CP Violation In and Beyond The Standard Model

Two Higgs Doublet Model Type II Corrections to Flavour Observables

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The Standard Model

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

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

- 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: $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$
- Has successfully described most 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. $\mathcal{R}(K^{(*)})$
- Sakharov Criteria for Baryogenesis:
  1. Baryon Number Violation - found in Sphalerons
  2. C and CP Violation - present but not enough
  3. First Order Phase Transition - only if $m_h < 60\,\mathrm{GeV}$

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:

$$\Phi_1 = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_0 + i\phi_3 \end{pmatrix} \qquad (2)$$

- 3 fields "eaten" by $W^{\pm}, Z$ bosons; 1 real field left, h
- Introduce the Hermitian conjugate for masses of all fermions

In 2HDM:

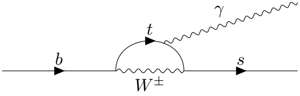
- Add a second doublet, now 8 scalar fields

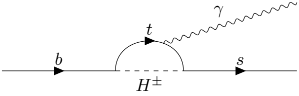
$$\Phi_2 = \begin{pmatrix} \phi_5 + i\phi_6 \\ \phi_4 + i\phi_7 \end{pmatrix} \qquad (3)$$

- 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?

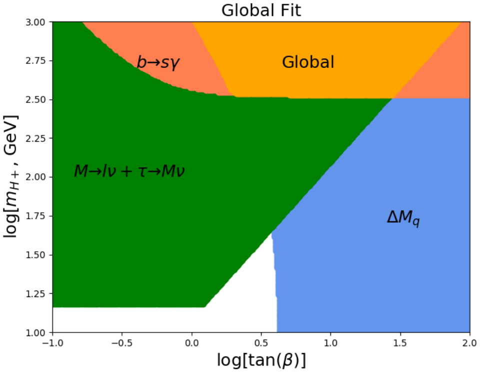
- Minimal Extension to SM
- Limited number of new parameters:
  - Masses of $H^{\pm}, H^0, A^0$; VEV ratio $\tan\beta = \frac{v_2}{v_1}$; scalar mixing angle
- Sakharov Criteria:
  1. Baryon Number Violation - Sphalerons
  2. C and CP violation - more of it
  3. First Order Phase Transition - now present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





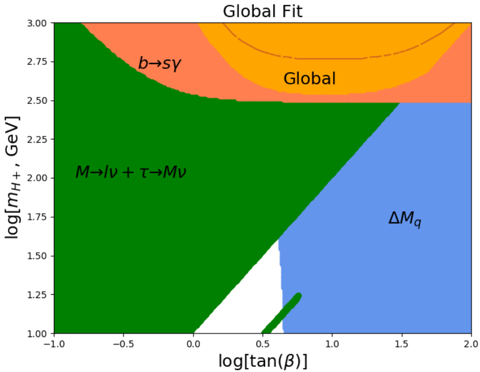
First Inputs

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



Statistical Fitting of Scans

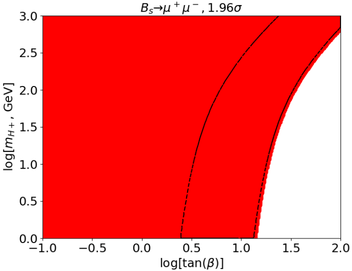
- Aimed to replicate process of original paper (see below)
- Scanned at 95% CL
- χ^2 fit to 1σ
- Replicated $m_{H^+} \gtrsim 316\,\text{GeV}$, 95% CL

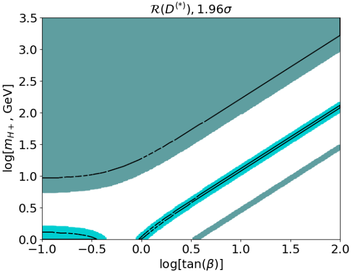


O Deschamps et al, Phys. Rev. D82 (2010) 073012, arxiv:0907.5135 [hep-ph]

New Inputs

- $B_s \to \mu^+\mu^-$
- $R(D^{(*)}) = \frac{\Gamma[B \to D^{(*)}\tau\nu]}{\Gamma[B \to D^{(*)} l\nu]}$

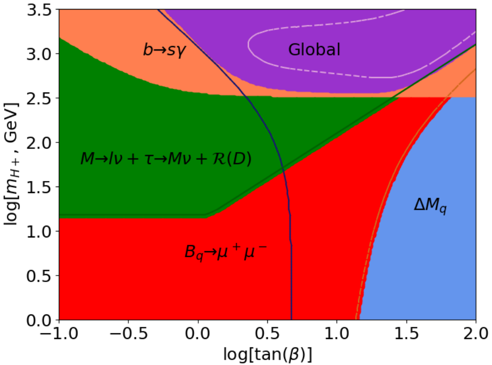




- 2HDM historically struggles fitting both $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$
- Does this kill the 2HDM?

Extended Global Fit

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



CKM Element Modifications

- CKM Matrix contains information of quark mixing
- In SM, a 3×3 unitary matrix
- Measurements would be incorrect in 2HDM; e.g. from leptonic decays, modified as

$$V_{ij} = \frac{V_{ij}^{SM}}{(1 + r_H)^2} \tag{4}$$

- Exclusive measurements from light quark mesons would have negligible change
- Possibility to improve unitarity constraints, e.g. second row currently sums to > 1
- Space for a fourth generation?

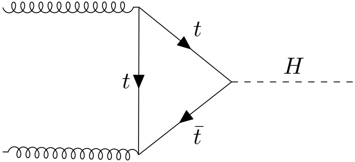
Four Generations?

Why SM4?

- 3×3 CKM $\rightarrow 4 \times 4$; 1 CP-violating phase to 3
- 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 $\approx$ 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

$$\kappa_u = -\kappa_{d,l} \tag{5}$$

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

$$\cos(\beta - \alpha) = \frac{2}{\tan\beta}, \qquad \cos(\beta - \alpha) = \sin 2\beta \tag{6}$$

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

Any Questions?