Higgs Beyond the Standard Model – theory (part 2)

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Outline

Lecture 1:
- Lightning review of SM Higgs
- Conceptual framework for extended Higgs sectors
- Higgs mixing: SM + Singlet
- New gauge structures: Georgi-Machacek model

Lecture 2: Two-Higgs-Doublet Model and its delights
- New fermion structures: Natural flavour cons. & 2HDM pheno
- More new fermion structures: Flavour violation
- New scalar potential options: CP violation
- Dark matter: Inert 2HDM

Introducing the Two-Higgs-Doublet Model (2HDM)

Add a second SU$(2)_L$ doublet of complex scalars with same hypercharge as SM Higgs. [T.D. Lee 1973; giant review article by Branco et al. 1106.0034]

SM: $\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \to$ physical Higgs boson h^0;
Goldstone bosons "eaten" by $W^\pm, Z$

2HDM: $\begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \to$ physical Higgs bosons $h^0, H^0, A^0, H^\pm$;
Goldstone bosons "eaten" by $W^\pm, Z$

Gauge-kinetic terms completely determined by gauge invariance:

$$\mathcal{L}_{gauge} = (\mathcal{D}^\mu \Phi_1)^\dagger (D_\mu \Phi_1) + (\mathcal{D}^\mu \Phi_2)^\dagger (D_\mu \Phi_2)$$

with the covariant derivative for both doublets same as in SM. Gauge boson masses become:

$$M_W^2 = \frac{g^2 v_1^2}{4} + \frac{g^2 v_2^2}{4}, \qquad M_Z^2 = \frac{(g^2 + g'^2) v_1^2}{4} + \frac{(g^2 + g'^2) v_2^2}{4}$$

Preserves $\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1$; requires $v_1^2 + v_2^2 = v_{\rm SM}^2$.

Introducing the Two-Higgs-Doublet Model (2HDM)

Define a new parameter $\tan\beta = v_2/v_1$.
Higgs boson couplings to W and Z are now shared between the two CP-even neutral fields:

$$\begin{aligned} \phi_1^{0,r} V_\mu V_\nu &\sim 2i\frac{M_V^2}{v_{\rm SM}} g_{\mu\nu} \times \cos\beta \\ \phi_2^{0,r} V_\mu V_\nu &\sim 2i\frac{M_V^2}{v_{\rm SM}} g_{\mu\nu} \times \sin\beta \end{aligned}$$

$\phi_1^{0,r}$ and $\phi_2^{0,r}$ are not mass eigenstates in general; just like in SM + singlet, there will be Higgs mixing by a new angle α:

$$h^0 = -\sin\alpha\,\phi_1^{0,r} + \cos\alpha\,\phi_2^{0,r}, \qquad H^0 = \cos\alpha\,\phi_1^{0,r} + \sin\alpha\,\phi_2^{0,r}$$

Physical Higgs couplings to W and Z then become:

$$\begin{aligned} h^0 V_\mu V_\nu &\sim 2i\frac{M_V^2}{v_{\rm SM}} g_{\mu\nu} \times \sin(\beta-\alpha) \\ H^0 V_\mu V_\nu &\sim 2i\frac{M_V^2}{v_{\rm SM}} g_{\mu\nu} \times \cos(\beta-\alpha) \end{aligned}$$

Introducing the Two-Higgs-Doublet Model (2HDM)

Mixing among the charged and the CP-odd components of the Higgs fields is controlled by $\tan\beta$ (since the composition of the Goldstone bosons is fixed by the relative vevs):

$$A^0 = -\sin\beta\,\phi_1^{0,i} + \cos\beta\,\phi_2^{0,i}, \qquad G^0 = \cos\beta\,\phi_1^{0,i} + \sin\beta\,\phi_2^{0,i}$$
$$H^+ = -\sin\beta\,\phi_1^{+} + \cos\beta\,\phi_2^{+}, \qquad G^+ = \cos\beta\,\phi_1^{+} + \sin\beta\,\phi_2^{+}$$

(Note that I am ignoring the possibility of CP violation, which would cause mixing among h^0, H^0, and A^0. More on this later.)

h^0 and H^0 can be produced singly via weak boson fusion:
- $pp \to W^*W^*$ (or Z^*Z^*) $\to h^0/H^0$

The other states can be produced in pairs via gauge interactions, in processes like:
- $pp \to Z^*/\gamma^* \to H^+H^-$
- $pp \to Z^* \to H^0A^0$ (or h^0A^0)
- $pp \to W^* \to H^\pm h^0$ (or $H^\pm H^0$ or $H^\pm A^0$)

(Production via fermion couplings coming soon!)

Introducing the 2HDM: Higgs basis

There is a simpler way to think about this mixing: the so-called "Higgs basis".

The two doublets have exactly the same quantum numbers; nothing stops us from redefining the two doublets as linear combinations of what we wrote before:

$$\Phi_v = \cos\beta\,\Phi_1 + \sin\beta\,\Phi_2, \qquad \Phi_0 = -\sin\beta\,\Phi_1 + \cos\beta\,\Phi_2$$

This basis is defined so that the vev lives entirely in Φ_v:

$$\Phi_v = \begin{pmatrix} G^+ \\ (v_{\rm SM} + (s_{\beta-\alpha}h^0 + c_{\beta-\alpha}H^0) + iG^0)/\sqrt{2} \end{pmatrix}$$

$$\Phi_0 = \begin{pmatrix} H^+ \\ ((c_{\beta-\alpha}h^0 - s_{\beta-\alpha}H^0) + iA^0)/\sqrt{2} \end{pmatrix}$$

$\Rightarrow$ Read off the gauge couplings. Only the combination of h^0 and H^0 that lives in Φ_v partakes of couplings of the form $hV_\mu V_\nu$, because these require one vev insertion.

2HDM fermion couplings

Most general gauge-invariant Yukawa couplings: generically just two copies of those of the SM:

$$\begin{aligned}\mathcal{L}_{Yuk.} &= -Y_{ij}^{d1}\bar{Q}_{Li}\Phi_1 d_{Rj} - Y_{ij}^{u1}\bar{Q}_{Li}\tilde{\Phi}_1 u_{Rj} - Y_{ij}^{\ell 1}\bar{L}_{Li}\Phi_1 e_{Rj} + \text{h.c.} \\ &\quad -Y_{ij}^{d2}\bar{Q}_{Li}\Phi_2 d_{Rj} - Y_{ij}^{u2}\bar{Q}_{Li}\tilde{\Phi}_2 u_{Rj} - Y_{ij}^{\ell 2}\bar{L}_{Li}\Phi_2 e_{Rj} + \text{h.c.}\end{aligned}$$

This immediately causes a phenomenological problem: flavour-changing neutral Higgs interactions.

Rotating to the fermion mass basis diagonalizes only the combinations $M^d = (Y^{d1}v_1 + Y^{d2}v_2)/\sqrt{2}$, etc.; orthogonal combinations are not diagonalized! In the Higgs basis:

$$\mathcal{L}_{Yuk.} = -\frac{\sqrt{2}M^d}{v_{\text{SM}}}\bar{Q}_L\Phi_v d_R - Y_0^d\bar{Q}_L\Phi_0 d_R + \cdots$$

Y_0^d is not automatically diagonalized by rotation to the fermion mass basis. Gives rise to processes like K^0–$\bar{K}^0$ and B^0–$\bar{B}^0$ oscillations at tree level from A^0 exchange. Very constrained!

2HDM fermion couplings: Natural Flavour Conservation

Traditional solution to avoid severe FCNC constraints: Natural Flavour Conservation [Glashow, Weinberg; Paschos 1977]

Philosophy: absence of large Higgs-mediated flavour-changing neutral currents (FCNCs) is due to symmetry structure of model, not tuning of parameters.

FCNCs can be avoided if the mass matrix in each sector of fermions (up-type quarks; down-type quarks; charged leptons) comes from coupling to exactly one Higgs doublet.

Example:

$$\begin{aligned}\mathcal{L}_{Yuk.} = & -Y_{ij}^{d1}\bar{Q}_{Li}\Phi_1 d_{Rj} - Y_{ij}^{u1}\bar{Q}_{Li}\tilde{\Phi}_1 u_{Rj} - Y_{ij}^{\ell 1}\bar{L}_{Li}\Phi_1 e_{Rj} + \text{h.c.} \\ & -Y_{ij}^{d2}\bar{Q}_{Li}\Phi_2 d_{Rj} - Y_{ij}^{u2}\bar{Q}_{Li}\tilde{\Phi}_2 u_{Rj} - Y_{ij}^{\ell 2}\bar{L}_{Li}\Phi_2 e_{Rj} + \text{h.c.}\end{aligned}$$

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Example:

$$\begin{aligned}\mathcal{L}_{Yuk.} = & -Y_{ij}^{d1}\bar{Q}_{Li}\Phi_1 d_{Rj} - 0\ \bar{Q}_{Li}\tilde{\Phi}_1 u_{Rj} - Y_{ij}^{\ell 1}\bar{L}_{Li}\Phi_1 e_{Rj} + \text{h.c.} \\ & - 0\ \bar{Q}_{Li}\Phi_2 d_{Rj} - Y_{ij}^{u2}\bar{Q}_{Li}\tilde{\Phi}_2 u_{Rj} - 0\ \bar{L}_{Li}\Phi_2 e_{Rj} + \text{h.c.}\end{aligned}$$

Only one Yukawa matrix for each type of fermion $\rightarrow$ automatically diagonalized in the mass basis.

2HDM fermion couplings: Natural Flavour Conservation

Implement Natural Flavour Conservation by imposing a Z_2 symmetry ($X \to -X$) acting on one of the Higgs fields and some of the right-handed fermion fields.

Choose $\Phi_1 \to -\Phi_1$, $\Phi_2 \to \Phi_2$. Then there are four physically-distinct choices of right-handed fermion charges:

	u_R	d_R	e_R	Φ_1	Φ_2	
Type I	$+$	$+$	$+$	$-$	u, d, ℓ	
Type II	$+$	$-$	$-$	d, ℓ	u	(same in MSSM)
Type X	$+$	$+$	$-$	ℓ	u, d	(a.k.a. Leptonic)
Type Y	$+$	$-$	$+$	d	u, ℓ	(a.k.a. Flipped)

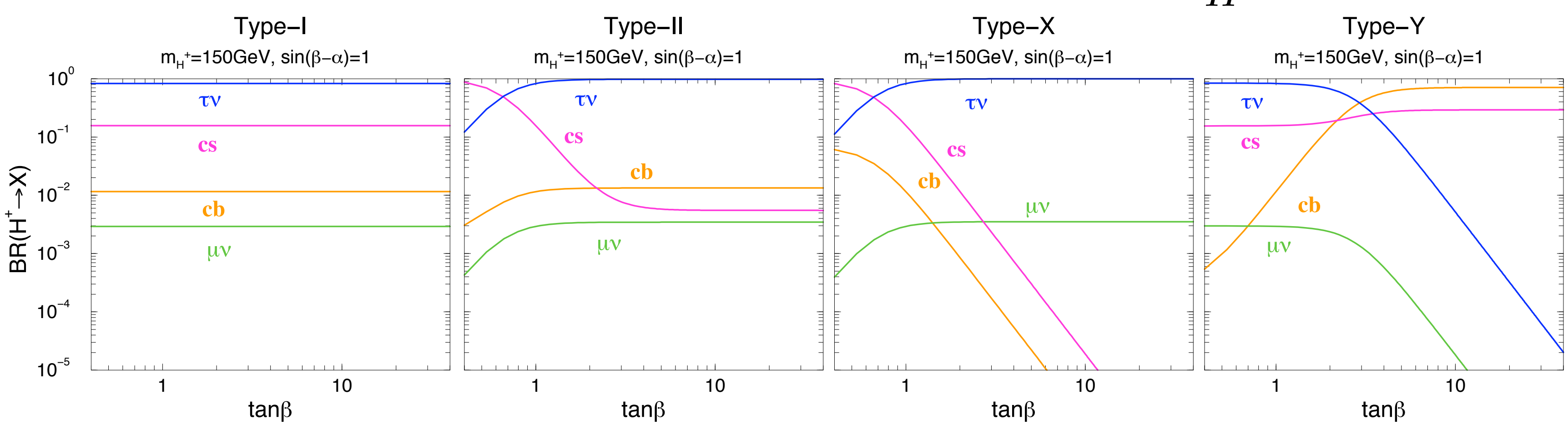
These choices control the pattern of the physical Higgs couplings to fermions.

2HDM fermion couplings: Natural Flavour Conservation

Example 1: Charged Higgs decays to fermions (all $\times \frac{ig}{\sqrt{2}M_W}$):

Model	$H^+\bar{u}_i d_j$	$H^+\bar{\nu}_i \ell_i$
Type I	$V_{ij}(\cot\beta\, m_{ui} P_L - \cot\beta\, m_{dj} P_R)$	$\cot\beta\, m_{\ell i} P_R$
Type II	$V_{ij}(\cot\beta\, m_{ui} P_L + \tan\beta\, m_{dj} P_R)$	$\tan\beta\, m_{\ell i} P_R$
Type X	$V_{ij}(\cot\beta\, m_{ui} P_L - \cot\beta\, m_{dj} P_R)$	$\tan\beta\, m_{\ell i} P_R$
Type Y	$V_{ij}(\cot\beta\, m_{ui} P_L + \tan\beta\, m_{dj} P_R)$	$\cot\beta\, m_{\ell i} P_R$

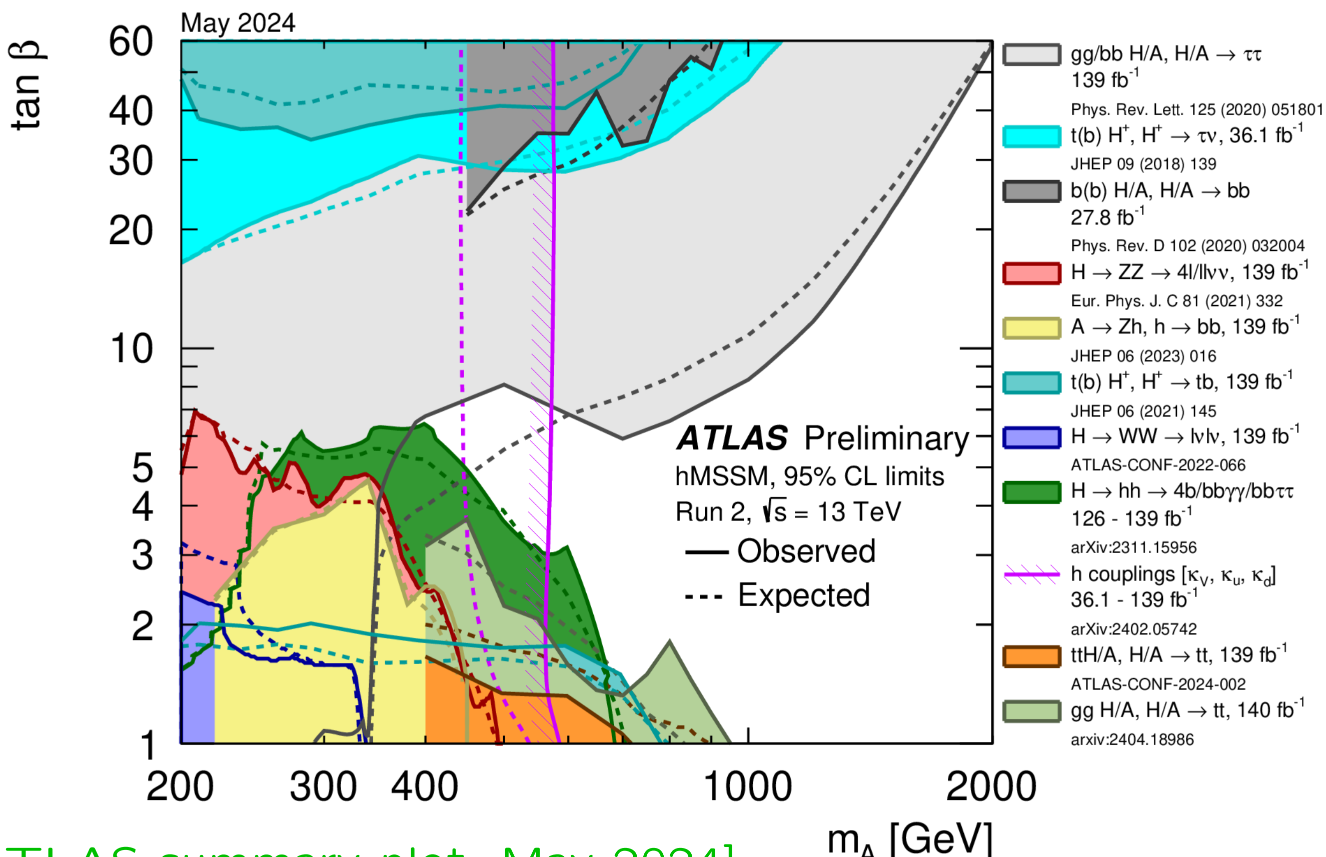
Physics controlled by $\tan\beta$ (can be large) and M_{H^+}.



Aoki et al, Phys. Rev. D80, 015017(2009)

2HDM fermion couplings: Natural Flavour Conservation

Example 2: $b\bar{b}$ (or gg) $\to H^0/A^0 \to \tau\tau$ gives very strong sensitivity in Type II (grey excluded area; plot is for an MSSM scenario).
Sensitivity greatly reduced in Type I & X (no production enhancement); a bit reduced in Type Y (less-sensitive $b\bar{b}$ final state).



[ATLAS summary plot, May 2024]

2HDM fermion couplings: flavour violation?

What if we allow flavour violation? $\Rightarrow$ Interesting new processes!
- $h^0 \to \tau\mu$, $t \to ch^0$, etc.

Two different types of motivation:

- Phenomenological models to address experimental anomalies (e.g. flavour-universality-violating meson decays)

- Symmetry-driven models to address theoretical puzzles (e.g. strong CP problem)

Have to obey stringent constraints from meson mixing & decays.

2HDM fermion couplings: flavour violation? - expt driven

Up to recently, there was a rather interesting deviation (a few sigma) from the SM in $R_{K^{(*)}}$:

$$R_{K^{(*)}} = \frac{\text{BR}(B \to K^{(*)}\mu^+\mu^-)}{\text{BR}(B \to K^{(*)}e^+e^-)}$$

Theoretically very "clean" observable: all of the hadronic uncertainties should cancel out! SM: e and μ should be entirely interchangeable aside from their masses.

Together with other "anomalies" in rare meson decays, this suggested new physics causing lepton universality violation.

One way to achieve this is a 2HDM with flavour violation.
- Allow the most generic Yukawa coups for both Higgs doublets.
- Apply constraints from other B decays.
- Check wiggle room for couplings to leptons not strictly proportional to their masses – can achieve [previously] observed deviation using a relatively light charged Higgs.

2HDM fermion couplings: flavour violation? - expt driven

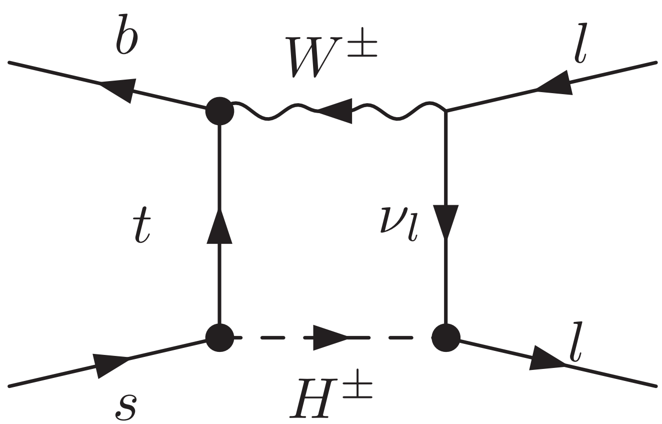
How does this work? Recall the Higgs basis:

$$\Phi_v = \begin{pmatrix} G^+ \\ (v_{SM} + (s_{\beta-\alpha} h^0 + c_{\beta-\alpha} H^0) + i G^0)/\sqrt{2} \end{pmatrix}$$

$$\Phi_0 = \begin{pmatrix} H^+ \\ ((c_{\beta-\alpha} h^0 - s_{\beta-\alpha} H^0) + i A^0)/\sqrt{2} \end{pmatrix}$$

Yukawa couplings to Φ_0 (where H^+ lives) need not be proportional to the fermion masses:

$$\mathcal{L}_{Yuk.} = -\frac{M^d v_{SM}}{\sqrt{2}} \bar{Q}_L \Phi_v d_R - Y_0^d \bar{Q}_L \Phi_0 d_R + \cdots$$



SM: W coupling to leptons universal; lepton flavour dependence is only from m_ℓ factors. Flavour violation introduces H^+ couplings not strictly proportional to m_ℓ.

[diagram from Arhrib et al., 1710.05898]

2HDM fermion couplings: flavour violation? - theory driven

One of the mysteries of the SM is the strong CP problem: why there is no observed CP violation in the strong interactions. Super tight constraint: neutron electric-dipole-moment constraint $\rightarrow$ relevant parameter $\lesssim 10^{-10}$ (vs. "natural" size $\sim \mathcal{O}(1)$).

- Usual solution is Peccei-Quinn mechanism $\rightarrow$ QCD axion

- Alternative solution is Nelson-Barr approach: no CP violation at all in the Lagrangian (so that strong-CP phase is zero); observed CP violation in CKM matrix comes from spontaneous breaking of CP. Have to also avoid loop-induced strong-CP phase up to 2 loops!

(In the SM, CP is explicitly violated by the Yukawa couplings.)

Very challenging model-building; seems to always give rise to some kind of extra flavour violation.

2HDM fermion couplings: flavour violation? - theory driven

Attempt to implement Nelson-Barr idea in 2HDM:

- Both doublets couple to all types of fermions.
- All entries in the Yukawa matrices are real.
- Yukawa matrices constrained by generation-dependent symmetry to have zeroes in certain strategic places.
- Generate the CP-violating phase of the CKM matrix from a relative phase between the vevs of the two doublets.

Example: Z_3 symmetry [Ferreira & Lavoura, 1904.08438]
Charges under Z_3: Φ_1 uncharged, Φ_2 charge 2;

Generation	Q_L	p_R	n_R
1	2	1	0
2	1	1	0
3	0	0	1

Any Lagrangian term must be (i) invariant under CP (i.e., real) and (ii) net charge 0 (mod 3) under the Z_3.

2HDM fermion couplings: flavour violation? - theory driven

Attempt to implement Nelson-Barr idea in 2HDM:

CP and Z_3 charges lead to highly restricted Yukawa matrices: e.g. for down quarks, (all entries real!) [Ferreira & Lavoura, 1904.08438]

$$Y^{d1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & b_1 \\ d_1 & f_1 & 0 \end{pmatrix} \qquad Y^{d2} = \begin{pmatrix} d_2 & f_2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & b_2 \end{pmatrix}$$

Ideal situation would be to spontaneously break CP.
This model requires explicit but soft CP and Z_3 breaking by the dimension-2 terms in the scalar potential.

- Generate the CKM matrix including its CP-violating phase!
- No strong-CP violation at tree level or one loop!
- Two-loop not yet checked (hard calc.); may be too large.
- FCNCs from Higgs exchange $\rightarrow$ constraints (manageable but kind of fine-tuned).
- Model-building: can we get spontaneous CP breaking?

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Lecture 2: Two-Higgs-Doublet Model and its delights
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- New scalar potential options: CP violation
- Dark matter: Inert 2HDM

2HDM scalar potential

Most general gauge-invariant scalar potential for the 2HDM is:

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

[Gunion & Haber hep-ph/0207010]

Imposing Z_2 sym ($\Phi_1 \to -\Phi_1$) for NFC kills off m_{12}^2, λ_6, and λ_7.

Minimize $\Rightarrow$ find v_1 and v_2 (trade them for m_{11}^2 and m_{22}^2).
Compute mass matrices $\Rightarrow$ find masses and mixing angle α.

Exact Z_2: all masses-squared $\sim \lambda v^2$; upper bound of $\sim$ 700 GeV!
Types II, X, and Y *excluded* by Bayesian global fit including LHC data (Chowdhury & Eberhardt, 2017)

Allow soft breaking of Z_2: reinstate $m_{12}^2 \Rightarrow$ decoupling limit; all 4 "Types" are fine because extra Higgses can be made heavier.

2HDM scalar potential and CP violation

Two of the parameters of the softly-broken-Z_2-symmetric scalar potential can be complex (only their relative phase is physical):

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

Most important effect is to induce mixing between h^0, H^0 and A^0: three neutral mass eigenstates, none of them CP eigenstates!

$$
\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \phi_v^{0,r} \\ \phi_0^{0,r} \\ \phi_0^{0,i} \end{pmatrix} = R \begin{pmatrix} c_\beta \phi_1^{0,r} + s_\beta \phi_2^{0,r} \\ -s_\beta \phi_1^{0,r} + c_\beta \phi_2^{0,r} \\ -s_\beta \phi_1^{0,i} + c_\beta \phi_2^{0,i} \end{pmatrix}
$$

(Convention: express scalars first in the Higgs basis; convenient since Goldstone boson is not affected by this new mixing.)

2HDM scalar potential and CP violation

New collider phenomena:

- Mixed-CP couplings of h^0_{125}: e.g. $h\bar{t}t \sim \frac{-im_t}{v}(a + i\gamma^5 b)$
(Rich LHC experimental program already!)

- All three neutral Higgs bosons (h_1, h_2, and h_3) couple to VV at tree level.
(Sum rule from orthogonality of mixing matrix: squares of couplings add up to SM strength.)

- Novel Higgs-to-Higgs decay: $h_3 \to h_1 h_2$ (two different-mass scalars in the final state).
(Real 2HDM: can have $H^0 \to h^0 h^0$, but no $A^0 \to H^0 h^0$ or $H^0 \to A^0 h^0$; forbidden by CP conservation!)

2HDM scalar potential and CP violation

Pattern of CP violation in Higgs couplings reveals whether CPV comes from scalar potential (only 1 new phase!) or from complex flavour-violating Yukawa couplings (different phases for different fermions!).

Example: Type-II Complex 2HDM: same R matrix for all couplings

$$h_1\bar{t}t \sim \frac{-im_t}{v}\left[(R_{11} + \cot\beta R_{12}) - i\gamma^5 R_{13}\cot\beta\right]$$

$$h_1\bar{\tau}\tau \sim \frac{-im_\tau}{v}\left[(R_{11} - \tan\beta R_{12}) - i\gamma^5 R_{13}\tan\beta\right]$$

Loop-induced CP-odd part of h_1VV coupling again comes entirely from the mixing – proportional to R_{13}.

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \phi_v^{0,r} \\ \phi_0^{0,r} \\ \phi_0^{0,i} \end{pmatrix} = R \begin{pmatrix} c_\beta\phi_1^{0,r} + s_\beta\phi_2^{0,r} \\ -s_\beta\phi_1^{0,r} + c_\beta\phi_2^{0,r} \\ -s_\beta\phi_1^{0,i} + c_\beta\phi_2^{0,i} \end{pmatrix}$$

2HDM scalar potential and CP violation

CP violation in scalar potential leads to 2HDM contribution to electric dipole moments (EDMs).

Electron EDM: $|d_e| < 4.1 \times 10^{-30} e\,\text{cm}$ (JILA 2022)
Full 2-loop calculation in Complex 2HDM (f depends on Type):

$$\left(\frac{1\ \text{TeV}}{M}\right)^2 \text{Im}(\lambda_5) \times f(\sin^2\beta, \cos^2\beta) \lesssim 0.5 - 1\%$$

Altmannshofer, Gori, Hamer, & Patel, 2020

A bit uncomfortably fine-tuned, even for heavy Higgses $\sim$TeV scale.

Nevertheless, there are good theoretical reasons to take the Complex 2HDM seriously: the known CP violation in quark Yukawa couplings generates divergent radiative corrections to the scalar potential CP phase... at 7 loops. Must have a counterterm in the theory, but the coefficient can be set tiny without worrying about it being regenerated by loops. [de Lima & me 2024]

A 2HDM variant for dark matter

Two basic facts about dark matter:
- It is electrically neutral (or at most, milli-charged).
- It has stuck around since the beginning of the universe (stable, or at least very long-lived).

Easiest way to make a particle stable is to have it be the lightest state that carries a particular conserved charge.
- Electron is stable because it's the lightest electrically-charged particle.
- Proton is stable because it's the lightest baryon.
  (Proton decay? $\leftrightarrow$ baryon number violation)

Dark matter model-building typically involves introducing a new conserved quantum number carried by the dark matter candidate.

A 2HDM variant for dark matter: Inert 2HDM

"Inert" 2HDM is built in exactly this way.

[Barbieri, Hall, & Rychkov, hep-ph/0603188]

Write down what's essentially the Type I 2HDM: Z_2 symmetry under which $\Phi_2 \to -\Phi_2$ while all other fields are unchanged.
$\to$ Yukawa couplings: all fermions couple to Φ_1 and none to Φ_2.

But now, choose the values of the scalar potential parameters so that Φ_2 does not get a vev. $\to Z_2$ remains unbroken!

Unbroken Z_2 prevents mixing between the two doublets:

$$\Phi_1 = \begin{pmatrix} G^+ \\ (v + h^0_{125} + iG^0)/\sqrt{2} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ (H^0 + iA^0)/\sqrt{2} \end{pmatrix}$$

The lightest member of Φ_2 is stable (choose parameters so that it is H^0 or A^0).

Collider signatures: $H^\pm$, H^0, A^0 pair-produced via gauge interactions; decay by W/Z emission to lightest Z_2-odd state, which escapes the detector as missing energy.

Summary of lecture 2 and Outlook

A sampling of all the things you can do with 2HDMs:
- Natural Flavour Conservation
- Flavour violation
- CP violation
- 2HDM for dark matter

A bit more emphasis on underlying theoretical motivations:
- Symmetries
- Attempts to solve theoretical problems in a more "natural" way
- Arguments from QFT about why violations of SM accidental-symmetries in more complicated models should not simply be ignored

Physics of extended Higgs sectors is rich and deep.
Experimental probes are getting more and more interesting.