PROCEEDINGS OF SCIENCE

Bottom quark mass effects on the $p_\perp^{\ell^+\ell^-}$ spectrum and the W mass determination

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We briefly discuss the role of the subprocesses initiated by bottom quarks in the study of the Drell-Yan observables and the treatment of the bottom quark mass effects; we eventually estimate the impact of these approximations in the high-precision determination of the W boson mass.

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1. Introduction

The very high-precision measurements of the observables of the Drell-Yan (DY) processes at the LHC is allowing a corresponding very high-precision determination of the basic electroweak (EW) parameters of the Standard Model (SM) lagrangian, like the W boson mass or the value of the weak mixing angle. These experimental results represent a formidable challenge for the theoretical predictions, whose residual error should match or possibly be smaller than the experimental one, but also for all the theoretical tools like the Monte Carlo event generators (cfr. ref. [1]) which are a fundamental element in the analysis and interpretation of the data. The EW parameters determination at the LHC is obtained via a template fit procedure: the best available SM description of a kinematical distribution, keeping the quantity of interest as free fit parameter, is compared to the data; the value of the parameter that maximizes the agreement is the "measured" value. Any theoretical uncertainty in the evaluation of the templates affects the template fit procedure and represents a theoretical systematic error on the EW parameter value[1].

The accurate simulation of the charged-current (CC) DY process requires an input concerning the transverse momentum spectrum of the lepton-pair, in particular at low transverse momenta, a region where perturbative fixed-order QCD predictions are not reliable. Since this input can not be directly measured from the data, it is common practice to rely on the knowledge of the neutral-current (NC) DY process and to extrapolate the relevant information from the NC to the CC lepton-pair transverse momentum spectrum. The different flavour composition of the partonic initial states makes a simple extrapolation from NC to CC difficult. The partonic subprocesses are weighted by the corresponding combinations of collinear proton parton distribution functions (PDF) and are entangled[2] by all the relations satisfied by the collinear PDFs. The latter play an important role in the NC case, where the shape of the lepton-pair transverse momentum is the outcome of the combination of the contributions due to the different flavours of quarks, each with its specific profile, even if the partonic cross sections in massless approximation are exactly the same for all the channels. In addition to these questions, one may notice the non negligible role of the bottom quark in NC-DY (it contributes to $\mathcal{O}(4-5)\%$ of the total cross section), while in the CC case this flavour appears only in CKM-suppressed subprocesses. This asymmetry between the two channels has to be taken into account for an accurate prediction of the CC differential spectra. An additional element that deserves investigation is given by the mass m_b of the bottom quark, much larger than the one of the first four flavours. Since the quarks in the proton are described as massless partons, but, on the other hand, the value $m_b \simeq 4.5$ GeV is comparable with one of the relevant scales in NC-DY, namely the position of the peak of the $p_\perp^{\ell^+\ell^-}$ distribution, it is interesting to analyze the impact of the mass corrections in the description of this spectrum.

These topics, and in particular the role of the bottom quark in the production of a lepton pair, are discussed in ref.[8] starting from the analysis of the associated production of a lepton pair and a $b\bar{b}$ pair, formulated in the so called four-flavour scheme (4FS), i.e. considering only four active flavours in the proton parameterization, while the bottom quark appears only in the final state and is described with exact fully massive kinematics. The comparison with the description of the production of a lepton pair in the so called five-flavour scheme (5FS), where the bottom is a

[1] For a detailed discussion of the role of EW and mixed QCDxEW corrections, see ref. [2, 3, 4]

[2] For a detailed description of the CC case, see refs. [5, 6, 7]

massless parton active in the proton, provides an estimate of the relevance of higher-order radiative corrections and of the bottom quark mass effects. Both the 4FS and the 5FS descriptions receive large QCD radiative corrections at next-to-leading (NLO) order, but also in specific phase-space corners where the resummation to all orders of logarithmically enhanced terms is needed; the latter is achieved in leading logarithmic (LL) accuracy via the Parton Shower (PS) algorithm. Matching NLO-QCD and QCD-PS corrections offers the first approximation with a reliable estimate of the central value of the predictions, while the remaining theoretical uncertainties can be studied by the canonical renormalization and factorization scale variations, but also comparing the 4FS and 5FS results and comparing the distributions computed with two different matching schemes, namely those available in the POWHEG and MG5_AMC@NLO formulations.

2. Lepton-pair production in association with a $b\bar{b}$ pair

In figure 1 we present the lepton-pair transverse momentum distribution computed in the 4FS in the process $pp \to \ell^+\ell^- b\bar{b}$ with a collider energy of 13 TeV, inclusive over the bottom quarks configurations. In the upper inset of the left plot we present the results obtained with POWHEG and MG5_AMC@NLO for different choices of the parameters which control, in the two codes, multiple parton emission and its matching with the fixed-order matrix elements; in the lower inset we present the relative size of the PDFs and QCD scale uncertainty bands. In the right plot of figure 1

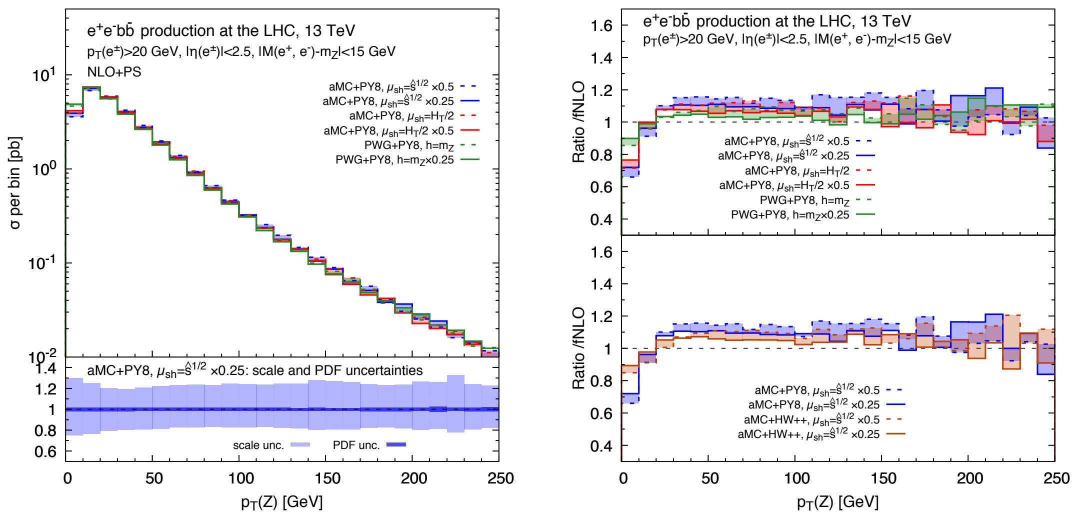

Figure 1: $p_\perp^{\ell^+\ell^-}$ distribution in the 4FS inclusive over the b-quark contribution. The colour codes are defined in ref.[8].

we study different sources of theoretical uncertainty. In the upper inset we show the relative impact of multiple parton emissions, simulated with the PYTHIA8 QCD PS, with respect to the fixed-order NLO prediction; the choices of different matching parameters and matching schemes are represented by the various colours, while the bands are obtained by varying the matching parameters in appropriate ranges (see ref. [8] for all the details and refs.[9, 10] for an analytic discussion about the energy scales that emerge in the characterization of this process). We observe that multiple parton emissions have a sizeable negative effect at low values of the lepton-pair transverse momentum, while they give a moderate positive enhancement for $p_\perp^{\ell^+\ell^-} \geq 30$ GeV. The formulations under study differ by higher-order QCD corrections and we can read an uncertainty ranging between $\mathscr{O}(\pm 5\%)$ and $\mathscr{O}(\pm 10\%)$ when $p_\perp^{\ell^+\ell^-} \geq 30$ GeV, while for smaller values of the transverse momentum the uncertainty is slightly larger. In the lower inset of the right plot of figure 1 we compare, in the MG5_AMC@NLO matching scheme, the different impact of multiple parton emissions as described by the PYTHIA8 and HERWIG++ QCD PS. We observe that also in this case the differences are due to higher-order QCD contributions and that they are similar in size to those due to the matching-scheme choice and matching parameter variation.

3. The inclusive lepton-pair transverse momentum distribution

While the bottom quark in the 5FS is a massless parton active in the proton, in the 4FS it appears only in the final state and it can be described with exact fully massive kinematics. In ref.[8] two alternative descriptions of the lepton-pair transverse momentum distribution have been compared, the one computed in the massless 5FS and a combination of 4FS and 5FS results. This comparison allows to estimate the impact of the bottom quark mass effects on this observable. The definition of two physical distributions, a lepton pair strictly without B hadrons (dubbed 5FS-

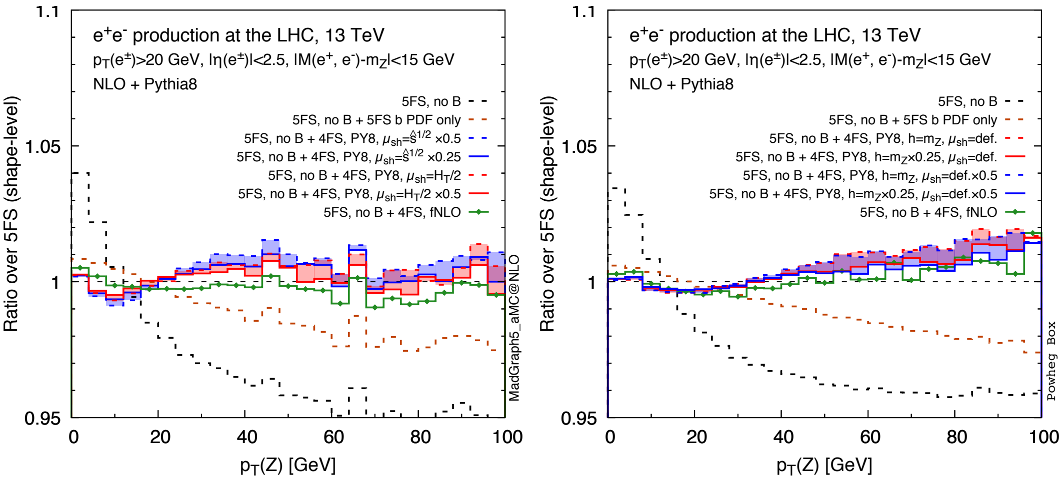

Figure 2: Ratio of the $p_\perp^{\ell^+\ell^-}$ distribution in the refined approximation including bottom-quark mass effects over the plain 5FS with MG5_AMC@NLO (left plot) and POWHEG (right plot).

Bveto in the following) and a lepton pair accompanied by at least one B hadron (the 4FS results), allows a separate treatment of these two complementary observables. Their orthogonality allows us to take their sum and to consider it as our alternative prediction for any DY observable. We apply this approach to the lepton-pair transverse-momentum distribution.

$$\frac{d\sigma^{\rm mass}}{dp_\perp^{\ell^+\ell^-}} = \frac{d\sigma^{\rm 5FS-Bveto}}{dp_\perp^{\ell^+\ell^-}} + \frac{d\sigma^{\rm 4FS}}{dp_\perp^{\ell^+\ell^-}}\,. \tag{3.1}$$

The impact of the combination eq.3.1 is illustrated by its ratio $\mathscr{R}(p_\perp^{\ell^+\ell^-})$ over the corresponding results obtained in the plain 5FS, defined as

$$\mathscr{R}(p_\perp^{\ell^+\ell^-}) = \left(\frac{1}{\sigma_{\rm fid}^{\rm mass}} \frac{d\sigma^{\rm mass}}{dp_\perp^{\ell^+\ell^-}} \bigg|_{\tt tuneX} \right) \cdot \left(\frac{1}{\sigma_{\rm fid}^{\rm 5FS}} \frac{d\sigma^{\rm 5FS}}{dp_\perp^{\ell^+\ell^-}} \bigg|_{\tt tuneX} \right)^{-1} \tag{3.2}$$

for a generic tune X of the parameters of the QCD PS; this ratio is plotted in figure 2. The distortion induced by the different treatment of the bottom quark mass effects is visible in the region $p_\perp^{\ell^+\ell^-} \leq 30$ GeV, even accounting for different sources of theoretical uncertainty, represented by the coloured bands.

4. Impact of different b-quark treatments on the W boson mass determination

A change in the parameterization of the perturbative contributions, active at low transverse momenta in the $p_\perp^{\ell^+\ell^-}$ distribution, may in turn have an impact on the determination of the QCD PS parameters values which are extracted, among others, from the analysis of the NC DY observables. The factor $1/\mathscr{R}(p_\perp)$ can be used to estimate the change in the predictions, if a new PS tune were determined relying on eq.3.1 for the description of the $p_\perp^{\ell^+\ell^-}$ distribution. Following this idea, the CC-DY observables have been simulated in the plain 5FS with a standard QCD-PS tune and reweighed by $1/\mathscr{R}(p_\perp^{\ell\nu})$. A template fit approach, whose results are shown in figure 3, has been used to express the difference between plain and reweighed CC-DY observables, sensitive to m_W, as a shift in the final m_W value; the latter is what one would observe when fitting the real data including or not the bottom quark mass effects.

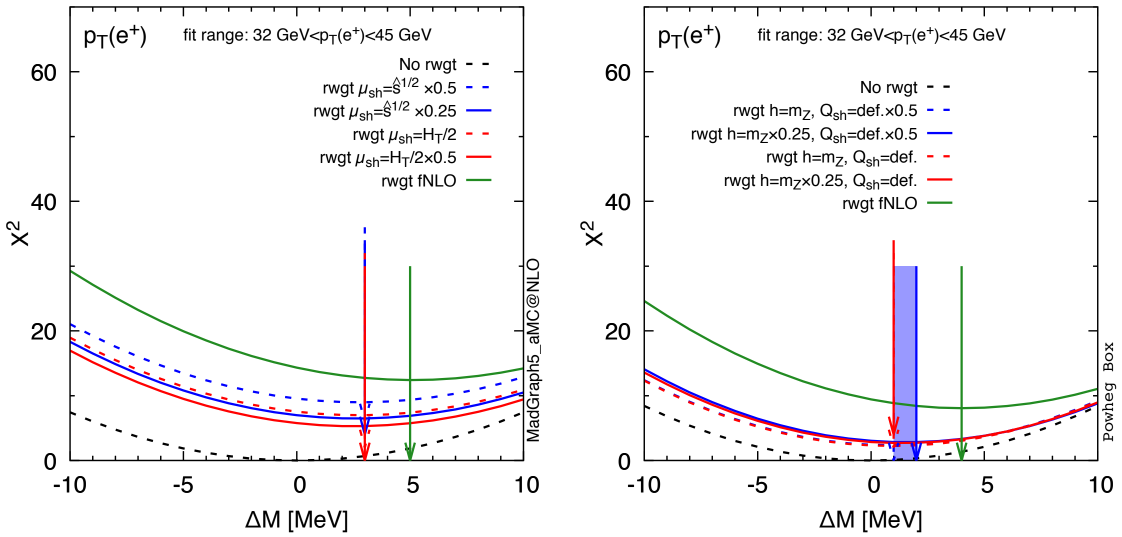

Figure 3: Result of the template fit to the CC-DY lepton transverse momentum distribution that include the improved bottom-quark effects in different QCD approximations, with MG5_aMC@NLO (left plot) and POWHEG (right plot). The fit is based on templates prepared in the massless 5FS.

5. Conclusions

The high-precision measurement of the $p_\perp^{\ell^+\ell^-}$ distribution, with a total experimental error below the 0.5% level over a large range of momenta, challenges the corresponding theoretical predictions. Several radiative corrections, which were so far considered subdominant, are becoming relevant at this level of precision; among them, the bottom quark mass effects may yield differences which can not be neglected in the prediction of the $p_\perp^{\ell^+\ell^-}$ distribution and also have a small but not negligible impact on other observables like the single lepton transverse momentum distribution. Due to the interplay between NC-DY and CC-DY, the determination of the W boson mass from the charged lepton transverse momentum distribution in CC-DY can receive a small but not vanishing shift $\Delta m_W \leq 5$ MeV due to bottom quark mass effects.

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