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:

$$\mathcal{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{gauge fields}} \underbrace{+i\bar{\Psi}\slashed{D}\Psi}_{\text{fermions}} \underbrace{+(D_\mu\Phi)^\dagger(D^\mu\Phi) - V(\Phi)}_{\text{Higgs}} \underbrace{-Y_{ij}\bar{\Psi}_i\Phi\Psi_j + h.c.}_{\text{Yukawa}}$$

➤ 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 $m_h < 60$ 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
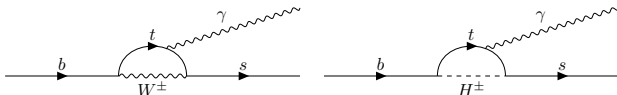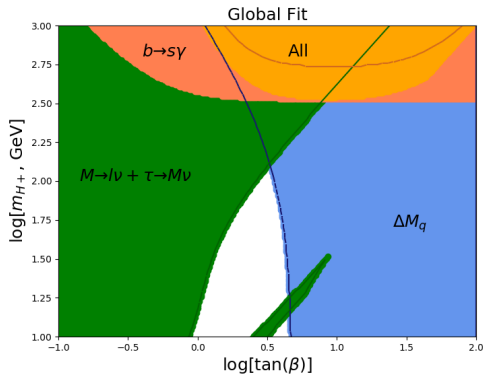
First Inputs

- ➤ 2σ scan
- ➤ Leptonic, mixing, and radiative
- ➤ No hard constraint on $\tan\beta$
- ➤ $m_{H^+} > 440\,\text{GeV}$
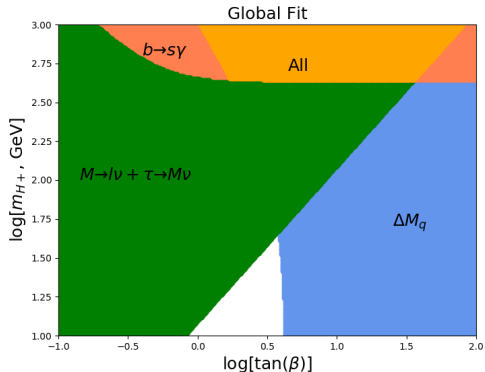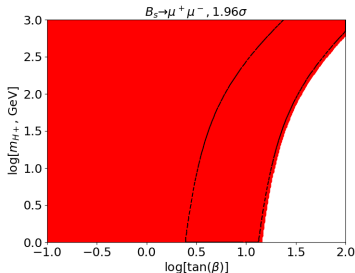
Statistical Fitting of Scans

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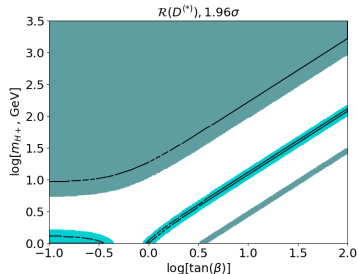- ➤ χ^2 fit to 1σ
- ➤ Replicated $m_{H^+} \gtrsim 316$ GeV, 95% CL

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

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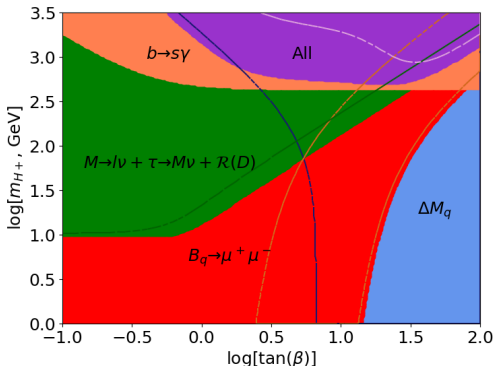
New Inputs

➤ $B_s \to \mu^+ \mu^-$

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

$B_s \to \mu^+ \mu^-$, 1.96σ

$\mathcal{R}(D^{(*)})$, 1.96σ

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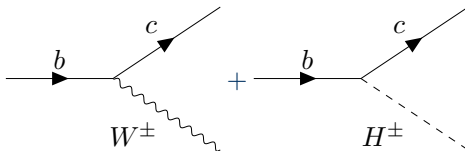
➤ Does this kill the 2HDM?

Extended Global Fit

- ➤ Added $B_s \to \mu^+ \mu^-$ and $\mathcal{R}(D)$
- ➤ $\mathcal{R}(D^*)$ not included
- ➤ 95% CL: $m_{H^+} > 530\,\text{GeV}$
- ➤ 1σ: $m_{H^+} > 870\,\text{GeV}$
- ➤ No hard constraint on $\tan\beta$

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

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 $\approx$ 9 times SM3 gluon fusion from heavy quarks
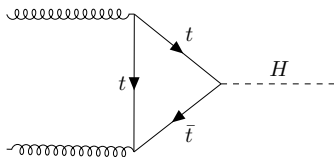
SM4 with 2HDM Type II

➤ A Chiral SM4 not excluded with 2HDM

➤ Introduce a "wrong sign" limit to cancel new Higgs couplings

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

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

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

➤ 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

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Any Questions?