Charm-Top flavour physics at the LHC(b)

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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.

- **Golden channels in Up flavour physics**
  - Direct CPV in SCS decays $D^0 \to K^+K^-(\pi^+\pi^-)$
  - CPV in $D^0 - \bar{D}^0$ mixing
  - Hadronic EDMs
  - FCNC top decays, FB asymmetry in $t\bar{t}$ production,...

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

- **Experiment:** $\Delta a_{CP} = a_{K^+K^-} - a_{\pi^+\pi^-}$
  - D^0 mesons from $D^{*+} \to D^0\pi^+$ decays [LHCb '11, CDF '11, Belle '08 and BaBar '07]
  $$\Delta a_{CP} = -(0.67 \pm 0.16)\%$$
  - D^0 mesons produced in semileptonic b-hadron decays [LHCb '13].
  $$\Delta a_{CP} = +(0.49 \pm 0.30 \pm 0.14)\%$$
  $$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}\,, \quad f = K^+K^-, \pi^+\pi^-$$

- **Is it possible Δa_{CP} @ % in the SM?** [Golden & Grinstein, '89, Brod et al. '12, Pirtskhalava et al. '12, Cheng et al., '12, Bhattacharya et al, '12, Feldmann et al., '12, Li et al., '12, Franco et al., 012]

$$\Delta a_{CP} \quad \approx \quad \frac{-2}{\sin\theta_c}\mathrm{Im}(V_{cb}^* V_{ub})\mathrm{Im}(\Delta R^{\mathrm{SM}}) = -(0.13\%)\mathrm{Im}(\Delta R^{\mathrm{SM}})$$

$\Delta R^{\mathrm{SM}} \approx \alpha_s(m_c)/\pi \approx 0.1$ in perturbation theory and $a_K^{\mathrm{dir}} = -a_\pi^{\mathrm{dir}}$ in the $SU(3)$ limit [Grossman, Kagan & Nir, '06].

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]

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

Testing direct charm-CPV

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

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

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

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

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

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

- $SU(3)$-Flavor Anatomy of Non-Leptonic Charm Decays taking into account $SU(3)$-breaking effects $m_s \neq m_{u,d}$ at the second order [Grossman, Robinson, '12; Hiller, Jung & Schacht, '12] Correlations between CP asymmetries ($D \to \pi^+\pi^-$ versus $D \to K^+K^-$, $D_s \to K_S\pi^+$ versus $D^+ \to K_S K^+$, $D^+ \to \pi^+\pi^0$, $D \to \pi^0\pi^0$, and $D \to K_S K_S$) allow to differentiate between different scenarios for the underlying dynamics, as well as between the standard model and various extensions.

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.
  - Large effects for the hadronic EDMs are unavoidable as they are also generated by the chromomagnetic operator.

- **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} in SUSY [Grossman, Kagan & Nir, '06], [Giudice, Isidori, & P.P, '12], [Hiller & Nir, '12],

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

$$\left(\delta^u_{12}\right)_{LR} \approx \frac{A m_c}{m_{\tilde{q}_{1,2}}}\,\theta_{12} \approx \left(\frac{A}{3}\right)\left(\frac{\theta_{12}}{0.5}\right)\left(\frac{\mathrm{TeV}}{m_{\tilde{q}_{1,2}}}\right) \times 10^{-3}\,,$$

$$\left|\Delta a^{\mathrm{SUSY}}_{CP}\right| \approx 0.6\% \frac{\left|\mathrm{Im}\left(\delta^u_{12}\right)_{LR}\right|}{10^{-3}}\left(\frac{\mathrm{TeV}}{m_{\tilde{q}_{1,2}}}\right)\,,$$

- **Split families:** $m_{\tilde{q}_{1,2}} \gg m_{\tilde{q}_3}$

$$\left(\delta^u_{12}\right)^{\mathrm{eff}}_{LR} \approx \frac{A m_t}{m_{\tilde{q}_3}}\left(\delta^u_{13}\right)_{LL}\left(\delta^u_{32}\right)_{RR} \approx \left(\frac{A}{3}\right)\frac{\left(\delta^u_{13}\right)_{LL}}{\lambda^3}\frac{\left(\delta^u_{32}\right)_{RR}}{\lambda}\left(\frac{\mathrm{TeV}}{m_{\tilde{q}_3}}\right) \times 10^{-3}\,,$$

$$\left|\Delta a^{\mathrm{SUSY}}_{CP}\right| \approx 0.6\% \frac{\left|\mathrm{Im}\left(\delta^u_{12}\right)^{eff}_{LR}\right|}{10^{-3}}\left(\frac{\mathrm{TeV}}{m_{\tilde{q}_3}}\right)\,,$$

- In many flavour models $\left(\delta^u_{12}\right)^{\mathrm{eff}}_{LR} \sim \left(\delta^u_{12}\right)_{LR}$ but still $\left(\delta^u_{12}\right)^{\mathrm{eff}}_{LR}$ provides the dominant effects if $m_{\tilde{q}_{1,2}} \gg m_{\tilde{q}_3}$.

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

Δa_{CP} in SUSY

- **Disoriented *A* terms**

$$(\delta^q_{ij})_{LR} \sim \frac{A\theta^q_{ij} m_{q_j}}{\tilde{m}}, \qquad (\delta^q_{ij})_{LL} \sim (\delta^q_{ij})_{RR} \sim 0 \qquad q = u, d \,,$$

	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.

- The MFV ansatz is based on the observation that, for vanishing Yukawa couplings, the SM quark sector exhibits an enhanced global symmetry

$$G_f = SU(3)_u \times SU(3)_d \times SU(3)_Q .$$

- The SM Yukawa couplings are formally invariant under G_f if the Yukawa matrices are promoted to spurions transforming appropriately under G_f.

- NP models are of MFV type if there is no new flavor structure beyond the SM Yukawas. In this case they are formally invariant under G_f.

$$\tilde{m}_Q^2 \sim \mathbf{1} + y_U y_U^\dagger + y_D y_D^\dagger,$$

$$\tilde{m}_U^2 \sim \mathbf{1} + y_U^\dagger y_D y_D^\dagger y_U + y_U^\dagger y_U y_U^\dagger y_U, \qquad \tilde{m}_D^2 \sim \mathbf{1} + y_D^\dagger y_D y_D^\dagger y_D + y_D^\dagger y_U y_U^\dagger y_D,$$

$$A_U \sim A\left(\mathbf{1} + y_U y_U^\dagger + y_D y_D^\dagger\right) y_U, \qquad A_D \sim A\left(\mathbf{1} + y_U y_U^\dagger + y_D y_D^\dagger\right) y_D,$$

$$(\delta^u_{LL})_{ij} \sim V_{i3} V_{j3}^* \, y_b^2, \qquad (\delta^d_{LL})_{ij} \sim V_{3i}^* V_{3j} \, y_t^2,$$

$$(\delta^u_{RR})_{ij} \sim y_i^U y_j^U \, V_{i3} V_{j3}^* \, y_b^2, \qquad (\delta^d_{RR})_{ij} \sim y_i^D y_j^D \, V_{3i}^* V_{3j} \, y_t^2,$$

$$(\delta^u_{LR})_{ij} \sim \frac{m_j^U A}{\tilde{m}_Q \tilde{m}_U} \, V_{i3} V_{j3}^* \, y_b^2, \qquad (\delta^d_{LR})_{ij} \sim \frac{m_j^D A}{\tilde{m}_Q \tilde{m}_D} \, V_{3i}^* V_{3j} \, y_t^2 .$$

- MFV allows for the presence of flavor-blind CPV phases.

$U(1)$ Flavor Models [Nir & Seiberg, '93]

- In $U(1)$ flavor symmetry models Yukawas are of the (hierarchical) form

$$(y_U)_{ij} \sim \epsilon^{Q_i+U_j}, \qquad (y_D)_{ij} \sim \epsilon^{Q_i+D_j} \qquad \epsilon \sim \lambda_c,$$

- Using $Q_3 = U_3 = 0$ as suggested by the large top Yukawa, all other charges can be expressed in terms of masses and CKM matrix elements

$$\epsilon^{Q_i} \sim V_{i3}, \qquad \epsilon^{U_i} \sim \frac{y_i^U}{V_{i3}}, \qquad \epsilon^{D_i} \sim \frac{y_i^D}{V_{i3}}.$$

- The structure of the soft masses as determined by $U(1)$ invariance is given by

$$\tilde{m}_Q^2 \sim \epsilon^{|Q_i-Q_j|}, \qquad \tilde{m}_U^2 \sim \epsilon^{|U_i-U_j|}, \qquad \tilde{m}_D^2 \sim \epsilon^{|D_i-D_j|},$$

$$A_U \sim \epsilon^{Q_i+U_j}, \qquad A_D \sim \epsilon^{Q_i+D_j},$$

$$(\delta^u_{LL})_{ij} \sim \frac{V_{i3}}{V_{j3}}|_{i\le j}, \qquad (\delta^d_{LL})_{ij} \sim \frac{V_{i3}}{V_{j3}}|_{i\le j},$$

$$(\delta^u_{RR})_{ij} \sim \frac{y_i^U V_{j3}}{y_j^U V_{i3}}|_{i\le j}, \qquad (\delta^d_{RR})_{ij} \sim \frac{y_i^D V_{j3}}{y_j^D V_{i3}}|_{i\le j},$$

$$(\delta^u_{LR})_{ij} \sim \frac{m_j^U A}{\tilde{m}_Q \tilde{m}_U}\frac{V_{i3}}{V^*_{j3}}, \qquad (\delta^d_{LR})_{ij} \sim \frac{m_j^D A}{\tilde{m}_Q \tilde{m}_D}\frac{V_{i3}}{V^*_{j3}},$$

- Major problems: $\epsilon_K \sim m_d/m_s$ and to a less extent ϵ'/ϵ and the neutron EDM.

Partial Compositeness (PC) [Rattazzi & collaborators, '12]

- PC is a seesaw-like mechanism that explains the hierarchy among the SM fermion masses by mixing with heavy resonances of a strongly coupled sector. characterized by the mass scale m_ρ and the coupling g_ρ.
- In the effective theory below m_ρ, every quark $(q, u, d)_i$ is accompanied by a spurion $\epsilon_i^{q,u,d} \lesssim 1$ that measures its amount of compositeness.

$$(y_U)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^u, \qquad (y_D)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^d,$$

- The structure of the soft masses at the scale m_ρ is

$$\tilde{m}_Q^2 \sim \mathbf{1} + \epsilon_i^q \epsilon_j^q, \qquad \tilde{m}_U^2 \sim \mathbf{1} + \epsilon_i^u \epsilon_j^u, \qquad \tilde{m}_D^2 \sim \mathbf{1} + \epsilon_i^d \epsilon_j^d,$$

$$A_U \sim g_\rho \epsilon_i^q \epsilon_j^u, \qquad A_D \sim g_\rho \epsilon_i^q \epsilon_j^d,$$

$$(\delta_{LL}^u)_{ij} \sim (\epsilon_3^q)^2 V_{i3} V_{j3}^*, \qquad (\delta_{LL}^d)_{ij} \sim (\epsilon_3^q)^2 V_{i3} V_{j3}^*,$$

$$(\delta_{RR}^u)_{ij} \sim \frac{y_i^U y_j^U}{V_{i3} V_{j3}^*} \frac{(\epsilon_3^u)^2}{y_t^2}, \qquad (\delta_{RR}^d)_{ij} \sim \frac{y_i^D y_j^D}{V_{i3} V_{j3}^*} \frac{(\epsilon_3^u)^2}{y_t^2},$$

$$(\delta_{LR}^u)_{ij} \sim \frac{m_j^U A}{\tilde{m}_Q \tilde{m}_U} \frac{V_{i3}}{V_{j3}^*}, \qquad (\delta_{LR}^d)_{ij} \sim \frac{m_j^D A}{\tilde{m}_Q \tilde{m}_D} \frac{V_{i3}}{V_{j3}^*}.$$

- PC vs. $U(1)$: i) same parametric structure for $A_{U,D} \sim y^{U,D}$, ii) higher suppression in PC w.r.t. $U(1)$ for the LL and RR sectors.

Comparison of flavour models

	MFV	PC	$U(1)$	$\mathrm{FGM}_{U,D}+U(1)$	$\mathrm{FGM}_{U}+U(1)$
$(\delta^u_{LL})_{ij}$	$V_{i3}V^*_{j3}y_b^2$	$(\epsilon^q_3)^2 V_{i3}V^*_{j3}$	$\frac{V_{i3}}{V_{j3}}\big\vert_{i\leq j}$	$V_{i3}V^*_{j3}y_t^2$	$V_{i3}V^*_{j3}y_t^2$
$(\delta^d_{LL})_{ij}$	$V^*_{3i}V_{3j}y_t^2$	$(\epsilon^q_3)^2 V_{i3}V^*_{j3}$	$\frac{V_{i3}}{V_{j3}}\big\vert_{i\leq j}$	$V^*_{3i}V_{3j}y_t^2$	$V^*_{3i}V_{3j}y_t^2$
$(\delta^u_{RR})_{ij}$	$y^U_i y^U_j V_{i3}V^*_{j3}y_b^2$	$\frac{y^U_i y^U_j}{V_{i3}V^*_{j3}}\frac{(\epsilon^u_3)^2}{y_t^2}$	$\frac{y^U_i V_{j3}}{y^U_j V_{i3}}\big\vert_{i\leq j}$	$\frac{y^U_i y^U_j}{V_{i3}V^*_{j3}}$	$\frac{y^U_i y^U_j}{V_{i3}V^*_{j3}}$
$(\delta^d_{RR})_{ij}$	$y^D_i y^D_j V^*_{3i}V_{3j}y_t^2$	$\frac{y^D_i y^D_j}{V_{i3}V^*_{j3}}\frac{(\epsilon^u_3)^2}{y_t^2}$	$\frac{y^D_i V_{j3}}{y^D_j V_{i3}}\big\vert_{i\leq j}$	$\frac{y^D_i y^D_j}{V_{i3}V^*_{j3}}$	$y^D_i y^D_j V^*_{3i}V_{3j}y_t^2$
$(\delta^u_{LR})_{ij}$	$y^U_j V_{i3}V^*_{j3}y_b^2$	$y^U_j\frac{V_{i3}}{V^*_{j3}}$	$y^U_j\frac{V_{i3}}{V^*_{j3}}$	$y^U_j\frac{V_{i3}}{V^*_{j3}}$	$y^U_j\frac{V_{i3}}{V^*_{j3}}$
$(\delta^d_{LR})_{ij}$	$y^D_j V^*_{3i}V_{3j}y_t^2$	$y^D_j\frac{V_{i3}}{V^*_{j3}}$	$y^D_j\frac{V_{i3}}{V^*_{j3}}$	$y^D_j\frac{V^*_{3i}}{V_{3j}}y_b^2$	$y^D_j V^*_{3i}V_{3j}y_t^2$

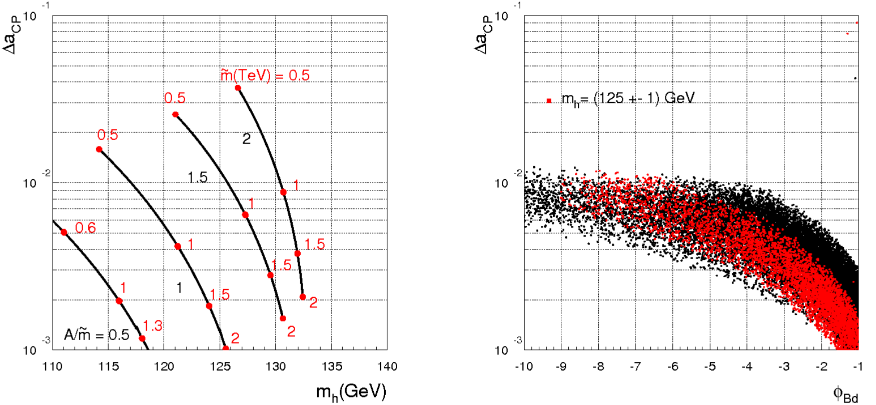
Table: Parametric suppression for mass insertions in various scenarios. $\mathrm{FGM}_{U,D}$ and $\mathrm{FGM}_U + U(1)$ stand for Flavored Gauge Mediation models [see the talk of R. Ziegler].

Comparison of flavour models

	MFV	PC	$U(1)$	$\mathrm{FGM}_{U,D}$	FGM_U	EXP.	OBS.
$\langle\delta^d\rangle^2_{12}$	$y_d y_s \lambda^{10}$	$\frac{y_d y_s}{g_\rho^2}$	$\frac{y_d}{y_s}$	$y_d y_s$	$y_d y_s \lambda^{10}$	7×10^{-8}	ϵ_K
$\langle\delta^u\rangle^2_{12}$	$y_u y_c \lambda^{10} y_b^4$	$\frac{y_u y_c}{g_\rho^2}$	$\frac{y_u}{y_c}$	$y_u y_c$	$y_u y_c$	1×10^{-5}	$\|q/p\|$, ϕ_D
$(\delta^u_{LR})_{12}$	$\frac{m_c A}{\tilde m^2}\lambda^5 y_b^2$	$\frac{m_c A}{\tilde m^2}\lambda$	$\frac{m_c A}{\tilde m^2}\lambda$	$\frac{m_c A}{\tilde m^2}\lambda$	$\frac{m_c A}{\tilde m^2}\lambda$	2×10^{-3}	Δa_{CP}
$(\delta^d_{LR})_{12}$	$\frac{m_s A}{\tilde m^2}\lambda^5$	$\frac{m_s A}{\tilde m^2}\lambda$	$\frac{m_s A}{\tilde m^2}\lambda$	$\frac{m_s A}{\tilde m^2}\lambda y_b^2$	$\frac{m_s A}{\tilde m^2}\lambda^5$	4×10^{-5}	ϵ'/ϵ
$(\delta^u_{LR})_{11}$	$\frac{m_u A}{\tilde m^2}$	$\frac{m_u A}{\tilde m^2}$	$\frac{m_u A}{\tilde m^2}$	$\frac{m_u A}{\tilde m^2}$	$\frac{m_u A}{\tilde m^2}$	4×10^{-6}	d_n
$(\delta^d_{LR})_{11}$	$\frac{m_d A}{\tilde m^2}$	$\frac{m_d A}{\tilde m^2}$	$\frac{m_d A}{\tilde m^2}$	$\frac{m_d A}{\tilde m^2} y_b^2$	$\frac{m_d A}{\tilde m^2}\lambda^6 y_b^2$	2×10^{-6}	d_n

Table: The bounds refer to $\tilde m = 1$ TeV and $\langle\delta^q\rangle^2_{12} \equiv (\delta^q_{LL})_{12}(\delta^q_{RR})_{12}$

MFV, PC & FGM models are much better under control than $U(1)$ or $U(2)$ flavour models. PC & FGM models provides also testable prediction.



$$\left(\delta^u_{12}\right)^{\rm eff}_{LR} \approx \frac{A m_t}{m_{\tilde{q}_3}} \left(\delta^u_{13}\right)_{LL} \left(\delta^u_{32}\right)_{RR} \approx \left(\frac{A}{3}\right) \frac{\left(\delta^u_{13}\right)_{LL}}{\lambda^3} \frac{\left(\delta^u_{32}\right)_{RR}}{\lambda} \left(\frac{\rm TeV}{m_{\tilde{q}_3}}\right) \times 10^{-3} ,$$

- Roboust prediction: $|\Delta a_{CP}| \sim 1\%$ implies a heavy Higgs boson and neutron EDM close to the current exp. bound.
- Less roboust (yet interesting) prediction: $|\Delta a_{CP}| \sim 1\%$ can improve the UT fit through a NP phase in B_d mixing

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**

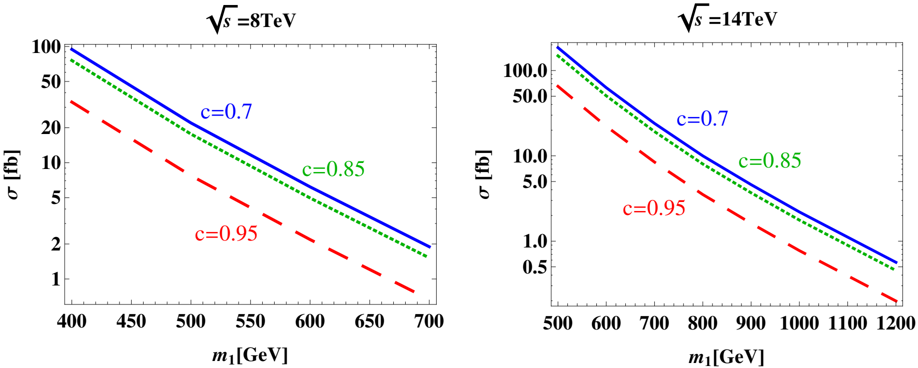
$$\frac{\Gamma(\tilde{g} \to \tilde{t} u_i)}{\Gamma(\tilde{g} \to \tilde{t} t)} = \left|(\delta^u_{i3})_{RR}\right|^2 \left[1 + O\left(\frac{m_t}{\tilde{m}_g}\right)\right].$$

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

Δa_{CP} vs. $t\bar{c}(c\bar{t}) + \not{E}_T$ signal at the LHC [Blanke, Giudice, P.P., Perez, & Zupan '13]



LO prediction for the $t\bar{c}(c\bar{t}) + \not{E}_T$ signal at the LHC from pair production of the flavour-mixed squark state with mass m_1, for $\sqrt{s} = 8$ TeV (left panel) and 14 TeV (right panel). Three different choices for the mixing angle $c = \cos\theta_R^{ct}$ are displayed: $c = 0.7$ (blue, solid), $c = 0.85$ (green, dotted), $c = 0.95$ (red, dashed).

$$\left|\Delta a_{CP}^{\mathrm{SUSY}}\right| \approx 0.6\% \left| \left(\frac{c_L^{ut} s_L^{ut}}{\lambda^3}\right) \left(\frac{m_t A_t/\tilde{m}_q^2}{0.1}\right) \left(\frac{c_R^{ct} s_R^{ct}}{\mathcal{O}(1)}\right) \right| \left(\frac{\mathrm{TeV}}{\tilde{m}}\right) .$$

[see the talk of M. Blanke]

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**

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

- **Effective Lagrangian**

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

- **Top FCNC decay widths**

$$\Gamma(t\to qZ) = \frac{\alpha_2}{32c_W^2}|g_Z^{qt}|^2\frac{m_t^3}{m_Z^2}\left(1-\frac{m_Z^2}{m_t^2}\right)^2\left(1+2\frac{m_Z^2}{m_t^2}\right),$$
$$\Gamma(t\to q\gamma) = \frac{\alpha}{4}|g_\gamma^{qt}|^2 m_t\,,$$
$$\Gamma(t\to qg) = \frac{\alpha_s}{3}|g_\gamma^{qt}|^2 m_t\,,$$
$$\Gamma(t\to qH) = \frac{m_t}{32\pi}|g_h^{qt}|^2\left(1-\frac{M_H^2}{m_t^2}\right)^2,$$

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

- **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**

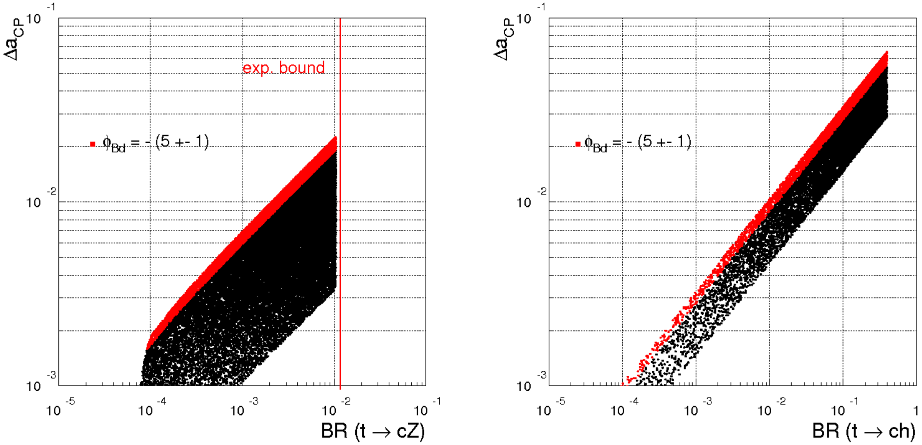
$$|d_n| \approx 3 \times 10^{-26} \left| \frac{{\rm Im}\left[(g_L^h)^*_{ut} (g_R^h)_{tu} \right]}{2 \times 10^{-7}} \right| \; e\,{\rm cm} \,,$$

- **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.

Conclusions

- It is quite plausible that new-physics contributions affect mostly the up 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].
- CP violation in D-meson systems (both CPV in the mixing and direct CPV) and also hadronic EDMs represent a unique probe of new-physics flavor effects, quite complementary to tests in K and B systems.
- Non-standard effects in charm physics can easily imply large effects in top FCNC decays, a large FB asymmetry in $t\bar{t}$ production [Hochberg & Nir, '11] or a a visible $t\bar{c}(c\bar{t}) + \not{E}_T$ signal within SUSY [Blanke et al, '13].
- From the model-builder side, the recent evidence of direct CPV in charm has stimulated new ideas and the construction of models departing in a controlled way from the MFV paradigm [Giudice, Isidori, P.P., '12; Rattazzi et al., '12; Calibbi, P.P., Ziegler, '13] which have a much broader (and hopefully testable) impact on low and high-p_T phenomenology.
- **The synergy of low-energy flavor data with the high-p_T part of the LHC program can still teach us a lot about the new physics at the TeV scale (if any) to be discovered with the upcoming 14 TeV LHC run.**