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On Partial Compositeness and the CP Asymmetry in Charm Decays

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based on 1205.5803, jointly with:

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Outline

- 0) The observed CPV in D decays
- 1) Partial Compositeness
- 2) Case of <u>Composite Higgs Models</u> with PC
- 3) Case of <u>Supersymmetry</u> with PC

0) The observed CPV in D decays
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2) Composite Higgs and PC
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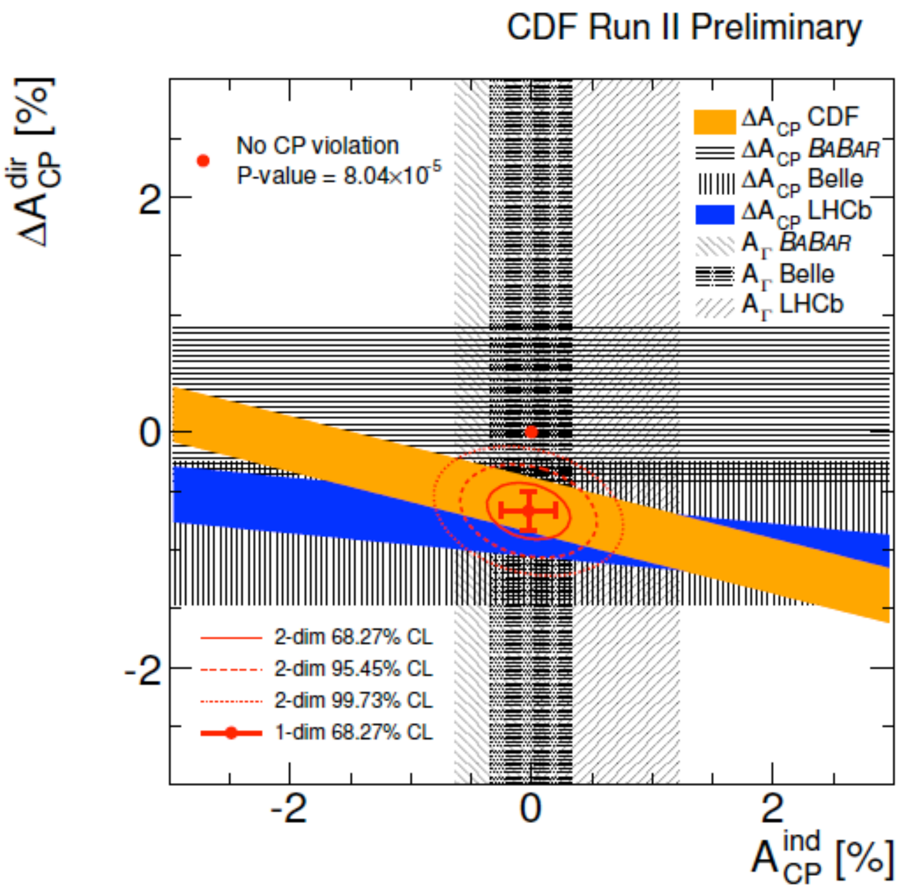
Starting point: direct CP-Violation in D decays



LHCb (November 2011) later confirmed by **CDF** (February 2012). World average:

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$
$$= (-0.67 \pm 0.16)\%$$

$$\left(A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)} \right)$$

Question: is it SM or BSM?

(see also Monday talk by J.Kamenik and today talks of F.Sala and R.Ziegler)

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.67 \pm 0.16)\%$$

Question: is it SM or BSM?

Answer: ?

- Size of SM effect can be estimated to be **0.1%**
[Grossman, Kagan, Nir 0609178]

- Enhancement of factor ~5 is **possible**
[Golden, Grinstein 1989],[Brod, Kagan, Zupan 1111.5000], [Brod, Grossman, Kagan, Zupan 1203.6659], [Franco, Mishima, Silvestrini 1203.3131]

- Interpretation in terms of NP is however **plausible**
[Isidori, Kamenik, Ligeti 1111.4987], [Giudice, Isidori, Paradisi 1202.6204], [Li, Lu, Yu 1203.3120], [Altmannshofer, Primulando, Yu, Yu 1202] etc...

→ Fair to say that:
Can be New Physics

- **Scope of this work**: assuming NP, need rationale for ΔF=1 vs ΔF=2.
→ Partial Compositeness natural possibility! We will study it *generically* both in Composite Higgs and Supersymmetric models.

brief intro to:

Partial Compositeness

(4D picture)

Original idea: [Kaplan, 1991]
For a modern discussion see e.g. [Contino et al 0612180]

- Elementary and composite sector mix through mass mixing:

$$\mathcal{L} = \mathcal{L}_{\text{elementary}} + \mathcal{L}_{\text{composite}} + \mathcal{L}_{\text{mixing}}$$

- SM fields are the light mass eigenstates:

$$|SM_n\rangle = \cos\varphi_n|\text{elementary}_n\rangle + \sin\varphi_n|\text{composite}_n\rangle$$

- "Degree of partial compositeness" = $\sin\varphi_n \equiv \epsilon_n$ (<< 1 for light fields)

Assuming coupling g_ρ (and mass scale m_ρ) in the composite sector, and totally composite Higgs:

$$(Y_u)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^u \qquad (Y_d)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^d \qquad (Y_e)_{ij} \sim g_\rho \epsilon_i^\ell \epsilon_j^e$$

" $\sim$ " ↔ typical size, up to O(1) coefficients

Diagonalization and CKM

- Yukawas are diagonalized through rotations:

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

where: $(L_u)_{ij} \sim (L_d)_{ij} \sim \min\left(\frac{\epsilon_i^q}{\epsilon_j^q}, \frac{\epsilon_j^q}{\epsilon_i^q}\right) \, , \qquad (R_{u,d})_{ij} \sim \min\left(\frac{\epsilon_i^{u,d}}{\epsilon_j^{u,d}}, \frac{\epsilon_j^{u,d}}{\epsilon_i^{u,d}}\right)$

- CKM matrix:

$$V_{CKM} = L_d^\dagger L_u \sim L_{u,d}$$

to naturally explain the size of quark mixings one needs:

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

(λ = Cabibbo angle)

⇒ everything is fixed up to 2 free parameters (e.g. g_ρ and ϵ_3^u)

Lepton sector

- If Dirac neutrinos and all analogous to the quark sector:

$$V_{PMNS} = L_e^\dagger L_\nu \quad \text{non hierarchical} \quad \Rightarrow \quad \epsilon_i^\ell/\epsilon_j^\ell \sim 1$$

- But smallness of neutrino masses suggests that they may have a different origin. If Majorana one can have bilinear:

$$Y_{ij} L_i L_j \mathcal{O}$$

⇒ neutrino mass matrix anarchic, ϵ_i^ν can be negligibly small

- In conclusion in the lepton sector $\epsilon_i^\ell/\epsilon_j^\ell$ are free parameters.

- We will make the most phenomenologically favorable choice:

$$\frac{\epsilon_i^\ell}{\epsilon_j^\ell} \sim \frac{\epsilon_i^e}{\epsilon_j^e} \sim \sqrt{\frac{m_i^e}{m_j^e}}$$

0) The observed CPV in D decays
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PC in Composite Higgs models

- Using NDA (see SILH [Giudice, Grojean, Pomarol, Rattazzi 0703164]):

$$\mathcal{L}_{\rm NDA} = \frac{m_\rho^4}{g_\rho^2}\left[\mathcal{L}^{(0)}\left(\frac{g_\rho \epsilon_i^a f_i^a}{m_\rho^{3/2}}, \frac{D_\mu}{m_\rho}, \frac{g_\rho H}{m_\rho}\right) + \frac{g_\rho^2}{16\pi^2}\mathcal{L}^{(1)}\left(\frac{g_\rho \epsilon_i^a f_i^a}{m_\rho^{3/2}}, \frac{D_\mu}{m_\rho}, \frac{g_\rho H}{m_\rho}\right) + \dots\right]$$

(+ fully "elementary" terms that respect flavor)

- Taking into account that dipoles come at 1 loop in tractable theories:

$$\mathcal{L}_{\Delta F=1} \sim \epsilon_i^a \epsilon_j^b g_\rho \frac{v}{m_\rho^2}\frac{g_\rho^2}{(4\pi)^2}\overline{f}_i^a \sigma_{\mu\nu} g_{\rm SM} F_{\rm SM}^{\mu\nu} f_j^b$$

$$+ \epsilon_i^a \epsilon_j^b \frac{g_\rho^2}{m_\rho^2}\overline{f}_i^a \gamma^\mu f_j^b i H^\dagger \overleftrightarrow{D}_\mu H$$

$$\mathcal{L}_{\Delta F=2} \sim \epsilon_i^a \epsilon_j^b \epsilon_k^c \epsilon_l^d \frac{g_\rho^2}{m_\rho^2}\overline{f}_i^a \gamma^\mu f_j^b \overline{f}_k^c \gamma_\mu f_l^d$$

(• Higgs mediated FCNC: we assume Higgs is PNGB, and the problem is avoided as in [Agashe, Contino 0906.1542] ~~$\overline{f}_i^a H f_j^b H^\dagger H$~~)

PC in Composite Higgs models

- Since the effect we look for comes from a dipole, we redefine:

$$\Lambda = \frac{4\pi}{g_\rho} m_\rho$$

$$\begin{aligned}
\mathcal{L}_{\Delta F=1} &= \epsilon_i^a \epsilon_j^b g_\rho v \frac{c^{ab}_{ij,g_{SM}}}{\Lambda^2} \overline{f}^a_i \sigma_{\mu\nu} g_{SM} F^{\mu\nu}_{SM} f^b_j \\
&+ \epsilon_i^a \epsilon_j^b g_\rho^2 \frac{(4\pi)^2}{g_\rho^2} \frac{c^{ab}_{ij}}{\Lambda^2} \overline{f}^a_i \gamma^\mu f^b_j \, iH^\dagger \overleftrightarrow{D}_\mu H \\
\mathcal{L}_{\Delta F=2} &= \epsilon_i^a \epsilon_j^b \epsilon_k^c \epsilon_l^d g_\rho^2 \frac{(4\pi)^2}{g_\rho^2} \frac{c^{abcd}_{ijkl}}{\Lambda^2} \overline{f}^a_i \gamma^\mu f^b_j \overline{f}^c_k \gamma_\mu f^d_l
\end{aligned}$$

- For ΔF=2, clearly better to have $g_\rho \sim 4\pi$

- To account for Δa_{CP}, using the results of [1111.4987] and [1201.6204]:

$$\overline{u_L} \sigma^{\mu\nu} g_s G_{\mu\nu} c_R$$

$$\Lambda = 10\ \mathrm{TeV}, \quad \mathrm{Im}(c^{qu}_{12,g}) \sim 1$$

Finetuning: between % and ‰

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$$\Lambda = 10 \text{ TeV}, \quad \text{Im}(c^{qu}_{12,g}) \sim 1$$

Other Flavor observables: quark sector

Operator $\Delta F = 2$	$\text{Re}(c) \times (4\pi/g_\rho)^2$	$\text{Im}(c) \times (4\pi/g_\rho)^2$	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	$6 \times 10^2 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	$2 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	Δm_K; ϵ_K
$(\bar{s}_R d_L)^2$	500	2	"
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	2×10^2	0.6	"
Operator $\Delta F = 1$	**$\text{Re}(c)$**	**$\text{Im}(c)$**	**Observables**
$\overline{s_R} \sigma^{\mu\nu} e F_{\mu\nu} b_L$	1		$B \to X_s$
$\overline{s_L} \sigma^{\mu\nu} e F_{\mu\nu} b_R$	2	9	"
$\overline{s_R} \sigma^{\mu\nu} g_s G_{\mu\nu} d_L$	-	0.4	$K \to 2\pi$; ϵ'/ϵ
$\overline{s_L} \sigma^{\mu\nu} g_s G_{\mu\nu} d_R$	-	0.4	"
$\bar{s}_L \gamma^\mu b_L\, H^\dagger i \overleftrightarrow{D}_\mu H$	$30 \left(\frac{g_\rho}{4\pi}\right)^2 (\epsilon_3^u)^2$		$B_s \to \mu^+\mu^-$
$\bar{s}_L \gamma^\mu b_L\, H^\dagger i \overleftrightarrow{D}_\mu H$	$6 \left(\frac{g_\rho}{4\pi}\right)^2 (\epsilon_3^u)^2$	$10 \left(\frac{g_\rho}{4\pi}\right)^2 (\epsilon_3^u)^2$	$B \to X_s \ell^+\ell^-$
Operator $\Delta F = 0$	**$\text{Re}(c)$**	**$\text{Im}(c)$**	**Observables**
$\overline{d} \sigma^{\mu\nu} e F_{\mu\nu} d_{L,R}$	-	3×10^{-2}	neutron EDM
$\overline{u} \sigma^{\mu\nu} e F_{\mu\nu} u_{L,R}$	-	0.3	"
$\overline{d} \sigma^{\mu\nu} g_s G_{\mu\nu} d_{L,R}$	-	4×10^{-2}	"
$\overline{u} \sigma^{\mu\nu} g_s G_{\mu\nu} u_{L,R}$	-	0.2	"

- Marginally compatible with bounds in quark sector. Some new effects around the corner
- Most robust expectation: new physics contribution to the neutron EDM

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Other Flavor observables: lepton sector

Leptonic Operator	Re(c)	Im(c)	Observables
$\bar{e}\sigma^{\mu\nu}eF_{\mu\nu}e_{L,R}$	-	8 x 10 $^{-3}$	electron EDM
$\bar{\mu}\sigma^{\mu\nu}eF_{\mu\nu}e_{L,R}$	4×10^{-3}		$\mu \to e\gamma$
$\bar{e}\gamma^{\mu}\mu_{L,R}\, H^{\dagger} i \overleftrightarrow{D}_{\mu} H$	$1.5 \left(\frac{g_\rho}{4\pi}\right) \frac{\epsilon_3^e}{\epsilon_3^\ell}$		$\mu(Au) \to e(Au)$

In conclusion:

- Marginally compatible with bounds in quark sector. Some new effects should be around the corner, especially neutron EDM.

- Lepton flavor and CP violation too large by a factor ~200.
  → need additional assumptions in a concrete model

- $K^+ \to \pi^+ \bar{\nu}\nu$ will be measured at 10% of SM prediction by NA62.
  Visible effects can be naturally there in this framework, provided:

$$c^{qq}_{12/21} \gtrsim 1.8\, (\epsilon_3^u)^2 \left(\frac{g_\rho}{4\pi}\right)^2$$

$$\left(\epsilon_i^a \epsilon_j^b \frac{(4\pi)^2}{\Lambda^2} c_{ij}^{ab}\, \overline{f}_i^a \gamma^\mu f_j^b\, J_\mu^{(Z)} \right)$$

Supersymmetry and PC

See also [Nomura,Papucci,Stolarski 2007-2008],[Dudas et al 1007.5208]

- Assume flavor scale $m_\rho \equiv \Lambda_F$ is lower than mediation scale, contrary to usual gauge mediation

Λ_{SUSY}

- Invoke at Λ_S a mechanism like gauge mediation, that ensures flavor universality of soft terms in the light sector

Λ_{Flavor}

- Yukawas are generated by linear couplings $\lambda_i^a f_i^a \mathcal{O}_i^a$

- From running and from integrating out the heavy fields, below m_ρ universality will be of the form: $\delta_{ij} + O(1)\,\epsilon_i\epsilon_j$

$$\begin{aligned}(m_q^2)_{ij} &\sim \tilde{m}_q^2\delta_{ij} + \epsilon_i^q\epsilon_j^q\tilde{m}_0^2 \\ (m_{u,d}^2)_{ij} &\sim \tilde{m}_{u,d}^2\delta_{ij} + \epsilon_i^{u,d}\epsilon_j^{u,d}\tilde{m}_0^2 \\ A_{ij}^{u,d} &\sim g_\rho\epsilon_i^q\epsilon_j^{u,d}A_0,\end{aligned}$$

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

<u>Without exact proportionality!</u>
"disoriented A-terms"
[Giudice,Isidori,Paradisi 1201.6204]

- Diagonalizing and using mass insertion approximation:

$$(\delta^{u,d}_{ij})_{LL} = (c^{u,d}_{ij})_{LL} \times \frac{\tilde{m}_0^2}{\tilde{m}^2}\,\epsilon^q_i \epsilon^q_j, \qquad (\delta^{u,d}_{ij})_{RR} = (c^{u,d}_{ij})_{RR} \times \frac{\tilde{m}_0^2}{\tilde{m}^2}\,\epsilon^{u,d}_i \epsilon^{u,d}_j,$$

$$(\delta^{u,d}_{ij})_{LR} = (c^{u,d}_{ij})_{LR} \times \; g_\rho\, \epsilon^q_i \epsilon^{u,d}_j \frac{v_{u,d}\, A_0}{\tilde{m}^2}, \qquad (\delta^{u,d}_{ij})_{RL} = (c^{u,d}_{ij})_{RL} \times \; g_\rho\, \epsilon^{u,d}_i \epsilon^q_j \frac{v_{u,d}\, A_0}{\tilde{m}^2}$$

- For simplicity (but not necessary): $\tilde{m}^2_{q,u,d} \sim \tilde{m}^2_{\ell,e} \sim \tilde{m}^2$

- Charm CP asymmetry needs:

$$\mathrm{Im}(c^u_{12})_{LR} \times \frac{A_0}{\tilde{m}} \times \left(\frac{1\ \mathrm{TeV}}{\tilde{m}}\right) \sim 8$$

We chose: $\tilde{m} \sim \tilde{m}_0 \sim 1\ \mathrm{TeV}$ and $A_0/\tilde{m} = 2$
(this means that we assume a mild enhancement $\mathrm{Im}(c^u_{12})_{LR} \sim$ 3-4)

Bounds from color breaking (stability):

$A_0/\tilde{m} < 3$ $\qquad (c^u_{12})_{LR} \times \frac{A_0}{\tilde{m}} < 15$

[Frere et al 1983]
[Alvarez-Gaume et al 1983]

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Parenthesis: R-Parity violation

$$W_{\not{B}} = \frac{1}{2}\lambda''_{ijk} u_i d_j d_k,$$
$$W_{\not{L}} = \frac{1}{2}\lambda_{ijk} L_i L_j e_k + \lambda'_{ijk} L_i Q_j d_k + \mu_i L_i H_u$$

- PC has natural suppression mechanism:

$$\lambda''_{ijk} \sim 2 g_{\not{B}} \epsilon_i^u \epsilon_j^d \epsilon_k^d \qquad \lambda_{ijk} \sim 2 g_{\not{L}} \epsilon_i^\ell \epsilon_j^\ell \epsilon_k^e \qquad \lambda'_{ijk} \sim g_{\not{L}} \epsilon_i^\ell \epsilon_j^q \epsilon_k^d \qquad \mu_i \sim \frac{g_{\not{L}}}{g_\rho} \epsilon_i^\ell \mu$$

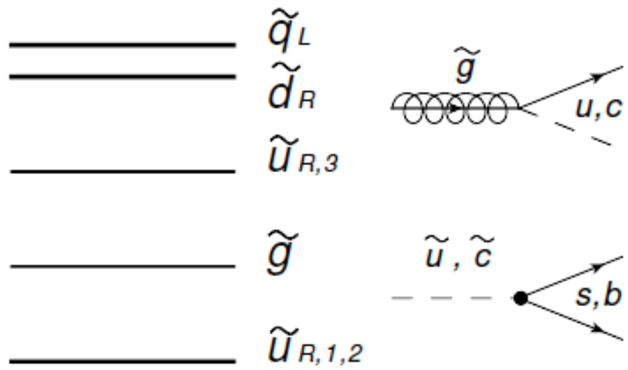
- From proton decay to $\pi^0 \ell^+$:

$$\epsilon_3^\ell (\epsilon_3^u)^3 \left(\frac{g_{\not{B}} g_{\not{L}}}{g_\rho^2}\right) \left(\frac{g_\rho}{4\pi}\right) \frac{\tan^2\beta}{\cos\beta} \lesssim 10^{-15} \left(\frac{\tilde{m}}{1\ \mathrm{TeV}}\right)^2$$

→ must assume L-conservation (also for ν-χ mixing)

- Collider Phenomenology: for example
  - can avoid multilepton signal (evade bound of [Allanach, Gripaios 1202.6616])
  - gg → 6j final state, no MET nor displaced vertex
  - bound from LSP pair production ~ 400 GeV

($pp \to \tilde{u}_i \tilde{u}_i^*, \tilde{u}_i \tilde{u}_i, \tilde{u}_i^* \tilde{u}_i^* \to 4j$ CMS, dijet resonances)



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Flavor bounds in the Supersymmetric case:

Coefficient	Upper bound	Observables
$(c^d_{13})_{LL}$	$20\left(\frac{1}{\epsilon^q_3}\right)^2$	$\Delta m_{B_d};\ S_{\psi K_S}$
$(c^d_{23})_{LL}$	$10\left(\frac{1}{\epsilon^q_3}\right)^2$	$B \to X_s\gamma$
$\sqrt{(c^u_{12})_{LL}(c^u_{12})_{RR}}$	$60\ g_\rho$	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$\sqrt{(c^d_{12})_{LL}(c^d_{12})_{RR}}$	$30\left(\frac{g_\rho}{t_\beta}\right)$	$\Delta m_K;\ \epsilon_K$
$\sqrt{(c^d_{13})_{LL}(c^d_{13})_{RR}}$	$100\left(\frac{g_\rho}{t_\beta}\right)$	$\Delta m_{B_d};\ S_{\psi K_S}$
$\sqrt{(c^d_{23})_{LL}(c^d_{23})_{RR}}$	$100\left(\frac{g_\rho}{t_\beta}\right)$	Δm_{B_s}
$(c^u_{12})_{LR}$	90	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(c^d_{12})_{LR}$	2	ϵ'/ϵ
$(c^d_{12})_{RL}$	2	ϵ'/ϵ
$(c^d_{13})_{RL}$	200	$\Delta m_{B_d};\ S_{\psi K_S}$
$(c^d_{23})_{LR}$	20	$B \to X_s\gamma$
$(c^d_{23})_{RL}$	8	$B \to X_s\gamma$
$(c^u_{11})_{LR}$	0.4	EDMs
$(c^d_{11})_{LR}$	0.09	EDMs
$(c^e_{12})_{LR,RL}$	0.6	$\mu \to e\gamma$
$(c^e_{11})_{LR}$	0.5	electron EDM

- As in CHM, quark flavor violation is under control.
- Again, robust expectation is neutron EDM aroud the corner
- Lepton sector: much improved! Reason: bino instead of gluino.
Suppression needed:
$1/200 \quad \to \quad 1/6$
ok if sleptons at 2-3 TeV
- Expect now effects also in $\mu \to e\gamma$ and electron EDM

Conclusions

- Flavor structure of Partial Compositeness can naturally explain the observed CP asymmetry in D decays
- Expectations: contributions around the present sensitivity to ϵ_K, ϵ'/ϵ and especially **neutron EDM**
- In Composite Higgs case, problems with Lepton FV
- In Supersymmetric case, LFV is ok and expect NP around the corner also in $\mu \to e\gamma$ and **electron EDM**. RPV is very motivated and can distort LHC phenomenology / evade bounds
- NP effects at level of 10% of SM value (future sensitivity of NA62) are naturally possible in $K \to \pi \nu \bar{\nu}$.
- Observable that may confirm BSM physics in dipole operators: **CPA in radiative D decays** [Isidori,Kamenik 1205.3164]

Backup

EWPT

$$\mathcal{L}_{\rm EWPT} \supset c_S \frac{g g'}{m_\rho^2} H^\dagger W_{\mu\nu} H B^{\mu\nu} + c_T \frac{g_\rho^2}{m_\rho^2} |H^\dagger D_\mu H|^2$$

$$\hat{S} = c_S \frac{m_W^2}{m_\rho^2} = 6.4 \times 10^{-5} c_S \left(\frac{10\ \text{TeV}}{\Lambda}\right)^2 \left(\frac{4\pi}{g_\rho}\right)^2$$

$$\hat{T} = -c_T \frac{g_\rho^2 v^2}{m_\rho^2} = -4.8 \times 10^{-2} c_T \left(\frac{10\ \text{TeV}}{\Lambda}\right)^2 .$$

→ need to assume that the strong sector respects custodial symmetry. In this case one finds $\epsilon_3^{u(q)} \lesssim 0.2\text{-}0.4$

$$\mathcal{L}_{\rm EWPT} \supset c_{H1} \bar{q}_{3L} \gamma^\mu q_{3L}\, i H^\dagger \overleftrightarrow{D}_\mu H$$

$$\left|\frac{\delta g_{b_L}}{g_{b_L}}\right| = 2|c_{H1}|(\epsilon_3^q)^2 (4\pi)^2 \frac{v^2}{\Lambda^2} \lesssim 0.25\%$$

$\epsilon_3^q \lesssim 0.15$

Top FCNC

$$\mathcal{O}^t_{H1} = \bar{q}_{iL}\gamma^\mu q_{3L}\, iH^\dagger \overleftrightarrow{D}_\mu H \qquad \mathcal{O}^t_{H2} = \bar{q}_{iL}\gamma^\mu \tau^a q_{3L}\, iH^\dagger \tau^a \overleftrightarrow{D}_\mu H$$

$$\mathcal{O}^t_{H3} = \bar{u}_{iR}\gamma^\mu u_{3R}\, iH^\dagger \overleftrightarrow{D}_\mu H$$

$$\sum_I \frac{c_I}{m_\rho^2}\mathcal{O}^t_I \equiv \frac{g}{2\cos\theta_w} Z_\mu\, \bar{u}_i (g_Z^{iL} P_L + g_Z^{iR} P_R)\gamma^\mu t$$

Where, for $i=1,2$: $g_Z^L = (-c_{H1} + c_{H2})\frac{2v^2}{m_\rho^2}, \qquad g_Z^R = -c_{H3}\frac{2v^2}{m_\rho^2}$

$$c_{H1(2)} \sim g_\rho^2 \epsilon_i^q \epsilon_3^q, \qquad c_{H3} \sim g_\rho^2 \epsilon_i^u \epsilon_3^u$$

$$BR(t \to cZ) \sim 2 \cdot 10^{-5} \left(\frac{10\ \text{TeV}}{\Lambda}\right)^4 (\epsilon_3^u)^4$$

Difficult to see at the LHC (sensitivity 10^{-4}), unless there is a mild enhancement. Negligible $t \to c\gamma$.

Structure of FV operators in Supersymmetric case

$$\mathcal{L}_{\Delta F=1} \sim \epsilon_i^a \epsilon_j^b g_\rho v \frac{1}{\Lambda^2} \overline{f}_i^a \sigma_{\mu\nu} g_{\rm SM} F_{\rm SM}^{\mu\nu} f_j^b$$

$$+ \epsilon_i^a \epsilon_j^b g_\rho^2 \frac{g_{\rm SM}^2}{g_\rho^2} \frac{1}{\Lambda^2} \overline{f}_i^a \gamma^\mu f_j^b i H^\dagger \overleftrightarrow{D}_\mu H$$

$$\mathcal{L}_{\Delta F=2} \sim \epsilon_i^a \epsilon_j^b \epsilon_k^c \epsilon_l^d g_\rho^2 \frac{g_{\rm SM}^2}{g_\rho^2} \frac{1}{\Lambda^2} \overline{f}_i^a \gamma^\mu f_j^b \overline{f}_k^c \gamma_\mu f_l^d$$

But now: $\Lambda = 4\pi \tilde{m}/g_{\rm SM}$

⇒ As CH case, with: $4\pi/g_\rho \to g_{\rm SM}/g_\rho$

Other bounds on RPV couplings

- Other bounds on B-violating coupling:

$$(\epsilon_3^u)^3 \left(\frac{g_{\not B}}{4\pi}\right) \tan^2\beta \lesssim 30 \left(\frac{150\ \mathrm{MeV}}{\tilde\Lambda}\right)^{5/2} \left(\frac{\tilde m}{1\ \mathrm{TeV}}\right)^{5/2} \qquad (pp \to K^+K^+)$$

$$(\epsilon_3^u)^3 \left(\frac{g_{\not B}}{4\pi}\right) \tan^2\beta \lesssim 5\times 10^{-8} \left(\frac{\tilde m}{1\ \mathrm{TeV}}\right)^{2} \frac{m_{3/2}}{1\ \mathrm{eV}} \qquad (p \to K^+\tilde G)$$

$$M_{\rm mess} \sim g_X \frac{\alpha}{4\pi} \frac{m_{3/2} M_P}{\tilde m} \gtrsim 10^{13}\ \mathrm{GeV} \left(\frac{1\ \mathrm{TeV}}{\tilde m}\right) g_X$$

→ reduced parameter space for gauge mediation

- Main bound on L-violating coupling (χ-ν mixing):

$$\left(\frac{g_{\not L}}{g_\rho}\right)^2 (\epsilon_3^\ell)^2 \lesssim 10^{-12} \left(\frac{\tilde m}{1\ \mathrm{TeV}}\right) \frac{1}{\cos^2\beta} \qquad (m_\nu < 1\ \mathrm{eV}).$$

L-violation must be small in any case

Size of RPV couplings

$$\lambda''_{ijk} \sim \left(\frac{g_{\not B}}{4\pi}\right)\left(\frac{\tan\beta}{3}\right)^2\left(\frac{\epsilon_3^u}{0.5}\right)^3 (\equiv \lambda_0) \times \begin{cases} 2.7\times 10^{-3} & (tbs) \\ 0.6\times 10^{-3} & (tbd) \\ 1.7\times 10^{-4} & (cbs) \\ 0.5\times 10^{-4} & (cbd) \\ 1.7\times 10^{-6} & (ubs) \\ 0.4\times 10^{-6} & (ubd) \end{cases}$$

A bit larger than in MFV [Csaki, Grossman, Heidenreich 1111.1239]

	$s\,b$	$b\,d$	$d\,s$
u	5×10^{-7}	6×10^{-9}	3×10^{-12}
c	4×10^{-5}	1.2×10^{-5}	1.2×10^{-8}
t	2×10^{-4}	6×10^{-5}	4×10^{-5}

$\tan\beta = 45$

LSP decay

- Decay of LSP into superpartner plus gravitino:

$$\Gamma_{\tilde{G}} \sim \frac{m_{LSP}^5}{8\pi m_{\tilde{G}}^2 M_P^2} \quad \Rightarrow \quad \tau_{LSP} = 3 \cdot 10^{10}\,\mathrm{m} \left(\frac{300\,\mathrm{GeV}}{m_{LSP}}\right)^5 \left(\frac{m_{\tilde{G}}}{1\,\mathrm{GeV}}\right)^2$$

- Neutralino-chargino and slepton LSP easily leads to displaced vertex:

(β = LSP velocity in lab frame)

(3b) $$\tau_{\chi-LSP} = 0.1\,\mathrm{mm}\frac{\beta}{\sqrt{1-\beta^2}}\left(\frac{150\,\mathrm{GeV}}{m_{LSP}}\right)^5\left(\frac{\tilde{m}}{500\,\mathrm{GeV}}\right)^4\lambda_0^{-2}$$

(4b) $$\tau_{\tilde{\ell}-LSP} = 0.02\,\mathrm{mm}\frac{\beta}{\sqrt{1-\beta^2}}\left(\frac{300\,\mathrm{GeV}}{m_{LSP}}\right)^7\left(\frac{\tilde{m}}{500\,\mathrm{GeV}}\right)^6\lambda_0^{-2}$$

(additional isolated leptons)

- Squark LSP decays promptly:

(2b) $$\tau_{\tilde{b}_L-LSP} = 0.03\,\mu\mathrm{m}\frac{\beta}{\sqrt{1-\beta^2}}\left(\frac{400\,\mathrm{GeV}}{m_{LSP}}\right)\left(\frac{7.5\cdot 10^{-3}}{\theta_{LR}^{\tilde{b}}}\right)^2\lambda_0^{-2}$$

($\theta_{LR}^{\tilde{b}} \sim m_b A_0/\tilde{m}^2$)

(4b) $$\tau_{\tilde{q}_L-LSP} = 4\,\mu\mathrm{m}\frac{\beta}{\sqrt{1-\beta^2}}\left(\frac{400\,\mathrm{GeV}}{m_{LSP}}\right)^7\left(\frac{\tilde{m}}{1\,\mathrm{TeV}}\right)^6\lambda_0^{-2}$$

(2b) $$\tau_{u_R(c_R)-LSP} = 4\,\mu\mathrm{m}(0.3\,\mathrm{nm})\frac{\beta}{\sqrt{1-\beta^2}}\left(\frac{400\,\mathrm{GeV}}{m_{LSP}}\right)\lambda_0^{-2}$$