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: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
- 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 $m_h < 60\,\text{GeV}$

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:

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

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

In 2HDM:

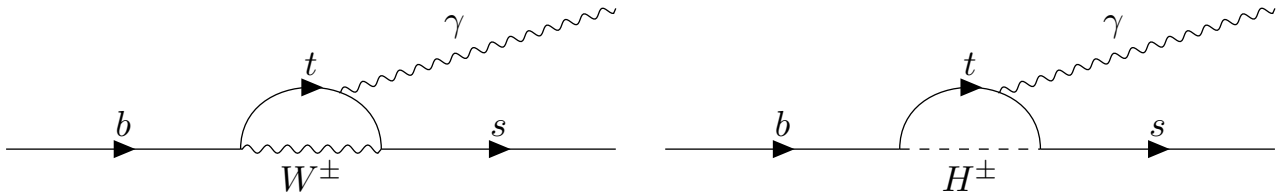
- Add a second doublet, now 8 scalar fields

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

- 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

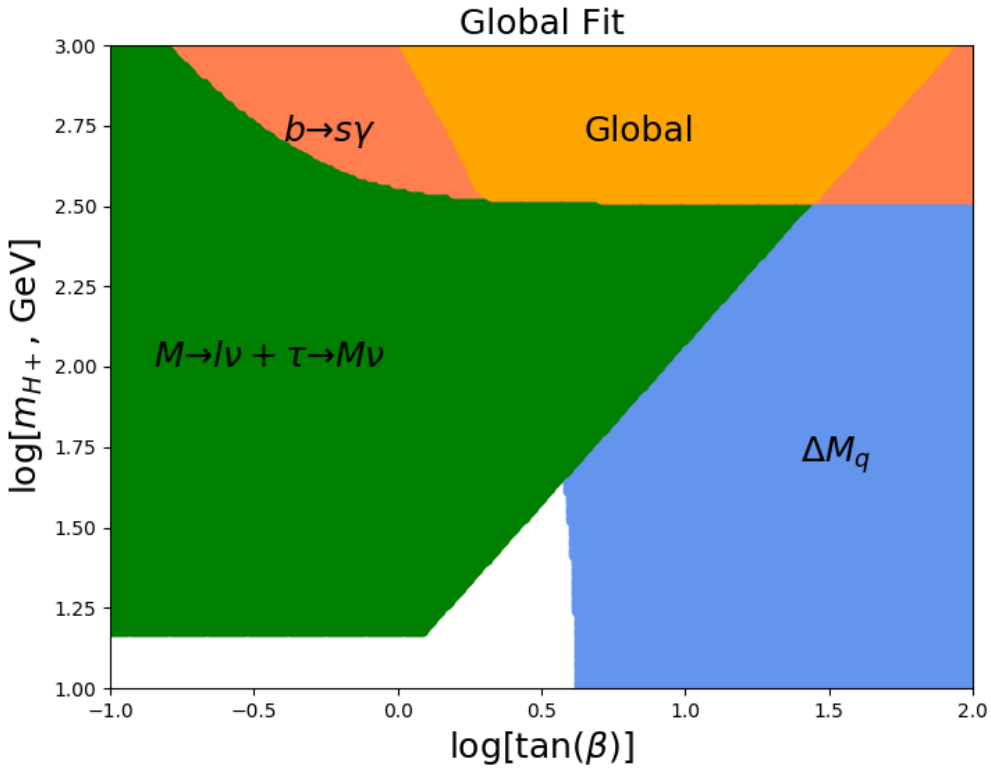
Why Two Higgs Doublet Model?

- 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



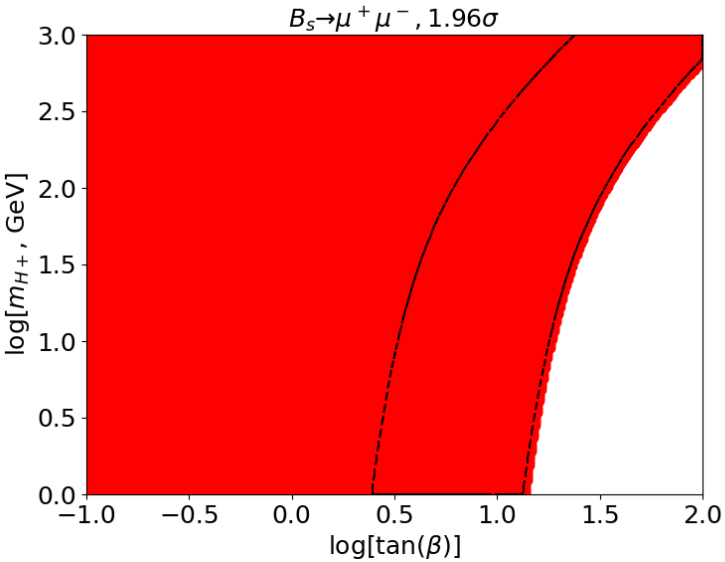
First Inputs

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

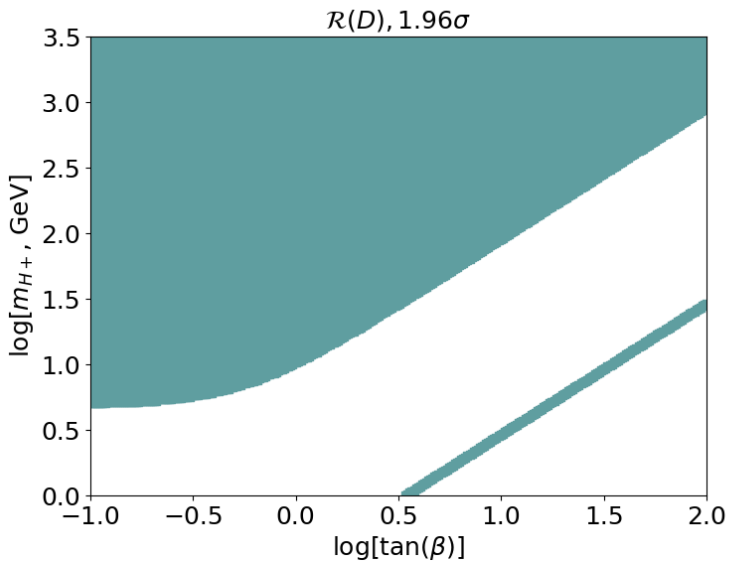


New Inputs

- $B_s \to \mu^+\mu^-$

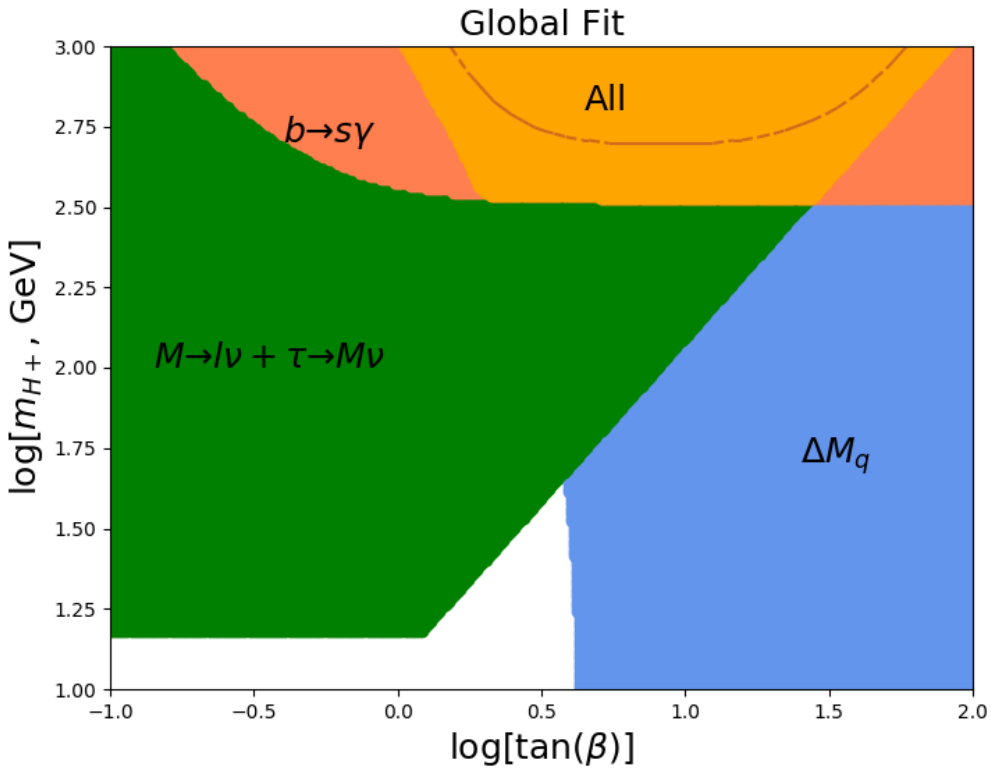


- $R(D^{(*)})$ BOTH



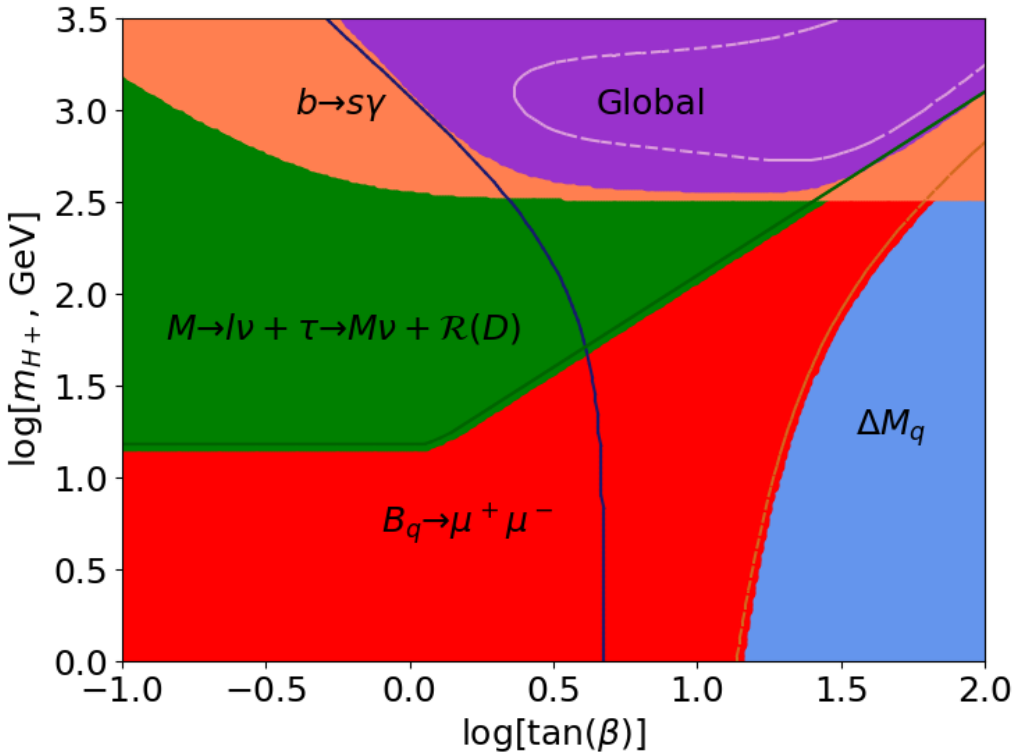
Statistical Fitting of Scans

- Scanning
- Sigma
- Chi



Extended Global Fit

- 95% CL: $m_{H^+} > 390\,\text{GeV}$
- 1σ: $m_{H^+} > 530\,\text{GeV}$
- $\tan\beta \gtrapprox 2$



CKM Element Modifications

Four Generations?

SM4 with 2HDM Type II

Any Questions?