Aspects of 3rd Generation Physics @ the LHC

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Outline

- Brief Introduction, importance of 3rd generation.
- Up type physics $D-\bar{D}$ mixing, tFCNC, data + theory.
- Implications of D0 & CDF results related to CPV $\in B_s-\bar{B}_s.$

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- Outlook, the LHC era.

Why 3rd generation ?

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

♦ Ironically, top sector, which also dominates CPV & custodial breaking, is poorly probed (also charm till recently).

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

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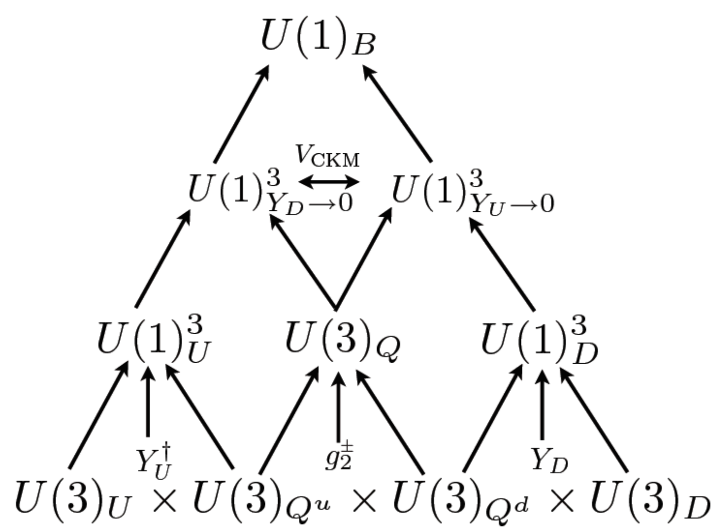

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- Deviation from SM predictions can be easily probed or severe bounds on new physics (NP) obtained.

Flavor Changing & CP Violating Physics

Constraining up flavor violation is important

♦ Down type flavor violation can be shut off via *alignment*, where anarchic NP is diagonal in the down mass basis.

careful domino *alignment*

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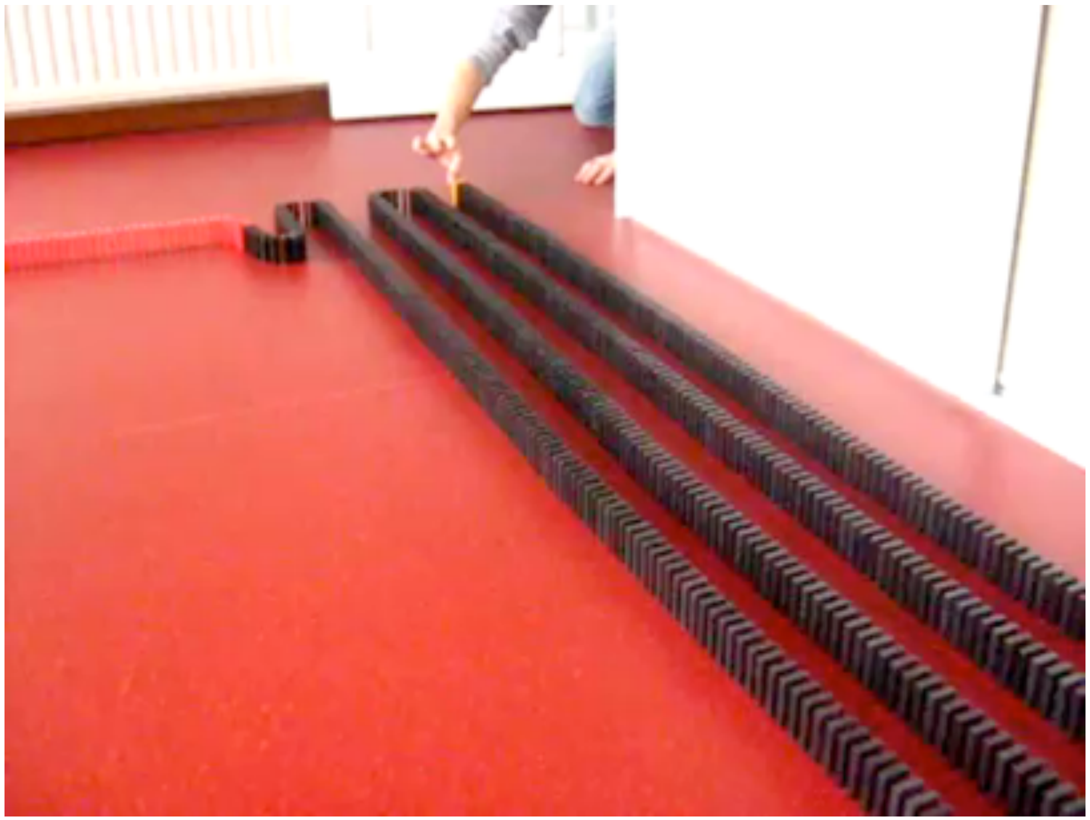

careful domino *alignment*

Up sector

Look Down

Look Up

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

δ

Δ

Huge recent progress in measurement of mass splitting & CP violation (CPV) in the D system:

- System parameters roughly determined (HFAG):

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

$$m \equiv \frac{m_1 + m_2}{2}, \qquad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2},$$
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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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Absence of D CPV a SM victory!

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The power of CPV in the D system

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

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

$$x_{12}^{\rm NP} \lesssim x_{12}^{\rm exp} \sim 0.012, \qquad x_{12}^{\rm NP} \sin\phi_{12}^{\rm NP} \lesssim x_{12}^{\rm exp} \sin\phi_{12}^{\rm exp} \sim 0.0022,$$

Gedalia, et. al (09).

long distance dominated?

Falk, et. al (02).

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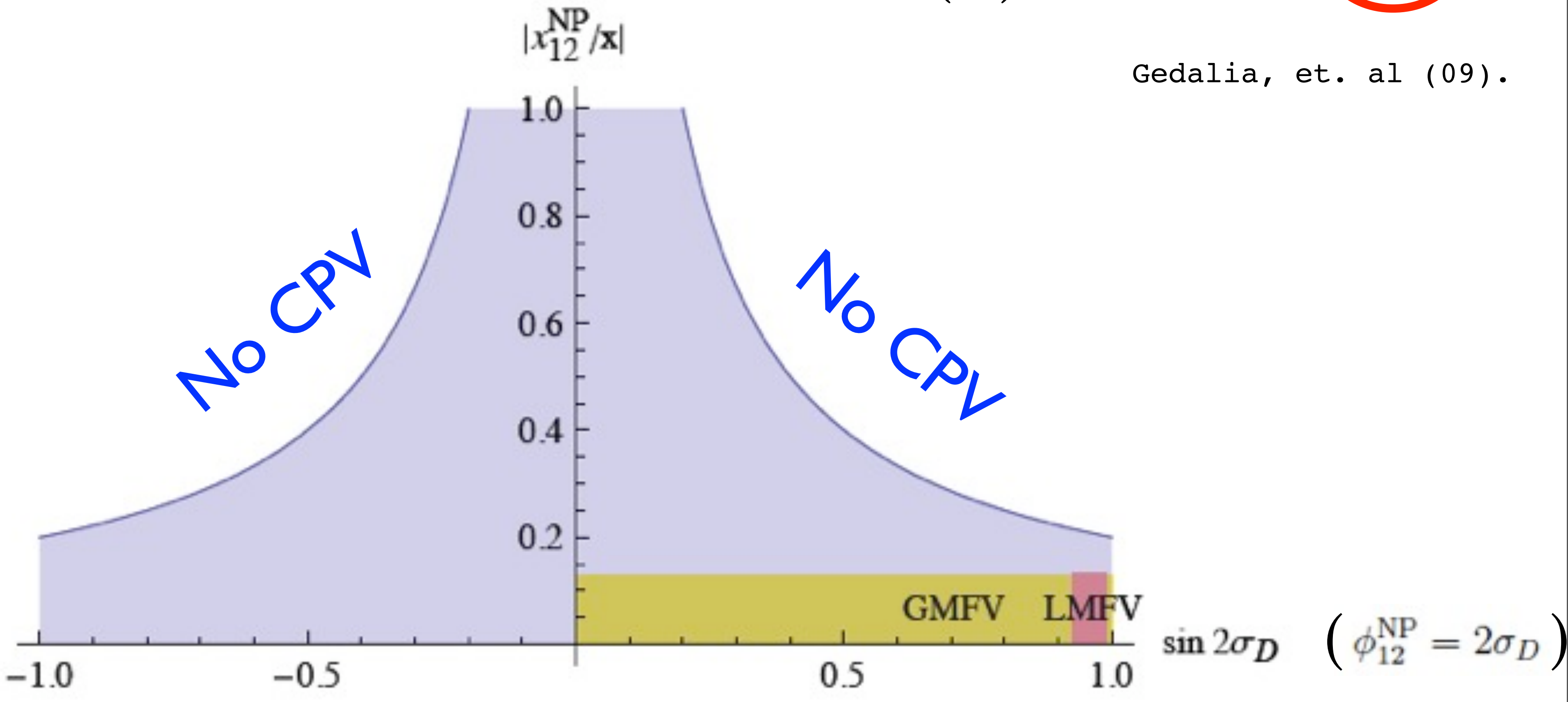
If x is due to NP then it missed a chance to revealed itself in $\mathcal{O}(1)$ CPV. ☹



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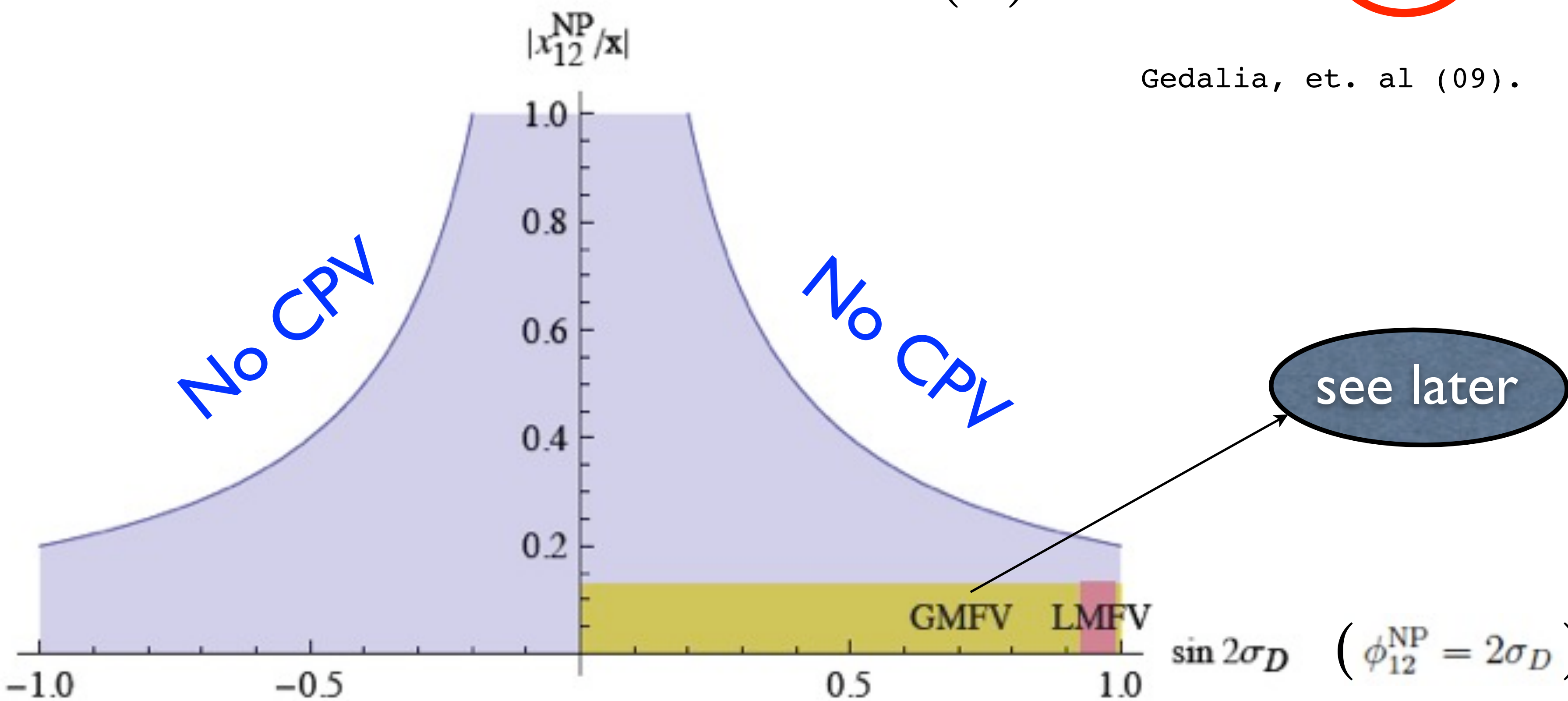

$(\phi_{12}^{\rm NP} = 2\sigma_D)$

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

$\Delta F = 2$ status

Isidori, Nir, GP (10)

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
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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 importance of up-type FCNC

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u-FCNC data remove immunities!

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

Robust model independent bounds:

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

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

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$K^0 - \overline{K^0}$
$+$
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$$\frac{1}{\Lambda_{\rm NP}^2}\left[z_1^K(\overline{d_L}\gamma_\mu s_L)(\overline{d_L}\gamma^\mu s_L) + z_1^D(\overline{u_L}\gamma_\mu c_L)(\overline{u_L}\gamma^\mu c_L) + z_4^D(\overline{u_L}c_R)(\overline{u_R}c_L)\right].$$

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

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

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

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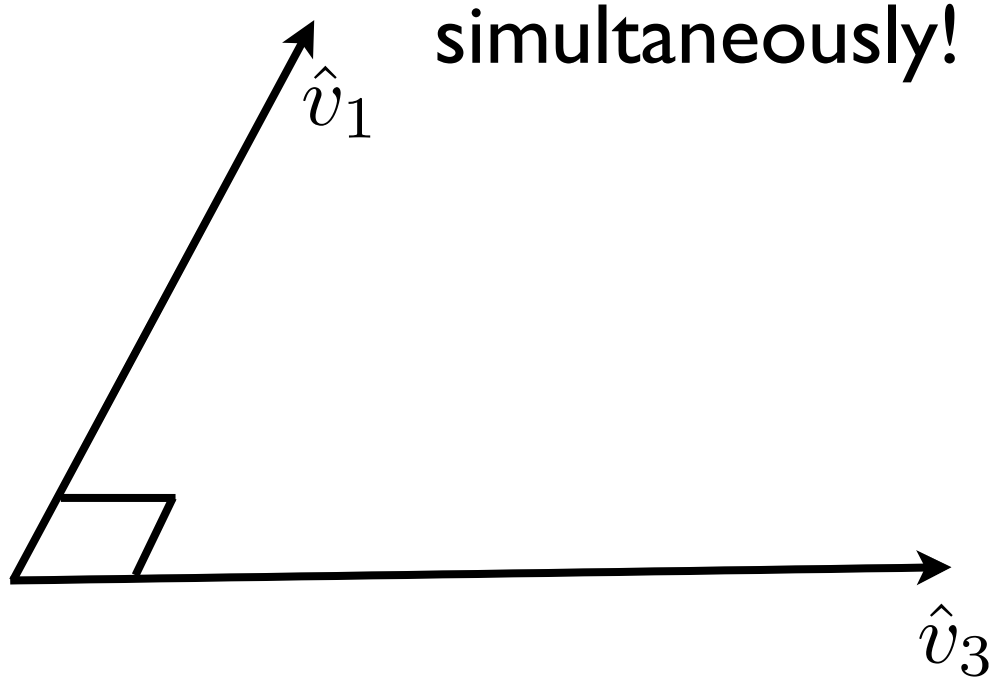

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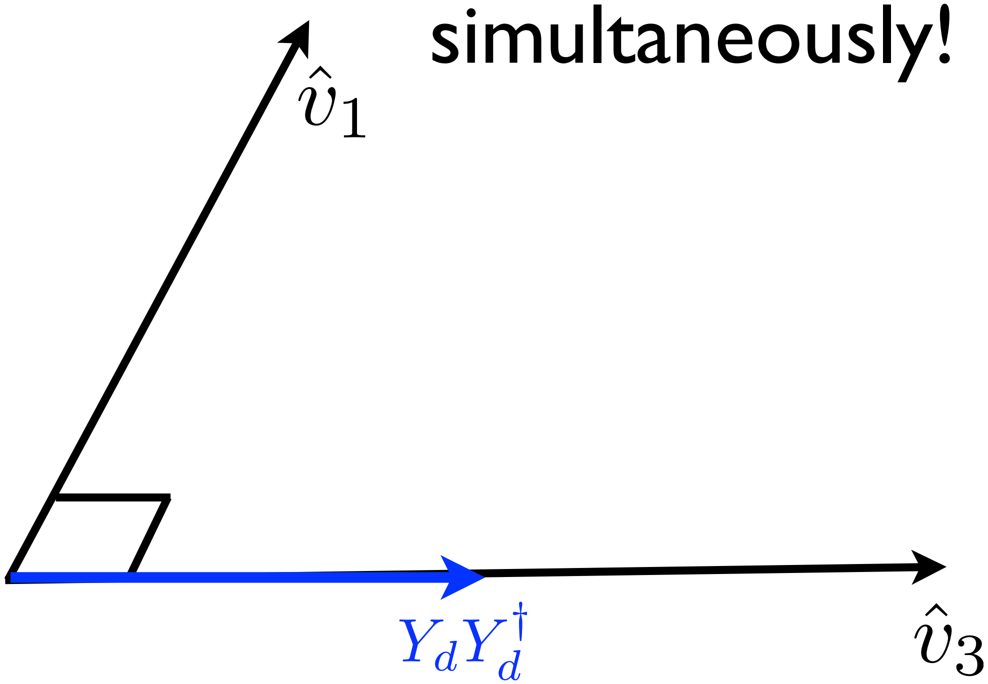

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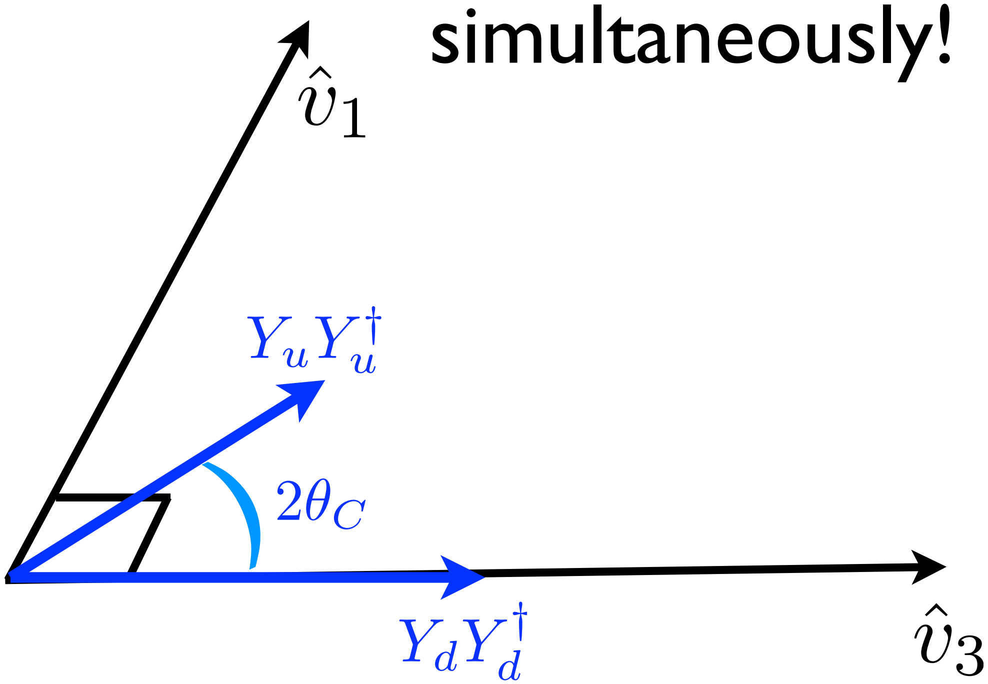

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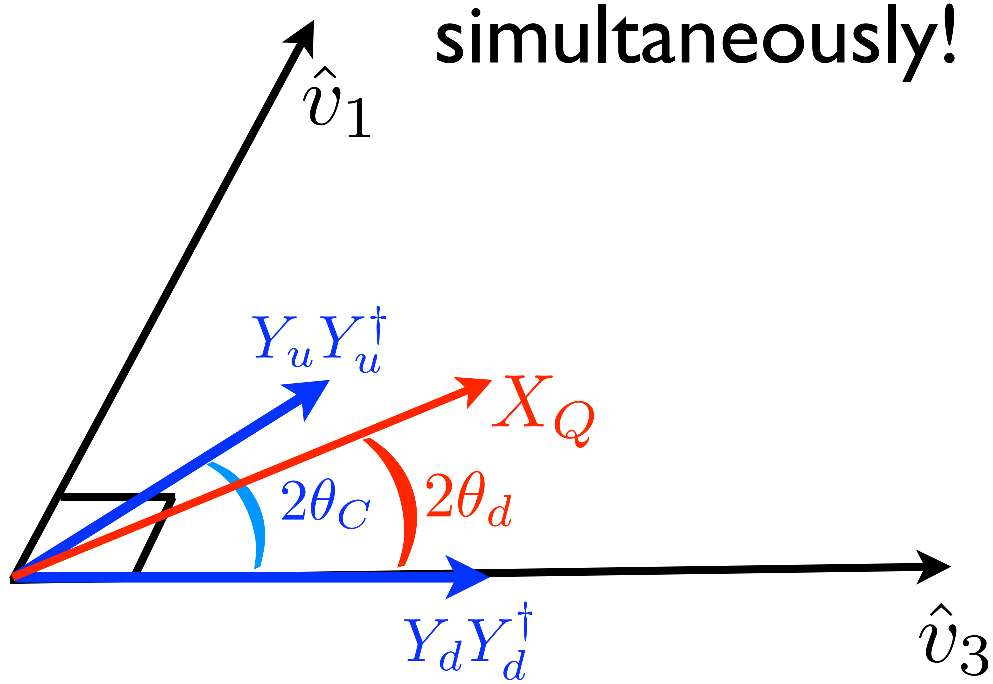

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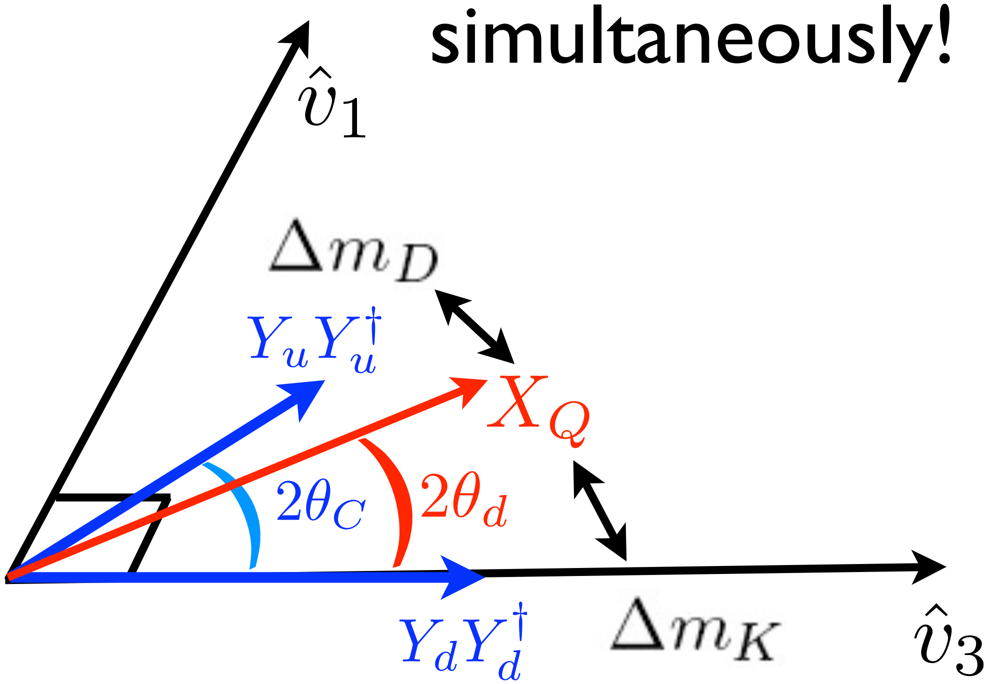

Can be understood in a covariant, basis independent manner (needed for 3gen')

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: $\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\not{\rm tr}}\,, \qquad \mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\not{\rm tr}}\,.$

Covariant basis, CPV (strongest bounds)

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

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

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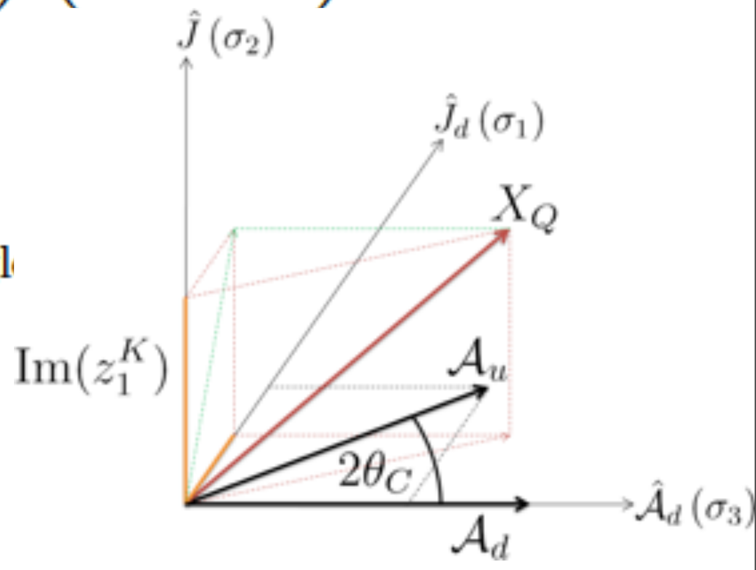
2gen' Jarlskog

- 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



Implications of CPV in $D^0 - \bar{D}^0$ mixing

(i) Model independent;
(ii) General minimal flavor violation (GMFV);
(iii) SUSY;
(iv) 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).

Robust (immune) bounds

$$L = |X_Q| = \left(X_Q^2 - X_Q^1\right)/2$$

$$(X^d)^2 + (X^J)^2 + (X^{J_d})^2 = (X^u)^2 + (X^J)^2 + (X^{J_u})^2 = 1$$

Constraining the eigenvalue difference of flavor violation source, indep' of it's direction!

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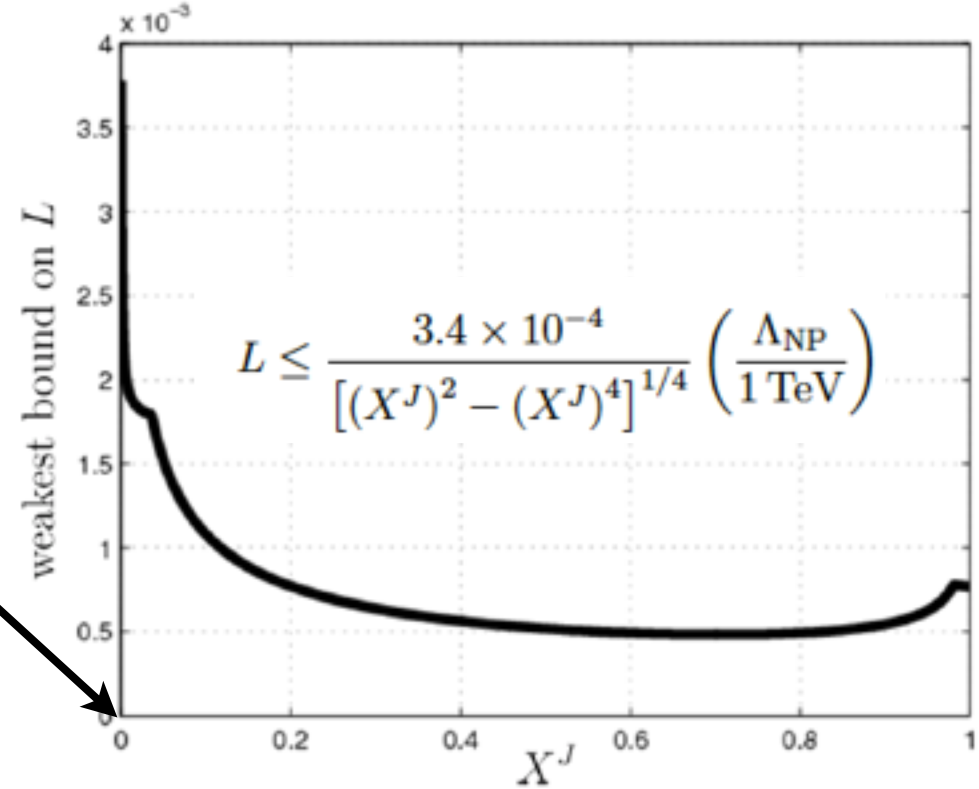

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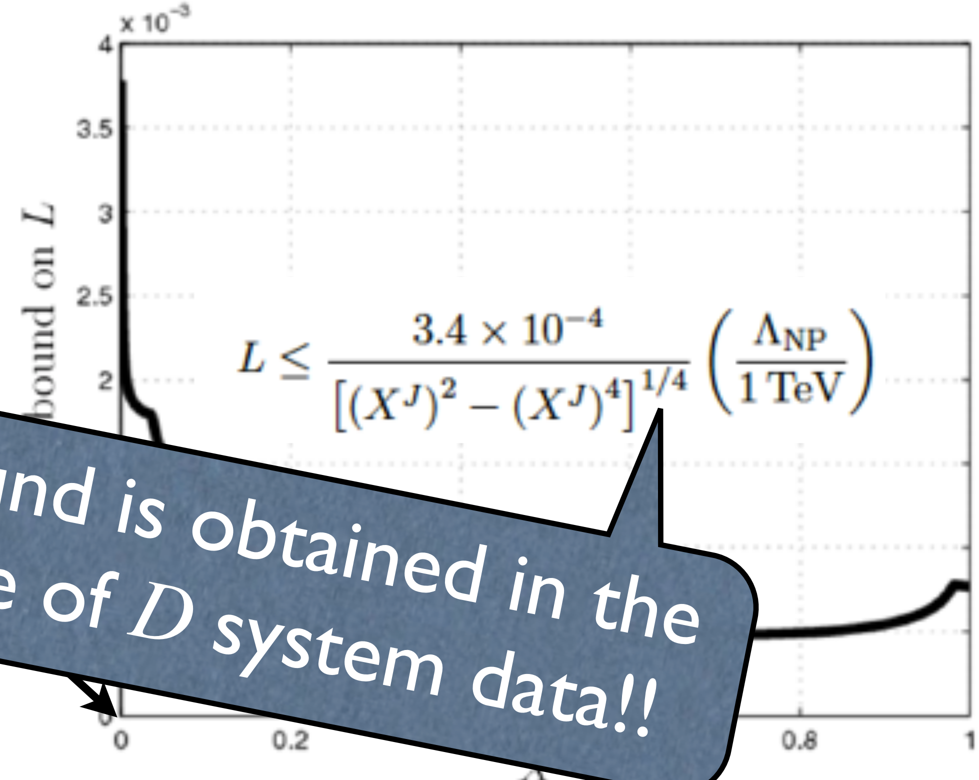

No CPV

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

CPV in D: Model Dependent Implications

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

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

- Comparable NP contributions from strange & bottom (unlike SM)

$$r_{sb} \equiv \frac{y_s^2}{y_b^2}\left|\frac{V_{us}^{\rm CKM}V_{cs}^{\rm CKM}}{V_{ub}^{\rm CKM}V_{cb}^{\rm CKM}}\right| \sim 0.5\,,$$

$$C_1^{cu} \propto \left[y_s^2\left(V_{cs}^{\rm CKM}\right)^* V_{us}^{\rm CKM} + (1 + r_{\rm GMFV})y_b^2\left(V_{cb}^{\rm CKM}\right)^* V_{ub}^{\rm CKM}\right]^2$$

$r_{\rm GMFV}$ result of resummation $\sum_n y_b^n$

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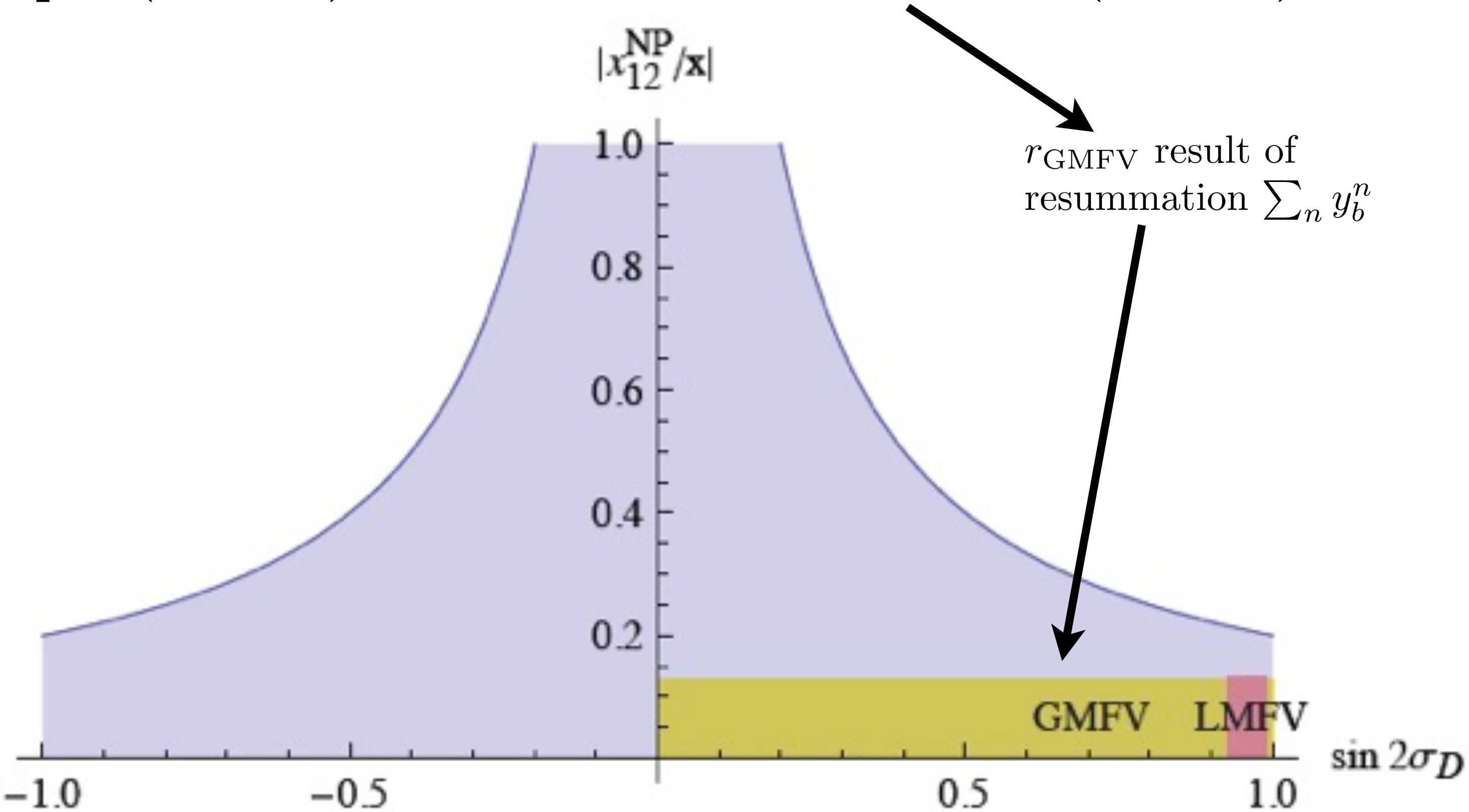

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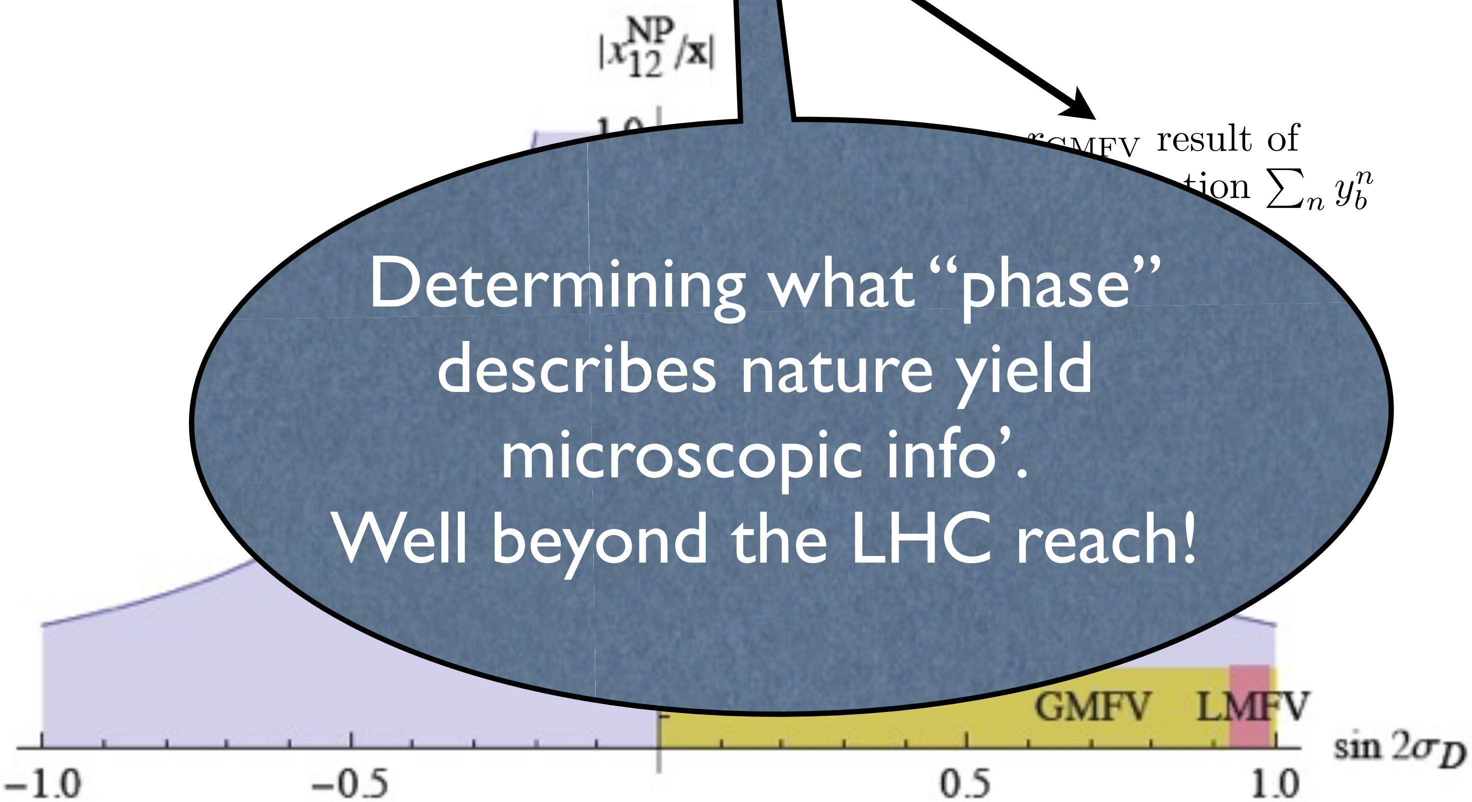


Determining what "phase" describes nature yield microscopic info'.
Well beyond the LHC reach!

SUSY+RS

SUSY (doom of alignment)

Robust

$$\frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_1}}{m_{\tilde{Q}_2} + m_{\tilde{Q}_1}} \leq \begin{cases} 0.034 & \text{maximal phases} \\ 0.27 & \text{vanishing phases} \end{cases}$$

squark doublets, 1TeV;

Generic

Gedalia, et. al (09).

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

average of the doublet & singlet mass splitting.

RS (constraining alignment)

Csaki, et. al (09).

Robust

$$m_{\rm KK} > 2.1 f_{Q_3}^2 \text{ TeV},$$

f_{Q_3} is typically in the range of 0.4-$\sqrt{2}$.

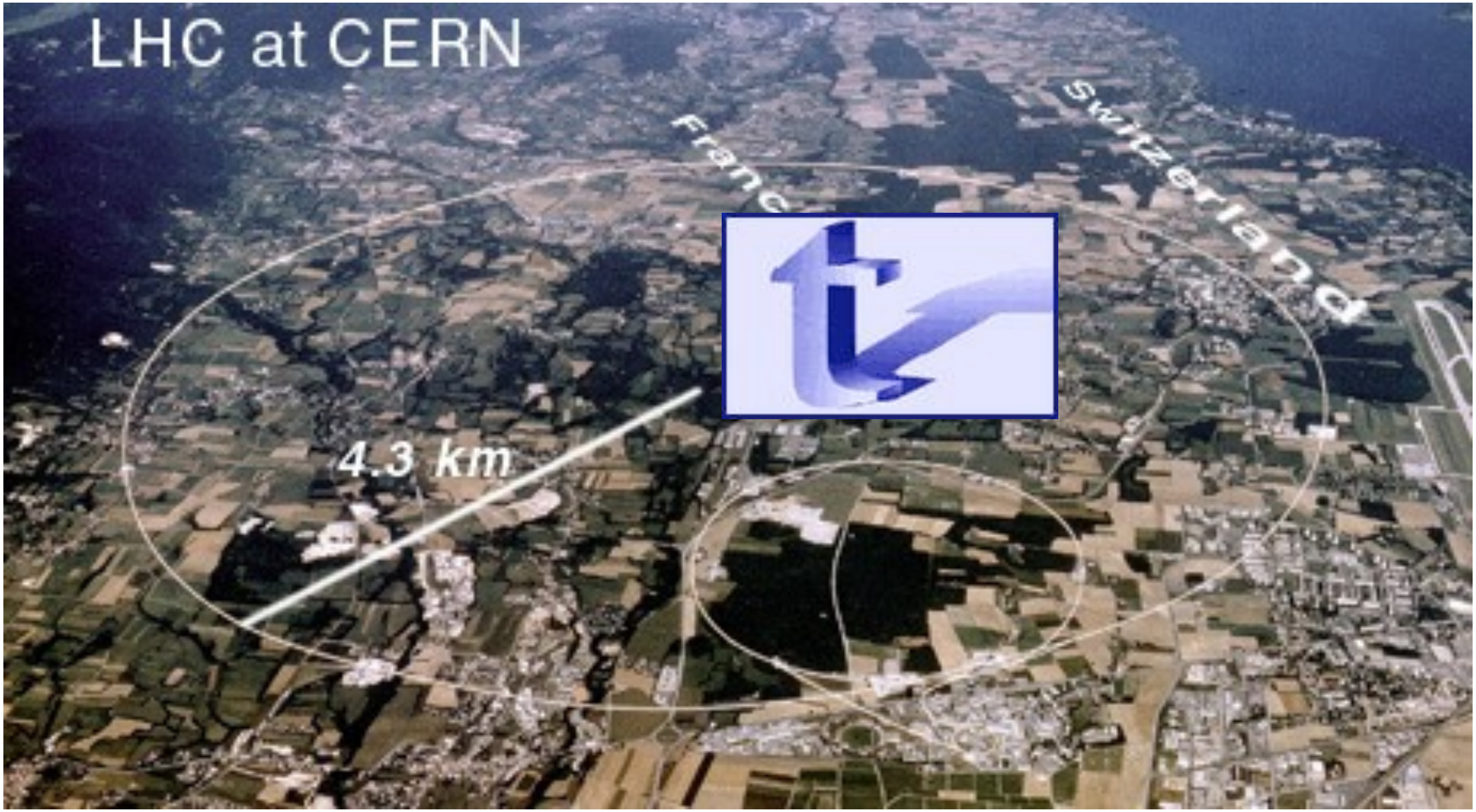
Generic

$$m_{\rm KK} > \frac{4.9\,(2.4)}{y_{5D}} \text{TeV}$$

IR (bulk) Higgs

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

3rd gen' Phys. @ the LHC



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.

$$\Downarrow$$

$$\textbf{Approximate } U(2) \textbf{ Limit of Massless Light Quarks}$$

The approximate U(2)

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

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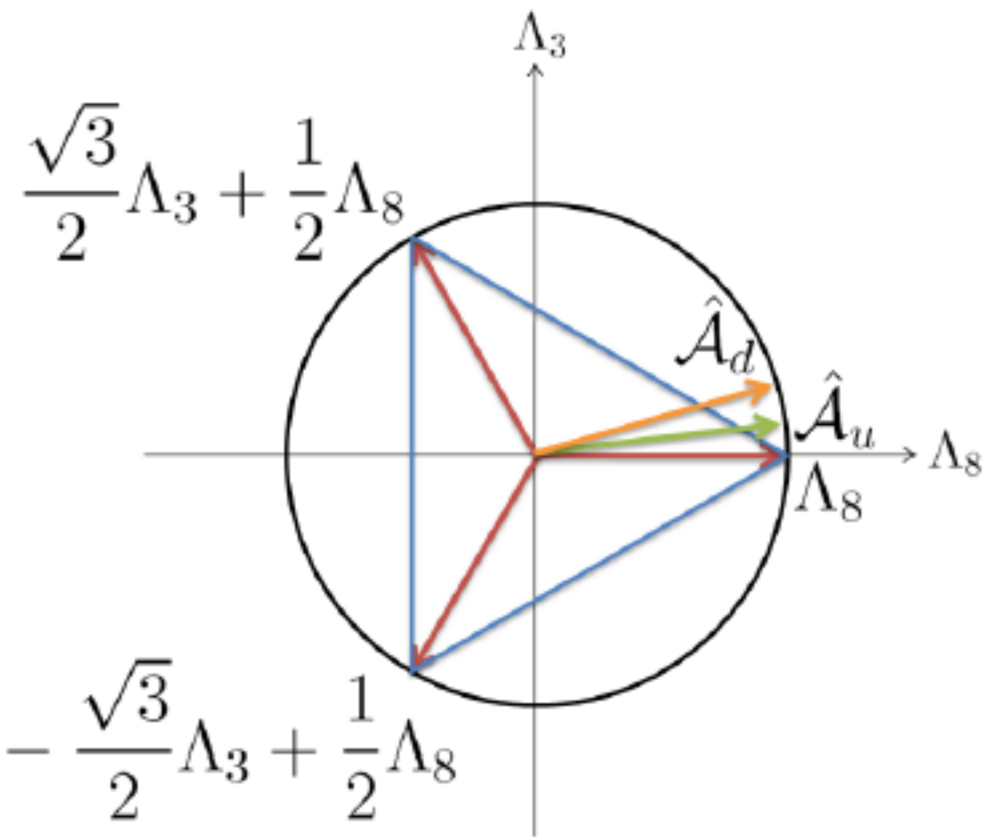
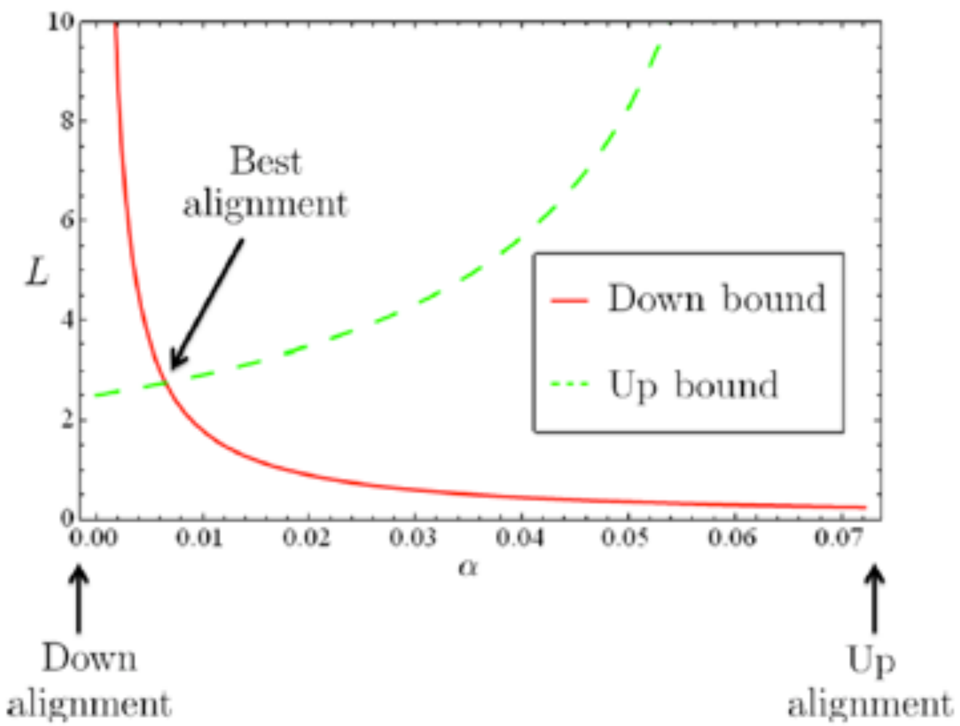


The bound

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

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

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



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

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}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	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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$(\bar{t}_L\gamma^\mu u_L)^2$	12		$7.1\ 10^{-3}$		$uu\to tt$

However, CPV in D system is stronger

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

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

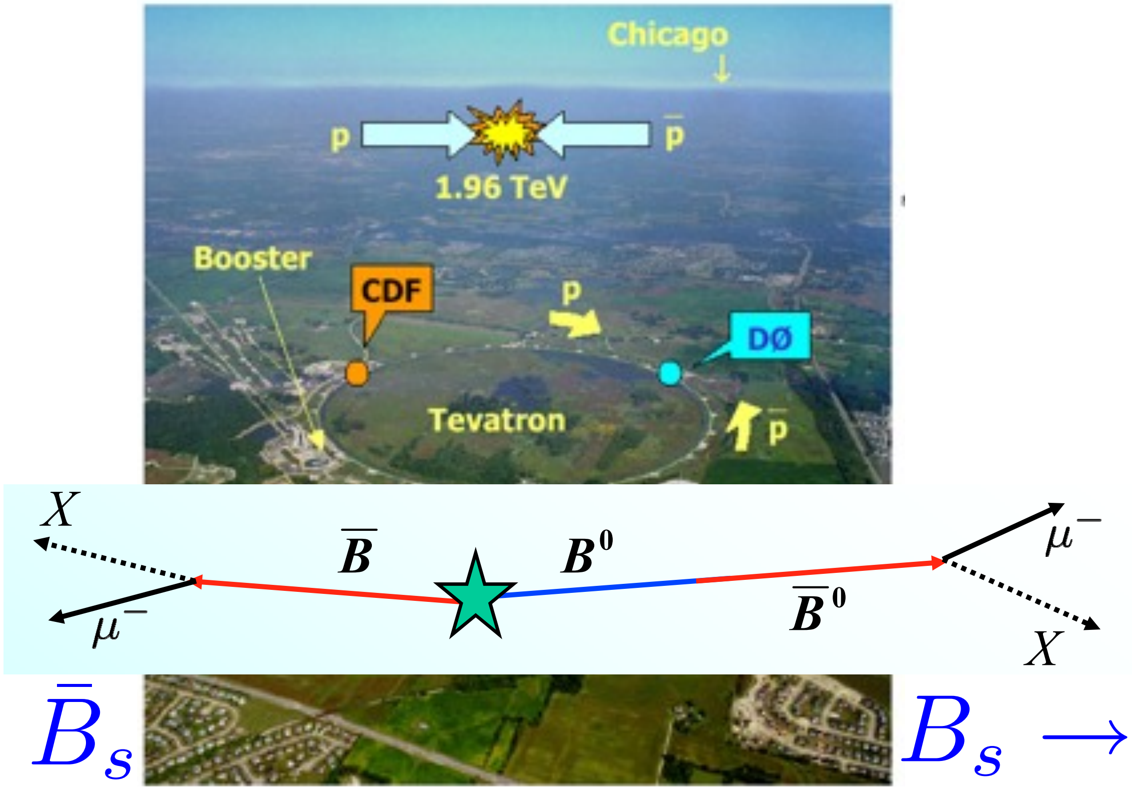
$$L < 12 \left(\frac{\Lambda_{\mathrm{NP}}}{1\,\mathrm{TeV}}\right) ; \quad \Lambda_{\mathrm{NP}} > 0.08\,(1)\,\mathrm{TeV} ,$$

for $uu \to tt$ and

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

for D mixing.

News from the Tevatron



$\psi\phi \leftarrow \bar{B}_s$ $B_s \to \psi\phi$

Ligeti, Papucci, GP, Zupan, to appear.

Dø reports 3.2σ in dimuon asymmetry; CDF improves $\Delta\Gamma_s$ vs. $S_{\psi\phi}$??

- **D0 result:** $a^b_{\rm SL} \equiv \dfrac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3},$

1005.2757.

fragmentation correlates $B_d \leftrightarrow B_s$

$$a^b_{\rm SL} = (0.506 \pm 0.043)\, a^d_{\rm SL} + (0.494 \pm 0.043)\, a^s_{\rm SL}\,.$$

Grossman et al. 06.

- Data favors NP in B_s : $\left(a^d_{\rm SL}\right)_{\rm exp} \ll a^b_{\rm SL} \Rightarrow a^s_{\rm SL} \sim a^b_{\rm SL}$

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- Assuming no direct CP => correlation with other observables:

$$\boxed{a^s_{\rm SL} = -\frac{|\Delta\Gamma_s|}{\Delta m_s}\, S_{\psi\phi} \Big/ \sqrt{1 - S^2_{\psi\phi}}\,,}$$

Ligeti et al. (06);
Grossman et al. (09).

Correlation with $\Delta\Gamma_s$ vs. $S_{\psi\phi}$

- D0 result can be written as:

$$-|\Delta\Gamma_s| \simeq \Delta m_s \big(2.0\, a_{\rm SL}^b - 1.0\, a_{\rm SL}^d\big) \sqrt{1 - S_{\psi\phi}^2} \,/\, S_{\psi\phi}\,.$$

Ligeti, Papucci, GP, Zupan.

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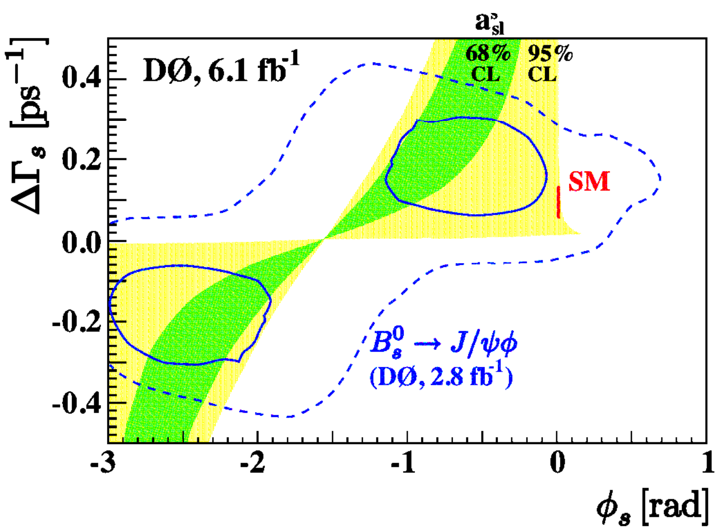
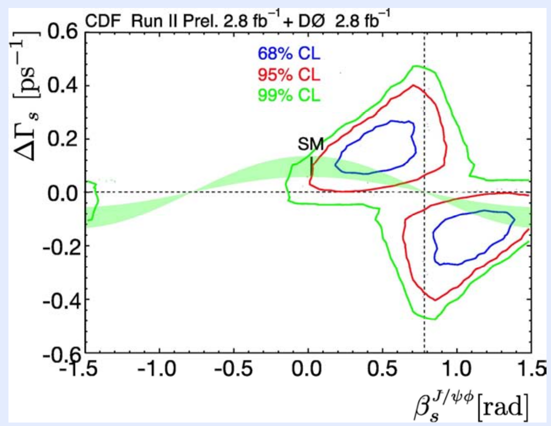
- Tevatron experiments also measure:

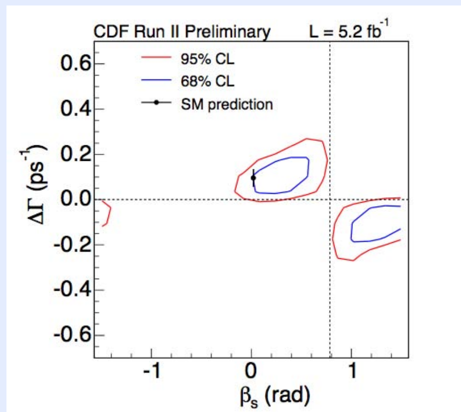




Tevatron combination: probability of observed deviation from SM = 3.4% (2.12 σ)

CDF Public Note 9787

New CDF measurement of β_s



Coverage adjusted 2D likelihood contours for β_s and $\Delta\Gamma$

P-value for SM point: 44% (0.8σ deviation)

Correlation with $\Delta\Gamma_s$ vs. $S_{\psi\phi}$

- **D0** result can be written as:

$$-|\Delta\Gamma_s| \simeq \Delta m_s \left(2.0\, a^b_{\rm SL} - 1.0\, a^d_{\rm SL}\right) \sqrt{1 - S^2_{\psi\phi}} \,/\, S_{\psi\phi} \,.$$

Ligeti, Papucci, GP, Zupan.

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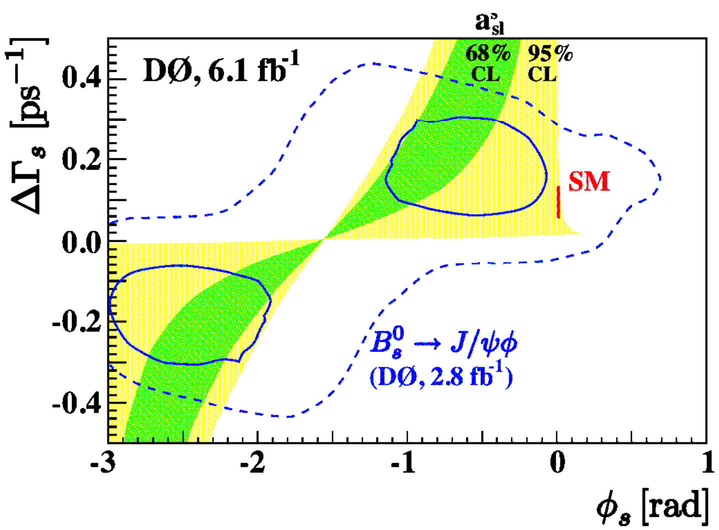

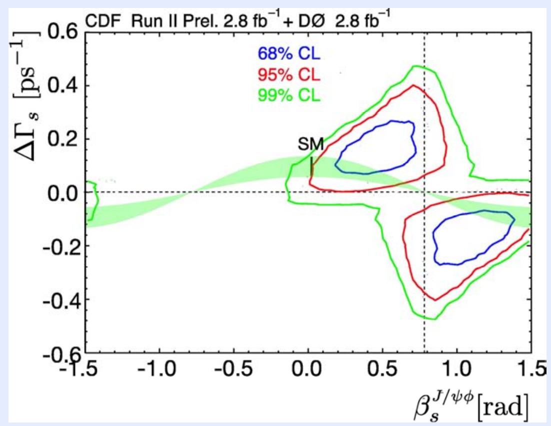

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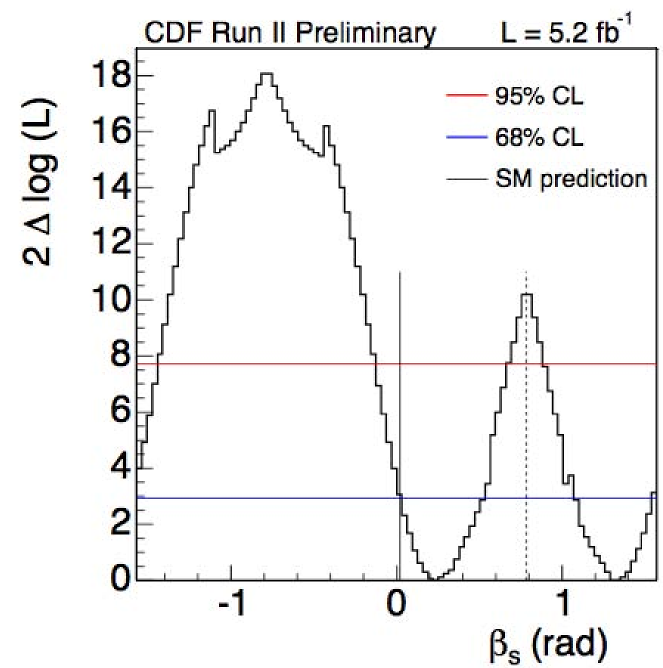

Allow for consistency check or making indep' $\Delta\Gamma_s$ fit (robustly bound NP)!

- Consistency check:

Ligeti, Papucci, GP, Zupan.

$$\left(a^b_{\rm SL}\right)_{\rm D\emptyset}: \qquad |\Delta\Gamma_s| \sim (0.28 \pm 0.15)\ \sqrt{1 - S_{\psi\phi}}/S_{\psi\phi}\ {\rm ps}^{-1}$$

$$\left(S_{\psi\phi}\right)_{\rm CDF+D\emptyset}: \quad (\Delta\Gamma_s,\, S_{\psi\phi}) \sim (0.15\,{\rm ps}^{-1},\, 0.64)$$

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- **Clean NP interpretation:** $M_{12}^{d,s} = \left(M_{12}^{d,s}\right)^{\rm SM}\left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$

($\Delta\Gamma_s$ is taken from the fit $\to$ not theory involved)

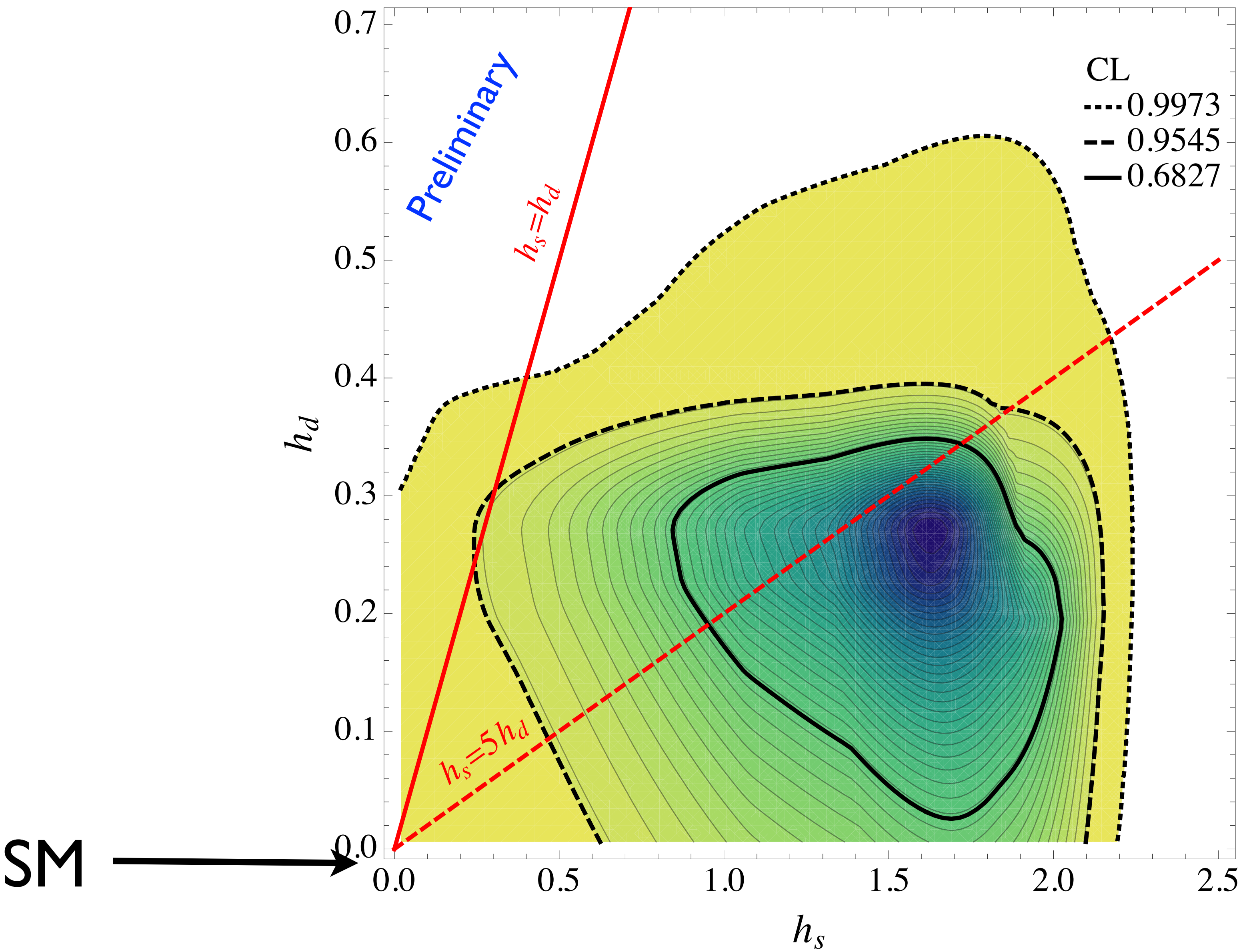
$$\begin{aligned}
\Delta m_q &= \Delta m_q^{\rm SM}\left|1 + h_q e^{2i\sigma_q}\right|,\\
\Delta\Gamma_s &= \Delta\Gamma_s^{\rm SM}\,\cos\left[\arg\left(1 + h_s e^{2i\sigma_s}\right)\right],\\
A^q_{\rm SL} &= \mathrm{Im}\left\{\Gamma^q_{12}/\left[M_{12}^{q,\rm SM}(1 + h_q e^{2i\sigma_q})\right]\right\},\\
S_{\psi K} &= \sin\left[2\beta + \arg\left(1 + h_d e^{2i\sigma_d}\right)\right],\\
S_{\psi\phi} &= \sin\left[2\beta_s - \arg\left(1 + h_s e^{2i\sigma_s}\right)\right].
\end{aligned}$$

Global fit's preliminary results

Ligeti, Papucci, GP, Zupan.

B_d vs. B_d systems

(we used CKMfitter)



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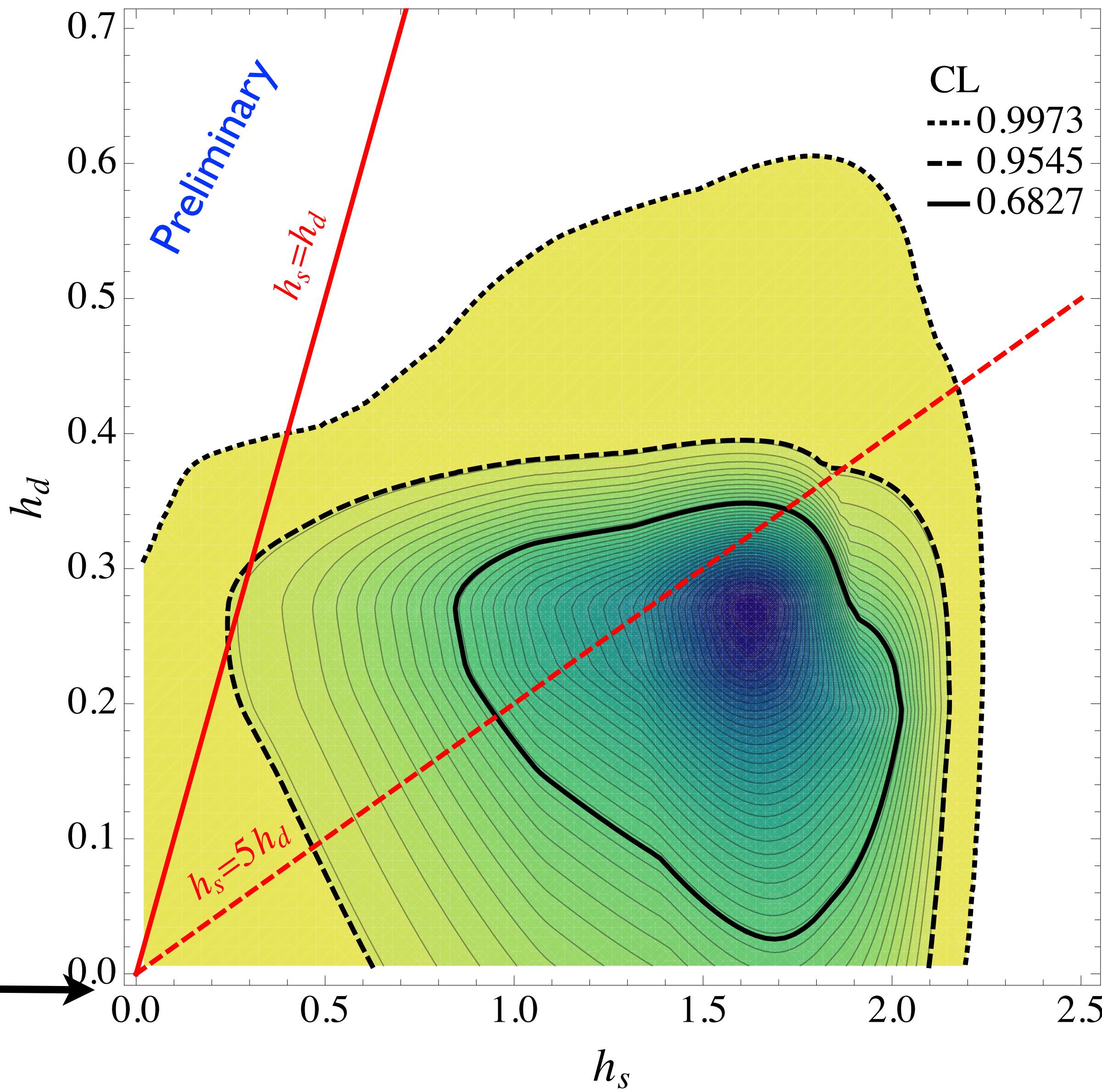


SM

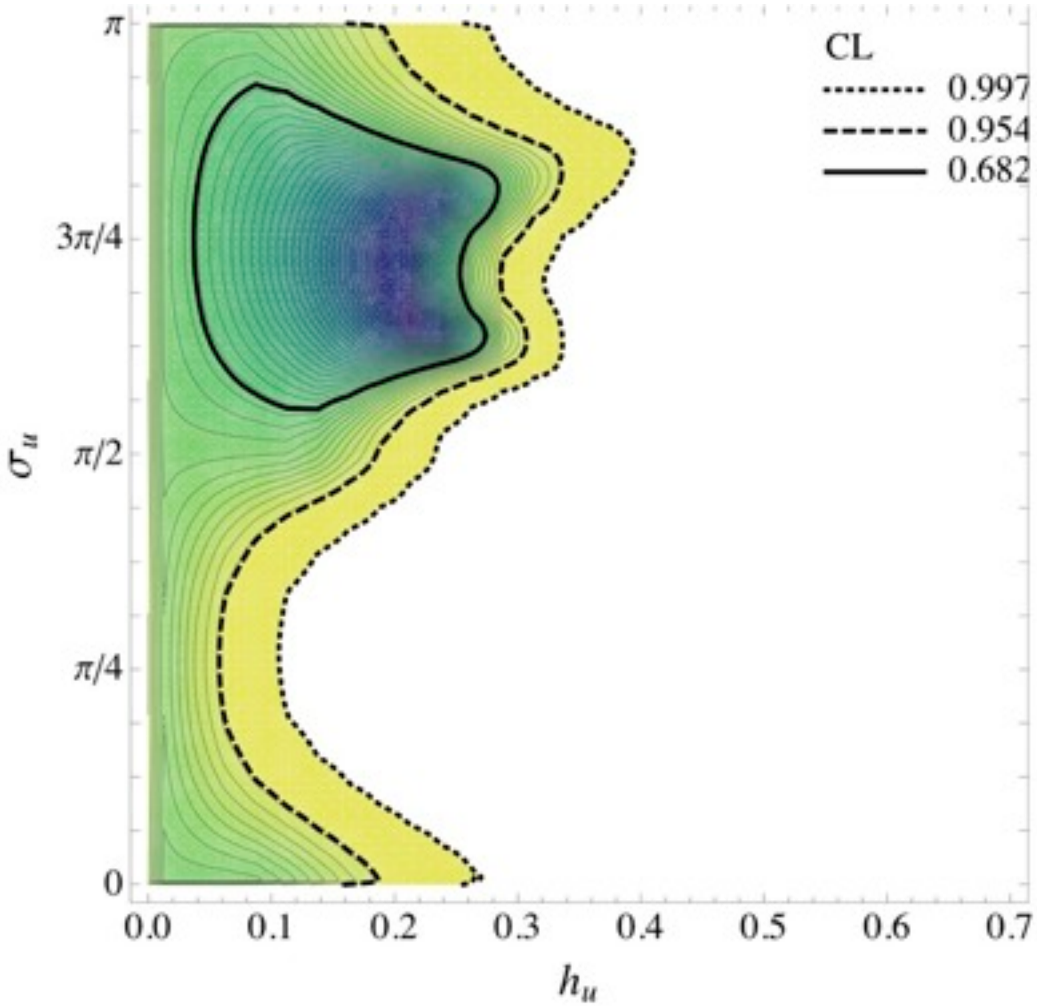
Data favors
$h_s > h_d$

Universal case: $h_d = h_s\ ,\quad \sigma_d = \sigma_s$

Ligeti, Papucci, GP, Zupan.

Preliminary

Viable with some tension.



Lessons from the data

Ligeti, Papucci, GP, Zupan.

♦ Tension with SM null prediction.

♦ $SU(2)_q$ approximate universality can accommodate data, a limit of many models, where NP effects are via 3rd gen'.

Ex.: general MFV (GMFV), MFV+flavor diag' phases.

Colangelo, et al. (09); Kagan, et al. (09).

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- What models naturally yield $h_s \gg h_d$??

Surprisingly: GMFV models dominated by (=> others as well):

$$O_4^{\rm NL} = \frac{c}{\Lambda^2_{\rm MFV;4}} \left[\bar{Q}_3 (A_d^m A_u^n Y_d)_{3i} d_i\right] \left[\bar{d}_3 (Y_d^\dagger A_d^{l,\dagger} A_u^{p,\dagger})_{3i} Q_i\right].$$

$$\Lambda_{\rm MFV;4} \gtrsim 13.2\, y_b \sqrt{m_s/m_b}\ {\rm TeV} = 2.9\, y_b\, {\rm TeV}$$

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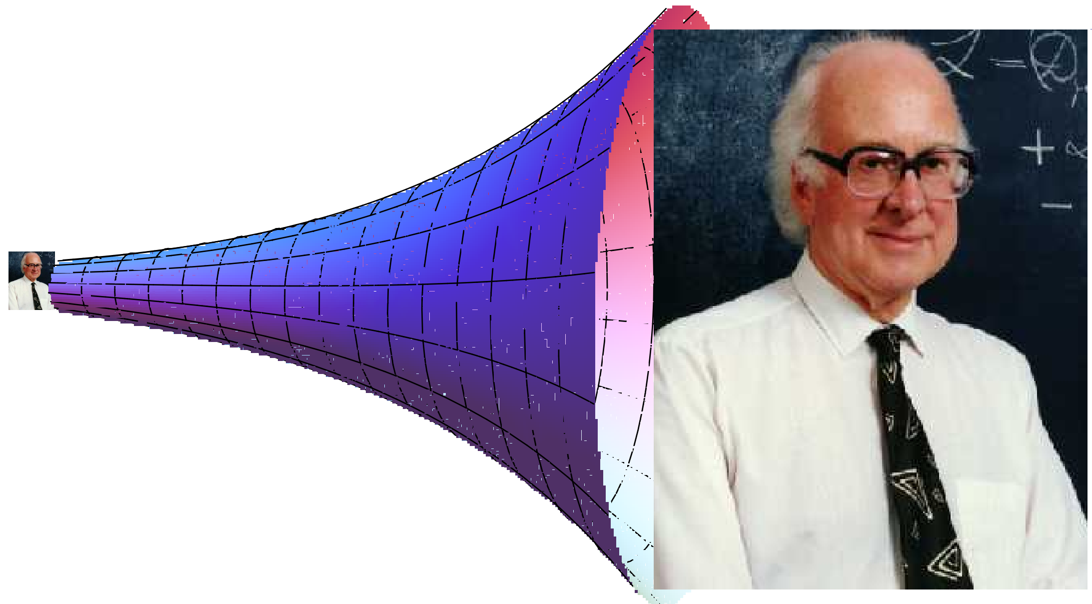
Warped Exra Dimension



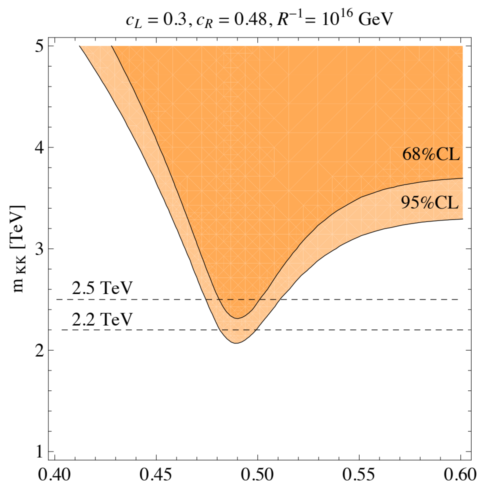
Randall Sundrum (RS)

Radical solutions to flavor problem

- Rattazzi-Zaffaroni's model: excellent protection but no solution for the little hierarchy problem.

- Is there a bulk version? Can one lower the KK scale?

(Delaunay,Lee & GP, to appear)



$$\text{Yes, } M_{\text{KK}} = \mathcal{O}(2\,\text{TeV})$$

- New type of LHC pheno', flavor gauge bosons.

Csaki, Lee, Weiler, in progress.

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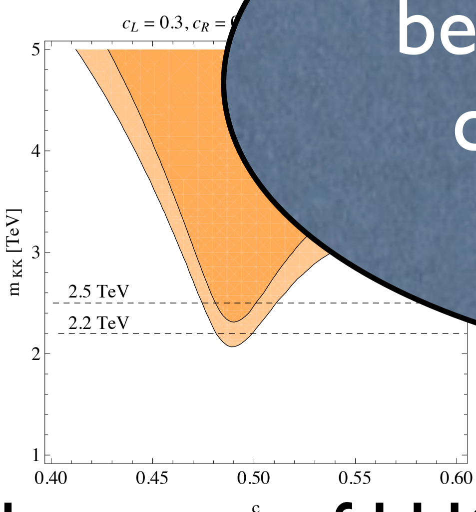

TeV)

These models generically belong to the GMFV class can be probed directly @ the LHC!

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Outlook: Flavor Diagonal Information

Template Overlap Method for Energy Correlations in Massive Jets

Almeida, Lee, GP, Sterman & Sung, to appear.

♦ Above framework show anomalies in $\left(\dfrac{d\sigma}{dm_{t\bar{t}}}\right)_{m_{t\bar{t}}\sim\mathrm{TeV}}$.

Agashe et al. (06); Lillie et al. (07).

♦ Can be observed provided that highly boosted tops can be distinguished from di-jet background - many approaches has been proposed with nice success.

♦ Can we be more systematic about the info' that can be extracted ?

Template Overlap Method for Energy Correlations in Massive Jets

Almeida, Lee, GP, Sterman & Sung, to appear.

- General characterization of the jet energy flow:

$$|t> \; = \; \text{top distribution}$$
$$|g> \; = \; \text{massless QCD distribution}$$

We need a probe distribution, $|f>$, such that

$$R = \left(\frac{<f|t>}{<f|g>}\right) \quad \text{is maximized.}$$

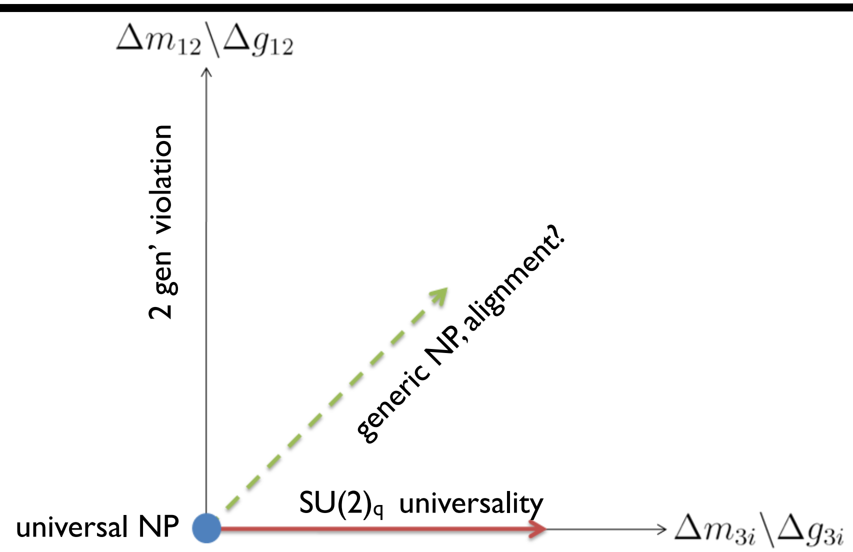
- No jet- manipulation just looking for maximal overlap function:

MC	Jet mass cut only		Mass cut + Ov + Pf	
	Top-jet efficiency [%]	fake rate [%]	Top-jet efficiency [%]	fake rate [%]
Pythia8	57.8	3.6	20.5	0.0216
MadGraph	52.3	3.7	10.5	0.0168
Sherpa	34.3	3.2	7	0.032

(Ov=overlap, Pf=planar-flow)

Possible linkage between low E & high E signals in 3rd generation physics @ the LHC era.

The importance of flavor diag' info; Connection with flavor conversion.



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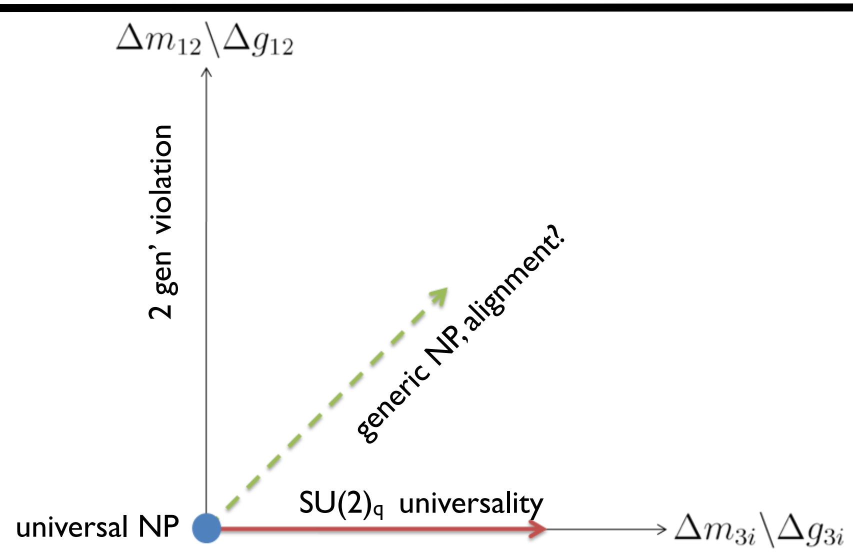
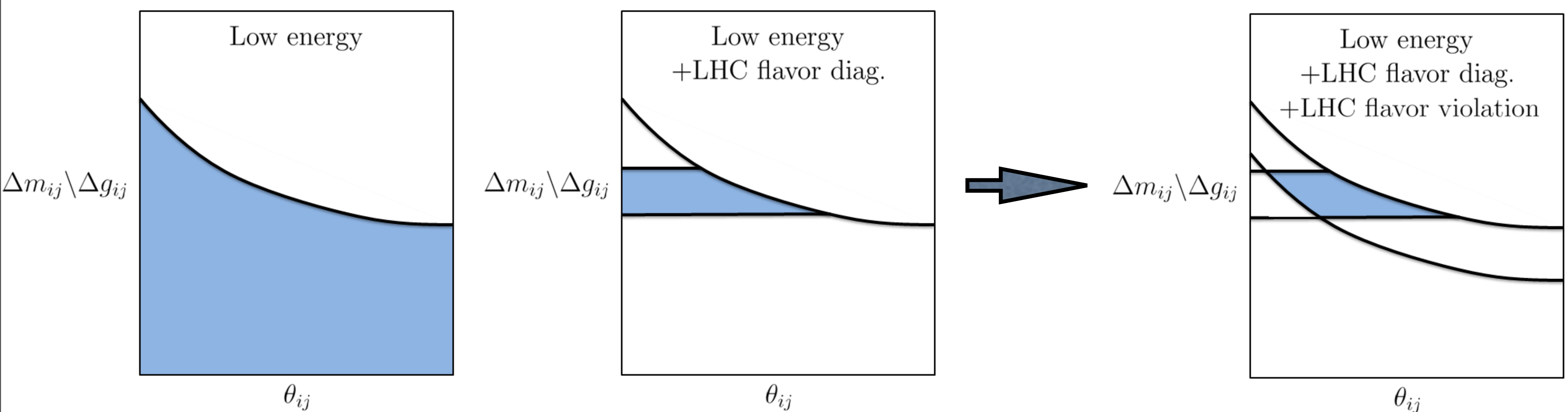
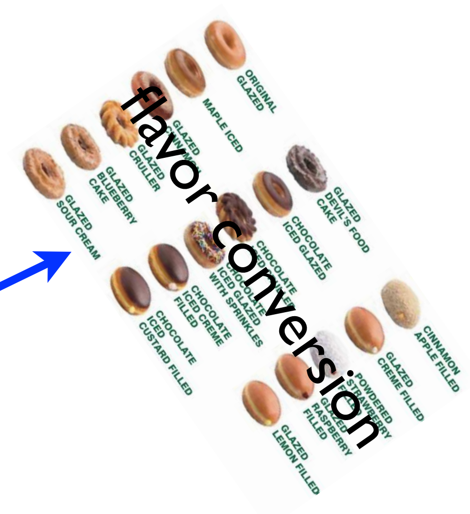


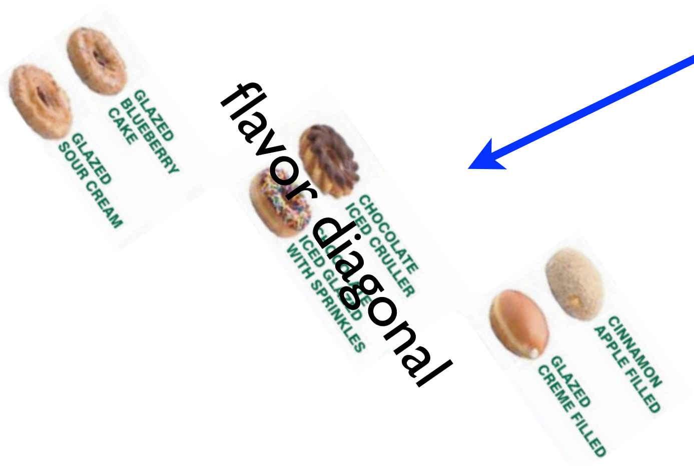


Grossman et al. (09); Gedalia & Perez (10)

Thank you



flavor conversion



flavor diagonal

Backups

Precision Measurements in D mixing

- Huge recent progress in measurement of mass splitting & CP violation (CPV) in the D system:

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$$\Delta m_D/m_D = (8.6 \pm 2.1) \times 10^{-15}$$
$$A_\Gamma = (1.2 \pm 2.5) \times 10^{-3}$$

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)};$$

$$A_\Gamma = \frac{1}{2}(|q/p| - |p/q|)y\cos\phi - \frac{1}{2}(|q/p| + |p/q|)x\sin\phi$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}. \qquad \lambda_{K^+K^-} = -|q/p|e^{i\phi},$$

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- System parameters roughly determined (HFAG):

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

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

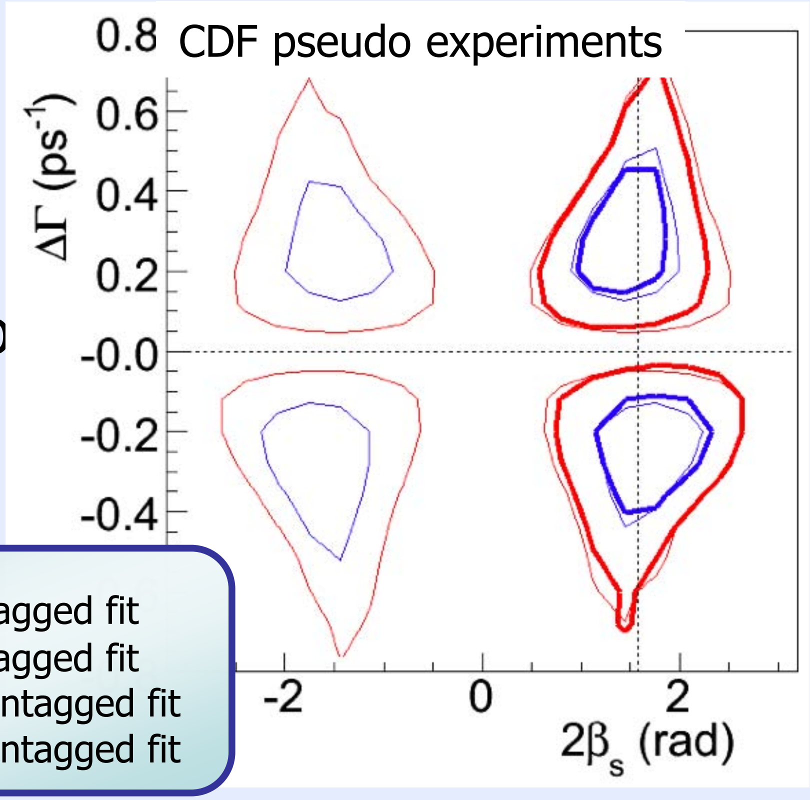
- Fit without flavour tagging, has four fold ambiguity:
  - β_s and $\Delta\Gamma$ symmetric
  - strong phases symmetric about pi

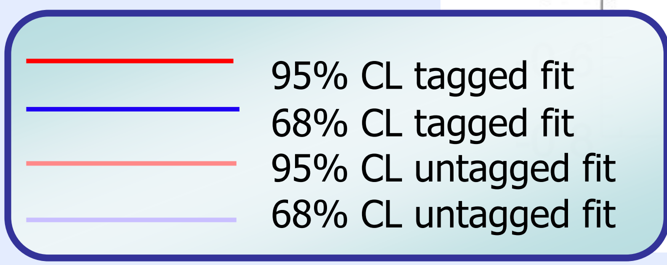
$$\begin{aligned} \beta_s &\rightarrow \frac{\pi}{2} - \beta_s \\ \Delta\Gamma &\rightarrow -\Delta\Gamma \\ \phi_{\|} &\rightarrow 2\pi - \phi_{\|} \\ \phi_{\perp} &\rightarrow \pi - \phi_{\perp} \end{aligned}$$

and

$$\begin{aligned} \beta_s &\rightarrow -\beta_s \\ \Delta\Gamma &\rightarrow -\Delta\Gamma \end{aligned}$$

- Addition of flavour tagging allows us to follo time dependence of B_s and $\overline{B}_s$ separately
  -> Removes half of the ambiguity





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

$$|z_1^K| \leq z_{\rm exp}^K = \boxed{8.8\times 10^{-7}}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

$$|z_1^D| \leq z_{\rm exp}^D = \boxed{5.9\times 10^{-7}}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

with CPV

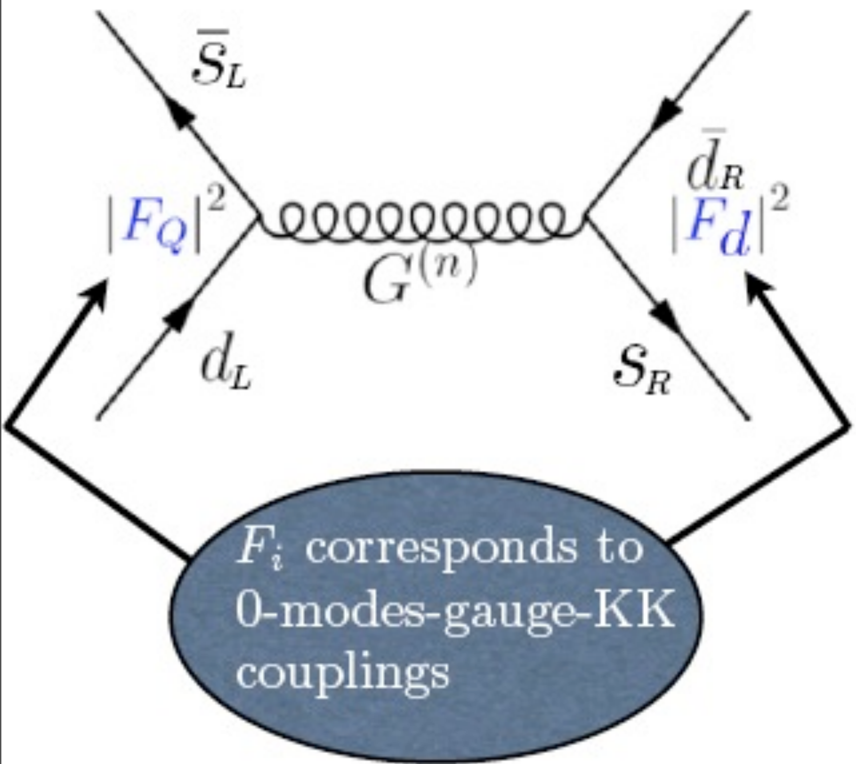
$$\mathcal{I}m(z_1^K) \leq z_{\rm exp}^{IK} = \boxed{3.3\times 10^{-9}}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

$$\mathcal{I}m(z_1^D) \leq z_{\rm exp}^{ID} = \boxed{1.0\times 10^{-7}}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

The RS "little" CP problem

♦ O(100) chiral enhancement for *LLRR* current yield

a severe bound on IR Higgs, $M_{\rm KK} = \mathcal{O}(10\,\text{TeV})$

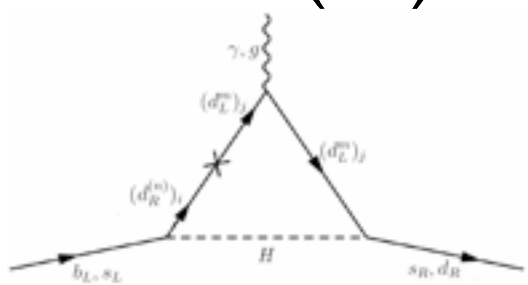


UTFit; Davidson, Isidori & Uhlig (07); Blanke et al.; Casagrande et al.; Csaki, Falkowski & Weiler; Agashe, Azatov & Zhu (08) Gedalia, GP & Isidori (09).

$$\Rightarrow \epsilon_K \propto F_Q^\dagger F_Q F_d^\dagger F_d \sim \frac{m_d m_s}{\left(Y_5^d\right)^2}$$

♦ Contributions to EDM's are O(20) larger than bounds.

Agashe, GP & Soni (04)



The RS "little" CP problem

- Combination of ϵ_K & $\epsilon'/\epsilon_K \Rightarrow M_{\mathrm{KK}} = \mathcal{O}(10\,\mathrm{TeV})$

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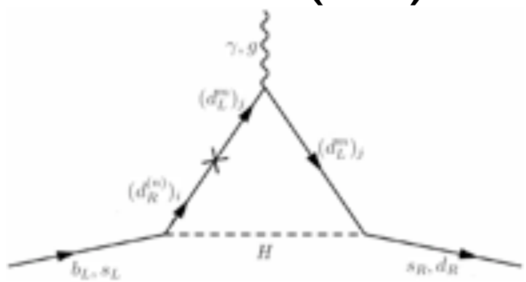

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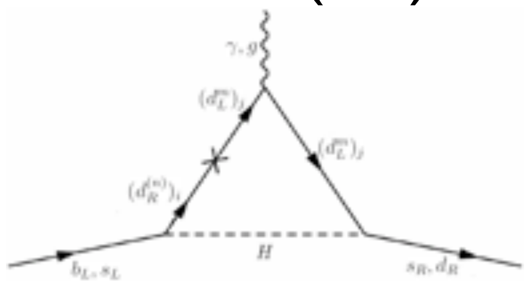
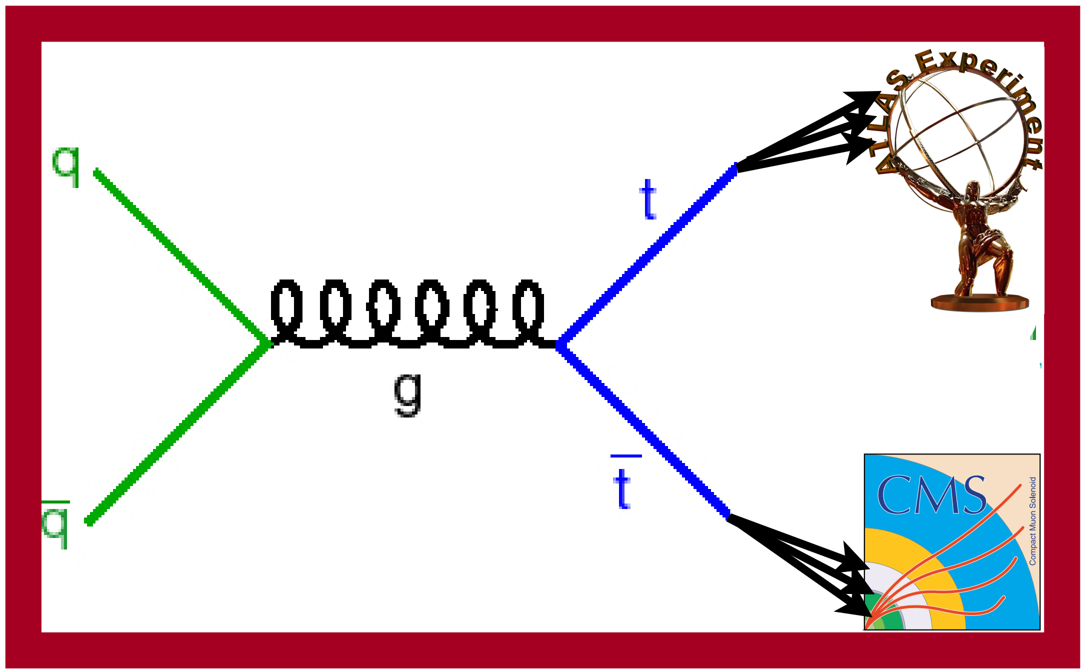


Severe tuning problem or fine tuning problem & null LHC pheno'.

Parametric solutions to the RS little CP problem & some LHC implications.



5D MFV & Shining

(either give up on solving the flavor puzzle, Rattazzi & Zaffaroni (00), Cacciapaglia, Csaki, Galloway, Marandella, Terning & Weiler (07) or)

- $Y_{u,d}$ => anarchic & the only source of flavor breaking.

Fitzpatrick, GP & Randall (07)

- Also, bulk masses are functions of same spurions:

$$C_{u,d} = Y^{\dagger}_{u,d} Y_{u,d} + \ldots, \quad C_Q = r Y_u Y_u^{\dagger} + Y_d Y_d^{\dagger} + \ldots,$$

$$\text{Shining} \Rightarrow \text{down alignment in the } r \to 0 \text{ limit.}$$

Csaki. et al. (09)

U-anarchy - constrained by *D* phys.

- 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): $y_{5\rm D}^d \gtrsim 3 y_{5\rm D}^u$ Csaki, et. al (09).

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

⇒ Factor of few improvement exclude models.

Radical solutions

- Rattazzi-Zaffaroni's model: excellent protection but no solution for the little hierarchy problem.

- Is there a bulk version? Can one lower the KK scale?

(Delaunay,Lee & GP, preliminary)

Custodial sym': Non-universal oblique corrections & FCNC's are under control;

Agashe, et al. (06)

Universal oblique corrections are problematic.

- New type of LHC pheno', flavor gauge bosons.

Csaki, Lee, Weiler, in progress.

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

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tFCNC vs. bFCNC, generic bounds

Fox, et. al (07).

Effective theory, dim' 6 operators:

$$O^u_{LL} = i\left[\overline{Q}_3\tilde{H}\right]\left[\left(\not{D}\tilde{H}\right)^\dagger Q_2\right] - i\left[\overline{Q}_3\left(\not{D}\tilde{H}\right)\right]\left[\tilde{H}^\dagger Q_2\right] + \text{h.c.}$$

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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

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Not valid if down alignment is at work 

2x Gedalia, et al. (10).

Covariant basis, CPV (strongest bounds)

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

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2gen' Jarlskog

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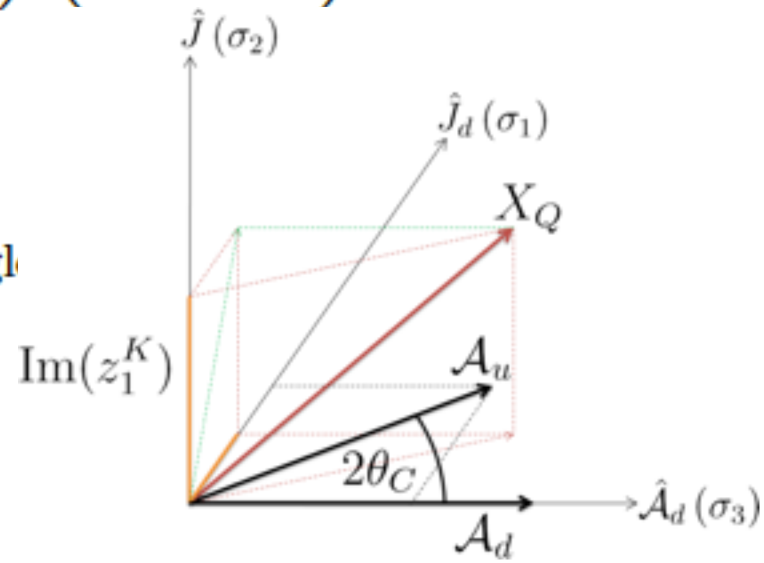
- CPV in $\Delta F = 2:$ $\quad \mathrm{Im}\left(z_1^{K,D}\right) = 2\left(X_Q \cdot \hat{J}\right)\left(X_Q \cdot \hat{J}_{u,d}\right)\,.$

$\mathrm{Im}(z_1^K)$ 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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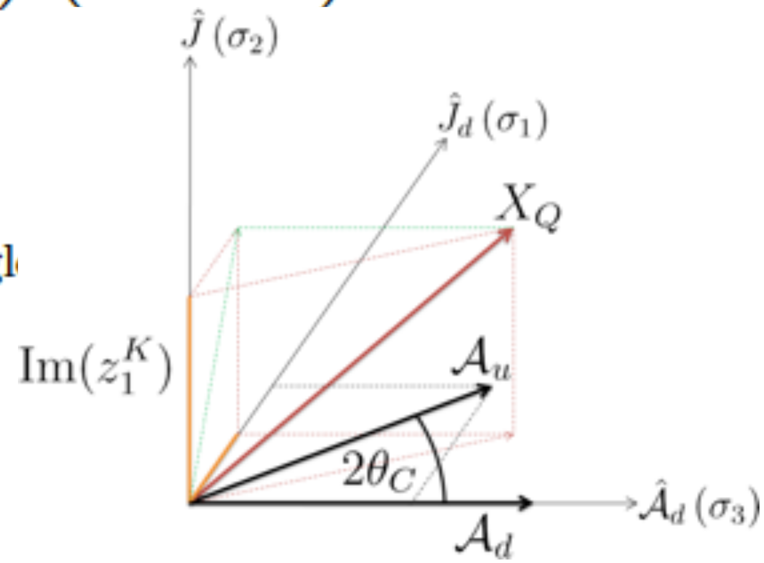

- Deriving a robust bound:

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

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