# 2HDM Pseudoscalar + DM Benchmarks

(Intended Summary of DM WG
2HDM Discussions over last ~2 Weeks)

Jose Miguel No
King's College London

LHC DM WG MEETING 20/06/17

# 2HDM + P(seudoscalar)

1404.3716, 1509.01110, 1611.04593, 1701.07427

## Parameter Executive Summary

$$V_{\rm 2HDM} = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \mu^2 \left[H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$

$$V_{\rm P} = \frac{1}{2} m_P^2 P^2 + \kappa\,(i\,P\,H_1^\dagger H_2 + \text{h.c.}) + \lambda_{P1} P^2 |H_1|^2 + \lambda_{P2} P^2 |H_2|^2$$

- 12 Parameters + $m_\chi$ + $y_\chi$
- 2 fixed by EWSB + 1 "fixed" by Higgs properties + 1 "fixed" by EWPO

### "Free" Parameters

| | | | |
|---|---|---|---|
| $m_a$ | $\sin\theta$ | enter | $m_\chi$ |
| $m_A$ | $\tan\beta$ | $g_{aAh}$, $g_{Haa}$ | $y_\chi$ |
| $m_H$ | $\lambda_3$, $\lambda_{P1}$, $\lambda_{P2}$ | $g_{haa}$ | |

Do not affect Kinematics

# 2HDM + P(seudoscalar)

## (Further) "Relevant" Constraints

- Boundedness from Below of Scalar Potential

  (+ Absolute Stability of EW Vacuum)

- Unitarity of 2 → 2 scattering processes

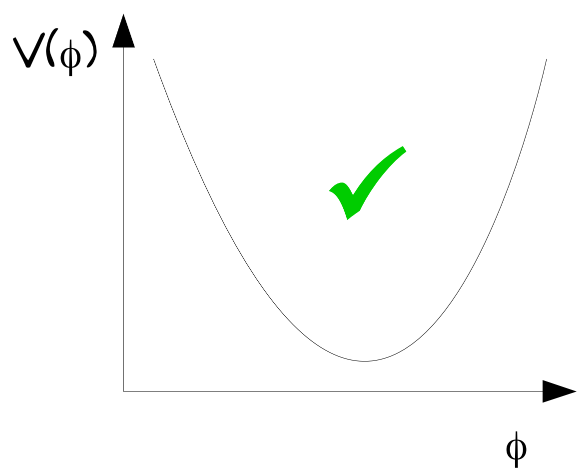
I will discuss these in detail

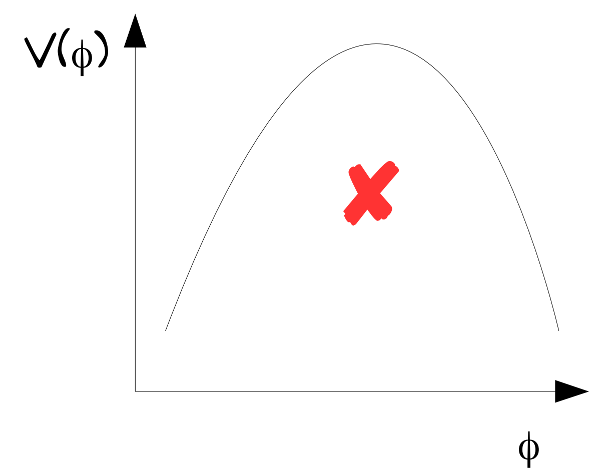
- Flavour (e.g. $\bar{B} \to X_s \gamma$ , $B_s \to \mu^+ \mu^-$)

...

# Boundedness from Below (BFB)

If ~~BFB~~ in V(ϕ), field(s) run away to ∓∞   (with V → -∞)




$$\begin{aligned} V_{\rm 2HDM} &= \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \mu^2 \left[ H_1^\dagger H_2 + {\rm h.c.} \right] \\ &+ \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 \\ &+ \lambda_4 \left| H_1^\dagger H_2 \right|^2 + \frac{\lambda_5}{2} \left[ \left( H_1^\dagger H_2 \right)^2 + {\rm h.c.} \right] \end{aligned}$$

$$\begin{aligned} V_{\rm P} &= \frac{1}{2} m_P^2 P^2 + \kappa \left( i\, P\, H_1^\dagger H_2 + {\rm h.c.} \right) \\ &+ \lambda_{P1}\, P^2 \, |H_1|^2 + \lambda_{P2}\, P^2\, |H_2|^2 + \lambda\, P^4 \end{aligned}$$

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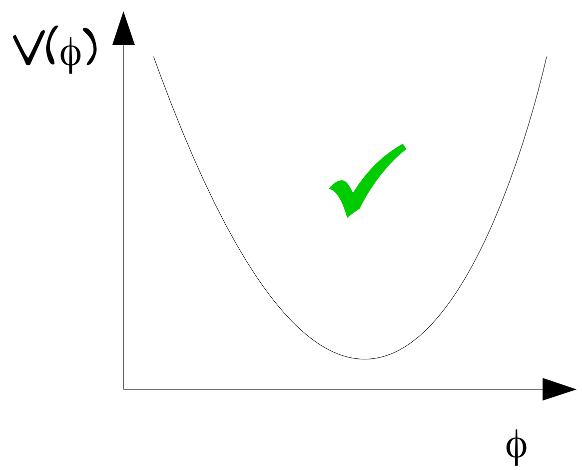


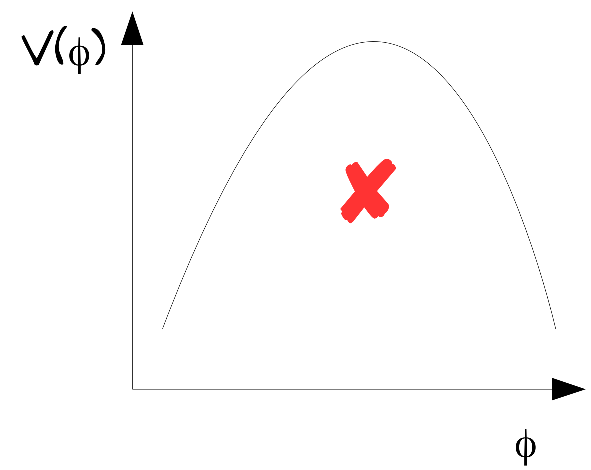


$$
\begin{aligned}
V_{\rm 2HDM} &= \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \mu^2 \left[ H_1^\dagger H_2 + {\rm h.c.} \right] \\
&+ \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 \\
&+ \lambda_4 \left| H_1^\dagger H_2 \right|^2 + \frac{\lambda_5}{2} \left[ \left( H_1^\dagger H_2 \right)^2 + {\rm h.c.} \right]
\end{aligned}
$$

$$
\begin{aligned}
V_{\rm P} &= \frac{1}{2} m_P^2 P^2 + \kappa \left( i\, P\, H_1^\dagger H_2 + {\rm h.c.} \right) \\
&+ \lambda_{P1} P^2 |H_1|^2 + \lambda_{P2} P^2 |H_2|^2 + \lambda P^4
\end{aligned}
$$

Here I will not discuss these

## How to Check?

Look at V(ϕ) at large field values ϕ ≫ v

hep-ph/0207010

**BFB:** $\lambda_1 > 0\,, \quad \lambda_2 > 0\,, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2}\,, \quad \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}$

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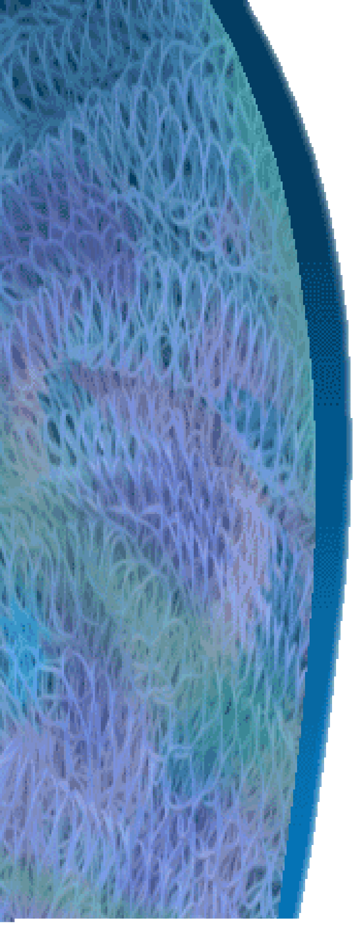
$m_{H^\pm} = m_H$

$$\frac{m_h^2}{v^2}(1 - t_\beta^{-2}) + \lambda_3\, t_\beta^{-2} > 0$$

$$\frac{m_h^2}{v^2}(1 - t_\beta^{2}) + \lambda_3\, t_\beta^{2} > 0$$

$\Rightarrow \lambda_3 \geq \frac{m_h^2}{v^2}$

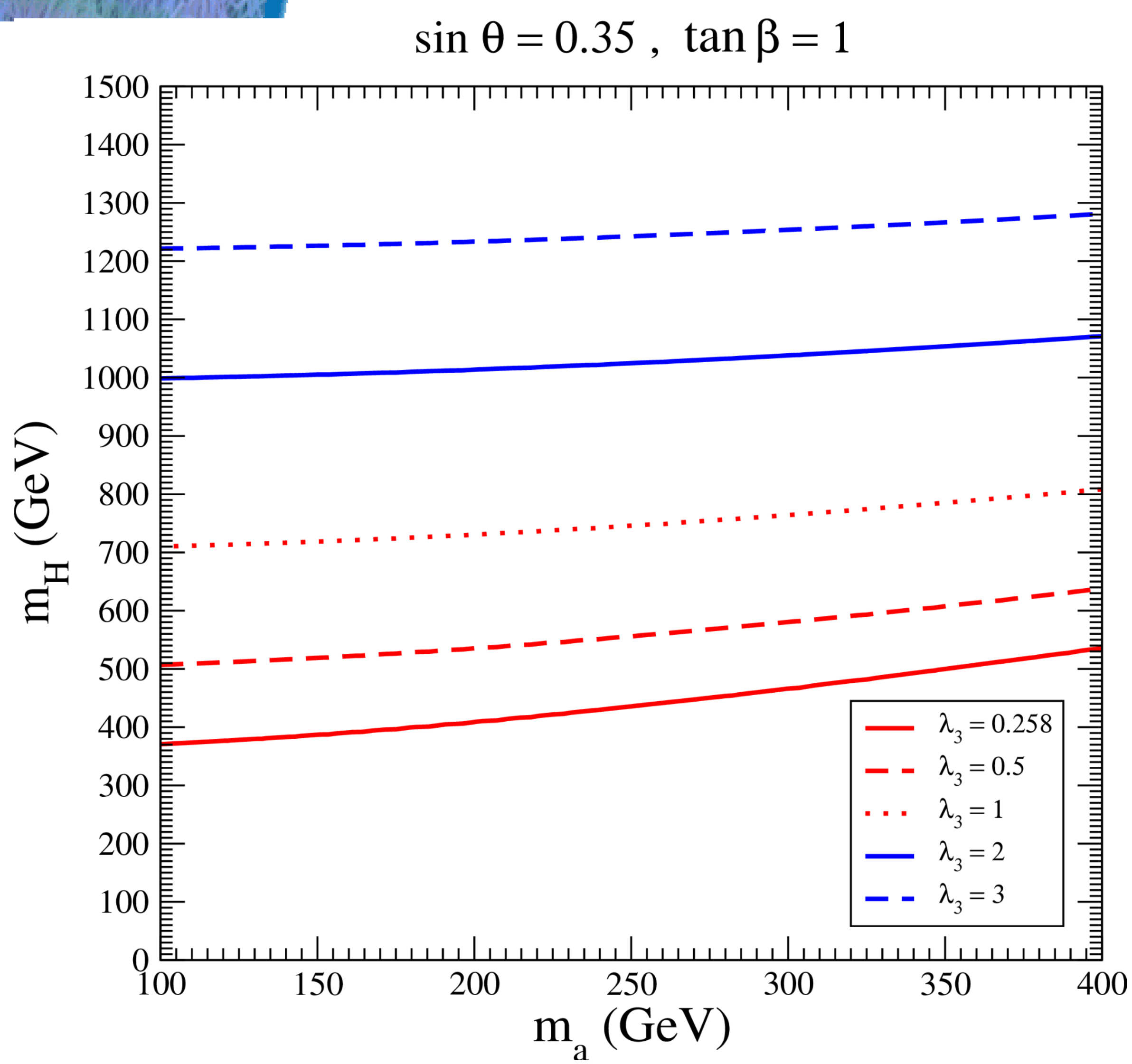


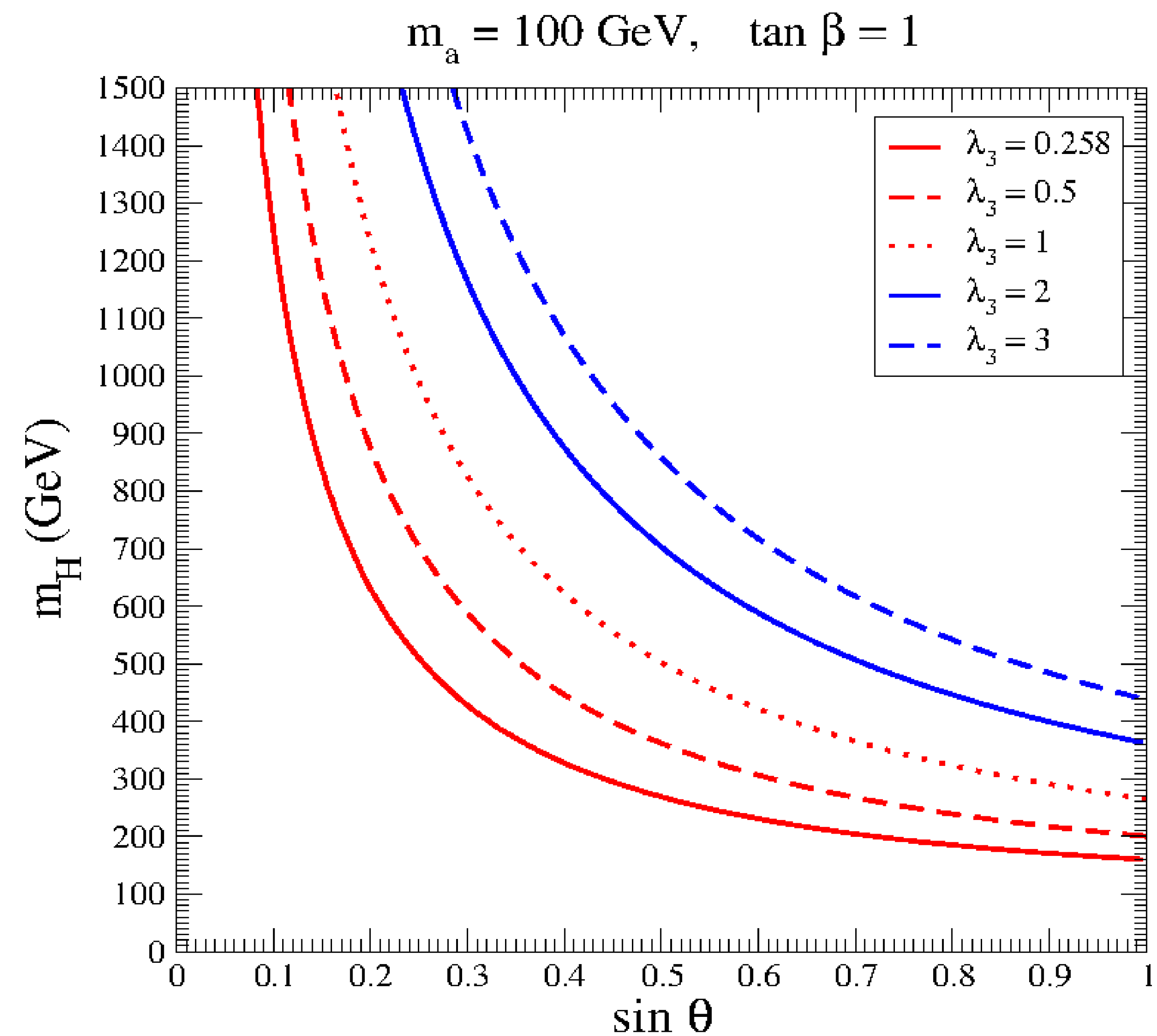
# Boundedness from Below (BFB)

**BFB:** $\lambda_1 > 0\,, \quad \lambda_2 > 0\,, \quad \lambda_3 > -\sqrt{\lambda_1\lambda_2}\,, \quad \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}$

$m_{H^\pm} = m_H$ $\qquad \lambda_3 \geq \frac{m_h^2}{v^2} = 0.258$

$m_A = m_H$ $\qquad$ (Better for $m_A > m_H$, worse for $m_A < m_H$)



# Boundedness from Below (BFB)

$m_{H^\pm} = m_H$ $m_A = m_H$ $\lambda_3 \geq 1 \quad (\text{e.g. } \lambda_3 \in [1,3])$

Increasing $\lambda_3$ may decrease $g_{aAh}$ (weakens mono-Higgs sensitivity)

$$g_{aAh} = \frac{c_\theta\, s_\theta}{m_H\, v}\left[m_h^2 + m_H^2 - m_a^2 - 2(\lambda_3 - \lambda_{P1} c_\beta^2 - \lambda_{P2} s_\beta^2) v^2\right]$$

Solution *(Martin Bauer & Oleg Brandt discussion)*: $\lambda_3 = \lambda_{P1} = \lambda_{P2}$

Impact on $g_{haa}$ (very minor effect on h → inv, given $m_a$ scan)

Choice of $\lambda_3$ impacts $g_{Haa}$ (effect on mono-Z)

$$g_{Haa} = \frac{1}{m_H\, v}\left[2\, t_{2\beta}^{-1}\, s_\theta^2\, (m_h^2 - \lambda_3 v^2) + s_{2\beta}\, c_\theta^2 v^2 (\lambda_{P1} - \lambda_{P2})\right]$$

- Absolute Stability of EW Vacuum (MS) 1303.5098

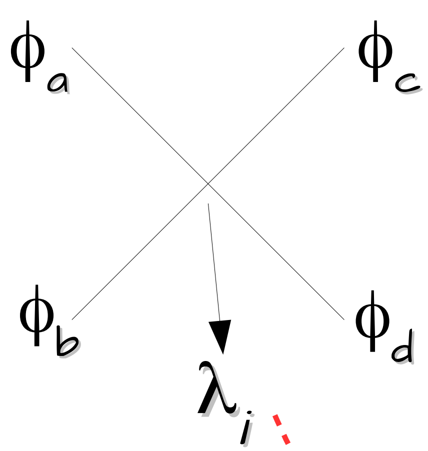
Even if BFB, EW vacuum may not be absolute minimum

For alignment/decoupling limit, MS requires $2m_{H^\pm}^2 - m_H^2 + m_h^2 > \lambda_3 v^2$

(for $m_{H+} = m_H$ & $\lambda_3 = 3$, $m_H > 400$ GeV OK)

- Unitarity hep-ph/0508020

2 → 2 Scatterings




Need to respect S-Matrix unitarity

Upper bound on 2HDM quartics → Upper bound on Mass Splittings

Generically less constraining than BFB

# Summary & Remarks

*"Implications from all indirect constraints - be it flavour, electroweak precision constraints or stability requirements - should be treated as preferred parameter space in a simplified model framework. It would contradict the idea of simplified models if these constraints were taken at face value."*

Well - justified to relax an indirect constraint if impact of the analysis (e.g. modified kinematics) and/or new phenomenology arises.

Initial (set of) 2HDM+P benchmarks

$$m_{H^\pm} = m_A = m_H \quad , \quad \lambda_3 = \lambda_{P1} = \lambda_{P2} \in [1, 3]$$ ?

Scalar widths beyond 30% only if ~~BFB~~

Maximum value of $m_H$ in scan ? Minimum value of $m_a$ ?

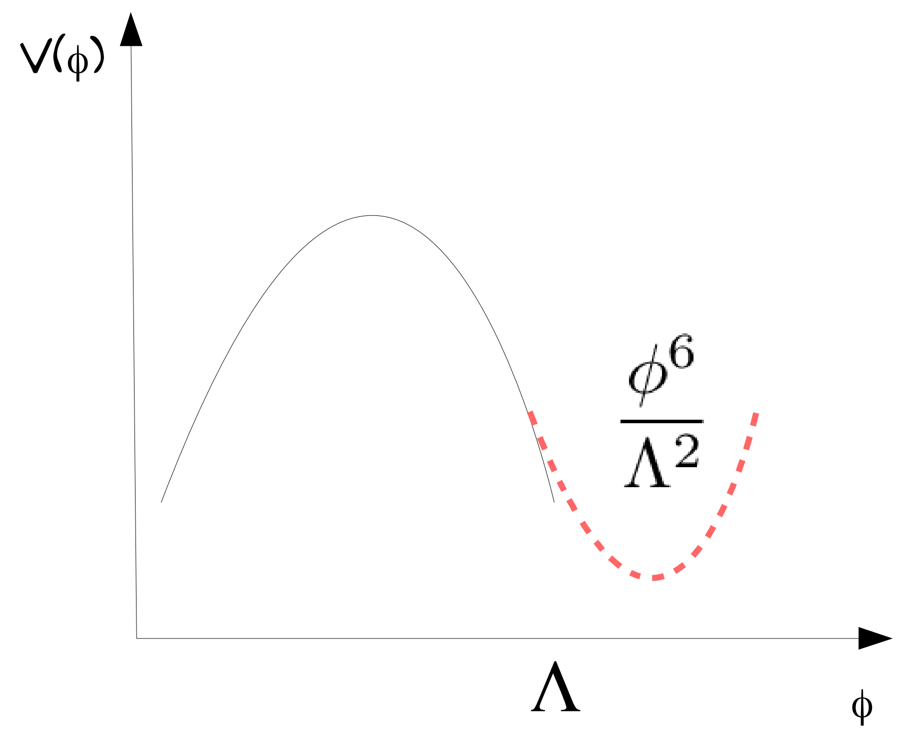
For later (to study in the meantime):

→ Impact of mass splittings among heavy states

→ Away from alignment/decoupling limit

# A (tiny) bit more on BFB...

Possible for BFB conditions to be sensitive to UV physics




This UV sensitivity of BFB generically leads to meta-stable EW vacuum