Interference effects in MSSM Higgs searches

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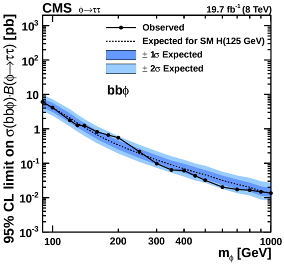
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

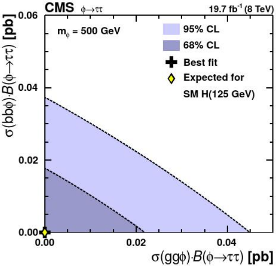
Interpretation of searches for additional scalars

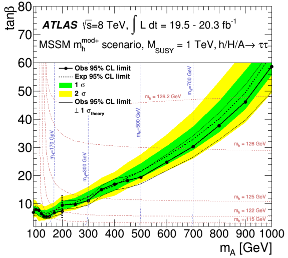
Experimental searches for $\Phi = h, H, A$

$\hookrightarrow$ talks by Köneke, Saxena, Vickey, Vormwald

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





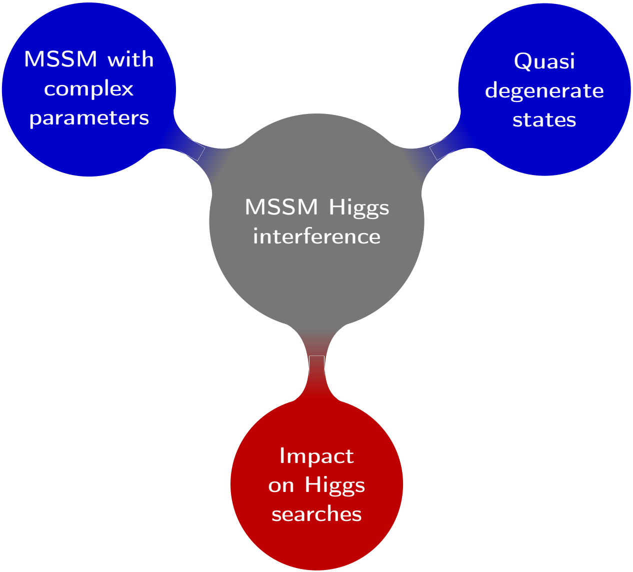


ATLAS-CONF-2014-049, CMS-HIG-13-021; ATLAS-CONF-2015-061, CMS-PAS-HIG-16-006

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

interference terms neglected, relevant especially with complex phases

Outline


MSSM with complex parameters
Quasi degenerate states
MSSM Higgs interference
Impact on Higgs searches

Complex phases in the MSSM Higgs sector

Motivation

- 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

Mixing and overlapping resonances

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

e.g. [Carena, Ellis, Pilaftsis, Wagner '00] [Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein '06]
[Williams, Weiglein '07] [Paßehr, Hollik]...

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

[EF, Weiglein (in preparation)]

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

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

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

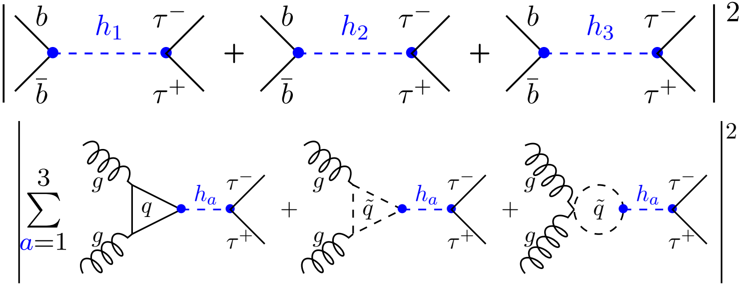
MSSM: Higgs bosons can be quasi degenerate and interfere

$\mathbb{R}$	h, H	$M_h \simeq M_H$ at high $\tan\beta$, low M_A
$\mathbb{C}$	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

Production, decay and interference with ϕ_{A_t}

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



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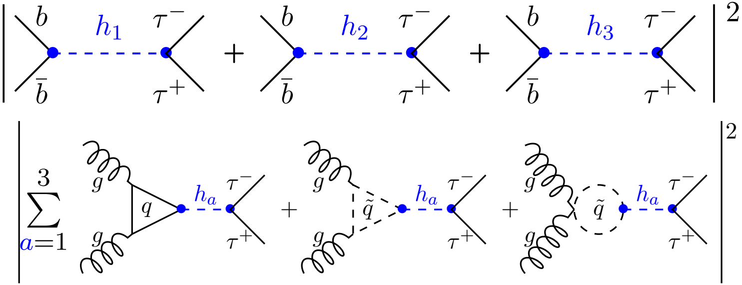


$\mathcal{CP}$-violating benchmark scenario

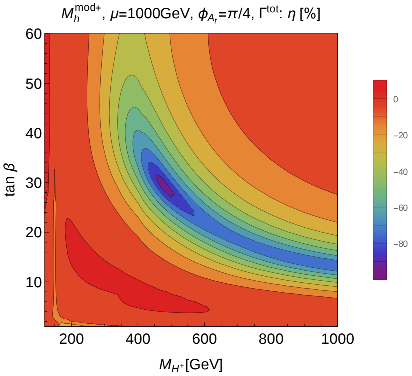
$M_h^{\text{mod}+}$ scenario with $\mu = 1000\,\text{GeV}$ and $\phi_{A_t} = \pi/4$

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

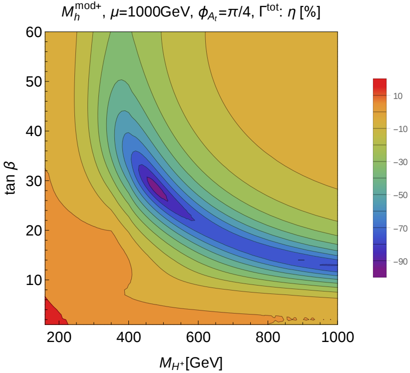
Interference effect in $\{b\bar{b}, gg\} \rightarrow h_a \rightarrow \tau\tau$

relative interference contribution $\boxed{\eta := \frac{\sigma_{\text{int}}(\phi_{A_t})}{\sigma_{\text{incoh}}(\phi_{A_t})}}$

$b\bar{b}h_a$ production



gluon fusion

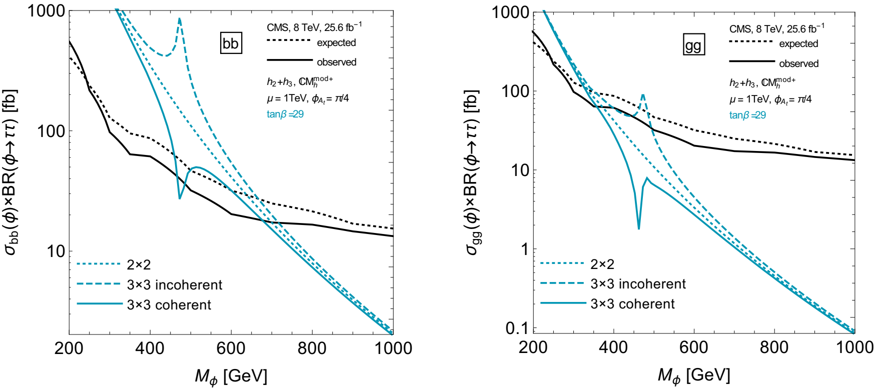


drastic, destructive interference effect

Comparison with experimental exclusion bounds

2 effects of $\not{C}\not{P}$-mixing on cross sections × BR

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



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

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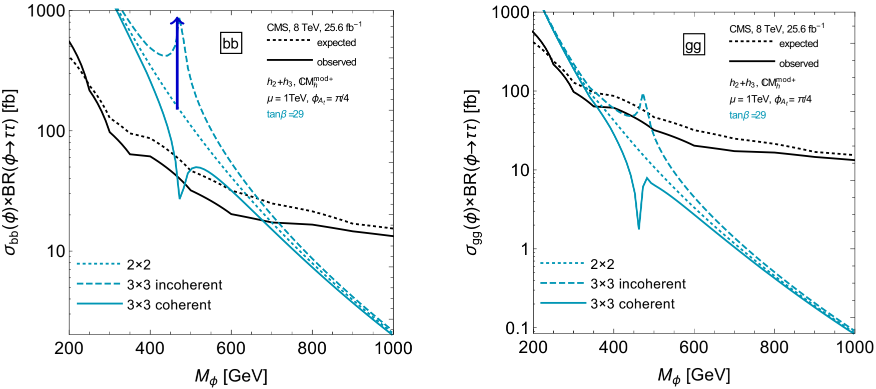

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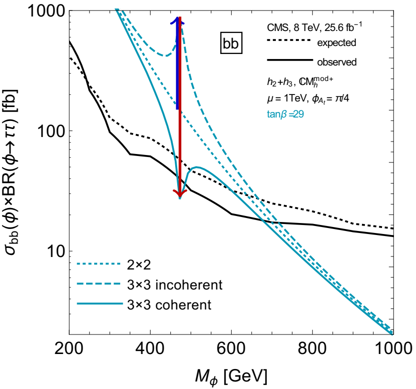
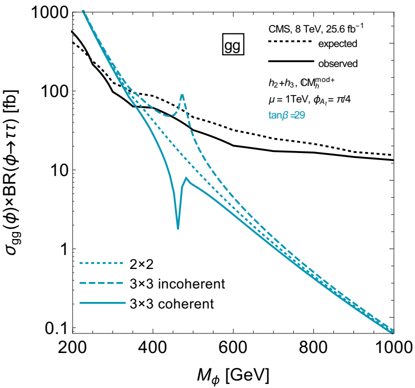
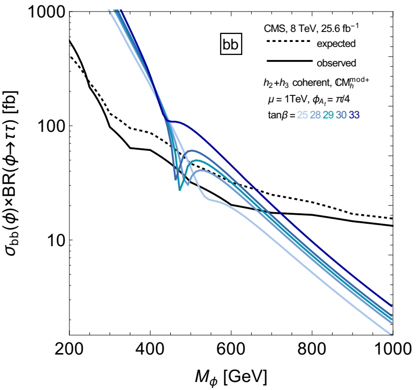
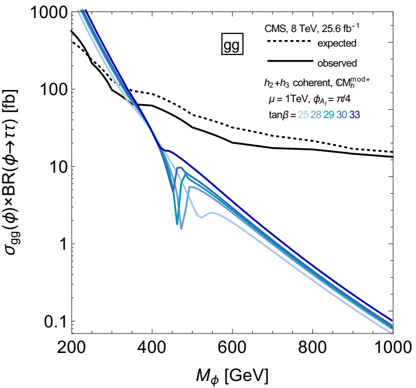




interference can suppress $\sigma_{\rm coh} < \sigma_{\rm exp}$ for some $(M_\phi, \tan\beta)$

tan β-dependence of coherent cross sections





- bb at $\tan\beta$ of strongest interference: few unexcluded M_ϕ
- bb at $\tan\beta$ at weaker interference: allowed region starts at lower M_ϕ
- gg: suppression relevant in 2D limits of (bb, gg) combination

systematic comparison of σ_{coh} vs σ_{exp} needed for each $(M_{H^\pm}, \tan\beta)$

Combination of precise building blocks

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

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

Combination of precise building blocks

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

↓

Interference incl. propagator corrections:

We included the interference terms by rescaling the production $P = b\bar{b}, gg$:

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

↓

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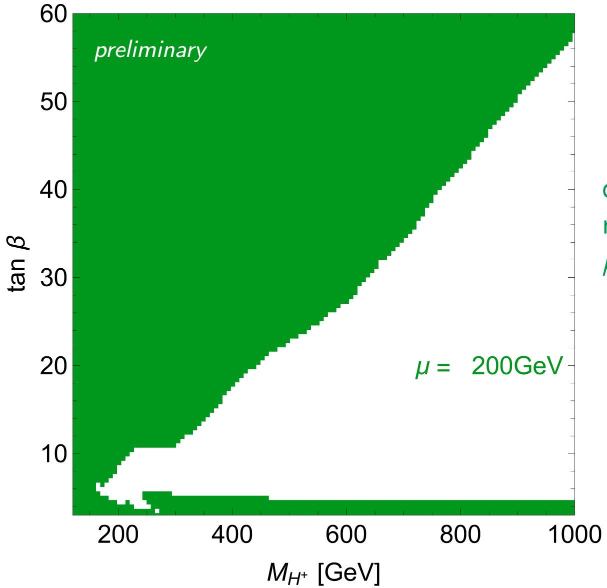
Decay: branching ratios for $h_a \to \tau^+\tau^-$ from FeynHiggs

⇓

Confront with experimental data: input for HiggsBounds

Impact of the interference on exclusion bounds

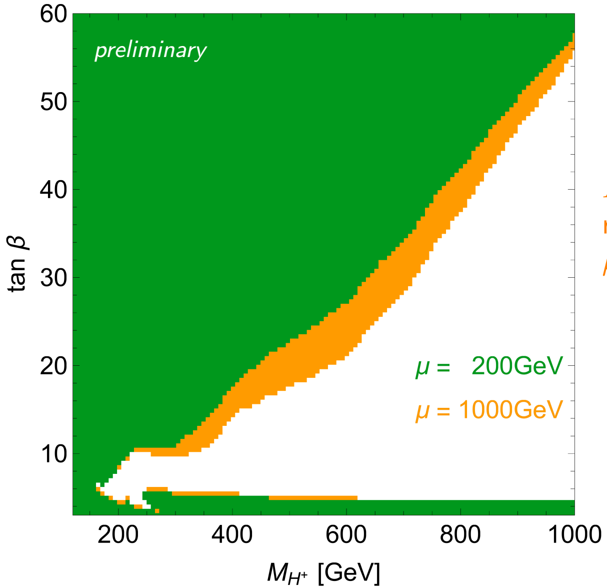
HiggsBounds



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

Impact of the interference on exclusion bounds

HiggsBounds



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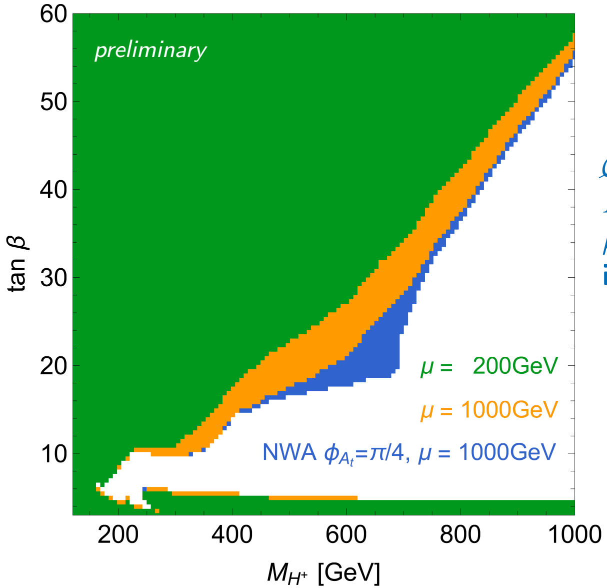
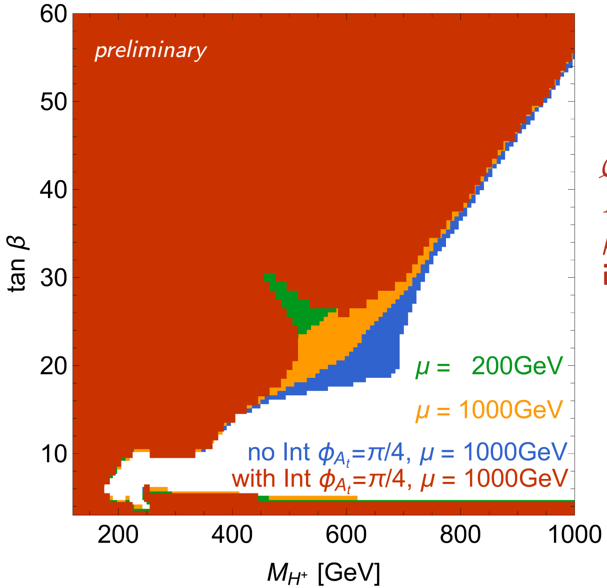


$\mathcal{CP}$ benchmark:
$M_h^{\mathrm{mod}+}$ with $\phi_{A_t} = \pi/4$
$\mu = 1000\,\mathrm{GeV}$
interference neglected

Impact of the interference on exclusion bounds

HiggsBounds with interference implementation



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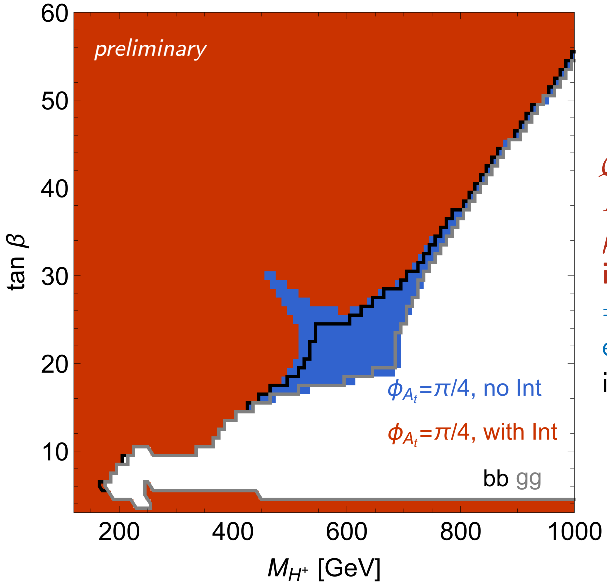

$\mathcal{CP}$ benchmark:
$M_h^{\mathrm{mod+}}$ with $\phi_{A_t} = \pi/4$
$\mu = 1000\,\mathrm{GeV}$
interference included
⇒ significant shift of exclusion bounds
impact of **bb** and **gg**

Summary: Interference in MSSM Higgs searches

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

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- **$\mathcal{CP}$-violating benchmark scenario** with ϕ_{A_t}
  - combination of bb and gg initiated processes
  - mixing-enhanced cross sections ($\hat{\mathbf{Z}}$)
  - destructive interference suppresses combined h_2, h_3 cross section
    $\hookrightarrow$ **interference has significant impact on exclusion limits**
    $\hookrightarrow$ incoherent sum $\sigma_H + \sigma_A$ not sufficient

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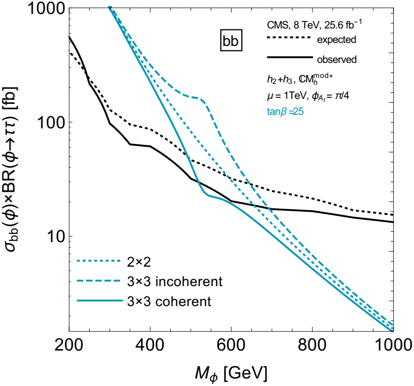
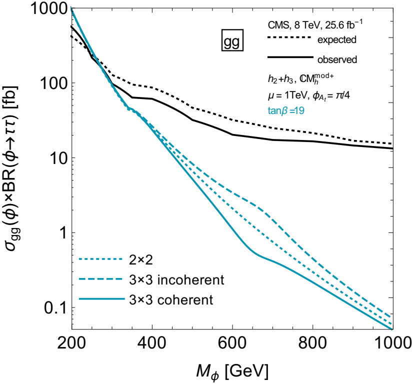
- Outlook:
  - use new `SusHiMi` cross sections for complex parameters
    [Liebler, Patel, Weiglein (in preparation)]
  - automatise interference calculation for `HiggsBounds`
  - update for Run II

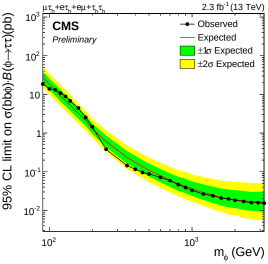
APPENDIX

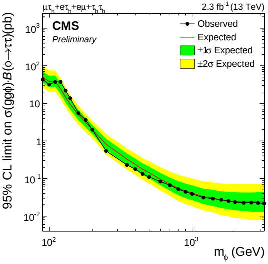
Coherent and incoherent cross sections

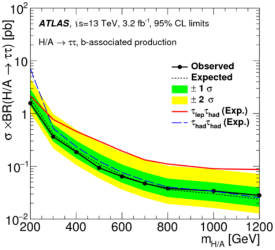


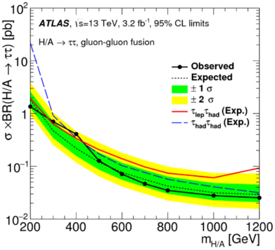


Bounds by CMS and ATLAS at 13 TeV

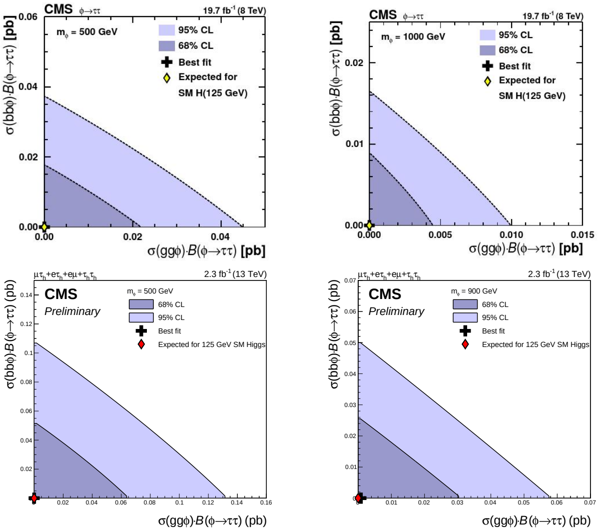








2D-limits



CMS φ→ττ
19.7 fb-1 (8 TeV)
m_φ = 500 GeV
95% CL
68% CL
Best fit
Expected for SM H(125 GeV)
σ(bbφ)·B(φ→ττ) [pb]
σ(ggφ)·B(φ→ττ) [pb]
CMS φ→ττ
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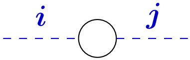
μτh+eτh+eμ+τhτh
2.3 fb-1 (13 TeV)
CMS
Preliminary
m_φ = 500 GeV
68% CL
95% CL
Best fit
Expected for 125 GeV SM Higgs
σ(bbφ)·B(φ→ττ) (pb)
σ(ggφ)·B(φ→ττ) (pb)
μτh+eτh+eμ+τhτh
2.3 fb-1 (13 TeV)
CMS
Preliminary
m_φ = 900 GeV
68% CL
95% CL
Best fit
Expected for 125 GeV SM Higgs
σ(bbφ)·B(φ→ττ) (pb)
σ(ggφ)·B(φ→ττ) (pb)

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

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}, $a = 1, 2, 3$

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

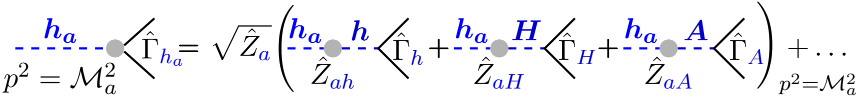
Finite wave function normalisation Z-factors

- 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]...

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

$$\begin{pmatrix} \hat{\Gamma}_{h_a} \\ \hat{\Gamma}_{h_b} \\ \hat{\Gamma}_{h_c} \end{pmatrix} = \hat{\mathbf{Z}} \cdot \begin{pmatrix} \hat{\Gamma}_{h} \\ \hat{\Gamma}_{H} \\ \hat{\Gamma}_{A} \end{pmatrix}, \quad \hat{\mathbf{Z}}_{aj} = \sqrt{\hat{Z}_a}\hat{Z}_{aj}$$



Breit-Wigner approximation of full propagators

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

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

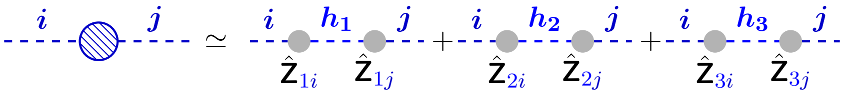
- approximation of **full propagator** (interaction basis) around $p^2 \simeq \mathcal{M}_{h_a}^2$:

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

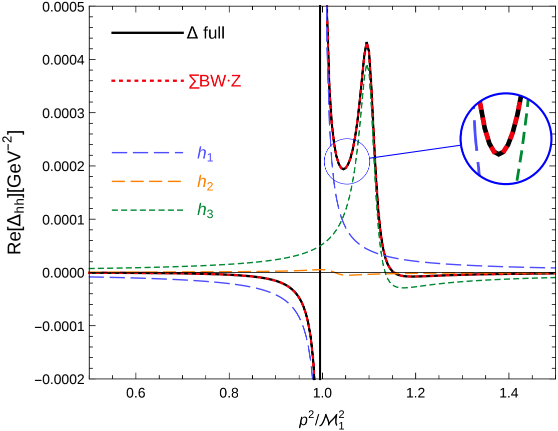
- consider all 3 complex poles $\mathcal{M}_a^2,\ a = 1,2,3$

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

[EF, Weiglein (in preparation)]



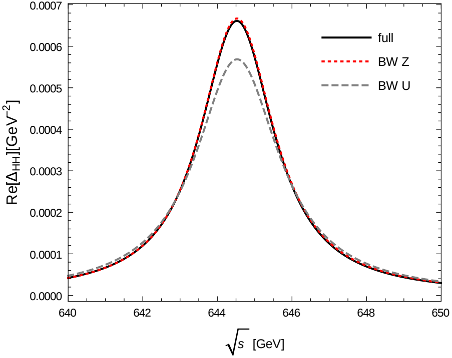
Comparison: Breit-Wigner and full propagators

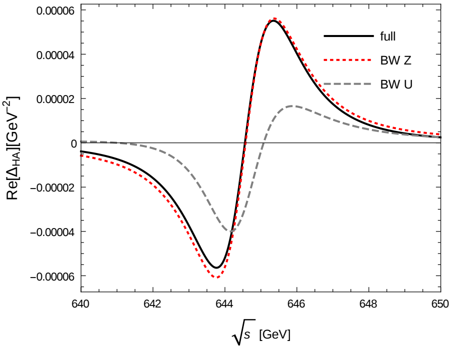


- scenario with 3 light Higgs bosons $\Rightarrow$ overlap of resonance regions

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

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

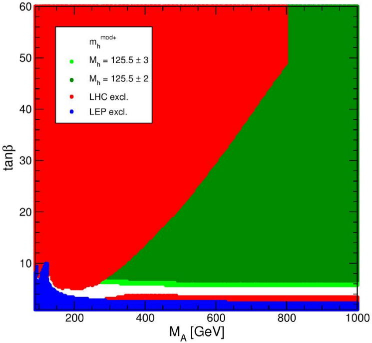




Benchmark scenario: $M_h^{\text{mod}+}$

$$
\begin{aligned}
M_{\text{SUSY}} &= 1000\,\text{GeV} \\
M_2 &= 200\,\text{GeV} \\
X_t^{\text{OS}} &= 1.5 M_{\text{SUSY}} \\
A_t &= A_b = A_\tau \\
M_3 &= 1500\,\text{GeV} \\
M_{\tilde{f}_3} &= M_{\text{SUSY}} \\
M_{\tilde{q}_{1,2}} &= 1500\,\text{GeV} \\
M_{\tilde{l}_{1,2}} &= 500\,\text{GeV} \\
\mu = \pm 200, \pm 500, &\quad \pm 1000\,\text{GeV}
\end{aligned}
$$

[Carena, Heinemeyer, Stål, Wagner, Weiglein '13]



Major part of open region compatible with M_h^{exp}

$\mathcal{CP}$ benchmark scenario

$M_h^{\text{mod}+}$ scenario with $\mu = 1000\,\text{GeV}$ and $\phi_{A_t} = \pi/4$

- effect of ϕ_{A_t} on cross section:

$$\delta := \frac{\sigma(\phi_{A_t})}{\sigma(0)} - 1$$

- Breit-Wigner approximation:

$$\epsilon := \frac{\sigma_{\text{BW}\hat{\mathbf{z}}}}{\sigma_{\text{full}}} - 1$$