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Electroweak input parameter schemes and precise theoretical predictions for Drell-Yan

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At hadron colliders, charged and neutral Drell-Yan processes can be used for a high precision determination of the W-boson mass and the weak mixing angle through template fits. Since these measurements rely on Monte Carlo templates, it is crucial to have both flexible and accurate event generators. In this contribution, we present the latest updates of the Z_ew-BMNNPV package for the simulation of the neutral-current Drell-Yan process in the POWHEG-BOX framework, ranging from the development of new electroweak input parameter/renormalization schemes, like the $\overline{\mathrm{MS}}$ one useful for the measurement of the $\overline{\mathrm{MS}}$ running of the weak mixing angle, to the implementation of higher-order fermionic corrections. We perform a detailed comparison of the predictions obtained in the different input parameter/renormalization schemes, discussing their main features and the related theory uncertainties.

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One of the goals of the precision physics program at the LHC and HL-LHC is the high-precision measurement of the sine of the effective leptonic weak mixing angle ($\sin^2\theta^l_{\rm eff}$) from neutral-current Drell-Yan data by means of a template fit approach. In particular, the observables of interest are the forward-backward asymmetry

$$A_{FB} = \frac{d\sigma_F/dM_{ll} - d\sigma_B/dM_{ll}}{d\sigma_F/dM_{ll} + d\sigma_B/dM_{ll}}, \quad \text{with} \quad \frac{d\sigma_F}{dM_{ll}} = \int_0^1 \frac{d\sigma}{dM_{ll}dc}, \quad \frac{d\sigma_B}{dM_{ll}} = \int_{-1}^0 \frac{d\sigma}{dM_{ll}dc},$$

(c being the cosine of the scattering angle of the lepton in the Collins-Soper frame) and/or the closely related A_4 coefficient of the angular decomposition for the Drell-Yan cross section. As template fit procedures rely on Monte Carlo predictions, the theory uncertainties affecting the simulations propagate through the measurement and become part of the total experimental error budget. It is thus crucial, on the one hand, to have accurate and flexible event generators and, on the other hand, to be able to quantify the uncertainties affecting the theory predictions. In this context, we released a new version [1] of the `Z_ew-BMNNPV` package [2] in the `POWHEG-BOX-V2` framework [3–5][1]. The code is a Monte Carlo event generator for neutral-current Drell-Yan at NLO QCD plus NLO EW accuracy with consistent matching to both QCD and QED parton shower. Several new features have been added in the new release of `Z_ew-BMNNPV` ranging from the calculation of the universal fermionic corrections up to $\mathcal{O}(\alpha^2)$ to the implementation of new electroweak input parameter schemes specifically designed for the measurement of $\sin^2\theta^l_{\rm eff}$ (and its $\overline{\rm MS}$ running variant $s^2_{W\,\overline{\rm MS}}(\mu)$) at hadron colliders.

An electroweak input parameter scheme consists in the definition of the three parameters of the electroweak sector of the Standard Model to be considered as independent: the values of these parameters are set to the corresponding experimental ones, while the other parameters are derived from them. Input parameter schemes also determine the renormalization strategies, as in on-shell schemes one requires that input parameters do not receive radiative corrections, while in $\overline{\rm MS}$ schemes the independent parameters can evolve via the RGE equations (in these schemes, experimental data are used to fix the starting vale of the running for a given reference scale $X_{\overline{\rm MS}}(\mu = \mu_{\rm ref}) = X_{\rm exp}$). In the `Z_ew-BMNNPV` package the following schemes have been implemented:

1. (α_X, M_W, M_Z) defined, for instance, in Refs. [6, 7];
2. $(\alpha_X, \sin^2\theta^l_{\rm eff}, M_Z)$ proposed in Ref. [8];
3. (α_0, G_μ, M_Z) the input parameter scheme used for the theory predictions at LEP1 (see [9]);
4. $(\alpha_{\overline{\rm MS}}(\mu), s^2_{W\,\overline{\rm MS}}(\mu), M_Z)$ proposed in Ref. [1] and based on the evolution equations of Refs. [10, 11];

where M_V ($V = W, Z$) are the gauge-boson masses, G_μ is the muon decay constant, and the short-hand notation α_X indicates that the scheme is available in three different variants employing α_0, $\alpha(M_Z)$, or G_μ.

The input parameter schemes based on $\sin^2\theta^l_{\rm eff}$ are particularly useful in the context of the direct determination of the sine of the effective weak-mixing angle at hadron colliders via template

[1]The code can be downloaded using the command `svn co --username anonymous --password anonymous svn://powhegbox.mib.infn.it/trunk/User-Processes-V2/Z_ew-BMNNPV`

fits, as they allow to generate Monte Carlo templates including EW corrections where $\sin^2\theta^l_{\rm eff}$ is an independent parameter (see the recent measurement in Ref. [12]). An additional feature of these schemes is that, since the renormalization condition on $\sin^2\theta^l_{\rm eff}$ imposes that it does not receive radiative corrections, it turns out that the dependence of A_{FB} on $\sin^2\theta^l_{\rm eff}$ is basically unchanged when moving from LO to NLO implying that the outcome of the template fit procedure should be very robust against radiative corrections. In analogy with the $(\alpha_X, \sin^2\theta^l_{\rm eff}, M_Z)$ schemes, the hybrid $\overline{\rm MS}$ scheme $(\alpha_{\overline{\rm MS}}(\mu), s^2_{W\,\overline{\rm MS}}(\mu), M_Z)$ could be used for the determination of $s^2_{W\,\overline{\rm MS}}(\mu)$ at hadron colliders: the sensitivity to the $\overline{\rm MS}$ running weak-mixing angle at the LHC and at the HL-LHC was investigated in Ref. [13]. In the public version of `Z_ew-BMNNPV`, the user can fix the reference scale for the RG evolution ($\mu_{\rm ref}$) and the actual independent parameters are the values of $\alpha_{\overline{\rm MS}}(\mu_{\rm ref})$ and $s^2_{W\,\overline{\rm MS}}(\mu_{\rm ref})$. In the following, we will also show $\overline{\rm MS}$ predictions labeled as *tuned*, where $s^2_{W\,\overline{\rm MS}}(\mu_{\rm ref=M_Z})$ is computed from α_0, G_μ, and M_Z using the expression of Δr in the $\overline{\rm MS}$ scheme (see Ref. [14]), Δr being the NLO electroweak corrections to the muon decay after subtraction of the QED corrections computed in the Fermi theory.

For all the schemes above, weak effects are included up to NLO. In the on-shell renormalized schemes (1)–(3), the leading fermionic corrections consist in the logarithms of light fermion masses over the weak scale (when α_0 is taken as input parameter) and in the top-mass enhanced corrections related to $\Delta\alpha$ and $\Delta\rho$, respectively. The former terms come from the effective running of α from the scale $q^2 = 0$ to $q^2 = M_Z^2$, with $\alpha(M_Z^2) = \alpha_0/(1-\Delta\alpha)$, while the latter are originated by the weak corrections to the W over Z mass ratio (at $\mathcal{O}(\alpha)$, $\Delta\rho = \sqrt{2}G_\mu M^2_{\rm top}/16\pi^2$). The universal fermionic corrections associated with $\Delta\alpha$ and $\Delta\rho$ are included up to $\mathcal{O}(\alpha^2)$ and are labeled as HO (higher orders) in the following. In the $\overline{\rm MS}$ scheme (4), large logarithmic effects are reabsorbed in the running of the couplings (note that in this scheme M_Z is renormalized on-shell).

At a given order in perturbation theory, predictions computed in any input parameter scheme are formally equivalent, however, the numerical results of such calculations will differ because of the truncation of the perturbative expansion: since the differences come from missing higher-order effects, one could take the numerical discrepancies as an estimate of the theory uncertainties affecting the predictions for the observable under consideration. A comparison of results obtained in the schemes listed above is shown in Fig. 1 for the dilepton invariant mass (M_{ll}, left) and for the forward-backward asymmetry (A_{FB}, right). In particular, for the M_{ll} distribution we show ratios of predictions, while for A_{FB} we take absolute differences since the asymmetry has a zero around the Z resonance. In both plots, the reference results are the ones using the $(\alpha(M_Z), \sin^2\theta^l_{\rm eff}, M_Z)$ input parameters, as the predictions in this scheme are not enhanced by $\Delta\alpha$ or $\Delta\rho$ terms. The results shown in the upper, middle, and lower panels are computed at LO, NLO, and NLO plus universal fermionic corrections, respectively. The renormalization scale in the $\overline{\rm MS}$ calculation is set to the dilepton invariant mass: as the running of the parameters $\alpha_{\overline{\rm MS}}(\mu)$ and $s^2_{W\,\overline{\rm MS}}(\mu)$ effectively reabsorbs large part of the corrections, we only show our best predictions for this scheme. In the calculation obtained with the (α_0, G_μ, M_Z) scheme, the actual value of α used is computed from α_0 via the on-shell running up to M_Z as in Ref. [9]. In Fig. 1, the spread in the predictions is larger for the invariant mass distribution, which is sensitive to overall effects related to the couplings and in particular to the specific variant of α used as input, while the effects are smaller for the asymmetry where the overall effects largely cancel. For the A_{FB} difference distribution, the main source of the

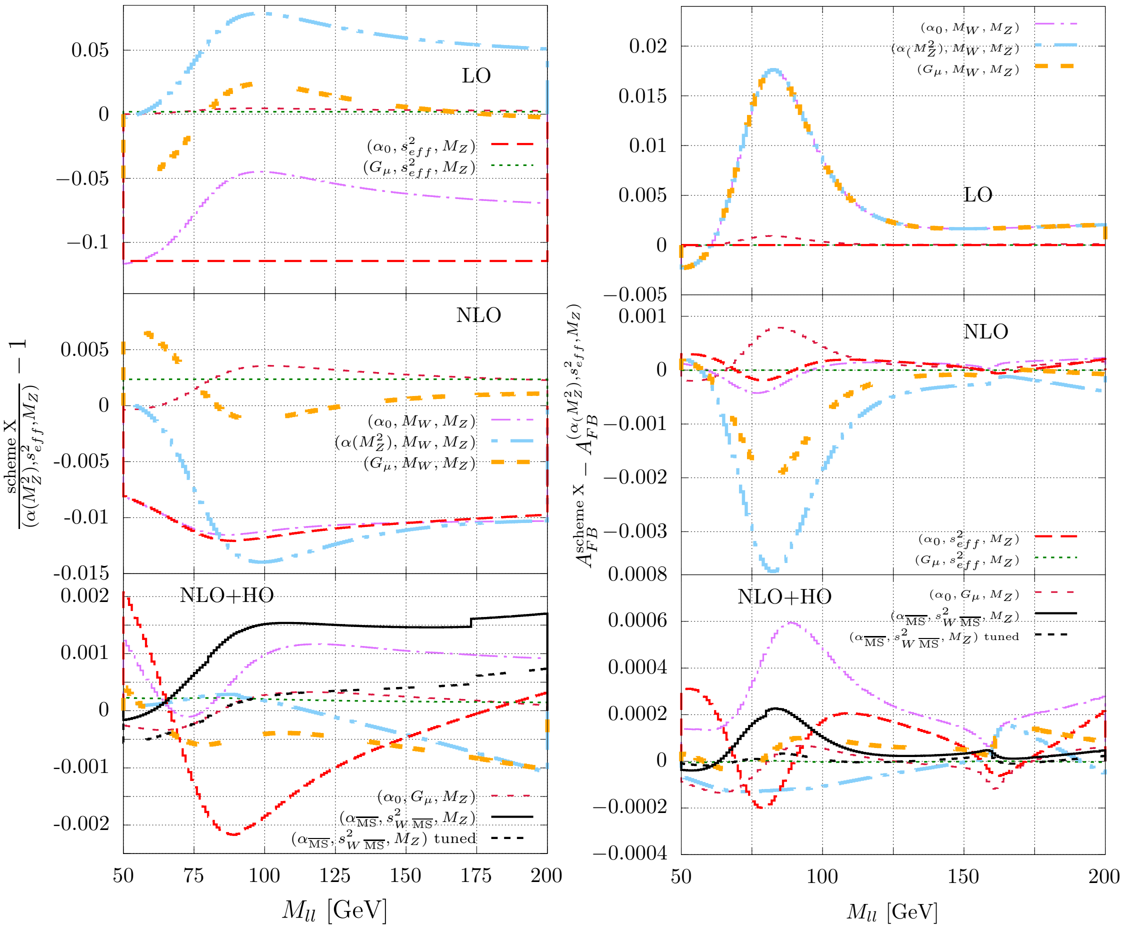

Figure 1: Comparison of the results obtained with the electroweak input parameter schemes described in the text. Left plot: ratio of the predictions for the invariant mass distribution of the l^+l^- system. Right plot: difference of the predictions for A_{FB}. Upper, central, and lower panel show LO, NLO (weak), and NLO (weak) plus leading fermionic corrections at $O(\alpha^2)$, respectively.

spread can be traced back to the different size of the corrections that the EW effects induce on the effective weak mixing angle. Figure 1 also shows that moving from LO to NLO+HO, the differences in the predictions become smaller and smaller[2] reaching the level of some permille for the invariant mass distribution and approximately 8×10^{-4} for the asymmetry difference. The resulting theory uncertainty from missing EW higher-orders is thus pretty large, in particular having in mind that the accuracy target on $\sin^2\theta^l_{\text{eff}}$ at HL-LHC ($\sim 16 \times 10^{-5}$) requires that the predictions for A_{FB} in the resonance region should be under control at the level of 10^{-4} or better.

The conservative approach outlined above, where all the schemes are treated on equal footing, might end up in a sizeable overestimate of the theory uncertainties from missing (EW) higher orders. In fact, one can argue that, at a given order in perturbation theory, predictions obtained within a specific scheme are more precise than the ones computed in terms of a different set of input parameters. For instance, one might look at the size of the known corrections: those schemes where

[2] At LO, the asymmetry difference involving schemes that only differ in the variant of α used as input is zero essentially by definition.

the corrections are large will also be the ones where the missing higher-order effects are expected to be large. This is typically the case for the schemes using α_0 as independent parameter: in Fig. 1 they are responsible for the largest deviation from zero in the lower panel of the A_{FB} difference plot and, if we ignore their contribution, the spread in the predictions at the Z peak boils down to some 10^{-5}.

In the comparison shown in Fig. 1, all schemes are treated as independent in the sense that the numerical values of the input parameters are taken from the corresponding measured ones and no attempt of tuning is made (except for the *tuned* $\overline{\text{MS}}$ predictions). Another possibility could be to follow the approach of [9], namely to tune all the schemes to the (α_0, G_μ, M_Z) one, basically by deriving M_W and $\sin^2\theta^l_{\text{eff}}$ from α_0 (with the on-shell running up to M_Z), G_μ and M_Z using the expression of Δr. We checked that resulting spread in the asymmetry predictions at the Z resonance is at most 5×10^{-5}.

As a conclusive remark, besides the aspects outlined above, there are other sources of theory errors affecting the predictions like, for instance, the parametric uncertainties related to the experimental error on the electroweak input parameters or on other parameters entering at loop level like the top mass and, for the α_0-based schemes, the light quark masses entering the on-shell running of α. Moreover, at the level of precision required for A_{FB}, also technical details of the calculation might induce theory uncertainties: one example is the choice of the strategy employed for the treatment of the unstable Z boson.

To summarize, we presented some of the features of the new release of the `Z_ew-BMNNPV` generator focusing, in particular, on the new input parameter schemes available and we performed a detailed comparison of the results with the aim of quantifying the theory uncertainties from missing higher-order weak corrections affecting the predictions in the context of the $\sin^2\theta^l_{\text{eff}}$ measurement at the LHC and at HL-LHC. A more realistic analysis, based on events generated at NLO EW (with fermionic HO)+NLO QCD with matching to QCD and QED parton showers would also allow one to assess the theory uncertainties from mixed QCD-EW effects (see, for instance, Ref. [15]), but this will be addressed in future publications.

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