Stefan Liebler
DESY Hamburg

Interference effects in heavy Higgs boson searches in a 2HDM + SusHi update

B9 and Higgs meeting - DESY

Hamburg - Apr. 2016

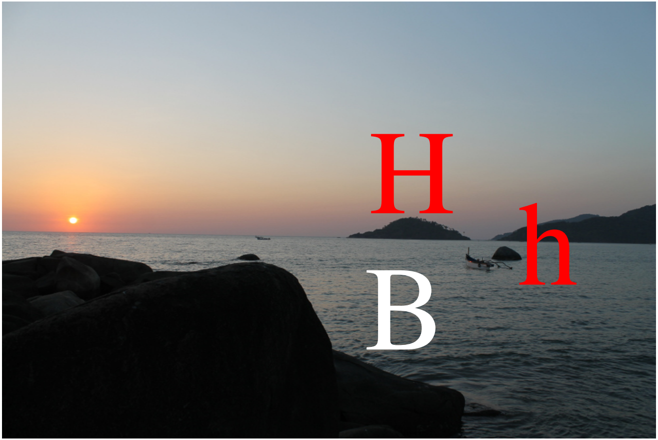
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

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

DESY

HELMHOLTZ | GEMEINSCHAFT

Interferences in heavy Higgs boson searches in a 2HDM



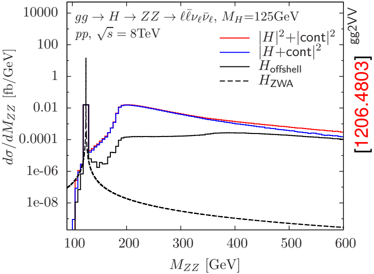
[Palolem 2016]

Interference of SM Higgs signal with the background in the off-shell region!

▷ First discussion: Off-shell contributions in $H \to VV^{(*)}$

[1206.4803; Kauer Passarino: Inadequacy of zero-width approximation for a light H boson signal]

[1305.2092, 1310.7011; Kauer: Interference effects for $H \to WW/ZZ \to l\bar{\nu}_l \bar{l}\nu_l$ searches in gluon fusion at the LHC]

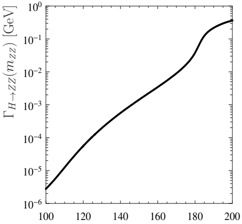


[1206.4803]

▷ Access to the Higgs width Γ_H

[1307.4935; Caola Melnikov]

$\to$ see talk in the last meeting!



[Prophecy4f]

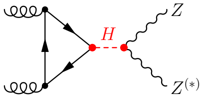
▷ Limitations of Higgs width constraint and opportunities:

[1310.1397, 1405.0285, 1405.1925, 1406.1757, 1406.6338, 1410.5440, 1410.5806]

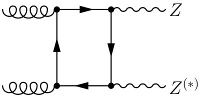
Relevant processes at the LHC: Have in mind $Z/Z^{(*)} \to l^+l^-/\nu\bar{\nu}$!

ggF:

S:



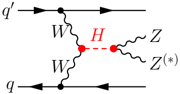
B:



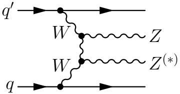
$+ \dots$

VBF:

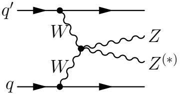
S:



B:



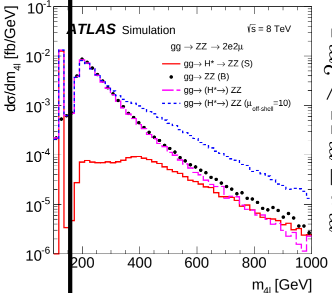
$+$



$+ \dots$

$HZZ^{(*)}: |S|^2$ | $H^{(*)}ZZ: |S|^2 + |B|^2 + 2\text{Re}(SB)$

$m_{4l} = m_{ZZ} < 2m_Z$

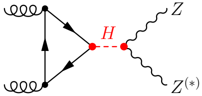


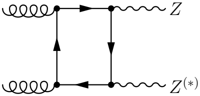
$m_{4l} = m_{ZZ} > 2m_Z$

[1503.01060]

Relevant processes at the LHC: Have in mind $Z/Z^{(*)} \to l^+l^-/\nu\bar{\nu}$!

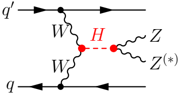
ggF:

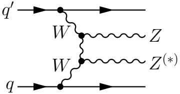
S: 

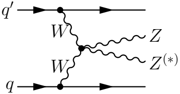
B: 

$+\dots$

VBF:

S: 

B: 

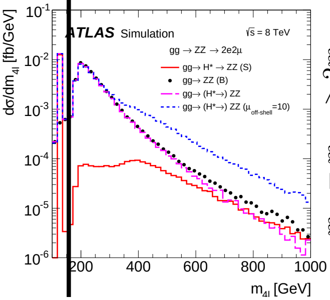
$+$ 

$+\dots$

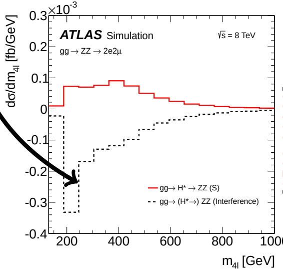
$HZZ^{(*)}$: $|S|^2$

$H^{(*)}ZZ$: $|S|^2 + |B|^2 + 2\mathrm{Re}(SB)$

$m_{4l} = m_{ZZ} < 2m_Z$



$m_{4l} = m_{ZZ} > 2m_Z$



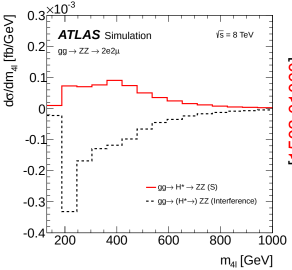
[1503.01060]

Theoretical issues:

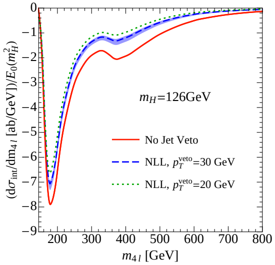
▷ Interference I is negative.

I restores unitarity in $W_L W_L \to W_L W_L$.

($\to$ Negative I affects sensitivity to Γ_H!)



[1503.01060]



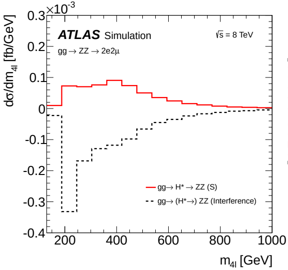
Interference dependent on jet vetos for $H \to WW$: [1405.5534; Moult Stewart]

Interference effects for ZZ+jet production: similar behaviour

[1409.1897; Campbell Ellis et al.: Interference effects for Higgs-mediated Z-pair plus jet production]

Theoretical issues:

▷ Interference I is negative.
I restores unitarity in $W_L W_L \to W_L W_L$.
($\to$ Negative I affects sensitivity to Γ_H!)



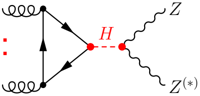
[1503.01060]

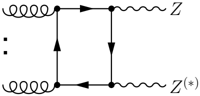
▷ Precision for gluon fusion:
S: known at N^{3}LO QCD
B: known at NLO QCD (since fall 2015)!
[1509.06734, 1511.08617; Melnikov et al.]

Previously K-factor

$$R_H^B = \frac{K(gg \to ZZ)}{K(gg \to H^{(*)} \to ZZ)}$$

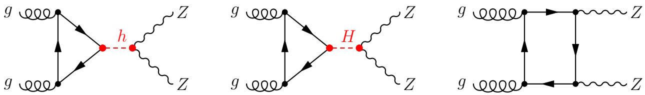
in ATLAS bound on Γ_H!
[1503.01060]

S:


B:


▷ Other issues:
Interference of $WW \to 2l2\nu$ and $ZZ \to 2l2\nu$ known (e.g. gg2VV [Kauer et al.])

How does this discussion interfere with the searches for heavy Higgs bosons in ZZ and WW channels?
Studies in the context of SM+Singlet: [1501.02139, 1502.04113, 1506.02257]
Answer in a Two-Higgs-Doublet Model (2HDM): [1512.07232; Greiner Liebler Weiglein]



$\rightarrow$ The heavy Higgs H (mass m_H) can interfere with h and background B.
▷ Higgs mixing angle α from (H_1^0, H_2^0) to (h, H) and $\tan\beta = v_2/v_1$ defines

$$g_V^h = \sin(\beta - \alpha) = s_{\beta-\alpha} \quad \text{and} \quad g_V^H = \cos(\beta - \alpha) = c_{\beta-\alpha} \quad .$$

$\rightarrow$ The combination $(g_V^h)^2 + (g_V^H)^2 = 1$ guarantees unitarization!
$\rightarrow$ If $g_V^h \rightarrow 1$, then $g_V^H \approx 0$. Expect weak signal with large interferences!

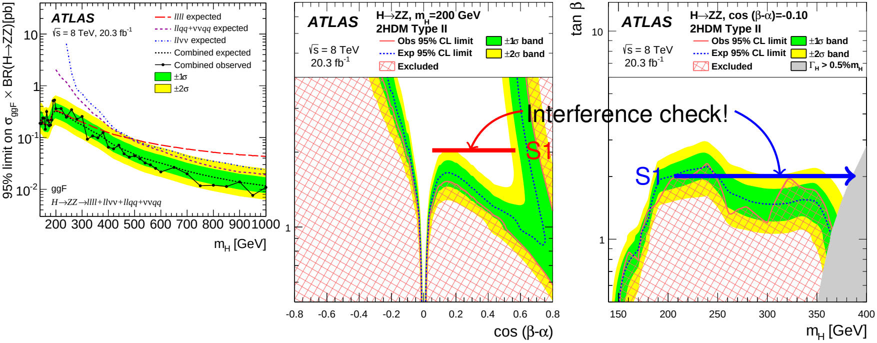
Experimental analyses in heavy Higgs boson searches $H \rightarrow WW/ZZ$:
▷ ATLAS ($H \rightarrow ZZ$ in Singlet+2HDM): No interference! [1507.05930]
▷ CMS ($H \rightarrow WW/ZZ$ in Singlet): Rescaled SM $H\cdot B$ interference! [1504.00936]

Is the assumption of no interference justified?

▷ In Run I it was indeed ok.

▷ In Run II consistent simulations in a 2HDM are on order.

Check of the 8 TeV ATLAS analysis (result of various channels): [1507.05930]



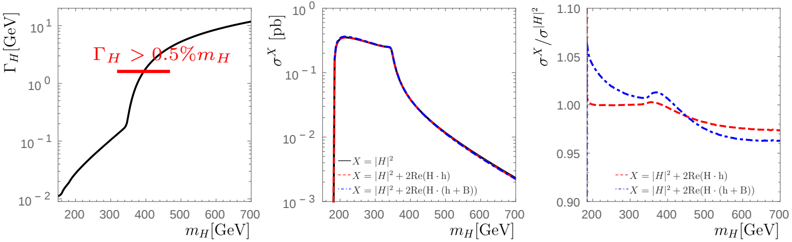
Implementation of $gg \to ZZ$ in a 2HDM in vh@nnlo [1210.5347, 1307.8122]

Implementation of $gg \to e^+e^-\mu^+\mu^-/e^+e^-\nu_l\bar{\nu}_l$ in a 2HDM with GoSam [1111.2034, 1404.7096]

with link to 2HDMC [0902.0851] for the calculation of the Higgs width Γ_H

Scenario S1: 2HDM type II with $\tan\beta = 2$,
$\sin(\beta-\alpha) = -0.995 \leftrightarrow \cos(\beta-\alpha) = -0.10$, $m_H = 200$ GeV, $\Gamma_H = 0.0277$ GeV
Relevant parameters for variation: m_H, $\cos(\beta-\alpha)$ and $\tan\beta$
Let's start with the previously mentioned m_H variation (for $\sqrt{s} = 8$ TeV):

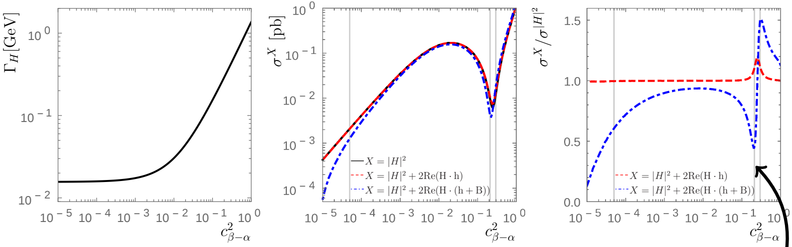
$$\sigma^X = \int_{m_H-15\text{GeV}}^{m_H+15\text{GeV}} dm_{ZZ} \frac{d\sigma^X(gg\to ZZ)}{dm_{ZZ}}$$



$\rightarrow$ Relevance of the interferences remains below 10%.
It's not so much the mass m_H and width Γ_H which determine the relevance of the interferences, i.e. masked region of ATLAS analysis is safe.

We continue with a variation of $\cos(\beta-\alpha)$ (for $\sqrt{s} = 8$ TeV):

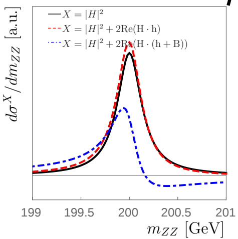
▷ Decay $H \to ZZ$ is determined by $g_V^H = \cos(\beta-\alpha) = c_{\beta-\alpha}$.



▷ Production $gg \to H$ involves g_t^H and g_b^H with

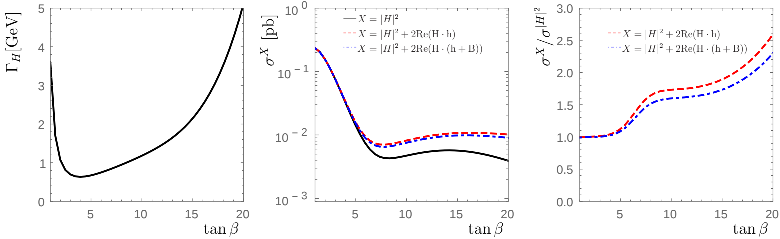
$$g_t^H = \frac{\sin\alpha}{\sin\beta} = -s_{\beta-\alpha}\frac{1}{\tan\beta} + c_{\beta-\alpha} \approx 0$$

at $\quad c^2_{\beta-\alpha} = 0.2,\ \tan\beta = 2\,.$



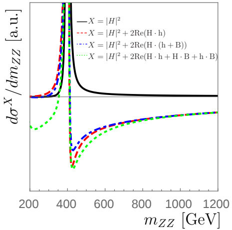
$\rightarrow$ Where couplings are small (in production or decay) interferences are large.

We are left with a variation of $\tan\beta$ (for $\sqrt{s} = 13$ TeV):
Scenario S2: 2HDM type II with $\tan\beta = 1$,
$\sin(\beta-\alpha) = 0.990$, $m_H = 400$ GeV, $\Gamma_H = 3.605$ GeV

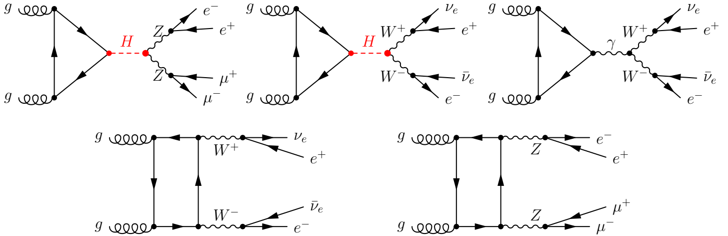


→ Pushing the bottom Yukawa g_b^H through $\tan\beta$ enhances interferences.

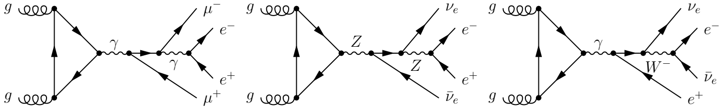
Not to forget at high invariant masses:
All interferences are of relevance:
$h \cdot B$ and $H \cdot B \leftrightarrow$ negative.
$h \cdot H$ can be large and have either sign!



We did our study also for the full process with `GoSam`:
Double-resonant W and Z contributions:

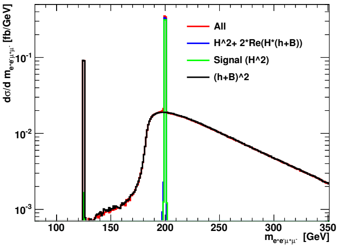


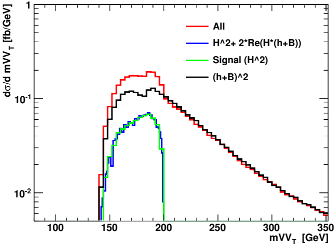
Single- and non-resonant W and Z contributions:



Implementation can be used for studies including all interferences, e.g. S1:

$gg \to e^+e^-\mu^+\mu^-$ $\qquad$ $gg \to e^+e^-\nu_l\bar{\nu}_l$





Employed cuts inspired by the ATLAS analysis:

$p_T^l > 10$ GeV, $|\eta_l| < 2.7$, $\Delta R^{ll'} > 0.1$, $m_{ll} > 5$ GeV, $E_T^{\mathrm{miss}} > 70$ GeV

Conclusion: For model interpretations all interferences should be included, even though this is tedious for the various channels (e.g. $gg \to l^+l^-q\bar{q}$).
Intermediate step: Correction factor for H with narrow width [1510.03450]
$\rightarrow$ This can be done at LO and multiplied to the NWA ($\sigma \cdot$ BR).

`SusHi Bento`: Beyond NNLO and the heavy top limit

[To be prepared!]

Disclaimer: `SusHi` [1212.3249; Harlander Liebler Mantler] calculates gluon fusion and bottom-quark annihilation cross sections for the Higgs bosons in the SM, 2HDM, MSSM and since `Sushi 1.5.0` the NMSSM. [1502.07972; Liebler]

`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 up to NNLO.
- ✓ soft expansion $(1-x)^n$ with $x = m_H^2/\hat{s}$ at different orders.
- ✓ $\mathrm{N}^3\mathrm{LO}$ contributions in soft expansion.

and cross sections from the annihilation of heavy quarks.

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 corrections come with full μ_R and μ_F-dependence.

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:

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

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 μ-term:

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

The physical mass eigenstates are obtained through the rotations:

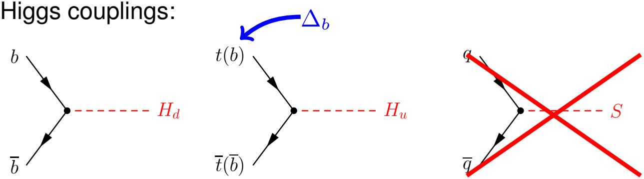
Mass eigenstates = Mixing matrix · Gauge eigenstates

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

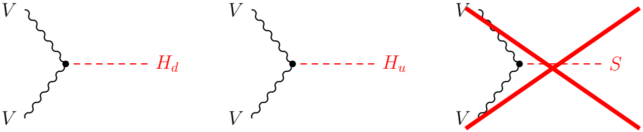
CP-odd sector: $(G^0, A_1, A_2)^T = \mathcal{R}^P \cdot \mathcal{R}^G \cdot (H_d^I, H_u^I, S^I)^T$

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

▷ Quark-Higgs couplings:

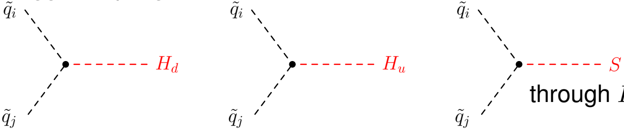


▷ Gauge boson ($V \in \{Z, W\}$)-Higgs couplings (for electroweak corrections):



→ 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 Δ_b corrections:
[Baglio et al. '13]

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

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

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 Δ_b)
- ✓ Inclusion of electroweak contributions by light quarks

Where does SusHi get the Higgs spectrum and the squark sector from?
$\rightarrow$ At first stage the user needs to provide simple SLHA-style input:$^{(*)}$

Specify model, Higgs $+\ldots$

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:

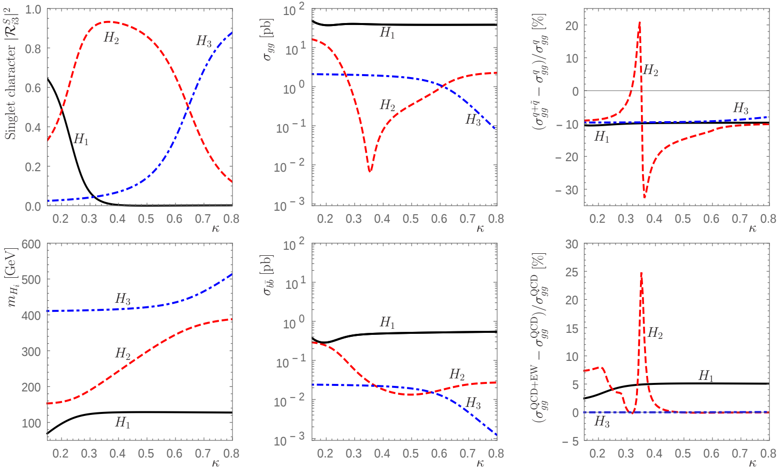
NMSSM since V 1.5.0

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, $\sqrt{s} = 8$ TeV

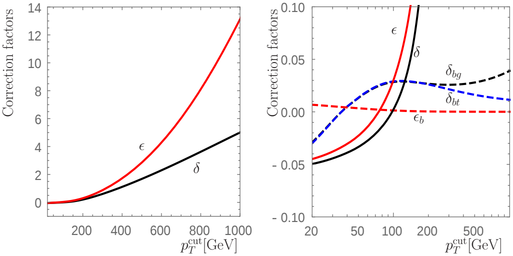
Dimension-5 operators

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

```
Block DIM5 # top example
   11     1.00      # c5h LO
  111     2.75      # c5h NLO
# c5h = 11 + as/pi * 111
```

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

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



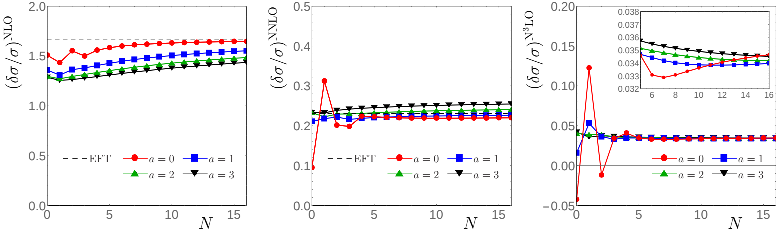
similar to [Grojean Salvioni Schlaffer Weiler '13]
see also [Ellis et al. '87]

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 NLO, NNLO and $\mathrm{N^3LO}$ 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]
  3   1   16   0    # N3LO: [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.
Includes the $\mathrm{N^3LO}$ results in soft expansion, see [Anastasiou et al. '13 '14 '15].
Convergence of the soft expansion as correction w.r.t. previous order:

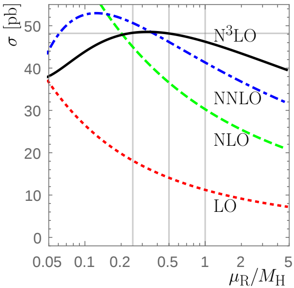


$\rightarrow$ This indicates a good convergence at higher orders.

Analytic calculation of μ_R dependence (for on-shell 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 μ_R dependence analytically starting from central scale μ_0.



Conclusion: Eagerly wait for the next release of

Not included in this talk: p_T Higgs distributions and the current efforts of CMS people to rescale predictions to the MSSM!