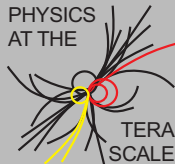


Stefan Liebler
DESY Hamburg

Higgs production with SusHi



Helmholtz Alliance
Terascale meeting 2015

Hamburg - Nov. 2015



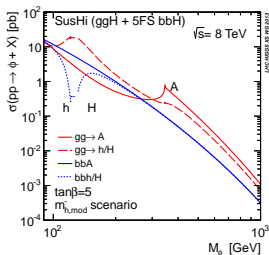
Universität Hamburg
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Particles, Strings,
and the Early Universe
Collaborative Research Center SFB 676

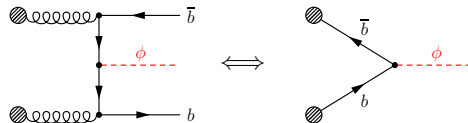


HELMHOLTZ
| **GEMEINSCHAFT**

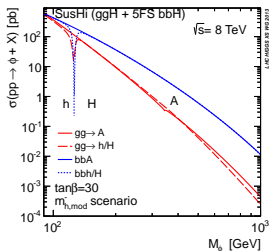
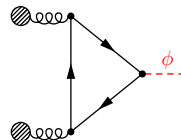
SusHi (SuperSymmetric Higgs) allows to calculate neutral Higgs boson production XS through **gluon fusion** and **bottom-quark annihilation** (5FS) in the SM, the 2HDM and the MSSM. [Harlander SL Mantler '12: <http://sushi.hepforge.org>]



Bottom-quark annihilation:



Gluon fusion:



extensively used in the LHCHSWG
 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 μ 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

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

and thus generate an effective μ -term:

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

The physical mass eigenstates are obtained through the rotations:

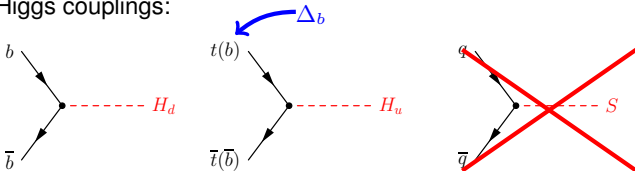
Mass eigenstates = **Mixing matrix** · **Gauge eigenstates**

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

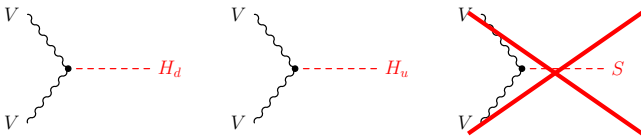
CP-odd sector: $(G^0, A_1, A_2)^T = \mathcal{R}^P \cdot \mathcal{R}^G \cdot (H_d^I, H_u^I, S^I)^T$

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

▷ Quark-Higgs couplings:

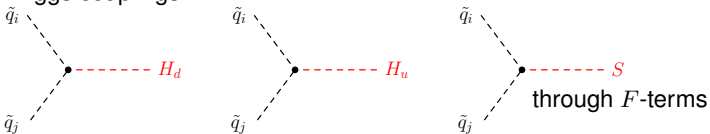


▷ Gauge boson ($V \in \{Z, W\}$)-Higgs couplings (for electroweak corrections):



→ Neglecting squarks no new contributions compared to the MSSM.

▷ Squark-Higgs couplings:



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 Δ_b corrections:

[Baglio et al. '13]

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

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

[Dittmaier Krämer Spira '03,

Dawson Jackson Reina Wackerath '04]

Similarly the 4FS cross section can be reweighted.

Implications for gluon fusion in SusHi:

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

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

- ✓ Inclusion of NLO third generation squark contributions (on top of Δ_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

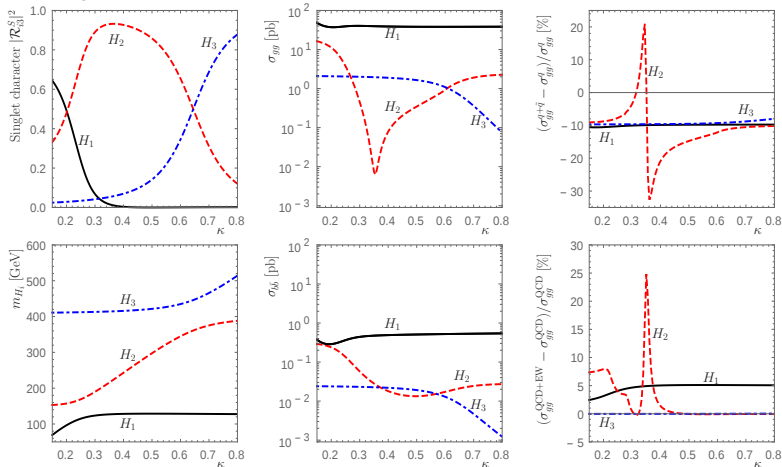
```

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.

Flashing results for the inclusive cross section (CP-even Higgs bosons):

Spectrum generator NMSSMCALC [Baglio et al., '13], Details: [1502.07972: SL '15]


 $\tan \beta = 2, A_\kappa = -20 \text{ GeV}, \lambda = 0.62, \mu = 200 \text{ GeV}, m_{H^\pm} = 400 \text{ GeV}, M_3 = 1.5 \text{ TeV}$
 $m_{\tilde{t}_1} = 544.7 \text{ GeV}, m_{\tilde{t}_2} = 941.2 \text{ GeV}, m_{\tilde{b}_1} = 749.4 \text{ GeV}, m_{\tilde{b}_2} = 757.4 \text{ GeV}$

SusHi allows to calculate η/y and p_T distributions at fixed order!
 However p_T distributions in $gg/b\bar{b} \rightarrow \phi$ diverge for $p_T \rightarrow 0$ 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]
 → 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 Degrossi 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])

▷ **aMC**SusHi - 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,

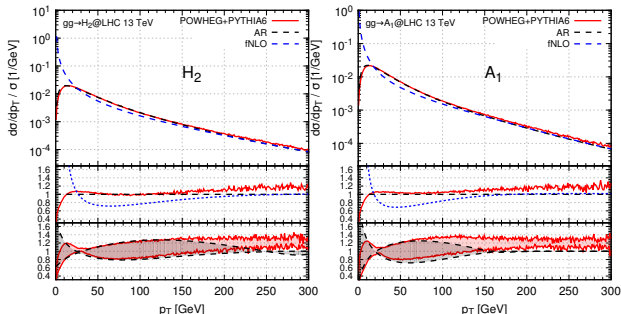
$Q_b = 39$ GeV,

$Q_{tb} = 47$ 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.
- ✓ μ_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.
- ✓ N³LO contributions in soft expansion.

The latter three corrections solely affect the top contribution:

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

All three corrections come with full μ_R and μ_F -dependence.

Dimension-5 operators (check also recent HIGLU implementation)

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

where $\mathcal{L}_{\text{theory}}$ describes any of the supported models.

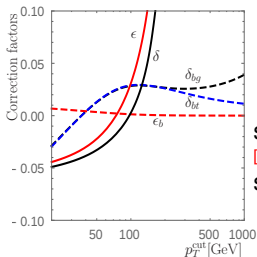
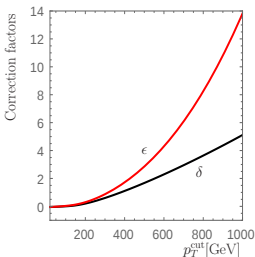
Together with BLOCK FACTORS you can access κ_t, κ_b

and for example investigate the degeneracy between κ_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

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

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



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

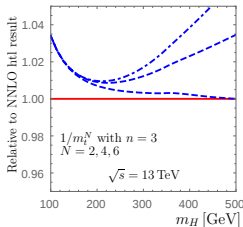
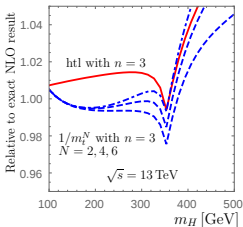
-1	3	# factor out exact LO result at LO(=1)/NLO(=2)/etc.
1	6	# expand through $1/m_t^N$ at NLO
2	6	# expand through $1/m_t^N$ at NNLO
10	1	# [0/1] match to high energy limit at NLO [n/y]
20	1	# [0/1] match to high energy limit at NNLO [n/y]

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 σ_0^t and the expansion operator \mathcal{T}_{N_k} .

Convergence within $\hat{s} < 4m_t^2 \rightarrow$ matching to high energy limit $\hat{s} \rightarrow \infty$ or $x \rightarrow 0$



Preliminary plots!

For the matching for $1/m_t$ terms and a possible extension to $N^3\text{LO}$ results SusHi now allows for a soft expansion around the threshold $x = m_H^2/\hat{s}$:
 Available orders at NLO and 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]
```

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

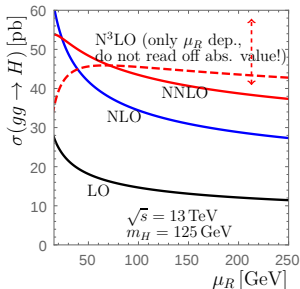
An order x^a can be taken out.

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

Analytic calculation of μ_R dependence
 (for OS parameters):

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

→ Obtain μ_R dependence analytically
 starting from central scale μ_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]

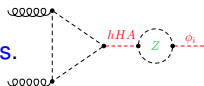
Admixture of h , H and A described through Z factors obtained by FeynHiggs

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

→ CP-violation either enters through **Z factors** or **squark loops**.

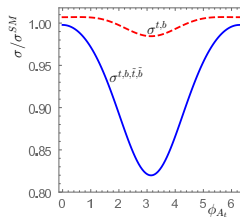
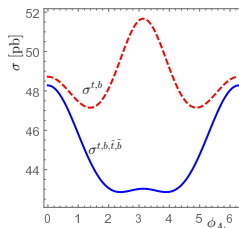
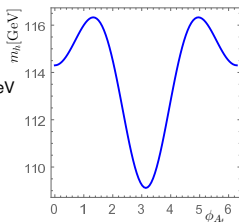
Form of the LO cross section:

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



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

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



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 μ_R dependence of gluon fusion in a single run.
- ✓ $1/m_t$ terms to the heavy top limit and soft expansion in gluon fusion.
- ✓ N³LO results to gluon fusion in soft expansion.
- ✓ $c\bar{c} \rightarrow H$ production.

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

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

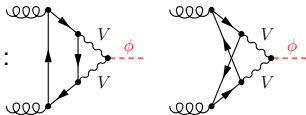
On the long term we also study CP-violating effects.

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**:

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

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

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

Supersymmetry enters g_V^ϕ 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 similar 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: $m_q, m_{\tilde{q}_1}, m_{\tilde{q}_2}, m_{\tilde{g}}, p^2 = m_\phi^2$

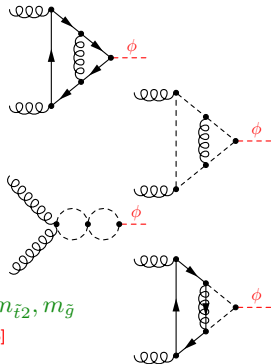
- ▷ Taylor expansion in small Higgs mass:

→ 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: $m_\phi, m_q \ll m_{\tilde{q}_1}, m_{\tilde{q}_2}, m_{\tilde{g}}$

→ 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:

→ Adopted to the new contributions in the NMSSM, e.g. amplitudes:

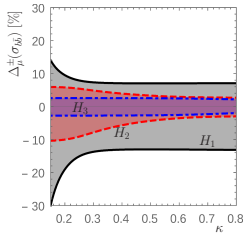
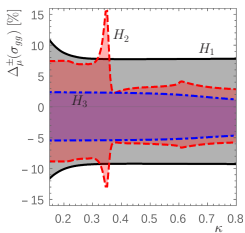
$$\mathcal{H}_d^R = \lambda_t [-m_t \mu s_{2\theta_t} F_t + \dots] + \dots, \quad \mathcal{H}_u^R = \lambda_b [-m_b \mu s_{2\theta_b} F_b + \dots] + \dots$$

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

Theory uncertainties: They are mostly equal to the MSSM case, see

[Bagnaschi Harlander SL Mantler Slavich Vicini '14]

▷ Renormalization and factorization scale uncertainties:



Δ^\pm : Difference w.r.t. central/default choice

Other uncertainties:

- ▷ from heavy SUSY masses expansion
- ▷ from missing Δ_b contr.
- ▷ from renormalization of Y_b

▷ PDF+ α_s uncertainties (mostly function of m_ϕ):

