Heavy Flavour Theory
(Current status, SM & Beyond)

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quark - lepton
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Outline

- Brief introduction, importance of flavor physics.

- Model independent information (effective field theory).

- Up type frontier, $D-\bar{D}$ mixing, tFCNC & importance for alignment.

- Implications of D0 & CDF results related to CPV $\in B_s-\bar{B}_s$.

- Outlook, the LHC era.

Why flavor phys. (CP Violation) ?

- Sensitive to ultra short distance phys. beyond direct reach.

$$\left[Br(K \to \mu^+\mu^-)(\mathrm{GIM}),\ \Delta m_K(m_c),\ \Delta m_B(m_t)\right]$$

- Flavor puzzle - parameters are small & hierarchical.

$$CP^{\mathrm{SM}} = J_{\mathrm{KM}} \frac{(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)}{v^{12}} = \mathcal{O}(10^{-22})$$

- Cosmological baryon asymmetry <=> new CPV (flavor?)

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

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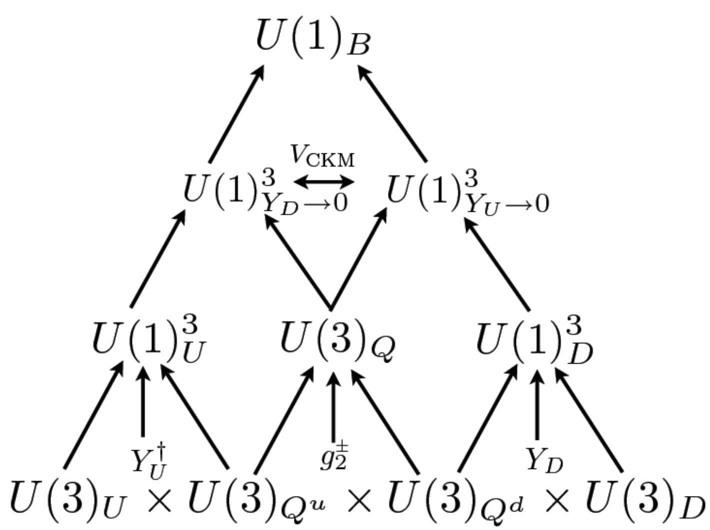

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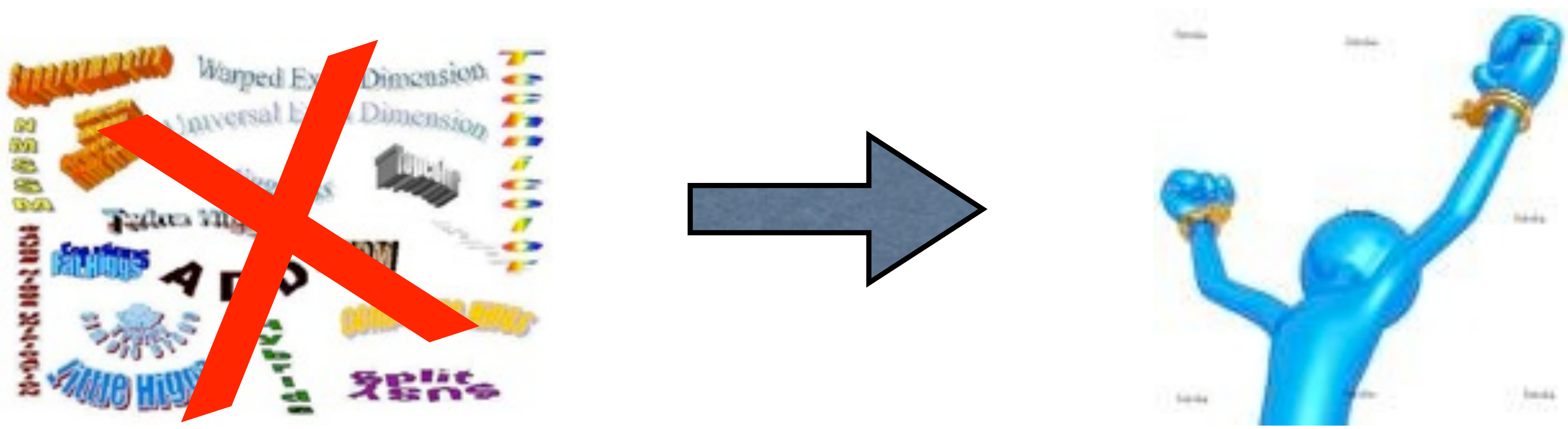
- Deviation from SM predictions can be easily probed or severe bounds on new physics (NP) obtained.

What do we know about the New Phys. flavor sector, model independently?



Generic bounds via effective theory

$\Delta F = 2$ processes among the cleanest.

In the SM proceed at loop and highly suppressed.

To leading order beyond the SM:

$$\frac{(\bar{q}_i q_j)(\bar{q}_i q_j)}{\Lambda_{\mathrm{NP}}^2}$$

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What are the bounds on Λ_{NP}

for different flavor transitions?

$\Delta F = 2$ status

Isidori, Nir & GP, Ann. Rev. Nucl. Part. Sci. (10)

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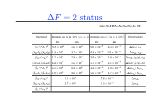
D-system falls only behind the K-one



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t-FCNC
stay
tuned!

D-system fall ... ind the K-one

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Recent CPV discussed shrotly stay tuned #2

t-FCNC stay tuned!

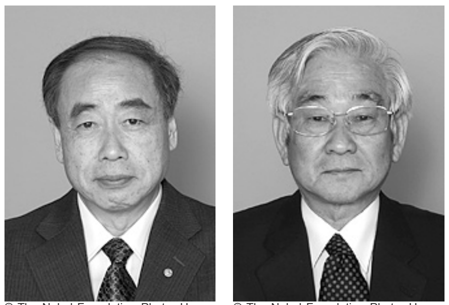
D-system fall[illegible]ind[illegible]e

What do we conclude ?

◆ SM mechanism to induce flavor & CPV

is successful.

The Nobel Prize in Physics



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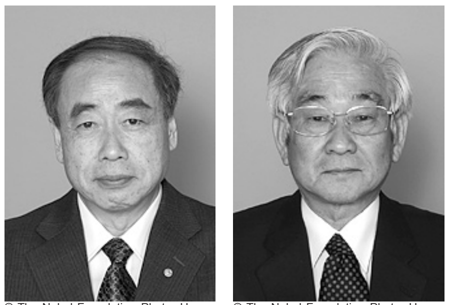

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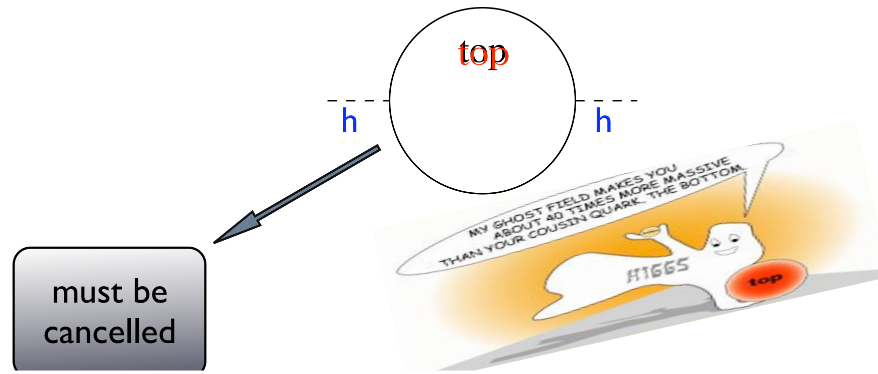
- Resulting bounds are too strong to allow for generic TeV-scale NP - tension with solving the fine tuning problem.

- Hint for underlying structure of microscopic laws of nature.

What kind of NP survives?

- Flavor blind/universal NP, for sure, but then cancellation of top divergencies looks like a miracle.



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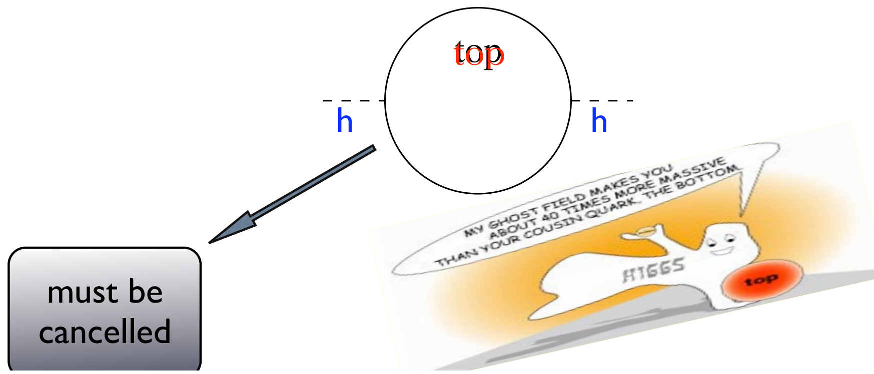

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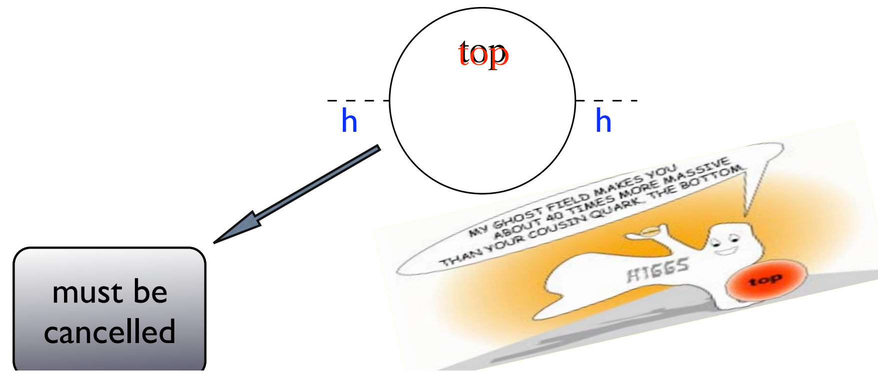

♦ Maybe NP flavor structure is controlled by SM one, minimal flavor violation (MFV) => more exciting then guessed, see later ...

♦ Maybe NP is anarchic but aligned.

uFCNC data, a crucial test of alignment

♦ 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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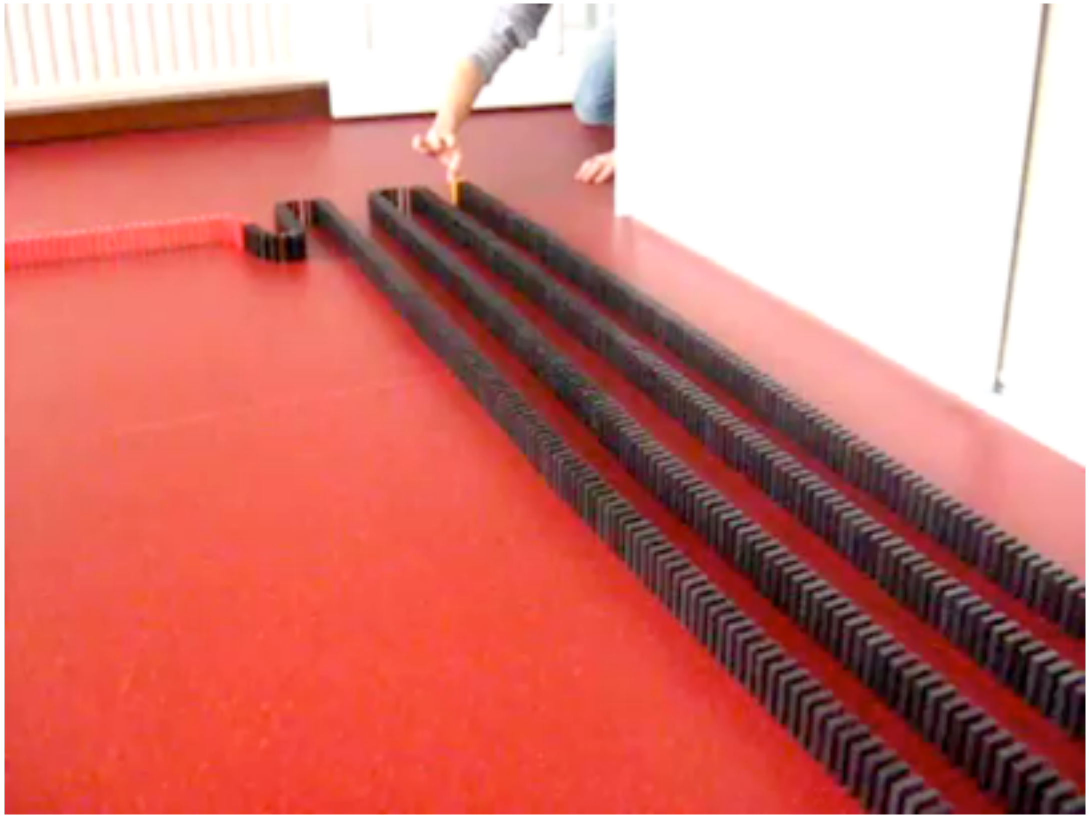

careful domino *alignment*

Up sector

Look Down

Look Up

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

ד

δ

Δ

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

- System parameters roughly determined (HFAG):

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

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

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

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

Bottom contribution is down by:

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

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

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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, PRL (07); Kagan and M. D. Sokolof, PRD (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, Grossman, Nir & GP, PRD (09).

long distance dominated?

Falk, et. al (02).

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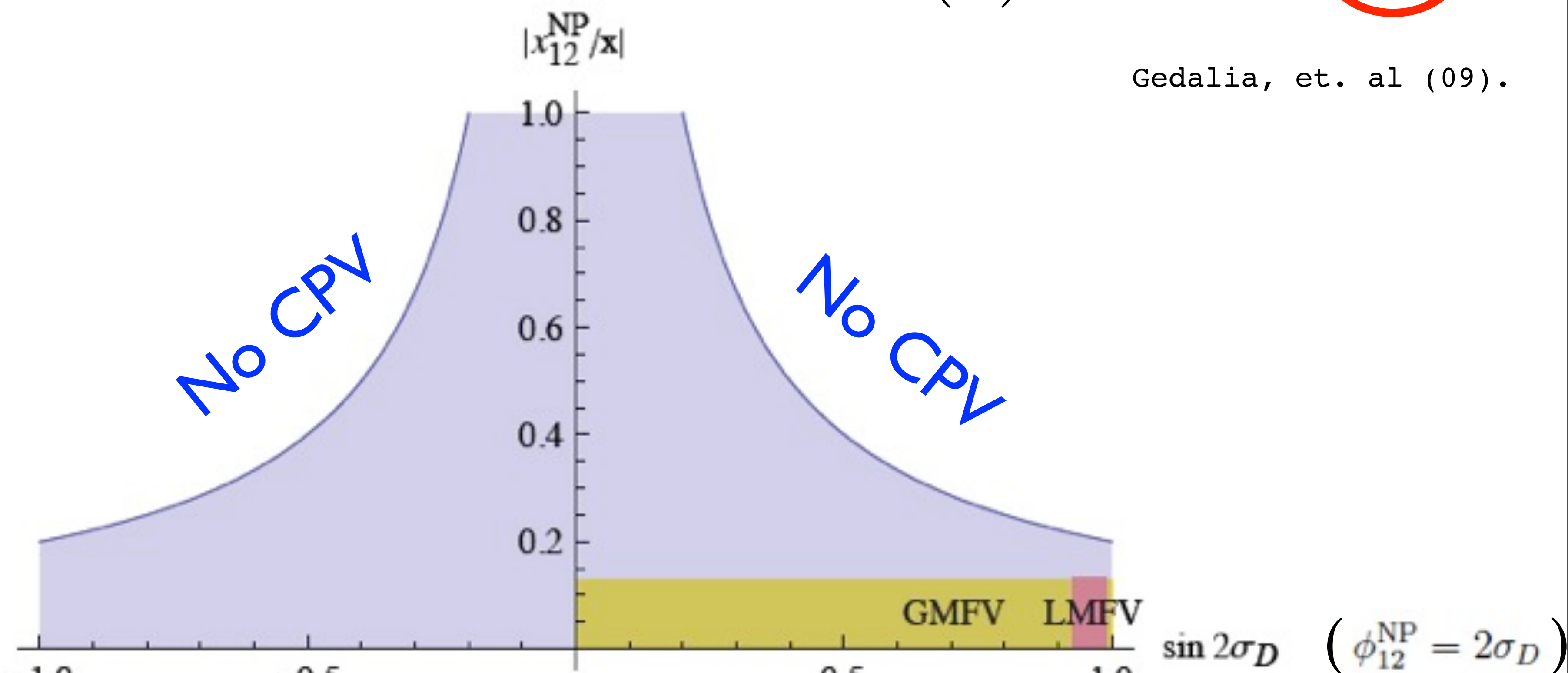

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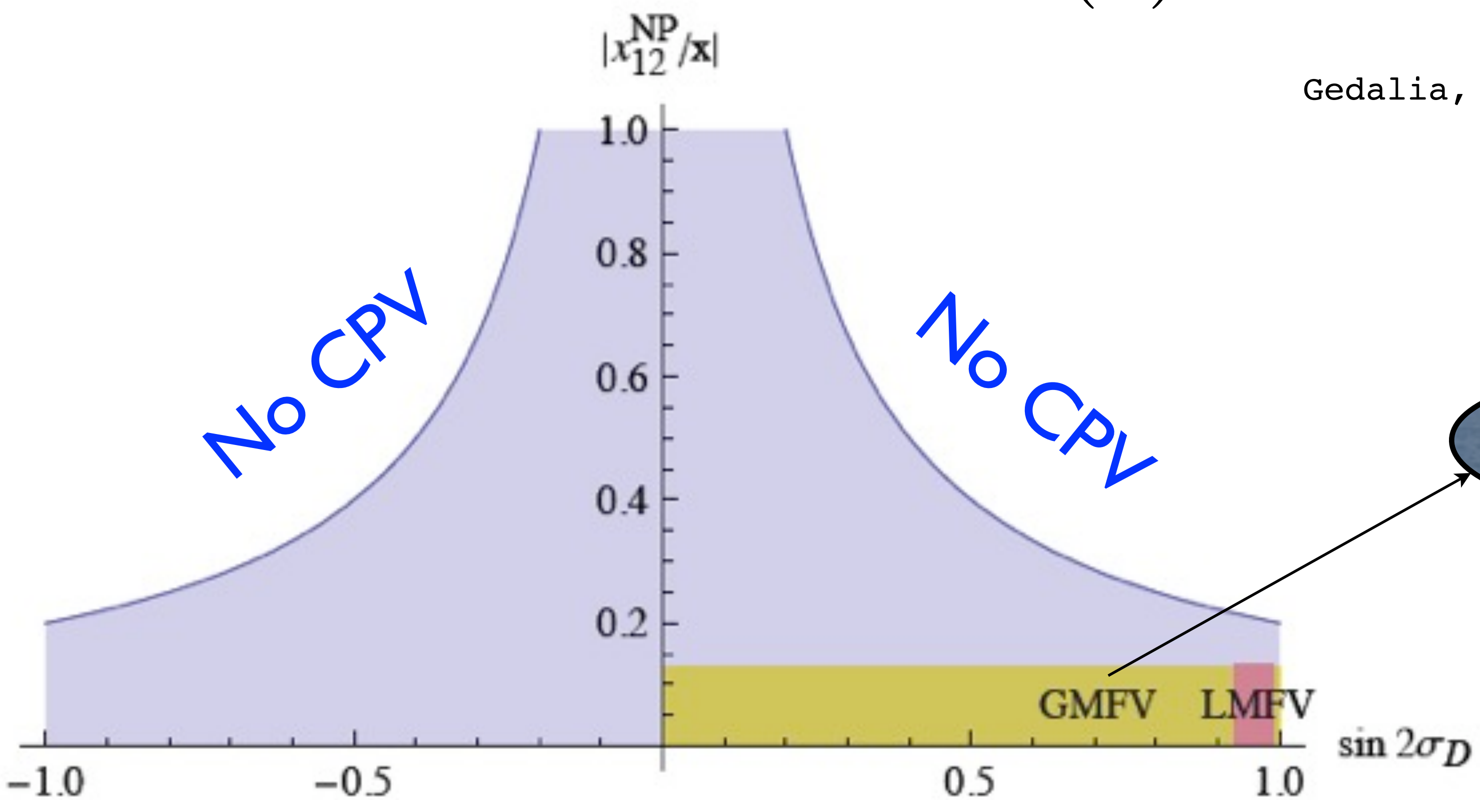

$(\phi_{12}^{\rm NP} = 2\sigma_D)$

The importance of up-type FCNC

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}	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
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$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	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}; $S_{\psi K_S}$
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What if down alignment is at work ?

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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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$+$

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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!

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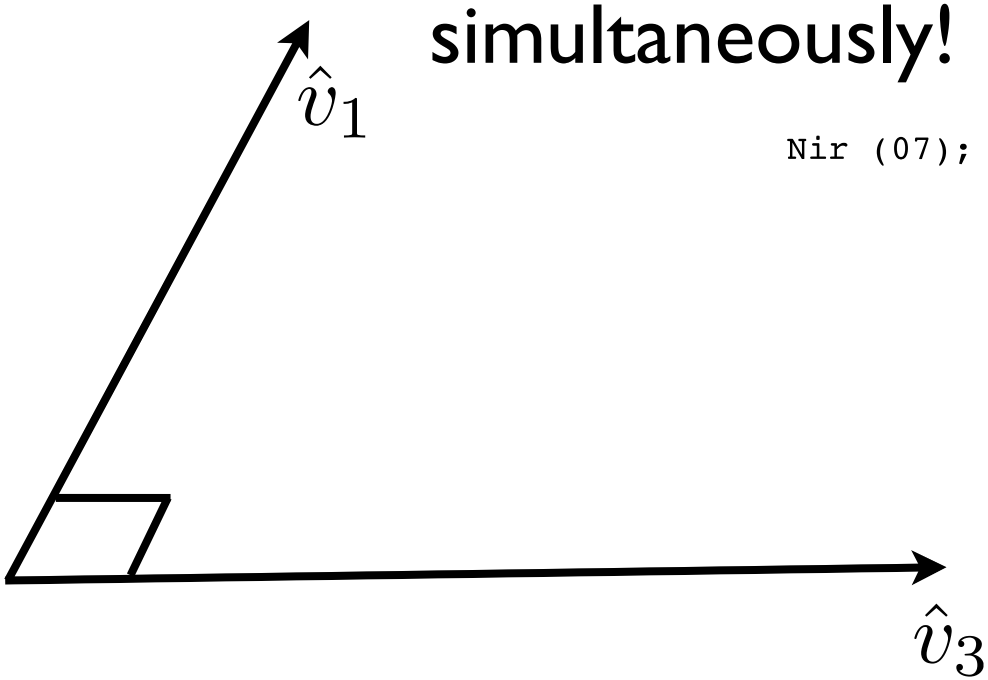

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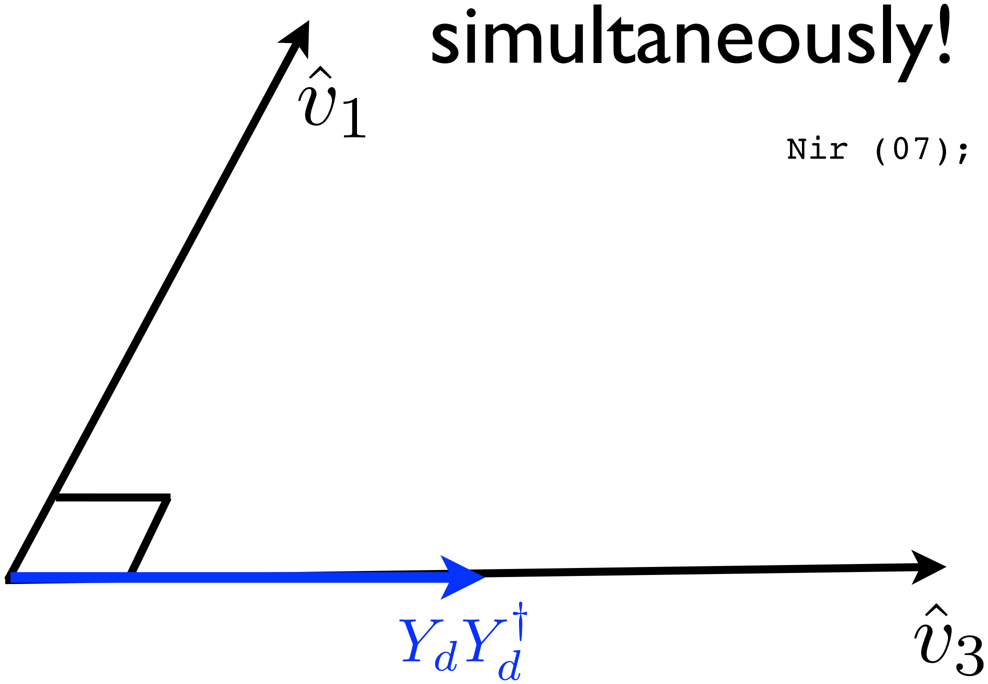

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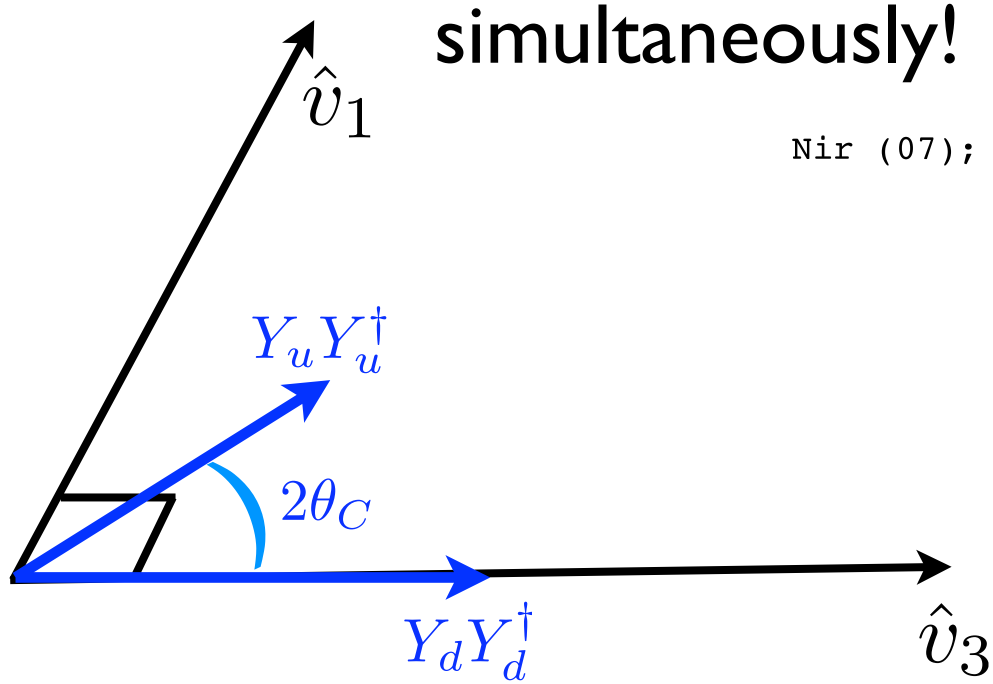

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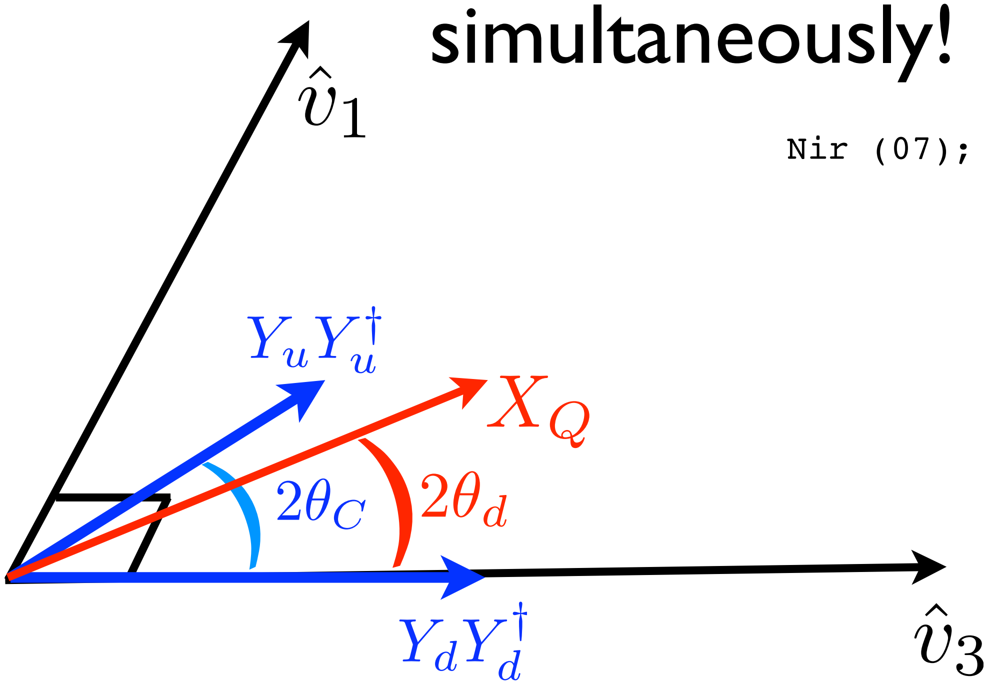

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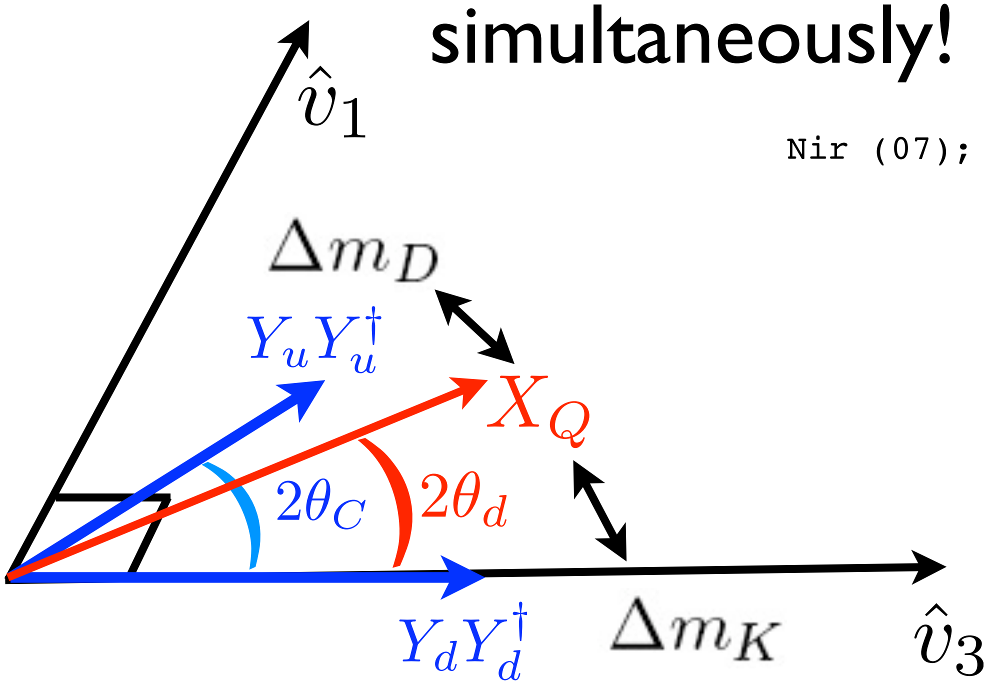

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Implications of CPV in $D^0 - \bar{D}^0$ mixing

(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

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

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

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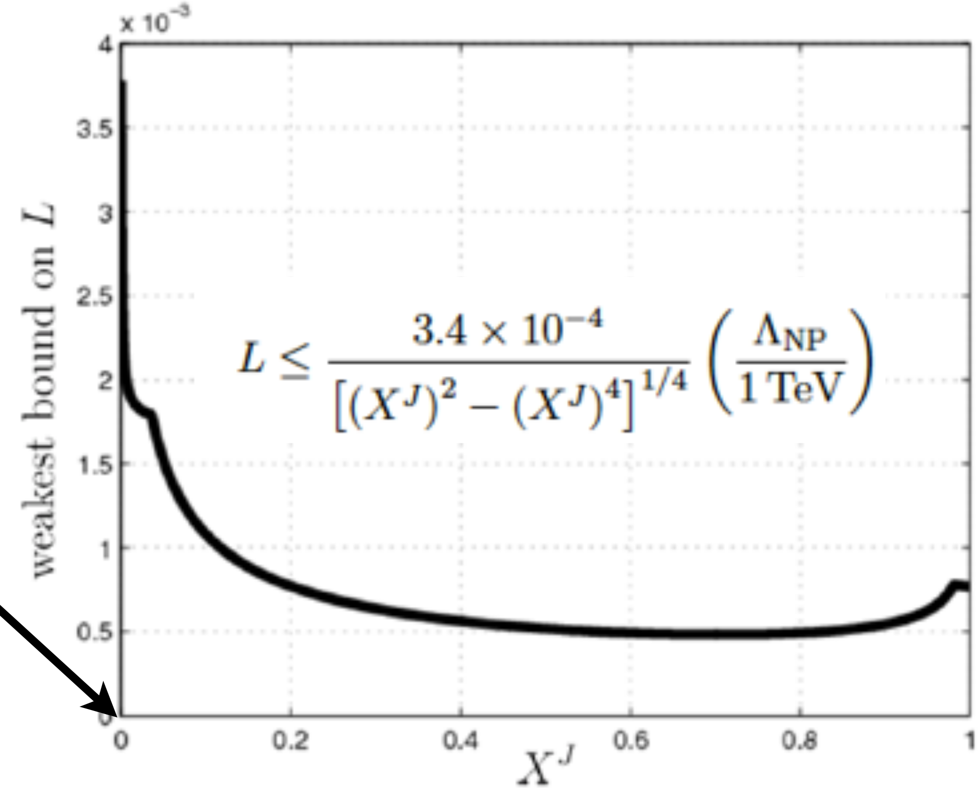

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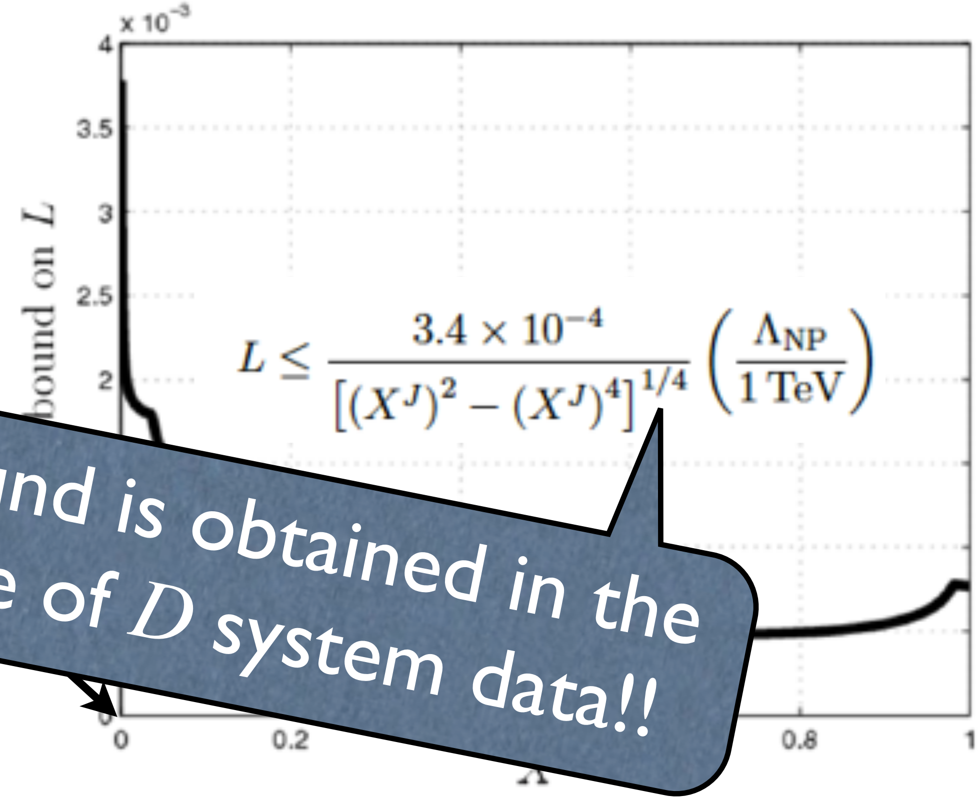

No CPV

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

CPV in D: Model Dependent Implications

(i) MFV (exciting #1); (ii) SUSY; (iii) Randall-Sundrum (RS).

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

Kagan, GP, Volanksy & Zupan, PRD (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
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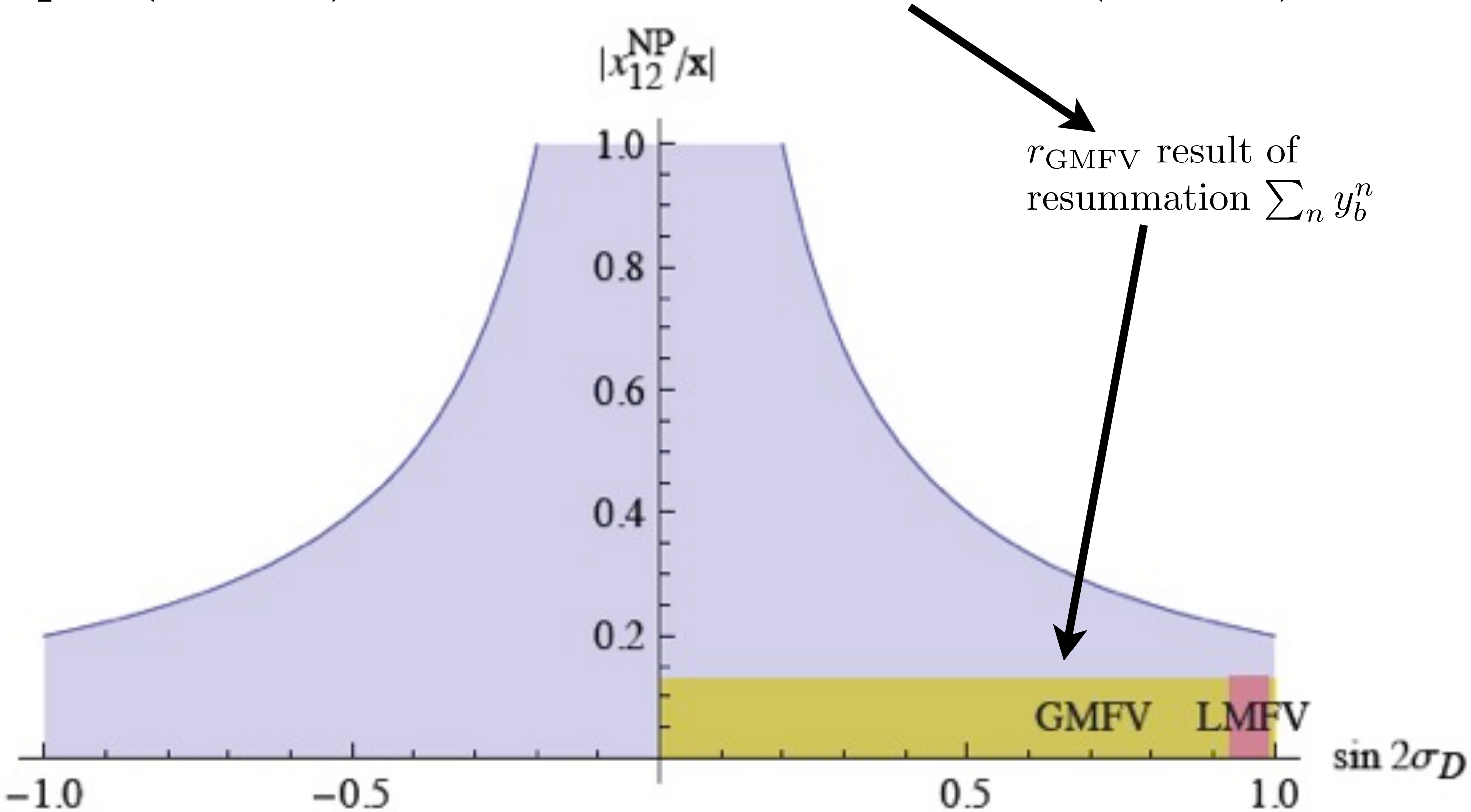

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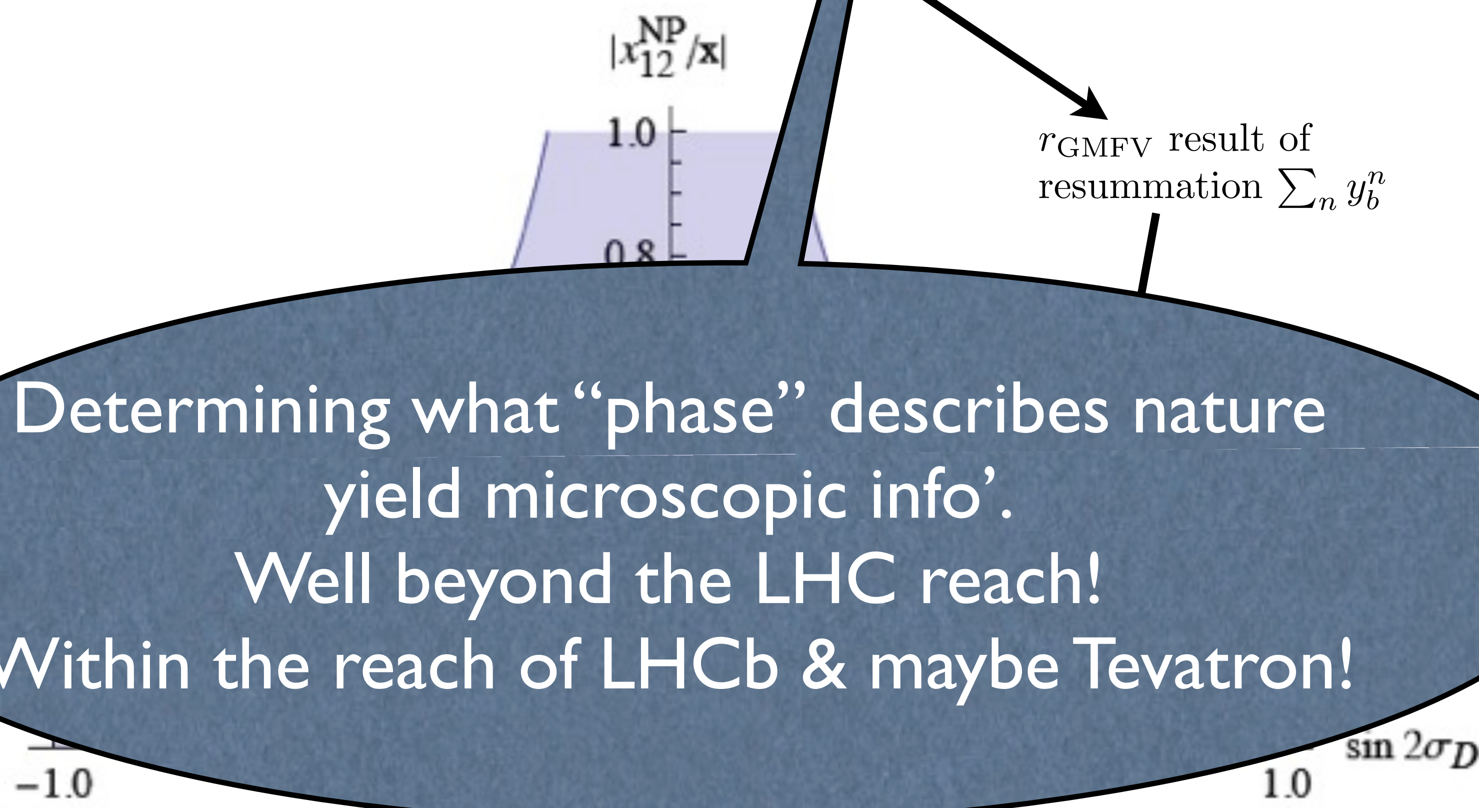


Determining what "phase" describes nature yield microscopic info'.
Well beyond the LHC reach!
Within the reach of LHCb & maybe Tevatron!

SUSY+RS

SUSY (doom of alignment)

Gedalia, et. al (09).

Robust

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

squark doublets, 1TeV;

Generic

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

average of the doublet & singlet mass splitting.

RS (constraining alignment)

Csaki, Falkowski & Weiler, PRD (09); Gedalia, et. al (09).

Robust

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

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

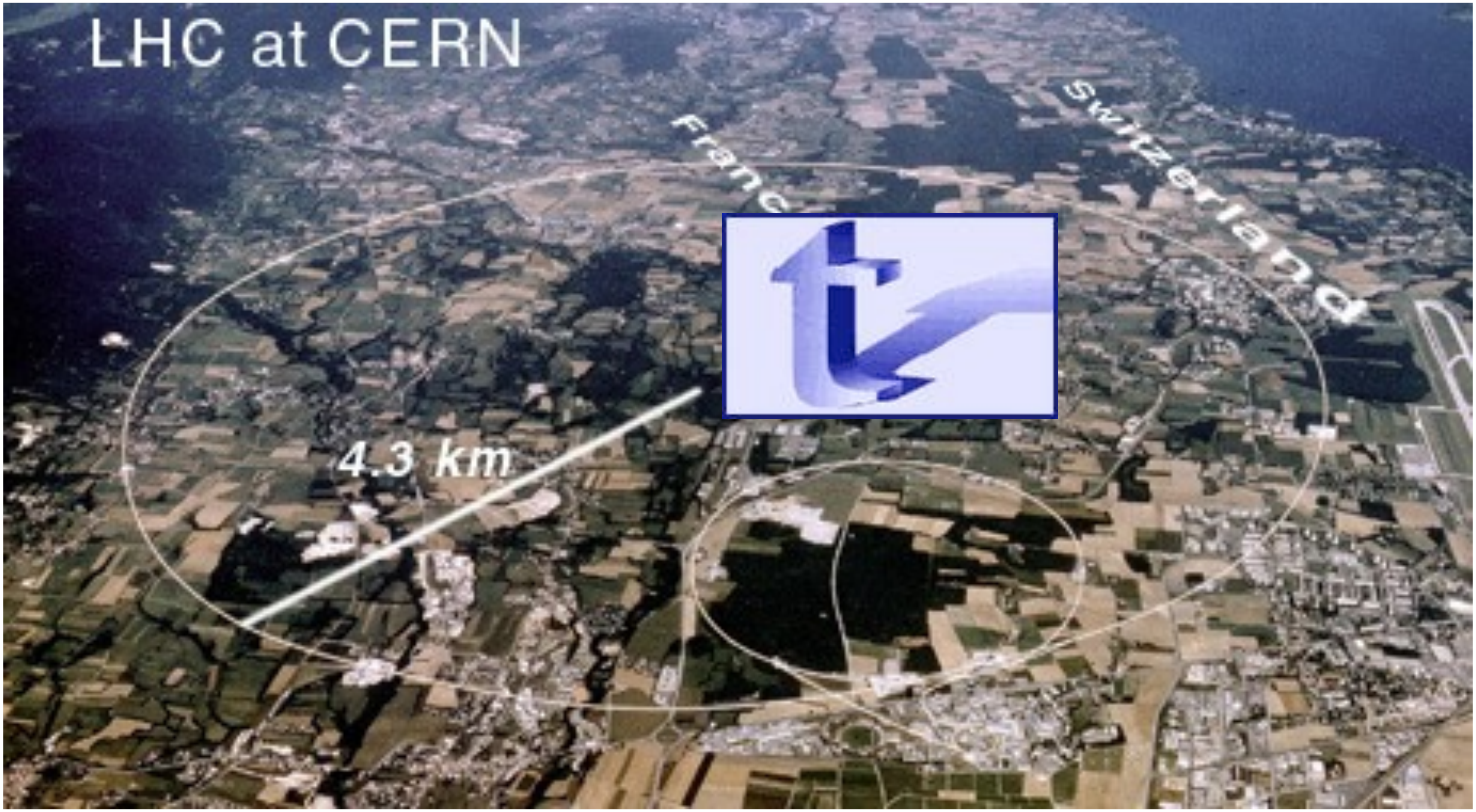
Generic

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

IR (bulk) Higgs

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

3rd gen' Phys. @ the LHC



Robust bounds for $\Delta t = 1$

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

Gedalia, Mannelli & GP, to appear in PLB (10).

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

- 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.

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?

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

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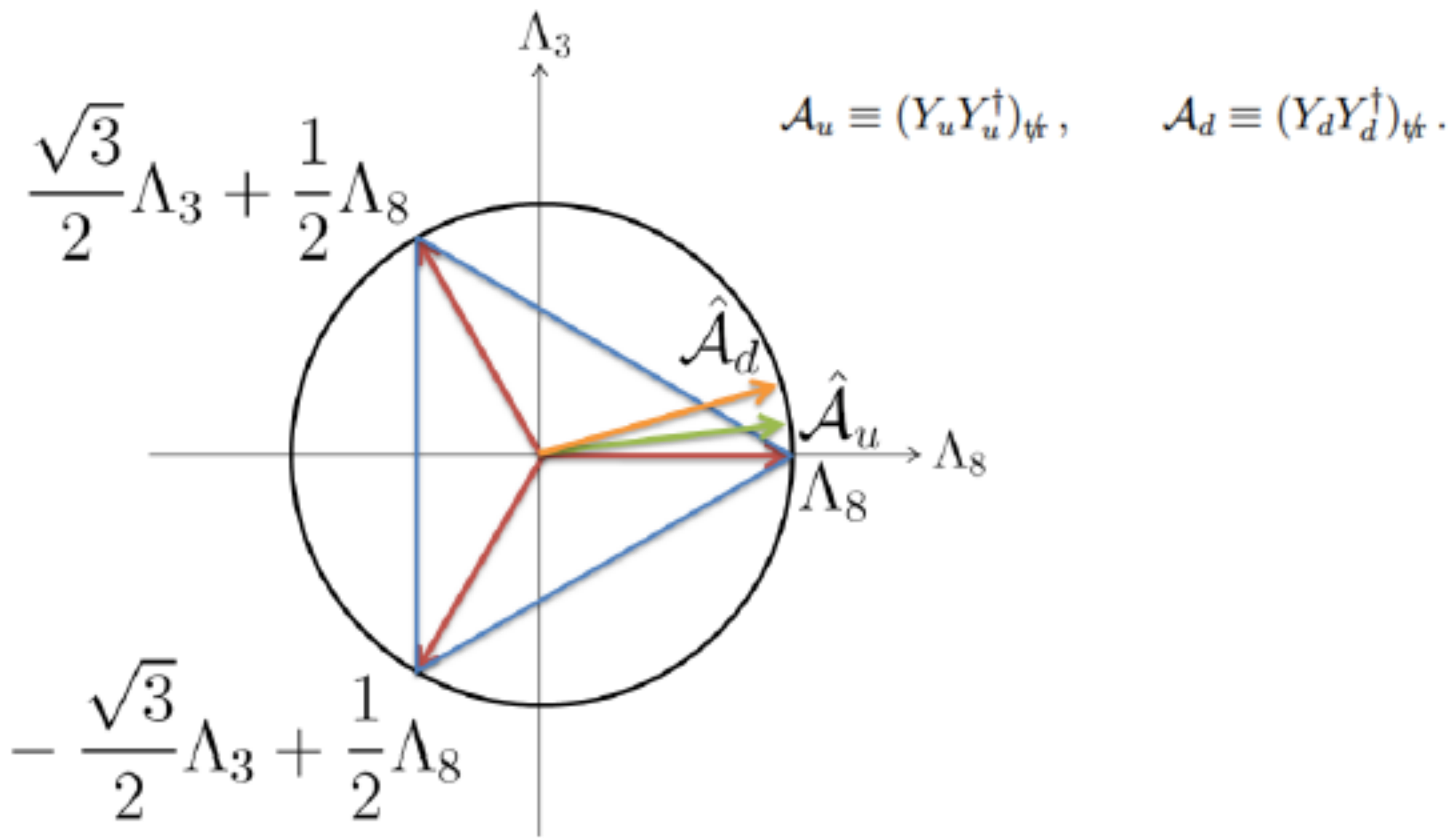

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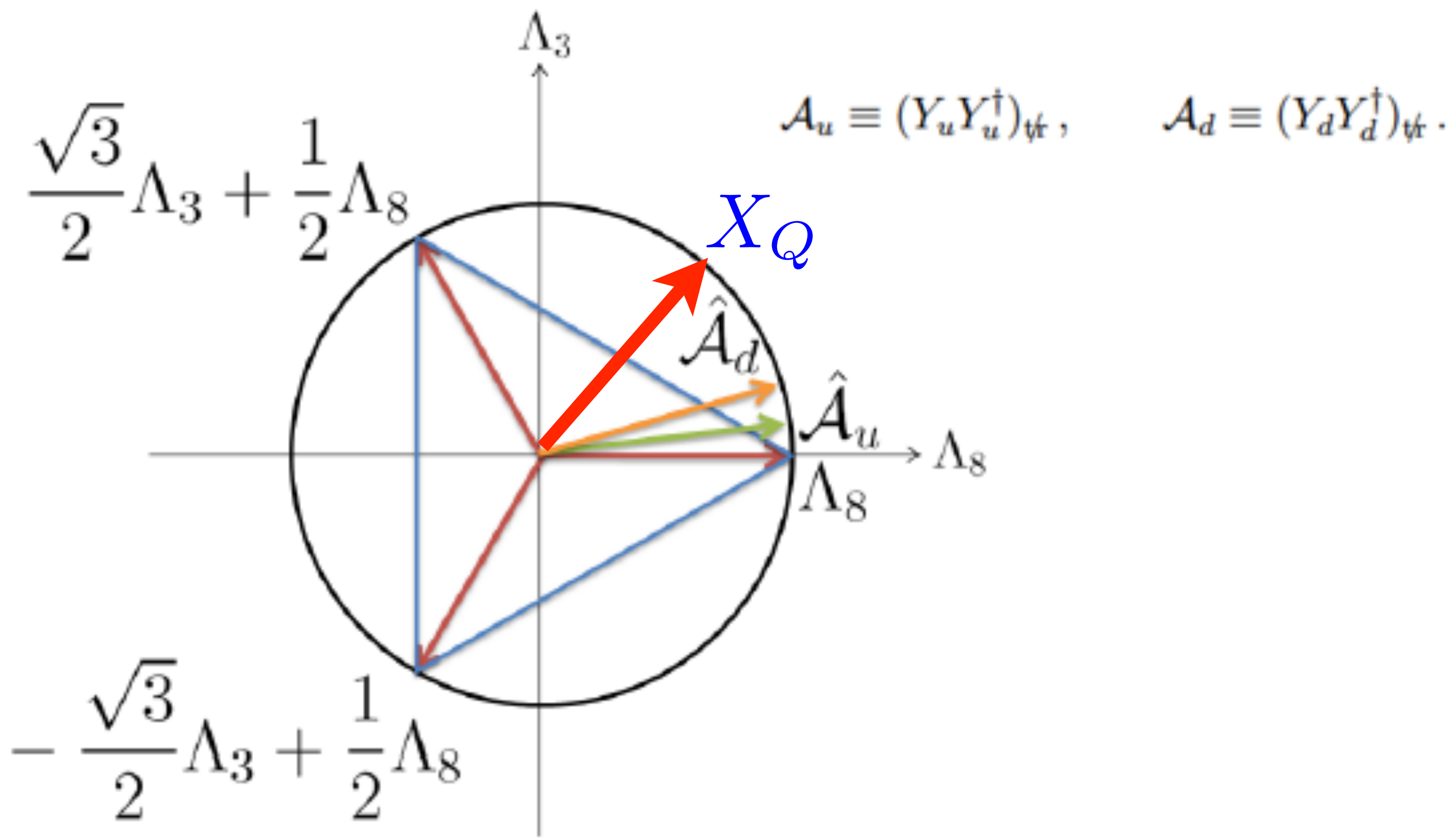

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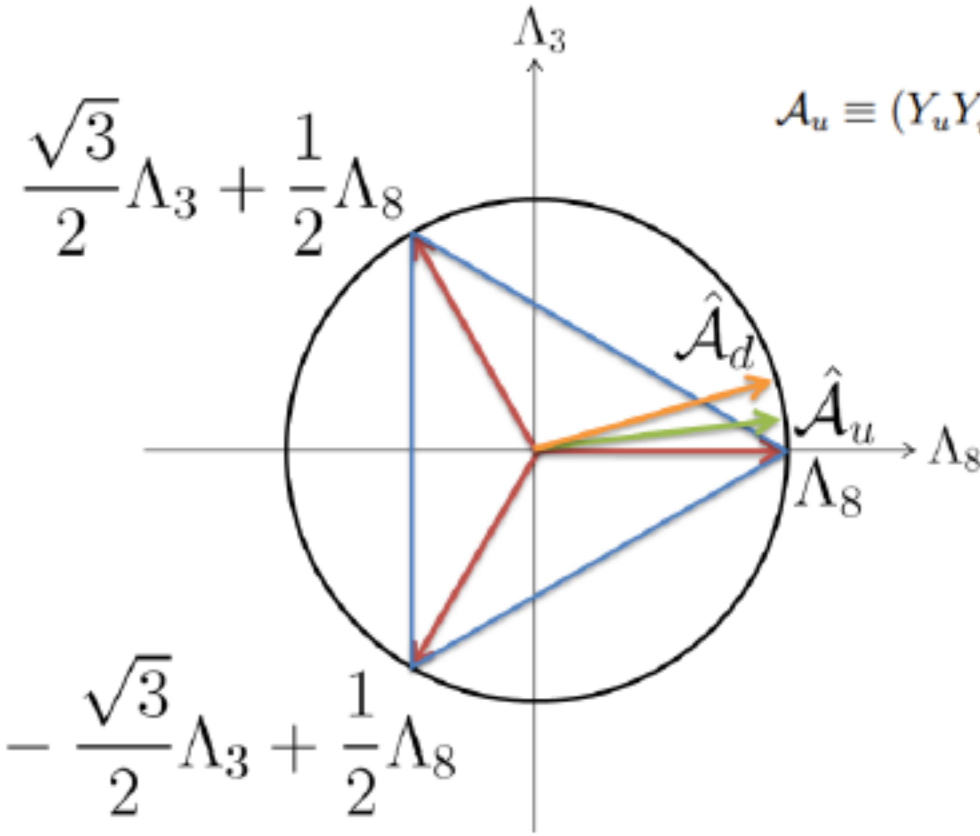

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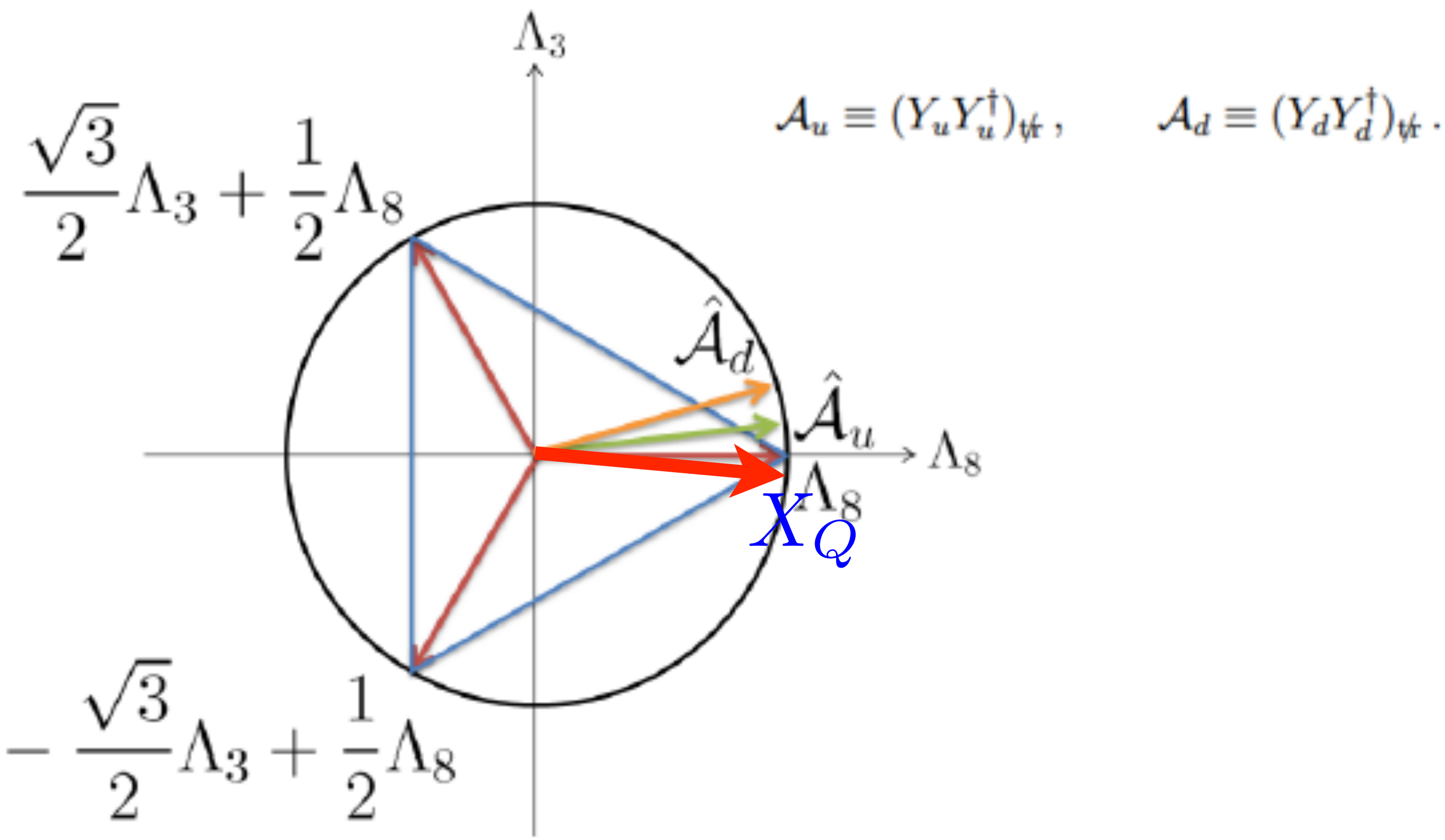

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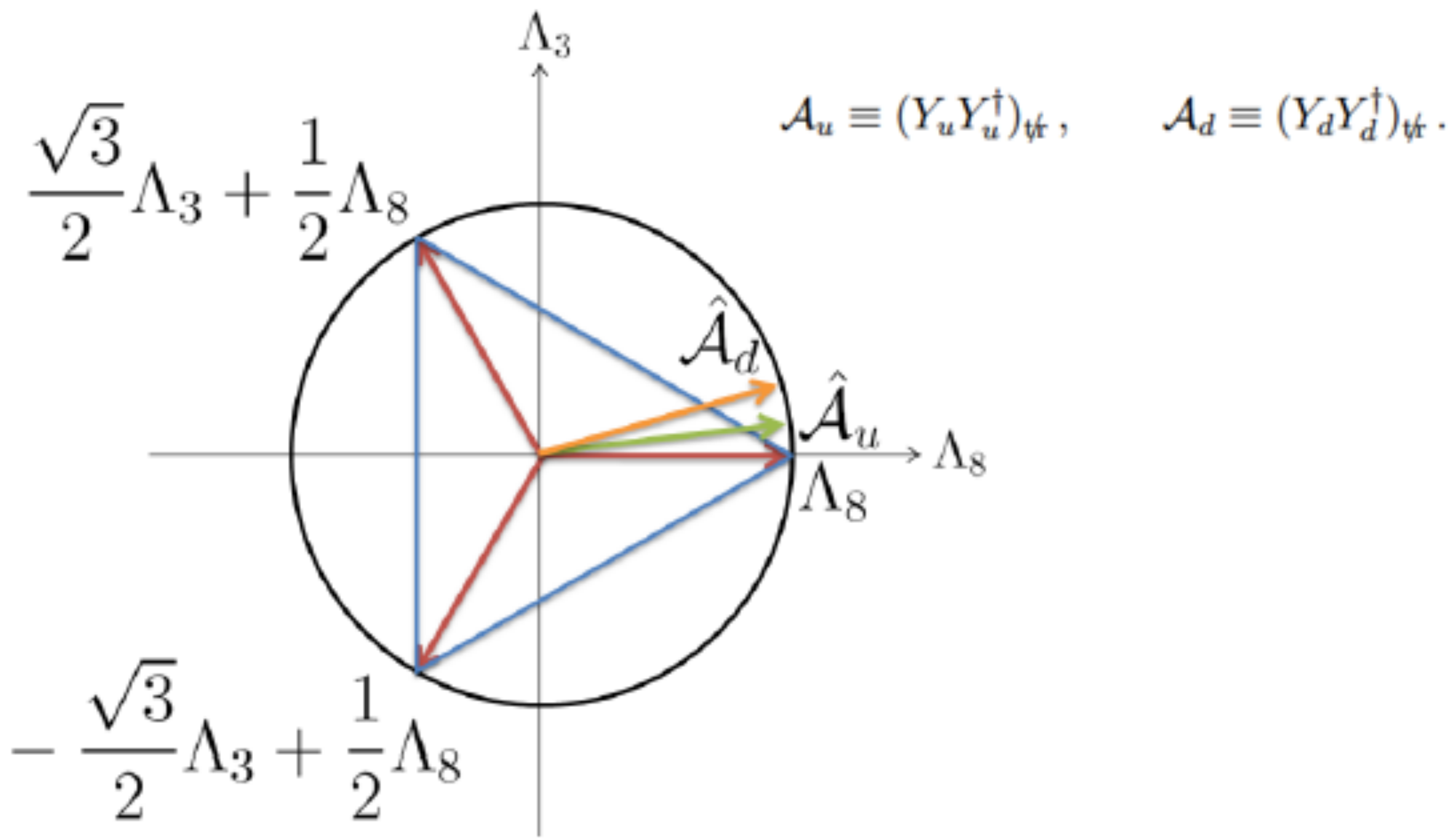

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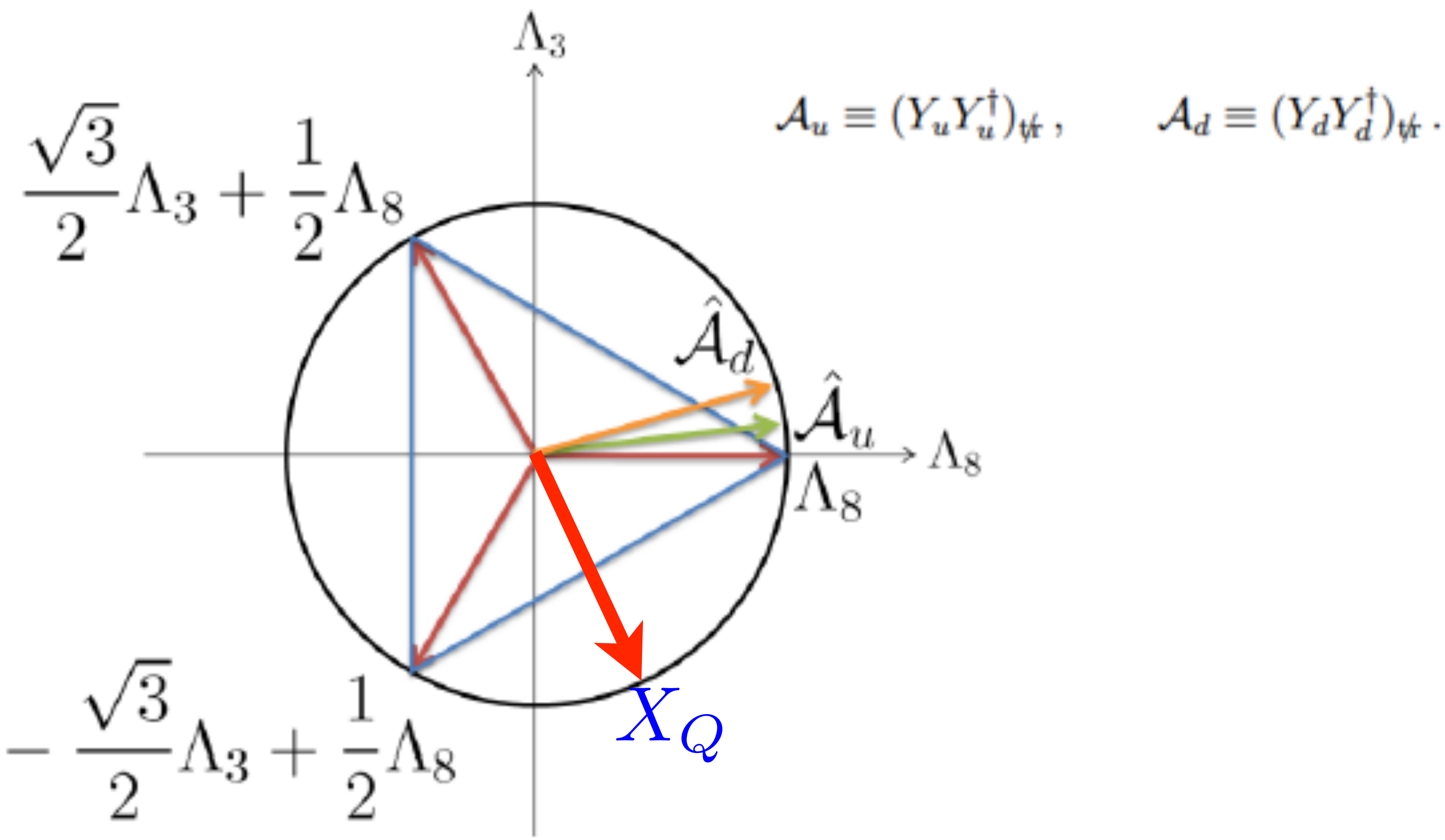


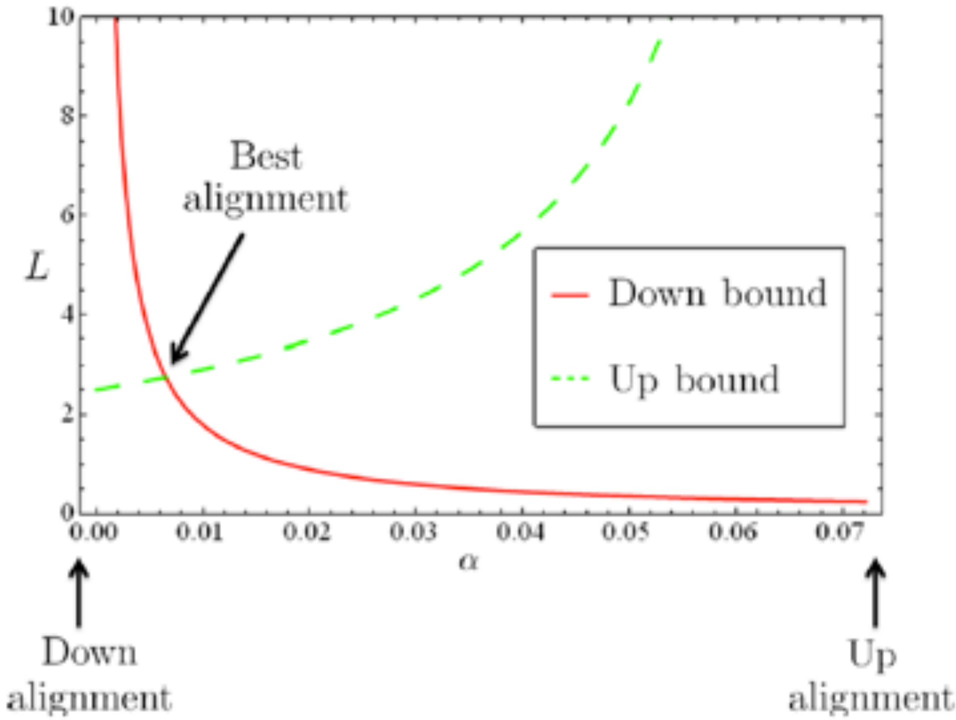
Can the LHC answer?

LHC projected bound

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

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

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



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

Gedalia, Mannelli & GP, 1003.3869 (10).

- Signal is in same sign tops: $uu \to tt$

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Bounds on Λ in TeV ($c_{ij}=1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) 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}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	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}
$(\bar{t}_L\gamma^\mu u_L)^2$	?		?		?

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

- Projected LHC bound, same sign tops.

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
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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:

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

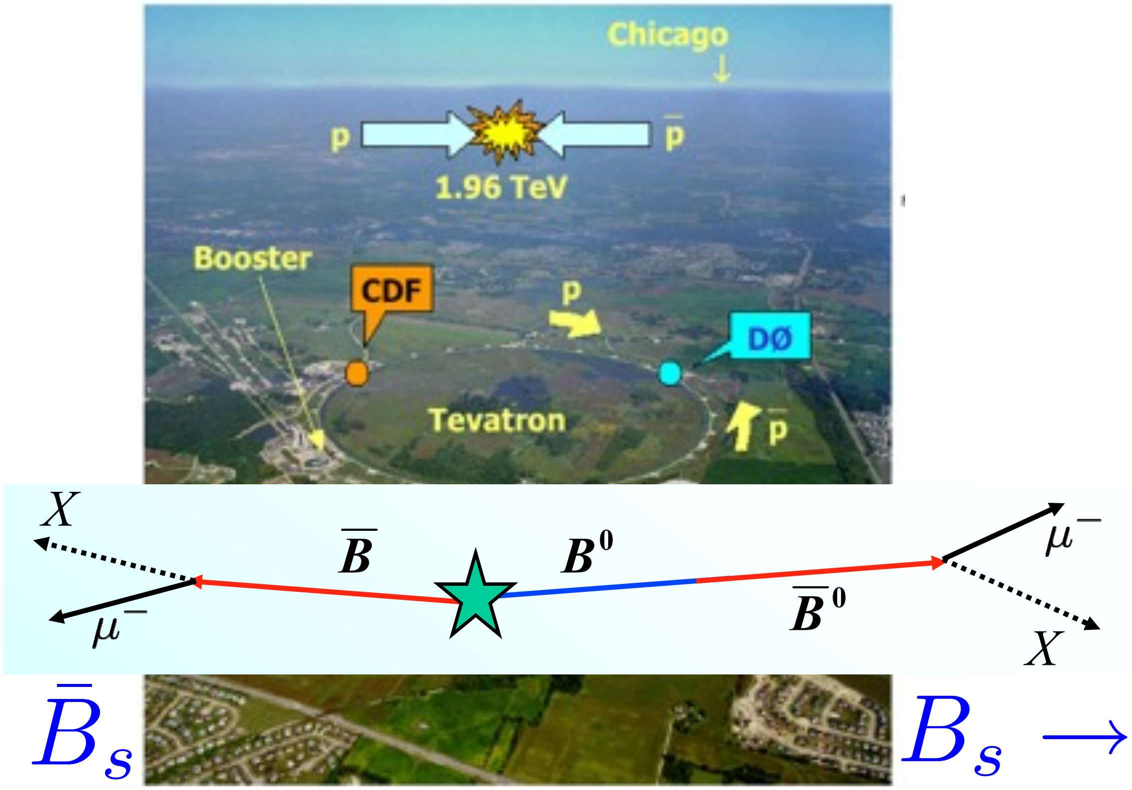
$$L < 12 \left(\frac{\Lambda_{\rm NP}}{1\,\mathrm{TeV}}\right) ; \quad \Lambda_{\rm NP} > 0.08\,(1)\,\mathrm{TeV} ,$$

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.

News from the Tevatron



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

Same sign leptons CP asymmetry, formalism

- Effective H for $B_q, \bar{B}_q$: $\mathcal{H} = M + i\Gamma/2\,;$

  Mass eigenstates: $|B_{L,H}\rangle = p|B_q\rangle + q|\bar{B}_q\rangle\,.$

  => $\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}}$

Hence: $a_{\rm SL} = \frac{1-|q/p|^4}{1+|q/p|^4}$ $\left(a^b_{\rm SL} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} \right)$

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$$M_{12} = |M_{12}|e^{i\phi_M} \quad , \quad \Gamma_{12} = |\Gamma_{12}|e^{i\phi_\Gamma} \; .$$

=> $$a_{\rm SL} = -\left|\frac{\Gamma_{12}}{M_{12}}\right| \sin(\phi_M - \phi_\Gamma).$$

$|\Gamma_{12}/M_{12}| \ll 1$ (valid for B and B_s mesons)

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$|\Gamma_{12}/M_{12}| \ll 1$ (valid for B and B_s mesons)

- SM (GIM): $a_{\rm SL}^{d,s} \sim \frac{m_c^2}{m_W^2}{\rm Im}\left(\frac{V_{cb}V_{cd,s}^*}{V_{tb}V_{td,s}^*}\right) = \mathcal{O}\left(10^{-2,-4}\right)$

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

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

Abazov, *et al.* [D0 Collaboration], PRD (2010).

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, Nir & Raz, PRL (06).

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

- Requires large new phase, $a^s_{\rm SL} = -\left|\dfrac{\Gamma_{12}}{M_{12}}\right|_s \sin(\phi_M - \phi_\Gamma)$.

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- Origin of phase? $\Delta\Gamma_s^{\rm NP} \Leftrightarrow$ overcome SM tree level and not violate other CPV, ex.: $b \to s\tau^+\tau^-$.

Dighe, Kundu & Nandi [0705.4547, 1005.4051]
Bauer & Dunn [1006.1629]

- Assuming no direct CP ↔ NP contributes to SM suppressed amplitudes => correlation \w other observables:

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- Assuming no direct CP ↔ NP contributes to SM suppressed amplitudes => correlation \w other observables:

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

Ligeti, Papucci & GP, PRL (06);
Grossman, Nir & GP, PRL (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, to appear in PRL.

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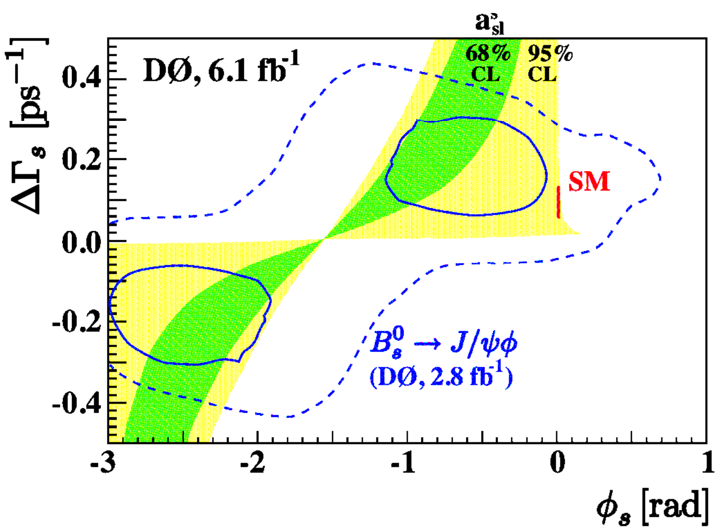
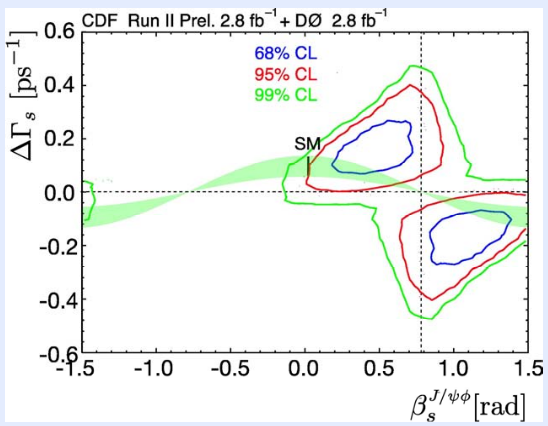
- **Tevatron experiments** also measure:

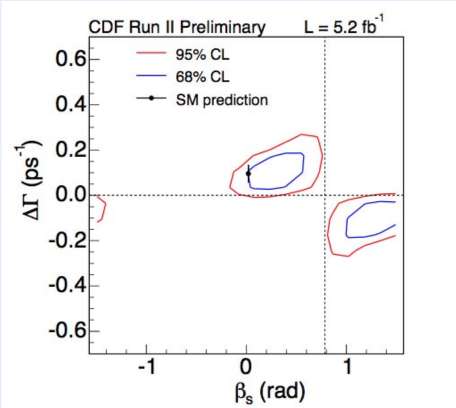




Tevatron combination: probability of observed deviation from SM = 3.4% (2.12 σ)

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:

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

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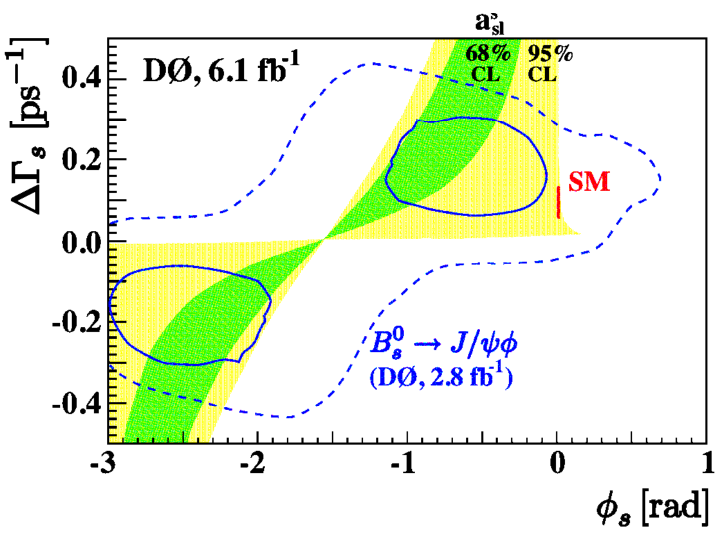

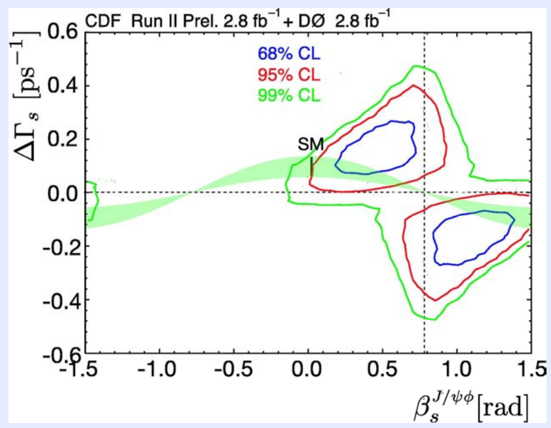

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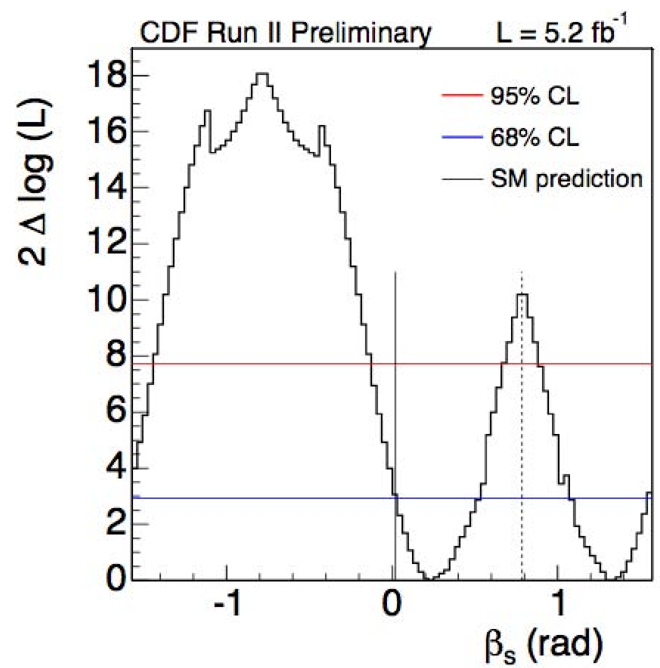


Combining $a_{\rm SL}^b$ & $\Delta\Gamma_s$ vs. $S_{\psi\phi}$

- Consistency check:

Ligeti, Papucci, GP, Zupan.

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

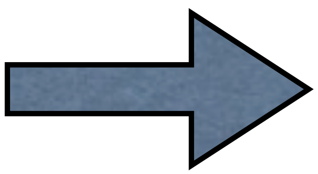
$$\left(S_{\psi\phi}\right)_{\rm CDF+D\O}: \quad (\Delta\Gamma_s,\, S_{\psi\phi}) \ \sim \ (0.15\,\mathrm{ps}^{-1},\ \ 0.5\,)$$

- Can use data to fit $\Delta\Gamma_s$ => no theory involved.

  Or compare with state of the art QCD predictions.

Lenz & Nierste, JHEP (07)

Model independent interpretation



Global NP fit

Ligeti, Papucci, GP, Zupan.

- **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 $\rightarrow$ not theory involved)

h_i : magnitude of NP normalized to SM.

σ_i : NP relative phase.

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

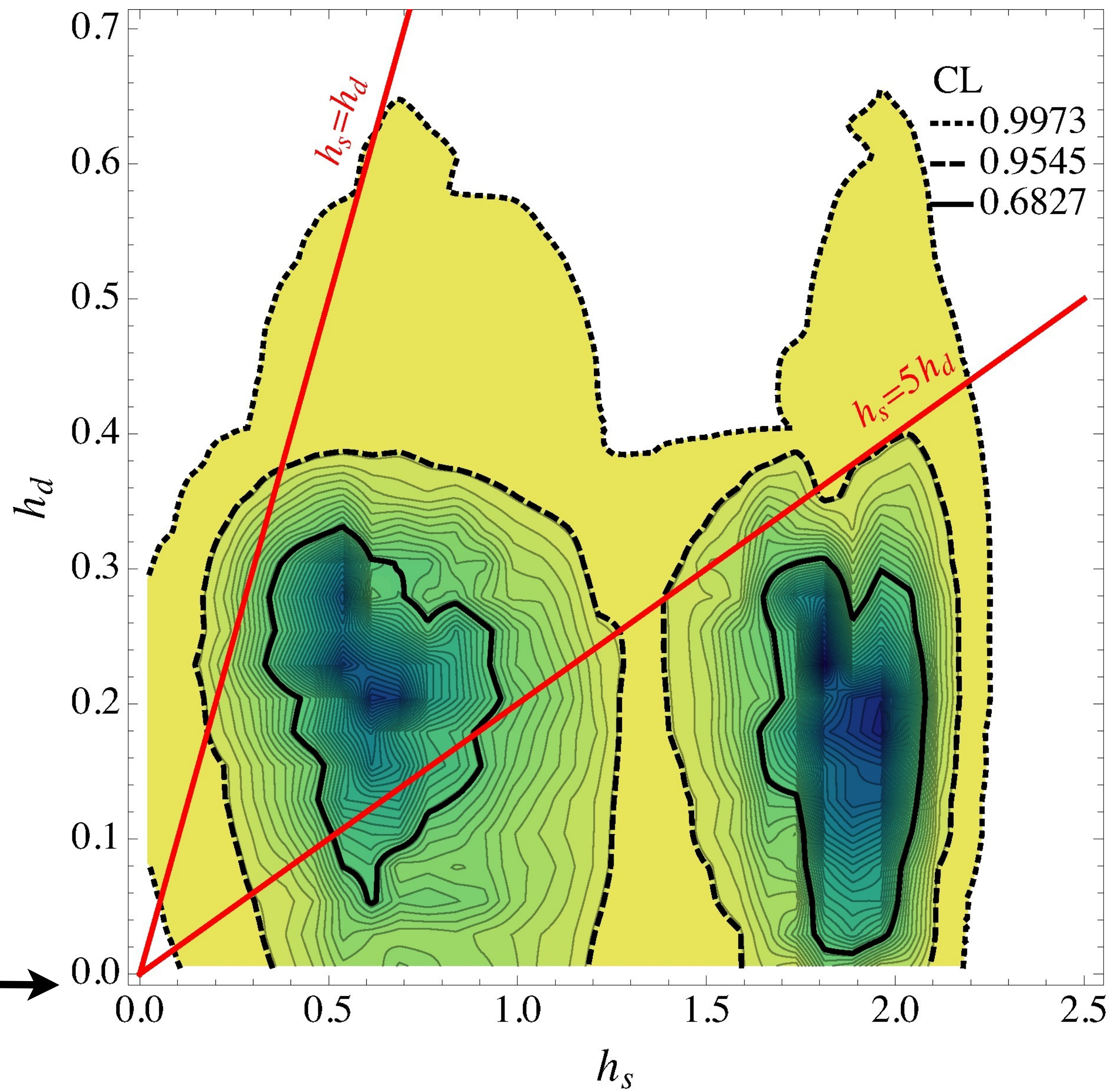
Global fit's results

Ligeti, Papucci, GP, Zupan.

(we used CKMfitter)

B_d vs. B_s systems

SM



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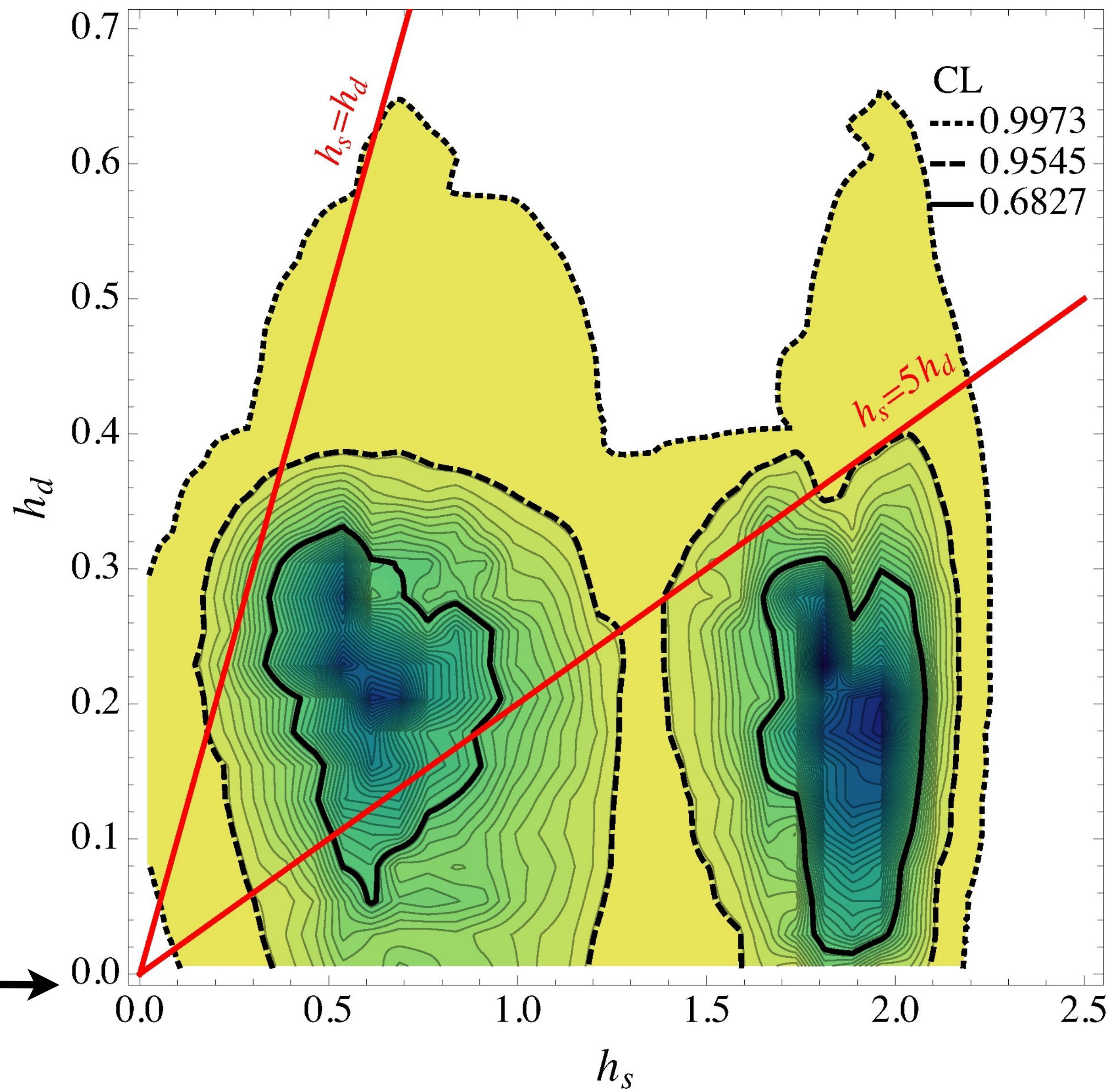
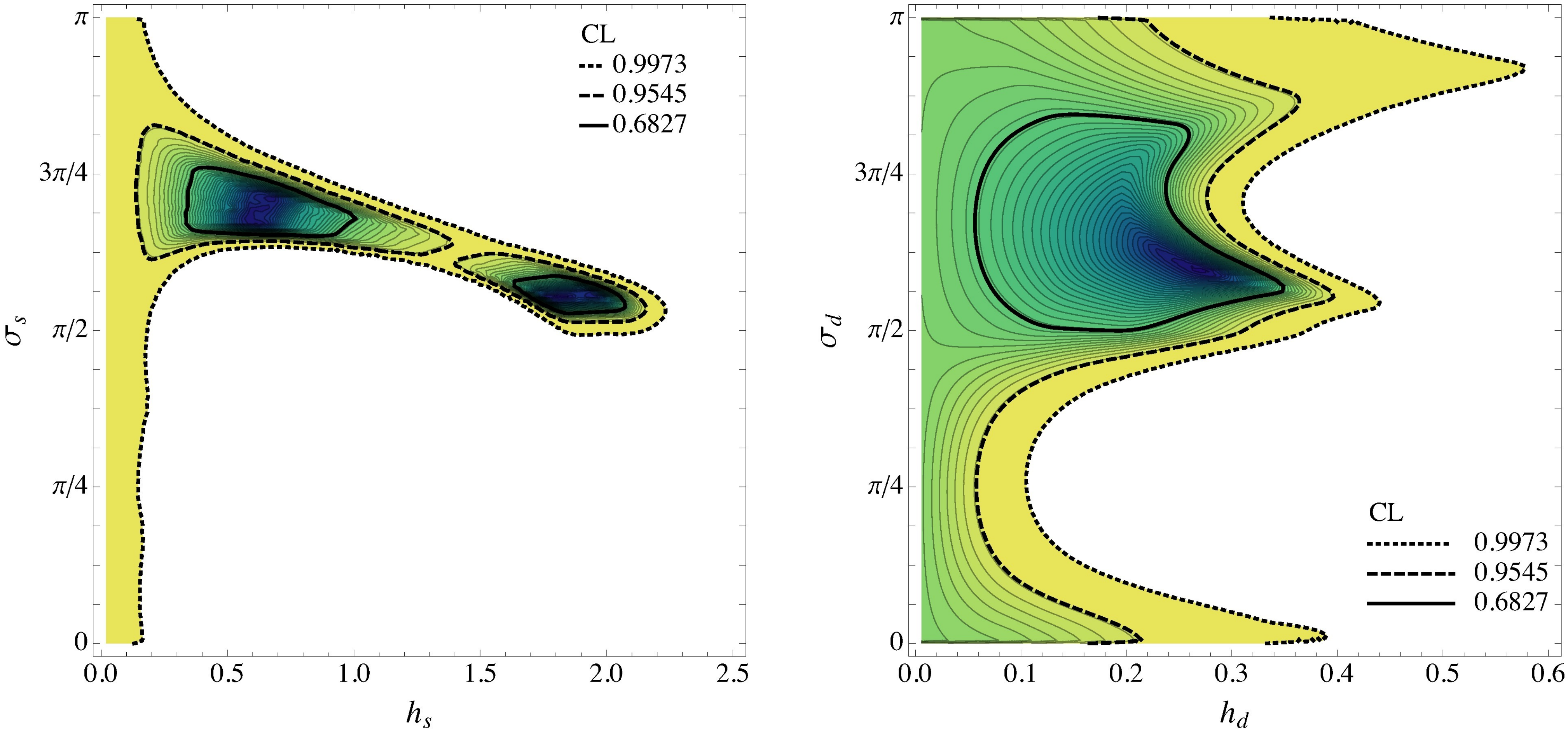


SM

Data favors
$h_s > h_d$

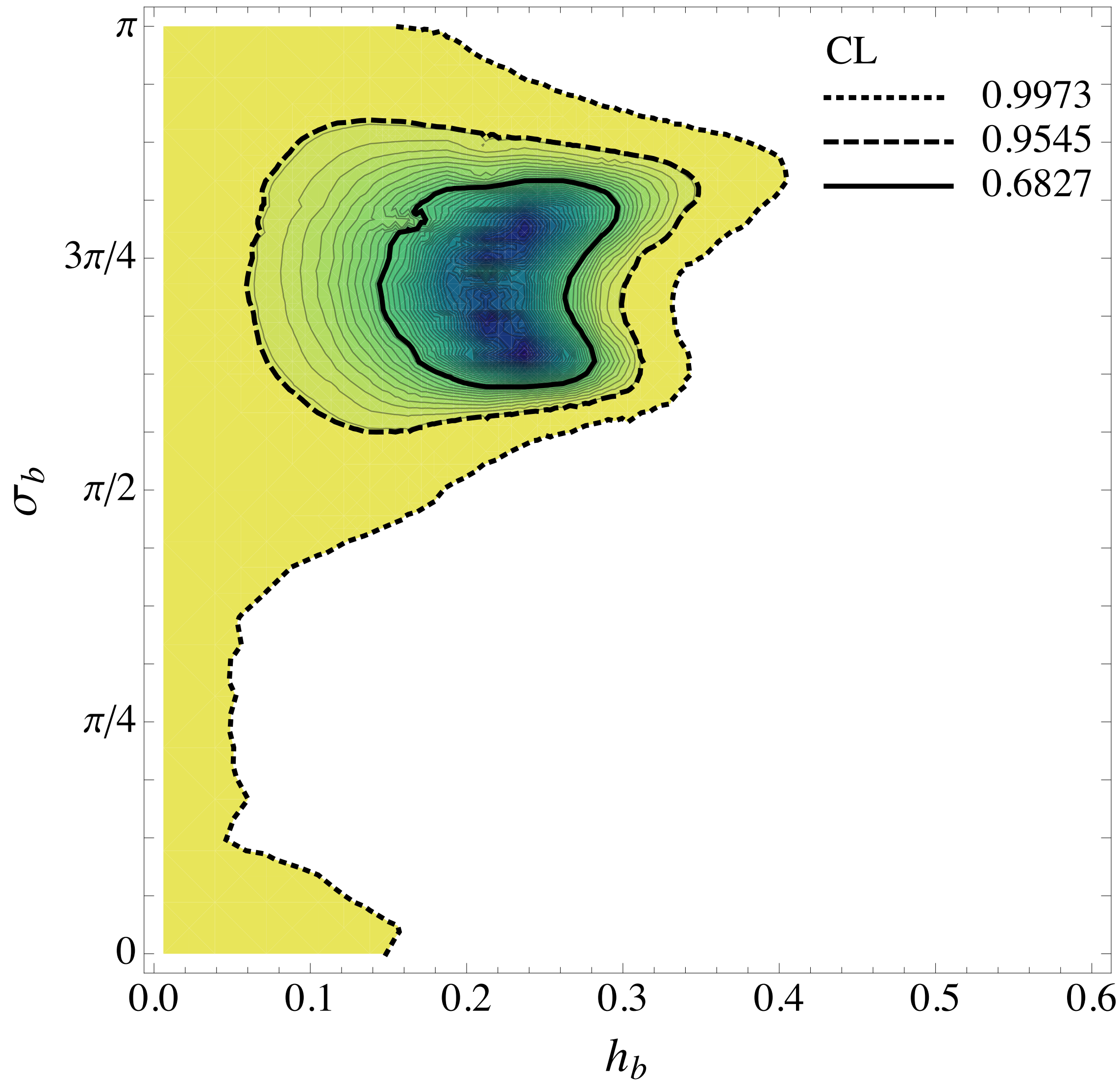
Allowed regions in the B_s & B_d systems.



The allowed ranges of h_s, σ_s (left) and h_d, σ_d (right) from the combined fit to all four NP parameters.

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

Viable with some tension.



The allowed h_b, σ_b range assuming $SU(2)$ universality.

Lessons from the data, model indep’

- Tension with SM null prediction.

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♦ Tension with SM null prediction.

♦ SU(2)$_q$ approx' universality, $h_s \sim h_d$, can accommodate data; arise in many models with NP effects via 3rd gen'.

Lessons from the data, model indep'

♦ Tension with SM null prediction.

♦ SU(2)$_q$ approx' universality, $h_s \sim h_d$, can accommodate data; arise in many models with NP effects via 3rd gen'.

♦ However, data favors $h_s \gg h_d$, seems more challenging.

(most theoretical explanation involved tuning of parameters)

Some Model Dependent Implications

GMFV: (i) EFT (ii) Higgs exchange (iii) warped Xtra dim'

GMFV(general minimal flavor violation): simple framework that account for data

- MFV (@ TeV) + flavor diag' phases => $O(1)$ CPV in b->d,s.

Colangelo, Nikolidakis & Smith, Eur. Phys. J. (09); Kagan, GP, Volansky & Zupan (09).

- Surprisingly it can accommodate both above cases:

$$(1)\, h_s \sim h_d\,, \quad (2)\, h_s \gg h_d\,.$$

Buras, Carlucci, Gori & Isidori, arXiv:1005.5310; Ligeti, Papucci, GP, Zupan.

MFV, effective operators

Ligeti, Papucci, GP, Zupan.

- **Universal solution:** $(h_s \sim h_d)$

$$\Lambda_{\mathrm{MFV};1,2,3} \gtrsim \{8.8,\ 13\, y_b,\ 6.8\, y_b\}\sqrt{0.2/h_b}\ \mathrm{TeV}\,.$$

$$O_1^{bq} = \bar{b}_L^{\alpha}\gamma_\mu q_L^{\alpha}\,\bar{b}_L^{\beta}\gamma_\mu q_L^{\beta},\ O_2^{bq} = \bar{b}_R^{\alpha} q_L^{\alpha}\,\bar{b}_R^{\beta} q_L^{\beta},$$

- **Non-univ. solution:** $(h_s \gg h_d)$

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

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

Scalar exchange

Buras, et al. (10); Dobrescu, et al. (10); Jung, et al. (10); Nir et al. (10).

- 2HDM a natural arena to generate flavor & CPV within MFV.

- Universal solution can easily be generated via $\mathcal{O}_2$

- Non-univ. solution only if $\mathcal{O}_4 \gg \mathcal{O}_2$

Vector exchange (KK gluon)

- Radical solution to little RS CP problem via bulk realization of Rattazzi & Zaffaroni's flavor model.

`Rattazzi & Zaffaroni, JHEP (01); Delaunay, Gedalia, Lee & GP, 1007.0243.`

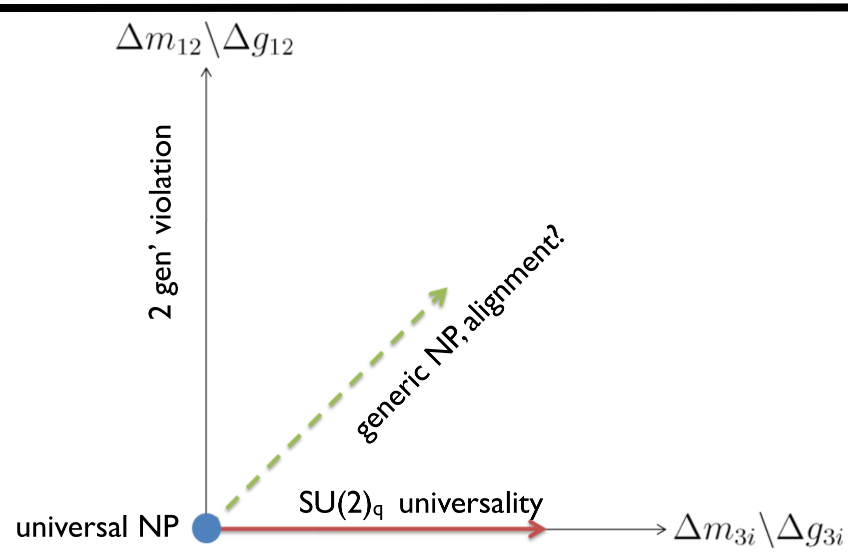
- New type of GMFV models with large LL and/or RR currents.

- Low KK scale + improve naturalness as a bonos => exciting LHC phenomenology => linkage between high & low pT data!

Outlook: Flavor Diagonal Information

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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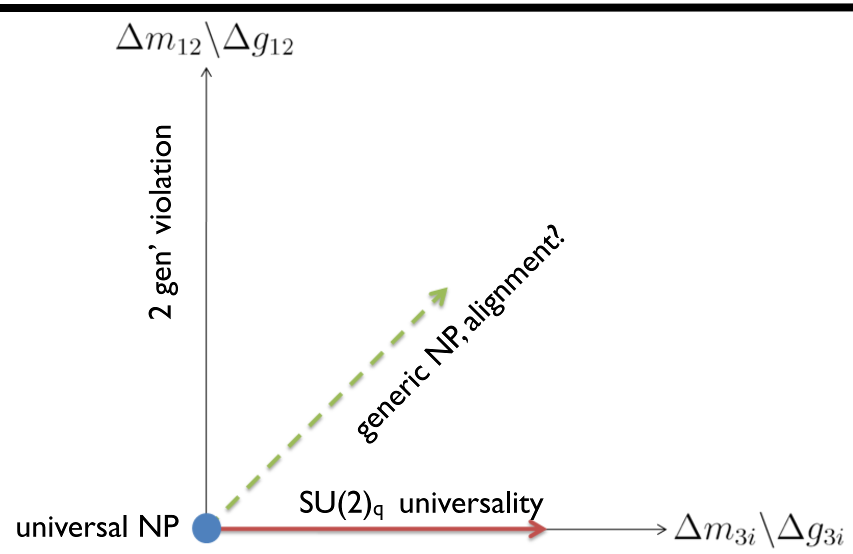
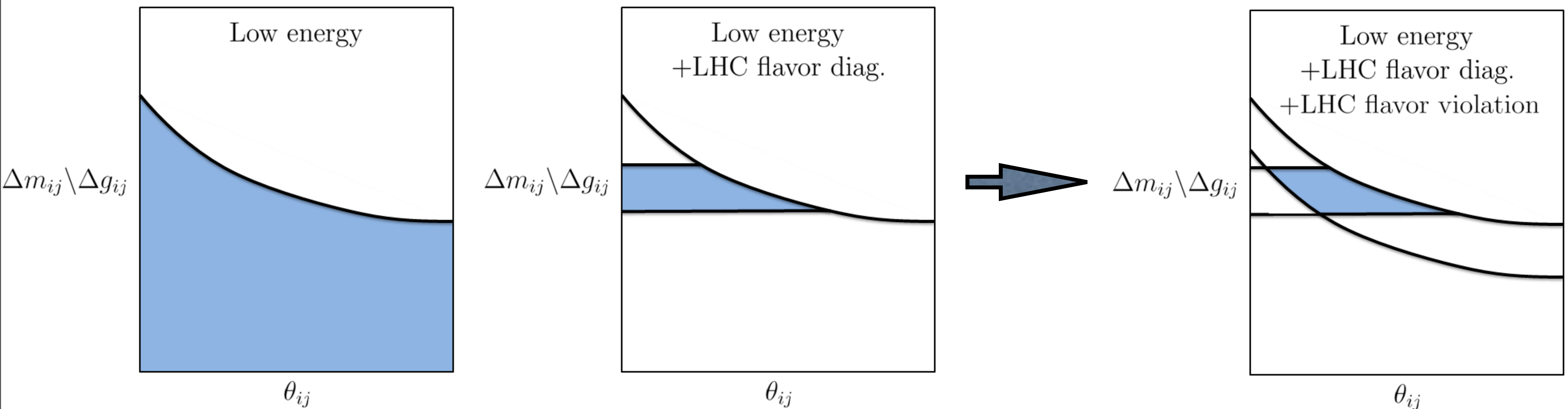
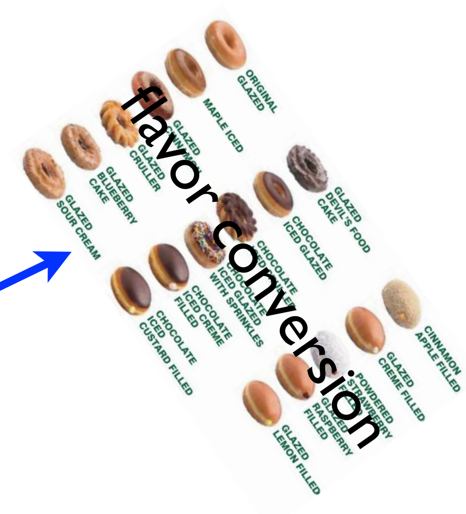




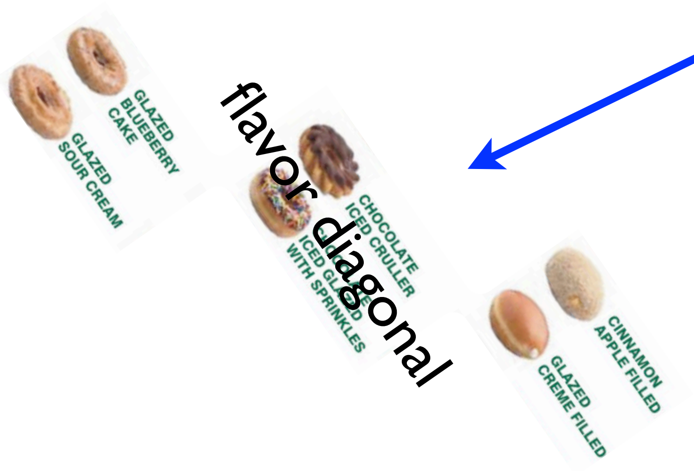
Grossman, Ligeti & Nir, Prog. Th. Phys. (09); Gedalia & Perez, TASI (10).

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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BABAR BELLE

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$$A_\Gamma = (1.2 \pm 2.5) \times 10^{-3}$$

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

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- System parameters roughly determined (HFAG):

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

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

The RS "little" CP problem

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

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

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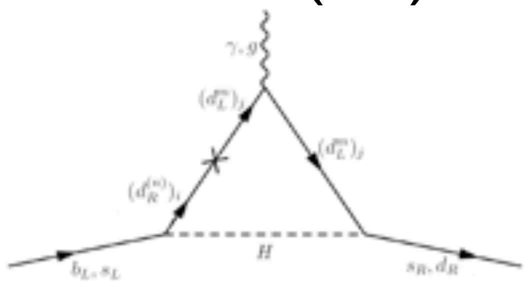

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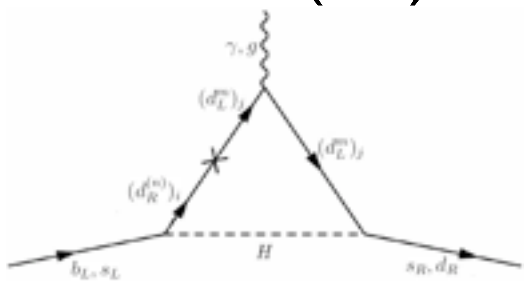

Severe tuning problem or fine tuning problem & null LHC pheno'.