Testing BSM Higgs Sectors with HiggsBounds and HiggsSignals

Tim Stefaniak

Deutsches Elektronen-Synchrotron DESY, Hamburg

DESY Theory Fellows Meeting 2017

December 12th, 2017

My personal trajectory so far...

My personal trajectory so far. . .

My personal trajectory so far. . .

2004-2006: Bremen (Physics Vordiplom)

My personal trajectory so far...

2006-2011: Göttingen (Physics Diplom)

My personal trajectory so far. . .

My personal trajectory so far. . .

2008: Uppsala (ERASMUS exchange)

My personal trajectory so far...

2009: Geneva (CERN Summer Student)

My personal trajectory so far...

2011-2014: Bonn (PhD in Physics)

supervised by Herbi Dreiner

Universität Bonn

Physikalisches Institut

Higgs Couplings and Supersymmetry in the Light of early LHC Results

Tim Stefaniak

We present phenomenological studies investigating the implications of early results from the Large Hadron Collider (LHC) for models beyond the Standard Model (BSM), mostly focusing on Supersymmetry (SUSY). Our work covers different aspects in this wide field of research. We describe the development and basic concepts of the public computer codes `HiggsBounds` (version 4) and `HiggsSignals`. These confront the Higgs sector predictions of BSM models with results from LEP, Tevatron and LHC Higgs searches. While `HiggsBounds` tests the model against experimental null-results, `HiggsSignals` evaluates the model's chi-squared compatibility with the signal rate and mass measurements of the Higgs boson, that was discovered by the LHC in 2012. We then perform a systematic study of potential deviations in the Higgs couplings from their Standard Model (SM) prediction. No significant deviations are found. Future capabilities of Higgs coupling determination at the later LHC stages and at the International Linear Collider (ILC) are explored. We also study the implications of the Higgs discovery for the Minimal Supersymmetric Standard Model (MSSM), considering either the light or the heavy $\mathcal{CP}$-even Higgs boson as the discovered state. We show that both interpretations are viable and discuss their phenomenology. Finally, we study the LHC signatures of resonant scalar lepton production, which may arise in SUSY models with R-parity violation (RPV). These are confronted with early LHC results, yielding constraints on the relevant RPV operators.

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My personal trajectory so far...

2014-2017: Santa Cruz (1st Postdoc)

w/ Howie Haber & Stefano Profumo

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2014-2017: Santa Cruz (1st Postdoc)

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My personal trajectory so far...

since Oct. 2017: DESY, Hamburg (2nd Postdoc)

A broad picture of my research

BSM theories

SUSY models
(conserved/broken R-parity)
Two Higgs Doublet Models
Scalar Singlet Extension
...

Experiment

LHC
(+ past and future colliders)
(+ other experiments)

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Implications ←

- Parameter Estimation ("Global Fits")
- Code Development
- Statistics

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missing information?

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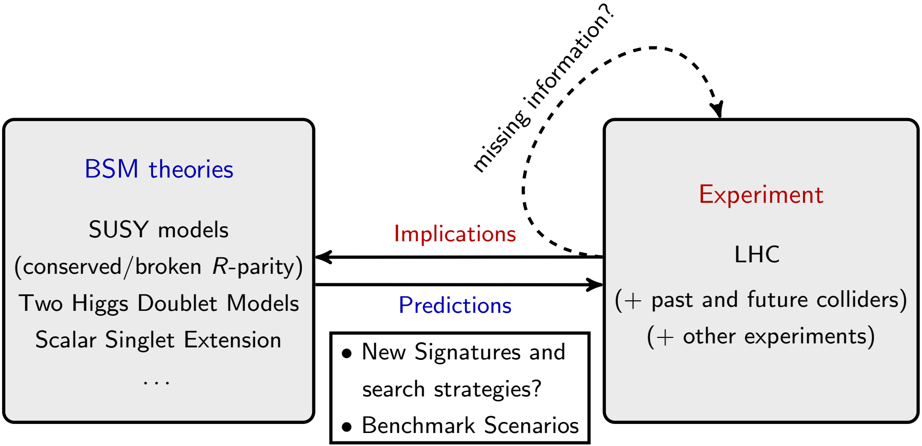

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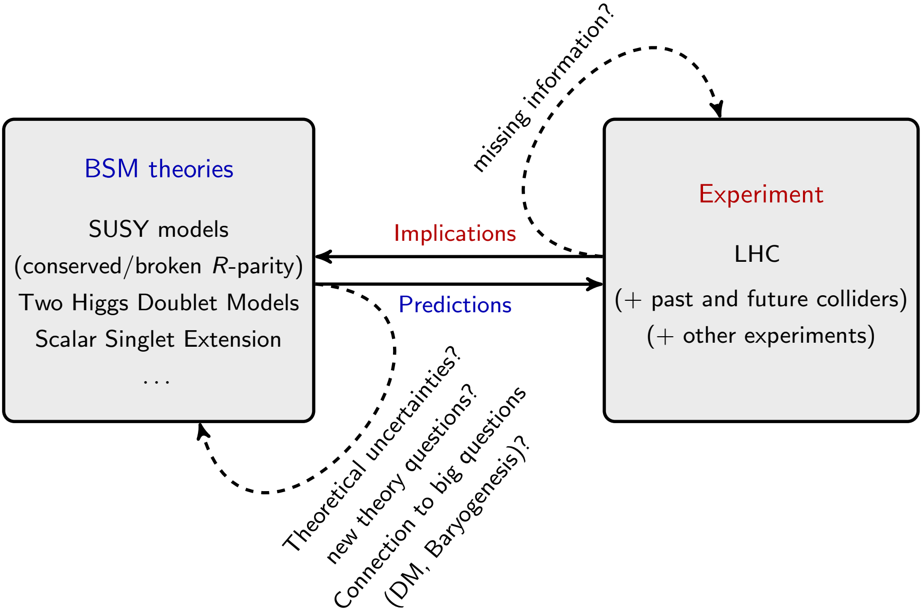


Outline

1. HiggsBounds and HiggsSignals
2. The MSSM Higgs sector
3. Charged Higgs boson in the 2HDM
4. Outlook: current projects

HiggsBounds

and

HiggsSignals

HiggsBounds and HiggsSignals: Code overview

Team: P. Bechtle, D. Dercks, S. Heinemeyer, T. Klingl, TS, G. Weiglein

http://higgsbounds.hepforge.org

HiggsBounds

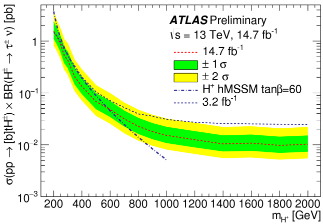
Confronts BSM Higgs sectors with exclusion limits from LEP, Tevatron and LHC Higgs searches

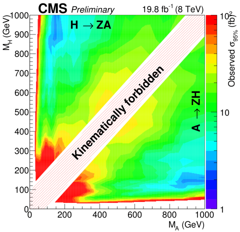
$\Rightarrow$ excluded/allowed at 95% C.L.

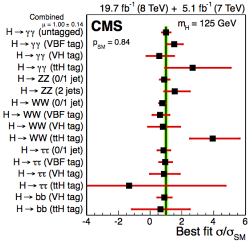
HiggsSignals

Confronts BSM Higgs sectors with LHC (& Tevatron) Higgs signal rate and mass measurements

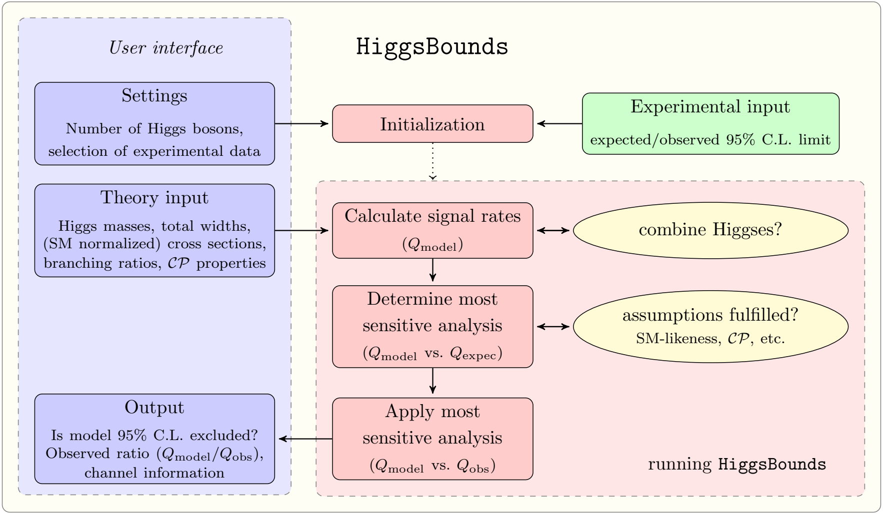
$\Rightarrow \chi^2$ (sep. for rates and mass)







HiggsBounds: Main structure



For LHC non-SM Higgs searches $\phi \to \tau^+\tau^-$ and LEP Higgs searches the full exclusion likelihood can be obtained.

HiggsSignals

- Same user input (theoretical predictions) as in HiggsBounds.
- calculates χ^2 for signal rate measurements

$$\chi^2_{\text{rates}} = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})^T (\mathbf{Cov})^{-1} (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu}),$$

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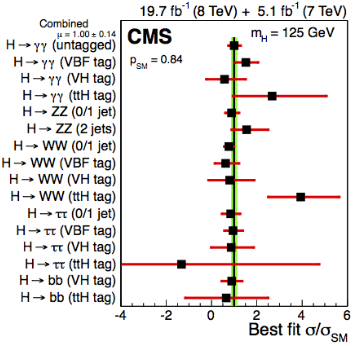

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$$\chi^2_{\text{rates}} = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})^T (\textbf{Cov})^{-1} (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu}),$$

$$\mu_{H\to XX} = \frac{\sum_i \epsilon^i_{\text{model}} \; [\sigma_i(pp\to H)\times \mathrm{BR}(H\to XX)]_{\text{model}}}{\sum_i \epsilon^i_{\text{SM}} \; [\sigma_i(pp\to H)\times \mathrm{BR}(H\to XX)]_{\text{SM}}},$$

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$$\chi^2_{\text{rates}} = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})^T (\mathbf{Cov})^{-1} (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu}),$$

Correlated uncertainties ($\Delta\mathcal{L}$, $\Delta\sigma_i$, $\Delta\mathrm{BR}$) or correlation matrices from experiment

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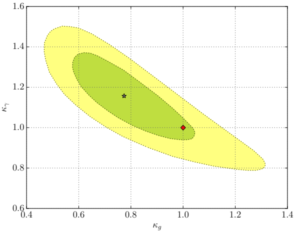

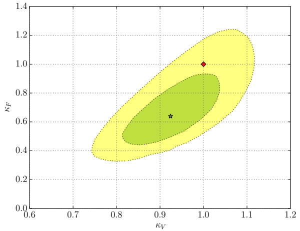

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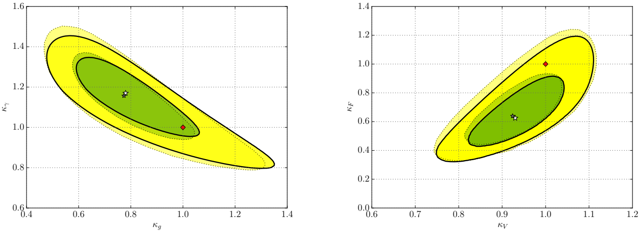
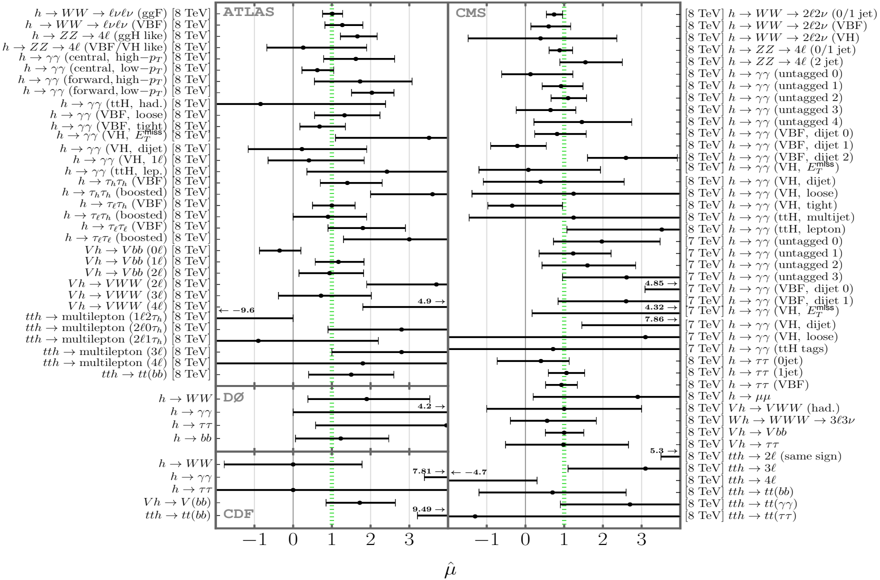


LHC Run-1 observables

in total: 85 signal rate + 4 mass measurements (July 2015)



The Higgs sector of the Minimal Supersymmetric Standard Model (MSSM)

[Bechtle, Heinemeyer, Stål, TS, Weiglein, Zeune, 1211.1955 (EPJC)]
[Bechtle, Haber, Heinemeyer, Stål, TS, Weiglein, Zeune, 1608.00638 (EPJC)]
[Profumo, TS, 1608.06945 (PRD)]
[Haber, Heinemeyer, TS, 1708.04416 (EPJC)]

The MSSM Higgs sector

- 2 complex Higgs doublets H_u, H_d $\Rightarrow$ 5 physical Higgs bosons (h, H, A, $H^\pm$)
- At tree-level, the Higgs sector has two parameters: M_A, $\tan\beta$ $= v_u/v_d$

$\Rightarrow$ Other Higgs boson masses are predictions:

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

$$M^2_{H^\pm} = M_A^2 + M_W^2$$

- Light Higgs mass M_h receives large radiative corrections.

  Dominant one-loop corrections from top/stop sector:

$$\delta M_h^2 = \frac{3 g_2^2 m_t^4}{8\pi^2 M_W^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right].$$

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

$\Rightarrow$ Weak scale supersymmetry predicts a light Higgs boson, $M_h \lesssim 135~\mathrm{GeV}$!

When do we obtain a Higgs with SM-like couplings?

Define the *Higgs basis* fields H_1, H_2, so that $\langle H_1^0 \rangle = v/\sqrt{2}$ and $\langle H_2^0 \rangle = 0$. Then the scalar doublet H_1 has SM tree-level couplings to all SM particles.

Alignment limit: If one of the $\mathcal{CP}$-even Higgs mass eigenstates $(h,\ H)$ is approximately aligned with $\mathrm{Re}(H_1^0)$, it has SM Higgs-like couplings.

[Gunion, Haber '02]

CP-even neutral Higgs squared-mass matrix (in *Higgs basis*):

$$\mathcal{M}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & M_A^2 + Z_5 v^2 \end{pmatrix},$$

M_A : CP-odd neutral Higgs (A) mass
Z_i : function of MSSM parameters

1. Alignment through decoupling ($m_A \gg Z_i v^2$ $(i = 1, 5, 6)$):
   $\sin(\beta - \alpha) \to 1$, light Higgs h with mass $m_h^2 \approx Z_1 v^2$ is SM-like.
2. Alignment without decoupling ($Z_6 \to 0$):
   Either light or heavy CP-even Higgs can be SM-like.

Alignment without decoupling in the MSSM

For $Z_6 v^2$ the leading terms (up to one-loop) are: $(M_Z, M_A \ll M_S)$

$$Z_6 v^2 \approx -s_{2\beta} \left\{ M_Z^2 c_{2\beta} - \frac{3v^2 s_\beta^2 y_t^4}{16\pi^2} \left[\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t(X_t+Y_t)}{2M_S^2} - \frac{X_t^3 Y_t}{12 M_S^4} \right] \right\}$$

with $X_t = A_t - \mu/\tan\beta$, $Y_t = A_t + \mu\tan\beta$.

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with $X_t = A_t - \mu/\tan\beta$, $Y_t = A_t + \mu\tan\beta$.

Obtain an approximate 1-loop alignment condition relating $\tan\beta$, μ, A_t and M_S:

$$\tan\beta \simeq \frac{32\pi^2}{3v^2 y_t^4} \cdot \frac{M_Z^2 + f(\mu^2, A_t^2, M_S^2)}{\frac{\mu A_t}{M_S^2}\left(\frac{A_t^2}{6M_S^2} - 1\right)}, \qquad \text{with} \quad |f(\mu^2, A_t^2, M_S^2)| < M_Z^2$$

Needs accidental cancellation of tree-level and loop-level effects.

[Carena, Haber, Low, Shah, Wagner '14]

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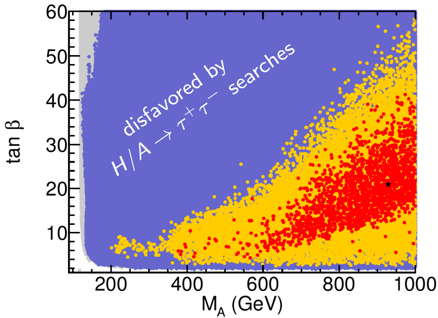
[Carena, Haber, Low, Shah, Wagner '14]

Leading two-loop $\mathcal{O}(\alpha_s h_t^2)$ corrections can be sizable. [Heinemeyer, Haber, TS '17]

Global fit of the pMSSM parameter space

[Bechtle, Haber, Heinemeyer, Stål, TS, Weiglein, Zeune, 1608.00638 (EPJC)]

- Combine HiggsSignals χ^2 (LHC Run-1) with other constraints
  ($b \to s\gamma$, $B_s \to \mu\mu$, $B_u \to \tau\nu$, $(g-2)_\mu$, M_W; Higgs & SUSY limits)
- 8 free parameters most relevant for Higgs sector
  (M_A, $\tan\beta$, μ, $M_{\tilde{q}_3}$, $M_{\tilde{\ell}_3}$, $M_{\tilde{\ell}_{1,2}}$, $M_1 = M_2/2$, A_t)



Light Higgs h is SM-like, $M_h \sim 125$ GeV

- All points
- HiggsBounds allowed
- $\Delta\chi^2 < 2.30$
- $\Delta\chi^2 < 5.99$
- $\star$ Best fit point

		only Higgs data	*all observables*
SM:	$\chi^2/\mathrm{ndf} =$	70.2/86	83.7/91
MSSM-h:	$\chi^2/\mathrm{ndf} =$	67.9/79	68.5/84

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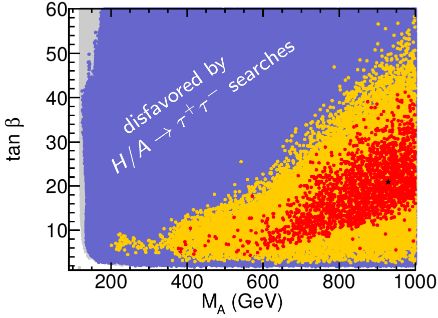

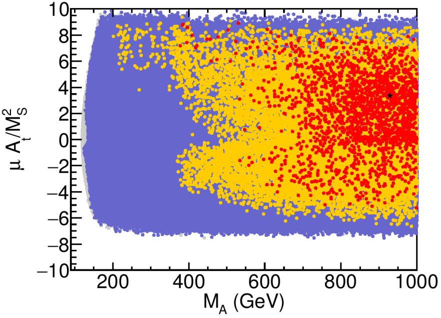

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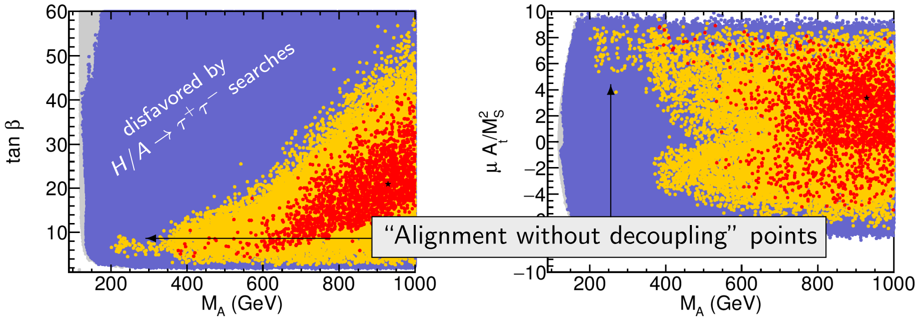

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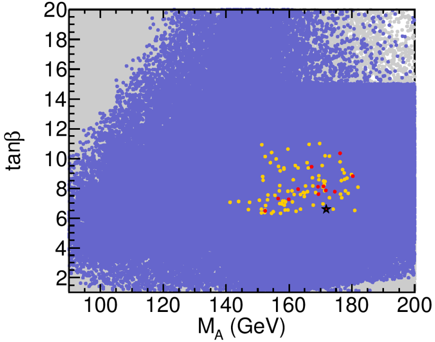

Heavy Higgs H is SM-like, $M_H \sim 125$ GeV

	only Higgs data	*all observables*
SM:	$\chi^2/\mathrm{ndf} = 70.2/86$	83.7/91
MSSM-h:	$\chi^2/\mathrm{ndf} = 67.9/79$	68.5/84
MSSM-H:	$\chi^2/\mathrm{ndf} = 70.0/80$	73.7/85

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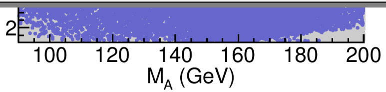
MSSM heavy Higgs interpretation is highly constrained:

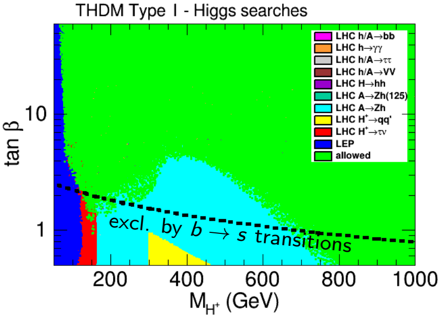
- $A \to \tau^+\tau^-$ searches sensitive at larger $\tan\beta$ values;
- LHC searches for $t \to H^+ b$, with $H^+ \to \tau\nu$:
  - charged Higgs mass must be $M_{H^+} \simeq m_t$ or above, and/or
  - competing decay $H^+ \to W^+ h$ sizable (yet unexplored!);
- Potentially large $b \to s\gamma$ contribution due to light charged Higgs;
- Higgs decay $H \to hh$ generally large if $M_h < M_H/2$ (exception exist);
- Vacuum stability?! We need $\mu \sim (6-8)M_S$!

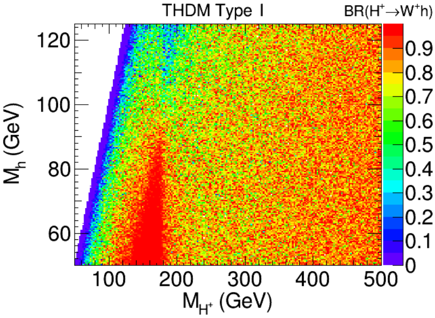


Heavy Higgs interpretation in the 2HDM

[Arbey, Mahmoudi, Stål, TS, 1706.07414]

- consider CP-conserving 2HDM with softly-broken $\mathbb{Z}_2$ symmetry (Type 1-4),
- assume $M_H = 125.09\ \mathrm{GeV}$, $\sin(\beta - \alpha) = 0$, $M_A = M_{H^+}$,
- scan over four parameters: M_{H^+}, M_h, $\tan\beta$ and m_{12}^2.





$\mathrm{BR}(H^+ \to W^+ h)$ can be very sizable and is experimentally unconstrained!

Outlook: some of my current projects

1. Definition of new MSSM benchmark scenarios for Higgs searches
   [w/ E. Fuchs, S. Heinemeyer, S. Liebler, S. Patel, P. Slavich, C. Wagner, G. Weiglein]
   (contribution to LHC Higgs XS WG)

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2. Implementation of Simplified Template Cross Sections in `HiggsSignals`; application to models with non-trivial modifications of the Higgs-p_T in $pp \to h + \mathrm{jet}$.
   [w/ `HiggsBounds` team + E. Bagnaschi]

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   [w/ E. Fuchs, S. Heinemeyer, S. Liebler, S. Patel, P. Slavich, C. Wagner, G. Weiglein]
   (contribution to LHC Higgs XS WG)

2. Implementation of Simplified Template Cross Sections in HiggsSignals; application to models with non-trivial modifications of the Higgs-p_T in $pp \to h + \mathrm{jet}$.
   [w/ HiggsBounds team + E. Bagnaschi]

3. LHC discovery potential for charged Higgs signature $H^\pm \to W^\pm h$, with a new scalar h with $m_h \lesssim 100\ \mathrm{GeV}$ and decaying to $b\bar{b}, \tau^+\tau^-$ or $\gamma\gamma$.
   [w/ M. Hence (SCIPP ATLAS group)]

Thanks for your attention!

Backup slides

MSSM Heavy Higgs interpretation: more plots