SusHi 2.0
Higgs production cross sections in BSM models

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A new upcoming version of SusHi is introduced. It features unified input for the Standard Model (SM) and beyond the SM models (BSM) parameters for higher-order total cross sections for Higgs production in gluon fusion, heavy-quark annhilation, as well as Higgsstrahlung. Like previous versions of SusHi, it provides links to codes like 2HDMC and FeynHiggs, but can also process standard SLHA output of spectrum generators like SOFTSUSY and SPheno.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

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1. Introduction

After the discovery of the Higgs boson in 2012 at the Large Hadron Collider (LHC) by the ATLAS and CMS collaborations [1, 2], the Higgs boson remains to be an interesting probe for precision tests of the Standard Model (SM) and the search for beyond the SM models (BSM). Therefore, in addition to precise measurements, precise predictions for Higgs observables in the SM and also beyond are required. Important processes to consider are single Higgs production and the production of a Higgs boson in association with a vector boson, so called Higgsstrahlung. Here, we want to give an update on the development of an upcoming version of SusHi [3–5], which will include cross-section predictions for single Higgs production in gluon fusion and heavy-quark annihilation and for Higgsstrahlung, the inclusion of the latter being a new feature realised by merging vh@nnlo [6–8] into SusHi.

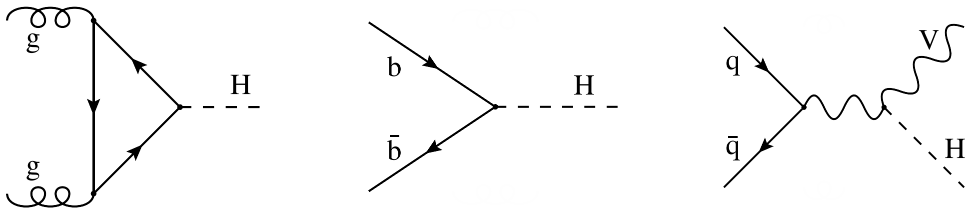
2. Higgs production in gluon fusion

The main production mode for the Higgs boson in the SM is gluon fusion. In SusHi it is implemented via the subprocedure ggh@nnlo. At leading order (LO) only two diagrams contribute to the process, where the Higgs boson is coupled to the two gluons via a heavy-quark triangle loop, see Fig. 1a. The partonic cross section at this order in the SM has been obtained in Ref. [9] At next-to-leading order (NLO), the partonic cross sections are still expressible analytically in the full SM [10, 11] and are implemented in SusHi with exact quark mass dependence. At next-to-next-to-leading order (NNLO) and next-to-next-to-next-to-leading order (N^3LO), partonic cross sections are implemented in the heavy top limit (HTL), meaning that the LO cross section is rescaled by the corresponding perturbative K-factor which is evaluated in the limit of an infinitely heavy top quark [12–16]. At NNLO (and NLO), comparison to the exact calculation [17] shows that this provides an excellent approximation at the few-permil level.

The cross section can also be obtained in various BSMs, for example in the Two-Higgs-doublet model (2HDM). In the 2HDM SusHi can not only compute cross section predictions for the production of the SM-like Higgs but also for the other uncharged Higgs bosons. This is achieved by adjusting the Yukawa coupling of the massive quarks to the Higgs. In the Minimal Supersymmetric SM (MSSM), also squark and gluino contributions are taken into account. SusHi uses results obtained in Refs. [14, 18–24] for the partonic cross sections in the MSSM.

3. Higgs production in heavy-quark annihilation

BSMs can enhance the coupling of the Higgs-like particles to the bottom quark, while possibly decreasing its coupling to the top quark at the same time. Therefore the production of a Higgs in bottom-quark annihilation can become sizeable. SusHi includes this process via the subprocedure bbh@nnlo. Also included is Higgs production in the annihilation of any two initial state quarks as described in Ref. [25]. The cross-section predictions for these processes can also be obtained in the MSSM and 2HDM. Here the SM result is re-weighted by the Yukawa coupling of the heavy quark to the Higgs-like particle. An example Feynman diagram is shown in Fig. 1b.



(a) LO diagram for Higgs production in gluon fusion.

(b) LO diagram for Higgs production in heavy-quark annihilation.

(c) LO diagram for Higgsstrahlung.

Figure 1: LO diagrams for the processes available in `SusHi 2.0` drawn with FeynGame [26].

4. Higgsstrahlung

The calculation of Higgsstrahlung cross-section predictions will be included in the upcoming version of `SusHi`. These predictions are part of `vh@nnlo` which will be merged into `SusHi`. Higgsstrahlung is the production of a vector boson in association with a Higgs boson: $\mathrm{pp} \to \mathrm{VH}$, $\mathrm{V} \in \{W^+, W^-, Z\}$. Up to NLO this process appears only in a Drell-Yan (DY)-like fashion: A virtual vector boson V^* is produced which subsequently radiates off a Higgs boson (hence the name "Higgsstrahlung"), as shown in Fig. 1c. These contributions can be calculated by integrating the product of the hadronic cross section for the production of the intermediate virtual vector boson $\sigma_{\mathrm{pp}\to\mathrm{V}^*}$ with the decay width of this intermediate particle to the final state $\mathrm{d}\Gamma_{\mathrm{V}^*\to\mathrm{VH}}/\mathrm{d}q^2$:

$$\sigma_{\mathrm{pp}\to\mathrm{VH}} = \int_{(m_\mathrm{H}+m_\mathrm{V})^2}^{s} \mathrm{d}q^2\, \sigma_{\mathrm{pp}\to\mathrm{V}^*} \frac{\mathrm{d}\Gamma_{\mathrm{V}^*\to\mathrm{VH}}}{\mathrm{d}q^2}. \tag{1}$$

`SusHi` builds on `zwprod` [27] for the calculation of the hadronic cross section of the production of the intermediate state which uses results obtained in Refs. [12, 28].
At NNLO, also other contributions have to be taken into account. The Higgs can couple to a top loop instead of an intermediate vector boson. In addition, for ZH production, also the gluon fusion channel, $\mathrm{gg} \to \mathrm{ZH}$, has to be taken into account.
BSM effects are included in a similar fashion to the Higgs production case in `SusHi`. In the 2HDM, production of all uncharged Higgs bosons together with the vector boson is allowed by adjusting the couplings of the Higgs to the other particles. In the MSSM squarks have to be considered for the gluon-initiated contribution. Additionally, in both the 2HDM and the MSSM, a Higgs boson can be produced which then decays into a vector boson and a Higgs with opposite parity.

5. Usage of SusHi

The compilation of `SusHi` requires LHAPDF [29–32] to be linked against it for the availability of parton density function (PDF) sets. This in turn means that all LHAPDF compatible PDF sets can be used in `SusHi`. The new version will also require linkage to the `CUBA` [33–35] library for `VEGAS` [36] Monte-Carlo (MC) integration and the `LoopTools` library [37–39] for the evaluation of box integrals in the gluon-gluon initiated contribution to ZH production.
Building `SusHi` results in an executable file which has to be called with a command line argument pointing to an input file. This input file follows the SUSY Les Houches Accord (SLHA) [40, 41]

format. If specified, SusHi will use a spectrum generator to generate input parameters not found in the input file. Afterwards, SusHi computes the cross sections requested in the input file and writes the results into an output file which also follows the SLHA format.
In the remainder of this section, we first describe the input file of SusHi followed by an overview of the usage of spectrum generators. Finally, the output file is discussed.

5.1 Input

The instructions for the calculations that the user wants SusHi to perform have to be written into the input file. This includes specifying what processes up to which orders are to be calculated. In the Higgsstrahlung case, also the different contributions can be turned on and off. One has to specify which collider, pp or p$\bar{\text{p}}$, at which centre of mass energy as well as the PDF set to be used amongst other things. The input has to follow the SLHA format as shown in Fig. 2. Essentially, parameters are grouped together in named *blocks*. These blocks are initiated by a line starting with the keyword **Block** followed by the name of the block. In the subsequent lines, the parameters belonging to this block are given by first stating the index, or in some cases indices, of the parameter and then the input value for this parameter. On the left side of Fig. 2, index 1 of the block PDFSPEC denotes the PDF set to be used via LHAPDF while index 10 indicates the PDF set member.

```
Block VEGAS
  10    10000
  11     5000
Block PDFSPEC
   1 PDF4LHC21_40_pdfas
  10        0
```

```
Block SIGMA
     1 5.32615250E-01
   111 2.02093466E-04
    10 1.18000798E-01
    11 5.32615250E-01
   110 2.02093466E-04
```

Figure 2: Excerpts of sample input (left) and output (right) files in the SLHA format.

In the upcoming version of SusHi, indices and/or blocks of some parameters will be changed compared to the current version in order to avoid conflicts with the input scheme for vh@nnlo.

5.2 Spectrum generators

Spectrum generators can be used to calculate Higgs masses and couplings, squark masses and other parameters used by SusHi in various BSMs from input containing more fundamental parameters of the theory. In particular FeynHiggs [42–50] and 2HDMC [51, 52] are tightly integrated and can be used straightforwardly in SusHi after linking against them.
FeynHiggs and 2HDMC are activated by including the blocks FEYNHIGGS and 2HDMC respectively. These blocks have to contain all the relevant input parameters for the given spectrum generator. There are two ways that SusHi interacts with these two spectrum generators. The library functions of the packages can either be used directly, or SusHi uses the command line modes. In the latter case, for FeynHiggs, an input file is created by SusHi which is subsequently read by FeynHiggs, whose output file is then read by SusHi. For 2HDMC, this program is called with the parameters specified directly in the command line. Nevertheless, 2HDMC also generates an output file in the SLHA format which is subsequently read by SusHi.
Support for FlexibleSUSY [53–55] and Himalaya [56] is also directly built into SusHi, albeit only in a command line mode. If the input file contains the block FLEXIBLESUSY, the whole

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input file gets converted into a `FlexibleSUSY`-compliant file which is then used as an input for `FlexibleSUSY`. The SLHA-formatted output is then read by `SusHi`, and the parameters that were calculated by `FlexibleSUSY` are used in the cross section prediction calculations.
Other spectrum generators like `SOFTSUSY` [57, 58] and `SPheno` [59–61] can be used as well. These generators have to be called manually such that they produce an output file in the SLHA format. This file can then be read by `SusHi` by specifying the filename in the `SPECTRUMFILE` block in its input. One can of course also create such a spectrum file by hand and use it in the same way.

5.3 Output

After processing the input and possibly calling spectrum generators to gather all the relevant parameters, `SusHi` calculates the requested cross-section predictions. The results are written into an output file following the SLHA format, just like the input file. This means that the results each belong to a specific index in a specific block. In Fig. 2, for example, index `11` of block `SIGMA` denotes the DY-like contribution to the Higgsstrahlung cross section at NNLO, and index `110` its MC integration error.
The output file also contains a reconstruction of the input file after the results of the calculation(s). Therefore, the output file can be used as an input file. This is useful for testing reproducibility but also has the practical advantage of not having to keep track of which output file belongs to which input parameter set.

6. Drell-Yan-like Higgsstrahlung at N^{3}LO

The DY part is the most important contribution to the Higgsstrahlung cross section as it is the only contribution that appears at LO and NLO. As shown in Eq. (1), two components are needed for the calculation of this contribution: the hadronic cross section for the production of the virtual vector boson and its decay width to the VH final state. The decay width does not entail pure Quantum Chromodynamics (QCD) corrections and therefore only the cross section for the production of the intermediate state has to be adjusted when going to higher orders. The hadronic cross section in turn is obtained from the partonic cross section via convolution with the PDFs. Therefore, corrections on the partonic cross sections for the production of an intermediate vector boson are necessary for higher orders in the DY contribution to Higgsstrahlung. These are available up to NNLO [62] and N^{3}LO [63, 64]. Their implementation in `SusHi` is a new feature of the upcoming version of `SusHi`.
For the DY part of the cross section it is straightforward to calculate not only total cross sections but also distributions in the invariant mass of the VH system. There are two possibilities for the calculation starting from Eq. (1): On the one hand, one can simply omit the integration over the virtuality of the intermediate vector boson. This yields the differential distribution:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m^2_{\mathrm{VH}}} = \sigma_{\mathrm{pp}\to\mathrm{V}^*} \frac{\mathrm{d}\Gamma_{\mathrm{V}^*\to\mathrm{VH}}}{\mathrm{d}m^2_{\mathrm{VH}}}. \tag{2}$$

This is the method used in `vh@nnlo`. On the other hand, one can, instead of getting rid of the integration altogether, simply restrict the range of the integration over the virtuality to bins. One gets a binned distribution:

$$\delta\sigma_{\mathrm{pp}\to\mathrm{VH}} = \int_{m_{\mathrm{VH}}^2-\frac{1}{2}\delta m_{\mathrm{VH}}^2}^{m_{\mathrm{VH}}^2+\frac{1}{2}\delta m_{\mathrm{VH}}^2} \mathrm{d}q^2\; \sigma_{\mathrm{pp}\to\mathrm{V}^*} \frac{\mathrm{d}\Gamma_{\mathrm{V}^*\to\mathrm{VH}}}{\mathrm{d}q^2}\,, \tag{3}$$

where δm_{VH}^2 denotes the bin width. The binned distribution is added to the new version of SusHi although also the differential distribution will be available at up to N^{3}LO.

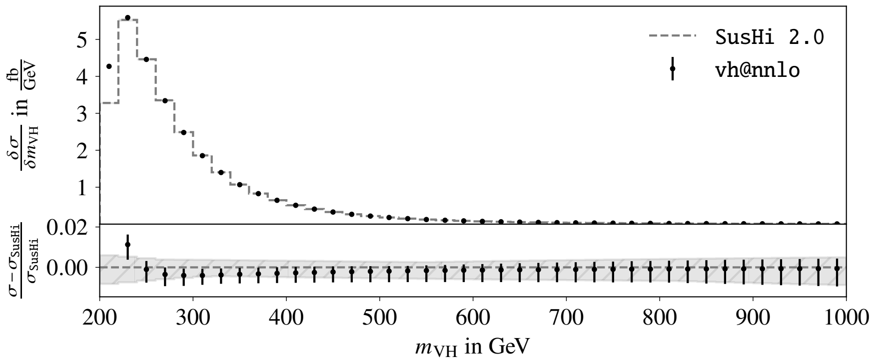

Figure 3: Distribution of the cross section for the DY-part of the Higgsstrahlung pp $\to$ W$^-$H cross section in the invariant mass of the W$^-$H system at NNLO. The dots with the error bars indicate the values obtained with vh@nnlo. The dashed line and the error band is the binned distribution calculated with the new implementation. The errors are given by a 7 point scale variation with a factor of 3.

A comparison between the two approaches can be seen in Fig. 3. The differences arise because the binned distribution consists of the averages of the differential distribution over the bins, while vh@nnlo evaluates the differential distribution according to Eq. (2) at the centre of each bin. The new implementation gives the averages according to Eq. (3), which are expected to differ from the values at the centres of the bins.

7. Summary

The upcoming version of SusHi will include Higgsstrahlung cross-section prediction in addition to single Higgs production as it incorporates vh@nnlo. Therefore vh@nnlo and SusHi will be merged into a single package. For the Higgsstrahlung process N^{3}LO corrections for the DY-part will be taken into account.

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