Bottom-quark mass effects in associated production with $Z$ and $H$ bosons

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In this study, predictions obtained in the four and in the five flavour schemes are compared for two important processes involving heavy flavours at the LHC: the production of a $Z$ or a Higgs boson in association with $b$ quarks. In particular we obtain predictions with SHERPA’s MC@NLO implementation for the four–flavour scheme, treating the $b$’s as massive, and with multijet merging at leading and next-to leading order for the five–flavour scheme.

While differences between the two schemes, at the inclusive level, are well understood from resummation of possibly large logs into the $b$-PDFs, differences in shape present a major problem for experimental measurements. We make use of data for $Z + b(\bar{b})$ production at the 7 TeV LHC to exhibit strengths and weaknesses of the different approaches and we use these results to validate predictions for $b$-associated Higgs-boson production at the 13 TeV Run II.

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1. 4F or 5F scheme?

The study of processes that involve heavy quarks in the LHC environment is of great importance for theorists and experimentalists alike. From the theory viewpoint, processes like $Z/W b$ are sensitive to the heavy-flavour content of the proton and are thus used to determine the $b$-PDF, which in turn is necessary to make predictions for processes like $b\bar{b} \rightarrow H$. In addition, Higgs production in bottom-quark fusion, although being characterised by a very small cross section in the SM, can be sensitive for BSM scenarios where the bottom Yukawa coupling is enhanced.

On the other hand, experimentalists, under the name of theory uncertainties, take the differences between a scheme in which the $b$ quark is treated as a massive, decoupled particle, and one in which it is treated on the same footing as any other light quark, as input. These two approaches are usually called 4F and 5F scheme respectively.

Although in principle, the 4F and the 5F schemes should have only subleading differences, historically they have been found to largely disagree both at the level of total inclusive cross section and at the level of differential distributions [4, 12, 51]. In this study we reconsider these differences. Firstly we examine the origin of the difference at the inclusive level in the case of Higgs production in bottom-quark fusion [2, 3]. Secondly we set-up the two schemes in such a way that they can be compared likes with likes in differential distributions [1].

2. Resummation vs mass effects

The difference between the two schemes can be expressed in the following, short, way. The 4FS accounts for mass, power suppressed, terms exactly at the accuracy of the perturbative order of the calculation. On the other hand the 5FS, neglects all power corrections proportional to the mass of the heavy quark and resums logs of $\mu_F/m_b$ to all order through DGLAP equations. This is achieved by defining a perturbatively generated $b$-PDF. In practice, this means that the leading-log (LL) term of the 5F scheme expression corresponds to the LO expression in the 4FS up to power suppressed terms, and so on for higher orders.

The question then reduces to: what is the source of the differences we see, are they mainly due to the resummation of the logs, or to the exact inclusion of power suppressed terms? An answer to this question can be obtained by comparing the 5FS prediction for Higgs production in $b$-quark fusion, with an expanded $b$-PDF to a given order, and the corresponding 4F prediction. As an example, in Fig. 1, we show a comparison between the 5F prediction at NLO, using the full $b$-PDF, the same NLO prediction obtained with a NLL-expanded $b$-PDF, also called $\tilde{b}$, and the baseline 4FS NLO prediction.

There are two main conclusions that can be taken from Fig. 1. The difference between the 5F scheme with an expanded $b$-PDF and the corresponding 4F scheme calculation is indeed very small, thus stating that power-corrections are indeed suppressed when looking at total rates, while the main difference is generated by the resummation of higher order logs. In addition, choosing a lower factorisation and renormalisation scale partially reduces this difference.

The conclusion that mass corrections for this process are small, can also be obtained by matching the 4F and the 5F scheme. This has been done at NLO+NNLL accuracy using the
Bottom-quark mass effects in associated production with \( Z \) and \( H \) bosons

Davide Napoletano

Figure 1: Comparison between a full 5FS and a 5FS in which an expanded \( b \)-PDF, or \( \tilde{b} \), is used at NLL. This latter scheme is further compared to the 4FS result (obtained for the fixed scale choice \( \mu_R = \mu_F = \frac{m_H + 2m_b}{4} \)) at NLO, brown solid line.

FONLL [2, 3, 16, 17] method and a method based on EFT [18, 19], and both methods have been found to agree. Results obtained in the FONLL approach are shown in Fig. 2.

It is thus clear that resummation of large logs is the dominant effect, and not including them has a larger impact than including mass corrections.

This is however only true for inclusive observables, like the total inclusive cross section. In order to study possible effects on differential observables, where a matching has not been performed yet, we need data. We therefore take as an example the production of a \( Z \) boson in association with at least one or two \( b \)-jets, and data are taken from the ATLAS [51] and CMS [52] collaborations.

3. \( Z\tilde{b}\bar{b} \) @ 7 TeV

While a detailed description of the simulation set-up can be found in [1], we briefly describe here the three samples presented in the following plots.

4F NLO (4F MC@NLO): In the four–flavour scheme, \( b \)-quarks are consistently treated as massive particles, only appearing in the final state. As a consequence, \( b \)-associated \( Z \)- and \( H \)-boson production proceeds through the parton-level processes \( gg \to Z/H + b\bar{b} \), and \( q\bar{q} \to Z/H + b\bar{b} \) at Born level. MC@NLO matching is obtained by consistently combining fully differential NLO QCD calculations with the parton shower, cf. [40, 41].

5F LO (5F MePs@LO): In the five–flavour scheme \( b \)-quarks are massless particles in the hard matrix element, while they are treated as massive particles in both the initial- and final-state parton shower. In the MePs@LO [42] samples we merge \( pp \to H/Z \) plus up to three jets at leading order; this includes, for instance, the parton–level processes \( b\bar{b} \to Z/H, gb \to Z/Hb, gg \to Z/Hb\bar{b}, \ldots \). To separate the various matrix-element multiplicities, independent of the
jet flavour, a jet cut of $Q_{\text{cut}} = 10$ GeV is used in the $Z$ case while $Q_{\text{cut}} = 20$ GeV is employed in $H$-boson production.

**5F NLO (5F MePS@NLO):** In the 5FS MePS@NLO scheme [43, 44], we account for quark masses in complete analogy to the LO case: the quarks are treated as massless in the hard matrix elements, but as massive in the initial- and final-state parton showering. Again, partonic processes of different multiplicity are merged similarly to the MePS@LO albeit retaining their next-to-leading-order accuracy. In particular, we consider the merging of the processes $pp \to H/Z$ plus up to two jets each calculated with MePS@LO accuracy further merged with $pp \to H/Z + 3j$ calculated at MePS@LO.

Results for the case of the ATLAS detector are shown in Figs. 3 for samples that exhibit at least
one additional $b$-jet, and in Figs. 4 for samples with at least two $b$-jets tagged in the final state. Results for the CMS detector can be found in [1], and yield similar conclusions.

For both samples, we find that the 5FS MePs@NLO prediction, the one that has the resummation of the initial state logs, is the one that performs best, in both normalisation and shape. The 4FS and the 5FS MePs@LO show good agreement in normalisation in the $\geq 2b$-jets case and in the $\geq 1b$-jet case, respectively, while in the opposite cases they both undershoot data, by a largely flat $\sim 20\%$. All in all the three sample perform roughly at the same level in terms of shapes, yielding essentially flat $K$-factors to one another. The good agreement is essentially due to the inclusion of the necessary higher multiplicity matrix element corrections in the 5FS for the $\geq 2b$-jets case, and with the NLO matching to the shower in the 4FS in the $\geq 1b$-jet case. It is also worth noticing that very low $\Delta R(b,b)$ effects are shadowed by the inclusion of hadronisation effects, which are necessary to compare with the available data points.
4. Hbb @ 13 TeV

We can finally extend the results obtained in the previous two sections to the case of the production of a Higgs boson in association with b-jets. Once again we separate between $\geq 1b$-jet and $\geq 2b$-jets samples. In the following, we exclude normalisation effects as they basically follow from the previous two sections. Results are shown in Figs. 5 for samples that exhibit at least one additional b-jet, and in Figs. 6 for samples with at least two b-jets tagged in the final state.

![Figure 5: $p_T$ of the H boson and of the leading b-jet in the $\geq 1b$-jet sample.](image1)

![Figure 6: $p_T$ of the H boson and azimuthal distance between the two leading b-jets in the $\geq 2b$-jet sample.](image2)

The results in the Higgs case seem to lead to the same conclusions obtained in the Z case, namely that, within theory uncertainties, the three sample largely agree in shape with the only difference being due to the normalisation. The only region in which a large ($\sim 40\%$) difference appears is in the very low $\Delta R(b,b)$ region, where the two b-jets can become collinear in the 5FS. Note that this effect would be largely canceled in samples that would include fragmentation effects.

5. Conclusions

Being able to provide with reliable simulations for LHC processes involving heavy quarks is...
necessary in order to precisely determine the background to many SM processes and BSM searches. This is particularly true for processes like $Zb\bar{b}$ and $Hb\bar{b}$ in which the choice between the 4F or the 5FS has historically proved to lead to large discrepancies.

In particular, matching the two schemes, it has been shown that the difference in the total rate predicted in the two schemes is principally a consequence of the inclusion of the resummation of initial state logs, and that mass effects play a very small role.

In addition, with this study, we show that also differences in shapes can be largely reduced when comparing the two schemes at the same level of accuracy. We check this claim in the case of $Zb\bar{b}$ production @ 7 TeV, where we have data to back up our hypothesis. We then extend our results to $Hb\bar{b}$ production @ 13 TeV, where data are not available. However we can make use of the combined conclusions obtained for the totally inclusive case and $Zb\bar{b}$, to get some information. Finally we find that indeed, even in this case, the two schemes do agree in terms of shapes, with differences being largely within scale uncertainties.

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References

[1] F. Krauss, D. Napoletano and S. Schumann, Phys. Rev. D 95 (2017) no.3, 036012 doi:10.1103/PhysRevD.95.036012 [arXiv:1612.04640 [hep-ph]].

[2] S. Forte, D. Napoletano and M. Ubiali, *Higgs production in bottom-quark fusion in a matched scheme*, Phys. Lett. B751 (2015), 331–337, [arXiv:1508.01529 [hep-ph]].

[3] S. Forte, D. Napoletano and M. Ubiali, *Higgs production in bottom-quark fusion: matching beyond leading order*, Phys. Lett. B763 (2016), 190–196, [arXiv:1607.00389 [hep-ph]].

[4] F. Maltoni, G. Ridolfi and M. Ubiali, JHEP 1207 (2012) 022 Erratum: [JHEP 1304 (2013) 095] doi:10.1007/JHEP04(2013)095, 10.1007/JHEP07(2012)022 [arXiv:1203.6393 [hep-ph]].

[5] R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, R. Pittau and P. Torrielli, *W and Z/γ∗ boson production in association with a bottom-antibottom pair*, JHEP 09 (2011), 061, [arXiv:1106.6019 [hep-ph]].

[6] M. Wiesemann, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni and P. Torrielli, *Higgs production in association with bottom quarks*, JHEP 02 (2015), 132, [arXiv:1409.5301 [hep-ph]].

[7] D.-de-Florian et-al., The The LHC Higgs Cross Section Working Group collaboration, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, arXiv:1610.07922 [hep-ph].

[8] M. Lim, F. Maltoni, G. Ridolfi and M. Ubiali, *Anatomy of double heavy-quark initiated processes*, JHEP 09 (2016), 132, [arXiv:1605.09411 [hep-ph]].
[9] T. Lin, E. W. Kolb and L.-T. Wang, Probing dark matter couplings to top and bottom quarks at the LHC, Phys. Rev. D88 (2013), no. 6, 063510, [arXiv:1303.6638 [hep-ph]]

[10] G. Aad et al., The ATLAS collaboration, Search for dark matter in events with heavy quarks and missing transverse momentum in pp collisions with the ATLAS detector, Eur. Phys. J. C75 (2015), no. 2, 92, [arXiv:1410.4031 [hep-ex]]

[11] N.-C. Chen, Z.-K. Kang and J.-L. Li, Missing particle associated with two bottom quarks at the LHC: Mono-b versus 2b with razor variables, arXiv:1608.00421 [hep-ph]

[12] R. V. Harlander and W. B. Kilgore, Higgs boson production in bottom quark fusion at next-to-next-to leading order, Phys. Rev. D68 (2003), 013001, [arXiv:hep-ph/0304035 [hep-ph]]

[13] S. Dawson, C. Jackson, L. Orr, L. Reina and D. Wackeroth, Associated Higgs production with top quarks at the large hadron collider: NLO QCD corrections, Phys.Rev. D68 (2003), 034022, [arXiv:hep-ph/0305087 [hep-ph]]

[14] F. Febres Cordero, L. Reina and D. Wackeroth, NLO QCD corrections to W boson production with a massive b-quark jet pair at the Tevatron pp collider, Phys.Rev. D74 (2006), 034007, [arXiv:hep-ph/0605102 [hep-ph]]

[15] R.---Harlander, M.---Krämer and M.---Schumacher, Bottom-quark associated Higgs-boson production: reconciling the four- and five-flavour scheme approach, arXiv:1112.3478 [hep-ph]

[16] M. Cacciari, M. Greco and P. Nason, The P(T) spectrum in heavy flavor hadroproduction, JHEP 9805 (1998), 007, [arXiv:hep-ph/9803400 [hep-ph]]

[17] S. Forte, E. Laenen, P. Nason and J. Rojo, Heavy quarks in deep-inelastic scattering, Nucl.Phys. B834 (2010), 116–162, [arXiv:1001.2312 [hep-ph]]

[18] M. Bonvini, A. S. Papanastasiou and F. J. Tackmann, Resummation and matching of b-quark mass effects in b\bar{b}H production, JHEP 11 (2015), 196, [arXiv:1508.03288 [hep-ph]]

[19] M. Bonvini, A. S. Papanastasiou and F. J. Tackmann, Matched predictions for the b\bar{b}H cross section at the 13 TeV LHC, JHEP 10 (2016), 053, [arXiv:1605.01733 [hep-ph]]

[20] M. A. G. Aivazis, J. C. Collins, F. I. Olness and W.-K. Tung, Leptoproduction of heavy quarks. II. A unified QCD formulation of charged and neutral current processes from fixed-target to collider energies, Phys. Rev. D50 (1994), 3102–3118, [hep-ph/9312319]

[21] M. A. G. Aivazis, F. I. Olness and W.-K. Tung, Leptoproduction of heavy quarks. I. General formalism and kinematics of charged current and neutral current production processes, Phys. Rev. D50 (1994), 3085–3101, [hep-ph/9312318]

[22] M. Krämer, F. I. Olness and D. E. Soper, Treatment of heavy quarks in deeply inelastic scattering, Phys.Rev. D62 (2000), 096007, [arXiv:hep-ph/0003035 [hep-ph]]

[23] A. Buckley et al., General-purpose event generators for LHC physics, Phys. Rept. 504 (2011), 145–233, [arXiv:1101.2599 [hep-ph]]

[24] T. Gleisberg, S. Höche, F. Krauss, A. Schälicke, S. Schumann and J. Winter, SHERPA 1.α, a proof-of-concept version, JHEP 02 (2004), 056, [hep-ph/0311263]

[25] T. Gleisberg, S. Höche, F. Krauss, M. Schönherr, S. Schumann, F. Siegert and J. Winter, Event generation with SHERPA 1.1, JHEP 02 (2009), 007, [arXiv:0811.4622 [hep-ph]]

[26] F. Krauss, R. Kuhn and G. Soff, AMEGIC++ 1.0: A Matrix Element Generator In C++, JHEP 02 (2002), 044, [hep-ph/0109036]
[27] T. Gleisberg and S. Höche, *Comix, a new matrix element generator*, JHEP 12 (2008), 039, [arXiv:0808.3674 [hep-ph]]

[28] C. F. Berger et al., *Automated implementation of on-shell methods for one-loop amplitudes*, Phys.Rev. D78 (2008), 036003, [arXiv:arXiv:0803.4180 [hep-ph]]

[29] S.-Badger, B.-Biedermann, P.-Uwer and V.-Yundin, *Numerical evaluation of virtual corrections to multi-jet production in massless QCD*, arXiv:1209.0100 [hep-ph]

[30] F. Cascioli, P. Maierhöfer and S. Pozzorini, *Scattering Amplitudes with Open Loops*, Phys.Rev.Lett. 108 (2012), 111601, [arXiv:1111.5206 [hep-ph]]

[31] T. Binoth et al., *A proposal for a standard interface between Monte Carlo tools and one-loop programs*, Comput. Phys. Commun. 181 (2010), 1612–1622, [arXiv:arXiv:1001.1307 [hep-ph]]

[32] A.-Denner, S.-Dittmaier and L.-Hofer, *COLLIER - A fortran-based Complex One-Loop Library in Extended Regularizations*, arXiv:1604.06792 [hep-ph]

[33] A. Denner, S. Dittmaier and L. Hofer, *A new parton shower algorithm: Shower evolution, matching at leading and next–to–leading order level*, PoS LL2014 (2014), 071, [arXiv:1407.0087 [hep-ph]]

[34] S. Catani and M. H. Seymour, *A general algorithm for calculating jet cross sections in NLO QCD*, Nucl. Phys. B485 (1997), 291–419, [hep-ph/9605323]

[35] S. Catani, S. Dittmaier, M. H. Seymour and Z. Trocsanyi, *The dipole formalism for next–to–leading order QCD calculations with massive partons*, Nucl. Phys. B627 (2002), 189–265, [hep-ph/0201036]

[36] T. Gleisberg and F. Krauss, *Automating dipole subtraction for QCD NLO calculations*, Eur. Phys. J. C53 (2008), 501–523, [arXiv:0709.2881 [hep-ph]]

[37] S. Schumann and F. Krauss, *A parton shower algorithm based on Catani-Seymour dipole factorisation*, JHEP 03 (2008), 038, [arXiv:0709.1027 [hep-ph]]

[38] S. Höche, S. Schumann and F. Siegert, *Hard photon production and matrix-element parton-shower merging*, Phys. Rev. D81 (2010), 034026, [arXiv:0912.3501 [hep-ph]]

[39] Z.-Nagy and D.-E. Soper, *A new parton shower algorithm: Shower evolution, matching at leading and next–to–leading order level*, hep-ph/0601021

[40] S. Frixione and B. R. Webber, *Matching NLO QCD computations and parton shower simulations*, JHEP 06 (2002), 029, [hep-ph/0204244]

[41] S. Höche, F. Krauss, M. Schönherr and F. Siegert, *A critical appraisal of NLO+PS matching methods*, JHEP 09 (2012), 049, [arXiv:1111.1220 [hep-ph]]

[42] S. Höche, F. Krauss, S. Schumann and F. Siegert, *QCD matrix elements and truncated showers*, JHEP 05 (2009), 053, [arXiv:0903.1219 [hep-ph]]

[43] T.-Gehrmann, S.-Höche, F.-Krauss, M.-Schönherr and F.-Siegert, *NLO QCD matrix elements + parton showers in e+e− → hadrons*, arXiv:1207.5031 [hep-ph]

[44] S. Höche, F. Krauss, M. Schönherr and F. Siegert, *QCD matrix elements + parton showers: The NLO case*, JHEP 1304 (2013), 027, [arXiv:1207.5030 [hep-ph]]

[45] R.-D. Ball et al., *The NNPDF collaboration, Parton distributions for the LHC Run II*, arXiv:1410.8849 [hep-ph]
[46] S. Höche, F. Krauss, M. Schönherr and F. Siegert, Next-to-leading order matrix elements and truncated showers, arXiv:1009.1477 [hep-ph]

[47] E. Bothmann, M. Schönherr and S. Schumann, Reweighting QCD matrix-element and parton-shower calculations, Eur. Phys. J. C76 (2016), 590, [arXiv:1606.08753 [hep-ph]]

[48] G. Aad et al., The ATLAS Collaboration collaboration, Measurement of the production cross section of jets in association with a Z boson in pp collisions at \( \sqrt{s} = 7 \) TeV with the ATLAS detector, JHEP 1307 (2013), 032, [arXiv:1304.7098 [hep-ex]]

[49] V. Khachatryan et al., The CMS collaboration, Measurements of jet multiplicity and differential production cross sections of Z+ jets events in proton-proton collisions at \( \sqrt{s} = 7 \) TeV, Phys. Rev. D91 (2015), no. 5, 052008, [arXiv:1406.3104 [hep-ex]]

[50] V. Khachatryan et al., The CMS collaboration, Measurements of the differential production cross sections for a Z boson in association with jets in pp collisions at \( \sqrt{s} = 8 \) TeV, arXiv:1611.03844 [hep-ex]

[51] G. Aad et al., The ATLAS Collaboration collaboration, Measurement of differential production cross-sections for a Z boson in association with b-jets in 7 TeV proton-proton collisions with the ATLAS detector, JHEP 1410 (2014), 141, [arXiv:1407.3643 [hep-ex]]

[52] S. Chatrchyan et al., The CMS Collaboration collaboration, Measurement of the cross section and angular correlations for associated production of a Z boson with b hadrons in pp collisions at \( \sqrt{s} = 7 \) TeV, JHEP 1312 (2013), 039, [arXiv:1310.1349 [hep-ex]]

[53] V. Khachatryan et al., The CMS collaboration, Measurements of the associated production of a Z boson and b jets in pp collisions at \( \sqrt{s} = 8 \) TeV, arXiv:1611.06507 [hep-ex]

[54] M. Cacciari, G. P. Salam and G. Soyez, The Anti-k(t) jet clustering algorithm, JHEP 0804 (2008), 063, [arXiv:0802.1189 [hep-ph]]

[55] A. Buckley, J. Butterworth, L. Lönnblad, D. Grellscheid, H. Hoeth, J. Monk, H. Schulz and F. Siegert, Rivet user manual, Comput. Phys. Commun. 184 (2013), 2803–2819, [arXiv:1003.0694 [hep-ph]]

[56] M. Cacciari, G. P. Salam and G. Soyez, FastJet user manual, Eur.Phys.J. C72 (2012), 1896, [arXiv:1111.6097 [hep-ph]]

[57] S. Dittmaier, M. Kramer, 1 and M. Spira, Higgs radiation off bottom quarks at the Tevatron and the CERN LHC, Phys. Rev. D70 (2004), 074010, [arXiv:hep-ph/0309204 [hep-ph]]

[58] S. Dawson, C. B. Jackson, L. Reina and D. Wackeroth, Exclusive Higgs boson production with bottom quarks at hadron colliders, Phys. Rev. D69 (2004), 074027, [arXiv:hep-ph/0311067 [hep-ph]]

[59] S. Dittmaier, A general approach to photon radiation off fermions, Nucl. Phys. B565 (2000), 69–122, [hep-ph/9904440]