SUSY 2013

Flavour & NP

How much can NP contribute to flavour observables?

Good agreement of SM tree-level mediated processes with exp.

Example: CKM unitarity:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0008(7)$$

From $0^+ \to 0^+ e\nu$ superallowed β decays: $|V_{ud}| = 0.97425(22)$

From $K^+ \to \pi^+ e\nu$ decay: $|V_{us}| = 0.2237(13)$

From $B \to X_u \ell\nu$: $|V_{ub}| = 4.2(5) \times 10^{-3}$

Testing of charged weak current universality between leptonic and semileptonic processes to $\mathcal{O}(1‰)$ level. (muon life time)

Consider NP contribution to SM (loop, CKM) suppressed observables.

$\Rightarrow$ can use CKM determination from tree-level observables

$|V_{us}|, |V_{cb}|, |V_{ub}|, \gamma$ from $B \to DK$ (α from $B \to \pi\pi$)

$\Rightarrow$ can predict SM contributions to loop observables

Example : NP in $B-\bar{B}$ mixing

$$M_{12} = M_{12}^{SM} \, r_d^2 \, e^{2i\theta_d}$$

heavy NP only contributing to dispersive amplitudes

change in magnitude — change in phase

$$\Delta m_B = r_d^2 \, (\Delta m_B)^{SM}$$

$$S^{(B)}_{\psi K_S} = \sin(2\beta + 2\theta_d)$$

$$a^{(d)}_{SL} = -\,\mathrm{Re}\left(\frac{\Gamma_{12}}{M_{12}}\right)^{SM} \frac{\sin\theta_d}{r_d^2} + \mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)^{SM} \frac{\cos 2\theta_d}{r_d^2}$$

$$\Delta m_B = 51.0(4) \times 10^{10}/s$$

$$S^{(B)}_{\psi K_S} = 0.671(24)$$ In SM with tree-level inputs: $\left[S^{(B)}_{\psi K_S}\right]^{tree}_{SM} = 0.76(4)$

$$A_{SL} = -0.2(7) \times 10^{-3}$$

$\Rightarrow$ NP in M_{12} with large phase relative to β is constrained to 20% - 30% of SM contribution $\Rightarrow$ CKM dominates CPV in $B-\bar{B}$ mixing

(similarly in $K^0-\bar{K}^0$: $\varepsilon_K = 1.596(13) \times 10^{-3}$, theory limited)

$\Rightarrow$ NP in M_{12} with phase aligned to β is constrained to be at most comparable to SM contribution.

(similarly in $K^0-\bar{K}^0$: $\Delta m_K = 52.93(9) \times 10^{8}/s$, theory limited)

In B_s mixing NP can be at most comparable to SM contribution regardless of the phase since $S^{SM}_{\psi\phi} \ll S^{exp}_{\psi\phi}$

The NP flavour puzzle

SM is not a complete theory of nature:

1.) Does not include (quantum) gravity => validity limited below $m_{Planck} \simeq 10^{19}$ GeV

2.) Does not include neutrino masses => validity limited below $M_{see-saw} \sim 10^{15}$ GeV

3.) Fine-tuning in EWSB scale compared to the large scales in (1), (2) suggests NP already at $\sim 4\pi v \sim 1$ TeV (possibly related to cosmological DM if wimp)

Given SM is EFT, need to consider additional terms consisting of SM field operators with canonical dimension $d>4$:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{M} \frac{C_M^{(d)}}{\Lambda^{d-4}} \mathcal{O}_M^{(d)}$$

{ SM fields only

- for natural theory: $C_M^{(d)} \sim \mathcal{O}(1)$ unless forbidden/suppressed by symmetry

For $\Lambda \sim$ TeV and without imposing additional symmetries BSM, the above condition is severely violated for several $\mathcal{O}_M^{(6)}$ which contribute to FC processes

"NP flavour puzzle" (if there is NP at TeV why haven't we seen effects in flavor observables?)

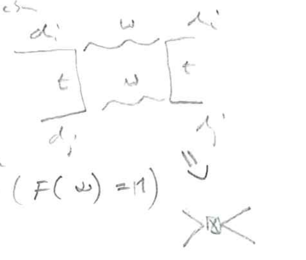
- similar to B & L violation, however B & L exact accidental (classically) symmetries of SM;

In SM flavour symmetry already broken...

Bounds on NP from $\Delta F = 2$ processes

In SM: dispersive contribution to $\Delta F = 2$ observables dominated by boxes with t-quarks

corrections due to c in K-K̄



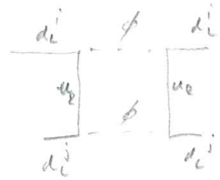
$$M_{12}^{SM} = \underbrace{\frac{G_F^2 m_t^2}{16\pi^2} \left(V_{ti}^* V_{tj}\right)^2}_{\frac{\left(Y_u Y_u^*\right)_{ij}}{128\pi^2 m_t^2}} \frac{\langle \bar{M} | (\bar{d}_L^i \gamma_\mu d_L^j)^2 | M\rangle}{2 m_M} F\left(\frac{m_t^2}{m_W^2}\right) + \dots$$

loop function $\mathcal{O}(1)$ $(F(\infty) = 1)$

$M = K^0, B^0, B_s$

$d^{i,j}$ – meson valence quarks

corresponds to Goldstone Higgs exchanges in the $g \to 0$ limit



Hadronic matrix elements:

$$\langle \bar{M} | (\bar{d}_L^i \gamma_\mu d_L^j)(\bar{d}_L^i \gamma^\mu d_L^j) | M\rangle = \frac{2}{3} f_M^2 m_M^2 \hat{B}_M$$

bag parameter

$1 \to 1$ particle

decay constant

$$\langle 0 | \bar{d}^i \gamma_\mu \gamma_5 d^j | M(p)\rangle \equiv i p_\mu f_M$$

$1 \to 0$ particle

Nonperturbative hadronic quantities computed numerically using lattice QCD methods.

Tremendous progress: $f_B = 0.186(4)$ GeV $\quad f_{B_s} = 0.224(5)$ GeV

$\hat{B}_B = 1.27(10) \quad \hat{B}_{B_s} = 1.33(6)$ [FLAG]

$f_K = 0.1563(9)$ GeV

$\hat{B}_K = 0.7661(99)$

$1 \to 0$ P.M.E.: decay constants: 1% – 5%

$1 \to 1$ P.M.E.: Bag parameters, form factors: ~ 1% – 10%

$1 \to 2$ P.M.E.: recent progress in K physics ($K \to \pi\pi$) ~ $\mathcal{O}$(30% – 1)

$$\mathcal{L}^{NP}_{\Delta F=2} = \frac{c_{sd}}{\Lambda^2}\left(\bar d_L \gamma^\mu s_L\right)^2 + \frac{c_{bd}}{\Lambda^2}\left(\bar d_L \gamma^\mu s_L\right)^2 + \frac{c_{bs}}{\Lambda^2}\left(\bar s_L \gamma^\mu b_L\right)^2$$

$$+ \frac{c_{cu}}{\Lambda^2}\left(\bar u_L \gamma^\mu c_L\right)^2 + \frac{c_{tu}}{\Lambda^2}\left(\bar u_L \gamma^\mu t_L\right)^2 + \frac{c_{tc}}{\Lambda^2}\left(\bar c_L \gamma^\mu t_L\right)^2$$

$$\Rightarrow \frac{M_{12}^M}{m_M} \sim c_{ij}\left(\frac{f_M}{\Lambda}\right)^2$$

$$\frac{\Delta m_K}{m_K} \sim 7\times 10^{-15} \Rightarrow \frac{\Lambda}{\sqrt{|c_{sd}|}} \gtrsim 10^3\ \mathrm{TeV} \quad \text{or} \quad |c_{sd}| \lesssim 10^{-6}\left(\frac{\Lambda}{\mathrm{TeV}}\right)^2$$

$$\frac{\Delta m_D}{m_D} \sim 9\times 10^{-15} \Rightarrow \frac{\Lambda}{\sqrt{|c_{cu}|}} \gtrsim 10^3\ \mathrm{TeV} \quad \text{or} \quad |c_{cu}| \lesssim 10^{-6}\left(\frac{\Lambda}{\mathrm{TeV}}\right)^2$$

$$\frac{\Delta m_B}{m_B} \sim 6\times 10^{-14} \Rightarrow \frac{\Lambda}{\sqrt{|c_{bd}|}} \gtrsim 4\times 10^2\ \mathrm{TeV} \quad \text{or} \quad |c_{bd}| \lesssim 5\times 10^{-6}\left(\frac{\Lambda}{\mathrm{TeV}}\right)^2$$

$$\frac{\Delta m_{B_s}}{m_{B_s}} \sim 2\times 10^{-12} \Rightarrow \frac{\Lambda}{\sqrt{|c_{bs}|}} \gtrsim 70\ \mathrm{TeV} \quad \text{or} \quad |c_{bs}| \lesssim 2\times 10^{-4}\left(\frac{\Lambda}{\mathrm{TeV}}\right)^2$$

In case of maximal phases:

$$\varepsilon_K \sim 2.3\times 10^{-3} \Rightarrow \frac{\Lambda}{\sqrt{\mathrm{Im}(c_{sd})}} \gtrsim 2\times 10^4\ \mathrm{TeV} \quad \text{or} \quad |\mathrm{Im}(c_{sd})| \lesssim 6\times 10^{-6}\left(\frac{\Lambda}{\mathrm{TeV}}\right)^2$$

$$\frac{A_\Gamma}{y_{CP}} \lesssim 0.2 \Rightarrow \frac{\Lambda}{\sqrt{\mathrm{Im}(c_{cu})}} \gtrsim 3\times 10^3\ \mathrm{TeV} \quad \text{or} \quad |\mathrm{Im}(c_{cu})| \lesssim 10^{-7}\left(\frac{\Lambda}{\mathrm{TeV}}\right)^2$$

$$S_{\psi K_S} = 0.67(2) \Rightarrow \frac{\Lambda}{\sqrt{\mathrm{Im}(c_{bd})}} \gtrsim 8\times 10^2\ \mathrm{TeV} \quad \text{or} \quad |\mathrm{Im}(c_{bd})| \lesssim 10^{-6}\left(\frac{\Lambda}{\mathrm{TeV}}\right)^2$$

$$S_{\psi\phi} = 0.1(2) \Rightarrow \frac{\Lambda}{\sqrt{\mathrm{Im}(c_{bs})}} \gtrsim 70\ \mathrm{TeV} \quad \text{or} \quad |\mathrm{Im}(c_{bd})| \lesssim 2\times 10^{-4}\left(\frac{\Lambda}{\mathrm{TeV}}\right)^2$$

NP with generic flavor structure irrelevant for EW hierarchy $\Lambda \gg$ TeV

In case of TeV NP, flavor structure far from generic

EFT analysis of SM contributions

Integrating out all particles, heavier than the neutral mesons

$$\frac{(M_{12}^{M})_{SM}}{M_M} \sim c_{ij}^{SM}\left(\frac{f_M}{\Lambda_{SM}}\right)^2$$

where: $\Lambda_{SM} \sim v$; $c_{ij}^{SM} \sim \frac{y_t^2}{64\pi^2}\left(V_{ti}^* V_{tj}\right)^2 \left(+ \frac{y_c^2}{64\pi^2}\left(V_{ci}^* V_{cj}\right)^2 \right)$

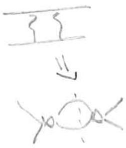
$$\mathrm{Im}\left(c_{sd}^{SM}\right) \sim \frac{y_t^2}{64\pi^2}\left|V_{td}V_{ts}\right|^2 \sim 10^{-10}$$

$$c_{sd}^{SM} \sim \frac{y_c^2}{64\pi^2}\left|V_{cd}V_{cs}\right|^2 \sim 5\times 10^{-9}$$

$$c_{bd}^{SM} \sim \frac{y_t^2}{64\pi^2}\left|V_{td}V_{tb}\right|^2 \sim 7\times 10^{-8}$$

$$c_{bs}^{SM} \sim \frac{y_t^2}{64\pi^2}\left|V_{tb}V_{ts}\right|^2 \sim 2\times 10^{-6}$$

$\frac{\Delta M_D}{M_D}$ LD dominated (real intermediate states)



Why TeV NP should be suppressed to levels comparable to SM estimates: ⇒ NP flavor puzzle!

Flavour measurements are a great probe of NP.

Example: Supersymmetry