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Higgs production in the 2HDM and the MSSM (`SusHi`)

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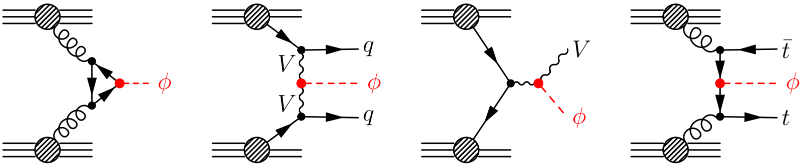
Theoretische Teilchenphysik
Fachbereich C
Bergische Universität Wuppertal

Higgs production processes:

$pp \to \phi$ | $pp \to qq\phi$ | $pp \to W\phi/Z\phi$ | $pp \to t\bar{t}\phi$

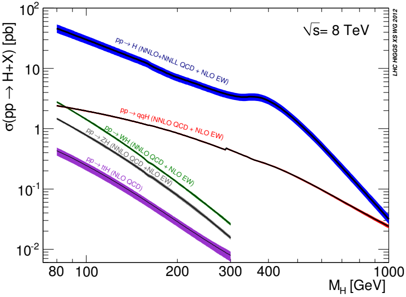


Gluon fusion
Bottom-quark annihilation

Vector boson fusion

Higgs Strahlung

$t\bar{t}H$ production



This talk: Status of
Higgs production through

- ▷ gluon fusion
- ▷ Higgs Strahlung

in the MSSM and the 2HDM.

Higgs sector of the MSSM:

Two $SU(2)$ doublets $\Phi_u = (\Phi_u^+, \Phi_u^0)^T$ and $\Phi_d = (\Phi_d^0, \Phi_d^-)^T$ mix as follows

CP-even Higgs CP-odd Higgs

$$\begin{pmatrix} \Phi_u^0 \\ \Phi_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h \\ H \end{pmatrix} + \frac{i}{\sqrt{2}} R_\beta \begin{pmatrix} G \\ A \end{pmatrix} .$$

8 degrees of freedom result in 5 physical particles: $h, H, A, H^\pm$.

MSSM Higgs sector input: $\tan\beta = \frac{v_u}{v_d}, m_A^2 \rightarrow m_{h,H}$, Higgs mixing angle α.

Higher orders e.g. by `FeynHiggs` [Frank Degrassi Hahn Heinemeyer Hollik Rzehak Slavich Weiglein Williams].

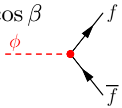
Relative strength of Higgs couplings for $\phi = \{h, H, A\}$ (w.r.t. SM couplings)

▷ to SM fermions g_f^ϕ: ▷ to gauge bosons g_V^ϕ: ▷ squark couplings $g_{\tilde{f}ij}^\phi$:

$$g_u^h = \frac{\cos\alpha}{\sin\beta}$$

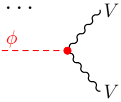
$$g_d^h = -\frac{\sin\alpha}{\cos\beta}$$

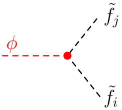
$\ldots$



$$g_V^h = \sin(\beta - \alpha)$$

$\ldots$





Vacuum structure of 2HDMs with Higgs doublets Φ_1 and Φ_2 generally rich.
Assumptions (used in 2HDM analyses by the LHC experiments):

- CP conservation in the Higgs sector
- No tree-level FCNCs

4 types of models can be distinguished by Yukawa couplings:

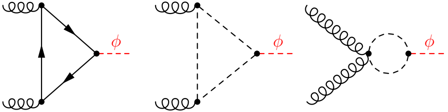
Type	u_R	d_R	e_R
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

$\sim$ MSSM

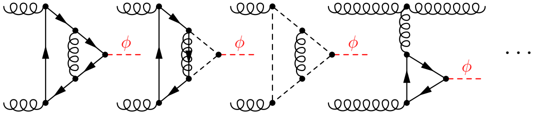
Physical particle content: $h, H, A, H^\pm$
2HDM input: $m_h, m_H, m_A, m_{H^\pm}$, $\tan\beta = v_1/v_2$, α (mixing $h - H$)

Relative couplings of Higgs fields: $g_f^\phi = F(\alpha, \beta)$, g_V^ϕ as before, $g_{\tilde{f}}^\phi = 0$
[Review of 2HDMs: The Higgs Hunter's guide; Branco Ferreira Lavoura Rebelo Sher Silva; arXiv:1106.0034]

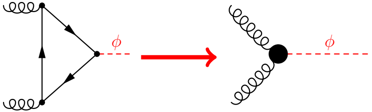
Gluon fusion: ▷ Leading order (LO) calculation:
quark loops in SM/2HDM (+squark loops in MSSM)



▷ Next-to-leading order (NLO) QCD calculation:
includes real contributions



▷ Next-to-NLO (NNLO) QCD calculation:
only known in “heavy top-limit” $m_H \ll 2m_t$



σ^{LO}

Correction $\sim 100\%$

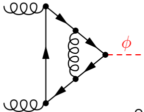
σ^{NLO}

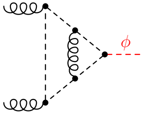
Correction $\sim 10\%$

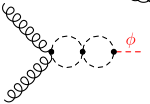
σ^{NNLO}

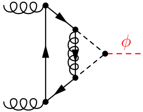
NLO virtual amplitudes:

- ▷ gluon-quark: known analytically (higher orders)
  [Spira Djouadi Graudenz Zerwas ’95; Harlander Kant ’05; . . .]
- ▷ gluon-squark: known analytically/numerically
  [Anastasiou Beerli Bucherer Daleo Kunszt ’06; Aglietti Bonciani Degrassi Vicini ’06; Mühlleitner Spira ’06; Bonciani Degrassi Vicini ’07]
- ▷ gluino-squark-quark contributions: semi-analytically known
  [Anastasiou Beerli Daleo ’08; Mühlleitner Spira Rzehak ’10]









Problem with gluino-quark-squark contributions:
Five different masses: $m_q, m_{\tilde{q}1}, m_{\tilde{q}2}, m_{\tilde{g}}, p^2 = m_\phi^2$

- ▷ Taylor expansion in small Higgs mass:
  $\longrightarrow$ top-stop-gluino contribution $m_\phi \ll m_t, m_{\tilde{t}1}, m_{\tilde{t}2}, m_{\tilde{g}}$
  [Harlander Steinhauser ’03 ’04 + Hofmann ’05; Degrassi Slavich ’08]
  (NNLO top-stop-gluino contr. [Pak Steinhauser Zerf ’10 ’12])
- ▷ Expansion in heavy SUSY masses: $m_\phi, m_q \ll m_{\tilde{q}1}, m_{\tilde{q}2}, m_{\tilde{g}}$
  $\longrightarrow$ quark-squark-gluino [Harlander Hofmann Mantler ’10; Degrassi Slavich ’10 + Di Vita ’11 ’12]

`SusHi` [Harlander Mantler SL '12] combines efforts achieved in the XS calculation:

(0. Link of `SusHi` to `FeynHiggs` or `2HDMC` [Eriksson Rathsman Stål '09].)

1. Calculate XS with quark contributions (using resummation) (YR1).
2. Add expanded squark/gluino contributions of third generation (in the MSSM).
3. Add NNLO top effects and electroweak contributions:

$$\sigma(pp \to \phi + X) = \sigma_{\text{NLO}}^{\text{MSSM/2HDM}}(1 + \delta_{\text{EW}}^{lq}) + (g_t^\phi)^2 \left(\sigma_{\text{NNLO}}^{t,\text{SM},0} - \sigma_{\text{NLO}}^{t,\text{SM},0}\right)$$

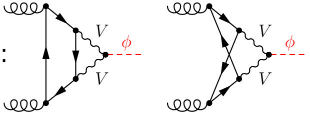
Electroweak contributions by light quarks

`ggh@nnlo`

(4. Add bottom-quark annihilation and calculate differential quantities.)

Electroweak contributions by light quarks: [Aglietti Bonciani Degrassi Vicini '04 '10]

Relevant diagrams with $V \in \{W, Z\}$:

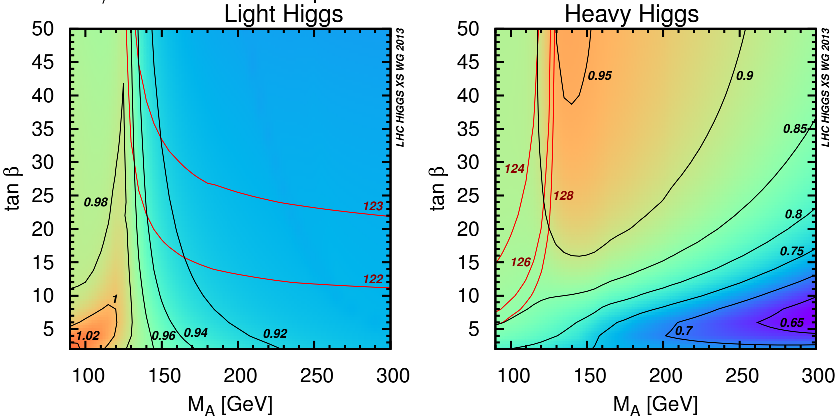


Example from new benchmark scenarios defined by [Carena et al.; arXiv:1302.7033]: "lightstop scenario"

$m_{\text{SUSY}} = 500$GeV, $\mu = 350$GeV, $X_t^{\text{OS}} = 2m_{\text{SUSY}}$ $\rightarrow$ stop masses:

$A_b = A_t$, $m_{\tilde{g}} = 1500$GeV, $m_{\tilde{l}_3} = 1000$GeV 325GeV and 670GeV

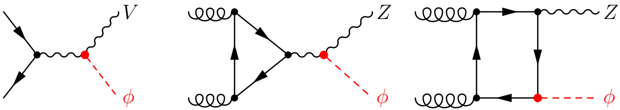
Ratio $\sigma^{\text{YR3}}/\sigma^{\text{YR1}}$ $\rightarrow$ Effect of squarks and electroweak contributions



[LHCHXSWG, YR3; arXiv:1307.1347]

Relevant diagrams for $pp \to V\phi$ at LO:

Drell-Yan like contributions | **Gluon-initiated contributions**



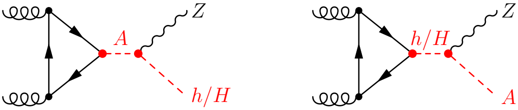
$$\sigma_{WH} = \sigma_{WH}^{\text{DY}}(1 + \delta_{WH,\text{EW}}), \qquad \sigma_{ZH} = \sigma_{ZH}^{\text{DY}}(1 + \delta_{ZH,\text{EW}}) + \sigma_{gg\to ZH}$$

Known corrections in the SM:

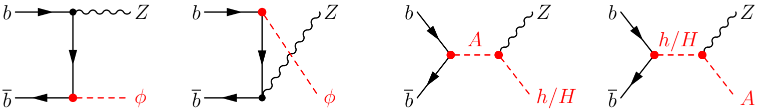
- σ_{VH}^{DY} calculated up to NNLO with `vh@nnlo` [Brein Djouadi Harlander Zirke '03 '12] with electroweak corrections [Ciccolini Dittmaier Krämer '03]
- $\sigma_{gg\to ZH}$ known at NLO [Altenkamp Dittmaier Harlander Rzehak Zirke '12]
- Top-induced corrections [Brein Harlander Wiesemann Zirke '11]

Procedure in the 2HDM: Reweight σ_{VH} with $(g_V^\phi)^2$?
Problem: Gluon-induced contributions are dependent on g_t^ϕ and g_b^ϕ as well!

Higgs Strahlung in the 2HDM: [Harlander SL Zirke '13]
Moreover resonant contributions to $gg \to Z\phi$:

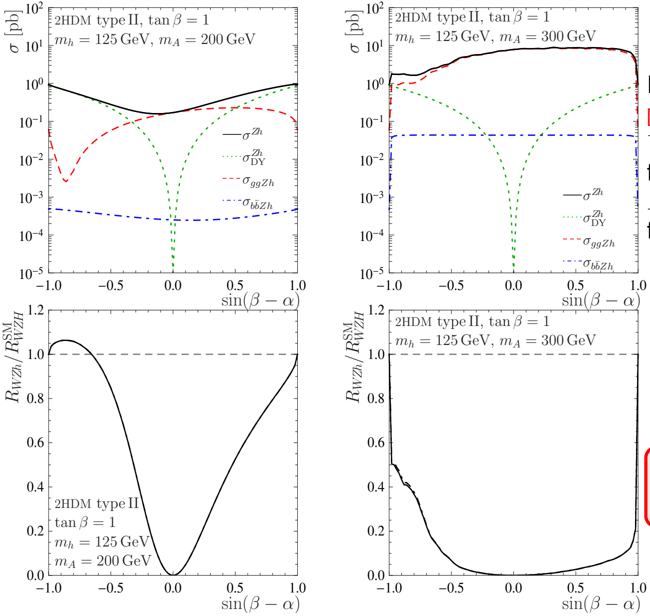


Even more contributions possible $b\bar{b} \to Z\phi$:



$\longrightarrow$ $pp \to Z\phi$ affected by various contributions.
$pp \to W\phi$ reweighted by $(g_V^\phi)^2$.
$\longrightarrow$ New physics effects in the ratio $R_{WZ\phi} = \sigma_{W\phi}/\sigma_{Z\phi}$!
Independent of ϕ decay mode, uncertainties reduced.

Implementation in `vh@nnlo` with link to `2HDMC`.



Example in the 2HDM:
[Harlander SL Zirke '13]
Vh production
for $\sqrt{s} = 14$ TeV
$R^{\mathrm{SM}}_{WZH} = 1.570$
for $m_H = 125$ GeV

Check the ratio:
$R_{WZ\phi} = \sigma_{W\phi}/\sigma_{Z\phi}$

We showed progress in the calculation of Higgs production for a neutral Higgs ϕ in the SM/MSSM/2HDM.

In case of gluon fusion/bottom-quark annihilation:

- calculation of MSSM/2HDM gluon fusion XS @NLO including all SUSY, NNLO top and electroweak contributions.
- calculation of MSSM/2HDM weighted bottom-quark annihilation XS.

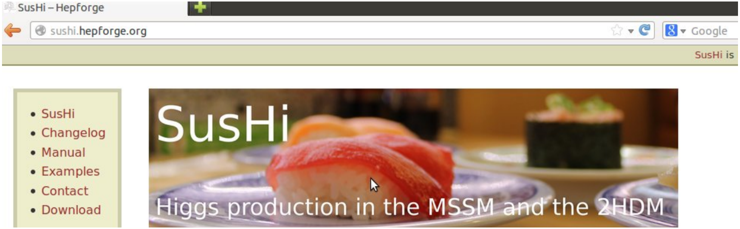
$\rightarrow$ `SusHi`

In case of Higgs Strahlung in the 2HDM calculation of all relevant contributions at least at LO $\leftrightarrow$ Ratio $\sigma_{W\phi}/\sigma_{Z\phi}$.

$\rightarrow$ `vh@nnlo` (2HDM version published soon.)

Many thanks for your attention!

Where can I get `SusHi/vh@nnlo`? http://sushi.hepforge.org and http://nnlo.de



How can the Higgs sector in a local $SU(2) \times U(1)$ gauge theory be extended?

Measurement of $\rho \sim 1.0004$ [PDG]

Introduce n scalar multiplets ϕ_i with:

- weak Isospin T_i
- weak hypercharge Y_i
- VEVs v_i of neutral comp.

$$\rho = \frac{\sum_{i=1}^{n} [T_i(T_i+1) - Y_i^2] v_i}{\sum_{i=1}^{n} 2 Y_i^2 v_i}$$

$\rightarrow$ Simplest version: Add multiplets with $T(T+1) = 3Y^2$
e.g. $SU(2)$ singlets with $Y = 0$, $SU(2)$ doublets with $Y = \pm\frac{1}{2}$, ...

Within this talk:

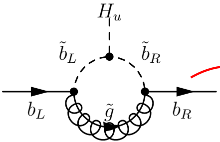
- Standard Model: One $SU(2)$ doublet
- Minimal Supersymmetric Standard Model (MSSM): Two $SU(2)$ doublets
- 2 Higgs Doublet Model (2HDM): Two $SU(2)$ doublets

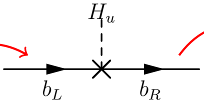
Resummation of large $\tan\beta$-enhanced terms in the MSSM

$$\mathcal{L} \supset -Y_t H_u Q t_R + Y_b H_d Q b_R$$

Using $\langle H_u \rangle = v_u, \langle H_d \rangle = v_d$ and $v_d^2 + v_u^2 = v^2, \tan\beta = v_u/v_d$ we define

$$Y_t = \frac{m_t}{v_u} = \frac{m_t}{v\sin\beta}, \qquad Y_b = \frac{m_b}{v_d} = \frac{m_b}{v\cos\beta}$$





$$\mathcal{L}^{\text{eff}} \supset Y_b H_d Q b_R - \tilde{Y}_b H_u^* Q b_R$$

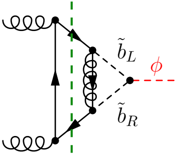
$$\Delta_b = \frac{\tilde{Y}_b v_u}{Y_b v_d} =: \epsilon \tan\beta$$

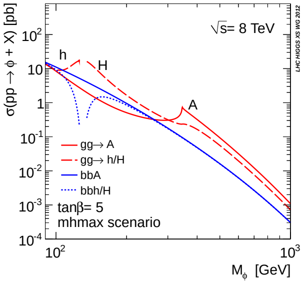
The effective Lagrangian motivates:

$$m_b = Y_b v_d + \tilde{Y}_b v_u = Y_b v_d (1 + \epsilon \tan\beta)$$

$$\Rightarrow \quad Y_b = \frac{m_b}{v_d(1+\Delta_b)}$$

This replacement implies a resummation of large $\tan\beta$-enhanced terms:





Enhancement of g_b^ϕ for large $\tan\beta$ in MSSM

Idea: Use results from 5FS and reweight accordingly with resummed MSSM couplings [Guasch Häfliger Spira '03]:

$$g_b^A = g_b^A \frac{1}{1+\Delta_b}\left(1 - \frac{1}{\tan^2\beta}\Delta_b\right)$$

$$g_b^h = g_b^h \frac{1}{1+\Delta_b}\left(1 - \frac{1}{\tan\beta\tan\alpha}\Delta_b\right)$$

$$g_b^H = g_b^H \frac{1}{1+\Delta_b}\left(1 + \frac{\tan\alpha}{\tan\beta}\Delta_b\right)$$

$$\left.\begin{aligned}\Delta_{Ab} &= -\frac{C_F}{2\pi}\alpha_s(\mu_r) m_{\tilde{g}} A_b I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}}) \\ \Delta_b &= \frac{C_F}{2\pi}\alpha_s(\mu_r) m_{\tilde{g}} \mu \tan\beta I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}})\end{aligned}\right\} \Delta_b \to \Delta_b \frac{1}{1+\Delta_{Ab}}$$

Specify model, collider, $\sqrt{s}$, Higgs, processes

Give SM input values

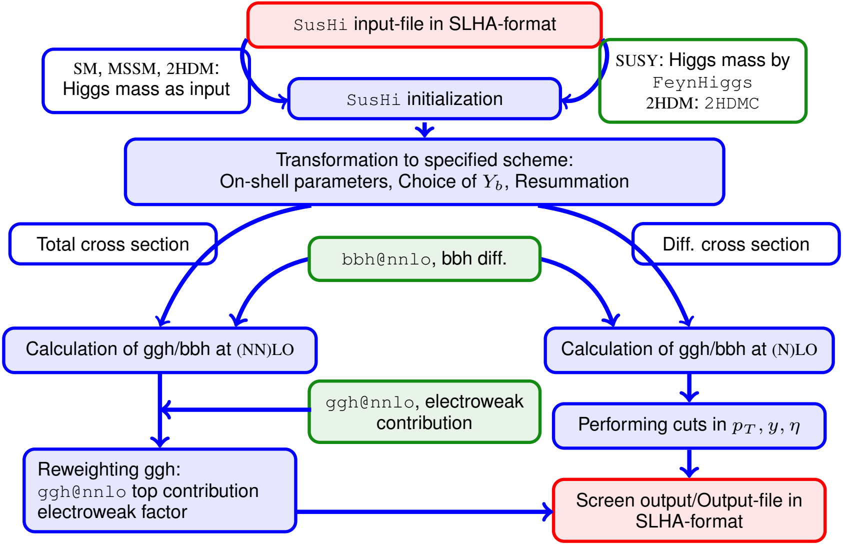
MSSM/2HDM input values: Link SusHi to

- ▷ FEYNHIGGS
- ▷ 2HDMC [Eriksson et al, arXiv: 0902.0851]

Specify PDF sets

Specify VEGAS input

```
Block SUSHI
  1    1          # model: 0 = SM, 1 = MSSM, 2 = 2HDM
  2    0          # 0 = scalar (h), 1 = pseudoscalar (A), 2 = scalar (H)
  3    0          # collider: 0 = p-p, 1 = p-pbar
  4    8000.d0    # center-of-mass energy in GeV
  5    2          # order ggh: -1 = off, 0 = LO, 1 = NLO, 2 = NNLO
                  #            3 = ~NNLO stop
  6    2          # order bbh: -1 = off, 0 = LO, 1 = NLO, 2 = NNLO
  7    1          # electroweak cont. for ggh:
                  # 0 = no, 1 = light quarks at NLO, 2 = SM EW factor
Block SMINPUTS            # Standard Model inputs
  1    1.27934000e+02     # alpha_em^(-1)(MZ) SM MSbar
.....
Block MINPAR              # SUSY breaking input parameters
  3    1.00000000e+01     # tanb
Block EXTPAR
  3    800.d0             # M_3
 11    2000.d0            # A_t
.....
Block ALPHA
 -8.3691204e-01           # mixing in Higgs sector
Block MASS
 25    120.76695d0        # Higgs mass h
.....
.....
Block PDFSPEC
  1    MSTW2008lo68cl.LHgrid              # name of pdf (lo)
  2    MSTW2008nlo68cl.LHgrid             # name of pdf (nlo)
  3    MSTW2008nnlo_asmzrange.LHgrid      # name of pdf (nnlo)
  4    0          # set number
Block VEGAS
  1    10000      # number of points
  2    5          # number of iterations
  3    10         # print: 0 = no output, 1 = prettyprint, 10 = table
```


SusHi input-file in SLHA-format
SM, MSSM, 2HDM: Higgs mass as input
SusHi initialization
SUSY: Higgs mass by FeynHiggs
2HDM: 2HDMC
Transformation to specified scheme:
On-shell parameters, Choice of Y_b, Resummation
Total cross section
bbh@nnlo, bbh diff.
Diff. cross section
Calculation of ggh/bbh at (NN)LO
Calculation of ggh/bbh at (N)LO
ggh@nnlo, electroweak contribution
Performing cuts in p_T, y, η
Reweighting ggh:
ggh@nnlo top contribution
electroweak factor
Screen output/Output-file in SLHA-format

Example output file

```
# Please cite the following papers (for this run):
# Harlander:2012pb
......
# Heinemeyer:1998np
# Degrassi:2002fi
# Frank:2006yh
Block SUSHIggh # Bon appetit
         1     1.59566551E+01    # ggh XS in pb
Block SUSHIbbh # Bon appetit
         1     2.67975811E-01    # bbh XS in pb
Block XSGGH # ggh MSSM-Cross sec. in pb (w/o EW)
         2     1.13849524E+01    # NLO
        21     1.14675980E+01    # NLO gg
        22    -1.02733041E-01    # NLO qg
        23     2.00874475E-02    # NLO qq
Block XSGGHEFF # ggh MSSM-Cross sec.
         1     1.49056433E+01    # ggh@NLO MSSM
         2     1.88154287E+01    # ggh@NNLO MSSM
         3     5.81396602E-02    # electroweak factor
Block XSBBH # bbh MSSM-Cross sec. in pb
         1     3.72508379E-01    # LO
         2     3.35738356E-01    # NLO
         3     2.67975811E-01    # NNLO
......
Block MASSOUT
         5     4.21300000E+00    # m_b(m_b), MSbar
         6     1.73200000E+02    # m_t(pole)
        23     9.11876000E+01    # m_Z
        24     8.03980311E+01    # m_W
        25     1.23484421E+02    # MSSM-Mh in GeV
   1000005     4.93350465E+02    # sbottom1 mass in GeV
   2000005     5.18897088E+02    # sbottom2 mass in GeV
   1000006     3.23616710E+02    # stop1 mass in GeV
   2000006     6.71663496E+02    # stop2 mass in GeV
```

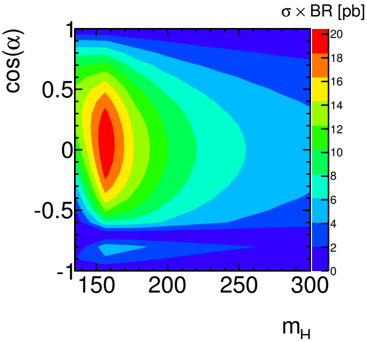
SusHi usage: Current ATLAS 2HDM analysis $\phi \to WW \to l\nu l\nu$

- Gluon fusion: σ from SusHi
- Vector boson fusion: $\sigma^{\text{VBF}} = \sigma^{\text{VBF,SM}} (g_V^\phi)^2$
- Decays:

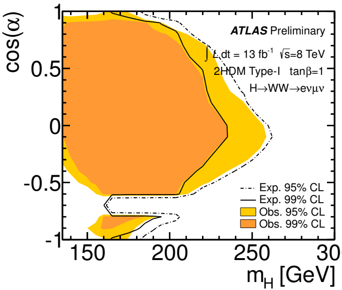
$$\text{BR}(\phi \to WW) = \frac{\Gamma(H \to WW)(g_W^\phi)^2}{\Gamma(H \to WW)(g_W^\phi)^2 + \Gamma(H \to b\bar{b})(g_b^\phi)^2}$$

2HDM type I with $\tan\beta = 1$ and light Higgs at $m_h = 125$ GeV

$\sigma(gg \to H) \times \text{BR}(H \to WW)$



Exclusion plot for heavy Higgs



[courtesy of ATLAS, ATLAS-CONF-2013-027]