Recent progress in the theory of Flavour Physics

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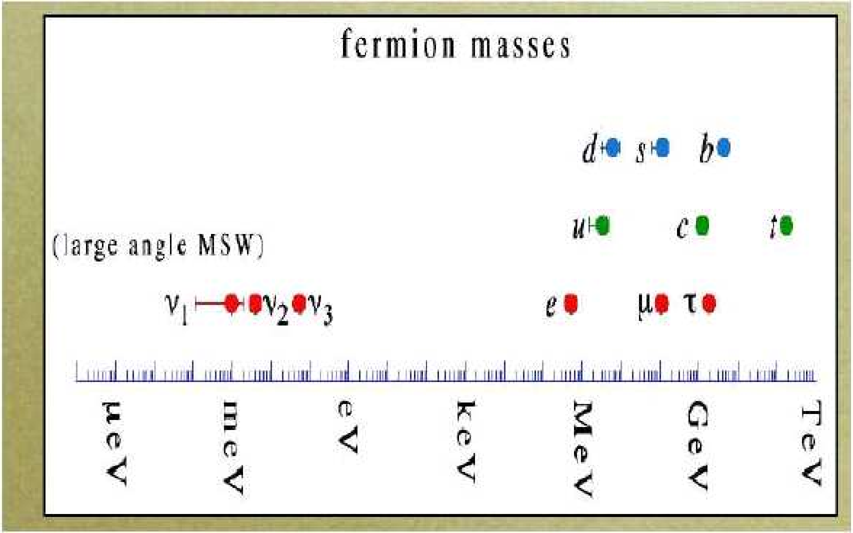
The fermion mass puzzle



SM flavour puzzle

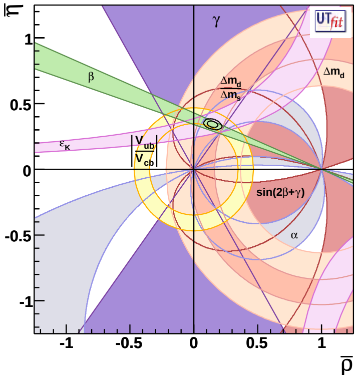
Smallness and Hierarchy

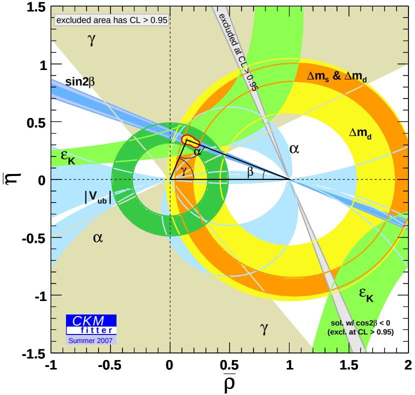
$$Y_t \sim 1, \quad Y_c \sim 10^{-2}, \quad Y_u \sim 10^{-5}$$
$$Y_b \sim 10^{-2}, \quad Y_s \sim 10^{-3}, \quad Y_d \sim 10^{-4}$$
$$Y_\tau \sim 10^{-2}, \quad Y_\mu \sim 10^{-3}, \quad Y_e \sim 10^{-6}$$
$$|V_{us}| \sim 0.2, \quad |V_{cb}| \sim 0.04, \quad |V_{ub}| \sim 0.004, \quad \delta_{\rm KM} \sim 1$$

- For comparison: $g_s \sim 1, \quad g \sim 0.6, \quad g' \sim 0.3, \quad \lambda \sim 1$
- The SM flavor parameters have structure: smallness and hierarchy
- Why? = The SM flavor puzzle

Nir

SM success

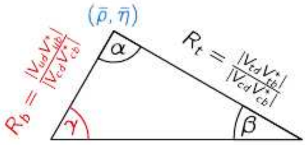


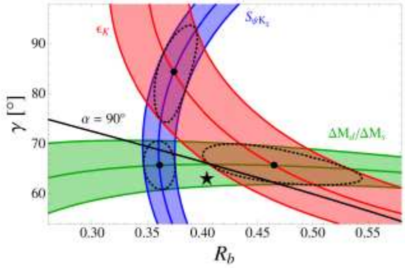


Very likely, flavour and CP violation in FC processes
are dominated by the CKM mechanism (Nir)

UT tensions

- Recent theoretical improvements in ϵ_K expose some tensions in the UT analysis [Lunghi & Soni, Buras & Guadagnoli]
- Look at ϵ_K, $S_{\psi K_S}$ ($\sin 2\beta$), $\Delta M_d / \Delta M_s$ in the R_b-γ plane
- R_b, γ can be obtained from tree-level processes





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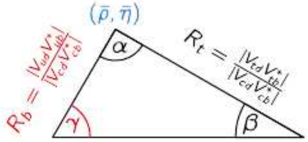

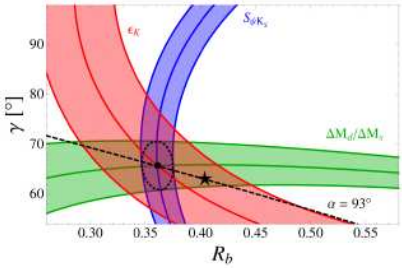

Possible solutions:

1. $+24\%$ NP effect in ϵ_K

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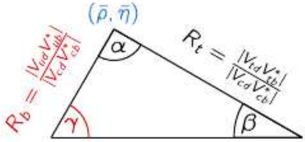

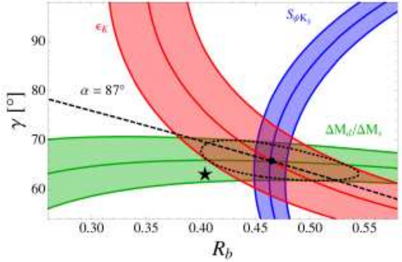

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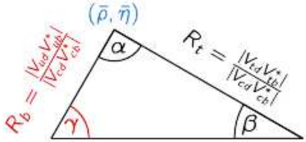
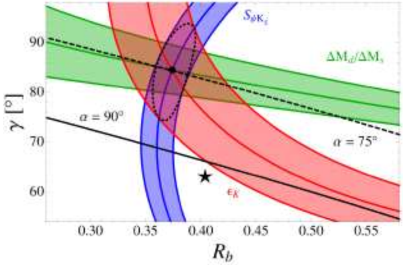




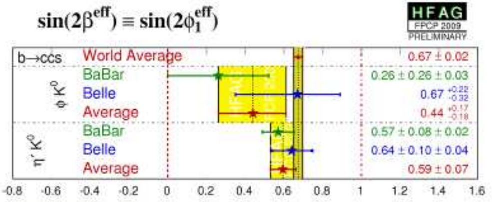
Possible solutions:

1. $+24\%$ NP effect in ϵ_K
2. $-6.5°$ NP phase in B_d mixing
3. -22% NP effect in $\Delta M_d/\Delta M_s$ (requiring $\alpha \sim 74°$)

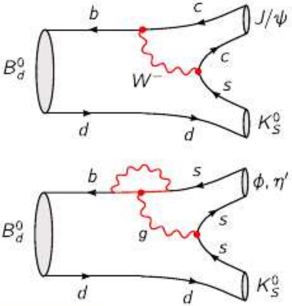
$\sin 2\beta_{eff}$ tensions

- In the SM, mixing-induced CP asymmetries in $B_d \to \psi K_S, \phi K_S, \eta' K_S$ all $\approx \sin 2\beta$
- $B_d \to \psi K_S$ dominated by tree level, ϕK_S and $\eta' K_S$ are loop-induced

Data indicate $S_{\phi K_S} < S_{\eta' K_S} < S_{\psi K_S}$



[adapted from HFAG]

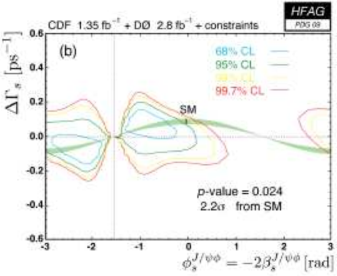


New physics in the decay amplitudes?

Can only be resolved at Super*B*

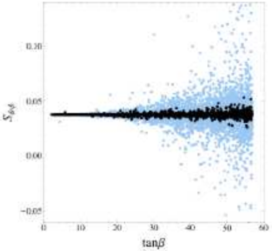
CPV in B_s mixing

- $S_{\psi\phi}$: mixing-induced CP asymmetry in $B_s \to J/\psi\phi$
- $S_{\psi\phi} = \sin 2(\beta_s + \phi_{B_s}^{\rm NP})$
- $S_{\psi\phi}^{\rm SM} \approx 0.035$

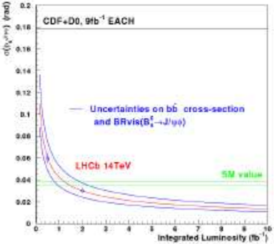


Recent Tevatron data favour
$0.20 \leq S_{\psi\phi} \leq 0.98$

New physics in the B_s mixing phase?



- Sizable $S_{\psi\phi}$ impossible in MFV MSSM
- Will be measured at LHCb



Minimal Flavor Violation

I. *The CKM fits* [constraints in the ρ-η plane]

These results are quite instructive if interpreted as bounds on the scale of new physics:

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(V_{tb}^* V_{td})^2}{16\,\pi^2 M_w^2} + c_{NP}\frac{1}{\Lambda^2}$$

contrbution of the new heavy degrees of freedom

c_{NP}:

- ~ 1 — tree/strong + generic flavour → $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\,\pi^2)$ — loop + generic flavour → $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (V_{ti}^* V_{tj})^2$ — tree/strong + MFV → $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (V_{ti}^* V_{tj})^2/(16\,\pi^2)$ — loop + MFV → $\Lambda \gtrsim 0.5$ TeV [K & B]

MFV (or something very similar at least for $s \to d$ & $b \to d$), is mandatory if we want to keep Λ in the TeV range

SUSY flavour and CP problems

The SUSY flavour problem

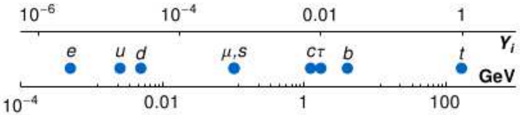
- Most of the 105 additional parameters in the MSSM violate flavour
- $O(1)$ values are strongly disfavoured by the excellent agreement of the SM with the flavour data

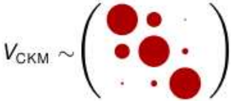
Possible solutions

1. Decoupling
   - Sfermion mass scale very high
   - Clashes with the gauge hierarchy problem
2. Degeneracy
   - Sfermion masses nearly degenerate
   - Arises in models with low-scale SUSY breaking
   - Partly spoiled by RG evolution
3. Alignment
   - Quark and squark mass matrices aligned

SM vs. SUSY flavour problems

Flavour violation is highly non-generic already in the SM!





The two problems should be related!

Minimal Flavour Violation (MFV)

- Yukawa couplings are the only sources of flavour violation
- Effective theory
- Pragmatic approach
- Pessimistic phenomenology

Flavour Models

- Flavour structure of Yukawa couplings and soft terms generated by spontaneous breaking of a flavour symmetry
- Ambitious approach
- Diverse phenomenology

Minimal Flavour Violation

- SM without Yukawa interactions: $SU(3)^5$ global **flavour symmetry**

$$\mathbf{SU(3)_u \otimes SU(3)_d \otimes SU(3)_Q \otimes SU(3)_e \otimes SU(3)_L}$$

- Yukawa interactions break this symmetry
- Proposal for any New Physics model:

Yukawa structures as the only sources of flavour violation

$$\Downarrow$$

Minimal Flavour Violation
Notice that MFV allows for new CPV phases!

NP search strategies

Where to look for New Physics?

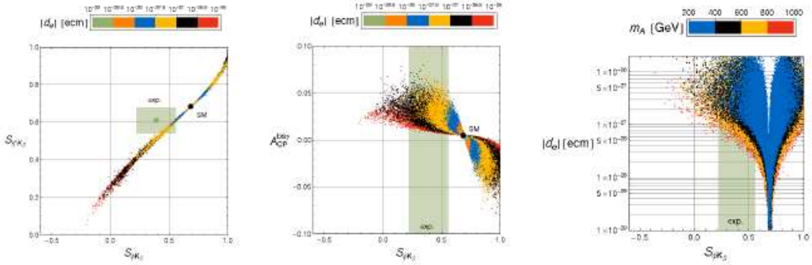
- **Processes very suppressed or even forbidden in the SM**
  - FCNC processes ($\mu \to e\gamma$, $\tau \to \mu\gamma$, $B^0_{s,d} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$)
  - CPV effects in the electron/neutron EDMs, $d_{e,n}$...
  - CPV in $B_{s,d}$ decay/mixing amplitudes

- **Processes predicted with high precision in the SM**
  - EWPO as $\Delta\rho$, $(g-2)_\mu$....
  - LU in $R_M^{e/\mu} = \Gamma(K(\pi) \to e\nu)/\Gamma(K(\pi) \to \mu\nu)$

Flavour Matrix

ELECTROWEAK STRUCTURE	FLAVOUR COUPLING: $b \to s$ [~ λ^2 in SM]	$b \to d$ [~ λ^3 in SM]	$s \to d$ [~ λ^5 in SM]
$\Delta F=2$ box	ΔM_{Bs} $A_{CP}(B_s \to \psi\phi)$, ϵ_{Bs}	ΔM_{Bd} $A_{CP}(B_d \to \psi K)$, ϵ_{Bd}	ϵ_K
$\Delta F=1$ 4-quark ops.	$A_{CP}(B_d \to \phi K)$	$A_{CP}(B_s \to \phi K)$	
gluon penguin	$A_{CP}(B_d \to \phi K)$ $[\Gamma, \Delta\Gamma_{CP}](B \to X_s \gamma)$	$[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\, \gamma)$	$\Gamma(K_L \to \pi^0 \ell\ell)$
γ penguin	$[\Gamma, \Delta\Gamma_{CP}](B \to X_s \gamma)$ $[\Gamma, \Delta\Gamma_{CP}](B \to X_s \ell\ell)$ $A_{FB}(B \to X_s \ell\ell)$	$[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\, \gamma)$ $[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\, \ell\ell)$ $A_{FB}(B \to \rho/\pi\, \ell\ell)$	$\Gamma(K_L \to \pi^0 \ell\ell)$
Z^0 penguin	$[\Gamma, \Delta\Gamma_{CP}](B \to X_s \ell\ell)$ $A_{FB}(B \to X_s \ell\ell)$ $\Gamma(B_s \to \mu\mu)$	$[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\, \ell\ell)$ $A_{FB}(B \to \rho/\pi\, \ell\ell)$ $\Gamma(B_d \to \mu\mu)$	$\Gamma(K^+ \to \pi^+ \nu\nu)$ $\Gamma(K_L \to \pi^0 \nu\nu)$ $\Gamma(K_L \to \pi^0 \ell\ell)$
H^0 penguin	$\Gamma(B_s \to \mu\mu)$	$\Gamma(B_d \to \mu\mu)$	

Flavor blind MSSM ≈ MFV + CPV



- CP violating $\Delta F = 0$ and $\Delta F = 1$ dipole amplitudes can be strongly modified
- $S_{\phi K_S}$ and $S_{\eta' K_S}$ can simultaneously be brought in agreement with the data
- sizeable and correlated effects in $A_{CP}^{bs\gamma} \simeq 1\% - 6\%$
- lower bounds on the electron and neutron EDMs at the level of $d_{e,n} \gtrsim 10^{-28}$ecm
- large and correlated effects in the CP asymmetries in $B \to K^* \mu^+ \mu^-$ (WA, Ball, Bharucha, Buras, Straub, Wick)

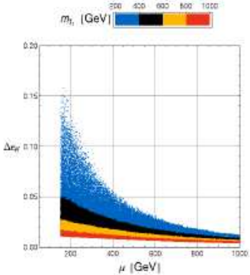
- the leading NP contributions to $\Delta F = 2$ amplitudes are not sensitive to the new phases of the FBMSSM
- CP violation in meson mixing is SM like
- i.e. small effects in $S_{\psi\phi}$, $S_{\psi K_S}$ and ϵ_K
- in particular: $0.03 < S_{\psi\phi} < 0.05$

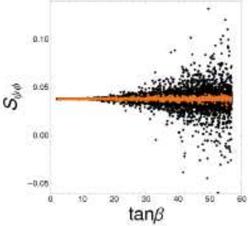
A combined study of all these observables and their correlations constitutes a very powerful test of the FBMSSM

Phenomenology of the flavor blind MSSM

① Kaon mixing

- The mixing amplitude M_{12}^K has no sensitivity to the new flavor blind phases
- Still, $\epsilon_K \propto \mathrm{Im}(M_{12}^K)$ can get a positive NP contribution up to 15%
- But only for a very light SUSY spectrum: $\mu, m_{\tilde{t}_1} \simeq 200\mathrm{GeV}$





② B_d and B_s mixing

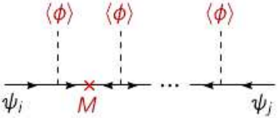
- Leading NP contributions to $M_{12}^{d,s}$ are insensitive to the new phases of a FBMSSM. (at least for moderate $\tan\beta$ ...)
- For large $\tan\beta$, the constraint from $b \to s\gamma$ does not allow for sizeable effects
- $S_{\psi K_S}$ and $S_{\psi\phi}$ are SM like ($S_{\psi\phi} \simeq 0.03 - 0.05$)

SUSY flavour models

Main idea: hierarchies in Yukawa couplings generated by spontaneous breakdown of flavour symmetry (horizontal symmetry, family symmetry)

- Generalization of the Froggat-Nielsen mechanism
- Yukawa hierarchies explained by different powers of small ϵ:

$$\Rightarrow Y_{ij} \propto \left(\frac{\langle\phi\rangle}{M}\right)^{(a_i+b_j)} = \epsilon^{(a_i+b_j)}$$



- Possible to relate Yukawa matrices and sfermion mass matrices/trilinear couplings

SUSY flavour models can explain the origin of the hierarchies in the Yukawa couplings *and* solve the SUSY flavour problem

- Many different viable models exist, with abelian or non-abelian flavour symmetries

Abelian vs. non-Abelian flavour models

Abelian vs. Non-abelian

- In most non-abelian models, 1st & 2nd generatio sfermions are approximately degenerate
  - Suppressed contributions to $1 \leftrightarrow 2$ transitions, in particular D^0-$\bar{D}^0$ mixing
- In abelian models, sfermions of different generations need not be degenerate
  - $O(1)$ 1-2 mass splitting leads to $O(\lambda)$ $(\delta_u^{LL})_{12}$ in the SCKM basis
  - Large effects in D^0-$\bar{D}^0$ mixing

Chirality structure of flavour violating terms

- Different flavour symmetries lead to different patterns of flavour violation
- Mass insertions: $M_{\tilde{d}}^2 = \mathrm{diag}(\tilde{m}^2) + \tilde{m}^2 \begin{pmatrix} \delta_d^{LL} & \delta_d^{LR} \\ \delta_d^{RL} & \delta_d^{RR} \end{pmatrix}$
- δ^{LL}, δ^{RR}, δ^{LR} fixed by the flavour symmetry (up to $O(1)$ factors)

Examples of flavour models

4 representative flavour models with different chirality structures in the $\tilde{d}$ sector:

AC model [Agashe, Carone]	AKM model [Antusch, King, Malinsky]	RVV model [Ross, Velasco-Sevilla, Vives]	δLL model [e.g. Hall, Murayama]
$U(1)$	$SU(3)$	$SU(3)$	$(S_3)^3$
Large, $O(1)$ RR mass insertions	Only CKM-like RR mass insertions	CKM-like LL & RR mass insertions	Only CKM-like LL mass insertions

AC model:

$$\delta_d^{LL} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & \lambda^2 \\ 0 & \lambda^2 & \cdot \end{pmatrix} \qquad \delta_d^{RR} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & 1 \\ 0 & 1 & \cdot \end{pmatrix}$$

AKM model:

$$\delta_d^{LL} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & 0 \\ 0 & 0 & \cdot \end{pmatrix} \qquad \delta_d^{RR} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^3 \\ \lambda^3 & \cdot & \lambda^2 \\ \lambda^3 & \lambda^2 & \cdot \end{pmatrix}$$

RVV model:

$$\delta_d^{LL} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^2 \\ \lambda^3 & \cdot & \lambda \\ \lambda^2 & \lambda & \cdot \end{pmatrix} \qquad \delta_d^{RR} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^2 \\ \lambda^3 & \cdot & \lambda \\ \lambda^2 & \lambda & \cdot \end{pmatrix}$$

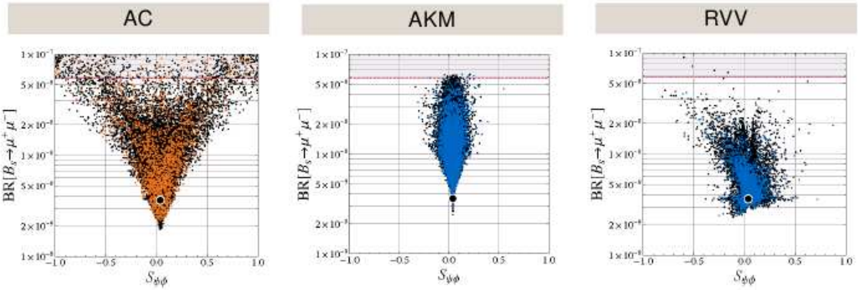
δLL model:

$$\delta_d^{LL} \sim \begin{pmatrix} \cdot & \lambda^5 & \lambda^3 \\ \lambda^5 & \cdot & \lambda^2 \\ \lambda^3 & \lambda^2 & \cdot \end{pmatrix} \qquad \delta_d^{RR} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & 0 \\ 0 & 0 & \cdot \end{pmatrix}$$

Altmannshofer et al. ’09

$Br(B_s \to \mu^+\mu^-)$ vs. $S_{\psi\phi}$

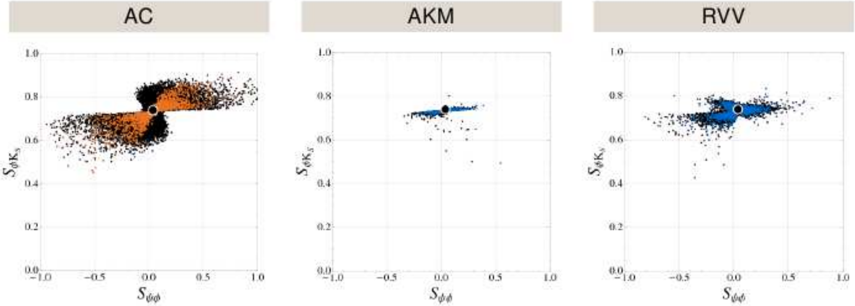
- Both observables can deviate significantly from the SM in all 3 models
- large $S_{\psi\phi}$ $\Rightarrow$ large BR($B_s \to \mu^+\mu^-$) in the AC and AKM models
- Correlation arises from dominance of Higgs penguin contributions



- Orange points: UT tension solved through contribution to $\Delta M_d / \Delta M_s$
- Blue points: UT tension solved through contribution to ϵ_K
- Scan ranges: $m_0 < 2$ TeV, $M_{1/2} < 1$ TeV, $|A_0| < 3m_0$, $5 < \tan\beta < 55$, $O(1)$ parameters varied within $[\frac{1}{2}, 2]$

$S_{\phi K_S}$ vs. $S_{\psi\phi}$

- In the AC model, both $S_{\phi K_S}$ and $S_{\psi\phi}$ can have large effects, but a simultaneous *enhancement* of $S_{\psi\phi}$ and *suppression* of $S_{\phi K_S}$ (as indicated by the data) is impossible
- $S_{\phi K_S}$ nearly SM-like in AKM and RVV models



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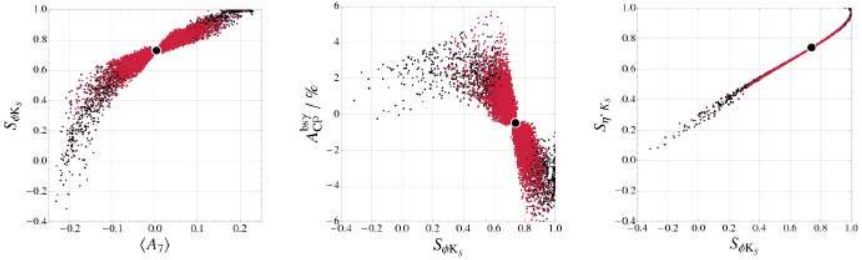
Model with purely left-handed currents

Pattern of NP effects in the δLL model:

- No large effects in $S_{\psi\phi}$
- Large, correlated effects in $S_{\phi K_S}$, $S_{\eta' K_S}$, $A_{CP}(b \to s\gamma)$, $\langle A_{7,8} \rangle$
- $\langle A_{7,8} \rangle$: T-odd CP asymmetries in $B \to K^* \ell^+ \ell^-$



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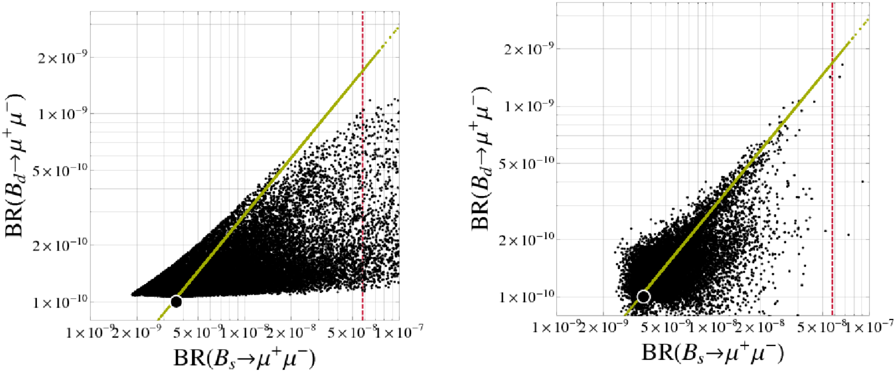
$Br(B_s \to \mu^+\mu^-)$ vs. $Br(B_d \to \mu^+\mu^-)$

Abelian (AC) **Non abelian (RVV)**



$Br(B_s \to \mu^+\mu^-)/Br(B_d \to \mu^+\mu^-) = |V_{ts}/V_{td}|^2$ **in MFV models**

CPV in D-physics

CPV in $D^0 - \bar{D}^0 \sim ((V_{cb}V_{ub})/(V_{cs}V_{us})) \sim \mathbf{10^{-3}}$ in the **SM**

- $\langle D^0|\mathcal{H}_{\rm eff}|\bar{D}^0\rangle = M_{12} - \frac{i}{2}\Gamma_{12}, \qquad |D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$
- $\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}, \qquad \phi = \mathrm{Arg}(q/p)$
- $x = \frac{\Delta M_D}{\Gamma} = 2\tau \mathrm{Re}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right]$
- $y = \frac{\Delta\Gamma}{2\Gamma} = -2\tau \mathrm{Im}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right]$

$$S_f = 2\Delta Y_f = \frac{1}{\Gamma_D}\left(\hat{\Gamma}_{\bar{D}^0\to f} - \hat{\Gamma}_{D^0\to f}\right)$$

$$\eta_f^{\rm CP} S_f = x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\phi - y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\phi$$

$$a_{\rm SL} = \frac{\Gamma(D^0 \to K^+\ell^-\nu) - \Gamma(\bar{D}^0 \to K^-\ell^+\nu)}{\Gamma(D^0 \to K^+\ell^-\nu) + \Gamma(\bar{D}^0 \to K^-\ell^+\nu)} = \frac{|q|^4 - |p|^4}{|q|^4 + |p|^4}$$

CPV in D-physics vs. neutron EDM in SUSY

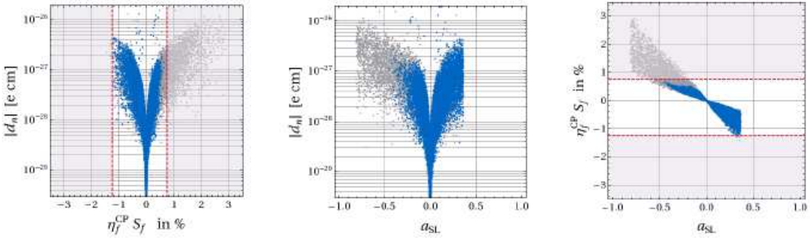


FIG. 3: Correlations between d_n and S_f (left), d_n and a_{SL} (middle) and a_{SL} and S_f (right) in SUSY alignment models. Gray points satisfy the constraints (8)-(10) while blue points further satisfy the constraint (11) from ϕ. Dashed lines stand for the allowed range (18) for S_f.

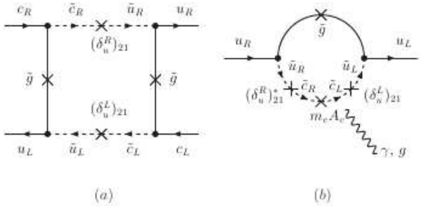


FIG. 2: Examples of relevant Feynman diagrams contributing (a) to $D^0 - \bar{D}^0$ mixing and (b) to the up quark (C)EDM in SUSY alignment models.

$K \to \pi\nu\bar{\nu}$ in the SM

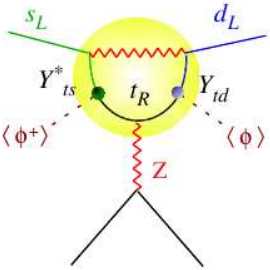
- $K \to \pi\nu\bar{\nu}$ processes offer a unique possibility in probing the underlying flavour mixing mechanism:
  - No SM tree-level contributions (FCNC decays);
  - One-loop SM contributions CKM-suppressed ($V_{ts}^* V_{td} \sim \lambda^5$);
  - High precision of the SM prediction thanks to short distance (e.w.) dynamics dominance:

$$\mathcal{H}_{\rm eff}^{(s.d.)} = \sum_{l=e,\mu,\tau} V_{ts}^* V_{td} \left[X_L (\bar{s}d)_{V-A} + X_R (\bar{s}d)_{V+A} \right] (\bar{\nu}_l \nu_l)_{V-A}$$

$$Br(K \to \pi\nu\bar{\nu}) \sim |X = X_L + X_R|^2$$

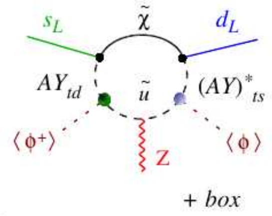
$$X \sim c_{SM} \frac{y_t^2 V_{ts}^* V_{td}}{16\pi^2 M_W^2}$$

$$X_L^{\rm SM} = 1.464 \pm 0.041\ , \quad X_R^{\rm SM} = 0$$

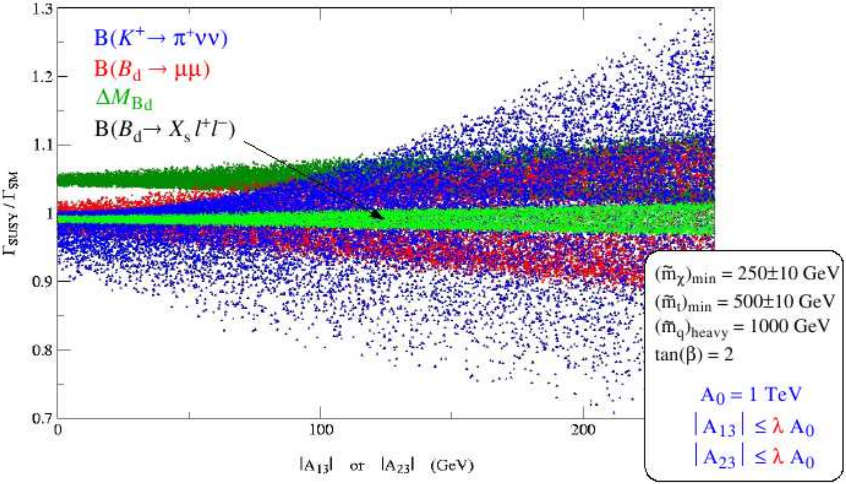


$K \to \pi\nu\bar{\nu}$ and NP

- $K \to \pi\nu\bar{\nu}$ has a **high sensitivity to NP** effects of many theories as SUSY, LHT, Z' models.....
- Large **NP** effects only if $\delta_{21} \not\sim V_{ts}^* V_{td}$ (beyond MFV)
- The dominant effects to $K \to \pi\nu\bar{\nu}$ arise from $\tilde{\chi}/\tilde{u}$ diagrams with double-MIA **[Colangelo, Isidori '98]**.
- Gluino-type amplitudes (LL, RR and LR-down squarks type mixings) essentially negligible contrary to ϵ_K, $b \to s\gamma$, $B^0 - \bar{B}^0$
- Minor effects within pure MFV.
- The maximal sensitivity to the up-type trilinear terms is obtained for
  - Light stop and charginos
  - small tan β

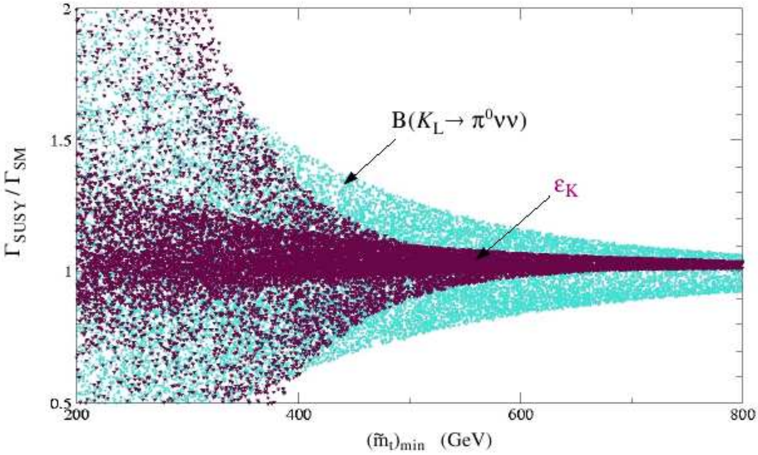


Chargino mediated $K \to \pi\nu\bar{\nu}$



Isidori et al., '06

Chargino mediated $K \to \pi\nu\bar{\nu}$



Isidori et al., ’06

LFV

- **Neutrino Oscillation** $\Rightarrow m_{\nu_i} \neq m_{\nu_j} \Rightarrow$ **LFV**
- **see-saw**: $m_\nu = \frac{(m_\nu^D)^2}{M_R} \sim eV$, $M_R \sim 10^{14-16} \Rightarrow m_\nu^D \sim m_{top}$
- LFV transitions like $\mu \to e\gamma$ @ 1 loop with exchange of
  - W and ν in the SM framework (GIM)

$$Br(\mu \to e\gamma) \sim \frac{m_\nu^4}{M_W^4} \leq 10^{-50} \qquad m_\nu \sim \mathrm{eV}$$

  - $\tilde{W}$ and $\tilde{\nu}$ in the MSSM framework (SUPER-GIM)

$$Br(\mu \to e\gamma) \sim \frac{m_\nu^{D\,4}}{\tilde{m}^4} \leq 10^{-11} \qquad m_\nu^D \sim m_{top}$$

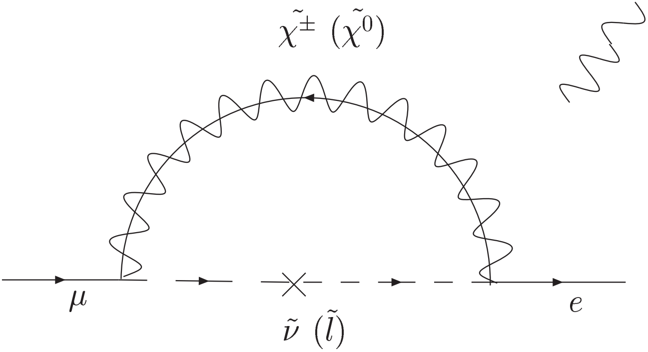
$$\Downarrow$$

- LFV signals are undetectable (detectable) in the SM (MSSM)

LFV in SUSY

LFV interactions – leptons/sleptons/gauginos

$$\mathcal{L} = \bar{\ell}_i \left(C^R_{ijA} P_R + C^L_{ijA} P_L \right) \tilde{\chi}^-_A \tilde{\nu}_j + \bar{\ell}_i \left(N^R_{ijA} P_R + N^L_{ijA} P_L \right) \tilde{\chi}^0_A \tilde{\ell}_j . \quad (1)$$



$$\left. \frac{BR(\ell_i \to \ell_j \gamma)}{BR(\ell_i \to \ell_j \nu_i \bar{\nu}_j)} \right|_{\rm Gauge} \simeq \frac{\alpha_{el}}{20\pi} \left(\frac{m_W^4}{m_{SUSY}^4} \right) \left(\delta^{21}_{LL} \right)^2 t^2_\beta \qquad \delta_{LL} \sim h^\nu h^{\nu\dagger}$$

RG induced LFV interactions in SUSY see-saw

- SUSY see-saw superpotential (MSSM + RN)

$$W = h^e L e^c H_1 + h^\nu L \nu^c H_2 + M_R \nu^c \nu^c + \mu H_1 H_2,$$

$$\mathcal{M}_\nu = -h^\nu M_R^{-1} h^{\nu\,T} v_2^2,$$

$$M^2_{\tilde{\ell}} = \begin{pmatrix} m_L^2(1+\delta_{LL}^{ij}) & (A-\mu t_\beta) m_\ell + m_L m_R \delta_{LR}^{ij} \\ (A-\mu t_\beta) m_\ell + m_L m_R {\delta_{LR}^{ij}}^\dagger & m_R^2(1+\delta_{RR}^{ij}) \end{pmatrix}$$

- If $h^e = h^e_{ij}\delta_{ij}$ and $M_R = M_{R\,ij}\delta_{ij} \Rightarrow h^\nu \neq h^\nu_{ij}\delta_{ij}$ in general.

$$\delta_{LL}^{ij} \approx -\frac{3}{8\pi^2}(h^\nu h^{\nu\dagger})_{ij} \ln\frac{M_X}{M_R},$$

[Borzumati & Masiero, ’86]

LFV in SUSY

h^ν **is unknown** $\Rightarrow$ **No model independent predictions for LFV**

$$h^\nu = U^\star_{\rm MNS}\, \mathcal{D}_{\sqrt{\mathcal{M}_\nu}}\, R^T\, \mathcal{D}_{\sqrt{M_R}}\, \frac{1}{v_2},$$

$R^\dagger R = 1 \Rightarrow$ **three angles** and **three phases**

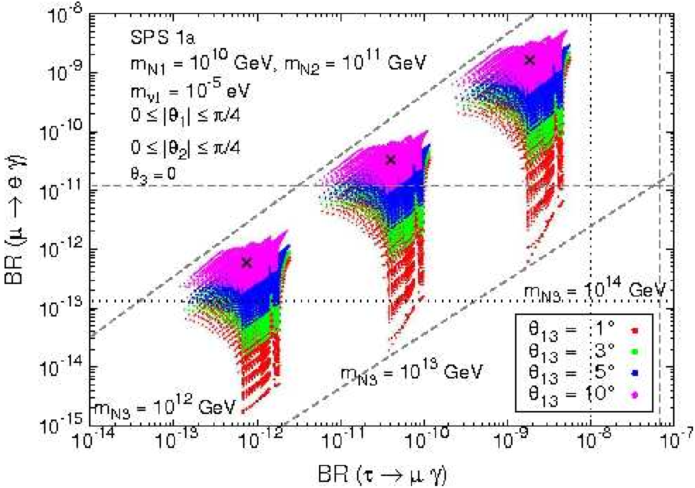
- ν_L **&** ν_R **hierarchical (and R real)**

$$\frac{B(\mu \to e\gamma)}{B(\tau \to \mu\gamma)} \sim \frac{|U_{e3}|^2}{B(\tau \to \mu\nu_\tau\bar{\nu}_\mu)}$$

- ν_L **hierarchical and** ν_R **degenerate (and R real)**

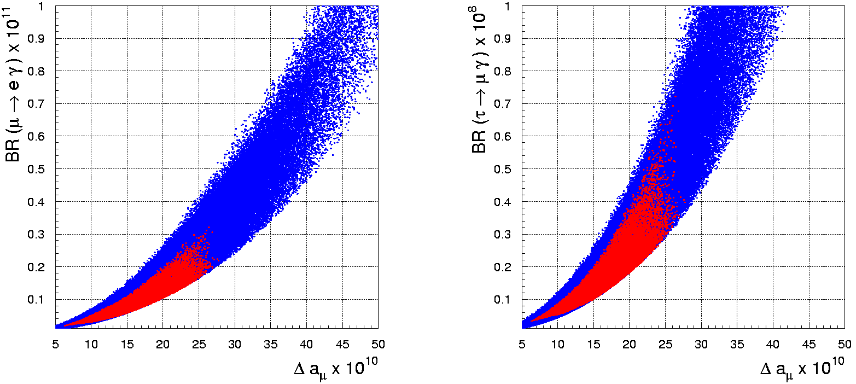
$$\frac{B(\mu \to e\gamma)}{B(\tau \to \mu\gamma)} \sim \frac{|s_{12}c_{12}\,(m_{sol}/m_{atm}) + U_{e3}|^2}{B(\tau \to \mu\nu_\tau\bar{\nu}_\mu)}$$

$\mu \to e\gamma$ and $\tau \to \mu\gamma$ in SUSY see-saw



Herrero et al., '06

$(g-2)_\mu$ vs $\ell_i \to \ell_j\gamma$



$|\delta_{LL}^{12}| = 10^{-4}$ and $|\delta_{LL}^{23}| = 10^{-2}$,

Isidori et al., 07

$$BR(\ell_i \to \ell_j\gamma) \approx \left[\frac{\Delta a_\mu}{30\times 10^{-10}}\right]^2 \times \begin{cases} 2\times 10^{-4}\,\left|\delta_{LL}^{12}\right|^2 & [\mu \to e] \\ 5\times 10^{-5}\,\left|\delta_{LL}^{23}\right|^2 & [\tau \to \mu] \end{cases}$$

RG induced Flavor Violating interactions in SUSY GUTs

- **SUSY SU(5)** [Barbieri & Hall, '95]

$$(\delta^{\tilde{q}}_{LL})_{ij} \sim h^u h^{u\dagger}{}_{ij} \sim h_t^2 V^{ik}_{CKM} V^{kj*}_{CKM} \rightarrow (\delta^{\tilde{\ell}}_{RR})_{ij} \simeq (\delta^{\tilde{q}}_{LL})_{ij}$$

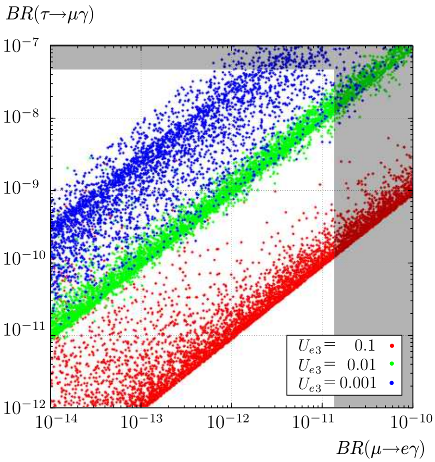
- **SUSY SU(5)+RN** [Yanagida et al., '95]

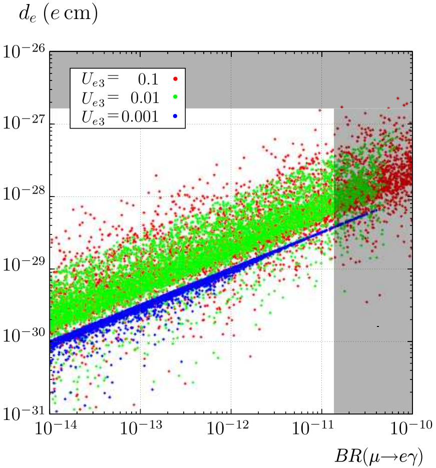
$$(\delta^{\tilde{\ell}}_{LL})_{ij} \sim (h^\nu h^{\nu\dagger})_{ij} \qquad \& \qquad (\delta^{\tilde{\ell}}_{RR})_{ij} \sim (h^u h^{u\dagger})_{ij}$$

- **SUSY SU(5)+RN** [Moroi, '00] **& SO(10)** [Chang et al., 02]

$$\sin\theta_{\mu\tau} \sim \frac{\sqrt{2}}{2} \Rightarrow (\delta^{\tilde{\nu}}_{LL})_{23} \sim 1 \Rightarrow (\delta^{\tilde{q}}_{RR})_{23} \sim 1$$

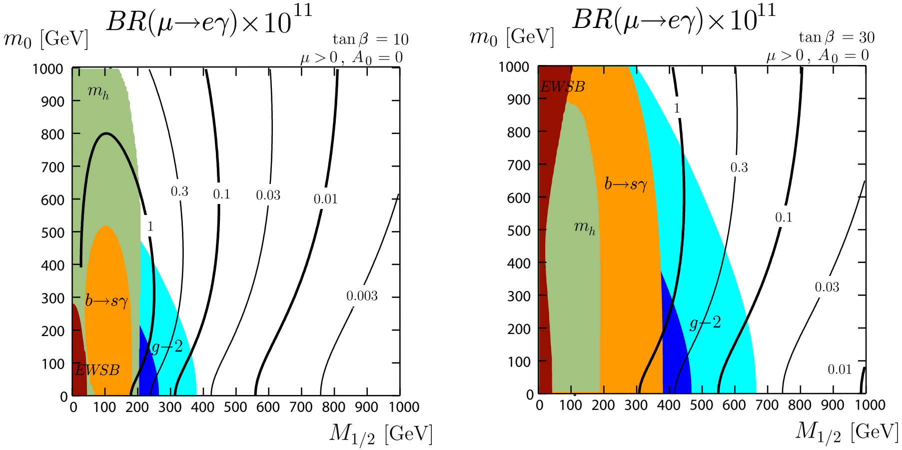
$\mu \to e\gamma$ and $\tau \to \mu\gamma$ in SUSY SU(5)+RN





Hisano et al. ’09

BR($\mu \to e\gamma$) in $SU(5)_{RN}$ and the LHC reach



hierarchical ν_L and N_R, $U_{e3} = 0.1$, $M_{N_3} = 10^{-13}$ GeV

Hisano et al. '09

Higgs Mediated LFV

- LFV Yukawa Interactions (if $\delta_{ij} = \tilde{m}^2_{ij}/\tilde{m}^2 \neq 0$):

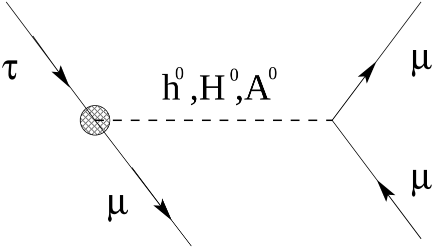
$$-\mathcal{L} \simeq (2G_F^2)^{\frac{1}{4}} \frac{m_\tau}{c_\beta^2} \left(\Delta_L^{3j} \overline{\tau}_R l_L^j + \Delta_R^{3j} \overline{\tau}_L l_R^j\right) \left(c_{\beta-\alpha} h^0 - s_{\beta-\alpha} H^0 - iA^0\right)$$

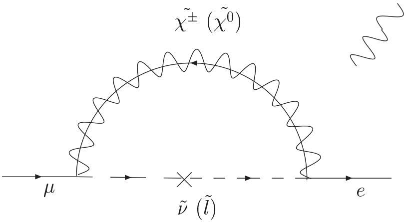
$$+ (8G_F^2)^{\frac{1}{4}} \frac{m_\tau}{c_\beta^2} \left(\Delta_L^{3j} \overline{\tau}_R \nu_L^j + \Delta_R^{3j} \nu_L^\tau \overline{l}_R^j\right) H^\pm + h.c.$$

$$\Delta_{3j} \sim \frac{\alpha_2}{4\pi} \delta_{3j}$$

- **Higgs** (gaugino) mediated LFV effects decouple as $m_H \to \infty$ ($m_{SUSY} \to \infty$),
- Key ingredients in the Higgs mediated LFV:
  - $\tan\beta \sim 50$
  - $\delta_{3j} \sim \mathcal{O}(1)$ and $m_{SUSY} \geq 1\mathrm{TeV}$

$\tau \to l_j X$ $(X = \gamma, \eta, f_0, l_j l_j (l_k l_k))$





$$\frac{BR(\tau\to 3\mu)}{BR(\tau\to\mu\nu\bar{\nu})} \simeq \left(\frac{\alpha_2}{48\pi}\right)^2 \left(\frac{m_\tau m_\mu}{M_H^2}\right)^2 \delta_{32}^2 t_\beta^6 \qquad \frac{BR(\tau\to\mu\gamma)}{BR(\tau\to\mu\nu\bar{\nu})} \simeq \frac{\alpha_{el}}{20\pi}\frac{m_w^4}{\tilde{m}^4}\delta_{32}^2 t_\beta^2$$

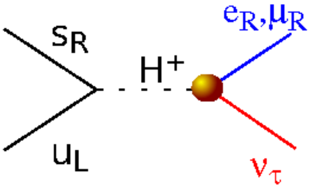
If $t_\beta \sim 50$ and $M_H \ll \tilde{m}$, i.e. $M_H \sim m_w$ and $\tilde{m} \sim TeV$

$$\Downarrow$$

$$\frac{BR(\tau\to 3\mu)}{BR(\tau\to\mu\gamma)} \not\propto \alpha_{el}$$

$\mu - e$ universality in $K \to l\nu$

$$R_K = (1 + \Delta r_K^{e-\mu}) = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}$$



$$eH^\pm\nu_\tau \to \frac{g_2}{\sqrt{2}}\frac{m_\tau}{M_W}\Delta_R^{31}\tan^2\beta$$

$$\Delta_R^{31} \sim \frac{\alpha_2}{4\pi}\,\delta_{RR}^{31}$$

$$\Delta_R^{31} \sim 5 \cdot 10^{-4} \quad t_\beta = 40 \quad M_{H^\pm} = 500\mathrm{GeV}$$

$$\Delta r_{K\,SUSY}^{e-\mu} \simeq \left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_R^{31}|^2\tan^6\beta \approx 10^{-2}$$

$$\Delta r_{K\,SUSY}^{e-\mu} \approx 10^{-2} \quad \Longrightarrow \quad Br^{th.(exp.)}(\tau \to eX) \leq 10^{-10(-7)}$$

Masiero, P.P., Petronzio, '05,'08

"DNA-Flavour Test"

	GMSSM	AC	RVV2	AKM	δLL	FBMSSM	
$S_{\phi K_S}$	★★★	★★★	●●	▪	★★★	★★★	SuperB
$A_{\rm CP}(B \to X_s\gamma)$	★★★	▪	▪	▪	★★★	★★★	
$B \to K^{(*)}\nu\bar{\nu}$	●●	▪	▪	▪	▪	▪	
$\tau \to \mu\gamma$	★★★	★★★	★★★	▪	★★★	★★★	
$D^0 - \bar{D}^0$	★★★	★★★	▪	▪	▪	▪	
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★★★	▪	▪	▪	★★★	★★★	vs.
$A_9(B \to K^*\mu^+\mu^-)$	★★★	▪	▪	▪	▪	▪	
$S_{\psi\phi}$	★★★	★★★	★★★	★★★	▪	▪	LHCb
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★★★	
ϵ_K	★★★	▪	★★★	★★★	▪	▪	
$K^+ \to \pi^+\nu\bar{\nu}$	★★★	▪	▪	▪	▪	▪	
$K_L \to \pi^0\nu\bar{\nu}$	★★★	▪	▪	▪	▪	▪	
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	
d_n	★★★	★★★	★★★	★★★	●●	★★★	
d_e	★★★	★★★	★★★	●●	▪	★★★	
$(g-2)_\mu$	★★★	★★★	★★★	●●	★★★	★★★	

Altmannshofer et al. '09

Isidori's view

Flavour physics in the LHC era

LHC [high p_T]

A *unique* effort toward the high-energy frontier

[to determine the energy scale of NP]

Flavour physics

Improved CKM fits

Rare B decays

CPV in the Bs system

LFV in μ & τ decays

Universality tests in B & K

EDMs

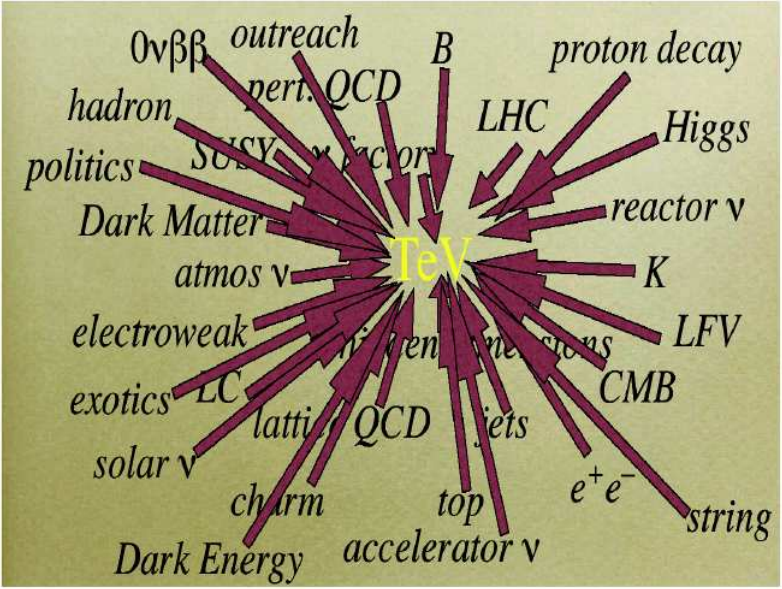
Rare K decays

g-2

A *collective* effort toward the high-intensity frontier

[to determine the flavour structure of NP]

Murayama’s view



Masiero's view