MSSM benchmark scenario with $\mathcal{CP}$ violation

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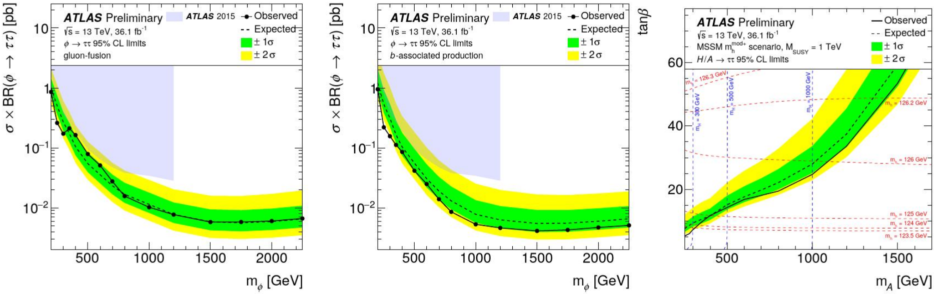
Interpretation of searches for additional scalars

Experimental searches for $\phi = h, H, A$ $\hookrightarrow$ talks this afternoon

production $\{gg \to \phi, b\bar{b}\phi\} \times$ **decay** $\phi \to \{\tau^+\tau^-, \mu^+\mu^-, b\bar{b}\}$



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

Limitation of interpretation in standard NWA ($\sigma_{\textbf{prod}} \times$ BR)

interference terms neglected, relevant especially with complex phases

Outline

1. **Complex parameters in the MSSM Higgs sector**
   - Motivation
   - $\mathbf{3} \times \mathbf{3}$ propagator mixing

2. **Phases in gg and $b\bar{b}$ Higgs production**

3. **$\mathcal{CP}$-violating interference effect**
   - Relative interference term
   - Definition of the $m_{h_1}^{125}$(CPVint) scenario

4. **Impact of interference effects on LHC Higgs searches**
   - $\sigma \times$ BR
   - Consequences of interference for exclusion bounds

Complex parameters in the MSSM Higgs sector

Motivation

- baryon asymmetry of the universe requires BSM $\mathcal{CP}$-violation
- MSSM Higgs sector is $\mathcal{CP}$-conserving at lowest order
- parameters from **other sectors** can be **complex**
  - trilinear couplings A_f
  - higgsino mass parameter μ
  - gaugino mass parameters M_1, M_3

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Constraints from EDMs

e.g. [Barger, Falk, Han, Jiang, Li, Plehn '01], [Ellis, Lee, Pilaftsis '09], [Li, Profumo, Ramsey-Musolf '10], [Arbey, Ellis, Godbole, Mahmoudi '14]

- least constrained and most relevant in Higgs sector: $\phi_{A_{t,b}}, \phi_{M_3}$

complex phases induce $\mathcal{CP}$-violation in Higgs sector via loops

3×3 propagator mixing and $\hat{\mathrm{Z}}$ factors

$\mathbb{C}$: $\mathcal{CP}$ eigenstates $\boldsymbol{h, H, A}$ $\rightarrow$ mass eigenstates $\boldsymbol{h_1, h_2, h_3}$

- 3×3 propagator matrix, p^2-dependent:

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

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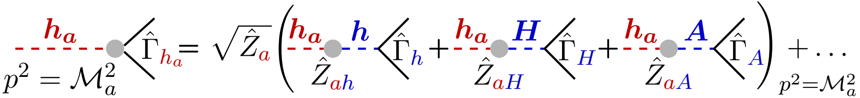
- correct on-shell properties of external Higgs bosons with mixing: $\hat{\mathbf{Z}}_{aj}$

[Chankowski, Pokorski, Rosiek '93], [Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein '07], [Williams, Rzehak, Weiglein '11]...

$$\hat{Z}_a = \frac{1}{1+\hat{\Sigma}^{\text{eff}\,\prime}_{ii}(\mathcal{M}^2_{h_a})}, \quad \hat{Z}_{aj} = \frac{\Delta_{ij}(\mathcal{M}^2_{h_a})}{\Delta_{ii}(\mathcal{M}^2_{h_a})}, \qquad \hat{\mathbf{Z}}_{aj} = \sqrt{\hat{Z}_a}\,\hat{Z}_{aj}$$



Breit-Wigner approximation of full propagators

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

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

- approximation of **full propagator** around $p^2 \simeq \mathcal{M}^2_{h_a}$:

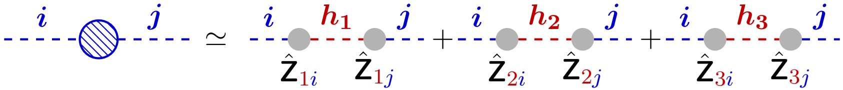
$$\Delta_{ii}(p^2) \simeq \Delta_a^{\mathrm{BW}}(p^2)\hat{\mathbf{Z}}^2_{ai}$$

- consider all 3 complex poles $\mathcal{M}^2_a,\ a = 1, 2, 3$

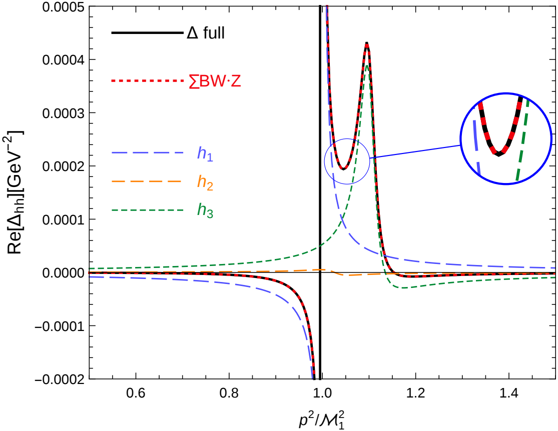
$$\Delta_{ij}(p^2) \simeq \sum_{a=1,2,3} \hat{\mathbf{Z}}_{ai}\Delta_a^{\mathrm{BW}}(p^2)\hat{\mathbf{Z}}_{aj}$$

[EF, Weiglein 1610.06193]

full mixing — Breit-Wigner propagators — on-shell $\hat{\mathbf{Z}}$-factors approximate mixing



Comparison: Breit-Wigner and full propagators



- example scenario $\Rightarrow$ overlap of resonance regions

Δ_{ij} very well approximated by **sum** of BW propagators and $\hat{\mathbf{Z}}$-factors

Mixing and overlapping resonances

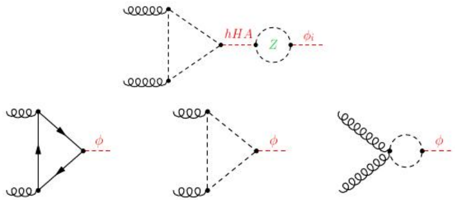
generally: $\Delta M \leq \Gamma_1 + \Gamma_2 \hookrightarrow$ overlapping resonances

MSSM: Higgs bosons can be quasi degenerate and interfere

$\mathbb{R}$	$\boldsymbol{h, H}$	$M_h \simeq M_H$ at high $\tan\beta$, low M_A
$\mathbb{C}$	$\boldsymbol{h_1, h_2, h_3}$	$M_{h_2} \simeq M_{h_3}$ in decoupling limit

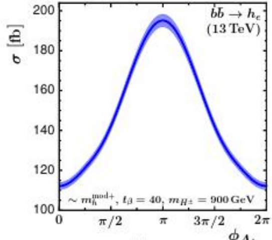
if $\mathbb{C}$: *incoherent* sum $\sigma_H + \sigma_A$ not sufficient in heavy Higgs searches

Phases in gg and $b\bar{b}$ Higgs production

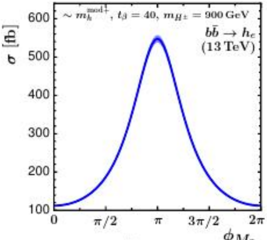


- $\hat{Z}$ factors
- squark loops
- Δ_b correction to the y_b- m_b relation

SusHiMi: Higgs production in the MSSM with complex parameters via $gg \to h_a,\ b\bar{b}h_a,\ a = 1, 2, 3$ [Liebler, Patel, Weiglein 1611.09308]

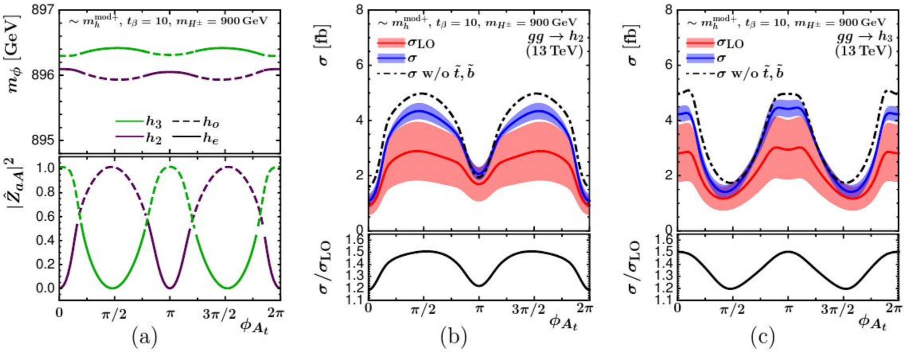


(a)



(b)

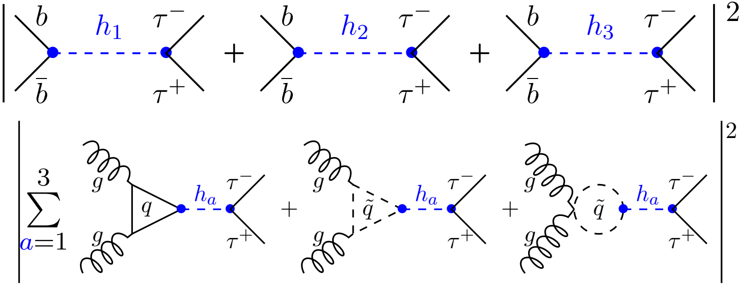
Phase dependence of highly admixed Higgs states



[Liebler, Patel, Weiglein 1611.09308]

Production, decay and interference

Higgs bosons as intermediate states in $\{b\bar{b}, gg\} \to h_a \to \tau\tau$

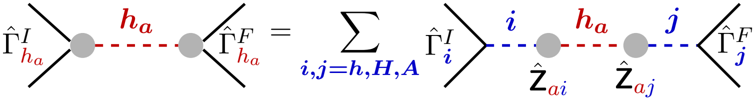


- phases have impact on masses, couplings, widths, cross sections, mixing
- $\not{C}\not{P}$ mixing and interference: coherent $|\sum h_a|^2$ vs. incoherent $\sum |h_a|^2$

Coherent and incoherent contribution

- amplitude of Higgs boson h_a exchanged in I$\to h_a \to$F with vert

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



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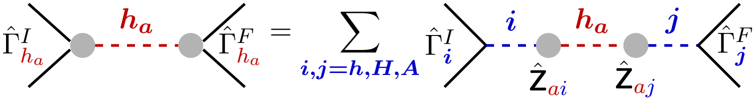


- coherent sum $|\mathcal{A}|^2_{\rm coh} = \left| \sum_{a=1}^3 \mathcal{A}_{h_a} \right|^2$ contains interference term
- incoherent sum $|\mathcal{A}|^2_{\rm incoh} = \sum_{a=1}^3 \left| \mathcal{A}_{h_a} \right|^2$
- interference term $|\mathcal{A}|^2_{\rm int} = |\mathcal{A}|^2_{\rm coh} - |\mathcal{A}|^2_{\rm inccoh} = \sum_{a<b} 2\,{\rm Re}\left[\mathcal{A}_{h_a}\mathcal{A}^*_{h_b}\right]$

Framework for the relative interference term

Approach: maintain factorisation into production $\times$ decay

$$\sigma(I \to h_a \to F) = \sum_a \sigma(I \to h_a) \times \mathrm{BR}(h_a \to F) + \boldsymbol{\sigma^{IF}_{\text{interference}}}$$
$$\simeq \sum_a \sigma(I \to h_a) \times \boldsymbol{\eta^{IF}_a} \times \mathrm{BR}(h_a \to F)$$

- generalised NWA includes interference
- σ, BR calculated at higher order
- relative interference $\eta^{IF} = \frac{\sigma^{IF}_{\text{int}}}{\sigma^{IF}_{\text{incoh}}}$ split into the individual h_a

  interference contributions: $\eta_a = \frac{\sigma_{\text{int}_{\text{ab}}}}{\sigma_{h_a}+\sigma_{h_b}} + \frac{\sigma_{\text{int}_{\text{ac}}}}{\sigma_{h_a}+\sigma_{h_c}}$ [EF, Weiglein 1705.05757]
- calculation of $\boldsymbol{\eta^{IF}_a}$ implemented in `SusHi`, integration over resonance region

Definition of the $m_{h_1}^{125}(\text{CPVint})$ scenario

motivated by large admixture of H, A into h_2, h_3

- h_2, h_3 almost degenerate
- mixing reflected in $\hat{\mathbf{Z}}$ matrix
- large imaginary parts of $\hat{\mathbf{Z}}$ matrix

$$M_{\text{SUSY}} = \mu = 1.5\,\text{TeV}$$

$$M_1 = 0.5\,\text{TeV}, \quad M_2 = 1\,\text{TeV}, \quad M_3 = 2.5\,\text{TeV} \cdot e^{i\phi_{M_3}}$$

$$A_t = (\mu \cot\beta + x \cdot M_{\text{SUSY}}) \cdot e^{i\phi_{A_t}}, \quad A_b = A_t, \quad A_\tau = |A_t|, \quad \phi_{A_t}$$

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

Version A

$\phi_{M_3} = \pi/3, \quad x = 1.8$

$M_{(L,E)_{1,2}} = 0.5\,\text{TeV}$

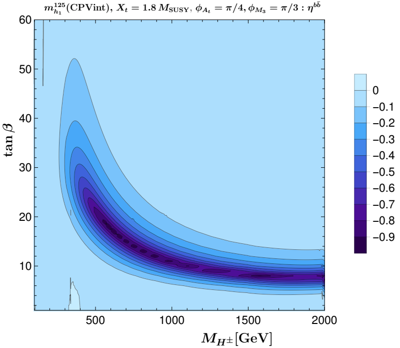
Version B

$\phi_{M_3} = 0, \quad x = 1.5$

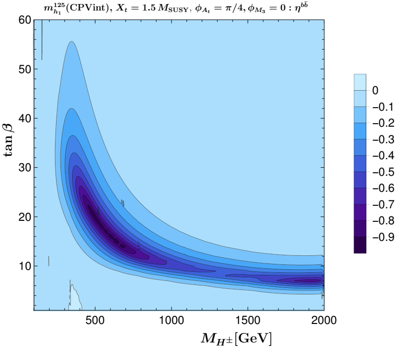
$M_{(L,E)_{1,2}} = M_{\text{SUSY}}$

Interference effect in $b\bar{b} \to h_a \to \tau\tau$

$m_{h_1}^{125}$(CPVint) A



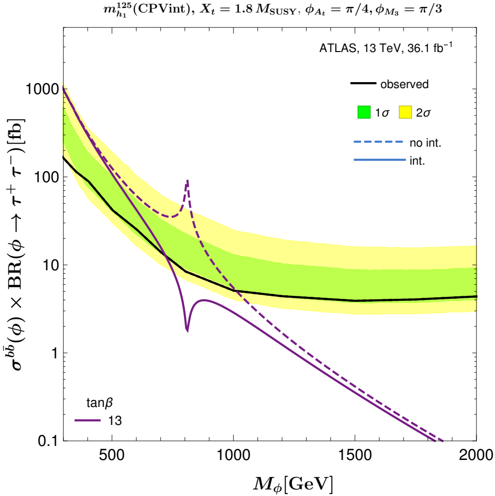
$m_{h_1}^{125}$(CPVint) B



drastic, destructive interference effect

Comparison with experimental exclusion bounds

$\hat{Z}$-enhancement of cross sections, reduction by destructive interference



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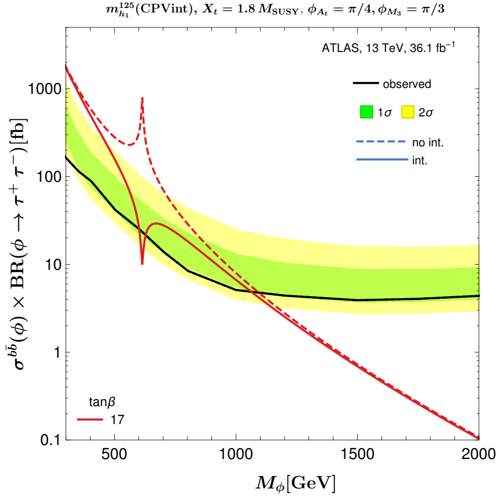

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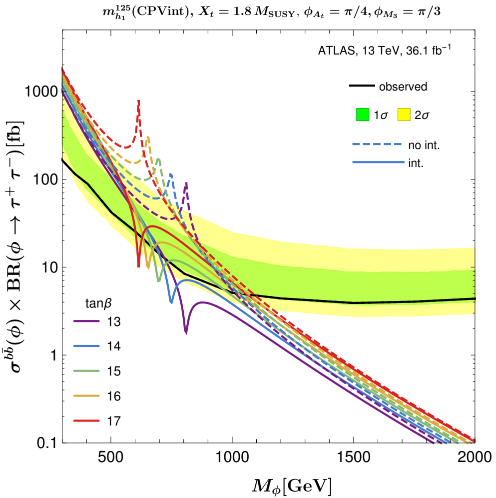

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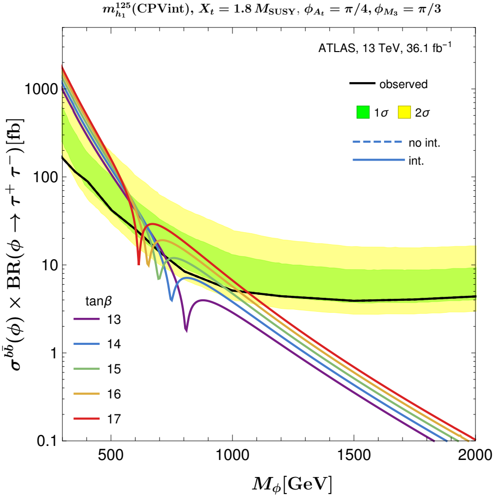

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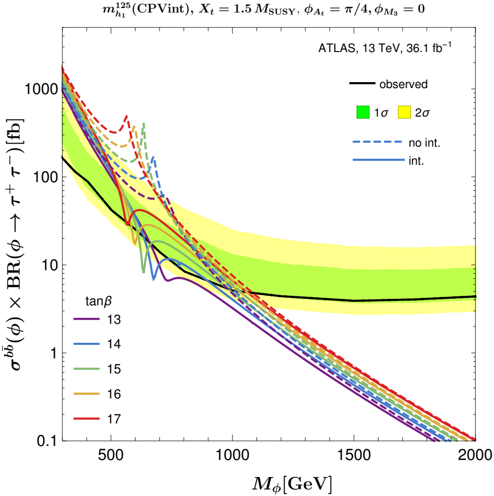

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Combination of precise building blocks

Production: cross sections of $b\bar{b} \to h_a$ and $gg \to h_a$ from `SusHiMi`

Decay: branching ratios for $h_a \to \tau^+\tau^-$ from `FeynHiggs`

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$\downarrow$

Interference incl. propagator corrections:

We included the interference terms by rescaling the production $\boldsymbol{P} = b\bar{b}$ (gg to be included later, here subdominant):

$$\frac{\sigma^{\text{MSSM}}(P \to h_a)}{\sigma^{\text{SM}}(P \to h)} \longrightarrow \frac{\sigma^{\text{MSSM}}(P \to h_a)}{\sigma^{\text{SM}}(P \to h)} \cdot (1 + \boldsymbol{\eta_a})$$

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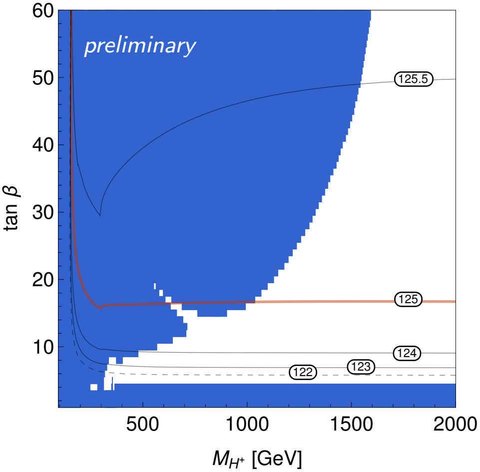
$\Downarrow$

Confront with experimental data: input for HiggsBounds

Impact on exclusion bound

HiggsBounds 5.2.0β* with SusHiMi and FeynHiggs 2.13.0**



$m_{h_1}^{125}$(CPVint) scenario A

- $\phi_{A_t} = \pi/4, \ \phi_{M_3} = \pi/3$
- $M_{h_1} = 125 \pm 3\,\text{GeV}$ in most of the plane
- $\phi \to \tau\tau$ ATLAS search sensitive to high masses

unexcluded "fjord" due to strong, destructive interference effect

*thanks to T. Stefaniak

**preliminary checks with FH 2.14.0β thanks to I. Sobolev and H. Bahl

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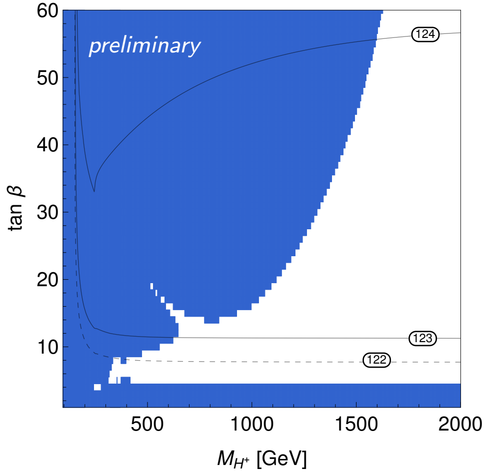

$m_{h_1}^{125}$(CPVint) scenario B

- $\phi_{A_t} = \pi/4, \ \phi_{M_3} = 0$
- $M_{h_1} \lesssim 124\,\text{GeV}$ in most of the plane due to lower X_t
- similar effect with varied input parameters

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Next steps

- include interference also in gluon fusion
  - similar relative effect $\eta^{gg} \sim \eta^{b\bar{b}}$ expected
  - but subdominant production in interference region $\Rightarrow$ less impact on exclusion
  - use 2-dimensional exclusion $(gg, b\bar{b})$ as soon as provided by ATLAS/CMS and included in `HiggsBounds`

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  - uncertainty of production (`SusHiMi`) and decay (`FeynHiggs`)
  - non-factorisable corrections to η
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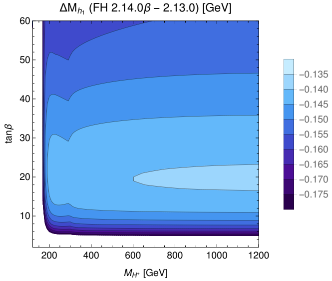
  - Higgs masses
- update to `FeynHiggs 2.14.0`
  - small downward shift of M_{h_1}
  - adjust X_t



Benchmark input for experimental analyses

for each ($M_{H^\pm}$, $\tan\beta$):

- ROOT files with standard inputs ($\rightarrow$ see Stefan's talk)
- relative interference factor $\boldsymbol{\eta_{\mathbf{IF}}}$ for production mode $I = b\bar{b},\ gg$ and decay channel $F = \tau\tau, b\bar{b}, t\bar{t}$

proceed with experimental analyses as usual

Summary: $\not{\mathcal{CP}}$ benchmark with $h_2 - h_3$ interference

- **propagator mixing** with loop-induced $\not{\mathcal{CP}}$
  - $h, H, A \to h_1, h_2, h_3$:
    full propagators approximated by BW-propagators with $\hat{\mathbf{Z}}$-factors

- **Higgs production** with complex parameters in `SusHiMi`

- **interference** factors η modify prediction of $\sigma \times \mathrm{BR}$

Summary: $\not{C}\not{P}$ benchmark with $h_2 - h_3$ interference

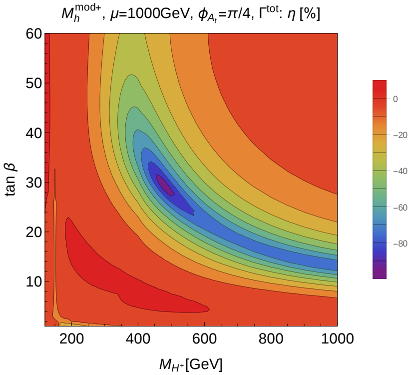
- **propagator mixing** with loop-induced $\not{C}\not{P}$
  - $\boldsymbol{h, H, A \to h_1, h_2, h_3}$:
    full propagators approximated by BW-propagators with $\hat{\mathbf{Z}}$-factors
- **Higgs production** with complex parameters in `SusHiMi`
- **interference** factors $\boldsymbol{\eta}$ modify prediction of $\sigma \times \mathrm{BR}$
- **$\mathcal{CP}$-violating benchmark scenario $m_{h_1}^{125}$(CPVint)** with ϕ_{A_t}, ϕ_{M_3}
  - mixing-enhanced cross sections
  - destructive interference suppresses combined h_2, h_3 rate
    $\hookrightarrow$ **interference has significant impact on exclusion limits**
    $\hookrightarrow$ incoherent sum $\sigma_H + \sigma_A$ not sufficient

APPENDIX

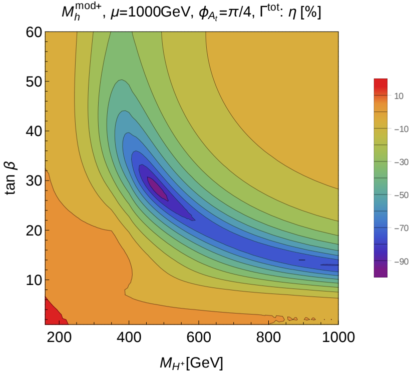
Interference effect in $\{b\bar{b}, gg\} \rightarrow h_a \rightarrow \tau\tau$

relative interference contribution $\boxed{\eta := \frac{\sigma_{\text{int}}(\phi_{A_t})}{\sigma_{\text{incoh}}(\phi_{A_t})}}$ in $\mathbb{C}M_h^{\text{mod+}}$ scenario

$b\bar{b}h_a$ production



gluon fusion



[EF, Weiglein 1705.05757]

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2 effects of $\mathcal{CP}$-mixing on cross sections × BR in $\mathbb{C}M_h^{\text{mod}+}$

enhancement by mixing $\hat{\mathbf{Z}}$-factors, reduction by destructive interference

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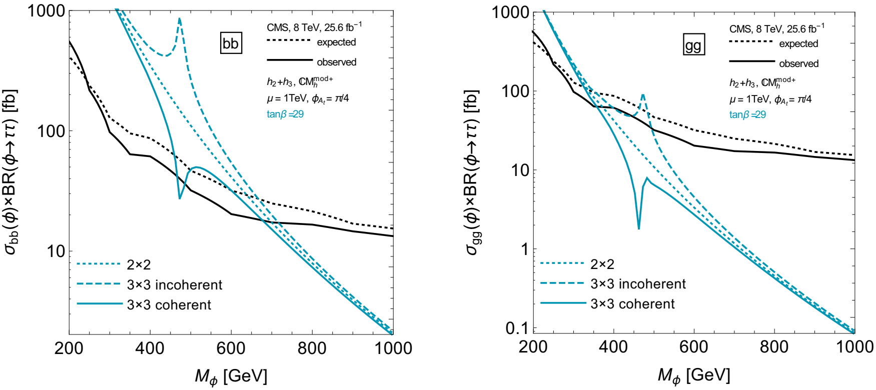

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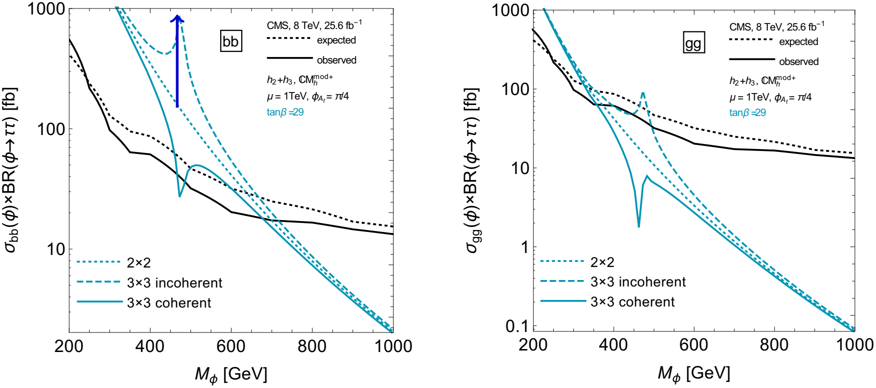

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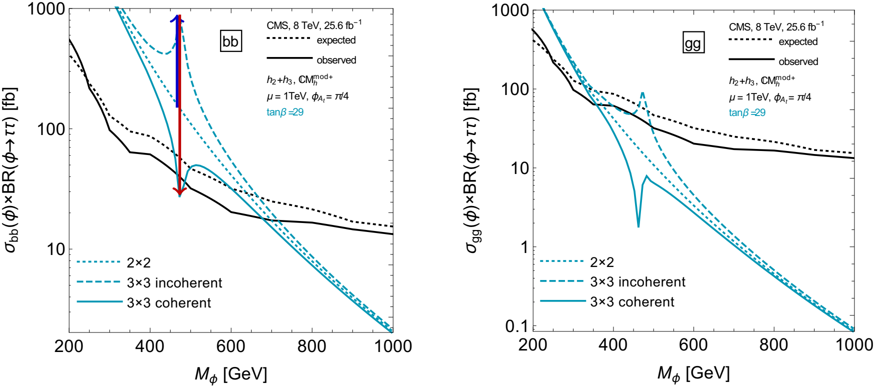
enhancement by mixing $\hat{\mathbf{Z}}$-factors, reduction by destructive interference

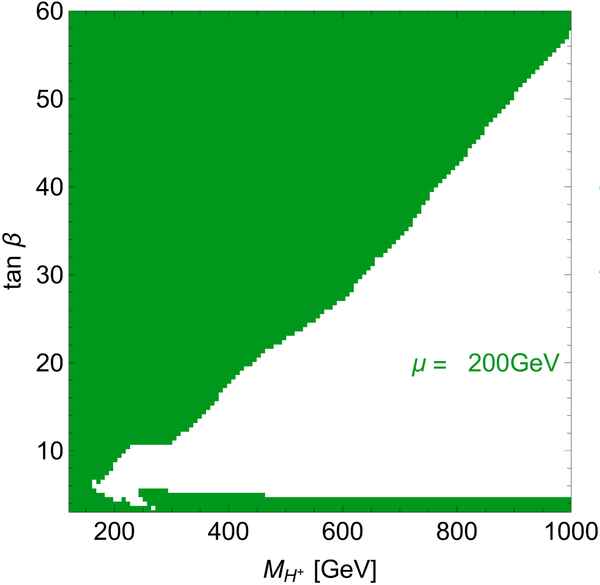
[EF, Weiglein 1705.05757]



interference can suppress $\sigma_{\text{coh}} < \sigma_{\text{exp}}$ for some $(M_\phi, \tan\beta)$

Impact of the interference on exclusion bounds

HiggsBounds 4.2.0

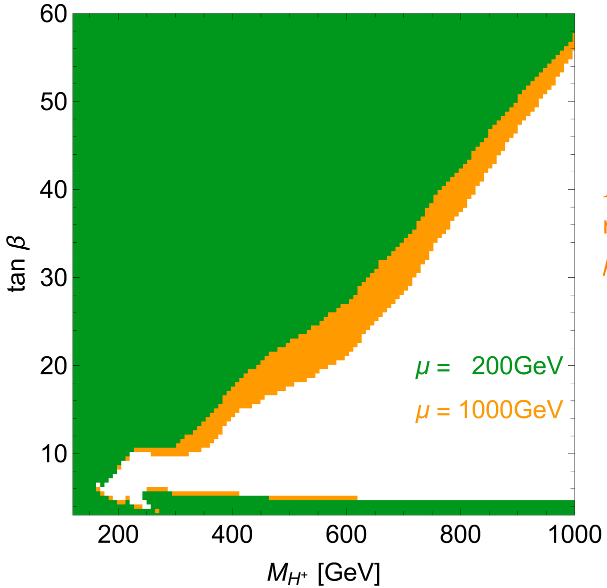


default $M_h^{\text{mod}+}$ scenario:
real parameters
$\mu = 200\,\text{GeV}$

[EF, Weiglein 1705.05757]

Impact of the interference on exclusion bounds

HiggsBounds 4.2.0

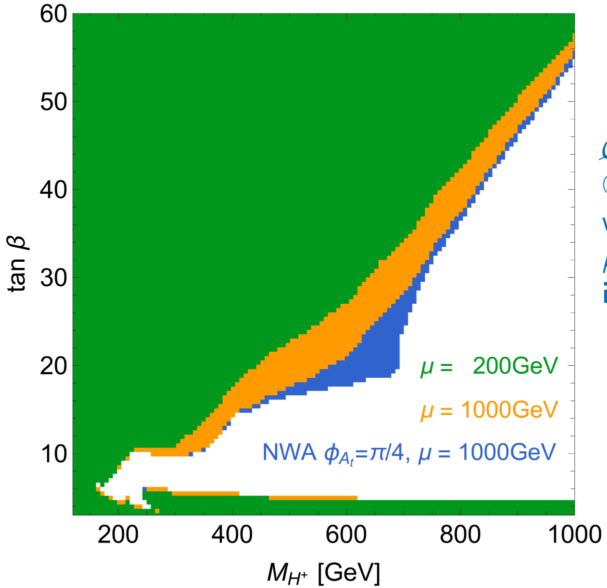


$M_h^{\mathrm{mod}+}$ scenario:
real parameters
$\mu = 1000\,\mathrm{GeV}$

[EF, Weiglein 1705.05757]

Impact of the interference on exclusion bounds

HiggsBounds 4.2.0

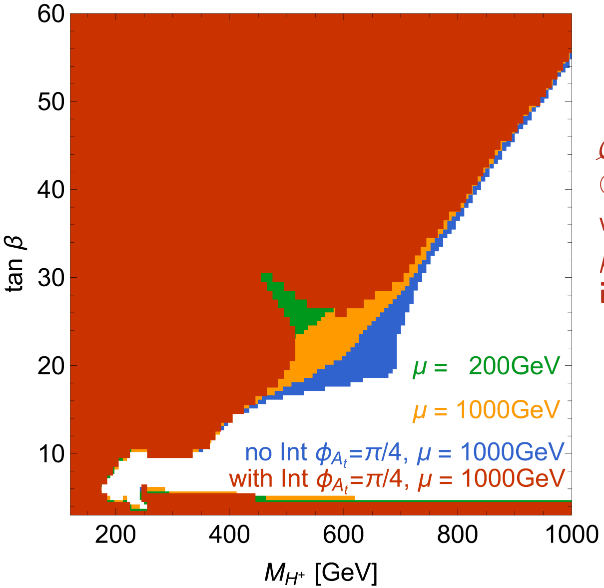


$\mathcal{CP}$ benchmark
$\mathbb{C}M_h^{\mathrm{mod+}}$:
with $\phi_{A_t} = \pi/4$
$\mu = 1000\,\mathrm{GeV}$
interference neglected

[EF, Weiglein 1705.05757]

Impact of the interference on exclusion bounds

HiggsBounds with interference implementation

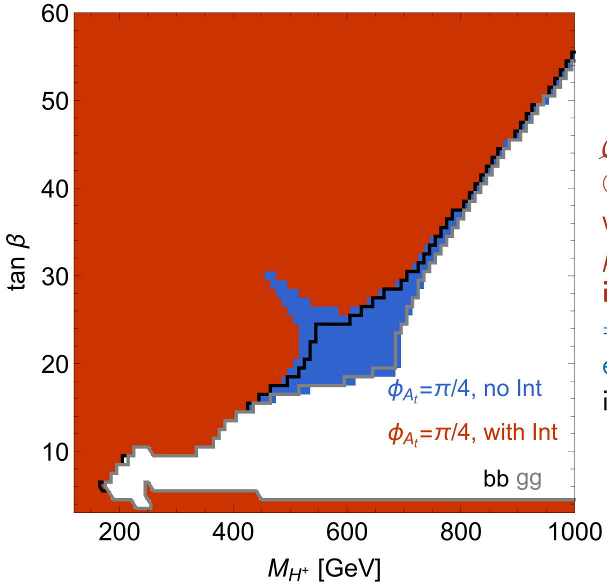


$\mathcal{CP}$ benchmark
$\mathbb{C}M_h^{\mathrm{mod}+}$:
with $\phi_{A_t} = \pi/4$
$\mu = 1000\,\mathrm{GeV}$
interference included

[EF, Weiglein 1705.05757]

Impact of the interference on exclusion bounds

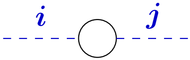
`HiggsBounds` with interference implementation



$\mathcal{CP}$ benchmark
$\mathbb{C}M_h^{\text{mod}+}$:
with $\phi_{A_t} = \pi/4$
$\mu = 1000\,\text{GeV}$
interference included
$\Rightarrow$ significant shift of exclusion bounds
impact of **bb** and gg

[EF, Weiglein 1705.05757]

Full mixing propagators



mixing self-energies $\hat{\Sigma}_{ij}(p^2)$, $\quad i, j = h, H, A$

- mass matrix $\mathbf{M}_{ij} = m_i^2 \delta_{ij} - \hat{\Sigma}_{ij}(p^2)$

2-point vertex functions: $\hat{\mathbf{\Gamma}}_{hHA} = i\left[p^2 \mathbf{1} - \mathbf{M}(p^2)\right]$

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

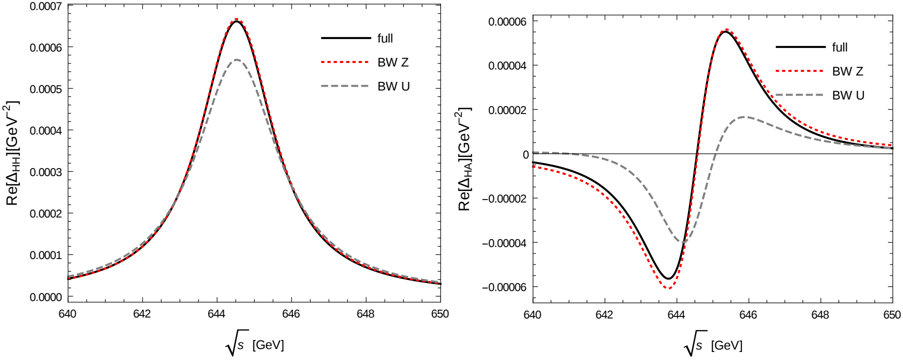
- diagonal propagator $\Delta_{ii}(p^2) = \frac{i}{p^2 - m_i^2 + \hat{\Sigma}_{ii}^{\rm eff}(p^2)}$

complex poles of propagators: $\boxed{\mathcal{M}_{h_a}^2 = M_{h_a}^2 - i M_{h_a} \Gamma_{h_a}}$

- higher-order masses M_{h_a} and widths Γ_{h_a}, $\; a = 1, 2, 3$

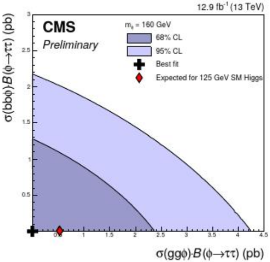
$\mathcal{CP}$ eigenstates $\boldsymbol{h, H, A}$ $\rightarrow$ mass eigenstates $\boldsymbol{h_1, h_2, h_3}$

$\hat{Z}$-factors vs. effective couplings

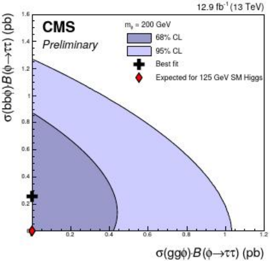


[EF, Weiglein 1610.06193]

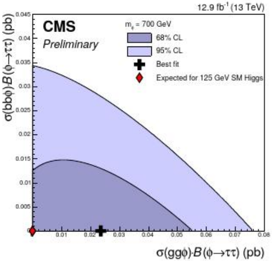
2D-limits [CMS PAS HIG-16-037]



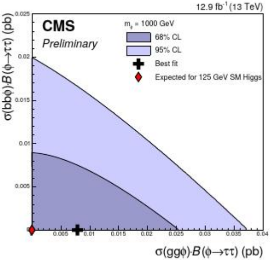
(d) $m_\phi = 160$ GeV



(e) $m_\phi = 200$ GeV



(g) $m_\phi = 700$ GeV



(h) $m_\phi = 1000$ GeV