PROCEEDINGS OF SCIENCE

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

Davide Napoletano[*]
Institute of Particle Physics Phenomenology, Durham University
E-mail: davide.napoletano@durham.ac.uk

Frank Krauss
Institute of Particle Physics Phenomenology, Durham University
E-mail: frank.krauss@durham.ac.uk

Steffen Schumann
II. Physikalisches Institut, Georg-August-Universität Göttingen, 37077 Göttingen, Germany
E-mail: steffen.schumann@phys.uni-goettingen.de

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.

XXV International Workshop on Deep-Inelastic Scattering and Related Subjects
3-7 April 2017
University of Birmingham, UK

[*]Speaker.

PoS(DIS2017)172

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 view point, processes like Z/Wb 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 $b\bar{b} \to H$. 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, 6, 18]. 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 μ_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

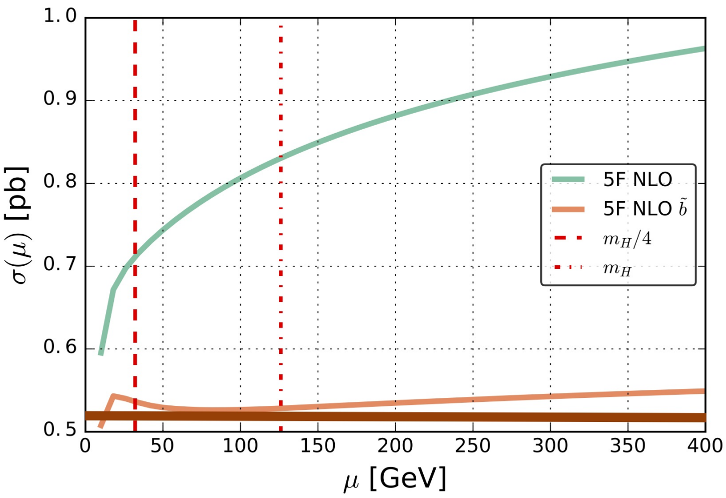

Figure 1: Comparison between a full 5FS and a 5FS in which an expanded b-PDF, or $\tilde{b}$, is used at NLL. This latter scheme is further compared to the 4FS result (obtained for the fixed scale choice $\mu_R = \mu_F = \frac{m_H+2m_b}{4}$) at NLO, brown solid line.

FONLL [2, 3, 7, 8] method and a method based on EFT [9, 10], and both methods have been found to agree. Results obtained in the FONLL approach are shown in Fig. 3.

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 [18] and CMS [19] collaborations.

3. $Zb\bar{b}$ @ 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. [13, 14].

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 [15] samples we merge $pp \to H/Z$ plus up to three jets at leading order; this includes, for instance, the parton–level processes $b\bar{b} \to Z/H$, $gb \to Z/Hb$, $gg \to Z/Hb\bar{b}$, ... To separate the various matrix-element multiplicities, independent of the

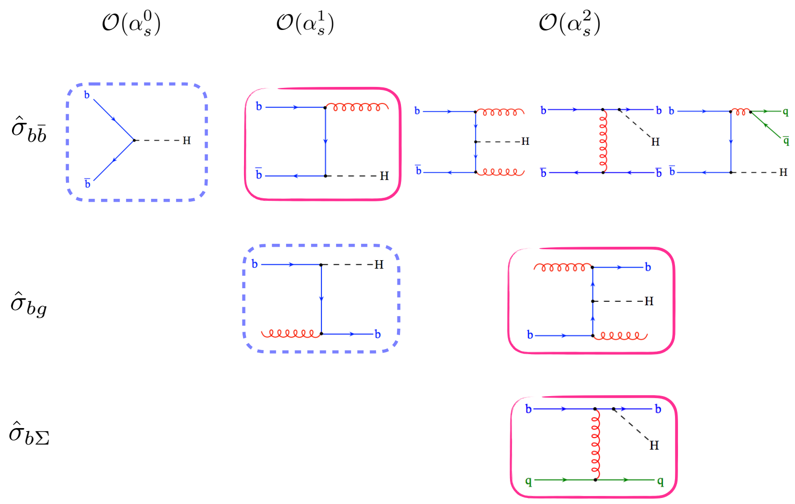

Figure 2: Representative examples of contributions to the 5FS computation which are subtracted and get replaced by massive 4FS contributions. The diagrams circled with a dashed line become massive in FONLL-A, while those circled with a solid pink line are those that must be additionally subtracted in the FONLL-B scheme. For details on the definition of the two schemes see [2, 3]

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 [16, 17], 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 MC@NLO 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. 4 for samples that exhibit at least one additional b-jet, and in Figs. 5 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

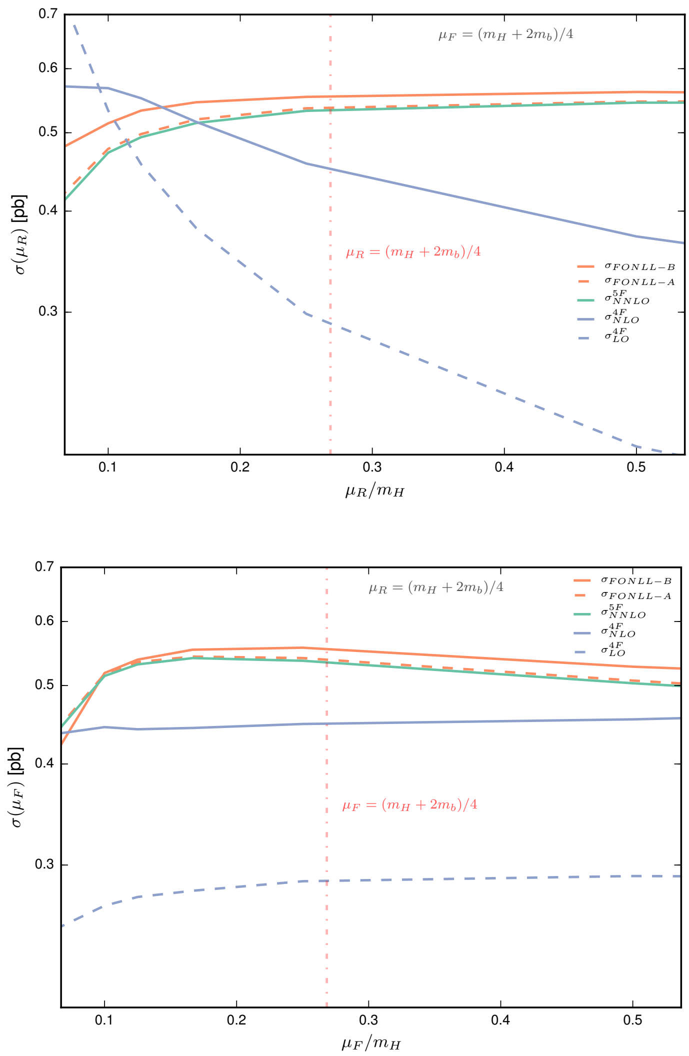

Figure 3: FONLL prediction at LO+NLL (FONLL-A) and at NLO+NNLL (FONLL-B) compared to the 4FS and the 5FS.

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. $Hb\bar{b}$ @ 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. 6 for samples that exhibit at least one additional b-jet, and in Figs. 7 for samples with at least two b-jets tagged in the final state.

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

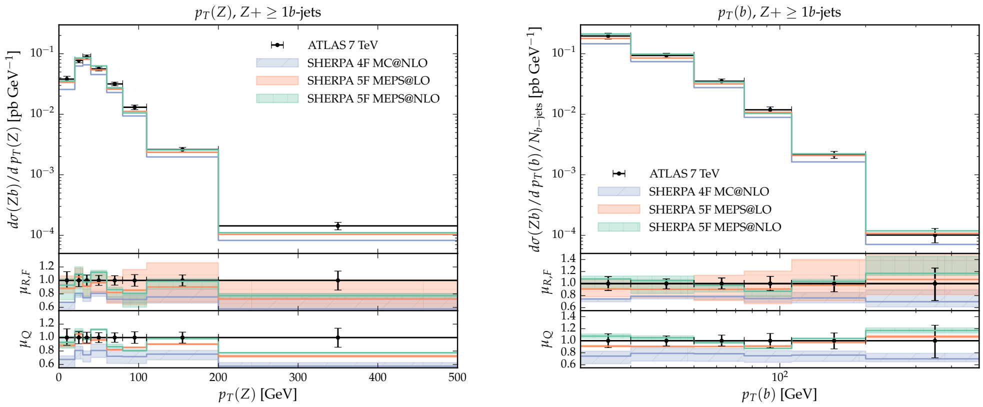

Figure 4: p_T of the Z boson and of the leading b-jet in the $\geq 1b$-jet sample for the ATLAS detector. Data taken from Ref. [18]

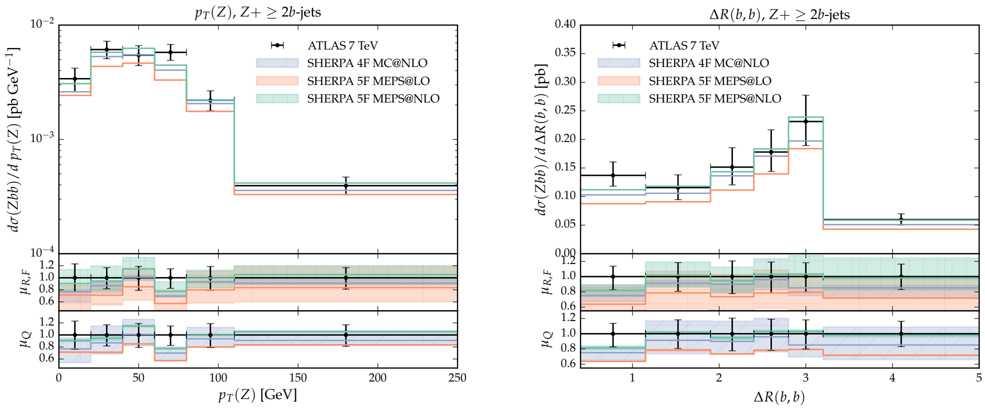

Figure 5: p_T of the Z boson and azimuthal distance between the two leading b-jets in the $\geq 2b$-jet sample for the ATLAS detector. Data taken from Ref. [18]

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 prove 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.

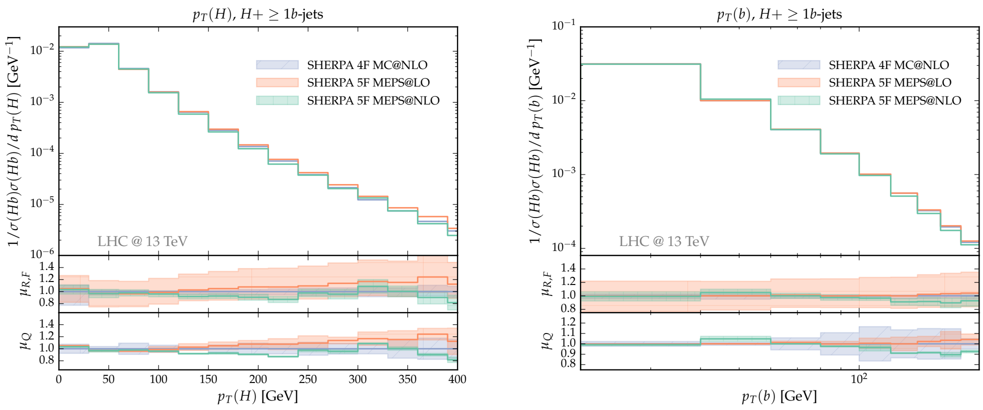

Figure 6: p_T of the H boson and of the leading b-jet in the $\geq 1b$-jet sample.

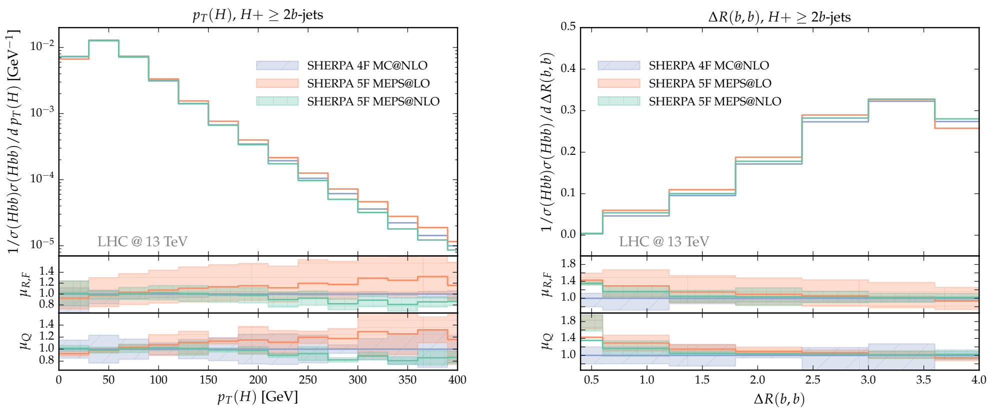

Figure 7: p_T of the H boson and azimuthal distance between the two leading b-jets in the $\geq 2b$-jet sample.

In addition, with this study, we show that also differences in shapes can be largely reduce 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.

Acknowledgements

We want to thank our colleagues from the SHERPA collaboration for fruitful discussions and technical support. We are also thankful to Stefano Forte, Maria Ubiali and Fabio Maltoni. We acknowledge financial support from the EU research networks funded by the Research Executive Agency (REA) of the European Union under Grant Agreements PITN-GA2012-316704 ("HiggsTools") and PITN-GA-2012-315877 ("MCnetITN"), by the ERC Advanced Grant MC@NNLO (340983), and from BMBF under contracts 05H12MG5 and 05H15MGCAA,

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] 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]]

[6] 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]]

[7] 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]]

[8] 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]]

[9] 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]]

[10] 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]]

[11] 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]]

[12] 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]

[13] Stefano Frixione and Bryan R. Webber. Matching NLO QCD computations and parton shower simulations. *JHEP*, 06:029, 2002.

[14] 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]]

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

[16] T. Gehrmann, S. Höche, F. Krauss, M. Schönherr and F. Siegert, *NLO QCD matrix elements + parton showers in $e^+e^- \to$ hadrons*, arXiv:1207.5031 [hep-ph]

[17] 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]]

[18] 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]]

[19] 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]]