Novel signatures of additional Higgs bosons at the LHC

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ATLAS Exotics & HDBS Workshop
Naples, 12 June 2019
Introduction
New physics in the Higgs sector?

- Cosmology
- Dark Matter (DM)
- Experimental anomalies
- BSM Higgs
- Vacuum stability
- Naturalness
- Part of UV theory (e.g. Supersymmetry)
Possible BSM effects:

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

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

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?

Tim Stefaniak (DESY) | BSM Higgs physics | ATLAS Exotics & HDBS workshop | 12 June 2019
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Theory meets Experiment: The hard truth of reality

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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** \((\Phi: SU(2)_L\) 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 \(\langle S \rangle \neq 0\).

\[
\langle S \rangle = 0 \Rightarrow \text{S is (highly constrained) DM candidate, no mixing with } \Phi;
\]

**Possible LHC signature:** invisible Higgs decay, \(h_{SM} \rightarrow SS\).

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

\[
\langle S \rangle \neq 0 \Rightarrow \text{S and } \Phi \text{ mix (with } \sin \alpha\text{)}; \text{Possible LHC Signatures:}
\]

1) Universally reduced signal strength of \(h_{SM}\),
2) New Higgs state in SM Higgs searches (strongly reduced \(\mu\)),
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]
Adding one real scalar singlet

Scalar potential \( (\Phi: SU(2)_L \text{ doublet, } S: SU(2)_L \text{ singlet}) \)

\[ V = -\mu^2 \Phi \Phi^\dagger - \mu_S^2 S^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 S^4 + \lambda_3 \Phi \Phi^\dagger S^2. \]

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\[ \text{[Feng, Profumo, Ubaldi '14; GAMBIT coll. '17]} \]

\[ \text{[Robens, TS '15,'16; id.+Ilnicka '18]} \]
After all constraints (*Higgs signal rates and limits, M_W, EW precision observables, perturbativity of couplings, vacuum stability*):

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

[Robens, TS ’15,’16; id.+Ilnicka ’18]

\[ \Rightarrow \text{LHC searches for } pp \rightarrow H \rightarrow h_{SM}h_{SM} \]

are slowly becoming sensitive.

*For comparison:* In SM,

\[ \sigma_{14\text{TeV}}(pp \rightarrow h_{SM}h_{SM}) \simeq 33 \text{ fb}. \]

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

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

[Robens, TS ‘15,‘16; id.+Ilnicka ‘18]

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

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[Dawson, Lewis, Robens, TS, Sullivan, *contr. to HH whitepaper (to appear)*]
**Adding two real scalar singlets**

| Scalar potential | $(\Phi: SU(2)_L$ doublet, $S, X: SU(2)_L$ singlets) |
|------------------|---------------------------------------------------|
| $\mathcal{V} = \mu_\Phi^2 \Phi^\dagger \Phi + \mu_S^2 S^2 + \mu_X^2 X^2 + \lambda_{\Phi} (\Phi^\dagger \Phi)^2 + \lambda_S S^4 + \lambda_X X^4 + \lambda_{\Phi S} \Phi^\dagger \Phi S^2 + \lambda_{\Phi X} \Phi^\dagger \Phi X^2 + \lambda_{S X} S^2 X^2.$ |

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.*
**Adding two real scalar singlets**

Scalar potential \( \Phi: SU(2)_L \) doublet, \( S, X: SU(2)_L \) singlets

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

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

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- **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*. 
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 $M_1$. ⇒
(May be different in other models.)

⇒ 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: \( \sigma(pp \rightarrow h_3) \approx \sigma(pp \rightarrow h_{SM}) \approx 50 \) pb.

\[ \begin{align*}
M_2 \text{ [GeV]} & \quad \text{BR}(h_{125} \rightarrow h_1 h_2) \\
0 & \quad 0.00 \\
10 & \quad 0.01 \\
20 & \quad 0.02 \\
30 & \quad 0.03 \\
40 & \quad 0.04 \\
50 & \quad 0.05 \\
60 & \quad 0.06 \\
70 & \quad 0.07 \\
80 & \quad 0.08 \\
90 & \quad 0.09 \\
100 & \quad 0.10 \\
110 & \quad 0.11 \\
120 & \quad 0.12 \\
\end{align*} \]

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

\[ \begin{align*}
\sigma_{13 \text{ TeV}}(h_1 h_2) & \lesssim 3 \text{ pb} \\
\end{align*} \]

Idea: use invariant masses to (recursively) look for resonances in the spectrum.
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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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**BENCHMARK SCENARIO 3:** \( h_3 \to h_1 h_2 \) **(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 \( \text{BR}(h_3 \to h_1 h_2) \sim (60 - 75)\% \).

**Triple-\( h_{125} \) signature \((M_2 > 250 \text{ GeV})\):**

**For** \( M_3 \lesssim 500 \text{ GeV} \): \( \sigma_{13} \text{ TeV}(pp \to h_3 \to h_1 h_2) \gtrsim 0.1 \text{ pb} \).
**Benchmark Scenario 6: \( h_3 \rightarrow h_2h_2 \) (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 \( \mu \approx 0.02 \), decay rate \( \text{BR}(h_3 \rightarrow h_2h_2) \sim (70 - 80)\% \).

![Graph showing the relationship between \( M_2 \) and \( M_3 \) with shaded regions indicating different scenarios.]

- if \( M_2 < 250 \text{ GeV} \Rightarrow W^+W^-W^+W^- \) final state seems most promising,
  \[ \rightarrow \text{first } h_3 \rightarrow h_2h_2 \text{ search: } \text{[ATLAS, 1811.11028]} \]
- if \( M_2 > 250 \text{ GeV} \Rightarrow \text{spectacular } h_{125}h_{125}h_{125}h_{125} \text{ signature! } \text{[rate } \lesssim \mathcal{O}(10 \text{ fb})\text{]} \]
Models with an additional scalar doublet (2HDM, MSSM)
2 complex $SU(2)_L$ doublets $\Rightarrow$ 5 Higgs states $h, H, A, H^\pm$

**Higgs potential (general basis):**

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

$\mathbb{Z}_2$ 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 $\in \mathbb{R}$. 
**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):** $(\Phi_1, \Phi_2: SU(2)_L$ 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.}] + \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.}]
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Extending the $\mathbb{Z}_2$ to the fermion sector suppresses tree-level FCNCs:

| Type | $u$ | $d$ | $\ell$ |
|------|-----|-----|-------|
| Type I | $\Phi_2$ | $\Phi_2$ | $\Phi_2$ |
| Type II | $\Phi_2$ | $\Phi_1$ | $\Phi_1$ |
| Type III | $\Phi_2$ | $\Phi_1$ | $\Phi_2$ |
| Type IV | $\Phi_2$ | $\Phi_2$ | $\Phi_1$ |

Two parameters govern the tree-level couplings:

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

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

Higgs-vector boson couplings:

hVV: $\sin(\beta - \alpha)$,  
HVV: $\cos(\beta - \alpha)$,  
AVV: 0.
2 complex $SU(2)_L$ doublets $\Rightarrow$ 5 Higgs states $h, H, A, H^{\pm}$

**Higgs potential (general basis):**

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

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

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| Type II | $\Phi_2$ | $\Phi_1$ | $\Phi_1$ |
| Type III | $\Phi_2$ | $\Phi_1$ | $\Phi_2$ |
| Type IV | $\Phi_2$ | $\Phi_2$ | $\Phi_1$ |

| coupling | Type I | Type II |
|----------|--------|---------|
| $huu$ | $\cos \alpha / \sin \beta$ | $\cos \alpha / \sin \beta$ |
| $hdd, h\ell$ | $\cos \alpha / \sin \beta$ | $-\sin \alpha / \cos \beta$ |
| $Huu$ | $\sin \alpha / \sin \beta$ | $\sin \alpha / \sin \beta$ |
| $Hdd, H\ell$ | $\sin \alpha / \sin \beta$ | $\cos \alpha / \cos \beta$ |
| $Auu$ | $-\cot \beta$ | $-\cot \beta$ |
| $Add, All$ | $\cot \beta$ | $-\tan \beta$ |
Higgs rates severely constrain the mixing angle $\cos(\beta - \alpha)$, and favor the *alignment limit*, $\cos(\beta - \alpha) \to 0$.

Heavy Higgs $H$ at 125 GeV equally viable (then: $\sin(\beta - \alpha) \to 0$).
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.
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 $C\mathcal{P}$-even Higgs boson]:

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

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

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

![Diagram showing maximal decay rate vs. $M_{H^\pm}$ and $M_H$](image)
**Charged-Higgs-to-neutral-Higgs decay signatures**

[TS, Wittbrodt (in progress)]

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

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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 $\gtrsim O(1 \text{ TeV})$;
- Neutral/charged *EW gauginos* and *Higgsinos* $\xrightarrow{\text{mix}}$ neutralinos/charginos.
The tree-level MSSM Higgs sector is a 2HDM of Type II with

\[
\lambda_1 = \lambda_2 = \frac{1}{4} (g^2 + g'^2), \quad \lambda_3 = \frac{1}{4} (g^2 - g'^2),
\]
\[
\lambda_4 = -\frac{1}{2} g^2, \quad \lambda_5 = \lambda_6 = \lambda_7 = 0.
\]

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

Predicted tree-level mass spectrum:

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

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

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

\[\Rightarrow\] with SUSY particles at TeV-scale we can get \(M_h \lesssim 135 \text{ GeV}\)!
**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 |
| $M_h^{125}$ (alignment) | $h$ couplings very SM-like even at low $M_A$ values |
| $M_H^{125}$ | heavier MSSM Higgs boson $H$ is SM-like at $\sim 125 \text{ GeV}$ |
| $M_h^{125}$ (CPV) | interference effects suppress heavy Higgs rate in $\tau^+\tau^-$ channel |

[Bahl et al. 1808.07542]

| $M_{h,EFT}^{125}$ | “standard” scenario for the low $\tan \beta$ region |
| $M_{h,EFT}^{125}(\tilde{\chi})$ | 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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|---------------|-------------------------------------------------|
| $M_{h_{125}}(\tilde{\tau})$ | 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 |
| $M_{h_{125}}$ (alignment) | $h$ couplings very SM-like even at low $M_A$ values |
| $M_{h_{125}}(\text{CPV})$ | heavier MSSM Higgs boson $H$ is SM-like at $\sim 125 \text{ GeV}$ |
| $M_{h_{125}}$,EFT | interference effects suppress heavy Higgs rate in $\tau^+\tau^-$ channel |

[Bahl et al. 1808.07542]

| $M_{h_{125}}$,EFT (\tilde{\chi}) | “standard” scenario for the low $\tan \beta$ region |
|--------------------------------|------------------------------------------------|
| $M_{h_{125}}$,EFT (\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)
$M_{h}^{125}$ 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 $\gtrsim 600 \text{ GeV}$).

Disfavored (2$\sigma$) by LHC Higgs rates $[\text{Run I + II (36 fb}^{-1})]$.

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

Excluded by $M_{h}$ $[M_{h} \neq (125 \pm 3) \text{ GeV}]$.
• 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.
**BENCHMARK SCENARIO: LIGHT NEUTRALINOS & CHARGINOS**

- Light neutralinos and charginos with masses $\sim (100 - 250)$ GeV.
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• Impact of $H/A \to \tau^+\tau^-$ search limit on parameter space weakened due to additional $H/A$ decay modes.
• Lifting EW-ino mass spectrum by $+100 \text{ GeV}$ does not alter heavy Higgs decays significantly (in relevant parameter region).
**M\textsubscript{h}^{125}(\tilde{\chi})** BENCHMARK SCENARIO: LIGHT NEUTRALINOS & CHARGINOS

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 \( M_A = 1 \text{ TeV}, \tan \beta = 10 \)):
  
  \[
  \begin{align*}
  pp &\rightarrow H \xrightarrow{30\%} \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp \quad \rightarrow (\tilde{\chi}_1^\mp W^\pm)(\tilde{\chi}_1^\mp Z) \quad \rightarrow W^\pm W^\mp Z + \not{E_T} \\
  pp &\rightarrow A \xrightarrow{9.4\%} \tilde{\chi}_2^\pm \tilde{\chi}_2^\mp \quad \rightarrow (\tilde{\chi}_1^\mp Z)(\tilde{\chi}_1^\mp Z) \quad \rightarrow W^\pm W^\mp ZZ + \not{E_T} \\
  \Rightarrow & \quad \text{multi-}W/Z\text{-boson + }\not{E_T}\text{ signatures.}
  \end{align*}
  \]

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

- Light neutralinos and charginos with masses \( \sim (100 - 250) \text{ GeV} \).

- Impact of \( H/A \rightarrow \tau^+\tau^- \) search limit on parameter space weakened due to additional \( H/A \) decay modes.

- Lifting EW-ino mass spectrum by \(+100 \text{ GeV}\) does not alter heavy Higgs decays significantly (in relevant parameter region).
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!
LHC results on the 125 GeV Higgs boson and searches for new scalar states have important implications for BSM Higgs models.

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

[Bechtle, Dercks, Heinemeyer, Klingl, TS, Weiglein, Wittbrodt]
Available at http://higgsbounds.hepforge.org.
**Singlet model:** (assume heavier Higgs at 125 GeV)

\[
\kappa = \sin \alpha, \quad \text{BR}(H \rightarrow \text{NP}) = \text{BR}(h_{SM} \rightarrow h Sh_S).
\]

⇒ 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

BR_{inv} invisible Higgs searches

Higgs rate measurements

(\ATLAS ± \CMS)

κ, κ_g, κ_γ, BR_{inv} fit (95% CL)

VBF/V H, H → inv (95% CL)
**Benchmark Scenario 2**: $h_3 \rightarrow h_1 h_2$ (*with* $h_2 = h_{125}$)

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

**Signature:**

Idea: generalize existing $H \rightarrow h_{125} h_{125}$ searches to this case (unknown $M_1$).
BENCHMARK SCENARIOS 4 & 5: $h_{\text{NON-SM}} \rightarrow h_1h_1$ (WITH $h_1 \neq h_{125}$)

- (Symmetric) decays to $h_1h_1$ not involving the SM-like Higgs boson,
- Production of non-SM heavier scalar with signal strength $\mu \simeq 0.06$,
  decay rates $\text{BR}(h_{\text{non-SM}} \rightarrow h_1h_1) \sim (70 - 100)\%$. 

![Graph showing $h_2 \rightarrow h_1h_1$](image1)

![Graph showing $h_3 \rightarrow h_1h_1$](image2)
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]

[Basler, Krause, Mühlleitner, Wittbrodt, Wlotzka '16]
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\[ \leftarrow \text{ATLAS Run-II 36 fb}^{-1} \text{ limit (roughly).} \]

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

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

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, $h \to \gamma\gamma$ rate.

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

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.

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

[Bernon, Gunion, Haber, Jiang, Kraml '15].
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Even in the alignment limit, $\cos(\beta - \alpha) \to 1$, charged Higgs effects on the Higgs rates do not decouple:

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

$$M_{H^+} \gg M_H \to -\frac{2M_{H^+}^2}{v},$$

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].

[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]
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: \( \tan \beta = 20 \), 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 \( M_h \)
Limit of alignment w/o decoupling at \( \tan \beta \simeq 52 \).

\[
M_{125}^{h} (\tilde{\tau}) \text{ scenario: LIGHT STAUS}
\]

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

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

\[
X_t = 2.8 \text{ TeV}, \quad A_b = A_t, \quad A_\tau = 800 \text{ GeV}.
\]
$M_{h}^{125}(\tilde{\tau})$ SCENARIO: LIGHT STAUS

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

$$BR(h \rightarrow \gamma\gamma)/BR(h \rightarrow \gamma\gamma)_{SM}$$

$$M_{Q3} = M_{U3} = M_{D3} = 1.5 \text{ TeV}, \quad M_{L3} = M_{E3} = 350 \text{ GeV},$$

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

$$X_t = 2.8 \text{ TeV}, \quad A_b = A_t, \quad A_{\tau} = 800 \text{ GeV}.$$
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].
$M_{h}^{125}$ (ALIGNMENT) SCENARIO

Limit of alignment w/o decoupling at \( \tan \beta \approx 7 \).

\[
M_{Q3} = M_{U3} = M_{D3} = 2.5 \text{ TeV}, \quad M_{L3} = M_{E3} = 2 \text{ TeV}, \\
\mu = 7.5 \text{ TeV}, \quad M_1 = 500 \text{ GeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV}, \\
A_t = A_b = A_\tau = 6.25 \text{ TeV}.
\]
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]
$M_{H}^{125}$ \textbf{SCENARIO: THE HEAVIER HIGGS $H$ IS SM-LIKE}

\hspace{1cm}

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

Excluded by $H \rightarrow hh$.

\begin{align*}
M_{Q3} &= M_{U3} = 750 \text{ GeV} - 2(M_{H^\pm} - 150 \text{ GeV}) , \\
\mu &= [5800 \text{ GeV} + 20 (M_{H^\pm} - 150 \text{ GeV})] M_{Q3} / (750 \text{ GeV}) , \\
A_t &= A_b = A_\tau = 0.65 M_{Q3}, \\
M_{D3} &= M_{L3} = M_{E3} = 2 \text{ TeV} , \\
M_1 &= M_{Q3} - 75 \text{ GeV}, \\
M_2 &= 1 \text{ TeV}, \\
M_3 &= 2.5 \text{ TeV} .
\end{align*}
\(M_{H}^{125}\) SCENARIO: CHARGED HIGGS PHENOMENOLOGY

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

⇒ Important signature: \(H^{\pm} \rightarrow W^{\pm} h\), with \(h \rightarrow b\bar{b}, \tau^+\tau^-\).
The heavier Higgs $H$ is SM-like

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

Excluded by $H \rightarrow hh$.

Excluded by $A \rightarrow \tau \tau$.

$M_{Q3} = M_{U3} = 750 \text{ GeV} - 2(M_{H^\pm} - 150 \text{ GeV})$,

$\mu = [5800 \text{ GeV} + 20(M_{H^\pm} - 150 \text{ GeV})] M_{Q3}/(750 \text{ GeV})$,

$A_t = A_b = A_\tau = 0.65 M_{Q3}$, $M_{D3} = M_{L3} = M_{E3} = 2 \text{ TeV}$,

$M_1 = M_{Q3} - 75 \text{ GeV}$, $M_2 = 1 \text{ TeV}$, $M_3 = 2.5 \text{ TeV}$.
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]

\[
M_{Q3} = M_{U3} = 750 \text{ GeV} - 2 \left( M_{H^\pm} - 150 \text{ GeV} \right),
\]
\[
\mu = [5800 \text{ GeV} + 20 \left( M_{H^\pm} - 150 \text{ GeV} \right)] M_{Q3} / (750 \text{ GeV}),
\]
\[
A_t = A_b = A_\tau = 0.65 M_{Q3}, \quad M_{D3} = M_{L3} = M_{E3} = 2 \text{ TeV},
\]
\[
M_1 = M_{Q3} - 75 \text{ GeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV}.
\]
$M_{h_1}^{125}$ (CPV) SCENARIO: NEUTRAL HIGGS BOSONS MIX ($h_1, h_2, h_3$)

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

$M_{h_1}^{125}$ (CPV) scenario

$M_{h_1}$ [GeV]

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

$\mu = 1.65$ TeV, $M_1 = M_2 = 1$ TeV, $M_3 = 2.5$ TeV, 

$|A_t| = \mu \cot \beta + 2.8$ TeV, $\phi_{A_t} = \frac{2\pi}{15}$, $A_b = A_\tau = |A_t|$
**$M_{h_1}^{125}$ (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)]
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.

$$M_{h}^{125} \text{ scenario } \rightarrow \ M_{h,EFT}^{125} \text{ scenario}$$

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

Similar (older) scenarios:

hMSSM [Djouadi et al. 1307.5205], low-$\tan \beta$-high scenario [LHCHXSWG-2015-002].
$M_{h,EFT}^{125}$ SCENARIO

Excluded by $H \to hh$ searches.

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
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]
Light electroweakinos lead to upward shift of $M_h$ by $\sim 1.5$ GeV.

$\Rightarrow$ Slightly lower $M_S$ values required as in $M_{h,\text{EFT}}^{125}$ scenario.
• Light electroweakinos lead to upward shift of $M_h$ by $\sim 1.5$ GeV.
  $\Rightarrow$ Slightly lower $M_S$ values required as in $M_{h,EFT}^{125}$ 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.
For $M_A \gtrsim 400$ GeV, heavy-Higgs-to-electroweakino decays are dominant.

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

Cascade decays preferred, leading to multi-$W/Z$-boson+$E_T$ signatures.

⇒ Dedicated experimental analyses of $H/A \rightarrow \tilde{\chi}\tilde{\chi}$ decays are well-motivated!
• 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 $\tan \beta$).

[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 $M_A \lesssim 1$ TeV.
- Direct searches for $pp \rightarrow H/A \rightarrow \tau^+\tau^-$ are sensitive to $M_A \lesssim 2.5$ 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.)]