Flavor Physics in and after the LHC era

Paride Paradisi

CERN

LC13
17 September 2013, ECT, Trento, Italy

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

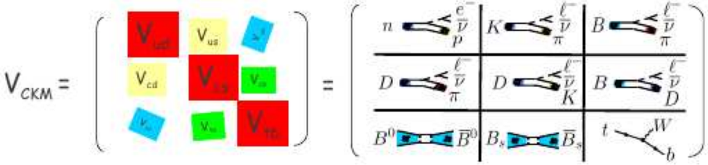
- $\mathcal{L}^{\rm SM}_{Kinetic+Gauge} + \mathcal{L}^{\rm SM}_{Higgs}$ has a large $U(3)^5$ global **flavour symmetry**

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

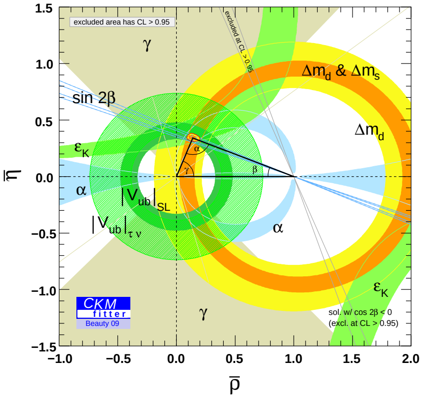
- $\mathcal{L}_{\rm Yukawa} = \bar{Q}_L \mathbf{Y_D} D_R \phi + \bar{Q}_L \mathbf{Y_U} U_R \tilde{\phi} + \bar{L}_L \mathbf{Y_L} E_R \phi + h.c$ break G down to

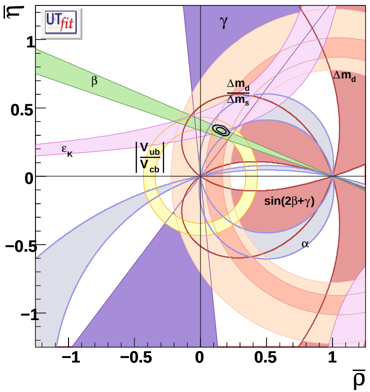
$$\mathbf{G} \rightarrow \mathbf{U(1)_B} \times \mathbf{U(1)_e} \times \mathbf{U(1)_\mu} \times \mathbf{U(1)_\tau}$$

- **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





Waiting for γ from tre level processes... ($B \to DK$) [see Langenbruch's talk]

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

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 $M = \pi, K$

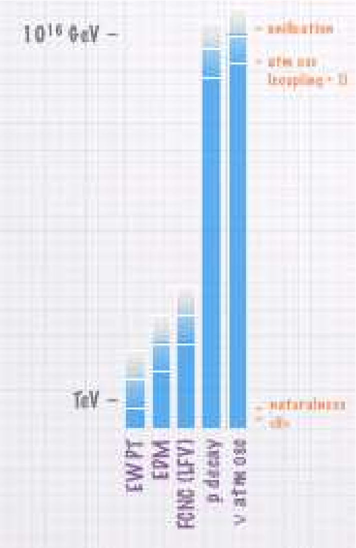
Experimental status

process	current exp.	future exp.
K^0 mixing	$\epsilon_K = (2.228 \pm 0.011) \times 10^{-3}$	—
D^0 mixing	$A_\Gamma = (-0.02 \pm 0.16)\%$	$\pm 0.007\%$ LHCb $\pm 0.06\%$ Belle II
B_d mixing	$\sin 2\beta = 0.68 \pm 0.02$	± 0.008 LHCb ± 0.012 Belle II
B_s mixing	$\phi_s = 0.01 \pm 0.07$	± 0.008 LHCb
$d_{\rm Hg}$	$< 3.1 \times 10^{-29}$ $e\mathrm{cm}$	–
$d_{\rm Ra}$	–	$\lesssim 10^{-29}$ $e\mathrm{cm}$
d_n	$< 2.9 \times 10^{-26}$ $e\mathrm{cm}$	$\lesssim 10^{-28}$ $e\mathrm{cm}$
d_p	–	$\lesssim 10^{-29}$ $e\mathrm{cm}$
d_e	$< 1.05 \times 10^{-27}$ $e\mathrm{cm}$ YbF	$\lesssim 10^{-30}$ $e\mathrm{cm}$ YbF, Fr
$\mu \to e\gamma$	$< 5.4 \times 10^{-13}$ MEG	$\lesssim 6 \times 10^{-14}$ MEG upgrade
$\mu \to 3e$	$< 1.0 \times 10^{-12}$ SINDRUM I	$\lesssim 10^{-16}$ Mu3e
$\mu \to e$ in Au	$< 7.0 \times 10^{-13}$ SINDRUM II	–
$\mu \to e$ in Al	–	$\lesssim 6 \times 10^{-17}$ Mu2e

Table: Summary of current and selected future expected experimental limits on CP violation in meson mixing, EDMs and lepton flavor violating processes.

[Altmannshofer, Harnik, & Zupan, '13]

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



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

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

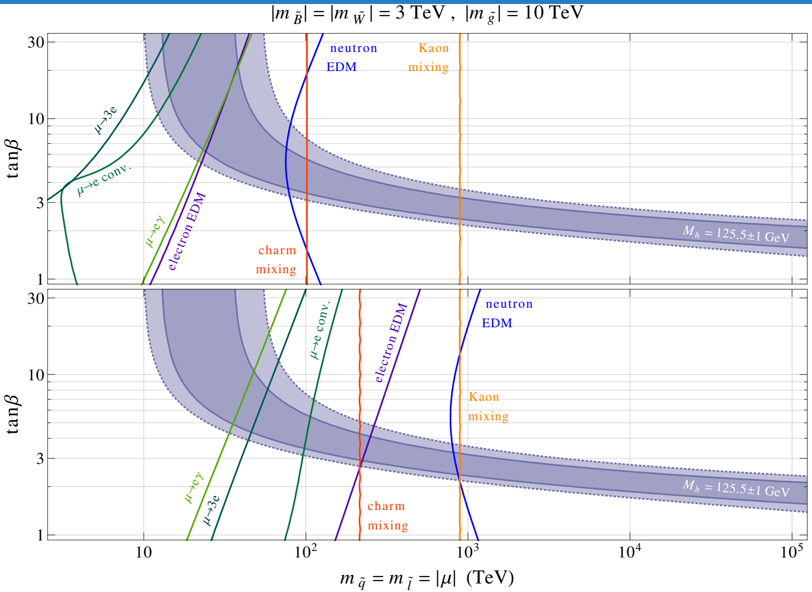
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d=6} \frac{c_{ij}^{(6)}}{\Lambda_{NP}^2} O_{ij}^{(6)}$$

[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}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{B_d\to\psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{B_d\to\psi K}$
$(\bar{b}_L\gamma^\mu s_L)^2$	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



Low energy constraints fixing $(\delta_A)_{ij} = 0.3$. The upper (lower) plot gives the reach of current (projected future) experimental results [Altmannshofer, Harnik, & Zupan, '13]

- **First evidence for $B_s \to \mu^+\mu^-$ discovery at LHCb, '12**

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

- **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

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

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

$B_s \to \mu^+\mu^-$ in the SM

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

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

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] $\to$ ~ -10% (*already included in exp. efficiency*)
- $\Delta\Gamma_s \neq 0$ [Bruyn *et al.* '12] $\to \sim +10\%$ (*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 $B_{s,d} \to \mu^+\mu^-$**

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

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

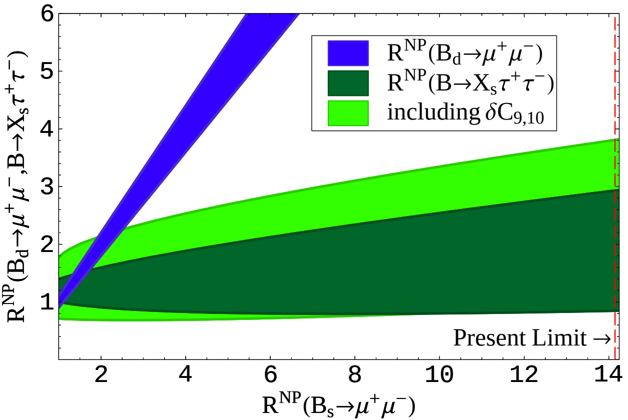
$$\mathcal{H}_{\rm SM}^{\rm eff} = C_{10} Q_{10} \qquad Q_{10} = \bar{b}_L \gamma^\mu q_L \bar{\ell}\gamma_\mu\gamma_5\ell, \qquad C_{10}^{\rm SM} \approx \frac{g_2^2}{16\pi^2}\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \,,$$

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

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

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

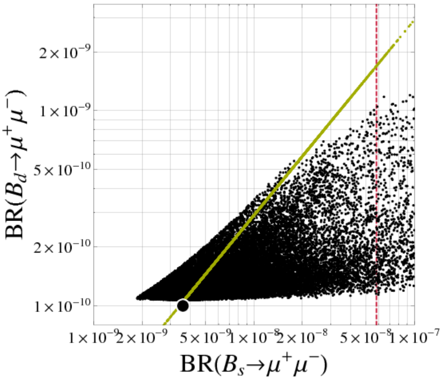
$$A = 2\frac{m_\mu}{m_{B_s}}\left(C_{10} - C'_{10}\right) + \frac{m_{B_s}}{m_b}\left(C_P - C'_P\right) \,, \qquad B = \frac{m_{B_s}}{m_b}\left(C_S - C'_S\right)$$



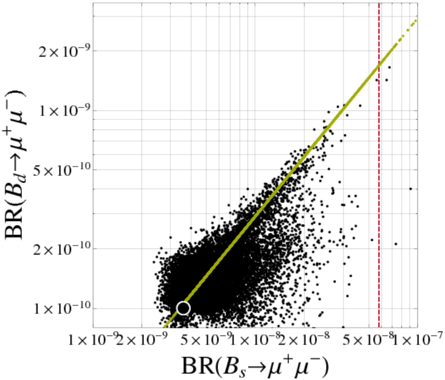
$$\frac{\Gamma(B_s \to \ell^+\ell^-)}{\Gamma(B_d \to \ell^+\ell^-)} \approx \frac{f_{B_s} m_{B_s}}{f_{B_d} m_{B_d}} \left| \frac{V_{ts}}{V_{td}} \right|^2 .$$

Powerful probe of MFV (Hurth 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_{FB}	$\frac{3}{4}S_6^s$	A_{FB}	A_{FB}	$-A_{FB}$	$-A_{FB}$	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).

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

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

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

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.

Up-quark flavor physics: motivations

- Processes involving K and B mesons have always been regarded as the most interesting probe of flavor and CP violation.
- In the SM, the largest flavor and CP violating effects appear in the down sector, since the top mass is the main source of flavor violation and charged-current loops are needed to communicate symmetry breaking, in agreement with the GIM mechanism.
- While these properties hold in the SM, there is no good reason for them to be true if new physics is present at the electroweak scale. In particular, it is quite plausible that new-physics contributions affect mostly the up-type sector, possibly in association with the mechanism responsible for the large top mass.
- SUSY models with squark alignment [Nir & Seiberg, '93] provide one example of theories with large flavor and CP violation in the up sector but this situation is fairly general in classes of models in which the flavor hierarchies are explained without invoking the MFV hypothesis [Giudice, Gripaios & Sundrum, '11].
- D-meson decays represent a unique probe of new-physics flavor effects, quite complementary to tests in K and B systems.

What/where to look for?

- "Golden" measurements in up-flavor physics:

  - Direct CP violation in singly-Cabibbo-suppressed decays
  - CPV in neutral D mesons mixing
  - Hadronic EDMs

  Low-energy flavor physics

  - FCNC top decays
  - FB asymmetry in $t\bar{t}$ production

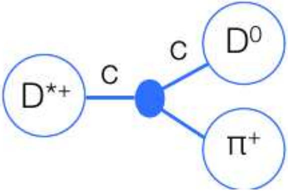
  High-p_T physics

Time-integrated CP asymmetries in $D^0 \to h^+h^-$

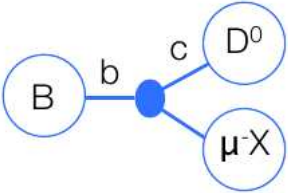
- Two-body decays of neutral D into charged hadrons (experimentally easy)
- Sensitive to both direct and indirect (mixing induced) CPV

$$A_{CP}(h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\bar{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) - \Gamma(\bar{D}^0 \to h^+h^-)}$$
$$\approx a_{CP}^{\rm dir}(h^+h^-) + \frac{\langle t \rangle}{\tau} a_{CP}^{\rm ind}$$

- Need to tag D^0 flavor at production time



or



New LHCb results

- D*-tagged analysis (preliminary result) [LHCb-CONF-2013-003]

$$\Delta A_{CP} = (-0.34 \pm 0.15 \pm 0.10)\%$$

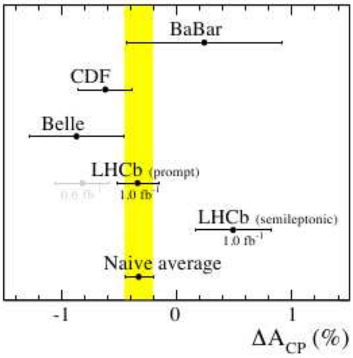
- Semileptonic B-tagged analysis [LHCb-PAPER-2013-003, arXiv:1303.2614]

$$\Delta A_{CP} = (+0.49 \pm 0.30 \pm 0.14)\%$$

- New HFAG average [March '13]

$$\Delta a_{CP}^{\text{dir}} = (-0.33 \pm 0.12)\%$$

$$a_{CP}^{\text{ind}} = (+0.01 \pm 0.16)\%$$



SM vs NP predictions

- Considering only the chromomagnetic operator as possible NP contribution

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

- $\Delta R^{SM} \approx \alpha_s(m_c)/\pi \approx 0.1$ in perturbation theory but a much larger non-perturbative effect is expected

- In SU(3) limit $a_{CP}(K^+K^-) = -a_{CP}(\pi^+\pi^-)$ which then should add constructively in Δa_{CP}

- In naive factorization $|{\rm Im}(\Delta R^{NP})| \approx 0.2$ [Grossman, Kagan, Nir '06] then

$$\Delta a_{CP}^{\rm NP} \approx 2\ {\rm Im}(C_8^{\rm NP} + C_8^{\prime\rm NP})$$

Other tests of direct CPV in charm

- If Δa_{CP} driven by the chromomagnetic opertator, then large direct CP asymmetries could show up in $D^0 \to V\gamma$ [Isidori, Kamenik '12; Lyon, Zwicky '12]

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

- SU(3)-flavor anatomy of non-leptonic decays taking into account SU(3)-breaking effects at the second order [Grossman, Robinson '12; Hiller, Jung, Schacht '12]
  - Correlations between CP asymmetries in different channels ($D_s^+ \to K_S \pi^+$ vs $D^+ \to K_S K^+$, $D^+ \to \pi^+ \pi^0$, $D^0 \to \pi^0 \pi^0$ and $D^0 \to K_S K_S$) allow to differentiate between different scenarios for the underlying dynamics, as well as between SM and various extensions

- Measurement of individual asymmetries rather than difference of asymmetries

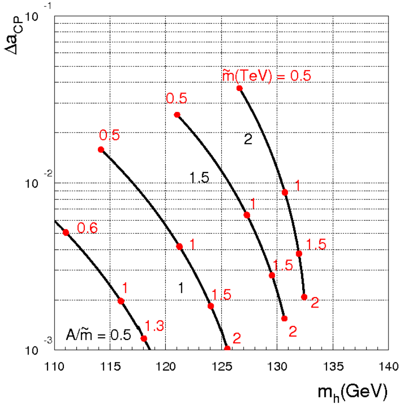
$$A_{CP}(K^+K^-) = (-0.32 \pm 0.21)\%$$
$$A_{CP}(\pi^+\pi^-) = (+0.31 \pm 0.22)\%$$

[CDF 10784, arXiv:1208.2517]

Δa_{CP} in SUSY

- **Disoriented A terms** [G.F.Giudice, G.Isidori, & P.P, '12]**, explicitly realized in Partial Compositeness frameworks** [Rattazzi et al., '12]

$$(\delta^q_{ij})_{LR} \sim \frac{A\theta^q_{ij} m_{q_j}}{\tilde{m}}, \qquad (\delta^q_{ij})_{LL} \sim (\delta^q_{ij})_{RR} \sim 0 \,,$$ [G.F.Giudice, G.Isidori, & P.P, '12]



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

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

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

- Down-quark FCNC under control thanks to the smallness of m_{down}.
- EDMs suppressed by $m_{u,d}$ yet close to the exp. bounds.
- Roboust prediction: $|\Delta a_{CP}| \sim 1\%$ implies a heavy Higgs boson!

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**

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

- **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**

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

- **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**

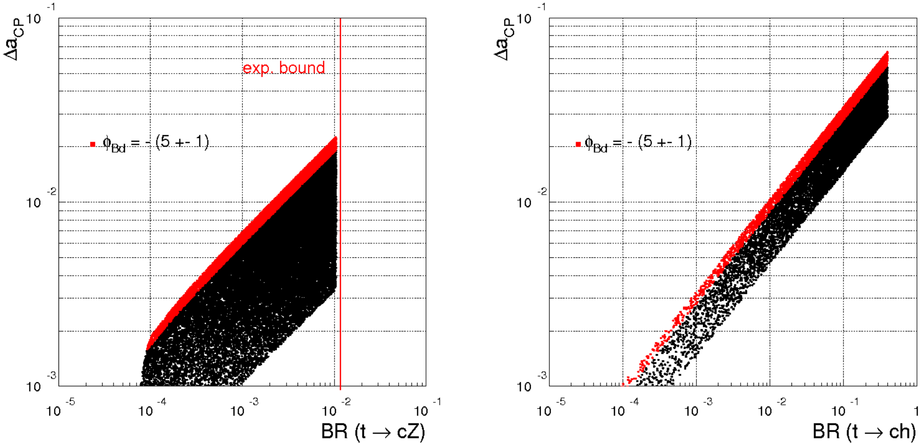
$$|d_n| \approx 3\times 10^{-26} \left| \frac{{\rm Im}\left[(g_L^h)^*_{ut}(g_R^h)_{tu}\right]}{2\times 10^{-7}} \right|\ e\,{\rm cm}\,,$$

- **Top FCNC**

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

Explicit realization of this setup in Partial Compositenes [Rattazzi & collaborators, '12] and Randall-Sundrum models [Delaunay, Kamenik, Perez, Randall, '12]

Δa_{CP} in scenarios with Z- and scalar-mediated FCNC [G.F.Giudice, G.Isidori, & P.P,



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.

CPV in neutral D-meson mixing

- Formalism

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

$$\langle D^0|\mathcal{H}_{\rm eff}|\bar{D}^0\rangle = M_{12} - \frac{i}{2}\Gamma_{12}, \qquad |D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}, \qquad \phi = {\rm Arg}(q/p)$$

$$x = \frac{\Delta m}{\Gamma} = 2\tau {\rm Re}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right], \qquad y = \frac{\Delta\Gamma}{2\Gamma} = -2\tau {\rm Im}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right]$$

- Observables

$$A_\Gamma = \frac{\hat{\tau}(\bar{D}^0 \to h^+h^-) - \hat{\tau}(D^0 \to h^+h^-)}{\hat{\tau}(\bar{D}^0 \to h^+h^-) + \hat{\tau}(\bar{D}^0 \to h^+h^-)} = -a_{CP}^{\rm ind}$$

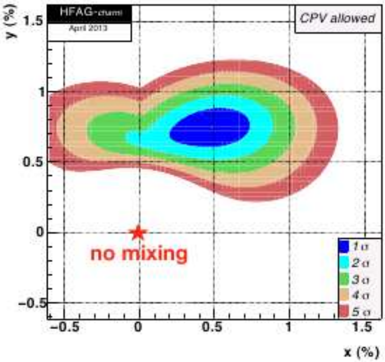
$$\approx \frac{y}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\phi - \frac{x}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\phi$$

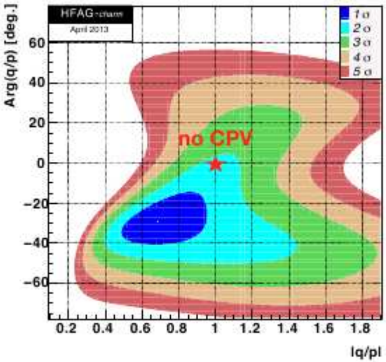
$$a_{\rm SL} = \frac{\Gamma(D^0 \to h^+\ell^-\nu) - \Gamma(\bar{D}^0 \to h^-\ell^+\nu)}{\Gamma(D^0 \to h^+\ell^-\nu) + \Gamma(\bar{D}^0 \to h^-\ell^+\nu)} = \frac{|q|^4 - |p|^4}{|q|^4 + |p|^4}$$

Experimental status

$$x = (0.49^{+0.17}_{-0.18})\%$$
$$y = (0.74 \pm 0.09)\%$$

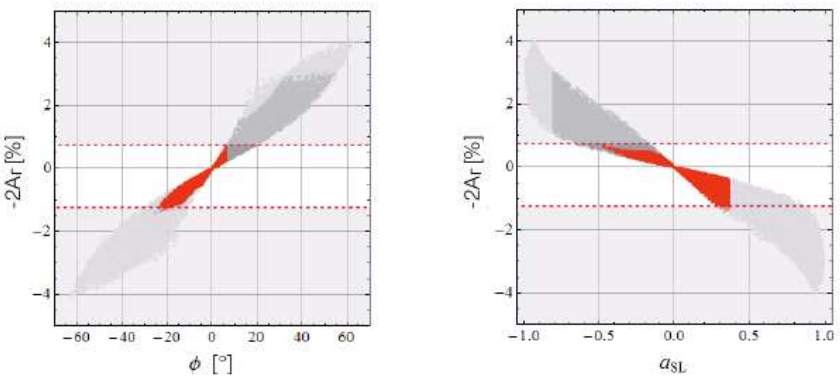
$$|q/p| = (0.69^{+0.17}_{-0.14})\%$$
$$\phi = (-29.6^{+8.9}_{-7.5})^\circ$$





Model independent CPV in mixing

[Altmannshofer, Buras, PP '10]



- light gray satisfies x∈[0.46,1.46]% and y∈[0.51,1.15]%
- darker gray further satisfies |q/p|∈[0.57,1.21]
- red is compatible with all above constraints plus ϕ∈[-22.5,6.3]°
- the dashed lines stand for the resulting allowed range for Aɾ

Leptonic dipoles: LFV, $(g-2)_\ell$, EDMs

- **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 $\Lambda_{NP} \equiv \tilde{m}$

$$Br(\mu \to e\gamma) \sim \frac{m_\nu^{D\,4}}{\tilde{m}^4}$$ [Borzumati & Masiero '86]

$$\Downarrow$$

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

$\ell \to \ell'\gamma$: model-independent analysis

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

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

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

  - **Δa_ℓ and leptonic EDMs are given by**

$$\Delta a_\ell = 2m_\ell^2\,{\rm Re}(A_{\ell\ell}), \qquad \frac{d_\ell}{e} = m_\ell\,{\rm Im}(A_{\ell\ell})\,.$$

  - **The branching ratios of $\ell \to \ell'\gamma$ are given by**

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

- **“Naive scaling”:**

$$\Delta a_{\ell_i}/\Delta a_{\ell_j} = m^2_{\ell_i}/m^2_{\ell_j}, \qquad d_{\ell_i}/d_{\ell_j} = m_{\ell_i}/m_{\ell_j}\,.$$

(for instance, if the new particles have an underlying SU(3) flavor symmetry in their mass spectrum and in their couplings to leptons, which is the case for gauge interactions).

[Giudice, P.P., & Passera, ’12]

Model-independent predictions

- $(g-2)_\ell$ **assuming "Naive scaling"** $\Delta a_{\ell_i}/\Delta a_{\ell_j} = m^2_{\ell_i}/m^2_{\ell_j}$

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

- **EDMs assuming "Naive scaling"** $d_{\ell_i}/d_{\ell_j} = m_{\ell_i}/m_{\ell_j}$

$$\begin{aligned} d_e &\simeq \left(\frac{\Delta a_e}{7\times 10^{-14}}\right) 10^{-24}\ \tan\phi_e\ \ e\,\mathrm{cm}\,, \\ d_\mu &\simeq \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right) 2\times 10^{-22}\ \tan\phi_\mu\ \ e\,\mathrm{cm}\,, \\ d_\tau &\simeq \left(\frac{\Delta a_\tau}{8\times 10^{-7}}\right) 4\times 10^{-21}\ \tan\phi_\tau\ \ e\,\mathrm{cm}\,, \end{aligned}$$

- $\mathrm{BR}(\ell_i \to \ell_j\gamma)$ **vs.** $(g-2)_\mu$

$$\begin{aligned} \mathrm{BR}(\mu\to e\gamma) &\approx 3\times 10^{-13}\left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)^2\left(\frac{\theta_{e\mu}}{10^{-5}}\right)^2, \\ \mathrm{BR}(\tau\to \ell\gamma) &\approx 4\times 10^{-8}\left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)^2\left(\frac{\theta_{\ell\tau}}{10^{-2}}\right)^2. \end{aligned}$$

[Giudice, P.P., & Passera, '12]

A concrete SUSY scenario: "Disoriented A-terms"

- **Challenge**: Large effects for $g-2$ keeping under control $\mu \to e\gamma$ and d_e
- **"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.
  - Flavor bounds of the down-sector are naturally satisfied thanks to the smallness of down-type quark/lepton masses.
  - This ansatz arises in scenarios with partial compositeness where we a natural prediction is $\theta^\ell_{ij} \sim \sqrt{m_i/m_j}$ [Rattazzi et al.,'12].

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

$$A^{\mu e}_L \sim \frac{\alpha}{\cos^2\theta_W}\,\delta^{\mu e}_{LR}\,, \qquad \frac{d_e}{e} \sim \frac{\alpha}{\cos^2\theta_W}\,\mathrm{Im}\delta^{ee}_{LR}\,.$$

- $(g-2)_\mu$ 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 $\tan\beta/\tan^2\theta_W \approx 100 \times (\tan\beta/30)$

$$\Delta a_\ell \sim \frac{\alpha}{\sin^2\theta_W}\,\tan\beta$$

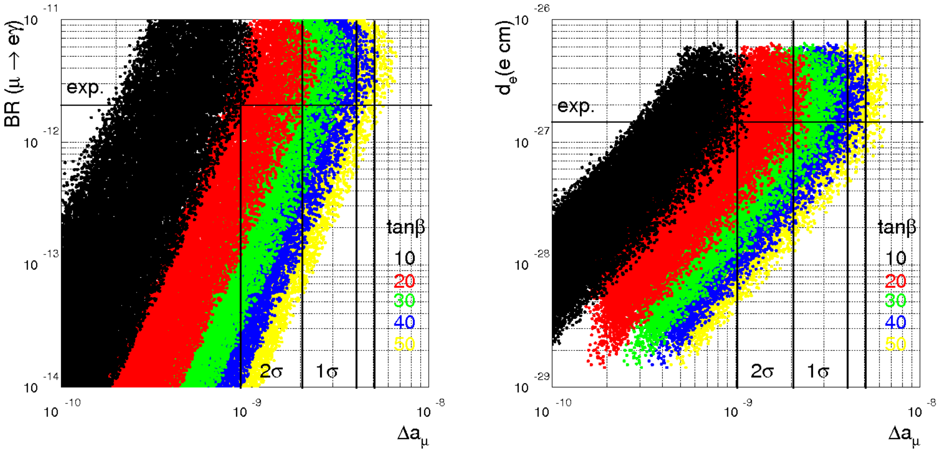
A concrete SUSY scenario: “Disoriented A-terms”

- **Numerical example**: $\tilde{m} = |A_e| = 1\ \mathrm{TeV}$, $\sin\phi_{A_e}$=1, $M_2 = \mu = 2M_1 = 0.2\ \mathrm{TeV}$, and $\tan\beta = 30$ [Giudice, P.P., & Passera, '12]

$$\begin{aligned}
\mathrm{BR}(\mu \to e\gamma) &\approx 6 \times 10^{-13} \left| \frac{A_\ell}{\mathrm{TeV}} \frac{\theta^\ell_{12}}{\sqrt{m_e/m_\mu}} \right|^2 \left(\frac{\mathrm{TeV}}{m_{\tilde{\ell}}}\right)^4 , \\
d_e &\approx 4 \times 10^{-28}\, \mathrm{Im}\left(\frac{A_\ell\, \theta^\ell_{11}}{\mathrm{TeV}}\right) \left(\frac{\mathrm{TeV}}{m_{\tilde{\ell}}}\right)^2 e\, \mathrm{cm} , \\
\Delta a_\mu &\approx 1 \times 10^{-9} \left(\frac{\mathrm{TeV}}{m_{\tilde{\ell}}}\right)^2 \left(\frac{\tan\beta}{30}\right) .
\end{aligned}$$

  - 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 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]

- LFV operators up to dimension-six

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2_{\rm LFV}}\,\mathcal{O}^{\rm dim-6} + \ldots\,.$$

$$\mathcal{O}^{\rm dim-6} \ni \;\; \bar{\mu}_R\,\sigma^{\mu\nu}\,H\,e_L\,F_{\mu\nu}\,,\;\; (\bar{\mu}_L\gamma^\mu e_L)\left(\bar{f}_L\gamma^\mu f_L\right)\,,\;\; (\bar{\mu}_R e_L)\left(\bar{f}_R f_L\right)\,,\;\; f = e, u, d$$

- the dipole-operator leads to $\ell \to \ell'\gamma$ while 4-fermion operators generate processes like $\mu \to eee$ and $\mu \to e$ conversion in Nuclei.
- When the dipole-operator is dominant:

$$\frac{{\rm BR}(\ell_i \to \ell_j\ell_k\bar{\ell}_k)}{{\rm BR}(\ell_i \to \ell_j\bar{\nu}_j\nu_i)} \simeq \frac{\alpha_{el}}{3\pi}\left(\log\frac{m^2_{\ell_i}}{m^2_{\ell_k}} - 3\right)\frac{{\rm BR}(\ell_i \to \ell_j\gamma)}{{\rm BR}(\ell_i \to \ell_j\bar{\nu}_j\nu_i)}\,,$$

$${\rm CR}(\mu \to e \text{ in N}) \simeq \alpha_{\rm em} \times {\rm BR}(\mu \to e\gamma)\,.$$

- ${\rm BR}(\mu \to e\gamma) \sim 10^{-12}$ implies ${\rm BR}(\mu \to eee) \leq 0.5 \times 10^{-14}$ and ${\rm CR}(\mu \to e \text{ in N}) \leq 0.5 \times 10^{-14}$.
- A combined analysis of $\mu \to e$ conversion on different target nuclei can discriminate among the underlying operators since the sensitivity of different processes to these operators is not the same [Okada et al. 2004].
- For three body LFV decays as $\mu \to eee$, an angular analysis of the signal would be crucial to shed light on the operator which is at work.

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	$1.4 \ldots 1.7$
$\frac{R(\mu \mathrm{Ti} \to e \mathrm{Ti})}{Br(\mu \to e\gamma)}$	$10^{-3} \ldots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$10^{-12} \ldots 26$

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

Testing new physics with the electron $g-2$

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

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

- **NP effects are expected to be of order $a_\ell^{\rm NP} \sim a_\ell^{\rm EW}$**

$$a_\mu^{\rm EW} = \frac{m_\mu^2}{(4\pi v)^2}\left(1-\frac{4}{3}\sin^2\theta_{\rm W}+\frac{8}{3}\sin^4\theta_{\rm W}\right)\approx 2\times 10^{-9}.$$

- **Main question: how could we check if the a_μ discrepancy is due to NP?**
- **Answer: testing new-physics effects in a_e** [Giudice, P.P, & Passera, '12]
- **"Naive scaling":** $\Delta a_{\ell_i}/\Delta a_{\ell_j} = m_{\ell_i}^2/m_{\ell_j}^2$

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

  - a_e has never played a role in testing beyond SM effects. From $a_e^{\rm SM}(\alpha) = a_e^{\rm EXP}$, we extract α which is is the most precise value of α available today!
  - The situation has now changed thanks to progresses both on the th. and exp. sides.

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

- **Using the second best determination of α from atomic physics $\alpha(^{87}\mathrm{Rb})$**

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

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

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

$$\underbrace{(0.6)_{\mathrm{QED4}},\ (0.4)_{\mathrm{QED5}},\ (0.2)_{\mathrm{HAD}},}_{(0.7)_{\mathrm{TH}}}\ (7.6)_{\delta\alpha},\ (2.8)_{\delta a_e^{\mathrm{EXP}}}. \tag{1}$$

  - 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} ($\delta a_e^{\mathrm{EXP}}$) 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.**

Supersymmetry and a_e

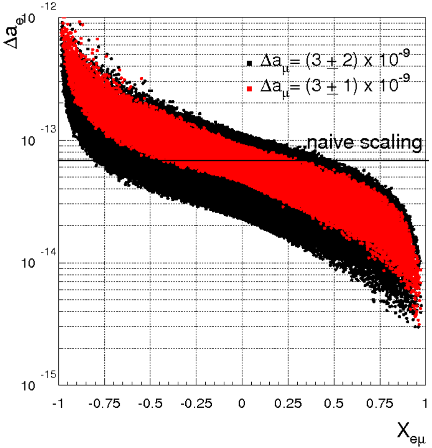
- SUSY contributions to a_ℓ comes from loops with exchange of chargino/sneutrino or neutralino/charged slepton.

- **Violations of "naive scaling"** can arise through sources of non-universalities in the slepton mass matrices in two possible ways

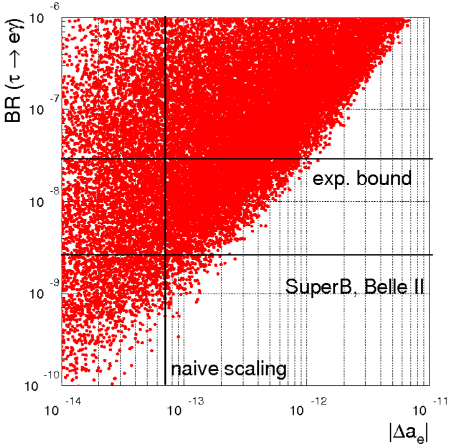
  - **Lepton flavor conserving (LFC) case**. The charged slepton mass matrix violates the global non-abelian flavor symmetry, but preserves $U(1)^3$. This case is characterized by non-degenerate sleptons ($m_{\tilde{e}} \neq m_{\tilde{\mu}} \neq m_{\tilde{\tau}}$) but vanishing mixing angles because of an exact alignment, which ensures that Yukawa couplings and the slepton mass matrix can be simultaneously diagonalized in the same basis.

  - **Lepton flavor violating (LFV) case**. The slepton mass matrix fully breaks flavor symmetry up to U(1) lepton number, generating mixing angles that allow for flavor transitions. Lepton flavor violating processes, such as $\mu \to e\gamma$, provide stringent constraints on this case. However, because of flavor transitions, a_e and a_μ can receive new large contributions proportional to m_τ (from a chiral flip in the internal line of the loop diagram), giving a new source of non-naive scaling.

Lepton flavor conserving case



Δa_e vs. $X_{e\mu} = (m^2_{\tilde{e}} - m^2_{\tilde{\mu}})/(m^2_{\tilde{e}} + m^2_{\tilde{\mu}})$



$\mathrm{BR}(\tau \to e\gamma)$ vs. $|\Delta a_e|$

Conclusions and future prospects

- **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 cleanest th. observables are cLFV processes, leptonic EDMs, LFU observables, rare B and K decays (especially $B_{s,d} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$), CPV in meson mixing
  - On the exp. side there are still excellent prospects of improvements in several clean channels: $\mu \to e\gamma$, $\mu N \to eN$, $\mu \to eee$, τ-LFV, EDMs, leptonic $(g-2)$, $B_{s,d} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$, CPV in B_s and D systems, γ from $B \to DK$.
  - The the origin of the $(g-2)_\mu$ discrepancy can be understood testing new-physics effects in the electron $(g-2)_e$. This would require improved measurements of $(g-2)_e$ and more refined determinations of α in atomic-physics experiments.

Conclusions

Irrespectively of whether the LHC will discover or not new particles, flavor physics will continue to teach us a lot!