

CP Violation In and Beyond The Standard Model

Two Higgs Doublet Model Type II Contributions to Flavour Observables

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The Standard Model

- One of the great achievements of the 20th Century, the Standard Model:

$$\mathcal{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{gauge fields}} + \underbrace{i\bar{\Psi}\not{D}\Psi}_{\text{fermions}} + \underbrace{(D_{\mu}\Phi)^{\dagger}(D^{\mu}\Phi) - V(\Phi)}_{\text{Higgs}} - \underbrace{Y_{ij}\bar{\Psi}_i\Phi\Psi_j}_{\text{Yukawa}} + h.c.$$

- A gauge field theory describing matter and its interactions with 25 fundamental particles
- Each particle is described by a field transforming under the gauge groups of the Standard Model: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
- Has successfully described numerous particle phenomena we have observed to date

Unsolved Problems of the Standard Model

- Quantum gravity; Dark matter; Neutrino masses
- Deviations between experiment and theory, e.g. $\mathcal{R}(K^{(*)})$ to $\approx 3\sigma$
- Sakharov Criteria for Baryogenesis:
 1. Baryon Number Violation - theorised in Sphalerons
 2. C and CP Violation - present but not enough
 3. First Order Phase Transition - only if $m_h < 60 \text{ GeV}$

To answer these questions, we need to consider models to extend our physics Beyond the Standard Model. These models should:

- preserve predictions in agreement with experiment
- agree with experimental bounds
- follow the structures of gauge field theory for a physical model, e.g. renormalisability

The Two Higgs Doublet Model Type II

In the Standard Model:

- One complex Higgs doublet, 4 scalar fields:

$$\Phi_1 = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_0 + i\phi_3 \end{pmatrix}$$

- 3 fields “eaten” by W^\pm, Z bosons; 1 real field left, h
- Introduce $\tilde{\Phi} = i\sigma_2 \Phi_1$ for masses of all fermions

In 2HDM:

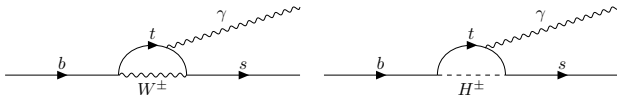
- Add a second doublet, now 8 scalar fields

$$\Phi_2 = \begin{pmatrix} \phi_5 + i\phi_6 \\ \phi_4 + i\phi_7 \end{pmatrix}$$

- Now 5 fields left - H^\pm, H^0, h^0, A^0
- No need for Hermitian conjugate
- In Type II, Φ_1 couples to down quarks; Φ_2 to up quarks and charged leptons

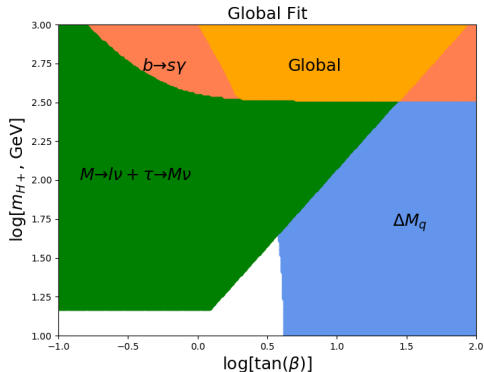
Why Two Higgs Doublet Model?

- Minimal Extension to SM
- Limited number of new parameters:
 - ➔ Masses of H^\pm, H^0, A^0 ; VEV ratio $\tan \beta = \frac{v_2}{v_1}$; scalar mixing angle
- Sakharov Criteria:
 1. Baryon Number Violation - Sphalerons
 2. C and CP violation - more of it
 3. First Order Phase Transition - now present
- Charged weak currents gain additional decay paths, replacing W^\pm with H^\pm - allows for easy constraining



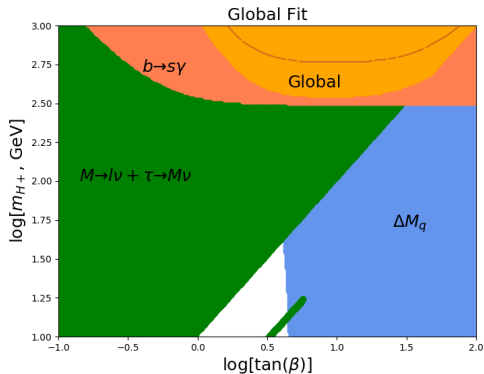
First Inputs

- 1σ scan
- Leptonic, mixing, and radiative
- No hard constraint on $\tan\beta$
- $m_{H^\pm} > 340$ GeV



Statistical Fitting of Scans

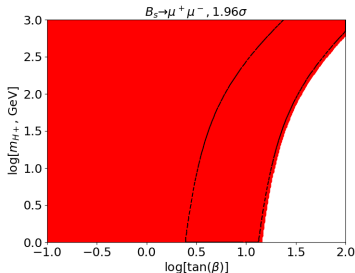
- Aimed to replicate process of original paper (see below)
- Used 2009 inputs
- Scanned at 95% CL
- χ^2 fit to 1σ
- Replicated $m_{H^+} \gtrsim 316$ GeV, 95% CL



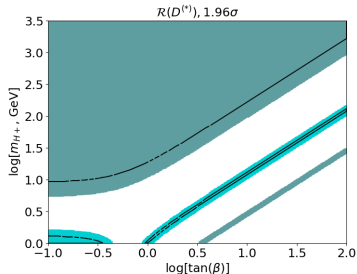
O Deschamps et al, Phys. Rev. D82 (2010) 073012, arxiv:0907.5135 [hep-ph]

New Inputs

➤ $B_s \rightarrow \mu^+ \mu^-$



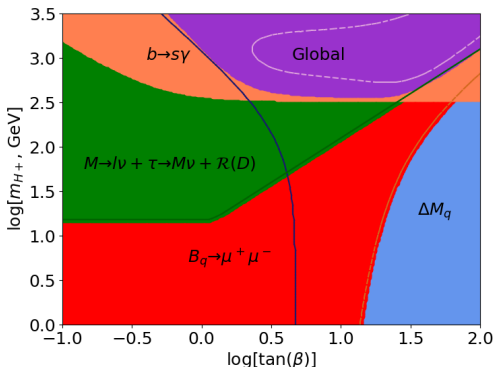
➤ $R(D^{(*)}) = \frac{\Gamma[B \rightarrow D^{(*)} \tau \nu]}{\Gamma[B \rightarrow D^{(*)} l \nu]}$



- 2HDM historically struggles fitting both $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$
- Does this kill the 2HDM?

Extended Global Fit

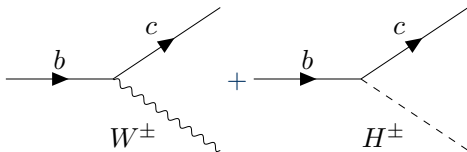
- Added $B_s \rightarrow \mu^+ \mu^-$ and $\mathcal{R}(D)$
- $\mathcal{R}(D^*)$ not included
- 95% CL: $m_{H^+} > 390$ GeV
- 1σ : $m_{H^+} > 530$ GeV
- $\tan \beta \gtrsim 2$



CKM Element Modifications

- CKM Matrix contains information of quark mixing
- In SM, a 3×3 unitary matrix
- Measurements would be modified in 2HDM as

$$V_{ij} = \frac{V_{ij}^{SM}}{f^{SM} + f^{2HDM}},$$



- Exclusive measurements from light quark mesons would have negligible change, but heavy quarks could introduce significant changes
- Possibility to improve unitarity constraints, e.g. second row currently sums to > 1

3. Extension to SM4

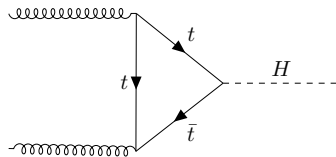
Four Generations?

Why SM4?

- ▶ 3×3 CKM $\rightarrow 4 \times 4$; $1 \rightarrow 3$ CP-violating phases; $3 \rightarrow 6$ mixing angles, θ_{ij}
- ▶ Jarlskog invariant could increase significantly - more CP violation!
- ▶ New heavy quarks, t' and b' , extra loop diagrams to change decay widths
- ▶ A simple extension, and no reason for 3, so why not 4?

Exclusion of Chiral SM4:

- ▶ Light neutrinos measured precisely as $N_\nu = 3$
- ▶ SM4 gluon fusion ≈ 9 times SM3 gluon fusion from heavy quarks



SM4 with 2HDM Type II

- A Chiral SM4 not excluded with 2HDM
- Introduce a “wrong sign” limit to cancel new Higgs couplings

$$\kappa_u = -\kappa_{d,l}$$

- For $\tan \beta \gg 2$, the wrong sign limit yields

$$\cos(\beta - \alpha) = \frac{2}{\tan \beta}, \quad \cos(\beta - \alpha) = \sin 2\beta$$

- These are equivalent in the large $\tan \beta$ limit
- Relations allow us to reduce free parameters of SM4×2HDM
- Aim to extend 2HDM scans to SM4 and constrain model using flavour observables

Any Questions?