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# Higgs production with SusHi

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Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

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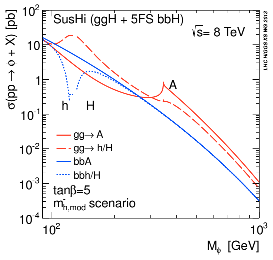
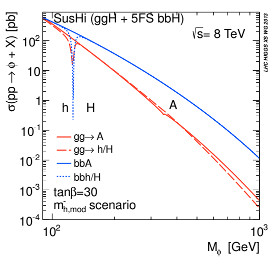
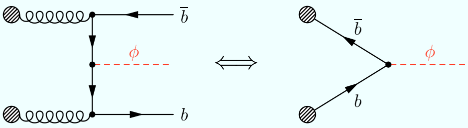
SusHi (SuperSymmetric Higgs) allows to calculate neutral Higgs boson production XS through **gluon fusion** and **bottom-quark annihilation** (5FS) in the SM, the 2HDM and the MSSM. [Harlander SL Mantler '12: http://sushi.hepforge.org]

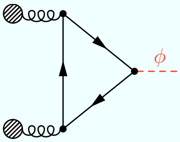



## Bottom-quark annihilation:




## Gluon fusion:




extensively used in the LHCHXSWG with links to FeynHiggs and 2HDMC

## New in SusHi 1.5.0 (March 2015) and recent add-ons

Served SusHi!

Implementation of the real NMSSM in SusHi: [SL '15]
What is new in the real NMSSM compared to the real MSSM?
The superpotential includes the singlet field $\hat{S}$, which generates $\mu$ dynamically:

$$W_{\text{NMSSM}} = W_{\text{MSSM,no}\mu} - \epsilon_{ab}\lambda\hat{S}\hat{H}_d^a\hat{H}_u^b + \frac{1}{3}\kappa\hat{S}^3$$

We expand the Higgs sector according to

$$H_{d/u} = \tfrac{1}{\sqrt{2}}(v_{d/u} + H_{d/u}^R + iH_{d/u}^I), \quad S = \tfrac{1}{\sqrt{2}}(v_s + S^R + iS^I)$$

and thus generate an effective $\mu$-term:

$$\mu = \tfrac{1}{\sqrt{2}}\lambda v_s$$

The physical mass eigenstates are obtained through the rotations:

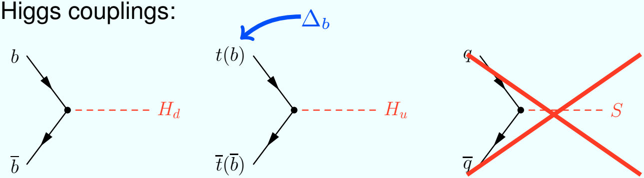
Mass eigenstates = Mixing matrix · Gauge eigenstates

CP-even sector: $(H_1, H_2, H_3)^T = \mathcal{R}^S \cdot (H_d^R, H_u^R, S^R)^T$

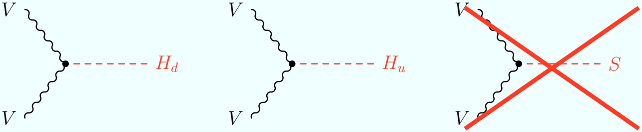
CP-odd sector: $(G^0, A_1, A_2)^T = \mathcal{R}^P \cdot \mathcal{R}^G \cdot (H_d^I, H_u^I, S^I)^T$

Relevant changes for Higgs production at the level of gauge eigenstates:

▷ Quark-Higgs couplings:

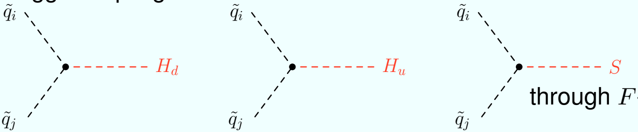



▷ Gauge boson ($V \in \{Z, W\}$)-Higgs couplings (for electroweak corrections):




→ Neglecting squarks no new contributions compared to the MSSM.

▷ Squark-Higgs couplings:




through $F$-terms

**Implications for bottom-quark annihilation in the 5FS:**
We proceed as in in the MSSM, i.e. calculate SM XS reweighted with the bottom-quark Yukawa coupling $Y_b$ taking into account NMSSM $\Delta_b$ corrections:
[Baglio et al. '13]

$$\tilde{Y}_b^{H_i} = \frac{Y_b^{H_i}}{1+\Delta_b}\left[1+\Delta_b\left(\frac{\mathcal{R}^S_{i2}}{\mathcal{R}^S_{i1}\tan\beta} + \frac{\mathcal{R}^S_{i3}v\cos\beta}{\mathcal{R}^S_{i1}v_s}\right)\right], \quad i\in\{1,2,3\}$$

$$\tilde{Y}_b^{A_i} = \frac{Y_b^{A_i}}{1+\Delta_b}\left[1+\Delta_b\left(-\frac{1}{\tan^2\beta} - \frac{\mathcal{R}^P_{i+1,3}v}{\mathcal{R}^P_{i+1,2}v_s\tan\beta}\right)\right], \quad i\in\{1,2\}.$$

Similarly the 4FS cross section can be reweighted. [Dittmaier Krämer Spira '03, Dawson Jackson Reina Wackeroth '04]

**Implications for gluon fusion in `SusHi`:**

$$\text{MSSM} \quad \sigma(pp\to\phi+X) = \sigma^{\text{MSSM}}_{\text{NLO}}(1+\delta^{lq}_{\text{EW}}) + (Y_t^\phi)^2\left(\Delta\sigma^{t,\text{SM},0}_{\text{NNLO}}\right)$$

$$\to\text{NMSSM} \quad \sigma(pp\to\phi+X) = \sigma^{\text{NMSSM}}_{\text{NLO}}(1+\delta^{lq}_{\text{EW}}) + (Y_t^\phi)^2\left(\Delta\sigma^{t,\text{SM},0}_{\text{NNLO}}\right)$$

- ✓ Inclusion of NLO third generation squark contributions (on top of $\Delta_b$)
- ✓ Inclusion of electroweak contributions by light quarks

Where does SusHi get the Higgs spectrum and the squark sector from?
→ At first stage the user needs to provide simple SLHA-style input:(∗)

Specify model, Higgs + . . .

Provide squark sector (Check renorm. schemes!)

Specify Higgs mixing
$\mathcal{R}^S$: NMHMIX
$\mathcal{R}^P \cdot \mathcal{R}^G$: NMAMIX or
$\mathcal{R}^P$: NMAMIXR

Provide Higgs masses

SusHi input: Scales, VEGAS, Individual contr., Renorm. schemes

```
Block  SUSHI
    1      3      # model:  0  =  SM,  1  =  MSSM,  2  =  2HDM,  3  =  NMSSM
    2      11     # 11,12,13  =  H1,H2,H3,  21,22=A1,A2
....
Block  MINPAR  #  tanb
    3          2.00000000e+00          #  tanb
Block  EXTPAR  #  SUSY  parameters
    3          1.80000000e+03          #  M_3
    11         1.80000000e+03          #  A_t
    43         7.40000000e+02          #  M_Q3
....
    61         6.20000000E-01          #  lambda
    65         2.00000000E+02          #  mu_eff
BLOCK  NMHMIX   #  Scalar  Higgs  mixing  matrix
   1   1       4.30591141E-01     #  R_H_11
   1   2       8.90438555E-01     #  R_H_12
   1   3      -1.47344659E-01     #  R_H_13
   2   1       2.66876782E-01     #  R_H_21
....
BLOCK  NMAMIX   #  Pseudoscalar  Higgs  mixing  matrix
   2   1      -6.74161819E-03     #  R_A_11
....
Block  MASS         #  NMSSM  Higgs  masses
    25       1.25820962E+02       #  H1
    35       2.10322178E+02       #  H2
    45       4.13826725E+02       #  H3
    36       1.51099000E+02       #  A1
    46       4.05344805E+02       #  A2
Block  ....
```

(∗) Use any NMSSM spectrum generator.

Typical output in case of an inclusive XS:

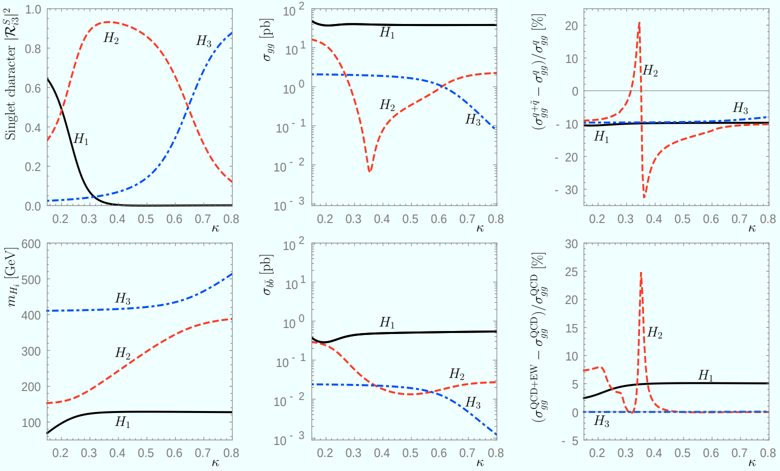
NMSSM since V 1.5.0

Please cite the papers!

Useful information also to reweight e.g. bbh 4FS XS

```
#--------------------------------------------------#
# SusHi: Supersymmetric Higgs production through  #
#  __      __          gluon fusion and bottom-quark #
# [_   | | [_   |_| |  annihilation                #
# __] |_| __] | | |                                #
#                      Version    1.5.0    Mar 2015  #
#--------------------------------------------------#
# Date: 02.06.2015 at 10:36:17                     #
# For the reconstructed input file, check below.   #
#--------------------------------------------------#
# Please cite the following papers (for this run):
# Harlander:2012pb
....
#--------------------------------------------------#
Block SUSHIinfo
     1      1.5.0       # SusHi version
Block SUSHIggh # Bon appetit
     1     4.01125098E+01    # ggh XS in pb
Block SUSHIbbh # Bon appetit
     1     4.76446524E-01    # bbh XS in pb
Block XSGGH # ggh cross sec. in pb (w/o EW)
     1     1.33528853E+01    # LO w/ NLO PDFs
     2     3.18704352E+01    # NLO
....
Block XSGGHEFF # ggh xsec
     1     3.82118989E+01    # ggh@NLO
     2     4.45482479E+01    # ggh@NNLO
     3     5.80108895E-02    # electroweak factor
....
Block BBHREWEIGHT # top and bottom reweighting factors
     1     9.95540569E-01    # g_t
     2     9.62577234E-01    # g_b incl. 1/(1+Delta_b)*..
....
```

Flashing results for the inclusive cross section (CP-even Higgs bosons):
Spectrum generator NMSSMCALC [Baglio et al., '13], Details: [1502.07972: SL '15]




$\tan\beta = 2$, $A_\kappa = -20$ GeV, $\lambda = 0.62$, $\mu = 200$ GeV, $m_{H^\pm} = 400$ GeV, $M_3 = 1.5$ TeV

$m_{\tilde{t}_1} = 544.7$ GeV, $m_{\tilde{t}_2} = 941.2$ GeV, $m_{\tilde{b}_1} = 749.4$ GeV, $m_{\tilde{b}_2} = 757.4$ GeV

SusHi allows to calculate $\eta/y$ and $p_T$ distributions at fixed order!
However $p_T$ distributions in $gg/b\bar{b} \to \phi$ diverge for $p_T \to 0$ at fixed order.
Thus: Need for resummation of Sudakov logarithms $\sim \log(p_T/m_\phi)$

**Bottom-quark annihilation:**

✓ NNLL+NNLO in the 5FS [Belyaev Nadolsky Yuan '06, Harlander Tripathi Wiesemann '14]

✓ Implementation of 4FS+5FS in MG5_aMC@NLO at NLO QCD + PS [Frederix et al. '14]
$\to$ Translation to extended Higgs sectors through reweighting with relative $Y_b$

**Gluon fusion:**

✓ NNLL+NNLO in the heavy top-limit
[Catani et al. '88, Yuan '92, Kauffman '92, Bozzi et al. '03 '05, Cao et al. '09, de Florian et al. '11, Catani Grazzini '11, Wang et al. '12]; in the context of SCET [Idilbi et al. '05, Gao et al. '05, Mantry et al. '10, Becher et al. '10 '12, Stewart et al. '11 '13] + Works from 2015

✓ Top-quark mass effects at NLL+NLO in SM
Bottom-quark contributions very recently at NLL+NLO in SM (with $\log(p_T/m_b)$)
[Bagnaschi Degrassi Slavich Vicini '11, Mantler Wiesemann '12, Grazzini Sargsyan '13, Banfi Monni Zanderighi '13]
Crucial question: Unphysical scale choices $(Q_t, Q_b, Q_{tb})$

Approaches in extended Higgs sectors (i.e. the 2HDM, MSSM):

▷POWHEG (gg_H_MSSM, gg_H_2HDM) - Resummation through parton shower
[Bagnaschi Degrassi Slavich Vicini '11, Bagnaschi Vicini '15]

(POWHEG-SusHi [Mantler unpublished])

▷aMCSusHi - SusHi amplitudes to MG5_aMC@NLO [Alwall et al. '14]
[Mantler Wiesemann '15]

▷MoRe-SusHi (Momentum-Resummed SusHi) - Analytic resummation
[Harlander Mantler Wiesemann '14]

Comparison for a 2HDM performed [Bagnaschi Harlander Mantler Vicini Wiesemann '15]

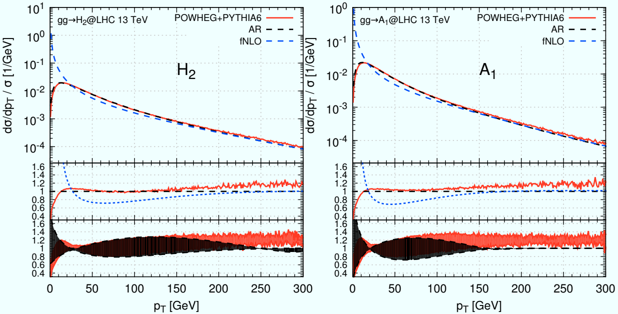
→ Extension of the approaches to the NMSSM [SL Mantler Wiesemann in prep.]

## Preliminary results:

Parameter point (see slide 9) with $\kappa = 0.5$

Resummation scale choice:

$H_2$: $Q_t = 59$ GeV,
$Q_b = 39$ GeV,
$Q_{tb} = 47$ GeV
$A_1$: $Q_t = 49$ GeV
$Q_b = 27$ GeV
$Q_{tb} = 35$ GeV



What will be part of SusHi 1.6.0?

In preparation: SusHi Bento - Beyond NNLO and the heavy-top limit
together with Robert Harlander and Hendrik Mantler

`Sushi 1.6.0` will incorporate w.r.t. gluon fusion

- ✓ contributions of dimension-$5$ operators to $gg\phi$ vertex.
- ✓ $\mu_{\mathrm{R}}$ uncertainty of gluon fusion in a single run at no CPU cost.
- ✓ $1/m_t$ corrections to incl. XS in heavy top-limit at different orders.
- ✓ soft expansion $(1-x)^n$ with $x = m_H^2/\hat{s}$ at different orders.
- ✓ $\mathrm{N}^3\mathrm{LO}$ contributions in soft expansion.

The latter three corrections solely affect the top contribution:

$$\sigma = \sigma_{\mathrm{NLO}} + \Delta_X \sigma^t \qquad \text{with} \qquad \Delta_X \sigma^t = \sigma_X^t - \sigma_{\mathrm{NLO}}^t$$

All three corrections come with full $\mu_R$ and $\mu_F$-dependence.

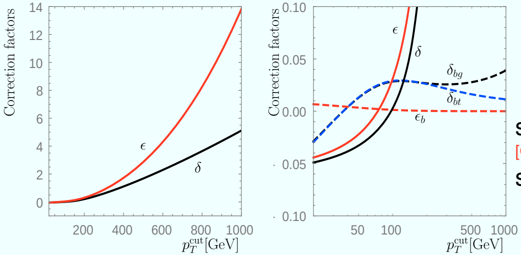
## Dimension-5 operators (check also recent HIGLU implementation)

$$\mathcal{L} = \mathcal{L}_{\text{theory}} + \sum_{i=1}^{N_1} \frac{\alpha_s}{12\pi v} c_5^{1i}\, H_{1i} G^a_{\mu\nu} G^{a,\mu\nu} + \sum_{i=1}^{N_2} \frac{\alpha_s}{8\pi v} c_5^{2i}\, H_{2i} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

```
Block DIM5 # MSSM example
   11    0.001       # c5h
   12    0.0004      # c5H
   21   -0.00006     # c5A
```

where $\mathcal{L}_{\text{theory}}$ describes any of the supported models.
Together with BLOCK FACTORS you can access $\kappa_t, \kappa_b$
and for example investigate the degeneracy between $\kappa_t$ and $c_5^H$ at NLO:
Define $\sigma(p_T^{\text{cut}}) = \int_{p_T > p_T^{\text{cut}}} dp_T d\sigma/dp_T$ and look at

$$\frac{\sigma(p_T^{\text{cut}})}{\sigma(p_T^{\text{cut}})(\kappa_t = 1, \kappa_b = 0, c_5^H = 0)} = (\kappa_t + c_5^H)^2 + \delta \kappa_t c_5^H + \epsilon (c_5^H)^2 + \delta_{bt}\kappa_b\kappa_t + \delta_{bg}\kappa_b c_5^H + \epsilon_b \kappa_b^2$$




similar to
[Grojean Salvioni Schlaffer Weiler '13]
see also [Ellis et al. '87]

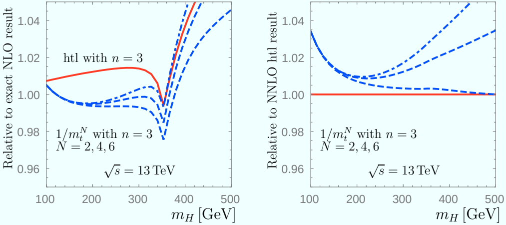
$1/m_t$ terms to incl. XS in the heavy top-limit (htl):
The heavy top-limit is known to be very precise for $m_H < 300\,$GeV (Diff. $1\%$).
Still include $1/m_t^N$ contributions at NLO ($N \leq 10$) and NNLO ($N \leq 6$) to htl.
[Marzani et al. '08, Harlander Mantler Marzani Ozeren '09, Harlander Ozeren '09, Pak Rogal Steinhauser '09]

```
Block GGHMT
  1   3   # factor out exact LO result at LO(=1)/NLO(=2)/etc.
  1   6   # expand through 1/mt^N at NLO
  2   6   # expand through 1/mt^N at NNLO
 10   1   # [0/1]: match to high energy limit at NLO  [n/y]
 20   1   # [0/1]: match to high energy limit at NNLO [n/y]
```

Partonic cross section $\hat{\sigma}$

$$\hat{\sigma}^t = \sigma_0^t \sum_{k=0}^{n} \frac{\mathcal{T}_{N_k}\hat{\sigma}^{t,(k)}}{\mathcal{T}_{N_k}\sigma_0^t} + \sum_{k\geq n+1} \mathcal{T}_{N_k}\hat{\sigma}^{t,(k)}\,.$$

with the LO cross section $\sigma_0^t$ and the expansion operator $\mathcal{T}_{N_k}$.
Convergence within $\hat{s} < 4m_t^2 \to$ matching to high energy limit $\hat{s} \to \infty$ or $x \to 0$




Preliminary plots!

For the matching for $1/m_t$ terms and a possible extension to $\mathrm{N^3LO}$ results SusHi now allows for a soft expansion around the threshold $x = m_H^2/\hat{s}$:
Available orders at $\mathrm{NLO}$ and $\mathrm{NNLO}$ are $(1-x)^N$ with $N \leq 16$.

```
Block GGHSOFT # parameters for soft expansion
 1  1  16  0   # NLO : [0/1=n/y] [order] sig(x)/x^[a]
 2  1  16  0   # NNLO: [0/1=n/y] [order] sig(x)/x^[a]
```

Expansion with operator $\mathcal{T}_N^x$ :  $x^a\,\mathcal{T}_N^x\left(\frac{\Delta\hat{\sigma}^t}{x^a}\right)$

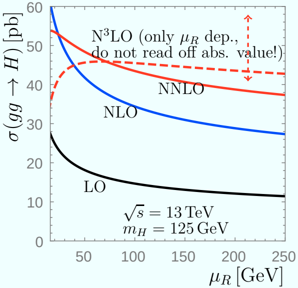
An order $x^a$ can be taken out.

Plan: Include the $\mathrm{N^3LO}$ results in soft expansion, see [Anastasiou et al. '15].

Analytic calculation of $\mu_R$ dependence (for OS parameters):

$$\sigma = \sum_{n\geq 0}\sum_{l=0}^{n}\left(\frac{\alpha_s(\mu_R)}{\pi}\right)^{n+2}\kappa_{nl}2^l\log^l(\mu_R/\mu_0)$$

$\rightarrow$ Obtain $\mu_R$ dependence analytically starting from central scale $\mu_0$.



Long term projects

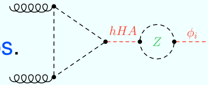
Unprepared fish!

Gluon fusion in case of CP-violation in the Higgs sector (first in the MSSM) together with Shruti Patel and Georg Weiglein

Early work: CP-violation in squark loops [Dedes Moretti '99]

Admixture of $h, H$ and $A$ described through $Z$ factors obtained by FeynHiggs

$$(\phi_1, \phi_2, \phi_3)^T = Z \cdot (h, H, A)^T$$



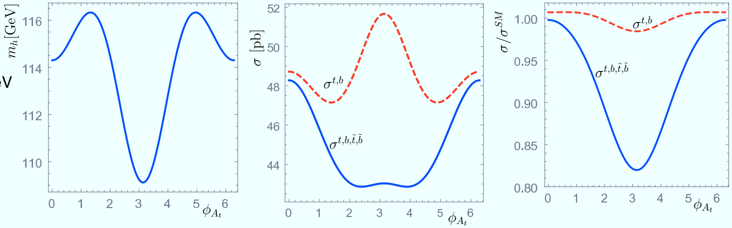

$\rightarrow$ CP-violation either enters through $Z$ factors or squark loops.

Form of the LO cross section:

$$\sigma_{\mathrm{LO}} \propto |Z_h A_h^{t,b,\tilde{t},\tilde{b}} + Z_H A_H^{t,b,\tilde{t},\tilde{b}} + Z_A A_A^{\tilde{t},\tilde{b}}|^2 + |Z_A A_A^{t,b}|^2$$


Preliminary results showing $\sigma = \sigma_{\mathrm{NNLO}}^{t,b} + \sigma_{\mathrm{LO}}^{t,b,\tilde{t},\tilde{b}} - \sigma_{\mathrm{LO}}^{t,b}$:

$\sqrt{s} = 13$ TeV
$m_{H^\pm} = 500$ GeV
$\tan\beta = 5$
$\mu = 1$ TeV
$m_g = 1.5$ TeV
$m_Q = 500$ GeV
$|A_t| = 1$ TeV



SusHi allows to calculate neutral Higgs boson cross sections through gluon fusion and bottom-quark annihilation meanwhile in the SM, MSSM, 2HDM and the NMSSM. Soon we want to include

- ✓ dimension-5 operators to the gluon vertex.
- ✓ analytic calculation of $\mu_R$ dependence of gluon fusion in a single run.
- ✓ $1/m_t$ terms to the heavy top limit and soft expansion in gluon fusion.
- ✓ $\mathrm{N}^3\mathrm{LO}$ results to gluon fusion in soft expansion.
- ✓ $c\bar{c} \to H$ production.

For differential distributions (in particular w.r.t. $p_T$) exist add-ons, namely

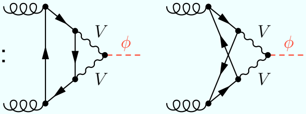
- ✓ (POWHEG-SusHi), MoRe-SusHi and aMCSusHi to resum logarithms.

On the long term we also study CP-violating effects.

Thank you for your attention!

✓ **Inclusion of elw. contributions by light quarks:** [Aglietti Bonciani Degrassi Vicini '04 '10]

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




Definition of SUSY electroweak correction factor:

$$\delta_{\rm EW}^{lq} = \frac{\alpha_{\rm EW}}{\pi} 2\text{Re}(\mathcal{A}^\phi \mathcal{A}^{\phi,\rm EW})/|\mathcal{A}^\phi|^2$$

$$\mathcal{A}^{\phi,\rm EW} = -\frac{3}{8}\frac{x_W}{s_W^2}\left[\frac{2}{c_W^2}\left(\tfrac{5}{4} - \tfrac{7}{3}s_W^2 + \tfrac{22}{9}s_W^4\right)A[x_Z] + 4A[x_W]\right] g_V^\phi$$

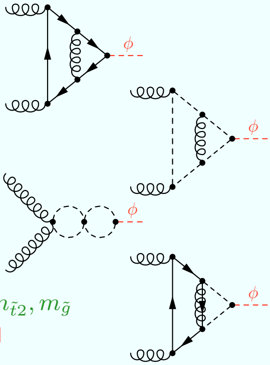
Complex mass scheme: $x_V = (m_V - i\frac{\Gamma_V}{2})^2/m_\phi^2$

Supersymmetry enters $g_V^\phi$ for CP-even Higgs bosons:

$$g_V^{Hi} = \mathcal{R}_{i1}^S \cos\beta + \mathcal{R}_{i2}^S \sin\beta$$

For moderate masses of SM-like Higgs results in similiar correction as SM electroweak correction factor [Actis Passarino Sturm Uccirati '08].

✓ **Inclusion of NLO squark contributions:**
(semi-analytically) known in the MSSM: gluon-quark, gluon-squark, gluino-squark-quark contributions
[Spira Djouadi Graudenz Zerwas '95; Harlander Kant '05; Anastasiou Beerli Bucherer Daleo Kunszt '06; Aglietti Bonciani Degrassi Vicini '06; Mühlleitner Spira '06; Bonciani Degrassi Vicini '07; Anastasiou Beerli Daleo '08; Mühlleitner Spira Rzehak '10]




Challenge for 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]
- ▷ 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]

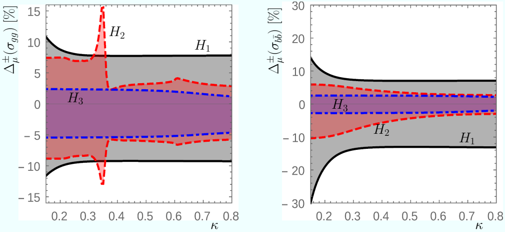
Results by [Degrassi Slavich '10 + Di Vita '11 '12] implemented in SusHi for the MSSM:
$\rightarrow$ Adopted to the new contributions in the NMSSM, e.g. amplitudes:

$$\mathcal{H}_d^R = \lambda_t \left[-m_t \mu s_{2\theta_t} F_t + \ldots\right] + \ldots, \ \mathcal{H}_u^R = \lambda_b \left[-m_b \mu s_{2\theta_b} F_b + \ldots\right] + \ldots$$

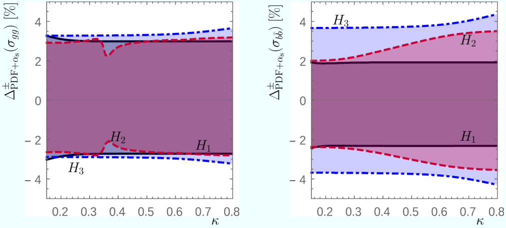
$$\mathcal{S}^R = \lambda_t \left[-\frac{1}{\sqrt{2}} m_t \lambda v_d s_{2\theta_t} F_t\right] + \lambda_b \left[-\frac{1}{\sqrt{2}} m_b \lambda v_u s_{2\theta_b} F_b\right]$$

Theory uncertainties: They are mostly equal to the MSSM case, see
[Bagnaschi Harlander SL Mantler Slavich Vicini '14]

▷Renormalization and factorization scale uncertainties:




▷PDF+$\alpha_s$ uncertainties (mostly function of $m_\phi$):




$\Delta^{\pm}$: Difference w.r.t. central/default choice

Other uncertainties:

▷from heavy SUSY masses expansion

▷from missing $\Delta_b$ contr.

▷from renormalization of $Y_b$