Heavy Higgs Searches in the MSSM with $\mathcal{CP}$ Violation

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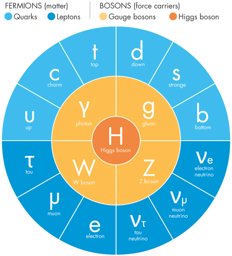
How does $\mathcal{CP}$ Violation affect the MSSM Higgs Sector?

1. Introduction and Motivation
2. MSSM Higgs sector with $\not{\mathcal{CP}}$
3. $\not{\mathcal{CP}}$ phase effects on Higgs production
4. Interference effects in MSSM Higgs searches
5. Summary

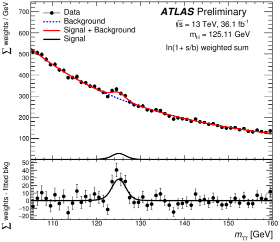
Introduction and Motivation

Minimal Supersymmetric Standard Model

Standard Model (SM)



A 125 GeV Higgs boson



Minimal Supersymmetric Standard Model

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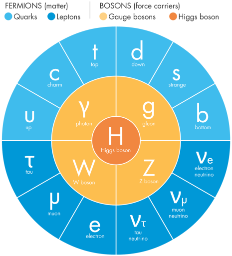
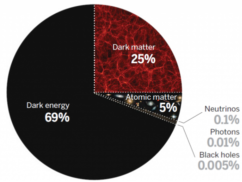


Baryon Asymmetry

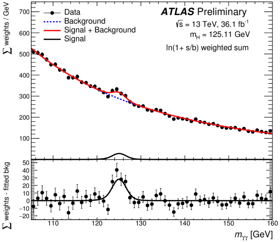
- $N_{\text{Matter}} > N_{\text{Antimatter}}$
- $\cancel{CP}$ needed to generate asymmetry
- Insufficient $\cancel{CP}$ in the SM to explain observed asymmetry

Dark Matter (DM)

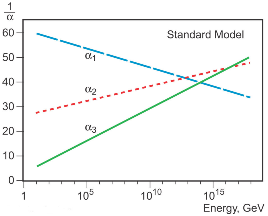


No DM candidate in the SM

A 125 GeV Higgs boson



Gauge coupling unification



Hierarchy Problem

$$\Delta M^2_{H^0} \propto \Lambda^2_{\text{NP}}$$

Minimal Supersymmetric Standard Model

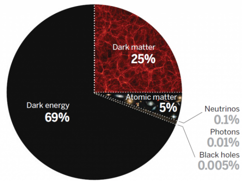
Minimal Supersymmetric SM

- $\mathcal{Q}\,|\text{Fermion}\rangle = |\text{Boson}\rangle$
  $\mathcal{Q}\,|\text{Boson}\rangle = |\text{Fermion}\rangle$
- Particle content= SM particles + *super*partners

Baryon Asymmetry

- $N_{\text{Matter}} > N_{\text{Antimatter}}$
- $\cancel{CP}$ needed to generate asymmetry
- Complex parameters in the MSSM provide additional $\cancel{CP}$

Dark Matter (DM)

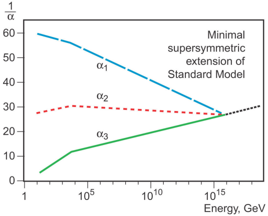


Lightest SUSY particle a DM candidate

A 125 GeV Higgs boson

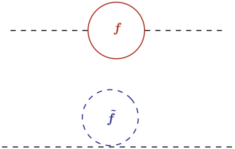
- MSSM predicts 3 neutral Higgs bosons
- Observed 125 GeV Higgs-state could belong to the MSSM

Gauge coupling unification



Hierarchy Problem

[E. Fuchs, Disputation '15]



$$\Delta M^2_{H^0} \propto \ln\left(\frac{m^2_{\tilde{f}}}{m^2_{f}}\right)$$

Searches for New Physics at the LHC

Two-pronged approach for new physics at the LHC

↙ ↘

Direct discovery
↪ Multiplicity

Indirect discovery
↪ Precision

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Theoretical predictions

- Needed to interpret discovery from production (σ) and decay (BR) of a particle
- Needed to extract information on possible new physics indirectly from data

What this means for the MSSM Higgs sector

- Need precise knowledge of σ and BR for additional Higgs states
- Precise prediction + measurement of 125 GeV Higgs properties (couplings, production rates, p_T spectrum..) can characterize underlying dynamics of particles and quantify potential deviations from the SM predictions

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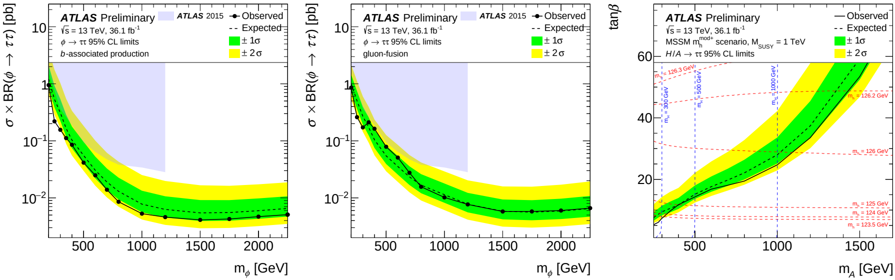
MSSM Heavy Higgs Searches

[E. Fuchs, talk at Higgs Days '17]

Interpretation of searches for additional scalars $\phi \in \{h, H, A\}$

- Standard Narrow Width Approximation (NWA): $\sigma_{\text{prod}} \times \text{BR}$
- Production $\{gg \to \phi, b\bar{b} \to \phi\} \times$ Decay $\{\phi \to \tau^+\tau^-, \mu^+\mu^-, b\bar{b}\}$



[ATLAS-CONF-2017-050, CMS-PAS-HIG-16-006]

Limitation: Neglects interference, especially important with $\mathcal{CP}$ **violation**

MSSM with $\mathcal{CP}$ Violation

Motivations

- BSM sources of $\not{\mathcal{CP}}$ needed to explain baryon asymmetry of the universe
- A $\mathcal{CP}$-violating Higgs sector gives rise to richer phenomenology
- **No scenario with $\not{\mathcal{CP}}$ in the Higgs sector considered so far in the context of the LHC-HXSWG**

What we need

- State of the art predictions of neutral Higgs masses, mixing, σ and BR taking into account $\not{\mathcal{CP}}$
- Framework for studying $\not{\mathcal{CP}}$ interference effects between neutral Higgs bosons
- Implementation into tools

Goal

Re-interpretation of experimental limits on heavy Higgs boson searches in light of $\not{\mathcal{CP}}$

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Higgs Sector of the MSSM with $\cancel{\mathcal{CP}}$

MSSM: Higgs sector at the lowest order

Two Higgs doublets

$$\mathcal{H}_1 = \begin{pmatrix} \boldsymbol{v_1} + \frac{1}{\sqrt{2}}(\boldsymbol{\phi_1^0} + i\boldsymbol{\chi_1^0}) \\ \boldsymbol{\phi_1^-} \end{pmatrix}, \quad \mathcal{H}_2 = e^{i\boldsymbol{\xi}} \begin{pmatrix} \boldsymbol{\phi_2^+} \\ \boldsymbol{v_2} + \frac{1}{\sqrt{2}}(\boldsymbol{\phi_2^0} + i\boldsymbol{\chi_2^0}) \end{pmatrix}$$

Electroweak Symmetry Breaking ⟶ 5 physical states

$$\boxed{\mathcal{CP}\text{-even } h, H,\ \mathcal{CP}\text{-odd } A,\ \text{Charged } H^{\pm}}$$

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Electroweak Symmetry Breaking ⟶ 5 physical states

$\mathcal{CP}$-even h, H, $\mathcal{CP}$-odd A, Charged $H^\pm$

Higgs Potential

$$\begin{aligned} V_H = & (|\mu|^2 + m^2_{\mathcal{H}_1})\mathcal{H}_1^\dagger\mathcal{H}_1 + (|\mu|^2 + m^2_{\mathcal{H}_2})\mathcal{H}_2^\dagger\mathcal{H}_2 \\ & + \frac{g_1^2 + g_2^2}{8}(\mathcal{H}_1^\dagger\mathcal{H}_1 - \mathcal{H}_2^\dagger\mathcal{H}_2)^2 - |m_{12}^2|e^{i\zeta}(\mathcal{H}_1\mathcal{H}_2 + h.c.) \end{aligned}$$

- $\mathcal{CP}$-violating ($\cancel{\mathcal{CP}}$) phase ξ vanishes at V_H^{min}, ζ rotated away

MSSM Higgs sector is $\mathcal{CP}$-conserving at lowest order

Complex parameters in the MSSM

105 new MSSM parameters + 19 from the SM

- Result from our ignorance of a SUSY-breaking mechanism
- Appear as masses, mixing angles and $\mathcal{CP}$-violating phases
- Minimal flavour violation $\Rightarrow$ 41 independent parameters

12 $\not{\mathcal{CP}}$ phases in the MSSM

- Trilinear couplings $A_f \to A_f = |A_f| e^{i\phi_{A_f}}$
- Higgsino mass parameter $\mu \to \mu = |\mu| e^{i\phi_\mu}$
- Gaugino mass parameters $\{M_1, M_3\} \to M_i = |M_i| e^{i\phi_{M_i}}$

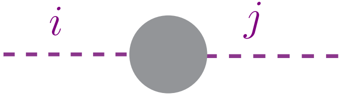
Experimental constraints from EDMs

- Electron, muon and neutron EDMs most restrictive for $\not{\mathcal{CP}}$ phases

  [Barger, Falk, Han, Jiang, Li, Plehn '01], [Ellis, Lee, Pilaftsis '09], [Li, Profumo, Ramsey-Musolf '10], [Arbey, Ellis, Godbole, Mahmoudi '14], [King, Mühlleitner, Nevzorov, Walz '15]

$\not{\mathcal{CP}}$ in Higgs sector

- $\not{\mathcal{CP}}$ in Higgs sector induced via loop corrections



$\boldsymbol{i, j \in \{h, H, A\}}$

- Dominant phases in the Higgs sector: $\boldsymbol{\phi_{A_{t,b}}, \phi_{M_3}, \phi_\mu}$

- Complex parameters induce $\not{\mathcal{CP}}$ 3×3 mixing beyond tree level

> Tree-level mass eigenstates $\boldsymbol{\{h, H, A\}}$ mix into loop-corrected mass eigenstates $\boldsymbol{\{h_1, h_2, h_3\}}$ with $\boldsymbol{M_{h_1} \leq M_{h_2} \leq M_{h_3}}$

- Input parameters: $t_\beta = \frac{v_2}{v_1}$ & $M_{H^\pm}$

Higgs mixing in the MSSM

How do we characterize mixing of external Higgs bosons?

- Admixed $h_a, a \in \{1,2,3\}$ need correct on-shell properties: mixing matrix $\hat{\mathbf{Z}}_{aj}$
  [Chankowski, Pokorski, Rosiek '93], [Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein, Williams '07, '11]...

- **$\hat{\mathbf{Z}}$ matrix elements** $\hat{\mathbf{Z}}_{aj} = \sqrt{\hat{Z}_a}\hat{Z}_{aj}$; $j \in \{h, H, A\}$

$$\swarrow \qquad \searrow$$

external wave function
normalisation factor

on-shell
transition ratio

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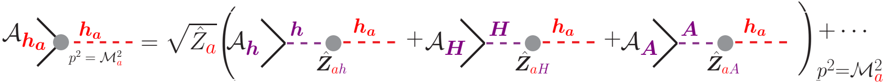
  external wave function normalisation factor

  on-shell transition ratio

- Amplitude for external Higgs h_a in terms of $\hat{\mathbf{Z}}$ factors:

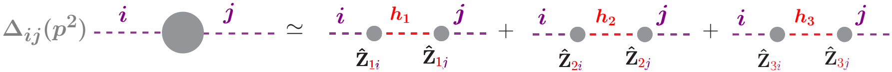


[E. Fuchs, PhD thesis; Fuchs, Weiglein '16, '17]

Higgs mixing in the MSSM

How do we characterize mixing of internal Higgs bosons?

- Consider internal Higgs bosons $\boldsymbol{h_a, a \in \{1,2,3\}}$ exchanged b/w two vertices
- Full mixing propagator $\Delta_{ij}(p^2)$, $\boldsymbol{i, j \in \{h, H, A\}}$ for the process approximated by $\hat{\mathbf{Z}}$ factors [E. Fuchs, PhD thesis; Fuchs, Weiglein '16, '17]



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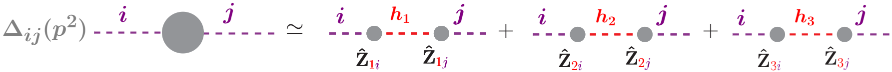


$$\hookrightarrow \boxed{\Delta_{ij}(p^2) \simeq \sum_{a\in\{1,2,3\}} \hat{\mathbf{Z}}_{ai}\,\Delta_a^{\mathrm{BW}}(p^2)\,\hat{\mathbf{Z}}_{aj}}$$

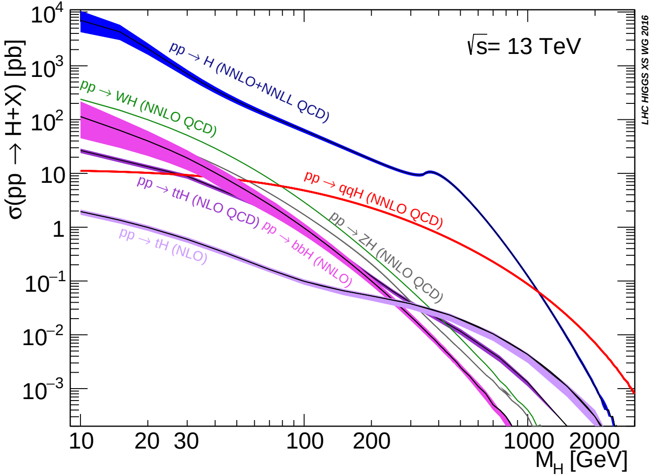
[Fuchs, Weiglein '17]

with the Breit-Wigner (BW) propagator with complex pole $\mathcal{M}_{h_a}^2$

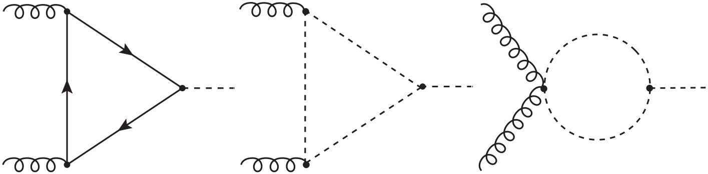
$$\Delta_a^{\mathrm{BW}}(p^2) = \frac{i}{p^2 - \mathcal{M}_{h_a}^2}$$

$\not{\mathcal{CP}}$ phases in Higgs production

Gluon Fusion in the SM



Gluon Fusion in the MSSM



- Gluon-Gluon-Higgs coupling mediated by loops of coloured (s)fermions
- Primary contribution from (s)top and (s)bottom (s)quarks.
- In the $\mathcal{CP}$-conserving MSSM, XS for gluon fusion Higgs production known at the N^{3}LO for top-quark contribution, and analytically/various expansions at NLO for other contributions
- The amplitudes for $\mathcal{CP}$-even (h and H) and $\mathcal{CP}$-odd (A) Higgs bosons are non-interfering

$\not{CP}$ phases in gluon fusion in the MSSM

$\not{CP}$ phases from **squark loops**, **Δ_b corrections** to bottom Yukawa coupling or **$\hat{\mathrm{Z}}$ factors**

$\not{\mathcal{CP}}$ phases in gluon fusion in the MSSM

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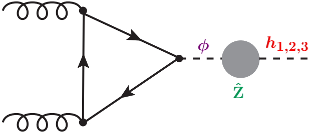
The $\hat{\mathrm{Z}}$ mixing matrix



$$\begin{pmatrix} \mathcal{A}_{h_1} \\ \mathcal{A}_{h_2} \\ \mathcal{A}_{h_3} \end{pmatrix} = \hat{\mathbf{Z}} \cdot \begin{pmatrix} \mathcal{A}_{h} \\ \mathcal{A}_{H} \\ \mathcal{A}_{A} \end{pmatrix}$$

$\not{C}\not{P}$ phases in gluon fusion in the MSSM

$\not{C}\not{P}$ phases from **squark loops**, **Δ_b corrections** to bottom Yukawa coupling or **$\hat{\mathrm{Z}}$ factors**

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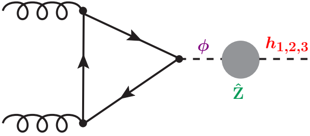

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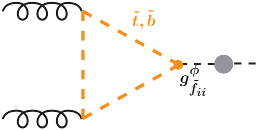
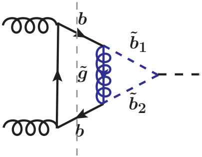
Higgs-squark vertex



- Higgs-squark couplings contain $\not{C}\not{P}$ phases
- Non-zero $g^{A}_{\tilde{f}ii}$ coupling

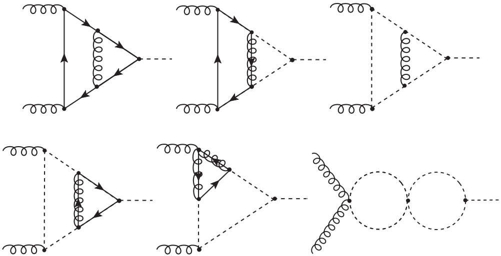
Complex Yukawa couplings

- Complex Δ_b corrections incorporated in effective bottom Yukawa coupling
- Non-zero terms $\propto (g^{\phi}_{b_L} - g^{\phi}_{b_R})$



Higher order corrections

Higher order contributions can arise from virtual loops

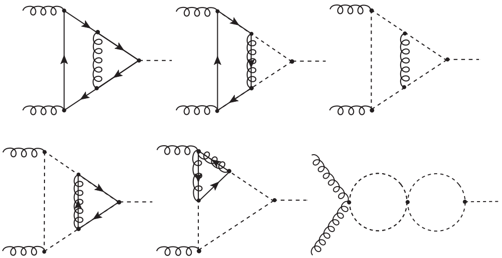


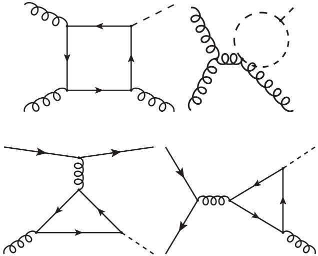
$$\sigma^{\mathrm{e/o}}_{\textsf{NLO}}(pp \to h_a + X) = \sigma_0^{h_a,\mathrm{e/o}} \tau_{h_a} \mathcal{L}^{gg}(\tau_{h_a}) \left[1 + C^{\mathrm{e/o}} \frac{\alpha_s}{\pi}\right]$$

- Known for the MSSM with real parameters analytically/in various expansions
- Need to be adapted and modified for the case of complex parameters

Higher order corrections

Higher order contributions can arise from virtual loops and real radiation





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Implementation to tools: SusHiMi and FeynHiggs

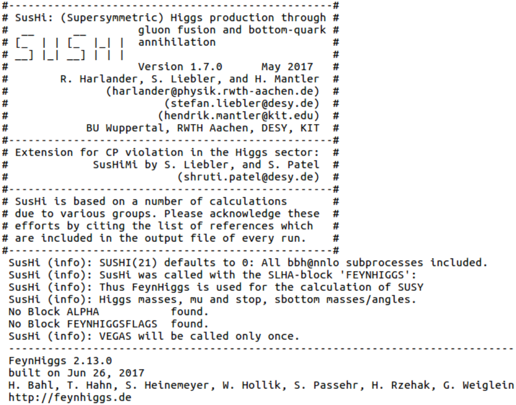
`SusHi`: neutral Higgs boson production XS through gluon fusion, $b\bar{b}$ (5FS) in SM, 2HDM, (N)MSSM. [Harlander Liebler Mantler '12, '16],[Liebler '15],[Liebler, SP, Weiglein '16]: sushi.hepforge.org

`FeynHiggs`: masses, couplings, $\hat{\mathbf{Z}}$ factors of the Higgs sector in MSSM.

[Hahn, Heinemeyer, Hollik, Rzehak, Weiglein]: feynhiggs.de

- **Implementation of gluon fusion and bottom quark annihilation XS in `SusHiMi`**

[Full details of the calculation in 1611.09308]

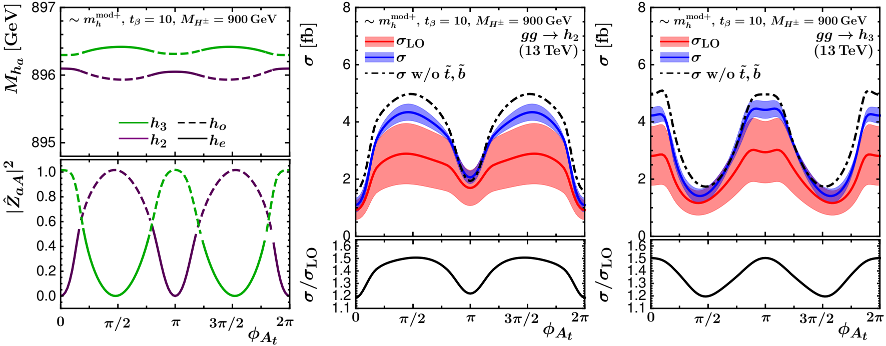


```
#--------------------------------------------------#
# SusHi: (Supersymmetric) Higgs production through #
#   __      __       gluon fusion and bottom-quark #
# [_  | | [_  |_| |  annihilation                  #
# __] |_| __] | | |                                #
#                    Version 1.7.0      May 2017   #
#        R. Harlander, S. Liebler, and H. Mantler  #
#               (harlander@physik.rwth-aachen.de)  #
#                        (stefan.liebler@desy.de)  #
#                       (hendrik.mantler@kit.edu)  #
#            BU Wuppertal, RWTH Aachen, DESY, KIT  #
#--------------------------------------------------#
# Extension for CP violation in the Higgs sector:  #
#             SusHiMi by S. Liebler, and S. Patel  #
#                          (shruti.patel@desy.de)  #
#--------------------------------------------------#
# SusHi is based on a number of calculations       #
# due to various groups. Please acknowledge these  #
# efforts by citing the list of references which   #
# are included in the output file of every run.    #
#--------------------------------------------------#
 SusHi (info): SUSHI(21) defaults to 0: All bbh@nnlo subprocesses included.
 SusHi (info): SusHi was called with the SLHA-block 'FEYNHIGGS':
 SusHi (info): Thus FeynHiggs is used for the calculation of SUSY
 SusHi (info): Higgs masses, mu and stop, sbottom masses/angles.
 No Block ALPHA           found.
 No Block FEYNHIGGSFLAGS  found.
 SusHi (info): VEGAS will be called only once.
 ------------------------------------------------------------------------------
 FeynHiggs 2.13.0
 built on Jun 26, 2017
 H. Bahl, T. Hahn, S. Heinemeyer, W. Hollik, S. Passehr, H. Rzehak, G. Weiglein
 http://feynhiggs.de
```

Gluon Fusion: Admixture of Higgs bosons

[Liebler, SP, Weiglein '16]

Variation of $\sigma(gg \to h_2, h_3)$ with ϕ_{A_t} in the $\sim m_h^{\mathrm{mod}+}$ scenario with $t_\beta = 10$



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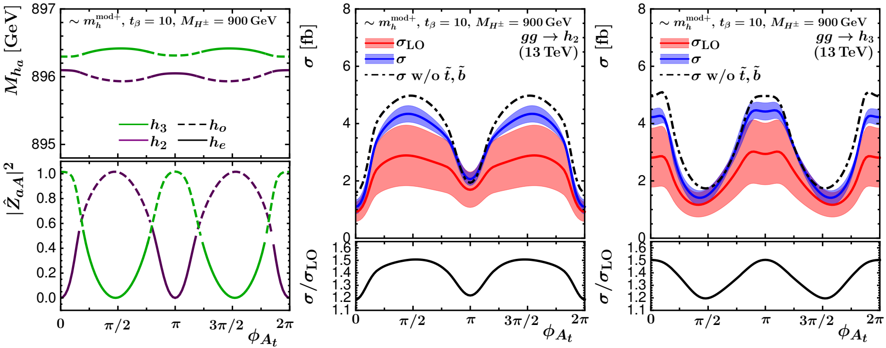

- Nearly mass degenerate and $\mathcal{CP}$-admixed h_2 and h_3
- Might not be possible to resolve h_2 and h_3 as separate signals
- Expt. measured quantity: total $\sigma \times$ BR with interference contributions

Interference effects in MSSM Higgs searches

Mixing and Overlapping Resonances

[E. Fuchs, talk at Higgs Days '17]

In general: $\Delta M \leq \Gamma_1 + \Gamma_2 \implies$ Overlapping resonances

Interfering Higgses in the MSSM

$\mathbb{R}$eal MSSM	$\boldsymbol{h, H}$	$M_h \simeq M_H$ at high $\tan\beta$, low M_A
$\mathbb{C}$omplex MSSM	$\boldsymbol{h_2}, \boldsymbol{h_3}$	$M_{h_2} \simeq M_{h_3}$ in the decoupling limit

If $\mathbb{C}$: incoherent sum $\sigma(H) + \sigma(A)$ insufficient in heavy Higgs searches

→ interference effects important

Standard NWA: Interference terms **neglected**

Interference in Higgs production and decay

[Fuchs, Weiglein '17]

- Amplitude of Higgs h_a exchanged in production and decay $I \to h_a \to F$

$$\mathcal{A}_{h_a} \equiv \hat{\Gamma}^I_{h_a} \Delta^{\mathrm{BW}}_a(p^2) \hat{\Gamma}^F_{h_a} = \sum_{i,j\in\{h,H,A\}} \hat{\Gamma}^I_i \hat{\mathbf{Z}}_{ai} \Delta^{\mathrm{BW}}_a(p^2) \hat{\mathbf{Z}}_{aj} \hat{\Gamma}^F_j$$

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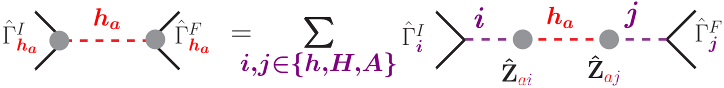
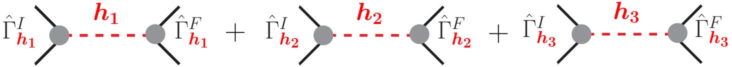


$$\mathcal{A}_{h_a} \equiv \hat{\Gamma}^I_{h_a}\Delta^{\mathsf{BW}}_a(p^2)\hat{\Gamma}^F_{h_a} = \sum_{i,j\in\{h,H,A\}} \hat{\Gamma^I_i}\hat{\mathbf{Z}}_{ai}\Delta^{\mathsf{BW}}_a(p^2)\hat{\mathbf{Z}}_{aj}\hat{\Gamma^F_j}$$

- Total amplitude $\mathcal{A}$ for $I \to h_1, h_2, h_3 \to F$:



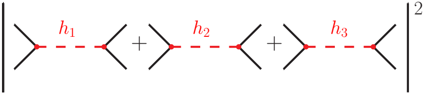
- Total $\sigma(I \to F) \propto |\mathcal{A}|^2$

Coherent and incoherent squared amplitudes

[Fuchs, Weiglein '17]

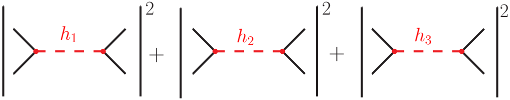
- $\cancel{\mathcal{CP}}$ phases $\Rightarrow \sigma(I \to h_1, h_2, h_3 \to F)$ contains interference terms $\mathcal{A}_{h_a}\mathcal{A}^*_{h_b} \neq 0$
- **Coherent sum** contains interference terms

$|\mathcal{A}|^2_{\text{coh}} =$



- **Incoherent sum** does not

$|\mathcal{A}|^2_{\text{incoh}} =$



- **Interference contribution** to $\sigma(I \to h_1, h_2, h_3 \to F)$

$$|\mathcal{A}|^2_{\text{int}} = |\mathcal{A}|^2_{\text{coh}} - |\mathcal{A}|^2_{\text{incoh}} = \sum_{a<b} 2\,\text{Re}[\mathcal{A}_{h_a}\mathcal{A}^*_{h_b}]$$

Theoretical predictions with interference factor

- Relative **interference term** for $I \rightarrow h_1, h_2, h_3 \rightarrow F$

$$\boldsymbol{\eta}^{\boldsymbol{IF}} = \frac{\sigma_{\text{int}}^{IF}}{\sigma_{\text{incoh}}^{IF}}$$

- Split into individual h_a interference contributions

$$\boldsymbol{\eta}_{\boldsymbol{a}}^{\boldsymbol{IF}} = \frac{\sigma_{\text{int}\,ab}^{IF}}{\sigma_{h_a}^{IF}+\sigma_{h_b}^{IF}} + \frac{\sigma_{\text{int}\,ac}^{IF}}{\sigma_{h_a}^{IF}+\sigma_{h_c}^{IF}}$$

Theoretical predictions with interference factor

- Relative **interference term** for $I \to h_1, h_2, h_3 \to F$

$$\eta^{IF} = \frac{\sigma^{IF}_{\text{int}}}{\sigma^{IF}_{\text{incoh}}}$$

- Split into individual h_a interference contributions

$$\eta^{IF}_a = \frac{\sigma^{IF}_{\text{int}\,ab}}{\sigma^{IF}_{h_a} + \sigma^{IF}_{h_b}} + \frac{\sigma^{IF}_{\text{int}\,ac}}{\sigma^{IF}_{h_a} + \sigma^{IF}_{h_c}}$$

Framework: modified $\sigma\times$ BR → Generalised Narrow Width Approximation

- Factorisation of production and decay of h_a rescaled by η^{IF}_a

$$\sigma(pp \to I \to h_{1,2,3} \to F) \simeq \sum_{a=1}^{3} \sigma(pp \to I \to h_a) \cdot (1 + \eta^{IF}_a) \cdot \mathrm{BR}(h_a \to F)$$

[Fuchs, Weiglein '17]

- η^{IF}_a calculation in `SusHiMi` for $I \in \{gg, b\bar{b}\}$ and $F \in \{\tau^+\tau^-, b\bar{b}, t\bar{t}\}$

[SP, Fuchs, Liebler, Weiglein '18, PhD thesis-SP '17]

- $\sigma(gg, b\bar{b})$ and η factors from `SusHiMi`, BRs from `FeynHiggs-2.14.3`

  $b\bar{b}$ XS reweighted from: [Bonvini, Papanastasiou,Tackmann '15,'16], [Forte, Napoletano,Ubiali '15,'16]

Benchmark Scenario: $M_{h_1}^{125}$(CPV)

[Bahl, Fuchs, Hahn, Heinemeyer, Liebler, SP, Slavich, Stefaniak, Wagner, Weiglein: 1808.07542]

Motivation

$\not{CP}$ scenarios not analysed by CMS and ATLAS so far

Defining the scenario → decoupling limit

- SM-like h_1 with $M_{h_1} \sim 125 \pm 3$ GeV in $\{M_{H^\pm}, \tan\beta\}$ plane
- $M_{h_2} \simeq M_{h_3}$ with strong $H - A$ admixture $\Rightarrow$ interference b/w h_2, h_3
- EDMs from $\not{CP}$ phases within expt. limits
- **Large interference universal feature of such scenarios**

$M_{h_1}^{125}$(CPV) parameter points

$$M_{\text{SUSY}} = 2\,\text{TeV}\,, \quad \mu = 1.65\,\text{TeV}\,,$$

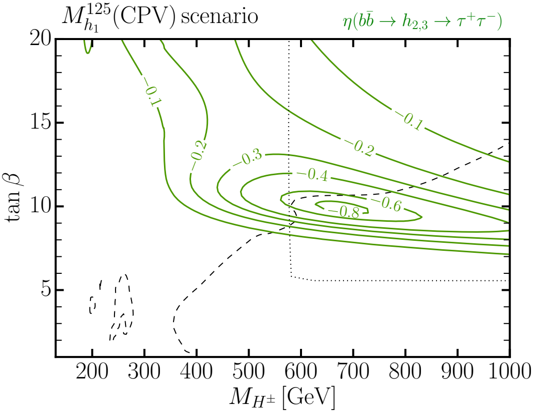
$$M_1 = M_2 = 1\,\text{TeV}, \quad M_3 = 2.5\,\text{TeV}\,,$$

$$|A_t| = \mu\cot\beta + 2.8\,\text{TeV}\,, \boldsymbol{\phi_{A_t} = \frac{2\pi}{15}}, \quad A_b = A_\tau = |A_t|\,,$$

$$M_{(Q,U,D,L,E)_3} = M_{(Q,U,D)_{1,2}} = M_{\text{SUSY}}$$

Interference factor in $M_{h_1}^{125}$(CPV) scenario

Plot of relative interference factor $\eta^{b\bar{b},\tau\tau}$ for $b\bar{b} \to h_2, h_3 \to \tau^+\tau^-$
($\eta^{gg,\tau\tau}$ contour similar in size and pattern)

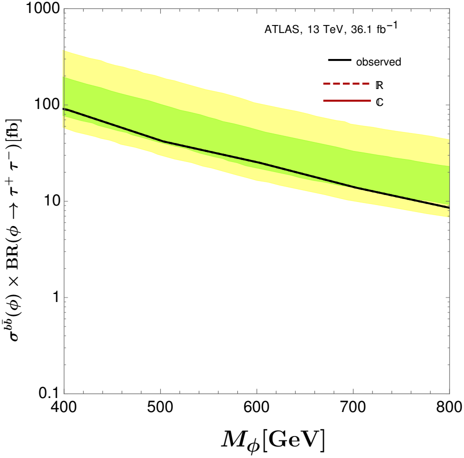


Large, destructive interference: $\eta_{\text{min}}^{b\bar{b},\tau\tau} \simeq -96\%$

[Bahl, Fuchs, Hahn, Heinemeyer, Liebler, SP, Slavich, Stefaniak, Wagner, Weiglein: 1808.07542]

Modified predictions with coherent $\sigma\times$ BR

Comparison of $\sigma\times$ BR containing $\eta^{b\bar{b},\tau\tau}$ with experimental limits



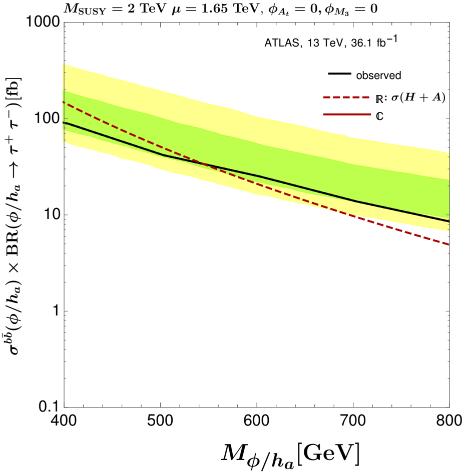
95 % CL upper limits on $\sigma\times$ BR for $b\bar{b}\to H/A\to\tau^+\tau^-$ by ATLAS at 13 TeV

[ATLAS-CONF-2016-085]

$\mathcal{CP}$-violation not taken into account in experimental analyses so far

Modified predictions with coherent $\sigma\times$ BR

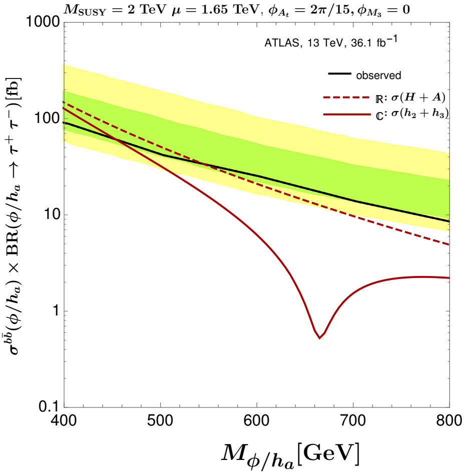
Comparison of $\sigma\times$ BR containing $\eta^{b\bar{b},\tau\tau}$ with experimental limits



Real MSSM:
$\sigma\times$ BR $(H+A)$ (**no** interference)
at $\tan\beta = 10$

Modified predictions with coherent $\sigma\times$ BR

Comparison of $\boldsymbol{\sigma}\times$ BR containing $\eta^{b\bar{b},\tau\tau}$ with experimental limits



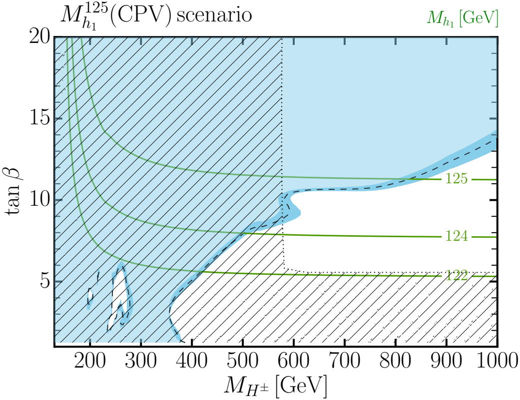
Complex MSSM:

Modified $\boldsymbol{\sigma}\times$ BR for h_2, h_3
interference at $\tan\beta = 10$

Impact on LHC exclusion bounds

`HiggsBounds-5.2.0beta`: $\boldsymbol{\sigma}\times$BR modified by $\boldsymbol{\eta}^{b\bar{b},\tau\tau}, \boldsymbol{\eta}^{gg,\tau\tau}$

- **Unexcluded "bay"** due to destructive interference around $\eta^{b\bar{b},\tau\tau} \lesssim -70\%$
- Minimal rate for $h_2, h_3 \sim 4\%$ of value without interference
- Even with full Run 2 luminosity, the bay might remain unexcluded
- Important to consider the possibility of a $\mathcal{CP}$-violating MSSM Higgs sector



[Bahl, Fuchs, Hahn, Heinemeyer, Liebler, SP, Slavich, Stefaniak, Wagner, Weiglein: 1808.07542]

Summary

Higgs sector of the MSSM

- $\not{\mathcal{CP}}$ gives rise to loop-corrected mass eigenstates h_1, h_2 and h_3

$\not{\mathcal{CP}}$ phases in Higgs production

- Strongly admixed h_2 and h_3 in $m_h^{\text{mod}+}$-inspired scenario → interference effects important

Impact of interference effects on MSSM Higgs searches

- Accounting for destructive interference contributions in $\sigma\times$ BR of $gg, b\bar{b} \to \tau^+\tau^-$ weakens LHC exclusion bounds

[Comic: XKCD]

Appendix

Propagators and self-energies

- The propagator matrix given by

$$\mathbf{\Delta}_{hHA}(p^2) = -\left[\hat{\mathbf{\Gamma}}_{hHA}(p^2)\right]^{-1} ,$$

- Irreducible 2-point vertex functions

$$\hat{\Gamma}_{ij}(p^2) = i\ [(p^2 - m_i^2)\delta_{ij} + \hat{\Sigma}_{ij}(p^2)]$$

form the elements of $\hat{\mathbf{\Gamma}}_{hHA}(p^2) = i\ [p^2\mathbf{1} - \mathbf{M}(p^2)]$

3×3 propagator matrix

$$\mathbf{\Delta}_{hHA}(p^2) = \begin{pmatrix} \Delta_{hh}(p^2) & \Delta_{hH}(p^2) & \Delta_{hA}(p^2) \\ \Delta_{Hh}(p^2) & \Delta_{HH}(p^2) & \Delta_{HA}(p^2) \\ \Delta_{Ah}(p^2) & \Delta_{AH}(p^2) & \Delta_{AA}(p^2) \end{pmatrix}$$

$$= i \begin{pmatrix} p^2 - m_h^2 + \hat{\Sigma}_{hh}(p^2) & \hat{\Sigma}_{hH}(p^2) & \hat{\Sigma}_{hA}(p^2) \\ \hat{\Sigma}_{Hh}(p^2) & p^2 - m_H^2 + \hat{\Sigma}_{HH}(p^2) & \hat{\Sigma}_{HA}(p^2) \\ \hat{\Sigma}_{Ah}(p^2) & \hat{\Sigma}_{AH}(p^2) & p^2 - m_A^2 + \hat{\Sigma}_{AA}(p^2) \end{pmatrix}^{-1} .$$

The neutral Higgs masses are determined as the complex poles of the propagators,

$$\mathcal{M}^2 = M^2 - iM\Gamma,$$

These complex poles are the roots of the determinant of the matrix $\hat{\mathbf{\Gamma}}_{hHA}(p^2)$,

$$\det\left[\hat{\mathbf{\Gamma}}_{hHA}(p^2)\right] = -\left(\det[\mathbf{\Delta}_{hHA}(p^2)]\right)^{-1} = 0 .$$

Definition of $\hat{\mathrm{Z}}$ factors

- $\hat{\mathbf{Z}}$ factors provide the correct normalisation of a matrix element with an external on-shell Higgs boson h_a, $a \in \{1, 2, 3\}$, at $p^2 = \mathcal{M}_a^2$

$$\lim_{p^2 \to \mathcal{M}_a^2} -\frac{i}{p^2 - \mathcal{M}_a^2} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_{hHA} \cdot \hat{\mathbf{Z}}^T \right)_{hh} = 1 \,,$$

$$\lim_{p^2 \to \mathcal{M}_b^2} -\frac{i}{p^2 - \mathcal{M}_b^2} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_{hHA} \cdot \hat{\mathbf{Z}}^T \right)_{HH} = 1 \,,$$

$$\lim_{p^2 \to \mathcal{M}_c^2} -\frac{i}{p^2 - \mathcal{M}_c^2} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_{hHA} \cdot \hat{\mathbf{Z}}^T \right)_{AA} = 1 \,.$$

- The wave function normalisation factors for an external Higgs boson $i \in \{h, H, A\}$

$$\hat{Z}_i^a := \mathrm{Res}_{\mathcal{M}_a^2} \{ \Delta_{ii}(p^2) \} = \frac{1}{1 + \hat{\Sigma}_{ii}^{\mathrm{eff}\prime}(\mathcal{M}_a^2)} \,.$$

- On-shell transition ratio

$$\hat{Z}_{ij}^a = \left. \frac{\Delta_{ij}(p^2)}{\Delta_{jj}(p^2)} \right|_{p^2 = \mathcal{M}_a^2} \,.$$

- Finally

$$\hat{\mathbf{Z}}_{aj} = \sqrt{\hat{Z}_a} \hat{Z}_{aj}$$

[E. Fuchs, PhD thesis; Fuchs, Weiglein '16, '17]

Calculation of interference terms

Amplitude of h_a

$$\mathcal{A}_{h_a} = \hat{\Gamma}^X_{h_a} \Delta^{\mathsf{BW}}_a(p^2) \hat{\Gamma}^Y_{h_a} = \sum_{i,j\in\{h,H,A\}} \left(\hat{\Gamma}^X_i \hat{\mathbf{Z}}_{ai}\right) \Delta^{\mathsf{BW}}_a(p^2) \left(\hat{\mathbf{Z}}_{aj} \hat{\Gamma}^Y_j\right)$$

$$= \sum_{i,j\in\{h,H,A\}} \hat{\Gamma}^X_i \left(\hat{\mathbf{Z}}_{ai} \Delta^{\mathsf{BW}}_a(p^2) \hat{\mathbf{Z}}_{aj}\right) \hat{\Gamma}^Y_j \, .$$

Interference contribution:

$$|\mathcal{A}|^2_{\mathsf{int}} = \ 2\mathsf{Re} \ \left[\mathcal{A}_{h_1}\mathcal{A}^*_{h_2} + \mathcal{A}_{h_2}\mathcal{A}^*_{h_3} + \mathcal{A}_{h_1}\mathcal{A}^*_{h_3}\right]$$

Mixing between the two heavy Higgses h_2 and h_3

$$|\mathcal{A}|^2_{\mathsf{int}} = \ 2\mathsf{Re} \ \left[\ \left(\hat{\Gamma}^I_{h_2} \Delta^{\mathsf{BW}}_2(\hat{s}) \hat{\Gamma}^F_{h_2}\right) \left(\hat{\Gamma}^I_{h_3} \Delta^{\mathsf{BW}}_3(\hat{s}) \hat{\Gamma}^F_{h_3}\right)^* \ \right]$$

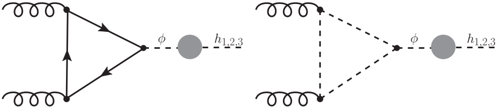
evaluated at $p^2 = \hat{s} = \left(\frac{M_{h_2}+M_{h_3}}{2}\right)^2$. [E. Fuchs, PhD thesis; Fuchs, Weiglein '16, '17]

Integrate over phase space

$$\sqrt{s}_{\min} = p - 5\left(\frac{\hat{\Gamma}_{h_2} + \hat{\Gamma}_{h_3}}{2}\right) , \quad \sqrt{s}_{\max} = p + 5\left(\frac{\hat{\Gamma}_{h_2} + \hat{\Gamma}_{h_3}}{2}\right) ,$$

$$\sigma(|\mathcal{A}|^2_{\mathsf{int}}) = \int_{s_{\min}}^{s_{\max}} ds \ 2\mathsf{Re} \ \left[\ \left(\hat{\Gamma}^I_{h_2} \Delta^{\mathsf{BW}}_2(s) \hat{\Gamma}^F_{h_2}\right) \left(\hat{\Gamma}^I_{h_3} \Delta^{\mathsf{BW}}_3(s) \hat{\Gamma}^F_{h_3}\right)^* \ \right] .$$

Leading order cross section



$$\sigma_{\text{LO}}(pp \to h_a) = \boldsymbol{\sigma_0^{h_a}} \tau_{h_a} \mathcal{L}^{gg}(\tau_{h_a}) \quad , \mathcal{L}^{gg}(\tau) = \int_\tau^1 \frac{dx}{x} g(x) g(\tau/x), \quad \tau_{h_a} = \frac{M_{h_a}^2}{s}$$

$$\boldsymbol{\sigma_0^{h_a}} = \frac{G_F \alpha_s^2(\mu_R)}{288\sqrt{\pi}} \left[\left| \mathcal{A}^{h_a,\text{e}} \right|^2 + \left| \mathcal{A}^{h_a,\text{o}} \right|^2 \right]$$

with $\mathcal{A}^{h_a,\text{e}} = \hat{\mathbf{Z}}_{ah} \boldsymbol{\mathcal{A}_+^h} + \hat{\mathbf{Z}}_{aH} \boldsymbol{\mathcal{A}_+^H} + \hat{\mathbf{Z}}_{aA} \boldsymbol{\mathcal{A}_-^A}$

and $\mathcal{A}^{h_a,\text{o}} = \hat{\mathbf{Z}}_{ah} \boldsymbol{\mathcal{A}_-^h} + \hat{\mathbf{Z}}_{aH} \boldsymbol{\mathcal{A}_-^H} + \hat{\mathbf{Z}}_{aA} \boldsymbol{\mathcal{A}_+^A}$

$$\boldsymbol{\phi_e = h, H:} \quad \mathcal{A}_+ = \sum_{q \in \{t,b\}} (a_{q,+} + \tilde{a}_q) \ , \quad \mathcal{A}_- = \sum_{q \in \{t,b\}} a_{q,-}$$

$$\boldsymbol{\phi = A:} \quad \mathcal{A}_- = \sum_{q \in \{t,b\}} (a_{q,-} + \tilde{a}_q) \ , \quad \mathcal{A}_+ = \sum_{q \in \{t,b\}} a_{q,+}^A$$

[Liebler, SP, Weiglein '16]

Full LO cross section

$$\boxed{\mathcal{A}_{+}^{\phi^e} = \sum_{q\in\{t,b\}} \left(a_{q,+}^{\phi^e} + \tilde{a}_q^{\phi^e}\right) , \quad \mathcal{A}_{-}^{\phi^e} = \sum_{q\in\{t,b\}} a_{q,-}^{\phi^e}}$$

$$a_{q,+}^{\phi^e} = \frac{1}{2}\left(g_{q_L}^{\phi^e} + g_{q_R}^{\phi^e}\right)\frac{3}{2}\tau_q^{h_a}\left[1 + (1-\tau_q^{h_a})f(\tau_q^{h_a})\right], a_{q,-}^{\phi^e} = \frac{i}{2}\left(g_{q_R}^{\phi^e} - g_{q_L}^{\phi^e}\right)\frac{3}{2}\tau_q^{h_a} f(\tau_q^{h_a}) ,$$

$$\tilde{a}_q^{\phi^e} = -\frac{3}{8}\tau_q^{h_a}\sum_{i=1}^{2} g_{\tilde{q}ii}^{\phi^e}\left[1 - \tau_{\tilde{q}i}^{h_a} f(\tau_{\tilde{q}i}^{h_a})\right] .$$

$$\boxed{\mathcal{A}_{-}^{A} = \sum_{q\in\{t,b\}} \left(a_{q,-}^{A} + \tilde{a}_q^{A}\right) , \quad \mathcal{A}_{+}^{A} = \sum_{q\in\{t,b\}} a_{q,+}^{A}}$$

$$a_{q,+}^{A} = \frac{1}{2}\left(g_{q_L}^{A} + g_{q_R}^{A}\right)\frac{3}{2}\tau_q^{h_a} f(\tau_q^{h_a}) , a_{q,-}^{A} = \frac{i}{2}\left(g_{q_L}^{A} - g_{q_R}^{A}\right)\frac{3}{2}\tau_q^{h_a}\left[1 + (1-\tau_q^{h_a})f(\tau_q^{h_a})\right] ,$$

$$\tilde{a}_q^{A} = -\frac{3}{8}\tau_q^{A}\sum_{i=1}^{2} g_{\tilde{q}ii}^{A}\left[1 - \tau_{\tilde{q}_i}^{h_a} f(\tau_{\tilde{q}_i}^{h_a})\right] .$$

$$f(\tau) = \begin{cases} \text{arcsin}^2 \frac{1}{\sqrt{\tau}}, & \tau \geq 1 \\ -\frac{1}{4}\left(\log\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right)^2, & \tau < 1 . \end{cases}$$

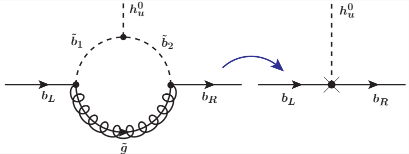
Δ_b corrections to bottom Yukawa coupling

- Leading $\tan\beta$ enhanced Δ_b corrections from gluino-sbottom loops absorbed in effective bottom Yukawa coupling

$$\mathcal{L}_{\text{eff}} = -\lambda_b \bar{b}_R \left[h_d^0 + \frac{\Delta_b}{t_\beta} h_u^{0*}\right] b_L + h.c.$$

$$\Delta_b = \frac{2}{3\pi}\alpha_s \mu^* M_3^* t_\beta I\left(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}}\right)$$

Eff. bottom Yukawa couplings with full Δ_b corrections @ LO

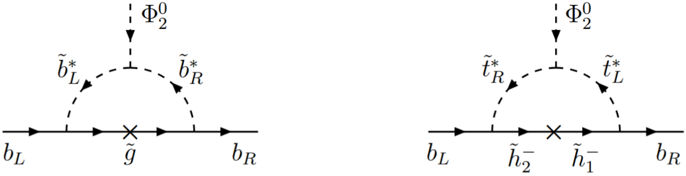


- $g^h_{b_L} = (g^h_{b_R})^* = \frac{1}{1+\Delta_b}\left[\frac{\sin\alpha}{\cos\beta} + \frac{\cos\alpha}{\sin\beta}\Delta_b\right]$
- $g^H_{b_L} = (g^H_{b_R})^* = \frac{1}{1+\Delta_b}\left[\frac{\cos\alpha}{\cos\beta} + \frac{\sin\alpha}{\sin\beta}\Delta_b\right]$
- $g^A_{b_L} = (g^A_{b_R})^* = \frac{1}{1+\Delta_b}\left[\tan\beta\left(1 - \frac{\Delta_b}{\tan^2\beta}\right)\right]$

- A *simplified* Δ_b correction used at NLO: $$g^\phi_{b_L} = g^\phi_{b_R} = \frac{1}{|1+\Delta_b|} f(\alpha,\beta)$$

[Banks '88],[Hall, Ratazzi, Sarid '94],[Hempfling '94],[Carena et al '00],[Williams,Rzehak,Weiglein '11]

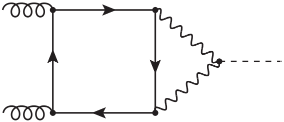
Δ_b corrections



$$
\begin{aligned}
&= \Delta m_b^{\tilde g} + \Delta m_b^{\tilde h} \\
&= \frac{2}{3}\frac{\alpha_s}{\pi}\mu^* M_3^* t_\beta I\left(m^2_{\tilde b_1}, m^2_{\tilde b_2}, m^2_{\tilde g}\right) + \frac{\alpha_t}{4\pi} A_t^* \mu^* t_\beta I\left(m^2_{\tilde t_1}, m^2_{\tilde t_2}, |\mu|^2\right)
\end{aligned}
$$

[1103.1335]

EW corrections



- Full NLO EW corrections are known only in SM
- For MSSM, EW amplitude constructed only for h and H
- No coupling of A to gauge bosons, EW corrections to $\mathcal{CP}$-odd Higgs negligible

$$\sigma^{\rm e}_{\textsf{NLO, EW}} = \sigma^{\rm e}_{\textsf{NLO}}(1+\delta^{\textsf{lf}}_{\textsf{EW}})$$

$$\delta^{\textsf{lf}}_{\textsf{EW}} = \frac{\alpha_{\textsf{EM}}}{\pi}\,\frac{2\textsf{Re}\left(\mathcal{A}^{h_a,\rm e}\mathcal{A}^{h_a,\textsf{EW}*}\right)}{|\mathcal{A}^{h_a,\rm e}|^2}$$

Electroweak amplitude **[Bonciani, Degrassi, Vicini '11]**

$$\mathcal{A}^{h_a,\textsf{EW}} = -\frac{3}{8}\;\frac{1}{x_W s_W^2}\left[\frac{2}{c_W^4}\left(\frac{5}{4}-\frac{7}{3}s_W^2+\frac{22}{9}s_W^4\right)A_1[x_Z]+4A_1[x_W]\right]$$
$$\cdot\left(-\hat{\mathbf{Z}}_{ah}\sin\alpha\cos\beta+\hat{\mathbf{Z}}_{aH}\cos\alpha\sin\beta\right)\;,$$

with

$$x_V = \frac{M_{h_a}^2}{\left(m_V - i\frac{\Gamma_V}{2}\right)^2}\,,\qquad V\in\{W,Z\}\,.$$

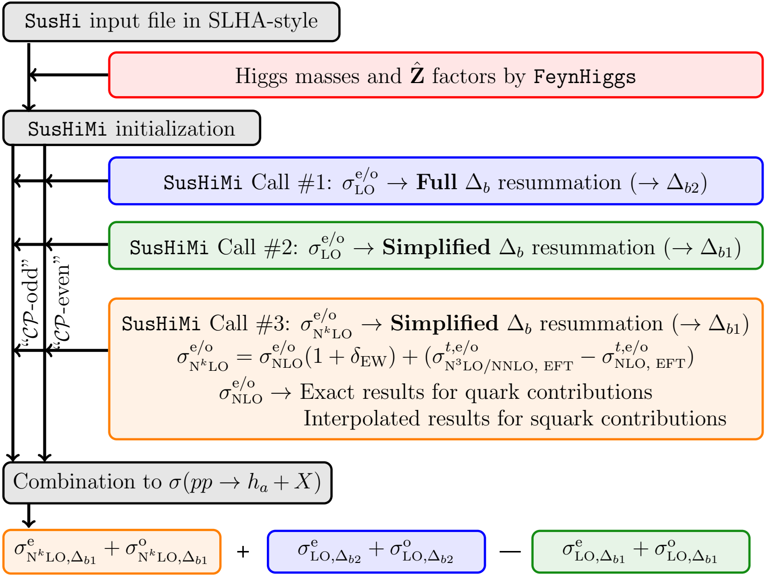
Gluon fusion beyond LO

- Complex Yukawa coupling only induced for the b-quark through Δ_b contributions.
- For g_t^ϕ, left- and right-handed components identical ⇒ can take over known higher-order QCD corrections to the top loop contribution
- For bottom contribution at NLO (SM) QCD, use simplified version of the Δ_b corrections to the bottom coupling ⇒ higher-order quark contributions, both real and virtual, of the same structure as in the $\mathcal{CP}$-conserving MSSM.
- **Real corrections:** only new ingredients are Higgs–squark couplings to the $\mathcal{CP}$-odd, $g^A_{\tilde{q}ii}$. Squark induced contributions of $\mathcal{CP}$-odd components $\propto g^A_{\tilde{q}ii}$ added as a complex component to the $\mathcal{CP}$-even couplings. Real corrections s split in $\Delta\sigma^{\mathrm{e}}$ and $\Delta\sigma^{\mathrm{o}}$
- **Virtual corrections:** Quark induced contributions taken over from `SusHi` [Harlander, Kant '05]. Squark induced contributions interpolated from real case (known in various expansions). Finally:

$$C^{\mathrm{e/o}} = 2\mathrm{Re}\left[\frac{\mathcal{A}^{h_a,\mathrm{e/o}}_{\mathsf{NLO}}}{\mathcal{A}^{h_a,\mathrm{e/o}}}\right] + \pi^2 + \beta_0 \log\left(\frac{\mu_{\mathsf{R}}^2}{\mu_{\mathsf{F}}^2}\right). \tag{1}$$

with $\mathcal{A}^{h_a,\mathrm{e}}_{\mathsf{NLO}} = \hat{\mathbf{Z}}_{ah}\mathcal{A}^{h}_{\mathsf{NLO}} + \hat{\mathbf{Z}}_{aH}\mathcal{A}^{H}_{\mathsf{NLO}}$ and $\mathcal{A}^{h_a,\mathrm{o}}_{\mathsf{NLO}} = \hat{\mathbf{Z}}_{aA}\mathcal{A}^{A}_{\mathsf{NLO}}$, μ_{F} denotes the factorisation scale, and $\beta_0 = 11/2 - n_f/3$ with $n_f = 5$.

SusHiMi



SusHi input file in SLHA-style

Higgs masses and $\hat{\mathbf{Z}}$ factors by FeynHiggs

SusHiMi initialization

SusHiMi Call #1: $\sigma^{\mathrm{e/o}}_{\mathrm{LO}} \to$ **Full** Δ_b resummation $(\to \Delta_{b2})$

SusHiMi Call #2: $\sigma^{\mathrm{e/o}}_{\mathrm{LO}} \to$ **Simplified** Δ_b resummation $(\to \Delta_{b1})$

SusHiMi Call #3: $\sigma^{\mathrm{e/o}}_{\mathrm{N^kLO}} \to$ **Simplified** Δ_b resummation $(\to \Delta_{b1})$

$$\sigma^{\mathrm{e/o}}_{\mathrm{N^kLO}} = \sigma^{\mathrm{e/o}}_{\mathrm{NLO}}(1+\delta_{\mathrm{EW}}) + (\sigma^{t,\mathrm{e/o}}_{\mathrm{N^3LO/NNLO,\ EFT}} - \sigma^{t,\mathrm{e/o}}_{\mathrm{NLO,\ EFT}})$$

$\sigma^{\mathrm{e/o}}_{\mathrm{NLO}} \to$ Exact results for quark contributions
Interpolated results for squark contributions

Combination to $\sigma(pp \to h_a + X)$

$$\sigma^{\mathrm{e}}_{\mathrm{N^kLO},\Delta_{b1}} + \sigma^{\mathrm{o}}_{\mathrm{N^kLO},\Delta_{b1}} + \sigma^{\mathrm{e}}_{\mathrm{LO},\Delta_{b2}} + \sigma^{\mathrm{o}}_{\mathrm{LO},\Delta_{b2}} - \sigma^{\mathrm{e}}_{\mathrm{LO},\Delta_{b1}} + \sigma^{\mathrm{o}}_{\mathrm{LO},\Delta_{b1}}$$

Benchmark Scenarios

Scenario Parameter	$\mathbf{m_h^{mod+}}$ **inspired**
m_t	173.2
$M_{H^\pm}$(or M_A)	*Varied*
$\tan\beta$	*Varied*
M_{SUSY}	1000
M_{l_3}	1000
X_t/M_{SUSY}	1.5
A_b	$\|A_t\|$
A_τ	$\|A_t\|$
μ	1000
M_1	250
M_2	500
M_3	$1500e^{i\phi_{M_3}}$
$M_{\tilde{q}_{1,2}}$	M_{SUSY}
$M_{\tilde{l}_{1,2}}$	M_{SUSY}
$A_{f\neq t,b,\tau}$	0

Theoretical uncertainties

PDF + α_s uncertainties

- Uncertainties in cross-section predictions can be induced by PDF fits and associated α_s
- `MMHT2014` PDF sets used for LO, NLO and NNLO for $gg\Phi$ and $bb\Phi$
- PDF + α_s uncertainties function of m_{h_a}
- Can be taken over from description for MSSM Higgses in `LHCHXSWG` report 4 [arXiV:1610.07922]

Scale uncertainties

- Central scale choice: $(\mu_R^0, \mu_F^0) = (m_{h_a}/2, m_{h_a}/2)$ for $gg\Phi$ and $(\mu_R^0, \mu_F^0) = (m_{h_a}, m_{h_a}/4)$ for $bb\Phi$
- Scale unc. obtained by taking maximal deviation from central scale choice $\{(2\mu_R^0, 2\mu_F^0), (2\mu_R^0, \mu_F^0), (\mu_R^0, 2\mu_F^0), (\mu_R^0, \mu_F^0/2), (\mu_R^0/2, \mu_F^0), (\mu_R^0/2, \mu_F^0/2)\}$
- $\Delta\sigma^{\text{scale}} = \sqrt{\left(\Delta\sigma^{\Delta_{b1}}_{\mathbf{N}^k\mathbf{LO}}\right)^2 + \left(\Delta\sigma^{\Delta_{b2}}_{\mathbf{LO}} - \Delta\sigma^{\Delta_{b1}}_{\mathbf{LO}}\right)^2}$

Interpolation uncertainties

- Interpolation of two-loop virtual squark-gluino contributions induces an unc. due to non-exact results
- $\Delta\sigma^{\text{int}} = \sin^2(\phi_z)|\sigma(0) - \sigma(\pi)|/2$

$b\bar{b}$ cross section

- `SusHi` employs the 5FS for the bottom-quark annihilation process for SM Higgs at NNLO QCD[1]
- For MSSM with real parameters, `SusHi` links `bbh@nnlo` for the inclusive cross section $\sigma_{b\bar{b}H^0}$ in the SM at NNLO QCD which uses $m_b^{\overline{\text{MS}}}(\mu_R)$ for the bottom-Yukawa coupling, subsequently reweighted by the resummed SUSY coupling g_b^ϕ
- For h_a production in the MSSM with $\not{\mathcal{CP}}$ in `SusHiMi`, the results for the SM Higgs boson reweighted to the MSSM with $|\hat{\mathbf{Z}}_{ah} g_b^h + \hat{\mathbf{Z}}_{aH} g_b^H|^2 + |\hat{\mathbf{Z}}_{aA} g_b^A|^2$, includes $\tan\beta$-enhanced squark effects through simplified Δ_b resummation
- In case of non-equal left- and right-handed couplings g_{b_L} and g_{b_R} due to the full resummation the SM cross section multiplied with

$$\begin{aligned} &|\hat{\mathbf{Z}}_{ah}(g_{bL}^h + g_{bR}^h) + \hat{\mathbf{Z}}_{aH}(g_{bL}^H + g_{bR}^H) + i\hat{\mathbf{Z}}_{aA}(g_{bL}^A - g_{bR}^A)|^2 \\ &+ |i\hat{\mathbf{Z}}_{ah}(g_{bR}^h - g_{bL}^h) + i\hat{\mathbf{Z}}_{aH}(g_{bR}^H - g_{bL}^H) + \hat{\mathbf{Z}}_{aA}(g_{bL}^A + g_{bR}^A)|^2 \,. \end{aligned}$$

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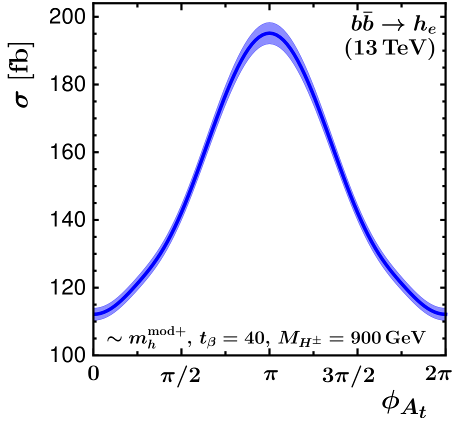
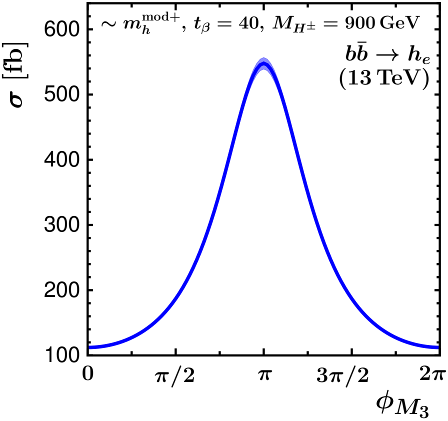
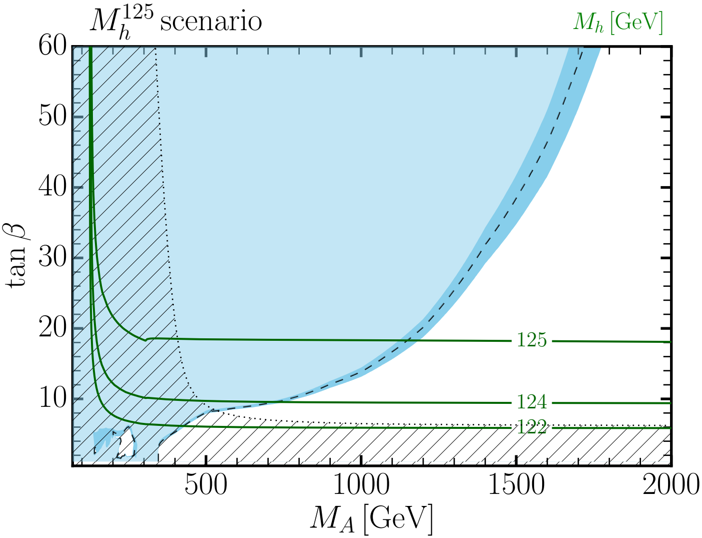
[1] Latest benchmark scenario uses the updated cross sections with resummed logs combining 4FS and 5FS [Bonvini, Papanastasiou,Tackmann,'15,'16],[Forte, Napoletano,Ubiali,'15,'16]

$b\bar{b}$ cross section

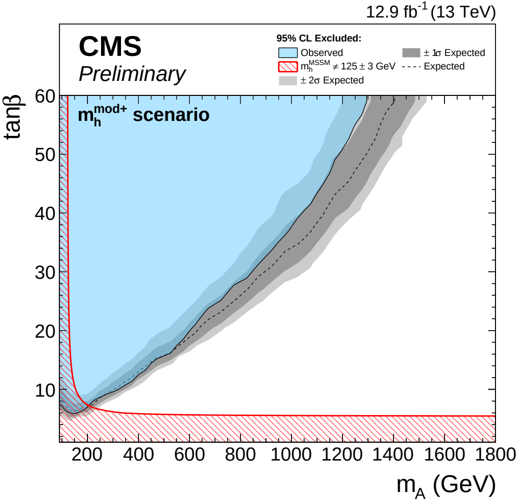




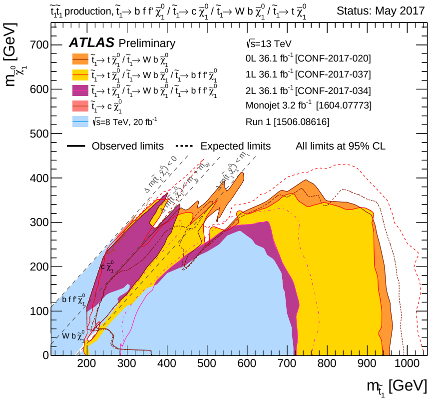
$\mathcal{CP}$-conserving M_h^{125} scenario

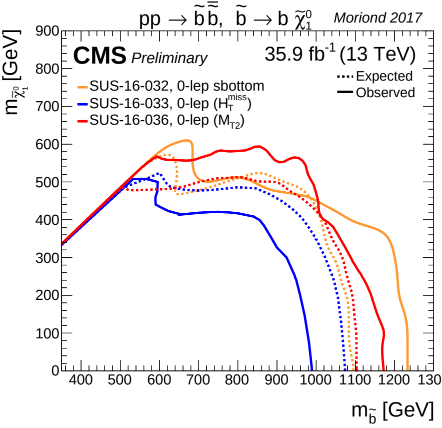


Heavy Higgs searches

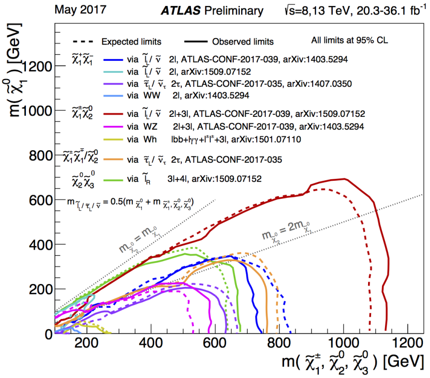


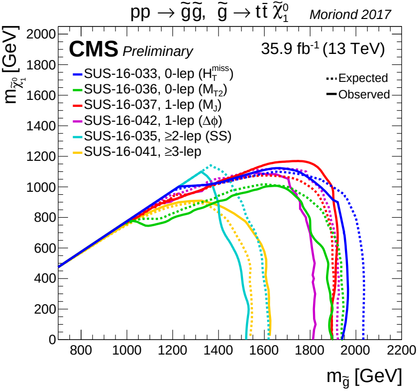
Stops and sbottoms





Gluino and chargino





Electric Dipole Moments (EDMs)

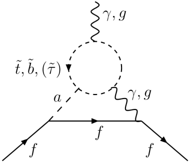
EDM experiments

eg:

- **ACME: Advanced Cold Molecule Electron EDM**
- **Storage Ring EDM collaboration**: proton, deuteron nuclei

SUSY contributions

eg[hep-ph/9902371]:



constraint	value [e cm]	Ref.
EDM electron d_e	$8.7 \cdot 10^{-29}$	[ACME '14]
EDM neutron d_n	$4.7 \cdot 10^{-26}$	[hep-ex/0602020]
EDM mercury d_{Hg}	$3.5 \cdot 10^{-29}$	[PhysRevLett.102.101601]

95% CL upper limits on the EDMs of the electron, neutron and mercury.

- MSSM contributions to EDMs contribute at the one-loop level, primarily involve the 1st 2 gen. of squark and sleptons
- Severe constraints on phases of A_q for $q \in \{u, d, s, c\}$ and A_l for $l \in \{e, \mu\}$
- Third-generation trilinear coupling phases weakly constrained [Li, Profumo, Ramsey-Musolf, '10]
- Maximal ϕ_{A_t} ruled out [1612.08090], however still significant room for variation