Higgs Physics Beyond the Standard Model

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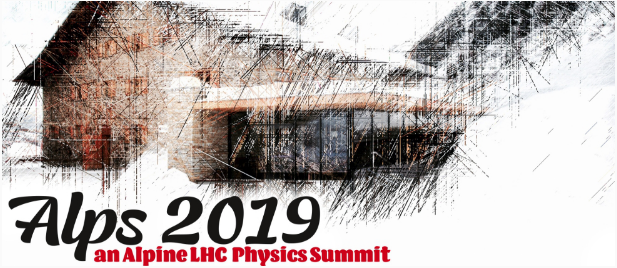
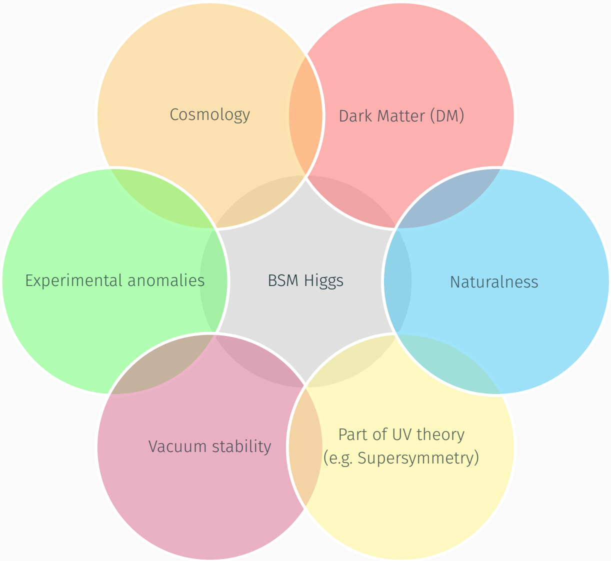
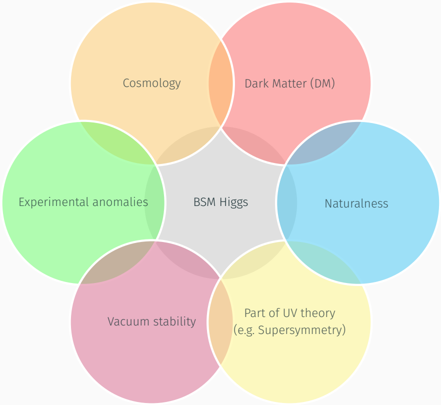


Introduction

New physics in the Higgs sector?





Possible BSM effects:

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

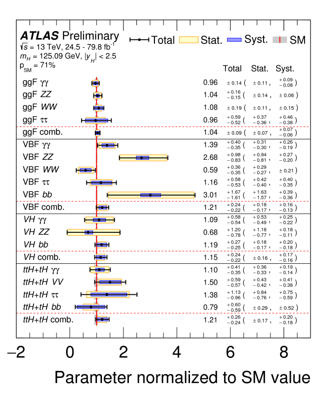
(II) Presence of additional (neutral/charged) scalar bosons;

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

...

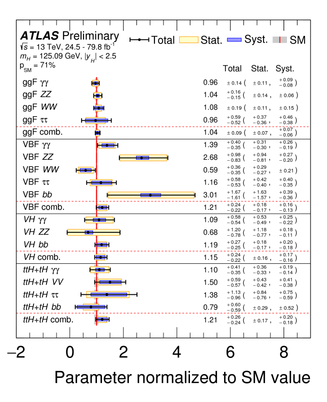
$\Rightarrow$ Higgs sector is an exciting place to look for new physics!

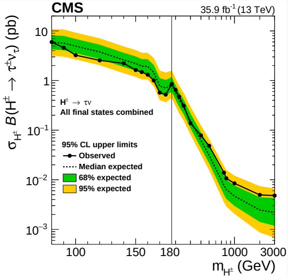
- 125 GeV Higgs boson: measurements consistent with SM hypothesis.



Theory meets Experiment: The hard truth of reality

- 125 GeV Higgs boson: measurements consistent with SM hypothesis.
- Searches for additional Higgs bosons: only limits, limits, limits, ...





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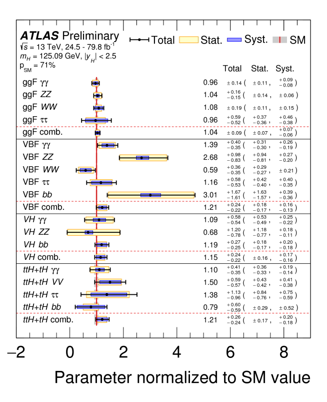

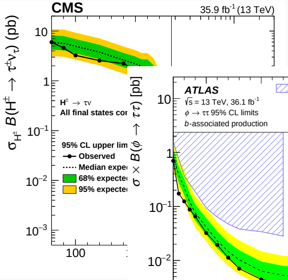

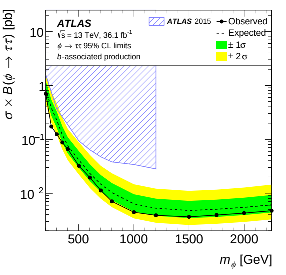

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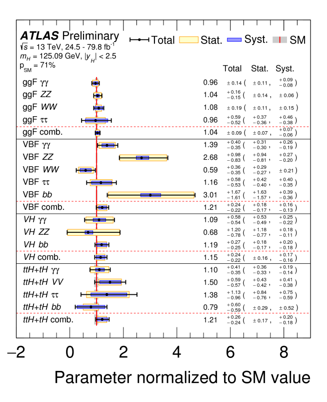

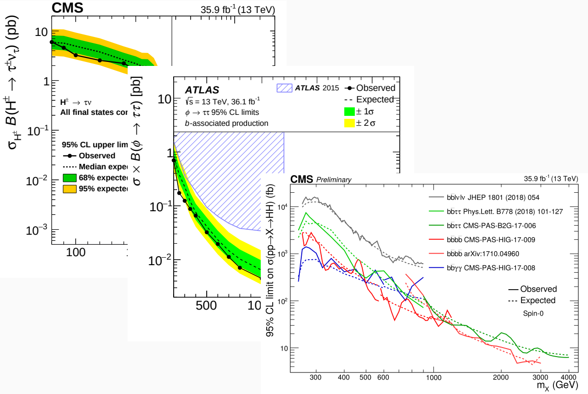

In addition: No signals in other new physics searches (SUSY, Dark Matter, ...), stringent limits on EDMs, ...

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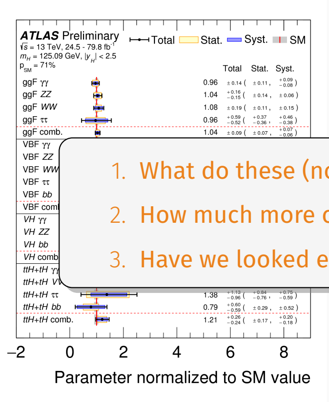
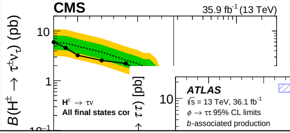
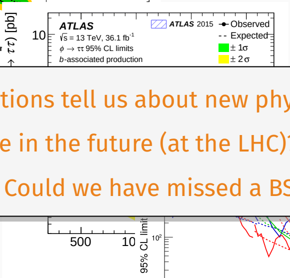
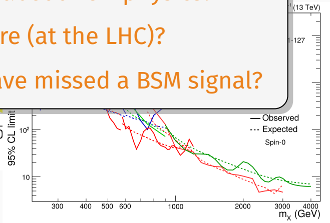








1. What do these (non-)observations tell us about new physics?
2. How much more can we probe in the future (at the LHC)?
3. Have we looked everywhere? Could we have missed a BSM signal?

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

Implications of the Higgs signal for new physics

Two approaches to assess the sensitivity to new physics:

1. **Effective field theory** (SMEFT): (in principle) model-independent; assumes NP is too heavy to be directly accessible at experiment.

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{d>4}$$

$\rightarrow$ consistent parametrization of deviations from SM expectation.

($\rightarrow$ K. Mimasu's talk)

2. **Renormalizable BSM models**: model-dependent; no restrictions on validity, all effects can (in principle) be taken into account.
$\rightarrow$ very predictive, possible complementarity to other observables.

In this talk, I will focus on concrete BSM models:

(I) SM + scalar singlets,

(II) SM + scalar doublet (2HDM, MSSM).

HiggsBounds

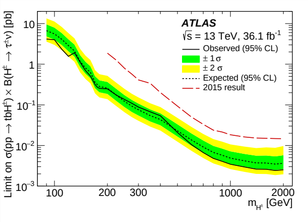
Tests BSM Higgs sectors against **exclusion limits** from LEP, Tevatron and LHC Higgs searches

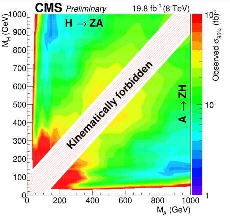
⇒ *excluded/allowed at* 95% C.L.

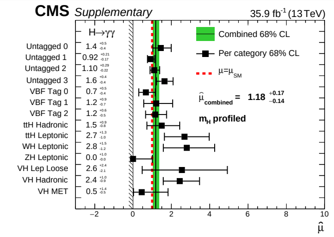
HiggsSignals

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

⇒ χ^2 *(sep. for rates and mass)*







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

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

Models with additional scalar singlets

Adding one real scalar singlet

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

$$\mathcal{V} = -\mu_\Phi^2 \Phi^\dagger \Phi - \mu_S^2 S^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger \Phi S^2.$$

Imposed $\mathbb{Z}_2$ symmetry ($S \to -S$), which is spontaneously broken if $\langle S \rangle \neq 0$.

$\langle S \rangle = 0 \Rightarrow$ S is (highly constrained) DM candidate, no mixing with Φ;

Possible LHC signature: invisible Higgs decay, $h_{SM} \to SS$.

[Feng, Profumo, Ubaldi '14; GAMBIT coll. '17] (→ P. Scott's talk)

$\langle S \rangle \neq 0 \Rightarrow$ S and Φ mix (with $\sin\alpha$); Possible LHC Signatures:

1) Universally reduced signal strength of h_{SM},
2) New Higgs state in SM Higgs searches (strongly reduced μ),
3) Singlet-like Higgs decaying into SM-like Higgs, $h_S \to h_{SM} h_{SM}$,
4) SM-like Higgs decaying into singlet-like Higgs, $h_{SM} \to h_S h_S$.

[Robens, TS '15,'16; *id.*+Ilnicka '18]

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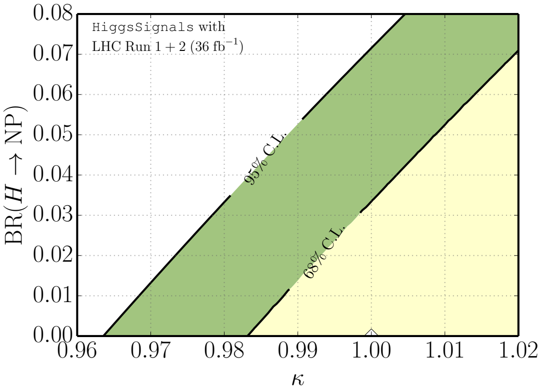
Impact of Higgs rate measurements at the LHC

Singlet model: (assume heavier Higgs at $125\ \mathrm{GeV}$)

$$\kappa = \sin\alpha, \quad \mathrm{BR}(\mathrm{H} \to \mathrm{NP}) = \mathrm{BR}(\mathrm{h_{SM}} \to \mathrm{h_S h_S}).$$



$\Rightarrow$ 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.

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[Feng, Profumo, Ubaldi '14]

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[Robens, TS '15,'16; *id.*+Ilnicka '18]

ADDING ONE REAL SCALAR SINGLET

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

$$\mathcal{V} = -\mu_\Phi^2 \Phi^\dagger \Phi - \mu_S^2 S^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger \Phi S^2.$$

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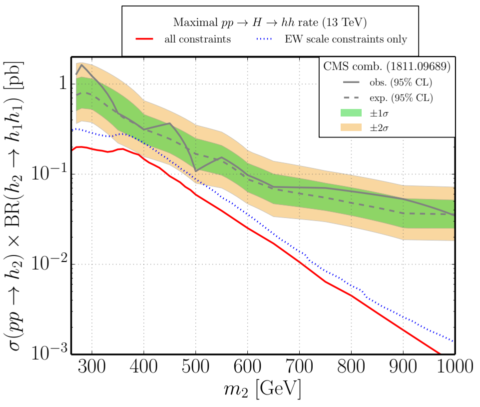
[Robens, TS '15,'16; *id.*+Ilnicka '18]

After all constraints (*Higgs signal rates and limits, M_W, EW precision observables, perturbativity of couplings, vacuum stability*):

$\Rightarrow$ $\mathrm{BR}(h_S \to h_{SM} h_{SM}) \lesssim (20-40)\%$ [Robens, TS '15,'16; *id.*+Ilnicka '18]



$\Rightarrow$ LHC searches for $pp \to H \to h_{SM} h_{SM}$ are slowly becoming sensitive.

For comparison: In SM, $\sigma_{14\mathrm{TeV}}(pp \to h_{SM} h_{SM}) \simeq 33$ fb.

[Dawson, Lewis, Robens, TS, Sullivan, *contr. to HH whitepaper (to appear)*]

ADDING TWO REAL SCALAR SINGLETS

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.

⇒ 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.

Again, Higgs couplings to SM fermions and bosons are *universally reduced by mixing*.

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

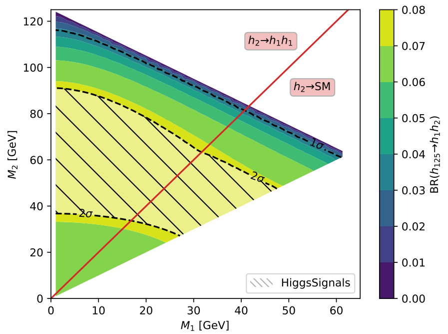
[Robens, TS, Wittbrodt (*in progress*)]

Rich phenomenology of $h_i \to h_j h_k$ decays. Various possibilities:

- three mass hierarchies: M_1, M_2 or $M_3 = 125$ GeV (with $M_1 \leq M_2 \leq M_3$),
- symmetric ($h_i \to h_j h_j$) and asymmetric ($h_3 \to h_1 h_2$) decays,
- cascade decays: $h_3 \to h_1 h_2 \to h_1 h_1 h_1$ and $h_3 \to h_2 h_2 \to h_1 h_1 h_1 h_1$.

$\Rightarrow$ Benchmark scenarios suggested to LHC-HXSWG HH subgroup.

$pp \to h_{125} \to h_1 h_2$



Example: $h_3 \simeq h_{\rm SM}$ at 125 GeV

$\sigma(pp \to h_3) \simeq \sigma(pp \to h_{\rm SM}) \sim 50$ pb,

$\mathrm{BR}(h_3 \to h_1 h_2)$ up to $7-8\%$,

if $M_2 > 2M_1 \Rightarrow \mathrm{BR}(h_2 \to h_1 h_1) \approx 100\%$,

($\to$ e.g., three pairings $m_{bb} \simeq M_1$)

if $M_2 < 2M_1 \Rightarrow h_2 \to$ SM particles.

($\to$ e.g., $m_{bb}^{(1)} \simeq M_1$ and $m_{bb}^{(2)} \simeq M_2$)

HIGGS-TO-HIGGS DECAY SIGNATURES ($\langle S \rangle \neq 0$, $\langle X \rangle \neq 0$)

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Example: $h_1 \simeq h_{SM}$ at $125\ \mathrm{GeV}$

$\sigma(pp \to h_3) \simeq 0.04 \cdot \sigma(pp \to h_{SM})|_{m=M_3}$

$\mathrm{BR}(h_3 \to h_{125} h_2)$ always $\gtrsim 60\%$.

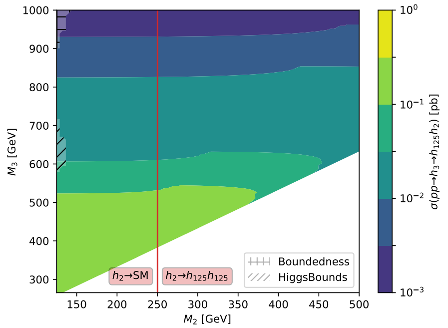
if $M_2 < 250\ \mathrm{GeV}$: $\Rightarrow h_2 \to$ SM particles.

if $M_2 > 250\ \mathrm{GeV}$:

$\Rightarrow \mathrm{BR}(h_2 \to h_{125} h_{125}) \approx 100\%$,

$\to$ spectacular triple-Higgs signature!

$pp \to h_3 \to h_{125} h_2$



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$\Rightarrow$ Benchmark scenarios suggested to LHC-HXSWG HH subgroup.

Example: $h_2 \simeq h_{SM}$ at 125 GeV

$\sigma(pp \to h_3) \simeq 0.06 \cdot \sigma(pp \to h_{SM})|_{M_3}$

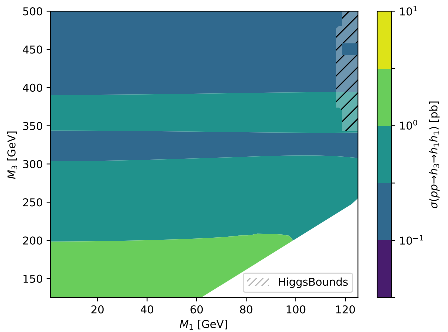
$\mathrm{BR}(h_3 \to h_1 h_1)$ always $\gtrsim 75\%$.

h_1 decays to SM particles

($\to$ e.g., two pairings $m_{bb} \simeq M_1$),

at large M_3, the h_1's become boosted.

$pp \to h_3 \to h_1 h_1$



Models with an additional scalar doublet (2HDM, MSSM)

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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$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + [\tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}]$$

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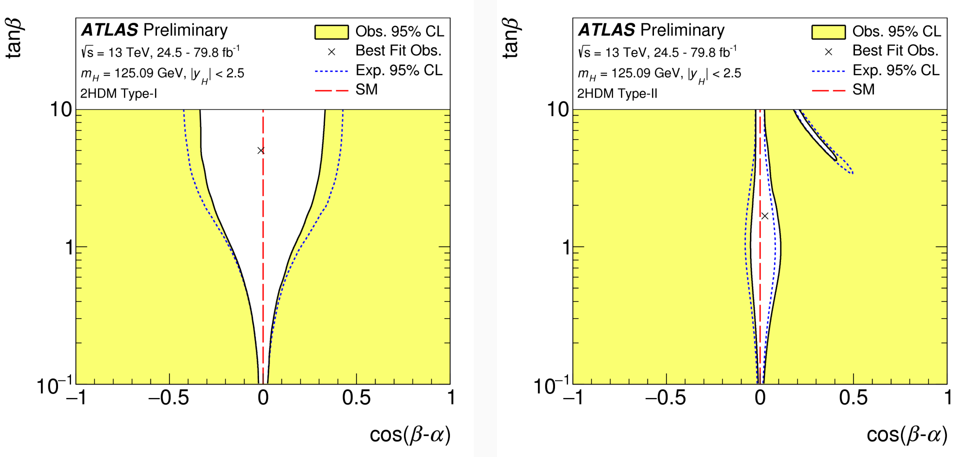
coupling	Type I	Type II
huu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
$hdd, h\ell\ell$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
Huu	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
$Hdd, H\ell\ell$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
Auu	$-\cot\beta$	$-\cot\beta$
$Add, A\ell\ell$	$\cot\beta$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

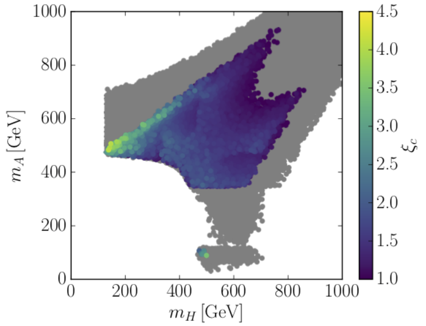
IMPACT OF HIGGS SIGNAL RATES (LIGHT HIGGS h AT 125 GeV)

[ATLAS-CONF-2019-005]



- Higgs rates severely constrain the mixing angle $\cos(\beta-\alpha)$, and favor the *alignment limit*, $\cos(\beta-\alpha) \to 0$.

1) 2HDM scenarios with strong first-order phase transition:



[Basler, Krause, Mühlleitner, Wittbrodt, Wlotzka '16]

Phase-transition strength, $\xi_c \equiv v_c/T_c$, typically larger for large $M_A - M_H$ ($\xi_c \gtrsim 1$ needed for EW baryogenesis).

$g_{HAZ} \propto \sin(\beta - \alpha) \to 1$ in alignment limit.

$\Rightarrow pp \to A \to HZ$ searches well-motivated.

[Dorsch, Huber, Mimasu, No '14]

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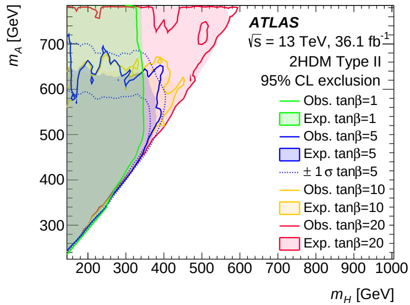

[ATLAS '18]

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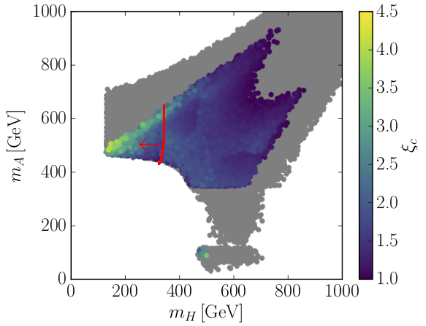

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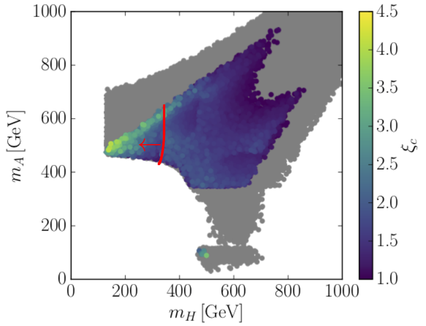

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[Basler, Krause, Mühlleitner, Wittbrodt, Wlotzka '16]

2) Inert Doublet Model

($\to$ A. Zarnecki's talk)

Z_2 symmetry is exact $\Rightarrow$ lightest Z_2-odd scalar is DM candidate.

$\Rightarrow$ invisible Higgs decays, Z_2-odd Higgs boson pair production, $h \to \gamma\gamma$ rate.

[Goudelis, Herrmann, Stål '13; Blinov, Profumo, TS '15; Dercks, Robens '18; ...]

Heavy Higgs boson H at $125\ \mathrm{GeV}$?

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 $M_h \in [M_H/2, 115]\ \mathrm{GeV}$.

Question:

Will we ever be able to tell whether h or H is at $125\ \mathrm{GeV}$?

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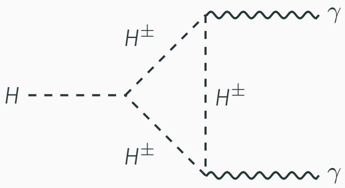
Even in the alignment limit, $\cos(\beta-\alpha)\to 1$, charged Higgs effects on the Higgs rates do not decouple:

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

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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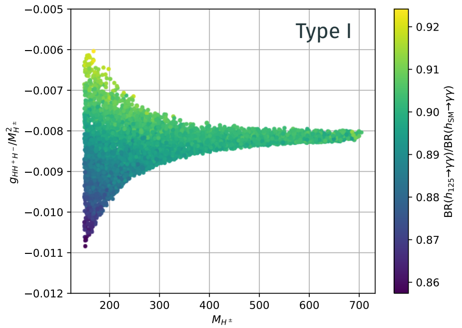
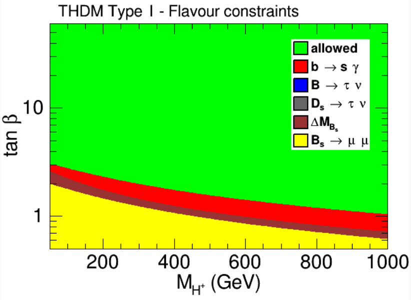
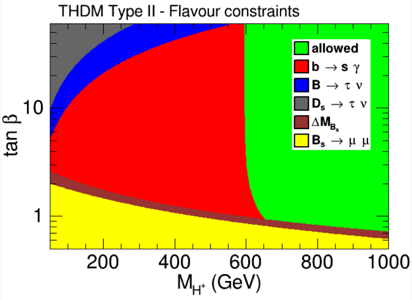


[TS, Wittbrodt (*in progress*)]

In Type II (and III), flavor constraints imposes $M_{H^+} \gtrsim 600\ \mathrm{GeV}$.

In Type I (and IV), the charged Higgs boson can be much lighter.



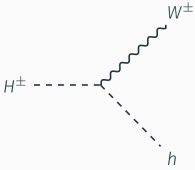


[Arbey, Mahmoudi Stål, TS '17]

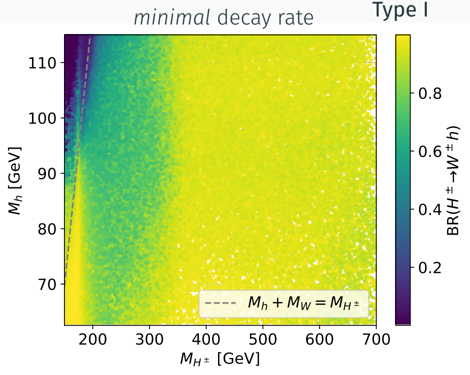
Charged Higgs bosons at the LHC

In the alignment limit with the heavy Higgs H at 125 GeV, the coupling $g_{H^\pm W^\mp h} \propto \cos(\beta - \alpha)$ is maximized!

$\Rightarrow$ sizable $H^\pm \to W^\pm h$ decay rates!



[TS, Wittbrodt (*in progress*)]



h 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.

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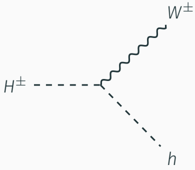

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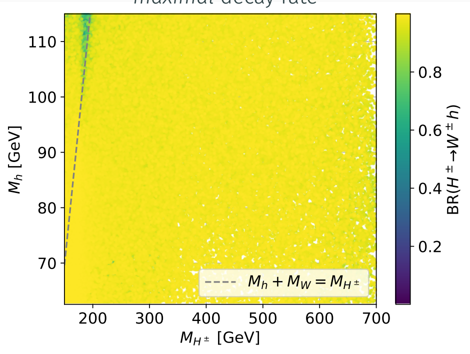
maximal decay rate

Type I



Uncovered charged Higgs boson signatures

[TS, Wittbrodt (*in progress*)]

Production process	Higgs decay processes	Final state particles
$pp \to H^\pm tb$	$H^\pm \to W^\pm h,\, h \to \begin{cases} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{cases}$	$tbW^\pm + \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix}$
$pp \to H^\pm h$	$H^\pm \to W^\pm h,\, h \to \begin{cases} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{cases}$	$W^\pm + \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix} \oplus \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix}$
$pp \to H^\pm W^\mp$	$H^\pm \to W^\pm h,\, h \to \begin{cases} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{cases}$	$W^\pm W^\mp + \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix}$
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	ZZ, $\gamma\gamma$	ZZ, $\gamma\gamma$
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Many new experimental opportunities for upcoming LHC Run(s)!

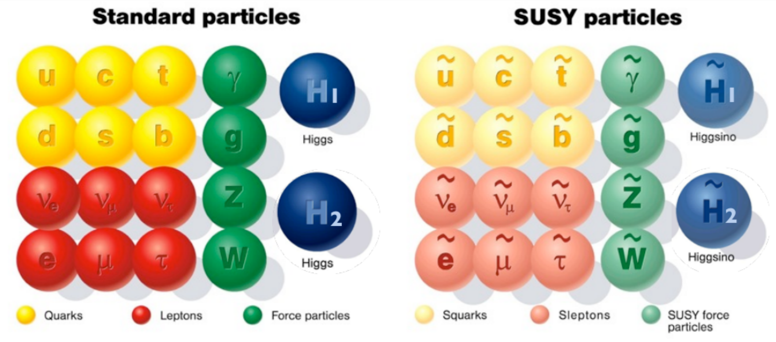
Direct searches for $H^\pm \to W^{\pm *}h$ *and* precision $H \to \gamma\gamma$ measurements:

$\Rightarrow$ conclusive statement whether h or H is SM-like Higgs at 125 GeV!

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:

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

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

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

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

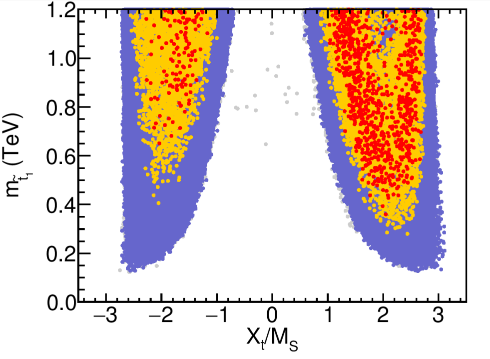
$\Rightarrow$ with SUSY particles at TeV-scale we can get $M_h \lesssim 135\,\mathrm{GeV}$!

The Role of the Higgs mass in the MSSM

Precise predictions & measurement of the SM-like Higgs mass:

$\Rightarrow$ important constraints on MSSM parameter space.

Fit of the pMSSM-8 to LHC Run-I data:



[Bechtle et al. '16]

All points with $M_h \in [120, 130]$ GeV
HiggsBounds allowed
$\Delta\chi^2 < 2.30$
$\Delta\chi^2 < 5.99$

(assumed theory uncert. $\Delta M_h = 3$ GeV)

$\Rightarrow$ need large stop mixing, X_t/M_S, and/or large stop masses.

The Role of the Higgs mass in the MSSM

Precise predictions & measurement of the SM-like Higgs mass:

⇒ important constraints on MSSM parameter space.

Theory predictions of M_h (state-of-the-art): (for a review: [Draper, Rzehak '16])

Most public codes include full 1-loop + dominant (strong, y_t) 2-loop corrections (and beyond) to M_h:

`FeynHiggs, SPheno/SARAH, SoftSUSY/FlexibleSUSY, SuSpect, …`

For small $\tan\beta$ or small mixing ($X_t \ll M_S$) multi-TeV stop masses required:

⇒ resummation of large logarithms needed:

`SusyHD`, `MhEFT`, `HSSUSY` ("EFT codes");

`FeynHiggs` (ver. $\geq$ 2.10), `FlexibleEFTHiggs`, `SPheno/SARAH` ("hybrid codes").

Still, non-negligible theory and parametric (m_t) uncertainty! [Allanach, Voigt '18]

THE ROLE OF THE HIGGS MASS IN THE MSSM

Precise predictions & measurement of the SM-like Higgs mass:

⇒ important constraints on MSSM parameter space.

Simplified benchmark point: *tanβ* = 20, all SUSY masses = 1 TeV, X_t varied to maximize M_h

(Higgs Days in Santander 2018)

Public Code	M_h [GeV]
SPheno 4.0.3	124.6
SuSpect 2.43	125.8
SoftSUSY 4.1.6	124.4
NMSSMTools 5.3.1	124.6
FeynHiggs 2.14.3	125.7

(SPheno, SuSpect, SoftSUSY, NMSSMTools:) Fixed-order calculations in the $\overline{\text{DR}}$ scheme *(no resummation)*

different treatment of top Yukawa cpl.

[taken from P. Slavich, HDays '18]

All of these codes include full 1-loop + dominant (strong+Yukawa) 2-loop corrections to M_h

New MSSM Higgs benchmark scenarios – Overview

[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
	[Bahl et al. 1808.07542]
$M_{h,\mathrm{EFT}}^{125}$	"standard" scenario for the low $\tan\beta$ region
$M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$	light EW-ino scenario for the low $\tan\beta$ region
	[Bahl, Liebler, TS 1901.05933]

(effort within the LHC Higgs Cross Section Working Group)

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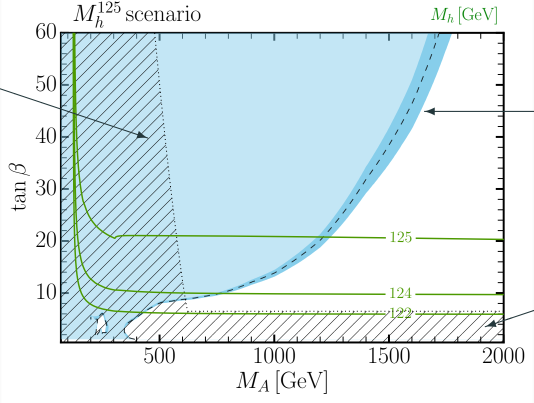
Disfavored (2σ) by LHC Higgs rates
[Run I + II (36 fb^{-1})]

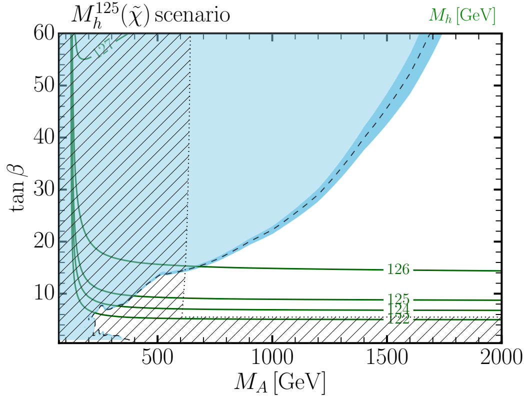


Excluded by
$pp \to H/A \to \tau^+\tau^-$
[CMS, 36 fb^{-1}]

Excluded by M_h
[$M_h \neq (125 \pm 3)$ GeV]

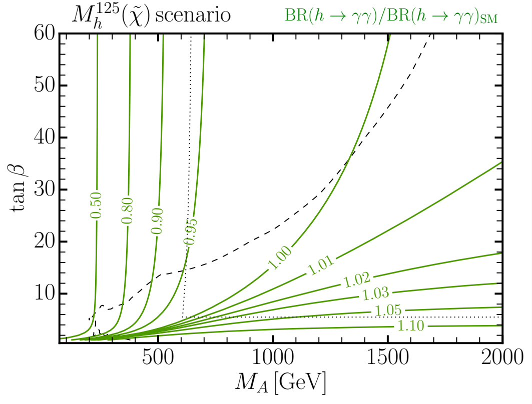
- Assumption: all SUSY particle masses are $\gtrsim 1$ TeV.
- Higgs rates & limits $\Rightarrow$ H, A and $H^\pm$ expected to be heavy (mass $\gtrsim 600$ GeV).

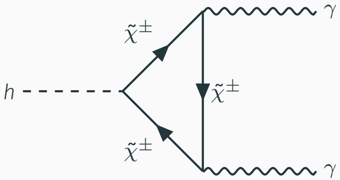
$M_h^{125}(\tilde{\chi})$ BENCHMARK SCENARIO: LIGHT NEUTRALINOS & CHARGINOS



- Assumption: 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 $\tan\beta$)

- Assumption: light neutralinos and charginos with masses $\sim (100 - 250)$ GeV.
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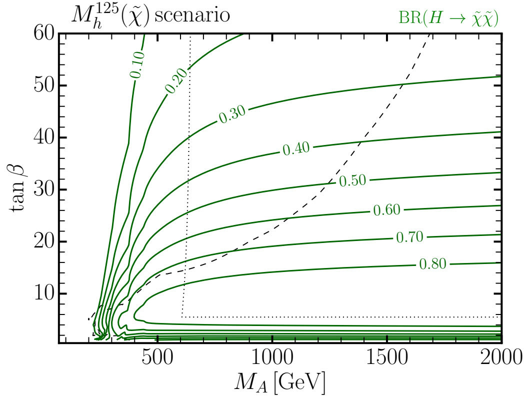

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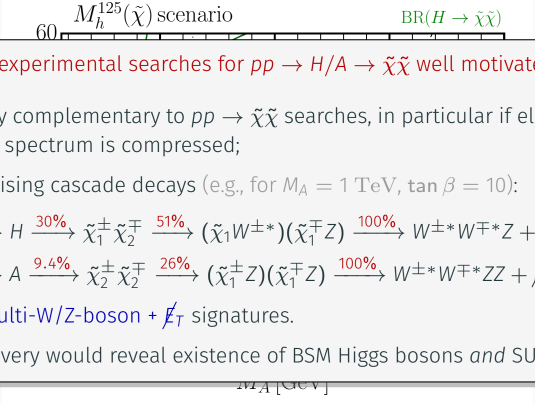


Dedicated experimental searches for $pp \to H/A \to \tilde{\chi}\tilde{\chi}$ well motivated:

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

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

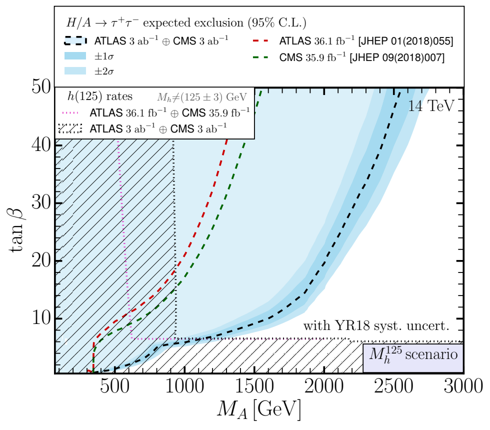
$$pp \to A \xrightarrow{9.4\%} \tilde{\chi}_2^{\pm}\tilde{\chi}_2^{\mp} \xrightarrow{26\%} (\tilde{\chi}_1^{\pm} Z)(\tilde{\chi}_1^{\mp} Z) \xrightarrow{100\%} W^{\pm *}W^{\mp *}ZZ + \not{E}_T$$

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

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

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

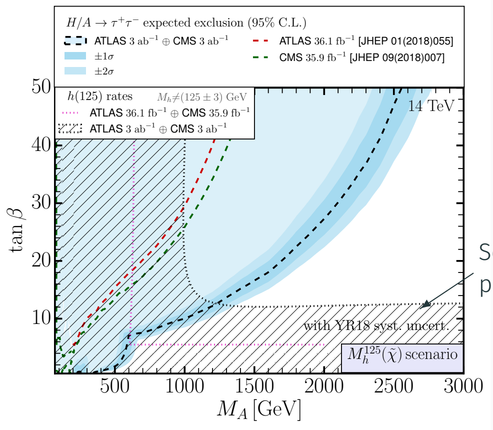
HL-LHC reach for the MSSM Higgs sector



- HL-LHC Higgs rate measurements will be sensitive to $M_A \lesssim 1$ TeV.
- Direct searches for $pp \to H/A \to \tau^+\tau^-$ are sensitive to $M_A \lesssim 2.5$ TeV (depending on tan β).

[Bahl, Bechtle, Heinemeyer, Liebler, TS, Weiglein, *contr. to* CERN-LPCC-2018-04]

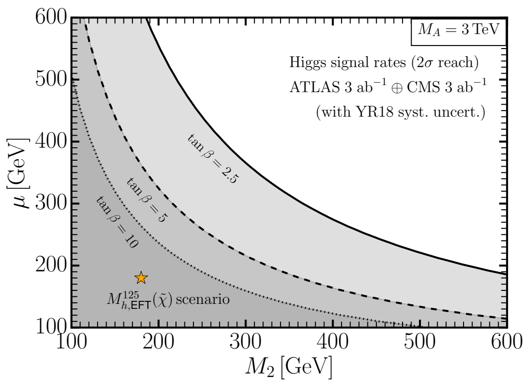
HL-LHC reach for the MSSM Higgs sector



- HL-LHC Higgs rate measurements will be sensitive to $M_A \lesssim 1\,\mathrm{TeV}$.
- Direct searches for $pp \to H/A \to \tau^+\tau^-$ are sensitive to $M_A \lesssim 2.5\,\mathrm{TeV}$ (depending on $\tan\beta$).

[Bahl, Bechtle, Heinemeyer, Liebler, TS, Weiglein, *contr. to* CERN-LPCC-2018-04]

HL-LHC reach for the MSSM Higgs sector



- Chargino contribution to $h \to \gamma\gamma \Rightarrow$ indirect sensitivity on the electroweakino sector from $h \to \gamma\gamma$ precision measurements.
- Interesting interplay with direct searches for electroweakinos.

[Bahl, Bechtle, Heinemeyer, Liebler, TS, Weiglein, (*in prep.*)]

Conclusions

Conclusions

LHC results on the 125 GeV Higgs boson and searches for new scalar states have important implications for BSM Higgs models.

$\Rightarrow$ Approximate alignment limit (i.e. SM-like Higgs couplings) is realized.

However: Still room for new Higgs discoveries in upcoming LHC runs!

- Additional Higgs bosons can be *lighter* or *heavier than* 125 GeV,
- some searches only become sensitive with more data (e.g. $H \to hh$ in Z_2-symmetric singlet extension),
- additional Higgs bosons may only be probed by new searches for so-far-uncovered signatures: $h_i \to h_j h_k$, $H^\pm \to W^\pm h$, $pp \to H/A \to \tilde{\chi}\tilde{\chi}$, ...

We need to be open-minded and consider all possible collider searches over full accessible kinematical range, and keep on searching!

Conclusions

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We need to be open-minded and consider all possible collider searches over full accessible kinematical range, and keep on searching!

Thank you very much for your attention!

Backup Slides

HiggsBounds

Theory input:
M_i, Γ_i^{tot}, XS's and BR's for all neutral and charged Higgs bosons.

Experimental input:
$\mathcal{O}(200)$ "model-independent" 95% C.L. limits from LEP, Tevatron and LHC.

"Combination" procedure:
Each Higgs boson h_i is *only* confronted with the observed limit of the experimental analysis that's *most sensitive* to it (judged by expected limit).

Result: parameter point is excluded/allowed at 95% $\mathrm{C.L.}$.

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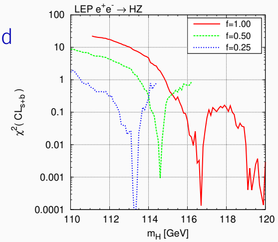
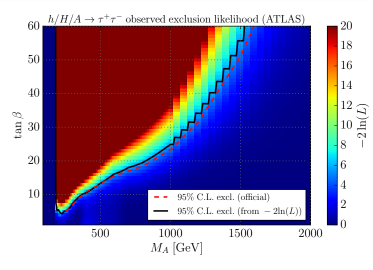
For specific searches the exclusion likelihood can be calculated.

$\longrightarrow$

(useful for global fits)





HiggsSignals: χ^2 calculation from Higgs signal rates

$$\chi^2_\mu = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})\, \mathsf{C}_{\boldsymbol{\mu}}{}^{-1}\, (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})$$

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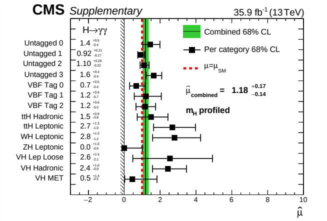
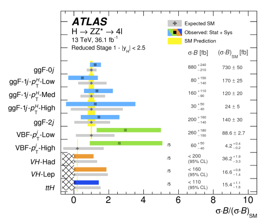
Measured signal strengths (in various forms):

(analysis assumes a SM-like Higgs signal)

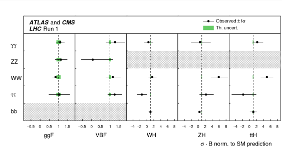


Signal strengths (μ) in exp. categories

(SM normalized rate)



STXS (absolute rate)



Signal strengths (μ) in pure channels

(SM normalized rate)

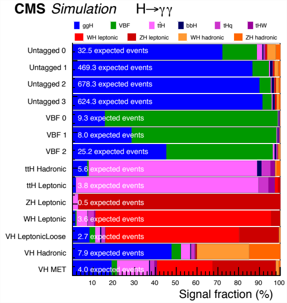
current version: 56 traditional μ obs. + 24 STXS obs. + 20 LHC-Run-1 obs.

HiggsSignals: χ^2 CALCULATION FROM HIGGS SIGNAL RATES

$$\chi^2_\mu = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})\, \mathbf{C}_\mu^{-1}\, (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})$$

Predicted signal strength:

$$\mu = \frac{\sum_i \epsilon_i \, [\sigma \times \mathrm{BR}]_i}{\sum_j \epsilon_{\mathrm{SM},j} \, [\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}]_j}$$



$\epsilon_{\mathrm{SM},i}$: signal efficiency of channel i in SM.

ϵ_i: signal efficiency of channel i in model.

default assumption: $\epsilon_i = \epsilon_{\mathrm{SM},i}$

$\epsilon_i \neq \epsilon_{\mathrm{SM},i}$ requires external MC simulation:

$\Rightarrow$ ϵ_i can then be set as additional input.

HiggsSignals: χ^2 calculation from Higgs signal rates

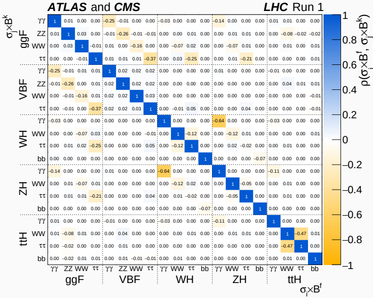
$$\chi^2_\mu = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})\, \mathsf{C}_{\boldsymbol{\mu}}^{-1}\, (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})$$

Covariance matrix

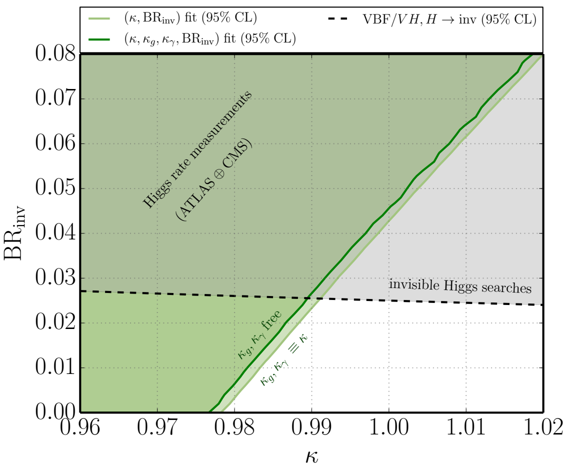
correlation matrices sometimes given by ATLAS/CMS (for subset of observables).

$\Rightarrow$ included in `HiggsSignals`.

Otherwise: treat luminosity uncertainty, theoretical σ and BR uncertainties as fully correlated.

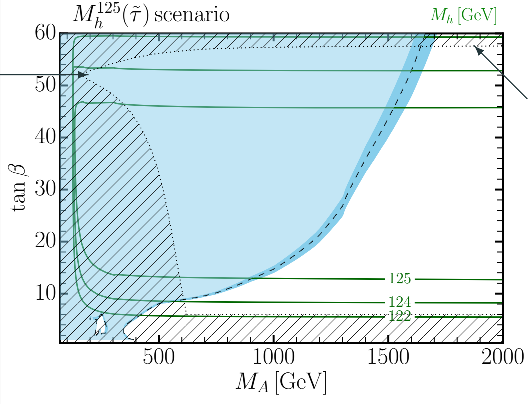


HL-LHC prospects on invisible Higgs decays



$M_h^{125}(\tilde{\tau})$ SCENARIO: LIGHT STAUS

Limit of alignment w/o decoupling at **tan** $\beta \simeq 52$.



too large $h \to \gamma\gamma$

$$M_{Q_3} = M_{U_3} = M_{D_3} = 1.5 \text{ TeV}, \quad M_{L_3} = M_{E_3} = 350 \text{ GeV},$$

$$\mu = 1 \text{ TeV}, \quad M_1 = 180 \text{ GeV}, \quad M_2 = 300 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$X_t = 2.8 \text{ TeV}, \quad A_b = A_t, \quad A_\tau = 800 \text{ GeV}.$$

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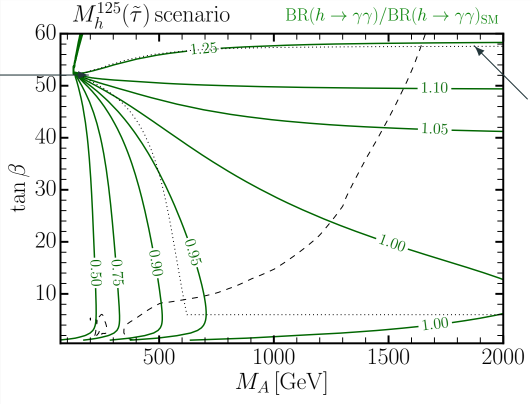

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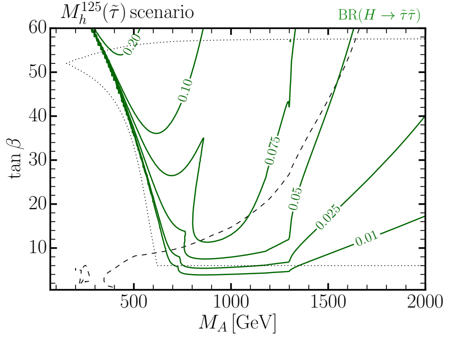
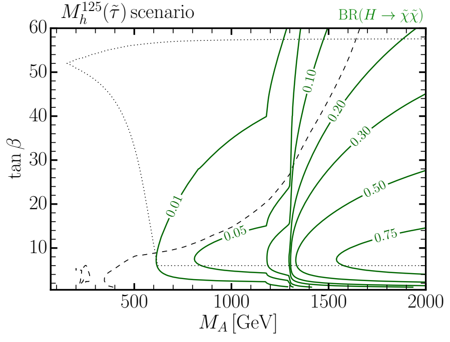
$M_h^{125}(\tilde{\tau})$ scenario: heavy Higgs to SUSY decays





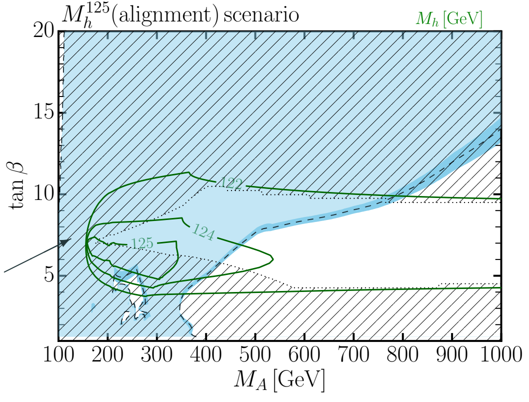
Both $H/A \to \tilde{\tau}\tilde{\tau}$ and $H/A \to \tilde{\chi}\tilde{\chi}$ possible.

$\Rightarrow$ additional H/A decays weaken the impact of $H/A \to \tau^+\tau^-$ constraints.

For recent proposals for a $H/A \to \tilde{\tau}\tilde{\tau}$ search, see

[Gori, Liu, Shakya 1811.11918], [Arganda, Martín-Lozano, Medina, Mileo 1804.10698].

M_h^{125}(ALIGNMENT) SCENARIO

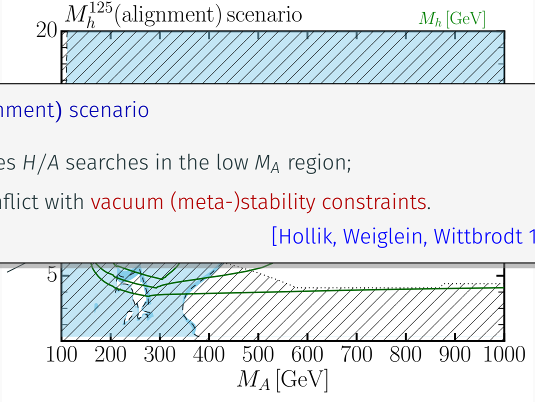


Limit of alignment w/o decoupling at **tan** $\beta \simeq 7$.

$$M_{Q_3} = M_{U_3} = M_{D_3} = 2.5 \text{ TeV}, \quad M_{L_3} = M_{E_3} = 2 \text{ TeV},$$

$$\mu = 7.5 \text{ TeV}, \quad M_1 = 500 \text{ GeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$A_t = A_b = A_\tau = 6.25 \text{ TeV}.$$



The M_h^{125}(alignment) scenario

(+) motivates H/A searches in the low M_A region;

(−) is in conflict with vacuum (meta-)stability constraints.

[Hollik, Weiglein, Wittbrodt 1812.04644]

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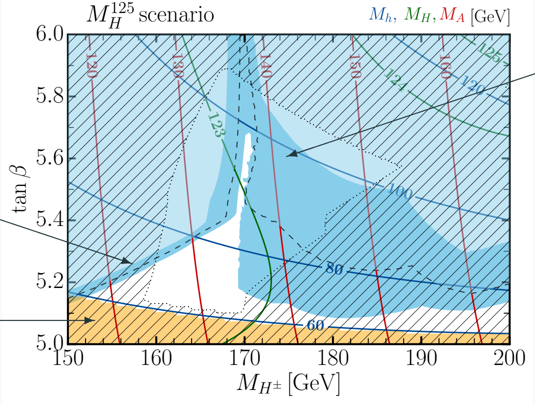
$$A_t = A_b = A_\tau = 6.25\ \text{TeV}\,.$$

M_H^{125} scenario: the heavier Higgs H is SM-like

Excluded by $H^\pm \to \tau\nu$.

Excluded by $H \to hh$.



Excluded by $A \to \tau\tau$.

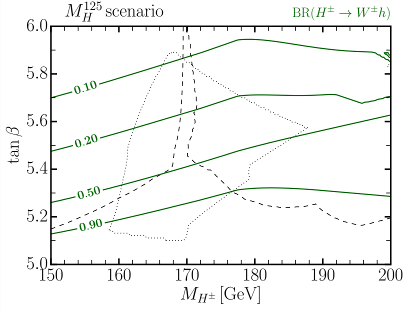
$$M_{Q_3} = M_{U_3} = 750\,\text{GeV} - 2\,(M_{H^\pm} - 150\,\text{GeV})\ ,$$

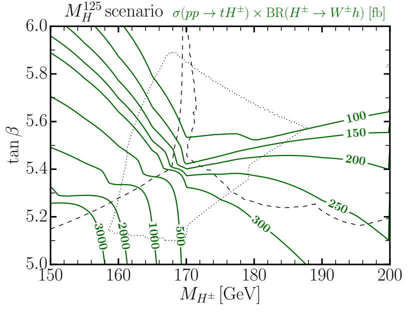
$$\mu = [5800\,\text{GeV} + 20\,(M_{H^\pm} - 150\,\text{GeV})]\ M_{Q_3}/(750\,\text{GeV})\ ,$$

$$A_t = A_b = A_\tau = 0.65\,M_{Q_3}, \quad M_{D_3} = M_{L_3} = M_{E_3} = 2\ \text{TeV}\ ,$$

$$M_1 = M_{Q_3} - 75\,\text{GeV}, \quad M_2 = 1\,\text{TeV}, \quad M_3 = 2.5\,\text{TeV}\ .$$

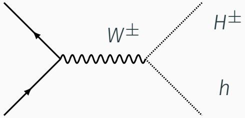
M_H^{125} scenario: charged Higgs phenomenology

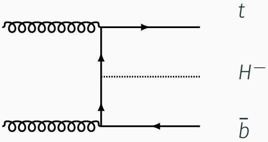




$H^\pm W^\mp h$ coupling $\propto \cos(\beta - \alpha) \approx 1$ if H is SM-like.

$\Rightarrow$ Important signature: $H^\pm \to W^\pm h$, with $h \to b\bar{b}, \tau^+\tau^-$.





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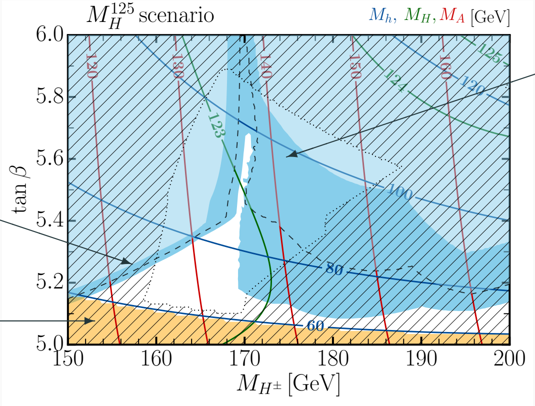

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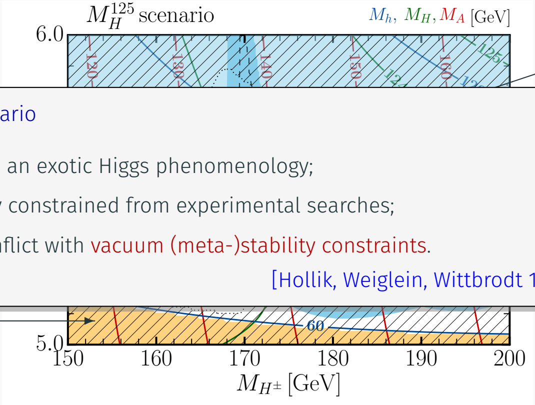
M_H^{125} scenario: the heavier Higgs H is SM-like



Excluded by $A \to \tau\tau$.

Ex
H

Ex
$H \to hh$.

The M_H^{125} scenario

- (+) features an exotic Higgs phenomenology;
- (−) is highly constrained from experimental searches;
- (−) is in conflict with vacuum (meta-)stability constraints.

[Hollik, Weiglein, Wittbrodt 1812.04644]

$$M_{Q_3} = M_{U_3} = 750\,\text{GeV} - 2\,(M_{H^\pm} - 150\,\text{GeV})\ ,$$

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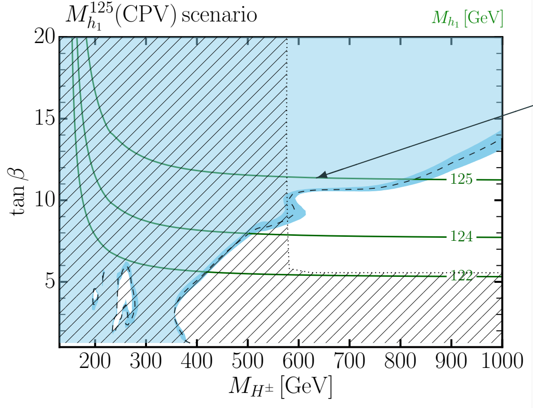
$M_{h_1}^{125}$(CPV) scenario: neutral Higgs bosons mix (h_1, h_2, h_3)



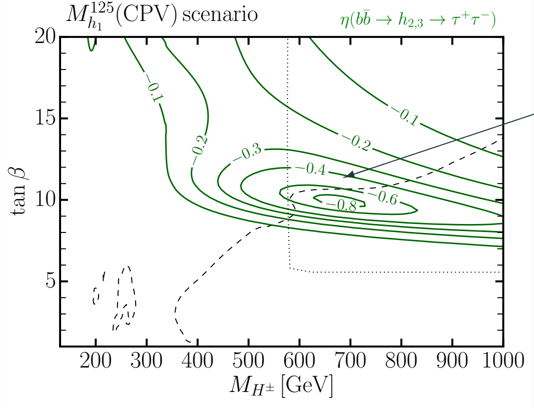
Destructive interference in $pp \to h_2/h_3 \to \tau\tau$.

$$M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} = 2 \text{ TeV},$$

$$\mu = 1.65 \text{ TeV}, \quad M_1 = M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV},$$

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

$M_{h_1}^{125}$(CPV) SCENARIO: $pp \to h_2/h_3 \to \tau^+\tau^-$ INTERFERENCE



Destructive interference in $pp \to h_2/h_3 \to \tau\tau$.

$$1 + \eta = \frac{\sigma(|h_2+h_3|^2)}{\sigma(|h_2|^2+|h_3|^2)}$$

Interference effects calculated and studied in [Fuchs, Weiglein 1705.05757].

⇒ Significant reduction of $\tau^+\tau^-$ signal rate!

However: Scenario in conflict with ACME 2018 electron EDM limit!

[ACME Nature **562**, 355–360 (2018)]

Re-opening the low $\tan\beta$ region

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

Allow *lower* $\tan\beta$ *values* by *tuning* $M_h = 125$ GeV *at every point*:

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

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

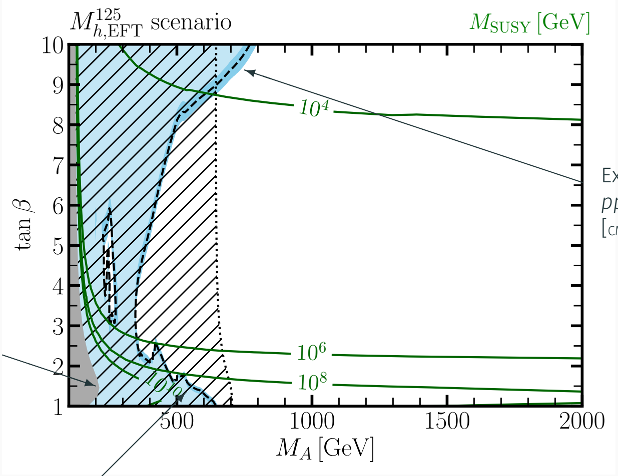
State-of-the-art calculation implemented in (yet unpublished) `FeynHiggs` version.

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

Similar (older) scenarios:

hMSSM [Djouadi et al. 1307.5205], low-$\tan\beta$-high scenario [LHCHXSWG-2015-002].

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

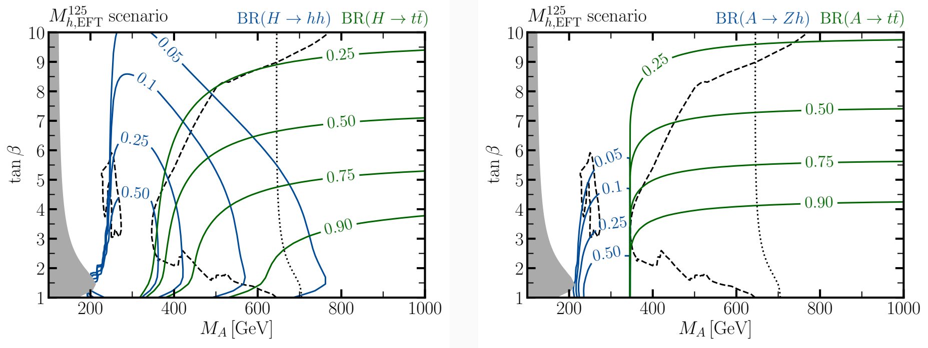


Excluded by
$pp \to H/A \to \tau^+\tau^-$
[CMS, 36 fb^{-1}]

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

Excluded by
$H \to hh$ searches.

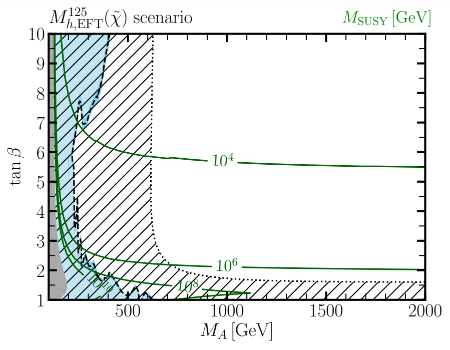
$M_{h,\text{EFT}}^{125}$ scenario: heavy Higgs decays



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

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

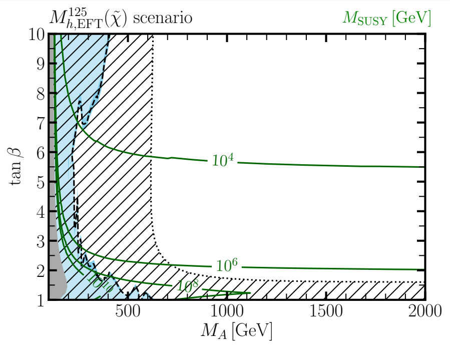
$M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$ SCENARIO

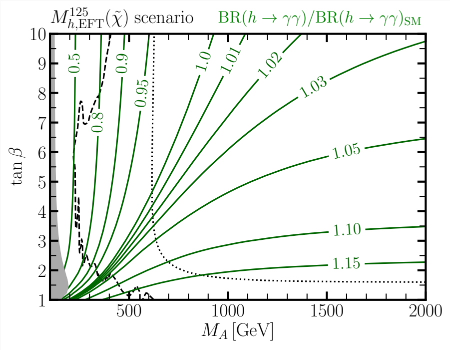


- Light electroweakinos lead to upward shift of M_h by ~ 1.5 GeV.

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

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





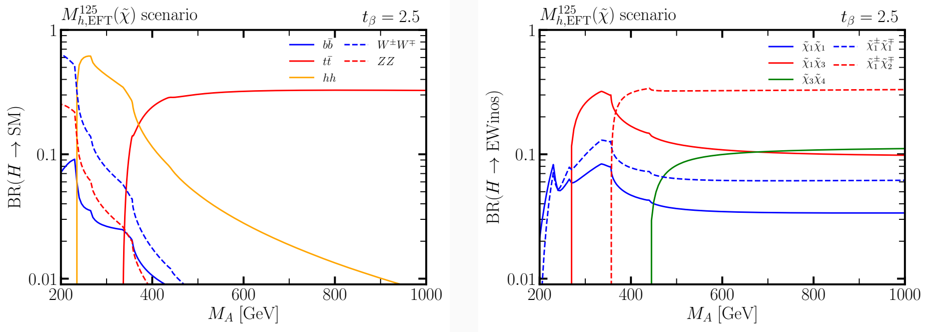
- Light electroweakinos lead to upward shift of M_h by ~ 1.5 GeV.

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

- 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.

$M_{h,\text{EFT}}^{125}(\tilde{\chi})$ 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!