Flavor physics in the LHC era

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Plan of Talk

1. Open questions
2. The SM and NP flavor puzzles
3. Messages from the B-factories, Tevatron, and LHCb
4. First evidence for $B_s \to \mu^+\mu^-$: implications and consequences
5. Three anomalies (hint of NP) and their experimental tests
   - Direct CPV in charm decays $D \to K^+K^-(\pi^+\pi^-)$ [Giudice, Isidori, & P.P., '12]
   - The anomalous magnetic moment of the muon $(g-2)$ [Giudice, P.P., & Passera '12]
   - The $h \to \gamma\gamma$ excess and the muon $(g-2)$ anomaly [Giudice, P.P., & Strumia '12]
6. The lepton flavor violation probe of NP
7. Conclusions and future perspectivies

Open questions

- **The origin of flavour is still, to a large extent, a mystery. The most important open questions can be summarized as follow:**
  - **Which is the organizing principle behind the observed pattern of fermion masses and mixing angles?**
  - **Are there extra sources of flavour symmetry breaking beside the SM Yukawa couplings which are relevant at the TeV scale?**
- **Related important questions are:**
  - **Which is the role of flavor physics in the LHC era?**
  - **Do we expect to understand the (SM and NP) flavor puzzles through the synergy and interplay of flavor physics and the LHC?**

Flavor Physics within the SM

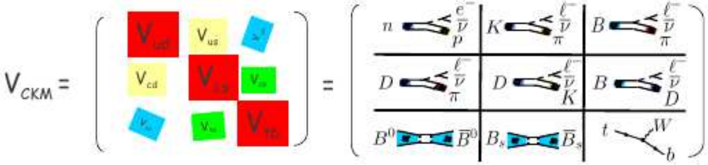
- $\mathcal{L}^{\rm SM}_{Kinetic+Gauge} + \mathcal{L}^{\rm SM}_{Higgs}$ has a large $U(3)^5$ global **flavour symmetry**

$$\mathbf{G} = \mathbf{U(3)^5} = \mathbf{U(3)_u} \otimes \mathbf{U(3)_d} \otimes \mathbf{U(3)_Q} \otimes \mathbf{U(3)_e} \otimes \mathbf{U(3)_L}$$

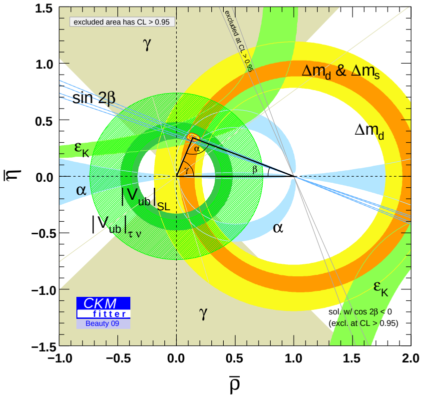
- $\mathcal{L}_{\rm Yukawa} = \bar{Q}_L \mathbf{Y_D} D_R \phi + \bar{Q}_L \mathbf{Y_U} U_R \tilde{\phi} + \bar{L}_L \mathbf{Y_L} E_R \phi + h.c$ break G down to

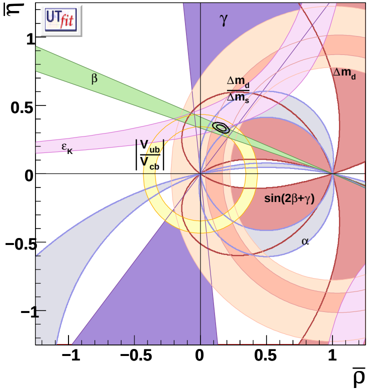
$$\mathbf{G} \to \mathbf{U(1)_B} \times \mathbf{U(1)_e} \times \mathbf{U(1)_\mu} \times \mathbf{U(1)_\tau}$$

- **CKM matrix**: $Y_U = V_{CKM} \times \mathrm{diag}(y_u, y_c, y_t)$ for $\mathbf{Y_D} = \mathrm{diag}(y_d, y_s, y_b)$



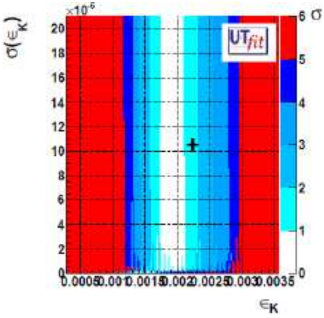
Messages from the B-factories



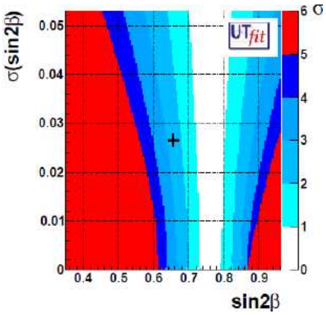


"Very likely, flavour and CP violation in FC processes are dominated by the CKM mechanism" (Nir)

UT tensions



fit vs. exp. $\approx -1.7\sigma$

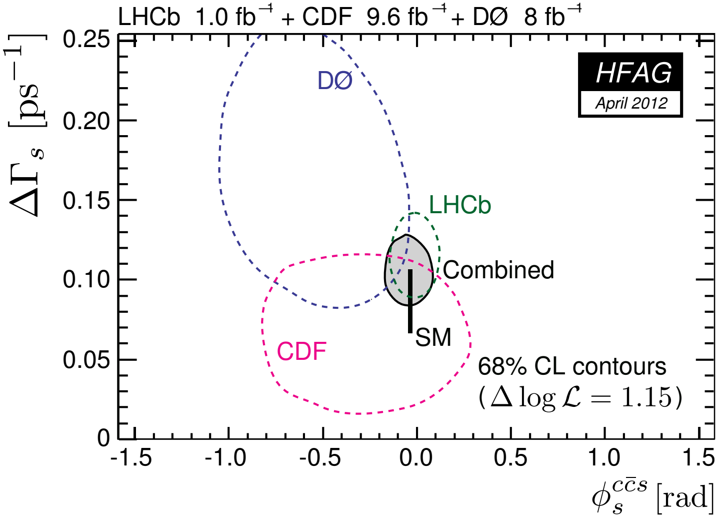


fit vs. exp. $\approx +2.6\sigma$

Similar conclusions from the CKMfitter collaboration ('10)

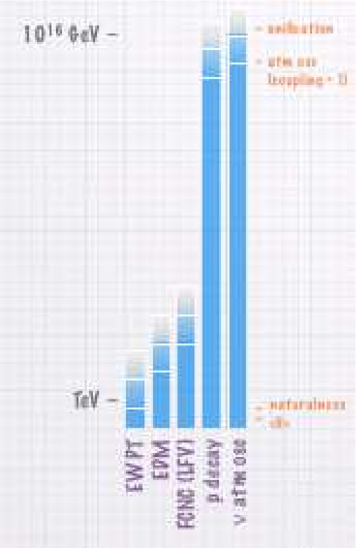
1. These "UT tension" are interesting but not significant yet.
2. To monitor the impact of BSM scenarios on the UT analyses.
3. To monitor the implications of possible solutions of the "UT tension" in BSM scenarios.

B_s mixing


LHCb 1.0 fb^{-1} + CDF 9.6 fb^{-1} + DØ 8 fb^{-1}
HFAG
April 2012
DØ
LHCb
Combined
SM
CDF
68% CL contours
$(\Delta \log \mathcal{L} = 1.15)$
$\Delta\Gamma_s$ [ps^{-1}]
0.25
0.20
0.15
0.10
0.05
0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
$\phi_s^{c\bar{c}s}$ [rad]

The NP “scale”

- **Gravity** $\Longrightarrow$ $\Lambda_{\text{Planck}} \sim 10^{18-19}\ \mathrm{GeV}$
- **Neutrino masses** $\Longrightarrow$ $\Lambda_{\text{see-saw}} \lesssim 10^{15}\ \mathrm{GeV}$
- **BAU**: evidence of CPV beyond SM
  - Electroweak Baryogenesis $\Longrightarrow$ $\Lambda_{\text{NP}} \lesssim \mathrm{TeV}$
  - Leptogenesis $\Longrightarrow$ $\Lambda_{\text{see-saw}} \lesssim 10^{15}\ \mathrm{GeV}$
- **Hierarchy problem**: $\Longrightarrow$ $\Lambda_{\text{NP}} \lesssim \mathrm{TeV}$
- **Dark Matter** $\Longrightarrow$ $\Lambda_{\text{NP}} \lesssim \mathrm{TeV}$



SM = effective theory at the EW scale

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d\geq 5} \frac{c_{ij}^{(d)}}{\Lambda_{NP}^{d-4}}\, O_{ij}^{(d)}$$

- $\mathcal{L}_{\text{eff}}^{d=5} = \frac{y_\nu^{ij}}{\Lambda_{\text{see-saw}}} L_i L_j \phi\phi$,
- $\mathcal{L}_{\text{eff}}^{d=6}$ generates FCNC operators

$$\mathbf{BR}(\ell_i \to \ell_j \gamma) \sim \frac{1}{\Lambda_{NP}^4}$$

The NP flavor problem

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d=6} \frac{c_{ij}^{(6)}}{\Lambda_{NP}^2}\, O_{ij}^{(6)}$$

[Isidori, Nir, Perez '10]

Operator	Bounds on Λ (TeV)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ε_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ε_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\vert q/p \vert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\vert q/p \vert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_{B_s}

$$\Downarrow$$

“Generic” flavor violating sources at the TeV scale are excluded

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

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

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

Yukawa structures as the only sources of flavour violation

$$\Downarrow$$

Minimal Flavour Violation [D'Ambrosio et al. '02]

Notice that MFV allows new "flavour blind" CPV phases!

[Kagan et al. '09] (model-independent)
[Ellis et al. '07] (SUSY)
[Colangelo et al., '08], [Smith et al. '09] (SUSY)
[Altmannshofer et al., '08,'09], [P.P & Straub, '09] (SUSY)
[Buras et al., '10,'10] (2HDM)

MFV & the NP flavor problem

$$(c^{\Delta F=1}_{\rm MFV})_{ij} \sim V^\star_{ti} V_{tj}\,, \qquad (c^{\Delta F=2}_{\rm MFV})_{ij} \sim (V^\star_{ti} V_{tj})^2$$

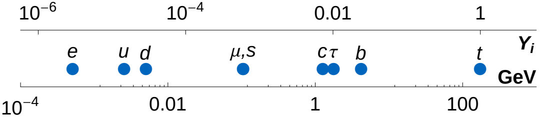
$\Delta F = 1,2$ MFV operators	Λ(TeV)	Observables
$H^\dagger \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right) (eF_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}
$H^\dagger_D \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right) (g_s G^a_{\mu\nu})$	3.4 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) (\overline{E}_R \gamma_\mu E_R)$	2.7 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) (eD_\mu F_{\mu\nu})$	1.5 TeV	$B \to X_s\ell^+\ell^-$

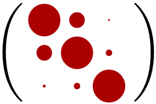
Observable	Experiment	MFV prediction	SM prediction
$\mathcal{A}_{\rm CP}(B_s \to \psi\phi)$	[0.10, 1.44] @ 95% CL	0.04(5)	0.04(2)
$\mathcal{A}_{\rm CP}(B \to X_s\gamma)$	$< 6\%$ @ 95% CL	< 0.02	< 0.01
$\mathcal{B}(B_d \to \mu^+\mu^-)$	$< 1.8 \times 10^{-8}$	$< 1.2 \times 10^{-9}$	$1.3(3) \times 10^{-10}$
$\mathcal{B}(B \to X_s\tau^+\tau^-)$	–	$< 5 \times 10^{-7}$	$1.6(5) \times 10^{-7}$
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	$< 2.6 \times 10^{-8}$ @ 90% CL	$< 2.9 \times 10^{-10}$	$2.9(5) \times 10^{-11}$

[D'Ambrosio et al. '02; Hurth et al. '08, Isidori, Nir & Perez '10]

SM vs. NP flavor problems

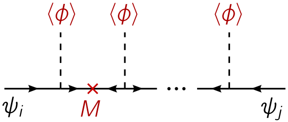
1. MFV is not a theory of flavour and it has not been probed yet.
2. Can the SM and NP flavour problems have a common explanation?
3. Is it possible to disentangle among different mechanisms solving flavour problems by means of their predicted pattern of deviation w.r.t. the SM predictions in flavour physics?



$V_{\rm CKM} \sim$ 

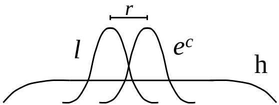
Froggat-Nielsen '79: Hierarchies from SSB of a Flavour Symmetry

$$\epsilon = \frac{\langle \phi \rangle}{M} \ll 1 \Rightarrow Y_{ij} \propto \epsilon^{(a_i+b_j)}$$



Arkani-Hamed & Schmaltz '99: Hierarchies from Extra Dimensions

$x = \mu r$	1	2	3	4	5
$e^{-\frac{x^2}{2}}$	1	10^{-1}	10^{-2}	10^{-4}	10^{-6}
	λ_t		$\cdots$		λ_e



The Gaussian wave functions of l and e^c overlap in an exponentially small region

$\Downarrow$

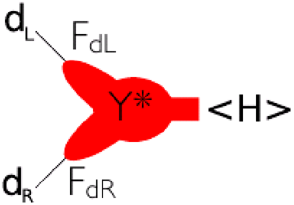
Small Yukawa couplings without Symmetries

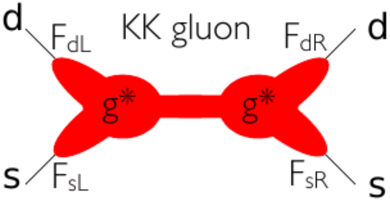
- **Flavor Models flavor protection**

[Lalak, Pokorski & Ross '10]

Operator	$U(1)$	$U(1)^2$	$SU(3)$	MFV
$(\overline{Q}_L X^Q_{LL} Q_L)_{12}$	λ	λ^5	λ^3	λ^5
$(\overline{D}_R X^D_{RR} D_R)_{12}$	λ	λ^{11}	λ^3	$(y_d y_s) \times \lambda^5$
$(\overline{Q}_L X^D_{LR} D_R)_{12}$	λ^4	λ^9	λ^3	$y_s \times \lambda^5$

- **RS flavor protection** [Gerghetta & Pomarol, '99; Huber, '03; Agashe, Perez & Soni, '04]





$$m_d \sim v\, F_{d_L} Y^\star F_{d_R}$$

$$(V_{CKM})_{ij} \sim F_{d_{L_i}} / F_{d_{L_j}}$$

$$(\epsilon_K)_{\mathbf{RS-GIM}} \sim \frac{(g^\star)^2}{M^2_{\rm KK}} \frac{\mathbf{m_d\, m_s}}{(v\ Y^\star)^2}$$

[Csaki, Falkowski & Weiler, '08]

[Blanke, Buras, Duling, Gori, Weiler, '08]

- **Why CP violation? Motivation:**
  - Baryogenesis requires extra sources of CPV
  - The QCD $\overline{\theta}$-term $\mathcal{L}_{CP} = \overline{\theta}\frac{\alpha_s}{8\pi}G\tilde{G}$ is a CPV source beyond the CKM
  - Most UV completion of the SM, e.g. the MSSM, have many CPV sources
  - However, TeV scale NP with $\mathcal{O}(1)$ CPV phases generally leads to EDMs many orders of magnitude above the current limits $\Rightarrow$ the New Physics CP problem.

- **How to solve the New Physics CP problem?**
  - Decoupling some NP particles in the loop generating the EDMs (e.g. hierarchical sfermions, split SUSY, 2HDM limit...)
  - Generating CPV phases radiatively $\phi^f_{CP} \sim \alpha_w/4\pi \sim 10^{-3}$
  - Generating CPV phases via small flavour mixing angles $\phi^f_{CP} \sim \delta_{fj}\delta_{fj}$ with $f = e, u, d$: maybe the absence of NP signals in FCNC processes and EDMs have a common origin?

NP search strategies

- **High-energy frontier: A unique effort to determine the NP scale**
- **High-intensity frontier (flavor physics): A collective effort to determine the flavor structure of NP**

Where to look for New Physics at the low energy?

- **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, $d_{e,n}$...
  - FCNC & CPV in $B_{s,d}$ & D decay/mixing amplitudes
- **Processes predicted with high precision in the SM**
  - EWPO as $(g-2)_{\mu,e}$: $a_\mu^{exp} - a_\mu^{SM} \approx (3 \pm 1) \times 10^{-9}$, a discrepancy at 3σ!
  - LU in $R_M^{e/\mu} = \Gamma(M \to e\nu)/\Gamma(M \to \mu\nu)$ with $M = \pi, K$

Experimental status

Observable	SM prediction	Theory error	Present result	Future error	Future Facility
$S_{B_s \to \psi\phi}$	**0.036**	≤ 0.01	$0.81^{+0.12}_{-0.32}$	0.01	**LHCb**
$S_{B_d \to \phi K}$	$\sin(2\beta)$	≤ 0.05	0.44 ± 0.18	0.1	LHCb
$A^d_{\rm SL}$	-5×10^{-4}	10^{-4}	$-(5.8 \pm 3.4)10^{-3}$	10^{-3}	LHCb
$A^s_{\rm SL}$	2×10^{-5}	$< 10^{-5}$	$(1.6 \pm 8.5)10^{-3}$	10^{-3}	LHCb
$A_{CP}(b \to s\gamma)$	< 0.01	< 0.01	-0.012 ± 0.028	0.005	Super-B
$\mathcal{B}(B \to \tau\nu)$	1×10^{-4}	$20\% \to 5\%$	$(1.73 \pm 0.35)10^{-4}$	5%	Super-B
$\mathcal{B}(B \to \mu\nu)$	4×10^{-7}	$20\% \to 5\%$	$< 1.3 \times 10^{-6}$	6%	Super-B
$\mathcal{B}(B_s \to \mu\mu)$	$(3.54 \pm 0.30)10^{-9}$	$20\% \to 5\%$	$(3.2^{+1.5}_{-1.2}) \times 10^{-8}$	10%	**LHCb**
$\mathcal{B}(B_d \to \mu\mu)$	$(1.07 \pm 0.10)10^{-10}$	$20\% \to 5\%$	$< 1.5 \times 10^{-8}$	**[?]**	**LHCb**
$B \to K\nu\bar{\nu}$	4×10^{-6}	$20\% \to 10\%$	$< 1.4 \times 10^{-5}$	20%	Super-B
$\lvert q/p \rvert_{D-\rm mix}$	1	$< 10^{-3}$	$(0.86^{+0.18}_{-0.15})$	0.03	Super-B
ϕ_D	0	$< 10^{-3}$	$-(9.6^{+8.3}_{-9.5})^\circ$	2°	Super-B
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	8.5×10^{-11}	8%	$(1.73^{+1.15}_{-1.05})10^{-10}$	10%	K factory
$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$	2.6×10^{-11}	10%	$< 2.6 \times 10^{-8}$	[?]	K factory

[Altmannshofer, Buras, Gori, Paradisi, and Straub, '09; Isidori, Nir, and Perez, '10]

Superstars of 2011-2013 in flavour physics: $\mu \to e\gamma$, $B_s \to \psi\phi$, $B_{s,d} \to \mu^+\mu^-$

- **First evidence for $B_s \to \mu^+\mu^-$ discovery at LHCb**

$$\mathrm{BR}(\mathrm{B_s} \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

- **Next goals after the $B_s \to \mu^+\mu^-$ discovery:**
  - Precision measurement of $B_s \to \mu^+\mu^-$
  - Discovery of $B_d \to \mu^+\mu^-$ (large NP effects are still allowed)
  - To monitor the ratio $\mathrm{BR}(B_s \to \mu^+\mu^-)/\Delta M_s$ and $\mathrm{BR}(B_s \to \mu^+\mu^-)/\mathrm{BR}(B_d \to \mu^+\mu^-)$: powerful tests of MFV
  - To look for non-standard effect in $B \to K(K^*)\ell^+\ell^-$ observables

Conclusions

We presented today an updated search for $B^0_{(s)} \to \mu^+\mu^-$ combining 7 TeV ($1.0\ fb^{-1}$) and 8 TeV ($1.1\ fb^{-1}$) data

We see an excess of $B^0_s \to \mu^+\mu^-$ signal above background expectation with a p-value of 5.3×10^{-4}, corresponding to $3.5\ \sigma$

this is the first evidence of $B^0_s \to \mu^+\mu^-$ decay!

A maximum likelihood fit to data yields

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2})\times10^{-9}$$

in agreement with SM expectation

On the same dataset, we set the most stringent limit on $B^0 \to \mu^+\mu^-$ decay:

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4\times10^{-10} \text{ at } 95\%\ \text{CL}$$

We warmly thank our colleagues in the CERN accelerator departments for the excellent performance of the LHC!!

talk by Palutan @ CERN, 2012/11/12, (see also arXiv:1211.2674)

$B^0_{s,d} \to \mu^+\mu^-$ and NP

FCNC processes as $B^0_{s,d} \to \mu^+\mu^-$ offer a unique possibility in probing the underlying flavour mixing mechanism of **NP**

- No SM tree-level contributions (FCNC decays)
- CKM suppression $\to BR(B^0_{s,d} \to \mu^+\mu^-) \sim |V_{ts(td)}|^2$
- Elicity suppression $\to BR(B^0_{s,d} \to \mu^+\mu^-) \sim m_\mu^2$
- Dominance of short distance effects $\to$ SM uncertainties well under control

$$\begin{aligned} \mathrm{BR}(\mathrm{B_s} \to \mu^+\mu^-)^{\mathrm{t}=0} &= (3.23 \pm 0.27) \times 10^{-9} \\ \mathrm{BR}(\mathrm{B_d} \to \mu^+\mu^-)^{\mathrm{t}=0} &= (1.07 \pm 0.10) \times 10^{-10} \end{aligned}$$

[Buras et al, '12]

- High sensitivity to NP effects: SUSY, 2HDM, LHT, Z', RS models.....

$$A(b \to d)_{\mathrm{FCNC}} \sim c_{\mathrm{SM}} \frac{y_t^2 V_{td}^* V_{tb}}{16\pi^2 M_W^2} + c_{\mathrm{NP}} \frac{\delta_{3d}}{16\pi^2 \Lambda_{NP}^2}$$

- **Recend developments concerning the SM prediction of $B_s \to \mu^+\mu^-$**

I) Updated prediction taking into account leading NLO EW (+ full NLO QCD) of the *photon-inclusive flavor-eigenstate* decay:

$$\mathrm{BR}^{(0)} = 3.2348 \times 10^{-9} \times \left(\frac{M_t}{173.2\ \mathrm{GeV}}\right)^{3.07} \left(\frac{f_{B_s}}{227\ \mathrm{MeV}}\right)^2 \left(\frac{\tau_{B_s}}{1.466\ \mathrm{ps}}\right) \left|\frac{V_{tb}^* V_{ts}}{4.05 \times 10^{-2}}\right|^2$$

$$= (3.23 \pm 0.15 \pm 0.23_{f_{B_s}}) \times 10^{-9}$$

~ 3% th. error, which could be further reduced with a full NLO EW calculation

SM prediction giving present best estimate of parametric inputs

Buras, Girrbach, Guadagnoli, G.I. '12

II) Correction factors in relating $\mathrm{BR}^{(0)}$ to the experimentally accessible rate

- Photon-energy cut [Buras *et al.* '12] → ~ -10% (*already included in exp. efficiency*)
- $\Delta\Gamma_s \neq 0$ [Bruyn *et al.* '12] → ~ + 10% (*not included yet in exp. results*)

- **To compare with experiments need a time integrated branching fraction, taking into account the finite width of the B_s system:**

$$\mathrm{BR}(\mathrm{B_s} \to \mu^+\mu^-)^{(<t>)} = \frac{1}{1-y_s}\mathrm{BR}(\mathrm{B_s} \to \mu^+\mu^-)^{(0)} = (3.54 \pm 0.30) \times 10^{-9}$$

Theory of $B_{s,d} \to \mu^+\mu^-$

- **Effective Hamiltonian for $B_{s,d} \to \mu^+\mu^-$**

$$\mathcal{H}^{\rm eff}_{\Delta F=1} = \mathcal{H}^{\rm eff}_{\rm SM} + C_S O_S + C_P O_P + C'_S O'_S + C'_P O'_P + {\rm h.c.},$$

- **SM and constrained MFV (CMFV) current**

$$\mathcal{H}^{\rm eff}_{\rm SM} = C_{10} Q_{10} \qquad Q_{10} = \bar{b}_L \gamma^\mu q_L \bar{\ell}\gamma_\mu\gamma_5\ell, \qquad C_{10}^{\rm SM} \approx \frac{g_2^2}{16\pi^2}\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \,,$$

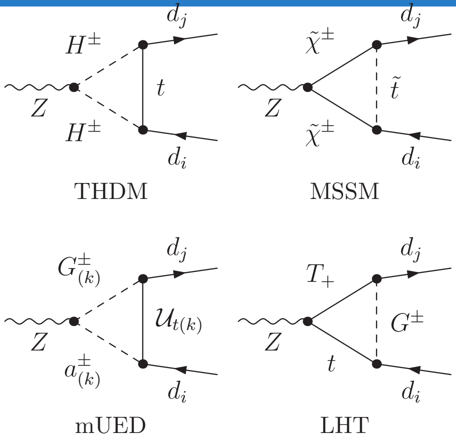
- **Scalar currents (2HDM, SUSY)**

$$O_S = \overline{d}^i_R d^j_L \bar{\ell}\ell \,, \qquad O_P = \overline{d}^i_R d^j_L \bar{\ell}\gamma_5\ell \,,$$
$$O'_S = \overline{d}^i_L d^j_R \bar{\ell}\ell \,, \qquad O'_P = \overline{d}^i_L d^j_R \bar{\ell}\gamma_5\ell \,.$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{\tau_{B_s} F_{B_s}^2 m_{B_s}^3}{32\pi}\sqrt{1 - 4\frac{m_\mu^2}{m_{B_s}^2}}\left(|B|^2\left(1 - 4\frac{m_\mu^2}{m_{B_s}^2}\right) + |A|^2\right)$$

$$A = 2\frac{m_\mu}{m_{B_s}} C_{10}^{\rm SM} + \frac{m_{B_s}}{m_b}\left(C_P - C'_P\right)\,, \quad B = \frac{m_{B_s}}{m_b}\left(C_S - C'_S\right)$$

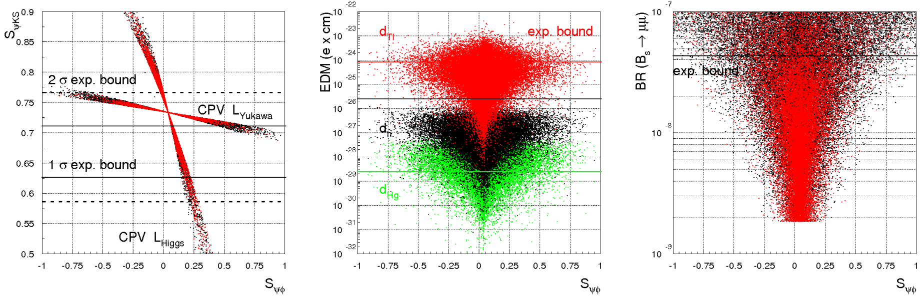
$B_s \to \mu^+\mu^-$ & CMFV



- **Zbb** $\to R_b^0, \mathcal{A}_b, A_{\rm FB}^{0,b}$
- **Zd_jd_i** $\to K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, $K_L \to \mu^+\mu^-$, $\bar{B} \to X_{d,s}\nu\bar{\nu}$, $B_{d,s} \to \mu^+\mu^-$
- **Zd_jd_i** vs **Zbb**

Observable	CMFV (95%CL)	SM (95%CL)	Exp.
$\mathcal{B}(B_d \to \mu^+\mu^-) \times 10^{10}$	[0.36, 2.03]	[0.87, 1.27]	$< 1.8 \times 10^2$
$\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^{9}$	[1.17, 6.67]	[2.92, 4.13]	$< 5.8 \times 10^1$

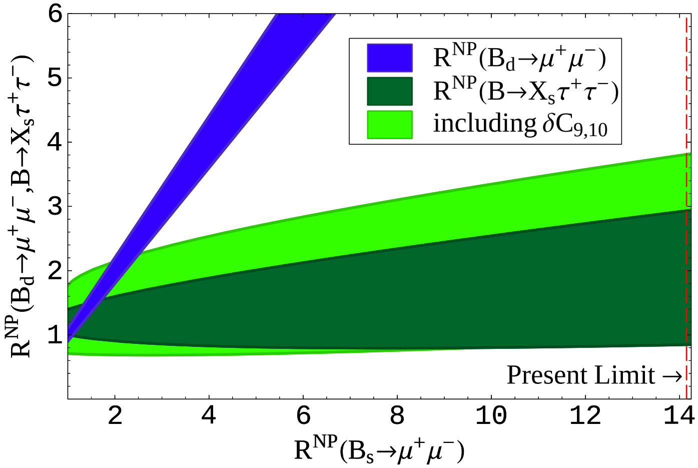
Haisch & Weiler '07



- Main messages:
  - The **“UT tension”** is “solved” by a **NP phase in B_d-mixing** ($S_{\psi K_S}$) implying a **large NP phase in B_s-mixing** ($S_{\psi\phi}$), in agreement with present data (ϵ_K remains SM-like).
  - **Non-standard** CPV effects in B_s mixing $S_{\psi\phi}$ imply **lower bounds for the EDMs** in the experimental reach as well as **non-standard** values for $\mathrm{BR}(B_{s,d} \to \mu^+\mu^-)$.
  - **An extended Higgs sector below the TeV** scale is required for such a pattern of deviation from the SM $\Rightarrow$ the **interplay** of **LHC** (M_H), **LHCb** ($S_{\psi\phi}$, $B_{s,d} \to \mu^+\mu^-$), and **EDMs experiments** (d_n, d_{Tl}, d_{Hg}) will probe or falsify the scenario.

[Buras, Isidori & P.P., ’10]

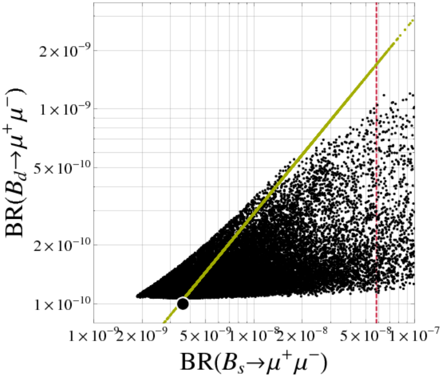
$B_s \to \mu^+\mu^-$ vs $B_d \to \mu^+\mu^-$ in MFV



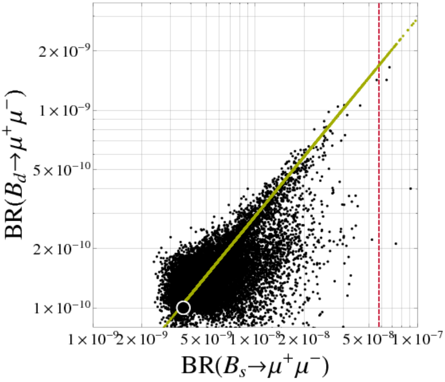
$$\frac{\Gamma(B_s \to \ell^+\ell^-)}{\Gamma(B_d \to \ell^+\ell^-)} \approx \frac{f_{B_s} m_{B_s}}{f_{B_d} m_{B_d}} \left| \frac{V_{ts}}{V_{td}} \right|^2 .$$

Powerful probe of MFV (Hurt et al. '08)

Abelian SUSY flavor model



Non abelian SUSY flavor model



[Altmannshofer et al., '09]

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

[Hurth, Isidori, Kamenik & Mescia, '08]

$B \to K^* \ell^+ \ell^-$ observables

Obs.	[46]	[47]	[16]	[48-50]	[51]	most sensitive to
F_L	$-S_2^c$	F_L		F_L	F_L	$C_{7,9,10}^{(\prime)}$
$A_{\rm FB}$	$\frac{3}{4}S_6^s$	$A_{\rm FB}$	$A_{\rm FB}$	$-A_{\rm FB}$	$-A_{\rm FB}$	C_7, C_9
S_5	S_5					C_7, C_7', C_9, C_{10}'
S_3	S_3	$\frac{1}{2}(1-F_L)A_T^{(2)}$			$\frac{1}{2}(1-F_L)A_T^{(2)}$	$C_{7,9,10}'$
A_9	A_9		$\frac{2}{3}A_9$		A_{im}	$C_{7,9,10}'$
A_7	A_7		$-\frac{2}{3}A_7^D$			$C_{7,10}^{(\prime)}$

Table 1: Dictionary between different notations for the $B \to K^* \mu^+ \mu^-$ observables and Wilson coefficients they are most sensitive to (the sensitivity to $C_7^{(\prime)}$ is only present at low q^2).

$$S_i = (I_i + \bar{I}_i) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}\,, \qquad A_i = (I_i - \bar{I}_i) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}\,.$$

see references in Altmannshofer, P.P., Straub, '11

New Physics scenarios

1. **Real left-handed currents**, $C_i \in \mathbf{R}$, $C_i' = 0$. This is realised e.g. in models with MFV in the definition of D'Ambrosio et al., i.e. no CP violation beyond the CKM phase.

2. **Complex left-handed currents**, $C_i \in \mathbf{C}$, $C_i' = 0$. This is realised e.g. in models with MFV and flavour-blind phases.

3. **Complex right-handed currents**, $C_i' \in \mathbf{C}$, $C_i = 0$.

4. **Generic NP**, $C_i \in \mathbf{C}$, $C_i' \in \mathbf{C}$.

5. Models with non-standard Z couplings: only $C_{9,10}^{(\prime)}$ with $C_9^{(\prime)} = -(1 - 4s_w^2)C_{10}^{(\prime)}$)

$$\chi^2(\vec{C}) = \sum_i \frac{\left(O_i^{\rm exp} - O_i^{\rm th}(\vec{C})\right)^2}{(\sigma_i^{\rm exp})^2 + (\sigma_i^{\rm th}(\vec{C}))^2} .$$

Altmannshofer, P.P., Straub, '11

$B \to K^* \ell^+ \ell^-$ observables

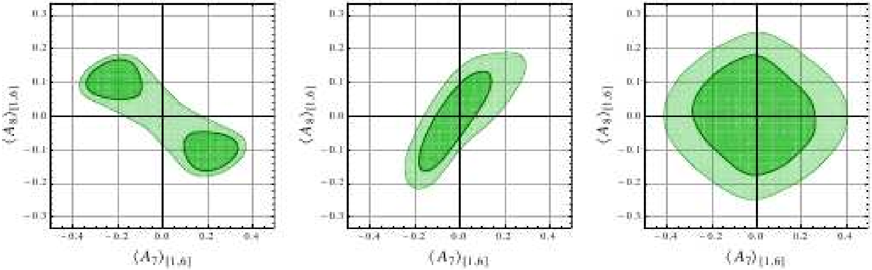


Figure 7: Fit predictions for the low-q^2 CP asymmetries $\langle A_{7,8} \rangle$ in $B \to K^* \mu^+ \mu^-$ in the case of complex left-handed currents (left), complex right-handed currents (centre) and generic NP (right). Shown are 68% and 95% C.L. regions.

Altmannshofer, P.P., Straub, '11

$B \to K^* \ell^+ \ell^-$ observables

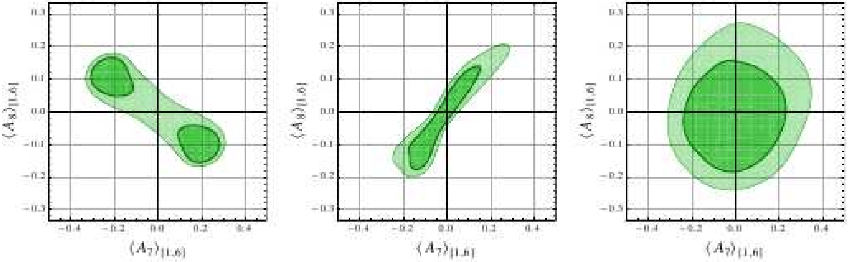


Figure 11: Fit predictions for the low-q^2 CP asymmetries $\langle A_{7,8} \rangle$ in $B \to K^* \mu^+ \mu^-$ for the scenario with left-handed (left), right-handed (centre) or generic (right) modified Z couplings. Shown are 68% and 95% C.L. regions.

Altmannshofer, P.P., Straub, '11

Scenario	$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$\mathrm{BR}(B_s \to \tau^+\tau^-)$	$\lvert\langle A_7\rangle_{[1,6]}\rvert$	$\lvert\langle A_8\rangle_{[1,6]}\rvert$	$\lvert\langle A_9\rangle_{[1,6]}\rvert$	$\langle S_3\rangle_{[1,6]}$
Real LH	$[1.0, 5.6] \times 10^{-9}$	$[2, 12] \times 10^{-7}$	0	0	0	0
Complex LH	$[1.0, 5.4] \times 10^{-9}$	$[2, 12] \times 10^{-7}$	< 0.31	< 0.15	0	0
Complex RH	$< 5.6 \times 10^{-9}$	$< 12 \times 10^{-7}$	< 0.22	< 0.17	< 0.12	$[-0.06, 0.15]$
Generic NP	$< 5.5 \times 10^{-9}$	$< 12 \times 10^{-7}$	< 0.34	< 0.20	< 0.15	$[-0.11, 0.18]$
LH Z peng.	$[1.4, 5.5] \times 10^{-9}$	$[3, 12] \times 10^{-7}$	< 0.27	< 0.14	0	0
RH Z peng.	$< 3.8 \times 10^{-9}$	$< 8 \times 10^{-7}$	< 0.22	< 0.18	< 0.12	$[-0.03, 0.18]$
Generic Z p.	$< 4.1 \times 10^{-9}$	$< 9 \times 10^{-7}$	< 0.28	< 0.21	< 0.13	$[-0.07, 0.19]$
scalar current	$< 1.1 \times 10^{-8}$	$< 1.3(2.3) \times 10^{-6}$	0	0	0	0

Table 3: Predictions at 95% C.L. for the branching ratios of $B_s \to \mu^+\mu^-$ and $B_s \to \tau^+\tau^-$ and predictions for low-q^2 angular observables in $B \to K^*\mu^+\mu^-$ (neglecting tiny SM effects below the percent level) in all the scenarios. The scenarios "Real LH", "Complex LH", "Complex RH", "Generic NP", "LH Z peng.", "RH Z peng.", and "Generic Z p." correspond to the scenarios discussed in sec. 3.2.1, sec. 3.2.2, sec. 3.2.3, sec. 3.2.4, sec. 4.1.1, sec. 4.1.2 and sec. 4.1.3 respectively, assuming negligible (pseudo)scalar currents. In the scenario "scalar current" *only* scalar currents are considered. The number quoted for $B_s \to \tau^+\tau^-$ in the "scalar current" scenario refers to the maximum value for its branching ratio in the case of dominant scalar (pseudoscalar) currents.

- **Experiment:** $\Delta a_{CP} = a_{K^+K^-} - a_{\pi^+\pi^-}$

$$\Delta a_{CP} = -(0.67 \pm 0.16)\%$$ [LHCb '11, CDF '11, Belle '08 and BaBar '07]

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}, \quad f = K^+K^-, \pi^+\pi^-$$

- **Is it possible Δa_{CP} @ % in the SM?**

- **Theory:** SCS decay amplitude $A_f(\bar{A}_f)$ of D^0 $(\bar{D}^0)$ to a CP eigenstate f

$$\begin{aligned} A_f &= A_f^T\, e^{i\phi_f^T} \left[1 + r_f\, e^{i(\delta_f + \phi_f)}\right], \\ \bar{A}_f &= \eta_{CP}\, A_f^T\, e^{-i\phi_f^T} \left[1 + r_f e^{i(\delta_f - \phi_f)}\right] \end{aligned}$$

Direct CPV $\Longleftrightarrow$ $r_f \neq 0$, $\delta \neq 0$ and $\phi_f \neq 0$

$$a_f^{\mathrm{dir}} \equiv \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} = -2 r_f \sin\delta_f \sin\phi_f$$

Effective Hamiltonian for $D^0 \to K^+K^-(\pi^+\pi^-)$

- **General Effective Hamiltonian** [Isidori, Kamenik, Ligeti & Perez, '11]

$$\mathcal{H}^{\rm eff-NP}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1,2,5,6} (C_i^q Q_i^q + C_i^{q\prime} Q_i^{q\prime}) + \sum_{i=7,8} (C_i Q_i + C_i' Q_i') + \mathrm{H.c.}\,,$$

$$\begin{aligned}
Q_1^q &= (\bar{u}q)_{V-A}\,(\bar{q}c)_{V-A}\,, \qquad Q_2^q = (\bar{u}_\alpha q_\beta)_{V-A}\,(\bar{q}_\beta c_\alpha)_{V-A}\,,\\
Q_5^q &= (\bar{u}c)_{V-A}\,(\bar{q}q)_{V+A}\,, \qquad Q_6^q = (\bar{u}_\alpha c_\beta)_{V-A}\,(\bar{q}_\beta q_\alpha)_{V+A}\,,\\
Q_7 &= -\frac{e}{8\pi^2}\, m_c\, \bar{u}\sigma_{\mu\nu}(1+\gamma_5) F^{\mu\nu}\, c\,,\\
Q_8 &= -\frac{g_s}{8\pi^2}\, m_c\, \bar{u}\sigma_{\mu\nu}(1+\gamma_5) T^a G_a^{\mu\nu}\, c\,,
\end{aligned}$$

- **$D-\bar{D}$ and ϵ'/ϵ constraints:** $|\Delta c| = 2$ **and** $|\Delta s| = 1$ **eff. ops are generated by "dressing"** $T\{\mathcal{H}^{\rm eff-NP}_{|\Delta c|=1}(x)\,\mathcal{H}^{\rm SM}_{|\Delta c|=1}(0)\}$ **and** $T\{\mathcal{H}^{\rm eff-NP}_{|\Delta c|=1}(x)\, H^{\rm SM}_{c.c}(0)\}$

Allowed	Ajar	Disfavored
$Q_{7,8}\,,\ Q'_{7,8}\,,$ $\forall f\ Q^{f\prime}_{1,2}\,,\ Q^{(c-u,b)\prime}_{5,6}$	$Q^{(c-u,8d,b,0)}_{1,2}\,,$ $Q^{(0)}_{5,6}\,,\ Q^{(8d)\prime}_{5,6}$	$Q^{s-d}_{1,2}\,,\ C^{(s-d)\prime}_{5,6}\,,$ $C^{s-d,c-u,8d,b}_{5,6}$

- The effects induced by $Q^{(\prime)}_{7,8}$ are suppressed by m_c^2/M_W^2!!

Time-integrated CP asymmetries in $D^0 \to K^+K^-(\pi^+\pi^-)$

- **“Relevant” Effective Hamiltonian**

$$\mathcal{H}^{\mathrm{eff-NP}}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_i C_i Q_i + \mathrm{h.c.}\,,$$

$$\begin{aligned} Q_8 &= \frac{m_c}{4\pi^2}\,\bar{u}_L \sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_R\,, \\ \tilde{Q}_8 &= \frac{m_c}{4\pi^2}\,\bar{u}_R \sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_L\,. \end{aligned}$$

- **Δa_{CP}: SM + NP**

$$\begin{aligned} \Delta a_{CP} &\approx \frac{-2}{\sin\theta_c}\left[\mathrm{Im}(V^*_{cb}V_{ub})\mathrm{Im}(\Delta R^{\mathrm{SM}}) + \sum_i \mathrm{Im}(C_i^{\mathrm{NP}})\mathrm{Im}(\Delta R^{\mathrm{NP}_i})\right] \\ &= -(0.13\%)\mathrm{Im}(\Delta R^{\mathrm{SM}}) - 9\sum_i \mathrm{Im}(C_i^{\mathrm{NP}})\,\mathrm{Im}(\Delta R^{\mathrm{NP}_i}) \end{aligned}$$

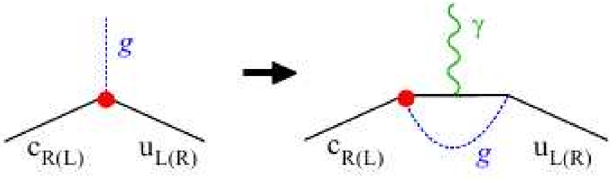
$\Delta R^{\mathrm{SM}} \approx \alpha_s(m_c)/\pi \approx 0.1$ in perturbation theory and $a_K^{\mathrm{dir}} = -a_\pi^{\mathrm{dir}}$ in the $SU(3)$ limit. In naive factorization $\left|\mathrm{Im}(\Delta R^{\mathrm{NP}_{8,\tilde{8}}})\right| \approx 0.2$ [Grossman, Kagan & Nir, ’06]

$$\Delta a_{CP}^{\mathrm{NP}} \approx 2\,\mathrm{Im}(C_8^{\mathrm{NP}} + C_8'^{\mathrm{NP}})$$

- **Lessons:**
  - On general grounds, models in which the primary source of flavor violation is linked to the breaking of chiral symmetry (left-right flavor mixing) are natural candidates to explain this effect, via enhanced chromomagnetic operators.
  - The challenge of model building is to generate the $\Delta C = 1$ chromomagnetic operator without inducing dangerous 4-fermion operators that lead to unacceptably large effects in $D^0 - \bar{D}^0$ mixing or in flavor processes in the down-type quark sector.
- **Questions:**
  - Which are the most natural NP theories to account for Δa_{CP} @ %?
  - How to test and discriminate among different new-physics models? Looking at connections between Δa_{CP} and other independent observables.

[G.F.Giudice, G.Isidori, & P.P, '12]

- **Δa_{CP} vs. direct CP violation in $D \to V\gamma$** [Isidori & Kamenik, '12]



$$|a_{(\rho,\omega)\gamma}| = 0.04(1) \left| \frac{\mathrm{Im}[C_7(m_c)]}{0.4 \times 10^{-2}} \right| \left[\frac{10^{-5}}{\mathcal{B}(D \to (\rho,\omega)\gamma)} \right]^{1/2} .$$

$$C_7^{(\prime)}(m_c) = \tilde{\eta} \left[\eta C_7^{(\prime)}(M_\star) + 8Q_u (\eta - 1)\, C_8^{(\prime)}(M_\star) \right],$$

$$C_8^{(\prime)}(m_c) = \tilde{\eta}\, C_8^{(\prime)}(M_\star),$$

$$\eta = \left[\frac{\alpha_s(M_\star)}{\alpha_s(m_t)}\right]^{\frac{2}{21}} \left[\frac{\alpha_s(m_t)}{\alpha_s(m_b)}\right]^{\frac{2}{23}} \left[\frac{\alpha_s(m_b)}{\alpha_s(m_c)}\right]^{\frac{2}{25}} ,$$

$$\tilde{\eta} = \left[\frac{\alpha_s(M_\star)}{\alpha_s(m_t)}\right]^{\frac{14}{21}} \left[\frac{\alpha_s(m_t)}{\alpha_s(m_b)}\right]^{\frac{14}{23}} \left[\frac{\alpha_s(m_b)}{\alpha_s(m_c)}\right]^{\frac{14}{25}} .$$

- **Δa_{CP} in SUSY: two scenarios**

$$\left|\Delta a_{CP}^{\rm SUSY}\right| \approx 0.6\% \left(\frac{\left|{\rm Im}\,(\delta^u_{12})^{eff}_{LR}\right|}{10^{-3}}\right)\left(\frac{\rm TeV}{\tilde m}\right) ,$$

- **Disoriented A terms (proportionality but not alignment with Yukawas)**

$$ {\rm Im}\,(\delta^u_{12})_{LR} \approx \frac{{\rm Im}(A)\,\theta_{12}\;m_c}{\tilde m} \approx \left(\frac{{\rm Im}(A)}{3}\right)\left(\frac{\theta_{12}}{0.5}\right)\left(\frac{\rm TeV}{\tilde m}\right) \times 10^{-3} ,$$

- **Split families: $m_{\tilde q_{1,2}} \gg m_{\tilde q_3}$, $(\delta^u_{33})_{RL} = A\,m_t/m_{\tilde q_3}$**

$$(\delta^u_{12})^{\rm eff}_{RL} = (\delta^u_{13})_{RR}\,(\delta^u_{33})_{RL}\,(\delta^u_{32})_{LL} , \qquad (\delta^u_{12})^{\rm eff}_{LR} = (\delta^u_{13})_{LL}\,(\delta^u_{33})_{RL}\,(\delta^u_{32})_{RR} .$$

$$(\delta^u_{32})_{LL} = O(\lambda^2),\quad (\delta^u_{13})_{RR} = O(\lambda^2) \quad \rightarrow \quad (\delta^u_{12})^{\rm eff}_{RL} = O(\lambda^4) = O(10^{-3}) ,$$
$$(\delta^u_{13})_{LL} = O(\lambda^3),\quad (\delta^u_{32})_{RR} = O(\lambda) \quad \rightarrow \quad (\delta^u_{12})^{\rm eff}_{LR} = O(\lambda^4) = O(10^{-3}) .$$

[G.F.Giudice, G.Isidori, & P.P, '12]

Δa_{CP} in SUSY

- **Disoriented *A* terms**

$$(\delta^q_{ij})_{LR} \sim \frac{A\theta^q_{ij} m_{q_j}}{\tilde{m}} \qquad q = u, d \ ,$$

	θ^q_{11}	θ^q_{12}	θ^q_{13}	θ^q_{23}
q=d	< 0.2	< 0.5	< 1	–
q=u	< 0.2	–	< 0.3	< 1

[G.F.Giudice, G.Isidori, & P.P, '12]

- Down-quark FCNC (in particular ϵ'/ϵ and $b \to s\gamma$) are under control thanks to the smallness of m_{down}
- EDMs are suppressed by $m_{u,d}$ (yet they are quite enhanced)
- Up-quark FCNC (induced by gluino & up-squarks) and Down-quark FCNC like $K \to \pi\nu\nu$ and $B_{s,d} \to \mu\mu$ (induced by charginos & up-squarks) receive the largest effects from disoriented *A* terms.

Partial Compositeness in SUSY [Rattazzi & collaborators, '12]

- MSSM soft terms in SUSY with Partial Compositeness [Rattazzi & collaborators, '12]:

$$(\delta^{u,d}_{ij})_{LL} \sim \frac{\tilde{m}_0^2}{\tilde{m}^2}\;\epsilon^q_i\epsilon^q_j, \qquad (\delta^{u,d}_{ij})_{RR} \sim \frac{\tilde{m}_0^2}{\tilde{m}^2}\;\epsilon^{u,d}_i\epsilon^{u,d}_j,$$
$$(\delta^{u,d}_{ij})_{LR} \sim g_\rho\;\epsilon^q_i\epsilon^{u,d}_j\;\frac{v_{u,d}\,A_0}{\tilde{m}^2}, \qquad (\delta^{u,d}_{ij})_{RL} \sim g_\rho\;\epsilon^{u,d}_i\epsilon^q_j\;\frac{v_{u,d}\,A_0}{\tilde{m}^2}, \tag{1}$$

$$(Y_u)_{ij} \sim g_\rho\epsilon^q_i\epsilon^u_j, \qquad (Y_d)_{ij} \sim g_\rho\epsilon^q_i\epsilon^d_j. \tag{2}$$

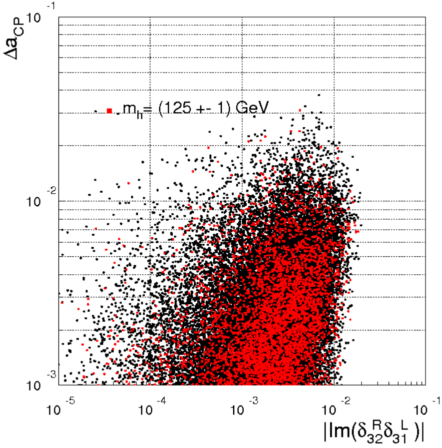
$$(L_u)_{ij} \sim (L_d)_{ij} \sim \frac{\epsilon^q_i}{\epsilon^q_j}, \qquad (R_{u,d})_{ij} \sim \frac{\epsilon^{u,d}_i}{\epsilon^{u,d}_j} \tag{3}$$

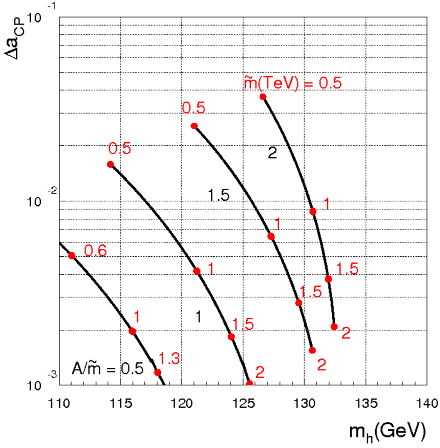
$$(L_u^\dagger Y_u R_u)_{ij} = g_\rho\epsilon^u_i\epsilon^q_i\delta_{ij} \equiv y^u_i\delta_{ij}\,, \qquad (L_d^\dagger Y_d R_d)_{ij} = g_\rho\epsilon^d_i\epsilon^q_i\delta_{ij} \equiv y^d_i\delta_{ij}\,, \tag{4}$$

$$\frac{\epsilon^q_1}{\epsilon^q_2} \sim \lambda \qquad \frac{\epsilon^q_2}{\epsilon^q_3} \sim \lambda^2 \qquad \frac{\epsilon^q_1}{\epsilon^q_3} \sim \lambda^3, \tag{5}$$

- **"We argued that Supersymmetric models of Partial Compositeness realize the 'disoriented A-terms' scenario advocated in [18], and therefore provide an ideal framework to explain the LHCb result.** [Rattazzi & collaborators, '12]"

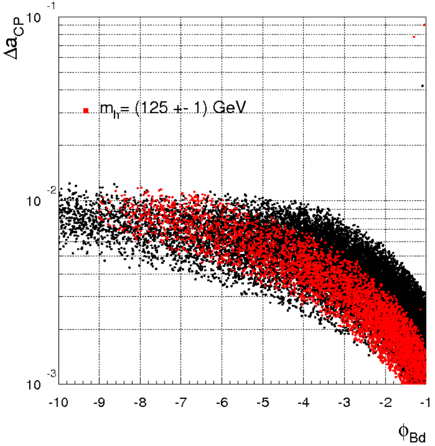
Δa_{CP} and SUSY [G.F.Giudice, G.Isidori, & P.P, '12]

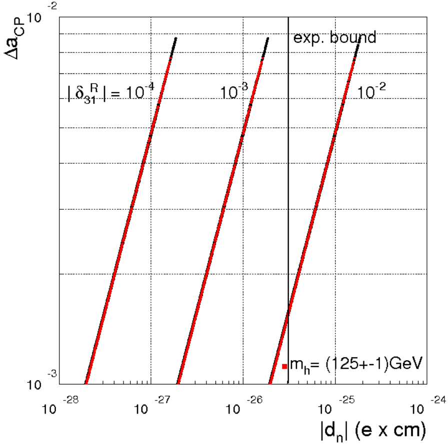




Left: 0.5 TeV $\leq \tilde{m}, \tilde{m}_g \leq 2$ TeV, $\tan\beta = 10$, $|A| \leq 3$.
Right: $|\mathrm{Im}[(\delta^u_{32})_{RR}(\delta^u_{31})_{LL}]| = 10^{-2}$, $\tilde{m} \leq 2$ TeV, and $A = 0.5, 1, 1.5, 2$.

Δa_{CP} and SUSY [G.F.Giudice, G.Isidori, & P.P, '12]





Left: $(\delta^u_{32})_{RR} = 0.2$ and $\phi_{\delta^L_{31}} \in \pm(30^\circ, 60^\circ)$, $|(\delta^d_{31})_{LL}| < 0.1$.

Right: $(\delta^u_{13})_{LL} = 10^{-2}$, $(\delta^u_{32})_{RR} = 0.2i$.

Top and stop phenomenology

- The effective $\Delta C = 1$ transition through stops opens up the possibility of observing flavor violations in the up-quark sector at the LHC.
  - **Production processes:** $pp \to \tilde{t}^* \tilde{u}_i$, where $\tilde{u}_i = \tilde{u}, \tilde{c}$. The rate for single $\tilde{u}_i$ production in association with a single stop is proportional to $(\delta^u_{i3})^2_{RR}$, since the mixings in the right-handed sector are larger then in the left sector.
  - **Flavor-violating stop decays**

$$\frac{\Gamma(\tilde{t} \to c\chi^0)}{\Gamma(\tilde{t} \to t\chi^0)} = \left|(\delta^u_{i3})_{RR}\right|^2 \left(1 - \frac{m_t^2}{\tilde{m}_t^2}\right)^{-2},$$

    where $u_i = u, c$ and χ^0 is the lightest neutralino.
  - **Flavor-violating gluino decays**

$$\frac{\Gamma(\tilde{g} \to \tilde{t} u_i)}{\Gamma(\tilde{g} \to \tilde{t} t)} = \left|(\delta^u_{i3})_{RR}\right|^2 \left[1 + O\left(\frac{m_t}{\tilde{m}_g}\right)\right].$$

    In models with split families, the gluino can decay only into $\tilde{g} \to \bar{t}\tilde{t},\ \bar{b}\tilde{b}$. Once we include flavor violation, the decay $\tilde{g} \to \bar{u}_i \tilde{t}$ is also allowed
  - **Flavor-violating top decays** [De Divitiis, Petronzio, Silvestrini, '97]

$$\mathrm{BR}(t \to qX) \sim \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{m_W}{m_{\mathrm{SUSY}}}\right)^4 |\delta^u_{3q}|^2$$

    where $m_{\mathrm{SUSY}} = \max(m_{\tilde{g}}, m_{\tilde{t}})$ for $X = \gamma, g, Z$ and $m_{\mathrm{SUSY}} = m_A$ for $X = h$. Even for $\delta^u_{3q} \sim 1$ and $m_{\mathrm{SUSY}} \gtrsim 3m_W$, $\mathrm{BR}(t \to qX) \lesssim 10^{-6}$.

New-physics scenarios with Z-mediated FCNC

- **Effective Lagrangian for FCNC couplings of the Z-boson to fermions**

$$\mathcal{L}_{\rm eff}^{Z-{\rm FCNC}} = -\frac{g}{2\cos\theta_W}\bar{F}_i\gamma^\mu \left[(g_L^Z)_{ij}\,P_L + (g_R^Z)_{ij}\,P_R\right] q_j\, Z_\mu + \text{ h.c.}$$

F can be either a SM quark ($F = q$) or some heavier non-standard fermion. If F is a SM fermion

$$(g_L^Z)_{ij} = \frac{v^2}{M_{\rm NP}^2}(\lambda_L^Z)_{ij} \qquad (g_R^Z)_{ij} = \frac{v^2}{M_{\rm NP}^2}(\lambda_R^Z)_{ij}$$

- **Direct CPV in charm**

$$\left|\Delta a_{CP}^{Z-{\rm FCNC}}\right| \approx 0.6\% \left|\frac{{\rm Im}\left[(g_L^Z)^*_{ut}(g_R^Z)_{ct}\right]}{2\times 10^{-4}}\right| \approx 0.6\% \left|\frac{{\rm Im}\left[(\lambda_L^Z)^*_{ut}(\lambda_R^Z)_{ct}\right]}{5\times 10^{-2}}\right| \left(\frac{1\ {\rm TeV}}{M_{\rm NP}}\right)^4$$

- **Neutron EDM**

$$|d_n| \approx 3\times 10^{-26}\left|\frac{{\rm Im}\left[(g_L^Z)^*_{ut}(g_R^Z)_{ut}\right]}{2\times 10^{-7}}\right|\ e\,{\rm cm}$$

- **Top FCNC**

$${\rm Br}(t\to cZ) \approx 0.7\times 10^{-2}\left|\frac{(g_R^Z)_{tc}}{10^{-1}}\right|^2$$

New-physics scenarios with scalar-mediated FCNC

- **Effective Lagrangian for FCNC scalar couplings to fermions**

$$\mathcal{L}_{\rm eff}^{h-{\rm FCNC}} = -\bar{q}_i \left[(g_L^h)_{ij}\, P_L + (g_R^h)_{ij}\, P_R \right] q_j\, h + \text{ h.c.}\,,$$

$$(g_L^h)_{ij} = \frac{v^2}{M_{\rm NP}^2} (\lambda_L^h)_{ij}\,, \qquad (g_R^h)_{ij} = \frac{v^2}{M_{\rm NP}^2} (\lambda_R^h)_{ij}\,,$$

- **Direct CPV in charm**

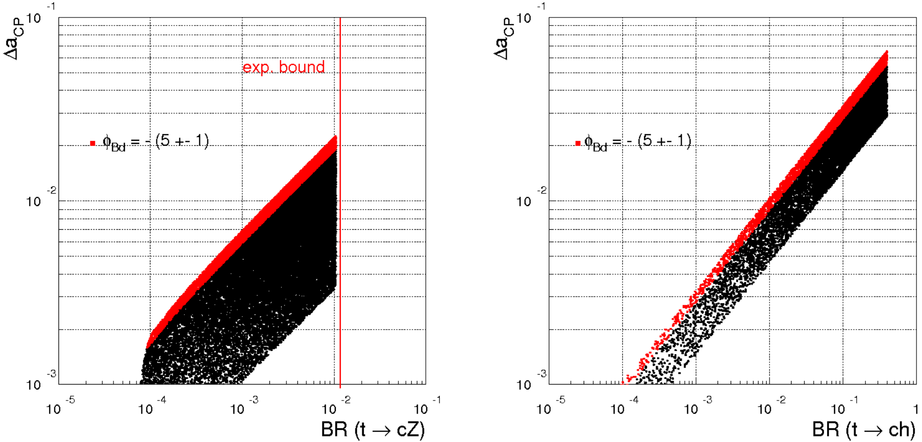
$$\left| \Delta a_{CP}^{h-{\rm FCNC}} \right| \approx 0.6\% \left| \frac{{\rm Im}\left[(g_L^h)^*_{ut} (g_R^h)_{tc} \right]}{2\times 10^{-4}} \right| \approx 0.6\% \left| \frac{{\rm Im}\left[(\lambda_L^h)^*_{ut} (\lambda_R^h)_{ct} \right]}{5\times 10^{-2}} \right| \left(\frac{1\ {\rm TeV}}{M_{\rm NP}} \right)^4 .$$

- **Neutron EDM**

$$|d_n| \approx 3\times 10^{-26} \left| \frac{{\rm Im}\left[(g_L^h)^*_{ut} (g_R^h)_{tu} \right]}{2\times 10^{-7}} \right| \ e\,{\rm cm}\,,$$

- **Top FCNC**

$${\rm Br}(t\to qh) \approx 0.4\times 10^{-2} \left| \frac{(g_R^h)^{tq}}{10^{-1}} \right|^2 ,$$



Left: $\mathrm{BR}(t \to cZ)$ vs. $\Delta a_{CP}^{Z-\mathrm{FCNC}}$. Right: $\mathrm{BR}(t \to ch)$ vs. $\Delta a_{CP}^{h-\mathrm{FCNC}}$. The plots have been obtained by means of the scan: $|(g_L^X)_{ut}| > 10^{-3}$, $|(g_R^X)_{ct}| > 10^{-2}$, where $X = Z, h$, with $\arg[(g_L^X)_{ut}] = \pm\pi/4$ and $\arg[(g_R^X)_{ct}] = 0$. The points in the red regions solve the tension in the CKM fits through a non-standard phase in B_d–$\bar{B}_d$ mixing, assuming for the corresponding down-type coupling $(g_L^X)_{db} = 5 \times 10^{-2}(g_L^X)_{ut}$.

CPV in D-physics

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

- $\langle D^0|\mathcal{H}_{\rm eff}|\bar{D}^0\rangle = M_{12} - \frac{i}{2}\Gamma_{12}, \qquad |D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$
- $\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}, \qquad \phi = \mathrm{Arg}(q/p)$
- $x = \frac{\Delta M_D}{\Gamma} = 2\tau \mathrm{Re}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right]$
- $y = \frac{\Delta\Gamma}{2\Gamma} = -2\tau \mathrm{Im}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right]$
- **The 95% C.L. allowed ranges by HFAG are**

$$x_{12} \in [0.25,\, 0.99]\,\%\,, \qquad y_{12} \in [0.59,\, 0.99]\,\%\,, \qquad \phi_{12} \in [-7.1^\circ,\, 15.8^\circ]\,,$$

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

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

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

[Nir et al.,Kagan et al., Petrov et al., Bigi et al., Buras et al., ...]

CPV in D-physics vs. neutron EDM in SUSY [Altmannshofer, Buras, & P.P, '10]

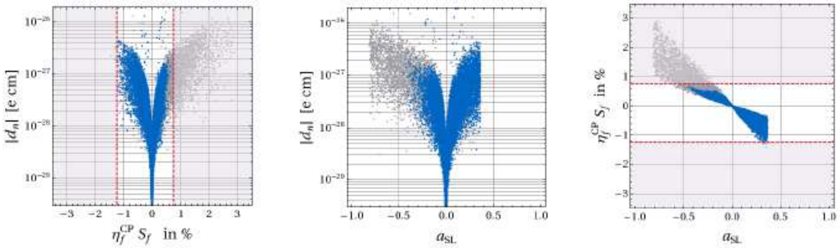


FIG. 3: Correlations between d_n and S_f (left), d_n and a_{SL} (middle) and a_{SL} and S_f (right) in SUSY alignment models. Gray points satisfy the constraints (8)-(10) while blue points further satisfy the constraint (11) from ϕ. Dashed lines stand for the allowed range (18) for S_f.

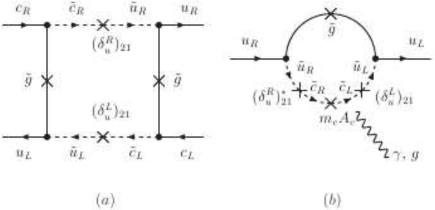


FIG. 2: Examples of relevant Feynman diagrams contributing (a) to $D^0 - \bar{D}^0$ mixing and (b) to the up quark (C)EDM in SUSY alignment models.

Testing new physics with the electron $g-2$

- **Longstanding muon $g-2$ anomaly**

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = 2.90(90)\times 10^{-9}\,, \qquad \mathbf{3.5\sigma}\ \textbf{discrepancy}$$

- **Main question: how to check if the a_μ discrepancy is due to NP?**
- **Answer: testing NP effects in a_e** [Giudice, P.P, & Passera, '12]
  - a_e has never played a role in testing ideas beyond the SM. In fact, it is believed that new-physics contaminations of a_e are too small to be relevant and, with this assumption, the measurement of a_e is employed to determine the value of the fine-structure constant α.
  - The situation has now changed, thanks to advancements both on the theoretical and experimental sides.
- **"Naive scaling":** $\Delta a_{\ell_i}/\Delta a_{\ell_j} = m_{\ell_i}^2/m_{\ell_j}^2$

$$\Delta a_e = \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)\, 0.7\times 10^{-13}\,, \qquad \Delta a_\tau = \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)\, 0.8\times 10^{-6}.$$

The Standard Model prediction of the electron $g-2$

- QED contribution [Kinoshita & Marciano, in *Quantum Electrodynamics* (1990)]

$$a_e^{\mathrm{QED}} = A_1 + A_2\left(\frac{m_e}{m_\mu}\right) + A_2\left(\frac{m_e}{m_\tau}\right) + A_3\left(\frac{m_e}{m_\mu}, \frac{m_e}{m_\tau}\right),$$

$$A_i = A_i^{(2)}\,(\alpha/\pi) + A_i^{(4)}\,(\alpha/\pi)^2 + A_i^{(6)}\,(\alpha/\pi)^3 + \cdots .$$

  - QED @ 1 loop [Schwinger, Phys. Rev. **73** (1948)]

$$C_1 = A_1^{(2)} = 1/2\,,$$

  - QED @ 2 loop [Sommerfield, Phys. Rev. **107** (1957); A. Petermann, Nucl. Phys. **5** (1958) 677.]

$$C_2 = A_1^{(4)} + A_2^{(4)}(m_e/m_\mu) + A_2^{(4)}(m_e/m_\tau) = -0.328\,478\,444\,002\,55\,(33).$$

  - QED @ 3 loop [Laporta & Remiddi, PLB **301** (1993), PLB **379** (1996)]

$$C_3 = 1.181\,234\,016\,816\,(11)\,, \qquad \delta a_e^{\mathrm{QED}} \sim 10^{-19}$$

  - QED @ 4 loop [Kinoshita and collaborators, PRL **99** (2007); PRD **77** (2008)]

$$C_4 = -1.9097\,(20)\,, \qquad \delta a_e^{\mathrm{QED}} \sim 5.8 \times 10^{-14}$$

  - QED @ 5 loop [Kinoshita and collaborators, 2012]

$$C_5 = 9.16\,(58) \qquad \delta a_e^{\mathrm{QED}} \sim 3.9 \times 10^{-14}$$

The Standard Model prediction of the electron $g-2$

- **Electroweak contribution** [Czarnecki, Krause and Marciano, PRL **76** (1996)]

$$a_e^{\mathrm{EW}} = 0.3854\,(42) \times 10^{-13}.$$

- **Hadronic contribution** [Jegerlehner & and Nyffeler, Phys. Rept. **477** (2009), Nomura & Teubner, '12]

$$a_e^{\mathrm{HAD}} = 16.82\,(16) \times 10^{-13},$$

- **Standard Model prediction of a_e and value of α**

$$a_e^{\mathrm{SM}}(\alpha) = a_e^{\mathrm{QED}}(\alpha) + a_e^{\mathrm{EW}} + a_e^{\mathrm{HAD}}$$

- **Experimental situation** [Gabrielse & collaborators, PRL **100** (2008), PRL **97** (2006), PRA **83** (2011)]

$$a_e^{\mathrm{EXP}} = 115\,965\,218\,07.3\,(2.8) \times 10^{-13}$$

- **Extracting α from $a_e^{\mathrm{SM}}(\alpha) = a_e^{\mathrm{EXP}}$**

$$\alpha\,(g{-}2) = 1/137.035\,999\,174\,(34)\;[0.25\,\mathrm{ppb}],$$

This is the most precise value of α available today!

.

- **Second best determination of α from atomic physics**

$$\alpha\,(^{87}\mathrm{Rb}) = 1/137.035\,999\,049\,(90)\,[0.66\,\mathrm{ppb}].$$

  - $\alpha\,(^{87}\mathrm{Rb})$ is deduced from the ratios h/M_{Rb} where $M_{\mathrm{Cs,Rb}}$ is from the mass ratios $M_{\mathrm{Cs,Rb}}/m_e$ [CODATA 2010].
  - The experimental scheme combines atom interferometry with Bloch oscillation [Cladé *et al.*, PRL **96** (2006), Cadoret *et al.*, PRL **101** (2008), Bouchendira *et al.*, PRL **106** (2011)].
  - $\alpha(^{87}\mathrm{Rb})$ agrees with $\alpha(g-2)$ at the 1.3σ level, and its uncertainty $\delta\alpha(^{87}\mathrm{Rb})$ is larger than $\delta\alpha(g-2)$ just by a factor of 2.7.

- **Determination of $a_e^{\mathrm{SM}}(\alpha)$ from $\alpha(^{87}\mathrm{Rb})$**

$$a_e^{\mathrm{SM}} = 115\,965\,218\,17.9\,(0.6)(0.4)(0.2)(7.6) \times 10^{-13}.$$

  - The first (second) error is from four(five)-loop QED coefficient, the third one is $\delta a_e^{\mathrm{HAD}}$, and the last (7.60×10^{-13}) from $\delta\alpha(^{87}\mathrm{Rb})$.
  - The uncertainties of the EW and two/three-loop QED contributions are negligible.
  - $\delta a_e^{\mathrm{SM}} = 7.64 \times 10^{-13}$ is about three times worse than $\delta a_e^{\mathrm{exp}}$ almost due to the uncertainty of the fine-structure constant $\alpha(^{87}\mathrm{Rb})$.

The Standard Model prediction of the electron $g - 2$

- **Standard Model vs. measurement**

$$\Delta a_e = a_e^{\rm EXP} - a_e^{\rm SM} = -10.6\,(8.1) \times 10^{-13},$$

  - Beautiful test of QED at four-loop level!
  - $\delta\Delta a_e = 8.1 \times 10^{-13}$ is dominated by $\delta a_e^{\rm SM}$ through $\delta\alpha(^{87}{\rm Rb})$.

- **Future improvements in the determination of Δa_e**

$$\underbrace{(0.6)_{\rm QED4},\ \ (0.4)_{\rm QED5},\ \ \ (0.2)_{\rm HAD},}_{(0.7)_{\rm TH}}\ \ (7.6)_{\delta\alpha},\ \ (2.8)_{\delta a_e^{\rm EXP}}. \qquad (6)$$

  - The first error, 0.6×10^{-13}, stems from numerical uncertainties in the four-loop QED. It can be reduced to 0.1×10^{-13} with a large scale numerical recalculation [Kinoshita]
  - The second error, from five-loop QED term may soon drop to 0.1×10^{-13}.
  - Experimental uncertainties 2.8×10^{-13} ($\delta a_e^{\rm EXP}$) and 7.6×10^{-13} ($\delta\alpha$) dominate. We expect a reduction of the former error to a part in 10^{-13} (or better) [Gabrielse]. Work is also in progress for a significant reduction of the latter error [Nez].

- **Δa_e at the 10^{-13} (or below) is not too far! This will bring a_e to play a pivotal role in probing new physics in the leptonic sector.**

Correlation between a_e and violation of lepton universality in LFC

- **Violations of "naive scaling"** for $(g-2)_\ell$ can arise in SUSY through sources of non-universalities in the slepton mass matrices with or without **lepton flavor violating sources.**

$$\Delta a_e \approx \Delta a_\mu \, \frac{m_e^2}{m_\mu^2} \frac{m_{\tilde\mu}^2}{m_{\tilde e}^2} \approx \frac{m_{\tilde\mu}^2}{m_{\tilde e}^2} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}} \right) 10^{-13} \,,$$

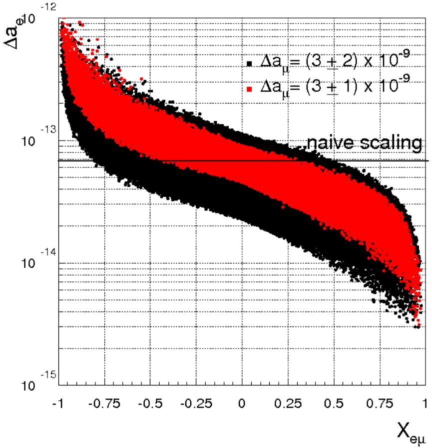
- In turn, these non-universalities will induce violations of lepton flavor universality such as $P \to \ell\nu$, $\tau \to P\nu$ (where $P = \pi, K$), $\ell_i \to \ell_j \bar\nu\nu$, $Z \to \ell\ell$ and $W \to \ell\nu$ through loop effects, which have been already tested at the 0.1% level

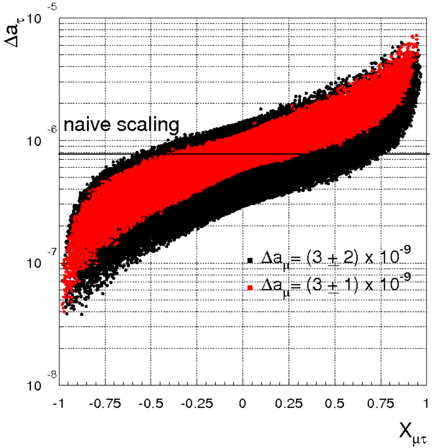
- Taking for example the process $P \to \ell\nu$, we can define the quantity

$$\frac{(R_P^{e/\mu})_{\rm EXP}}{(R_P^{e/\mu})_{\rm SM}} = 1 + \Delta r_P^{e/\mu} \,, \quad \Delta r_{\rm P}^{e/\mu} \sim \frac{\alpha}{4\pi} \left(\frac{m_{\tilde e}^2 - m_{\tilde\mu}^2}{m_{\tilde e}^2 + m_{\tilde\mu}^2} \right) \frac{v^2}{\min(m_{\tilde e,\tilde\mu}^2)} \,, \,.$$

  - $R_P^{e/\mu} = \Gamma(P \to e\nu)/\Gamma(P \to \mu\nu)$
  - $\Delta r_P^{e/\mu} \neq 0$ signals the presence of new physics violating LFU.

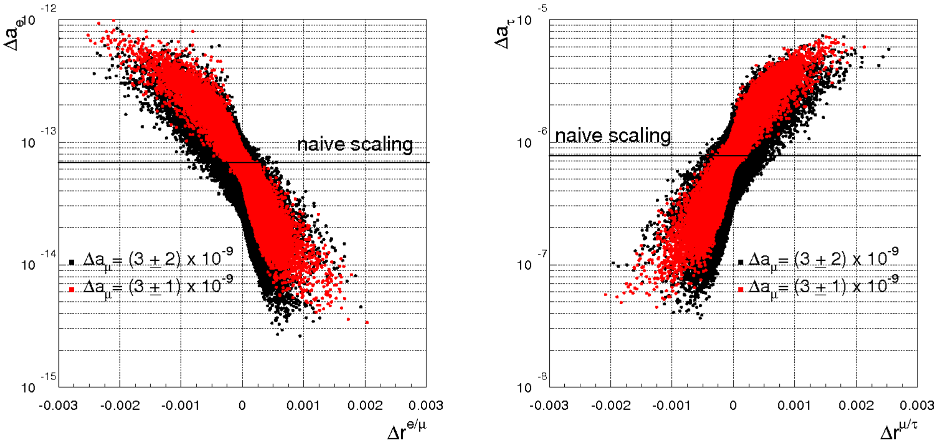
Lepton flavor conserving case





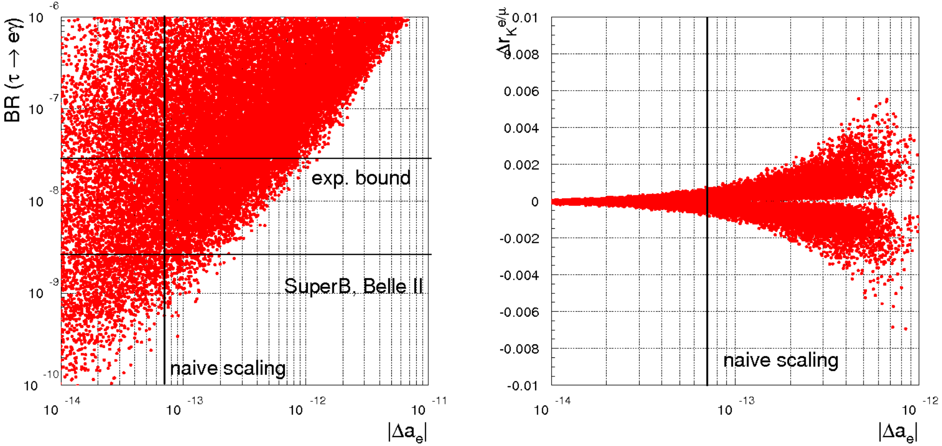
Left: Δa_e as a function of $X_{e\mu} = (m^2_{\tilde{e}} - m^2_{\tilde{\mu}})/(m^2_{\tilde{e}} + m^2_{\tilde{\mu}})$. Right: Δa_τ as a function of $X_{\mu\tau} = (m^2_{\tilde{\mu}} - m^2_{\tilde{\tau}})/(m^2_{\tilde{\mu}} + m^2_{\tilde{\tau}})$. Black points satisfy the condition $1 \leq \Delta a_\mu \times 10^9 \leq 5$, while red points correspond to $2 \leq \Delta a_\mu \times 10^9 \leq 4$.

Lepton flavor conserving case



Left: $\Delta r_{\rm P}^{e/\mu}$ vs. Δa_e, where $\Delta r_{\rm P}^{e/\mu}$ measures violations of lepton universality in $\Gamma(P \to e\nu)/\Gamma(P \to \mu\nu)$ with $P = K, \pi$. Right: $\Delta r_{\rm P}^{\mu/\tau}$ vs. Δa_τ where $\Delta r_{\rm P}^{\mu/\tau}$ measures violations of lepton universality in $\Gamma(P \to \mu\nu)/\Gamma(\tau \to P\nu)$.

Lepton flavor violating case



Left: $\mathrm{BR}(\tau \to e\gamma)$ vs. $|\Delta a_e|$. Right: $\Delta r_K^{e/\mu}$ vs. $|\Delta a_e|$. The vertical line corresponds to the prediction for Δa_e assuming NS, setting Δa_μ equal to its central value $\Delta a_\mu = 3 \times 10^{-9}$.

- **The experimental situation can roughly summarized as follow:**
  - The $h \to b\bar{b}$ search is performed via Higgs production in association with a W (Z).
  - The search of $\gamma\gamma jj$ has been done mostly through VBF (with a partial contamination from ggh) but also by means of inclusive analyses.
  - All the other channels can be considered basically as inclusive.
- **The overall picture emerging from the new LHC data is the following:**
  - WW^*, ZZ^* data are in a quite good agreement with the SM expectations.
  - $h \to \gamma\gamma$ shows an excess.
  - Taking into account all data the weighted average of all rates reads

$$\frac{\text{Measured Higgs rate}}{\text{SM prediction}} = 1.02 \pm 0.15 \qquad 6.9\sigma \text{ away from } 0!$$

- **Signal strength parameters** $\mu = \sigma \times \mathrm{BR}/(\sigma \times \mathrm{BR})_{\mathrm{SM}}$

$$(\mu_i)_{incl.} = \frac{\sum_j \sigma_j \times \mathrm{Br}[h \to i]}{\left(\sum_j \sigma_j \times \mathrm{Br}[h \to i]\right)_{\mathrm{SM}}}, \qquad j = ggh, VBF, Vh,$$

$$(\mu_i)_{excl.} = \frac{\sigma_j \times \mathrm{Br}[h \to i]}{(\sigma_j \times \mathrm{Br}[h \to i])_{SM}}, \qquad j = VBF, Vh,$$

Enhancing $h \to \gamma\gamma$ in SUSY

- **In SUSY, many new particles can affect $\Gamma(h \to \gamma\gamma)$, however most of them do not lead to the desired effect.**
  - Stops give contributions to the $h \to gg$ coupling that overcompensate the effect in the photon coupling, thus reducing $\sigma(pp \to h)\mathrm{BR}(h \to \gamma\gamma)$.
  - The charged Higgs and charginos give small effects in the Higgs-photon coupling.
  - The only viable SUSY candidate for an increased di-photon rate is a light stau which, in presence of a large left-right mixing, increases the Higgs-photon coupling.

$$\Gamma(h \to \gamma\gamma) \sim \left| F_1\left(\frac{4M_W^2}{m_h^2}\right) + N_c Q_t^2 F_{1/2}\left(\frac{4m_t^2}{m_h^2}\right) + \sum_{i=1,2} g_{h\tilde{\tau}_i\tilde{\tau}_i} \frac{M_Z^2}{m_{\tilde{\tau}_i}^2} F_0\left(\frac{4m_{\tilde{\tau}_i}^2}{m_h^2}\right)\right|^2 ,$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\mathrm{SM}}} \approx \left(1 + 0.025\,\frac{|m_\tau \mu \tan\beta \sin 2\theta_{\tilde{\tau}}|}{m_{\tilde{\tau}_1}^2}\right)^2 , \qquad \sin 2\theta_{\tilde{\tau}} \approx -\frac{2m_\tau \mu \tan\beta}{m_{\tilde{\tau}_1}^2 - m_{\tilde{\tau}_2}^2} .$$

- **A significant enhancement of $\Gamma(h \to \gamma\gamma)$ requires:**
  - $m_{\tilde{\tau}_1} \sim 100$ *GeV* and must correspond to a maximally mixed state.
  - Higgsinos are around or even above the TeV. The Wino, gluino, and squarks must be sufficiently heavy to avoid LHC bounds and to explain the Higgs mass.
  - The LSP condition corners the Bino to have the right properties to account for dark matter, through Bino-stau coannihilation.

Correlation between $h \to \gamma\gamma$ and $(g-2)_\mu$

- **Leading SUSY effects to δa_μ captured by the approximate expression**

$$\delta a_\mu \approx 2.8 \times 10^{-9} \left(\frac{\tan\beta}{20}\right) \left(\frac{300\ \mathrm{GeV}}{\tilde{m}}\right)^2 \left[\frac{1}{8}\frac{10}{\mu/\tilde{m}} + \frac{\mu/\tilde{m}}{10}\right] .$$

  - The first contribution comes from chargino exchange with an underlying Higgsino/Wino mixing and it decouples for large μ.
  - The second term arises from pure Bino exchange with an underlying smuon left-right mixing and therefore it grows with μ anf therefore correlated with $\Gamma(h \to \gamma\gamma)$

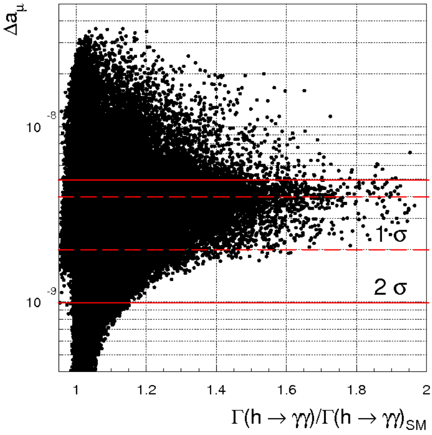
$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\mathrm{SM}}} \approx \left(1 + 0.025\, \frac{|m_\tau \mu \tan\beta \sin 2\theta_{\tilde{\tau}}|}{m^2_{\tilde{\tau}_1}}\right)^2 ,$$

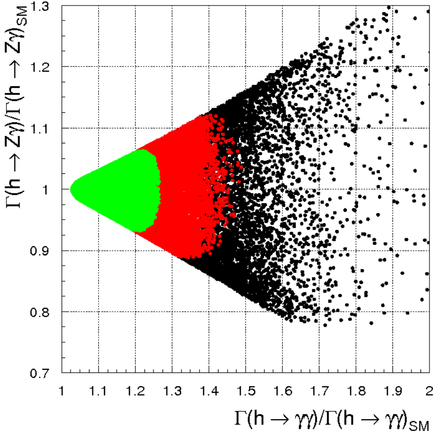
- **EWPOs ($\Delta\rho$) induced by large LR soft terms which break $SU(2)$**

$$\Delta\rho = \frac{G_{\mathrm{F}}}{4\sqrt{2}\pi^2}\left[\sin^2\theta_{\tilde{\tau}} f(m^2_{\tilde{\nu}}, m^2_{\tilde{\tau}_1}) + \cos^2\theta_{\tilde{\tau}} f(m^2_{\tilde{\nu}}, m^2_{\tilde{\tau}_2}) - \sin^2\theta_{\tilde{\tau}}\cos^2\theta_{\tilde{\tau}} f(m^2_{\tilde{\tau}_1}, m^2_{\tilde{\tau}_2})\right] .$$

- $h \to Z\gamma$ is suppressed since $Z\tilde{\tau}_i\tilde{\tau}_i$ is proportional to $1 - 4\sin^2\theta_{\mathrm{W}}$, which is accidentally small.
- LFU breaking effects in the $\mu(e)/\tau$ sector are generated up to the per-mill level.

Correlation between $h \to \gamma\gamma$ and $(g-2)_\mu$





[Giudice, P.P., Strumia, '12]

LFV frameworks

- **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) with $\Lambda_{NP} \equiv M_R$

$$Br(\mu \to e\gamma) \sim \frac{m_\nu^{D\,4}}{M_R^4} \leq 10^{-50}$$

  - $\tilde{W}$ and $\tilde{\nu}$ in the MSSM framework (SUPER-GIM) with $\Lambda_{NP} \equiv \tilde{m}$

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

$$\Downarrow$$

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

Experimental status

Process	Present	Future	Experiment
BR($\mu \to e\,\gamma$)	1.2×10^{-11}	$\mathcal{O}(10^{-13})$	**MEG, PSI**
BR($\mu \to e\,e\,e$)	1.1×10^{-12}	$\mathcal{O}(10^{-14})$	?
BR($\mu + \mathrm{Ti} \to e + \mathrm{Ti}$)	1.1×10^{-12}	$\mathcal{O}(10^{-18})$	J-PARC
BR($\tau \to e\,\gamma$)	1.1×10^{-7}	$\mathcal{O}(10^{-8})$	SuperB
BR($\tau \to e\,e\,e$)	2.7×10^{-7}	$\mathcal{O}(10^{-9})$	SuperB
BR($\tau \to e\,\mu\,\mu$)	$2. \times 10^{-7}$	$\mathcal{O}(10^{-9})$	SuperB
BR($\tau \to \mu\,\gamma$)	6.8×10^{-8}	$\mathcal{O}(10^{-8})$	SuperB
BR($\tau \to \mu\,\mu\,\mu$)	2×10^{-7}	$\mathcal{O}(10^{-9})$	LHCb
BR($\tau \to \mu\,e\,e$)	2.4×10^{-7}	$\mathcal{O}(10^{-9})$	SuperB
$\lvert d_{Tl} \rvert$ [e cm]	$< 9.0 \times 10^{-25}$	$\approx 10^{-29}$	Pospelov & Ritz, 2005
$\lvert d_{Hg} \rvert$ [e cm]	$< 3.1 \times 10^{-29}$	?	?
$\lvert d_n \rvert$ [e cm]	$< 2.9 \times 10^{-26}$	$\approx 10^{-28}$	PSI, Institute Laue-Langevin

$\tau\mu Z$ *effective operators*

$$g_Z m_Z^2 \left[A_L^Z \, \mu\tau + A_R^Z \, \mu^c\tau^c + \mathrm{h.c.} \right] Z_\mu , \tag{7}$$

$$g_Z \left[C_L^Z \, \mu\tau + C_R^Z \, \mu^c\tau^c + \mathrm{h.c.} \right] \Box Z_\mu , \tag{8}$$

$$g_Z \left[iD_L^Z \, \mu\tau^c + iD_R^Z \, \mu^c\tau + \mathrm{h.c.} \right] Z_{\mu\nu} , \tag{9}$$

- The operators in (7) are chirality conserving and have no derivatives, so they originate from $SU(2)_W \times U(1)_Y$-invariant operators with two Higgs $\Rightarrow m_Z^2$

$$(L_\mu L_\tau) \left(H_1^\dagger iD_\mu H_1 \right), \quad (L_\mu \sigma^a L_\tau) \left(H_1^\dagger \sigma^a iD_\mu H_1 \right), \quad (\mu^c \tau^c) \left(H_1^\dagger iD_\mu H_1 \right) .$$

- The operators in (8) are chirality conserving with two derivatives, so they originate from $SU(2)_W \times U(1)_Y$-invariant operators with no Higgs.
- The operators in (9) are chirality flipping (dipole) and come from $SU(2)_W \times U(1)_Y$-invariant operators with one Higgs field $\Rightarrow m_\tau$.

[see e.g., Brignole & Rossi, '04]

$\tau\mu\gamma$ effective operators

$$e\left[C_L\,\mu\tau + C_R\,\mu^c\tau^c + \mathrm{h.c.}\right]\Box A_\mu, \qquad (10)$$

$$e\left[iD_L\,\mu\tau^c + iD_R\,\mu^c\tau + \mathrm{h.c.}\right]F_{\mu\nu}. \qquad (11)$$

$\tau\mu ff$ effective operators

$$\sum_f \left[(\mu\tau)\left(B_L^{f_L}\,f + B_L^{f_R}\,f^c\right) + (\mu^c\tau^c)\left(B_R^{f_L}\,f + B_R^{f_R}\,f^c\right) + \mathrm{h.c.}\right]. \qquad (12)$$

$\tau\mu$ Higgs effective operators

$$\mathcal{L}^{\mathrm{eff}}_{\mathrm{Higgs}\ \mu\tau} = -\frac{h_\tau}{\sqrt{2}\mathrm{c}_\beta}(\Delta_L^*\,\tau^c\mu + \Delta_R\,\mu^c\tau)\left[\mathrm{c}_{\beta-\alpha}h - \mathrm{s}_{\beta-\alpha}H - \mathrm{i}A\right] + \mathrm{h.c.}, \qquad (13)$$

[see e.g., Brignole & Rossi, '04]

LFV: model-independent analysis

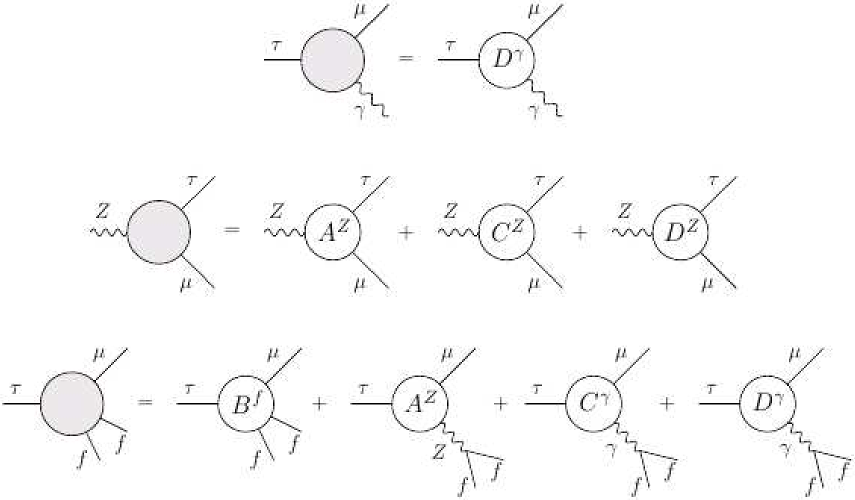


Figure 1: The different contributions to $\tau \to \mu\gamma$, $Z \to \mu\tau$ and $\tau \to \mu f f$ decays.

LFV: model-independent analysis

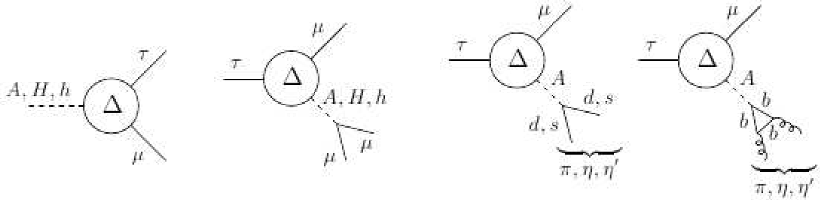


Figure 4: Δ-contributions to the Higgs boson decays $A, H, h \to \mu\tau$ and to the decays $\tau \to 3\mu$, $\tau \to \mu\pi$, $\tau \to \mu\eta$, $\tau \to \mu\eta'$. In the last diagram, curly lines denote gluons.

Correlations

- ***D*-dominance**

$$\frac{BR(\tau^- \to \mu^- e^+ e^-)}{BR(\tau^- \to \mu^-)} \simeq \frac{\alpha}{3\pi}\left(\log\frac{2}{m_e^2} - 3\right) \simeq 10^{-2} \quad (14)$$

$$\frac{BR(\tau^- \to \mu^- \mu^+ \mu^-)}{BR(\tau^- \to \mu^-)} \simeq \frac{\alpha}{3\pi}\left(\log\frac{2}{m_\mu^2} - \frac{11}{4}\right) \simeq 2.2 \times 10^{-3} \quad (15)$$

$$\frac{BR(\tau^- \to \mu^- \rho^0)}{BR(\tau^- \to \mu^-)} \simeq 2.5 \times 10^{-3}. \quad (16)$$

- ***C*-dominance.**

$$BR(\tau^- \to \mu^- \rho^0) \simeq BR(\tau^- \to \mu^- \mu^+ \mu^-) \simeq 1.5 \times BR(\tau^- \to \mu^- e^+ e^-). \quad (17)$$

- ***A^Z*-dominance.**

$$BR(Z \to \mu^+ \tau^-) \simeq 3 \times BR(\tau^- \to \mu^- e^+ e^-), \quad (18)$$

$$BR(\tau^- \to \mu^- \rho^0) \simeq 1.8 \times BR(\tau^- \to \mu^- e^+ e^-), \quad (19)$$

$$BR(\tau^- \to \mu^- \pi^0) \simeq 2.7 \times BR(\tau^- \to \mu^- e^+ e^-), \quad (20)$$

$$BR(\tau^- \to \mu^- \eta) \simeq 0.8 \times BR(\tau^- \to \mu^- e^+ e^-), \quad (21)$$

$$BR(\tau^- \to \mu^- \eta') \simeq 0.7 \times BR(\tau^- \to \mu^- e^+ e^-), \quad (22)$$

$$BR(\tau^- \to \mu^- \mu^+ \mu^-) \simeq 1.5 \times BR(\tau^- \to \mu^- e^+ e^-). \quad (23)$$

Pattern of LFV in NP models

- **Ratios like** $Br(\mu \to e\gamma)/Br(\tau \to \mu\gamma)$ **probe the NP flavor structure**
- **Ratios like** $Br(\mu \to e\gamma)/Br(\mu \to eee)$ **probe the NP operator at work**

ratio	LHT	MSSM	SM4
$\frac{Br(\mu\to eee)}{Br(\mu\to e\gamma)}$	$0.02\ldots 1$	$\sim 2\cdot 10^{-3}$	$0.06\ldots 2.2$
$\frac{Br(\tau\to eee)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.4$	$\sim 1\cdot 10^{-2}$	$0.07\ldots 2.2$
$\frac{Br(\tau\to \mu\mu\mu)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots 0.4$	$\sim 2\cdot 10^{-3}$	$0.06\ldots 2.2$
$\frac{Br(\tau\to e\mu\mu)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.3$	$\sim 2\cdot 10^{-3}$	$0.03\ldots 1.3$
$\frac{Br(\tau\to \mu ee)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots 0.3$	$\sim 1\cdot 10^{-2}$	$0.04\ldots 1.4$
$\frac{Br(\tau\to eee)}{Br(\tau\to e\mu\mu)}$	$0.8\ldots 2$	~ 5	$1.5\ldots 2.3$
$\frac{Br(\tau\to \mu\mu\mu)}{Br(\tau\to \mu ee)}$	$0.7\ldots 1.6$	~ 0.2	$1.4\ldots 1.7$
$\frac{\mathrm{R}(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots 10^{2}$	$\sim 5\cdot 10^{-3}$	$10^{-12}\ldots 26$

[Buras et al., '07, '10]

General structure of new-physics contributions

- **NP effects are encoded in the effective Lagrangian**

$$\mathcal{L} = e\frac{m_\ell}{2}\left(\bar{\ell}_R \sigma_{\mu\nu} A_{\ell\ell'} \ell'_L + \bar{\ell}'_L \sigma_{\mu\nu} A^\star_{\ell\ell'} \ell_R\right) F^{\mu\nu} \qquad \ell, \ell' = e, \mu, \tau\,,$$

- **The amplitude $A_{\ell\ell'}$ and therefore Δa_ℓ can be written as**

$$A_{\ell\ell'} = \frac{1}{(4\pi\,\Lambda_{\rm NP})^2}\left[\left(g^L_{\ell k}\, g^{L*}_{\ell' k} + g^R_{\ell k}\, g^{R*}_{\ell' k}\right) f_1(x_k) + \frac{v}{m_\ell}\left(g^L_{\ell k}\, g^{R*}_{\ell' k}\right) f_2(x_k)\right]\,,$$

  - **The leptonic $g-2$ is given by**

$$\Delta a_\ell = 2m_\ell^2\, \mathrm{Re}(A_{\ell\ell}).$$

  - **The leptonic EDM, d_ℓ, is given by**

$$\frac{d_\ell}{e} = m_\ell\, \mathrm{Im}(A_{\ell\ell})\,.$$

  - **The branching ratio of $\ell \to \ell'\gamma$ is given by**

$$\frac{\mathrm{BR}(\ell \to \ell'\gamma)}{\mathrm{BR}(\ell \to \ell'\nu_\ell\bar{\nu}_{\ell'})} = \frac{48\pi^3\alpha}{G_F^2}\left(|A_{\ell\ell'}|^2 + |A_{\ell'\ell}|^2\right)\,,$$

- **Challenge**: Large effects for $g-2$ keeping under control $\mu \to e\gamma$ and d_e

A concrete SUSY scenario: "Disoriented A-terms"

- **"Disoriented A-terms"** [Giudice, Isidori & P.P., '12]:

$$(\delta^{ij}_{LR})_f \sim \frac{A_f \theta^f_{ij} m_{f_j}}{m_{\tilde{f}}} \qquad f = u, d, \ell \,,$$

  - Flavor and CP violation is restricted to the trilinear scalar terms (invoked in [Giudice, Isidori & P.P., '12] to explain direct CP violation in charm decays $D \to KK, \pi\pi$).
  - Flavor bounds of the down-sector are naturally satisfied thanks to the smallness of down-type quark/lepton masses.
  - A natural realization of this ansatz arises in scenarios with partial compositeness where $\theta^\ell_{ij} \sim \sqrt{m_i/m_j}$ [Rattazzi et al.,'12].

- $\mu \to e\gamma$ and d_e are generated only by $U(1)$ interactions

$$A_L^{\mu e} = \frac{\alpha\, M_1\, \delta^{\mu e}_{LR}}{2\pi \cos^2\theta_W\, m^2_{\tilde{\ell}}\, m_\mu}\, f_n(x_1)\,, \qquad \frac{d_e}{e} = \frac{\alpha\, \mathrm{Im}\,(M_1 \delta^{ee}_{LR})}{2\pi \cos^2\theta_W\, \tilde{m}^2}\, f_n(x_1)\,.$$

- $(g-2)_\mu$ is generated by $SU(2)$ interactions and is $\tan\beta$ enhanced therefore the relative enhancement w.r.t. $\mu \to e\gamma$ and d_e is $\tan\beta / \tan^2\theta_W \approx 100 \times (\tan\beta/30)$

$$\Delta a_\ell \simeq \frac{\alpha\, m^2_\ell\, \tan\beta}{\pi \sin^2\theta_W\, \tilde{m}^2}\, f'(x_2)$$

A concrete SUSY scenario: “Disoriented A-terms”

- **Numerical example**: $\tilde{m} = |A_e| = 1\ \mathrm{TeV}$, $\sin\phi_{A_e}$=1, $M_2 = \mu = 2M_1 = 0.2\ \mathrm{TeV}$, and $\tan\beta = 30$

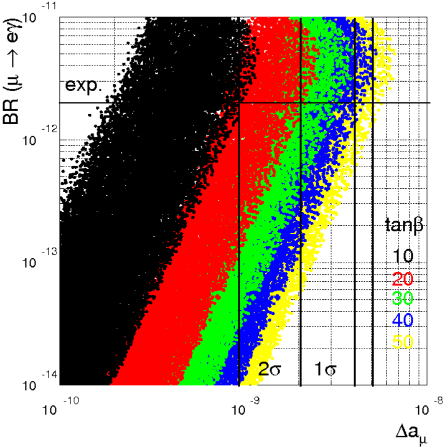
$$\mathrm{BR}(\mu \to e\gamma) \approx 6 \times 10^{-13} \left| \frac{A_\ell}{\mathrm{TeV}} \frac{\theta^\ell_{12}}{\sqrt{m_e/m_\mu}} \right|^2 \left(\frac{\mathrm{TeV}}{m_{\tilde{\ell}}} \right)^4 ,$$

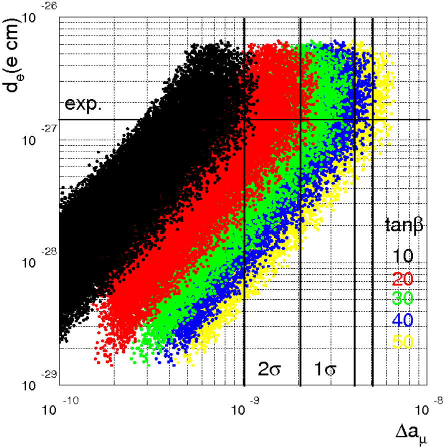
$$d_e \approx 4 \times 10^{-28}\ \mathrm{Im} \left(\frac{A_\ell\, \theta^\ell_{11}}{\mathrm{TeV}} \right) \left(\frac{\mathrm{TeV}}{m_{\tilde{\ell}}} \right)^2 e\,\mathrm{cm} ,$$

$$\Delta a_\mu \approx 1 \times 10^{-9} \left(\frac{\mathrm{TeV}}{m_{\tilde{\ell}}} \right)^2 \left(\frac{\tan\beta}{30} \right) .$$

  - Disoriented A-terms can account for $(g-2)_\mu$, satisfy the bounds on $\mu \to e\gamma$ and d_e, while giving predictions for $\mu \to e\gamma$ and d_e within experimental reach.
  - The lightest Higgs boson mass $m_h \approx 125$ GeV can be naturally accounted for thanks to large A-terms.
  - The electron $(g-2)$ follows “naive scaling”.

A concrete SUSY scenario: “Disoriented A-terms”





Predictions for $\mu \to e\gamma$, Δa_μ and d_e in the disoriented A-term scenario with $\theta^\ell_{ij} = \sqrt{m_i/m_j}$. Left: $\mu \to e\gamma$ vs. Δa_μ. Right: d_e vs. Δa_μ [Giudice, P.P., & Passera, ’12]

RG induced Quark & Lepton FV interactions in SUSY GUTs

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

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

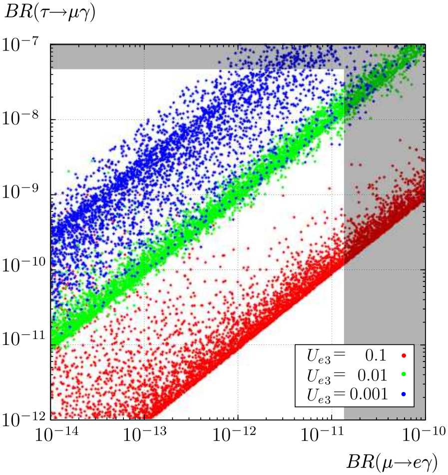
- **SUSY SU(5)+RN** [Yanagida et al., '95]

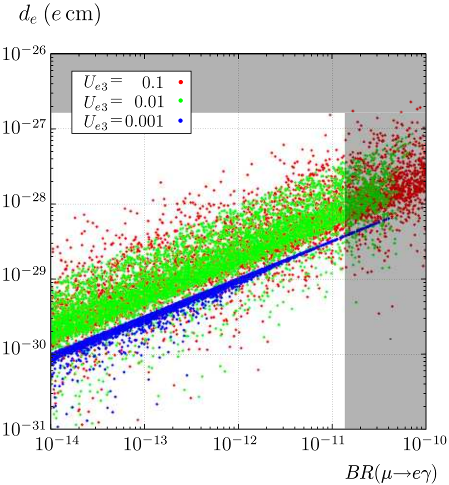
$$(\delta^{\tilde{\ell}}_{LL})_{ij} \sim (h^\nu h^{\nu\dagger})_{ij} \qquad \& \qquad (\delta^{\tilde{\ell}}_{RR})_{ij} \sim (h^u h^{u\dagger})_{ij}$$

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

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

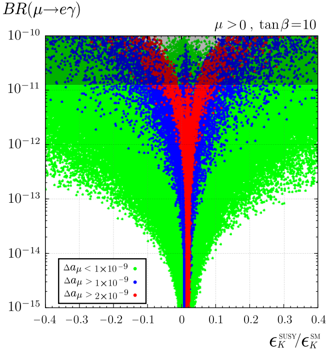
$\mu \to e\gamma$ and $\tau \to \mu\gamma$ in SUSY SU(5)+RN

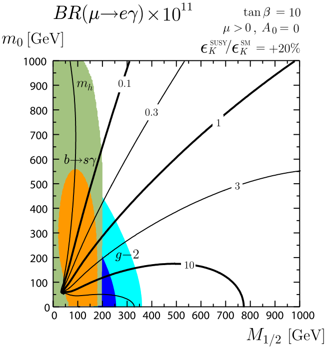




hierarchical ν_L and N_R [Hisano, Nagai, P.P. & Shimizu, '09]

Quark-Lepton correlations in SUSY SU(5)+RN

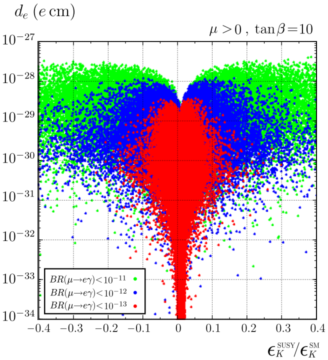


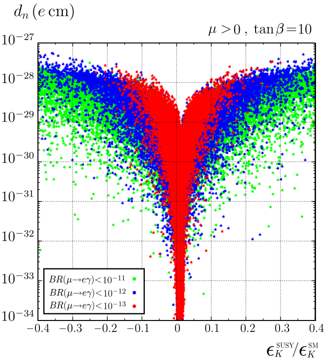


- Main messages:
  - Parameter scan: $(m_0, M_{1/2}) < 1\,\mathrm{TeV}$, $|A_0| < 3m_0$, $\tan\beta = 10$ and $\mu > 0$. Hierarchical ν_L & N_R, $10^{11} \leq M_{\nu_3}(\mathrm{GeV}) \leq 10^{15}$ and $10^{-5} \leq U_{e3} \leq 0.1$.
  - The **"UT tension"** is "solved" through SUSY effects in ϵ_K implying a **lower bound** for $\mathrm{BR}(\mu \to e\gamma)$ in the reach of MEG.
  - A simultaneous explanation for both the $(g-2)_\mu$ and the **UT anomalies** implies $\mathrm{BR}(\mu \to e\gamma) \geq 10^{-12}$ and SUSY particles in the LHC reach.

[Buras, Nagai & P.P., '10]

Quark-Lepton correlations in SUSY SU(5)+RN

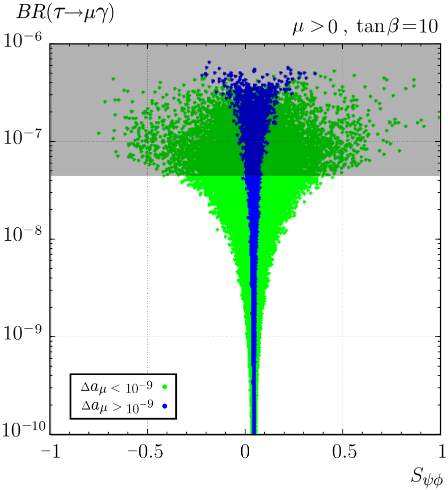


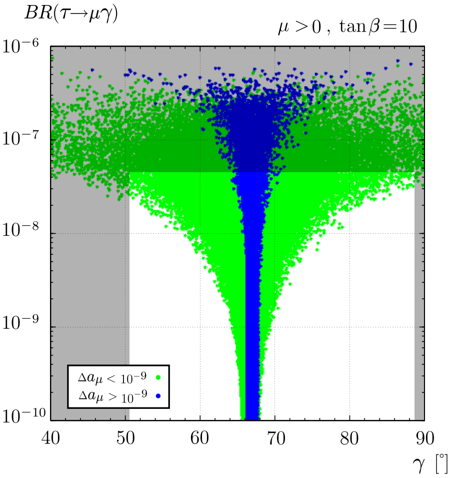


- Main messages:
  - Parameter scan: $(m_0, M_{1/2}) < 1\,\mathrm{TeV}$, $|A_0| < 3m_0$, $\tan\beta = 10$ and $\mu > 0$. Hierarchical ν_L & N_R, $10^{11} \leq M_{\nu_3}(\mathrm{GeV}) \leq 10^{15}$ and $10^{-5} \leq U_{e3} \leq 0.1$.
  - Sizable **non-standard** effects in ϵ_K always implies large values for the **electron and neutron EDMs**, in the reach of the planned experimental resolutions.

[Buras, Nagai & P.P., '10]

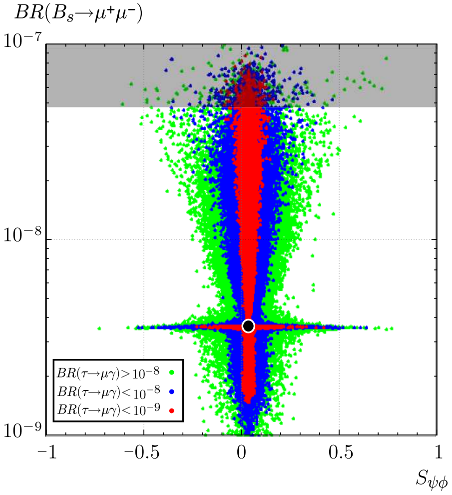
Quark-Lepton correlations in SUSY SU(5)+RN

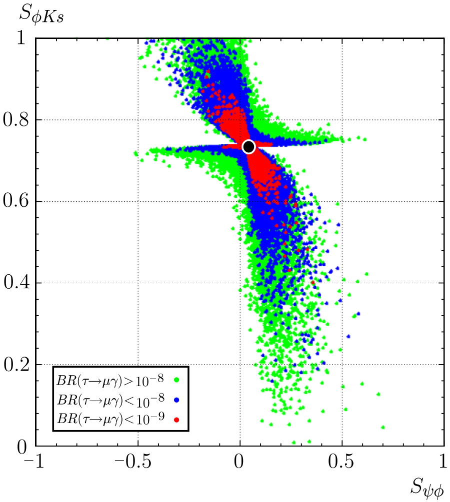




hierarchical ν_L and N_R [Buras, Nagai & P.P., '10]

Quark-Lepton correlations in SUSY SU(5)+RN





hierarchical ν_L and N_R [Buras, Nagai & P.P., '10]

Conclusions and future prospects

- **The important questions in view of ongoing/future experiments are**:
  - What are the expected deviations from the SM predictions induced by TeV NP?
  - Which observables are not limited by theoretical uncertainties?
  - In which case we can expect a substantial improvement on the experimental side?
  - What will the measurements teach us if deviations from the SM are [not] seen?

- **(Personal) answers**:
  - The expected deviations from the SM predictions induced by NP at the TeV scale with generic flavor structure are already ruled out by many orders of magnitudes.
  - On general grounds, we can expect any size of deviation below the current bounds.
  - The theoretical limitations are highly process dependent. Several channels involving leptons in the final state, and selected time-dependent asymmetries, have a theoretical errors well below the current experimental sensitivity.
  - On the experimental side there are still excellent prospects of improvements in several clean channels like $B_{s,d}$, D, K, π (LFU tests in $K, \pi_{\ell 2}$), LFV processes ($\mu \to e\gamma$, $\mu Ti \to eTi$), EDMs (d_n, d_{Tl}) and $(g-2)_e$.

Conclusions and future prospects

- **There is no doubt that new low-energy flavor data will be complementary with the high-p_T part of the LHC program.**
- **The synergy of both data sets (including the Higgs boson properties, which are certainly very much related to flavor,) can teach us a lot about the new physics at the TeV scale.**