IL NUOVO CIMENTO Vol. 35 C, N. 3 Maggio-Giugno 2012
DOI 10.1393/ncc/i2012-11215-8

Colloquia: TOP2011

W boson plus heavy flavour (theory)

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ricevuto l' 1 Marzo 2012
pubblicato online il 28 Maggio 2012

Summary. — In this talk we give an overview of the theory status for the predictions of W boson production in association with bottom quarks with relevance to top quark phenomenology.

PACS 14.70.Fm – W bosons.
PACS 14.65.Fy – Bottom quarks.
PACS 12.38.Bx – Perturbative calculations.

1. – Introduction

The irreducible background to top quark production is the production of W bosons in association with bottom quarks. In this talk we will address the recent theoretical developments in the predictions of these background processes. In sect. **2** the recent NLO calculations for the full $pp \to W^+W^-b\bar{b}$ process are discussed. In sect. **3** the differences between the four and five-flavour scheme calculations are spelled out in the context of W boson production in association with heavy quarks. In sect. **4** we present results for the recent calculations for W-boson production in association with heavy quarks matched to a parton shower at NLO accuracy.

2. – $W^+W^-b\bar{b}$ at NLO

Up to about a year ago, all calculations for top quark pair production beyond the lowest order made use of the fact that the top quarks are narrow. In a good approximation they are described by on-shell particles. The width of the top quark is ignored and therefore the narrow width approximation can be pursued. However, the top quarks are not stable particles and decay almost immediately. If we want to include the decays of the top quarks, including all finite width effects, gauge invariance tells us to also include single and non-resonant contributions, *i.e.* all diagrams contributing to the $pp \to W^+W^-b\bar{b}$ process.

Recently two groups computed the full NLO corrections to the process $pp \to W^+W^-b\bar{b}$ with both W bosons decaying leptonically [1]. For inclusive observables the single and non-resonant contributions have a very small effect. However, when cuts are applied to remove the double resonant contributions the effects are larger. Furthermore, the NLO corrections cannot be described by an overall scaling factor of the LO, see ref. [1] for more details. These very impressive NLO calculations can be used to describe top quark pair production (in the di-lepton channel) and their irreducible backgrounds together in a consistent way, taking into account all finite-width and interference effects at NLO accuracy.

Unfortunately, both these calculations use the massless approximation for the b quarks. This means that these calculations can only be used when both b jets are resolved. So, even though all the diagrams contributing to the W associated single top production in the four-flavour scheme are contained in these calculations, they cannot be used to describe the contribution of this process (and the interference with top quark pair production and the non-resonant contributions): in the four-flavour scheme the b quarks need to be treated as massive particles and do not need to be resolved.

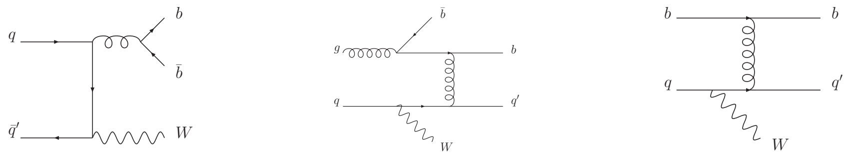
3. – Four- and five-flavour calculations

Let us elaborate on the differences and similarities between the four- and five-flavour schemes. In the context of top quark physics the best-known example in which the four- and five-flavour schemes were compared is the t-channel single-top production process [2]. The difference is, in short, that in the four-flavour scheme the PDF does not contain b quarks: all b quarks are generated in the matrix elements and cannot come directly from the proton. In a five-flavour scheme the description of the PDF contains the $g \to b\bar{b}$ splitting. This leads to the following considerations:

- Contrary to the four-flavour scheme, for factorisation to be valid the mass of the b quark (m_b) has to be neglected in the matrix elements when performing a calculation in the five-flavour scheme. Note that the starting scale for the evolution in the PDF still depends on m_b, so the mass does enter the predictions. In ref. [2] it has been shown that the uncertainties from the m_b are similar in size in both schemes.
- For initial-state b quark in the five-flavour scheme, the evolution of the PDFs resums logarithms of $\log(m_b/\mu_F)$, where μ_F is the factorisation scale. Initial state radiation is described at leading logarithmic accuracy only. In the four-flavour scheme these logarithms are not resummed, but the non-logarithmic contributions to the $g \to b\bar{b}$ splitting are already included at LO. When including NLO corrections in the four-flavour scheme, the first logarithms are included. Similarly, when including NLO corrections in the five-flavour scheme, also the first non-logarithmic contributions due to radiation are correctly included.
- The running of the strong coupling α_s depends on the number of flavours.

The $m_b = 0$ approximation in the five-flavour scheme can be improved systematically by replacing (higher order) contributions that have no b quarks in the initial state, by corresponding contributions in which $m_b \neq 0$. With this improvement the four and five-flavour scheme descriptions become exactly equivalent when all orders in perturbation theory are included.

For W-boson production in association with (b-)jets the usage of the four and five-flavour scheme calculations can be a bit confusing; it depends on the channel which is the correct description in either scheme. For example, consider the following channels: W boson plus 1 or 2 jets with 1 or 2 b-tags or a bb-tag (inclusive or exclusive) (a bb-jet is jet containing two B hadrons). In general, these are different processes and have therefore different matrix elements contributing.



(a) (b) (c)

Fig. 1. – Representative LO Feynman diagrams for the W boson + heavy flavour processes. Diagrams are taken from refs. [3].

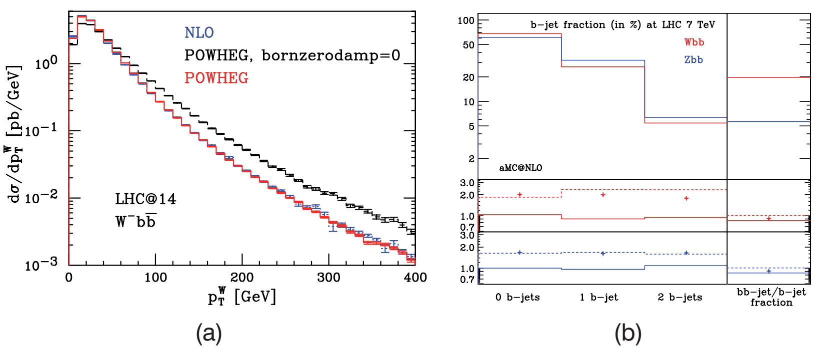
In the four-flavour scheme, there are no initial-state b quarks. Therefore, the processes above are all described by the same matrix elements, see fig. 1(a). There is one exception and that is the description of a W boson plus 2 jets with (exactly) 1 tag. It is better described by the LO diagram in fig. 1(b). However, given that this process is only known at LO, and that the NLO corrections to the process of fig. 1(a) already include these contributions at the real-emission level, there is really one calculation that fits all in the four-flavour scheme: the NLO description of the $pp \to Wb\bar{b}$ process.

In the five-flavour scheme the situation is more complicated. There is no single computation that can provide consistent predictions for all channels. When requiring 2 b-tags or a bb-jet, the same diagrams as in the four-flavour scheme are appropriate (in principle with $m_b = 0$). On the other hand, if only 1 b-tag is requested, there is another set of diagrams that contributes at LO, see fig. 1(c). These diagrams have an explicit b quark in the initial state. The NLO five-flavour scheme calculation has a smaller theoretical uncertainty from renormalisation and factorisation scale dependence.

The authors of ref. [3] studied how to consistently include the b quark mass to improve the five-flavour scheme calculation. This leads to a mixture of the four- and five-flavour scheme calculations, which gives the most precise predictions at fixed order in perturbation theory for the processes W boson plus 1 or 2 jets with (at least) 1 b-tag.

4. – $Wb\bar{b}$ in the four-flavour scheme matched to the parton shower at NLO

On the other hand, the four-flavour scheme calculation is one that fits all. Recently, this computation has been matched to the parton shower at NLO accuracy [4].



(a) (b)

Fig. 2. – (Colour on-line) POWHEG predictions for the transverse momentum of the W boson (a) for the 14 TeV LHC and aMC@NLO predictions for the total rate of 0, 1, and 2 b jets (b) for the 7 TeV LHC. For plot (b) the lower insets the ratio with the fixed-order LO (crosses), NLO (solid) and LO+PS (dashed) are given. Plots are taken from refs. [4].

The first group uses the POWHEG matching prescription [5] as implemented in the POWHEG BOX [6]. The leptonic decay and finite width effects of the W boson are included, but correlations between production and decay are only accurate up to LO in perturbation theory. In fig. 2(a) the predictions for the transverse momentum of the W boson are given at the 14 TeV LHC. The blue curve is the fixed-order NLO results, and the black curve is the POWHEG prediction out of the box. As can be seen, the black curve overshoots the NLO results by quite a large amount. There are two reasons for this: away from the Sudakov region, the real-emission configuration is enhanced by a factor $\bar{B}/B$ which can be artificially large when the outgoing lepton from the W decay is anti-parallel with the incoming quark because for those configurations $B \to 0$; and non-singular phase-space regions should not be exponentiated, as this may enhance the ratio $\bar{B}/B$ even more. When the corresponding parameters are properly tuned, the POWHEG results (red curve) agree with the fixed order NLO.

The second group uses the aMC@NLO tool [7] to compute all the contribution to the process $pp \to l\nu_l b\bar{b}$ at NLO accuracy and match this process to the parton shower using the MC@NLO matching technique [8]. The process is generated within the MadFKS framework [9], using the virtual corrections from MadLoop [10]. In fig. 2(b), the fraction of events with 0, 1 or 2 b jets as predicted by aMC@NLO are shown for the 7 TeV LHC. As the fourth column, also the fraction of b jets that have two B hadrons is given. Interesting is to see that the latter ratio is much larger for $Wb\bar{b}$ compared to $Zb\bar{b}$ due to the fact that in $Wb\bar{b}$ the b quarks are coming from a $g \to b\bar{b}$ splitting in the matrix elements while for $Zb\bar{b}$ there are also contributions in which the Z boson couples directly to the b quarks.

5. – Conclusions

In this talk we discussed the recent progress in computations for W boson plus heavy flavour processes. We discussed that the NLO computation of the $WWb\bar{b}$ process can be used to describe the top pair production signal and irreducible backgrounds consistently, but it cannot be used directly to estimate the top backgrounds to other processes. For processes with b quarks two descriptions exists (four- and five-flavour schemes) that are equivalent when all orders in perturbation theory are included. For the description of the production of a W boson plus up to 2 jets with b-tags, the NLO computation in the four-flavour scheme to the $pp \to Wb\bar{b}$ process can be used for all. This process is available matched to the parton shower in the POWHEG BOX and aMC@NLO frameworks.

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