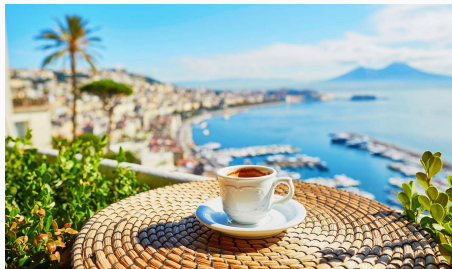


Novel signatures of additional Higgs bosons at the LHC

Tim Stefaniak

Deutsches Elektronen-Synchrotron DESY

Email: tim.stefaniak@desy.de

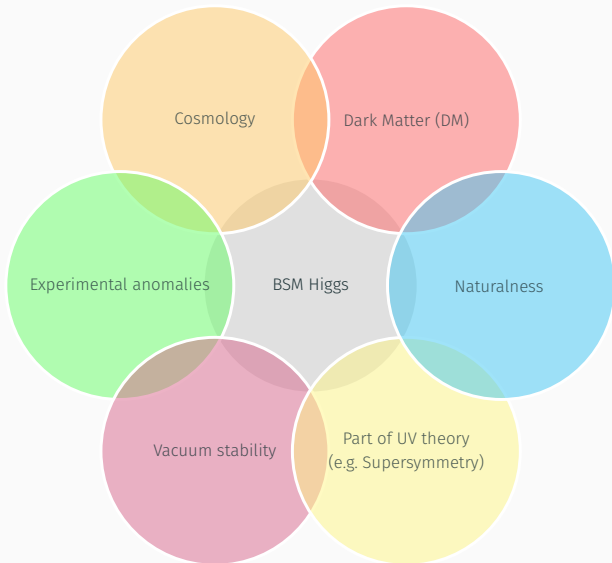


ATLAS Exotics & HDBS Workshop

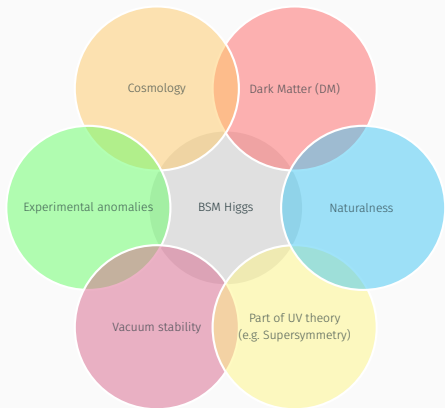
Naples, 12 June 2019

Introduction

NEW PHYSICS IN THE HIGGS SECTOR?



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;

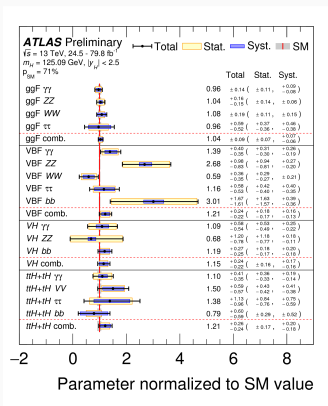
(III) Presence of other new particles (e.g. SUSY particles) interacting with the Higgs boson.

...

⇒ Higgs sector is an exciting place to look for new physics!

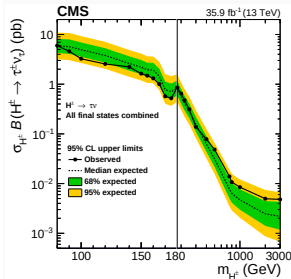
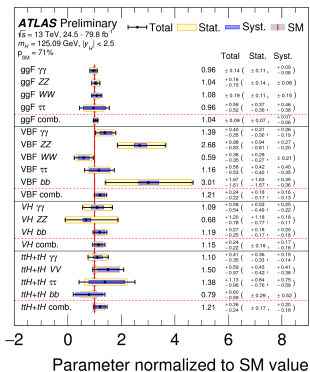
THEORY MEETS EXPERIMENT: THE HARD TRUTH OF REALITY

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



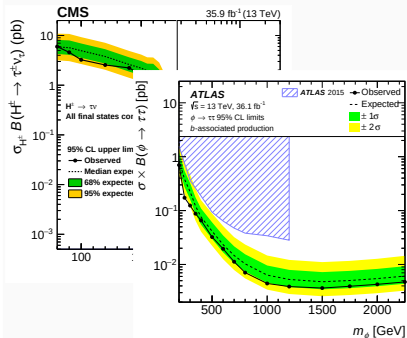
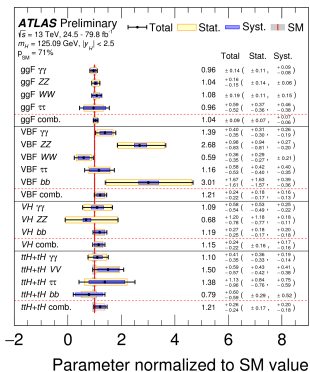
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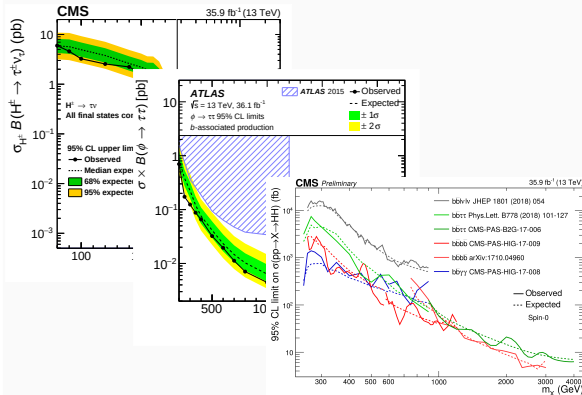
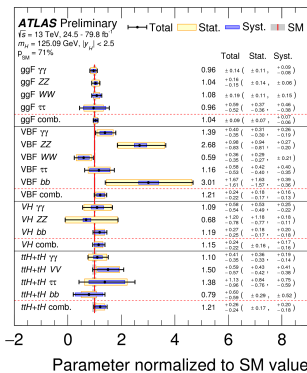
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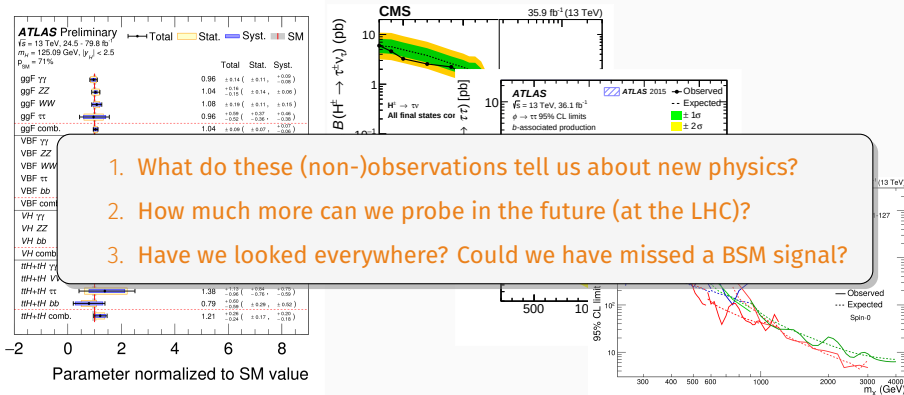
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In addition: No signals in other new physics searches (SUSY, Dark Matter, ...), stringent limits on EDMs, ...

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Explore the LHC signatures of

- Models with additional scalar singlets:
 - one real scalar field
 - two real scalar fields
- Models with additional scalar doublet:
 - Two Higgs Doublet Model (2HDM)
 - Minimal Supersymmetric Standard Model (MSSM)

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 ($S \rightarrow -S$), 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, $h_{SM} \rightarrow SS$.

[Feng, Profumo, Ubaldi '14; GAMBIT coll. '17]

$\langle S \rangle \neq 0 \Rightarrow$ 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, $h_S \rightarrow h_{SM} h_{SM}$,
- 4) SM-like Higgs decaying into singlet-like Higgs, $h_{SM} \rightarrow h_S h_S$.

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

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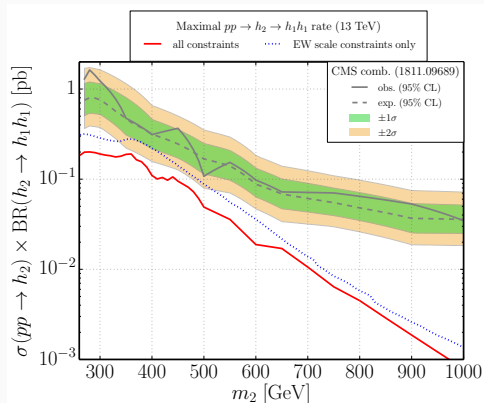
[Robens, TS '15,'16; *id.*+Ilnicka '18]

RESONANT DOUBLE HIGGS PRODUCTION RATES ($\langle S \rangle \neq 0$)

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

$$\Rightarrow \text{BR}(h_S \rightarrow h_{\text{SM}} h_{\text{SM}}) \lesssim (20 - 40)\%$$

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



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

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

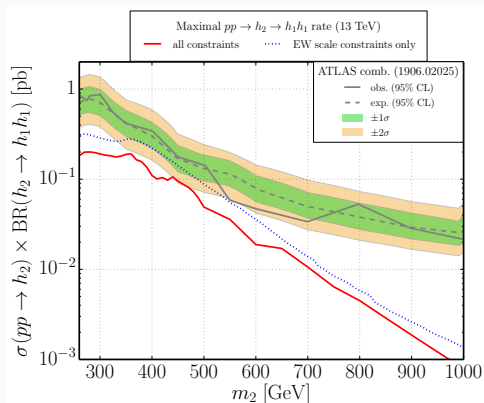
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Imposed $\mathbb{Z}_2 \times \mathbb{Z}'_2$ symmetry, which is spontaneously broken by singlet vevs.

$\Rightarrow$ 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.

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

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

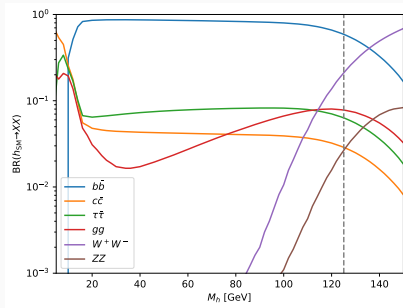
[Robens, TS, Wittbrodt (in progress)]

Rich phenomenology of $h_i \rightarrow h_j h_k$ 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 ($h_i \rightarrow h_j h_j$) and asymmetric ($h_3 \rightarrow h_1 h_2$) decays,
- cascade decays: $h_3 \rightarrow h_1 h_2 \rightarrow h_1 h_1 h_1$ and $h_3 \rightarrow h_2 h_2 \rightarrow h_1 h_1 h_1 h_1$.

In this model:

The lightest Higgs state h_1 decays identically as a SM Higgs boson at M_1 . $\Rightarrow$
(May be different in other models.)

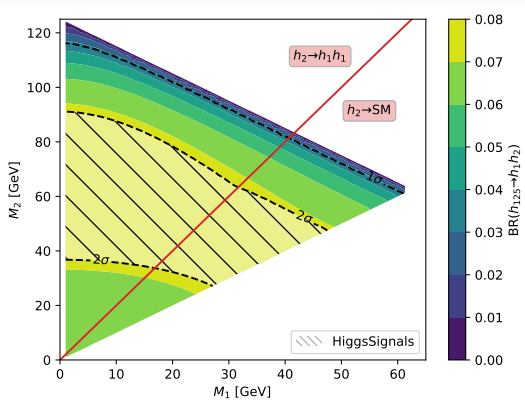


$\Rightarrow$ Several benchmark scenarios suggested to LHC-HXSWG HH subgroup.

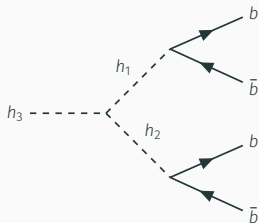
(see also backup slides)

BENCHMARK SCENARIO 1: $h_3 \rightarrow h_1 h_2$ (WITH $h_3 = h_{125}$)

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



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

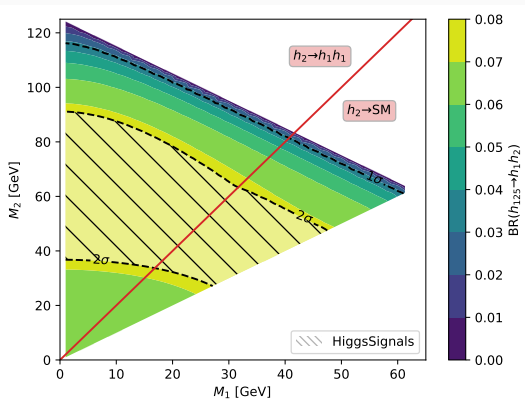


$$\sigma_{13 \text{ TeV}}(h_1 h_2) \lesssim 3 \text{ pb}$$

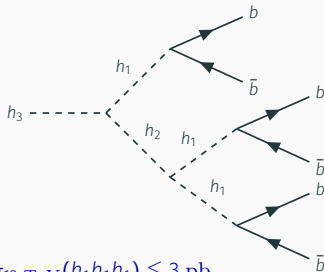
Idea: use invariant masses to (recursively) look for resonances in the spectrum.

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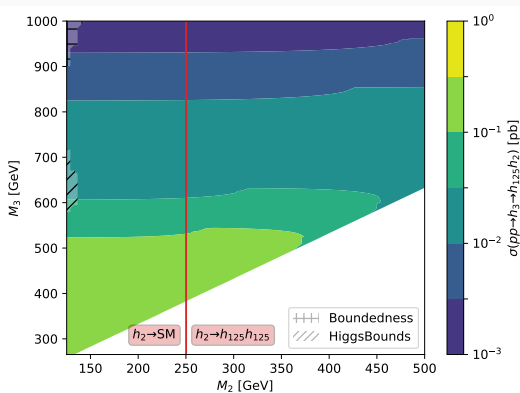
Triple- h_1 signature ($M_2 > 2M_1$), e.g.



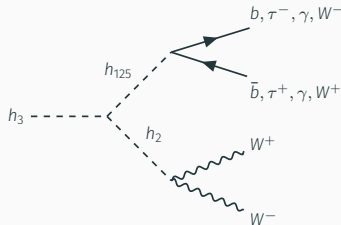
Idea: use invariant masses to (recursively) look for resonances in the spectrum.

BENCHMARK SCENARIO 3: $h_3 \rightarrow h_1 h_2$ (WITH $h_1 = h_{125}$)

- Two heavy scalars with unknown masses $125 \text{ GeV} < M_2 < M_3$,
- Production of h_3 with signal strength $\mu \simeq 0.04$,
decay rate $\text{BR}(h_3 \rightarrow h_1 h_2) \sim (60 - 75)\%$.



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

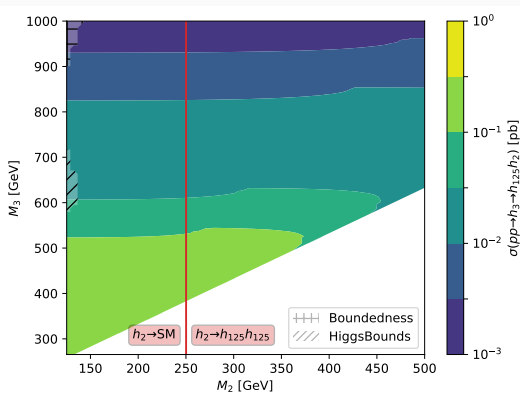


For $M_3 \lesssim 500 \text{ GeV}$:

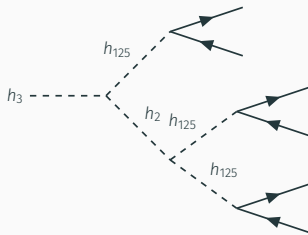
$$\sigma_{13 \text{ TeV}}(pp \rightarrow h_3 \rightarrow h_1 h_2) \gtrsim 0.1 \text{ pb.}$$

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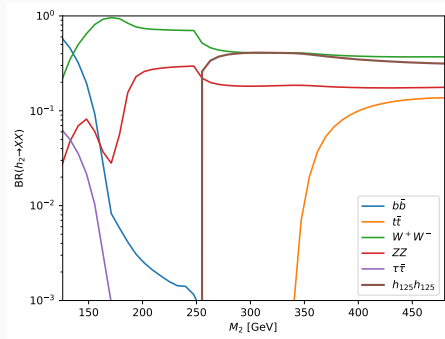
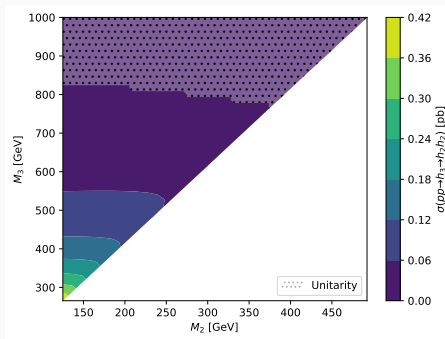


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BENCHMARK SCENARIO 6: $h_3 \rightarrow h_2 h_2$ (WITH $h_1 = h_{125}$)

- Two heavy scalars with unknown masses $125 \text{ GeV} < M_2 < M_3$,
- Production of h_3 with signal strength $\mu \simeq 0.02$,
decay rate $\text{BR}(h_3 \rightarrow h_2 h_2) \sim (70 - 80)\%$.



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

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*):

$(\Phi_1, \Phi_2: SU(2)_L \text{ doublets})$

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

$\mathbb{Z}_2$ symmetry ($\Phi_1 \rightarrow +\Phi_1, \Phi_2 \rightarrow -\Phi_2$) 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:

Two parameters govern the tree-level couplings:

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

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

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

Higgs-vector boson couplings:

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

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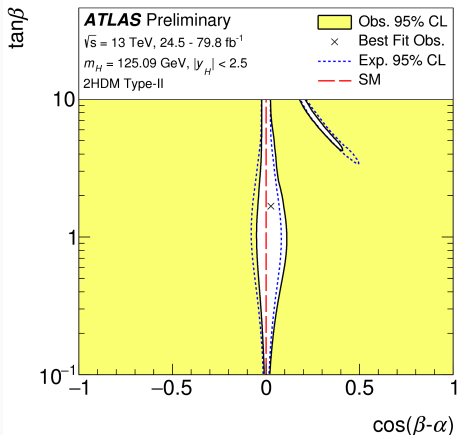
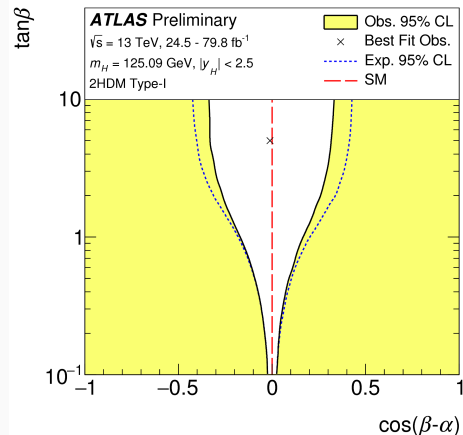
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coupling	Type I	Type II
$h u u$	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$
$h d d, h \ell \ell$	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$
$H u u$	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$
$H d d, H \ell \ell$	$\sin \alpha / \sin \beta$	$\cos \alpha / \cos \beta$
$A u u$	$-\cot \beta$	$-\cot \beta$
$A d d, A \ell \ell$	$\cot \beta$	$-\tan \beta$

[ATLAS-CONF-2019-005]

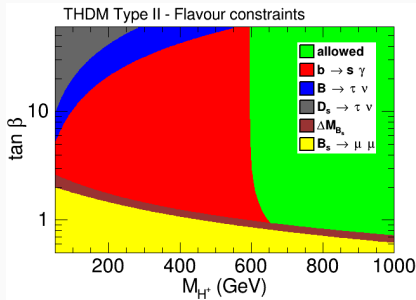
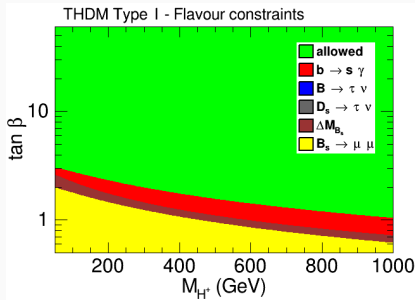


- Higgs rates severely constrain the mixing angle $\cos(\beta - \alpha)$, and favor the **alignment limit**, $\cos(\beta - \alpha) \rightarrow 0$.
- Heavy Higgs H at 125 GeV equally viable (then: $\sin(\beta - \alpha) \rightarrow 0$).

WHERE IS THE CHARGED HIGGS BOSON?

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

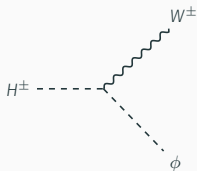
LHC searches mostly focus on fermionic final states ($H^\pm \rightarrow \tau\nu$, $H^\pm \rightarrow tb$).

Important fact (in 2HDM):

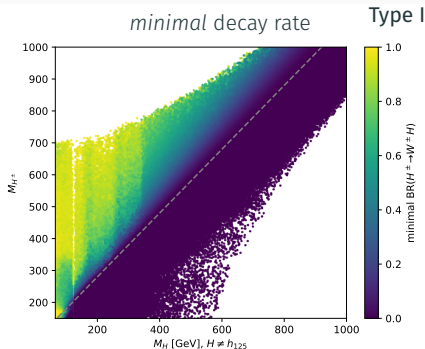
In the alignment limit the $H^\pm W^\mp \phi$ coupling is maximized
[ϕ denotes the non-SM-like $\mathcal{CP}$ -even Higgs boson]:

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

⇒ sizable $H^\pm \rightarrow W^\pm \phi$ decay rates!



[TS, Wittbrodt (in progress)]



CHARGED HIGGS BOSONS AT THE LHC

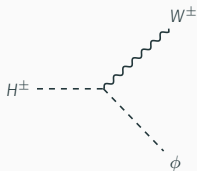
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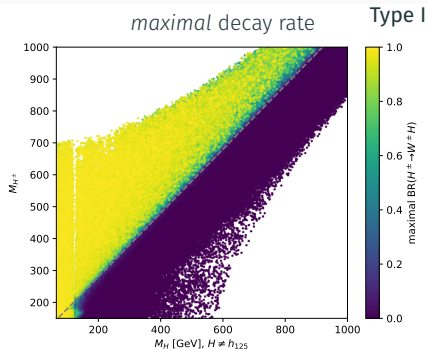
In the alignment limit the $H^\pm W^\mp \phi$ coupling is maximized
[ϕ denotes the non-SM-like $\mathcal{CP}$ -even Higgs boson]:

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

⇒ sizable $H^\pm \rightarrow W^\pm \phi$ decay rates!



[TS, Wittbrodt (in progress)]



CHARGED-HIGGS-TO-NEUTRAL-HIGGS DECAY SIGNATURES

[TS, Wittbrodt (in progress)]

Production process	Higgs decay processes	Final state particles
$pp \rightarrow H^\pm tb$	$H^\pm \rightarrow W^\pm \phi, \phi \rightarrow \begin{cases} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{cases}$	$tbW^\pm + \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix}$
$pp \rightarrow H^\pm \phi$	$H^\pm \rightarrow W^\pm \phi, \phi \rightarrow \begin{cases} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{cases}$	$W^\pm + \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix} \oplus \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix}$
$pp \rightarrow H^\pm W^\mp$	$H^\pm \rightarrow W^\pm \phi, \phi \rightarrow \begin{cases} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{cases}$	$W^\pm W^\mp + \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix}$
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CHARGED-HIGGS-TO-NEUTRAL-HIGGS DECAY SIGNATURES

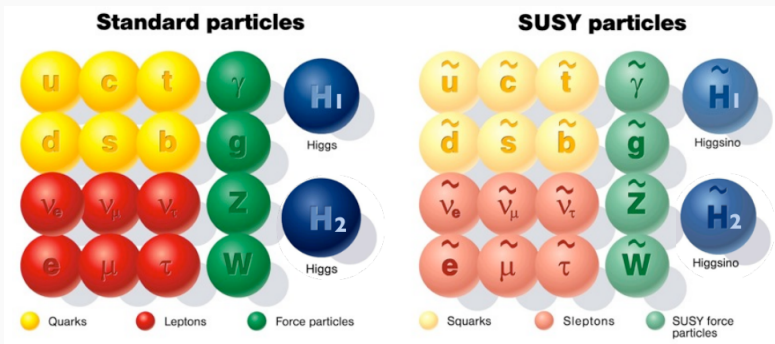
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$\Rightarrow$ Many new experimental opportunities for upcoming LHC Run(s)!		
$pp \rightarrow H^\pm W^\mp$	$H^\pm \rightarrow W^\pm \phi, \phi \rightarrow \begin{cases} \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{cases}$	$W^\pm W^\mp + \begin{bmatrix} \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix}$
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THE MINIMAL SUPERSYMMETRIC STANDARD MODEL (MSSM)

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

⇒ Introduce *superpartners* for every SM field.



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

MSSM HIGGS SECTOR

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

$$\begin{aligned}\lambda_1 &= \lambda_2 = \frac{1}{4}(g^2 + g'^2), & \lambda_3 &= \frac{1}{4}(g^2 - g'^2), \\ \lambda_4 &= -\frac{1}{2}g^2, & \lambda_5 &= \lambda_6 = \lambda_7 = 0.\end{aligned}$$

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

Predicted **tree-level** mass spectrum:

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

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

$$(\Delta M_h^2)_{1L}^{t,\tilde{t}} \approx \frac{3m_t^4}{2\pi^2 V^2} \left[\log \left(\frac{M_S^2}{m_t^2} \right) + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12M_S^2} \right) \right]$$
$$\begin{aligned}(M_A \gg M_Z, \tan \beta \gg 1) \\ X_t &= A_t - \mu / \tan \beta, \\ M_S &= \sqrt{M_{\tilde{t}_1} M_{\tilde{t}_2}}.\end{aligned}$$

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

NEW MSSM HIGGS BENCHMARK SCENARIOS – OVERVIEW

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

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

M_h^{125}	“standard” scenario, all SUSY masses $\gtrsim 1 \text{ TeV}$
$M_h^{125}(\tilde{\tau})$	light staus: sizable effect on $h \rightarrow \gamma\gamma$ at large $\tan\beta$
$M_h^{125}(\tilde{\chi})$	light EW-inos: new decay channels for heavy Higgs bosons
$M_h^{125}(\text{alignment})$	h couplings very SM-like even at low M_A values
M_H^{125}	heavier MSSM Higgs boson H is SM-like at $\sim 125 \text{ GeV}$
$M_h^{125}(\text{CPV})$	interference effects suppress heavy Higgs rate in $\tau^+\tau^-$ channel
[Bahl et al. 1808.07542]	
$M_{h,\text{EFT}}^{125}$	“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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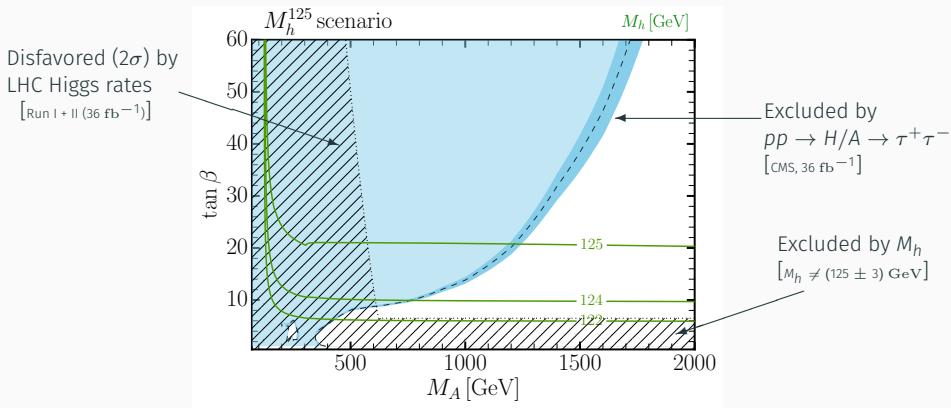
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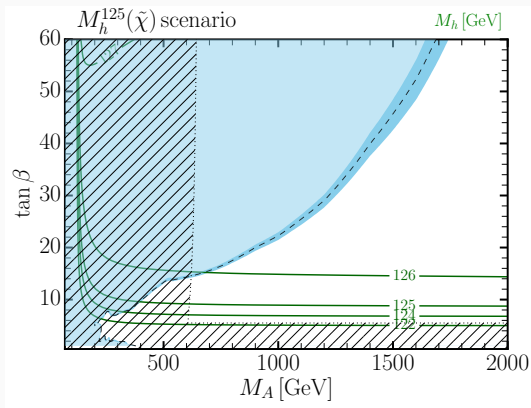
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M_h^{125} BENCHMARK SCENARIO



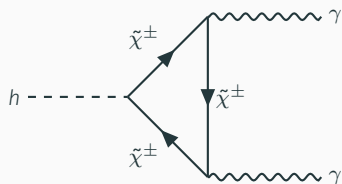
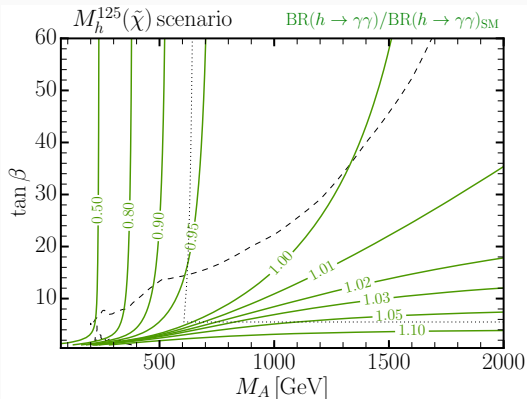
- Assumption: all SUSY particle masses are $\gtrsim 1 \text{ TeV}$.
- Higgs rates & limits $\Rightarrow H, A$ and $H^\pm$ expected to be heavy (mass $\gtrsim 600 \text{ GeV}$).

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



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

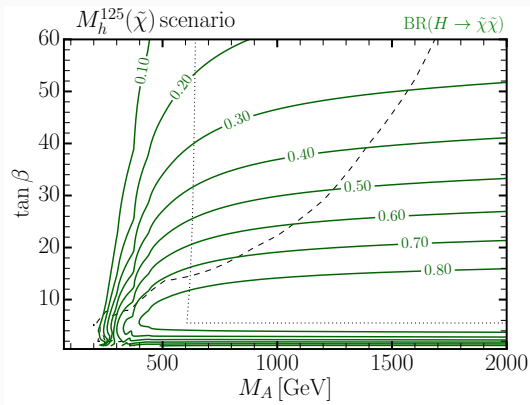
$M_h^{125}(\tilde{\chi})$ BENCHMARK SCENARIO: LIGHT NEUTRALINOS & CHARGINOS



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

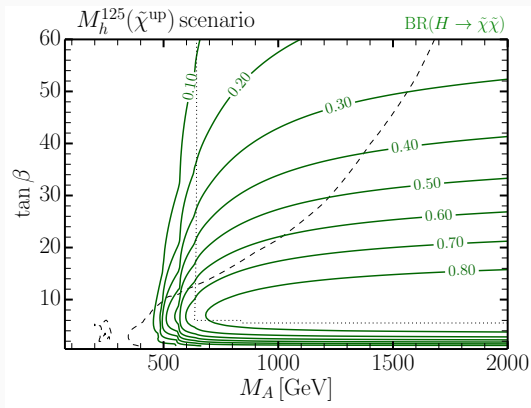
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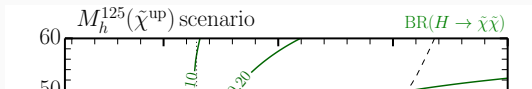


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Dedicated experimental searches for $pp \rightarrow H/A \rightarrow \tilde{\chi}\tilde{\chi}$ well motivated:

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

$$pp \rightarrow H \xrightarrow{30\%} \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp \xrightarrow{51\%} (\tilde{\chi}_1^\pm W^\pm)(\tilde{\chi}_1^\mp Z) \xrightarrow{100\%} W^\pm W^\mp Z + \cancel{E}_T$$

$$pp \rightarrow A \xrightarrow{9.4\%} \tilde{\chi}_2^\pm \tilde{\chi}_2^\mp \xrightarrow{26\%} (\tilde{\chi}_1^\pm Z)(\tilde{\chi}_1^\mp Z) \xrightarrow{100\%} W^\pm W^\mp ZZ + \cancel{E}_T$$

$\Rightarrow$ multi-W/Z-boson + $\cancel{E}_T$ signatures.

- Discovery would reveal existence of BSM Higgs bosons *and* SUSY particles!
- Light neutralinos and charginos with masses $\sim (100 - 250)$ GeV.
- Impact of $H/A \rightarrow \tau^+\tau^-$ search limit on parameter space weakened due to additional H/A decay modes.
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Conclusions

CONCLUSIONS

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

⇒ **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. $H \rightarrow hh$ in Z_2 -symmetric singlet extension),
- additional Higgs bosons may only be probed by **new searches for so-far-uncovered signatures**: $h_i \rightarrow h_j h_k$, $H^\pm \rightarrow W^\pm h$, $pp \rightarrow H/A \rightarrow \tilde{\chi}\tilde{\chi}$, ...

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

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Thank you very much for your attention!

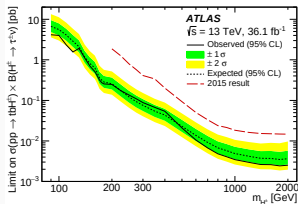
Backup Slides

PUBLIC TOOLS FOR TESTING BSM MODELS WITH HIGGS RESULTS

HiggsBounds

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

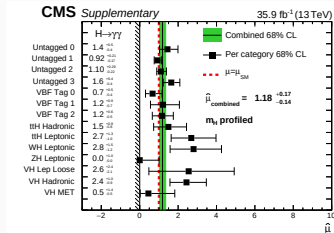
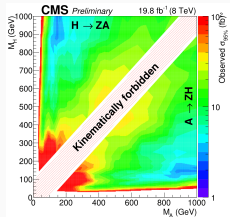
⇒ *excluded/allowed at 95% C.L.*



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]

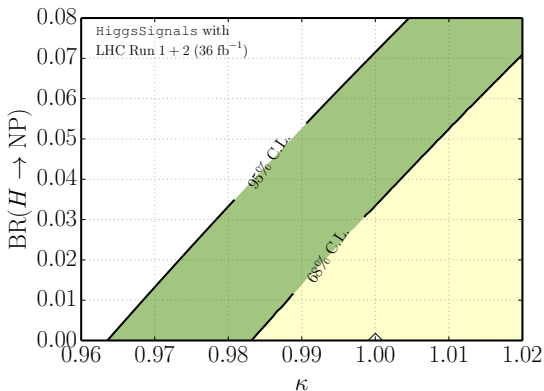
Available at <http://higgsbounds.hepforge.org>.

IMPACT OF HIGGS RATE MEASUREMENTS AT THE LHC

Singlet model:

(assume heavier Higgs at 125 GeV)

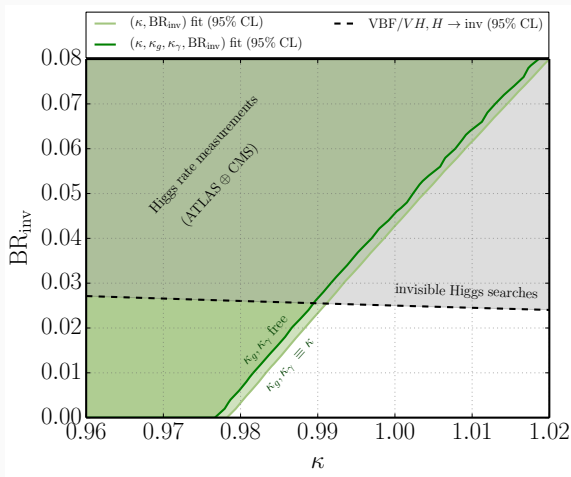
$$\kappa = \sin \alpha, \quad \text{BR}(H \rightarrow \text{NP}) = \text{BR}(h_{\text{SM}} \rightarrow h_{\text{S}} h_{\text{S}}).$$



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

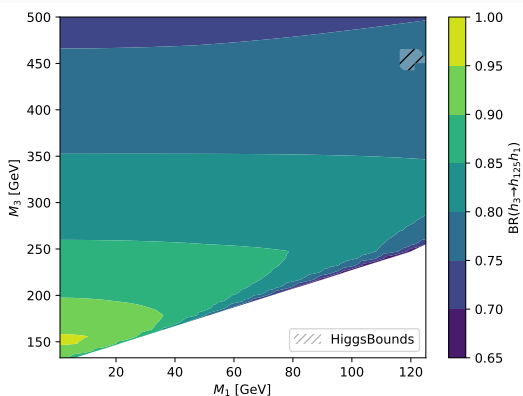
Note: further constraints arise from LEP Higgs searches.

HL-LHC PROSPECTS ON INVISIBLE HIGGS DECAYS

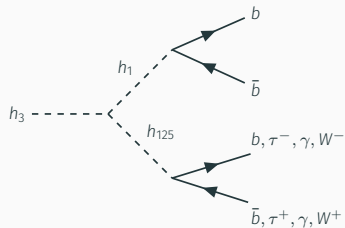


BENCHMARK SCENARIO 2: $h_3 \rightarrow h_1 h_2$ (WITH $h_2 = h_{125}$)

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



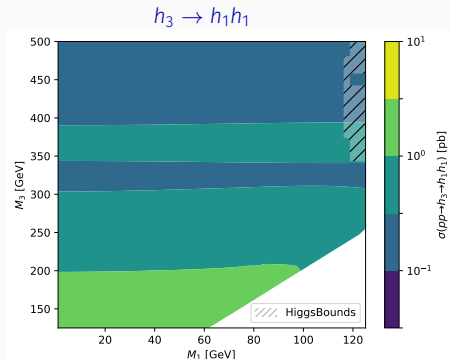
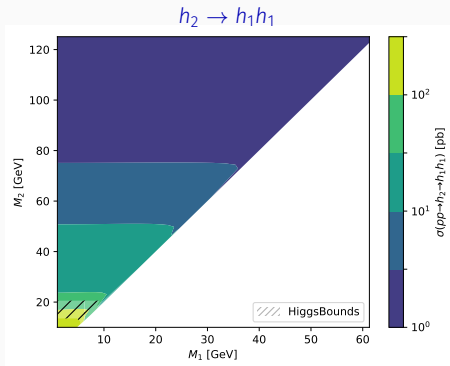
Signature:



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

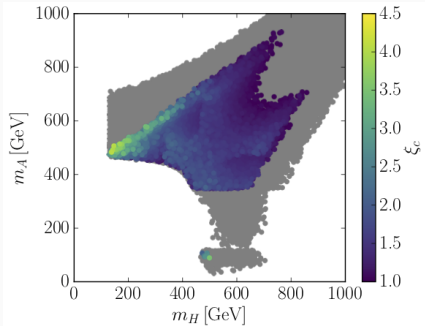
BENCHMARK SCENARIOS 4 & 5: $h_{\text{NON-SM}} \rightarrow h_1 h_1$ (WITH $h_1 \neq h_{125}$)

- (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 $\text{BR}(h_{\text{non-SM}} \rightarrow h_1 h_1) \sim (70 - 100)\%$.



INTERPLAY OF COLLIDER SEARCHES, COSMOLOGY AND DARK MATTER

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



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).

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

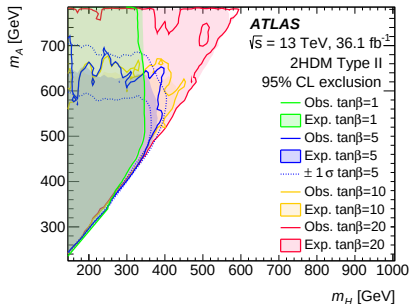
$\Rightarrow pp \rightarrow A \rightarrow HZ$ searches well-motivated.

[Dorsch, Huber, Mimasu, No '14]

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[ATLAS '18]

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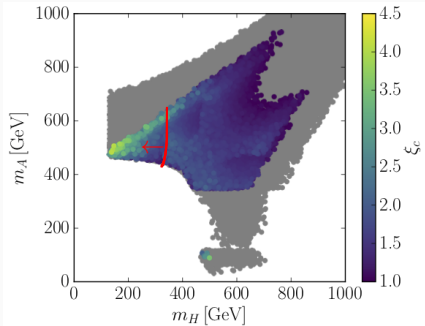
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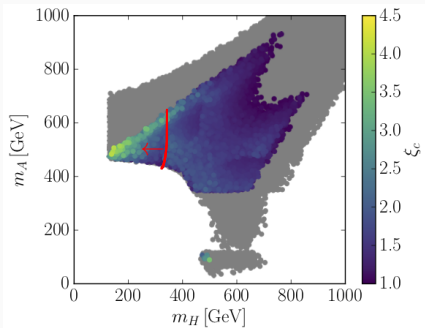
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$\Leftarrow$ ATLAS Run-II 36 fb^{-1} limit (roughly).

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2) Inert Doublet Model

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, $h \rightarrow \gamma\gamma$ rate.

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

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.

Question:

Will we ever be able to tell whether h or H is at 125 GeV?

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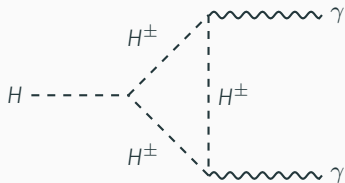
Even in the alignment limit, $\cos(\beta - \alpha) \rightarrow 1$, charged Higgs effects on the Higgs rates do not decouple:

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

because $\bar{m}^2 \equiv 2m_{12}^2 / \sin(2\beta) \lesssim \mathcal{O}(v^2)$
imposed by unitarity and stability
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$\Rightarrow$ suppression of the $H \rightarrow \gamma\gamma$ rate!

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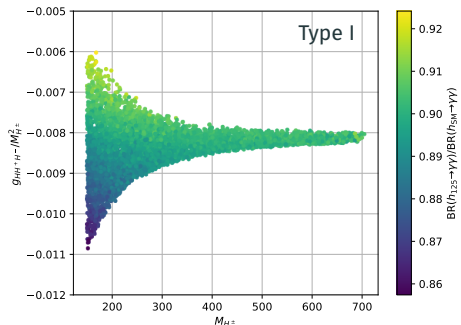
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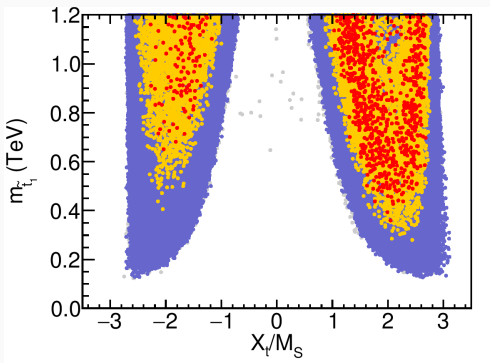
[TS, Wittbrodt (*in progress*)]

THE ROLE OF THE HIGGS MASS IN THE MSSM

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

⇒ important constraints on MSSM parameter space.

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



- 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)

⇒ need large stop mixing, X_t/M_S ,
and/or large stop masses.

[Bechtle et al. '16]

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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. ≥ 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: $\tan\beta = 20$, 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

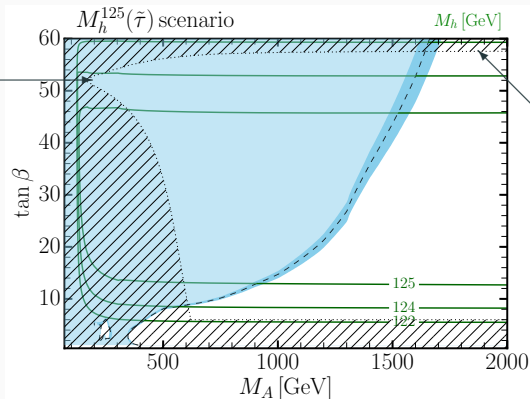
} Fixed-order
calculations
in the $\overline{\text{DR}}$ scheme
(no resummation)
different treatment
of top Yukawa cpl.

[taken from P. Slavich, HDays '18]

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

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

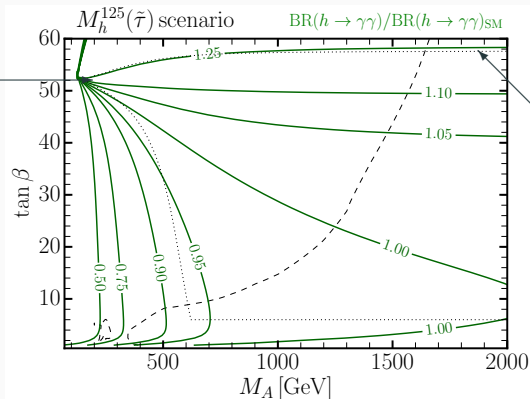
Limit of alignment
w/o decoupling at
 $\tan \beta \simeq 52$.



$$\begin{aligned}
 M_{Q_3} &= M_{U_3} = M_{D_3} = 1.5 \text{ TeV}, & M_{L_3} &= M_{E_3} = 350 \text{ GeV}, \\
 \mu &= 1 \text{ TeV}, & M_1 &= 180 \text{ GeV}, & M_2 &= 300 \text{ GeV}, & M_3 &= 2.5 \text{ TeV}, \\
 X_t &= 2.8 \text{ TeV}, & A_b &= A_t, & A_\tau &= 800 \text{ GeV}.
 \end{aligned}$$

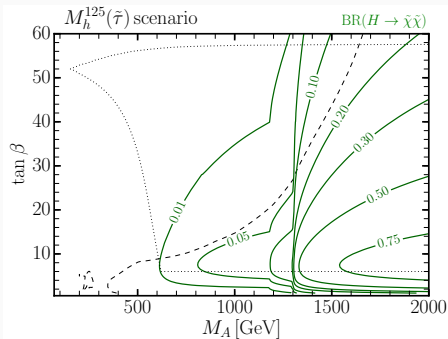
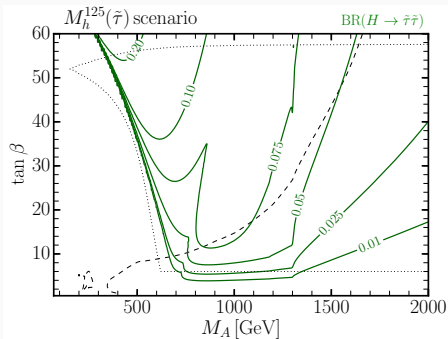
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 \end{aligned}$$

$M_h^{125}(\tilde{\tau})$ SCENARIO: HEAVY HIGGS TO SUSY DECAYS



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

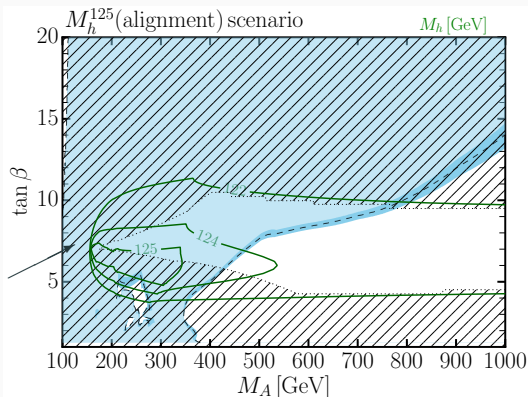
$\Rightarrow$ additional H/A decays weaken the impact of $H/A \rightarrow \tau^+\tau^-$ constraints.

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

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

$M_h^{125}(\text{ALIGNMENT})$ SCENARIO

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



$$\begin{aligned} M_{Q_3} &= M_{U_3} = M_{D_3} = 2.5 \text{ TeV}, & M_{L_3} &= M_{E_3} = 2 \text{ TeV}, \\ \mu &= 7.5 \text{ TeV}, & M_1 &= 500 \text{ GeV}, & M_2 &= 1 \text{ TeV}, & M_3 &= 2.5 \text{ TeV}, \\ A_t &= A_b = A_\tau = 6.25 \text{ TeV}. \end{aligned}$$

M_h^{125} (ALIGNMENT) SCENARIO

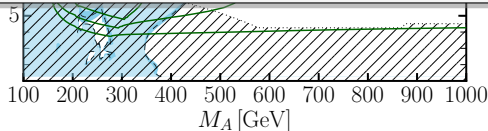


The M_h^{125} (alignment) scenario

- (+) motivates H/A searches in the low M_A region;
- (-) is in conflict with vacuum (meta-)stability constraints.

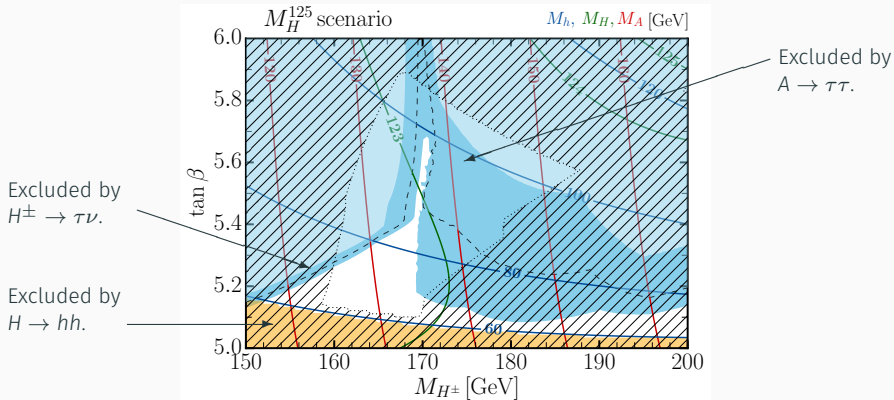
[Hollik, Weiglein, Wittbrodt 1812.04644]

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



$$\begin{aligned} M_{Q_3} &= M_{U_3} = M_{D_3} = 2.5 \text{ TeV}, & M_{L_3} &= M_{E_3} = 2 \text{ TeV}, \\ \mu &= 7.5 \text{ TeV}, & M_1 &= 500 \text{ GeV}, & M_2 &= 1 \text{ TeV}, & M_3 &= 2.5 \text{ TeV}, \\ A_t &= A_b = A_\tau = 6.25 \text{ TeV}. \end{aligned}$$

M_H^{125} SCENARIO: THE HEAVIER HIGGS H IS SM-LIKE



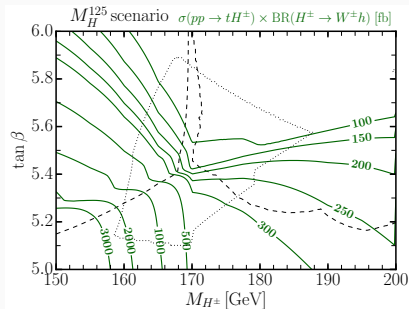
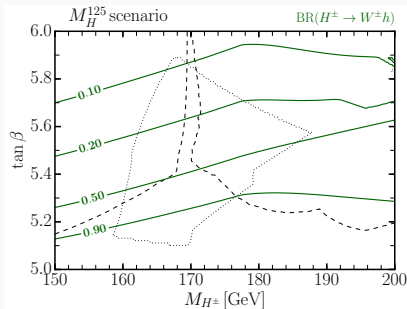
$$M_{Q_3} = M_{U_3} = 750 \text{ GeV} - 2 (M_{H^\pm} - 150 \text{ GeV}) ,$$

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

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

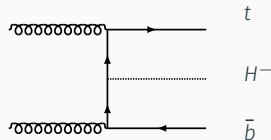
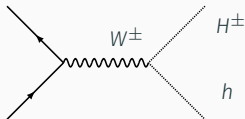
$$M_1 = M_{Q_3} - 75 \text{ GeV} , \quad M_2 = 1 \text{ TeV} , \quad M_3 = 2.5 \text{ TeV} .$$

M_H^{125} SCENARIO: CHARGED HIGGS PHENOMENOLOGY

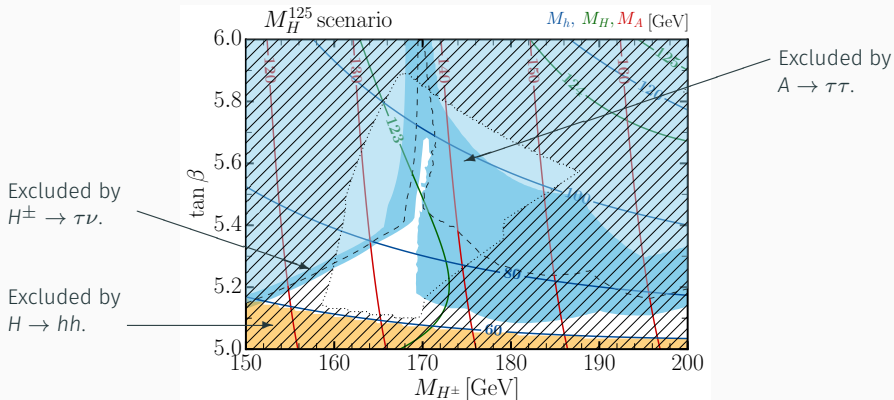


$H^\pm W^\mp h$ coupling $\propto \cos(\beta - \alpha) \approx 1$ if H is SM-like.

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



M_H^{125} SCENARIO: THE HEAVIER HIGGS H IS SM-LIKE



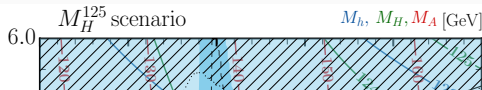
$$M_{Q_3} = M_{U_3} = 750 \text{ GeV} - 2 (M_{H^\pm} - 150 \text{ GeV}) ,$$

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

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

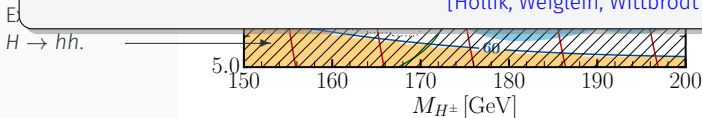
M_H^{125} SCENARIO: THE HEAVIER HIGGS H IS SM-LIKE



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]



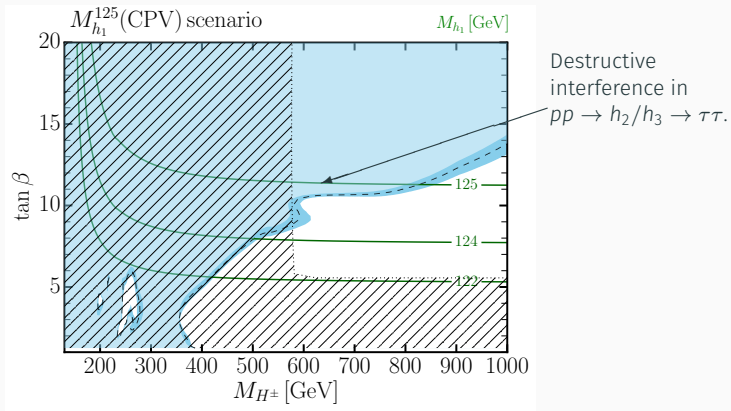
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$$M_1 = M_{Q_3} - 75 \text{ GeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV} .$$

$M_{h_1}^{125}(\text{CPV})$ SCENARIO: NEUTRAL HIGGS BOSONS MIX (h_1, h_2, h_3)

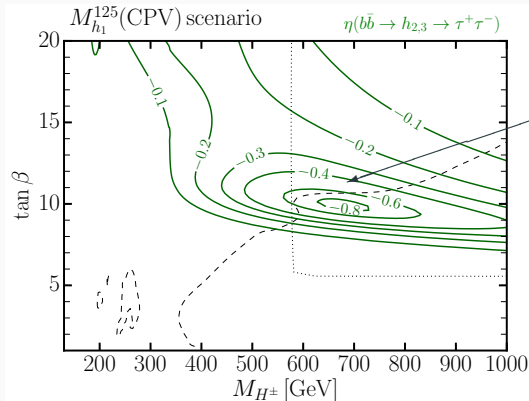


$$M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} = 2 \text{ TeV},$$

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

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

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



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

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

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). [\[Bah, Hollik 1805.00867\]](#)

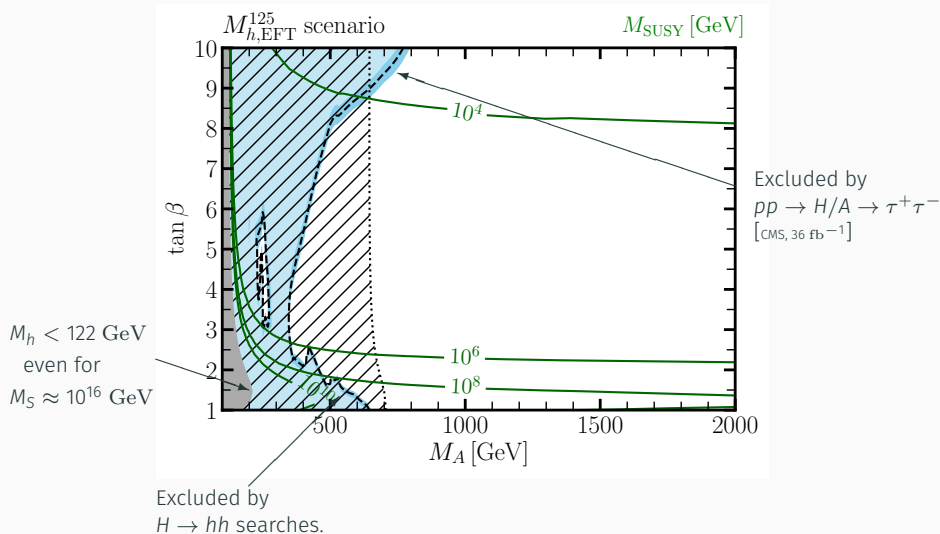
State-of-the-art calculation implemented in (yet unpublished) **FeynHiggs** version.

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

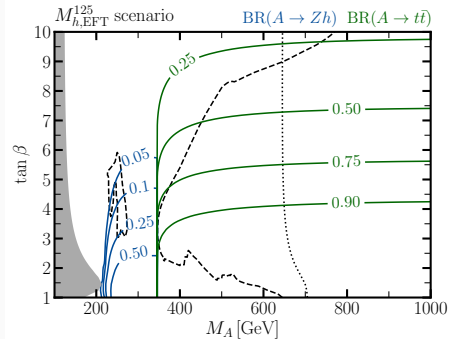
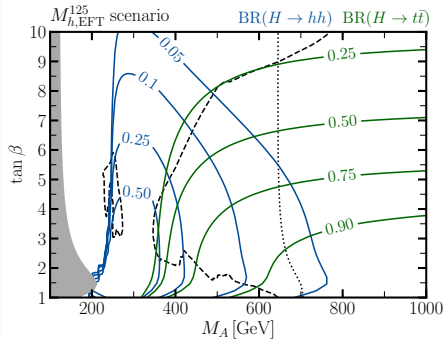
Similar (older) scenarios:

hMSSM [\[Djouadi et al. 1307.5205\]](#), low- $\tan \beta$ -high scenario [\[LHCHSWG-2015-002\]](#).

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



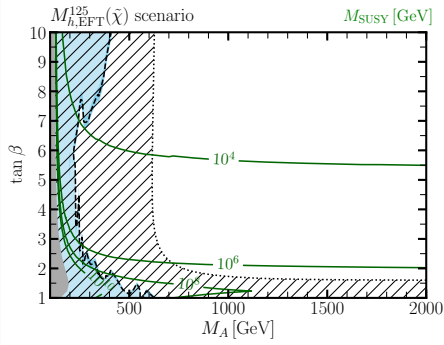
$M_{h,\text{EFT}}^{125}$ SCENARIO: HEAVY HIGGS DECAYS



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

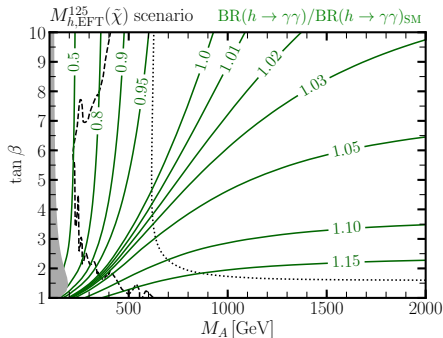
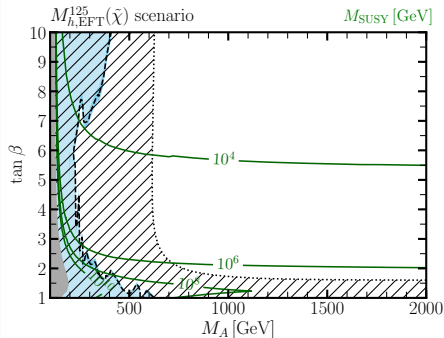
Very recent discussion of $H/A \rightarrow t\bar{t}$ signal+BG interference effects and discovery prospects: [\[Djouadi, Ellis, Popov, Quevillon 1901.03417\]](#)

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



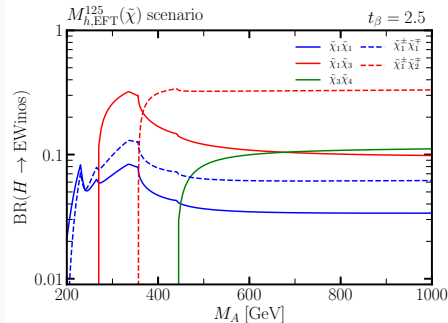
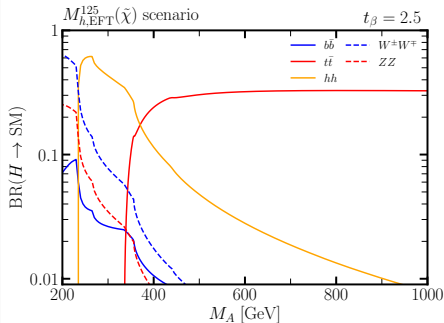
- Light electroweakinos lead to upward shift of M_h by ~ 1.5 GeV.
 $\Rightarrow$ Slightly lower M_S values required as in $M_{h,\text{EFT}}^{125}$ scenario.

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



- Light electroweakinos lead to upward shift of M_h by ~ 1.5 GeV.
 $\Rightarrow$ Slightly lower M_S values required as in $M_{h,\text{EFT}}^{125}$ scenario.
- Light charginos lead to $h \rightarrow \gamma\gamma$ 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



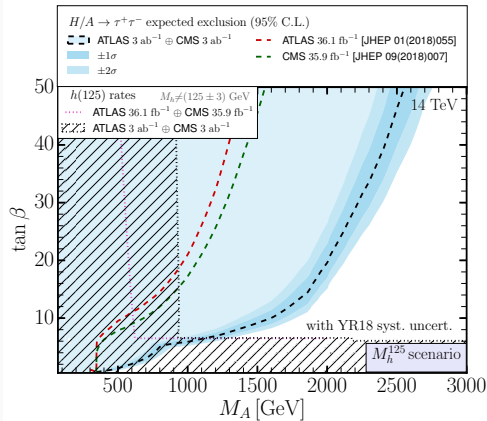
For $M_A \gtrsim 400$ GeV, heavy-Higgs-to-electroweakino decays are dominant.

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

Cascade decays preferred, leading to multi-W/Z-boson+ $\cancel{E}_T$ signatures.

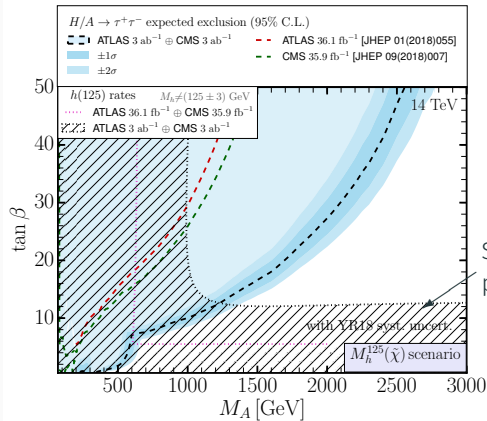
$\Rightarrow$ Dedicated experimental analyses of $H/A \rightarrow \tilde{\chi}\tilde{\chi}$ decays are well-motivated!

HL-LHC REACH FOR THE MSSM HIGGS SECTOR



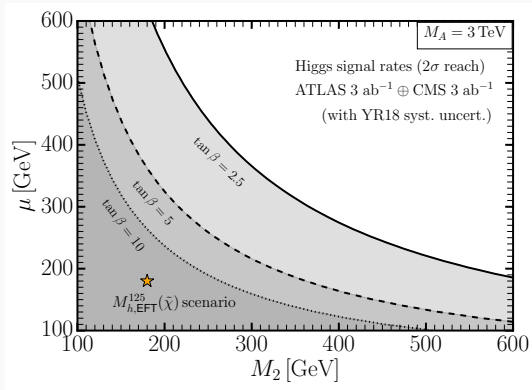
- HL-LHC Higgs rate measurements will be sensitive to $M_A \lesssim 1$ TeV.
- Direct searches for $pp \rightarrow H/A \rightarrow \tau^+\tau^-$ are sensitive to $M_A \lesssim 2.5$ TeV (depending on $\tan \beta$).

HL-LHC REACH FOR THE MSSM HIGGS SECTOR



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HL-LHC REACH FOR THE MSSM HIGGS SECTOR



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