$\Delta F = 1$ Constraints on Minimal Flavor Violation

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New Physics Flavor Problem

The SM accurately describes high energy physical phenomena up to $\mu_W \gtrsim 100$ GeV.

It is however known to be incomplete – gravity, unification.

But if it is an effective theory, at what scale ($\Lambda < \Lambda_{\mathrm{Planck},GUT}$) does it break down?

$$\mathcal{L}(\mu_W) = \underbrace{\Lambda^2 H^\dagger H}_{\text{EW scale}} + \lambda (H^\dagger H)^2 + \mathcal{L}_{SM}^{\text{gauge}} + \mathcal{L}_{SM}^{\text{Yukawa}} + \underbrace{\frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \dots}_{\text{FCNC, CPV, etc.}}$$

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EW hierarchy problem suggests: $\Lambda \lesssim 1$ TeV
Flavor bounds on generic NP operators:

$s \to d$:	$\Lambda \gtrsim 2 \times 10^5$ TeV	from ϵ_K
$b \to d$:	$\Lambda \gtrsim 2 \times 10^3$ TeV	from $A_{CP}(B_d \to \Psi K_s)$, Δm_d
$b \to s$:	$\Lambda \gtrsim 40$ TeV	from $Br(B \to X_s \gamma)$

recent analysis
UT*fit* '07

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EW hierarchy problem suggests: $\Lambda \lesssim 1$ TeV
Flavor bounds on generic NP operators: $\Lambda \sim 10^2 - 10^5$ TeV

Tension between these estimates of expected NP scales.

MFV Hypothesis

D'Ambrosio et al. hep-ph/0207036

All flavor symmetry breaking in and beyond the SM is proportional to the SM Yukawas:

- CKM is the only source of flavor mixing even beyond SM
- All (non-helicity suppressed) tree level and CP violating processes are constrained to their SM values
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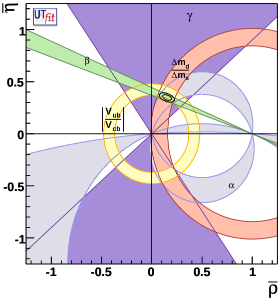

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Single Higgs doublet or low $\tan\beta = v_u/v_d$

- NP FCNCs in the down quark sector are driven by the large top Yukawa (λ_t)
- SM operator basis in the effective weak Hamiltonian is complete

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Large $\tan\beta$

- bottom Yukawa contributions become important as $\lambda_b(\sim m_b \tan\beta/v_u) \sim \lambda_t$
- partial lifting of helicity suppression in the down sector
- new density operators contribute to the effective weak Hamiltonian

MFV Signals

$\Delta F = 2$

- box loop mediated in the SM, few operators contributing
- moderate sensitivity to large $\tan\beta$ scenario
- K, B_q oscillation observables

recent UT*fit* analysis (0707.0636 [hep-ph])

$\Delta F = 1$

- penguin loop mediated in the SM, many operators contributing (orthogonal to $\Delta F = 2$)
- interesting role of large $\tan\beta$ scenario
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No updated model independent analysis in the recent years.

$\Delta F = 2$ processes

$$\mathcal{H}_{\rm eff}^{\Delta F=2} = \frac{G_F^2 m_W^2}{8\pi^2} |V_{ti}^* V_{tj}|^2 C_0 \left[\bar{d}_i \gamma_\mu (1-\gamma_5) d_j\right]^2$$

$$C_0(\mu_W) \to C_0(\mu_W)^{SM} (= S_0(x_t)/2) + \delta C_0$$

The shift can than we translated in terms of the tested energy scale $(\Lambda_0 = \lambda_t \sin^2(\theta_W) m_W / \alpha_{em} \sim 2.4\ \ \text{TeV})$

$$\delta C_0 = 2a \frac{\Lambda_0^2}{\Lambda^2}$$

where $a \sim 1$ for tree level NP contributions and $a \sim 1/16\pi^2$ for loop suppressed NP contributions

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UT*fit* 0707.0636 [hep-ph]

small tan β

NP shift δC_0 is a universal factor for K and B_q mixing:

$$\Lambda > 5.5 \text{ TeV @95\% Prob.}$$

large tan β

$\lambda_b \tan\beta$ contributions break NP universality between Kaon and B sectors:

$$\Lambda > 5.1 \text{ TeV @95\% Prob.}$$

At very large tan β

new operator contributes due to Higgs exchange in loop

$$\frac{a'}{\Lambda^2}\lambda_i\lambda_j \left[\bar{d}_i(1-\gamma_5)d_j\right]\left[\bar{d}_i(1+\gamma_5)d_j\right]$$

with a' being the $\tan\beta$ enhanced loop factor – relevant contributions to B_s mixing: bound on the charged Higgs mass

$$m_H^+ > 5\sqrt{a'}(\tan\beta/50) \text{ TeV @95\% Prob.}$$

$\Delta F = 1$ processes

$$\mathcal{H}_{eff}^{\Delta F=1} = \frac{G_F \alpha_{em}}{2\sqrt{2}\pi \sin^2\theta_W} V_{ti}^* V_{tj} \sum_n C_n \mathcal{Q}_n + \text{h.c.}$$

Independent NP contributions to the various operators: $C_i = C_i^{SM} + \delta C_i$

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EM and QCD dipole operators

$$\mathcal{Q}_{7\gamma} = \frac{2}{g^2} m_j \bar{d}_{iL} \sigma_{\mu\nu} d_{jR} (eF_{\mu\nu}) \qquad \mathcal{Q}_{8G} = \frac{2}{g^2} m_j \bar{d}_{iL} \sigma_{\mu\nu} T^a d_{jR} (g_s G^a_{\mu\nu})$$

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$$\mathcal{Q}_{9V} = 2 \bar{d}_{iL} \gamma_\mu d_{jL} \; \bar{\ell} \gamma_\mu \ell \qquad \mathcal{Q}_{10A} = 2 \bar{d}_{iL} \gamma_\mu d_{jL} \; \bar{\ell} \gamma_\mu \gamma_5 \ell$$

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density operator at large $\tan\beta$

$$\mathcal{Q}_{S-P} = 4(\bar{d}_{iL} d_{jR})(\bar{\ell}_R \ell_L)$$

Z-penguin operator

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NP contributions in QCD penguin operators neglected.

Observables

Theoretically most clean observables used to bound NP contributions:

- $\mathbf{Br(B \to X_s \ell^+ \ell^-)}$ measured in 4 bins. We ommit the charmonium resonance region.

  Operators contributing: $\mathcal{Q}_{7\gamma}$, $\mathcal{Q}_{8G}$, $\mathcal{Q}_{9V}$, $\mathcal{Q}_{10A}$, $\mathcal{Q}_{S-P}$

  We use partial NNLO result including all NP contributions and rescale the expressions so that our SM prediction agrees with the full NNLO EM corrected result (only needed for the high q^2 region).

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- **$\mathbf{Br(K^+ \to \pi^+ \nu \bar{\nu})}$** hints.

  Operator contributing: $\mathcal{Q}_{\nu\bar{\nu}}$

  Theoretically clean by combining $K\ell 3$ experimental data.

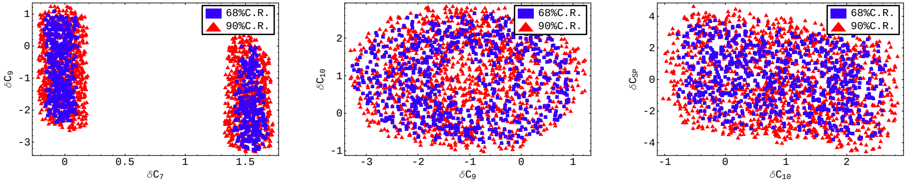
Inputs and Strategy

- CKM Inputs:
  - Use UUT fit correlated results from tree level observables and CKM phase.
- Known NP Correlations:
  - $C_{7\gamma}$ and C_{8G} always appear in the same quadratic combination – form degenerate ellipses in the parameter plane. We omit δC_{8G} from the fit.
  - $C_{\nu\bar{\nu}}$ contributes only to $K^+ \to \pi^+ \nu\bar{\nu}$. Perform a separate fit.
- Fit procedure:
  - MC sampling of input parameter space. Combined fit of all correlated observables (minimal $\chi^2/\text{d.o.f} \simeq 0.5$, SM $\chi^2/\text{d.o.f} \simeq 1$).

Results

Discrete ambiguities and correlations

- $\delta C_{7\gamma}$ is bounded up to a single discrete ambiguity from $B \to X_s\gamma$.
- δC_{10A} and δC_{9V} contribute comparably in the higher q^2 regions of $B \to X_s\ell^+\ell^-$ resulting in a bound on their quadratic combination (ellipse).
- δC_{S-P} is then mostly bounded by $B_s \to \mu^+\mu^-$
- A slight correlation develops between $\delta C_{7\gamma}$ and δC_{9V} due to their interference term, dominating the low q^2 region in $B \to X_s\ell^+\ell^-$.
- Small correlation also between δC_{10A} and δC_{S-P} due to their interference in $B_s \to \mu^+\mu^-$.



Limits

Conservative estimate

Taking into account all correlations and discrete ambiguities (allowing for fine-tuned solutions).

$\delta C_{7\gamma}$	$\Lambda > 1.6$ TeV @ 95% Prob.
δC_{8G}	$\Lambda > 1.2$ TeV @ 95% Prob.
δC_{9V}	$\Lambda > 1.4$ TeV @ 95% Prob.
δC_{10A}	$\Lambda > 1.5$ TeV @ 95% Prob.
δC_{S-P}	$\Lambda > 1.2$ TeV @ 95% Prob.
$\delta C_{\nu\bar{\nu}}$	$\Lambda > 1.5$ TeV @ 95% Prob.

Bounds are convention dependent. Compared to previous analysis (D'Ambrosio et al. hep-ph/0207036):

- Factor of $1/\sqrt{2}$ for penguin operators.
- Factor of e, g_s for $\delta C_{7\gamma,8G}$

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Individual couplings

Due to the small correlations, the bounds do not improve dramatically. Exceptions are $\delta C_{7\gamma,8G}$ and δC_{9V}. Especially if we discard the fine-tuned solution for the former.

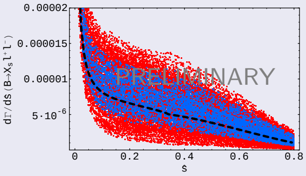
$\delta C_{7\gamma}$	$\Lambda > 2.0(5.3)$ TeV @ 95% Prob.
δC_{8G}	$\Lambda > 1.4(3.1)$ TeV @ 95% Prob.
δC_{9V}	$\Lambda > 1.6$ TeV @ 95% Prob.

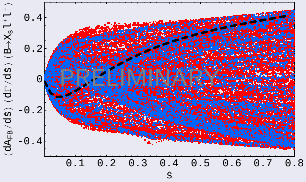
Window for new physics in other observables

Using NP parameter combinations within the 95% C.L. regions of our fit, we make predictions for other observables.

Observables to discriminate between SM and MFV NP

- **$dA_{FB}(B \to X_s \ell^+ \ell^-)/dq^2$ and its zero:**
  Present bounds still allow for the full range of possible predictions for both the integrated A_{FB} as well as for the position or absence of the zero of $(dA_{FB}/dq^2)/(d\Gamma/dq^2)$.





- Similar results for the exclusive channel $B \to K^* \ell^+ \ell^-$.

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Observables to invalidate MFV and probe large $\tan\beta$

- $(\mathbf{d\Gamma(B \to K\mu^+\mu^-)/dq^2})/(\mathbf{d\Gamma(B \to Ke^+e^-)/dq^2})$:
  In the SM this ratio is close to 1. In MFV with large $\tan\beta$ up to $\mathcal{O}(10\%)$ deviations in the high q^2 region are still allowed.

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- $\mathbf{Br(B_d \to \mu^+\mu^-) < 1.2 \times 10^{-9}}$
  Similar suppression for other $b \to d$ transitions.

Summary

- Model independent bounds can be set on the complete set of MFV NP contributions (also in the limit of large $\tan\beta$).
  - Bounds on NP contributions in $\Delta F = 2$ processes very constraining
  - In $\Delta F = 1$ processes, presently only $\delta C_{7\gamma}$ (δC_{8G}) bounds of comparable strength
  - Most uncertainties dominated by experiment - improvement welcome.

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- Prospects for other observables:
  - A lot of room left for large MFV NP contributions: (zero of) $A_{FB}(B \to X_s \ell^+ \ell^-)$, $A_{FB}(B \to K^* \ell^+ \ell^-)$
  - Possibilities to invalidate MFV: $|V_{td}/V_{ts}|^2 \sim 4\%$ $B_d \to \mu^+\mu^-$, $B \to X_d \gamma$, $B \to X_d \ell^+ \ell^-$, etc. should be suppressed.
  - Distinctive new signals of large $\tan\beta$: $d\Gamma(B \to K\mu^+\mu^-)/dq^2)/(d\Gamma(B \to Ke^+e^-)/dq^2)$

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  - Distinctive new signals of large $\tan\beta$:
    $d\Gamma(B \to K\mu^+\mu^-)/dq^2)/(d\Gamma(B \to Ke^+e^-)/dq^2)$
- Also these bounds are consistent with new degrees of freedom being found at the LHC

Tree level NP d.o.f. exchange:	$\Lambda \gtrsim 1$ TeV
Loop NP d.o.f. exchange:	$\Lambda \gtrsim 100$ GeV