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α_s from inclusive $W^{\pm}$ and Z cross sections in proton-proton collisions at the LHC

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Twenty-eight different measurements of inclusive $W^{\pm}$ and Z cross sections in pp collisions at the LHC are compared to the corresponding theoretical predictions, at NNLO accuracy in perturbative QCD including NLO electroweak corrections, in order to extract the QCD coupling at the Z pole, $\alpha_s(m_Z)$. The theoretical cross sections are computed for four different parton distribution functions (PDFs): CT14, HERAPDF 2.0, MMHT14, and NNPDF 3.0. The calculated cross sections reproduce well the data within experimental and theoretical uncertainties. A linear fit of the α_s dependence of the theoretical cross sections is used to extract the $\alpha_s(m_Z)$ value that best reproduces the measured cross sections. The 28 $\alpha_s(m_Z)$ values extracted from each measurement are combined into a single result by properly taking into account their uncertainties and correlations. The following NNLO values of the QCD coupling for each one of the PDF sets are obtained: $\alpha_s(m_Z) = 0.1181 \pm 0.0016$ (CT14), 0.1209 ± 0.0015 (MMHT14), and 0.1163 ± 0.0019 (NNPDF 3.0), with a final uncertainty at the 1.5% level, in good agreement with the $\alpha_s(m_Z)$ world average.

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Introduction

The QCD coupling is the least accurately known of all fundamental interaction couplings: the current world average at the Z boson mass, $\alpha_s(m_Z) = 0.1181 \pm 0.0011$, has a 0.9% uncertainty [1]. New extraction methods with different types of experimental and theoretical uncertainties than those of the current determinations are needed in order to eventually improve the precision on $\alpha_s(m_Z)$ through a combined analysis of all existing results [2]. In this context, we propose a novel approach to extract $\alpha_s(m_Z)$ based on the comparison of inclusive $W^{\pm}$ and Z production cross sections measured at the LHC [3, 4, 5, 6, 7, 8, 9, 10, 11] to next-to-next-to-leading-order (NNLO) perturbative QCD (pQCD) calculations [12]. The method is similar to the one used to extract α_s from the inclusive $t\bar{t}$ cross sections at hadron colliders [13, 14], except that the underlying physical process is quite different: whereas $\sigma(t\bar{t})$ depends at leading order (LO) on α_s albeit with ~5% theoretical and experimental uncertainties, $\sigma(\mathrm{W,Z})$ is precisely known (down to ~1% experimental and theoretical uncertainties) but at the Born level is a pure electroweak process with a dependence on $\alpha_s(m_Z)$ that comes only through higher-order pQCD corrections. Implementing in MCFM v8.0 [12] at LO and NNLO accuracy the typical fiducial cuts of the $\mathrm{pp}, \mathrm{p\bar{p}} \to \mathrm{W}^{\pm}, \mathrm{Z}+\mathrm{X}$ measurements performed at the Tevatron and LHC, one can see that the higher-order QCD terms increase the Born W, Z cross sections by around 30%:

Fiducial W, Z cross sections:	CDF	D0	ATLAS	CMS	LHCb
NNLO/LO ratio	1.35	1.35	1.22	1.33	1.29

thereby confirming their significant dependence on $\alpha_s(m_Z)$.

Experimental data

Table 1 collects all the fiducial cross sections for W^+, W^-, and Z production measured in pp collisions at various center-of-mass energies ($\sqrt{s}$ = 7, 8, 13 TeV) by ATLAS (7 results), CMS (12 results), and LHCb (9 results). The experimental selection criteria on lepton transverse momentum p_T and pseudorapidity η are listed along with the measured experimental cross sections and their uncertainties. The ℓ, μ, e labels refer to different measurements performed in the fully leptonic, muonic, or electronic final-states respectively. In terms of experimental uncertainties, the integrated luminosity is the largest source (1–5%, fully correlated for a given experiment at a given $\sqrt{s}$), the systematics one amounts to a 1–3% effect (partially correlated among measurements, see later), and the statistical one (0–2%, fully uncorrelated among measurements) is the smallest one.

Cross sections: data vs. NNLO

We use MCFM v8.0 [12] to calculate the cross sections at NNLO pQCD accuracy with four PDF sets: CT14 [15], HERAPDF 2.0 [16], MMHT14 [17], and NNPDF 3.0 [18], interfaced through LHAPDF v6.1.6 [19]; and for 5 or 7 different input QCD coupling values over the range $\alpha_s(m_Z) =$ 0.115–0.121. The experimental kinematical cuts on the final state lepton(s) for each system, listed in Table 1, were implemented in the code. For all the 28 systems shown in Table 1, this resulted in about 20 000 computing jobs. Since MCFM does not include electroweak corrections, we used MCSANC v1.01 [20] to compute them: For each system, we calculated the NLO pQCD cross section

Table 1: Summary of the experimental W^+, W^-, and Z cross sections measured at the LHC. The lepton acceptance cuts (ℓ for inclusive leptons, and μ, e for individual muon or electron final-states; p_T^ν for the missing p_T) are listed, along with the statistical, systematic, and integrated luminosity uncertainties.

ATLAS (pp, $\sqrt{s}$ = 7 TeV)	
$p_T^\ell > 25$ GeV, $p_T^\nu > 25$ GeV, $\lvert\eta^\ell\rvert < 2.5$, $m_T > 40$ GeV	$\sigma(W^+) = 2947 \pm 1_{(stat)} \pm 15_{(syst)} \pm 53_{(lum)}$ pb $= 2947 \pm 55$ pb
$p_T^\ell > 25$ GeV, $p_T^\nu > 25$ GeV, $\lvert\eta^\ell\rvert < 2.5$, $m_T > 40$ GeV	$\sigma(W^-) = 1964 \pm 1_{(stat)} \pm 11_{(syst)} \pm 35_{(lum)}$ pb $= 1964 \pm 37$ pb
$p_T^\ell > 20$ GeV, $\lvert\eta^\ell\rvert < 2.5$, $66 < m_Z < 116$ GeV	$\sigma(Z) = 502.2 \pm 0.3_{(stat)} \pm 1.7_{(syst)} \pm 9.0_{(lum)}$ pb $= 502.2 \pm 9.2$ pb
ATLAS (pp, $\sqrt{s}$ = 8 TeV)	
$p_T^\ell > 20$ GeV, $\lvert\eta^\ell\rvert < 2.4, 66 < m_Z < 116$ GeV	$\sigma(Z) = 537.10$ pb $\pm 0.45\%_{(syst)} \pm 2.8\%_{(lum)} = 537.10 \pm 15.23$ pb
ATLAS (pp, $\sqrt{s}$ = 13 TeV)	
$p_T^\ell > 25$ GeV, $p_T^\nu > 25$ GeV, $\lvert\eta^\ell\rvert < 2.5$, $m_T > 50$ GeV	$\sigma(W^+) = 4.53 \pm 0.01_{(stat)} \pm 0.09_{(syst)} \pm 0.10_{(lum)}$ nb $= 4.53 \pm 0.13$ nb
$p_T^\ell > 25$ GeV, $p_T^\nu > 25$ GeV, $\lvert\eta^\ell\rvert < 2.5$, $m_T > 50$ GeV	$\sigma(W^-) = 3.50 \pm 0.01_{(stat)} \pm 0.07_{(syst)} \pm 0.07_{(lum)}$ nb $= 3.50 \pm 0.10$ nb
$p_T^\ell > 25$ GeV, $\lvert\eta^\ell\rvert < 2.5$, $66 < m_Z < 116$ GeV	$\sigma(Z) = 0.779 \pm 0.003_{(stat)} \pm 0.006_{(syst)} \pm 0.016_{(lum)}$ nb $= 0.779 \pm 0.017$ nb
CMS (pp, $\sqrt{s}$ = 7 TeV)	
$p_T^e > 25$ GeV, $\lvert\eta^e\rvert < 2.5$	$\sigma(W_e^+) = 3.404 \pm 0.012_{(stat)} \pm 0.067_{(syst)} \pm 0.136_{(lum)}$ nb $= 3.404 \pm 0.152$ nb
$p_T^e > 25$ GeV, $\lvert\eta^e\rvert < 2.5$	$\sigma(W_e^-) = 2.284 \pm 0.010_{(stat)} \pm 0.043_{(syst)} \pm 0.091_{(lum)}$ nb $= 2.284 \pm 0.101$ nb
$p_T^e > 25$ GeV, $\lvert\eta^e\rvert < 2.5$, $60 < m_Z < 120$ GeV	$\sigma(Z_e) = 0.452 \pm 0.005_{(stat)} \pm 0.010_{(syst)} \pm 0.018_{(lum)}$ nb $= 0.452 \pm 0.021$ nb
$p_T^\mu > 25$ GeV, $\lvert\eta^\mu\rvert < 2.1$	$\sigma(W_\mu^+) = 2.815 \pm 0.009_{(stat)} \pm 0.042_{(syst)} \pm 0.113_{(lum)}$ nb $= 2.815 \pm 0.121$ nb
$p_T^\mu > 25$ GeV, $\lvert\eta^\mu\rvert < 2.1$	$\sigma(W_\mu^-) = 1.921 \pm 0.008_{(stat)} \pm 0.027_{(syst)} \pm 0.077_{(lum)}$ nb $= 1.921 \pm 0.082$ nb
$p_T^\mu > 20$ GeV, $\lvert\eta^\mu\rvert < 2.1$, $60 < m_Z < 120$ GeV	$\sigma(Z_\mu) = 0.396 \pm 0.003_{(stat)} \pm 0.007_{(syst)} \pm 0.016_{(lum)}$ nb $= 0.396 \pm 0.018$ nb
CMS (pp, $\sqrt{s}$ = 8 TeV)	
$p_T^e > 25$ GeV, $\lvert\eta^e\rvert < 1.44$, $1.57 < \lvert\eta^e\rvert < 2.5$	$\sigma(W_e^+) = 3.54 \pm 0.02_{(stat)} \pm 0.11_{(syst)} \pm 0.09_{(lum)}$ nb $= 3.54 \pm 0.14$ nb
$p_T^e > 25$ GeV, $\lvert\eta^e\rvert < 1.44$, $1.57 < \lvert\eta^e\rvert < 2.5$	$\sigma(W_e^-) = 2.39 \pm 0.01_{(stat)} \pm 0.06_{(syst)} \pm 0.06_{(lum)}$ nb $= 2.39 \pm 0.09$ nb
$p_T^e > 25$ GeV, $\lvert\eta^e\rvert < 1.44$, $1.57 < \lvert\eta^e\rvert < 2.5$, $60 < m_Z < 120$ GeV	$\sigma(Z_e) = 0.45 \pm 0.01_{(stat)} \pm 0.01_{(syst)} \pm 0.01_{(lum)}$ nb $= 0.45 \pm 0.02$ nb
$p_T^\mu > 25$ GeV, $\lvert\eta^\mu\rvert < 2.1$	$\sigma(W_\mu^+) = 3.10 \pm 0.01_{(stat)} \pm 0.04_{(syst)} \pm 0.08_{(lum)}$ nb $= 3.10 \pm 0.09$ nb
$p_T^\mu > 25$ GeV, $\lvert\eta^\mu\rvert < 2.1$	$\sigma(W_\mu^-) = 2.24 \pm 0.01_{(stat)} \pm 0.02_{(syst)} \pm 0.06_{(lum)}$ nb $= 2.24 \pm 0.06$ nb
$p_T^\mu > 25$ GeV, $\lvert\eta^\mu\rvert < 2.1$, $60 < m_Z < 120$ GeV	$\sigma(Z_\mu) = 0.40 \pm 0.01_{(stat)} \pm 0.01_{(syst)} \pm 0.01_{(lum)}$ nb $= 0.40 \pm 0.02$ nb
LHCb (pp, $\sqrt{s}$ = 7 TeV)	
$p_T^\ell > 20$ GeV, $2.0 < \eta^\ell < 4.5$	$\sigma(W^+) = 878.0 \pm 2.1_{(stat)} \pm 6.7_{(syst)} \pm 9.3_{(en)} \pm 15.0_{(lum)}$ pb $= 878.0 \pm 19.0$ pb
$p_T^\ell > 20$ GeV, $2.0 < \eta^\ell < 4.5$	$\sigma(W^-) = 689.5 \pm 2.0_{(stat)} \pm 5.3_{(syst)} \pm 6.3_{(en)} \pm 11.8_{(lum)}$ pb $= 689.5 \pm 14.5$ pb
$p_T^\ell > 20$ GeV, $2.0 < \eta^\ell < 4.5$, $60 < m_Z < 120$ GeV	$\sigma(Z) = 76.0 \pm 0.3_{(stat)} \pm 0.5_{(syst)} \pm 1.0_{(en)} \pm 1.3_{(lum)}$ pb $= 76.0 \pm 1.7$ pb
LHCb (pp, $\sqrt{s}$ = 8 TeV)	
$p_T^e > 20$ GeV, $2.0 < \eta^e < 4.25$	$\sigma(W_e^+) = 1124.4 \pm 2.1_{(stat)} \pm 21.5_{(syst)} \pm 11.2_{(en)} \pm 13.0_{(lum)}$ pb $= 1124.4 \pm 27.6$ pb
$p_T^e > 20$ GeV, $2.0 < \eta^e < 4.25$	$\sigma(W_e^-) = 809.0 \pm 1.9_{(stat)} \pm 18.1_{(syst)} \pm 7.0_{(en)} \pm 9.4_{(lum)}$ pb $= 809.0 \pm 21.6$ pb
$p_T^\mu > 20$ GeV, $2.0 < \eta^\mu < 4.5$	$\sigma(W_\mu^+) = 1093.6 \pm 2.1_{(stat)} \pm 7.2_{(syst)} \pm 10.9_{(en)} \pm 12.7_{(lum)}$ pb $= 1093.6 \pm 18.3$ pb
$p_T^\mu > 20$ GeV, $2.0 < \eta^\mu < 4.5$	$\sigma(W_\mu^-) = 818.4 \pm 1.9_{(stat)} \pm 5.0_{(syst)} \pm 7.0_{(en)} \pm 9.5_{(lum)}$ pb $= 818.4 \pm 13.0$ pb
$p_T^\mu > 20$ GeV, $2.0 < \eta^\mu < 4.5$, $60 < m_Z < 120$ GeV	$\sigma(Z_\mu) = 95.0 \pm 0.3_{(stat)} \pm 0.7_{(syst)} \pm 1.1_{(en)} \pm 1.1_{(lum)}$ pb $= 95.0 \pm 1.7$ pb
LHCb (pp, $\sqrt{s}$ = 13 TeV)	
$p_T^\ell > 20$ GeV, $2.0 < \eta^\ell < 4.5$, $60 < m_Z < 120$ GeV	$\sigma(Z) = 194.3 \pm 0.9_{(stat)} \pm 3.3_{(syst)} \pm 7.6_{(lum)}$ pb $= 194.3 \pm 8.3$ pb

with electroweak corrections on and off, and applied this ratio to the MCFM results at NNLO accuracy. We calculated the PDF uncertainties using the procedures corresponding to each PDF set (i.e. using their corresponding symmetric or asymmetric eigenvalues or replicas). To assess the uncertainty from missing higher-order corrections, we varied the renormalization and factorization scales from their default values ($\mu_{R,F} = m_{W,Z}$) by factors of 2 and 1/2, and took the maximum variation in the cross section from the central value. All in all, in terms of theoretical uncertainty sources, the largest one is associated with the PDF uncertainty ($\sim$2–3%), followed by the theoretical scale uncertainty (about 1%), and the numerical uncertainty (around 0.7%).

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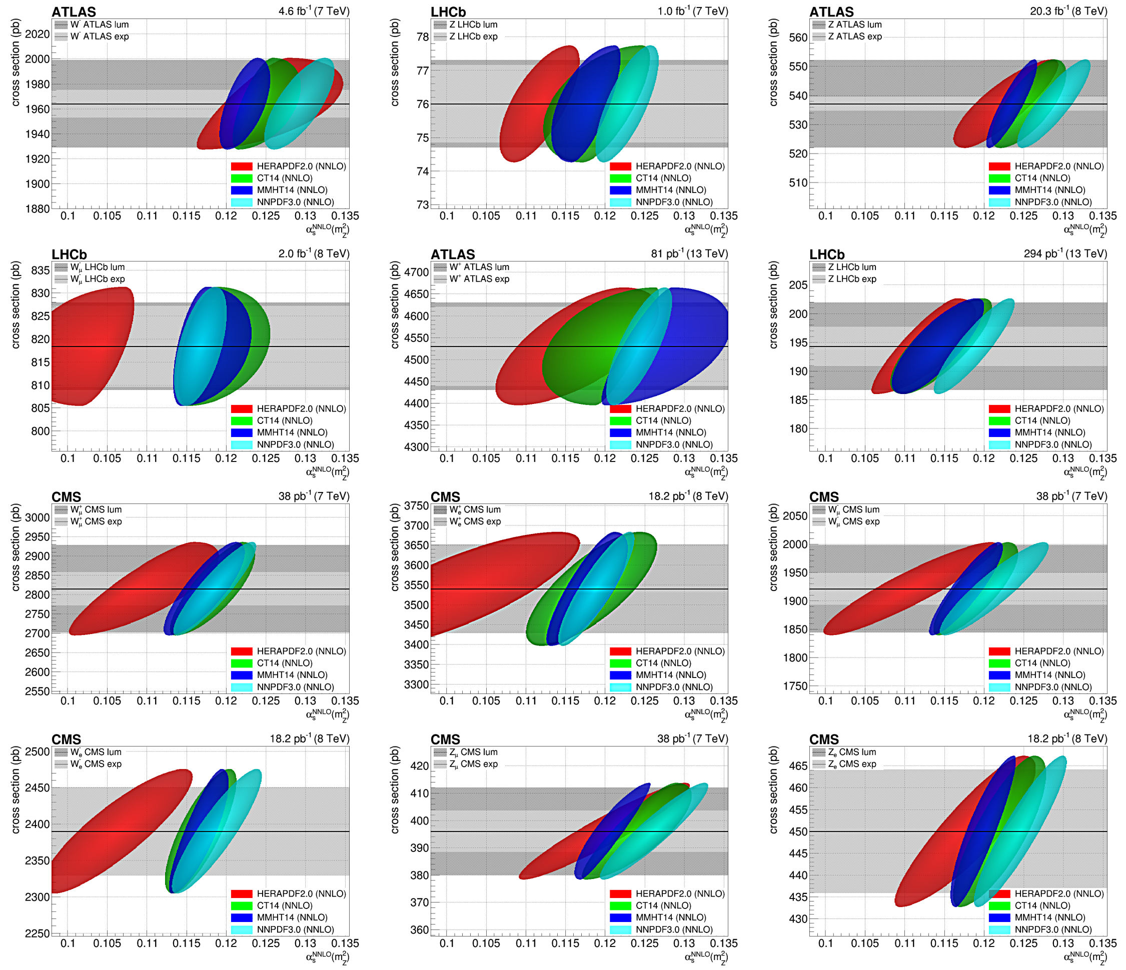

Figure 1: Examples of experimental $W^{\pm}$ and Z cross sections (lines with grey uncertainty bands) compared to theoretical NNLO predictions (ellipsoids, for each PDF set) as a function of $\alpha_s(m_Z)$.

Figure 1 shows a comparison of a subset of representative W^+, W^-, and Z cross sections measured at the LHC (horizontal black line with grey bands indicating the experimental uncertainties) compared to the NNLO theoretical predictions as a function of $\alpha_s(m_Z)$ (ellipsoids). The ellipsoids width results from the convolution of theoretical and experimental systematic uncertainties. All theoretical predictions agree with the experimental data within uncertainties, although not always for the same fixed value of $\alpha_s(m_Z)$, in particular for the HERAPDF 2.0 results, a fact that indicates some underlying tensions. Usually, a hierarchy of NNLO cross section predictions as a function of $\alpha_s(m_Z)$ is apparent with, for $\alpha_s(m_Z) = 0.1181$ fixed at the world average, the results obtained with HERAPDF 2.0 (NNPDF 3.0) overestimating (underestimating) the experimental data.

Extraction of $\alpha_s(m_Z)$

To extract the value of $\alpha_s(m_Z)$ preferred by each experimental measurement, we proceed as follows. First, we fit to a first-order polynomial the observed dependence of the theoretical cross section on $\alpha_s(m_Z)$ for each individual system (such a linear fit goes through the ellipsoids plotted in Fig. 1). The slope of this curve indicates the sensitivity of the theoretical cross section to the underlying $\alpha_s(m_Z)$ value. The plots of Fig. 1 indicate that the predictions obtained with HERA-PDF 2.0 (MMHT14) have the smallest (largest) slope, i.e. have the least (most) sensitivity to α_s variations. The crossing point of each theoretical $\sigma^{th}_{W,Z}$-versus-$\alpha_s(m_Z)$ curve with the experimental cross section (straight flat line in Fig. 1) gives the preferred $\alpha_s(m_Z)$ value for each system. It can be easily shown that the theoretical and experimental uncertainties of the cross sections can be properly propagated to the derived $\alpha_s(m_Z)$ value by dividing each cross section uncertainty by the slope of the $\sigma^{th}_{W,Z}$-versus-$\alpha_s(m_Z)$ curve.

The procedure described above yields 28 extractions of $\alpha_s(m_Z)$ for each one of the 4 PDF sets. Those are combined properly into a single $\alpha_s(m_Z)$ value per PDF by taking into account their correlations and uncertainties using the CONVINO tool (with the Neyman χ^2 prescription) [21]. For the correlations between different measurements, we make the following assumptions. The experimental statistical and theoretical numerical errors are fully uncorrelated. The integrated luminosity is taken to have a 0.5 correlation at the same $\sqrt{s}$ for different experiments, full correlation within the same experiment at the same $\sqrt{s}$, and zero for different $\sqrt{s}$. For the PDF and scales, we calculate the Pearson correlation coefficients for all data points and take it as the correlations of their corresponding uncertainties. For the experimental systematic uncertainties, we did a detailed study based on the CMS measurements [6, 7] and, preliminarily, apply the same CMS correlations to both LHCb and ATLAS results. This leads to relatively strong correlations of the experimental measurements performed with the same lepton. We then insert the 28 $\alpha_s(m_Z)$ results per PDF and their correlation matrices into CONVINO, with a χ^2 minimization taking into account asymmetric uncertainties, to determine the best $\alpha_s(m_Z)$ value per PDF set. This combination gives the results shown in Fig. 2.

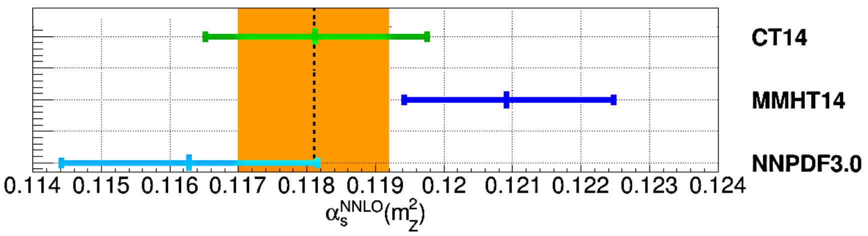

Figure 2: Final $\alpha_s(m_Z)$ obtained by combining the 28 individual extractions based on the $W^{\pm}$, Z cross sections listed in Table 1 for the CT14, MMHT14, and NNPDF 3.0 parton densities, compared to the world-average (orange box).

For CT14 we obtain $\alpha_s(m_Z) = 0.1181 \pm 0.0016$, for MMHT14: $\alpha_s(m_Z) = 0.1209 \pm 0.0015$, and for NNPDF 3.0: $\alpha_s(m_Z) = 0.1163 \pm 0.0019$. In this preliminary analysis, CONVINO did not converge on a stable result for HERAPDF 2.0. We see that despite the fact that PDF uncertainties are asymmetric for all sets except NNPDF 3.0, the final $\alpha_s(m_Z)$ uncertainties turn out to be symmetric. All extractions are in reasonable agreement with each other and with the world average, considering that the uncertainty bars correspond to one standard deviation.

In order to test the stability of our α_s extraction, we ran an analysis to determine the sensitivity of each final $\alpha_s(m_Z)$ value on the data sets, their individual correlations and uncertainties. Figure 3 shows, for each PDF, the $\alpha_s(m_Z)$ results obtained with the default assumptions (top point), with symmetrized PDF uncertainties (second point), when adding an extra 1% statistical uncertainty to all cross sections (third point), when using only the 7 or 8 TeV cross sections (fourth and fifth point), when assuming the integrated luminosity to be fully correlated at the same $\sqrt{s}$ between different experiments (sixth point), when dividing the PDF or experimental systematic correlations by a factor of two (seventh and eighth point), and when using only 7 TeV results and in addition also symmetrizing the PDF errors or adding an extra 1% uncorrelated uncertainty (last two points). This figure shows that the derived $\alpha_s(m_Z)$ values mostly remain within one standard deviation of the default results plotted in Fig. 2.

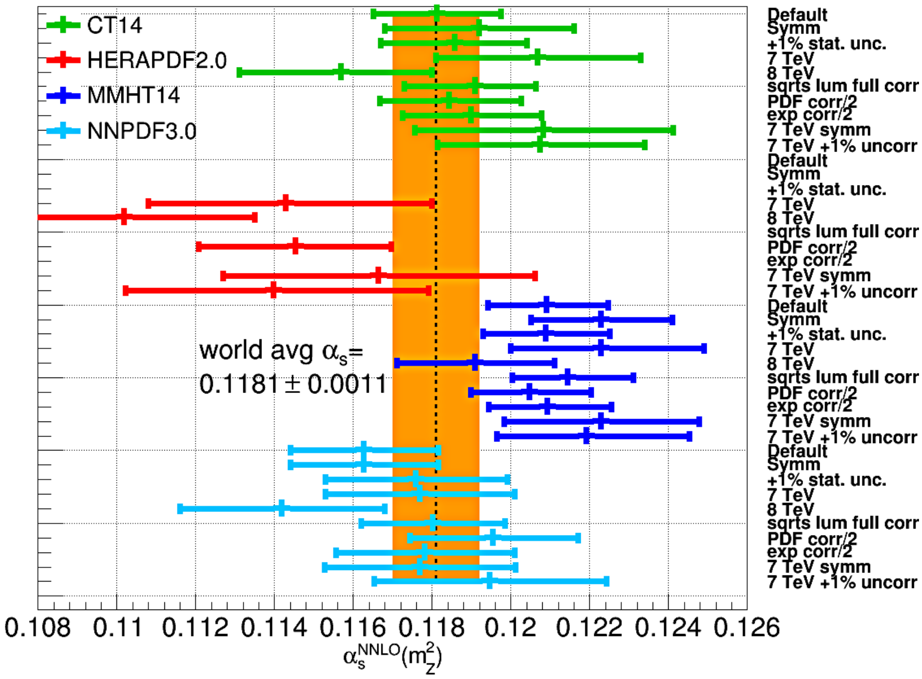

Figure 3: Overview of the study of the sensitivity of the final $\alpha_s(m_Z)$ value extracted per PDF to various assumptions on the data, the theoretical and experimental uncertainties and on their correlations.

Summary and conclusions

We have used 28 measurements of the inclusive fiducial $W^{\pm}$ and Z production cross sections in proton-proton collisions at $\sqrt{s} = 7$, 8, and 13 TeV, carried out in the electron and muon decay channels by the ATLAS, CMS, and LHCb experiments, to extract the QCD coupling at the Z mass pole $\alpha_s(m_Z)$. The procedure is based on a detailed comparison of the measured weak boson cross sections to theoretical calculations computed at NNLO accuracy with the CT14, HERAPDF2.0, MMHT14, and NNPDF3.0 parton densities. The overall data–theory agreement is good within the experimental and theoretical uncertainties, but the CT14 and MMHT14 parton densities seem to provide the overall best description of all experimental data for the default value of the QCD coupling, $\alpha_s(m_Z) = 0.118$ in all PDF sets. A procedure has been employed to combine the 28 individual α_s extractions per PDF into a single value by properly taking into account all individual sources of experimental and theoretical uncertainties and their correlations. The following QCD coupling values are extracted at NNLO accuracy: $\alpha_s(m_Z) = 0.1181 \pm 0.0016$ (CT14),

0.1209 ± 0.0015 (MMHT14), and 0.1163 ± 0.0019 (NNPDF3.0). The largest propagated uncertainties, combined here in quadrature into a single uncertainty for each final $\alpha_s(m_Z)$ value, are associated with the experimental integrated luminosity and theoretical intra-PDF uncertainties. In this preliminary analysis, using the correlation matrices derived from the CMS experiment alone, the combination procedure did not converge on a stable result for HERAPDF 2.0. All other three $\alpha_s(m_Z)$ extractions appear robust and stable with respect to variations in the data and theory cross sections, their uncertainties, and correlations. The final values are fully compatible with the world average value, and have competitive $\sim$1.5% uncertainties that are similar to those obtained with other precise methods, such as e.g. hadronic τ lepton decays [22].

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