Up-type flavor violation

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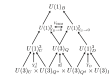
Indirect Searches for NP @ the time of LHC

Outline

- Brief Intro', the importance of uFCNC measurements.
- $D - \bar{D}$ mixing, data & the SM.
- Generic & model independent bounds, covariant formalism.
- Some model dependent info'.
- Third generation, covariant, flavor violation & the LHC.
- Conclusions / outlook.

Why Up ?

- SM way to induce flavor conversion & CPV is unique. 

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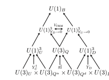
- SM way to induce flavor conversion & CPV is unique. 

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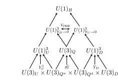
- SM way to induce flavor conversion & CPV is unique. 

- Absence of observed deviation from SM predictions implies severe bound on new physics (NP).

- Most of precise information involves K, B mesons, linked to down type FCNC.

- Most severe hierarchy problem is induced by the top sector, which is indeed extended in most of natural NP models.

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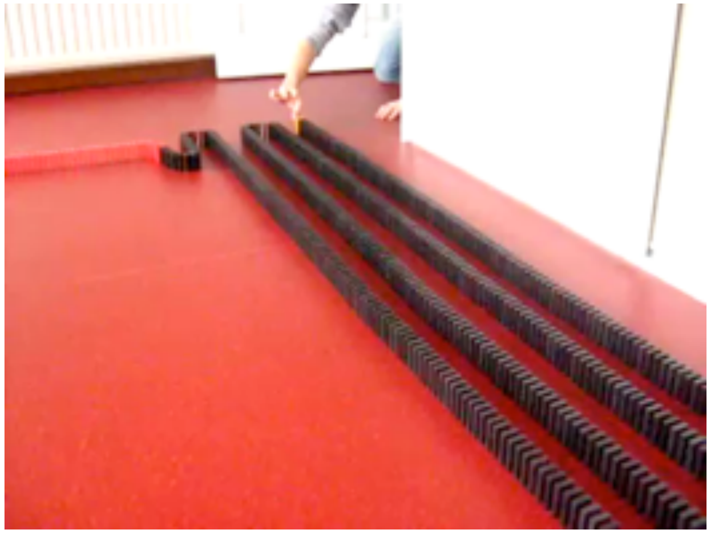

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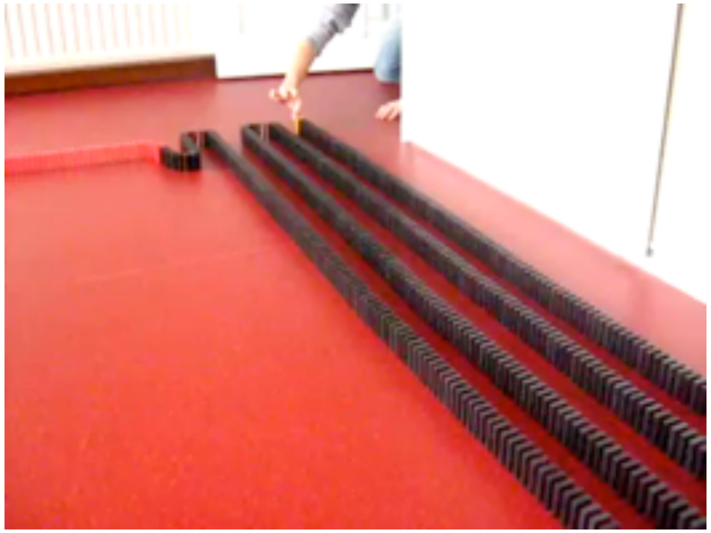

careful domino *alignment*

Up sector

Look Down

Look Up

$D^0 - \bar{D}^0$ *Mixing*

δ

Δ

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BABAR

BELLE

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- System parameters roughly determined (HFAG):

$$\begin{aligned} x &= (1.00 \pm 0.25) \times 10^{-2}, \\ y &= (0.77 \pm 0.18) \times 10^{-2}, \\ 1 - |q/p| &= +0.06 \pm 0.14, \\ \phi &= -0.05 \pm 0.09, \end{aligned}$$

$$m \equiv \frac{m_1 + m_2}{2}, \qquad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2},$$
$$x \equiv \frac{m_2 - m_1}{\Gamma}, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}.$$

Absence of D CPV - Another SM Victory

SM: D system is controlled by 2 gen' physics $\Rightarrow$ CP conserving

Bottom contribution is down by:

$$\mathcal{O}\left(\frac{m_c^2}{m_b^2} \times \frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*}\right) = 10^{-4}$$

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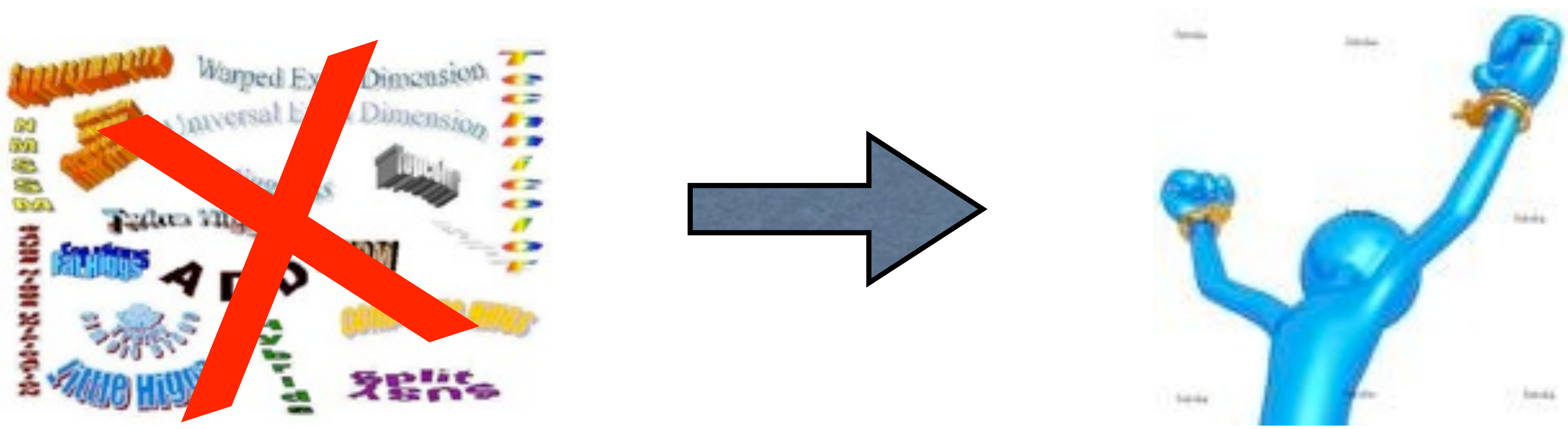
If x is due to NP then it missed a chance to revealed itself in $\mathcal{O}(1)$ CPV.

What do we know about the NP flavor sector, model independently?



$\Delta F = 2$ status

Isidori, Nir, GP (10)

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D-system falls only behind the K-one

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t-FCNC
stay
tuned!

D-system fall ind the K-one

The power of CPV in the D system

Assuming no direct CP: [Golowich, Pakvasa & Petrov (07); Kagan and M. D. Sokolof (09)]

$$y_{12} \equiv |\Gamma_{12}|/\Gamma, \qquad x_{12} \equiv 2|M_{12}|/\Gamma, \qquad \phi_{12} \equiv \arg(M_{12}/\Gamma_{12}).$$

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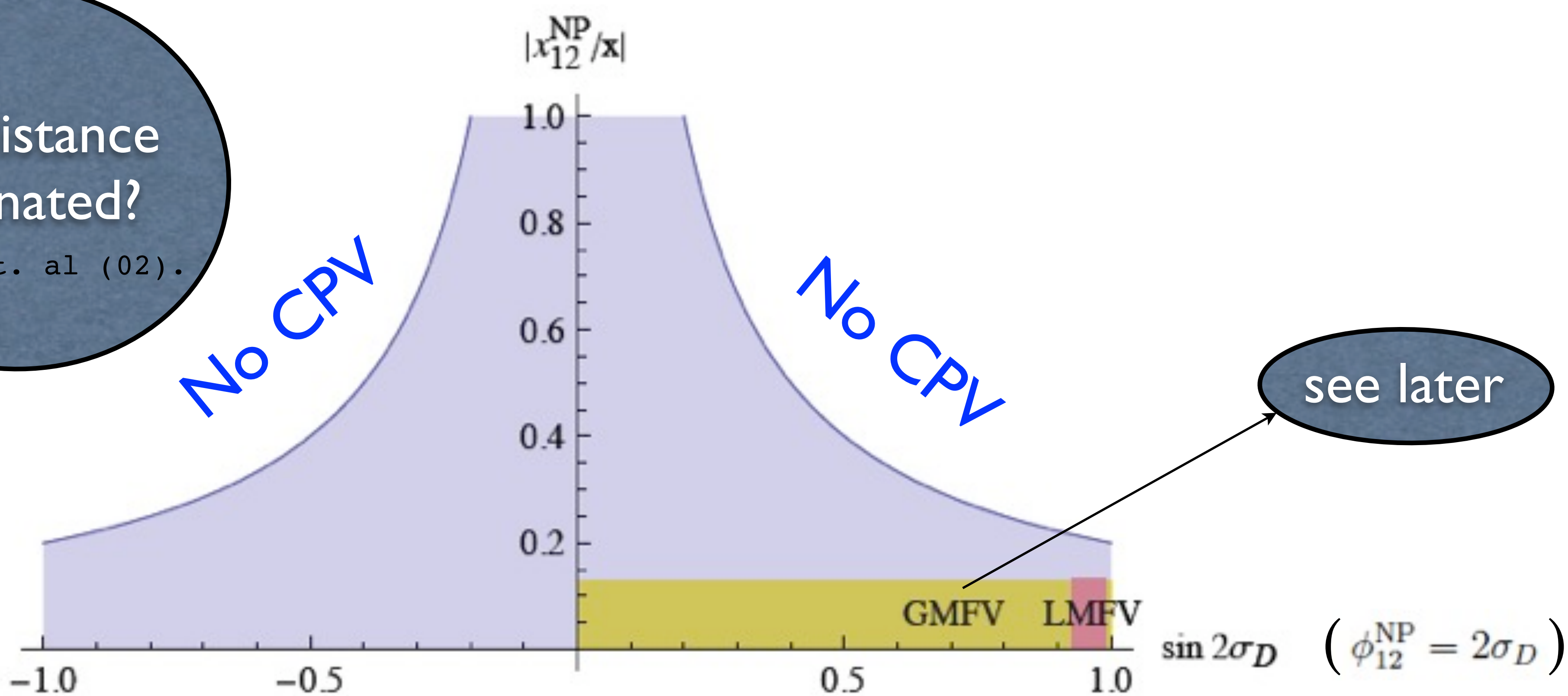

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u-FCNC data remove immunities!

2-gen' effective theory for $\Delta F = 2$

Robust model independent bounds:

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[More info' in Δc=1, Golowich, et. al (09), Kagan & Sokolof (09)]

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(i) robust *(ii) LLRR* - stronger, but model dependent.

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[More info' in Δc=1, Golowich, et. al (09), Kagan & Sokolof (09)]

Combining $K^0 - \overline{K^0}$ & $D^0 - \overline{D^0}$ mixings

- Powerful model indep' bound.

$$\frac{1}{\Lambda_{\rm NP}^2}\left[z_1^K(\overline{d_L}\gamma_\mu s_L)(\overline{d_L}\gamma^\mu s_L) + z_1^D(\overline{u_L}\gamma_\mu c_L)(\overline{u_L}\gamma^\mu c_L) + z_4^D(\overline{u_L}c_R)(\overline{u_R}c_L)\right].$$

no CPV $\longleftrightarrow$

$$|z_1^K| \le z_{\rm exp}^K = \boxed{8.8\times10^{-7}}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

$$|z_1^D| \le z_{\rm exp}^D = \boxed{5.9\times10^{-7}}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

with CPV $\longleftrightarrow$

$$\mathcal{I}m(z_1^K) \le z_{\rm exp}^{IK} = \boxed{3.3\times10^{-9}}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

$$\mathcal{I}m(z_1^D) \le z_{\rm exp}^{ID} = \boxed{1.0\times10^{-7}}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

Two gen' flavor structure (no CPV)

When effects of $SU(2)_L$ breaking are small, the terms that lead to z_1^K and z_1^D have the form

$$\frac{1}{\Lambda_{\rm NP}^2}(\overline{Q_{Li}}(X_Q)_{ij}\gamma_\mu Q_{Lj})(\overline{Q_{Li}}(X_Q)_{ij}\gamma^\mu Q_{Lj}),$$

One cannot eliminate the constraint from K & D systems simultaneously! Nir (07); Blum et. al. (09).

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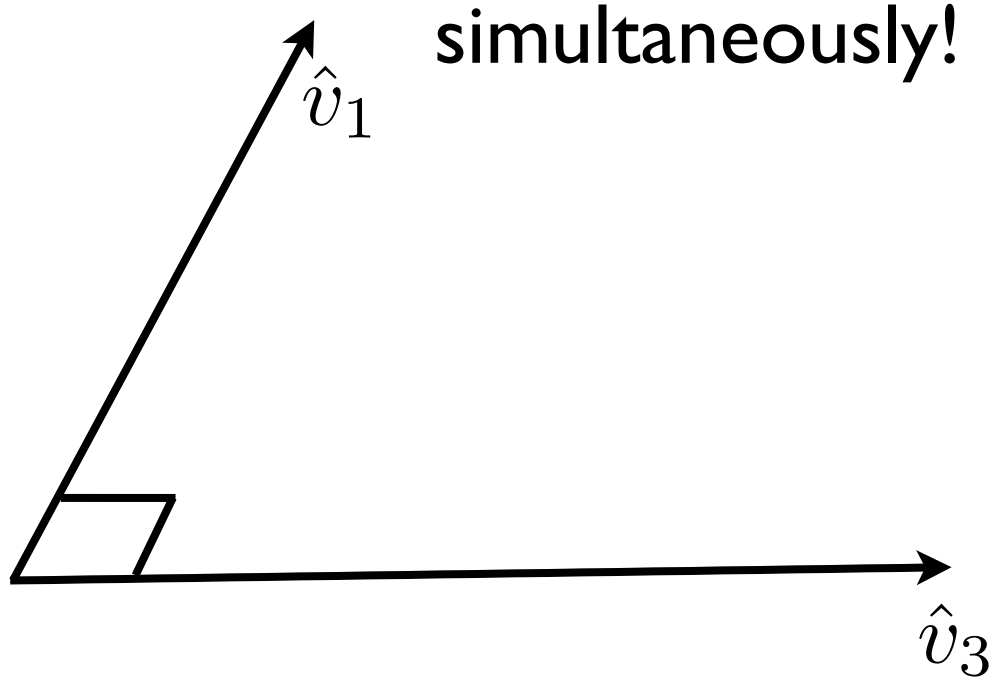

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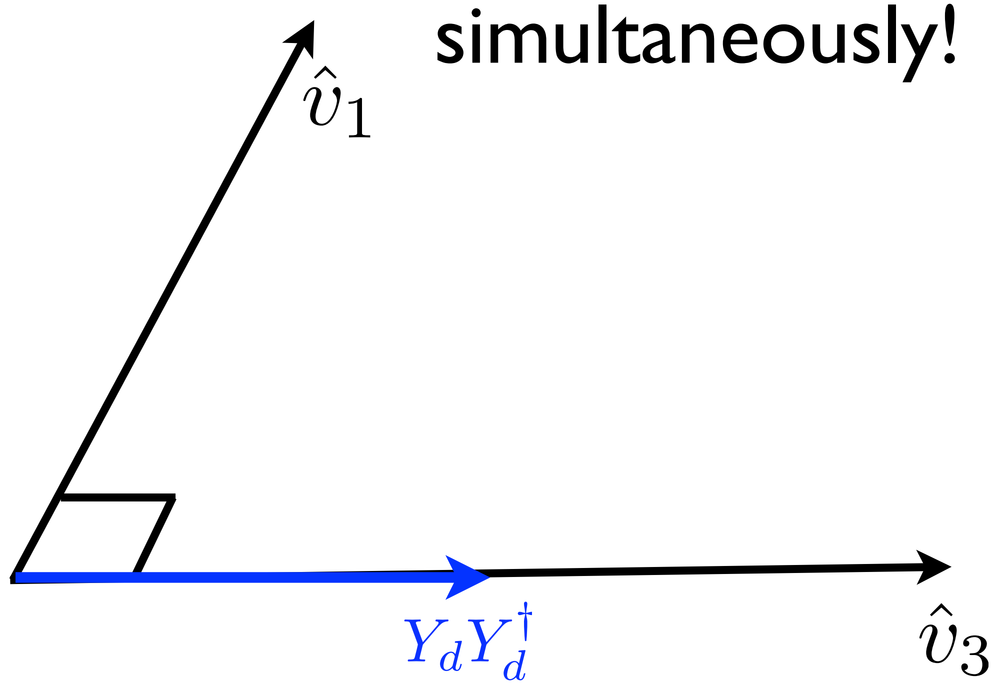

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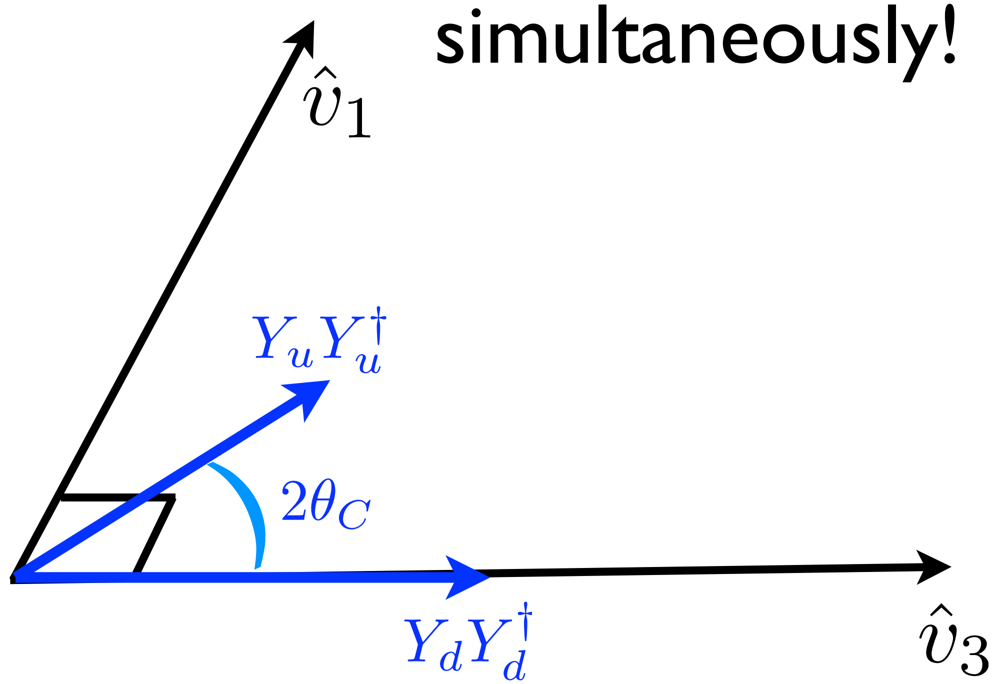

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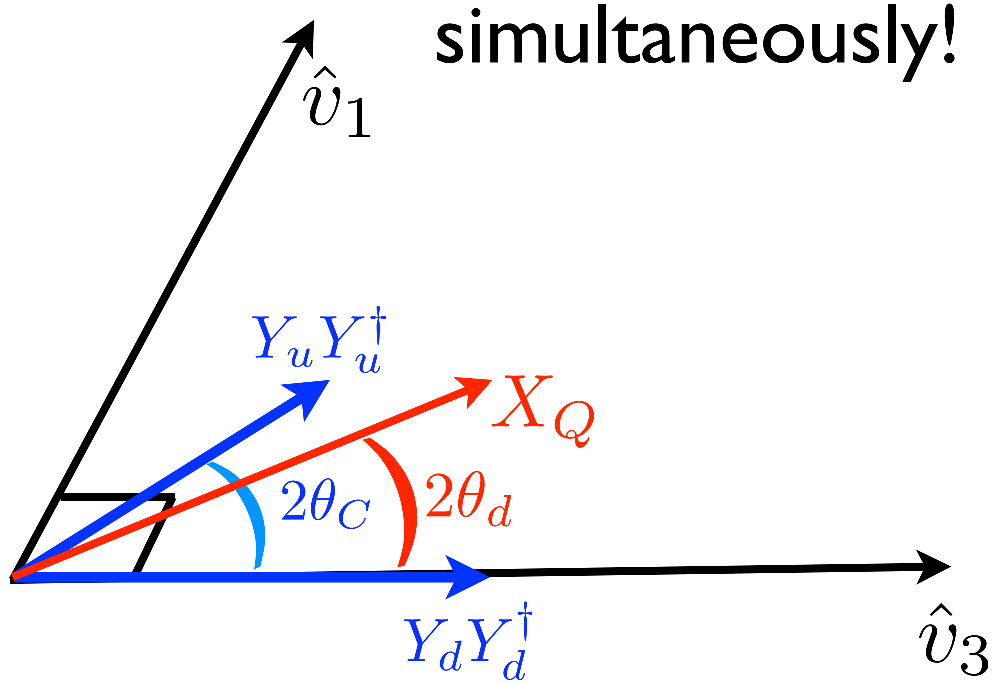

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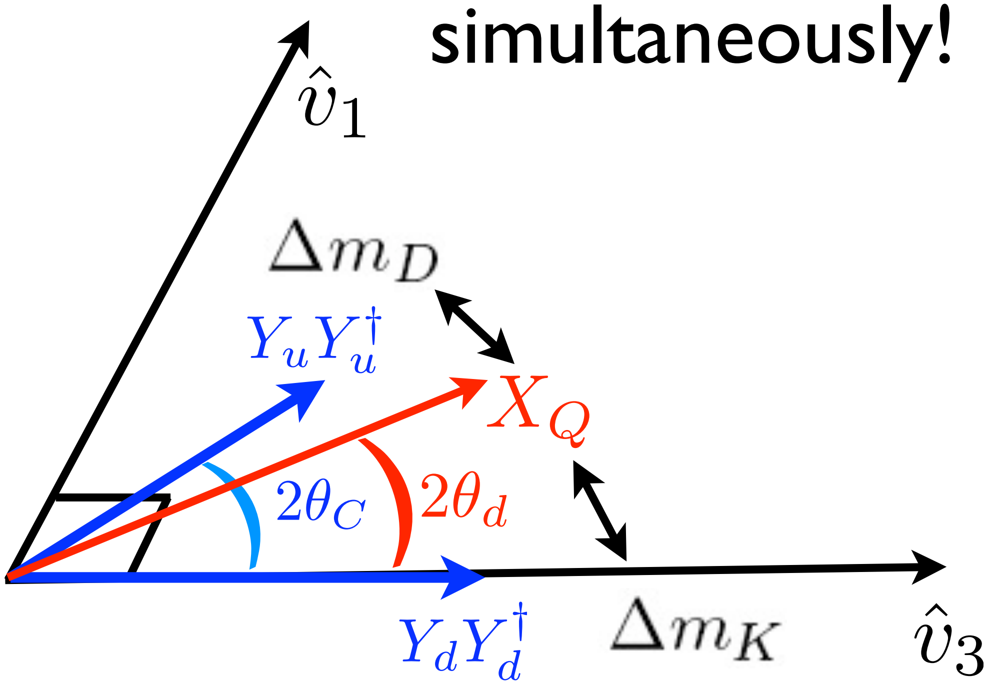

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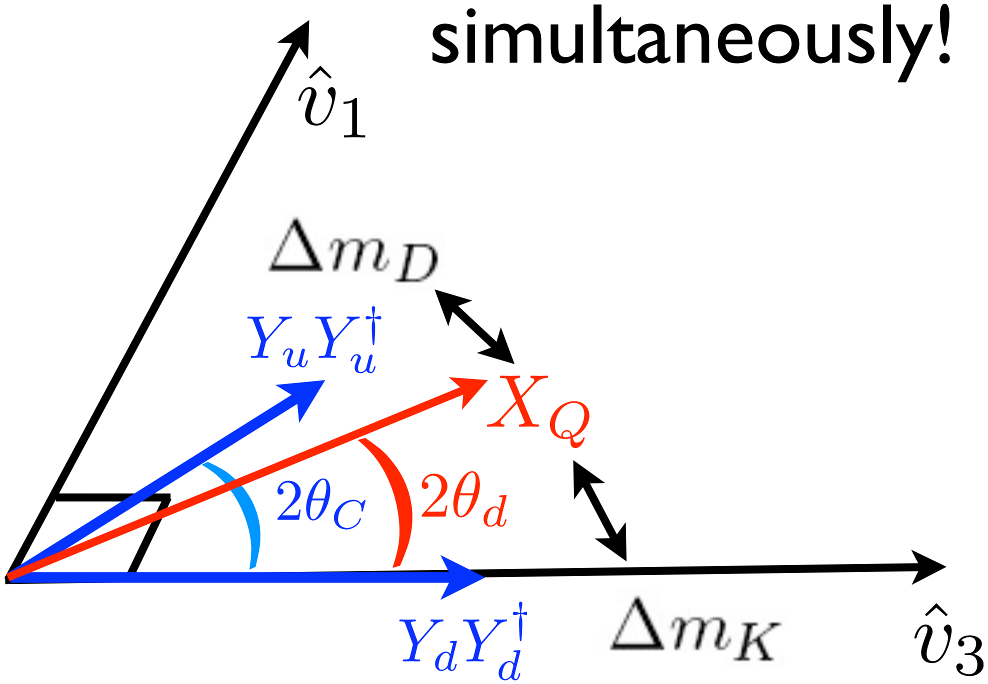
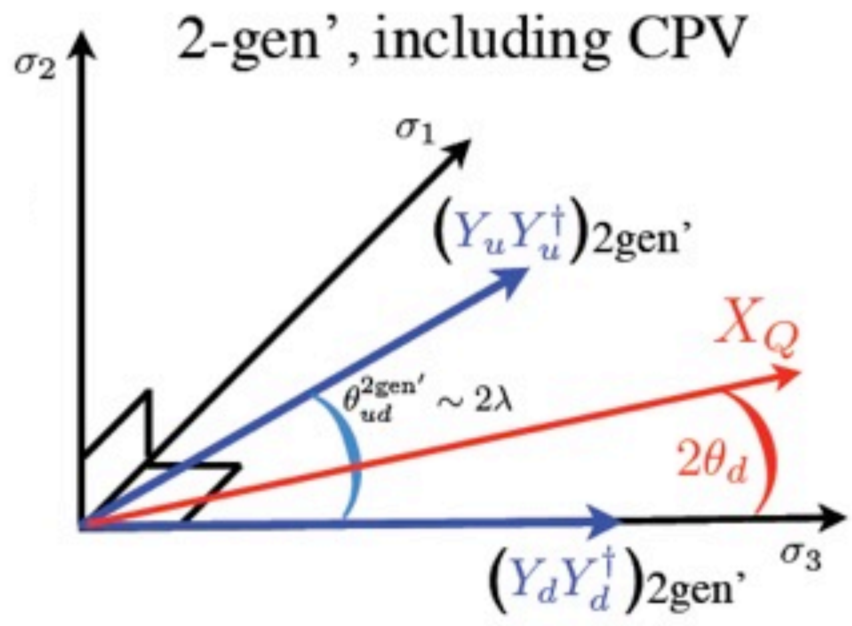


$$\lambda_Q = {\rm diag}(\lambda_1, \lambda_2),\ \ \lambda_{12} = \frac{1}{2}(\lambda_1 + \lambda_2),\ \ \delta_{12} = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2},\ \ \Lambda_{12} = \delta_{12}\lambda_{12}.$$

Constraining the flavor structure with CPV

CPV, γ $(\sin\gamma = \hat{v}_2)$, yield strong constraint on

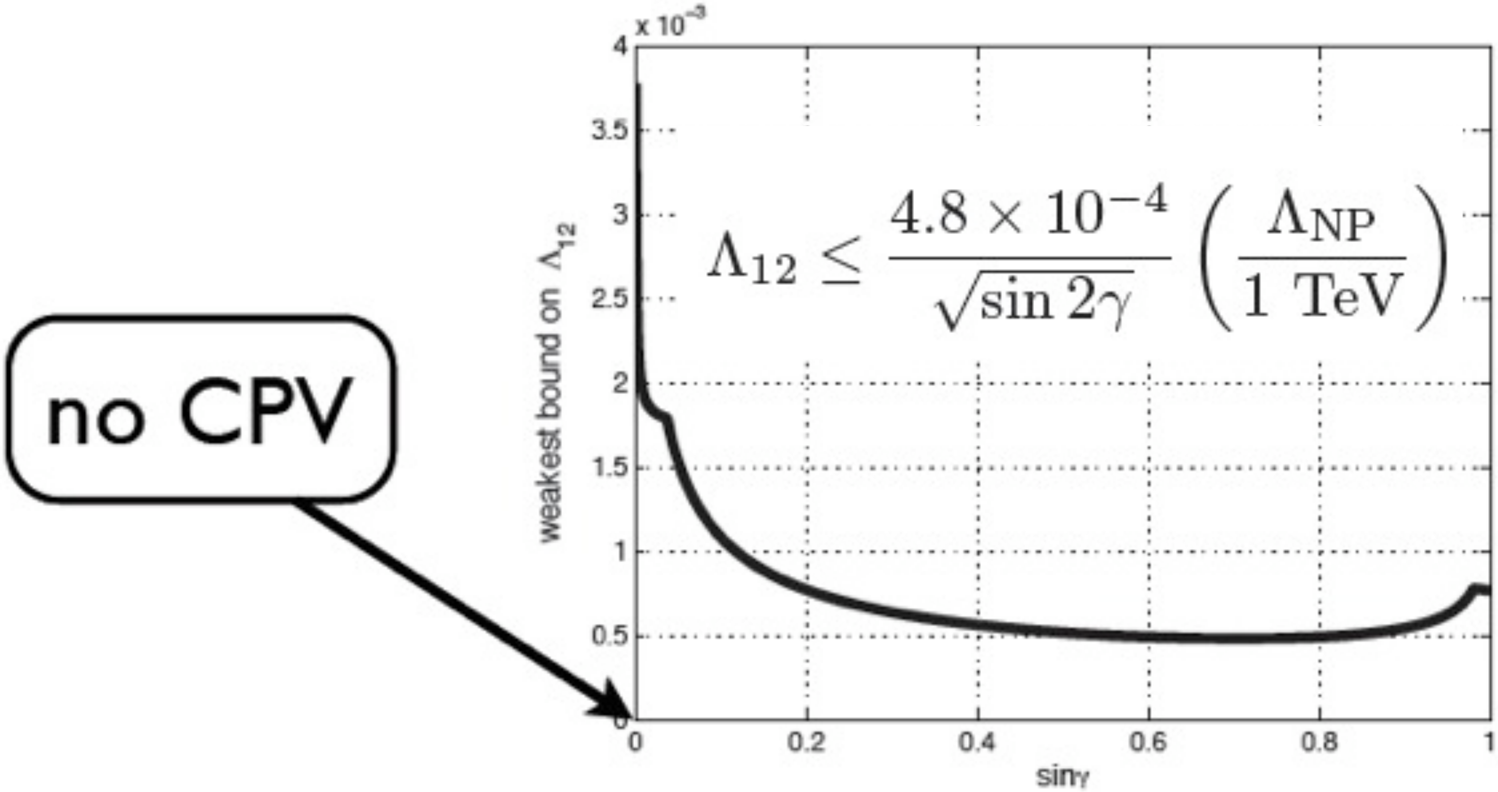
$$\Lambda_{12} = \delta_{12}\lambda_{12}.$$



$$z_1^K = \Lambda_{12}^2(\hat{v}_1 - i\hat{v}_2)^2,$$
$$z_1^D = \Lambda_{12}^2(\cos 2\theta_c \hat{v}_1 - \sin 2\theta_c \hat{v}_3 - i\hat{v}_2)^2.$$

Constraining the flavor structure with CPV

CPV, γ $(\sin\gamma = \hat{v}_2)$, strongly constrains $\Lambda_{12} = \delta_{12}\lambda_{12}$.



The weakest Λ_{12}-bound as function of $\sin\gamma$.

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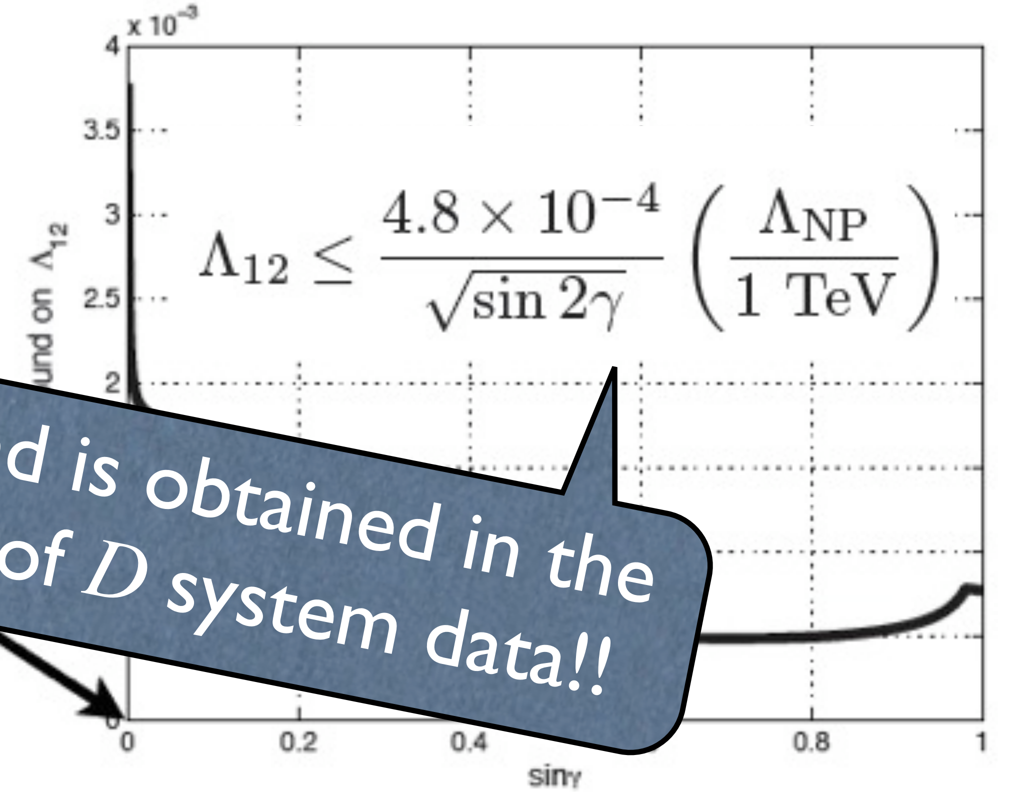

The weakest Λ_{12}-bound as function of $\sin\gamma$.

no

No bound is obtained in the absence of D system data!!

Covariant, basis independent, description of flavor violation

2 x [Gedalia, Mannelli, GP (10)]

Can be understood in a covariant, basis independent manner (needed for 3gen')

Two generation case:

- Any Hermitian 2x2 matrix => expressed as sum of Pauli matrices.
- A matrix corresponds to a vector in SU(2) space.
- Can define set of operations, like scalar product and cross product:

$$|\vec{A}| \equiv \sqrt{\frac{1}{2}\mathrm{tr}(A^2)}\,, \quad \vec{A}\cdot\vec{B} \equiv \frac{1}{2}\mathrm{tr}(A\,B)\,, \quad \vec{A}\times\vec{B} \equiv -\frac{i}{2}\,[A,B]\ ,$$

$$\cos(\theta_{AB}) \equiv \frac{\vec{A}\cdot\vec{B}}{|\vec{A}||\vec{B}|} = \frac{\mathrm{tr}(A\,B)}{\sqrt{\mathrm{tr}(A^2)\mathrm{tr}(B^2)}}\,.$$

- The SM basic vectors: $\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\not{tr}}\,, \qquad \mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\not{tr}}\,.$

Covariant basis, 2 gen'

- Define a covariant, physical, basis using the SM basis vectors:

$$\hat{\mathcal{A}}_{u,d} \equiv \frac{\mathcal{A}_{u,d}}{|\mathcal{A}_{u,d}|}\,, \quad \hat{J} \equiv \frac{\mathcal{A}_d \times \mathcal{A}_u}{|\mathcal{A}_d \times \mathcal{A}_u|}\,, \quad \hat{J}_{u,d} \equiv \hat{\mathcal{A}}_{u,d} \times \hat{J}\,.$$

- Up,down flavor violation is misalignment between SM mass basis unit vector & new sources of flavor breaking:

$$\left|z_1^{D,K}\right| = \left|X_Q \times \hat{\mathcal{A}}_{u,d}\right|^2 .$$ (say in $\frac{z_1}{\Lambda_{\rm NP}^2} O_1 = \frac{1}{\Lambda_{\rm NP}^2} \left(\overline{Q}_i (X_Q)_{ij} \gamma_\mu Q_j\right) \left(\overline{Q}_i (X_Q)_{ij} \gamma^\mu Q_j\right)$)

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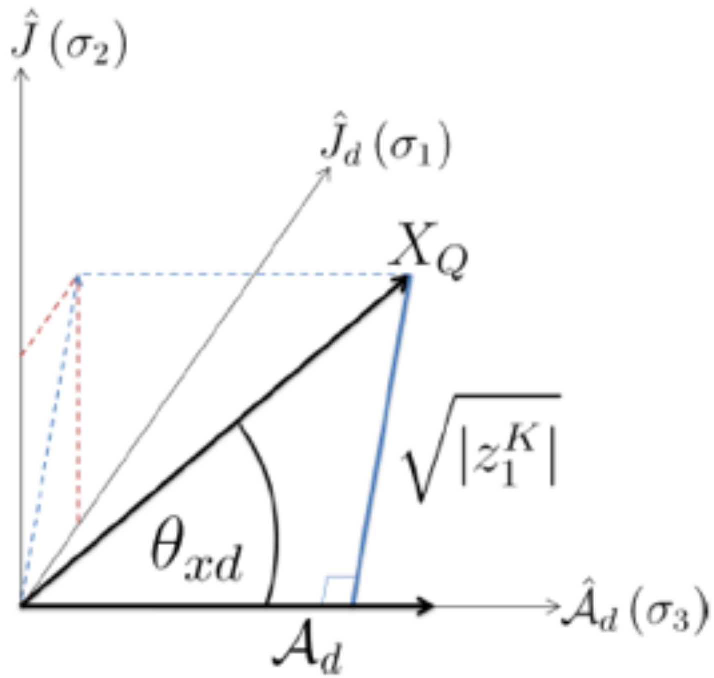
contribution of X_Q to $K^0 - \overline{K^0}$ mixing, Δm_K, given by the solid blue line.

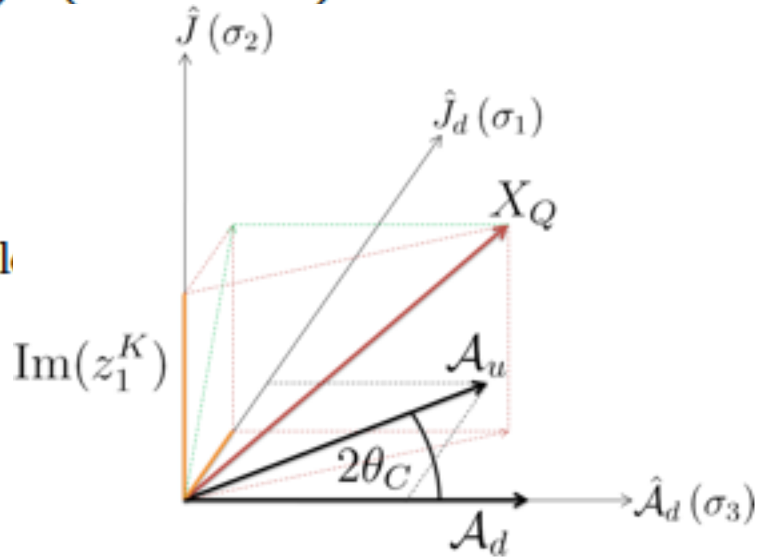


Covariant basis, CPV

- CPV in $\Delta F = 2:$ $\quad \mathrm{Im}\left(z_1^{K,D}\right) = 2\left(X_Q \cdot \hat{J}\right)\left(X_Q \cdot \hat{J}_{u,d}\right)$.

$\mathrm{Im}(z_1^K)$ is twice the product of the two solid orange lines.

Note that the angle between $\mathcal{A}_d$ and $\mathcal{A}_u$ is twice the Cabibbo angl



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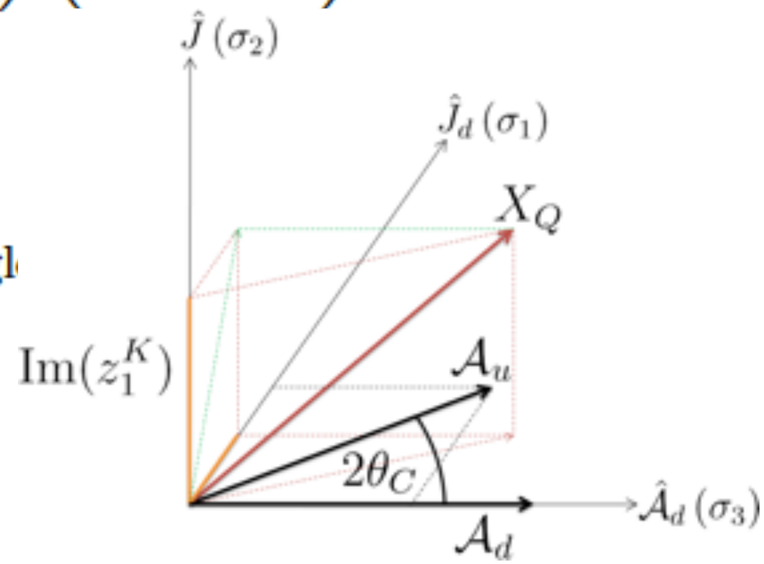

- Deriving a robust bound:

In the covariant bases $-\quad X_Q = X^{u,d}\hat{\mathcal{A}}_{u,d} + X^J\hat{J} + X^{J_{u,d}}\hat{J}_{u,d}$,

and the two bases are related through

$$X^u = \cos 2\theta_C X^d - \sin 2\theta_C X^{J_d}\,, \quad X^{J_u} = -\sin 2\theta_C X^d - \cos 2\theta_C X^{J_d}\,,$$

Previous result reproduced- $X^J = \Lambda_{12}\sin\gamma \quad \tan\alpha = \frac{X^{J_d}}{X^J}$

Covariant basis - physical interpretation

- The axis $\hat{J}$ is the 2-gen' "Jarlskog": $X^J \propto \mathrm{tr}\left(X_Q\left[\mathcal{A}_d, \mathcal{A}_u\right]\right) \neq 0\,,$

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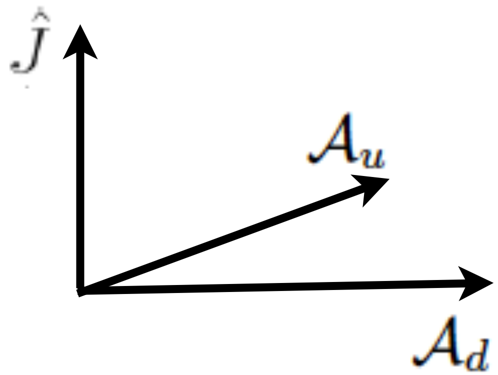

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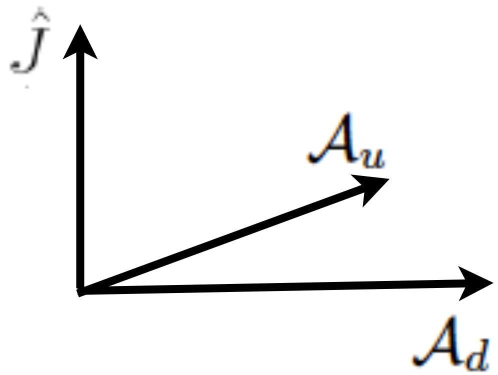

- The axes $\hat{J}_{u,d}$ dials CPV in $\Delta F = 2$ (new model indep' condition):

$$X^{J_{u,d}} \propto \mathrm{tr}\left(X_Q\left[\mathcal{A}_{u,d}, \left[\mathcal{A}_d, \mathcal{A}_u\right]\right]\right) \neq 0$$

Gedalia, Mannelli, GP (10)

CPV in $D^0 - \bar{D}^0$ mixing, model dependent implications:

(i) Minimal flavor violation (MFV);
(ii) SUSY;
(iii) Randall-Sundrum (RS).

Ciuchini, et al. (07); Csaki, et al. (08); Kagan, et al. (09); Gedalia, et al. (09,10,10); Blum, et al. (09); Buras et. al.; Csaki, et al. (09); Bauer, et al. (09); Bigi, et al. (09); Altmannshofer, et al. (09,10); Blanke, et al. (09); Crivellin & Davidkov (10).

Minimal flavor violation (MFV)

General MFV (GMFV) vs. Linear MFV (LMFV):

Volanksy, et. al (09); Gedalia, et. al (09).

$\text{Large } \tan\beta \Rightarrow \text{CPV.}$

LMFV: If dominated by $\sim Y_d Y_d^\dagger$ asym' is known.

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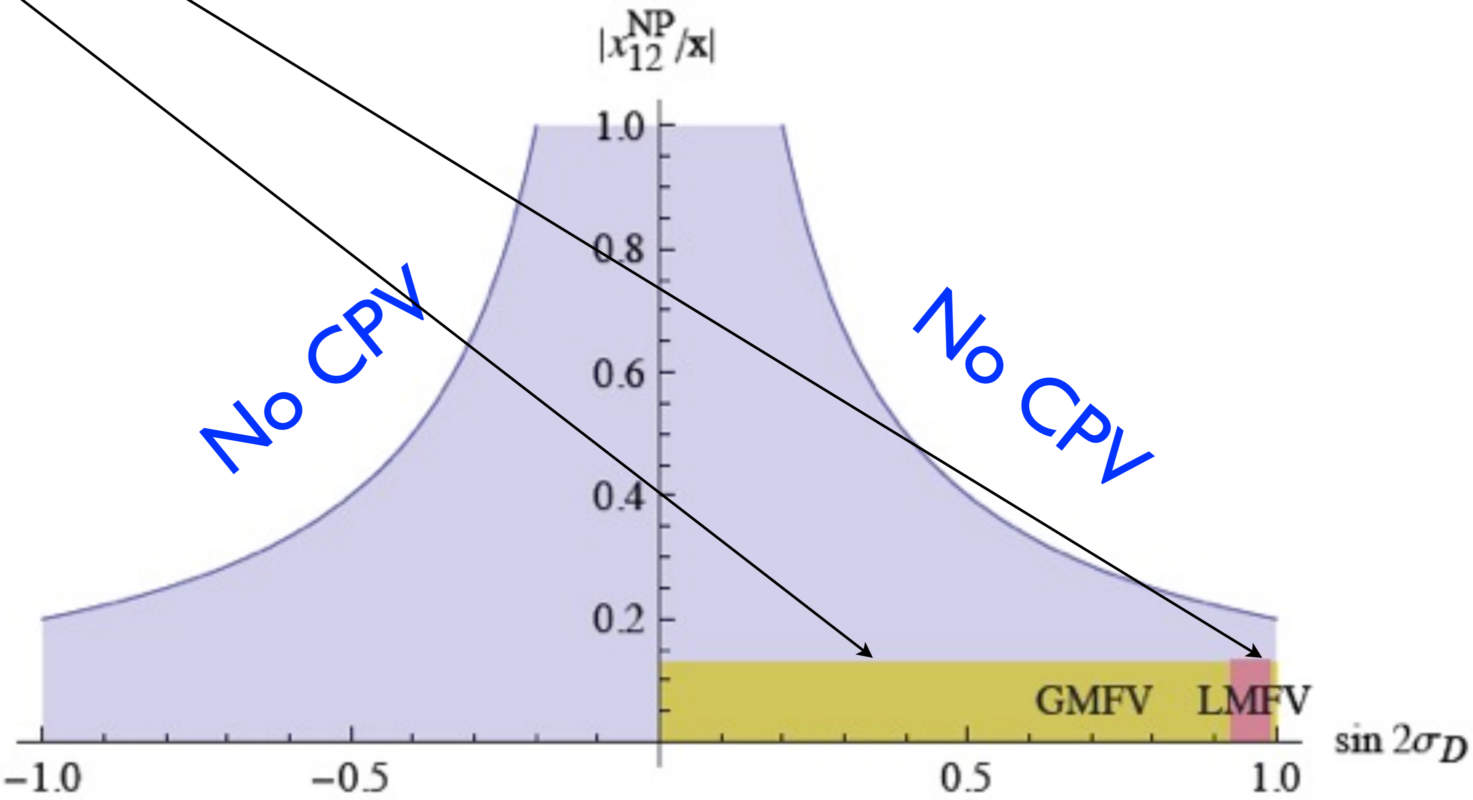

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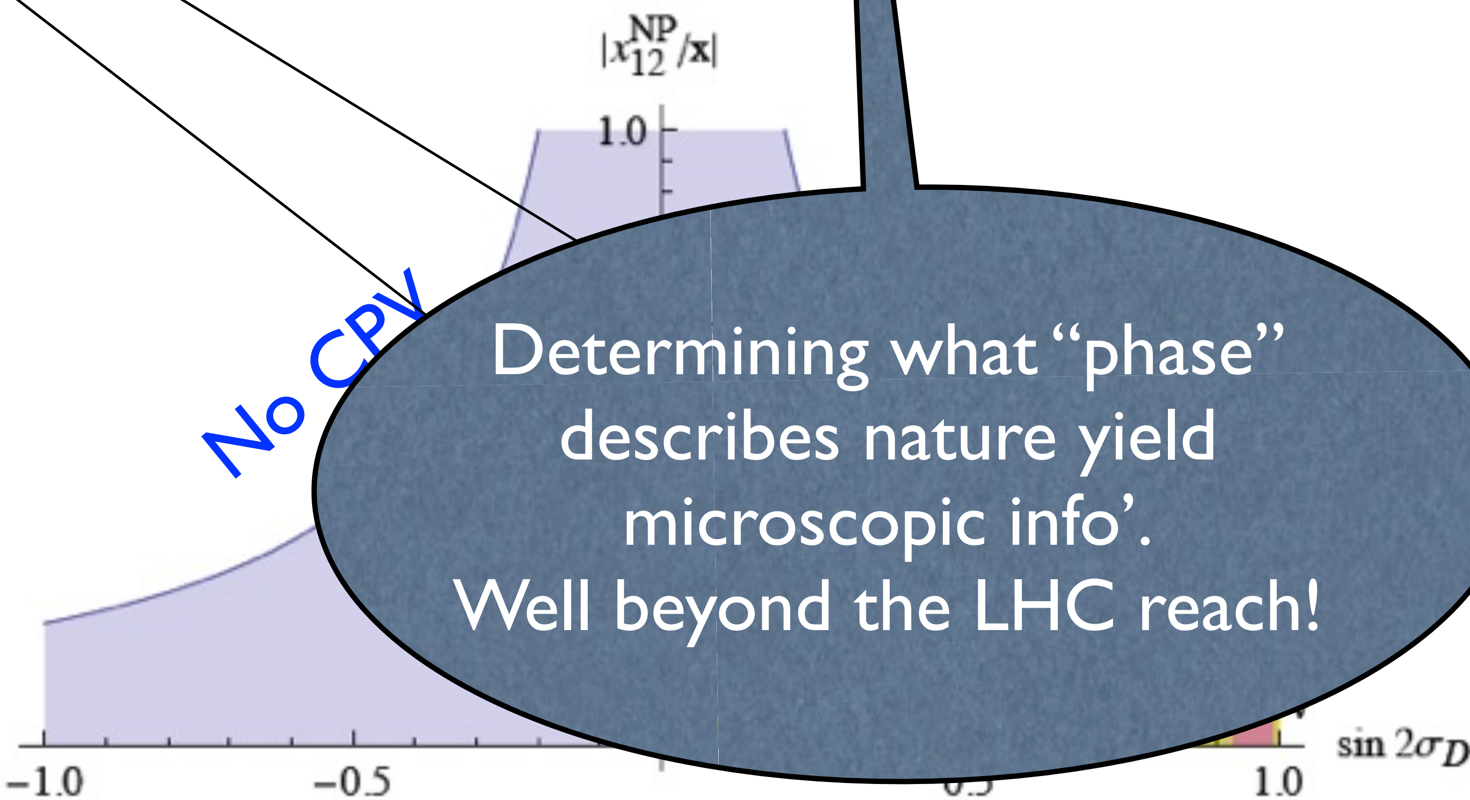

Determining what "phase" describes nature yield microscopic info'.
Well beyond the LHC reach!

SUSY

- Alignment models [O(1) phase]: Nir & Seiberg (93).

$$\frac{m_{\tilde{Q}_2}-m_{\tilde{Q}_1}}{m_{\tilde{Q}_2}+m_{\tilde{Q}_1}} \lesssim 0.05-0.14,$$

$$\frac{m_{\tilde{u}_2}-m_{\tilde{u}_1}}{m_{\tilde{u}_2}+m_{\tilde{u}_1}} \lesssim 0.02-0.04.$$

First bound => up squark doublets, 1TeV;

Second => average of the doublet & singlet mass splitting.

Gedalia, et. al (09).

- A "sweet spot" could exist where bounds are weaker:

$$x \sim 2.4 \qquad x = m_{\tilde{g}}^2/m_{\tilde{q}}^2$$

Crivellin & Davidkov (10).

- Possible correlation with EDM's:

$$d_n \gtrsim 10^{-(28-29)} e \text{ cm}$$

Altmannshofer, et. al (09).

Warped Models (RS) (see A. Weiler's talk)

- Generic warped models (up-type anarchy): Agashe, et. al (04,06).

Observable	$M_G^{\min}$[TeV]		$y_{5D}^{\min}$ or $f_{Q_3}^{\max}$	
	IR Higgs	$\beta = 0$	IR Higgs	$\beta = 0$
CPV-B_d^{LLLL}	$12 f_{Q_3}^2$	$12 f_{Q_3}^2$	$f_{Q_3}^{\max} = 0.5$	$f_{Q_3}^{\max} = 0.5$
CPV-B_d^{LLRR}	$4.2/y_{5D}$	$2.4/y_{5D}$	$y_{5D}^{\min} = 1.4$	$y_{5D}^{\min} = 0.82$
CPV-D^{LLLL}	$0.73 f_{Q_3}^2$	$0.73 f_{Q_3}^2$	no bound	no bound
CPV-D^{LLRR}	$4.9/y_{5D}$	$2.4/y_{5D}$	$y_{5D}^{\min} = 1.6$	$y_{5D}^{\min} = 0.8$
ϵ_K^{LLLL}	$7.9 f_{Q_3}^2$	$7.9 f_{Q_3}^2$	$f_{Q_3}^{\max} = 0.62$	$f_{Q_3}^{\max} = 0.62$
ϵ_K^{LLRR}	$49/y_{5D}$	$24/y_{5D}$	above (6.7)	$y_{5D}^{\min} = 8$

Gedalia, et. al (09);
Isidori, et. al (10).

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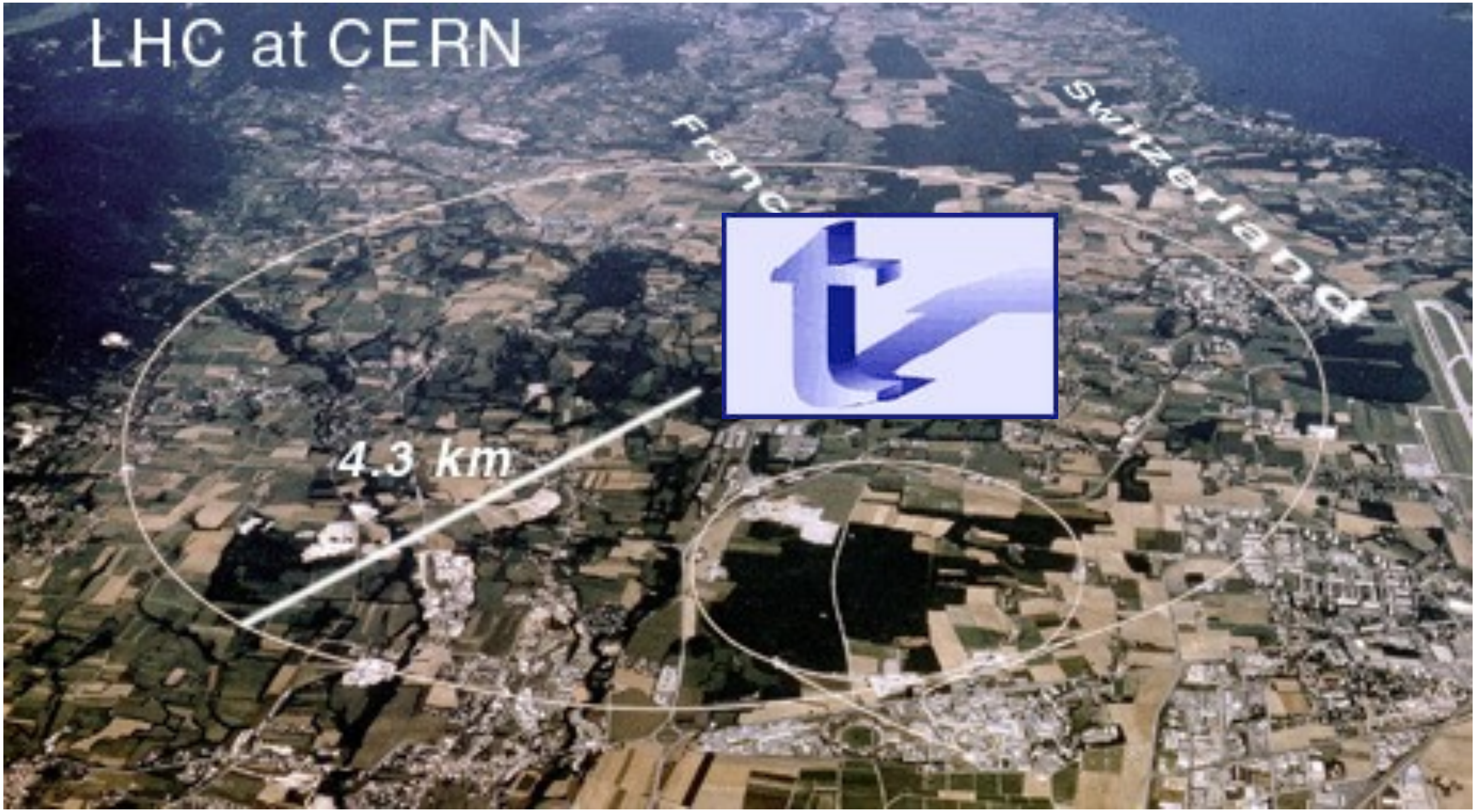
Gedalia, et. al (09);
Isidori, et. al (10).

♦ RS alignment (via shining): $y_{5\mathrm{D}}^{d} \gtrsim 3 y_{5\mathrm{D}}^{u}$ Csaki, et. al (09).

$$\frac{1}{2} \lesssim y_{5\mathrm{D}} \lesssim \frac{2\pi}{N_{\mathrm{KK}}} \quad \text{for brane Higgs}\,; \qquad \frac{1}{2} \lesssim y_{5\mathrm{D}} \lesssim \frac{4\pi}{\sqrt{N_{\mathrm{KK}}}} \quad \text{for bulk Higgs}\,,$$

Factor of few improvement exclude models.

3rd gen' Phys. @ the LHC



Top FCNC (tFCNC), $\Delta t = 1$

- LHC: study int' $\sim 10^{6-7}\ t\bar{t}/yr$
- Top FCNC: $t \to q, Z, \gamma, G$. $(q = u + c)$
  (also $t \to qh$ & single top production)
- SM: $BR(t \to qZ, \gamma, G) \sim 10^{-12}$.
  (Díaz-Cruz (89); Eilam, Hewett & Soni (90))
- LHC (100fb^{-1}): $BR(t \to qZ, \gamma) \gtrsim 10^{-5}$.
  (Carvalho, *et. al* (05))

tFCNC vs. bFCNC, generic bounds

Fox, et. al (07).

Effective theory, dim' 6 operators:

$$
\begin{aligned}
O^u_{LL} &= i\left[\overline{Q}_3\tilde{H}\right]\left[(\not{D}\tilde{H})^\dagger Q_2\right] - i\left[\overline{Q}_3(\not{D}\tilde{H})\right]\left[\tilde{H}^\dagger Q_2\right] + \text{h.c.} \\
O^h_{LL} &= i\left[\overline{Q}_3\gamma^\mu Q_2\right]\left[H^\dagger \overleftrightarrow{D}_\mu H\right] + \text{h.c.}\,, \\
O^w_{RL} &= g_2\left[\overline{Q}_2\sigma^{\mu\nu}\sigma^a\tilde{H}\right] t_R W^a_{\mu\nu} + \text{h.c.}\,, \\
O^b_{RL} &= g_1\left[\overline{Q}_2\sigma^{\mu\nu}\tilde{H}\right] t_R B_{\mu\nu} + \text{h.c.}\,, \\
O^w_{LR} &= g_2\left[\overline{Q}_3\sigma^{\mu\nu}\sigma^a\tilde{H}\right] c_R W^a_{\mu\nu} + \text{h.c.}\,, \\
O^b_{LR} &= g_1\left[\overline{Q}_3\sigma^{\mu\nu}\tilde{H}\right] c_R B_{\mu\nu} + \text{h.c.}\,, \\
O^u_{RR} &= i\,\bar{t}_R\gamma^\mu c_R\left[H^\dagger \overleftrightarrow{D}_\mu H\right] + \text{h.c.}\,.
\end{aligned}
$$

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tFCNC vs. bFCNC, generic bounds

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	C^u_{LL}	C^h_{LL}	C^w_{RL}	C^b_{RL}	C^w_{LR}	C^b_{LR}	C^u_{RR}
direct bound	9.0	9.0	6.3	6.3	6.3	6.3	9.0
LHC sensitivity	0.20	0.20	0.15	0.15	0.15	0.15	0.20
$B \to X_s\gamma,\ X_s\ell^+\ell^-$	$[-0.07,\ 0.036]$	$[-0.017,\ -0.01]$ $[-0.005,\ 0.003]$	$[-0.09, 0.18]$	$[-0.12, 0.24]$	$[-14, 7]$	$[-10, 19]$	—
$\Delta F = 2$	0.07	0.014	0.14	—	—	—	—
semileptonic	—	—	—	—	$[0.3, 1.7]$	—	—
best bound	0.07	0.014	0.15	0.24	1.7	6.3	9.0
Λ for $C_i = 1$ (min)	3.9 TeV	8.3 TeV	2.6 TeV	2.0 TeV	0.8 TeV	0.4 TeV	0.3 TeV
$\mathcal{B}(t \to cZ)$ (max)	7.1×10^{-6}	3.5×10^{-7}	3.4×10^{-5}	8.4×10^{-6}	4.5×10^{-3}	5.6×10^{-3}	0.14
$\mathcal{B}(t \to c\gamma)$ (max)	—	—	1.8×10^{-5}	4.8×10^{-5}	2.3×10^{-3}	3.2×10^{-2}	—
LHC Window	Closed*	Closed*	Ajar	Ajar	Open	Open	Open

tFCNC vs. bFCNC, generic bounds

Fox, et. al (07).

	C^u_{LL}	C^h_{LL}	C^w_{RL}	C^b_{RL}	C^w_{LR}	C^b_{LR}	C^u_{RR}
direct bound	9.0	9.0	6.3	6.3	6.3	6.3	9.0
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Looks as if B-phys. strongly constraint LH operators!

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~~Looks as if B-phys strongly constraint LH operators!~~

Not valid if down alignment is at work 

2x Gedalia, et al. (10).

Robust bounds for $\Delta t = 1$

$$O^h_{LL} = i\left[\overline{Q}_i \gamma^\mu (X_Q^{\Delta F=1})_{ij} Q_j\right]\left[H^\dagger \overleftrightarrow{D}_\mu H\right]$$

$\mathrm{Br}(B \to X_s \ell^+ \ell^-)$ $\qquad\qquad$ $\mathrm{Br}(t \to (c,u)Z)$

- 3-gen' case the structure is much richer (8 Gell-Mann matrices), a covariant treatment is necessary. Simplification: @ LHC light quark jets look the same.

$$\Downarrow$$

Approximate $U(2)$ Limit of Massless Light Quarks

The approximate U(2)

0th order question for a 3x3 adjoint:
Is a residual U(2) conserved?

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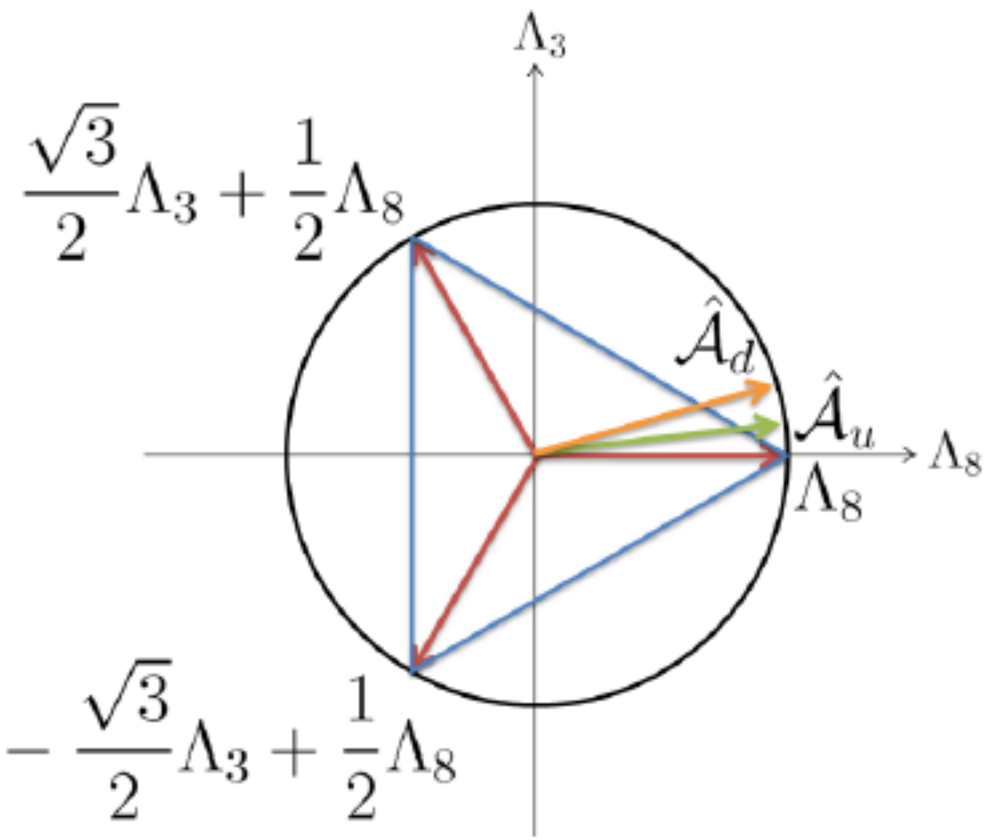

Covariant description of approx' U(2)

- Without loss of generality:

$$\mathcal{A}_d = \frac{y_b^2}{3}\begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 2 \end{pmatrix}, \qquad \mathcal{A}_u = y_t^2\begin{pmatrix} \spadesuit & 0 & 0 \\ 0 & \spadesuit & \spadesuit \\ 0 & \spadesuit & \spadesuit \end{pmatrix},$$

- CKM has a single phase:

$$\theta \cong \sqrt{\theta_{13}^2 + \theta_{23}^2}\,,$$

- SM massless quarks are broken to active & sterile states:

$$\begin{array}{c} U(1)_Q \times U(1)_B \\ \Big\uparrow V_{\rm CKM} \\ U(2)_Q \times U(1)_{Q_3} \\ \Big\uparrow \mathcal{A}_{u,d}\ \ (V_{\rm CKM} \to \mathbb{1}_3) \\ U(3)_Q \end{array}$$

Covariant basis

- Start as in 2 gen': $\hat{\mathcal{A}}_{u,d} \equiv \frac{\mathcal{A}_{u,d}}{|\mathcal{A}_{u,d}|}\,, \quad \hat{J} \equiv \frac{\mathcal{A}_d \times \mathcal{A}_u}{|\mathcal{A}_d \times \mathcal{A}_u|}\,, \quad \hat{J}_{u,d} \equiv \hat{\mathcal{A}}_{u,d} \times \hat{J}\,.$

- Add a Cartan: $\hat{\mathcal{A}}_{u,d}$ and $\hat{C}_{u,d} \equiv 2\hat{J} \times \hat{J}_{u,d} - \sqrt{3}\hat{\mathcal{A}}_{u,d}\,,$

or

$$\hat{\mathcal{A}}'_{u,d} \equiv \hat{J} \times \hat{J}_{u,d} \quad \text{and} \quad \hat{J}_Q \equiv \sqrt{3}\hat{J} \times \hat{J}_{u,d} - 2\hat{\mathcal{A}}_{u,d}\,.$$

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- Any adjoint can decompose according to:

$$X_Q^{\Delta F=1} = X'^{u,d}\hat{\mathcal{A}}'_{u,d} + X^J\hat{J} + X^{J_{u,d}}\hat{J}_{u,d} + X^{J_Q}\hat{J}_Q + X^{\vec{D}}\hat{\vec{D}}\,.$$

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Robust projected bound (assuming no signal) & *t*/*b* flavor violation

- Overall 3rd gen' flavor violation: $\frac{2}{\sqrt{3}} \left| X_Q \times \hat{\mathcal{A}}_{u,d} \right| \,,$

which extracts $\sqrt{|(X_Q)_{13}|^2 + |(X_Q)_{23}|^2}$ in each basis.

- The bounds:

$$\mathrm{Br}(B \to X_s \ell^+ \ell^-) \longrightarrow \left|C^h_{LL}\right|_b < 0.018 \left(\frac{\Lambda_{\rm NP}}{1\,\mathrm{TeV}}\right)^2 ,$$

$$\mathrm{Br}(t \to (c,u) Z) \longrightarrow \left|C^h_{LL}\right|_t < 0.18 \left(\frac{\Lambda_{\rm NP}}{1\,\mathrm{TeV}}\right)^2 ,$$

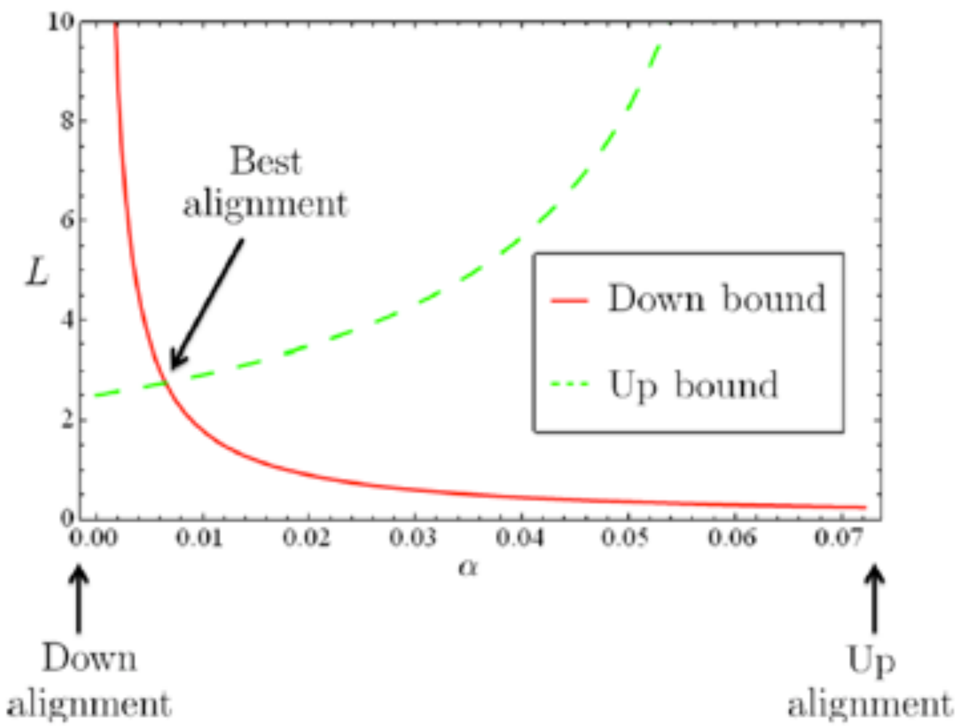
$$\frac{4}{3} \left| X_Q^{\Delta F=1} \times \hat{\mathcal{A}}_{u,d} \right|^2 = (X^J)^2 + (X^{J_{u,d}})^2 \,, \quad X^{J_u} = \cos 2\theta\, X^{J_d} + \sin 2\theta\, X^{\prime d} \,,$$

The bound

$$\text{(i)} \quad \alpha = 0\,, \quad L < 2.5\left(\frac{\Lambda_{\rm NP}}{1\,\text{TeV}}\right)^2; \quad \Lambda_{NP} > 0.63\,(7.9)\ \text{TeV}\,,$$

$$\text{(ii)} \quad \alpha = \frac{\sqrt{3}\,\theta}{1+r_{tb}}\,, \quad L < 2.8\left(\frac{\Lambda_{\rm NP}}{1\,\text{TeV}}\right)^2; \quad \Lambda_{NP} > 0.6\,(7.6)\ \text{TeV}\,,$$

$$\tan\alpha \equiv \frac{X^{J_d}}{X^d} \qquad L \equiv \left|X_Q^{\Delta F=1}\right| \qquad r_{tb} \equiv \left|C_{LL}^h\right|_t / \left|C_{LL}^h\right|_b$$



$\Delta F = 2\,,\ \left[(\bar{t},\bar{b})_L X_Q (u,d)_L\right]^2$

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

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$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}
$(\bar{t}_L\gamma^\mu u_L)^2$	12		$7.1\ 10^-3$		$uu \to tt$

However, CPV in D system is stronger

Despite $\mathcal{O}(\lambda_C^5)$ suppression:

$$\mathrm{Im}(z_1^D) < 1.1 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\,\mathrm{TeV}}\right)^2 ,$$

$$L < 12 \left(\frac{\Lambda_{\rm NP}}{1\,\mathrm{TeV}}\right) ; \quad \Lambda_{\rm NP} > 0.08\,(1)\,\mathrm{TeV} ,$$

for $uu \to tt$ and

$$L < 1.8 \left(\frac{\Lambda_{\rm NP}}{1\,\mathrm{TeV}}\right) ; \quad \Lambda_{\rm NP} > 0.57\,(7.2)\,\mathrm{TeV} ,$$

for D mixing.

Also applied to SUSY & RS => weak but robust bounds.

Outlook, Flavor at the LHC Era

LHC era ~ up FCNC, however, regarding tFCNC, despite orders mag' improvement => constraints rather weak.

What if no deviation are observed including in *u*-FCNC (or any other low *E* observable)? Can bound NP.

Flavor diagonal NP (spectrum or couplings, say KK gluon BRs) could be exciting, especially deviation from U(2).

LMFV vs. GMFV could be next decade question:

LMFV lies on $\mathcal{A}_u$-$\mathcal{A}_d$ plane;
GMFV lies on large-axes sub-manifold .

Backups