Flavor Physics in the LHC Era

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Physics at the LHC 2011

Outline

- Introduction, importance of flavor physics.
- Insights on the scale of new flavor physics.
- Alignment & uFCNC, (th) news from the D mixing frontier.
- Top phys. & flavor diagonal information @ the LHC.

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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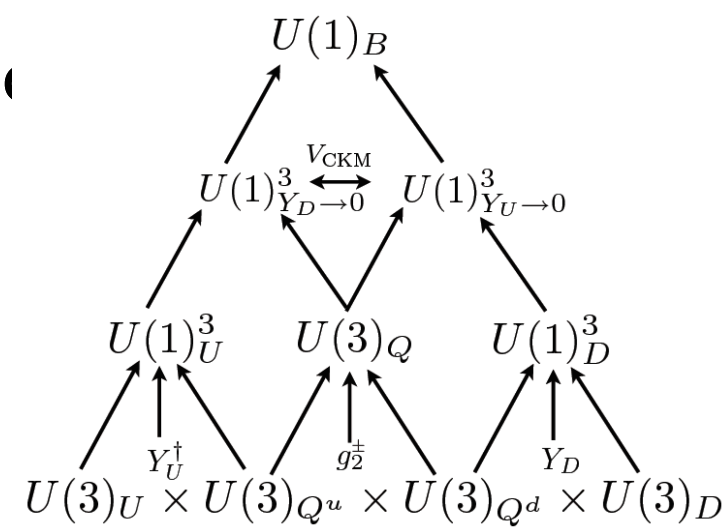

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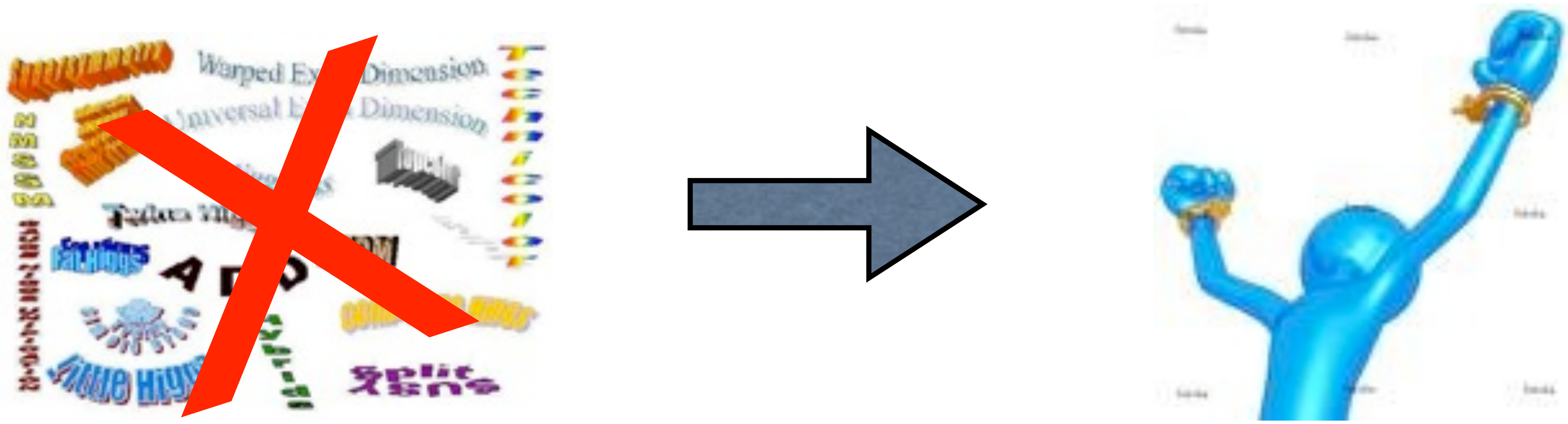
- Deviation from SM predictions can be easily probed or severe bounds on new physics (NP) obtained.

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 $\Lambda_{\rm NP}$

for different flavor transitions?

$\Delta F = 2$ status

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

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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$\bar{L}_i \sigma^{\mu\nu} e_{Rj} H F_{\mu\nu}$	1.7×10^4			$Br\,(\mu \to e\gamma)$
	3.3×10^2			$Br\,(\tau \to \mu\gamma)$
	2.6×10^2			$Br\,(\tau \to e\gamma)$
$(\bar{\mu}\gamma^\mu P_L e)\,(\bar{u}\gamma_\mu P_L u)$	1.9×10^2			$\frac{\sigma(\mu^- Ti \to e^- Ti)}{\sigma(\mu^- Ti \to capture)}$

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Very very strong ...

What do we conclude ?

- SM mechanism to induce flavor & CPV is successful.

The Nobel Prize in Physics

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$\Delta F = 2$ status

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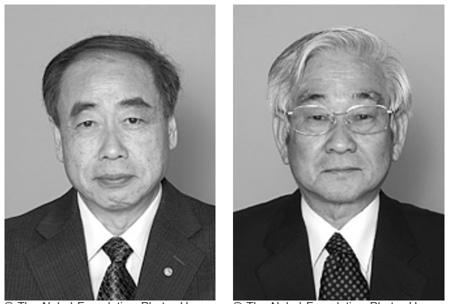

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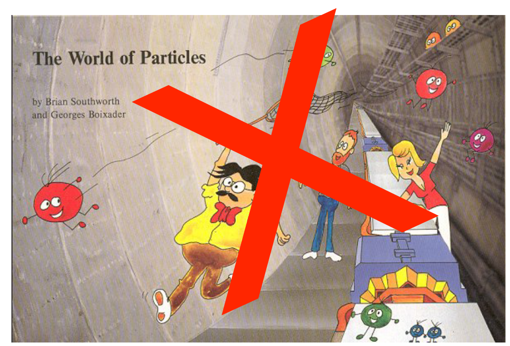

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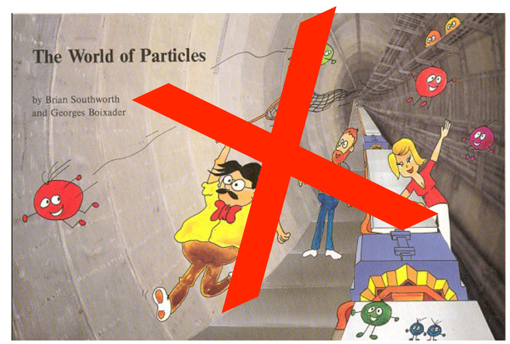
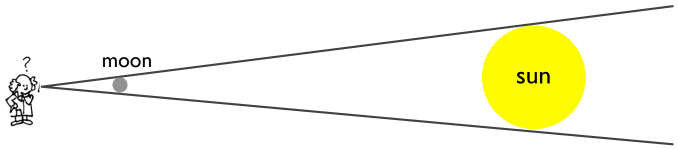


- Hint for underlying structure of microscopic laws of nature.

What about the fine tuning problem ?



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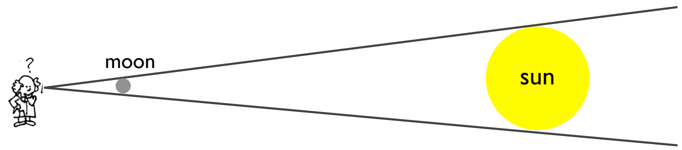
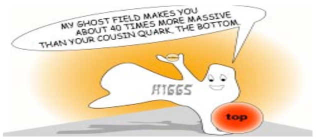
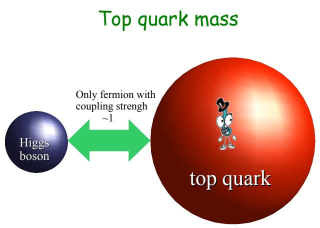
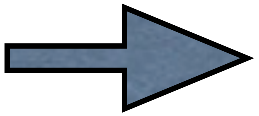
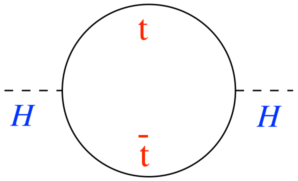


- The most severe problem is due to top coupling:









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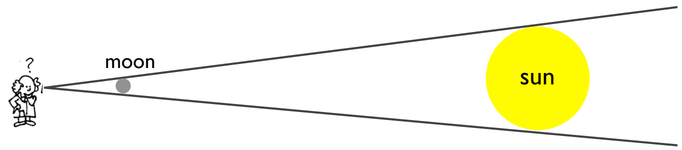

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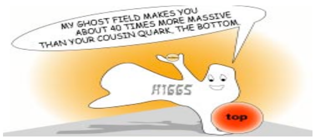

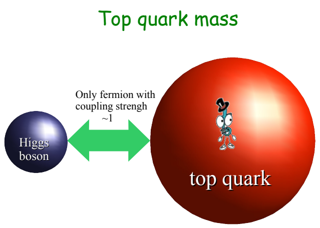

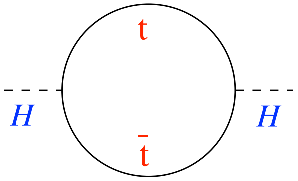

$$\text{Assume cutoff } \Lambda = 7\,\text{TeV};\ \delta_t m_h^2 = \frac{3}{8\pi^2} y_t^2 \Lambda^2 \sim 1.4\text{TeV}^2$$

$$m^2_{h,\text{phys}} = m^2_{\text{tree}} + \delta_t m_h^2 = m^2_{\text{tree}} + 1.4\,\text{TeV}^2 \approx 0.01\,\text{TeV}^2$$

fine tuning of worse than 1:100 !

However little is known on tFCNC

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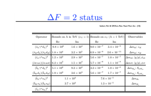

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$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	[illegible]	[illegible]	[illegible]
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2				
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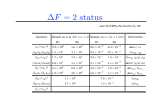
$(\bar{t}_L\gamma^\mu u_L)^2$					

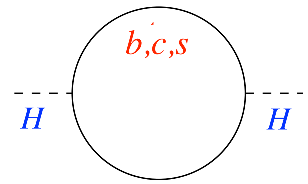
Do not directly couple to 3rd generation!



Reverse the logic with light flavors

D. Grossman, Hochberg, GP & Soreq, to appear; see also: Barbieri et al. JHEP (10).

- How large of non-univ. cutoff to sustain < $1{:}100$ fine tuning?



$$s: \;\; \Rightarrow \Lambda_s \lesssim 2\times 10^4\,\mathrm{TeV}$$

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Operator	Bounds on Λ in TeV ($c_{ij} = 1$)	
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$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4
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$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3
	1.1×10^2	
	3.7×10^2	

Tension with LLRR CP violation (CPV)!

Reverse the logic with light flavors

◆ How large of cutoff to sustain fine tuning of less than 1:100 ?

$s: \quad \Rightarrow \Lambda_s \lesssim 2 \times 10^4\ \mathrm{TeV}$

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$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2
[illegible]	1.9×10^3	3.6×10^3
[illegible]	1.1×10^2	
[illegible]	3.7×10^2	

B system: only case with tension with LLLL operators; Dramatic improvement expected in D system!

What kind of NP survives?

- Flavor blind/universal NP, for sure, but very restrictive.

(spoiled by RGE)

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- Maybe NP is anarchic but aligned.

uFCNC data, a crucial test of alignment

♦ Down & lepton flavor violation => removed via alignment, where anarchic NP is diagonal in down/charged-lepton mass basis.

[Nir & Seiberg, PLB (93); Fitzpatrick, GP & Randall, PRL (08); Csaki, GP, Surujon, & Weiler, PRD (09)]

careful domino *alignment*

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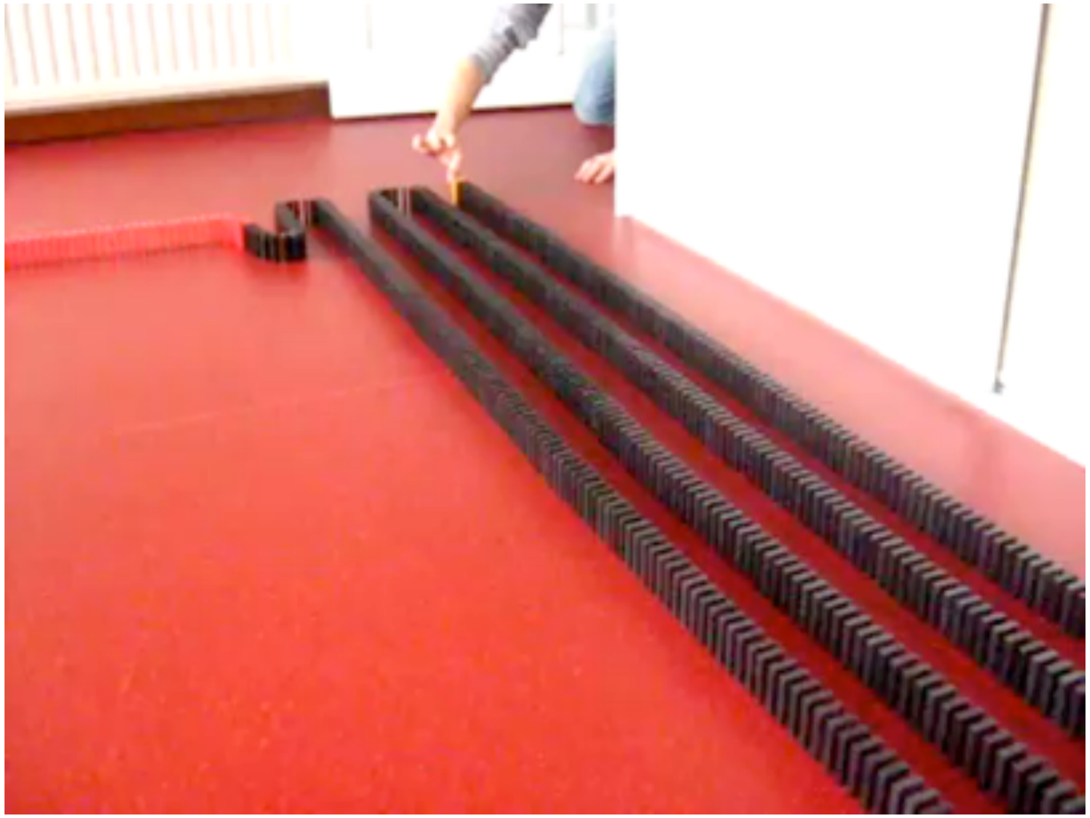

careful domino *alignment*

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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}
$(\bar{t}_L\gamma^\mu u_L)^2$					

$\bar{L}_i\sigma^{\mu\nu}e_{Rj}HF_{\mu\nu}$	1.7×10^4			$Br\,(\mu\to e\gamma)$
	3.3×10^2			$Br\,(\tau\to\mu\gamma)$
	2.6×10^2			$Br\,(\tau\to e\gamma)$
$(\bar{\mu}\gamma^\mu P_L e)\,(\bar{u}\gamma_\mu P_L u)$	1.9×10^2			$\frac{\sigma(\mu^- Ti\to e^- Ti)}{\sigma(\mu^- Ti\to capture)}$

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[illegible]	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; $\lvert q/p \rvert, \phi_D$
[illegible]	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	[illegible]
[illegible]	[illegible]	3.6×10^3	5.6×10^{-7}	[illegible]	[illegible]
[illegible]	1.1×10^2		7.6×10^{-5}		[illegible]
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$(\bar t_L \gamma^\mu u_L)^2$					

[illegible]	1.7×10^4			$Br\,(\mu \to e\gamma)$
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$(\bar s_L \gamma^\mu d_L)^2$	[illegible] $\times 10^2$	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}	$\Delta m_K;\ \epsilon_K$
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$(\bar c_R u_L)(\bar c_L u_R)$	6.2 [illegible]	[illegible]	[illegible]	[illegible] $\times 10^{-8}$	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar b_L \gamma^\mu d_L)^2$	[illegible]	[illegible]	[illegible]	[illegible]	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar b_R d_L)(\bar b_L d_R)$	[illegible]	[illegible]	[illegible]	[illegible]	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar b_L \gamma^\mu s_L)^2$	[illegible]	[illegible]	[illegible]	[illegible]	Δm_{B_s}
$(\bar b_R s_L)(\bar b_L s_R)$	3.7×10^2	[illegible]	1.3×10^{-7}	[illegible]	Δm_{B_s}
$(\bar t_L \gamma^\mu u_L)^2$					

uFCNC remove immunities

$L_i \sigma^{\mu\nu} e_{Rj} F_{\mu\nu}$	1.7×10^4 3.3×10^2 [illegible]			$Br(\mu \to e\gamma)$ $Br(\tau \to \mu\gamma)$ $Br(\tau \to e\gamma)$
$(\bar\mu \gamma^\mu P_L e)(\bar u \gamma_\mu P_L u)$	1.9×10^2			$\frac{\sigma(\mu^- Ti \to e^- Ti)}{\sigma(\mu^- Ti \to capture)}$

Up sector

Look Down

Look Up

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

ד

δ

$\varDelta$

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:

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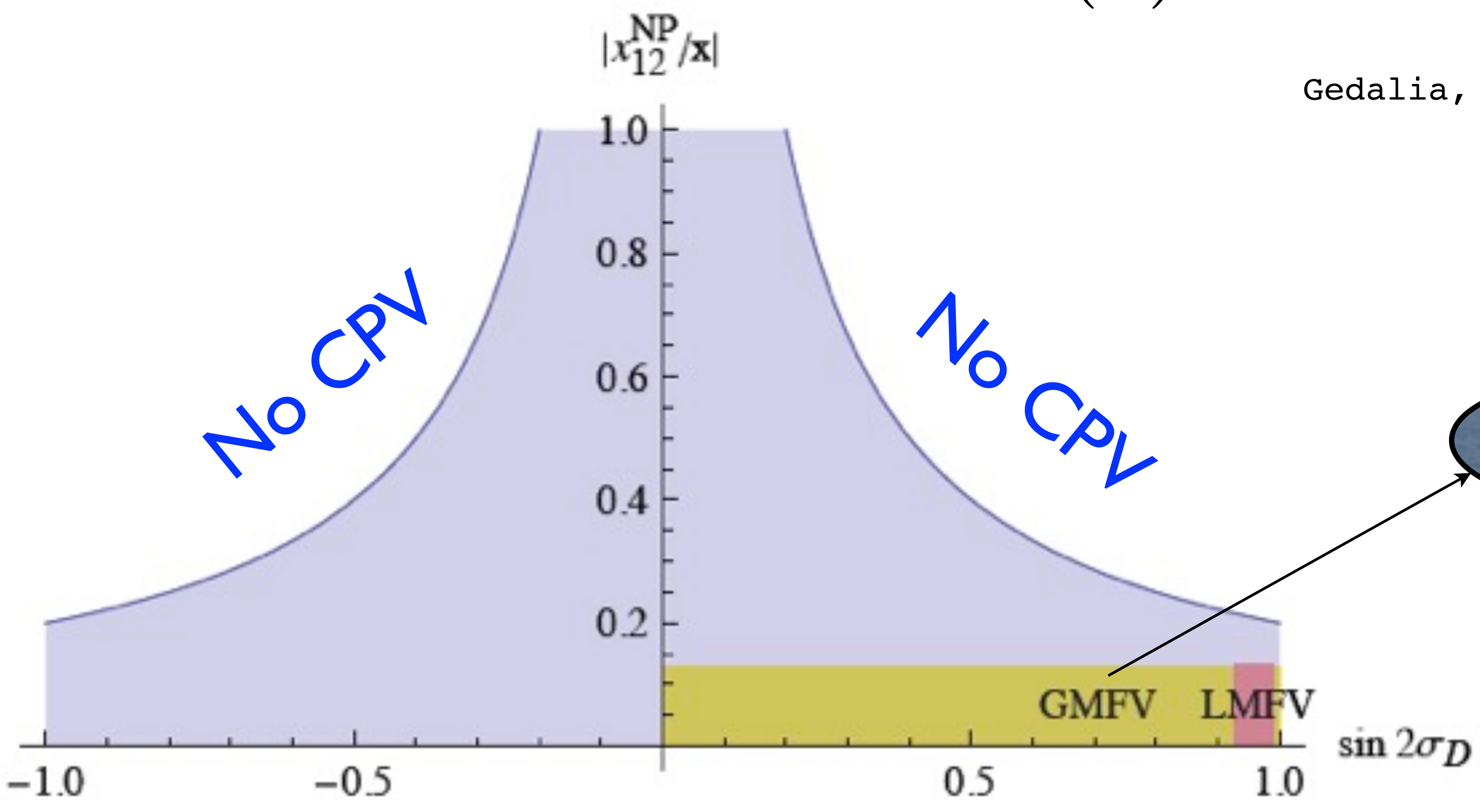
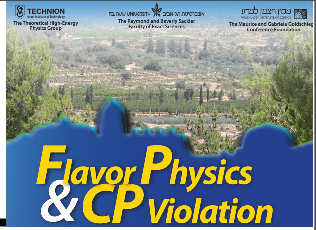
If x is due to NP then it missed a chance to revealed itself in $\mathcal{O}(1)$ CPV. ☹

Gedalia, et. al (09).



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

Update from FPCP11



Imposing $a^{\text{dir}}(KK, \pi\pi) < 0.002$, corresponding to models with no new weak phases in SCS decays, and for no new weak phases in CF/DCS decays, obtain

$$\phi_{12} = 0.03 \pm 0.09 \; [\text{rad}]$$

Combine the Belle, BaBar, and CDF KK, $\pi\pi$ time-integrated measurements

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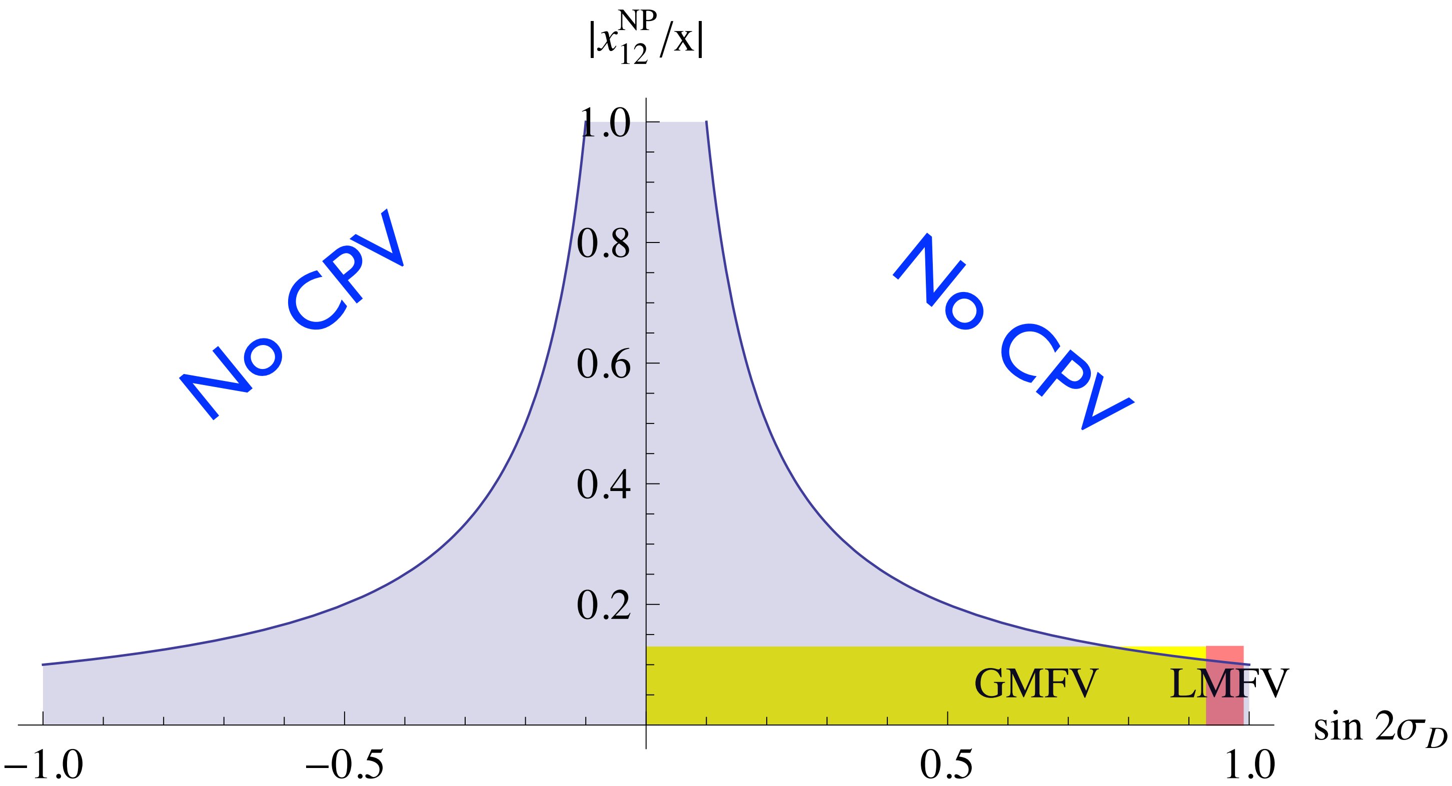

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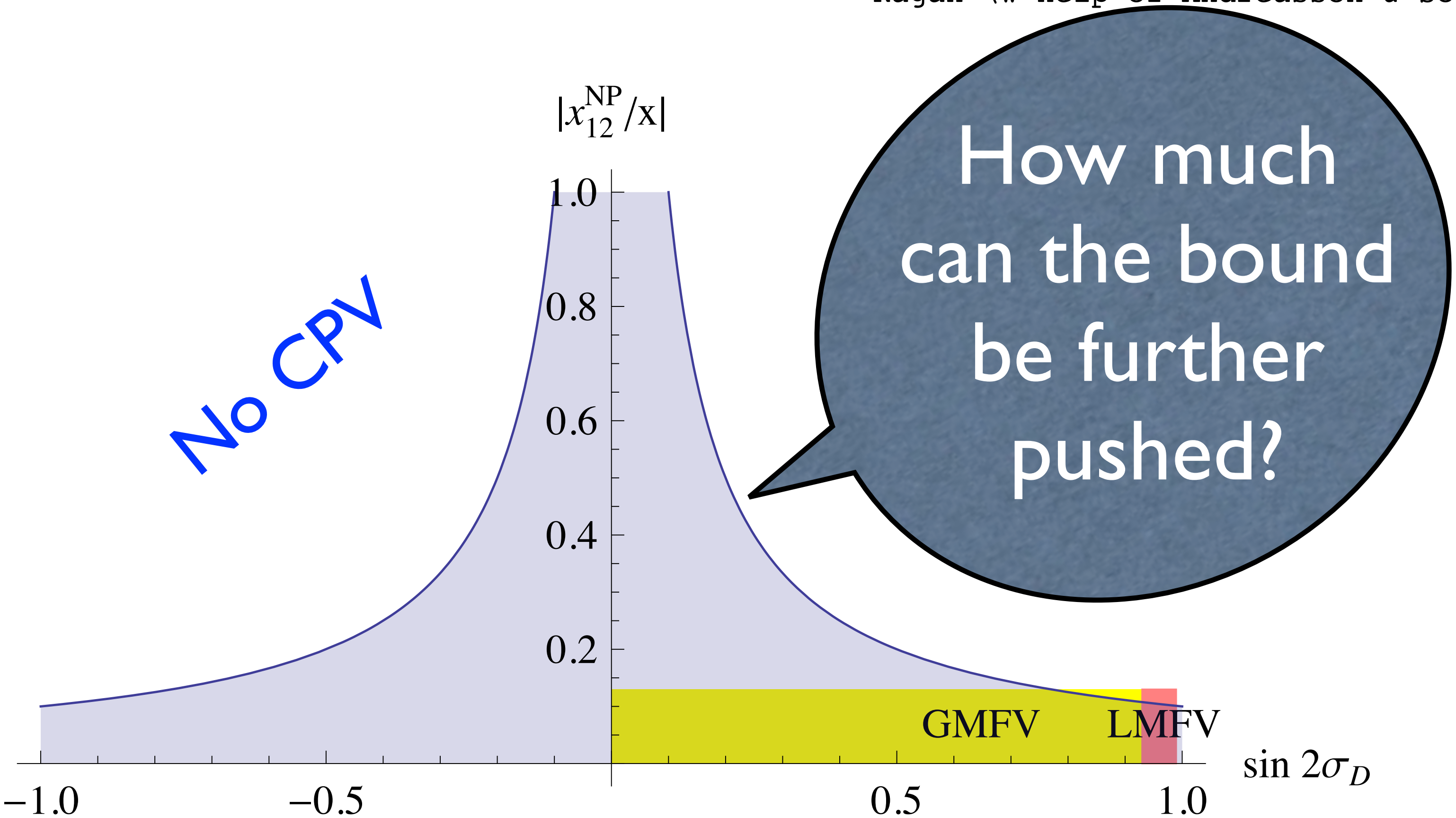

Robust bound on SM CPV in the D system

Knowledge of SU(3) breaking yield bound:

- Take $|\epsilon_s|, \;\; |\epsilon_d| < 1$ $\quad \Rightarrow \quad |\phi_{12}|^{\text{SM}} < 0.01$

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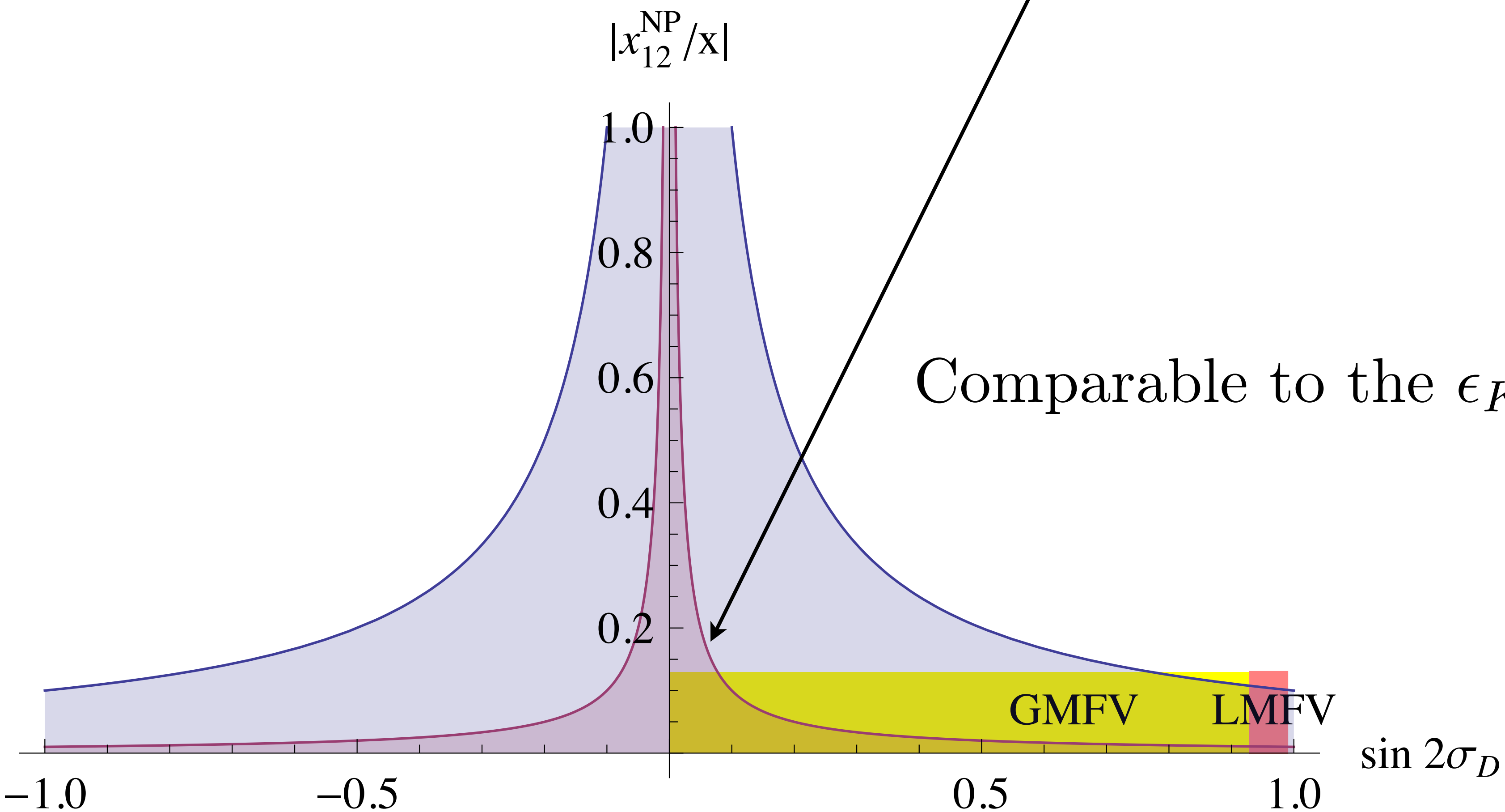

Comparable to the ϵ_K bound!

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

Model independent bounds:

(i) robust/immune *(ii) LLRR* - stronger, not immuned.

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[More info' in Δc=1, Fajfer, Singer, Zupan (03); Golowich, Hewett, Pakvasa, Petrov (09), Kagan, Sokolof (09)]

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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

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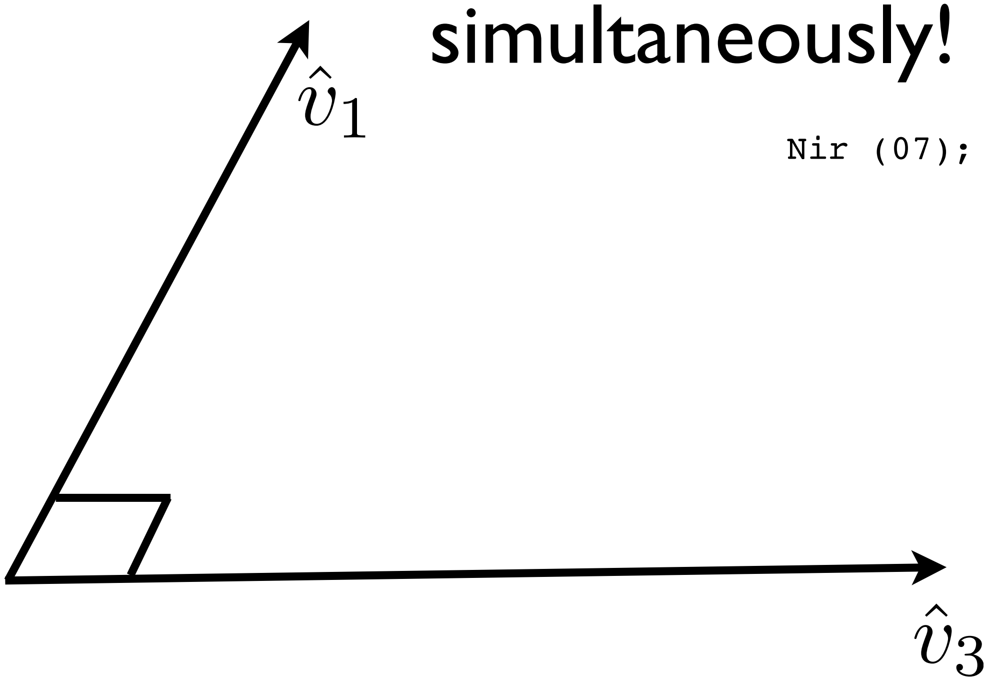

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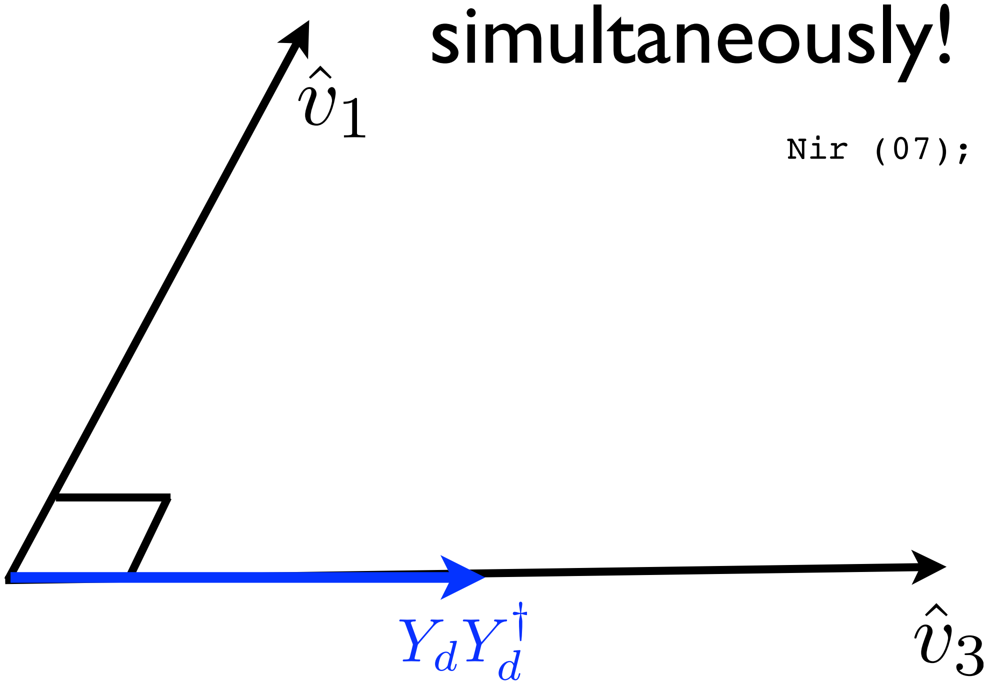

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Two gen' flavor structure (no CPV)

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

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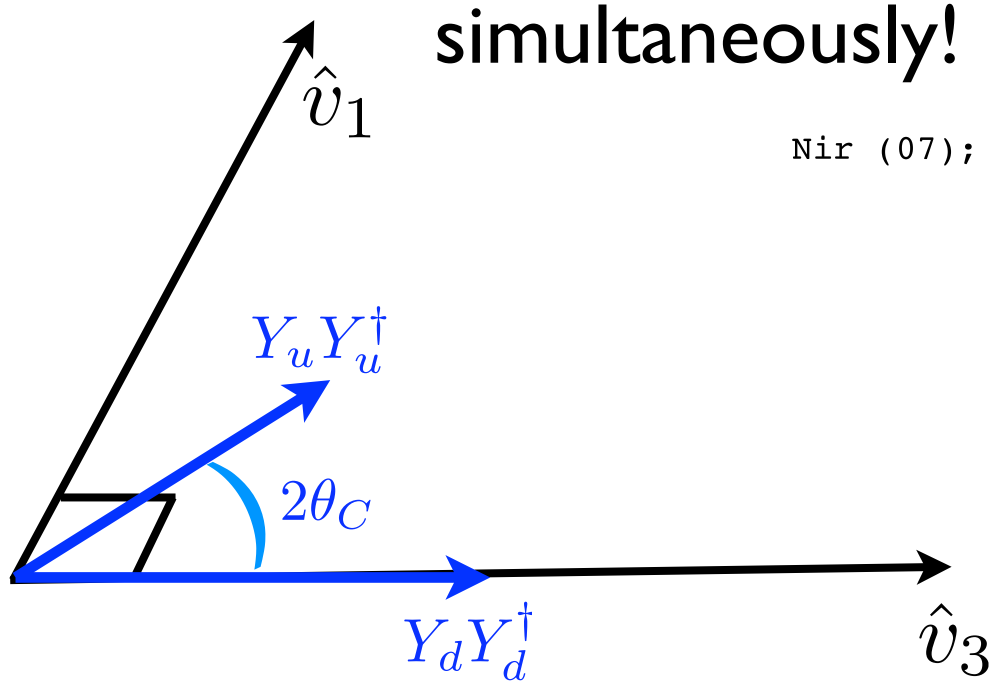
One cannot eliminate the constraint from K & D systems simultaneously!



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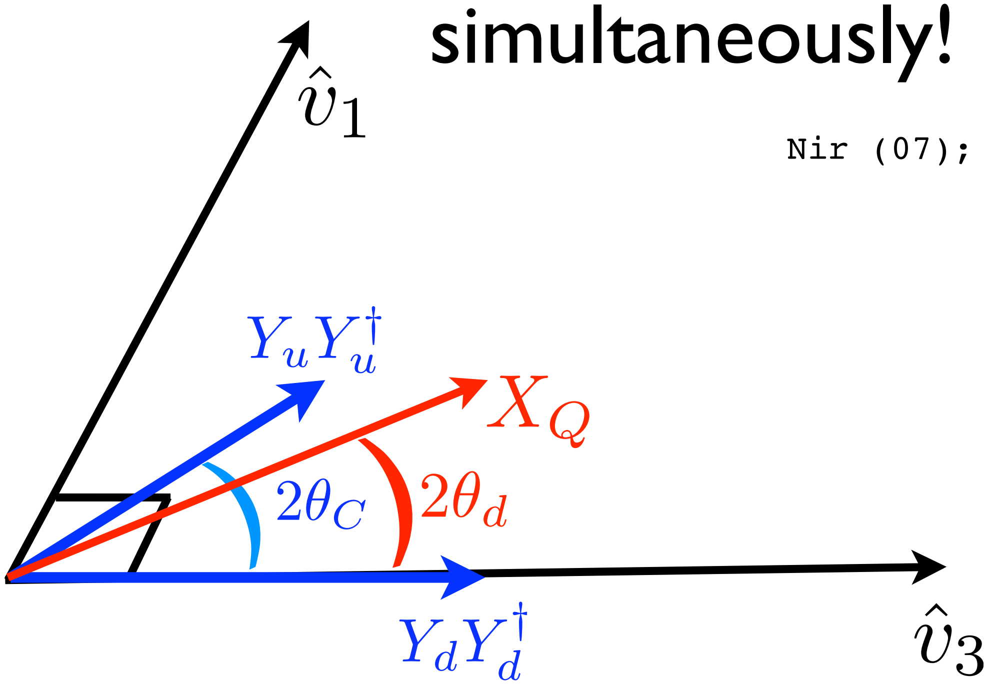

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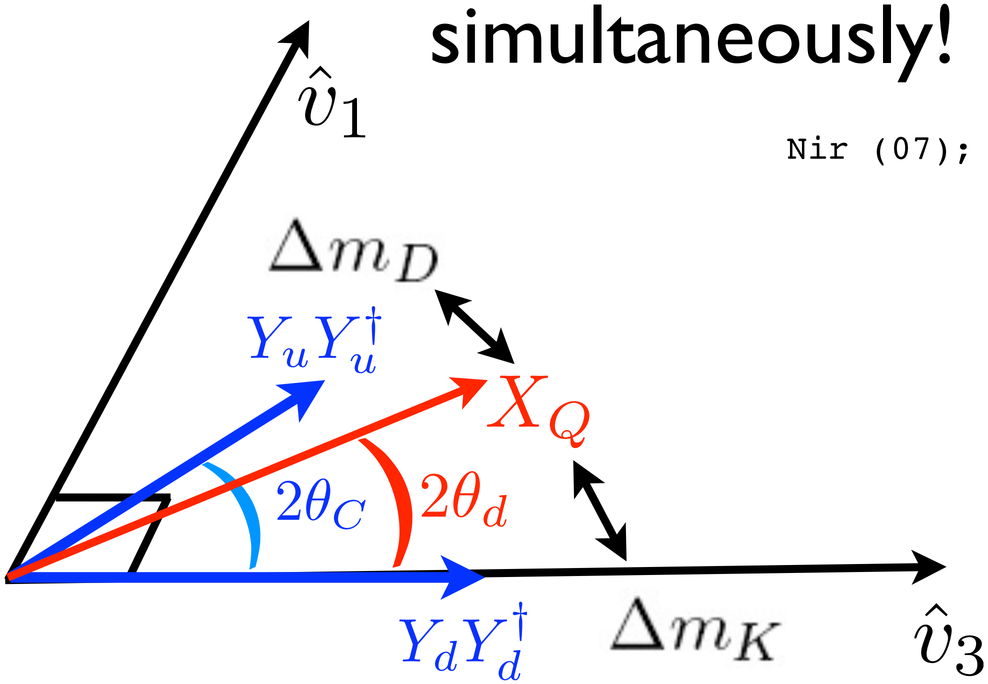

Implications of CPV in $D^0 - \bar{D}^0$ mixing

(i) Model independent;
(ii) General minimal flavor violation (GMFV);

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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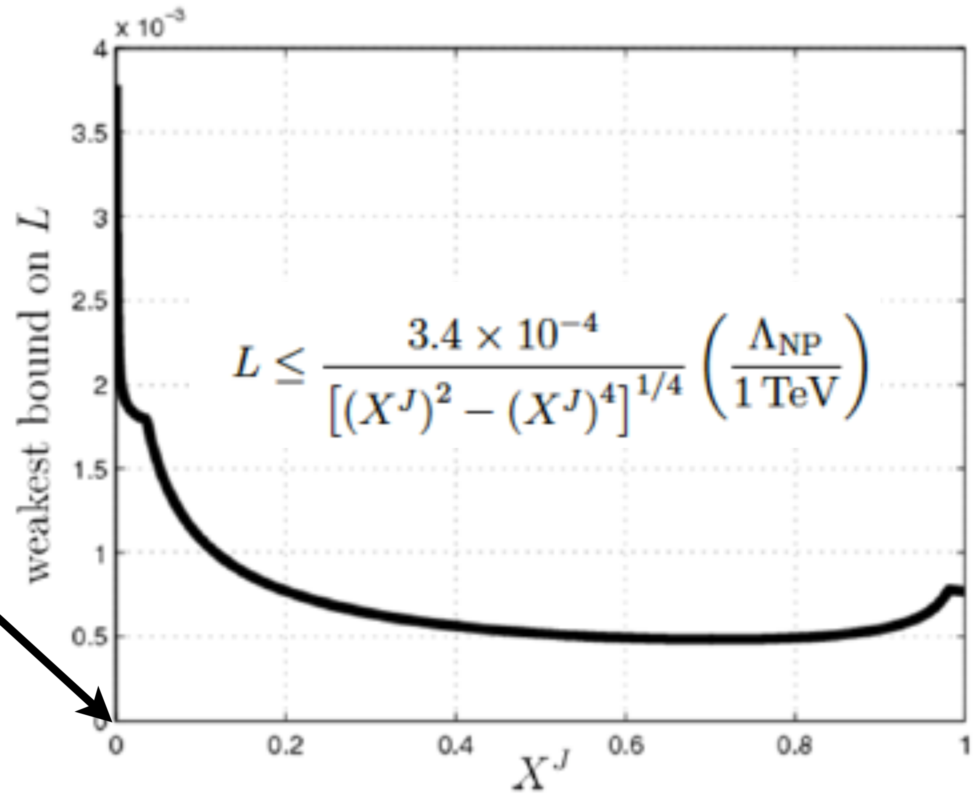

$X^J \in 0..1 \; =$ strength of CPV.

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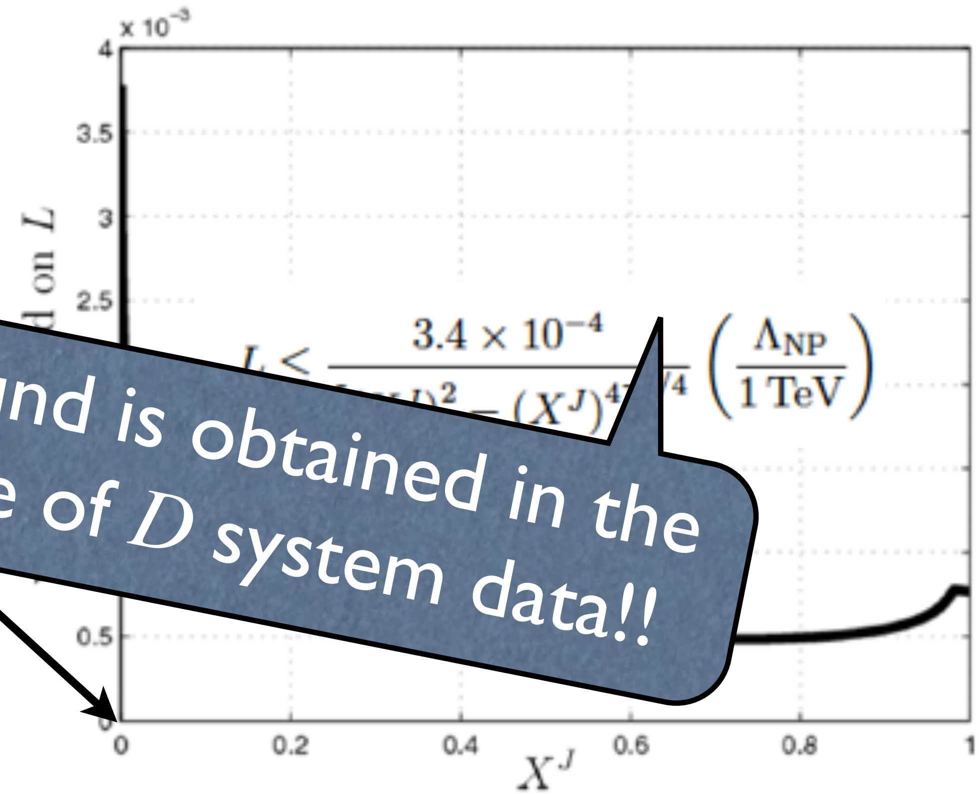

No bound is obtained in the absence of D system data!!

$X^J \in 0..1$ = strength of CPV.

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)

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

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

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

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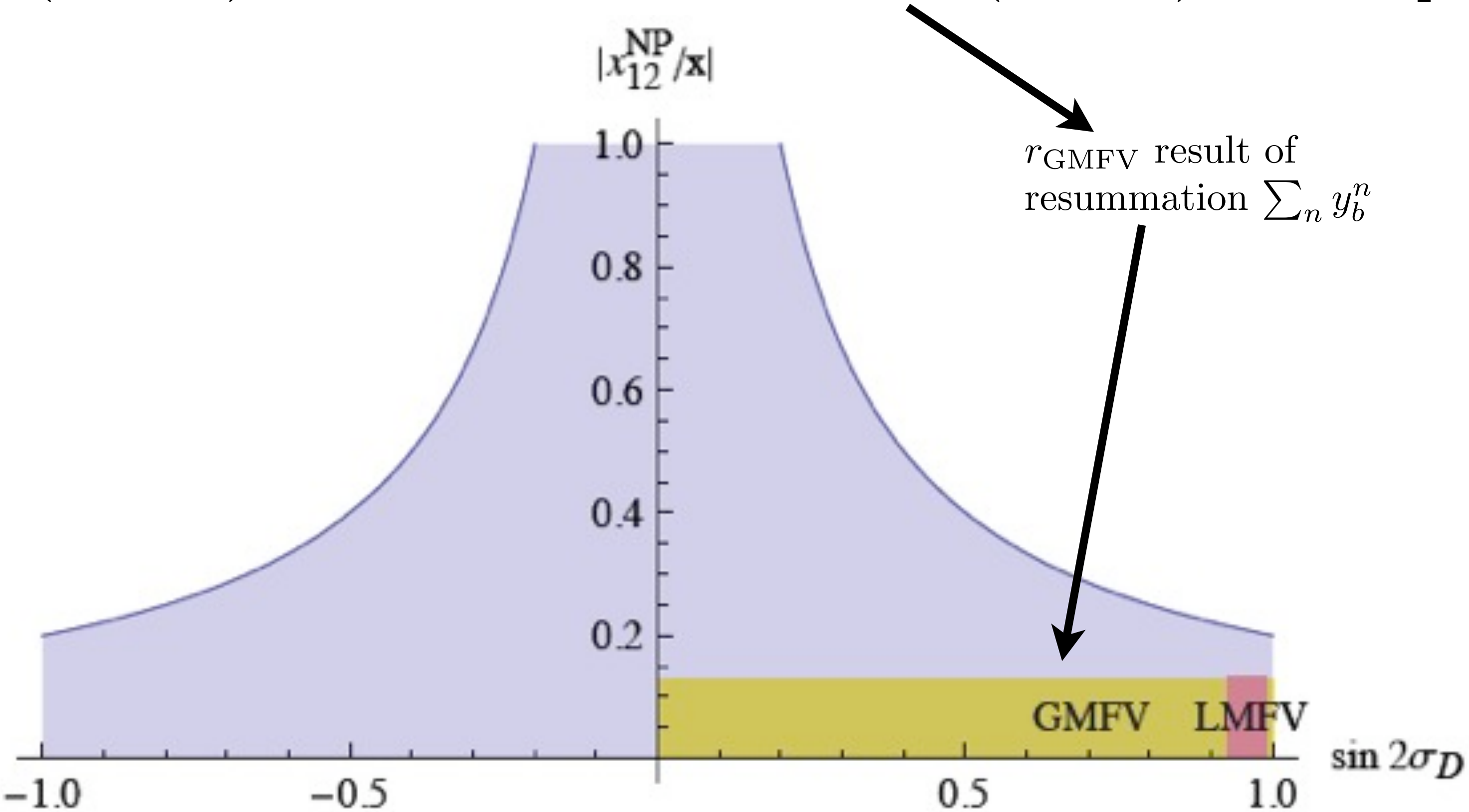

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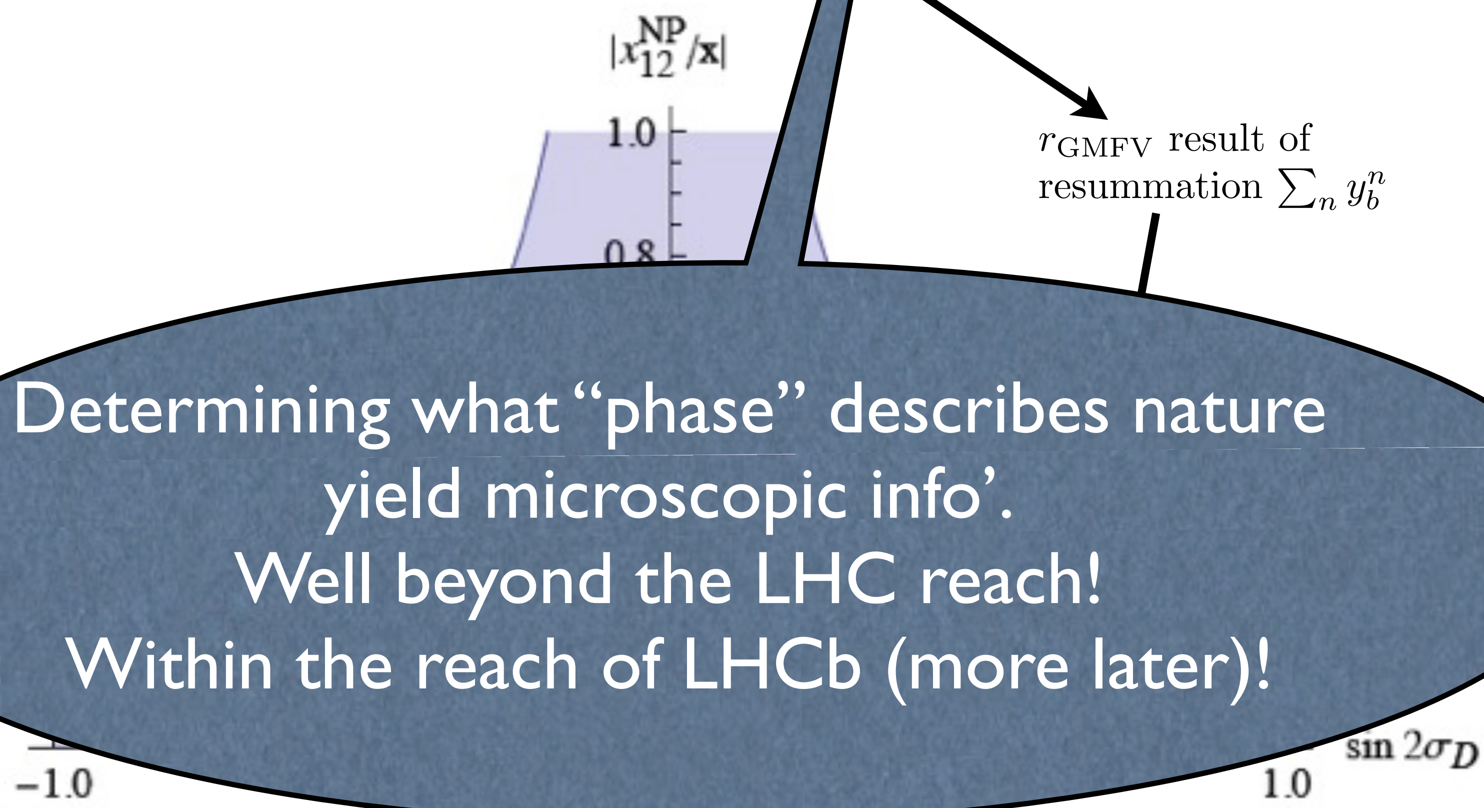


Determining what "phase" describes nature yield microscopic info'.
Well beyond the LHC reach!
Within the reach of LHCb (more later)!

Alignment: SUSY+RS

SUSY (doom of alignment)

Gedalia, et. al (09).

Robust

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

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

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

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

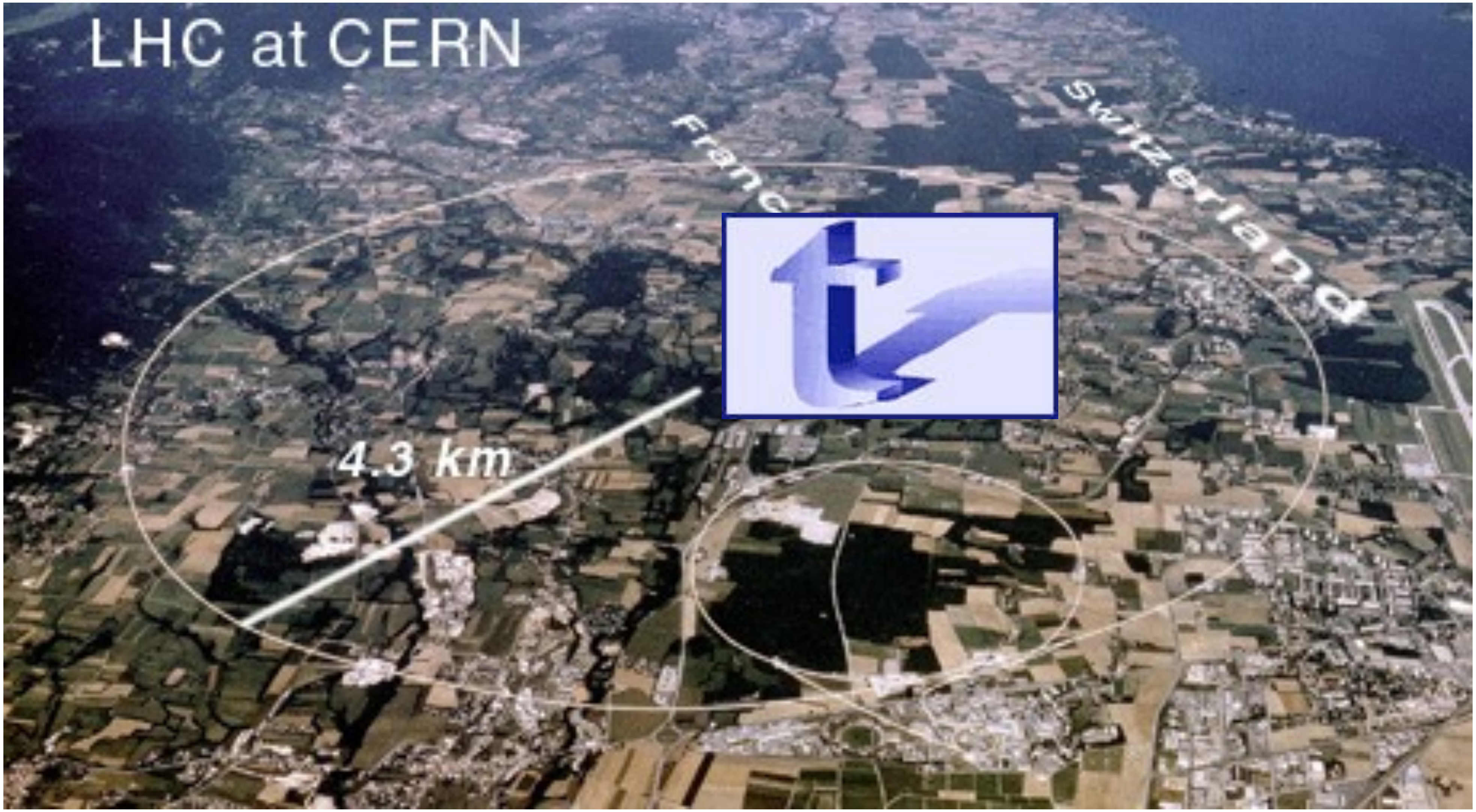
Generic

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

IR (bulk) Higgs

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

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, PLB; PRD (10).

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

$$(B^0_d - \bar{B}^0_d) \qquad (uu \to tt)$$

- 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

Flavor Diagonal Information

The approximate U(2)

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

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

$$\Lambda_3 = \frac{1}{\sqrt{2}}\mathrm{diag}(1,-1,0),$$

$$\Lambda_8 = \frac{1}{\sqrt{6}}\mathrm{diag}(1,1,-2),$$

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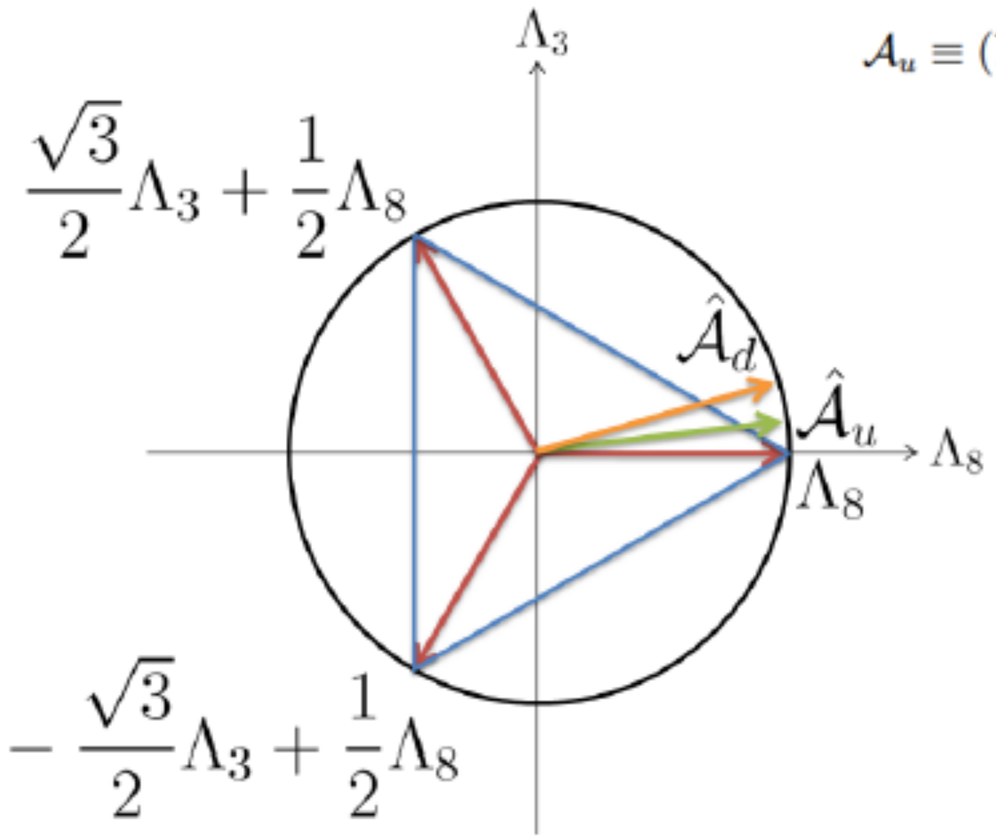

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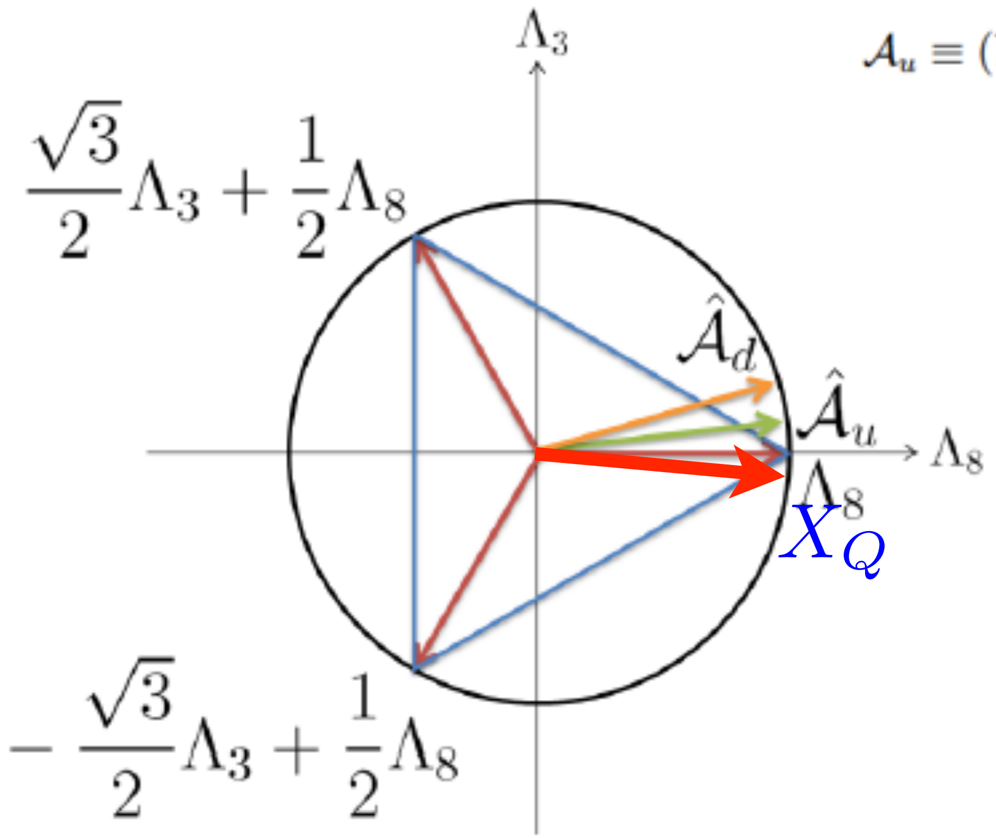

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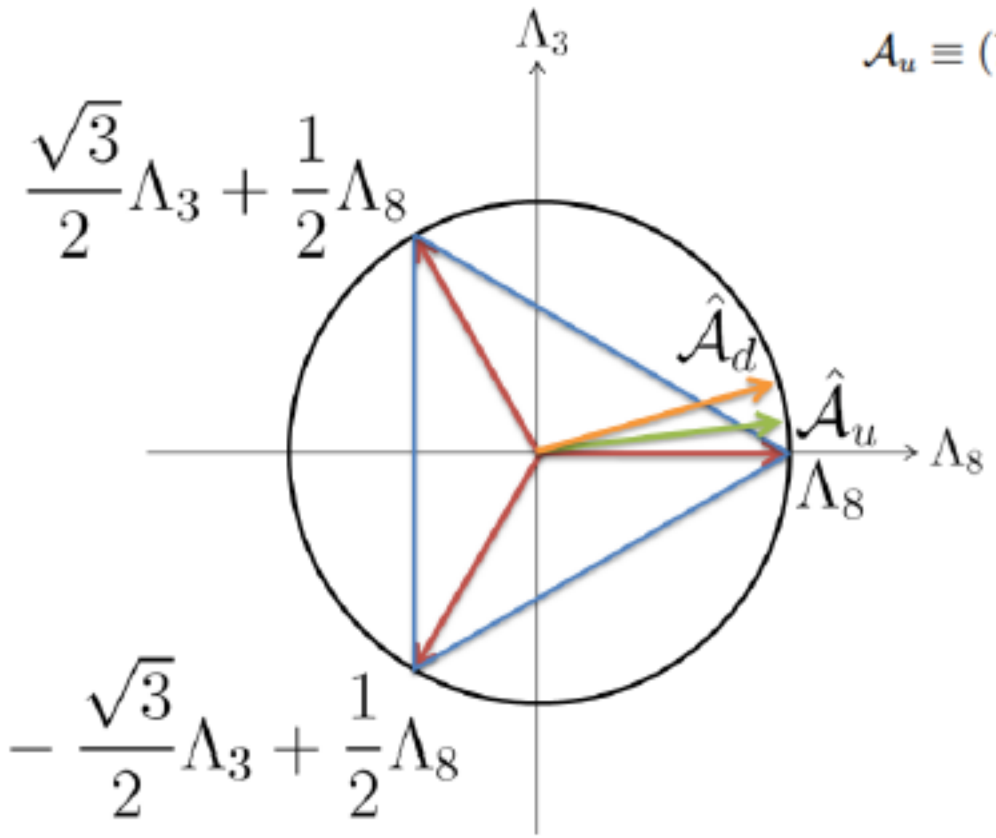

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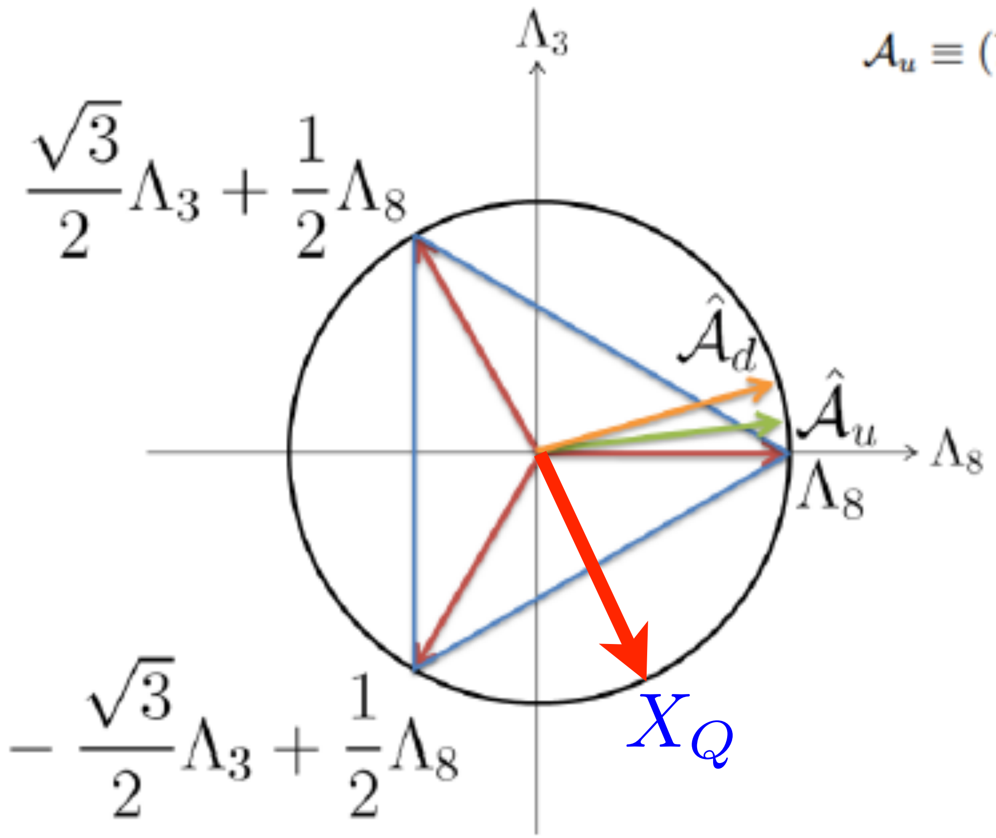

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Breaking of U(2) => sensation!
Can the LHC answer?

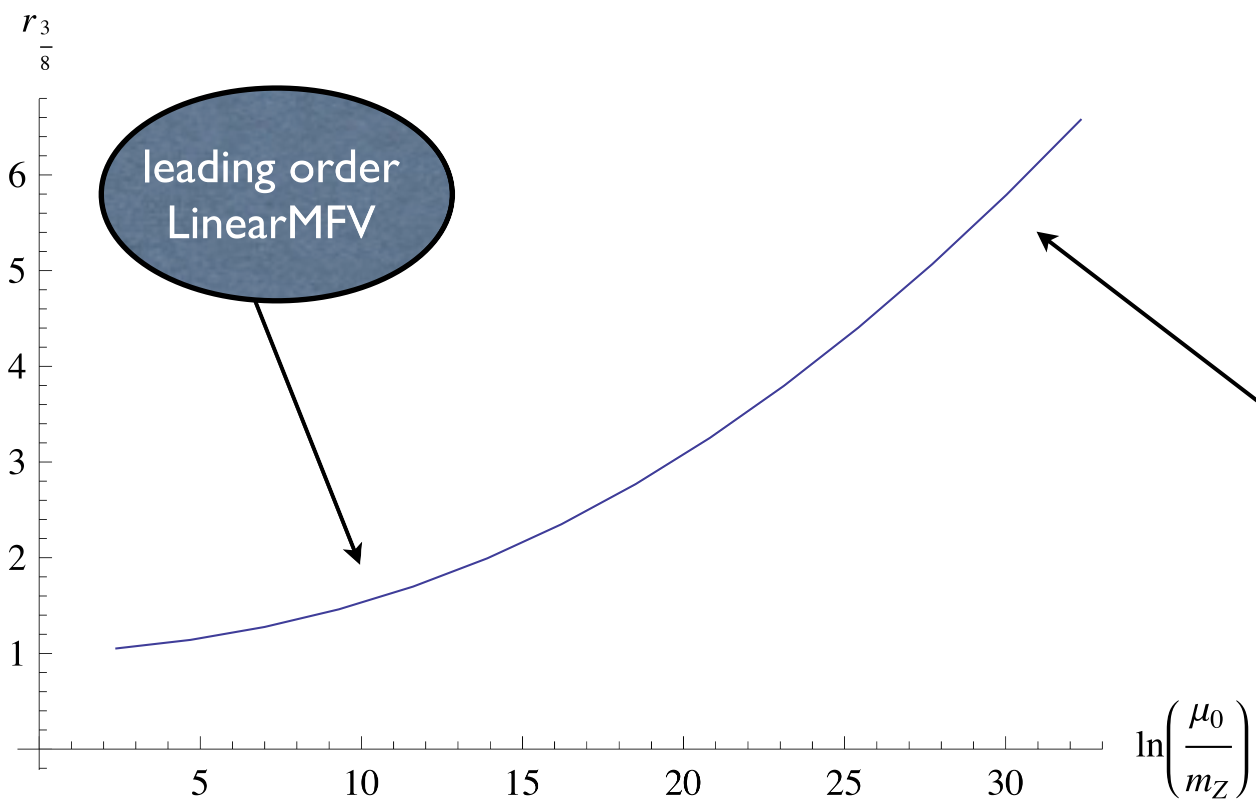
Refining the question: SUSY example, U(2) vs U(3) breaking & t-resummation, within MFV

Spectrum (flavor diag') is affected by amount or running.

(same holds for leptons)

$$r_{3/8} = \frac{1}{n_{3/8}} \frac{\mathrm{Tr}(\Lambda_3 m^2_{Q_L})}{\mathrm{Tr}(\Lambda_8 m^2_{Q_L})} \,,$$

$$n_{3/8} = \frac{\mathrm{Tr}(\Lambda_3 m_u^2)}{\mathrm{Tr}(\Lambda_8 m_u^2)} \sim 1.1 \cdot 10^{-5}, \quad m_u^2 = \mathrm{diag}(0, m_c^2, m_t^2),$$



Feng, et al., PRD (09); D. Grossman, Hochberg, GP & Soreq, in preparation.

Same thing for 5D warped model (flavor triviality)

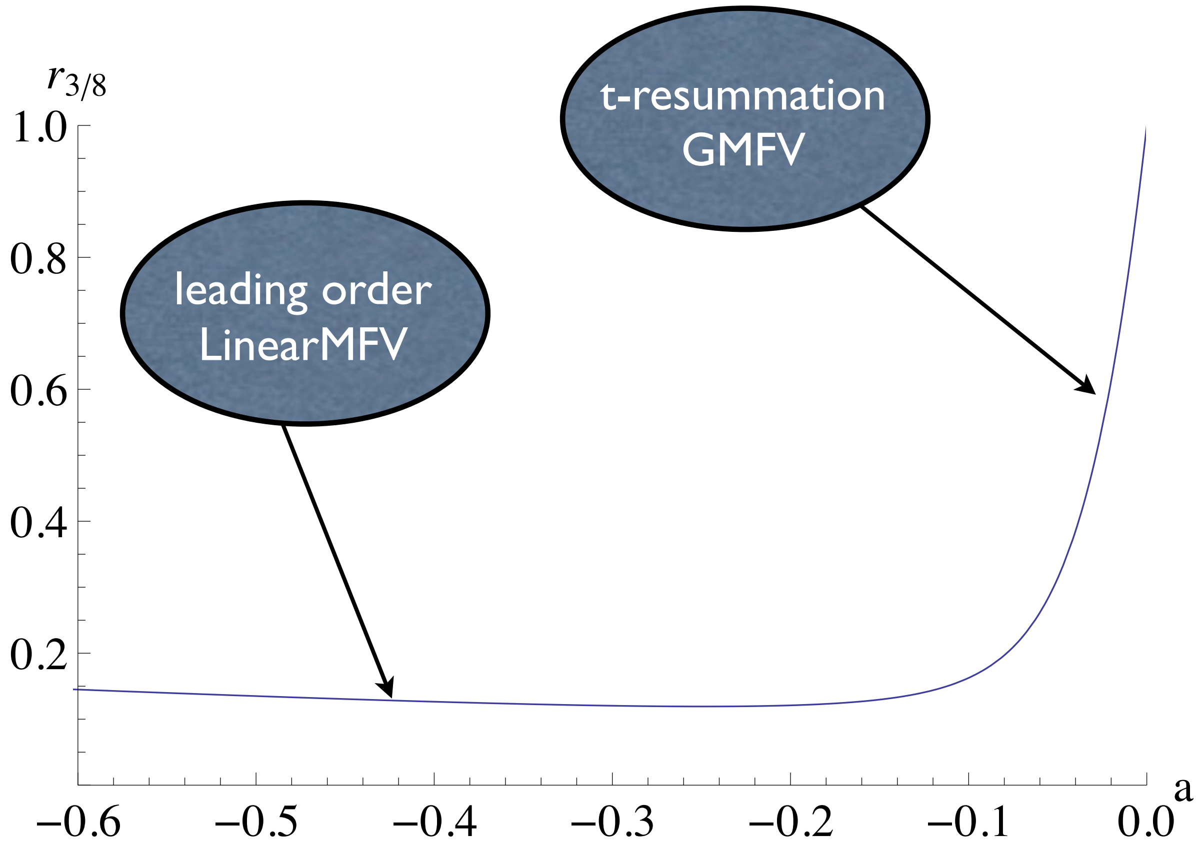
Partial widths (flavor diag') is affected by 5D mass/anomalous dim'.

The effective coupling of quarks to the first KK-gluon is given by, [10]:

$$g_{ij}^2 = \frac{1-2c_u^{ij}}{1-\epsilon^{1-2c_u^{ij}}}\frac{\sqrt{2}}{J_1(2.4)}\frac{0.7}{6-4c_u^{ij}}\left(1+e^{c_u^{ij}/2}\right)\,, \qquad \epsilon \approx 10^{-16}\,,$$

$$c_u^{ij} = c\delta_{ij} + a(Y_u Y_u^\dagger)_{ij}\,.$$

Delaunay, Gedalia, Lee, GP & Ponton, (10); (11).



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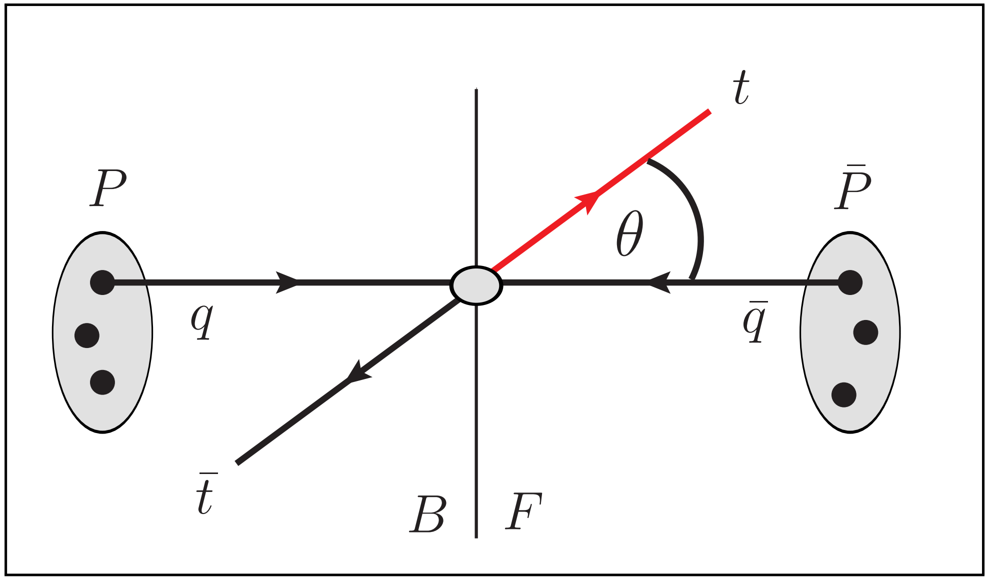
The top-flavor connection



top experimental anomalies

- D0 inclusive: $A_{fb} = (8 \pm 4(\text{stat}) \pm 1(\text{syst}))\%$

- CDF had-lep, differential:

$$A^{t\bar{t}}(M_{t\bar{t}} < 450 \text{ GeV}/c^2) = -0.116 \pm 0.153 \qquad A^{t\bar{t}}(|\Delta y| < 1.0) = 0.026 \pm 0.118$$
$$A^{t\bar{t}}(M_{t\bar{t}} \geq 450 \text{ GeV}/c^2) = 0.475 \pm 0.114 \qquad A^{t\bar{t}}(|\Delta y| \geq 1.0) = 0.611 \pm 0.256$$

- CDF di-lepton: $A_{\text{true}} = 0.417 \pm 0.148(\text{stat.}) \pm 0.053(\text{syst.})$

- CDF di-lepton, differential (not-unfolded):

$$\begin{aligned} A_{\text{obs}}^{<450 \text{ GeV}} &= 0.104 \pm 0.066(\text{stat.}) \qquad (\text{Pred.}: \ 0.003 \pm 0.031) \\ A_{\text{obs}}^{>450 \text{ GeV}} &= 0.212 \pm 0.096(\text{stat.}) \qquad (\text{Pred.}: \ -0.040 \pm 0.055) \ . \end{aligned}$$

- CDF boosted tops $(p_T^J > 400\text{GeV}, \ 130\text{GeV} < m_J < 210\text{GeV})$:

$$\text{"Excess"} \sim \left[3.2 - 6.1\left(1 - R_{\text{mass}}\right)\right]\sigma, \ R_{\text{mass}} \simeq 0.89 \ \Rightarrow 2.6\,\sigma$$

Eshel et al. (11); Blum et al. (11).

Naively, the AFB has nothing to do with flavor

The two leading interpretation linked to flavor physics:

(I) AFB from hard physics:

(i) Requires that $g_{t\bar{t}} = -g_{u\bar{u}}$. Chivukula, et al. (10); Cao, et al. (10); Delaunay, et al.; Aguilar-Saavedra, et al. (11).

(ii) ATLAS+CMS dijets bound implies $g_{u\bar{u}}/g_{t\bar{t}} \sim \frac{1}{5}$.

ATLAS; CMS; Bai, et al. (11); Papucci-Perez, night discussion.

Flavor diagonal
but not universal/blind!!

Naively, the AFB has nothing to do with flavor

The two leading interpretation linked to flavor physics:

(II) AFB from particle exchange (many models):

(i) Again dijet kills the universal case.

Grinstein, et al.; Ligeti, et al. (11)

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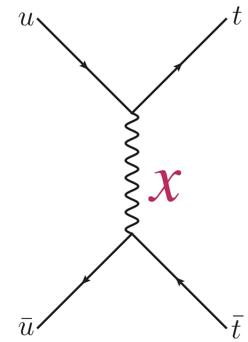

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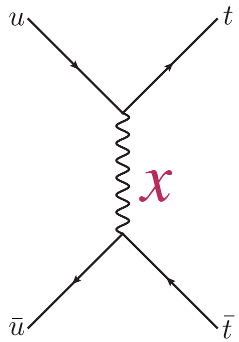

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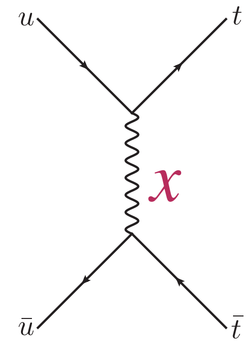

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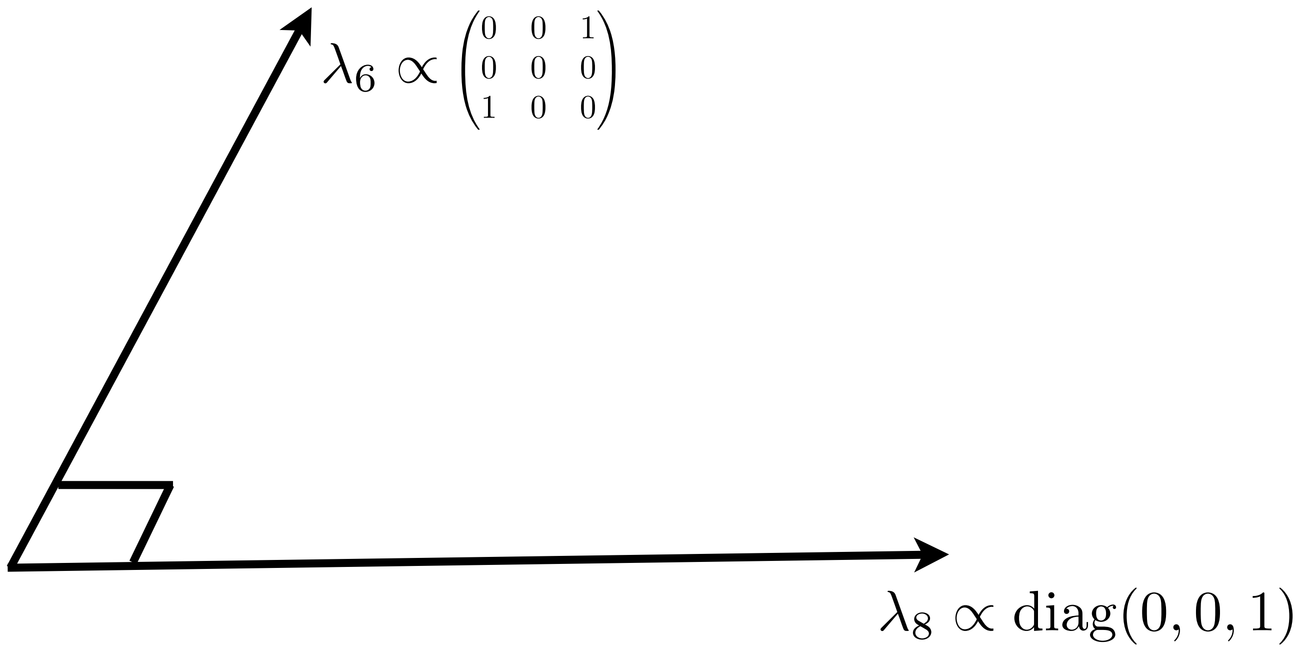

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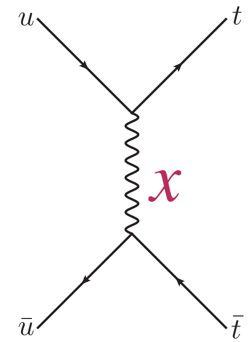

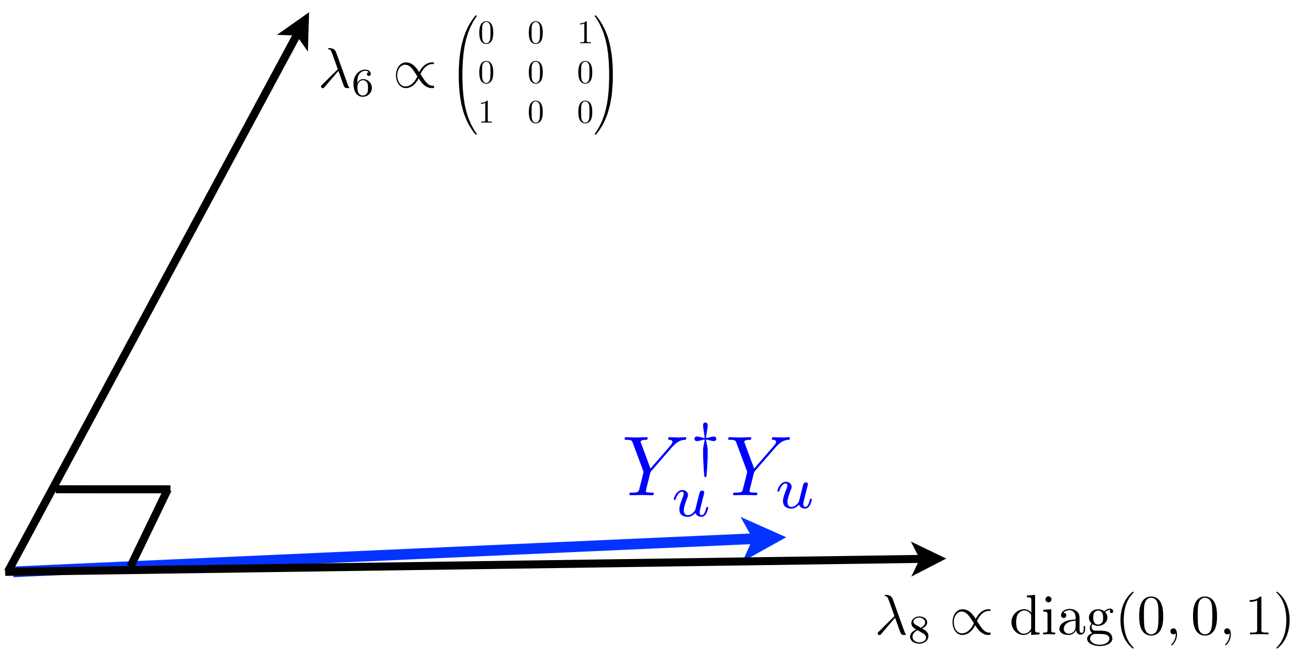

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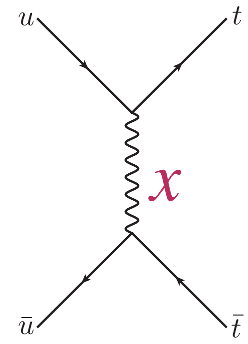

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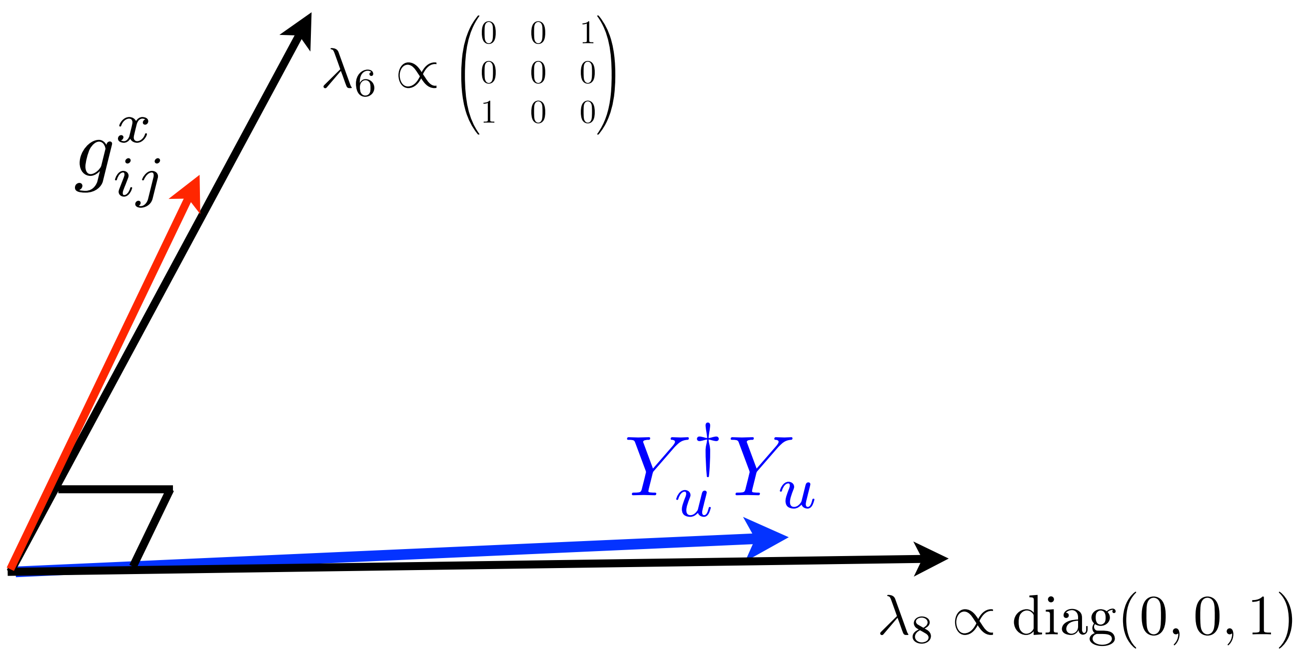

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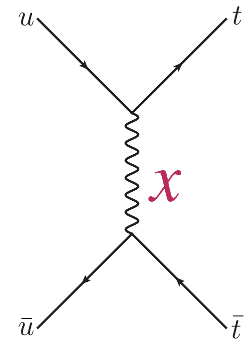

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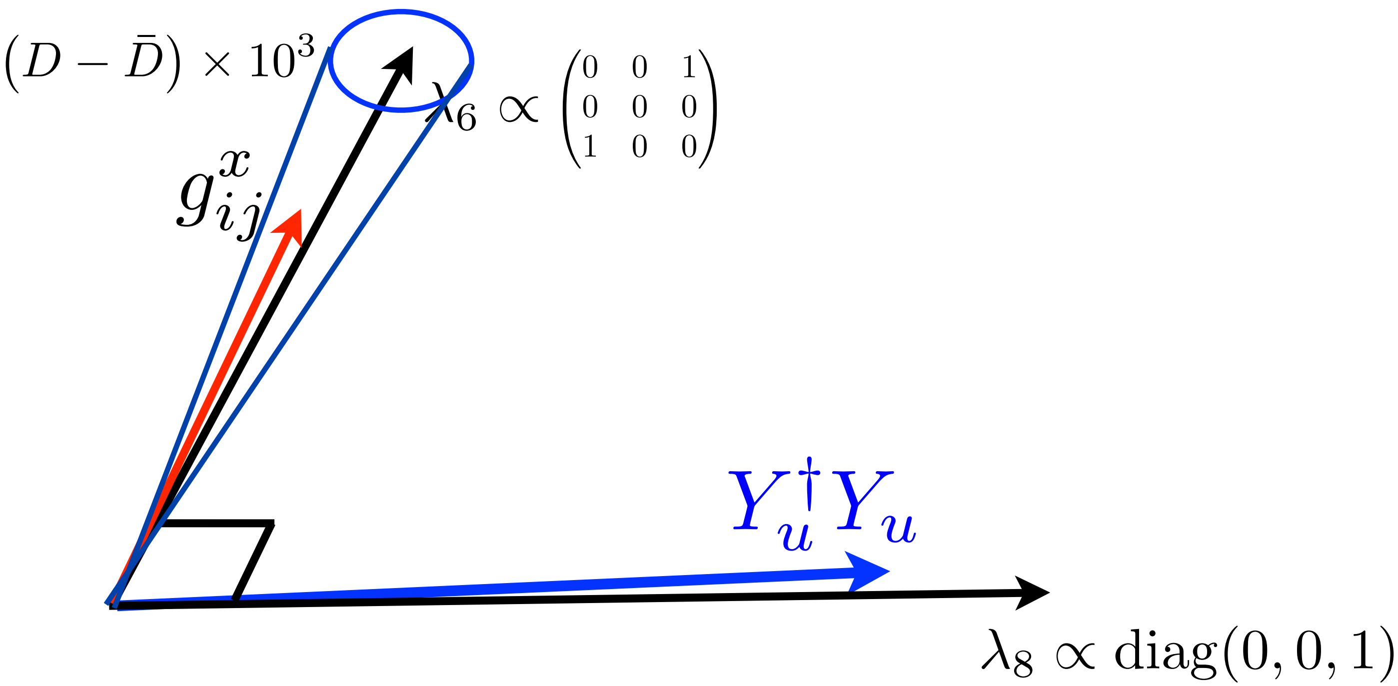

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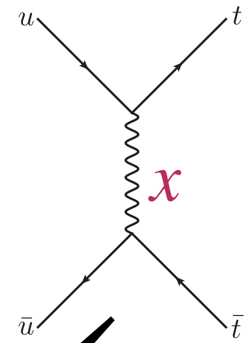
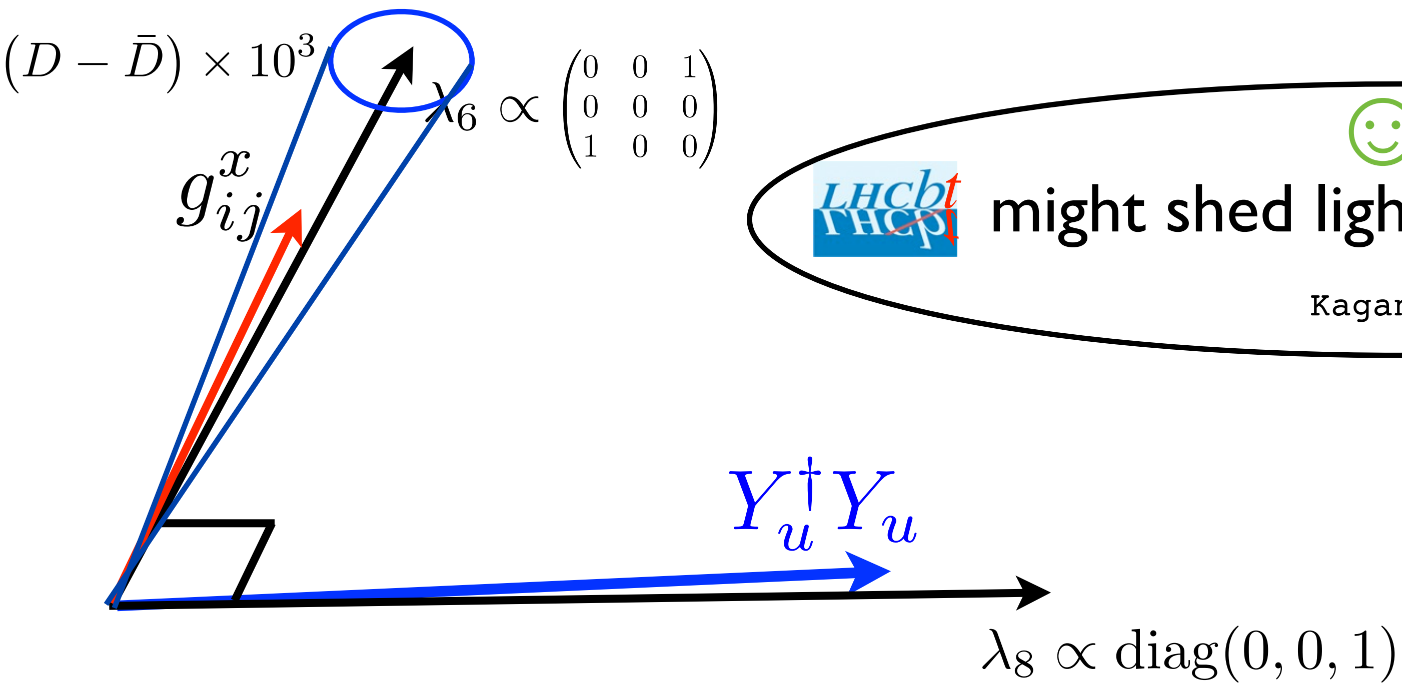




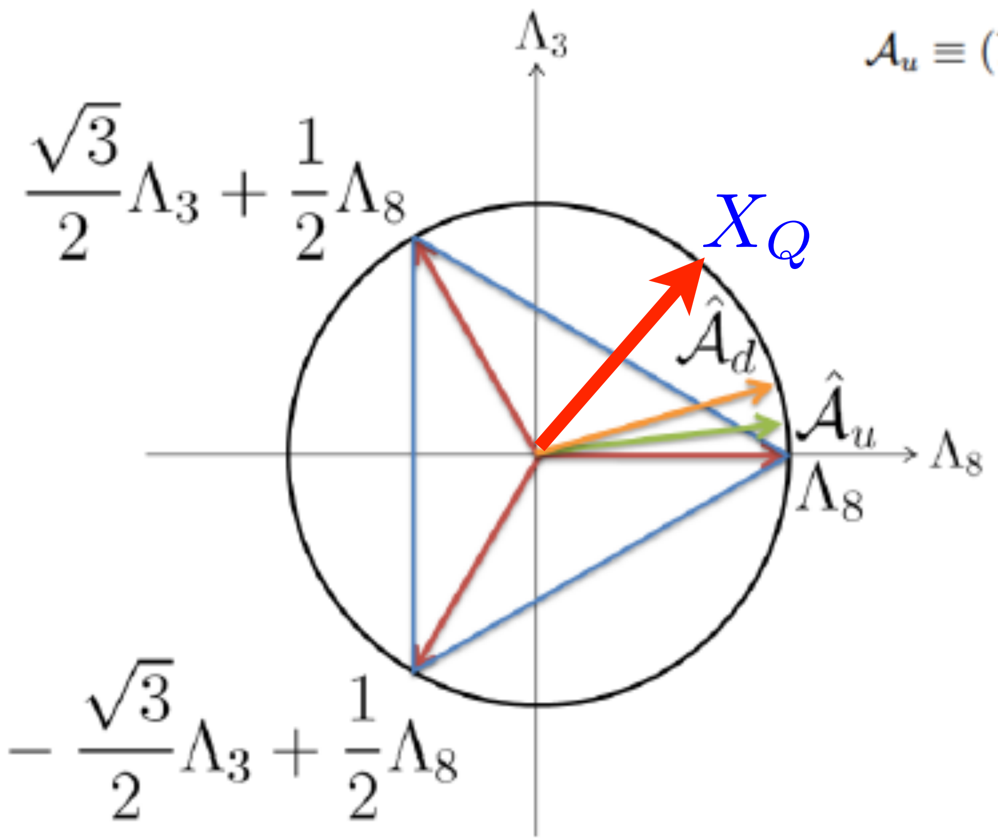
☺

LHCb might shed light via: $A^{t\bar{t}}_\eta = \left(\frac{d\sigma^t/d\eta - d\sigma^{\bar{t}}/d\eta}{d\sigma^t/d\eta + d\sigma^{\bar{t}}/d\eta}\right)_{\eta\in 2-5}$

Kagan, et al. (11)

(2-pages) Summary

New physics flavor diagonal structure (spectrum or couplings) => microscopic information.



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

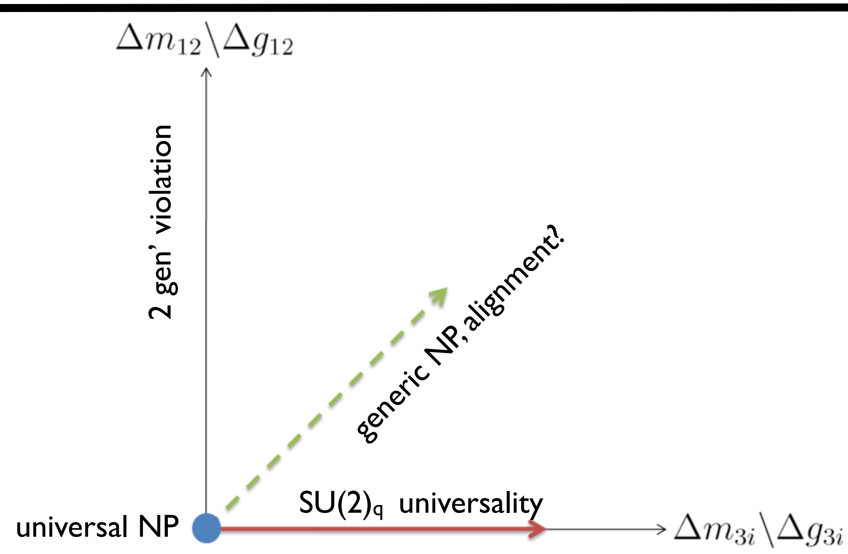
$$\Lambda_3 = \frac{1}{\sqrt{2}}\mathrm{diag}(1,-1,0),$$

$$\Lambda_8 = \frac{1}{\sqrt{6}}\mathrm{diag}(1,1,-2),$$

Can the LHC answer?

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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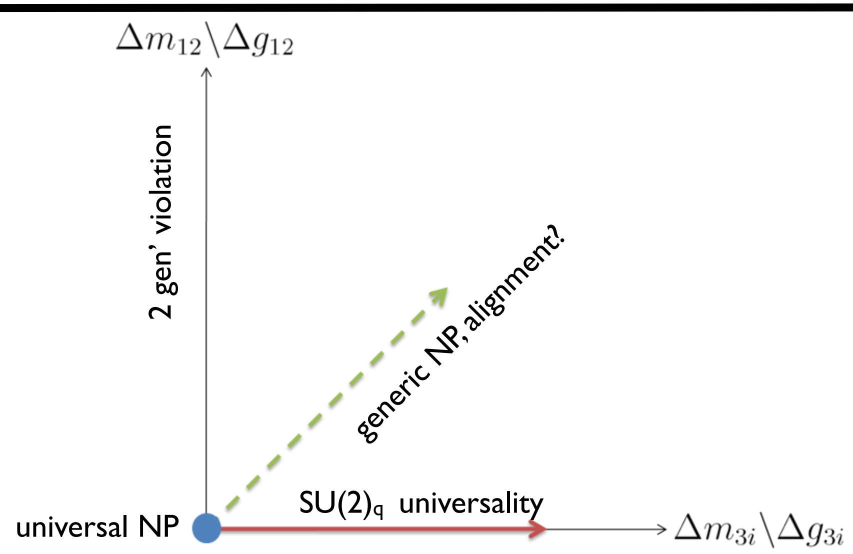
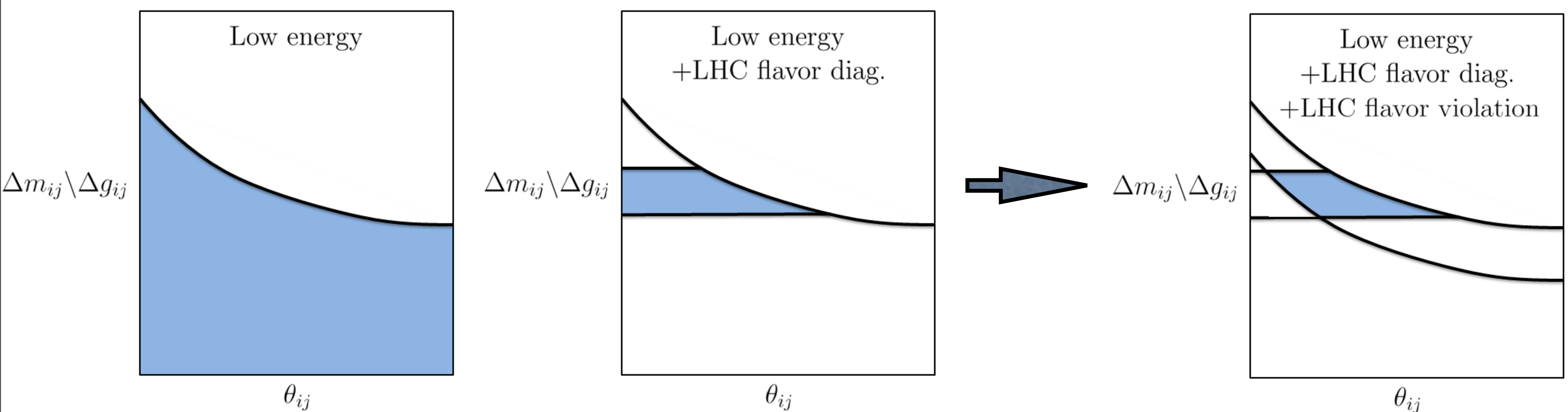
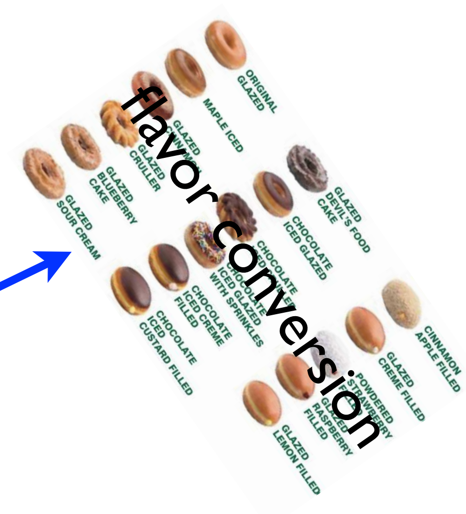




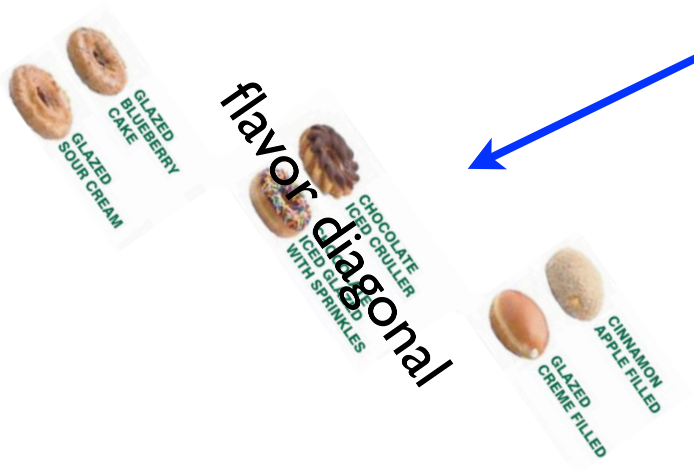
Grossman, Ligeti & Nir, Prog. Th. Phys. (09); Gedalia & Perez, TASI (10).

Thank you

flavor conversion



flavor diagonal

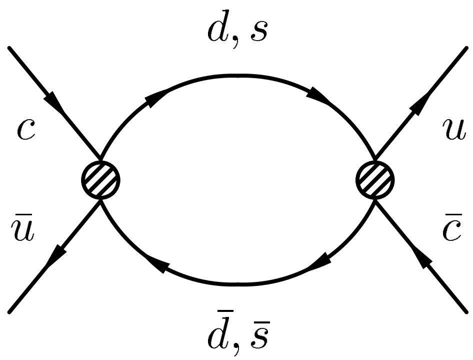


Backups

Robust bound on SM CPV in the D system

Kagan, FPCP11.

$$\Gamma_{12} = -\left(\lambda_s^2\,\Gamma_{ss} + 2\lambda_s\lambda_d\,\Gamma_{sd} + \lambda_d^2\,\Gamma_{dd}\right), \qquad \text{where} \quad \lambda_p = V_{cp}V_{up}^*$$



Γ_{xy} in the OPE picture

$$\begin{aligned}
\Gamma_{ss}&: \quad \text{via SCS operators } c \to s\bar{s}u \\
\Gamma_{dd}&: \quad \text{via SCS operators } c \to d\bar{d}u \\
\Gamma_{sd}&: \quad \text{via CF \& DCS operators } c \to s\bar{d}u\,,\ \ c \to d\bar{s}u
\end{aligned}$$

- from a sum over decays to common exclusive final states Falk et al.:

$$\lambda_s^2\Gamma_{ss} = \Gamma \sum_n \eta_{\mathrm{CP}}(n)\cos\delta_n \sqrt{\mathcal{B}(D^0 \to n)\mathcal{B}(D^0 \to \bar{n})}\,,\ \ \ldots.$$

δ_n = strong phase difference between $\mathcal{A}(D^0 \to n)$ and $\mathcal{A}(\bar{D}^0 \to n)$; $\eta_{\mathrm{CP}} = \pm 1$

Grossman, Kagan & Ligeti, to appear.

Robust bound on SM CPV in the D system

Kagan, FPCP11.

$$\phi_{12} = \arg(M_{12}/\Gamma_{12}) \approx -\mathrm{Im}(\delta\,\Gamma_{12}/\Gamma^0_{12}) \quad \Rightarrow$$

$$\phi_{12} = 2\,|\lambda_b \lambda_s|\,\sin\gamma\,\frac{\Gamma_{sd}}{\Gamma^0_{12}}\left(\frac{\Gamma_{sd}-\Gamma_{dd}}{\Gamma_{sd}} + \left|\frac{\lambda_b}{\lambda_s}\right|\cos\gamma\,\frac{\Gamma_{dd}}{\Gamma_{sd}}\right)$$

- Introduce additional $SU(3)_F$ breaking parameters:

$$\epsilon_d \equiv \frac{\Gamma_{dd}-\Gamma_{sd}}{\Gamma_{sd}}, \qquad \epsilon_s \equiv \frac{\Gamma_{ss}-\Gamma_{sd}}{\Gamma_{sd}}$$

- The bounds for CKM, y central values:

$$|\phi_{12}| < 2\left|\frac{\lambda_b\,\lambda_s\,\sin\gamma}{y}\right| \times |\epsilon_d|\,(1+\epsilon_\Gamma/2) = 0.008\,|\epsilon_d|\,(1+\epsilon_\Gamma)$$

$$|\phi_{12}| < 2\left|\frac{\lambda_b\,\lambda_s\,\sin\gamma}{y}\right| \times |\epsilon_s|\,(1+\epsilon_\Gamma/2) + 2\left|\frac{\lambda_b}{\lambda_s}\sin\gamma\right| = 0.008\,|\epsilon_s|\,(1+\epsilon_\Gamma/2)$$

  - data $\Rightarrow$ canonical $SU(3)_F$ breaking, $\epsilon_\Gamma \approx (10-30)\%$

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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

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

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

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

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

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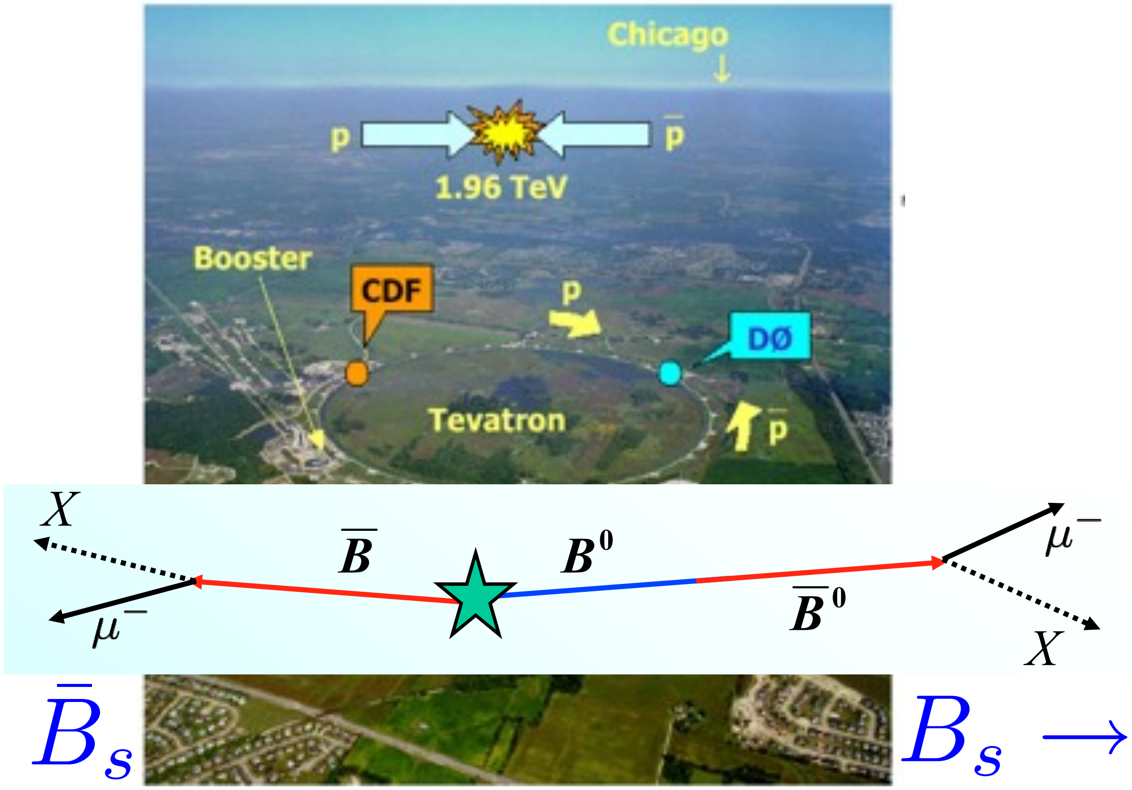
- System parameters roughly determined (HFAG):

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

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

News from the Tevatron (& preliminary from the LHCb)



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

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

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

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- 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. $S_{\psi\phi}$ & LHCb sees 1.2 σ??

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

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, PRL.

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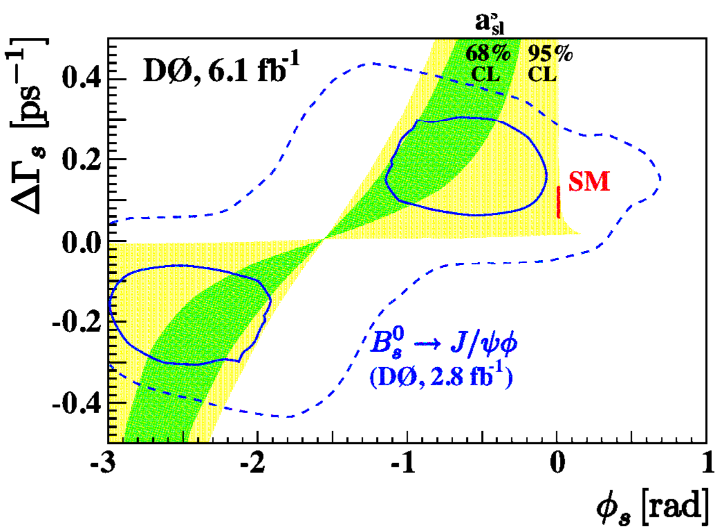
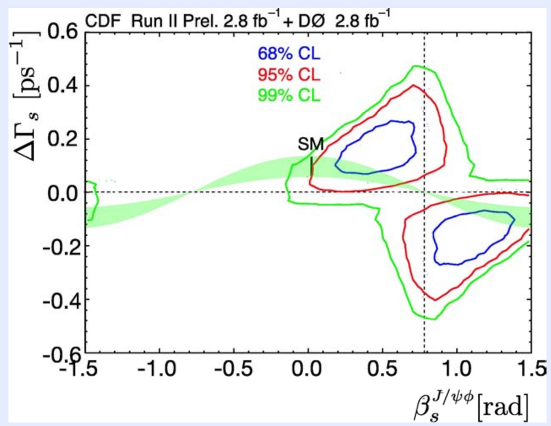
- **Tevatron experiments** also measure:

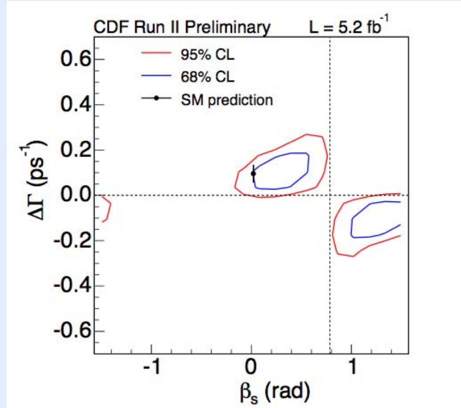




Tevatron combination: probability of observed deviation from SM = 3.4% (2.12 σ)

CDF Public Note 9787

New CDF measurement of β_s



Coverage adjusted 2D likelihood contours for β_s and ΔΓ

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, PRL.

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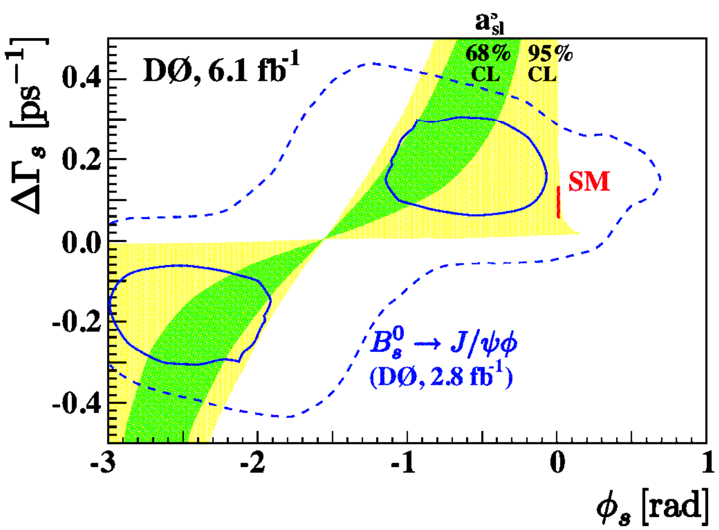

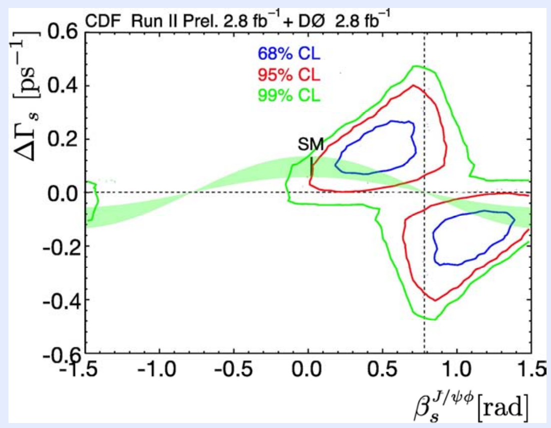

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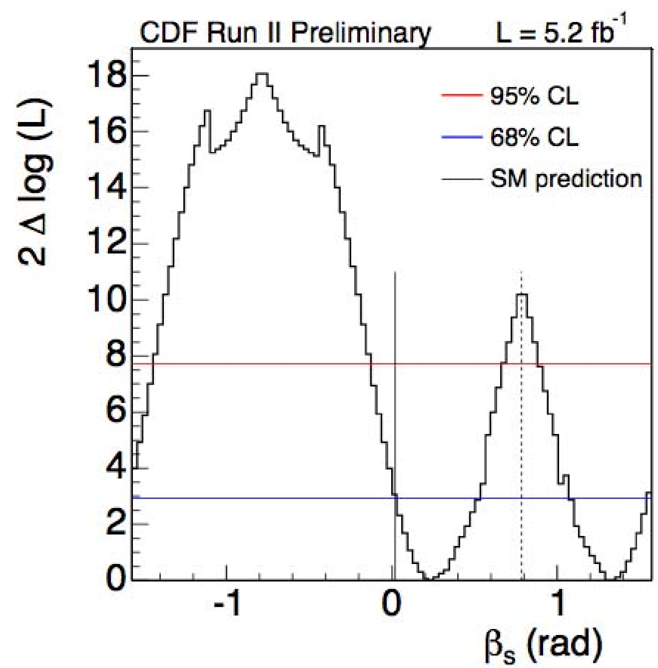


Combining $a_{\rm SL}^b$ & $\Delta\Gamma_s$ vs. $S_{\psi\phi}$

- Consistency check:

Ligeti, Papucci, GP, Zupan.

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

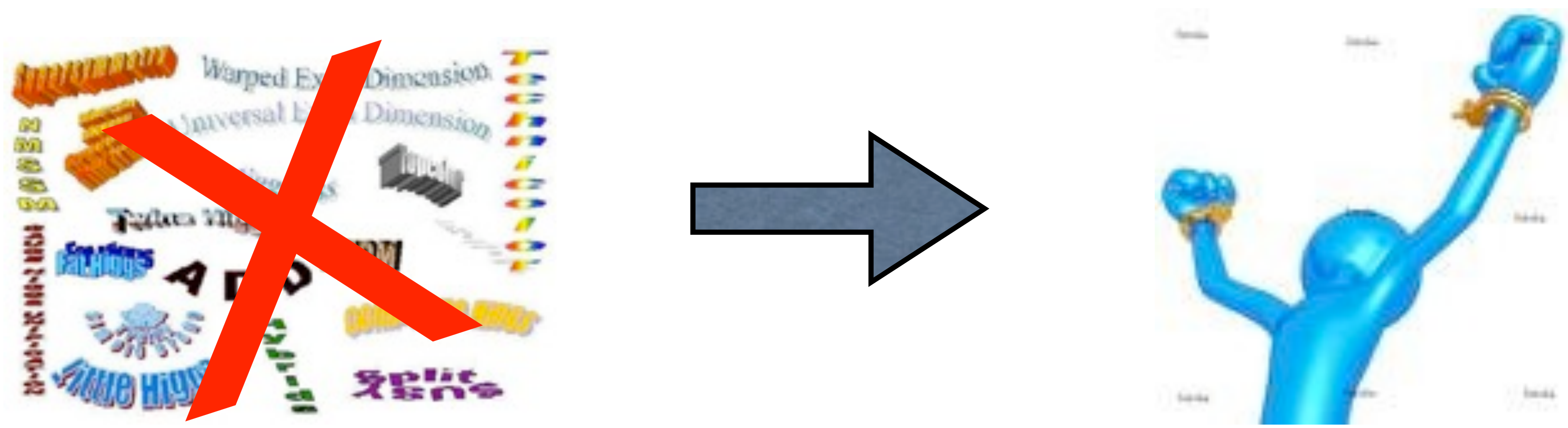
$$\left(S_{\psi\phi}\right)_{\rm CDF+D\O} : \quad (\Delta\Gamma_s,\, S_{\psi\phi}) \sim \left(0.15\,{\rm ps}^{-1},\ \ 0.5\right)$$

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

  Or compare with state of the art QCD predictions.

  Lenz & Nierste, JHEP (07); 1102.4274 (11).

Model independent interpretation



Global NP fit

- **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.

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

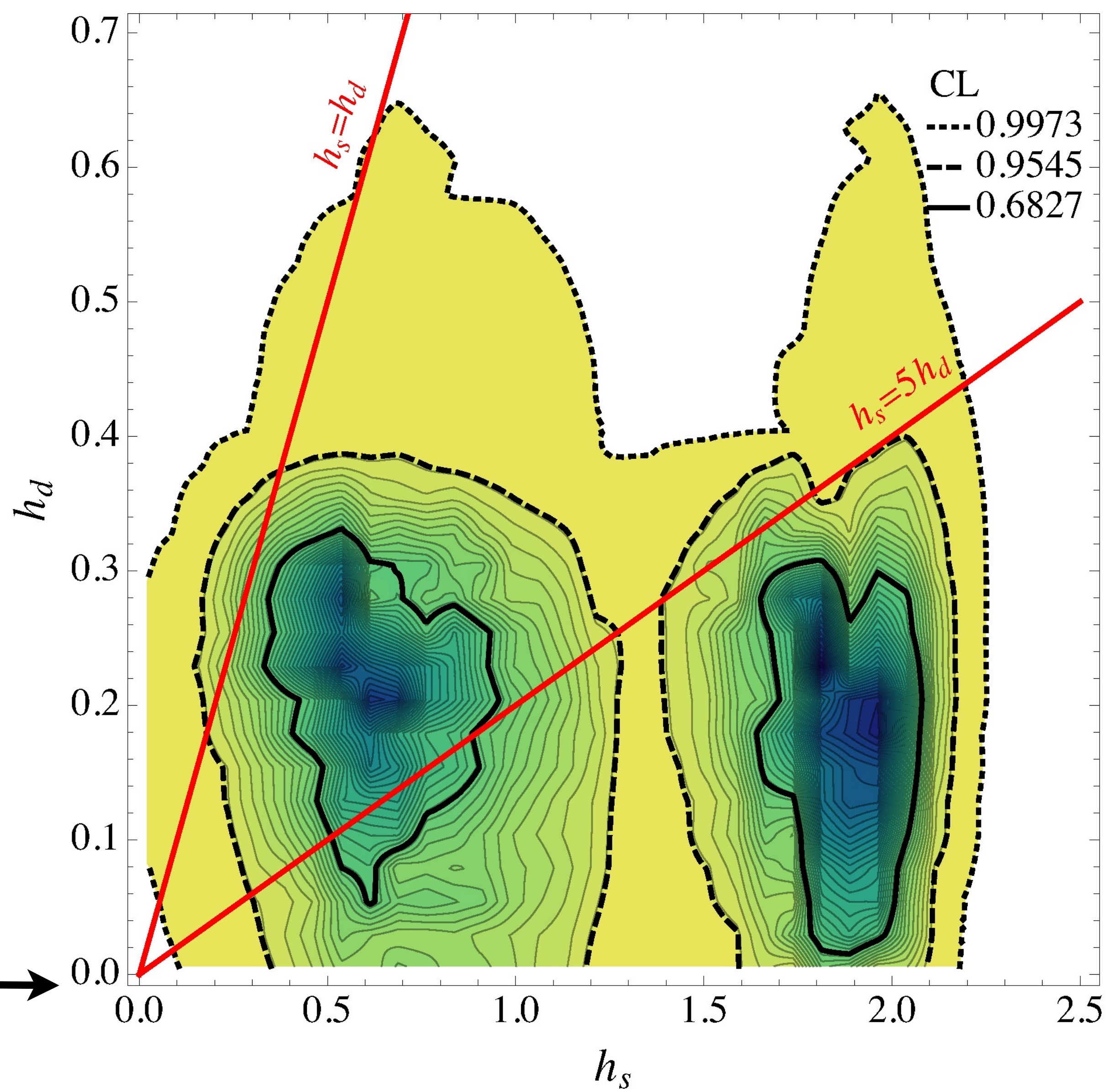
Global fit's results

Ligeti, Papucci, GP, Zupan.

(we used CKMfitter)

B_d vs. B_s systems

SM



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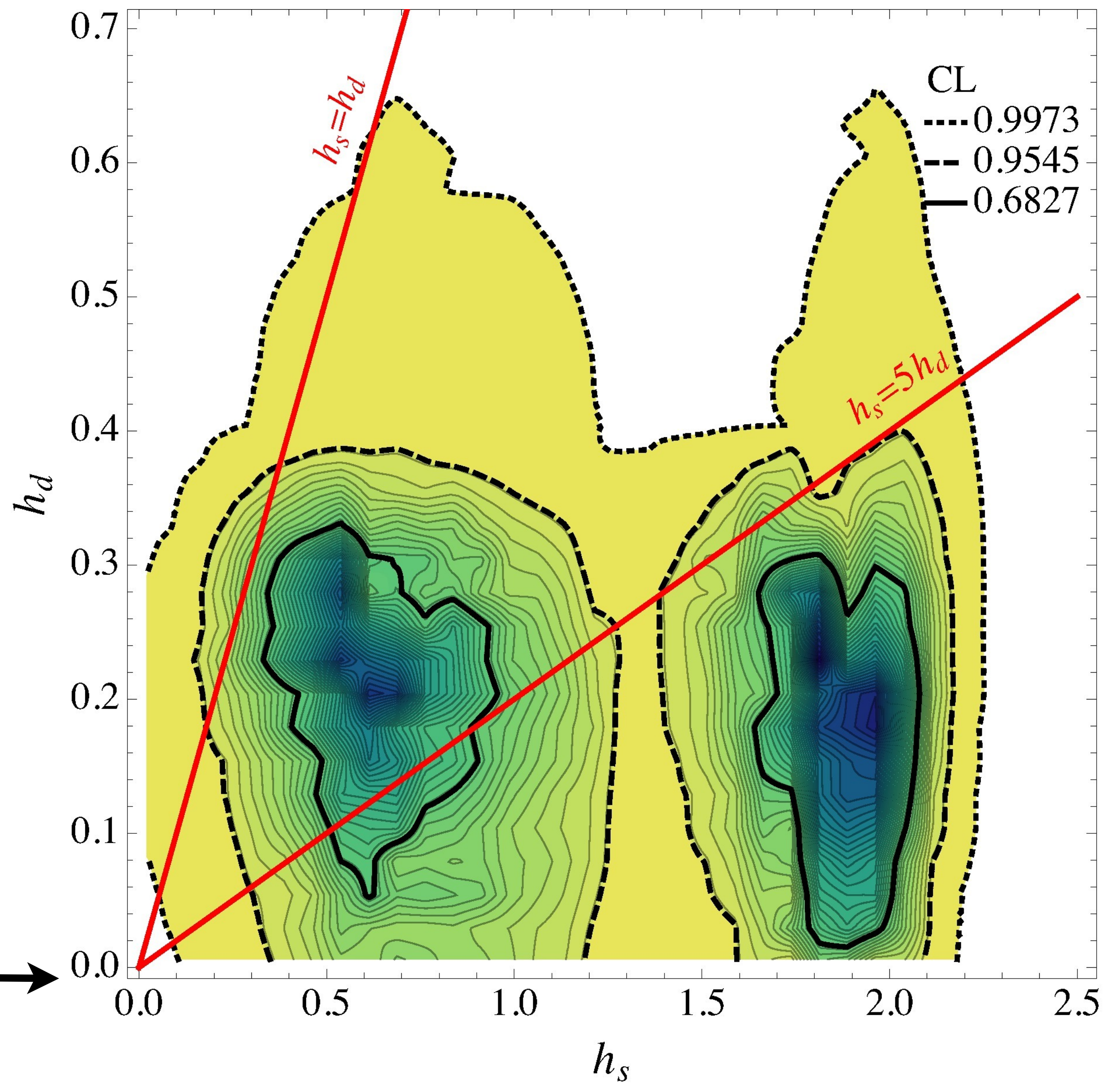
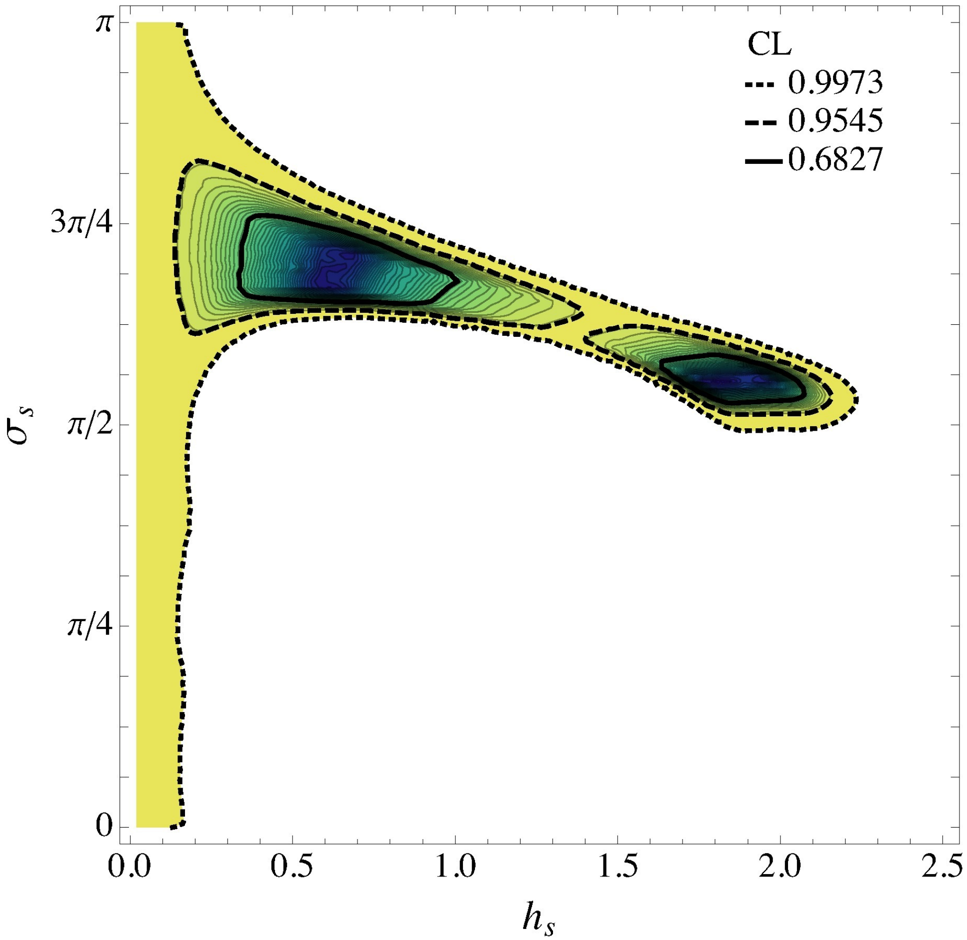
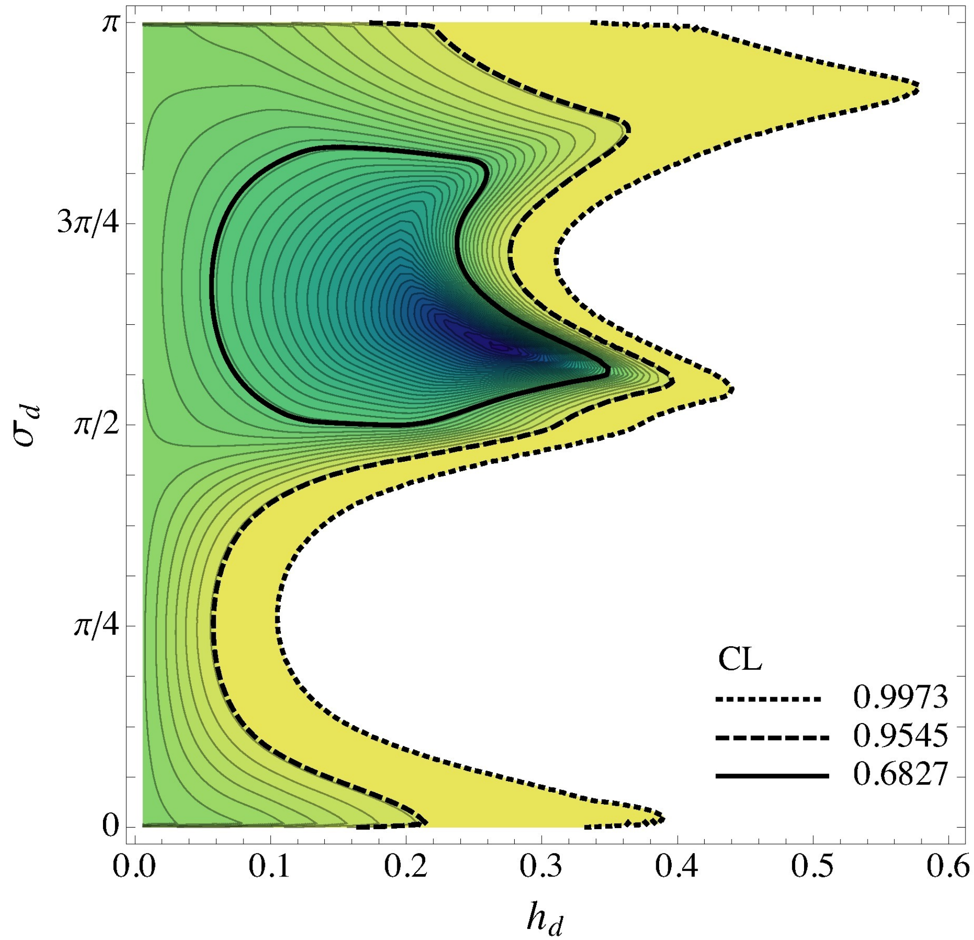


SM

Data favors $h_s > h_d$

Allowed regions in the B_s & B_d systems.

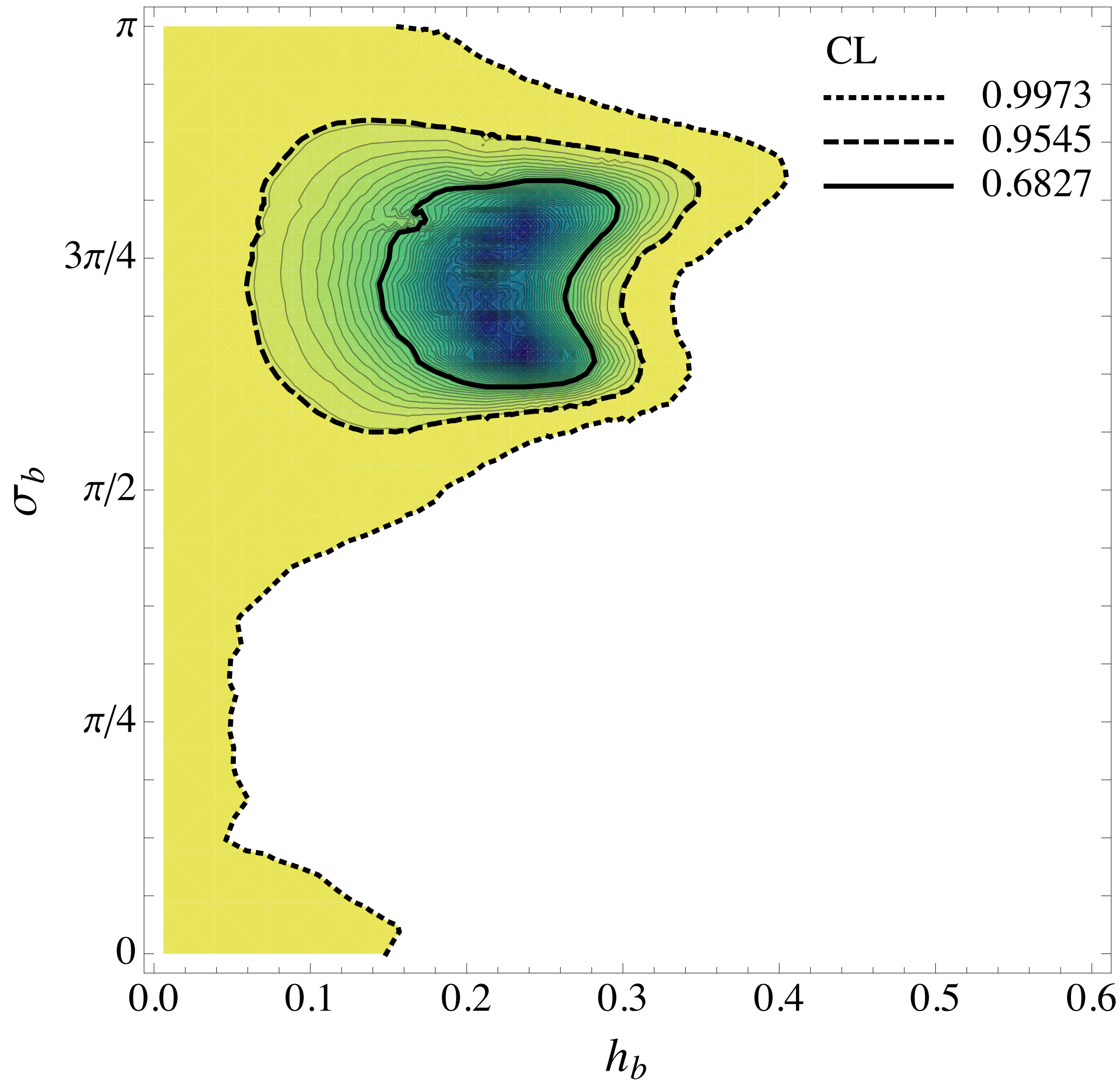




The allowed ranges of h_s, σ_s (left) and h_d, σ_d (right) from the combined fit to all four NP parameters.

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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- 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 $h_s \gg h_d$, 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:** $(h_s \sim h_d)$

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

$$O_1^{bq} = \bar b_L^\alpha \gamma_\mu q_L^\alpha\, \bar b_L^\beta \gamma_\mu q_L^\beta,\ O_2^{bq} = \bar b_R^\alpha q_L^\alpha\, \bar b_R^\beta q_L^\beta,$$

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

$$O_4^{\rm NL} = \frac{c}{\Lambda^2_{\rm MFV;4}} \big[\bar Q_3 (A_d^m A_u^n Y_d)_{3i} d_i\big]\big[\bar d_3 (Y_d^\dagger A_d^{l,\dagger} A_u^{p,\dagger})_{3i} Q_i\big].$$

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

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.

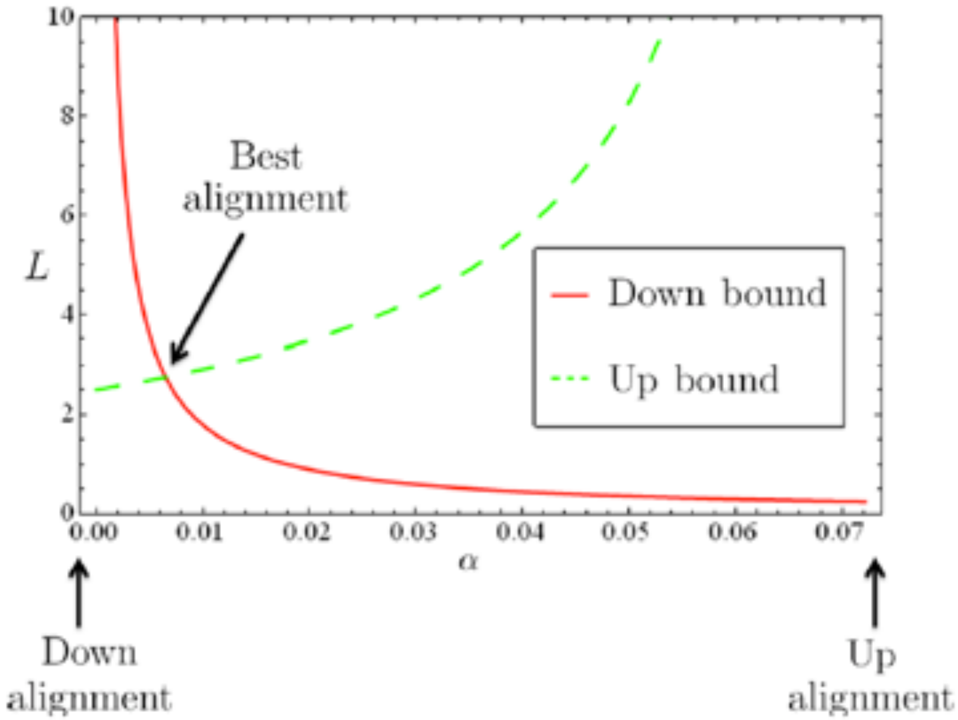
♦ Low KK scale + improve naturalness as a bonos => exciting LHC phenomenology => linkage between high & low pT data!

LHC projected bound

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

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

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



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

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	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}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\,d_L)(\bar{s}_L d_R)$	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 ($c_{ij}=1$) 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}
$(\bar{t}_L\gamma^\mu u_L)^2$	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.