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Charged Higgs boson production around the top quark mass threshold

Martin FLECHL*
Institute of High Energy Physics, Austrian Academy of Sciences
E-mail: martin.flechl@cern.ch

To estimate the cross section of charged Higgs boson production with a mass close to the top quark mass, several production modes and their interference have to be taken into account. In the following, the motivation to compute estimates for the cross section in this mass regime is discussed, and two different approaches are compared. A summary of the results of a recent, fully consistent approach correct at next-to-leading order, is given. Finally, practical implications of the available calculations for interpreting experimental results are discussed.

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1. Introduction

Charged Higgs bosons $H^{\pm}$ appear in many extensions of the standard model (SM), in particular when adding additional doublets or triplets to its scalar sector. Here, the focus is on charged Higgs bosons in 2-Higgs-doublet models (2HDM) including the special case of the Higgs sector of the minimal supersymmetric extension of the standard model (MSSM). In a 2HDM, the dominant production mode for a charged Higgs boson depends on its mass. For masses below the top quark mass, a charged Higgs boson would be dominantly produced in top quark decays. Therefore, the production cross section is proportional to the top quark pair production times the branching ratio $t \rightarrow H^{+}b$. The dominant mode of $H^{\pm}$ production for $m_{H^{\pm}} > m_t$ in a 2HDM is via the process $pp \rightarrow tH^{\pm} + X$. There are two equivalent ways to describe this process in the context of perturbation theory. The 5-flavor scheme (5FS), in which large initial-state logarithms are resummed in bottom quark parton distributions and where the leading tree-level contribution is $gb \rightarrow tH^{\pm}$; and the 4-flavor scheme (4FS), in which gluon splitting leads to the required b quarks (leading tree-level contribution: $gg \rightarrow tH^{\pm}b$). Examples for dominant leading-order (LO) diagrams for light and heavy charged Higgs boson production are shown in Fig. 1.

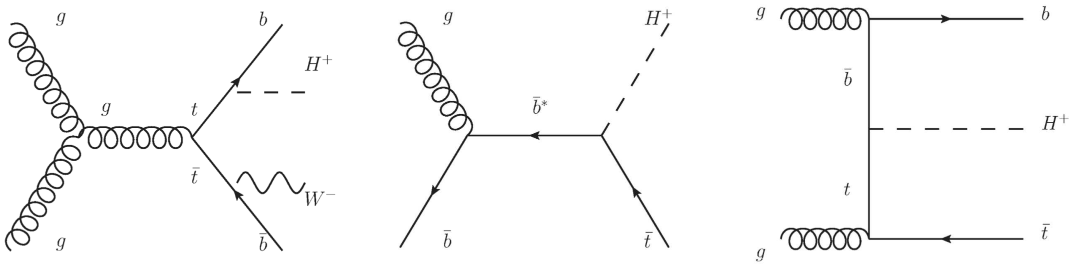

Figure 1: Examples for dominant LO charged Higgs boson production diagrams for a 2HDM. Left: via a resonant top quark pair. Center: via gb fusion. Right: via gg fusion.

The LHC experiments exclude most of the MSSM parameter space for a light charged Higgs boson. For heavy charged Higgs bosons, a sizable region at high $\tan\beta$ is excluded, see Fig. 2. Note that the LHC experiments do not provide any sensitivity projections or exclusion limits in the region around the top quark mass. The reason is that until recently, no predictions with sufficient accuracy have been available for this region.

In the following, the relevant processes in this so-called intermediate region are investigated and strategies to deal with this region are presented. Then, recent results in the form of the first consistent predictions at next-to-leading-order (NLO) accuracy are discussed. Finally, practical implications of using the calculations in the context of experimental searches are discussed.

2. Region around the top quark mass

For values of the charged Higgs boson mass close to the top quark mass, contributions with and without additional resonant top quarks are of similar size and thus both have to be considered in a coherent way, i.e. including their interference terms. For example, the tree-level processes gg →

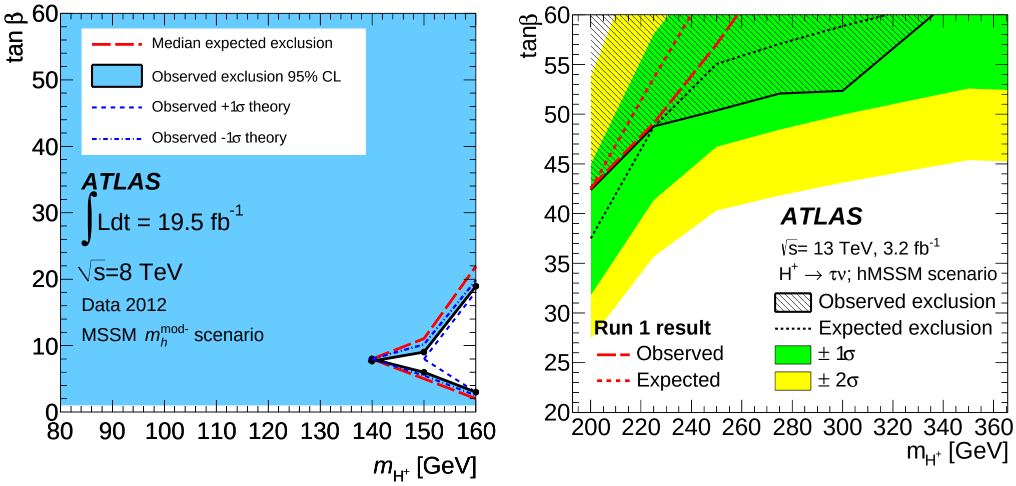

Figure 2: Exclusion limits for charged Higgs boson production from ATLAS. Left: $m_{\mathrm{H}^\pm} < 160$ GeV [1], Right: $m_{\mathrm{H}^\pm} > 200$ GeV [2]. No results are given for the mass region between 160 GeV and 200 GeV, and the same is the case for CMS.

$\mathrm{tbH}^\pm$ and $\mathrm{gg} \to \mathrm{tt} \to \mathrm{tbH}^\pm$ (with and without a second resonant top quark) interfere; and so does $\mathrm{gg} \to \mathrm{tt} \to \mathrm{tbH}^\pm$ with NLO contributions to $\mathrm{gb} \to \mathrm{tH}^\pm$. Fig. 3 shows the current recommendation from the LHC Higgs cross section working group (LHCHXSWG) for the low-mass and high-mass case: There is a gap from 160 GeV to 200 GeV, where both contributions are of O(1 pb).

The leading-order cross section predictions are subject to large scale uncertainties (about 50%) and k factors (ratio of NLO to LO cross section) of about 1.5 (and even higher for the case with two resonant top quarks). Thus the minimum requirement for satisfactory predictions of cross sections for the intermediate mass region are NLO accuracy with a correct (or approximately correct) treatment of interference effects at the same accuracy.

What is the typical impact of the interference terms on the cross section? This is investigated in Ref. [8]. For $\tan\beta = 30$, in a 2HDM type-II, the interference is destructive and its size, relative to the single-resonant $\mathrm{tH}^\pm$ cross section, is about $4\% - 14\%$, decreasing with $m_{\mathrm{H}^\pm}$ from 160 GeV to 100 GeV. The effect is decreased to $4\% - 9\%$ if a second b-tagged jet with $p_{\mathrm{T}} > 30$ GeV is vetoed. The impact of the interference on the total cross section can thus be of a similar size as the total uncertainties on the cross section. There are two potential strategies to deal with the intermediate mass region:

- Strategy I: incoherent sum: add the contributions incoherently, and then subtract the interference term approximately.

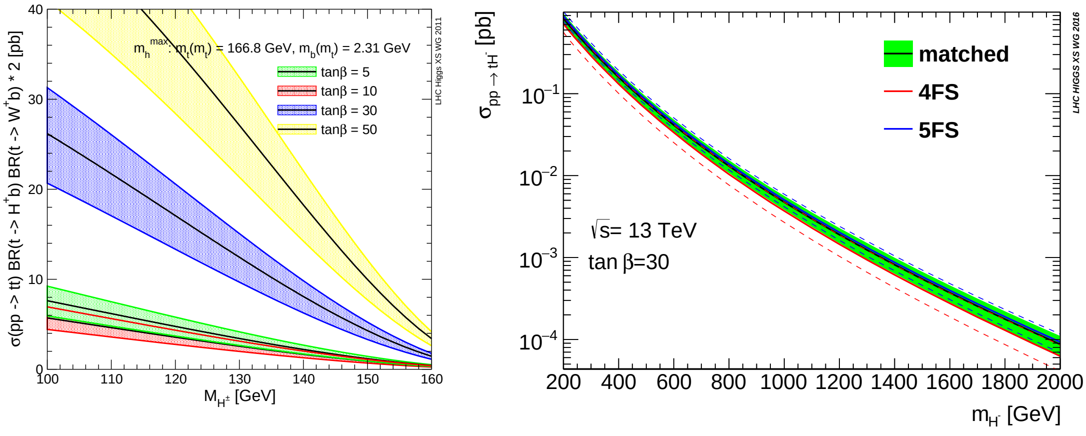

Figure 3: LHCHXSWG recommendations for charged Higgs bosons. Left: Charged Higgs boson production in top quark pair events [3] at $\sqrt{s} = 8$ TeV. The corresponding 13 TeV values scale by $\sigma(\mathrm{t\bar{t}}, 13\mathrm{TeV})/\sigma(\mathrm{t\bar{t}}, 8\mathrm{TeV}) \approx 3.3$. Right: Charged Higgs boson production in $\mathrm{gg/gb} \to \mathrm{tH}^\pm + X$ without resonant top quarks at $\sqrt{s} = 13$ TeV [4, 5, 6, 7].

- Strategy II: coherent sum: fully consistent treatment of all terms and their interference.

3. Strategy I: incoherent sum

The advantage of this approach is that it can reuse existing results and can thus be more easily implemented. The different contributions, which are all known at least at NLO, are added first incoherently. Then, the interference term is subtracted. The subtraction cannot be done in a fully consistent way and thus remains an approximation. However, as long as the uncertainty associated to the approximation is negligible compared to the total cross section uncertainty (about 10% – 20%), this is a viable way. In any case, it remains much more challenging to implement a similar procedure for differential cross sections or to simulate events.

The strategy is illustrated in Fig. 4. In the 5FS, the LO process $\mathrm{gg} \to \mathrm{tH}^\pm$ does not receive any contributions from events with two resonant top quarks. For NLO predictions, diagrams with on-shell top quark pairs are removed from the NLO corrections to $\mathrm{gg} \to \mathrm{tH}^\pm$ in order to avoid double-counting but $\mathrm{t\bar{t}}$ contributions with off-shell $\mathrm{t}^* \to \mathrm{bH}^\pm$ decays are retained. In order to do this in a well-defined way, the narrow-width approximation is used, neglecting terms of $O(\Gamma_\mathrm{t}/m_\mathrm{t})$. Then the LO contribution from events with two resonant top quarks is calculated separately and both contributions are summed.

As pointed out, the advantage of this approach is that it is simple and that all ingredients to use it have been available for many years. The main drawback here (using the 5FS) is that the different contributions enter at different order. In particular, the NLO cross section for $\mathrm{tH}^\pm$ production in-

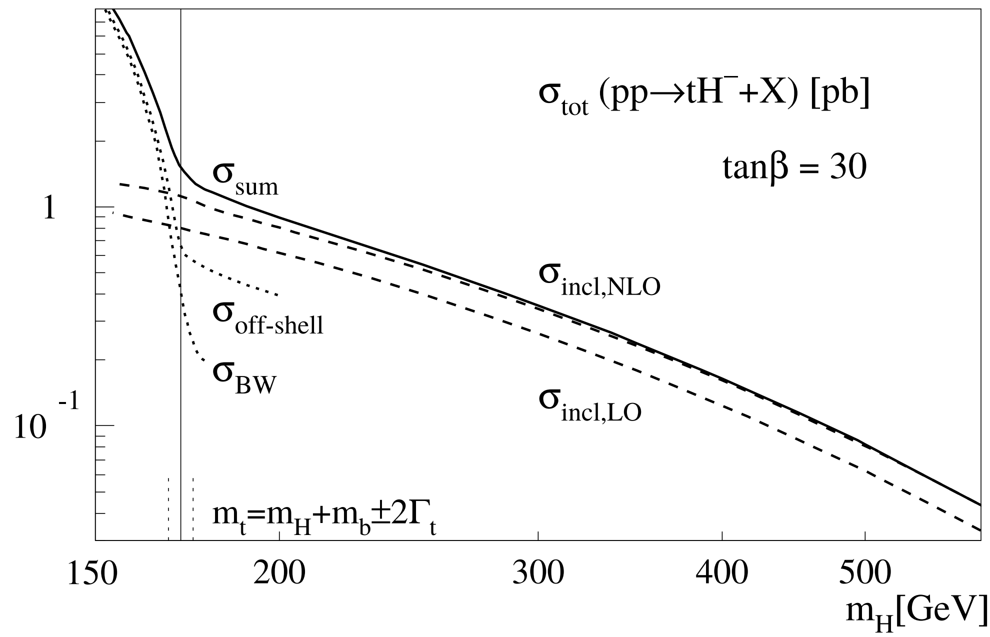

Figure 4: $tH^- + X$ production cross section (in pb) as a function of $m_{H^\pm}$ for $\tan\beta = 30$ at $\sqrt{s} = 14$ TeV in the 5FS [6]. Separately shown are the production via intermediate top quark pair $\mathrm{pp} \to \mathrm{t\bar{t}^*}$ with $\mathrm{\bar{t}^*} \to \mathrm{\bar{b}H^-}$ in the Breit-Wigner approximation (σ_{BW}) and including the complete set of off-shell diagrams, $\sigma_{\mathrm{off-shell}}$, the production without a second intermediate top quark (σ_{incl}) at LO and NLO and the sum of all contributing processes (σ_{sum}).

cludes $\mathrm{t\bar{t}}$ production only at LO while this process is known at NNLO+next-to-leading-log (NNLL) accuracy and has a sizable k factor. Furthermore, interference effects are neglected which is not a major problem within the 5FS as they only enter at NLO. Finally, effects related to the top quark width are neglected.

4. Strategy II: coherent sum

Since July 2016, a coherent calculation of the total $\mathrm{tH}^\pm + X$ cross section in the intermediate region is available [9]. This means that for the first time, a well-defined, consistent and elegant solution is available at NLO accuracy. The computation considers the full process $\mathrm{pp} \to \mathrm{H^\pm W^\mp bb}$, with the main tree-level diagrams shown in Fig. 5.

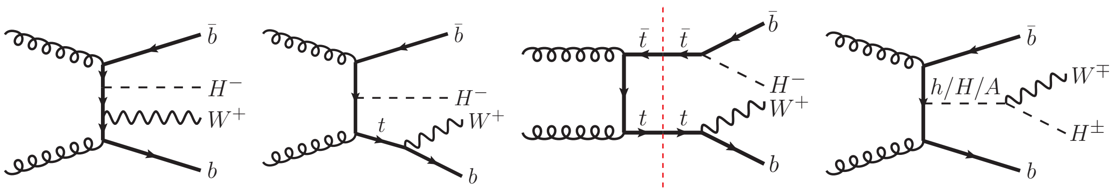

Figure 5: Diagrams with (from left to right) 0, 1, 2 resonant top quarks or a neutral Higgs boson contributing at LO to the $\mathrm{tH}^\pm$ cross section in the intermediate-mass region [9].

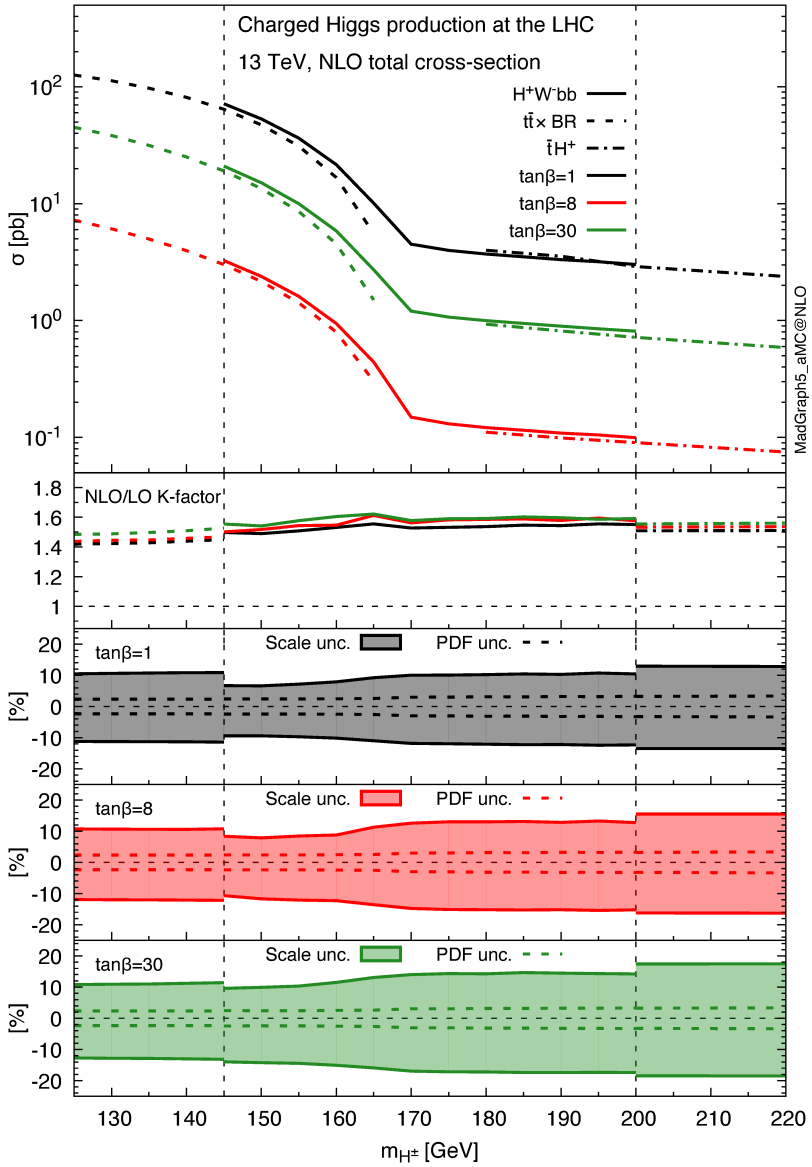

Figure 6: Result of the coherent intermediate-mass calculations at NLO [9]. At the mass boundaries, the results are compared to numbers using a similar setup as typically used for low- and high-mass charged Higgs boson computations.

The computation is carried out with MADGRAPH5_AMC@NLO [10], improved with resonance-aware FKS subtraction. For the results, the contribution from diagrams with neutral Higgs bosons is neglected since this contribution is at most about $1\% - 7\%$ for 2HDM parameter values still allowed by the LHC results. This helps to avoid an additional model dependence of the result. The top width as function of the charged Higgs boson mass and $\tan\beta$ is taken into account, using a complex-mass scheme to calculate it at NLO accuracy. Massive bottom quarks are used in the context of the 4FS. Fixed renormalization and factorisation scales, $\mu_R = \mu_F = 125$ GeV, are applied which match the scales typically used for heavy charged Higgs bosons at the mass boundary (200

GeV) and are similar to the values used for calculating the top quark pair production cross section (m_t), relevant for light charged Higgs bosons. The mass range $145 < m_{H^\pm}$ [GeV] < 200 is scanned. The result is shown in Fig. 6.

Good agreement with the low and heavy charged Higgs boson calculations is observed at the mass boundaries. Note however that this is not a comparison to the results recommended by the LHCHXSWG: In order to allow for a consistent comparison, here the renormalization and factorisation scale for a light charged Higgs boson is set to 125 GeV, and all calculations are at NLO accuracy (while the LHCHXSWG recommendations for light charged Higgs bosons include a top quark pair cross section at NNLO accuracy). The heavy charged Higgs boson line includes only the 4FS calculations. The residual small differences at the mass borders are dominantly due to missing single-resonant contributions (at $m_{H^\pm} = 145$ GeV) and missing non-resonant contributions (at $m_{H^\pm} = 200$ GeV).

The resulting k factor agrees with expectations ($1.5 - 1.6$, with only mild dependence on $m_{H^\pm}$ and $\tan\beta$). The scale uncertainties amount to $10\% - 20\%$, increasing with higher $m_{H^\pm}$ values and also slightly with $\tan\beta$ (due to the scale dependence of the bottom Yukawa coupling). The PDF uncertainties are small in comparison, about $2\% - 4\%$.

The results show differences at the level of a few per cent with respect to the LHCHXSWG recommendations at the mass boundaries. The differences are understood (see above) and are significantly smaller than the associated uncertainties. Note, however, that currently it is not possible to simulate events at the same accuracy (NLO) in the intermediate mass region.

5. Practical implications for interpreting experimental results

While recent results are an important step towards interpreting LHC data and determining sensitivity in the context of charged Higgs boson searches, there are a few practical implications which need to be considered.

Discontinuities at mass thresholds. As discussed above, when interpreting data over the whole relevant charged Higgs boson mass range, discontinuities appear at the chosen mass thresholds of 145 GeV and 200 GeV. While this might give rise to unphysical features in exclusion plots it is currently not a significant problem as the discontinuities are well below the typical uncertainties of the involved calculations ($10\% - 20\%$). However, this also implies that in the intermediate mass region, information from current state–of-the-art computations is not propagated (nor is it clear whether there is a consistent way to do it): the implicit top quark pair production cross section enters at NLO (while corrections at NNLO+NNLL are already known), and only the 4FS calculation is used close to the high-mass border (while the 5FS is expected to give a similar or better description of the total cross section without resonant top quarks in this region). A simple fix would be to rescale cross sections close to 145 GeV with the ratio of the NNLO to NLO top quark pair production cross sections, and the values close to 200 GeV with the ratio of Santander-matched to 4FS cross sections.

Higher-order corrections specific to supersymmetric scenarios. The leading supersymmetric QCD corrections can be folded in to the general 2HDM type-II cross sections as usual. The major part factorizes and is known as Δ_b correction. The procedure is the same as for the high-mass charged Higgs boson cross sections. Note, however, that for $\tan\beta < 10$, non-factorizable corrections can become of the same order as the uncertainties on the total cross section (about 10%).

Other types of 2HDM. The numbers given are for a type-II 2HDM. However, they can be translated to a type-I, type-X or type-Y 2HDM model at good approximation. This is described e.g. in Ref. [5]. For a type-I 2HDM, unlike for type II, the term proportional to the bottom Yukawa coupling is not enhanced at high $\tan\beta$ and the top quark Yukawa term dominates over the whole $\tan\beta$ range. Thus the cross sections for type-I and type-II are similar at low $\tan\beta$ (e.g., $\tan\beta = 1$) and for high $\tan\beta$, the cross section can be obtained by rescaling the low-$\tan\beta$ cross section with $\cot^2\beta$. So far, this is the same procedure as for high-mass predictions. However, in the intermediate-mass region, in addition top-quark-width effects have to be taken into account. This is non-trivial and neglecting this effect can lead to a bias at the level of up to 20%.

SM top quark pair background. If the charged Higgs boson leads to a significant change of the top quark width, this implies a non-zero branching ratio $B(t \to bH^{\pm})$ which in turn means a departure from the usual assumption of close to 100% of the top quarks decaying to bW. This leads to a decrease of the SM top quark pair production background expectation in data analysis. Effectively, the expected number of signal-plus-background events is lower than summing the number of events for the background-only hypothesis to the number of expected signal events, decreasing the analysis sensitivity. To take this into account, the branching ratio for given values of $m_{H^{\pm}}$ and $\tan\beta$ have to used in the building of the signal-plus-background model. The values are presented in Fig. 7.

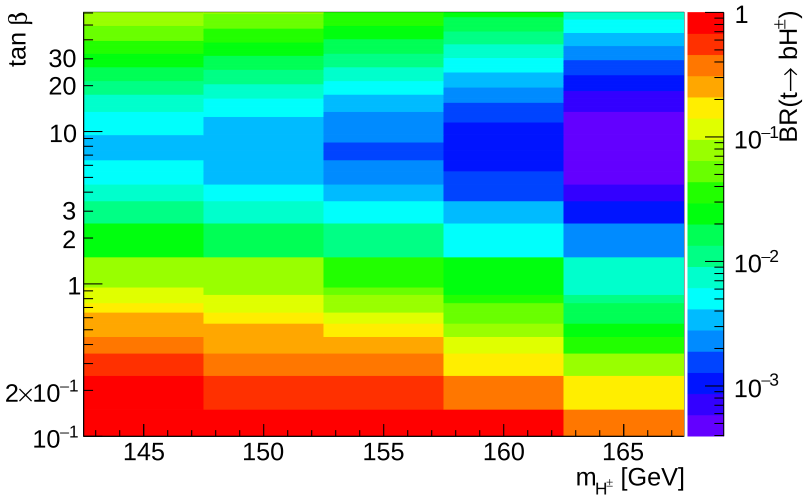

Figure 7: Branching ratio $B(t \to bW)$ in the intermediate mass region for a type-II 2HDM [11].

Simulation. As pointed out, currently there are no tools available to generate events matching the NLO accuracy of the total-cross-section computation for the intermediate mass region. Possibly the best option currently available is to simulate the process $pp \to H^{\pm}W^{\mp}bb$ at LO using 4FS prescriptions, e.g. using MADGRAPH5, and to rescale the generated events to the NLO cross section. A slight refinement can be achieved by using MADGRAPH5 to produce a merged sample with up to one additional jet described by the matrix element. However, the validity of this approach depends on whether the k factor is approximately constant in the probed phase space region – and currently, this assumption cannot be tested. In the future, MADGRAPH5 can be modified to enable the production of differential distributions at NLO accuracy [11]. While this still does not allow for the production of events at NLO accuracy, it would make it possible to test the underlying assumption on the k factor dependence.

6. Conclusions

The intermediate mass region has seen a lot of progress recently with the first coherent NLO calculation becoming available. While there are a few minor practical implications to be considered, this now allows the LHC experiments to produce first exclusion limits and sensitivity estimates for a charged Higgs boson in the intermediate mass region. The main remaining question is on how to simulate events in this mass region.

References

[1] ATLAS Collaboration, *Search for charged Higgs bosons decaying via $H^+ \to \tau^+\nu$ in fully hadronic final states using pp collision data at $\sqrt{s} = 8$ TeV with the ATLAS detector*, JHEP 03 (2015) 088.

[2] ATLAS Collaboration, *Search for charged Higgs bosons produced in association with a top quark and decaying via $H^\pm \to \tau\nu$ using pp collision data recorded at $\sqrt{s} = 13$ TeV by the ATLAS detector*, Phys. Lett. B 759 (2016) 555.

[3] LHC Higgs Cross Section Working Group, *Handbook of LHC Higgs Cross Sections: 2. Differential Distributions*, arXiv:1201.3084.

[4] LHC Higgs Cross Section Working Group, *Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector*, arXiv:1610.07922.

[5] M. Flechl, R. Klees, M. Krämer, M. Spira, M. Ubiali, *Improved cross-section predictions for heavy charged Higgs boson production at the LHC*, Phys.Rev. D91 (2015) 075015.

[6] E.L. Berger, T. Han, J. Jiang, T. Plehn, *Associated Production of a Top Quark and a Charged Higgs Boson*, Phys.Rev. D71 (2005) 115012.

[7] S. Dittmaier, M. Krämer, M. Spira, M. Walser, *Charged-Higgs-boson production at the LHC: NLO supersymmetric QCD corrections*, Phys.Rev. D83 (2011) 055005

[8] C. Weydert, S. Frixione, M. Herquet, M. Klasen, E. Laenen, T. Plehn, G. Stavenga, C. D. White, *Charged Higgs boson production in association with a top quark in MC@NLO*, Eur.Phys.J.C67 (2010) 617.

[9] C. Degrande, R. Frederix, V. Hirschi, M. Ubiali, M. Wiesemann, M. Zaro, *Accurate predictions for charged Higgs production: closing the $m_{H^\pm} \sim m_t$ window*, arXiv:1607.05291.

[10] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, M. Zaro, *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, JHEP 07 (2014) 079.

[11] M. Zaro, private communication (2016).