STUFF about the Two Higgs Doublet Model

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Higgs

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Atlantis

The STUFF

(random selection of things Pedro's interested in)

- **Symmetries of the 2HDM: *what a waste*!**
- **One-loop vacuum structure of 2HDM.**
- **750 GeV anomaly and 2HDM: a tale of how a model *nearly* died.**
- **tth – how LHC is looking at it sideways.**
- **Run II amazing data: the importance of "h" precision studies.**

• **LHC discovered a new particle with mass ~125 GeV.**

• **Up to now, all is compatible with the Standard Model (SM) Higgs particle.**

BORING!

Two-Higgs Dublet model, 2HDM (Lee, 1973) : one of the easiest extensions of the SM, with a richer scalar sector. Can help explain the matter-antimatter asymmetry of the universe, provide dark matter candidates, …

G.C. Branco, P.M. Ferreira, L. Lavoura, M. Rebelo, M. Sher, J.P Silva, Physics Reports 716, 1 (2012)

The Two-Higgs Doublet potential

Most general SU(2) × U(1) scalar potential:

$$
\begin{aligned}
V &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{H.c.}] \\
&\quad + \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1) \\
&\quad \times (\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 \\
&\quad + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \text{H.c.}]
\end{aligned}
$$

m^2_{12}, λ_5, λ_6 and λ_7 **complex - seemingly 14 independent real parameters**

Most frequently studied model: softly broken theory with a Z_2 symmetry,

MODEL I: Only Φ_2 couples to fermions.

MODEL II: Φ_2 couples to up-quarks, Φ_1 to down quarks and leptons.

...

Symmetries of the potential of 2HDM

Higgs Family Symmetries:

Z_2: $\Phi_1 \rightarrow \Phi_1 \quad , \quad \Phi_2 \rightarrow -\Phi_2$

U(1): $\Phi_1 \rightarrow \Phi_1 \quad , \quad \Phi_2 \rightarrow e^{i\theta}\,\Phi_2 \qquad \theta \neq \{0\,,\,\pi\}$

U(2): $\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \rightarrow U \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \qquad \forall_{U \in U(2)}$

Generalized CP Transformations:

CP1: $\Phi_1 \rightarrow \Phi_1^* \quad , \quad \Phi_2 \rightarrow \Phi_2^*$

CP2: $\Phi_1 \rightarrow \Phi_2^* \quad , \quad \Phi_2 \rightarrow -\Phi_1^*$

CP3: $\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \rightarrow \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \Phi_1^* \\ \Phi_2^* \end{pmatrix} \qquad 0 < \theta < \pi/2$

Symmetries of the potential of 2HDM

symmetry	m_{11}^2	m_{22}^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	
Z_2			0					real	0	0	7
U(1)			0					0	0	0	6
U(2)		m_{11}^2	0		λ_1		$\lambda_1 - \lambda_3$	0	0	0	3
CP1			real					real	real	λ_6	10
CP2		m_{11}^2	0		λ_1			real	0	0	5
CP3		m_{11}^2	0		λ_1			$\lambda_1 - \lambda_3 - \lambda_4$ (real)	0	0	4

$$
\begin{aligned}
V = {} & m_{11}^2(\varphi_1^\dagger\varphi_1) + m_{11}^2(\varphi_2^\dagger\varphi_2) \\
& + \frac{1}{2}\lambda_1(\varphi_1^\dagger\varphi_1)^2 + \frac{1}{2}\lambda_1(\varphi_2^\dagger\varphi_2)^2 + \lambda_3(\varphi_1^\dagger\varphi_1)(\varphi_2^\dagger\varphi_2) \\
& + (\lambda_1 - \lambda_3)(\varphi_1^\dagger\varphi_2)(\varphi_2^\dagger\varphi_1)
\end{aligned}
$$

Symmetries of the LAGRANGIAN of 2HDM

symmetry	m_{11}^2	m_{22}^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	
Z_2			0					real	0	0	7
U(1)			0					0	0	0	6
U(2)		m_{11}^2	0		λ_1		$\lambda_1 - \lambda_3$	0	0	0	3
CP1			real					real	real	λ_6	10
CP2		m_{11}^2	0		λ_1			real	0	0	5
CP3		m_{11}^2	0		λ_1			$\lambda_1 - \lambda_3 - \lambda_4$ (real)	0	0	4

Three generations of massive fermions: CP1, Z_2, U(1) and CP3 (but bad CKM!)

Plus **absence of tree-level FCNC: Z_2, U(1)**

Remainder *USELESS*...? Not necessarily so...

One-loop contributions to inert minima in 2HDM

Z_2-symmetric model:

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + h.c.\right)$$
$$+\frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right]$$

Tree-level vacuum solutions:

INERT: $v_1^2 = -\dfrac{2\,m_{11}^2}{\lambda_1}$, provided $m_{11}^2 < 0$.

FERMIONS MASSIVE – SM-LIKE PHENOMENOLOGY

INERT-LIKE: $v_2^2 = -\dfrac{2\,m_{22}^2}{\lambda_2}$, provided $m_{22}^2 < 0$.

FERMIONS MASSLESS – UNPHYSICAL VACUUM

These minima can coexist in the potential, which raises a troubling possibility...

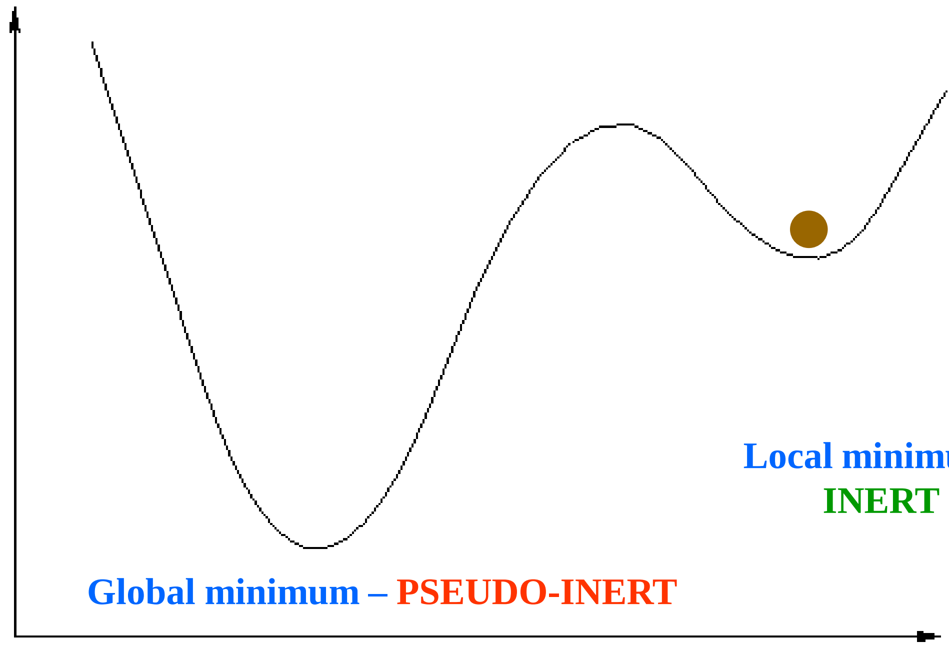
$v \neq 246\ GeV$

$m_W \neq 80\ GeV$

$m_t = 0!$

$m_e = 0!$

$\ldots$



$v = 246\ GeV$

$m_W = 80\ GeV$

$m_t = 173\ GeV$

$m_e = 0.511\ MeV$

$\ldots$

Tree-Level Conclusions:

Inert and inert-like minima can coexist in the potential if $m_{11}^2 < 0$ *and* $m_{22}^2 < 0$.

$$V_I - V_{IL} = \frac{1}{2}\left(\frac{m_{22}^4}{\lambda_2} - \frac{m_{11}^4}{\lambda_1}\right)$$

$$= \frac{1}{4}\left[\left(\frac{m_{H\pm}^2}{{v_2}^2}\right)_{IL} - \left(\frac{m_{H\pm}^2}{v_1^2}\right)_I\right] v_1^2\, {v_2}^2$$

Tree-level to one-loop...

$$V = V_0 + V_1 ,$$

$$V_1 = \frac{1}{64\pi^2} \sum_\alpha n_\alpha \, m_\alpha^4(\varphi_i) \left[\log\left(\frac{m_\alpha^2(\varphi_i)}{\mu^2} \right) - \frac{3}{2} \right]$$

$$\frac{\partial V}{\partial \varphi_i} = \frac{\partial V_0}{\partial \varphi_i} + \frac{1}{32\pi^2} \sum_\alpha n_\alpha m_\alpha^2 \frac{\partial m_\alpha^2}{\partial \varphi_i} \left[\log\left(\frac{m_\alpha^2}{\mu^2} \right) - 1 \right]$$

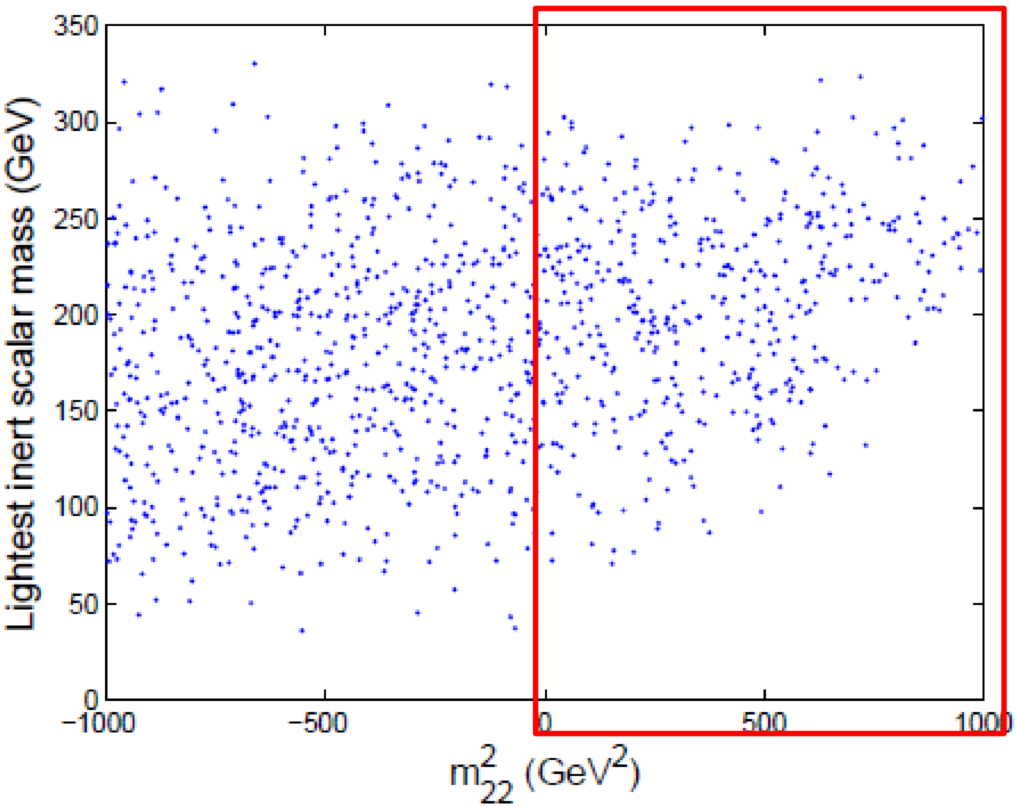
$$m_h^2 = m_{h0}^2 + \frac{1}{32\pi^2} m_{h1}^2 ,$$

$$\begin{aligned} m_{h1,s}^2 = {} & \lambda_1 A(m_{G_0}) + 2\lambda_1 A(m_{G_0^\pm}) + 3\lambda_1 A(m_{h_0}) + \lambda_{345} A(m_{H_0}) + \bar{\lambda}_{345} A(m_{A_0}) + 2\lambda_3 A(m_{H_0^\pm}) \\ & + \lambda_1^2 v_1^2 B(m_{G_0}, m_{G_0}, p^2) + 2\lambda_1^2 v_1^2 B(m_{G_0^\pm}, m_{G_0^\pm}, p^2) + 9\lambda_1^2 v_1^2 B(m_{h_0}, m_{h_0}, p^2) \\ & + \lambda_{345}^2 v_1^2 B(m_{H_0}, m_{H_0}, p^2) + \bar{\lambda}_{345}^2 v_1^2 B(m_{A_0}, m_{A_0}, p^2) + 2\lambda_3^2 v_1^2 B(m_{H_0^\pm}, m_{H_0^\pm}, p^2) \end{aligned}$$

Tree-level results:

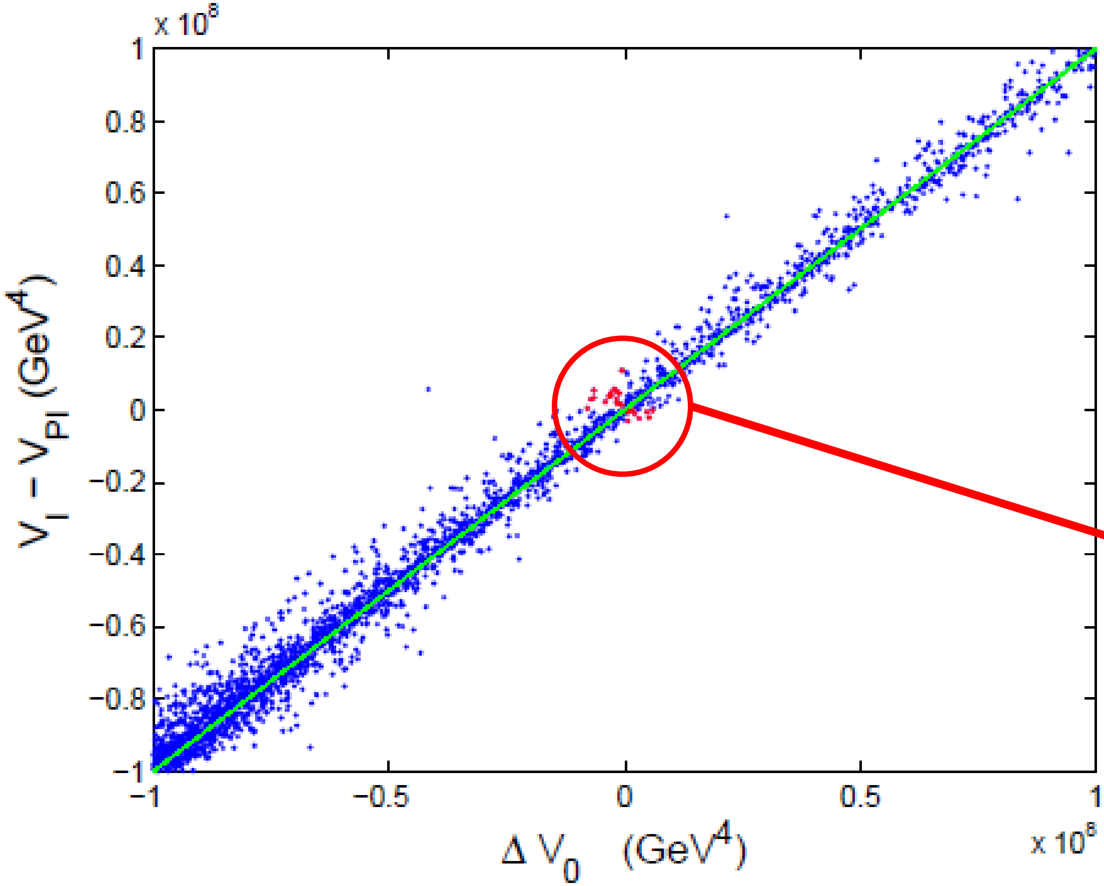
Inert and inert-like minima can coexist in the potential if $m_{11}^2 < 0$ *and* $m_{22}^2 < 0$.

One-loop results:



IMPOSSIBLE TO HAVE SIMULTANEOUS MINIMA IN THIS REGION AT TREE-LEVEL!

One-loop Potential values

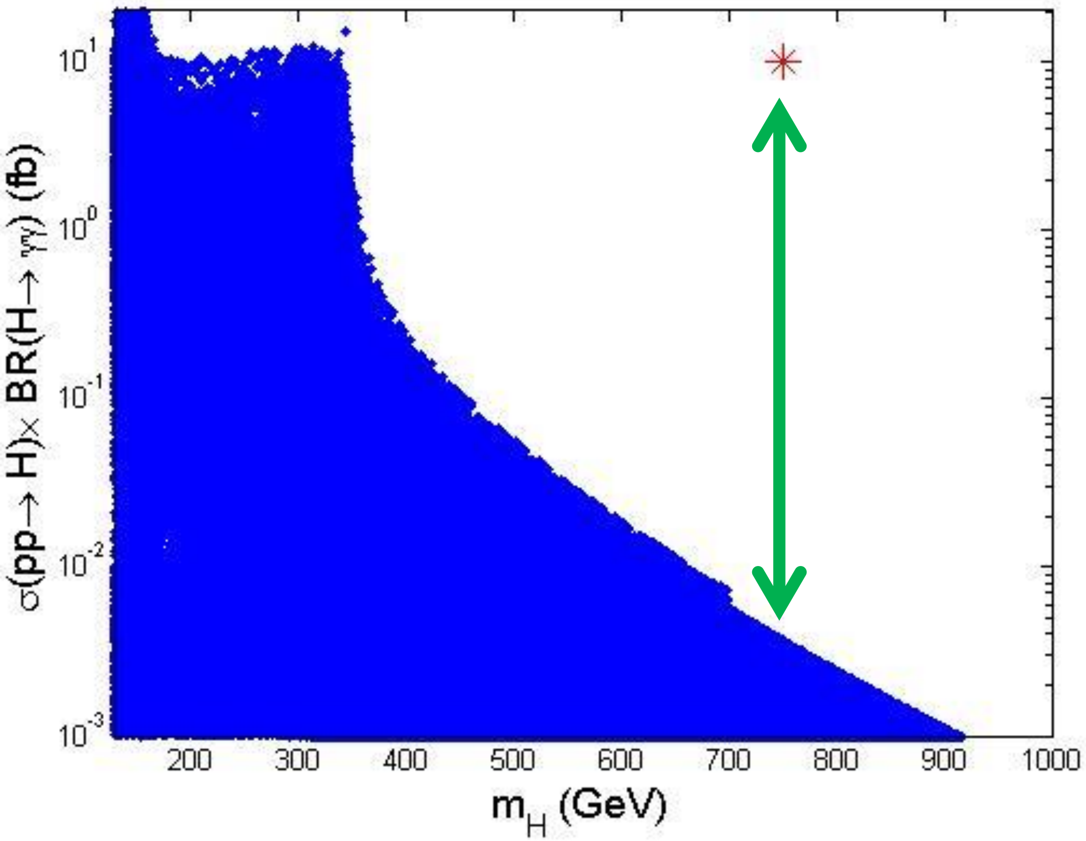


Inversion of minima

Tree-level Potential values

$$\Delta V_0 = \frac{1}{4}\left[\left(\frac{m_{H\pm}^2}{{v_2}^2}\right)_{IL} - \left(\frac{m_{H\pm}^2}{v_1^2}\right)_{I}\right] v_1^2\, {v_2}^2$$

The 750 GeV *WHATEVER...*

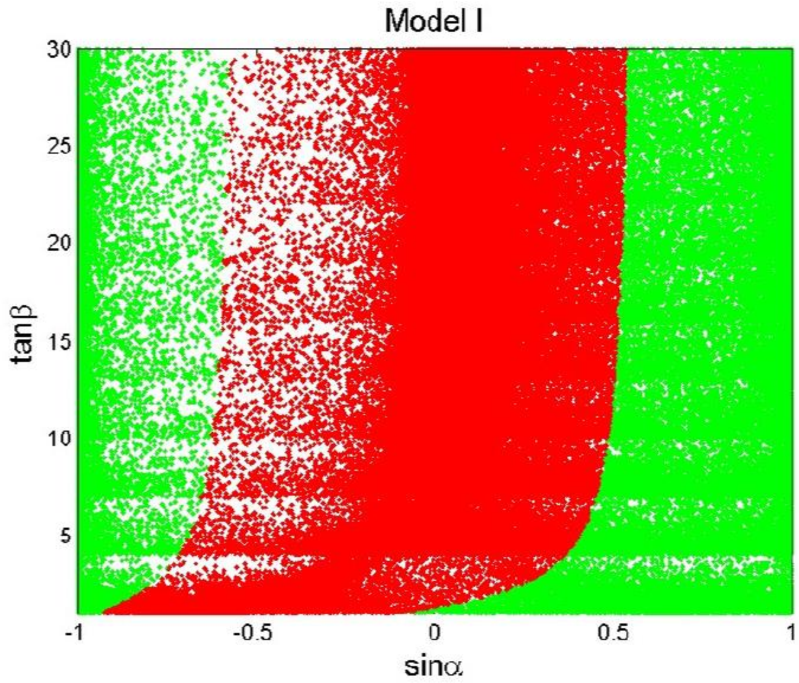


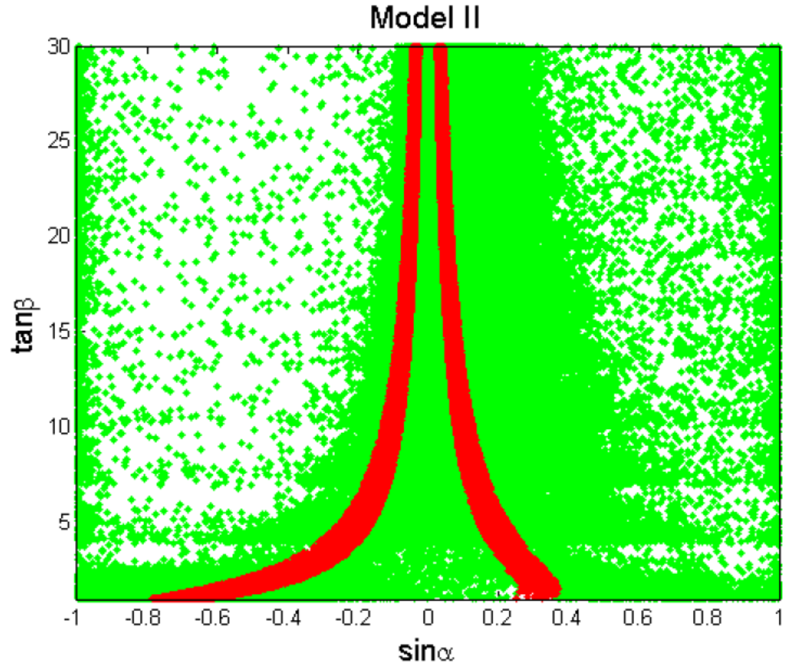
BLUE:
theoretically acceptable points +
B physics +
requiring that "h" is SM-like,

$$0.7 \leq \frac{\sigma(pp \to H) BR(H \to ZZ)}{\sigma^{SM}(pp \to H) BR^{SM}(H \to ZZ)} \leq 1.3$$

The tth *we-learned-our-lessons-from-the-750-GeV-fiasco-and-we're-not-actually-taking-it-seriously-honest-guv* anomaly

Run-I parameter space restrictions





Model I

$$k_t = \frac{\cos\alpha}{\sin\beta} > 0$$

$$k_b = \frac{\cos\alpha}{\sin\beta} > 0$$

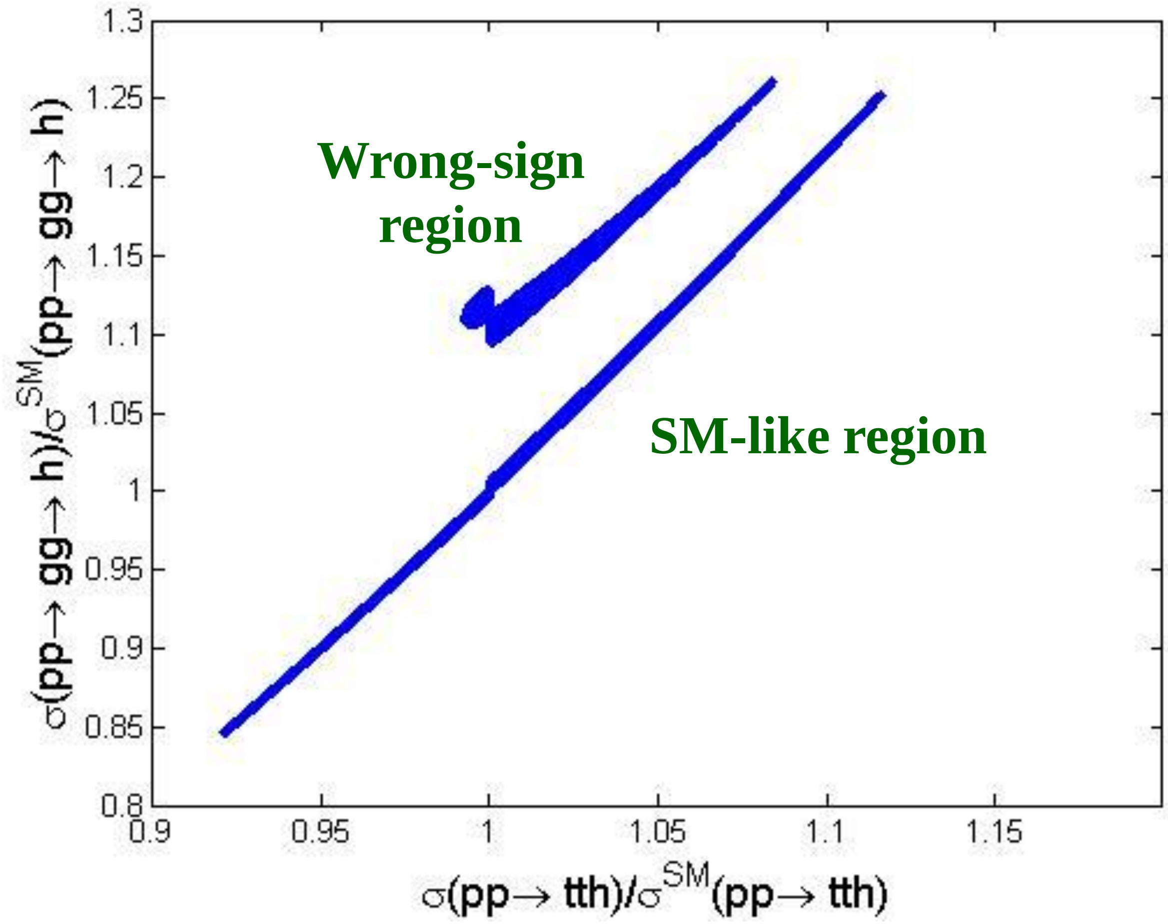
Model II

$$k_t = \frac{\cos\alpha}{\sin\beta} > 0$$

$$k_b = \frac{\sin\alpha}{\cos\beta} > 0 \text{ or } < 0$$

Wrong-Sign Limit

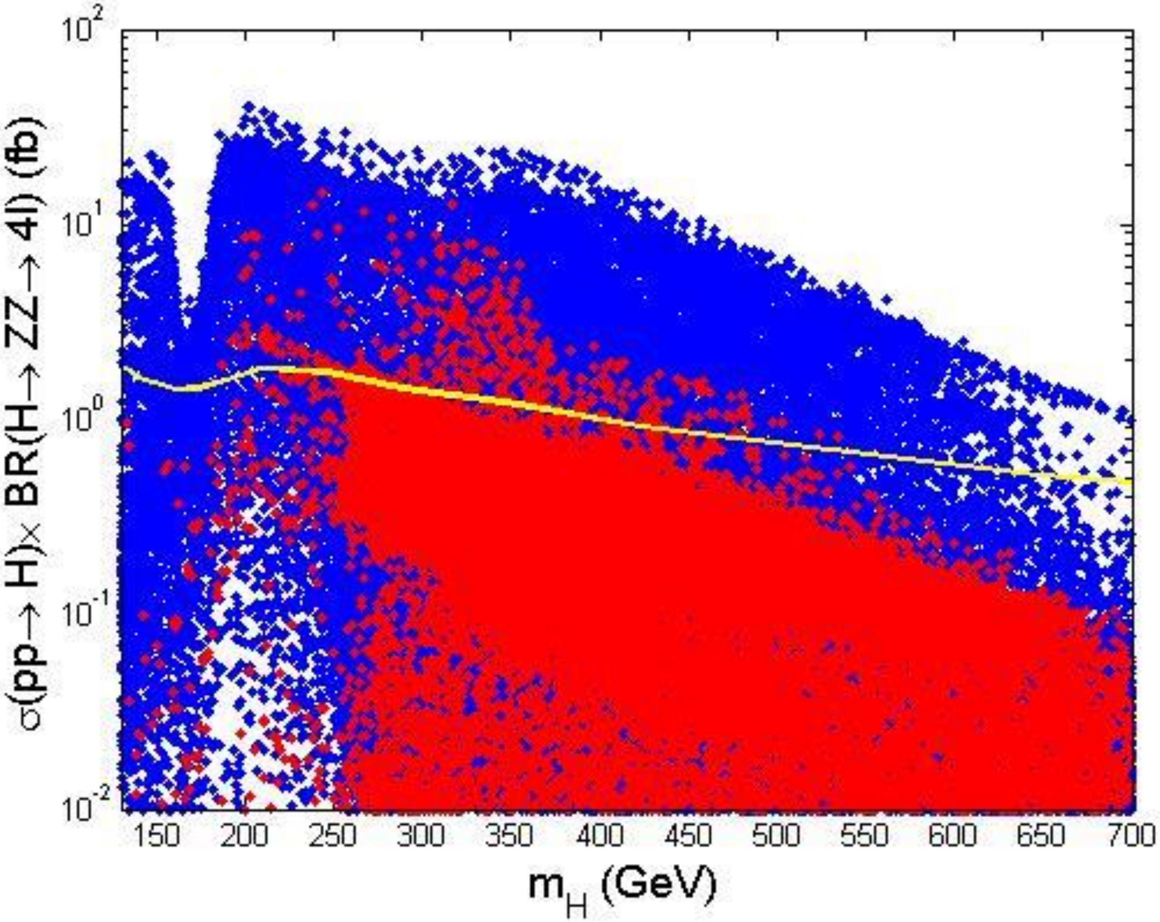
σ_{tth} *versus* σ_{ggh} in model II



LHC – YOU HAVE THE WRONG RESULT!

The Importance of Being ~~Earnest~~ h

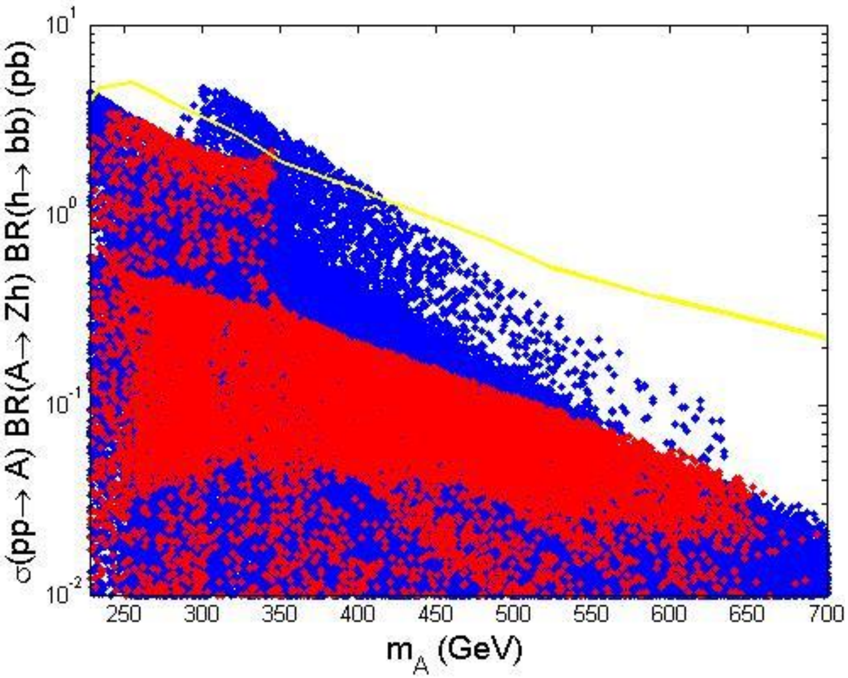
Run II has limits on high mass resonances in the 4 lepton channel...



(yellow line upper bound on non-observation from CMS PAS HIG-16-033)

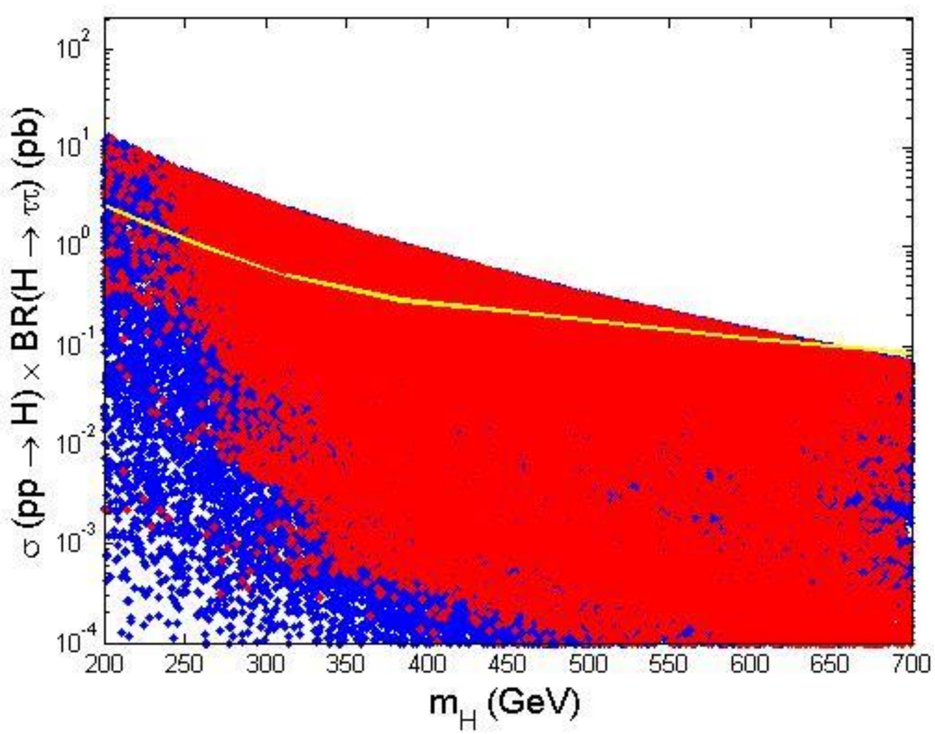
(red points are what remains after demanding "h" rates are within 30% of SM values)

(ATLAS limit)



Demanding "h" behaviour being SM-like complies with latest high-mass exclusions...

(ATLAS limit)



... Though not for *ALL* observables

NOT AWESOME CONCLUSIONS

• STILL NO EXTRA SCALARS!

SO-SO CONCLUSIONS

• 750 GeV a bust... But we learned quite a lot from it.

AWESOME CONCLUSIONS

• Run II already providing amazing data.

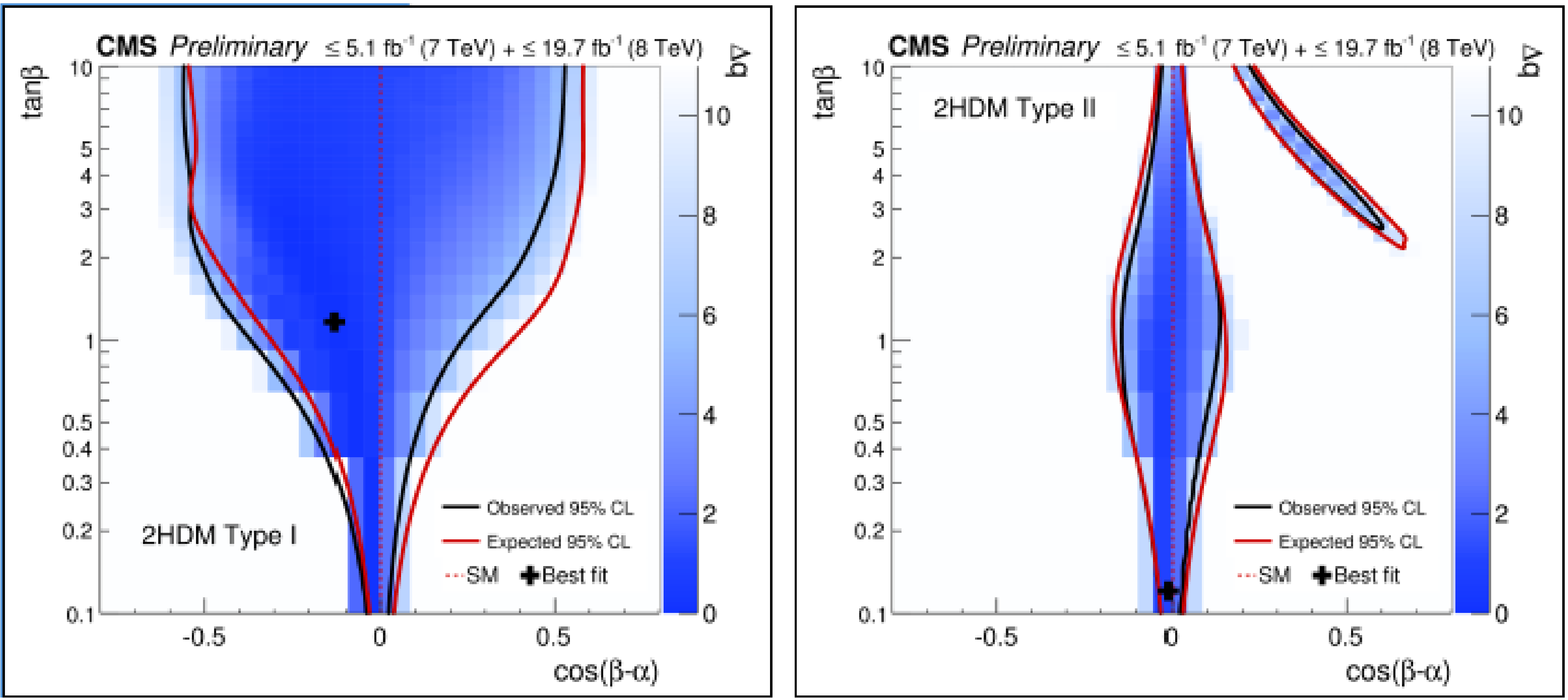
• Already excluding significant regions of 2HDM parameter space.

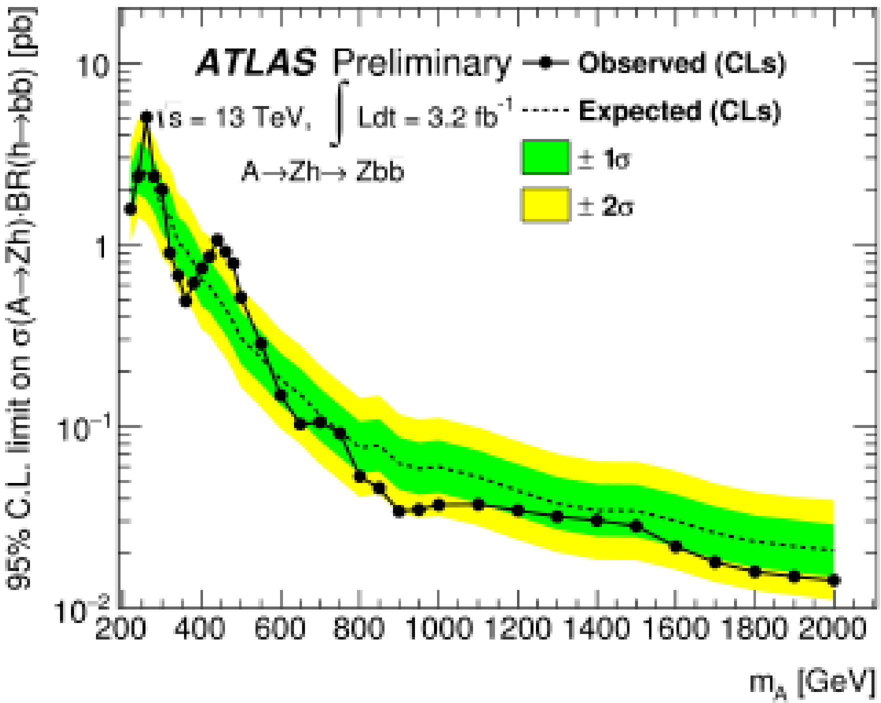
NOT-SO-AWESOME CONCLUSIONS

- **All of this is tree-level. Possibility of RG-improving? Need to use 1-Loop effective potential?**

- **No cosmological considerations undertaken – that calculation is arguable...**

- **Discriminant exists for more complicated versions of the model (no Z_2 symmetry) but it can no longer be cast in a nice analytical expression.**


CMS Preliminary ≤ 5.1 fb⁻¹ (7 TeV) + ≤ 19.7 fb⁻¹ (8 TeV)
tanβ
Δν
2HDM Type I
Observed 95% CL
Expected 95% CL
SM
Best fit
cos(β-α)
CMS Preliminary ≤ 5.1 fb⁻¹ (7 TeV) + ≤ 19.7 fb⁻¹ (8 TeV)
tanβ
Δν
2HDM Type II
Observed 95% CL
Expected 95% CL
SM
Best fit
cos(β-α)



ATLAS Preliminary
√s = 13 TeV, ∫ Ldt = 3.2 fb⁻¹
A→Zh→ Zbb
Observed (CLs)
Expected (CLs)
± 1σ
± 2σ
95% C.L. limit on σ(A→Zh)·BR(h→bb) [pb]
m_A [GeV]
10
1
10⁻¹
10⁻²
200 400 600 800 1000 1200 1400 1600 1800 2000