Direct CP violation in charm and flavor mixing beyond the SM

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Fourth Workshop on Theory, Phenomenology and Experiments in Flavour Physics
12 June 2012, Capri, Italy

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

- **Processes predicted with high precision in the SM**
  - EWPO as $(g-2)_\mu$: $a_\mu^{exp} - a_\mu^{SM} \approx (3 \pm 1) \times 10^{-9}$, a discrepancy at 3σ!
  - LU in $R_M^{e/\mu} = \Gamma(M \to e\nu)/\Gamma(M \to \mu\nu)$ with $M = \pi, K$

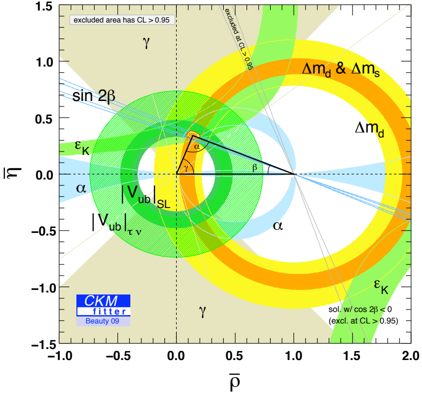
Experimental status

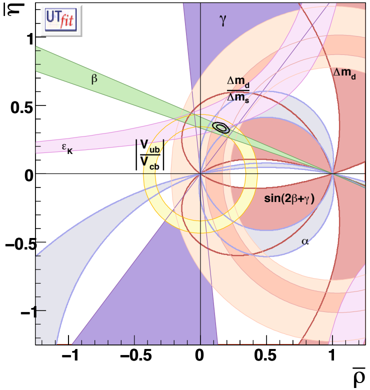
Observable	SM prediction	Theory error	Present result	Future error	Future Facility
$S_{B_s\to\psi\phi}$	**0.036**	$\lesssim 0.01$	$\lesssim \|0.2\|$	0.01	**LHCb**
$S_{B_d\to\phi K}$	$\sin(2\beta)$	$\lesssim 0.05$	0.44 ± 0.18	0.1	LHCb
$A^d_{\rm SL}$	-5×10^{-4}	10^{-4}	$-(5.8 \pm 3.4)10^{-3}$	10^{-3}	LHCb
$A^s_{\rm SL}$	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
$\mathcal{B}(B_s\to\mu^+\mu^-)$	3×10^{-9}	$20\% \to 5\%$	$< 4.5 \times 10^{-9}$	10%	**LHCb**
$\mathcal{B}(B_d\to\mu^+\mu^-)$	1×10^{-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
$\|q/p\|_{D-\rm mixing}$	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]

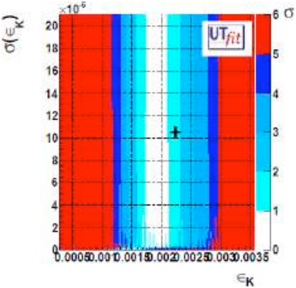
Superstars of 2011-2013 in flavour physics: $\mu \to e\gamma$, $B_s\to\psi\phi$, $B_{s,d}\to\mu^+\mu^-$

Messages from the B-factories

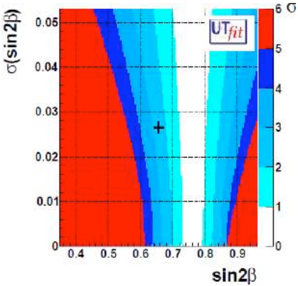




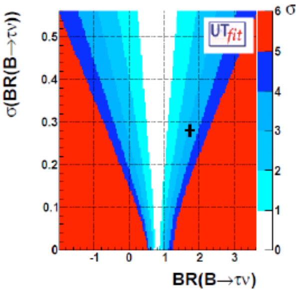
"Very likely, flavour and CP violation in FC processes are dominated by the CKM mechanism" (Nir)



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



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



fit vs. exp. $\approx -3.2\sigma$

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.

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

- **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?** **See Silvestrini's talk**

- **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 $\phi_f \neq 0$

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

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

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

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

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

- $D-\bar{D}$ **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**

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

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

- **Δa_{CP}: SM + NP**

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

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

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

Lessons & Questions

- **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]

Testing direct charm-CPV

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

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

$$C_7^{(\prime)}(m_c) = \tilde{\eta} \left[\eta C_7^{(\prime)}(M_\star) + 8 Q_u (\eta - 1) C_8^{(\prime)}(M_\star) \right], \quad (2)$$

$$C_8^{(\prime)}(m_c) = \tilde{\eta}\, C_8^{(\prime)}(M_\star), \quad (3)$$

$$\eta = \left[\frac{\alpha_s(M_\star)}{\alpha_s(m_t)} \right]^{\frac{2}{21}} \left[\frac{\alpha_s(m_t)}{\alpha_s(m_b)} \right]^{\frac{2}{23}} \left[\frac{\alpha_s(m_b)}{\alpha_s(m_c)} \right]^{\frac{2}{25}} , \quad (4)$$

$$\tilde{\eta} = \left[\frac{\alpha_s(M_\star)}{\alpha_s(m_t)} \right]^{\frac{14}{21}} \left[\frac{\alpha_s(m_t)}{\alpha_s(m_b)} \right]^{\frac{14}{23}} \left[\frac{\alpha_s(m_b)}{\alpha_s(m_c)} \right]^{\frac{14}{25}} . \quad (5)$$

- In SUSY one can find [P.P., to appear]

$$|a^{\mathrm{SUSY}}_{(\rho,\omega)\gamma}| \approx 5 \left| \Delta a^{\mathrm{SUSY}}_{CP} \right| \times \left[\frac{10^{-5}}{\mathcal{B}(D \to (\rho,\omega)\gamma)} \right]^{1/2} \lesssim 10\% . \quad (6)$$

Δa_{CP} in SUSY [Grossman, Kagan & Nir, '06], [Giudice, Isidori, & P.P, '12]

- **Direct** "12" **transition**

$$C_8^{(\tilde g)} = -\frac{\sqrt{2}\pi\alpha_s \tilde m_g}{G_F m_c}\frac{(\delta^u_{12})_{LR}}{\tilde m_q^2}\, g_8(x_{gq})\,, \quad g_8(1) = -\frac{5}{36}$$

- **Effective** "12" = "13" × "32" **transition: quasi-degenerate squarks**

$$C_8^{(\tilde g)} = -\frac{\sqrt{2}\pi\alpha_s \tilde m_g}{G_F m_c}\frac{(\delta^u_{13})_{LL}\,(\delta^u_{33})_{LR}\,(\delta^u_{32})_{RR}}{\tilde m_q^2}\, F(x_{gq})\,, \quad F(1) = -\frac{11}{360}$$

- **Effective** "12" = "13" × "32" **transition: split squark-families**

$$C_8^{(\tilde g)} = -\frac{\sqrt{2}\pi\alpha_s \tilde m_g}{G_F m_c}\frac{(\delta^u_{13})_{LL}\,(\delta^u_{33})_{LR}\,(\delta^u_{32})_{RR}}{\tilde m_{q_3}^2}\, g_8(x_{gq})$$

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

- **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]

D^0–$\bar{D}^0$ mixing

- **The D^0–$\bar{D}^0$ transition amplitude can be decomposed into a dispersive (M_{12}) and an absorptive (Γ_{12}) component:**

$$\langle D^0 | \mathcal{H}_{\rm eff} | \bar{D}^0 \rangle \quad = \quad M_{12}^D - \frac{i}{2}\Gamma_{12}^D \, .$$

- **Physical parameters**

$$x_{12} \equiv 2\frac{|M_{12}^D|}{\Gamma^D} \, , \quad y_{12} \equiv \frac{|\Gamma_{12}^D|}{\Gamma^D} \, , \quad \phi_{12} \equiv \arg\left(\frac{M_{12}^D}{\Gamma_{12}^D}\right) ,$$

- **The 95% C.L. allowed ranges by HFAG are**

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

- **Effective Hamiltonian**

$$\mathcal{H}_{\rm eff}^{\Delta C=2} = \frac{1}{(1~{\rm TeV})^2} \sum_i z_i Q_i^{cu} + {\rm H.c.} \, ,$$

$$Q_2^{cu} = \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta \, , \qquad Q_3^{cu} = \bar{u}_R^\alpha c_L^\beta \bar{u}_R^\beta c_L^\alpha \, ,$$
$$Q_4^{cu} = \bar{u}_R^\alpha c_L^\alpha \bar{u}_L^\beta c_R^\beta \, , \qquad Q_5^{cu} = \bar{u}_R^\alpha c_L^\beta \bar{u}_L^\beta c_R^\alpha \, ,$$

$$|z_2| < 1.6 \times 10^{-7} \, , \qquad |z_3| < 5.8 \times 10^{-7} \, ,$$
$$|z_4| < 5.6 \times 10^{-8} \, , \qquad |z_5| < 1.6 \times 10^{-7} \, ,$$

Δa_{CP} vs. D^0–$\bar{D}^0$ & ϵ'/ϵ in SUSY

- Δa_{CP}

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

- **D^0–$\bar{D}^0$ mixing**

$$z_2^{(\tilde{g})} \approx -5\times 10^{-10}\left(\frac{\rm TeV}{m_{\tilde{q}}}\right)^2\left[\frac{(\delta^u_{12})_{RL}}{1\times 10^{-3}}\right]^2 ,$$

$$z_4^{(\tilde{g})} \approx -2\times 10^{-10}\left(\frac{\rm TeV}{m_{\tilde{q}}}\right)^2\frac{(\delta^u_{12})_{LR}\,(\delta^u_{12})_{RL}}{(1\times 10^{-3})^2} ,$$

- ϵ'/ϵ

$$\frac{\epsilon'/\epsilon}{(\epsilon'/\epsilon)_{SM}} \sim \frac{(\delta^u_{12})_{LR}\,(\delta^u_{22})_{RL}}{\lambda^5}\frac{M_W^2}{\tilde{m}^2} \sim \frac{m_c^2 M_W^2}{\tilde{m}^4}\frac{A^2\theta^u_{12}}{\lambda^5} ,$$

- Values of $(\delta^u_{12})_{LR,RL} \sim 10^{-3}$ leading to $\Delta a_{CP} \approx 0.6\%$ are well below the current bounds from $D^0 - \bar{D}^0$ mixing
- NP contribution to ϵ'/ϵ are generated through loops of charginos and up-squarks, but they are suppressed by $(\delta^u_{12})_{LR}\,(\delta^u_{22})_{RL}/\tilde{m}^2 \sim m_c^2/\tilde{m}^4$ and therefore they remains insignificant, even for $(\delta^u_{12})_{LR} \sim 10^{-3}$.

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.

Δa_{CP} in SUSY with split squark families

- **Δa_{CP} in the split family scenario**

$$\Delta a_{CP} \approx 2 \times \mathrm{Im} C_8^{(\tilde{g})} = -\frac{2\sqrt{2}\pi\alpha_s \tilde{m}_g}{G_F m_c} \frac{\mathrm{Im}\left[(\delta^u_{13})_{LL}\,(\delta^u_{33})_{LR}\,(\delta^u_{32})_{RR}\right]}{\tilde{m}^2_{q_3}}\; g_8(x_{gq})$$

- **EDMs in the split family scenario**

$$\left\{\frac{d_u}{e},\; d_u^c\right\} = -\frac{\alpha_s m_{\tilde{g}}}{2\pi \tilde{m}^2_{q_3}}\; f_3^{d_u, d_u^c}(x_{gq})\, \mathrm{Im}\left[(\delta^u_{13})_{LL}(\delta^u_{33})_{LR}(\delta^u_{31})_{RR}\right]\;,$$

- **Δa_{CP} vs. the neutron EDM in the split family scenario**

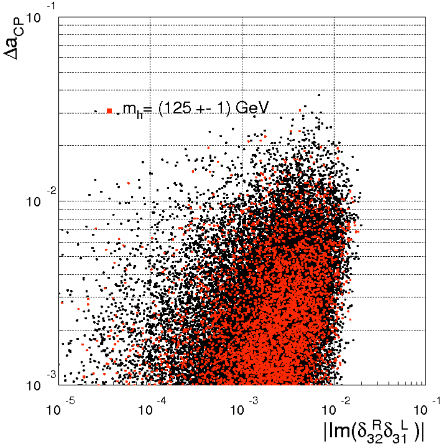
$$\left|\Delta a_{CP}^{\mathrm{SUSY}}\right| \approx 2 \times 10^{-3} \times \left|\frac{d_n}{3 \times 10^{-26}}\right| \left|\frac{\mathrm{Im}\,(\delta^u_{32})_{RR}}{0.2}\right| \left|\frac{10^{-3}}{\mathrm{Im}\,\left(\delta^u_{31}\right)_{RR}}\right|\;.$$

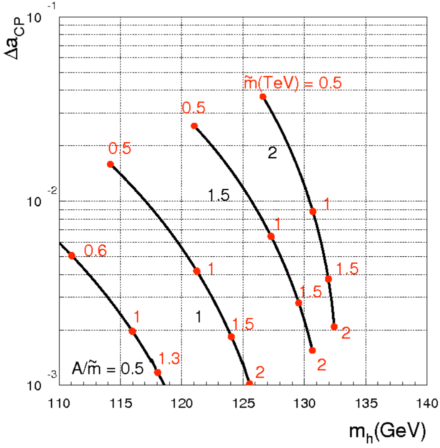
where $(\delta^u_{33})_{RL} \approx A\; m_t/\tilde{m}$. A strong hierarchical structure in the off-diagonal terms of the RR up-squark mass matrix is required. This happens for instance models of alignment

$$(\delta^u_{ij})_{RR} \sim \frac{m_{u_i}/m_{u_j}}{|V_{ij}|} \;\Rightarrow \frac{(\delta^u_{31})_{RR}}{(\delta^u_{32})_{RR}} \sim \frac{m_u}{\lambda m_c} \sim 10^{-2}$$

[G.F.Giudice, G.Isidori, & P.P, '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 $A = 0.5, 1, 1.5, 2$.

Formalism for $B_{d,s}$ mixing amplitudes

- **Theory:**

$$M_{12}^q = \left(M_{12}^q\right)_{\rm SM} C_{B_q} e^{2i\varphi_{B_q}} , \qquad \Delta M_q = 2\left|M_{12}^q\right| = (\Delta M_q)_{\rm SM} C_{B_q} \qquad (q=d,s) .$$

$$S_{\psi K_S} = \sin(2\beta + 2\varphi_{B_d}) , \qquad S_{\psi\phi} = \sin(2|\beta_s| - 2\varphi_{B_s}) ,$$

$$\sin(2\beta)_{\rm tree} = 0.775 \pm 0.035 , \qquad \sin(2\beta_s)_{\rm tree} = 0.038 \pm 0.003 \qquad \text{(CKM fit)}.$$

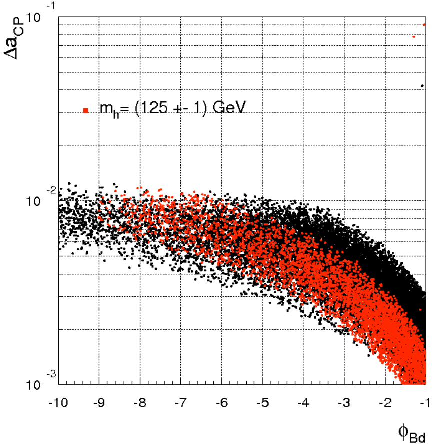
- **Experiments:**

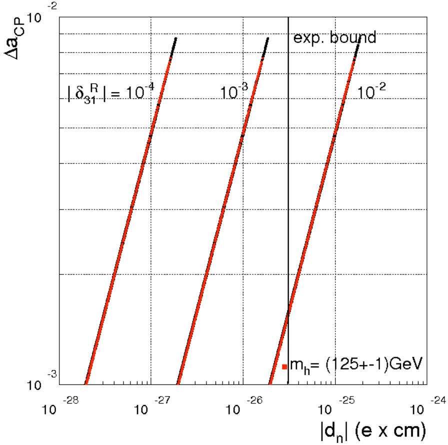
$$S_{\psi K_S}^{\rm exp} = 0.676 \pm 0.020 , \qquad S_{\psi\phi(f_0)}^{\rm exp} = -0.03 \pm 0.18 .$$

- **Δa_{CP} vs. $S_{\psi K_S}$ in SUSY with split squark families**

$$M_{12}^q \approx \left(M_{12}^q\right)^{\rm SM} \left[1 + \frac{\left(\delta_{3q}^d\right)_{LL}^2}{V_{tq}^2} F_0\right] , \qquad F_0 \approx \frac{1}{3}\left(\frac{g_s}{g}\right)^4 \frac{m_W^2}{\tilde m_{q_3}^2}$$

$$\Delta a_{CP} \sim {\rm Im}\left[\left(\delta_{13}^u\right)_{LL}\left(\delta_{33}^u\right)_{LR}\left(\delta_{32}^u\right)_{RR}\right] , \qquad (\Delta S_{\psi K_S})_{\rm NP} \sim {\rm Im}\left[\frac{\left(\delta_{31}^d\right)_{LL}^2}{V_{td}^2}\right]$$





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**

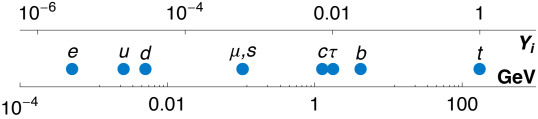
$$\frac{\Gamma(\tilde{g} \to \tilde{t} u_i)}{\Gamma(\tilde{g} \to \tilde{t} t)} = \left|(\delta^u_{i3})_{RR}\right|^2 \left[1 + O\left(\frac{m_t}{\tilde{m}_g}\right)\right].$$

    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 $m_{\mathrm{SUSY}} \gtrsim 3m_W$, $\mathrm{BR}(t \to qX) \lesssim 10^{-6}$.

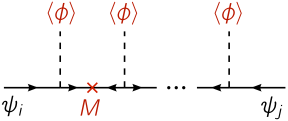
SM vs. NP flavor puzzle



$V_{\rm CKM} \sim$ 

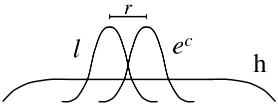
Froggat-Nielsen '79: Hierarchies from SSB of a Flavour Symmetry

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



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

$$\Downarrow$$

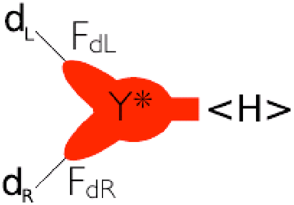
Small Yukawa couplings without Symmetries

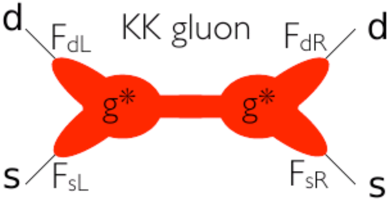
- **Flavor Models flavor protection**

[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]





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

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

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

[Csaki, Falkowski & Weiler, '08]

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

Δa_{CP} in SUSY alignment models [Nir & Seiberg]

- In SUSY alignment models it turns out that [Nir & Seiberg]

$$\left(\delta^u_{21}\right)^{\rm eff}_{RL} = \left(\delta^u_{22}\right)_{RL}\left(\delta^u_{21}\right)_{LL} \sim \frac{Am_c}{\tilde{m}}\lambda.$$

- $(\delta^u_{21})_{LL} \sim \lambda$ arises from the $SU(2)$ relation $\tilde{M}^{(u)2}_{LL} = V\tilde{M}^{(d)2}_{LL}V^\dagger$ and the assumption of non-degeneracy for different squark families

$$(\tilde{M}^{(u)2}_{LL})_{21} \approx (\tilde{M}^{(d)2}_{LL})_{21} + \lambda\left[(\tilde{M}^{(d)2}_{LL})_{22} - (\tilde{M}^{(d)2}_{LL})_{11}\right] .$$

$$\left(\delta^u_{21}\right)_{LL} \approx \lambda\,\frac{\Delta\tilde{m}^2_{21}}{\tilde{m}^2}\ ,$$

- The bounds from D–$\bar{D}$ mixing imply $|\,(\delta^u_{21})_{LL}\,| < 3\times 10^{-2}$ for TeV squarks, and $(\delta^u_{22})_{RL} \approx Am_c/\tilde{m} < 10^{-3}$ from vacuum stability.
- In SUSY alignment models $\Delta a^{\rm SUSY}_{CP} \ll 10^{-3}$
- **SUSY flavour models:** "We explore the possibility that a major part of the asymmetry comes from supersymmetric contributions. The leading candidates are models where the flavor structure of the trilinear scalar couplings is related to the structure of the Yukawa couplings via approximate flavor symmetries, particularly $U(1)$, $[U(1)]^2$ and $U(2)$. The typical value of the supersymmetric contribution to the asymmetry is $\Delta A^{\rm SUSY}_{CP} \sim 0.001$, but it could be accidentally enhanced by order one coefficients." [Nir & collaborators, '12]

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

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

$$(\delta_{ij}^{u,d})_{LL} \sim \frac{\tilde{m}_0^2}{\tilde{m}^2}\, \epsilon_i^q \epsilon_j^q, \qquad (\delta_{ij}^{u,d})_{RR} \sim \frac{\tilde{m}_0^2}{\tilde{m}^2}\, \epsilon_i^{u,d} \epsilon_j^{u,d},$$
$$(\delta_{ij}^{u,d})_{LR} \sim g_\rho\, \epsilon_i^q \epsilon_j^{u,d}\, \frac{v_{u,d}\, A_0}{\tilde{m}^2}, \qquad (\delta_{ij}^{u,d})_{RL} \sim g_\rho\, \epsilon_i^{u,d} \epsilon_j^q\, \frac{v_{u,d}\, A_0}{\tilde{m}^2}, \tag{7}$$

$$(Y_u)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^u, \qquad (Y_d)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^d. \tag{8}$$

$$(L_u)_{ij} \sim (L_d)_{ij} \sim \frac{\epsilon_i^q}{\epsilon_j^q}, \qquad (R_{u,d})_{ij} \sim \frac{\epsilon_i^{u,d}}{\epsilon_j^{u,d}} \tag{9}$$

$$(L_u^\dagger Y_u R_u)_{ij} = g_\rho \epsilon_i^u \epsilon_i^q \delta_{ij} \equiv y_i^u \delta_{ij}\,, \qquad (L_d^\dagger Y_d R_d)_{ij} = g_\rho \epsilon_i^d \epsilon_i^q \delta_{ij} \equiv y_i^d \delta_{ij}\,, \tag{10}$$

$$\frac{\epsilon_1^q}{\epsilon_2^q} \sim \lambda \qquad \frac{\epsilon_2^q}{\epsilon_3^q} \sim \lambda^2 \qquad \frac{\epsilon_1^q}{\epsilon_3^q} \sim \lambda^3, \tag{11}$$

- **"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]**"**

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**

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

Top FCNC

- **Effective Lagrangian**

$$
\begin{aligned}
-\mathcal{L}^{\rm eff} &= \frac{g}{2c_W}\,\bar{q}\gamma_\mu\left(g^{qt}_{ZL}P_L + g^{qt}_{ZR}P_R\right)tZ^\mu + \frac{e}{2m_t}\bar{q}\left(g^{qt}_{\gamma L}P_L + g^{qt}_{\gamma R}P_R\right)\sigma_{\mu\nu}tF^{\mu\nu} \\
&+ \frac{g_s}{2m_t}\bar{q}\left(g^{qt}_{gL}P_L + g^{qt}_{gR}P_R\right)\sigma_{\mu\nu}T^a tG^{a\mu\nu} + \bar{q}\left(g^{qt}_{hL}P_L + g^{qt}_{hR}P_R\right)tH + \mathrm{h.c.}
\end{aligned}
$$

- **Top FCNC decay widths**

$$
\begin{aligned}
\Gamma(t\to qZ) &= \frac{\alpha_2}{32c_W^2}|g^{qt}_Z|^2\frac{m_t^3}{m_Z^2}\left(1-\frac{m_Z^2}{m_t^2}\right)^2\left(1+2\frac{m_Z^2}{m_t^2}\right), \\
\Gamma(t\to q\gamma) &= \frac{\alpha}{4}|g^{qt}_\gamma|^2 m_t\,, \\
\Gamma(t\to qg) &= \frac{\alpha_s}{3}|g^{qt}_\gamma|^2 m_t\,, \\
\Gamma(t\to qH) &= \frac{m_t}{32\pi}|g^{qt}_h|^2\left(1-\frac{M_H^2}{m_t^2}\right)^2,
\end{aligned}
$$

where $|g^{qt}_X|^2 = (|g^{qt}_{XL}|^2 + |g^{qt}_{XR}|^2)$ with $X = Z,\gamma,g,h$.

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**

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

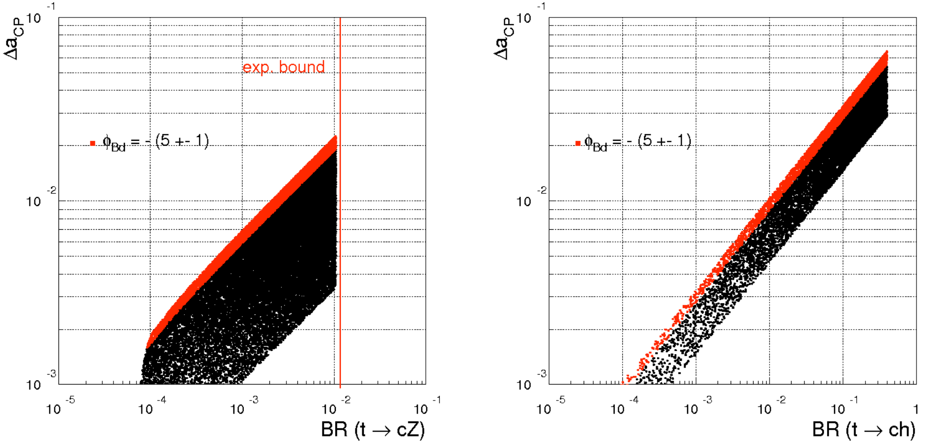
- **Neutron EDM**

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

- **Top FCNC**

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

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, assuming for the corresponding down-type coupling $(g_L^X)_{db} = 5 \times 10^{-2}(g_L^X)_{ut}$.

Conclusions and future prospects

- 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 the evidence for direct charm-CPV 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.

- Which are the most natural NP theories to account for Δa_{CP} @ %? Supersymmetric models of Partial Compositeness [Rattazzi & collaborators, '12] realize the 'disoriented A-terms' scenario [Giudice, Isidori, & P.P., '12] and therefore provide an ideal framework to explain the LHCb result.

- How to test and discriminate among different new-physics models? Direct CP violation in $D \to V\gamma$ is one of the most important test of NP in Δa_{CP} [Isidori & Kamenik].

- **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 can teach us a lot about the new physics at the TeV scale.**