Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Revisiting the Yukawa Type I for the 2HDMS With a 95 GeV Higgs Boson Including the Recent ATLAS Results

Bachelor-Colloquium

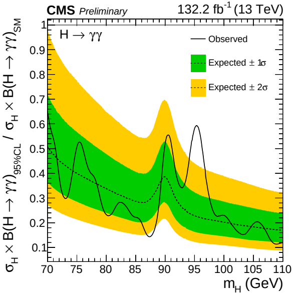
Dominik Heintz

First Supervisor: Prof. Dr. Gudrid Moortgat-Pick
Second Supervisor: Prof. Dr. Sven Heinemeyer
Collaborators: Daniel Schieber, Cheng Li

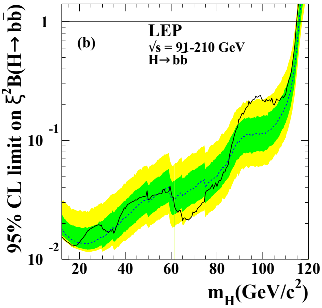
Hamburg 16.05.2024

The 95 GeV Excess

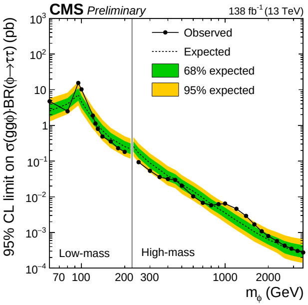
Motivation



(a) [CMS, 2023]



(b) [LEP, 2003]



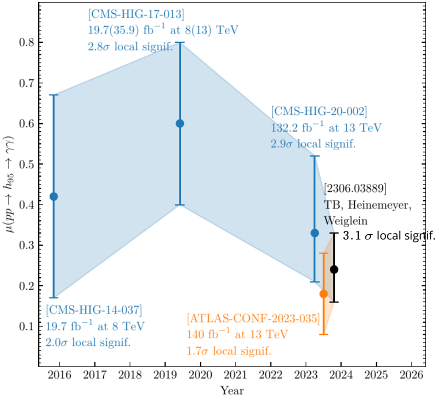
(c) [CMS, 2022]

Local significance and signal strength at 95.4 GeV [T. Biekötter et al., 2023]:

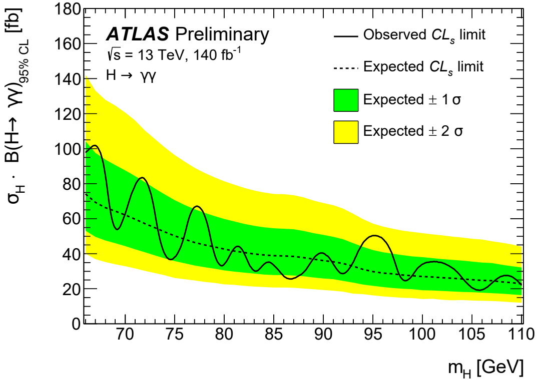
$2.9\,\sigma$	$2.3\,\sigma$	$2.6\,\sigma$
$\mu^{\text{CMS}}_{\gamma\gamma} = 0.33^{+0.19}_{-0.12}$	$\mu^{\text{LEP}}_{b\bar{b}} = 0.117 \pm 0.057$	$\mu^{\text{CMS}}_{\tau\tau} = 1.2 \pm 0.5$

Experimental Value of $\mu_{\gamma\gamma}$ went down over time

Motivation



(a) [Thomas Biekötter, 2023]



(b) [ATLAS, 2023]

Recent ATLAS Results

Motivation

- The “model-dependent” analysis of the full Run 2 data of ATLAS found an excess at: [ATLAS, 2023]

$$95.4\,\mathrm{GeV} \quad \text{with:} \quad 1.7\,\sigma$$

- This leads to a signal strength of [T. Biekötter et al., 2023]:

$$\mu_{\gamma\gamma}^{\mathrm{ATLAS}} = \frac{\sigma^{\mathrm{exp}}\left(pp \to \phi \to \gamma\gamma\right)}{\sigma^{\mathrm{SM}}\left(pp \to H_{\mathrm{SM}}^{0} \to \gamma\gamma\right)} = 0.18 \pm 0.10$$

with $m_{H_{\mathrm{SM}}^{0}} = 95.4\,\mathrm{GeV}$.

- $\mu_{\gamma\gamma}^{\mathrm{ATLAS}}$ and $\mu_{\gamma\gamma}^{\mathrm{CMS}}$ can be combined [T. Biekötter et al., 2023]:

$$\mu_{\gamma\gamma}^{\mathrm{exp}} = \mu_{\gamma\gamma}^{\mathrm{ATLAS+CMS}} = 0.24^{+0.09}_{-0.08}$$

- This corresponds to an excess at:

$$95.4\,\mathrm{GeV} \quad \text{with:} \quad 3.1\,\sigma$$

Definition of 2HDMS

2HDMS

- Two Higgs Doublet Model with a complex Singlet:

$$\Phi_1 = \begin{pmatrix} \chi_1^+ \\ v_1 + \frac{\rho_1 + i\eta_1}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \chi_2^+ \\ v_2 + \frac{\rho_2 + i\eta_2}{\sqrt{2}} \end{pmatrix} \qquad S = v_S + \frac{\rho_S + i\eta_S}{\sqrt{2}}$$

- We define:

$$\tan(\beta) = \frac{v_2}{v_1} \qquad \sqrt{v_1^2 + v_2^2} = v = \frac{246.22}{\sqrt{2}}\,\text{GeV}$$

- V_{2HDMS} obeys the symmetries $\mathbb{Z}_2$ and $\mathbb{Z}_3$:

$$\mathbb{Z}_2: \qquad \Phi_1 \to \Phi_1 \qquad \Phi_2 \to -\Phi_2 \qquad S \to S$$

$$\mathbb{Z}_3: \qquad \begin{pmatrix} \Phi_1 \\ \Phi_2 \\ S \end{pmatrix} \to \begin{pmatrix} 1 & & \\ & e^{i2\pi/3} & \\ & & e^{-i2\pi/3} \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \\ S \end{pmatrix}$$

Basis Change

2HDMS

$$V_{\text{2HDMS}} = m_{11}^2 \left(\Phi_1^\dagger \Phi_1\right) + m_{22}^2 \left(\Phi_2^\dagger \Phi_2\right) + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right) \left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right) \left(\Phi_2^\dagger \Phi_1\right)$$
$$+ m_S^2 \left(S^\dagger S\right) + \lambda_1' \left(S^\dagger S\right) \left(\Phi_1^\dagger \Phi_1\right) + \lambda_2' \left(S^\dagger S\right) \left(\Phi_2^\dagger \Phi_2\right) + \frac{\lambda_3''}{4} \left(S^\dagger S\right)^2 + \left(-m_{12}^2 \Phi_1^\dagger \Phi_2 + \frac{\mu_{S1}}{6} S^3 + \mu_{12} S \Phi_1^\dagger \Phi_2 + \textbf{h.c.}\right)$$

<u>Interaction Basis:</u>

$\tan(\beta)$

$\lambda_{1,2,3,4}$

$\lambda_{1,2}', \lambda_3''$

m_{12}^2

μ_{S1}, μ_{12}

v_S

$\Longleftrightarrow$

<u>Mass Basis:</u>

- $\tan(\beta)$
- Scalar Higgs h_1, h_2, h_3: $m_{h_1} < m_{h_2} < m_{h_3}$
- Pseudo scalar Higgs a_1, a_2: $m_{a_1} < m_{a_2}$
- Charged Higgs $H^\pm$: $m_{H^\pm}$
- Mixing angles: $\alpha_{1,2,3,4}$
- Vacuum expectation value of S: v_s

$\Rightarrow$ **12** degrees of freedom

Couplings

2HDMS

$$-\mathcal{L}_Y = \sum_{\text{up-type}} iY_u \bar{Q}_L \sigma_2 \Phi_i u_R + \sum_{\text{down-type}} Y_d \bar{Q}_L \Phi_j d_R + \sum_{\text{leptons}} Y_l \bar{L}_L \Phi_k l_R + \text{h.c.}$$

To determine the couplings, the Yukawa Lagrangian is investigated. We differentiate **4** Yukawa Types:

	Type I	Type II	Type III	Type IV
Up-type Φ_i	Φ_2	Φ_2	Φ_2	Φ_2
Down-type Φ_j	Φ_2	Φ_1	Φ_2	Φ_1
Lepton Φ_k	Φ_2	Φ_1	Φ_1	Φ_2

In Type I we have:

$$c_{h_i ff} = \frac{g_{h_i ff}}{g_{H_{SM} ff}} = c_{h_i tt} = c_{h_i bb} = c_{h_i \tau\tau}$$

$$c_{h_i VV} = \frac{g_{h_i VV}}{g_{H_{SM} VV}} = c_{h_i ZZ} = c_{h_i WW}$$

Comparison to 2HDMS Type II

2HDMS

- In Type II we found the approximate correlation [Li, 2023]:

$$\mu_{\gamma\gamma}^{theo} \propto \frac{|c_{h_1tt}|^2}{|c_{h_1bb}|^2}$$

- In Type I: $c_{h_1tt} = c_{h_1bb} = c_{h_1ff}$
  - It is harder to achieve high $\mu_{\gamma\gamma}^{theo}$
  - **However:** We were able to find other possibilities to achieve high $\mu_{\gamma\gamma}^{theo}$

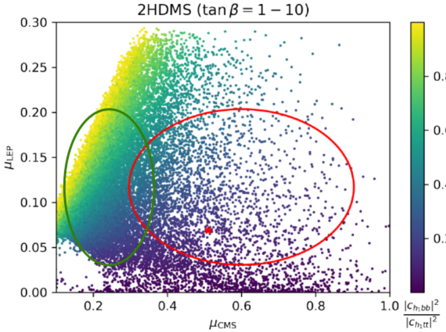


Figure: 2HDMS Type II [Li, 2023]:
Red ellipse $1\,\sigma$ range of old:
$\mu_{\gamma\gamma}^{CMS} = 0.6 \pm 0.2$[CMS, 2017],
Green ellipse $1\,\sigma$ range of new:
$\mu_{\gamma\gamma}^{exp} = 0.24^{+0.09}_{-0.08}$[T. Biekötter et al., 2023]

Alignment Limit

2HDMS

Alignment Limit

The Alignment Limit is when h_2 couples like the SM Higgs:

$$c_{h_2 ff} \to 1$$
$$c_{h_2 VV} \to 1$$

For the 2HDMS this is for [Li, 2023]:

$$\sin^2(\alpha_2) \to 1$$
$$|\sin(\beta - \alpha_1 - \mathrm{sgn}(\alpha_2)\alpha_3)| \to 1$$

Constraints

Implementation

Theoretical Constraints:

- Tree-Level perturbative unitarity
- Boundedness from below
- Vacuum stability
  - $m_{12}^2 > 0$ [Barroso et al., 2013]

Experimental Constraints:

- STU-Parameters
- Flavor constraints
- HiggsTools [Bahl et al., 2023]

HiggsTools:

HiggsBounds: [P. Bechtle et al., 2010]

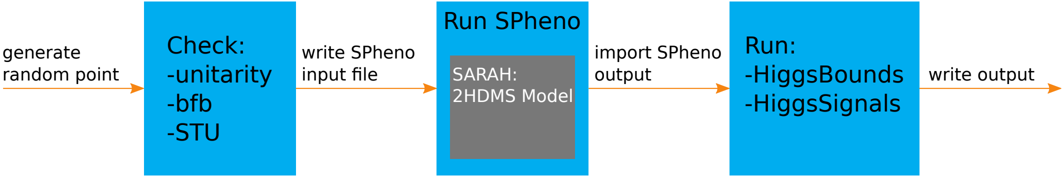
- Compares the Model against a large number of experimental results, including the latest ATLAS results

HiggsSignals: [Philip Bechtle et al., 2014]

- Compares the Model against properties of the $125\,\mathrm{GeV}$ Higgs
- Returns χ^2_{125}
  - Allowed if χ^2_{125} is in 95% CL interval of SM

Overview Software Implementation

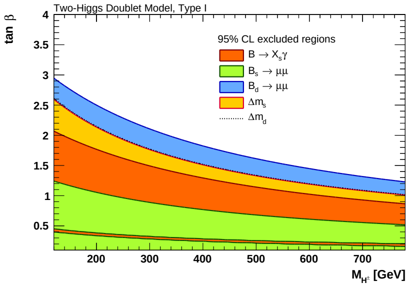
Implementation



SPheno: [Porod, 2003; Porod et al., 2012] SARAH: [F. Staub, 2012; Florian Staub, 2014]

Flavor Constraints

Implementation



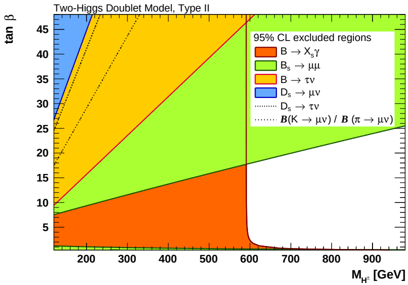


Figure: [Haller et al., 2018]

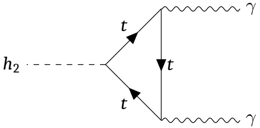
⇒ Type I allows much smaller $m_{H^\pm}$ than Type II

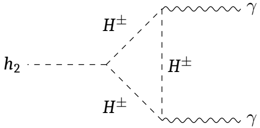
HiggsSignals 1.
Implementation

- Implementation Type II:
  - HiggsSignals calculates SM branching ratios: $\Rightarrow \quad {\chi^2_{125}}^{\text{SM}}$
  - HiggsSignals calculates 2HDMS BRs based on SPheno output: $\Rightarrow \quad \chi^2_{125}$
  - Point is allowed by HiggsSignals, if χ^2_{125} is within the 95% C.L. interval of ${\chi^2_{125}}^{\text{SM}}$:

$$\Delta\chi^2_{125} = \chi^2_{125} - {\chi^2_{125}}^{\text{SM}} < 5.99$$

- Problem in Type I: Because of small $m_{H^\pm}$, $H^\pm$ has influence on BR$(h_2 \to \gamma\gamma)$:



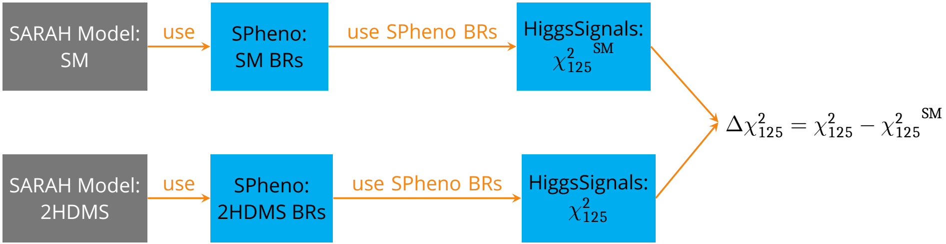


- This is not considered by HiggsSignals, if only given the SPheno output

HiggsSignals 2.

Implementation

- Not possible: SPheno calculates 2HDMS and HiggsSignals calculates SM BRs
- Solution: Use SPheno to calculate SM and 2HDMS branching ratios:



- Upside: Good comparability between χ^{2}_{125} and $\chi^{2}_{125}{}^{\text{SM}}$
- Downside: HiggsSignals is more accurate in calculating the SM properties

Fitting the 95 GeV Excesses

Implementation

- Theoretical signal strengths calculated using the narrow width approximation with $m_{H_{\mathrm{SM}^0}} = m_{h_1}$ [Li, 2023]:

$$\mu_{\gamma\gamma}^{\mathrm{theo}} = |c_{h_1 ff}|^2 \frac{\mathrm{BR}_{\mathrm{2HDMS}}(h_1 \to \gamma\gamma)}{\mathrm{BR}_{\mathrm{SM}}(H_{\mathrm{SM}}^0 \to \gamma\gamma)}$$

$$\mu_{\tau\tau}^{\mathrm{theo}} = |c_{h_1 ff}|^2 \frac{\mathrm{BR}_{\mathrm{2HDMS}}(h_1 \to \tau\tau)}{\mathrm{BR}_{\mathrm{SM}}(H_{\mathrm{SM}}^0 \to \tau\tau)}$$

$$\mu_{b\bar{b}}^{\mathrm{theo}} = |c_{h_1 VV}|^2 \frac{\mathrm{BR}_{\mathrm{2HDMS}}(h_1 \to b\bar{b})}{\mathrm{BR}_{\mathrm{SM}}(H_{\mathrm{SM}}^0 \to b\bar{b})}$$

- χ_{95}^2 is given by:

$$\chi_{95}^2 = \left(\frac{\mu_{\gamma\gamma}^{\mathrm{theo}} - \mu_{\gamma\gamma}^{\mathrm{exp}}}{\Delta_{\mu_{\gamma\gamma}^{\mathrm{exp}}}}\right)^2 + \left(\frac{\mu_{b\bar{b}}^{\mathrm{theo}} - \mu_{b\bar{b}}^{\mathrm{LEP}}}{\Delta_{\mu_{b\bar{b}}^{\mathrm{LEP}}}}\right)^2 + \left(\frac{\mu_{\tau\tau}^{\mathrm{theo}} - \mu_{\tau\tau}^{\mathrm{CMS}}}{\Delta_{\mu_{\tau\tau}^{\mathrm{CMS}}}}\right)^2$$

- “Best-Fit” Point has minimal χ_{tot}^2 [Li, 2023]:

$$\chi_{\mathrm{tot}}^2 = \chi_{95}^2 + \chi_{125}^2$$

Selected Parameter Space

Parameter Space

With $m_{h_1} < m_{h_2} < m_{h_3}, m_{a_1}, m_{a_2}$ and $m_{a_1} < m_{a_2}$ the parameter space is:

$m_{h_1} \in (94, 97)$ GeV $\quad m_{h_2} = 125.09$ GeV $\quad m_{a_1}, m_{a_2}, m_{h_3} \in (130, 1700)$ GeV

$\sin(\beta - \alpha_1 - \text{sgn}(\alpha_2)\alpha_3) \in \pm(0.95, 1) \quad \alpha_2 \in \pm(0.65, 2.52) \quad m_{H^\pm} \in (120, 1700)$ GeV

$$\alpha_1 \in (-\pi, \pi) \qquad \alpha_4 \in \pm\left(\frac{\pi}{4}, \frac{3\pi}{4}\right) \qquad v_s \in (40, 2000)\ \text{GeV}$$

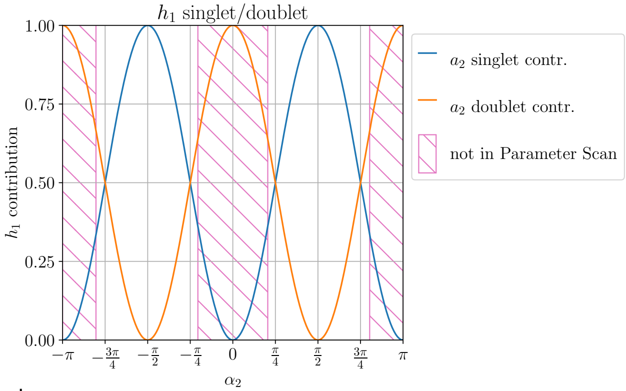
Table: $\tan(\beta)$ intervals

$\tan(\beta) \in (1, 3)$
$\tan(\beta) \in (3, 10)$
$\tan(\beta) \in (10, 20)$

$\Rightarrow$ In this talk, focus on: $\tan(\beta) \in (10, 20)$,
because $\tan(\beta) \in (10, 20)$ has overall Best-Fit point

Singlet/Doublet Like h_1

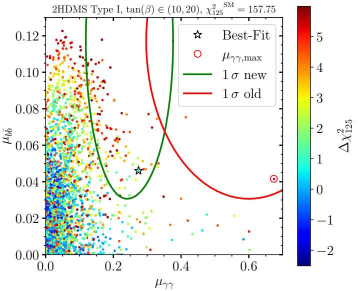
Parameter Space

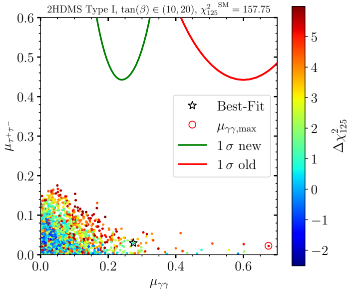


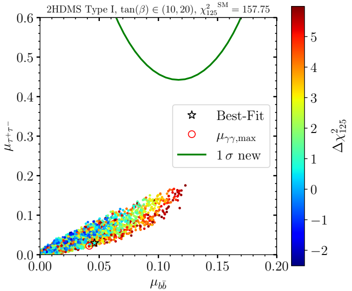
- Range of α_2 is chosen:
  - To make h_1 mostly singlet-like
  - Also allow h_1 weakly doublet-like

Results $\tan(\beta) \in (10, 20)$

Results







Best-Fit point:

$$m_{H^\pm} = 170.6\ \mathrm{GeV}$$

Red ellipse $1\,\sigma$ of old $\mu^{\mathrm{CMS}}_{\gamma\gamma}$

$$\mu^{\mathrm{CMS}}_{\gamma\gamma} = 0.6 \pm 0.2$$
$$\mu^{\mathrm{LEP}}_{b\bar{b}} = 0.117 \pm 0.057$$
$$\mu^{\mathrm{CMS}}_{\tau\tau} = 1.2 \pm 0.5$$

Green ellipse $1\,\sigma$ of new μ^{exp}

$$\mu^{exp}_{\gamma\gamma} = \mu^{\mathrm{ATLAS+CMS}}_{\gamma\gamma} = 0.24^{+0.09}_{-0.08}$$
$$\mu^{\mathrm{LEP}}_{b\bar{b}} = 0.117 \pm 0.057$$
$$\mu^{\mathrm{CMS}}_{\tau\tau} = 1.2 \pm 0.5$$

$$\mu_{\gamma\gamma}^{\text{theo}} = \left|c_{h_1 ff}\right|^2 \frac{\text{BR}_{\text{2HDMS}}\left(h_1 \to \gamma\gamma\right)}{\text{BR}_{\text{SM}}\left(H_{SM}^0 \to \gamma\gamma\right)} \qquad \text{with: } m_{H_{\text{SM}}^0} = m_{h_1}$$

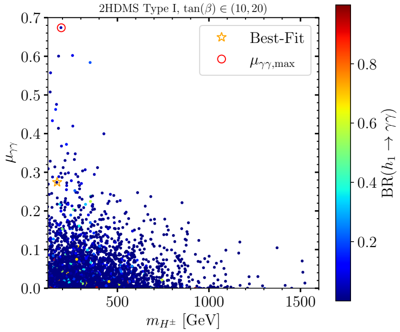
Increasing $\mu_{\gamma\gamma}$ by increasing:

- $\left|c_{h_1 ff}\right|^2$
- $\text{BR}_{\text{2HDMS}}\left(h_1 \to \gamma\gamma\right)$

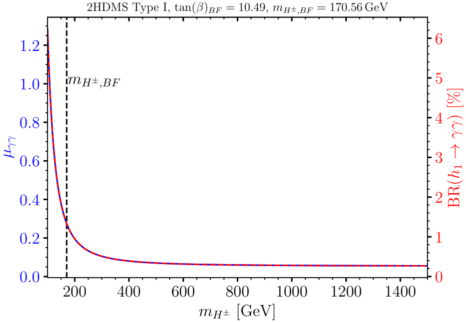
But, $\left|c_{h_1 ff}\right|^2$ and $\text{BR}_{\text{2HDMS}}\left(h_1 \to \gamma\gamma\right)$ have a convoluted interdependency.

Small $m_{H^\pm}$

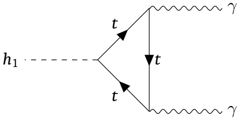
High $\mu_{\gamma\gamma}^{\text{theo}}$

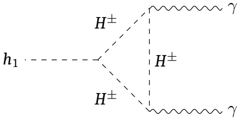


Best-Fit $\tan(\beta) \in (10, 20)$, vary $m_{H^\pm} \in [100, 1500]$ GeV



$\Rightarrow$ Small $m_{H^\pm}$ increases BR $(h_1 \to \gamma\gamma) \Rightarrow \mu_{\gamma\gamma}^{\text{theo}}$

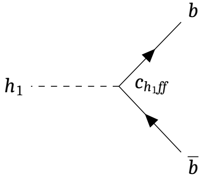




c_{h_1ff} and BR$(h_1 \to \gamma\gamma)$ 1.

High $\mu_{\gamma\gamma}^{\text{theo}}$

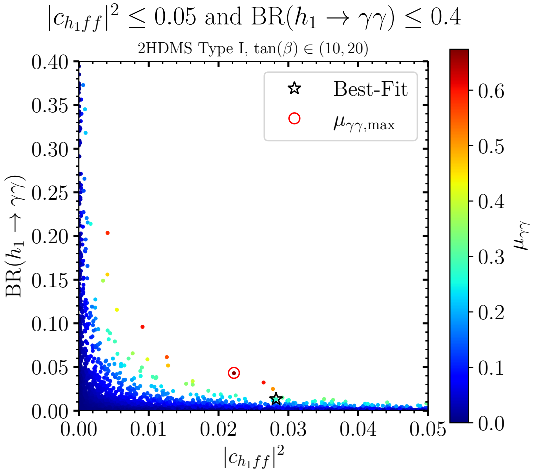
- $\mu_{\gamma\gamma}^{\text{theo}} = |c_{h_1ff}|^2 \frac{\text{BR}_{\text{2HDMS}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H^0_{SM} \to \gamma\gamma)}$, $m_{H^0_{\text{SM}}} = m_{h_1}$



- To further investigate $\mu_{\gamma\gamma}^{\text{theo}}$ with:

$$|c_{h_1ff}|^2 = \frac{\sin(\alpha_1)\cos(\alpha_2)}{\sin(\beta)}$$

$\Rightarrow$ Vary α_1 and α_2

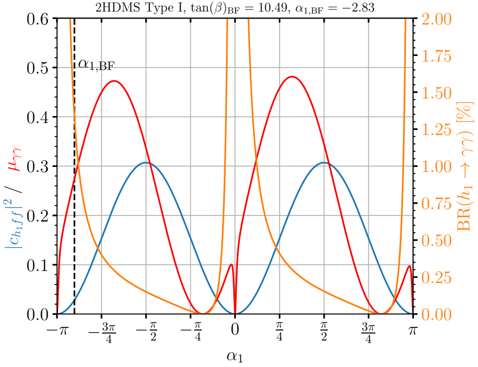


c_{h_1ff} and BR$(h_1 \to \gamma\gamma)$ 2.

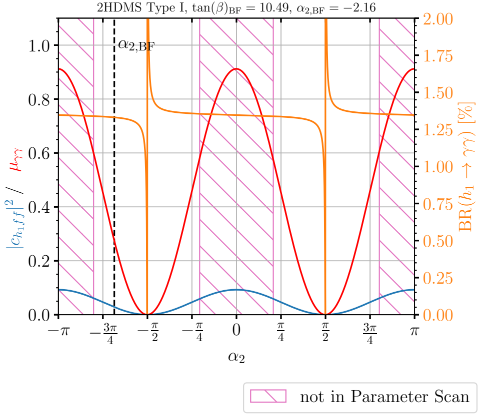
High $\mu_{\gamma\gamma}^{\text{theo}}$

$\Rightarrow$ For Best-Fit point vary $\alpha_1 \in [-\pi, \pi]$ (left) and $\alpha_2 \in [-\pi, \pi]$ (right)

Best-Fit $\tan(\beta) \in (10, 20)$, vary $\alpha_1 \in [-\pi, \pi]$



Best-Fit $\tan(\beta) \in (10, 20)$, vary $\alpha_2 \in [-\pi, \pi]$



$\Rightarrow$ $\mu_{\gamma\gamma}^{\text{theo}}(\alpha_1, \alpha_2)$ has maxima

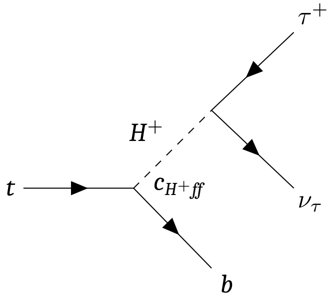
Direct charged Higgs Production 1.

High $\mu_{\gamma\gamma}^{\text{theo}}$

- If $m_{H^\pm} < m_t$, $H^\pm$ can be produced directly: $t \to H^+ b$ [Philip Bechtle et al., 2020]
- $H^+ \to \tau^+ \nu_\tau$ has been found to be the dominant decay channel
  - HiggsBounds has limits on H^+ decays
- c_{H^+ff} is identical for 2HDM and 2HDMS
  - For the 2HDM there is [Gunion et al., 2000]:

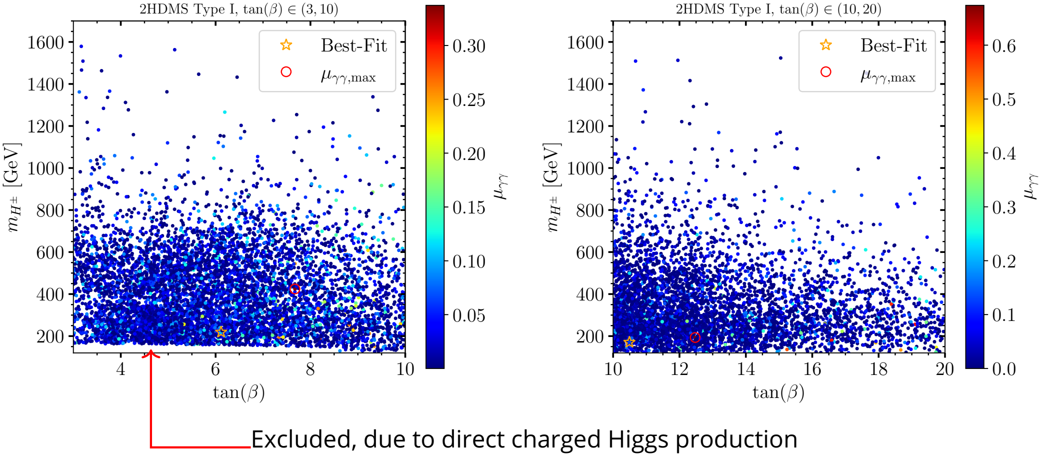
$$c_{H^+ff} \propto \cot \beta$$

- For small $\tan(\beta)$: $m_{H^\pm}$ is constrained, due to direct $H^\pm$ production



Direct charged Higgs Production 2.

High $\mu_{\gamma\gamma}^{\text{theo}}$



Excluded, due to direct charged Higgs production

Modified Parameter Space

High $\mu_{\gamma\gamma}^{\text{theo}}$ Parameter Space

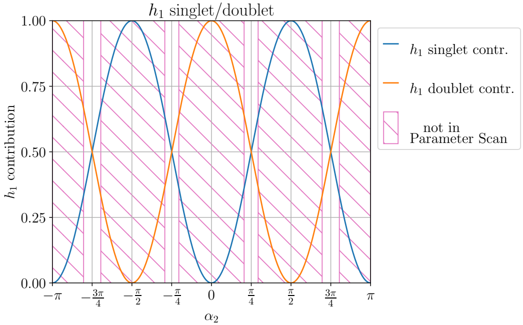
$$m_{h_1} \in (94, 97)\ \text{GeV} \qquad m_{h_2} = 125.09\ \text{GeV} \qquad m_{a_1}, m_{a_2}, m_{h_3} \in (130, 600)\ \text{GeV}$$

$$\sin(\beta - \alpha_1 - \text{sgn}(\alpha_2)\alpha_3) \in \pm(0.95, 1) \qquad m_{H^\pm} \in (120, 600)\ \text{GeV}$$

$$\alpha_1 \in (-\pi, \pi) \qquad \alpha_4 \in \pm\left(\frac{\pi}{4}, \frac{3\pi}{4}\right) \qquad v_s \in (40, 2000)\ \text{GeV}$$

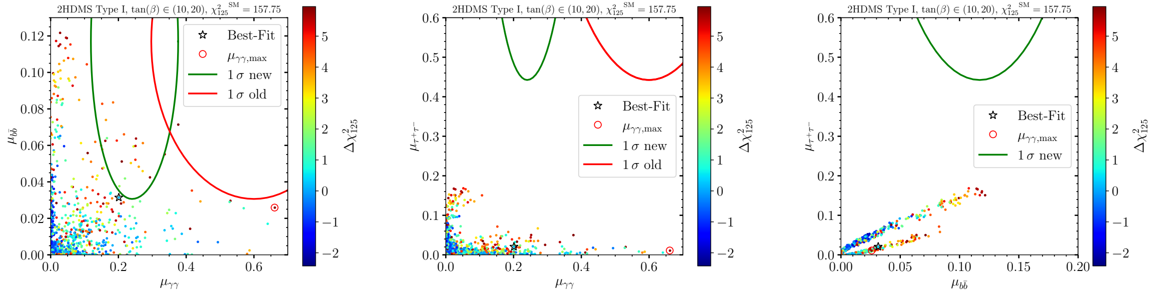
Additionally:

- $\alpha_2 \in \pm(0.65, 0.92) \cup \pm(2.19, 2.52)$
- $\tan(\beta) \in (10, 20)$
- Not possible to be close to maxima of $\mu_{\gamma\gamma}^{\text{theo}}(\alpha_1)$ and $\mu_{\gamma\gamma}^{\text{theo}}(\alpha_2)$ simultaneously:
  - singlet contribution of h_2 would be too big $\Rightarrow$ excluded by HiggsSignals



Result

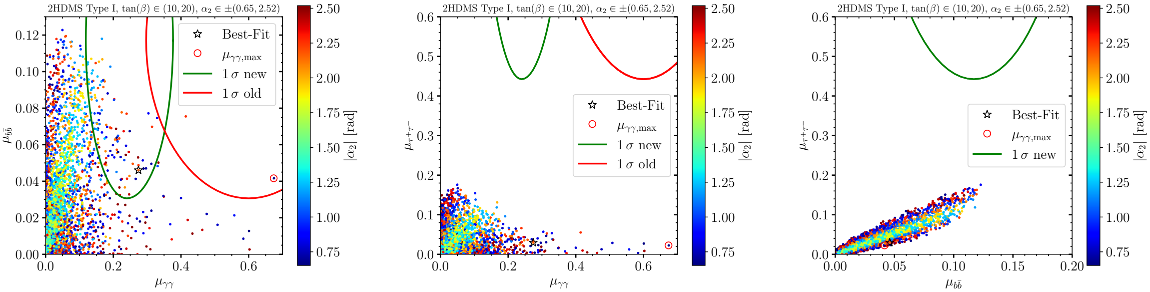
High $\mu_{\gamma\gamma}^{\text{theo}}$ Parameter Space



- Comparable amount of points with high $\mu_{\gamma\gamma}^{\text{theo}}$, but much smaller scan: **811** points in comparison to **4874** for previous scan

Comparison to old Parameter Scan

High $\mu_{\gamma\gamma}^{\text{theo}}$ Parameter Space



- Yellow to light-blue points are missing in modified Parameter Space
- Modified Parameter Space behaves as expected
- Possibilities to increase $\mu_{\gamma\gamma}^{\text{theo}}$ will be rated as successful

Summary & Outlook

Summary:

- It is possible to reach the necessary $\mu_{\gamma\gamma}^{\text{theo}}$ and $\mu_{b\bar{b}}^{\text{theo}}$ with a 2HDMS Type I
- The excesses in the $\gamma\gamma$, $b\bar{b}$ and $\tau^+\tau^-$-Channel can not be fitted with a 2HDMS Type I simultaneously (similar to 2HDMS Type II)
- In contrast to our first assumptions, it is possible to reach high $\mu_{\gamma\gamma}^{\text{theo}}$ with a 2HDMS Type I. The easiest ways to increase $\mu_{\gamma\gamma}^{\text{theo}}$ are:
  - Small $m_{H^\pm}$
  - Find maximum of $|c_{h_1 ff}|^2 \cdot \mathrm{BR}_{\text{2HDMS}}\left(h_1 \to \gamma\gamma\right)$
  - Large $\tan(\beta)$

Outlook:

- Implement vacuum stability and flavor constraints more accurately
- Perform the same analysis for the 2HDMS Type III and N2HDM Type I/III (Next to Two Higgs Doublet Model: 2 Doublets, 1 real Singlet)
- Different HiggsSignals implementation: Let HiggsSignals calculate SM and 2HDMS branching ratios, explicitly pass underestimated BRs from SPheno

Thank you!

Contact

Dominik Heintz	**II. Institut für Theoretische Physik, Universität Hamburg**	**dominik.heintz@desy.de**
Sven Heinemeyer	Instituto de Física Teórica UAM-CSIC	Sven.Heinemeyer@cern.ch
Cheng Li	School of Science, Sun Yat-Sen University	cheng.li@desy.de
Gudrid Moortgat-Pick	II. Institut für Theoretische Physik, Universität Hamburg / DESY	gudrid.moortgat-pick@desy.de
Daniel Schieber	II. Institut für Theoretische Physik, Universität Hamburg	Daniel.Schieber@desy.de

Bibliography I

CMS (2023). *Search for a standard model-like Higgs boson in the mass range between 70 and 110* GeV *in the diphoton final state in proton-proton collisions at* $\sqrt{s} = 13$ TeV. Tech. rep. Geneva: CERN. URL: http://cds.cern.ch/record/2852907.

LEP (July 2003). In: *Physics Letters B* 565, pp. 61–75. ISSN: 0370-2693. DOI: 10.1016/s0370-2693(03)00614-2. URL: http://dx.doi.org/10.1016/S0370-2693(03)00614-2.

CMS (2022). *Searches for additional Higgs bosons and vector leptoquarks in* $\tau\tau$ *final states in proton-proton collisions at* $\sqrt{s} = 13$ TeV. Tech. rep. Geneva: CERN. URL: http://cds.cern.ch/record/2803739.

Biekötter, T., S. Heinemeyer, and G. Weiglein (2023). *The 95.4 GeV di-photon excess at ATLAS and CMS*. arXiv: 2306.03889 [hep-ph].

Biekötter, Thomas (2023). "Mounting evidence for a 95 GeV Higgs boson." Higgs Days at Santander 2023. URL: http://hdays.csic.es/HDays23/talks/Tuesday/biekoetter.pdf.

ATLAS (2023). *Search for diphoton resonances in the 66 to 110 GeV mass range using 140 fb*$^{-1}$ *of 13 TeV pp collisions collected with the ATLAS detector*. Tech. rep. Geneva: CERN. URL: http://cds.cern.ch/record/2862024.

Li, Cheng (2023). "Phenomenology of extended Two-Higgs-Doublets models." PhD thesis. Staats-und Universitätsbibliothek Hamburg Carl von Ossietzky.

CMS (2017). *Search for new resonances in the diphoton final state in the mass range between 70 and 110 GeV in pp collisions at* $\sqrt{s} = 8$ *and 13 TeV*. Tech. rep. Geneva: CERN. URL: http://cds.cern.ch/record/2285326.

Barroso, A. et al. (June 2013). "Metastability bounds on the two Higgs doublet model." In: *Journal of High Energy Physics* 2013.6. ISSN: 1029-8479. DOI: 10.1007/jhep06(2013)045. URL: http://dx.doi.org/10.1007/JHEP06(2013)045.

Bibliography II

Bahl, H. et al. (Oct. 2023). “HiggsTools: BSM scalar phenomenology with new versions of HiggsBounds and HiggsSignals.” In: *Computer Physics Communications* 291, p. 108803. ISSN: 0010-4655. DOI: 10.1016/j.cpc.2023.108803. URL: http://dx.doi.org/10.1016/j.cpc.2023.108803.

Bechtle, P. et al. (Jan. 2010). “HiggsBounds: Confronting arbitrary Higgs sectors with exclusion bounds from LEP and the Tevatron.” In: *Computer Physics Communications* 181.1, pp. 138–167. ISSN: 0010-4655. DOI: 10.1016/j.cpc.2009.09.003. URL: http://dx.doi.org/10.1016/j.cpc.2009.09.003.

Bechtle, Philip et al. (Feb. 2014). “HiggsSignals: Confronting arbitrary Higgs sectors with measurements at the Tevatron and the LHC.” In: *The European Physical Journal C* 74.2. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-013-2711-4. URL: http://dx.doi.org/10.1140/epjc/s10052-013-2711-4.

Porod, W. (June 2003). “SPheno, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at e+e- colliders.” In: *Computer Physics Communications* 153.2, pp. 275–315. ISSN: 0010-4655. DOI: 10.1016/s0010-4655(03)00222-4. URL: http://dx.doi.org/10.1016/S0010-4655(03)00222-4.

Porod, W. and F. Staub (Nov. 2012). “SPheno 3.1: extensions including flavour, CP-phases and models beyond the MSSM.” In: *Computer Physics Communications* 183.11, pp. 2458–2469. ISSN: 0010-4655. DOI: 10.1016/j.cpc.2012.05.021. URL: http://dx.doi.org/10.1016/j.cpc.2012.05.021.

Staub, F. (2012). *Sarah*. arXiv: 0806.0538 [hep-ph].

Staub, Florian (June 2014). “SARAH 4: A tool for (not only SUSY) model builders.” In: *Computer Physics Communications* 185.6, pp. 1773–1790. ISSN: 0010-4655. DOI: 10.1016/j.cpc.2014.02.018. URL: http://dx.doi.org/10.1016/j.cpc.2014.02.018.

Haller, J. et al. (Aug. 2018). “Update of the global electroweak fit and constraints on two-Higgs-doublet models.” In: *The European Physical Journal C* 78.8. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-018-6131-3. URL: http://dx.doi.org/10.1140/epjc/s10052-018-6131-3.

Bibliography III

Bechtle, Philip et al. (Dec. 2020). "HiggsBounds-5: testing Higgs sectors in the LHC 13 TeV Era." In: *The European Physical Journal C* 80.12. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-020-08557-9. URL: http://dx.doi.org/10.1140/epjc/s10052-020-08557-9.

Gunion, John F. et al. (2000). *The Higgs Hunter's Guide*. Vol. 80.

Flavor Constraints

Appendix

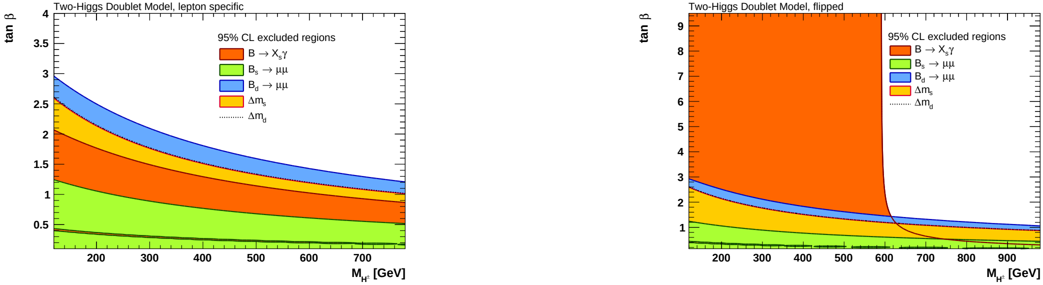
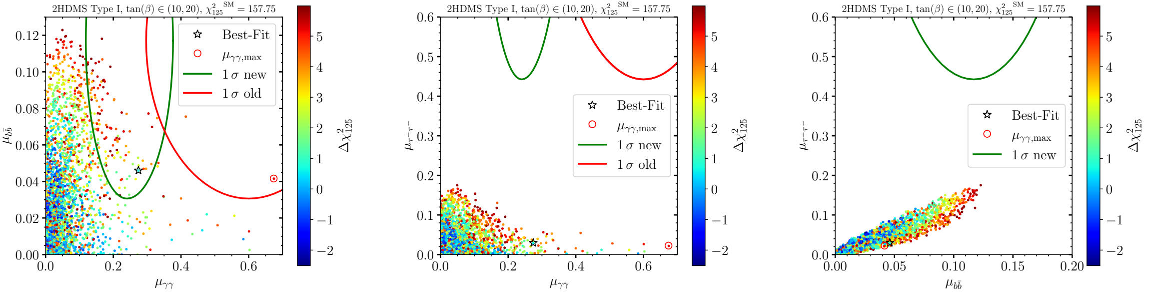


Figure: [Haller et al., 2018]

Results $\tan(\beta) \in (10, 20)$

Appendix



Best-Fit point:

Parameter	m_{h_1}	m_{h_2}	m_{h_3}	m_{a_1}	m_{a_2}		$m_{H^\pm}$	v_S
[GeV]	94.339	125.09	281.6	237.3	240.2		170.6	430.1

Parameter	$\tan(\beta)$	α_1	α_2	α_3	α_4	$\sin(\beta - \alpha_1 - \text{sgn}(\alpha_2)\alpha_3)$	χ^2_{tot}
[a.u.]	10.491	-2.834	-2.155	-2.805	1.318	0.998	165.6

Best-Fit Point $\tan(\beta)) \in (10, 20)$

Appendix

Parameter	m_{h_1}	m_{h_2}	m_{h_3}	m_{a_1}	m_{a_2}	$m_{H^\pm}$	v_s
[GeV]	94.339	125.09	281.6	237.3	240.2	170.6	430.1

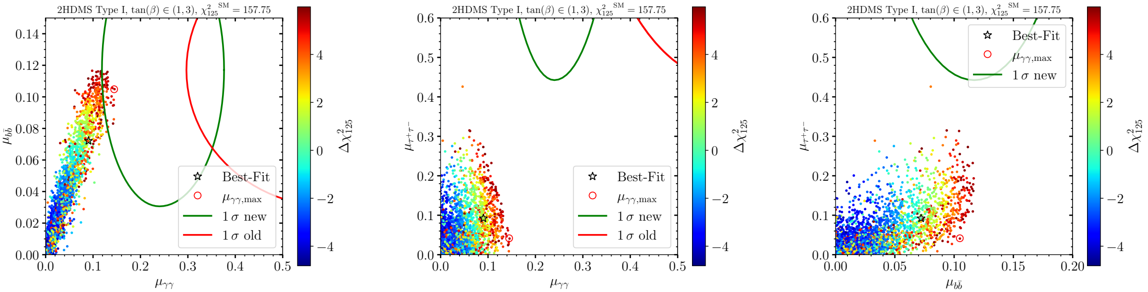
Parameter	$\tan(\beta)$	α_1	α_2	α_3	α_4	$\sin(\beta - \alpha_1 - \text{sgn}(\alpha_2)\alpha_3)$	χ^2_{tot}
[a.u.]	10.491	-2.834	-2.155	-2.805	1.318	0.998	165.6

h_1 Channel	BR [%]	h_2 Channel	BR [%]	h_3 Channel	BR [%]
$h_1 \to b\bar{b}$	78.88	$h_2 \to b\bar{b}$	58.01	$h_3 \to h_1 h_1$	87.84
$h_1 \to \tau^- \tau^+$	8.73	$h_2 \to W^- W^+$	20.88	$h_3 \to h_2 h_1$	4.40
$h_1 \to gg$	7.02	$h_2 \to gg$	9.08	$h_3 \to W^+ H^-$	3.85
$h_1 \to c\bar{c}$	3.74	$h_2 \to \tau^- \tau^+$	6.73	$h_3 \to W^- H^+$	3.85
$h_1 \to \gamma\gamma$	1.33	$h_2 \to c\bar{c}$	2.74	$h_3 \to h_2 h_2$	0.05
$h_1 \to W^- W^+$	0.24	$h_2 \to Z^0 Z^0$	2.26		
		$h_2 \to \gamma\gamma$	0.25		

a_1 Channel	BR[%]	a_2 Channel	BR [%]	$H^\pm$ Channel	BR [%]
$a_1 \to Z^0 h_1$	98.50	$a_2 \to Z^0 h_1$	98.33	$H^+ \to \bar{s}c$	56.76
$a_1 \to Z^0 h_2$	1.46	$a_2 \to Z^0 h_2$	1.63	$H^+ \to \tau^+ \nu_\tau$	38.86
$a_1 \to gg$	0.02	$a_2 \to gg$	0.02	$H^+ \to \bar{d}c$	3.02
$a_1 \to b\bar{b}$	0.01			$H^+ \to \bar{b}c$	1.19
				$H^+ \to \mu^+ \nu_\mu$	0.14

Results $\tan(\beta) \in (1, 3)$

Appendix

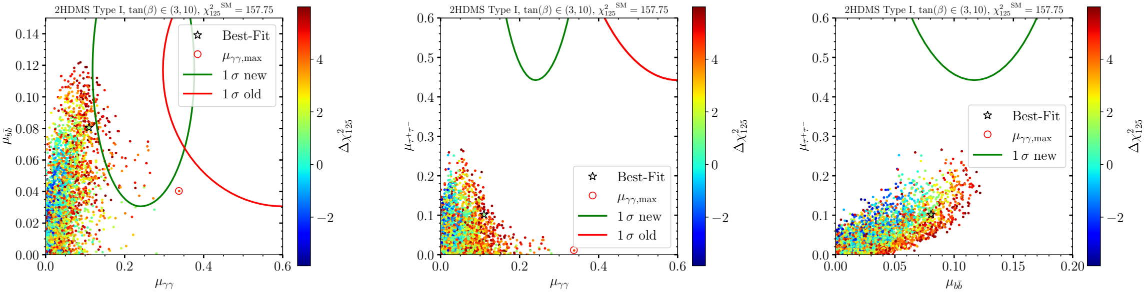


Best-Fit point:

Parameter	m_{h_1}	m_{h_2}	m_{h_3}	m_{a_1}	m_{a_2}	$m_{H^\pm}$	v_s
[GeV]	96.418	125.09	573.5	361.6	550.1	499.1	195.8
Parameter	$\tan(\beta)$	α_1	α_2	α_3	α_4	$\sin\left(\beta - (\alpha_1 + \mathrm{sgn}(\alpha_2)\alpha_3)\right)$	χ^2_{tot}
[a.u.]	2.498	1.422	1.851	1.291	2.093	-0.999	166.7

Results $\tan(\beta) \in (3, 10)$

Appendix

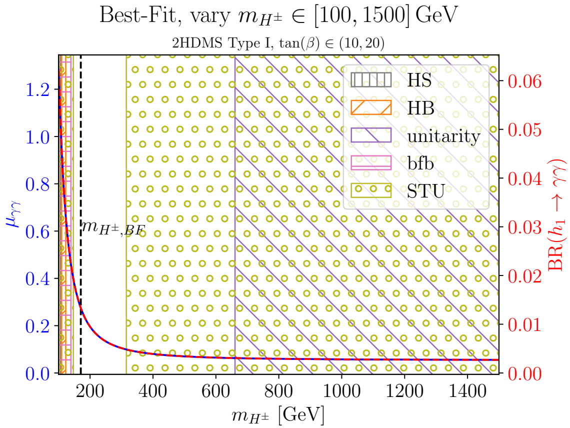


Best-Fit point:

Parameter	m_{h_1}	m_{h_2}	m_{h_3}	m_{a_1}	m_{a_2}	$m_{H^\pm}$	v_s
[GeV]	96.891	125.09	288.7	207.5	286.1	218.8	600.0

Parameter	$\tan(\beta)$	α_1	α_2	α_3	α_4	$\sin\left(\beta - (\alpha_1 + \mathrm{sgn}(\alpha_2)\alpha_3)\right)$	χ^2_{tot}
[a.u.]	6.115	-1.236	-1.242	-4.150	-2.111	-0.998	166.6

$m_{H^\pm}$-Constraints
Appendix



$\tan(\beta)_{\mathrm{BF}} = 10.49$, $m_{H^\pm,\mathrm{BF}} = 170.56$ GeV

h_2 singlet contribution

Appendix