Novel signatures of additional Higgs bosons at the LHC

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LHC Physics Discussion

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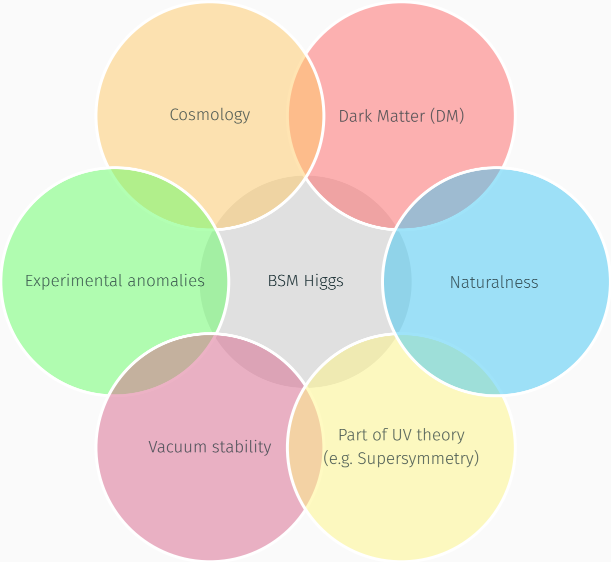
New physics in the Higgs sector?



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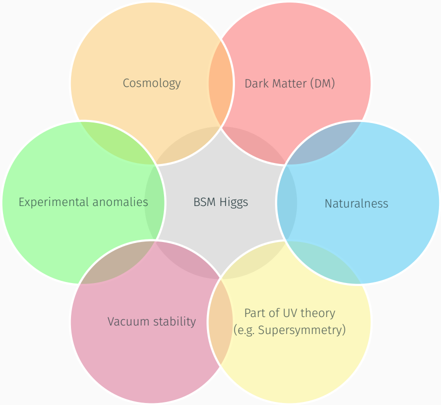


Possible BSM effects:

(I) Modifications of 125 GeV Higgs boson properties (couplings, decay rates, $\mathcal{CP}$);

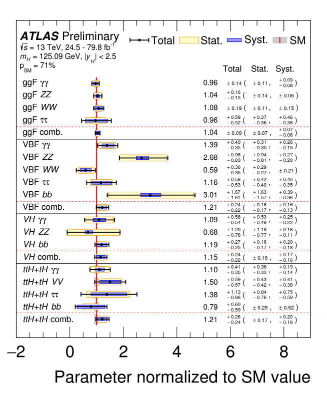
(II) Presence of additional (neutral/charged) scalar bosons;

(III) Presence of other new particles (e.g. SUSY particles) interacting with the Higgs boson.

...

$\Rightarrow$ Higgs sector is an exciting place to look for new physics!

- 125 GeV Higgs boson: measurements consistent with SM hypothesis.



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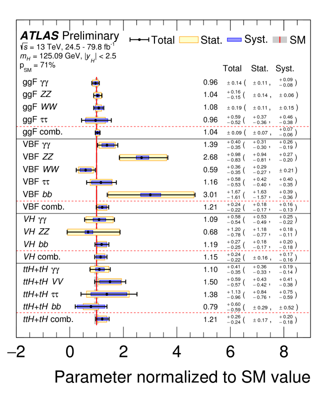
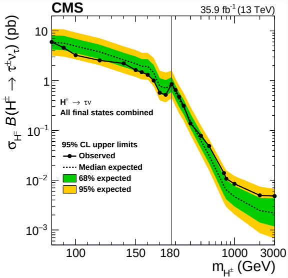
- Searches for additional Higgs bosons: only limits, limits, limits, ...





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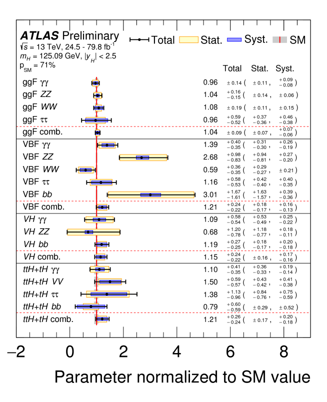

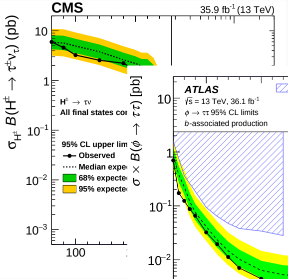

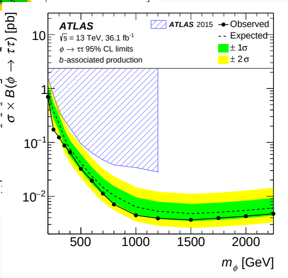

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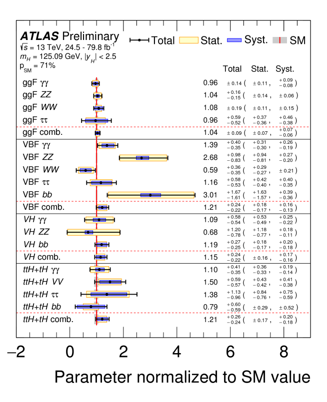

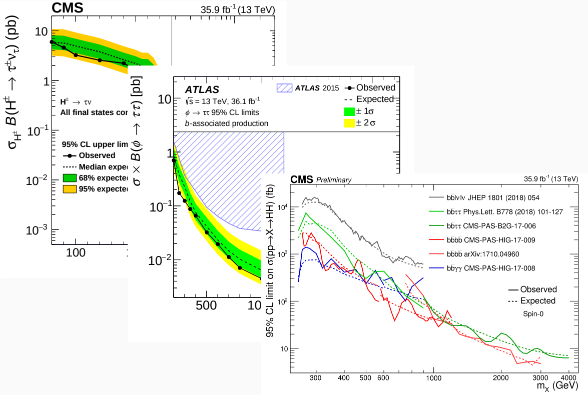

In addition: No signals in other new physics searches (SUSY, Dark Matter, ...), stringent limits on EDMs, ...

Searching for additional scalars at the LHC

Main LHC search channels for neutral and charged scalars:

$pp \to \phi \to \tau^+\tau^-$
$pp \to \phi \to t\bar{t}$
$pp \to \phi \to VV$ $(V = W^\pm, Z)$
$pp \to \phi \to \gamma\gamma$
$pp \to Z\phi \to Z(\text{invisible})$
$pp \to \phi \to h_{125}h_{125}$
$pp \to h_{125} \to \phi\phi$
$pp \to \phi_2 \to \phi_1 Z$

$pp \to tb\phi^\pm$, $\phi^\pm \to \tau\nu$
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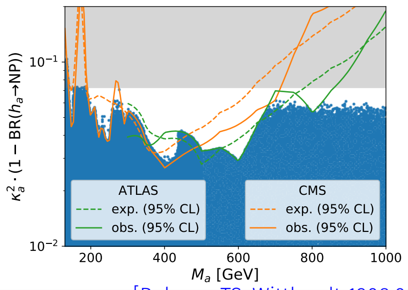

[Robens, TS, Wittbrodt 1908.08554]

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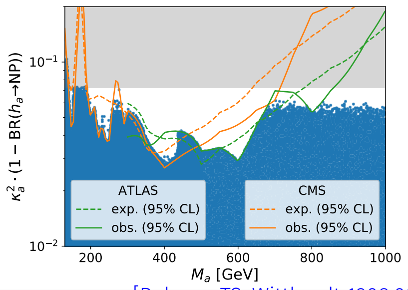

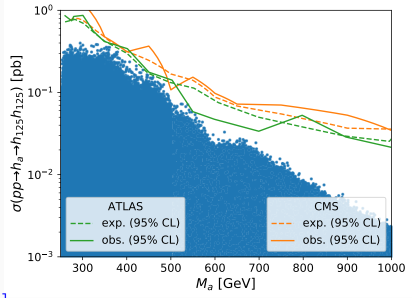

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Are there any (well-motivated) signatures missing? $\Rightarrow$ **Yes!** E.g.:

1. $pp \to \phi_i(+X), \ \phi_i \to \phi_j\phi_k$ $\to$ Two Real Scalar Singlet extension
2. $pp \to \phi^\pm(+X), \ \phi^\pm \to W^\pm\phi$ $\to$ Two Higgs Doublet Model
3. $pp \to \phi \to$ new particles $\to$ MSSM (backup slides)

Scalar Singlet Extensions of the SM

Additional scalar boson(s) only couple to SM gauge bosons and fermions if singlet field(s) mix with SM Higgs field. E.g., for a real singlet field s,

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_{\mathrm{SM}} \\ s \end{pmatrix}$$

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Couplings of h_a to SM particles

- rescaled *universally* by κ_a,
- orthogonality of mixing matrix: $\Rightarrow$ sum rule $\sum_a {\kappa_a}^2 = 1$.

Multi-scalar couplings

- originate from scalar potential parameters,
- can be very different to SM-like Higgs self-coupling.

The Two-Real-Singlet-Model (TRSM)

Scalar potential (Φ: $SU(2)_L$ doublet, S, X: $SU(2)_L$ singlets)

$$\mathcal{V} = \mu_\Phi^2 \Phi^\dagger \Phi + \mu_S^2 S^2 + \mu_X^2 X^2 + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_S S^4 + +\lambda_X X^4 + \lambda_{\Phi S} \Phi^\dagger \Phi S^2 + \lambda_{\Phi X} \Phi^\dagger \Phi X^2 + \lambda_{SX} S^2 X^2.$$

Imposed $\mathbb{Z}_2 \times \mathbb{Z}_2'$ symmetry, which is spontaneously broken by singlet vevs.

$\Rightarrow$ three $\mathcal{CP}$-even neutral Higgs bosons: h_1, h_2, h_3

Two interesting cases:

Case (a): $\langle S \rangle \neq 0, \langle X \rangle = 0 \Rightarrow X$ is DM candidate;

Case (b): $\langle S \rangle \neq 0, \langle X \rangle \neq 0 \Rightarrow$ all scalar fields mix.

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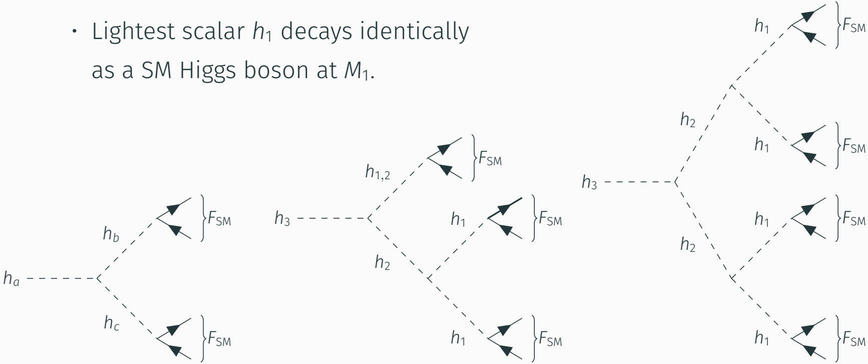
$\rightarrow$ *Model parameters*: 3 masses, 3 mixing angles, 3 vevs.

[Robens, TS, Wittbrodt 1908.08554]

Higgs-to-Higgs decay signatures ($\langle S \rangle \neq 0$, $\langle X \rangle \neq 0$)

Rich phenomenology of $h_i \to h_j h_k$ decays: [Robens, TS, Wittbrodt 1908.08554]

- h_1, h_2 or h_3 could be SM-like Higgs boson at 125 GeV,
- possible cascade decays ⇒ 3- and 4-Higgs boson final states!
- Lightest scalar h_1 decays identically as a SM Higgs boson at M_1.



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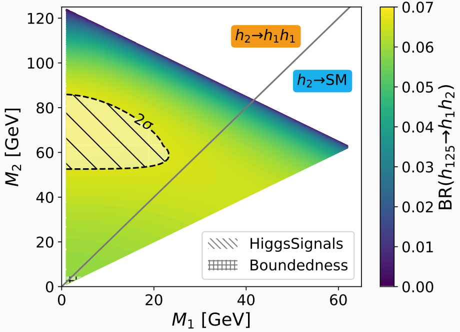
benchmark plane	h_{125} candidate	target signature	possible successive decays
BP1	h_3	$h_{125} \to h_1 h_2$	$h_2 \to h_1 h_1$ if $M_2 > 2M_1$
BP2	h_2	$h_3 \to h_1 h_{125}$	-
BP3	h_1	$h_3 \to h_{125} h_2$	$h_2 \to h_{125} h_{125}$ if $M_2 > 250\ \mathrm{GeV}$
BP4	h_3	$h_2 \to h_1 h_1$	-
BP5	h_2	$h_3 \to h_1 h_1$	-
BP6	h_1	$h_3 \to h_2 h_2$	$h_2 \to h_{125} h_{125}$ if $M_2 > 250\ \mathrm{GeV}$

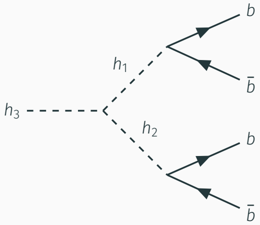
Benchmark scenarios suggested to LHC-HXSWG HH subgroup.

Benchmark plane 1: $h_3 \to h_1 h_2$ (with $h_3 = h_{125}$)

- Two light scalars with unknown masses $M_1, M_2 < 125\ \mathrm{GeV}$,
- Production of h_3 identical to SM Higgs: $\sigma(pp \to h_3) \simeq \sigma(pp \to h_{SM}) \sim 50\ \mathrm{pb}$.



$h_2 h_1$ signature ($M_2 < 2M_1$), e.g.



$\sigma_{13\ \mathrm{TeV}}(h_1 h_2) \lesssim 3\ \mathrm{pb}$

Idea: use invariant masses to (recursively) look for resonances in the spectrum.

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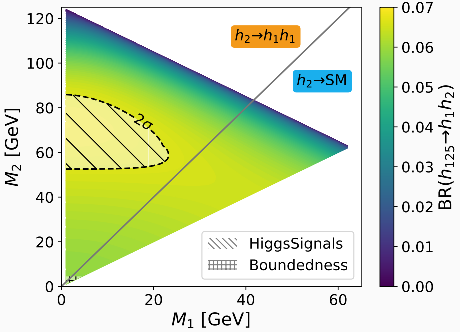
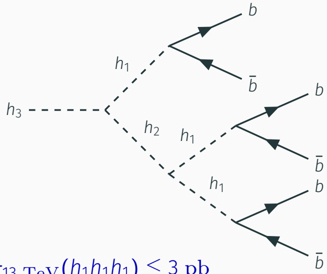


Triple-h_1 signature ($M_2 > 2M_1$), e.g.



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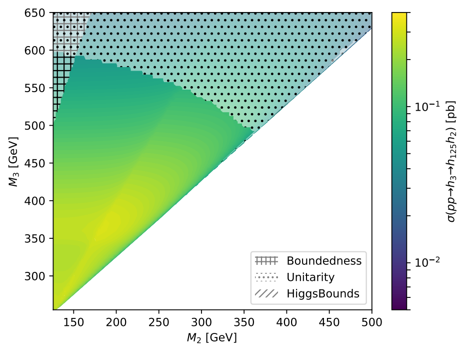
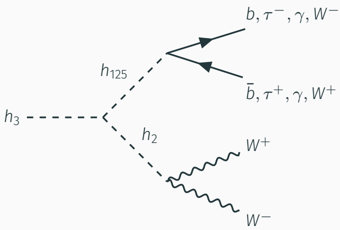
Idea: use invariant masses to (recursively) look for resonances in the spectrum.

Benchmark plane 3: $h_3 \to h_1 h_2$ (with $h_1 = h_{125}$)

- Two heavy scalars with unknown masses $125\ \mathrm{GeV} < M_2 < M_3$,
- Production of h_3 with signal strength $\mu \simeq 0.057$,
  decay rate $\mathrm{BR}(h_3 \to h_1 h_2) \sim (35 - 50)\%$.



$h_{125} h_2$ signature ($M_2 < 250$ GeV), e.g.



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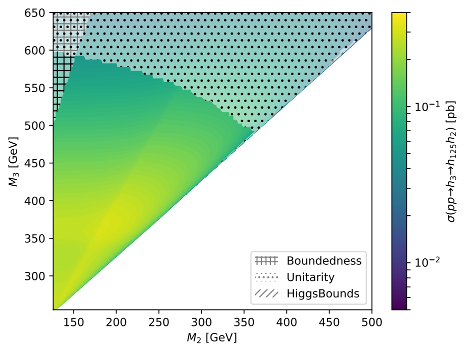
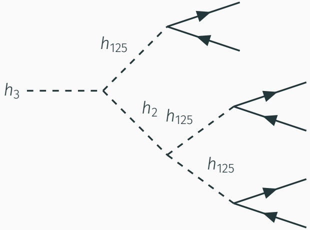


Triple-h_{125} signature ($M_2 > 250\ \mathrm{GeV}$):



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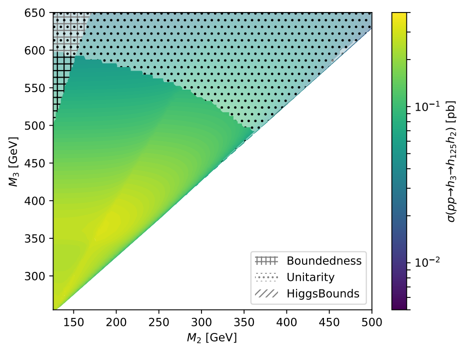
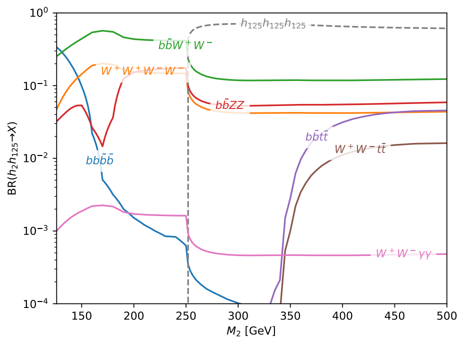
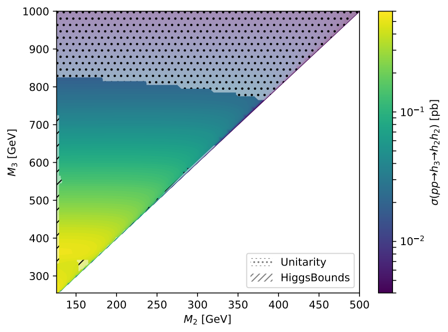


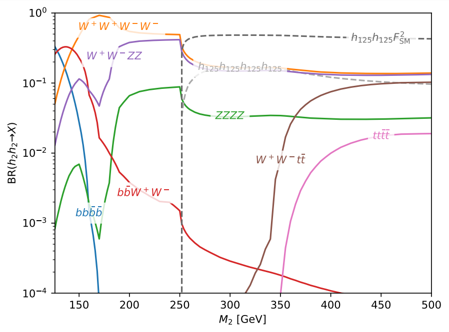
$\mathrm{BR}(h_2 h_1 \to \dots)$



Benchmark plane 6: $h_3 \to h_2 h_2$ (with $h_1 = h_{125}$)

- Two heavy scalars with unknown masses $125\ \mathrm{GeV} < M_2 < M_3$,
- Production of h_3 with signal strength $\mu \simeq 0.06$, decay rate $\mathrm{BR}(h_3 \to h_2 h_2) \sim (70 - 80)\%$.





- if $150 \leq M_2 \leq 250\ \mathrm{GeV} \Rightarrow W^+W^-W^+W^-$ final state seems most promising,
  $\to$ first $h_3 \to h_2 h_2$ search: [ATLAS, 1811.11028]
- if $M_2 > 250\ \mathrm{GeV} \Rightarrow$ spectacular $h_{125}h_{125}h_{125}h_{125}$ signature! [rate $\lesssim \mathcal{O}(10\ \mathrm{fb})$]

EXTRAPOLATION OF $pp \to H \to h_{125}h_{125} \to b\bar{b}b\bar{b}$ SEARCH

Consider $gg \to S_1 \to S_2S_2 \to b\bar{b}b\bar{b}$.

Extrapolation of current CMS search:

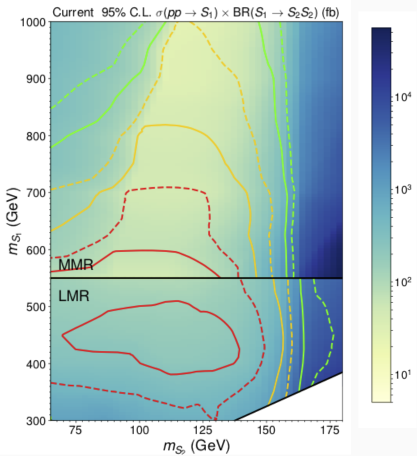
- modify $m_{b\bar{b}}$ criteria (for the case $M_{S_2} \neq 125~\mathrm{GeV}$).

For increasing M_{S_2}:

- QCD multi-b-jet background contamination in signal region (slowly) decreases,
- Signal rate (quickly) decreases with $\mathrm{BR}(H_2 \to b\bar{b})$.

$\Rightarrow$ Relevant for $M_2 \lesssim 150~\mathrm{GeV}$ (in TRSM).

[Barducci, Mimasu, No, Vernieri, Zurita, '19]



$\sin^2\alpha_1 = 0.003$ | $\sin^2\alpha_1 = 0.03$ | $\sin^2\alpha_1 = 0.2$
$\sin^2\alpha_1 = 0.005$ | $\sin^2\alpha_1 = 0.05$ | $\sin^2\alpha_1 = 0.5$
$\sin^2\alpha_1 = 0.01$ | $\sin^2\alpha_1 = 0.1$ | $\sin^2\alpha_1 = 1$

(assumes $\mathrm{BR}(S_2 \to S_1S_1) = 100\%$

Two-Higgs-Doublet Model (2HDM) $\Rightarrow$ 5 Higgs states $h, H, A, H^{\pm}$

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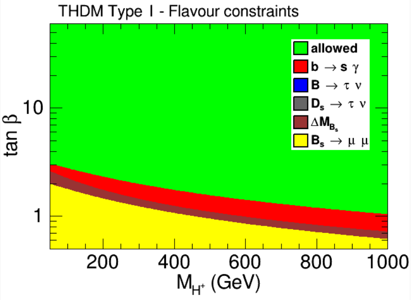
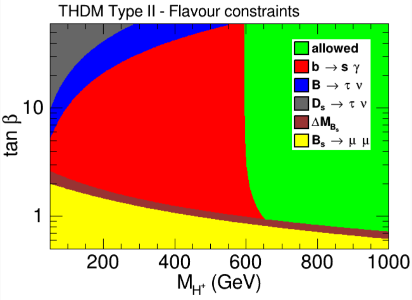
- Flavor observables $\Rightarrow$ constraints in $(M_{H^{\pm}}, \tan\beta)$ plane.





[Arbey, Mahmoudi Stål, TS '17]

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- Higgs measurements prefer *approximate alignment limit*:

$$g_{hVV} \propto \sin(\beta-\alpha) \approx 1, \quad \text{if light Higgs boson } h \text{ at } 125\ \mathrm{GeV},$$
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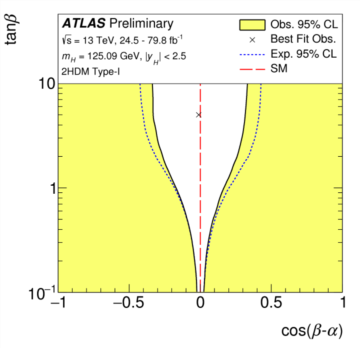

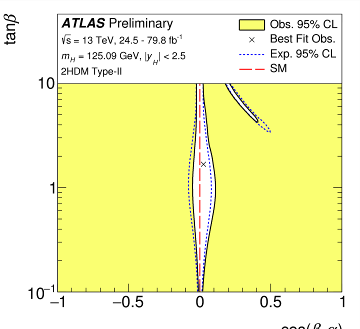

[ATLAS-CONF-2019-005]

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Important fact (in 2HDM):

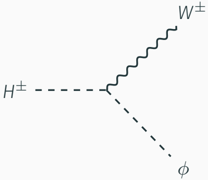
In the alignment limit the $H^\pm W^\mp \phi$ coupling is maximized

[ϕ denotes the non-SM-like $\mathcal{CP}$-even Higgs boson]:

$$g_{H^\pm W^\mp h} \propto \cos(\beta-\alpha), \quad g_{H^\pm W^\mp H} \propto \sin(\beta-\alpha)$$

$\Rightarrow$ If kinematically allowed: sizable $H^\pm \to W^\pm \phi$ decay rates!

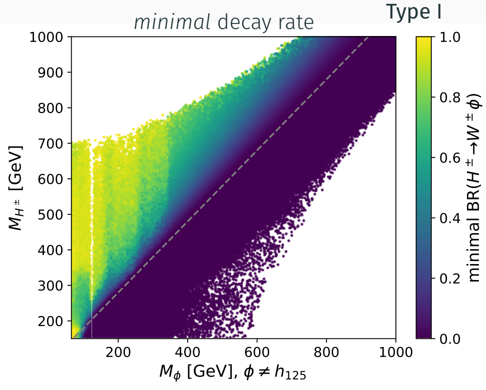
Charged-Higgs-to-neutral-Higgs decay signatures



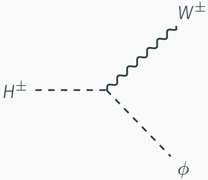
ϕ mostly decays to $b\bar{b}$, $\tau^+\tau^-$, or to $WW^*, ZZ^*, \gamma\gamma$ (if fermiophobic limit).

Current LHC $H^\pm$ searches mostly focus on fermionic final states ($\tau\nu_\tau$, tb).

$\Rightarrow$ become insensitive if bosonic $H^\pm$ decay modes dominate.



[TS 1908.10900], [TS, Wittbrodt (*in progress*)]



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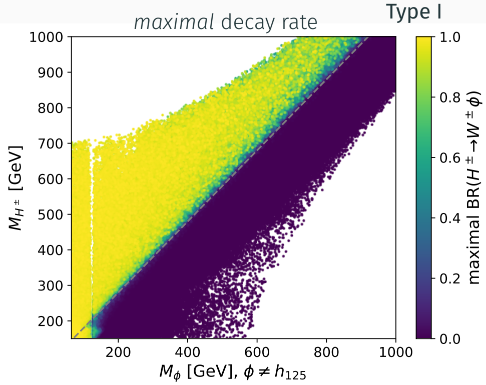

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Charged-Higgs-to-neutral-Higgs decay signatures

[TS, Wittbrodt (*in progress*)]

Production process	Higgs decay processes	Final state particles
$pp \to H^\pm tb$	$H^\pm \to W^\pm \phi, \phi \to \begin{cases} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{cases}$	$tbW^\pm + \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix}$
$pp \to H^\pm \phi$	$H^\pm \to W^\pm \phi, \phi \to \begin{cases} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{cases}$	$W^\pm + \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix} \oplus \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix}$
$pp \to H^\pm W^\mp$	$H^\pm \to W^\pm \phi, \phi \to \begin{cases} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{cases}$	$W^\pm W^\mp + \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix}$
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DESY-CMS efforts (D. Brunner, D. Krücker, I. Melzer-Pellmann).

[TS, Wittbrodt (*in progress*)]

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	bb … ZZ $\gamma\gamma$	bb … ZZ $\gamma\gamma$; bb … ZZ $\gamma\gamma$

$\Rightarrow$ Many new experimental opportunities for upcoming LHC Run(s)!

Heavy Higgs boson H at 125 GeV?

Can be realized in all 2HDM Types, with $\cos(\beta - \alpha) \approx 1$ (alignment limit), and light Higgs boson h with $g_{hVV} \approx 0$, and $M_h \in [M_H/2, 115]$ GeV.

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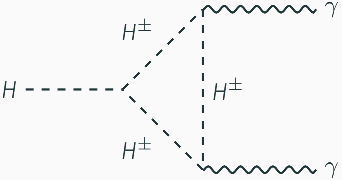
$$g_{HH^+H^-} \xrightarrow{c_{\beta-\alpha}\to 1} -\frac{1}{v}\left(M_H^2 + 2M_{H^+}^2 - 2\overline{m}^2\right) \xrightarrow{M_{H^+}\gg M_H} -\frac{2M_{H^+}^2}{v},$$



because $\overline{m}^2 \equiv 2m_{12}^2/\sin(2\beta) \lesssim \mathcal{O}(v^2)$ imposed by unitarity and stability conditions.

$\Rightarrow$ suppression of the $H \to \gamma\gamma$ rate!

[Bernon, Gunion, Haber, Jiang, Kraml '15].

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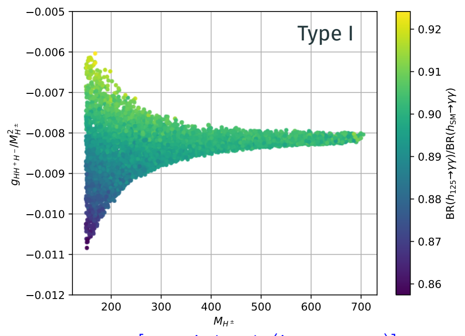

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Conclusions

Higgs-to-Higgs decays can appear at large rates in simple BSM models.

$\Rightarrow$ Dedicated LHC searches for these signatures are highly motivated!

$\phi_i \to \phi_j \phi_k$:

We provided six scenarios in the two-real-singlet model as benchmarks for

- searches that generalize existing $H \to h_{125} h_{125}$ and $h_{125} \to hh$ searches to masses $\neq 125\ \mathrm{GeV}$ and/or un-identical Higgs bosons in final state,
- novel searches for three- or four-Higgs final states that originate from cascade decays.

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- naturally appears in 2HDM in the alignment limit if $M_\phi < M_\phi^\pm$;
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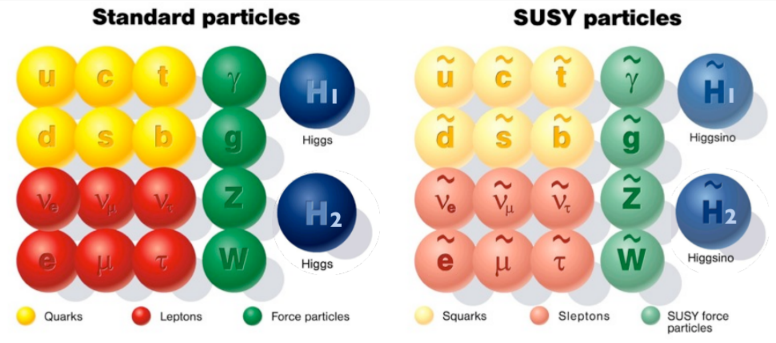
Thank you very much for your attention!

Backup Slides

THE MINIMAL SUPERSYMMETRIC STANDARD MODEL (MSSM)

SUSY: Hypothetical space-time symmetry relating fermions & bosons.

$\Rightarrow$ Introduce *superpartners* for every SM field.



- SUSY cannot be exact. Expect SUSY masses $\gtrsim \mathcal{O}(1\ \mathrm{TeV})$;
- Neutral/charged EW gauginos and Higgsinos $\xrightarrow{mix}$ neutralinos/charginos.

MSSM Higgs sector

The tree-level MSSM Higgs sector is a 2HDM of Type II with

$$\lambda_1 = \lambda_2 = \tfrac{1}{4}(g^2 + g'^2), \qquad \lambda_3 = \tfrac{1}{4}(g^2 - g'^2),$$
$$\lambda_4 = -\tfrac{1}{2}g^2, \qquad \lambda_5 = \lambda_6 = \lambda_7 = 0.$$

It is described by only two parameters: M_A, $\tan\beta$

Predicted tree-level mass spectrum:

$$M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right] \quad \Rightarrow M_h^{\text{tree}} \leq M_Z\ !$$
$$M_{H\pm}^2 = M_A^2 + M_W^2$$

(SM-like) Higgs mass M_h receives large radiative corrections:

$$(\Delta M_h^2)_{1L}^{t,\tilde{t}} \approx \frac{3m_t^4}{2\pi^2 v^2}\left[\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

$(M_A \gg M_Z, \tan\beta \gg 1)$
$X_t = A_t - \mu/\tan\beta$,
$M_S = \sqrt{M_{\tilde{t}_1} M_{\tilde{t}_2}}$.

$\Rightarrow$ with SUSY particles at TeV-scale we can get $M_h \lesssim 135\ \mathrm{GeV}$!

New MSSM Higgs benchmark scenarios – Overview

[Bagnaschi, Bahl, Fuchs, Hahn, Heinemeyer, Liebler, Patel, Slavich, TS, Wagner, Weiglein]

6 scenarios with fixed scale $M_S \sim \mathcal{O}(\mathrm{TeV})$, 2 scenarios with variable M_S.

M_h^{125}	"standard" scenario, all SUSY masses $\gtrsim 1\ \mathrm{TeV}$
$M_h^{125}(\tilde{\tau})$	light staus: sizable effect on $h \to \gamma\gamma$ at large $\tan\beta$
$M_h^{125}(\tilde{\chi})$	light EW-inos: new decay channels for heavy Higgs bosons
$M_h^{125}(\mathrm{alignment})$	h couplings very SM-like even at low M_A values
M_H^{125}	heavier MSSM Higgs boson H is SM-like at $\sim 125\ \mathrm{GeV}$
$M_h^{125}(\mathrm{CPV})$	interference effects suppress heavy Higgs rate in $\tau^+\tau^-$ channel

[Bagnaschi et al. 1808.07542]

$M_{h,\mathrm{EFT}}^{125}$	"standard" scenario for the low $\tan\beta$ region
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[Bahl, Liebler, TS 1901.05933]

(effort within the LHC Higgs Cross Section Working Group)

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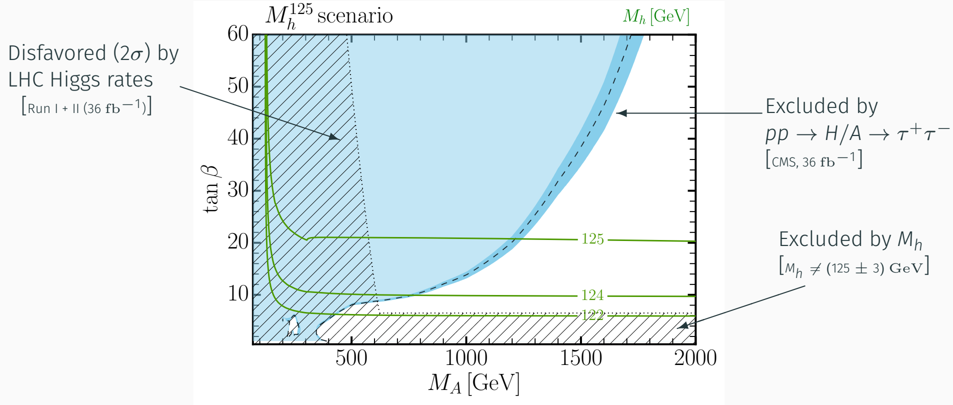
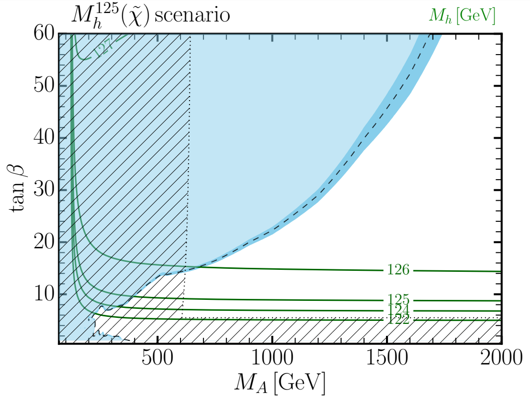
M_h^{125} BENCHMARK SCENARIO



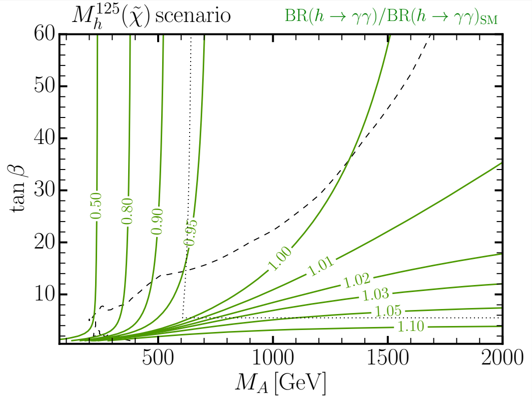
- Assumption: all SUSY particle masses are $\gtrsim 1\ \mathrm{TeV}$.
- Higgs rates & limits $\Rightarrow$ H, A and $H^{\pm}$ expected to be heavy (mass $\gtrsim 600\ \mathrm{GeV}$).

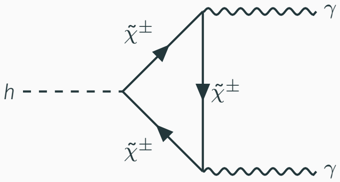
$M_h^{125}(\tilde{\chi})$ BENCHMARK SCENARIO: LIGHT NEUTRALINOS & CHARGINOS



- Light neutralinos and charginos with masses $\sim (100 - 250)$ GeV.
- Impact of $H/A \to \tau^+\tau^-$ search limit on parameter space weakened due to additional H/A decay modes.

$M_h^{125}(\tilde{\chi})$ BENCHMARK SCENARIO: LIGHT NEUTRALINOS & CHARGINOS





(large for $\mu \approx M_2$ and low $\tan\beta$)

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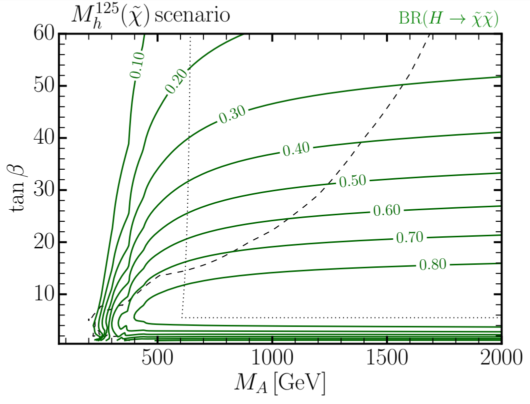

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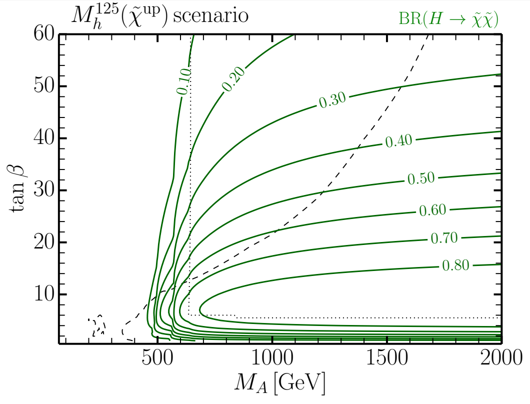

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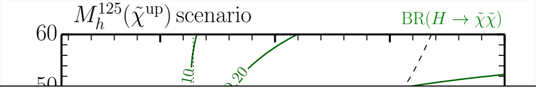

Dedicated experimental searches for $pp \to H/A \to \tilde{\chi}\tilde{\chi}$ well motivated:

- highly complementary to $pp \to \tilde{\chi}\tilde{\chi}$ searches, in particular if electroweakino mass spectrum is compressed;
- promising cascade decays (e.g., for $M_A = 1\,\mathrm{TeV}$, $\tan\beta = 10$):

$$pp \to H \xrightarrow{30\%} \tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp} \xrightarrow{51\%} (\tilde{\chi}_1 W^{\pm *})(\tilde{\chi}_1^{\mp} Z) \xrightarrow{100\%} W^{\pm *}W^{\mp *}Z + \not{E}_T$$

$$pp \to A \xrightarrow{9.4\%} \tilde{\chi}_2^{\pm}\tilde{\chi}_2^{\mp} \xrightarrow{26\%} (\tilde{\chi}_1^{\pm} Z)(\tilde{\chi}_1^{\mp} Z) \xrightarrow{100\%} W^{\pm *}W^{\mp *}ZZ + \not{E}_T$$

$\Rightarrow$ multi-W/Z-boson + $\not{E}_T$ signatures.

- Discovery would reveal existence of BSM Higgs bosons *and* SUSY particles!

- Light neutralinos and charginos with masses $\sim (100 - 250)$ GeV.
- Impact of $H/A \to \tau^+\tau^-$ search limit on parameter space weakened due to additional H/A decay modes.
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Re-opening the low $\tan\beta$ region

Standard scenarios: $M_h < 122\,\mathrm{GeV}$ for **tan** $\beta \lesssim 6$, because $M_S \sim (1-2)\,\mathrm{TeV}$.

Allow *lower* **tan** β *values* by *tuning* $M_h = 125\,\mathrm{GeV}$ *at every point*:

$$\mathcal{O}(\mathrm{TeV}) \lesssim M_S \lesssim 10^{16}\,\mathrm{GeV}.$$

Employ an effective field theory (EFT) calculation with a low-energy 2HDM (plus electroweakinos and/or gluinos). [Bahl, Hollik 1805.00867]

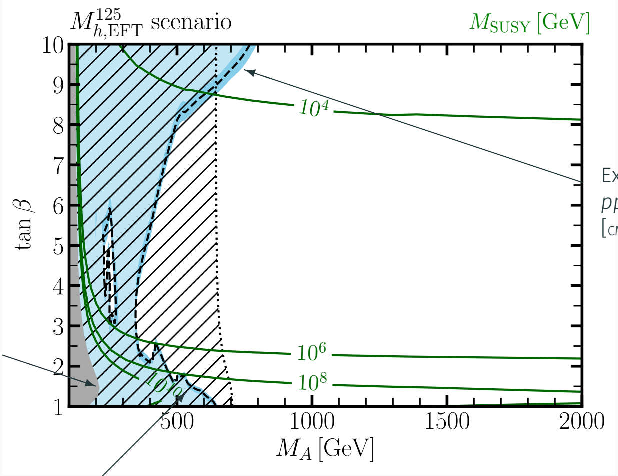
State-of-the-art calculation implemented in (yet unpublished) `FeynHiggs` version.

$$M_h^{125} \text{ scenario} \longrightarrow M_{h,\mathrm{EFT}}^{125} \text{ scenario}$$
$$M_h^{125}(\tilde{\chi}) \text{ scenario} \longrightarrow M_{h,\mathrm{EFT}}^{125}(\tilde{\chi}) \text{ scenario}$$

Similar (older) scenarios:

hMSSM [Djouadi et al. 1307.5205], low-**tan** β-high scenario [LHCHXSWG-2015-002].

$M_{h,\mathrm{EFT}}^{125}$ SCENARIO

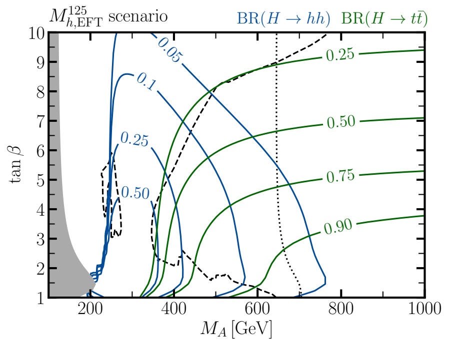


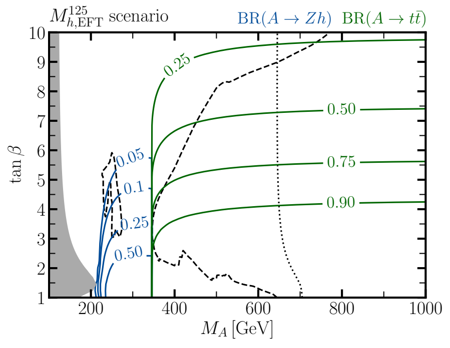
Excluded by
$pp \to H/A \to \tau^+\tau^-$
[CMS, 36 fb^{-1}]

$M_h < 122$ GeV
even for
$M_S \approx 10^{16}$ GeV

Excluded by
$H \to hh$ searches.

$M_{h,\text{EFT}}^{125}$ scenario: heavy Higgs decays

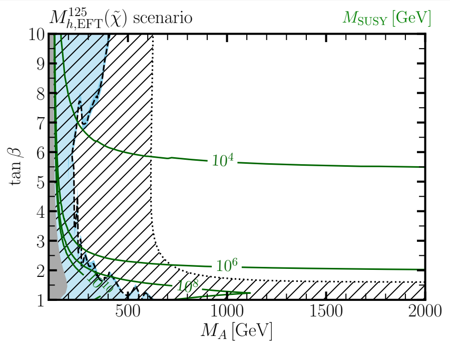




Important search channels: $H \to hh$ and $H/A \to t\bar{t}$.

Recent discussion of $H/A \to t\bar{t}$ signal+BG interference effects and discovery prospects: [Djouadi, Ellis, Popov, Quevillon 1901.03417]

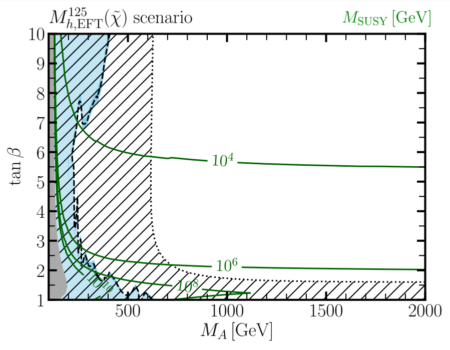
$M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$ SCENARIO

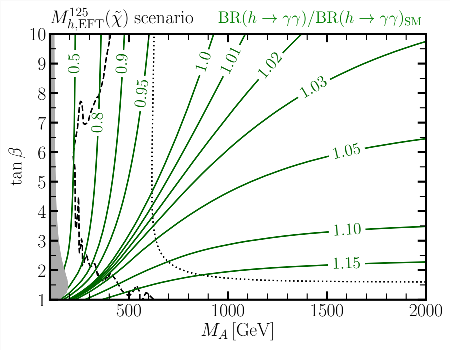


- Light electroweakinos lead to upward shift of M_h by ~ 1.5 GeV.

  $\Rightarrow$ Slightly lower M_S values required as in $M_{h,\mathrm{EFT}}^{125}$ scenario.

$M^{125}_{h,\mathrm{EFT}}(\tilde{\chi})$ SCENARIO





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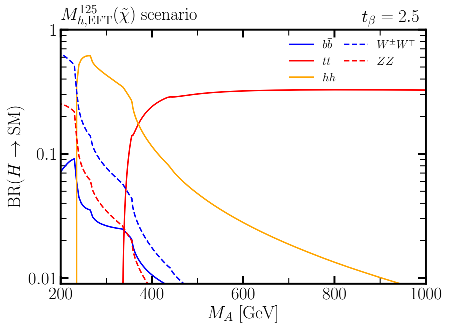
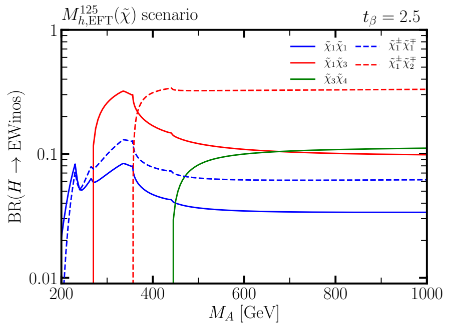
  $\Rightarrow$ Slightly lower M_S values required as in $M^{125}_{h,\mathrm{EFT}}$ scenario.

- Light charginos lead to $h \to \gamma\gamma$ enhancement at low $\tan\beta$.

  $\Rightarrow$ very low $\tan\beta$ values are constrained by LHC Higgs signal rates.

$M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$ scenario: heavy Higgs decays





For $M_A \gtrsim 400$ GeV, heavy-Higgs-to-electroweakino decays are dominant.

As in the standard $M_h^{125}(\tilde{\chi})$ scenario:

Cascade decays preferred, leading to multi-W/Z-boson+$\not{E}_T$ signatures.

$\Rightarrow$ Dedicated experimental analyses of $H/A \to \tilde{\chi}\tilde{\chi}$ decays are well-motivated!

Public tools for testing BSM models with Higgs results

HiggsBounds

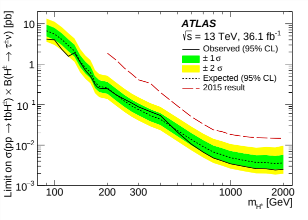
Tests BSM Higgs sectors against exclusion limits from LEP, Tevatron and LHC Higgs searches

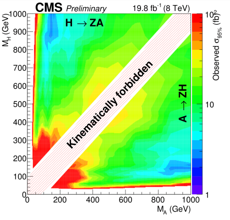
$\Rightarrow$ *excluded/allowed at* 95% C.L.

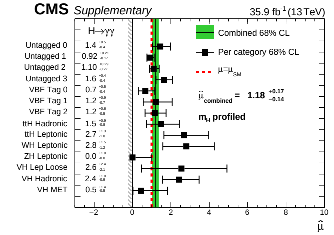
HiggsSignals

Tests BSM Higgs sectors against LHC (& Tevatron) Higgs signal rate and mass measurements

$\Rightarrow \chi^2$ *(sep. for rates and mass)*







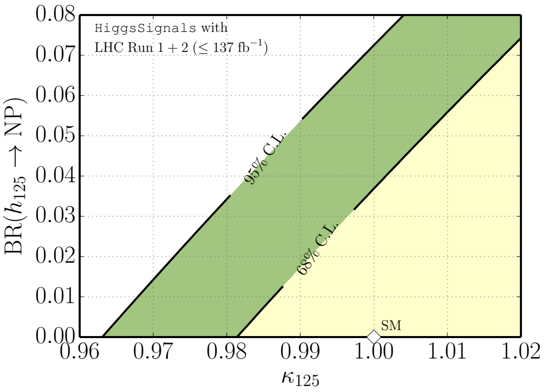
[Bechtle, Heinemeyer, Klingl, TS, Weiglein, Wittbrodt]

Available at `http://higgsbounds.hepforge.org`.

Impact of Higgs rate measurements at the LHC

Singlet model: (assume heavier Higgs at 125 GeV)

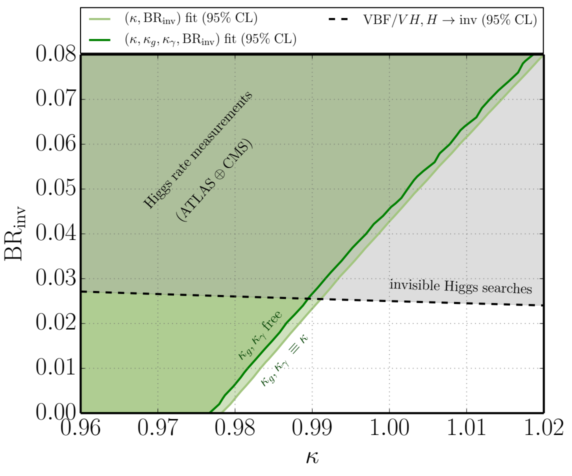
$$\kappa = \sin\alpha, \quad \mathrm{BR}(\mathrm{H} \to \mathrm{NP}) = \mathrm{BR}(\mathrm{h}_{\mathrm{SM}} \to \mathrm{h}_{\mathrm{S}}\mathrm{h}_{\mathrm{S}}).$$



$\Rightarrow$ Light Higgs h_S must have very reduced couplings $g/g_{SM} = \cos\alpha \lesssim 0.26$.

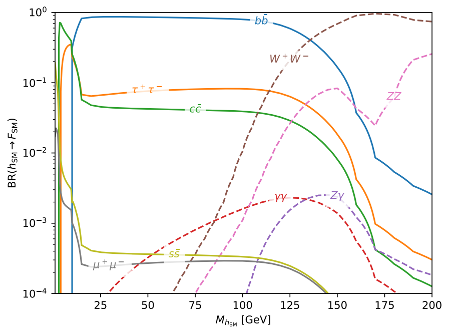
Note: further constraints arise from LEP Higgs searches.

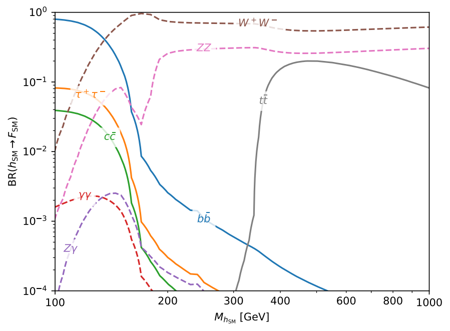
HL-LHC prospects on invisible Higgs decays



See Section 6 in [Cepeda et al., 1902.00134].

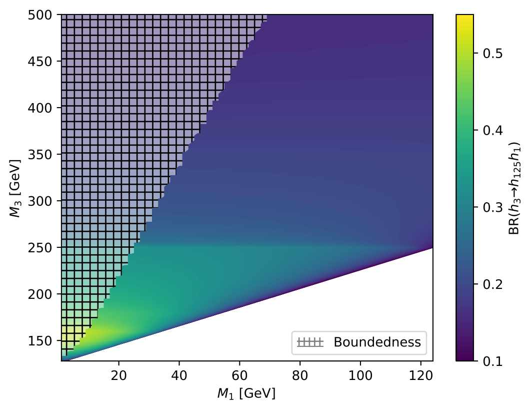
SM-like Higgs boson decay rates



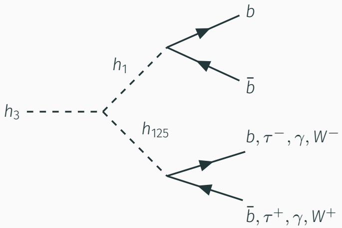


Benchmark scenario 2: $h_3 \to h_1 h_2$ (with $h_2 = h_{125}$)

- One light and one heavy scalar with unknown masses $M_1 < 125\ \mathrm{GeV} < M_3$,
- Production of h_3 with signal strength $\mu \simeq 0.04$.



Signature:

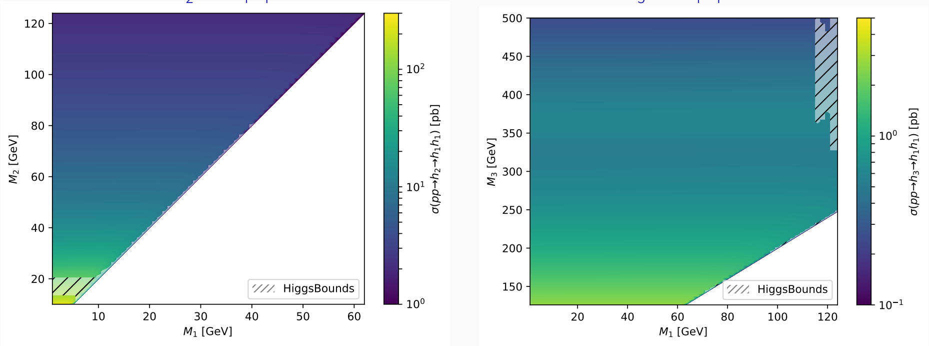


Idea: generalize existing $H \to h_{125} h_{125}$ searches to this case (unknown M_1).

Benchmark scenarios 4 & 5: $h_{\text{non-SM}} \to h_1 h_1$ (with $h_1 \neq h_{125}$)

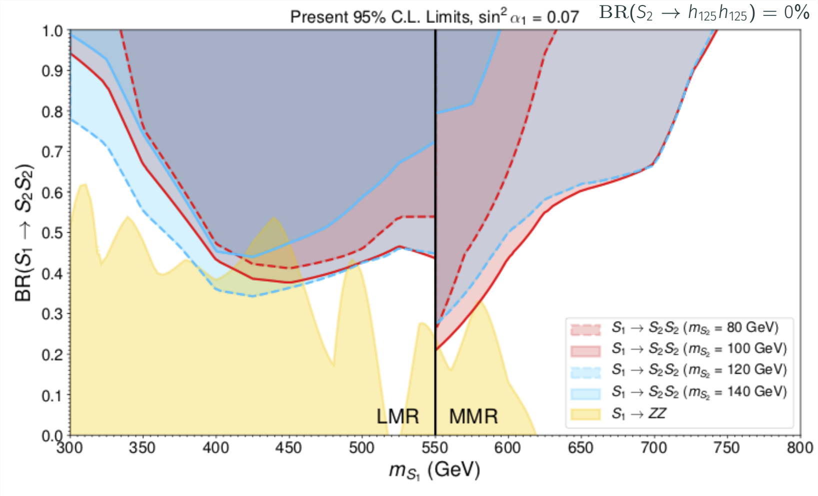
- (Symmetric) decays to $h_1 h_1$ not involving the SM-like Higgs boson,
- Production of non-SM heavier scalar with signal strength $\mu \simeq 0.06$, decay rates $\mathrm{BR}(h_{non-SM} \to h_1 h_1) \sim (70 - 100)\%$.

$h_2 \to h_1 h_1$ $\qquad$ $h_3 \to h_1 h_1$



Extrapolation of $pp \to H \to h_{125}h_{125} \to b\bar{b}b\bar{b}$ search

[Barducci, Mimasu, No, Vernieri, Zurita, '19]



Complementarity with LHC searches for $pp \to S_1 \to$ SM particles.

CP-conserving Two Higgs Doublet Model (2HDM)

2 complex $SU(2)_L$ doublets $\Rightarrow$ 5 Higgs states h, H, A, $H^{\pm}$

Higgs potential (*general basis*): (Φ_1, Φ_2: $\mathrm{SU}(2)_L$ doublets)

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_2 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2$$
$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + [\tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}]$$

$\mathbb{Z}_2$ symmetry ($\Phi_1 \to +\Phi_1, \Phi_2 \to -\Phi_2$) is softly broken if $m_{12}^2 \neq 0$.

Assuming CP conservation, we can choose all parameters $\in \mathbb{R}$.

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Extending the $\mathbb{Z}_2$ to the fermion sector suppresses tree-level FCNCs:

2HDM	u	d	ℓ
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Type III	Φ_2	Φ_1	Φ_2
Type IV	Φ_2	Φ_2	Φ_1

Two parameters govern the tree-level couplings:

$$\tan\beta = v_2/v_1$$

$$\begin{pmatrix} \sqrt{2}\mathrm{Re}(\Phi_2) - v_2 \\ \sqrt{2}\mathrm{Re}(\Phi_1) - v_1 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

Higgs-vector boson couplings:

hVV: $\sin(\beta - \alpha)$, HVV: $\cos(\beta - \alpha)$, AVV: 0.

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coupling	Type I	Type II
huu	$\cos\alpha / \sin\beta$	$\cos\alpha / \sin\beta$
$hdd, h\ell\ell$	$\cos\alpha / \sin\beta$	$-\sin\alpha / \cos\beta$
Huu	$\sin\alpha / \sin\beta$	$\sin\alpha / \sin\beta$
$Hdd, H\ell\ell$	$\sin\alpha / \sin\beta$	$\cos\alpha / \cos\beta$
Auu	$-\cot\beta$	$-\cot\beta$
$Add, A\ell\ell$	$\cot\beta$	$-\tan\beta$