

Novel signatures of additional Higgs bosons at the LHC

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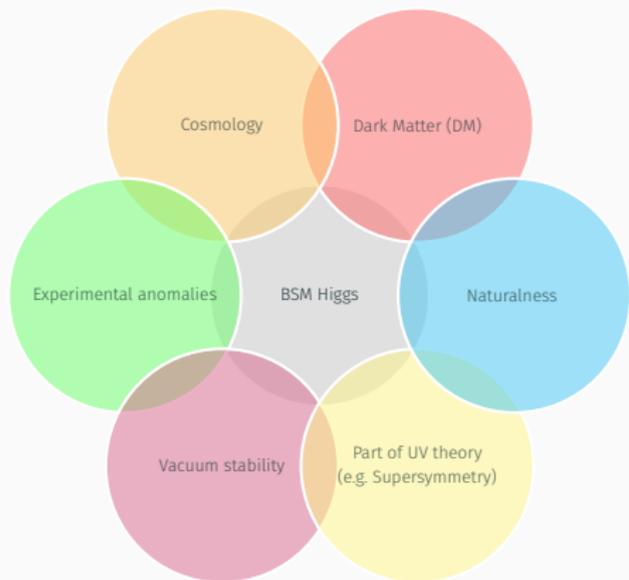


HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

LHCP2020 – Online

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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!

- 125 GeV Higgs boson: measurements consistent with SM hypothesis.
- Searches for additional Higgs bosons: no serious hints for a signal.

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

What does this mean for BSM physics at the TeV-scale?

- BSM physics at higher energy scale \gg TeV? \Rightarrow Need new collider?
- Maybe BSM signals are too faint or too rare? \Rightarrow Need more data?
- Have we overlooked a signal? \Rightarrow Unexplored BSM signatures?

Main LHC search channels for neutral and charged scalars:

$$\begin{array}{ll} pp \rightarrow \phi \rightarrow \tau^+ \tau^- & pp \rightarrow tb\phi^\pm, \phi^\pm \rightarrow \tau\nu \\ pp \rightarrow \phi \rightarrow t\bar{t} & pp \rightarrow tb\phi^\pm, \phi^\pm \rightarrow tb \\ pp \rightarrow \phi \rightarrow VV (V = W^\pm, Z) & pp \rightarrow qq\phi^\pm, \phi^\pm \rightarrow W^\pm Z \\ pp \rightarrow \phi \rightarrow \gamma\gamma & \\ pp \rightarrow Z\phi \rightarrow Z(\text{invisible}) & \\ pp \rightarrow \phi \rightarrow h_{125}h_{125} & \\ pp \rightarrow h_{125} \rightarrow \phi\phi & \\ pp \rightarrow \phi_2 \rightarrow \phi_1 Z & \end{array}$$

Are there any (well-motivated) signatures missing?

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Are there any (well-motivated) signatures missing?

⇒ **Yes!** “Higgs-to-Higgs decay signatures”

- (i) involving two BSM neutral scalars: $pp \rightarrow \phi_i(+X), \phi_i \rightarrow \phi_j\phi_k$
→ Two Real Scalar Singlet extension
- (ii) involving a charged scalar: $pp \rightarrow \phi^\pm(+X), \phi^\pm \rightarrow W^\pm\phi$
→ Two Higgs Doublet Model

SCALAR SINGLET EXTENSIONS OF THE SM

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

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

Define $\kappa_1 \equiv \cos \alpha$, $\kappa_2 \equiv -\sin \alpha$.

Couplings of h_a to SM particles

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

Multi-scalar couplings

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

THE TWO-REAL-SINGLET-MODEL (TRSM)

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

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

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

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

Two interesting cases:

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

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

[Robens, TS, Wittbrodt 1908.08554]

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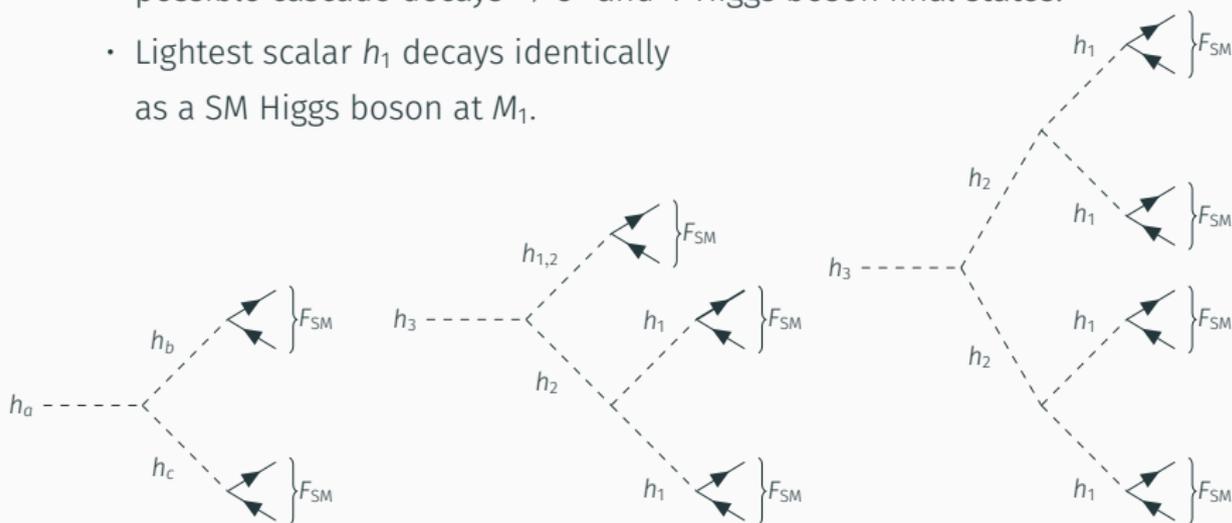
\rightarrow Model parameters: 3 masses, 3 mixing angles, 3 vevs.

[Robens, TS, Wittbrodt 1908.08554]

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

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

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



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

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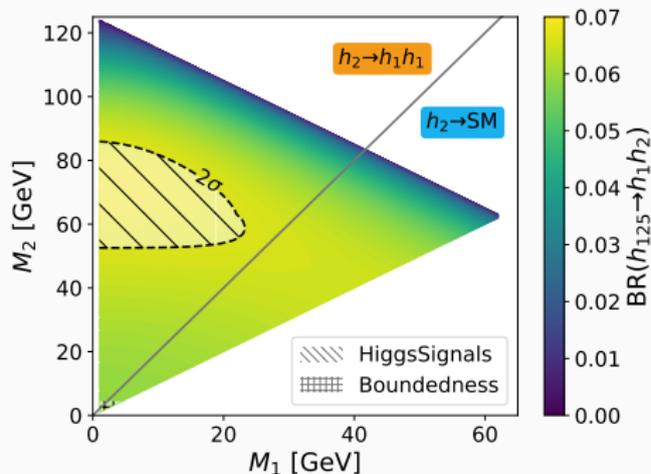
benchmark plane	h_{125} candidate	target signature	possible successive decays
BP1	h_3	$h_{125} \rightarrow h_1 h_2$	$h_2 \rightarrow h_1 h_1$ if $M_2 > 2M_1$
BP2	h_2	$h_3 \rightarrow h_1 h_{125}$	-
BP3	h_1	$h_3 \rightarrow h_{125} h_2$	$h_2 \rightarrow h_{125} h_{125}$ if $M_2 > 250$ GeV
BP4	h_3	$h_2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

Benchmark scenarios suggested to LHC-HXSWG HH subgroup.

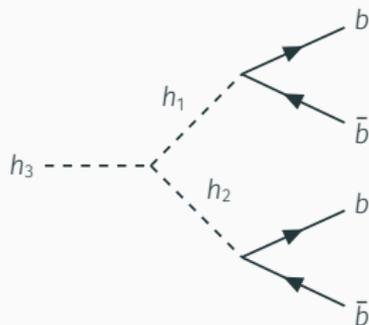
(\rightarrow more information in backup slides!)

BENCHMARK PLANE 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 as in SM: $\sigma(pp \rightarrow h_3) \simeq \sigma(pp \rightarrow h_{SM}) \sim 50$ pb.



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

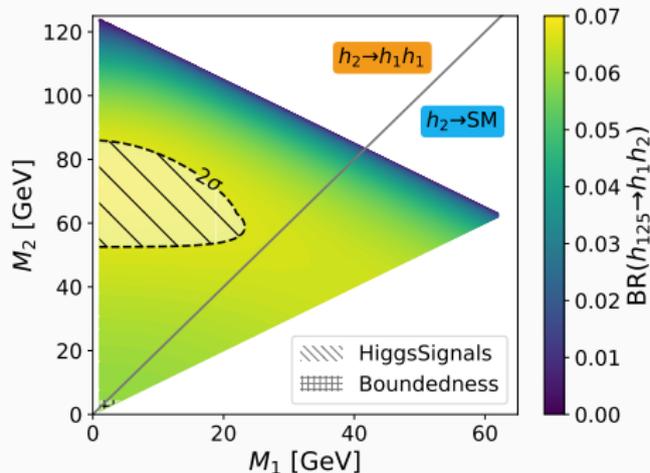


$\sigma_{13 \text{ TeV}}(h_1 h_2) \lesssim 3$ pb

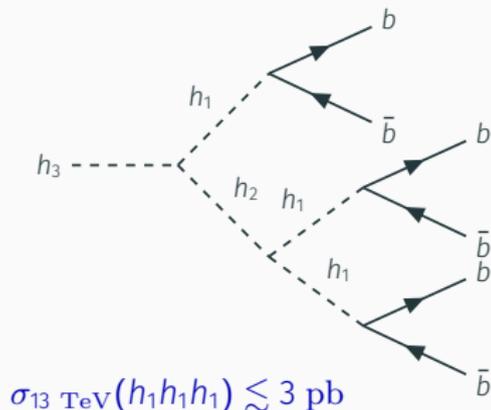
Idea: use invariant masses to look for resonances in the spectrum.

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



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

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

- **Flavor observables** constrain the $(M_{H^\pm}, \tan \beta)$ plane.
 \Rightarrow Light H^\pm is allowed in the 2HDM of Type-1.
- **Higgs measurements** prefer *approximate alignment limit*:

$$g_{hWV} \propto \sin(\beta - \alpha) \approx 1, \quad \text{if light Higgs boson } h \text{ at } 125 \text{ GeV,}$$
$$g_{HWV} \propto \cos(\beta - \alpha) \approx 1, \quad \text{if heavy Higgs boson } H \text{ at } 125 \text{ GeV.}$$

Important fact (in 2HDM):

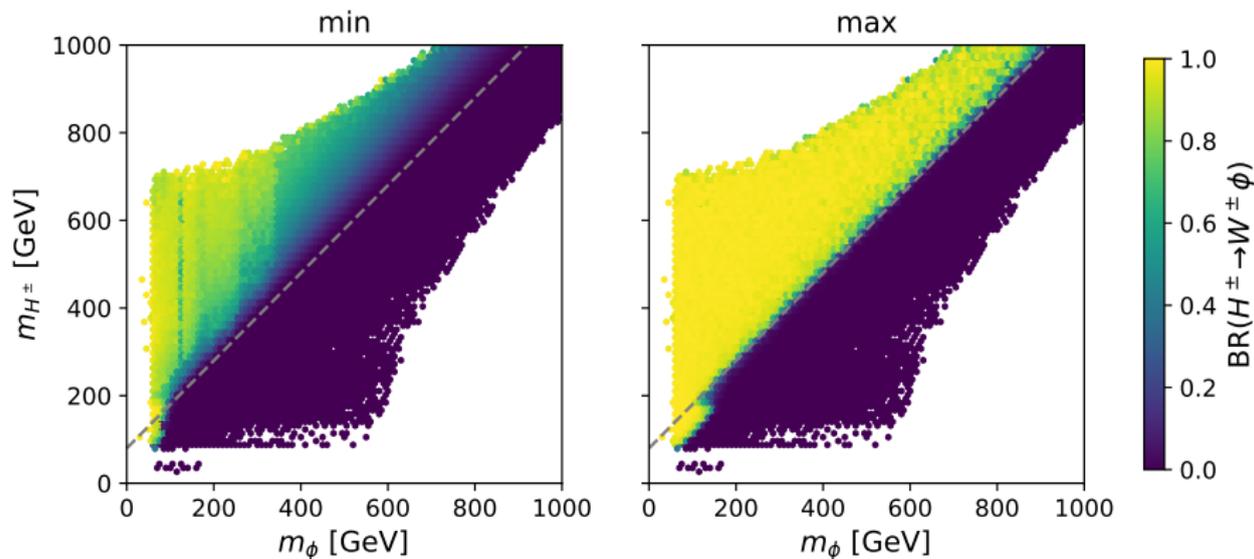
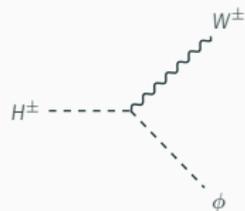
In the alignment limit the $H^\pm W^\mp \phi$ coupling is maximized
[ϕ denotes the non-SM-like \mathcal{CP} -even Higgs boson]:

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

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

CHARGED-HIGGS-TO-NEUTRAL-HIGGS DECAY SIGNATURES

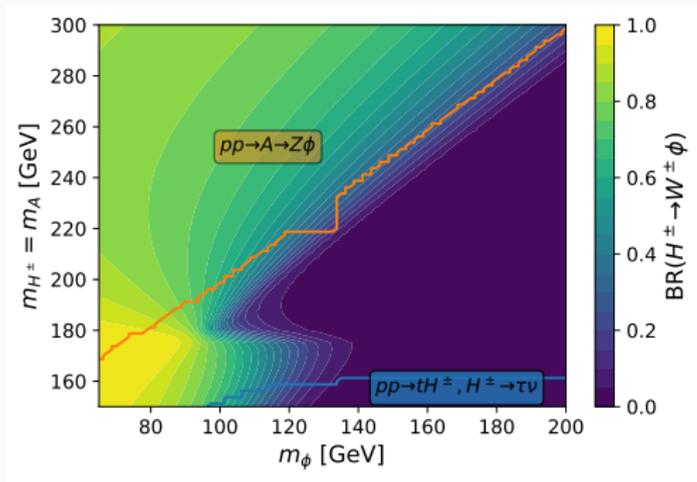
Minimal and maximal values of $\text{BR}(H^\pm \rightarrow W^\pm \phi)$
in allowed parameter space (2HDM Type-1):



[TS, Wittbrodt (*in progress*)] (see also [Arhrib, et al. '20])

$H^\pm \rightarrow W^\pm \phi$ BENCHMARK SCENARIO

[TS, Wittbrodt (in progress)]



2HDM parameters:

$$\cos(\beta - \alpha) = 0 \text{ or } 1 \quad (\text{exact alignment limit})$$

$$\tan \beta = 3$$

$$m_{12}^2 = 500 \text{ GeV}^2$$

$$m_{h_{125}} = 125 \text{ GeV}$$

- neutral Higgs boson ϕ mostly decays to $b\bar{b}$ and $\tau^+\tau^-$,
- promising charged Higgs production channels:
 $pp \rightarrow tbH^\pm$ ($\sigma_{13 \text{ TeV}} \lesssim 10 \text{ pb}$) and $pp \rightarrow H^\pm \phi$ ($\sigma_{13 \text{ TeV}} \lesssim 100 \text{ fb}$).

(\rightarrow backup slides)

CHARGED-HIGGS-TO-NEUTRAL-HIGGS DECAY SIGNATURES

[TS, Wittbrodt (*in progress*)]

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

⇒ Many new experimental opportunities for upcoming LHC Run(s)!

CONCLUSIONS

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

⇒ Dedicated LHC searches for these signatures are highly motivated!

$\phi_i \rightarrow \phi_j \phi_k$:

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

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

$\phi^\pm \rightarrow W^\pm \phi$:

- naturally appears in **2HDM in the alignment limit** if $M_\phi < M_\phi^\pm$;
- **high complementarity** to standard charged Higgs searches ($tb, \tau\nu$).

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Thank you very much for your attention!

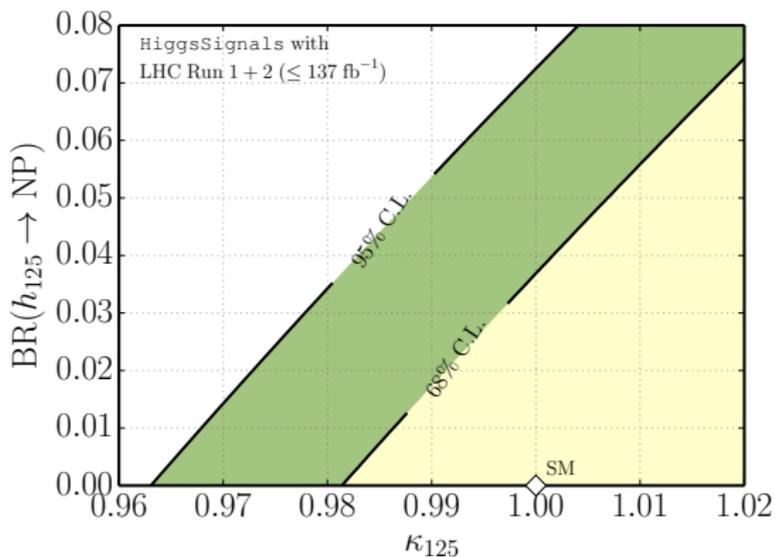
Backup Slides

IMPACT OF HIGGS RATE MEASUREMENTS AT THE LHC

Singlet model:

(assume heavier Higgs at 125 GeV)

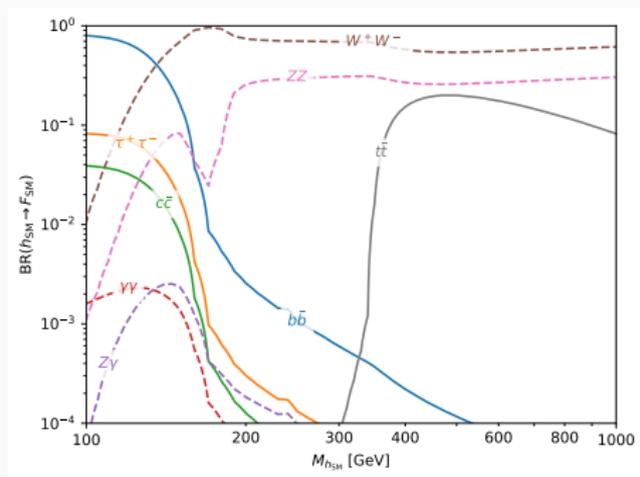
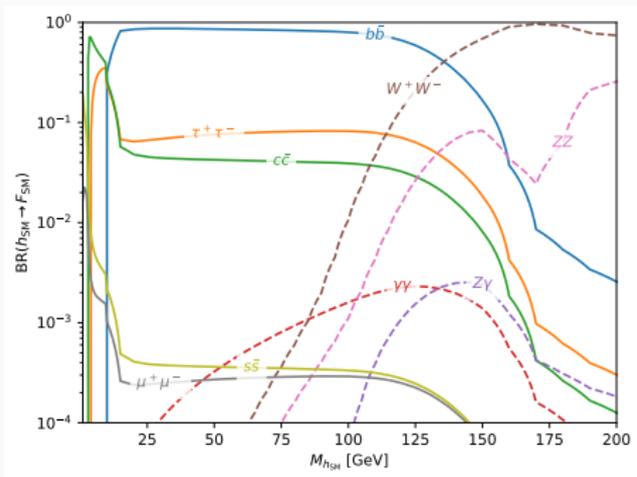
$$\kappa = \sin \alpha, \quad \text{BR}(H \rightarrow \text{NP}) = \text{BR}(h_{\text{SM}} \rightarrow h_S h_S).$$



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

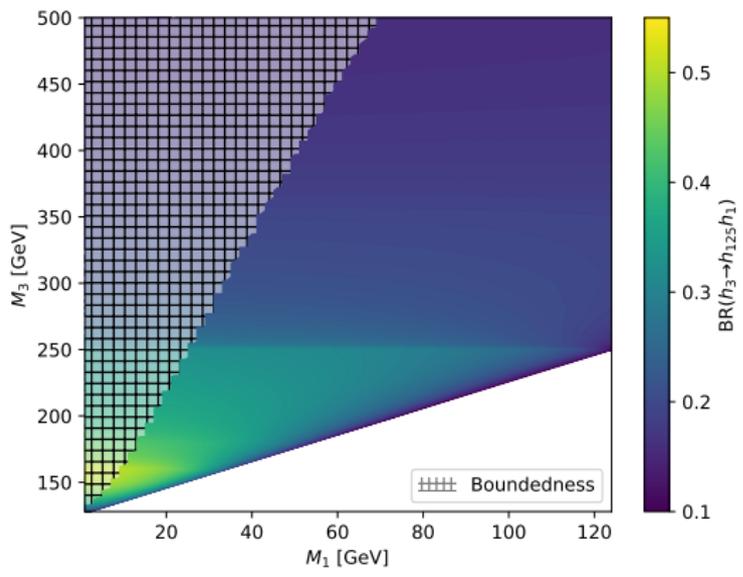
Note: further constraints arise from LEP Higgs searches.

SM-LIKE HIGGS BOSON DECAY RATES

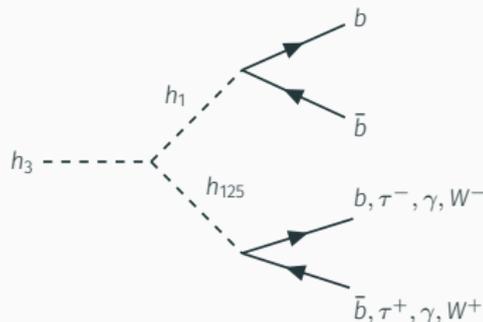


BENCHMARK SCENARIO 2: $h_3 \rightarrow h_1 h_2$ (WITH $h_2 = h_{125}$)

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



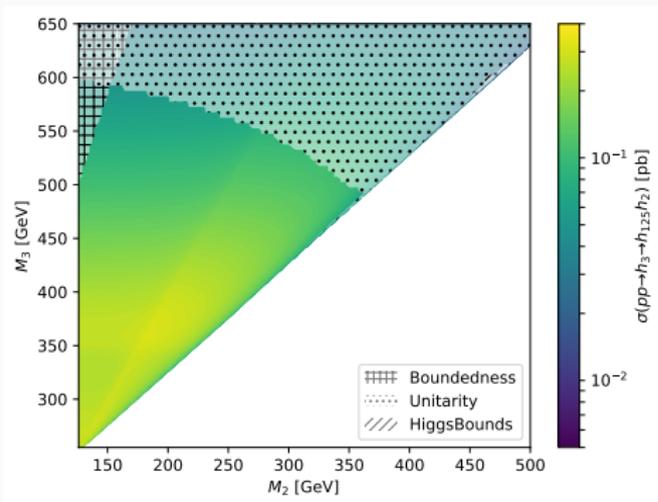
Signature:



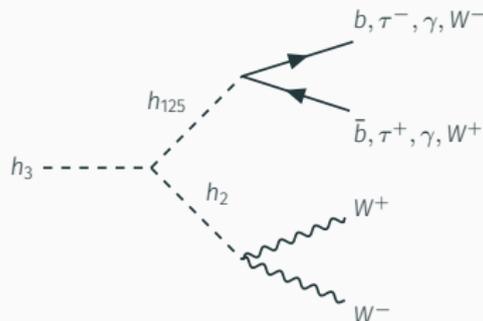
Idea: generalize existing $H \rightarrow h_{125} h_{125}$ searches to this case (unknown M_1).

BENCHMARK PLANE 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 $\mu \simeq 0.057$,
decay rate $\text{BR}(h_3 \rightarrow h_1 h_2) \sim (35 - 50)\%$.

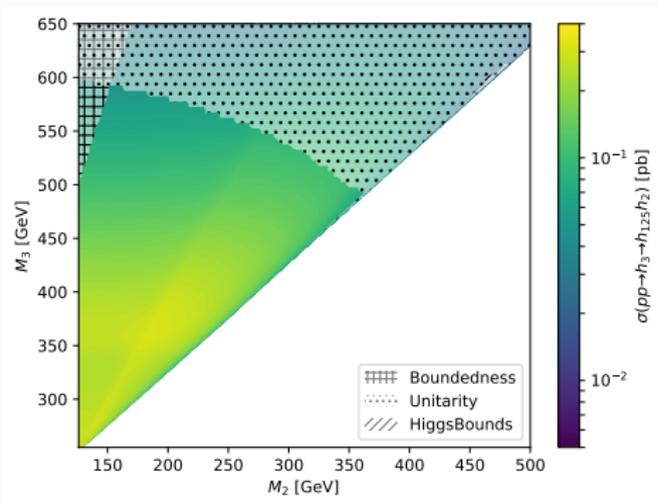


$h_{125} h_2$ signature ($M_2 < 250 \text{ GeV}$), e.g.

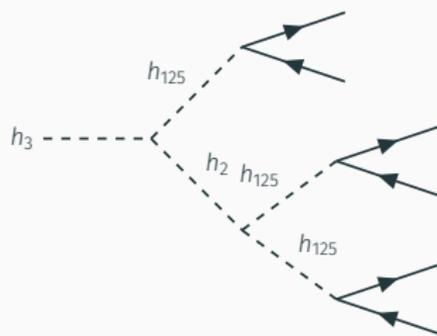


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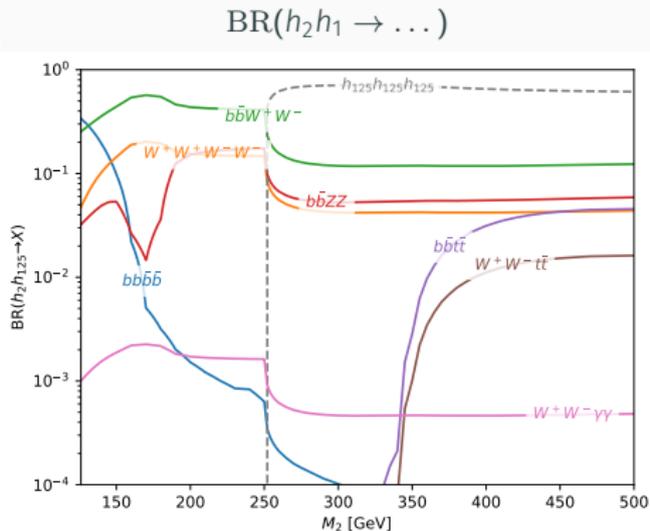
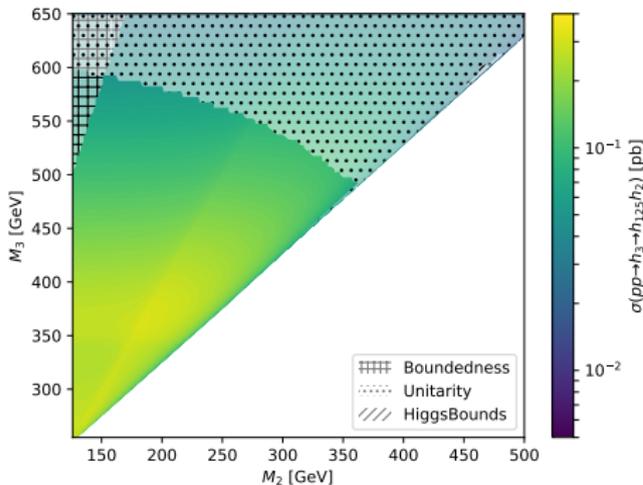


Triple- h_{125} signature ($M_2 > 250 \text{ GeV}$):



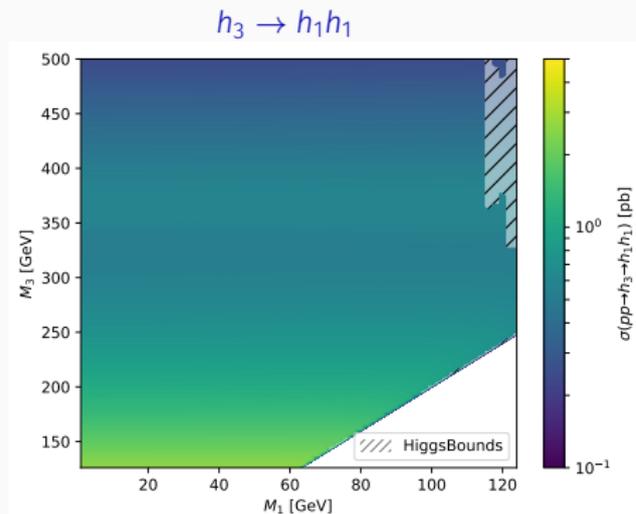
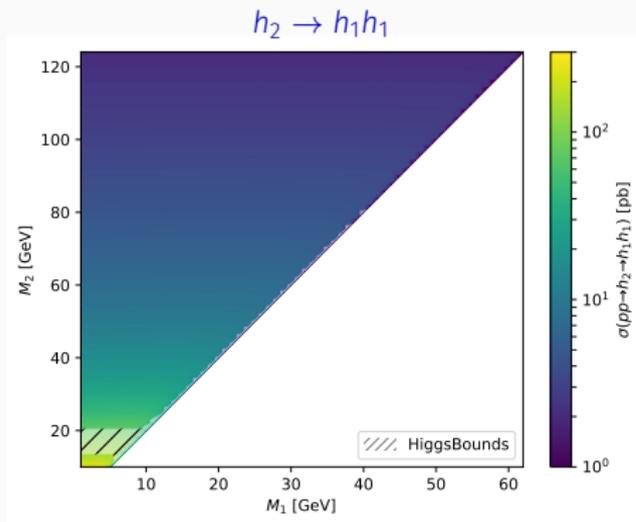
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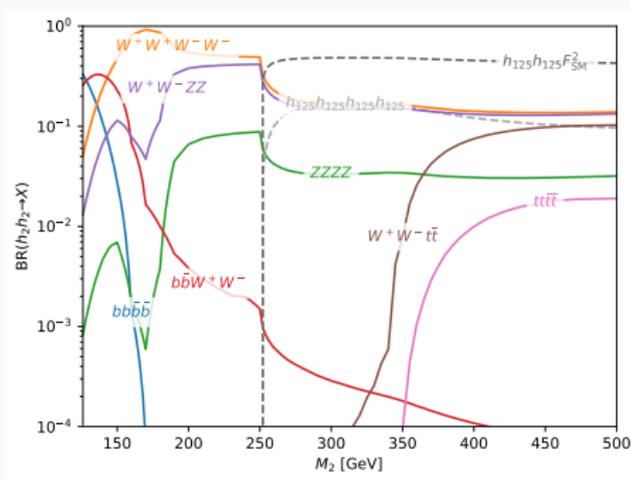
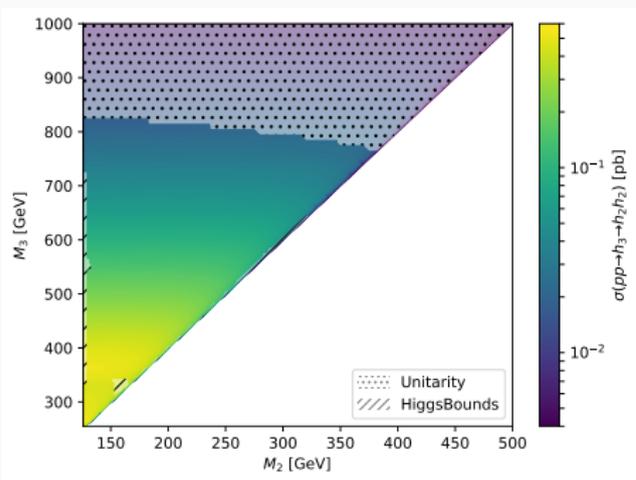
BENCHMARK SCENARIOS 4 & 5: $h_{\text{NON-SM}} \rightarrow h_1 h_1$ (WITH $h_1 \neq h_{125}$)

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



BENCHMARK PLANE 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 $\mu \simeq 0.06$,
decay rate $\text{BR}(h_3 \rightarrow h_2 h_2) \sim (70 - 80)\%$.



- if $150 \leq M_2 \leq 250 \text{ GeV} \Rightarrow W^+ W^- W^+ W^-$ 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 $\lesssim \mathcal{O}(10 \text{ fb})$]

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

Consider $gg \rightarrow S_1 \rightarrow S_2 S_2 \rightarrow b\bar{b}b\bar{b}$.

Extrapolation of current CMS search:

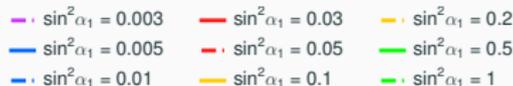
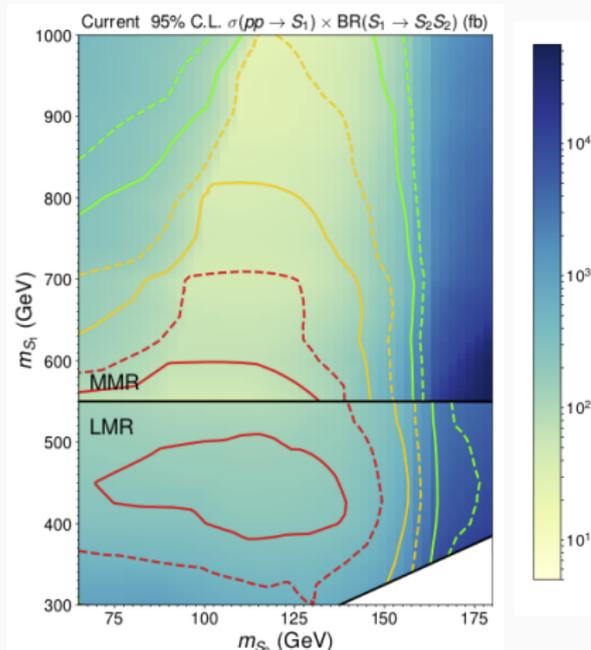
- modify $m_{b\bar{b}}$ criteria
(for the case $M_{S_2} \neq 125$ GeV).

For increasing M_{S_2} :

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

⇒ Relevant for $M_2 \lesssim 150$ GeV (in TRSM).

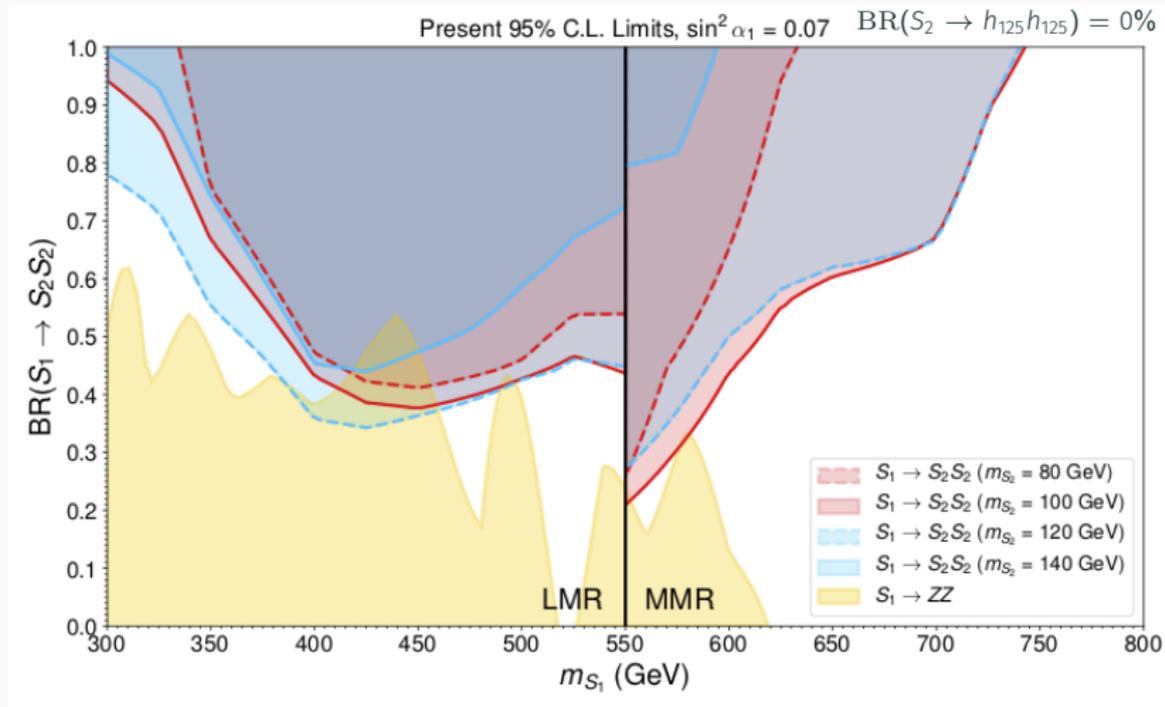
[Barducci, Mimasu, No, Vernieri, Zurita, '19]



(assumes $\text{BR}(S_2 \rightarrow S_1 S_1) = 100\%$)

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

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



Complementarity with LHC searches for $pp \rightarrow S_1 \rightarrow \text{SM particles}$.

CP-CONSERVING TWO HIGGS DOUBLET MODEL (2HDM)

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

Higgs potential (*general basis*):

$(\Phi_1, \Phi_2: SU(2)_L$ 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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2 complex $SU(2)_L$ doublets \Rightarrow 5 Higgs states h, H, A, H^\pm

Higgs potential (*general basis*):

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

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

\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 $\in \mathbb{R}$.

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:

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

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

Higgs-vector boson couplings:

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

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*):

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

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

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

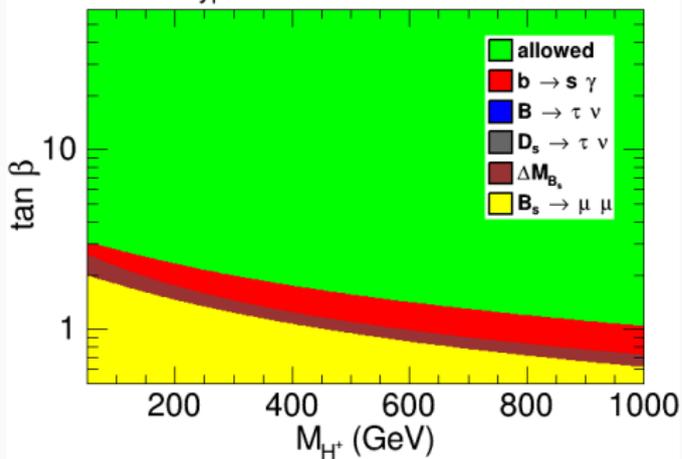
2HDM	u	d	ℓ
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Type III	Φ_2	Φ_1	Φ_2
Type IV	Φ_2	Φ_2	Φ_1

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

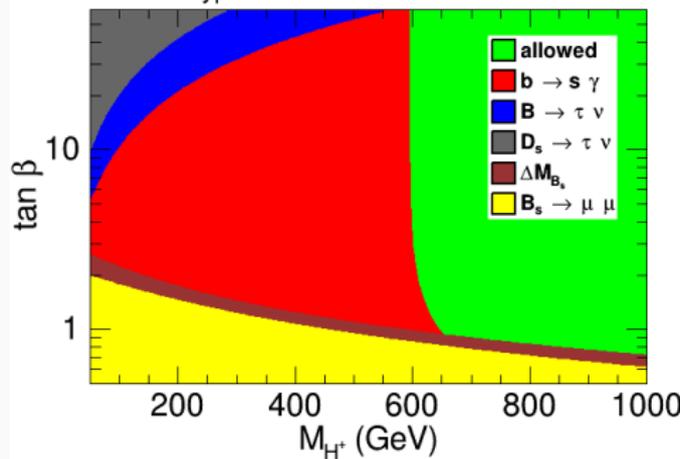
FLAVOR CONSTRAINTS IN THE 2HDM

[Arbey, Mahmoudi, Stål, TS '17]

THDM Type I - Flavour constraints

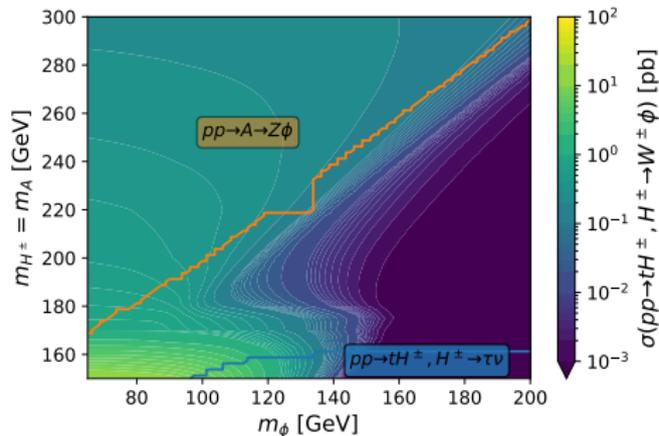


THDM Type II - Flavour constraints

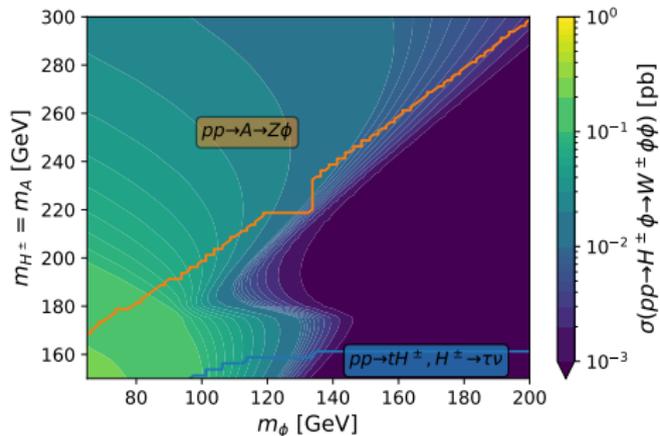


$H^\pm \rightarrow W^\pm \phi$ BENCHMARK SCENARIO: PRODUCTION RATES (13 TeV)

$pp \rightarrow tbH^\pm$ production



$pp \rightarrow H^\pm \phi$ production



includes NLO QCD corrections [Degrande et al. '16].