How can an extended scalar sector improve your life?

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KIT particle physics colloquium

21 July 2022

This study is funded through national funds by FCT - Fundação para a Ciência e a Tecnologia, I.P., in the frame of the projects UIDB/00618/2020, CERN/FIS-PAR/0014/2019 and PTDC/FIS-PAR/31000/2017

Outline

- The Higgs potential and its many scalar extensions - new particles and new couplings (including dark matter)
- CP violation
- Vacuum structure

The Higgs potential
and its many scalar extensions

Extensions of the SM - why are we happy?

- It provides Dark Matter candidates compatible with all available experimental constraints.
- It provides new sources of CP-violation.
- It improves the stability of the SM.
- It provides a means of having a strong first order phase transition.
- It provides a 125 GeV scalar in agreement with all data.
- You get a bunch of extra scalars, keeping the experimentalist busy and happy.

The 2-Higgs doublet model (general)

Potentials are usually used in minimal versions using ad-hoc symmetries. We just want them to suit our goals. The most general 2HDM is

$$V_{2HDM} = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.)$$
$$\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$\left\{ \frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right](\Phi_1^\dagger\Phi_2) + h.c. \right\}$$

With the fields defined as (VEVs may be complex)

$v_2 = 0$, dark matter, IDM

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$$

Allows for a decoupling limit

The Z_2 symmetric version is

Complex - CP-violation

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

The 2-Higgs doublet model (IDM)

So to get dark matter we just need to set to zero the VEV of one of the doublets

$m_{12}^2 = 0$, minimum condition

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

With

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG_0) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H_0 + iA_0) \end{pmatrix}$$

CP violation not possible. To have CP-violation and dark matter one needs to further extend the model. Add a singlet.

$$\Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H_0 + iA_0) \end{pmatrix}$$

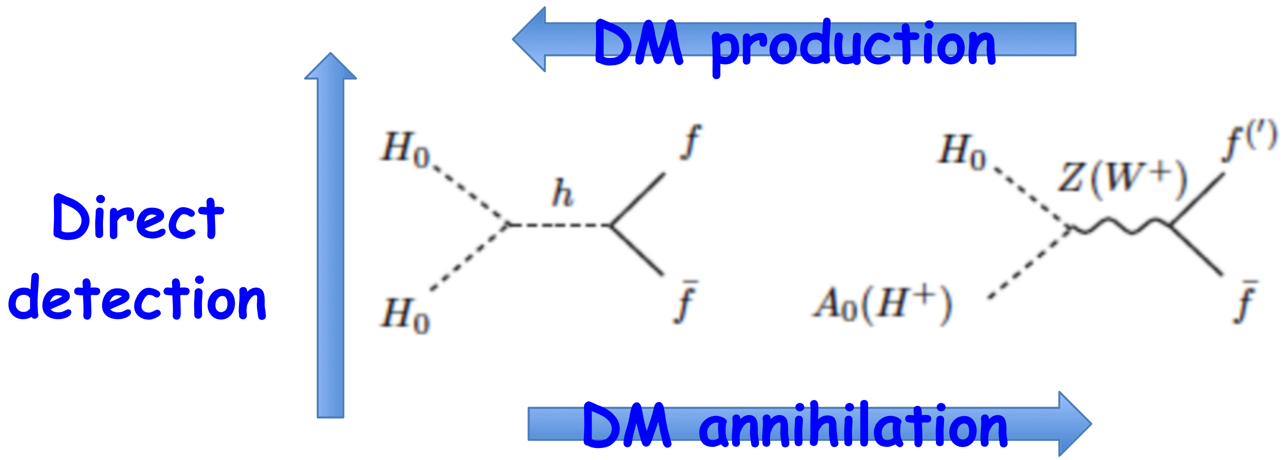
Inert doublet

Inert scalars

There is an exact discrete symmetry that forces the second doublet to have only stable particles.

$$\Phi_2 \to -\Phi_2$$

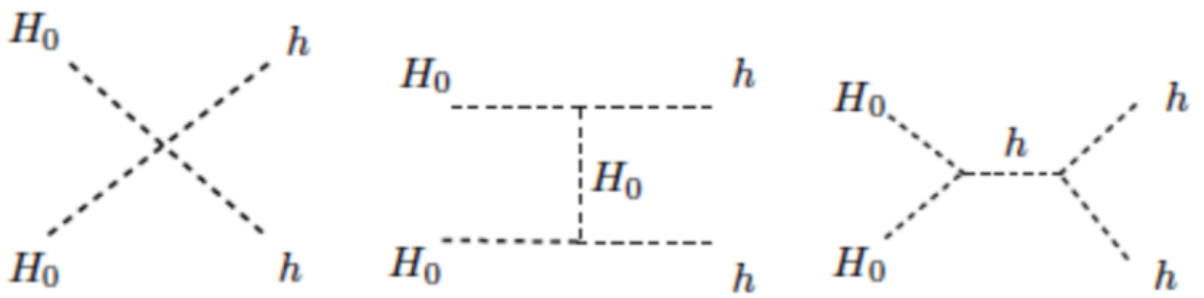
Dark Matter (IDM)



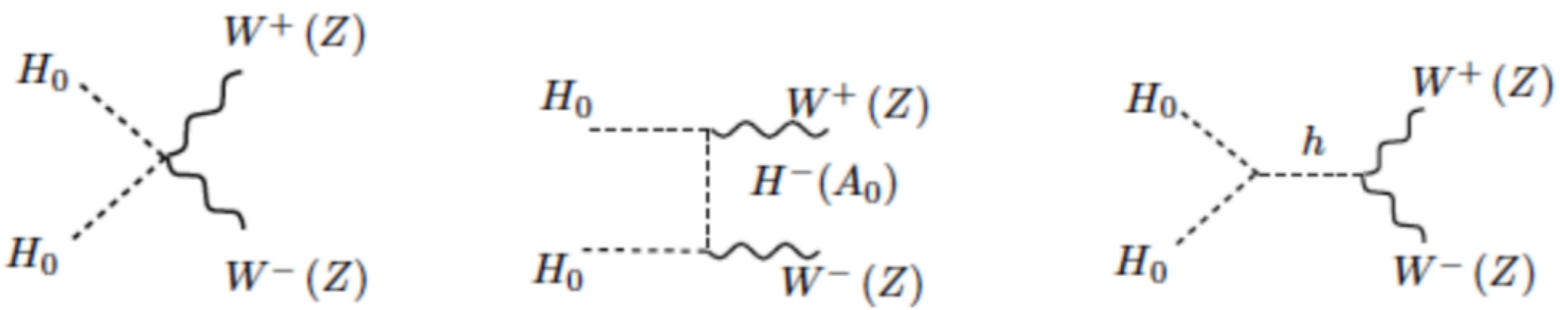
Fermions

WIMPs - Weakly interacting massive particles.

Model constrained mainly by relic density and direct detection.

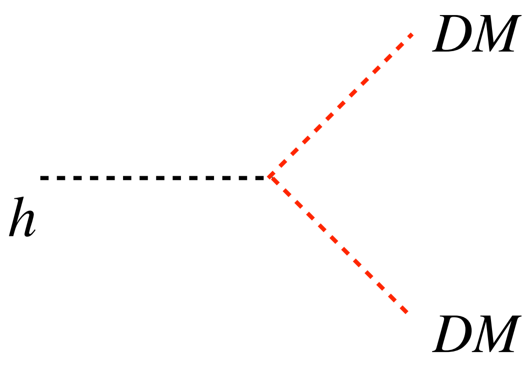


Higgs

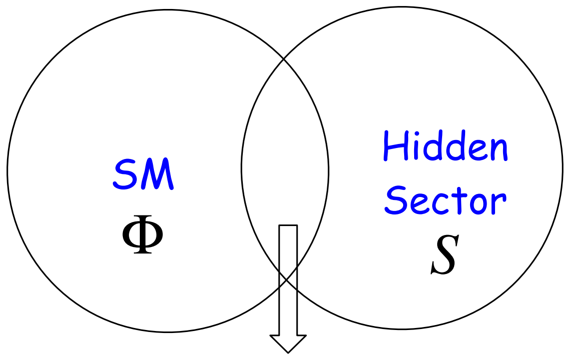


Gauge bosons

Dark Matter (IDM)

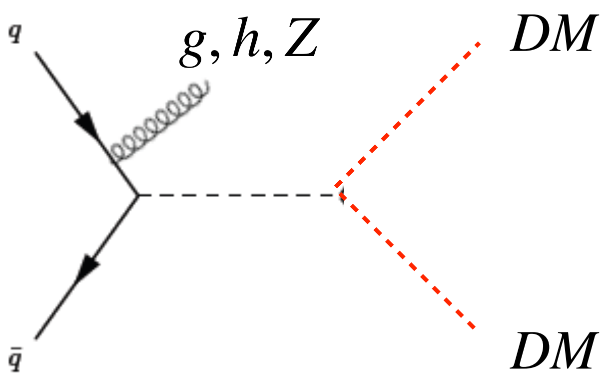


Model should conserve "darkness" - we need a stable particle. The invisible width of the Higgs and the dark matter direct detection experiments set a bound on the so-called portal coupling(s).



$$V_{portal} = \Phi^\dagger \Phi\, S^2$$

Searches need some kind of handle



$$q\bar{q} \to (g, h, Z, \ldots)\, DM\, DM$$

$$Z(q\bar{q}) = Z(q)Z(\bar{q}) = 1 \times 1 = 1$$

$$Z(q\bar{q}) = Z(H)Z(DM)Z(DM) = 1 \times (-1) \times (-1) = 1$$

The "simplest" potentials

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{m_S^2}{2}\Phi_S^2$$
$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + h.c.\right] + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2$$

Particle (type) spectrum depends on the symmetries imposed on the model, and whether they are spontaneously broken or not.

In the N2HDM there are two charged particles and 4 neutral.

with fields

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix} \qquad \Phi_S = v_S + \rho_S$$

magenta $\Longrightarrow$ SM

magenta + blue $\Longrightarrow$ RxSM (also CxSM)

magenta + black $\Longrightarrow$ 2HDM (also C2HDM)

magenta + black + blue + red $\Longrightarrow$ N2HDM

The model can be CP violating or not.

softly broken Z_2 : $\Phi_1 \to \Phi_1;\ \Phi_2 \to -\Phi_2$

softly broken Z_2 : $\Phi_1 \to \Phi_1;\ \Phi_2 \to -\Phi_2;\ \Phi_S \to \Phi_S$

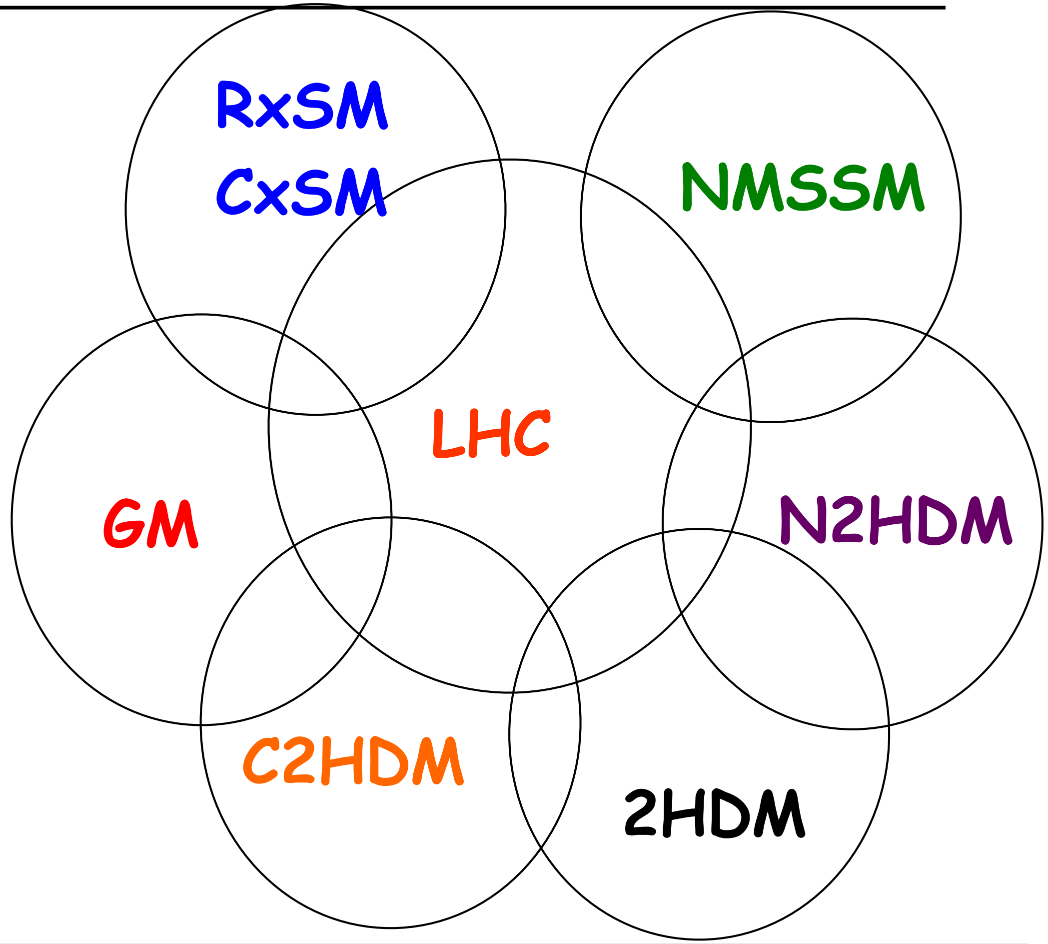
exact Z_2' : $\Phi_1 \to \Phi_1;\ \Phi_2 \to \Phi_2;\ \Phi_S \to -\Phi_S$

- **m^2_{12} and λ_5 real** 2HDM
- **m^2_{12} and λ_5 complex** C2HDM

Extensions of the SM

	CxSM (RxSM)	2HDM	C2HDM	N2HDM
Model	SM+Singlet	SM+Doublet	SM+Doublet	2HDM+Singlet
Scalars	$h_{1,2,(3)}$ (CP even)	H, h, A, $H^\pm$	$H_{1,2,3}$ (no CP), $H^\pm$	$h_{1,2,3}$ (CP-even), A, $H^\pm$
Motivation	DM, Baryogenesis	$+\ H^\pm$	+ CP violation	+ ...

- There is a 125 GeV Higgs (other scalars can be lighter and/or heavier).
- Models (except singlet extensions) can be CP-violating.
- They all have ρ=1 at tree-level.
- You get a few more scalars (CP-odd or CP-even or with no definite CP)
- They can have dark matter candidates (or not)



h_{125} couplings (gauge)

Lightest Higgs coupling modifiers (to gauge bosons)

$$g^{hVV}_{2HDM} = \sin(\beta - \alpha) g^{hVV}_{SM}$$

CP-VIOLATING 2HDM

$$g^{hVV}_{C2HDM} = \cos\alpha_2 \, g^{hVV}_{2HDM}$$

"PSEUDOSCALAR" COMPONENT (DOUBLET)

$$|s_2| = 0 \;\Rightarrow\; h_1 \text{ is a pure scalar,}$$
$$|s_2| = 1 \;\Rightarrow\; h_1 \text{ is a pure pseudoscalar}$$

$$g^{hVV}_{N2HDM} = \cos\alpha_2 \, g^{hVV}_{2HDM}$$

SINGLET COMPONENT

$(a+ib)$

SM + REAL SINGLET

$$g^{hVV}_{RxSM} = \cos\alpha_1 \, g^{hVV}_{SM}$$

SM + COMPLEX SINGLET

$$g^{hVV}_{CxSM} = \cos\alpha_1 \cos\alpha_2 \, g^{hVV}_{SM}$$

REAL COMPONENT

IMAGINARY COMPONENT

Yukawa couplings

There are other (better) reasons to use extra symmetries. In extension with more than one doublet tree-level FCNC appear (constrained by experiment).

1. **Fine tuning** – for some reason the parameters that give rise to tree-level FCNC are small
   Example: Type III models

2. **Flavour alignment** – for some reason we are able to diagonalise simultaneously both the mass term and the interaction term. Example: Aligned models

3. **Use symmetries**– for some reason L is invariant under some symmetry

   3.1 Naturally small tree-level FCNCs. Example: BGL-type Models discrete symmetries make the FCNC terms proportional to CKM elements

   3.2 No tree-level FCNCs. Example: Type I 2HDM Z_2 symmetries cancel all tree-level FCNCs. In the particular case of type I the symmetries are such that only one doublet couples to all quarks and leptons

h_{125} couplings (Yukawa)

Type I $\kappa_U^I = \kappa_D^I = \kappa_L^I = \dfrac{\cos\alpha}{\sin\beta}$

Type II $\kappa_U^{II} = \dfrac{\cos\alpha}{\sin\beta}$ $\kappa_D^{II} = \kappa_L^{II} = -\dfrac{\sin\alpha}{\cos\beta}$

Type F(Y) $\kappa_U^F = \kappa_L^F = \dfrac{\cos\alpha}{\sin\beta}$ $\kappa_D^F = -\dfrac{\sin\alpha}{\cos\beta}$

Type LS(X) $\kappa_U^{LS} = \kappa_D^{LS} = \dfrac{\cos\alpha}{\sin\beta}$ $\kappa_L^{LS} = -\dfrac{\sin\alpha}{\cos\beta}$

These are coupling modifiers relative to the SM coupling. May increase Yukawa relative to the SM.

III = I' = Y = Flipped = 4…

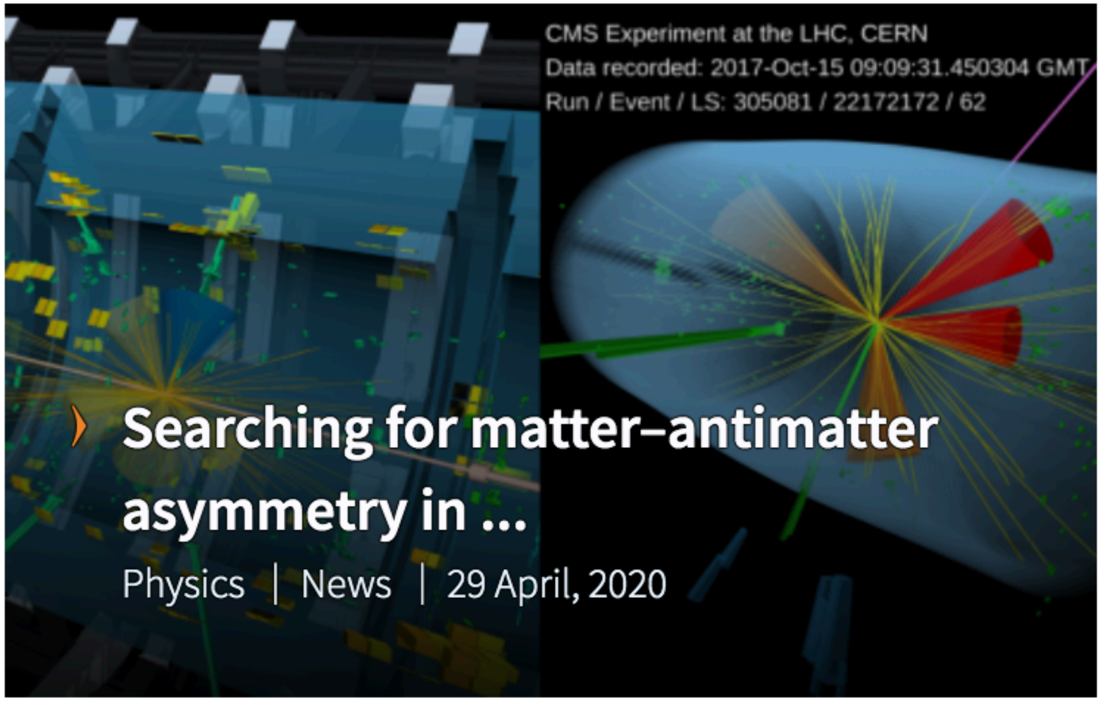
IV = II' = X = Lepton Specific= 3…

$$Y_{C2HDM} = \cos\alpha_2 Y_{2HDM} \pm i\gamma_5 \sin\alpha_2 \tan\beta (1/\tan\beta)$$

$$Y_{N2HDM} = \cos\alpha_2 Y_{2HDM}$$

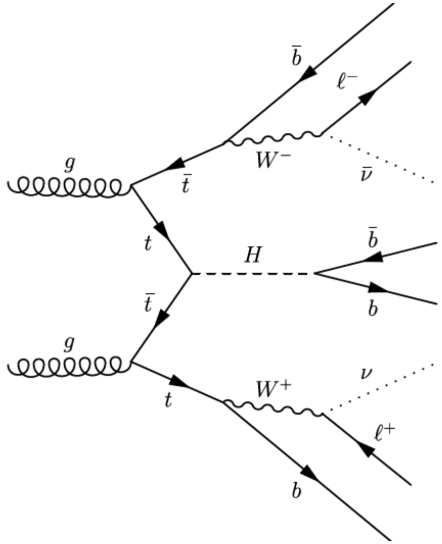
CP-violation

The C and the P in CP violation



CERN's news page

Picture refers to Higgs production in association with a pair of top quarks



$\gamma\gamma$

The CP-nature of the Higgs is still not known (we know it is not a pure CP-odd state). We need to probe Yukawa couplings: tth (production) and ττh (decay).

Two remarks: a) 2HDM in CP-violating form used as benchmark model

b) alignment limit - H_{125} has exactly the SM couplings

CP-violation from C violation

CP violation from C violation

Suppose we have a 2HDM extension of the SM but with no fermions. Also let us assume for the moment that the theory conserves C and P separately. The C and P quantum numbers of the Z boson is

$$C(Z_\mu) = P(Z_\mu) = -1$$

Because we have vertices of the type hhh and HHH,

$$P(h) = P(H) = 1;\; C(h) = C(H) = 1$$

Since the neutral Goldstone couples derivatively to the Z boson (and mixes with the A)

$$P(G_0) = P(A) = 1;\; C(G_0) = C(A) = -1 \qquad C(Z_\mu \partial^\mu A h) = 1; P(Z_\mu \partial^\mu A h) = 1$$

Or without being sloppy

$$C Z_\mu C^{-1} = -Z_\mu; \quad P Z_\mu P^{-1} = Z^\mu$$

And

$$P \partial^\mu G_0 Z_\mu P^{-1} = \partial_\mu G_0 Z^\mu$$

CP violation from C violation

In the absence of fermions, invariance under P is guaranteed. If the bosonic Lagrangian violates CP, any resulting CP-violating phenomena must be associated with a P-conserving C-violating observable.

Let us now consider the CP-violating 2HDM, with scalar states h_1, h_2, h_3 . Let us make our life harder by considering we are in the alignment limit (h_1 is SM like). In this limit the vertices that are CP-violating

$$h_3h_3h_3; \quad h_3h_2h_2; \quad h_3H^+H^-; \quad h_3h_3h_3h_1; \quad h_3h_2h_2h_1; \quad h_3h_1H^+H^-;$$

A different choice of the parameters of the potential would interchange h_2 and h_3.

A combination of 3 decays signals CP-violation

$$h_2H^+H^-; \quad h_3H^+H^-; \quad Zh_2h_3$$

$$h_2h_kh_k; \quad h_3H^+H^-; \quad Zh_2h_3; \quad (k=2,3) \quad (2 \leftrightarrow 3)$$

$$h_2h_kh_k; \quad h_3h_lh_l;\,; \quad Zh_2h_3; \quad (k,l=2,3)$$

CP violation from C violation

There are many other combinations if one moves away from the alignment limit

$$\boxed{h_1 \to ZZ(+)h_2 \to ZZ(+)h_2 \to h_1 Z}$$

Combinations of three decays

Forbidden in the exact alignment limit

$$\boxed{h_1 \to ZZ \;\Leftarrow\; CP(h_1) = 1}$$

$$\boxed{h_3 \to h_2 h_1 \;\Rightarrow\; CP(h_3) = CP(h_2)}$$

Decay	CP eigenstates	Model
$h_3 \to h_2 Z \quad CP(h_3) = -CP(h_2)$	None	C2HDM, other CPV extensions
$h_{2(3)} \to h_1 Z \quad CP(h_{2(3)}) = -1$	2 CP-odd; None	C2HDM, NMSSM,3HDM...
$h_2 \to ZZ \quad CP(h_2) = 1$	3 CP-even; None	C2HDM, cxSM, NMSSM,3HDM...

C2HDM T1 $H_{SM}=H_1$

Particle	H_1	H_2	H_3	H^+
Mass [GeV]	125.09	265	267	236
Width [GeV]	$4.106\ 10^{-3}$	$3.265\ 10^{-3}$	$4.880\ 10^{-3}$	0.37
σ_{prod} [pb]	49.75	0.76	0.84	

Resonance production : $\sigma_{prod}(H_2) \times BR(H_2\text{->}H_1H_1) = 760\text{ fb} \times 0.252 = 192\text{ fb}$
$+\ \sigma_{prod}(H_3) \times BR(H_3\text{->}H_1H_1) = 840\text{ fb} \times 0.280 = 235\text{ fb}$

Test of CP in decays:

- $\sigma_{prod}(H_3) \times BR(H_3\text{->}H_1H_1) = 235$ fb
- $\sigma_{prod}(H_3) \times BR(H_3\text{->}ZH_1) = 76$ fb

- $\sigma_{prod}(H_2) \times BR(H_2\text{->}H_1H_1) = 192$ fb
- $\sigma_{prod}(H_2) \times BR(H_2\text{->}ZH_1) = 122$ fb

C2HDM at future colliders

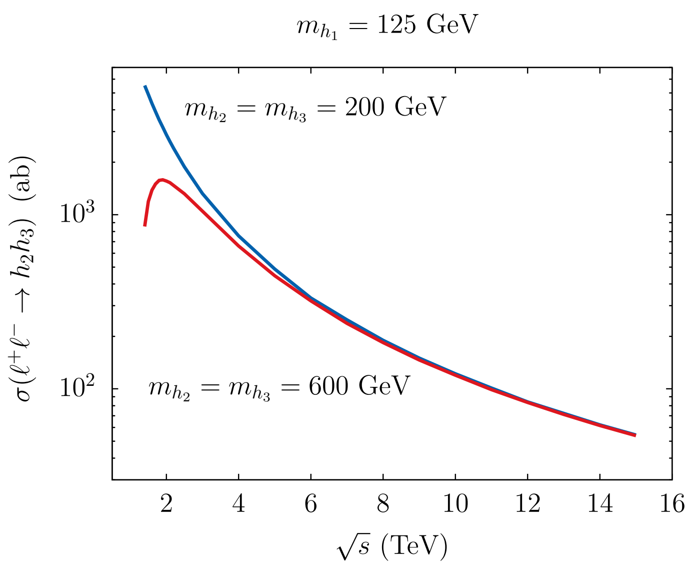
It could happen that at the end of the last LHC run we just move closer and closer to the alignment limit and to a very CP-even 125 GeV Higgs. Considering a few future lepton colliders

Accelerator	$\sqrt{s}$ (TeV)	Integrated luminosity (ab^{-1})
CLIC	1.5	2.5
CLIC	3	5
Muon Collider	3	1
Muon Collider	7	10
Muon Collider	14	20

$$h_2H^+H^-; \quad h_3H^+H^-; \quad Zh_2h_3$$

$$h_2h_kh_k; \quad h_3H^+H^-; \quad Zh_2h_3; \quad (k=2,3) \quad (2 \leftrightarrow 3)$$

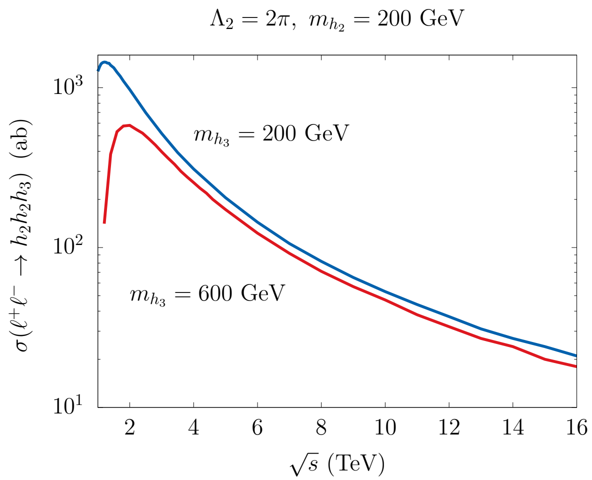
$$h_2h_kh_k; \quad h_3h_lh_l;; \quad Zh_2h_3; \quad (k,l=2,3)$$

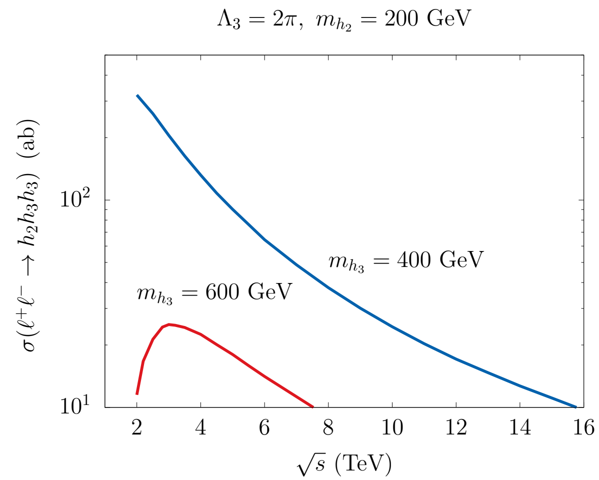


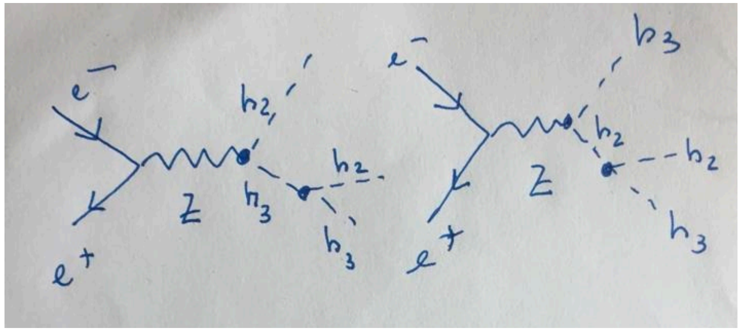
This is an s-channel process with a Z exchange and therefore a gauge coupling. We still need to detect the 2 scalars.

C2HDM at future colliders

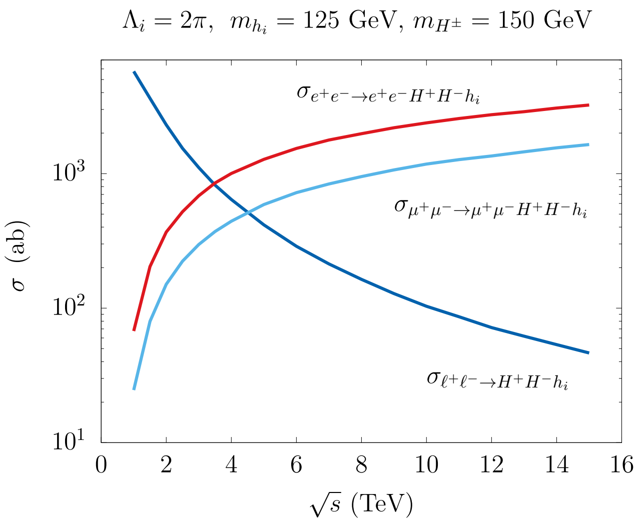
If the new particles are heavier we will need more energy. Still it will be a hard task.

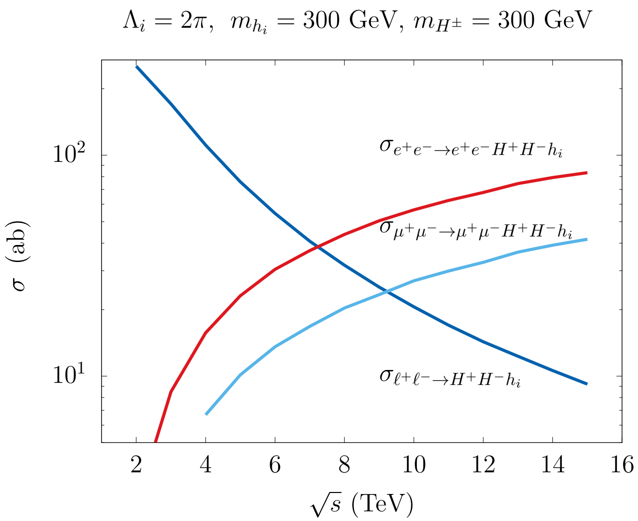


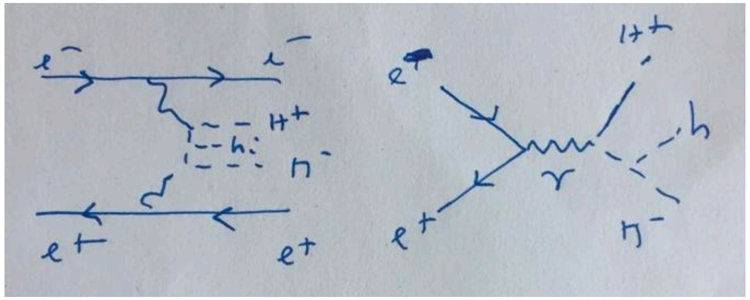




$h_2h_3h_3; \quad h_3h_2h_2; \quad Zh_2h_3$







$h_2H^+H^-; \quad h_3H^+H^-; \quad Zh_2h_3$

CP-violation from P violation

CP violation from P violation

When fermions are included the picture changes

$\bar{\psi}\psi$ C even P even -> CP even

$\bar{\psi}\gamma_5\psi$ C even P odd -> CP odd

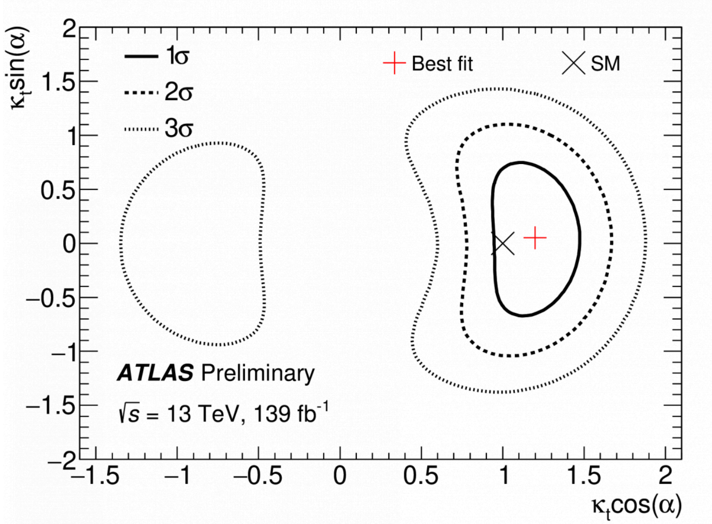
C conserving, CP violating interaction

$$\boxed{\bar{\psi}(a + ib\gamma_5)\psi\,\phi}$$

To probe this type of CP-violation we need one Higgs only.

$$\boxed{pp \to (h \to \gamma\gamma)\bar{t}t}$$

Consistent with the SM. Pure CP-odd coupling excluded at 3.9σ, and |α| > 43° excluded at 95% CL.



$$\mathscr{L}^{CPV}_{\bar{t}th} = -\frac{y_f}{\sqrt{2}}\,\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)\,t\,h$$

$$\kappa_t = \kappa\,\cos\alpha$$

$$\tilde{\kappa}_t = \kappa\,\sin\alpha$$

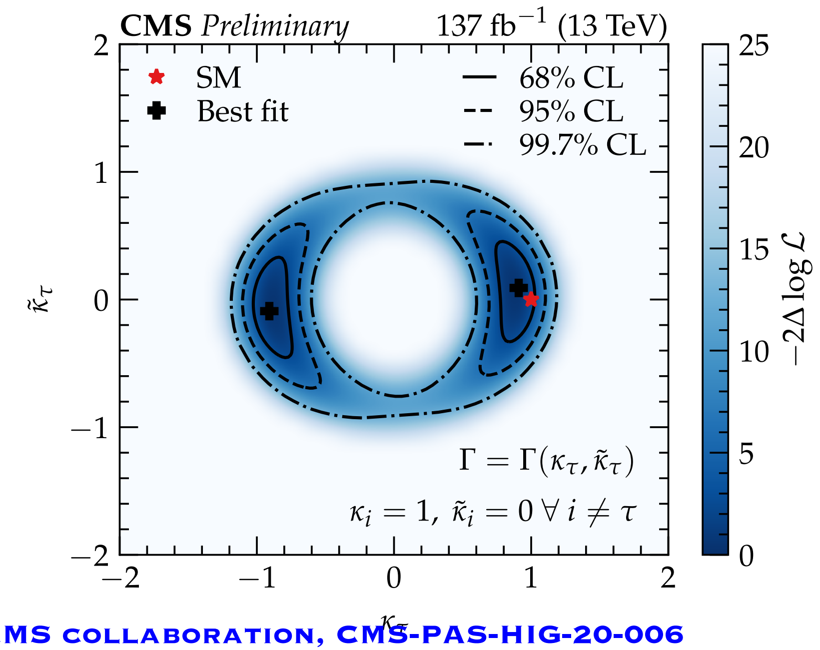
Rates alone already constrained a lot the CP-odd component.

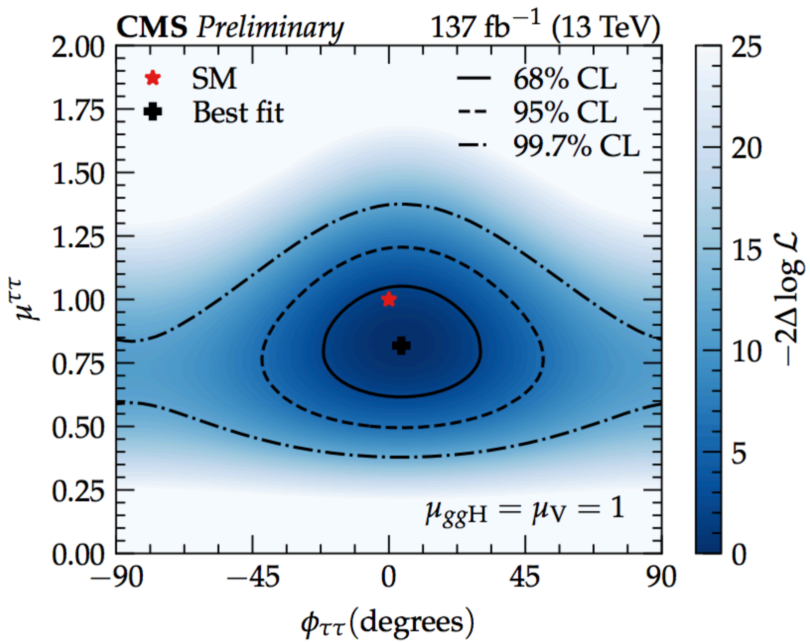
Measurement of CPV angle in ττh

$$pp \to h \to \tau^+\tau^-$$

$$\mathscr{L}^{CPV}_{\bar{\tau}\tau h} = -\frac{y_f}{\sqrt{2}}\,\bar{\tau}(\kappa_\tau + i\tilde{\kappa}_\tau\gamma_5)\,\tau\, h$$

Mixing angle between CP-even and CP-odd τ Yukawa couplings measured 4 ± 17°, compared to an expected uncertainty of ±23° at the 68% confidence level, while at the 95% confidence level the observed (expected) uncertainties were ±36° (±55)°. Compatible with SM predictions.





$$\phi_{\tau\tau} = \alpha$$

CMS collaboration, CMS-PAS-HIG-20-006

Nothing is planned for the remaining fermions!

CP violation from P violation (but strange!)

There is a different way to look at the same problem

$$\alpha_1 = \pi/2$$

$$\bar{t}(a_t + i b_t \gamma_5) t\, \phi \qquad b_t \approx 0 \qquad a_t\, \bar{t} t \phi$$ **Scalar**

$$\bar{\tau}(a_\tau + i b_\tau \gamma_5) \tau\, \phi \qquad a_\tau \approx 0 \qquad b_\tau\, \bar{\tau} \tau\, \phi$$ **Pseudoscalar**

If an experiment can tell us that ϕ couples approximately as scalar do top quarks and as a pseudoscalar to tau leptons, it is a sign of CP-violation.

$$g^{hVV}_{C2HDM} = \cos\alpha_2\, \cos(\beta - \alpha_1) g^{hVV}_{SM}$$

$$g^{hVV}_{C2HDM} = \cos\alpha_2\, \cos(\beta - \alpha_1) g^{hVV}_{SM}$$

$$g^{huu}_{C2HDM} = \left(\cos\alpha_2 \frac{\sin\alpha_1}{\sin\beta} - i \frac{\sin\alpha_2}{\tan\beta}\gamma_5 \right) g^{hff}_{SM}$$

$$g^{hbb}_{C2HDM} = \left(\cos\alpha_2 \frac{\cos\alpha_1}{\cos\beta} - i \sin\alpha_2\, \tan\beta\, \gamma_5 \right) g^{hff}_{SM}$$

Close to 1

$$g^{hVV}_{C2HDM} = \cos\alpha_2\, \sin\beta\, g^{hVV}_{SM}$$

$$g^{huu}_{C2HDM} = \left(\frac{\cos\alpha_2}{\sin\beta} - i \frac{\sin\alpha_2}{\tan\beta}\gamma_5 \right) g^{hff}_{SM}$$

Small

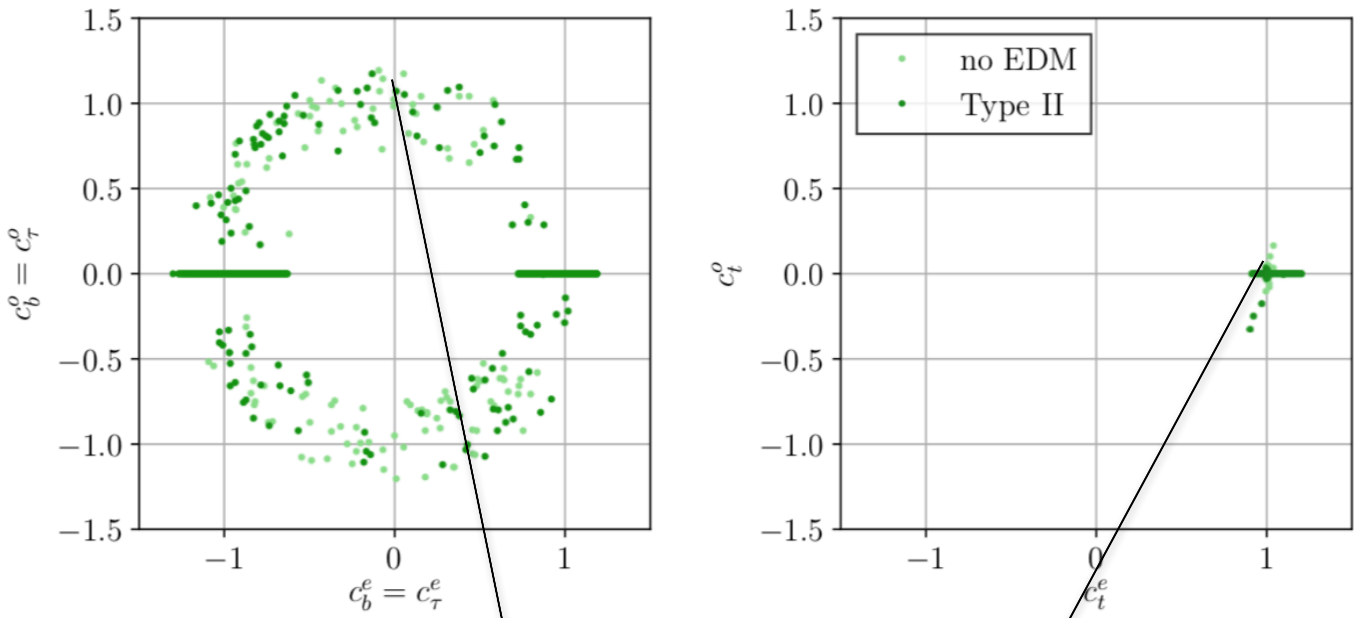
$$g^{hbb}_{C2HDM} = \left(- i \sin\alpha_2\, \tan\beta\, \gamma_5 \right) g^{hff}_{SM}$$

Can be large

Experiment tells us

$$\frac{\sin\alpha_2}{\tan\beta} \ll 1 \qquad \textbf{But} \qquad \sin\alpha_2\, \tan\beta = \mathcal{O}(1)$$

CP violation from P violation (but strange!)



$$Y_{C2HDM} = a_F + i\gamma_5 b_F$$

$$b_U \approx 0;\ a_D \approx 0$$

A Type II model where H_2 is the SM-like Higgs.

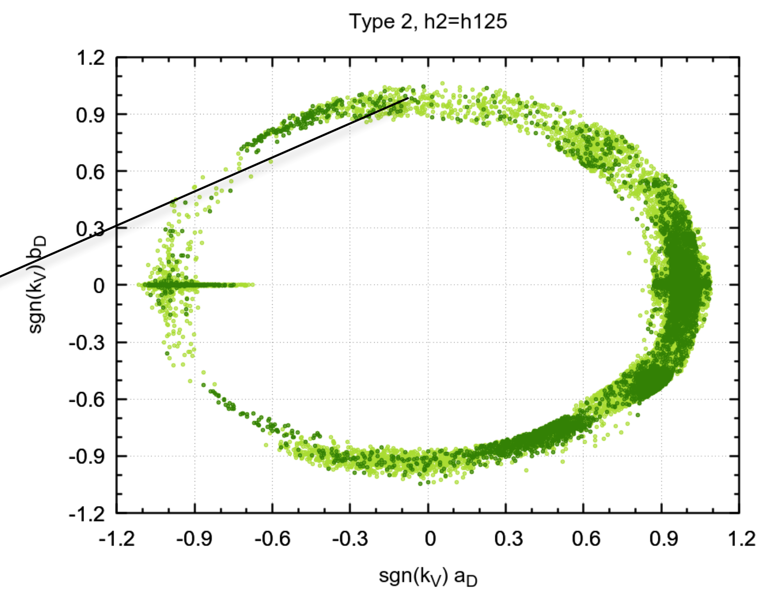
Find two particles of the same mass one produced in Association with tops as CP-even

$$h_2 = H; pp \to Ht\bar{t}$$

and the other decaying to taus as CP-odd

$$h_2 = A \to \tau^+\tau^-$$

With the latest EDM result



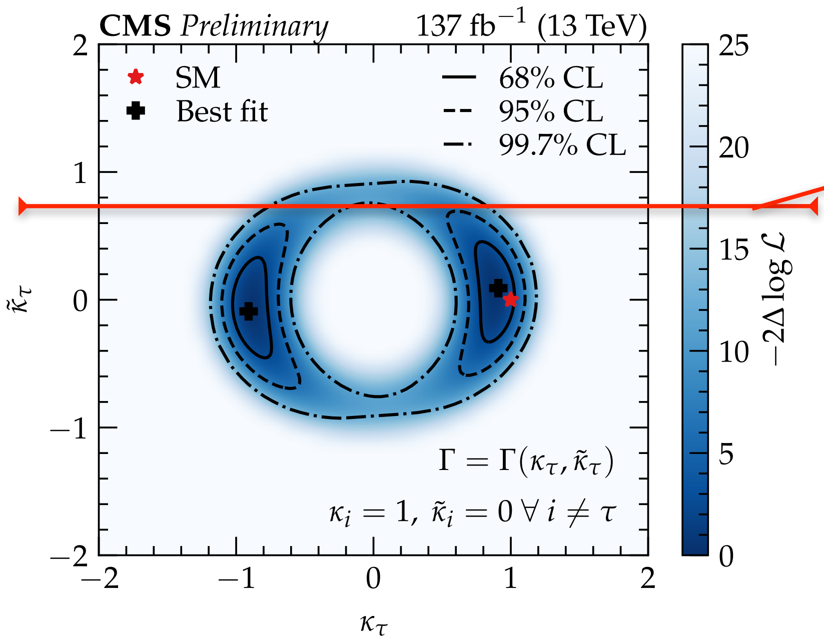
Measurement of CPV angle in ττh

$$\boxed{pp \to h \to \tau^+\tau^-}$$

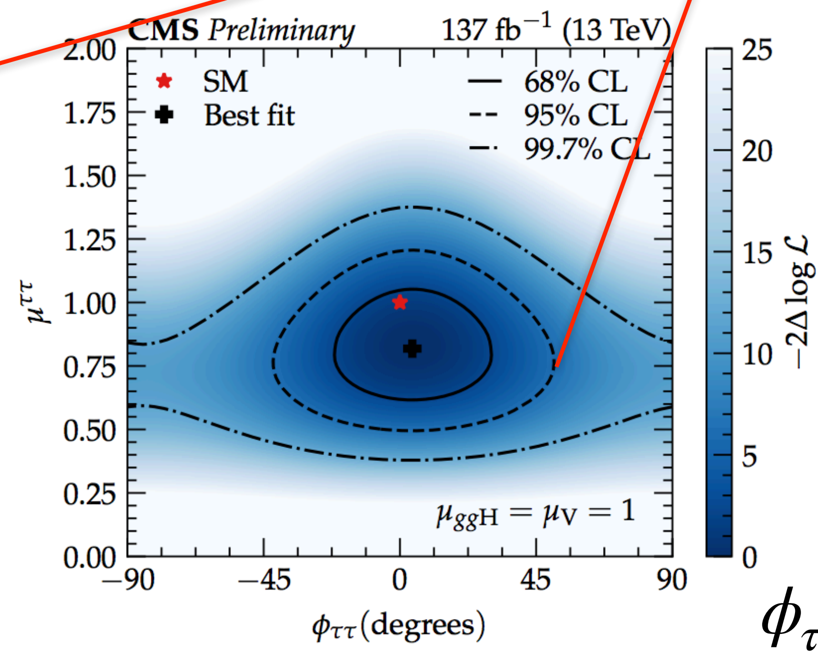
$$\mathcal{L}^{CPV}_{\bar{\tau}\tau h} = -\frac{y_f}{\sqrt{2}}\,\bar{\tau}(\kappa_\tau + i\tilde{\kappa}_\tau\gamma_5)\,\tau\, h$$

Mixing angle between CP-even and CP-odd τ Yukawa couplings measured 4 ± 17°, compared to an expected uncertainty of ±23° at the 68% confidence level, while at the 95% confidence level the observed (expected) uncertainties were ±36° (±55)°. Compatible with SM predictions.

Scenario excluded at 95% CL

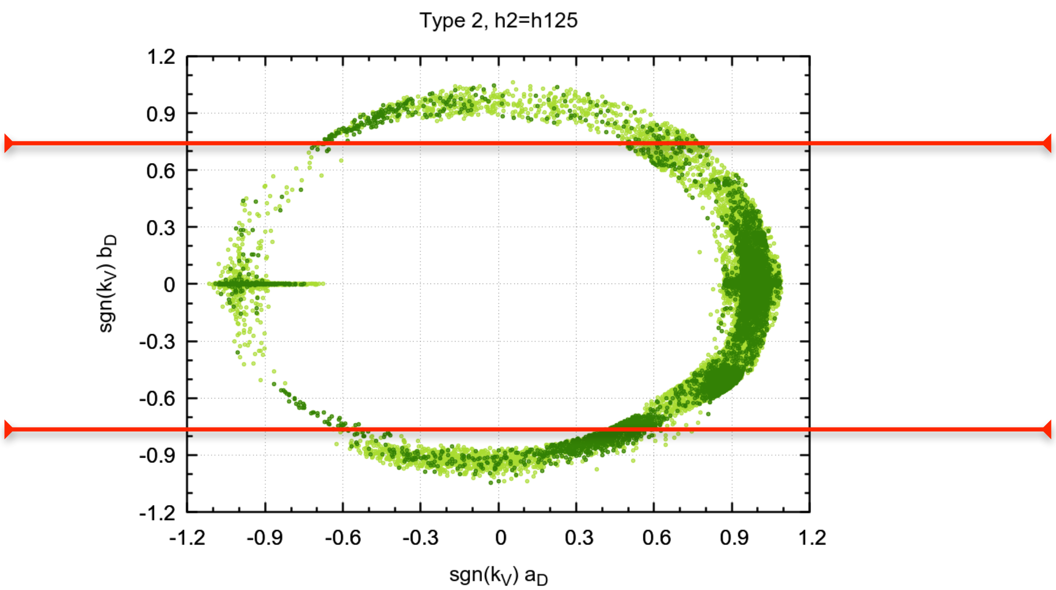


CMS collaboration, CMS-PAS-HIG-20-006



$$\phi_{\tau\tau} = \alpha$$

CP violation from P violation (but strange!)



LHC (direct) experiments give us information beyond EDMs.

Find two particles with the same mass, one produced CP-even associated with tops

$$h_2 = H; pp \to Ht\bar{t}$$

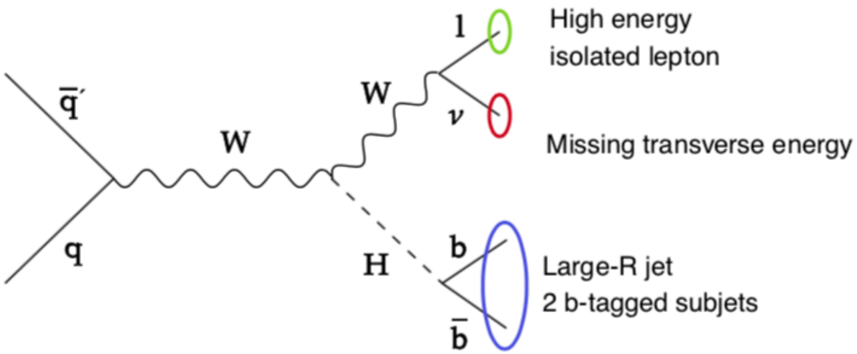
and the other decaying to taus as CP-odd

$$h_2 = A \to \tau^+\tau^-$$

Probing one Yukawa coupling is not enough!

CP-violation from loops

CP violation from loops (hWW)

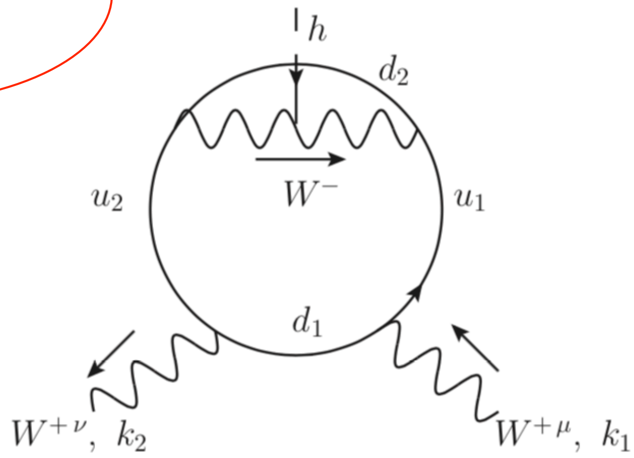


In this case we start with the most general WWh vertex

Term coming from a CPV operator.
Contribution from the SM at 2-loop

$$\mathscr{M}(hW^+W^-) \sim a_1^{W^+W^-} m_W^2 \epsilon^*_{W^+}\epsilon^*_{W^-} + a_3^{W^+W^-} f^{*+}_{\mu\nu}\tilde{f}^{*-\,\mu\nu}$$

Term in the SM at tree-level
but also in models with CP-violation



$$\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}} \in [-0.81, 0.31]$$

Present experimental bound
from ATLAS and CMS

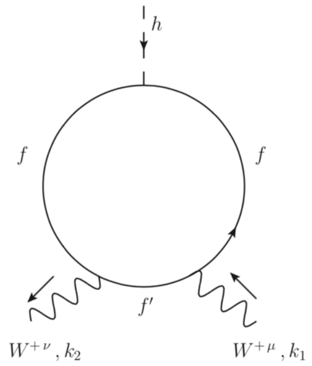
CMS collaboration, PRD100 (2019) 112002.

ATLAS collaboration, EPJC 76 (2016) 658.

The SM contribution should be proportional to the Jarlskog invariant J = Im($V_{ud}V_{cd}^*\ V_{cs}V_{cd}^*$) = 3.00×10^{-5} . The CPV hW^+W^- vertex can only be generated at two-loop.

CP violation from loops (hWW)

THE C2HDM



Starting with f=t and f'=b

Is it worth it?

$$i\mathcal{M}_{tb}^{\text{C2HDM}} \sim \frac{ig^2 N_c c_t^o}{16\pi^2 v} \frac{m_t^2}{m_W^2} |V_{tb}|^2 \epsilon_{\mu\nu\rho\sigma} k_1^\rho k_2^\sigma \mathcal{I}_1\left(\frac{m_t^2}{m_W^2}, \frac{m_b^2}{m_W^2}\right)$$

$$\mathcal{I}_1(x,y) \equiv \int_0^1 d\alpha \frac{\alpha^2}{\alpha x + (1-\alpha)y - \alpha(1-\alpha)}$$

And because f=b and f'=t can also contribute, the final result is

$$c_{\text{CPV}}^{\text{C2HDM}} = \frac{N_c g^2}{32\pi^2}|V_{tb}|^2 \left[\frac{c_t^o m_t^2}{m_W^2}\mathcal{I}_1\left(\frac{m_t^2}{m_W^2}, \frac{m_b^2}{m_W^2}\right) + \frac{c_b^o m_b^2}{m_W^2}\mathcal{I}_1\left(\frac{m_b^2}{m_W^2}, \frac{m_t^2}{m_W^2}\right)\right]$$

$$c_{\text{CPV}} = 2\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}}$$

$$\boxed{c_{\text{CPV}}^{\text{C2HDM}} \simeq 6.6 \times 10^{-4} \sim \mathcal{O}(10^{-3})}$$

USING ALL EXPERIMENTAL (AND THEORETICAL) BOUNDS

Sensitivity projections for future colliders (hWW)

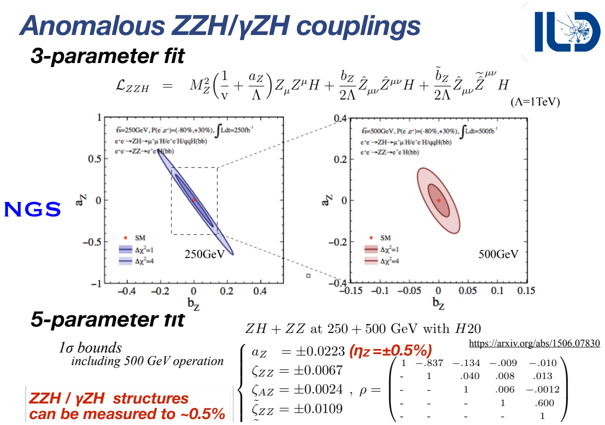
Table 10: Summary of the 95% CL intervals for $f_{a3}\cos(\phi_{a3})$, under the assumption $\Gamma_H = \Gamma_H^{SM}$, and for Γ_H under the assumption $f_{ai} = 0$ for projections at 3000 fb^{-1}. Constraints on $f_{a3}\cos(\phi_{a3})$ are multiplied by 10^4. Values are given for scenarios S1 (with Run 2 systematic uncertainties [47]) and the approximate S2 scenario, as described in the text.

Parameter	Scenario	Projected 95% CL interval
$f_{a3}\cos(\phi_{a3}) \times 10^4$	S1, only on-shell	$[-1.8, 1.8]$
$f_{a3}\cos(\phi_{a3}) \times 10^4$	S1, on-shell and off-shell	$[-1.6, 1.6]$
Γ_H (MeV)	S1	$[2.0, 6.1]$
Γ_H (MeV)	S2	$[2.0, 6.0]$

CMS PAS FTR-18-011

$$\gamma/\kappa = c_z = \mathcal{O}(10^{-2})$$

Slide from Keisuke Fujii's presentation at Higgs Couplings 2018, Tokyo



Most comprehensive study performed for the ILC. The work presents results are for polarised beams P (e^-, e^+) = (–80%, 30%) and two CM energies 250 GeV (and an integrated luminosity of 250 fb^{-1}) and 500 GeV (and an integrated luminosity 500fb^{-1}).

Limits obtained for an energy of 250 GeV were $c^W_{CPV} \in [-0.321, 0.323]$ and $c^Z_{CPV} \in [-0.016, 0.016]$. For 500 GeV we get $c^W_{CPV} \in [-0.063, 0.062]$ and $c^Z_{CPV} \in [-0.0057, 0.0057]$.

Ogawa, PhD Thesis (2018)

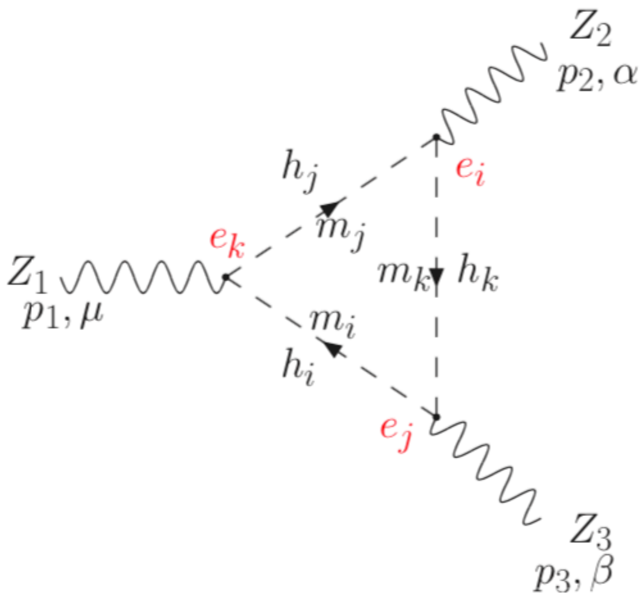
Therefore models such as the C2HDM may be (barely) within the reach of these machines. Can be used to constraint the C2HDM at loop-level

CP violation from loops (ZZZ)

Another possibility of detecting P-even CP-violating signals is via loops. Remember CP-violation could be seen via the combination

$$\boxed{\begin{array}{ll} h_2 \to h_1 Z & CP(h_2) = -\,CP(h_1) \\ h_3 \to h_1 Z & CP(h_3) = -\,CP(h_1) \\ h_3 \to h_2 Z & CP(h_3) = -\,CP(h_2) \end{array}}$$

So we can take these three processes and build a nice Feynman diagram



And see if it is possible to extract information from the measurement of the triple ZZZ anomalous coupling.

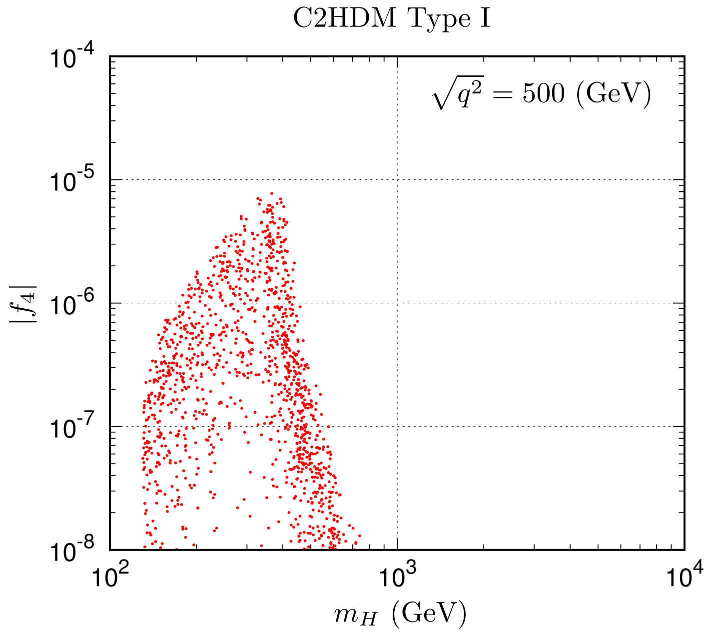
CP violation from loops (ZZZ)

The most general form of the vertex includes a P-even CP-violating term of the form

$$i\Gamma_{\mu\alpha\beta} = -\, e\frac{p_1^2 - m_Z^2}{m_Z^2}\, f_4^Z \left(g_{\mu\alpha}p_{2,\beta} + g_{\mu\beta}p_{3,\alpha}\right) + \ldots$$

CMS COLLABORATION, EPJC78 (2018) 165. $-1.2\times 10^{-3} < f_4^Z < 1.0\times 10^{-3}$

ATLAS COLLABORATION, PRD97 (2018) 032005. $-1.5\times 10^{-3} < f_4^Z < 1.5\times 10^{-3}$



PLOT FROM JHEP 04 (2018) 002,
FOR THE C2HDM

Also available for invisible scalars

Two doublets + one singlet and one exact Z_2 symmetry

$$\Phi_1 \to \Phi_1, \qquad \Phi_2 \to -\Phi_2, \qquad \Phi_S \to -\Phi_S$$

with the most general renormalizable potential

$$\begin{aligned} V = {} & m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 + (A\Phi_1^\dagger \Phi_2 \Phi_S + h.c.) \\ & + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2) + h.c.\right] + \frac{m_S^2}{2}\Phi_S^2 + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \end{aligned}$$

and the vacuum preserves the symmetry

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG_0) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\rho + i\eta) \end{pmatrix} \qquad \Phi_S = \rho_S$$

The potential is invariant under the CP-symmetry

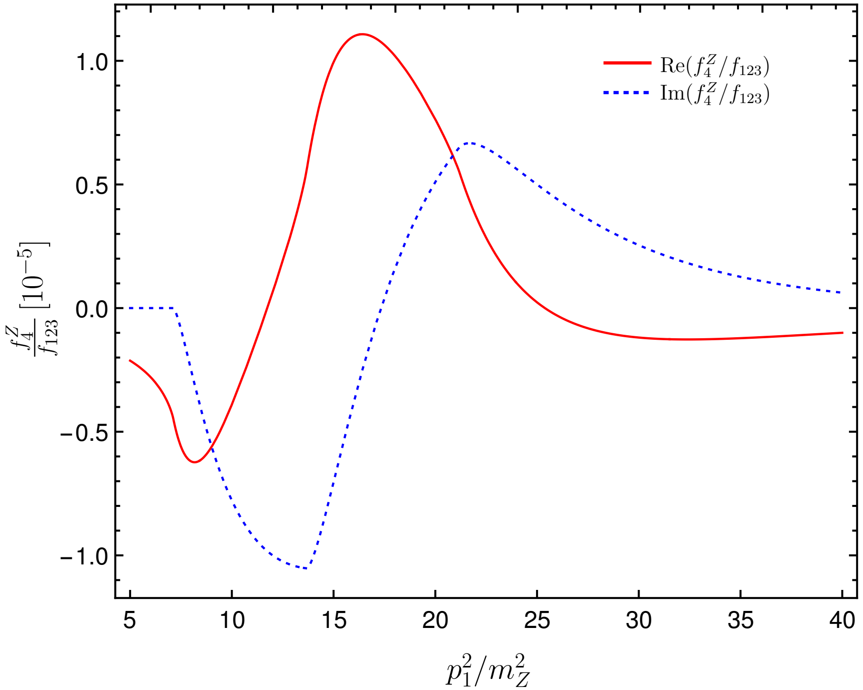
$$\Phi_1^{CP}(t,\vec{r}) = \Phi_1^*(t,-\vec{r}), \qquad \Phi_2^{CP}(t,\vec{r}) = \Phi_2^*(t,-\vec{r}), \qquad \Phi_S^{CP}(t,\vec{r}) = \Phi_S(t,-\vec{r})$$

except for the term $(A\Phi_1^\dagger\Phi_2\Phi_S + h.c.)$ for complex A

Also available for invisible scalars

In our model it has the simple expression

$$f_4^Z(p_1^2) = -\frac{2\alpha}{\pi s_{2\theta_W}^3}\frac{m_Z^2}{p_1^2 - m_Z^2} f_{123} \sum_{i,j,k} \epsilon_{ijk}\, C_{001}(p_1^2, m_Z^2, m_Z^2, m_i^2, m_j^2, m_k^2) \qquad f_{123} = R_{13}R_{23}R_{33}$$



The form factor f_4 normalised to f_{123} for m_1=80.5 GeV, m_2=162.9 GeV and m_3=256.9 GeV as a function of the squared off-shell Z-boson 4-momentum, normalised to m_Z^2.

But the bounds we have from present measurements by ATLAS and CMS, show that we are still two orders of magnitude away from what is needed to probe these models. 3HDMs may get us closer.

CP-violation and the singlet

CP and the scalar extension

Let us consider again the singlet extension - the SM plus a Y=0 complex singlet $\Phi_S = (S + iA)$ with a symmetry $A \to -A$. There is a CP transformation

$$\Phi_S \to \Phi_S^* \quad \Rightarrow \quad A \to -A$$

so, if A would get a VEV, CP would be broken. However the potential has 2 CP symmetries

$$\Phi \to \Phi^* \qquad \Phi_S \to \Phi_S^* \qquad (1)$$

$$\Phi \to \Phi^* \qquad \Phi_S \to \Phi_S \qquad (2)$$

Symmetry (2) can be seen as a CP symmetry as long as no new fermions are added to the theory.

Therefore even if (1) is broken there is still one unbroken CP symmetry (2) and the model is CP-conserving.

Transformation (2) ceases to be a CP transformation with e.g. the introduction of vector-like quarks.

CP and the scalar extension

There is another way (more algebraical) to look at the problem. You have two scalar fields

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h_D \end{pmatrix} \quad ; \quad \Phi_S = (S + iA)$$

Forget for now about the singlet and write all the terms where scalars appear except for the potential. The Yukawa Lagrangian gives you terms of the form

$$\bar{f} f h_D$$

The kinetic scalar Lagrangian gives you terms of the form

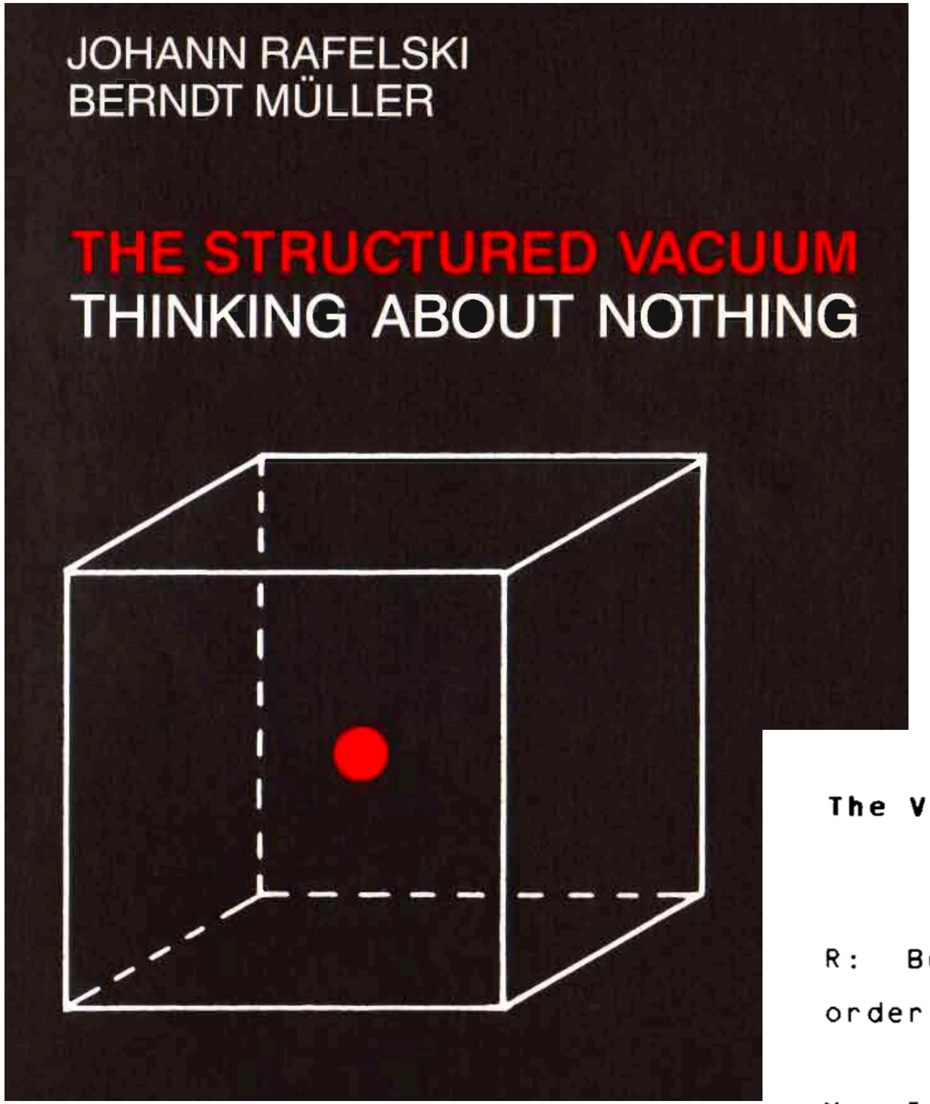
$$V V h_D$$

So h_D is CP-even. Now from the potential you only find the mass eigenstates for the scalars, h_1, h_2, h_3 and you rotate

$$h_D = a_1 h_1 + a_2 h_2 + a_3 h_3$$

and so h_1, h_2, h_3 have the same CP h_D.

Vacuum structure



The Vacuum and the Laws of Nature

R: But is understanding of the vacuum important in order to understand the laws of physics?

M: Indeed so. The surprising thing that we have learnt in the last decade is that the vacuum is very important in understanding the laws of physics and that it comes in addition to the laws of physics. You may have the same set of laws of physics operating in a different vacuum and they would describe very different phenomena.

Charge breaking in the SM

You start with

$$< \Phi_{SM} > = \binom{0}{v} \qquad Q_{SM} < \Phi_{SM} > = \left(I_3 + \frac{Y}{2}\right) < \Phi_{SM} > = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \binom{0}{v} = 0$$

But you could have started with

$$< \Phi_{SM} > = \begin{pmatrix} v_1 + i v_2 \\ v_3 + i v_4 \end{pmatrix}$$

Now use the kinetic scalar term to find the mass matrix of the gauge bosons.

and you find the mass spectrum (for the gauge bosons)

$$m_1^2 = m_2^2 = \frac{g^2 v^2}{4} \qquad v^2 = v_1^2 + v_2^2 + v_3^2 + v_4^2$$

$$m_3^2 = \; = \frac{v^2}{4}(g^2 + g'^2 Y^2)$$

$$\boxed{m_4^2 = 0}$$

It's the photon

So U(1) survives and charge is always conserved. Is this obvious?

CB and CP breaking in the SM

Yes because you can use the SU(2) freedom to perform the rotation

$$< \Phi_{SM} > = \begin{pmatrix} v_1 + i v_2 \\ v_3 + i v_4 \end{pmatrix} \quad \rightarrow \quad < \Phi_{SM} > = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Using a more general vacuum would just mean to redefine the charge operator.

For the same reason any phase in the vacuum can be rotated away. This means that no spontaneous CP can occur. And the potential is also explicitly CP conserving.

The SM has no CB and no CP violation in the potential.

The result also holds for any extension with singlets with Y=0 because they do not contribute to the mass matrix of the gauge bosons (CP case discussed previously).

CB in the 2HDM

Let us move to the 2HDM. Now we have 2 doublets and 8 possible VEVs

$$< \Phi_k > = \begin{pmatrix} v_1^k + i v_2^k \\ v_3^k + i v_4^k \end{pmatrix}$$

We can use the SU(2) $\times$ U(1) freedom to write the most general form for the vacuum

$$< \Phi_1 > = \begin{pmatrix} v_a \\ v_b \end{pmatrix} \qquad < \Phi_2 > = \begin{pmatrix} 0 \\ v_c e^{i\theta} \end{pmatrix}$$

and you find the mass spectrum (for the gauge bosons)

$$m_1^2 = m_2^2 = \frac{g^2 v^2}{4} \qquad v^2 = v_a^2 + v_b^2 + v_c^2$$

$$m_3^2 = = \frac{1}{8}\left[v^2(g^2 + g'^2 Y^2) + \sqrt{v^4(g^2 + g'^2 Y^2)^2 - 16 g^2 g'^2 v_a^2 v_c^2 Y^2} \right]$$

$$m_4^2 = \frac{1}{8}\left[v^2(g^2 + g'^2 Y^2) - \sqrt{v^4(g^2 + g'^2 Y^2)^2 - 16 g^2 g'^2 v_a^2 v_c^2 Y^2} \right]$$

Is it the photon?

CB in the 2HDM

Let us have a closer look at the photon mass

$$m_4^2 = \frac{1}{8}\left[v^2(g^2 + g'^2 Y^2) - \sqrt{v^4(g^2 + g'^2 Y^2)^2 - 16 g^2 g'^2 v_a^2 v_c^2 Y^2}\right]$$

There are two ways to recover a zero mass for the photon

$$v_c = 0 \quad \Rightarrow \quad <\Phi_1> = \begin{pmatrix} v_a \\ v_b \end{pmatrix} \qquad <\Phi_2> = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \qquad \Rightarrow \qquad \text{SM}$$

$$v_a = 0 \quad \Rightarrow \quad <\Phi_1> = \begin{pmatrix} 0 \\ v_b \end{pmatrix} \qquad <\Phi_2> = \begin{pmatrix} 0 \\ v_c e^{i\theta} \end{pmatrix} \qquad \Rightarrow \qquad \text{Vacua are aligned}$$

Or else charge is broken - possible in the 2HDM

Suppose we live in a 2HDM, are we in danger?

Vacua in the 2HDM

The Z2 softly broken 2HDM

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

explicitly CP-conserving because m^2_{12} and λ_5 are real.

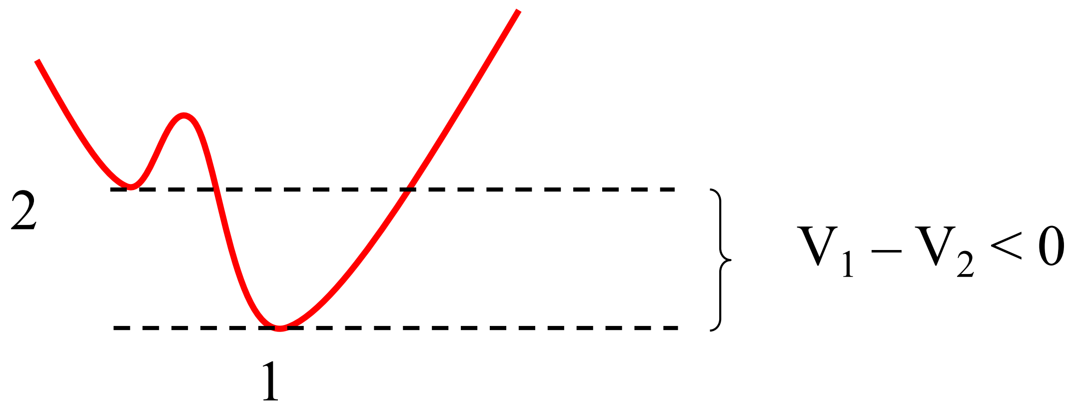
The most general vacuum structure is

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix} \quad ; \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_{cb} \\ v_2 + i v_{cp} \end{pmatrix}$$

- CP conserving (N) $\quad \langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix} \quad ; \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}$
- Charge breaking (CB) $\quad \langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1' \end{pmatrix} \quad ; \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} \alpha \\ v_2' \end{pmatrix}$
- CP breaking (CP) $\quad \langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1' + i\delta \end{pmatrix} \quad ; \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2' \end{pmatrix}$

Compare minima

1. Start by writing the potential, which for the 2HDM is just a function $V(\Phi_1, \Phi_2)$
2. Find the stationary points (SP) of V
3. Classify the SP (minima, saddle points, maxima) – look at the values of the squared masses
4. You will find three types of SP – the CP-conserving (aka normal), the charge breaking and the CP breaking ones
5. You just have to write the potential at each SP and call it V_N, V_{CB} and V_{CP}, respectively
6. Compare the depths of the different V at each SP



Vacua in the 2HDM

After some time you find

$$V_{CB} - V_{\mathcal{N}} = \frac{m_{H^\pm}^2}{2v^2}\left[(v_2 v_1' - v_1 v_2')^2 + v_1^2\alpha^2\right]$$

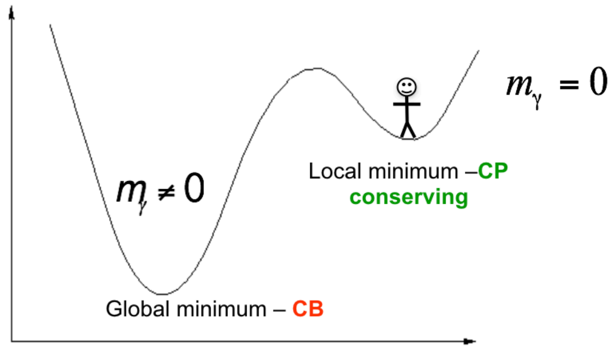
Difference of the values of the potential at the CB SP and at the N SP

If N is a minimum (note that the charged Higgs mass is calculated at the N SP)

$$V_{CB} - V_{\mathcal{N}} = \frac{m_{H^\pm}^2}{2v^2}\left[(v_2 v_1' - v_1 v_2')^2 + v_1^2\alpha^2\right] > 0$$

We get

$$V_{\mathcal{N}} < V_{CB}$$



It can also be shown that not only the N minimum is below the CB SP, but the CB SP is a saddle point.

Valid for the most general 2HDM

A similar result holds for the simultaneous existence of a N and a CP breaking minima.

$$V_{CB} - V_{\mathcal{N}} = \frac{m_A^2}{2v^2}\left[(v_2 v_1' - v_1 v_2')^2 + v_1^2\delta^2\right]$$

Vacua in the 2HDM

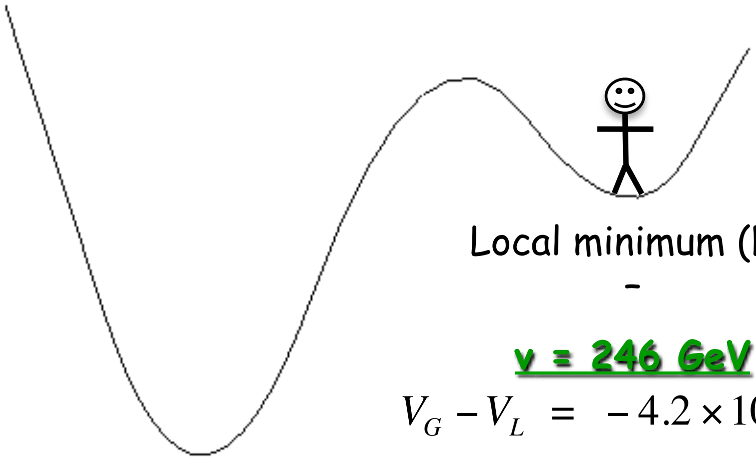
Vacua in the 2HDM (at tree-level) - all spontaneous

1. **2HDM have at most two minima**
2. **Minima of different nature never coexist**
3. **Unlike Normal, CB and CP minima are uniquely determined**
4. **If a 2HDM has only one normal minimum, it is the absolute minimum - all other SP if they exist are saddle points**
5. **If a 2HDM has a CP-breaking minimum, it is the absolute minimum - all other SP if they exist are saddle points**

But there is still the possibility of having two CP-conserving minima!

Vacua in the 2HDM

Two normal minima - <u>potential with the soft breaking term</u>



$$V_{\mathcal{N}_2} - V_{\mathcal{N}_1} = \frac{1}{2}\left\{\left(\frac{m_{H^\pm}^2}{v^2}\right)_{\mathcal{N}_2} - \left(\frac{m_{H^\pm}^2}{v^2}\right)_{\mathcal{N}_1}\right\}\left[(v_2 v_1' - v_1 v_2')^2\right]$$

Local minimum (N) - $m_W = 80.4 \text{ GeV}$

v = 246 GeV

$$V_G - V_L = -4.2 \times 10^8 \text{ GeV}$$

Global minimum (N) - $m_W = 107.5 \text{ GeV}$

v = 329 GeV

THE PANIC VACUUM!

and this is one that can actually occur...

However, two CP-conserving minima can coexist – we can force the potential to be in the global one by using a simple condition.

$$\text{D} = m_{12}^2\left(m_{11}^2 - k^2 m_{22}^2\right)\left(\tan\beta - k\right) \qquad k = \left(\frac{\lambda_1}{\lambda_2}\right)^{1/4}$$

$$D = \frac{1}{8v^8\, s_\beta^4\, c_\beta^2}\left(-a_1\,\mu^2 + b_1\right)\left(a_2\,\mu^2 - 2\,b_2\right)$$

Our vacuum is the global minimum of the potential if and only if D > 0.

From 2 to infinity

The most general potential for an NHDM is

$$V = \mu_{ij}^2 (\Phi_i^\dagger \Phi_j) + \lambda_{ijkl} (\Phi_i^\dagger \Phi_j)(\Phi_k^\dagger \Phi_l)$$

where the indices range from 1 to N and the parameters can be complex.

We have shown that a basis can be chosen such that the comparison between SP reduces to the case of 3 doublets for charge breaking and to the 2HDM case for CP breaking. So the main results are:

- In a NHDM CB minima can coexist with CP-conserving ones - the 2HDM is a very peculiar model

- In a NHDM CP minima cannot coexist with CP-conserving ones - the 2HDM result holds for an arbitrary number of doublets

Conclusions

- It is now clear that an extended scalar sector may indeed improve your life
- It provides DM
- It provides new sources of CP-violation
- It is testable at the LHC and future colliders
- Summing it all, it provides countless hours of fun for both Professors and Students