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# $b$ QUARK MASS EFFECTS IN ASSOCIATED PRODUCTION[*]

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In this work, we study an extension of the commonly used 5F scheme, where $b$ quarks are treated as massless partons, in which full mass effects are retained in both the initial and in the final state. We name this scheme 5F massive scheme (5FMS). We implement this scheme in the Sherpa Monte Carlo event generator at MePs@Nlo accuracy, and we compare it for two relevant cases for the LHC: $b\bar{b} \to H$ and $pp \to Zb$.

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## 1. Introduction

Processes with heavy quarks in the initial state, in particular associated production processes, have seen in recent years a renewed interest [1–9]. From the theoretical point of view, they are interesting applications of multiscale processes with largely different scales. Ratio of these large scales can give rise to large logarithms which might spoil the convergence of the perturbative series. To avoid this, one can consider the $b$ as a massless parton, and construct a $b$-PDF which resums this potentially large collinear logarithms, at the price of neglecting mass effects. An alternative point of view can be that of treating the $b$ quark as a massive, decoupled particle, which is only produced in the final state, or treating the $b$ quark as a massless parton on the same footing as the other, thus contributing to the QCD evolution. In this way, one is able to retain full mass effects at the price of keeping the aforementioned possibly large collinear logs.

The former of these two approaches is called *five-flavour* (5F) scheme and would schematically correspond to the right-hand side plot of Fig. 1, while the latter is referred to as *four-flavour* (4F) scheme and is represented

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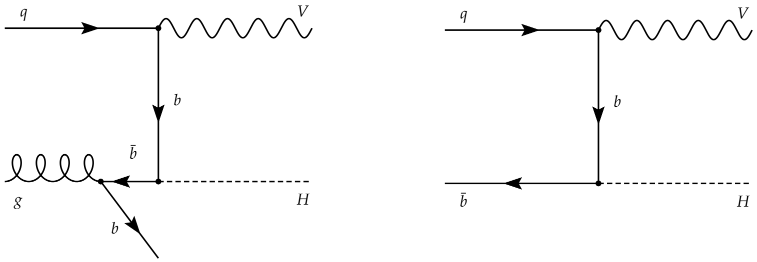

Fig. 1. 4F (left plot) *versus* 5F (right plot) scheme diagrams for $VH$ production.

in the left plot of Fig. 1. These two approaches have generally been used in a complementary, with the old way of saying being:

> *use the 4FS for exclusive observables,*
> *and the 5FS for inclusive observables.*

Many studies have however now shown that the 5FS scheme performs generally better both when compared to data (see Fig. 2), [1], or when comparing it with a matched calculation [4,8], although this too is only true up to a certain extent. There are, in fact, regions of phase space where one might still want to include exact mass effects, which would, in principle, require the use of the 4FS.

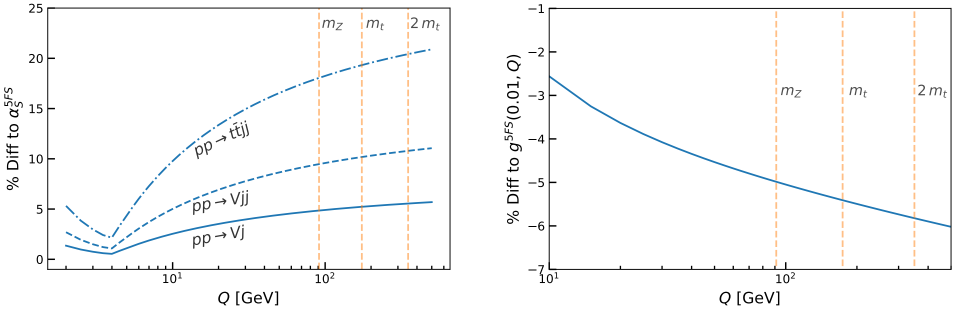

Fig. 2. In the plot, there is shown the error that is made when taking and $\alpha_s$ and a gluon PDF in the 4FS with respect to the 5FS baseline. As it can be seen, the two effects partially mitigate each other, although this is true only for processes that start at a low enough power of $\alpha_s$, and have a large gluon contribution.

In this work, we investigate the possibility of using a scheme, built upon the 5FS, with exact mass dependence. We name this scheme five-flavour-massive-scheme (5FMS). We implement the necessary ingredients to perform calculations in this scheme in the Sherpa Monte Carlo event generator [10], at Mc@Nlo accuracy [11,12]. A detailed description of this scheme and its implementation can be found in [13].

## 2. Including mass effects

### *2.1. Fixed order*

In order to study the effects introduced by this new scheme, we take an explicit example: $b\bar{b} \to H$. Reference diagrams that contribute to the *next-to-leading* order are shown in Fig. 3. At the level of partonic matrix elements, the only difference between the 5FS and the 5FMS is that in the latter full mass dependence is retained, including the initial state. As the infrared divergent structure is modified by the presence of the $b$ mass, that acts as a collinear regulator, a modification of the standard Catani–Seymour subtraction is required [13]. With this in place, we can generate *fixed-order* events, see Fig. 4. As an example observable, we focus on the $p_{\mathrm{T}}$ of the produced $H$ boson.

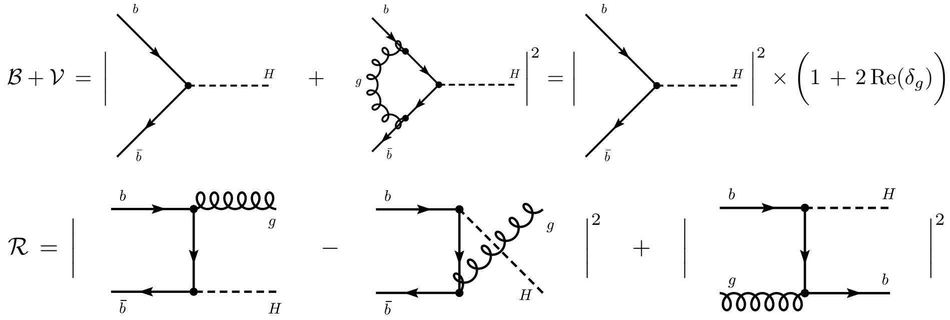

Fig. 3. Virtual and Real contributions to $b\bar{b} \to H$.

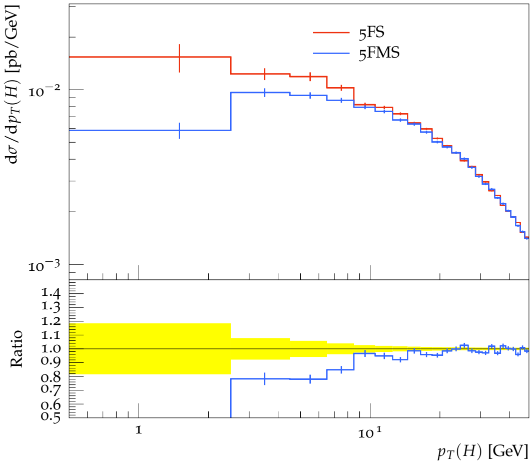

Fig. 4. Comparison of the 5F and the 5FM scheme.

We know that mass effects contribute only a few percent to the total cross section for this process. In addition, we know that they are power suppressed and we expect them to scale like $m_b^2/p_{\mathrm{T}}^2$. This is, indeed, roughly the behaviour shown in Fig. 4.

### 2.2. Mc@Nlo

We now want to study what happens when this scheme is matched to the parton shower. Since we do not have a theoretical reference here, we use $pp \to Zb$ data [14] from Atlas. In particular, we replicate the set-up used in [1], and we compare it with the 5FS MePs@Nlo line referenced therein, see Fig. 5. The difference with respect to that set-up is that we have Mc@Nlo accuracy only for the core $pp \to Z$ processes, while extra jet contributions that are merged on top of that only come at leading order

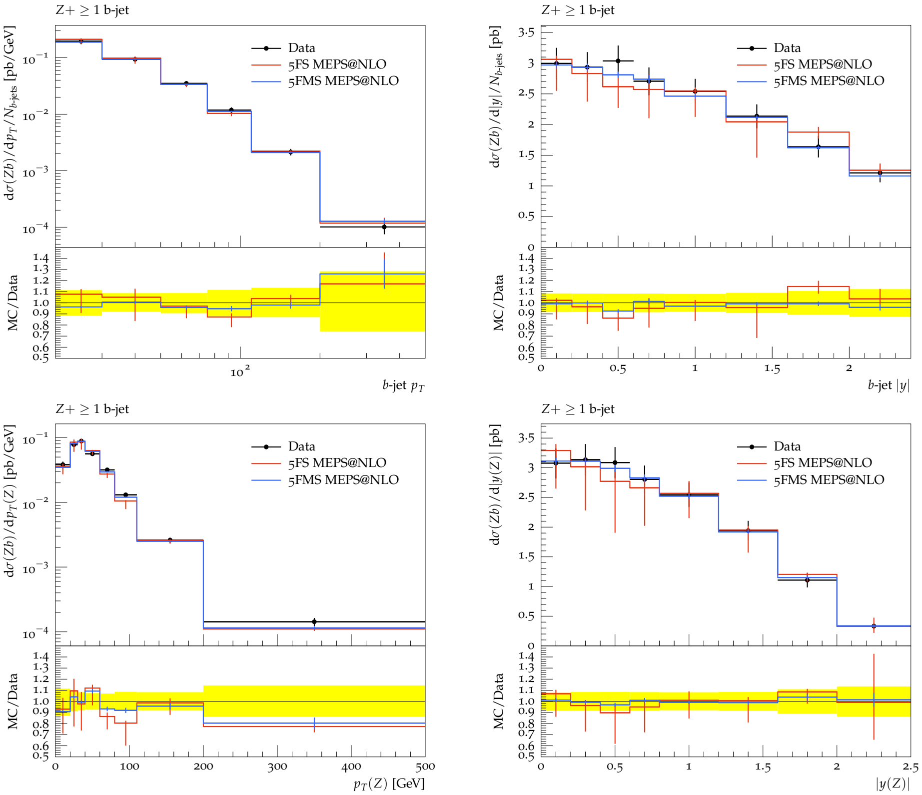

Fig. 5. We show prediction obtained in the 5FS, massless, at MePs@Nlo accuracy, with up to 2 jets at NLO plus up to three jets at leading order. The 5FMS prediction, on the other hand, includes only the 0 jet contribution at NLO, while the 1,2 and 3 jets contributions are merged with LO accuracy.

accuracy. Strictly speaking thus, we should compare the 5FMS MePs@Nlo here with the 5F MePs@Lo prediction of [1], however, we expect some mass effects to make up for some of the differences in accuracy.

As our aim is to investigate mass effects, in $b$-initiated processes, we look at events in which at least one jet containing a $b$ is tagged, and we plot distributions for the leading $b$-jet and the $Z$-boson $p_{\mathrm{T}}$ and $y$ against data. These plots are reported in Fig. 5. As it can be seen, this new scheme performs rather well and, indeed, it shows the same type of compatibility with data of the 5FS MePs@Nlo prediction, which is reassuring.

Further details and studies on this new scheme can be found in [13].

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## REFERENCES

[1] F. Krauss, D. Napoletano, S. Schumann, *Phys. Rev. D* **95**, 036012 (2017) [`arXiv:1612.04640 [hep-ph]`].

[2] D. Napoletano, F. Krauss, `arXiv:1706.10072 [hep-ph]`.

[3] S. Forte, D. Napoletano, M. Ubiali, *Phys. Lett. B* **751**, 331 (2015) [`arXiv:1508.01529 [hep-ph]`].

[4] S. Forte, D. Napoletano, M. Ubiali, *Phys. Lett. B* **763**, 190 (2016) [`arXiv:1607.00389 [hep-ph]`].

[5] F. Maltoni, G. Ridolfi, M. Ubiali, *J. High Energy Phys.* **1207**, 022 (2012) [*Erratum ibid.* **1304**, 095 (2013)] [`arXiv:1203.6393 [hep-ph]`].

[6] M. Lim, F. Maltoni, G. Ridolfi, M. Ubiali, *J. High Energy Phys.* **1609**, 132 (2016) [`arXiv:1605.09411 [hep-ph]`].

[7] M. Bonvini, A.S. Papanastasiou, F.J. Tackmann, *J. High Energy Phys.* **1511**, 196 (2015) [`arXiv:1508.03288 [hep-ph]`].

[8] M. Bonvini, A.S. Papanastasiou, F.J. Tackmann, *J. High Energy Phys.* **1610**, 053 (2016) [`arXiv:1605.01733 [hep-ph]`].

[9] V. Bertone *et al.*, `arXiv:1711.03355 [hep-ph]`.

[10] T. Gleisberg *et al.*, *J. High Energy Phys.* **0902**, 007 (2009) [`arXiv:0811.4622 [hep-ph]`].

[11] T. Gehrmann *et al.*, *J. High Energy Phys.* **1301**, 144 (2013) [`arXiv:1207.5031 [hep-ph]`].

[12] S. Höche, F. Krauss, M. Schönherr, F. Siegert, *J. High Energy Phys.* **1304**, 27 (2013) [`arXiv:1207.5030 [hep-ph]`].

[13] F. Krauss, D. Napoletano, `arXiv:1712.06832 [hep-ph]`.

[14] M. Aaboud *et al.* [ATLAS Collaboration], *J. High Energy Phys.* **1712**, 024 (2017) [`arXiv:1708.03299 [hep-ex]`].