Flavour physics

within and beyond the Standard Model

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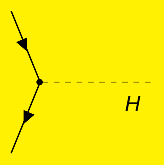
Contents

Yukawa sector

Yukawa coupling of the Higgs field:

$$y_{ij}\bar{f}_i f_j (v + H)$$



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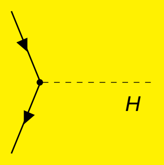

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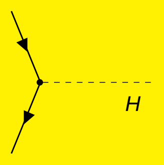

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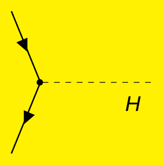

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10 parameters in the quark sektor,
10 or 12 parameters in the lepton sector.

Expand the CKM matrix V in $V_{us} \simeq \lambda = 0.2246$:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3\left(1+\frac{\lambda^2}{2}\right)(\overline{\rho}-i\overline{\eta}) \\ -\lambda - iA^2\lambda^5\overline{\eta} & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\overline{\rho}-i\overline{\eta}) & -A\lambda^2 - iA\lambda^4\overline{\eta} & 1 \end{pmatrix}$$

with the Wolfenstein parameters λ, A, $\overline{\rho}$, $\overline{\eta}$

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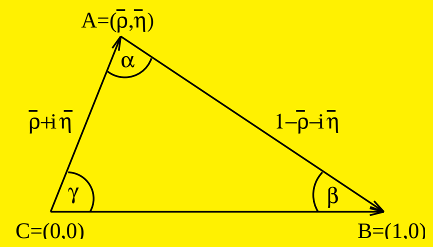
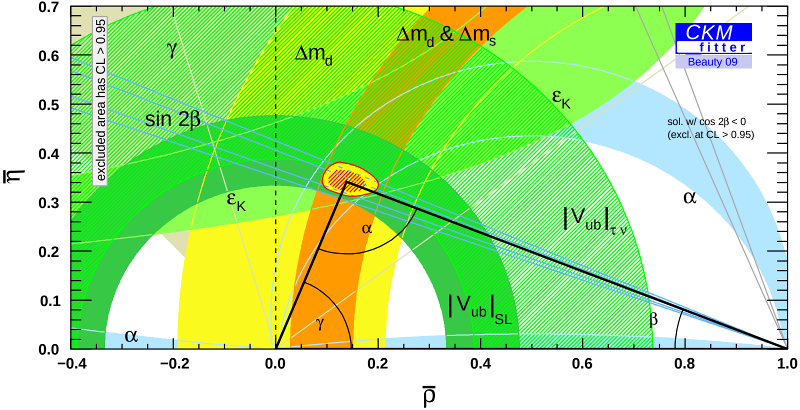
Unitarity triangle:

Exact definition:

$$\overline{\rho}+i\overline{\eta} = -\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} = \left|\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right| e^{i\gamma}$$



Experimental status of the unitarity triangle



consistent with the Standard Model

CKM mechanism confirmed at $\sim 2\sigma$.

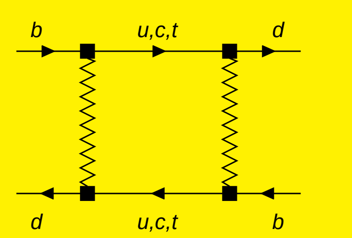
LHC era: directly plot new physics contribution
Generic parametrisation:

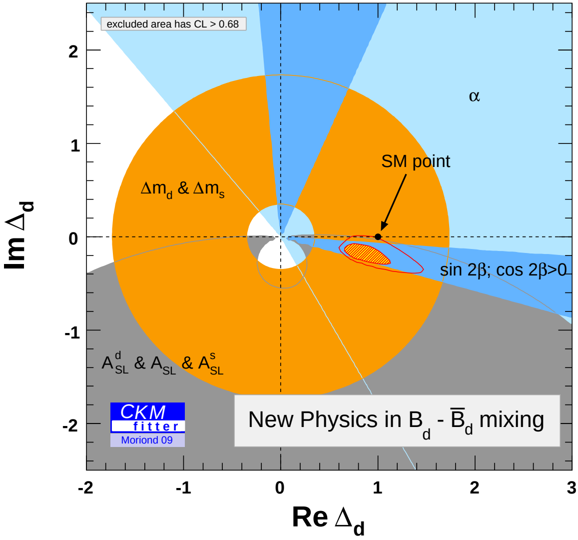
Define the complex parameter Δ_d in the $\mathrm{B_d} - \overline{\mathrm{B}}_\mathrm{d}$ mixing amplitude M_{12}^d through

$$M_{12}^d \equiv M_{12}^{\mathrm{SM,d}} \cdot \Delta_d \, .$$

In the Standard Model $\Delta_d = 1$. Alex Lenz, U.N. 2006

$M_{12}^{\mathrm{SM,d}} \propto$





Consistent with SM at CL$\geq$ 95%.

Less tension with new physics in $B_d - \bar{B}_d$ mixing, $B_s - \bar{B}_s$ mixing or $K - \bar{K}$ mixing.

Lunghi,Soni 2008
Buras,Guadagnoli 2008

Progress on ϵ_K:

$$\epsilon_K \equiv \frac{\langle(\pi\pi)_{I=0}|K_{\rm long}\rangle}{\langle(\pi\pi)_{I=0}|K_{\rm short}\rangle}$$

involves

$$\langle K|\overline{d}_L\gamma_\nu s_L\,\overline{d}_L\gamma^\nu s_L|\overline{K}\rangle \propto \widehat{B}_K$$

New lattice calculation: $\widehat{B}_K = 0.724(8)(29)$

Aubin, Laiho, Van de Water, PRD 81 (2010) 014507, 0905.3947 [hep-lat]

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2% upward shift of ϵ_K from long-distance contributions to $\operatorname{Im} M_{12}$.

Buras, Guadagnoli, Isidori 1002.3612

Mass differences: $\Delta m_q \simeq 2|M_{12}|^q$

$$\Delta m_{B_d}^{\rm exp} = (0.507 \pm 0.005)\ {\rm ps}^{-1}$$

$$\Delta m_{B_s}^{\rm exp} = (17.77 \pm 0.10 \pm 0.07)\ {\rm ps}^{-1}$$

Hadronic matrix element entering M_{12}^q, $q = d, s$:

$$\langle B_q | \overline{q}_L \gamma_\nu b_L\, \overline{q}_L \gamma^\nu b_L | \overline{B}_q \rangle \ \propto\ f_{B_q}^2 \widehat{B}_{B_q}$$

CKM elements:

$$\left|\frac{V_{td}}{V_{ts}}\right| = \sqrt{\frac{\Delta m_{B_d}}{\Delta m_{B_s}}}\sqrt{\frac{M_{B_s}}{M_{B_d}}}\,\xi$$

with

$$\xi \equiv \frac{f_{B_s}\sqrt{\widehat{B}_{B_s}}}{f_{B_d}\sqrt{\widehat{B}_{B_d}}}$$

The status of ξ was summarised by C. Aubin at Lattice'09. My bold average:

$$\xi = 1.23 \pm 0.04$$

implying

$$\frac{|V_{td}|}{|V_{ts}|} = 0.210 \pm 0.007,$$

which translates to the side R_t of the UT:

$$R_t = 0.92 \pm 0.03$$

Same game with $\mathrm{B_s - \overline{B}_s}$ mixing:

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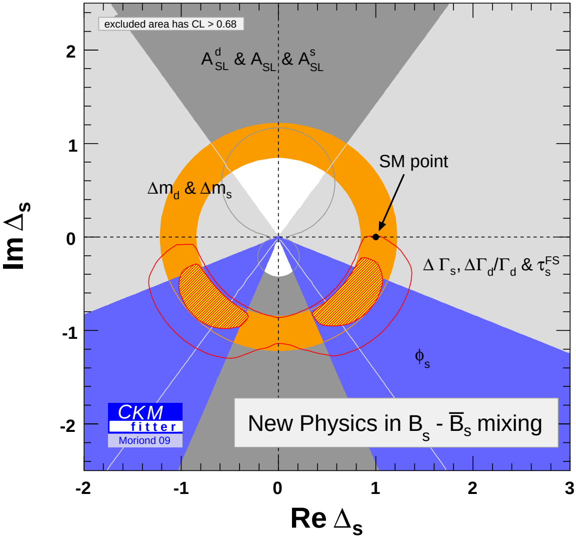
Measurements constraining Δ_s:

mass difference Δm_s,
width difference $\Delta \Gamma_s$,
CP asymmetry in flavour-specific (e.g semi-leptonic) decays a_{fs},
CP asymmetry in $B_s \to J/\psi\phi$.



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Supersymmetry

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SUSY flavour problem

TeV–scale new physics is dominantly minimally flavour–violating (MFV).

Minimal Flavour Violation

Symmetry-based definition (D'Ambrosio et al., 2002):

The gauge sector is invariant if all quark fields are rotated in flavour space: $[U(3)]^3$ symmetry.

MFV: This $[U(3)]^3$ symmetry is only broken by the Yukawa couplings $Y_{jk}^{u,d}$.

$\Rightarrow$ All squark-mediated FCNCs involve the same CKM elements as the SM amplitudes.

Naive definition:

MFV: Only W–quark, H^+–quark and chargino–squark loops violate flavour and all involve the same CKM elements.

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Flavour universality: SUSY-breaking is flavour-blind.

Bilinear squark mass terms:

$$M_{jk}^{\tilde{Q},LL}, M_{jk}^{\tilde{u},RR}, M_{jk}^{\tilde{u},RR} \propto \delta_{jk}$$

Trilinear terms:

$$A_{jk}^{u,d} \propto Y_{jk}^{u,d}$$

If flavour universality is imposed at some (high or low) scale, the symmetry-based definition of MFV is fulfilled at any scale.

In practice: The naive definition is good enough, even if flavour universality is imposed at a very high scale such as $M_{\rm GUT}$.

Typical impact of new physics on FCNC loop processes in MFV scenarios: corrections of order $\frac{M_{\rm ew}^2}{M_{\rm NP}^2} = \mathcal{O}(5\%)$.

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Present-day experiments are sensitive to MFV effects, if the loop suppression is offset by some parametric enhancement.

$\Rightarrow$ large-tan β scenarios in the MSSM

Large tan β

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- Interesting case of Yukawa unification, $y_b \approx y_t$:

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- Large $\tan\beta \Leftrightarrow$ small v_d

tan β-enhancement

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$$m_b \propto v_d \quad , \quad \delta m_b \propto loop \cdot v_u$$

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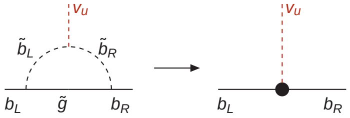
- Such $\mathcal{O}(1)$ corrections must be resummed to all orders.

Resummation of tan β-enhanced corrections

1. Effective Lagrangian in the decoupling limit

[Hall,Rattazzi,Sarid; Hamzaoui,Pospelov,Toharia; Babu,Kolda; Buras,Chankowski,Rosiek,Slawianowska;Isidori,Retico Dedes,Pilaftsis;Beneke,Ruiz-Femenia,Spinrath; Gorbahn,Jäger,UN,Trine]

Assume $M_{\text{SUSY}} \gg M_{\text{EW}}, M_{A^0}, M_{H^+}$ and integrate out SUSY fields, keep only Higgs and SM fields, e.g.

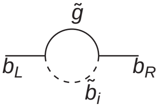


Result: Effective two-Higgs-doublet model with FCNC couplings of neutral Higgs bosons H^0 and A^0.

$\Rightarrow$ Higgs-mediated FCNCs.

2. Calculation in the full MSSM beyond decoupling (this talk)

- renormalization of bottom mass via self-energies like



$$= m_b \Delta_b = m_b \epsilon_b \tan\beta$$

- Bottom Yukawa coupling:

$$y_b = \frac{m_b \left[1 - \Delta_b + \Delta_b^2 - \ldots\right]}{v \cos\beta} = \frac{m_b}{v \cos\beta} \frac{1}{1 + \Delta_b}$$

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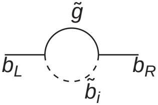

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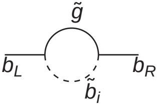

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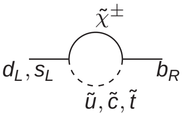
$$\epsilon_b = -\frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu^* C_0(m_{\tilde{g}}, m_{\tilde{b}_1}, m_{\tilde{b}_2})$$

+chargino and neutralino contributions

One-loop self-energy:



$$= m_b \frac{\epsilon_{FC} \tan\beta}{1 + \epsilon_b \tan\beta} V_{tb}^* V_{ti}$$

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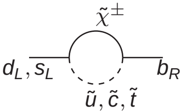

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. . . to be cancelled by a matrix-valued field renormalisation:

$$\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}^{\text{bare}} = \left(1 + \frac{\delta Z^L}{2}\right) \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

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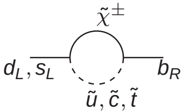

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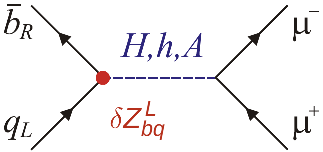
Important: $\delta Z^{L,R} \propto \tan\beta$, so that $\delta Z^{L,R}$ counts as $\mathcal{O}(1)$ in $\tan\beta$ -resummed perturbation theory.

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

Holy grail of the large-tan β MSSM: $B_s \to \mu^+\mu^-$



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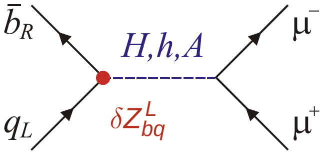


Current experimental bound:

$$Br(B_s \to \mu^+\mu^-)^{\text{exp}} \lesssim 13 \cdot Br(B_s \to \mu^+\mu^-)^{\text{SM}} \qquad @95\%\text{CL.}$$

[CDF 2009, DØ 2009]

$$\Rightarrow \quad \left[\frac{\tan\beta}{50}\right]^6 \left[\frac{450\,\text{GeV}}{M_A}\right]^4 \lesssim 1$$

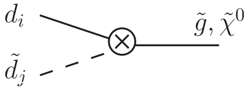
for equal SUSY mass parameters.

$\Rightarrow$ excludes large Higgs-mediated effects in B_s–$\overline{B}_s$ mixing or nonleptonic decays

[Altmannshofer et al.; Beneke et al.]

FCNC gluino couplings

Effect: $\delta Z^{L,R}$ induces flavour-changing gluino and neutralino couplings:



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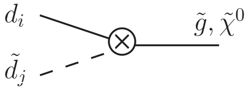
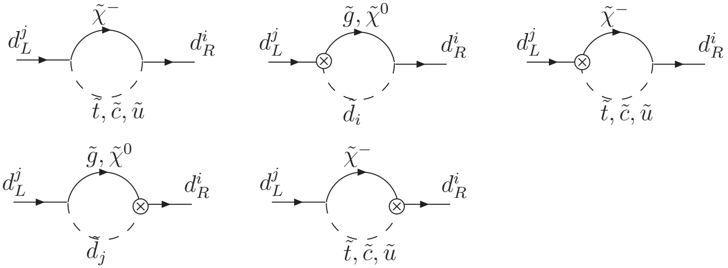


Self-energy including enhanced corrections:



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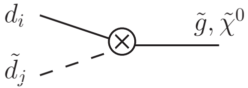
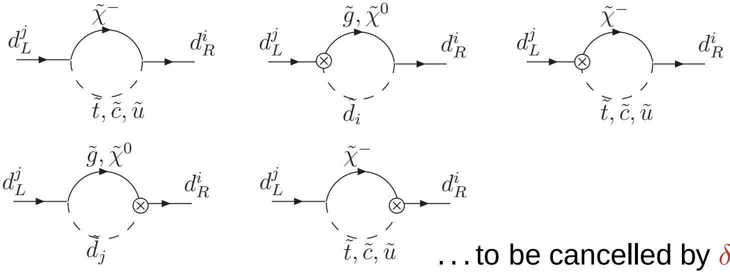


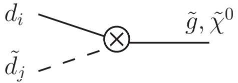
Self-energy including enhanced corrections:



...to be cancelled by $\delta Z_{ij}^{L,R}$.

$\Rightarrow$ Implicit equation for $\delta Z_{ij}^{L,R}$.

Application: $B_d \to \phi K_S$



Assess the flavour-changing gluino-squark loops entering the Wilson coefficients in $\mathcal{H}_{\text{eff}}^{\Delta B=1}$:

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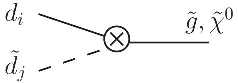
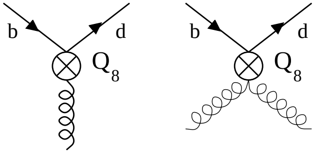


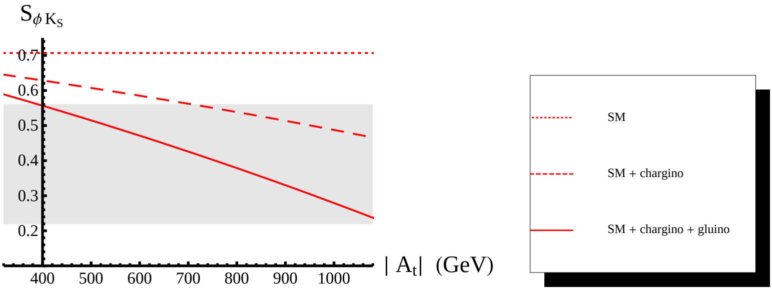
Assess the flavour-changing gluino-squark loops entering the Wilson coefficients in $\mathcal{H}_{\text{eff}}^{\Delta B=1}$:

negligible effects on coefficients of four-quark operators and C_7 , but important for chromomagnetic coefficient C_8 .



Application: $B_d \to \phi K_S$

- Mixing-induced CP asymmetry in $B_d \to \phi K_S$ in naive factorization, including $\tan\beta$ -enhanced corrections to C_8 :



Here $\mu = 800$ GeV is used, compatible with $\mathcal{B}(\bar{B} \to X_s \gamma)$.

Hofer, UN, Scherer

Flavour violation from trilinear terms

Origin of the SUSY flavour problem: Misalignment of squark mass matrices with Yukawa matrices.
Unorthodox solution: Set Y^u_{ij} and Y^d_{ij} to zero, except for $(i,j) = (3,3)$.

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Radiative flavour violation: S. Weinberg 1972

flavour from soft SUSY terms:

W. Buchmüller, D. Wyler 1983,
F. Borzumati, G.R. Farrar,
N. Polonsky, S.D. Thomas 1998, 1999
J. Ferrandis, N. Haba 2004

Today:

Strong constraints from FCNCs probed at B factories.

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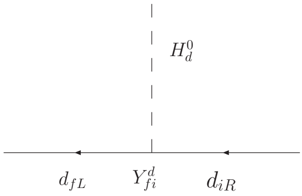
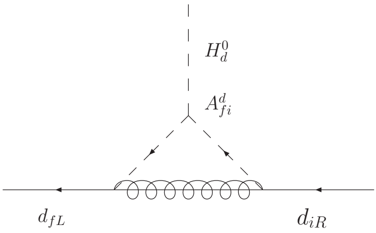
But: Radiative flavour violation in the MSSM is still viable, albeit only with A^d_{ij} and A^u_{ij} entering

$$M^{\tilde{d}\,LR}_{ij} = A^d_{ij} v_d + \delta_{i3}\delta_{j3} y_b \mu v_u, \qquad M^{\tilde{u}\,LR}_{ij} = A^u_{ij} v_u + \delta_{i3}\delta_{j3} y_t \mu v_d.$$

Andreas Crivellin, UN, PRD 79 (2009) 035018



H_d^0
d_{fL}
Y^d_{fi}
d_{iR}



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Flavour symmetries

Gauge sector: $[U(3)]^3$

Yukawa sector: Keep Yukawa couplings for the third generation, because $y_t \sim 1$ and y_b and y_τ successfully unify.

$$[U(2)]^3 \times U(1)$$

$$\Rightarrow \quad Y^d = \mathrm{diag}(0,0,y_b) \text{ and } Y^u = \mathrm{diag}(0,0,y_t).$$

Ferrandis, Haba 2004

$M_{jk}^{\tilde{Q},LL}, M_{jk}^{\tilde{q},RR}$: same $[U(2)]^3 \times U(1)$ symmetry as Yukawa sector (e.g. through universality at a high scale)

$A_{ij}^{\tilde{u}\,LR}$, $A_{ij}^{\tilde{d}\,LR}$: spurion fields breaking $[U(2)]^3 \times U(1)$ to $U(1)_B$

(also destroy the symmetry of $M_{jk}^{\tilde{Q},LL}, M_{jk}^{\tilde{q},RR}$ through renormalisation, but do not generate dangerous flavour violation.)

Electric dipole moments

Darkest corner of the MSSM: The phases of A^q_{ii} and μ generate too large EDMs. If light quark masses are generated radiatively through soft SUSY-breaking terms, this “supersymmetric CP problem” is substantially alleviated:

- The phases of A^q_{ii} and m_q are aligned, i.e. zero.
- The phase of μ (essentially) does not enter the EDMs at the one-loop level, because the Yukawa couplings of the first two generations are zero.

Borzumati, Farrar, Polonsky, Thomas 1998,1999

Flavour and SUSY GUTs

Linking quarks to neutrinos: Flavour mixing:
quarks: Cabibbo-Kobayashi-Maskawa (CKM) matrix
leptons: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

Consider SU(5) multiplets:

$$\overline{\mathbf{5}}_1 = \begin{pmatrix} d_R^c \\ d_R^c \\ d_R^c \\ e_L \\ -\nu_e \end{pmatrix}, \qquad \overline{\mathbf{5}}_2 = \begin{pmatrix} s_R^c \\ s_R^c \\ s_R^c \\ \mu_L \\ -\nu_\mu \end{pmatrix}, \qquad \overline{\mathbf{5}}_3 = \begin{pmatrix} b_R^c \\ b_R^c \\ b_R^c \\ \tau_L \\ -\nu_\tau \end{pmatrix}.$$

If the observed large atmospheric neutrino mixing angle stems from a rotation of $\overline{\mathbf{5}}_2$ and $\overline{\mathbf{5}}_3$, it will induce a large $\tilde{b}_R - \tilde{s}_R$-mixing (Moroi).

$\Rightarrow$ new b_R–s_R transitions from gluino–squark loops possible.

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However, the flavour structure of the dimension-5 terms is a priori arbitrary, spoiling the SU(5) GUT relation

$$Y_{\mathrm{GUT}} \equiv Y_d = Y_l^\top$$

between the down-quark and lepton Yukawa matrices.

$\Rightarrow$ The connection between lepton-flavour physics and quark-flavour physics is lost.

Model-independent parametrisation:

$$Y_d = Y_{\text{GUT}} + k_d \frac{\sigma}{M_{\text{Planck}}} Y_\sigma \,, \qquad Y_l^\top = Y_{\text{GUT}} + k_e \frac{\sigma}{M_{\text{Planck}}} Y_\sigma .$$

where $\sigma = \mathcal{O}\left(M_{\text{GUT}}\right)$ is a linear combination of Higgs vevs, the matrix Y_σ stems from dimension-5 Yukawa couplings, and $k_d \neq k_e$ from GUT breaking.

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where $\sigma = \mathcal{O}\,(M_{\rm GUT})$ is a linear combination of Higgs vevs, the matrix Y_σ stems from dimension-5 Yukawa couplings, and $k_d \neq k_e$ from GUT breaking.

If the universality condition for the trilinear terms is invoked at the GUT scale,

$$A_l = A_d = A_0 Y_{\rm GUT},$$

(or above the GUT scale) any misalignment between $Y_{\rm GUT}$ and Y_σ will lead to a low-energy theory with non-minimal flavour violation, because $A_l \not\propto \ Y_l$ and $A_d \not\propto \ Y_d$.

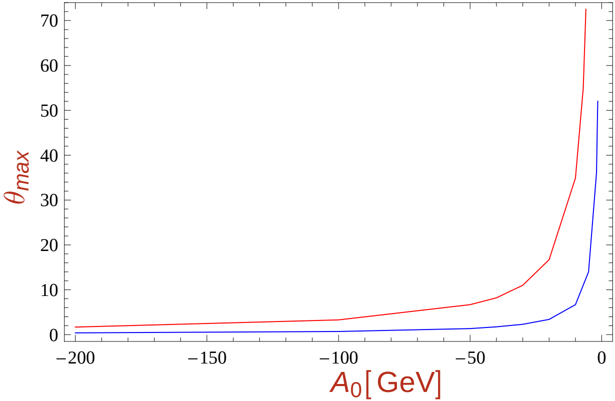
Lepton flavour physics:

Parametrisation of the extra $(1,2)$ rotation:

$$A_l \simeq A_0 \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} Y_l$$

Severe constraint: $Br(\mu \to e\gamma)$.

Upper bound for θ (in degrees) as a function of A_0:



All other parameters: SPS1a and SPS1b.

Girrbach, Mertens, UN, Wiesenfeldt 2009

see also: Borzumati and Yamashita 2009

In the quark sector one is also sensitive to a possible CP phase. The CP-violating parameter ϵ_K tightly constrains the mixing angle.

Trine, Westhoff, Wiesenfeldt 2009.

Conclusions

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- In GUT models with soft SUSY breaking at or above M_{GUT} the dimension-5 Yukawa terms must be aligned (in the first two generations) with the dimension-4 terms to satisfy the bounds from $Br(\mu \to e\gamma)$ and ϵ_K unless A_0 is small at M_{GUT}.

Backup: parameter points

Scan ranges for C_7 and C_8: $\tan\beta = 40 - 60$, any value for φ_{A_t},

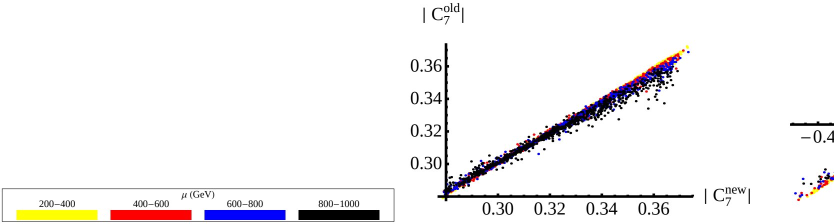
	min (GeV)	max (GeV)
$\tilde{m}_{Q_L}, \tilde{m}_{u_R}, \tilde{m}_{d_R}$	250	1000
$\lvert A_t \rvert$	100	1000
μ, M_1, M_2	200	1000
M_3	300	1000
m_{A^0}	200	1000

Parameter point used for $S_{\phi K_S}$:

$\tilde{m}_{Q_L}, \tilde{m}_{u_R}, \tilde{m}_{d_R}$	600 GeV	$\tan\beta$	50
μ	800 GeV	m_{A^0}	350 GeV
M_1	300 GeV	M_2	400 GeV
M_3	500 GeV	φ_{A_t}	$3\pi/2$

Backup: C_7 and other operators

- effect of gluino-squark contribution in $C_7(m_b)$ accidentally small (suppressed by a numerical factor from loop function)



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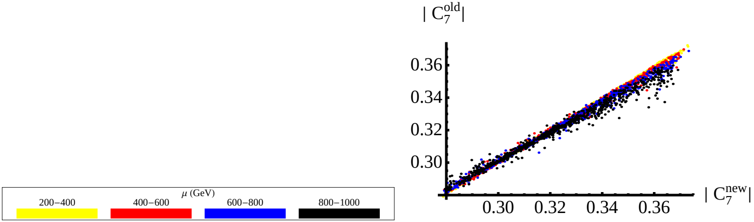

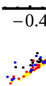

- effective four-quark operators in $\mathcal{H}^{\Delta B=1}$ and $\mathcal{H}^{\Delta B=2}$: gluino-squark loops suppressed by GIM-like cancellation between $\tilde{b}$- and $\tilde{s}$-loops $\rightarrow$ negligible compared to chargino-squark loops

Backup: Non-local tan β-enhanced effects

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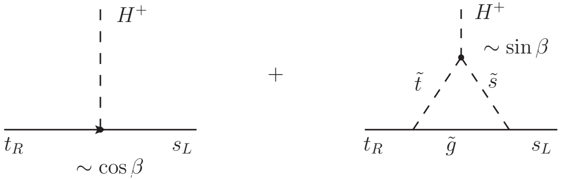

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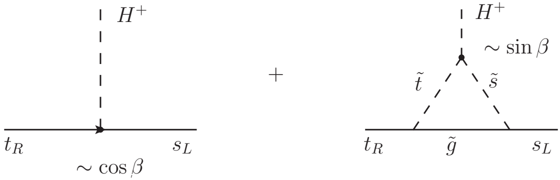

- this effect is local only in the decoupling limit, but cannot be cast into a Feynman rule in the full calculation