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EW and mixed QCD-EW effects in the W boson mass determination

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We present some selected results from Ref. [1] where we performed a comprehensive analysis of the impact of the QED, electroweak and mixed QCD-electroweak corrections to the determination of the W boson mass at hadron colliders.

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1. Introduction

The W boson mass (M_W) has been measured by the CDF [2] and DØ [3] experiments at TEVATRON with an experimental error of 19 Mev and 23 MeV, respectively. The ATLAS collaboration at CERN published a measurement of M_W with an error of 19 MeV [4] and both the ATLAS and the CMS experiments are planning to measure M_W with a final error of 15 MeV (or eventually 10 MeV). Such a precision requires a careful assessment of the theoretical uncertainties that affect the W mass determination.

At hadron colliders M_W is measured from distributions like the charged lepton p_T or the lepton-neutrino transverse mass (M_T) in charged Drell-Yan production using a template fit procedure. The templates are generated by Monte Carlo event generators with a given theoretical accuracy which are affected by theoretical uncertainties. On the one hand, there are perturbative uncertainties coming from the missing higher-order corrections and, on the other hand, there are also non-perturbative uncertainties such as the ones related to the PDFs or the modeling of the p_T of the W boson. These uncertainties propagate to the W mass measurement.

2. Technical details of the calculation and tools

Our strategy for the determination of the theoretical uncertainties in the W mass measurement follows the experimental procedure. We consider two sets of Monte Carlo samples: the first one corresponds to the pseudodata and play the rôle of data in our analysis, while the samples in the other set are the templates. The templates are generated with different values of M_W using a reweighting procedure[1] and are fitted to the pseudodata. The theoretical uncertainties are defined as the shifts in the W mass (ΔM_W) that are the difference between the nominal value of M_W in the pseudodata and the result of the fit. We focus on the perturbative uncertainties of electroweak (EW) and mixed QCD-EW origin. The event samples are produced with the event generators HORACE [5, 6] and POWHEG-BOX-V2 [7, 8, 9] (W_EW-BMNNP package [10]).

HORACE is a Monte Carlo event generator for Drell-Yan production that can generate events at NLO EW accuracy matched with QED Parton Shower (PS). The fully differential HORACE result can be cast in the form:

$$d\sigma_{\mathrm{HORACE}} = d\sigma_0 \left[1 + \delta_\alpha + \sum_{n=2}^{\infty} \delta'_{\alpha^n} \right], \tag{2.1}$$

where δ_α stands for the one-loop EW corrections, while the sum in Eq. (2.1) represents the QED PS contribution containing soft and virtual multiple-photon radiation in leading logarithmic approximation. Note that the matching procedure replaces the first PS radiation with the exact $\mathcal{O}(\alpha)$ one.

The W_EW-BMNNP package of POWHEG-BOX-V2 is an event generator for charged Drell-Yan that can produce events at NLO QCD+NLO EW accuracy matched with both QCD and QED PS. The POWHEG predictions can be written as follows:

$$d\sigma_{\mathrm{POWHEG}} = d\sigma_0 \left[1 \; + \; \delta_{\alpha_s} + \delta_\alpha + \sum_{m=1,n=1}^{\infty} \delta'_{\alpha_s^m \alpha^n} + \sum_{m=2}^{\infty} \delta'_{\alpha_s^m} + \sum_{n=2}^{\infty} \delta'_{\alpha^n} \right]. \tag{2.2}$$

[1] The reweighting is well defined since the templates never include EW corrections.

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	Templates	Pseudodata	M_W shifts (MeV)
1	LO	POWHEG(QCD) NLO	56.0 ± 1.0
2	LO	POWHEG(QCD)+PYTHIA(QCD)	74.4 ± 2.0
3	LO	HORACE(EW) NLO	-94.0 ± 1.0
4	LO	HORACE (EW,QEDPS)	-88.0 ± 1.0
5	LO	POWHEG(QCD,EW) NLO	-14.0 ± 1.0
6	LO	POWHEG(QCD,EW) `two-rad`+PYTHIA(QCD)+PHOTOS	-5.6 ± 1.0

Table 1: W mass shifts (in MeV) induced by different sets of perturbative corrections and evaluated with templates computed at LO. M_W is extracted from the M_T distribution in $\mu^+\nu$ production at the LHC at 14 TeV.

Besides the NLO EW+QED PS and the NLO QCD+QCD PS corrections, Eq. (2.2) contains a mixed QCD-EW contribution coming from the application of a QED (QCD) PS on events including NLO QCD (NLO EW) corrections.

While HORACE provides an internal implementation of the QED PS, POWHEG relies on external shower Monte Carlo programs, that in our calculation are PYTHIA8 [11] and PYTHIA8 in combination with PHOTOS [12, 13].

3. Mixed QCD-EW corrections

Table 1 summarizes the shifts in the W mass extracted from the M_T distribution in the bare muon channel corresponding to several classes of higher-order corrections ranging from the fixed-order NLO QCD and/or NLO EW to the full simulation at NLO QCD+NLO EW matched with QCD and QED PS. From Tab. 1 it is possible to estimate the impact of the mixed QCD-EW corrections in Eq. (2.2). We find that the mixed QCD-EW contributions introduce a shift of -16±3 MeV, in agreement with the results of Ref. [14] (-14 MeV) where the two-loop corrections $\mathscr{O}(\alpha\alpha_\mathrm{S})$ were computed in pole approximation.

4. Results for the LHC

In Table 2 M_W is extracted from the charged lepton p_T and from the M_T distributions in the bare muon and in the dressed electron setup. The templates are generated at NLO QCD+QCD PS, while the pseudodata are generated at NLO QCD+QCD PS+QED PS (samples [1]-[2]) and at NLO QCD+NLO EW matched with QCD and QED PS (samples [3]-[4]).

The differences between lines [1] and [2] ([3] and [4]) in Tab. 2 come from the different implementation of the QED PS in PYTHIA and in PHOTOS. The numerical impact of these differences on the W mass determination is large in the setup of lines [1]-[2], while it is strongly reduced in the setup of lines [3]-[4], where the first radiation is provided by POWHEG at NLO EW and the two predictions start to differ at $\mathscr{O}(\alpha^2)$.

Taking the difference between lines [3] and [1] (or [4] and [2]) we get an estimate of the impact of the non-logarithmic QED corrections, weak corrections and mixed QCD-EW corrections. The numerical results are summarized in Tab. 3.

	$pp \to W^+$, $\sqrt{s} = 14$ TeV		M_W shifts (MeV)			
	Templates accuracy: NLO-QCD+QCD$_{PS}$		$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^l	M_T	p_T^l
1	NLO-QCD+(QCD+QED)$_{PS}$	PYTHIA	-95.2±0.6	-400±3	-38.0±0.6	-149±2
2	NLO-QCD+(QCD+QED)$_{PS}$	PHOTOS	-88.0±0.6	-368±2	-38.4±0.6	-150±3
3	NLO-(QCD+EW)+(QCD+QED)$_{PS}$`two-rad`	PYTHIA	-89.0±0.6	-371±3	-38.8±0.6	-157±3
4	NLO-(QCD+EW)+(QCD+QED)$_{PS}$`two-rad`	PHOTOS	-88.6±0.6	-370±3	-39.2±0.6	-159±2

Table 2: W mass shifts (in MeV) induced by multiple QED FSR and mixed QCD-EW corrections at the LHC at 14 TeV.

		ΔM_W(MeV) bare muons	
	QED FSR model	M_T	p_T^l
LHC	PYTHIA	+6.2 ± 0.8	+29 ± 4
	PHOTOS	-0.6 ± 0.8	-2 ± 4

Table 3: Impact of the non-logarithmic QED corrections, weak corrections and mixed QCD-EW corrections on the W mass determination at the LHC at 14 TeV in the bare muon setup.

5. Higher order EW corrections

All possible consistent choices of input parameter scheme are equivalent at a given order in perturbation theory and the numerical differences between the predictions in these schemes are higher-order effects. In Ref. [1] we considered the α_0 scheme (with $\alpha_0 = 1/137.035999074$) and two variants of the G_μ scheme, with $\alpha_\mu^{\rm tree} = \sqrt{2} G_\mu M_W^2 \sin^2\theta_W/\pi$ and $\alpha_\mu^{\rm 1-loop} = \alpha_\mu^{\rm tree}(1-\Delta r)$, respectively. In all the three schemes, the coupling between final state photons and fermions is α_0. The theoretical uncertainties on the W mass determination are collected in Tab. 4. The shifts in M_W are of order 10 MeV at NLO EW, while they decrease down to 2 MeV at NLO EW+QED PS.

The unresolved radiation of a lepton pair is an $\mathcal{O}(\alpha^2)$ effect that has been implemented in HORACE using a running value of α together with appropriate modifications of the Sudakov form factor. The shifts in M_W due to lepton-pair radiation are collected in Tab. 5, where we see an effect of approximately 5 MeV in the muon setup and 3 MeV in the electron setup.

6. Conclusions

We reported on the results of Ref. [1], where we studied the theoretical uncertainties on the W boson mass determination coming from QED, EW and mixed QCD-EW corrections. The Monte Carlo samples used at the LHC for the determination of M_W are generated at NLO QCD+QCD PS+QED PS: we found that the missing non-logarithmic QED corrections, weak corrections and mixed QCD-EW corrections introduce a theoretical uncertainty of a few MeV depending on the

$p\bar{p} \to W^+$, $\sqrt{s} = 1.96$ TeV Templates accuracy: LO Pseudodata accuracy		Input scheme	M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	p_T^l
1	HORACE NLO-EW	α_0	-101±1	-117±2
2		$G_\mu - I$	-112±1	-130±1
3		$G_\mu - II$	-101±1	-117±1
4	HORACE NLO-EW+QED-PS	α_0	-70±1	-81±1
5		$G_\mu - I$	-72±2	-83±1
6		$G_\mu - II$	-72±1	-82±2

Table 4: W mass shifts (in MeV) induced by different choices of the input parameter scheme at the TEVATRON.

$pp \to W^+$, $\sqrt{s} = 14$ TeV Templates accuracy: LO Pseudo–data accuracy		M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	p_T^ℓ	$W^+ \to e^+\nu$ M_T	p_T^ℓ
1	HORACE FSR-LL	-89±1	-97±1	-179±1	-195±1
2	HORACE FSR-LL + Pairs	-94±1	-102±1	-182±2	-199±1

Table 5: W mass shifts (in MeV) induced by lepton-pair radiation at the LHC at 14 TeV.

setup and on the tools used for the description of multiple QED FSR. We found that our approximated estimate of the mixed QCD-EW corrections is in agreement with the results of Ref. [14] based on an NNLO calculation in pole approximation. We also studied the impact on the W boson mass determination of higher-order effects such as pair radiation.

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