

## Status of the W-boson mass averaging project

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We present the current status of the W-boson mass averaging project, an ongoing effort aimed at combining Tevatron and LHC measurements. Methods are presented to accurately evaluate the effect of PDFs and other modelling variations on existing measurements. Based on this approach, the measurements can be corrected to a common modelling reference and to the same PDFs, and subsequently combined accounting for PDF correlations in a quantitative way. We discuss the combination procedure, and the impact of improvements in the theoretical description of W-boson production and decay.

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## 1. Introduction

The W-boson mass,  $m_W$ , is a fundamental parameter of the Standard Model, and its value one of the most important inputs to global electroweak fits [1]. Its current world average is dominated by the hadron collider measurements performed by the CDF [2] and D0 [3] Collaborations at the Tevatron and by the ATLAS [4] and LHCb [5] Collaborations at the LHC. In this contribution, we report on the current status of the Tevatron/LHC W-boson mass combination effort, aiming to provide a world average of  $m_W$  determinations endorsed by the experimental collaborations. Such a combination is particularly motivated in light of the discrepancy between the most recent CDF measurement and the results from the other experiments.

At hadron colliders, measurements of  $m_W$  rely on template fits to kinematic peaks of distributions determined from the leptonic decays of the W boson, such as the lepton transverse momentum,  $p_T^l$ , or the W-boson transverse mass  $m_T^W$ . These final-state distributions carry information about the decaying particle mass, but are also affected by the description of W-boson production and decay, such as the rapidity and transverse momentum distributions and its polarization. Predictions of these observables are obtained using Monte Carlo (MC) event generators with input parton distribution functions (PDFs). With each measurement relying on a different generator and PDF choice, prior to combining the measurements a coherent theoretical treatment is required to estimate uncertainty correlations. These modelling differences further motivate small adjustments to the measured values or uncertainties, an effect which has been neglected in past combinations [6].

Beyond the interest of improving the overall measurement precision on  $m_W$ , through this combination effort we establish a methodology to combine present and upcoming measurements of  $m_W$  and enable possible updates of the physics modelling (e.g. PDFs,  $p_T^W$ ) as our theoretical knowledge improves. In addition, as more electroweak measurements become dominated by PDF uncertainties (i.e.  $m_W$  and  $\sin^2 \theta_{W,\ell}^{\text{eff.}}$ ), this methodology will permit to consistently correlate them in global electroweak fits.

## 2. Combination strategy

For a consistent combination of different measurements, their correlations need to be determined. The main source of correlations among the  $m_W$  measurements comes from the knowledge of the proton structure, embedded in the PDFs. Due to the different center-of-mass energies and initial states ( $pp$  vs  $p\bar{p}$ ) at which the measurements are performed this correlation is however non-trivial. Uncertainties related to the  $p_T^W$  distribution, while significant in size, are evaluated independently in each experiment through a detailed analysis of Z-boson production, and are hence assumed to be uncorrelated. Other sources of theoretical uncertainties, such as electroweak corrections, are typically very small, and their detailed correlation knowledge do not affect the combination. Experimental uncertainties are expected to be uncorrelated between experiments.

The combination of  $m_W$  results is performed in a two-step procedure. At first, the results have to be translated to a common reference model. The full procedure to correct the published  $m_W$  values is decomposed into QCD and PDF effects, and allows to improve existing experimental results to include progress in theoretical prediction and PDF determinations. The published  $m_W$

values  $m_W^{\text{published}}$  of each experiment is subject to the correction:

$$m_W^{\text{updated}} = m_W^{\text{published}} - \delta m_W^{\text{QCD}} - \delta m_W^{\text{PDF}}, \quad (1)$$

where  $\delta m_W^{\text{QCD}}$  incorporates any eventual corrections to the QCD modelling beyond the originally quoted uncertainties, and  $\delta m_W^{\text{PDF}}$  brings all measurements to a common PDF set. The results such obtained are then combined properly across experiments including correlations. The model dependence of the result is evaluated by repeating this procedure for a relevant set of PDF determinations.

### 3. Detector Emulation

The original  $m_W$  measurements have been performed at detector level, and reproducing the analyses and detector simulations used by the experiments is a challenging task. Instead, we make use of a parametrized detector response, tuned on publicly available information (lepton energy/momentum scale and resolution, efficiencies; recoil response) and applied on large Monte Carlo event samples at particle-level, generated with varying QCD modelling assumptions and PDF sets. This approach has been found sufficient for a reliable evaluation of variations in the underlying generator-level distributions, such as PDF uncertainties and extrapolations, and effects in the lepton angular distributions. After event selection it can reproduce published distributions at the % level, with systematic uncertainty on  $\delta m_W$  estimated to be at the level of 1-2 MeV.

### 4. QCD modelling aspects

We concentrate here on the description of the angular distribution of the decay leptons. After integrating over azimuthal angle, we can express the W-boson cross-section to all orders in the strong coupling as:

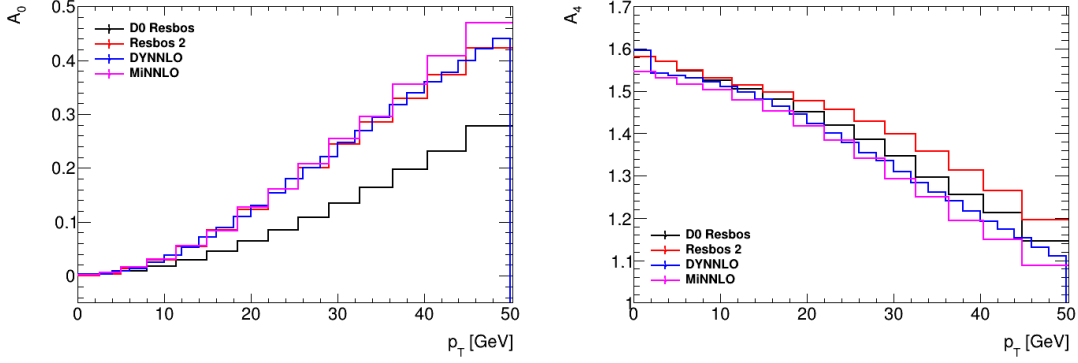
$$\sigma = \sigma_{\text{unpol}} \left[ (1 + \cos^2 \theta_{CS}) + \frac{A_0}{2} (1 - 3 \cos^2 \theta_{CS}) + A_4 \cos \theta_{CS} \right], \quad (2)$$

with  $\sigma_{\text{unpol}}$  the unpolarised cross-section,  $\cos \theta_{CS}$  the polar angle in the Collins-Soper frame [7], and  $A_0$  and  $A_4$  angular coefficients which will in general depend on the boson kinematics. Theoretical predictions at fixed-order for the angular coefficients are currently known up to  $O(\alpha_S^3)$  [8, 9], and describe to a very good degree of accuracy the measured coefficients at the LHC [10].

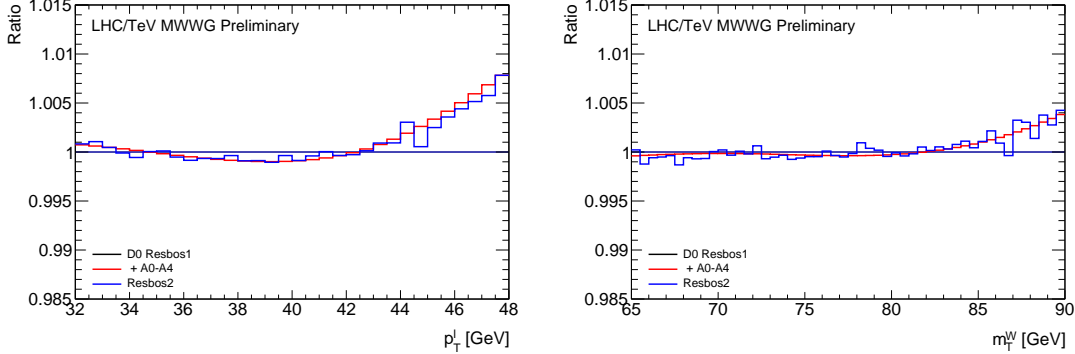
Different theoretical predictions have been used for the various  $m_W$  measurements, reflecting the theoretical state of the art at the time of their preparation. For the descriptions of the W-boson production and decay, CDF used events generated with the Resbos-C [11] code at NLO+NLL while the Resbos-CP [12] code at NNLO+NNLL has been used by D0. ATLAS and LHCb relied on parton shower generated events from Pythia8 [13], but reweighted the angular distributions to  $O(\alpha_S^2)$  fixed-order predictions from DYNNLO [14].

We generated event samples using the same MC generation chain as the original measurements. In addition, MC samples have been generated using Powheg Z\_EW [15], MiNNLOPS [16, 17] and an updated version of Resbos (dubbed here Resbos2) with an improved treatment of spin correlations [18]. This allows to study the impact of computing  $\delta m_W^{\text{QCD}}$  and  $\delta m_W^{\text{PDF}}$  with predictions at different theoretical accuracies.

We compare in Fig. 1 different predictions for  $A_0$ ,  $A_4$  a function of  $p_T^W$ . Large differences can be seen between the Resbos-CP version employed by D0 and the modern event generator or fixed-order codes. Similar differences are also observed with respect to the Resbos-C version used by CDF. This is explained as the legacy Resbos codes do not perform a consistent resummation of all the angular coefficients, but only  $A_4$  and  $\sigma_{\text{unpol}}$  receive corrections from the resummation. This behavior has been corrected in ResBos2, which largely reproduces the fixed-order behavior.



**Figure 1:** The angular coefficients  $A_0$  (left plot) and  $A_4$  (right plot) in W-boson production shown as a function of  $p_T^W$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV. The predictions from the legacy D0 version of Resbos (black) are compared to predictions from an updated version of Resbos (red), fixed-order predictions at  $O(\alpha_S)$  from DYNLO (blue) and MC predictions at  $O(\alpha_S^2)$  from MiNNLOPS (magenta).



**Figure 2:** Relative effect of the generator corrections  $\delta m_W^{\text{QCD}}$  on the lepton transverse momentum (left plot) and W-boson transverse mass distributions (right plot), after including detector effect and applying the  $p_T^W$  constraint. The correction is obtained by reweighting the angular coefficients to the Resbos 2 predictions (red) and shown with respect to the D0 legacy Resbos-CP code (black) and compared to the directly generated Resbos2 predictions (blue).

We evaluated a correction by reweighting the angular coefficients in the original D0 Resbos-CP sample to the  $O(\alpha_S)$  prediction of the Resbos2 sample, and compare it with the shift obtained by directly fitting the Resbos2 distributions. The impact of this correction for the D0 measurement is shown in Tab. 1. When constraining the  $p_T^W$  distribution to stay unchanged under the corrections yields shifts of  $7.3 \pm 1.1$  MeV and  $8.4 \pm 1.0$  MeV for the  $p_T^l$  and  $m_T$  fits. If the  $p_T^W$  distribution is instead left unconstrained, shifts of  $13.9 \pm 1.1$  MeV and  $10.3 \pm 1.0$  MeV for the  $p_T^l$  and  $m_T$  fits

Correction	$\delta m_W^{\text{QCD}}$ [MeV]					
	$p_T^W$ -constrained			No constraint		
	$p_T^l$	$m_T$	$p_T^y$	$p_T^l$	$m_T$	$p_T^y$
Invariant mass	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Rapidity	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
$A_0$	7.6	10.0	15.8	16.0	12.6	19.5
$A_1$	-2.4	-1.9	-1.8	-1.2	-1.6	-1.4
$A_2$	-3.0	-2.6	2.9	-4.2	-3.0	2.3
$A_3$	2.9	1.6	-0.5	3.5	1.8	-0.2
$A_4$	2.4	-0.1	-0.5	0.1	-0.7	-1.0
$A_0 - A_4$	7.6	7.0	16.0	14.1	9.1	18.9
Total	7.6	7.0	16.0	14.1	9.1	18.9
RESBos2	7.3±1.1	8.4±1.0	16.6±1.2	13.9±1.1	10.3±1.0	19.8±1.2
Non-closure	-0.3±1.1	1.4±1.0	0.6±1.2	-0.2±1.1	1.2±1.0	0.9±1.2

**Table 1:** Impact of the angular coefficients reweighting in the D0 RESBos-CP events to those of RESBos2, compared to a direct fit of RESBos1 to RESBos2. Results are shown for the  $p_T^l$ ,  $p_T^y$  and  $m_T^W$  distributions with and without a constraint to leave the  $p_T^W$  unchanged.

are obtained. As the measurements constrain  $p_T^W$  only through the measured  $p_T^Z$  distribution, these numbers are to be considered as an upper bound of the effect.

## 5. Summary

We presented studies towards a first combination of Tevatron and LHC measurements of  $m_W$ . Measurement correlations are dominated by PDF uncertainties and are evaluated through a simplified emulation of the detector response. Extensive comparisons against state-of-the-art QCD predictions highlighted the need to correct the Tevatron  $m_W$  determinations for the treatment of lepton angular distributions in W-boson decays in the legacy Resbos codes. In the context of the D0 measurement, correcting the spin correlations affects the result at the level of -10 MeV, depending on the distribution used in the fit.

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