

MSSM Implications of Higgs Searches during LHC Run 1

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in collaboration and discussions with

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Higgs interpretations within the MSSM?

The discovered Higgs boson at ~ 125 GeV looks very SM-like!

① What are the possible interpretations within the Minimal Supersymmetric Standard Model (MSSM)?

- ▶ In the *decoupling limit* ($M_A \gg M_Z$) the light Higgs h becomes SM-like.
- ▶ In the *alignment limit*, the light Higgs h obtains SM-like couplings due to an accidental cancellation of tree-level and loop-level effects. It occurs *independently* of the remaining Higgs spectrum (choice of M_A).
- ▶ Can the heavy Higgs H still be the discovered particle?

② Can the MSSM yield a better fit to the Higgs data than the SM?

[P. Bechtle, S. Heinemeyer, O. Stål, TS, G. Weiglein, L. Zeune, 1211.1955] addressed these questions in November 2012.

Here: Preliminary analysis with updated observables and constraints!

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:

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

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

- Light Higgs mass M_h receives large radiative corrections.

Dominant one-loop corrections from top/stop sector:

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

$$(M_A \gg M_Z, \tan\beta \gg 1)$$

$$(X_t = A_t - \mu \cot\beta, M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}})$$

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

Obtaining a light Higgs with SM-like couplings

[J. Gunion, H. Haber, hep-ph/0207010]

Look at CP conserving 2HDM in the Higgs basis ($\langle H_1^0 \rangle = v/\sqrt{2}$, $\langle H_2^0 \rangle = 0$):

$$\mathcal{V} \ni \dots \frac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \dots + \left[\frac{1}{2} Z_5 (H_1^\dagger H_2)^2 + Z_6 (H_1^\dagger H_1)(H_1^\dagger H_2) + \text{h.c.} \right] + \dots$$

The CP -even neutral Higgs squared-mass matrix is

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

with mixing angle $c_{\beta-\alpha} \equiv \cos(\beta - \alpha)$.

- If $Z_1 < Z_5 + M_A^2/v^2$ and $Z_6 = 0$, then $c_{\beta-\alpha} = 0$ and h is identical to SM Higgs boson (*alignment limit*).
- If $M_A^2 \gg Z_i v^2$, then $m_h^2 \simeq Z_1 v^2$ and $|c_{\beta-\alpha}| \ll 1 \Rightarrow h$ becomes SM-like (*decoupling limit*).

Alignment without decoupling in the MSSM

[M. Carena, I. Low, N. Shah, C. Wagner, 1310.2248; same + H. Haber, 1410.4969]

In the MSSM, $Z_6 = 0$ can be obtained through an accidental cancellation between tree-level and loop-level effects.

Approximate alignment condition at 1-loop ($\tan \beta \gg 1$):

$$\tan \beta = \left(m_h^2 + m_Z^2 + \frac{3m_t^4\mu^2}{4\pi^2 v^2 M_S^2} \left(\frac{A_t^2}{2M_S^2} - 1 \right) \right) / \left(\frac{3m_t^4}{4\pi^2 v^2} \frac{\mu A_t}{M_S^2} \left(\frac{A_t^2}{6M_S^2} - 1 \right) \right).$$

solution exists if $\mu A_t (A_t^2 - 6M_S^2) > 0$.

Alignment occurs at large $\mu \gtrsim M_S$.

m_h^{alt} benchmark scenario:

$$A_t/M_S = 2.45,$$

$$M_2 = 2M_1 = 200 \text{ GeV},$$

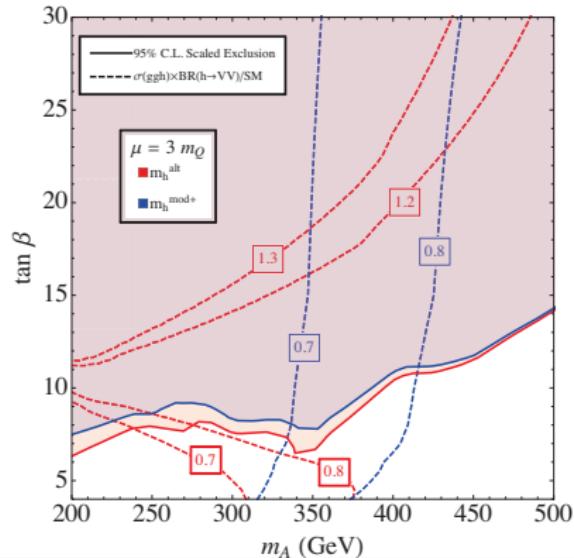
$$M_3 = 1.5 \text{ TeV},$$

$$m_{\tilde{\ell}} = m_{\tilde{q}} = M_S \geq 1 \text{ TeV},$$

$$A_\ell = A_q = A_t,$$

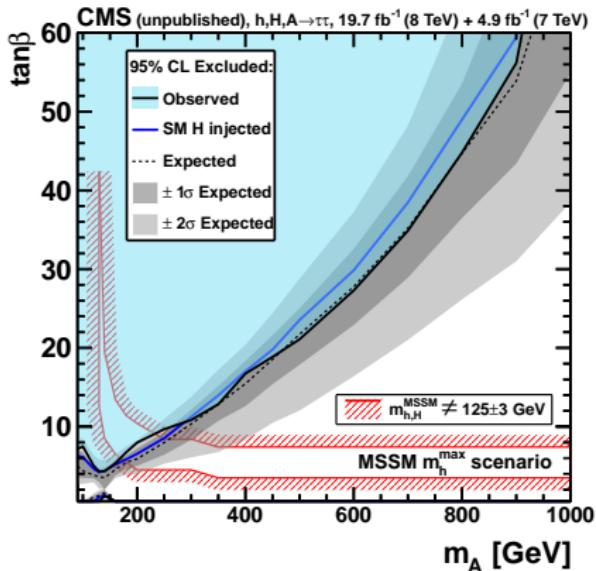
μ adjustable.

At low M_A and $\tan \beta$, tune $M_S \geq 1 \text{ TeV}$ to obtain acceptable Higgs mass, $m_h \geq 122 \text{ GeV}$.

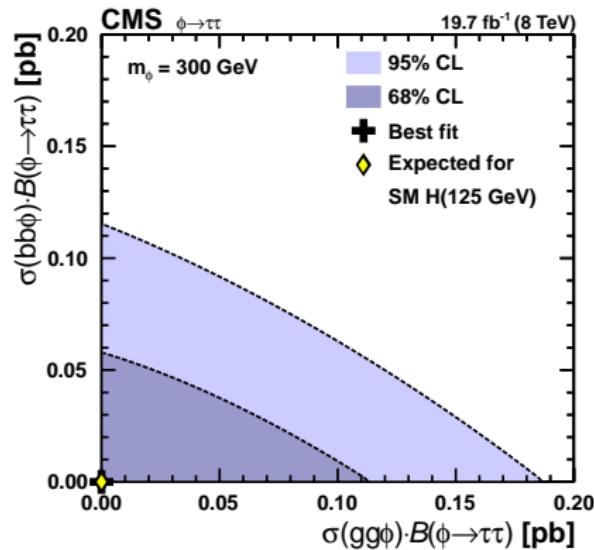


Implications of MSSM $h/H/A \rightarrow \tau^+\tau^-$ searches

- LHC searches for $gg, b\bar{b} \rightarrow h/H/A \rightarrow \tau^+\tau^-$ are very sensitive at large $\tan\beta$.
- Recent CMS results are given for the standard MSSM benchmark scenarios and a toy model with a single resonance. [CMS, 1408.3316]



MSSM benchmarks scenario



likelihood in $(m_\phi, \sigma_{gg\phi}, \sigma_{bb\phi})$

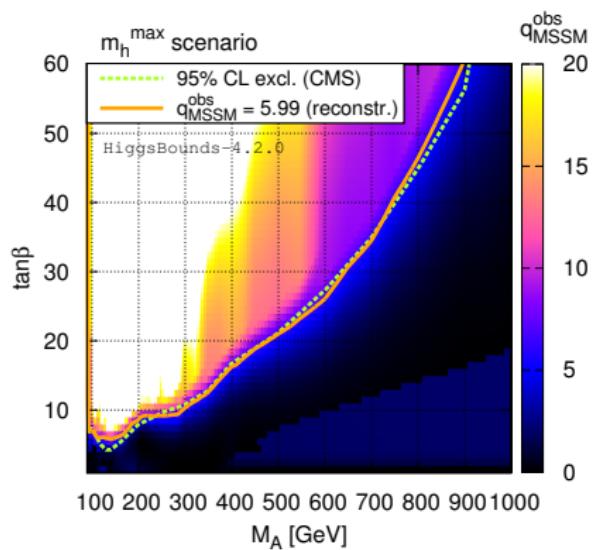
Reproduction of exclusion likelihood for arbitrary models

[P. Bechtle, S. Heinemeyer, O. Stål, TS, G. Weiglein, 1507.06706]

A full likelihood for the exclusion is very useful for global BSM fits.

Simple algorithm:

- ① Add signal rates of Higgs bosons with similar masses (difference $\leq 20\% \cdot m_i$),
- ② Obtain *expected* exclusion likelihood from the grid for each Higgs boson combination,
- ③ For Higgs combination with maximal expected q_{MSSM} , evaluate *observed* likelihood as final result.



validation with MSSM benchmarks

Available since December 2014 in public code **HiggsBounds-4.2.0**.
(<http://higgsbounds.hepforge.org>)

Global fit of the phenomenological MSSM

PRELIMINARY

Perform a random scan over 7 MSSM parameters (~ 10 million points):

$$M_A, \quad \tan \beta, \quad \mu > 0, \quad M_{\tilde{q}_3}, \quad M_{\tilde{\ell}}, \quad M_2, \quad A_t = A_b = A_\tau \quad (+ m_{top})$$

use [FeynHiggs-2.10.2](#) and [SuperIso-3.3](#) for MSSM predictions.

Construct global χ^2 from observables:

- Higgs mass and signal rates ([HiggsSignals-1.4.0](#))
- Low energy observables (LEO): $b \rightarrow s\gamma$, $B_s \rightarrow \mu\mu$, $B_u \rightarrow \tau\nu$, $(g-2)_\mu$, M_W
- exclusion likelihood from CMS $\phi \rightarrow \tau\tau$ search ([HiggsBounds-4.2.0](#))
- LEP Higgs exclusion likelihood, χ^2_{LEP} , if relevant. ([HiggsBounds-4.2.0](#))

Further constraints:

- 95% CL Higgs exclusion limits (*w/o MSSM $\phi \rightarrow \tau\tau$ limits*) ([HiggsBounds-4.2.0](#))
- Sparticle mass limits from LEP, (fixed $m_{\tilde{q}_{1,2}} = m_{\tilde{g}} = 1.5$ TeV to evade LHC limits)
- Require neutral lightest supersymmetric particle (LSP).

Best-fit points

	Higgs data			Higgs data + LEO		
	χ^2/ν	χ^2_ν	\mathcal{P}	χ^2/ν	χ^2_ν	\mathcal{P}
SM ($m_h = 125.1$ GeV)	77.4/89	0.87	0.80	92.7/94	0.99	0.52
MSSM light Higgs h	75.1/83	0.90	0.72	78.6/88	0.89	0.75
MSSM heavy Higgs H	76.5/83	0.92	0.68	81.5/88	0.93	0.67

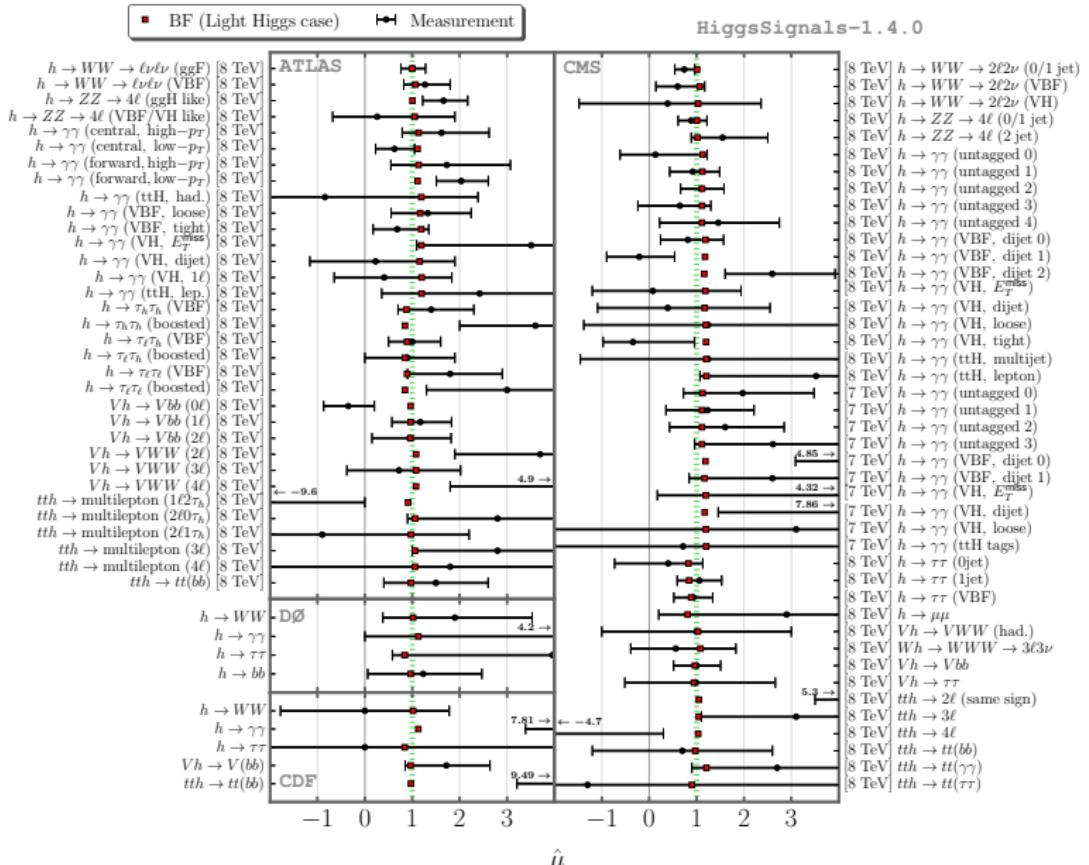
number degrees of freedom: $\nu = n_{\text{obs}} - n_{\text{param}}$

- SM and both MSSM cases provide similar fit to the Higgs data.
- Including LEOs, SM fit becomes worse, mainly due to $(g-2)_\mu$.

	M_A (GeV)	$\tan \beta$	μ (GeV)	A_0 (GeV)	$M_{\tilde{q}_3}$ (GeV)	$M_{\tilde{\ell}}$ (GeV)	M_2 (GeV)
MSSM h	902	35.8	1297	3555	1380	325	239
MSSM H	160	7.0	4802	-175	662	422	336

Light Higgs interpretation

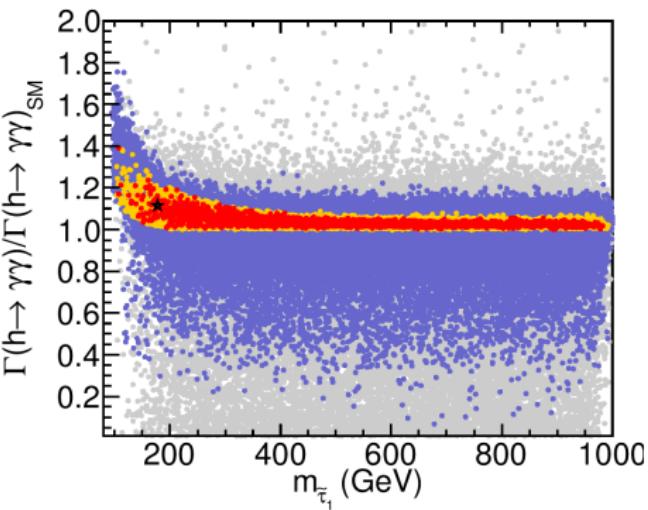
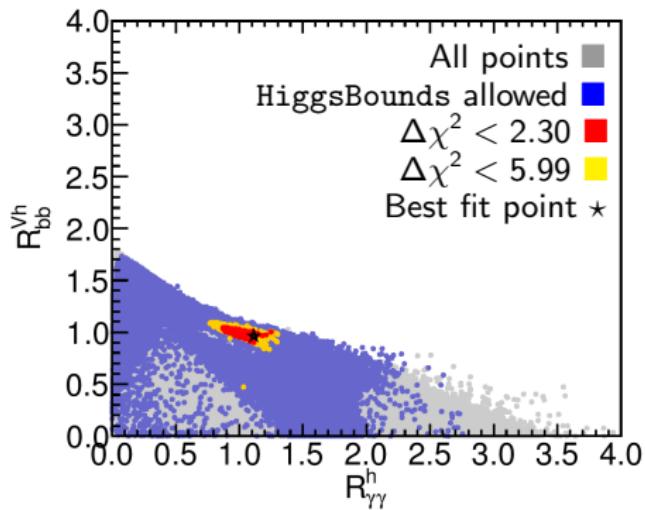
Best-Fit (*light Higgs case*) – Higgs signal rates



Higgs rates in the preferred regions

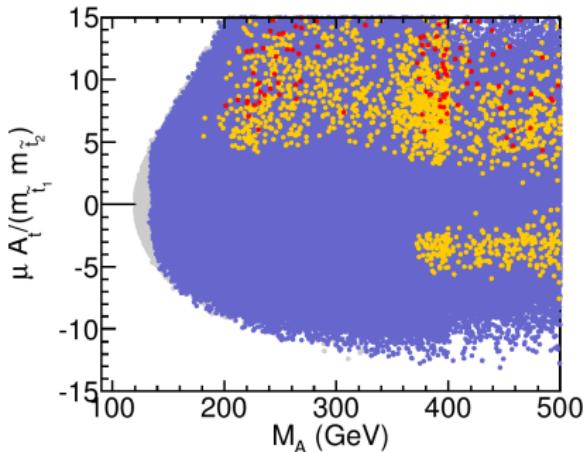
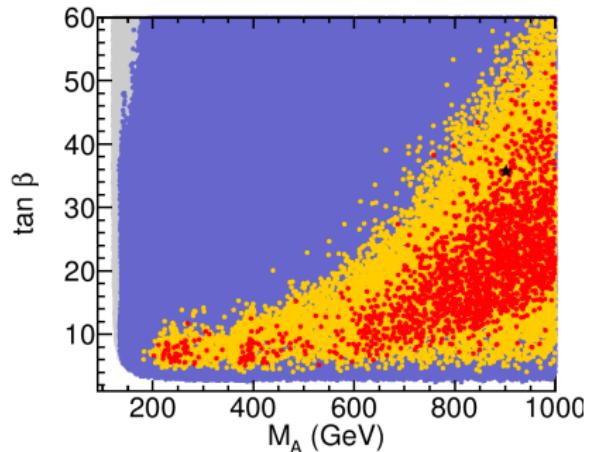
Preference for very SM Higgs-like signal rates: $R_{XX}^h \equiv \frac{\sum_i [\sigma_i^{\text{LHC8}} \times \text{BR}(h \rightarrow XX)]_{\text{MSSM}}}{\sum_i [\sigma_i^{\text{LHC8}} \times \text{BR}(h \rightarrow XX)]_{\text{SM}}}$

$$R_{VV}^h = 1.00^{+0.03}_{-0.12}, \quad R_{\gamma\gamma}^h = 1.12^{+0.10}_{-0.23}, \quad R_{bb}^{Vh} = 0.98^{+0.06}_{-0.04}, \quad R_{\tau\tau}^h = 0.83^{+0.23}_{-0.05}$$



- Light $\tilde{\tau}_1$ leads to small $H \rightarrow \gamma\gamma$ enhancement.
(also preferred by $(g - 2)_\mu$ due to assumed slepton mass universality)

Favored parameter regions



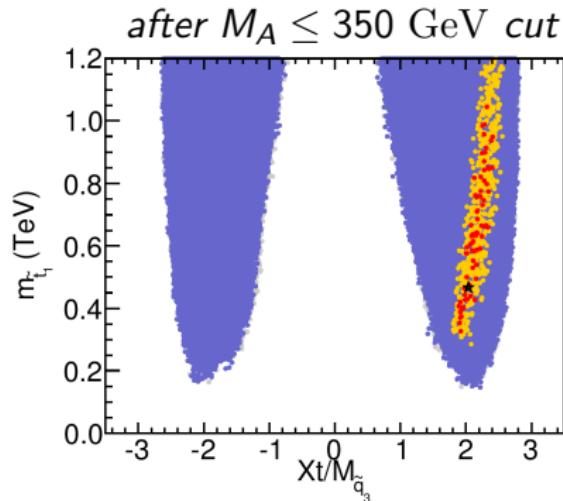
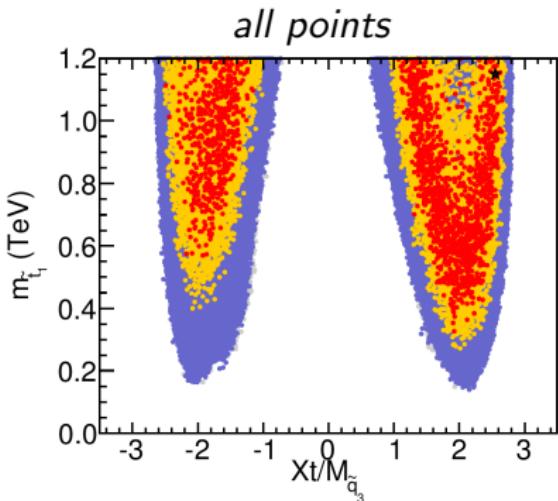
- Bulk of favored points have $M_A \gtrsim 350$ GeV \Rightarrow *decoupling limit*.
- points survive down to $M_A \gtrsim 200$ GeV \Rightarrow *alignment limit*.

Approximate 1-loop alignment condition:

$$\tan \beta \sim 1 / \frac{\mu A_t}{M_S^2} \left(\frac{A_t^2}{6M_S^2} - 1 \right)$$

- \Rightarrow Alignment occurs at small(ish) $\tan \beta$ values if $\mu A_t / M_S^2$ is large.
 \Rightarrow Positive A_t preferred (for $\mu > 0$) in alignment region.

Implications for the \tilde{t} sector

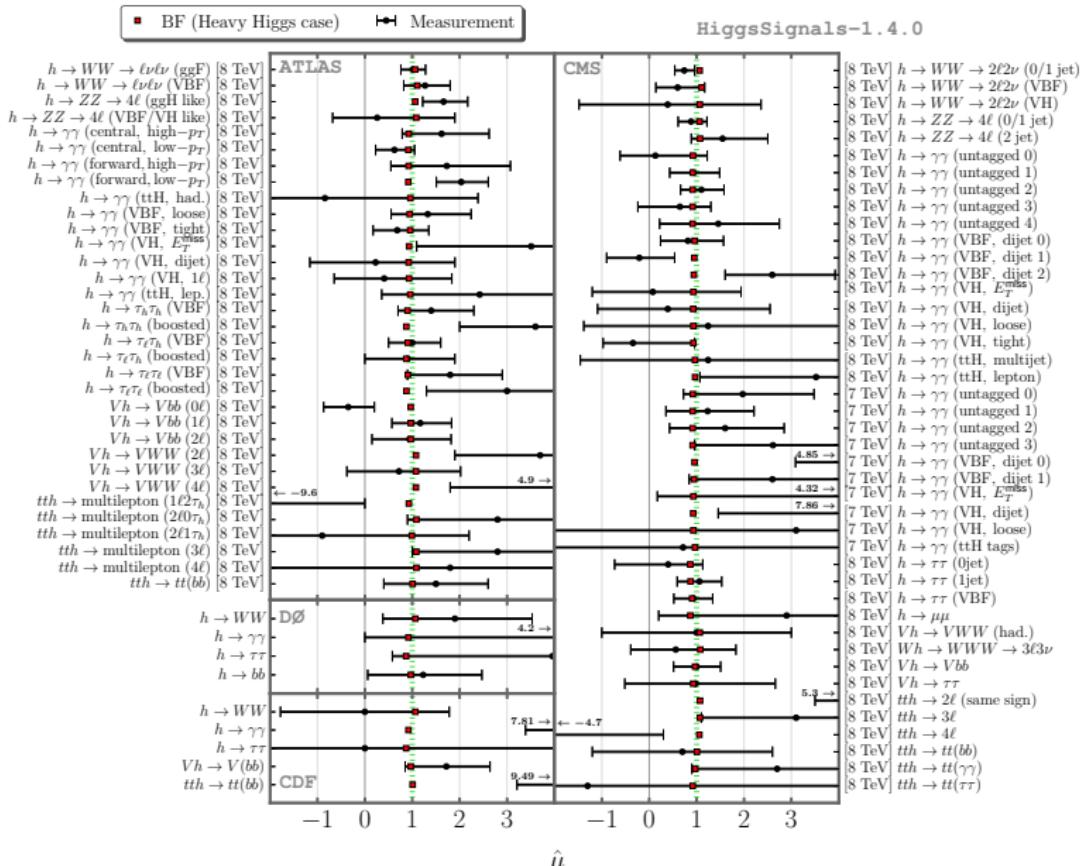


- Higgs mass ~ 125 GeV excludes zero stop mixing (unless $\tilde{t}_{1,2}$ very heavy)
- Light stops down to ~ 300 GeV possible.
- Alignment region prefers large positive X_t branch (for $\mu > 0$).

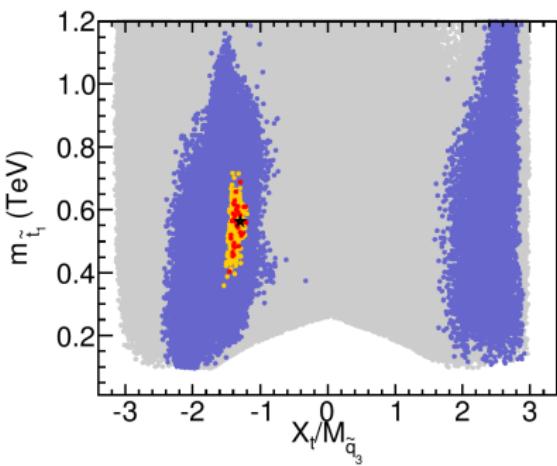
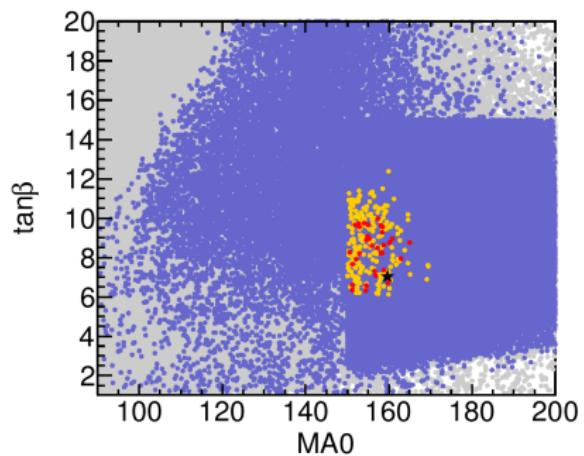
Note: Direct constraints from LHC stop searches not yet included!

Heavy Higgs interpretation

Best-Fit (heavy Higgs case) – Higgs signal rates

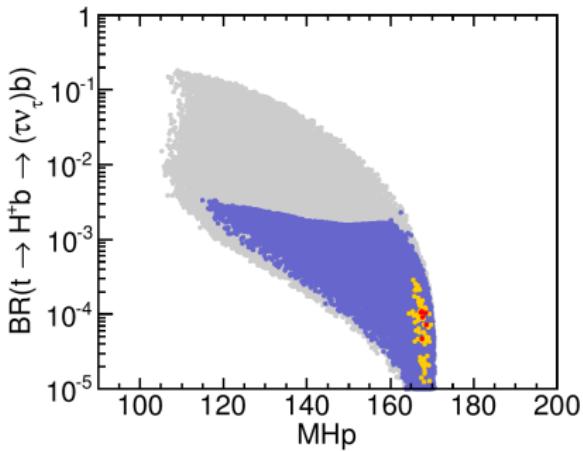
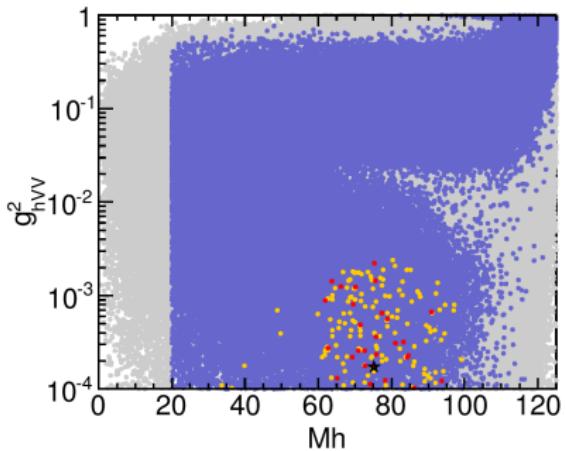


Favored parameter regions



- Allowed parameter region **very limited**: characterized by $M_A \sim (150 - 170)$ GeV and large $\mu \gtrsim 5M_S$.
- Light stop masses $m_{\tilde{t}_1} \sim (350 - 700)$ GeV preferred.

Where are the other Higgs states?



- Light Higgs h with mass $m_h \sim (60 - 100)$ GeV has extremely reduced coupling to vector bosons \Rightarrow beyond LEP reach!
- LHC searches for $gg \rightarrow h \rightarrow \gamma\gamma$ are also not (yet) sensitive.
- Charged Higgs H^\pm lies at kinematic threshold of $t \rightarrow H^\pm b$.
 $H^\pm \rightarrow \tau\nu_\tau$ decay rate suppressed by competing decay $H^\pm \rightarrow hW^\pm$.

Summary

We performed a **7-dimensional pMSSM fit** in light of the latest Higgs measurements and constraints, as well as low energy observables:

⇒ All three possible MSSM interpretations,

- (i) light Higgs in *decoupling limit*,
- (ii) light Higgs in *alignment limit*,
- (iii) *heavy Higgs* at 125 GeV,

provide a very good fit!

Alignment region and heavy Higgs interpretation only possible in very limited parameter space with large μ/M_S .

Open points for future work:

- Incorporation of constraints from **direct SUSY searches at the LHC**,
- Investigation of constraints from **vacuum stability**, especially in alignment limit and heavy Higgs case.

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Thank you for your attention!

Backup Slides

Scan ranges for the pMSSM-7 fit

Parameter	Minimum	Maximum
M_A [GeV]	90	1000
$\tan \beta$	1	60
μ [GeV]	200	4000
$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3}$ [GeV]	200	1500
$M_{\tilde{L}_i} = M_{\tilde{E}_i}$ [GeV]	200	1500
A_f	$-3M_{\tilde{Q}_3}$	$3M_{\tilde{Q}_3}$
M_2 [GeV]	200	500

$$M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}} = M_3 = 1.5 \text{ TeV}$$

Low energy observables in the pMSSM-7 fit

Observable	Experimental value	SM prediction
$\text{BR}(B \rightarrow X_s \gamma)$	$(3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$	$(3.08 \pm 0.22) \times 10^{-4}$
$\text{BR}(B_s \rightarrow \mu^+ \mu^-)$	$(2.9 \pm 0.7) \times 10^{-9}$	$(3.87 \pm 0.50) \times 10^{-9}$
$\text{BR}(B_u \rightarrow \tau \nu_\tau)$	$(1.14 \pm 0.22) \times 10^{-4}$	$(0.80 \pm 0.12) \times 10^{-4}$
δa_μ	$(30.2 \pm 9.0) \times 10^{-10}$	—
M_W	$(80.385 \pm 0.015) \text{ GeV}$	$(80.361 \pm 0.004) \text{ GeV}$

$(\Delta^{\text{MSSM}} \text{BR}(B \rightarrow X_s \gamma) = 0.65 \times 10^{-4}$, linearly comb. w/ add. MSSM unc. 0.15×10^{-4})

Best fit points:

	Light Higgs case			Heavy Higgs case		
LEO	O_i	χ_h^2	Pull	O_i	χ_h^2	Pull
$\text{BR}(B \rightarrow X_s \gamma) \times 10^4$	3.81	0.34	0.58	3.22	0.11	-0.33
$\text{BR}(B_s \rightarrow \mu^+ \mu^-) \times 10^9$	3.26	0.18	0.42	3.87	1.27	1.13
$\text{BR}(B_u \rightarrow \tau \nu_\tau) \times 10^5$	7.78	2.09	-1.45	7.84	2.03	-1.42
$\delta a_\mu \times 10^{10}$	29.5	0.01	-0.08	22.1	0.81	-0.90
$M_W \text{ [GeV]}$	80.381	0.02	-0.14	80.373	0.17	-0.42