Ref. [10], yielding a value of 0.23148 ± 0.00033 for $\sin^2\theta^{\ell}_{\text{eff}}$.

The most precise measurements to-date at the LHC are the recently published one from the CMS collaboration [14], yielding a value of 0.23101 ± 0.00053 for $\sin^2\theta^{\ell}_{\text{eff}}$, and the preliminary result from the ATLAS collaboration [15], yielding a value of 0.23140 ± 0.00036 for $\sin^2\theta^{\ell}_{\text{eff}}$. The largest contribution to the systematic uncertainties in these measurements is that from the parton distribution functions (PDFs). The CMS measurement is given for the specific choice of the NNPDF30 PDF set [16] with a corresponding uncertainty of $\pm 31 \cdot 10^{-5}$ extracted from replicas. The use of different PDF sets, as illustrated for the dimuon channel in Figure 1, corresponds to a total spread of $\sim 65 \cdot 10^{-5}$ which is not included in the total uncertainty of the measurement. Similarly, the ATLAS measurement is given for the specific choice of the MMHT14 PDF set [17] with a corresponding uncertainty of $\pm 24 \cdot 10^{-5}$ extracted from Hessian eigenvalues. The use of different PDF sets, as illustrated in Table 1, corresponds to a total spread of $\pm 28 \cdot 10^{-5}$ which is not included in the total uncertainty of the measurement. Even though previous measurements at the Tevatron and at the LHC have also proceeded in this way, a more rigorous approach to the treatment of the PDF uncertainties is mandatory for the future since they will become even more dominant with higher statistics at higher centre-of-mass energies. Similar issues arise when evaluating and profiling the PDF uncertainties in the measurement of the W-boson mass [18]. Two studies were presented to the PDF4LHC forum concerning these points already in March 2018 [19, 20]

The purpose of this note is to summarise the PDF issues which have been discussed in the context of various precision analyses using the Drell-Yan process at the LHC and to provide specific requests to the experts from the PDF4LHC forum, with the goal of progressing sufficiently in our mutual understanding of how to deal with PDFs and their uncertainties for the combinations of precision EW measurements to be performed between the different LHC experiments with the full run-2 dataset in the next years.

	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^{\ell}_{\rm eff}$	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	39	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31

Table 1: Spread of values obtained for $\sin^2\theta^{\ell}_{\rm eff}$ by ATLAS using different PDF sets as quoted in Ref. [15]. The uncertainty values are given in units of 10^{-5}.

2 Summary of PDF issues to be discussed

The issues discussed within the LHC precision EW working group are summarised below, based on discussions at meetings earlier this year:

1. Which global PDF sets would wish to be considered in these studies? Hopefully this could start with the most recent sets, namely ABM16, CT14, MMHT14, and NNPDF3.1. Is it worth considering also the PDF4LHC set? From the list of issues raised below, wouldn't it seem more useful to study separately the sets entering this combination, or possibly even their successors?

2. What should be done in terms of studying further the impact of enhanced strangeness? Is there consensus that strangeness is indeed enhanced at low x compared to what was assumed before LHC data arrived? Is there consensus that different measurements at higher x are somewhat in tension concerning this and has this tension been properly quantified yet? In short, how should one treat this issue in the context of precision EW measurements at the LHC?

3. Could the experts from each global PDF set define precisely which theory they use for inclusive Drell-Yan production? Non-experts assume that it is perturbative QCD at NNLO precision?

4. Could the experts from each global PDF set define precisely which uncertainties are included in the output of their fits on top of the data uncertainties from the measurements used in the fit? Is it correct that normally no uncertainties related to higher-order QCD corrections (based on QCD perturbative scale variations) or to parton-shower effects are included? Because of this, should one even consider using measurements of the Z-boson transverse momentum in PDF fits once one has observed that the theoretical uncertainties due to higher-order corrections (which are now known to $O(\alpha_s^3)$) are larger than the PDF uncertainties in the kinematic region of interest where most of the events are?

5. What about uncertainties related to QED/EW corrections? All PDF sets now explicitly include a photon PDF which should account for a large fraction of QED ISR corrections to the predictions, but are their uncertainties, even though small when considered in an inclusive sense, included as additional nuisance parameters in the global PDF sets since the LUX parameterisation was adopted a few years ago? Clearly the authors of Luxqed provide several nuisance parameters but to most users from the experimental community it is not even clear which PDF sets still in use in simulated samples include Luxqed or not, let alone whether the uncertainties related to the photon PDF are accessible or not.

6. What about other parametric uncertainties, especially those related to heavy flavours which contribute very differently to W-boson and Z-boson production? In particular, is there any consensus on intrinsic charm, as recently studied within the context of NNPDF?

7. What about non-perturbative effects not covered by the previous point such as intrinsic k_T (see studies shown in June including flavour-dependent TMDs)?

8. What are the uncertainties assigned by each global PDF set to the methodology (assumptions such as strangeness suppression, technical implementation of theoretical predictions, fit machinery, number of parameters, etc) and parameterisations used? Are these considered to be negligible, and if so why? Are many of them correlated between different PDF sets since some of the assumptions must be very similar?

9. Would it be possible to provide global fits based on the same datasets from the main groups? These should preferably contain only LHC data related closely to precision Drell-Yan measurements which are not used by ongoing analyses, for simplicity, one could say that no 13 TeV data should be included, nor should jet data or top data from all hadron colliders be included perhaps. The most relevant data are those in the (x, Q^2) range relevant to on-shell W/Z-boson production, so clearly DY data from the Tevatron. HERA data, and other data should be included as deemed best by the experts.

10. For the above global fits, would it be possible to provide separately the uncertainties which are correlated between the different PDF sets and those which are not.

11. Is it possible to define a set of criteria whereby a given PDF set may be rejected because it does not agree with measurements based on the full run-2 datasets from the LHC experiments? Examples of such disagreements between data and predictions have been mentioned by CMS (W-boson charge asymmetry and measurement of $\sin^2\theta^{\ell}_{\rm eff}$ at 8 TeV) and ATLAS (W/Z-boson precision differential measurements at 7 TeV) participants in the LHC precision EW recent meetings.

12. Vice-versa, could criteria be defined whereby PDF sets exclude certain measurements from their fits? This has happened over the past years frequently for e.g. jet measurements, but it has also happened a few times for Drell-Yan measurements.

13. Where are the limitations or advantages to using eigenvector-based uncertainties versus replicas in terms of maintaining fidelity to the underlying parton distributions after profiling, and what is the best way to quantify this more precisely?

14. Are there still unresolved technical issues with PDFs and their uncertainty treatment which require more study and could be relevant for the studies in this context? Examples mentioned among non-experts in the field are the reweighting issues raised by NNPDF authors a while ago and the need to rescale certain PDF uncertainties from 90% CL to 68% CL.

In the March PDF4LHC meeting earlier this year, presentations were given based on the work documented in Refs. [19, 20] but there was no time for any in-depth discussion, so PDF experts are invited to look at the studies presented there, in particular at Table 4 and Figure 9 of the former one, which highlight, respectively, the importance of addressing in a quantitative way the uncertainties related to the differences between different global PDF sets and the differences between theory predictions including parton-shower effects, as used by the experiments, and the purely perturbative predictions used by the PDF fits.

3 Requests from precision EW working group

The main request from the LHC precision working group are captured by points 9 to 11 above. It is clear that this would require quite some work, but it should be emphasised that this work would certainly be very beneficial for the future legacy run-2 papers of the ATLAS, CMS and LHCb collaborations and is even mandatory to produce any meaningful combinations of results when the time will come to do this with data. A number of experimental colleagues in this working group are motivated to work together with PDF experts using pseudo-data at 13 TeV to assess how best to arrive at answers to the questions above and of course to those which will inevitably arise in the course of this joint work. The key point above concerning how we may converge on a better treatment of PDF uncertainties and the correlations between the uncertainties from different PDF sets for precision EW measurements at the LHC cannot be overemphasised: it is sufficient to look at hadron collider compared to lepton collider results in global EW fits to see the importance of dealing convincingly with the uncertainties which dominate these measurements at hadron colliders but do not exist at lepton colliders.

The above list of questions and requests is by no means exhaustive, nor has it been extensively reviewed by the whole LHC precision EW working group. There are also many theory colleagues working on precise predictions for future measurements, in particular concerning the least well modelled observable in Drell-Yan production, namely the transverse momentum of the W/Z bosons, and the impact of PDFs on such predictions is undoubtedly also very relevant and should be discussed in the context of the two sets of meetings proposed below.

4 Summary

This note hopefully paves the way towards fruitful interactions and work between the PDF4LHC forum experts and experimental and theoretical colleagues in the LHC precision EW working group. This is planned to start already in the precision EW working group meeting mid-November (week 12th to 16th of November) and will be followed up with a half-day discussion in the next PDF4LHC forum on 13th of December.

References

[1] SLD Electroweak Group, DELPHI, ALEPH, SLD, SLD Heavy Flavour Group, OPAL, LEP Electroweak Working Group, L3 Collaboration, ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, LEP and SLD Electroweak Working Groups, *Phys. Rept.* **427** (2006) 257–454, hep-ex/0509008.

[2] ALEPH, DELPHI, L3, and OPAL Collaborations, LEP Electroweak Working Group, hep-ex/0612034.

[3] CDF Collaboration, *Phys. Rev. Lett.* **106** (2011) 241801, 1103.5699.

[4] CDF Collaboration, *Phys. Rev.* **D88** (2013), no. 7 072002, [Erratum: Phys. Rev.D88,no.7,079905(2013)], 1307.0770.

[5] CDF Collaboration, *Phys. Rev.* **D89** (2014), no. 7 072005, 1402.2239.

[6] CDF Collaboration, *Phys. Rev.* **D93** (2016), no. 11 112016, 1605.02719.

[7] D0 Collaboration, *Phys. Rev.* **D84** (2011) 012007.

[8] D0 Collaboration, *Phys. Rev. Lett.* **115** (2015) 041801.

[9] D0 Collaboration, *Submitted to Phys. Rev. Lett.* (2017) 1710.09351.

[10] CDF and D0 Collaborations, *Submitted to Phys. Rev. D* (2018) 1801.06283.

[11] CMS Collaboration, *Phys. Rev. D* **84** (2011) 112002, 1110.2682.

[12] ATLAS Collaboration, *JHEP* **09** (2015) 049, 1503.03709.

[13] LHCb Collaboration, *JHEP* **11** (2015) 190, 1509.07645.

[14] CMS Collaboration, *submitted to Eur. Phys. J. C.* (2018) 1806.00863.

[15] ATLAS Collaboration, *ATLAS-CONF-2018-037* (2018).

[16] NNPDF Collaboration, NNPDF Collaboration, *JHEP* **04** (2015) 040, 1410.8849.

[17] L. A. Harland-Lang, A. D. Martin, P. Motylinski, and R. S. Thorne, *Eur. Phys. J.* **C75** (2015), no. 5 204, 1412.3989.

[18] ATLAS Collaboration, *Eur. Phys. J. C* **78** (2018) 110, 1701.07240.

[19] ATLAS Collaboration, "Impact of parton distribution functions on precision measurements of Drell-Yan observables". ATL-PHYS-PUB-2018-004, 2018.

[20] CMS Collaboration, "A proposal for the measurement of the weak mixing angle at the HL-LHC". CMS-PAS-FTR-17-001, 2017.