Aspects of 3rd Generation Physics @ the LHC

Gilad Perez

Weizmann Institute

Z. Ligeti, M. Papucci, GP & J.Zupan (10);
C. Delaunay, O. Gedalia, S.J. Lee & GP (10).

3rd Workshop on Theory, Phenomenology & Experiments in Heavy Flavour Physics, Capri 2010

Outline

- Introduction: importance of 3rd generation.

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

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- Summary.

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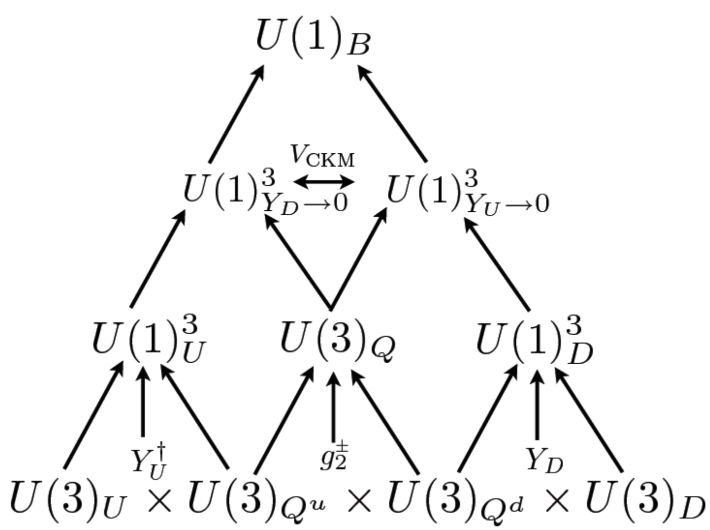

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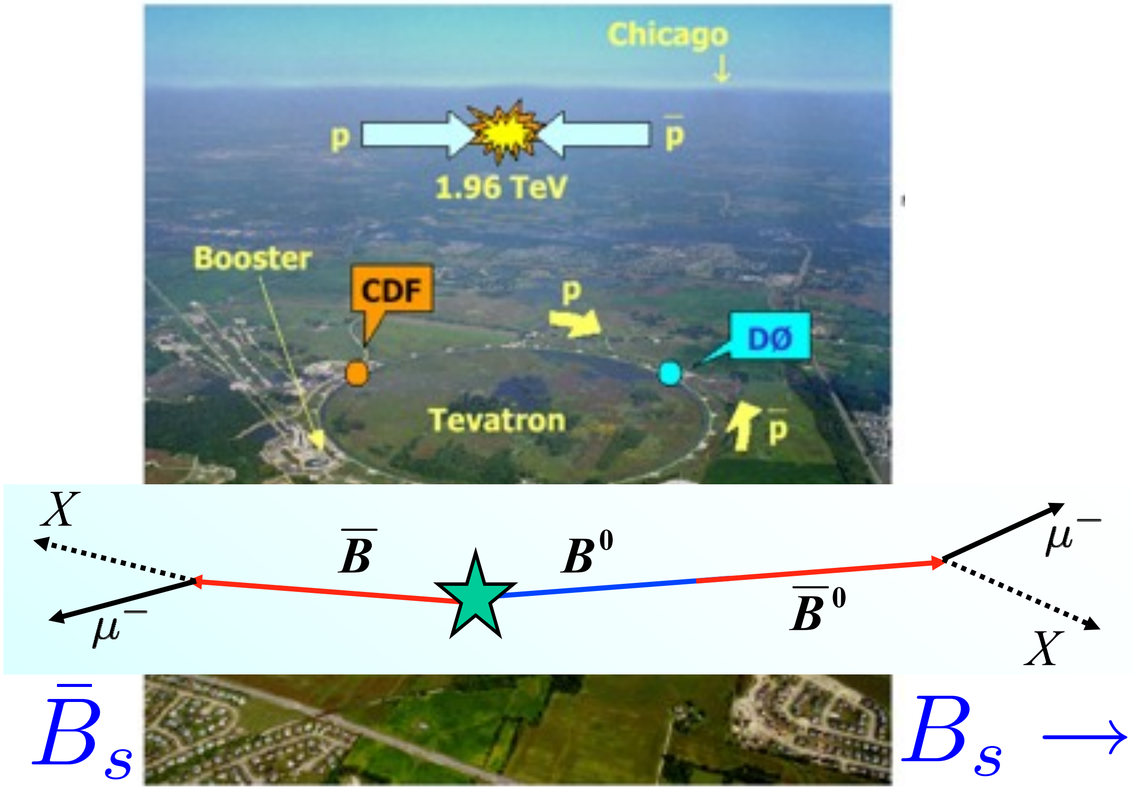
♦ Deviation from SM predictions can be easily probed or severe bounds on new physics (NP) obtained.

Flavor Changing & CP Violating Physics

News from the Tevatron



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

Ligeti, Papucci, GP, Zupan (10).

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

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

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

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

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

- D0 result can be written as:

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

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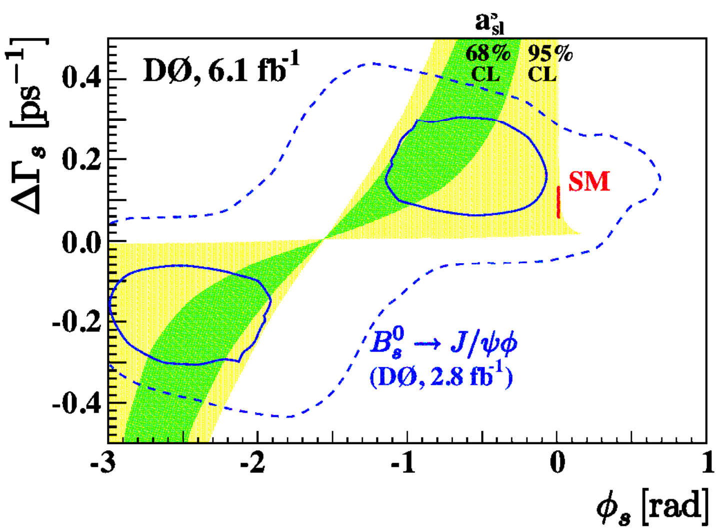
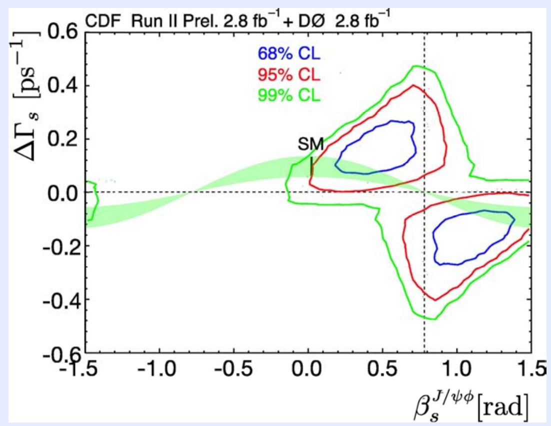
- **Tevatron experiments** also measure:

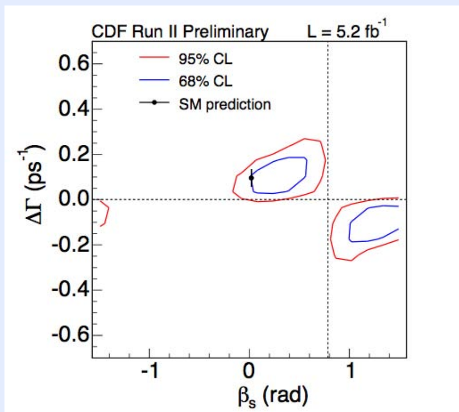




Tevatron combination: probability of observed deviation from SM = 3.4% (2.12 σ)

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. $S_{\psi\phi}$

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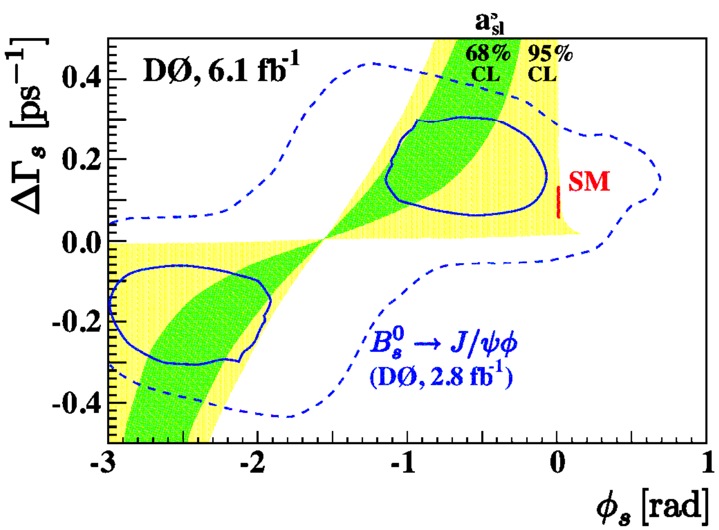

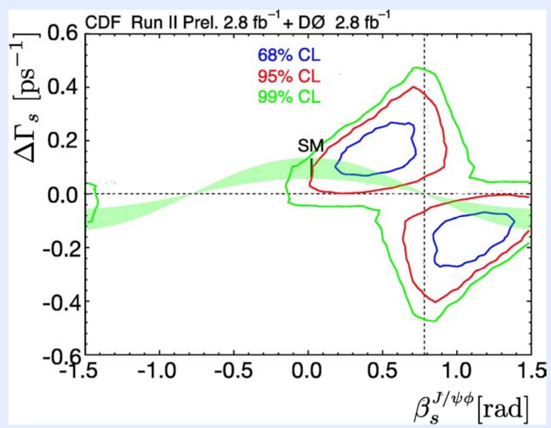

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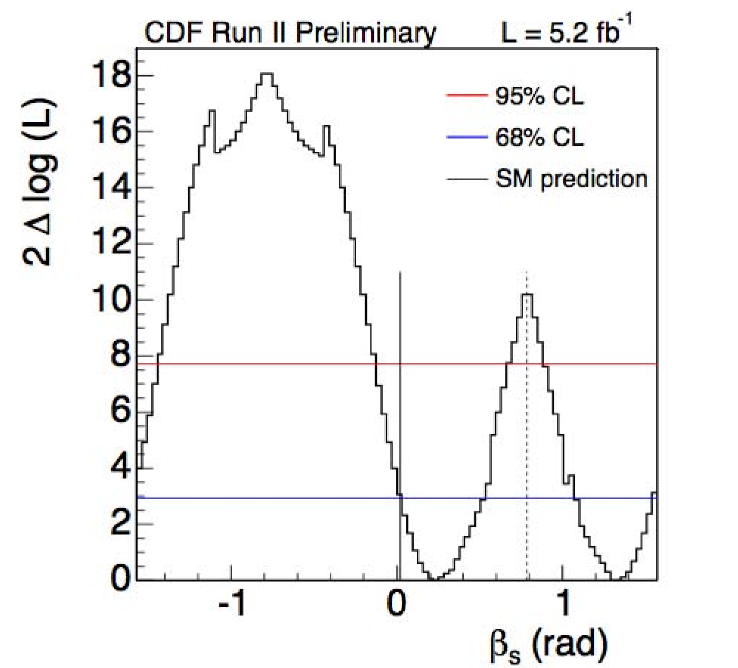

Allow for consistency check or making indep' $\Delta\Gamma_s$ fit (robustly bound NP)!

- **Consistency check:**

Ligeti, Papucci, GP, Zupan.

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

↕

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

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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)

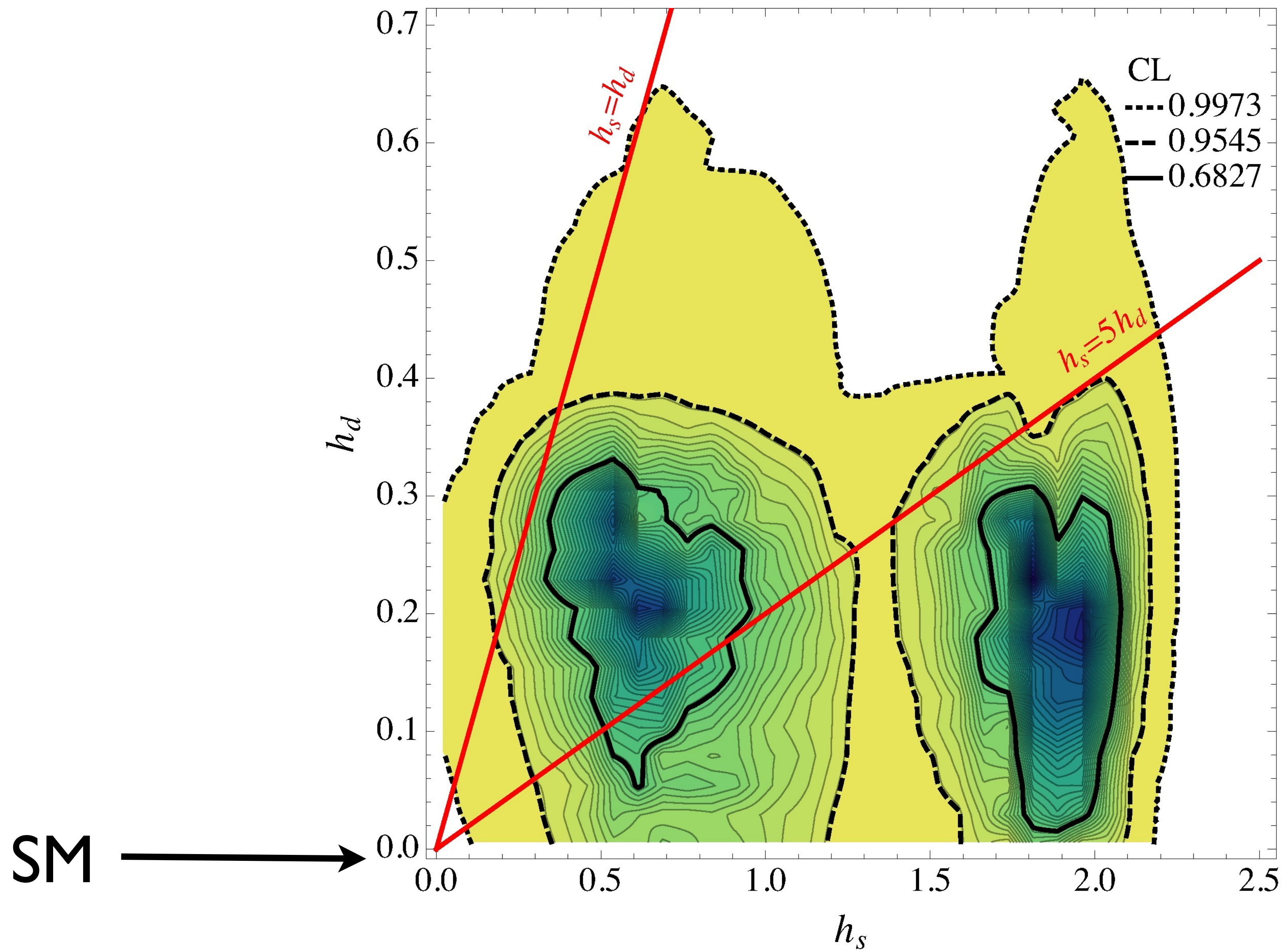
$$\begin{aligned}
\Delta m_q &= \Delta m_q^{\rm SM}\left|1 + h_q e^{2i\sigma_q}\right|,\\
\Delta\Gamma_s &= \Delta\Gamma_s^{\rm SM}\,\cos\left[\arg\left(1 + h_s e^{2i\sigma_s}\right)\right],\\
A^q_{\rm SL} &= {\rm Im}\left\{\Gamma^q_{12}/\left[M_{12}^{q,{\rm SM}}(1 + h_q e^{2i\sigma_q})\right]\right\},\\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

Global fit's results

Ligeti, Papucci, GP, Zupan.

(we used CKMfitter)

B_d vs. B_d systems



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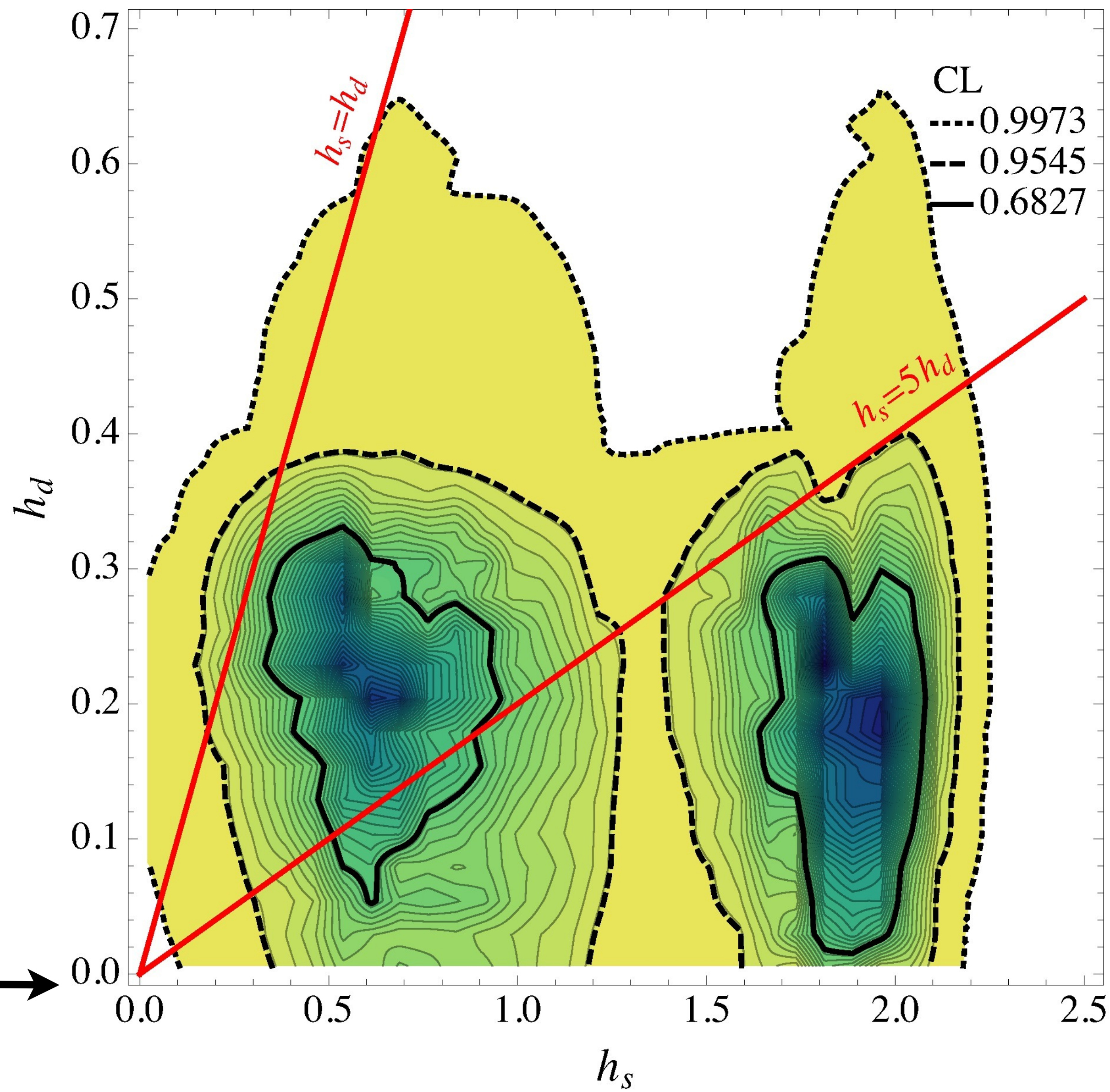
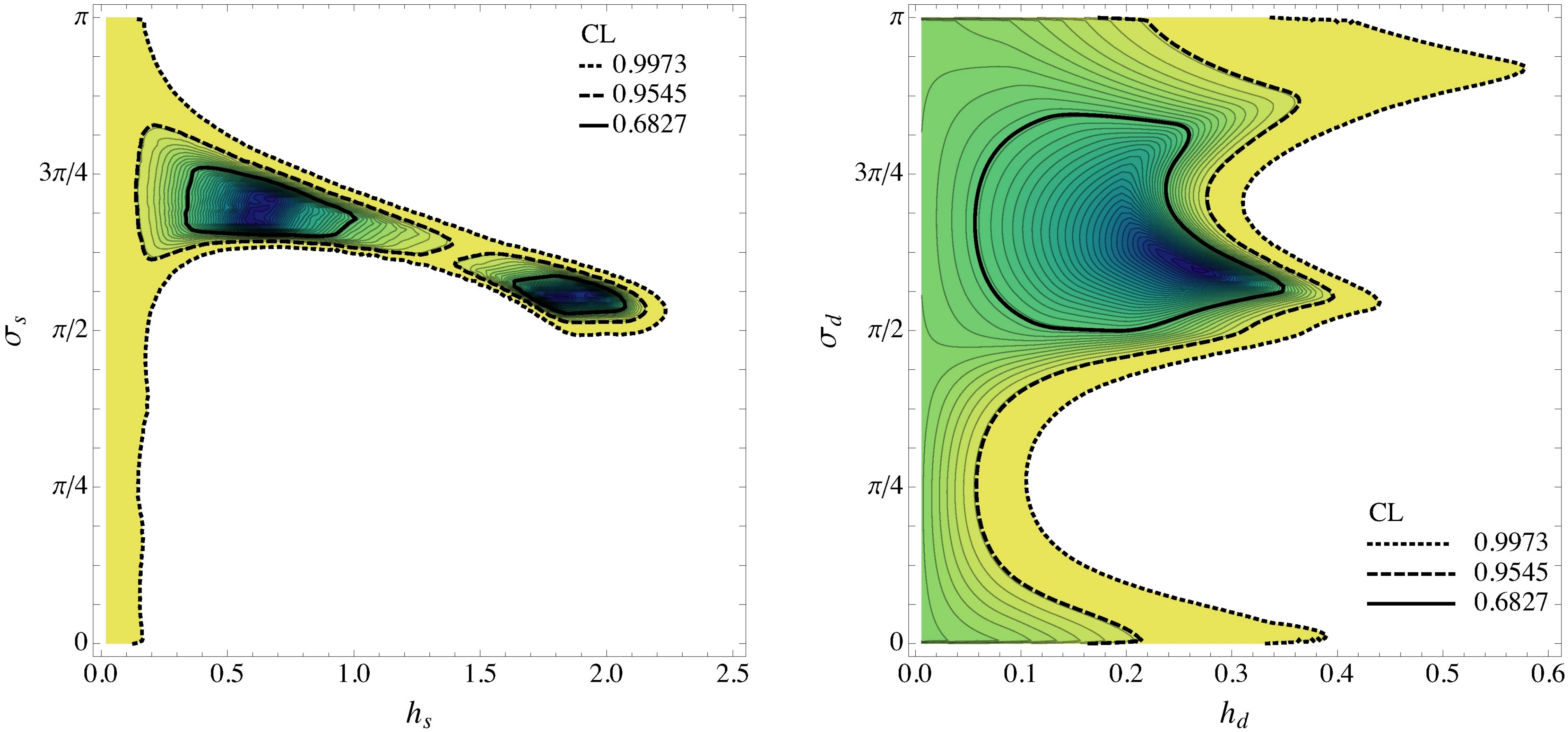


SM →

Data favors $h_s > h_d$

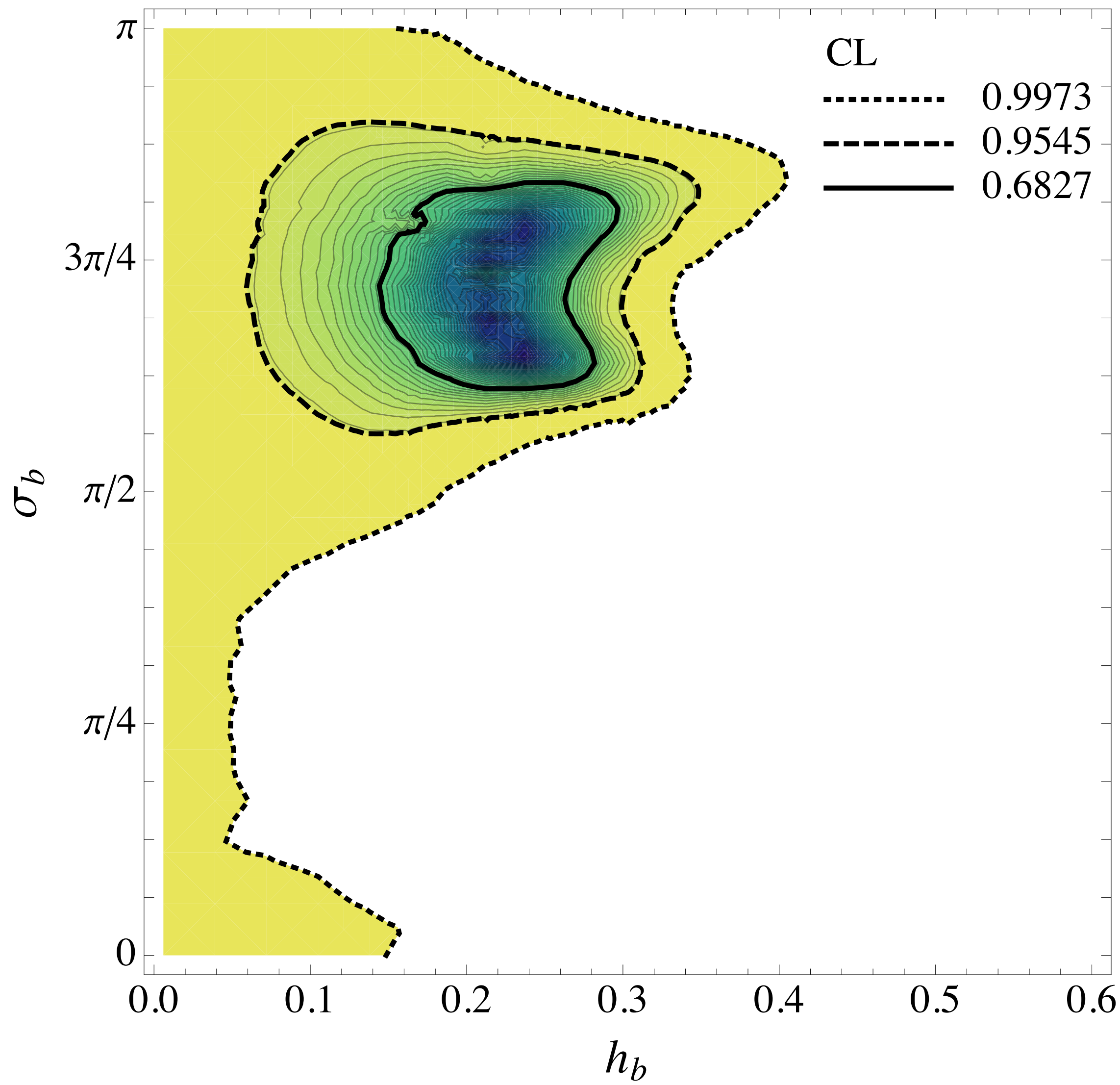
Allowed regions in the B_s & B_d systems.



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.

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

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

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

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

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

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

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

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

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

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What is GMFV (general MFV) ??

GMFV: L_{inear}MFV vs N_{on}LMFV

Kagan, GP, Volansky & Zupan (09);
2 x Gedalia, Mannelli, GP (10).

What defines MFV (minimal flavor violation) Pheno'?

- Is CPV is broken only by the Yukawa or flavor diag' phase are present?

- Is the down type flavor group is broken "strongly"?

- Is the up type flavor group is broken "strongly"?

Linear MFV vs. non-linear MFV (NLMFV)

Kagan, GP, Volansky & Zupan (09).

The top Yukawa is large (possibly also bottom one) no justification to treat it perturbatively.

"LO" MFV expansion valid only for $\bar{Q} f(\epsilon_u Y_U, \epsilon_d Y_D) Q$

$\epsilon_{u,d} \ll 1$

Large "logs" or anomalous dim' => $\epsilon_{u,d} = \mathcal{O}(1)$

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We distinguish between 2 cases LMFV & NLMFV:

- *Linear MFV (LMFV)*: $\epsilon_{u,d} \ll 1$ and the dominant flavor breaking effects are captured by the lowest order polynomials of $Y_{u,d}$.
- *Non-linear MFV (NLMFV)*: $\epsilon_{u,d} \sim O(1)$, higher powers of $Y_{u,d}$ are important, and a truncated expansion in $y_{t,b}$ is not possible.

General MFV, non-linear MFV (NLMFV)

Idea: spearate the small (large) eigenvalues, expand linearly (non-linearly) small (large) flavor breaking.

$$Y_U \sim \text{diag}\,(0, 0, y_t) \text{ and } Y_D \sim \text{diag}\,(0, 0, y_b)$$

$$V_{\text{CKM}} = \mathbf{1}_3 + \mathcal{O}(\theta_{ud}) \qquad \theta_{ud} \sim \lambda^2$$

broken generators

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broken generators

$$\mathcal{H}^{\text{SM}} = U(2)_Q \times U(2)_U \times U(2)_D \times U(1)_3$$

$$\mathcal{G}^{\text{SM}} = U(3)_Q \times U(3)_U \times U(3)_D$$

The broken symmetry generators live in $\mathcal{G}^{\text{SM}}/\mathcal{H}^{\text{SM}}$ cosets.

theory is described by a $[U(3)/U(2)\times U(1)]^2$ non-linear σ-model.

(*cf.* little Higgs models with collective breaking.)

The formalism

Without loss of generality the Y's can be written as:

$$Y_{U,D} = e^{i\hat{\rho}_Q} e^{\pm i\hat{\chi}/2} \tilde{Y}_{U,D} e^{-i\hat{\rho}_{u,d}},$$

where the reduced Yukawa spurions, $\tilde{Y}_{U,D}$, are $\tilde{Y}_{U,D} = \begin{pmatrix} \phi_{u,d} & 0 \\ 0 & y_{t,b} \end{pmatrix}$.

Here $\phi_{u,d}$ are 2×2 complex spurions, while $\hat{\chi}$ and $\hat{\rho}_i$, $i = Q, U, D$, are the 3×3 matrices spanned by the broken generators. Explicitly,

$$\hat{\chi} = \begin{pmatrix} 0_{2\times 2} & \chi \\ \chi^\dagger & 0 \end{pmatrix}, \qquad \hat{\rho}_i = \begin{pmatrix} 0_{2\times 2} & \rho_i \\ \rho_i^\dagger & \theta_i \end{pmatrix},$$

The ρ_i shift under the broken generators $\Rightarrow$ "Goldstone bosons", have no physical significance.

Separating small & large spurions

Trick: flavor invariance is obtained by moding-out fields:

$$\tilde{u}_L = e^{-i\hat{\chi}/2} e^{-i\hat{\rho}_Q} u_L, \quad \tilde{d}_L = e^{i\hat{\chi}/2} e^{-i\hat{\rho}_Q} d_L, \quad \tilde{u}_R = e^{-i\hat{\rho}_u} u_R, \quad \tilde{d}_R = e^{-i\hat{\rho}_d} d_R.$$

Form reducible representations of $\mathcal{H}^{\rm SM}$, $\tilde{d}_{L,R} = (\tilde{d}^{(2)}_{L,R}, 0) + (0, \tilde{b}_{L,R})$.

Also $\phi_{u,d}$ (χ) form appropriate bi-fundamentals (fundeamental) of $\mathcal{H}^{\rm SM}$.

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d-type flavor violation is obtained by shifting to d-mass basis:

$$Y_U = V_{\rm CKM}^\dagger {\rm diag}\,(m_u, m_c, m_t),\ Y_D = {\rm diag}\,(m_d, m_s, m_b)$$

$$\rho_Q = \chi/2,\ \hat{\rho}_{u,d} = 0,\ \phi_d = {\rm diag}\,(m_d, m_s)/m_b,$$

$$\chi^\dagger = i(V_{td}, V_{ts}), \qquad \phi_u = V_{\rm CKM}^{(2)\dagger}\,{\rm diag}\left(\frac{m_u}{m_t}, \frac{m_c}{m_t}\right). \quad \left((\phi_u)_{12} \sim \lambda^5 \right)$$

GMFV Predictions

LO flavor violation comes from:

Kaon phys. (no CPV): $\overline{\tilde{d}_L^{(2)}}\phi_u\phi_u^\dagger\tilde{d}_L^{(2)}, \ \overline{\tilde{d}_L^{(2)}}\chi\chi^\dagger\tilde{d}_L^{(2)}.$

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B phys.: $\overline{\tilde{d}_L^{(2)}}\chi\tilde{b}_L, \ \overline{\tilde{d}_L^{(2)}}\chi\tilde{b}_R,$ & possibly (B_s only) from $\overline{\tilde{d}_R^{(2)}}\phi_d^\dagger\chi\tilde{b}_R.$

B: RH currents are non-Hermitians allows for new CPV.

(SUSY: Colangelo et. al., 0807.0801[ph])

Genericaly, CPV in B_s bounds on in B_d system .

(without light RH currents they are fully correlated)

GMFV vs. LMFV & CPV in $D^0 - \bar{D}^0$ mixing

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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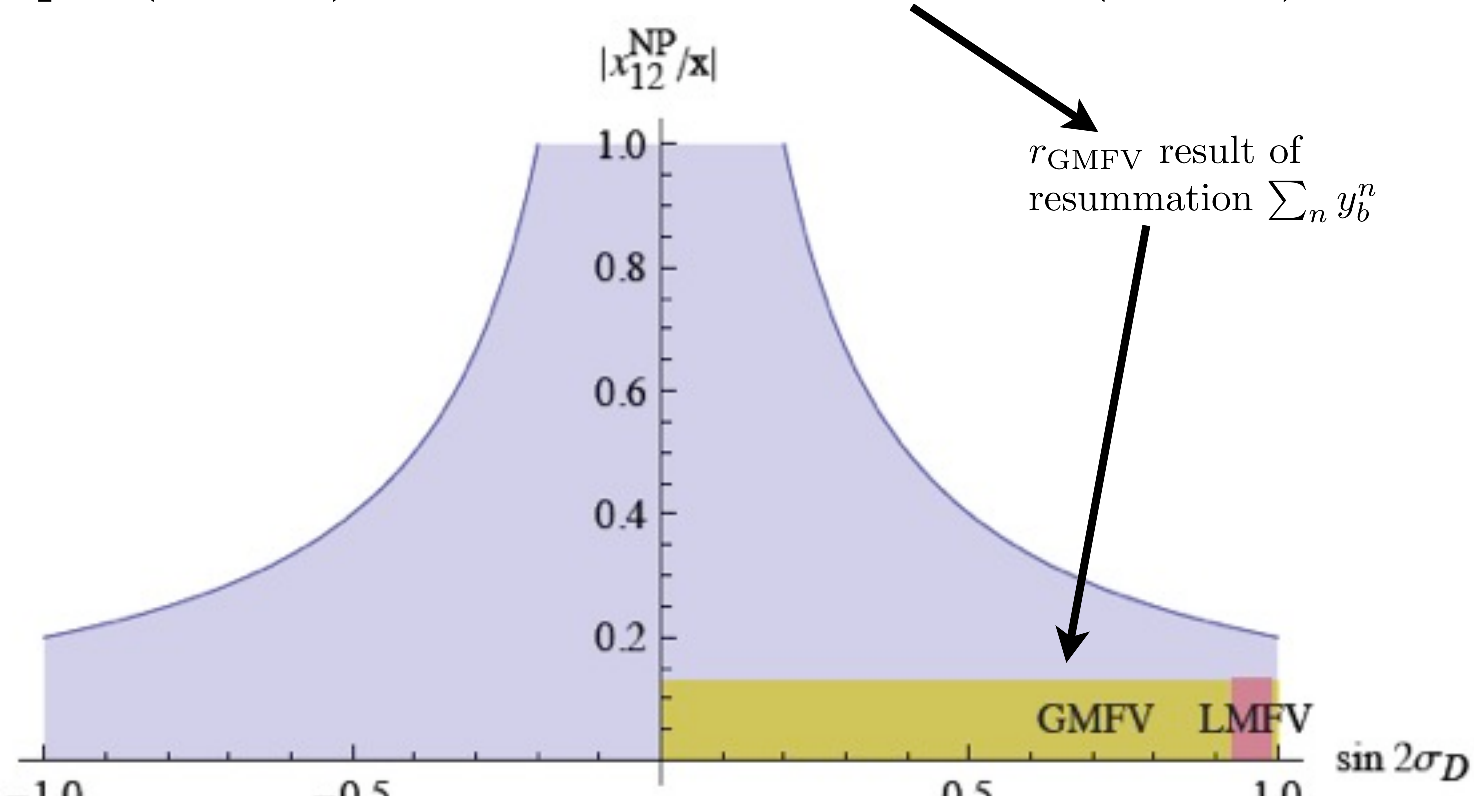

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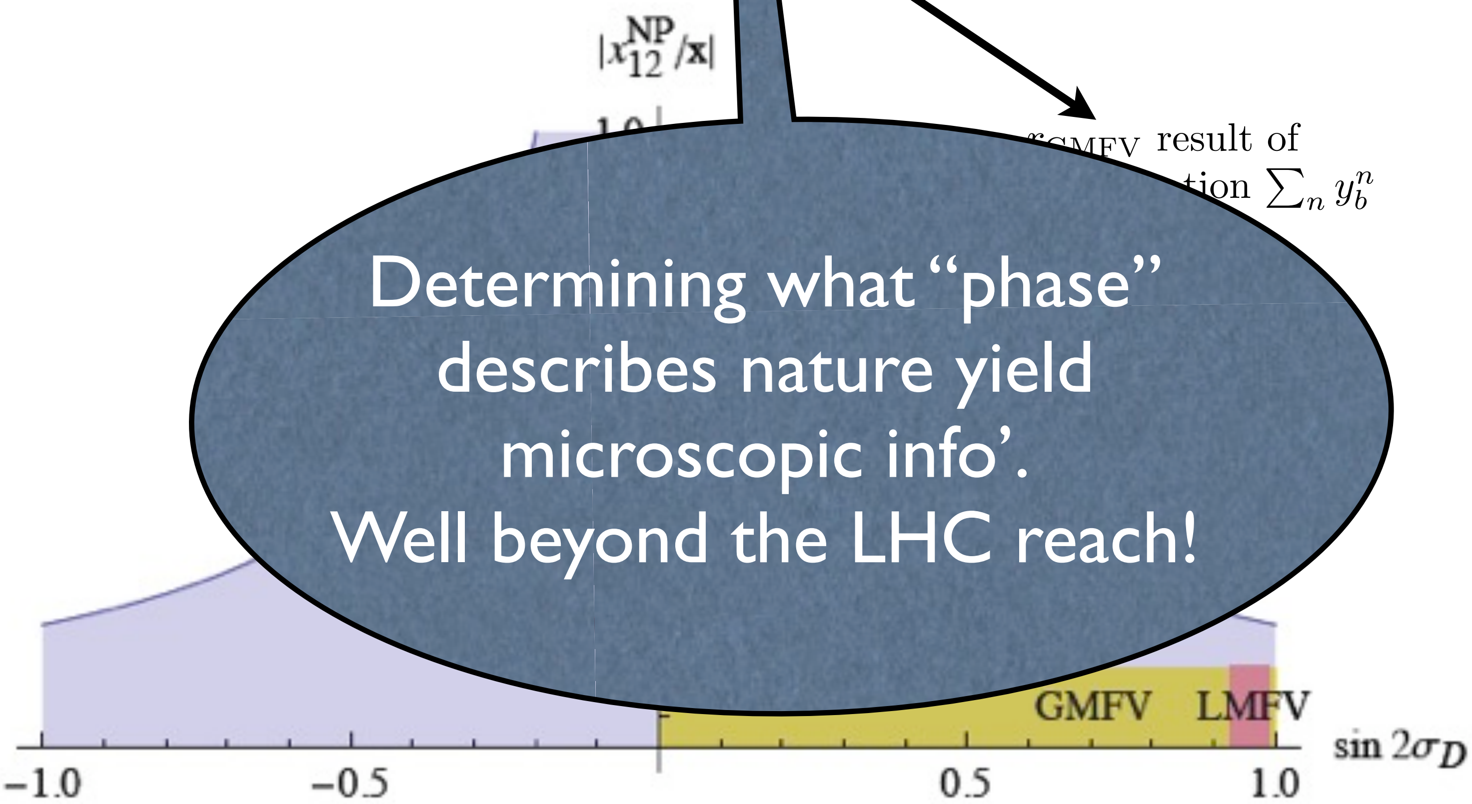

Determining what "phase" describes nature yield microscopic info'.
Well beyond the LHC reach!

Emergence of 3rd gen' CPV in covariant formalism (MFV)

Gedalia, et. al (09).

- Even in 2-gen' case (with flavor diag' CPV) one gets MFV-CPV:

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

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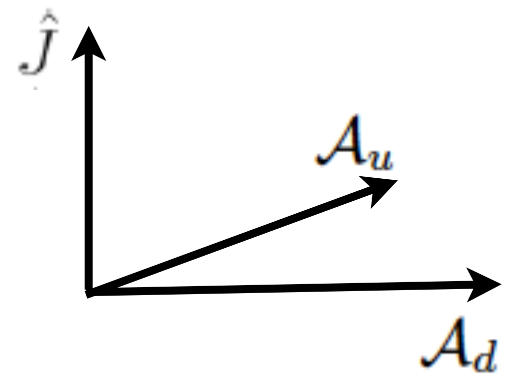

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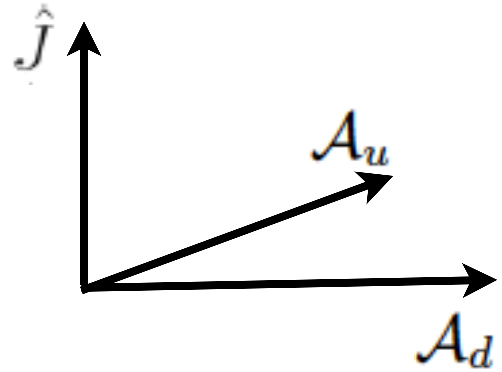

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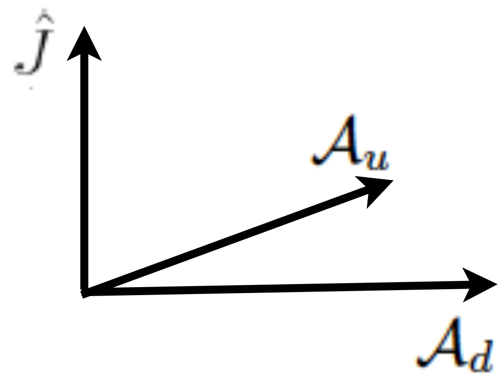

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If $X^{\mathrm{NP}} \propto [\mathcal{A}_u, \mathcal{A}_d] \Rightarrow$ new CPV (GMFV)!

Underlying physics of GMFV & $h_s \gg h_s$?

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Recall we need

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

$$\Lambda_{\mathrm{MFV};4} \gtrsim 13.2\, y_b \sqrt{\frac{m_s}{m_b}\frac{0.5}{h_s}}\ \mathrm{TeV} = 2.9\, y_b \sqrt{\frac{0.5}{h_s}}\ \mathrm{TeV}$$

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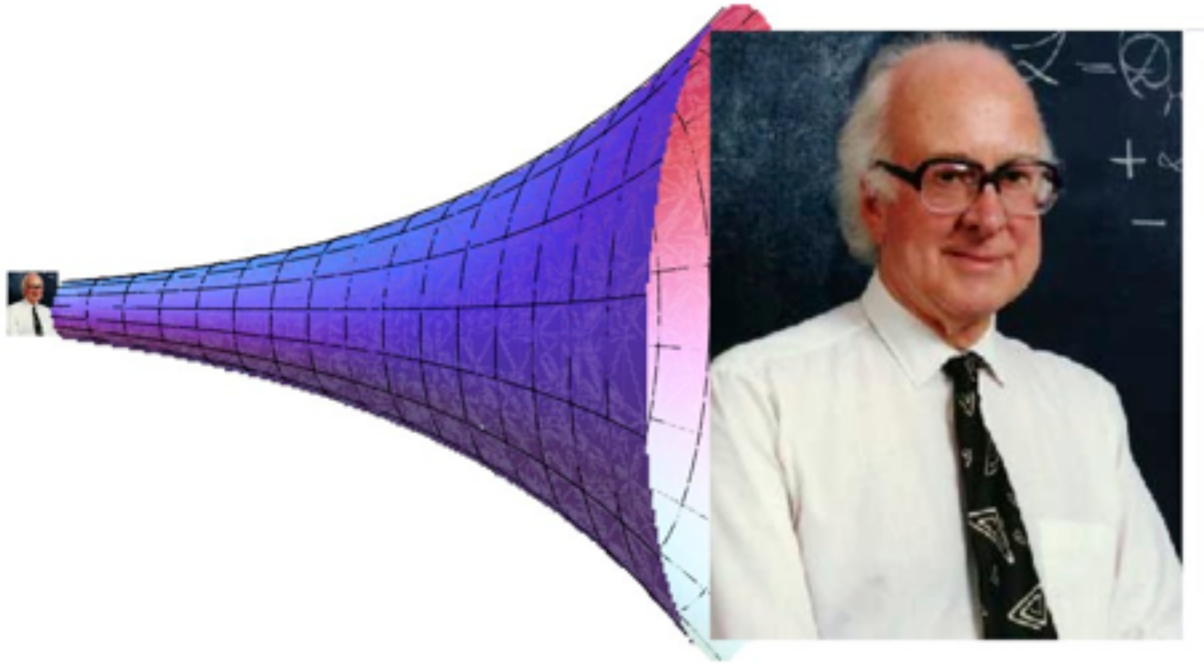
Next: other interesting way + insight on EW physics! (LLRR)

Warped Exra Dimension



Randall Sundrum (RS)

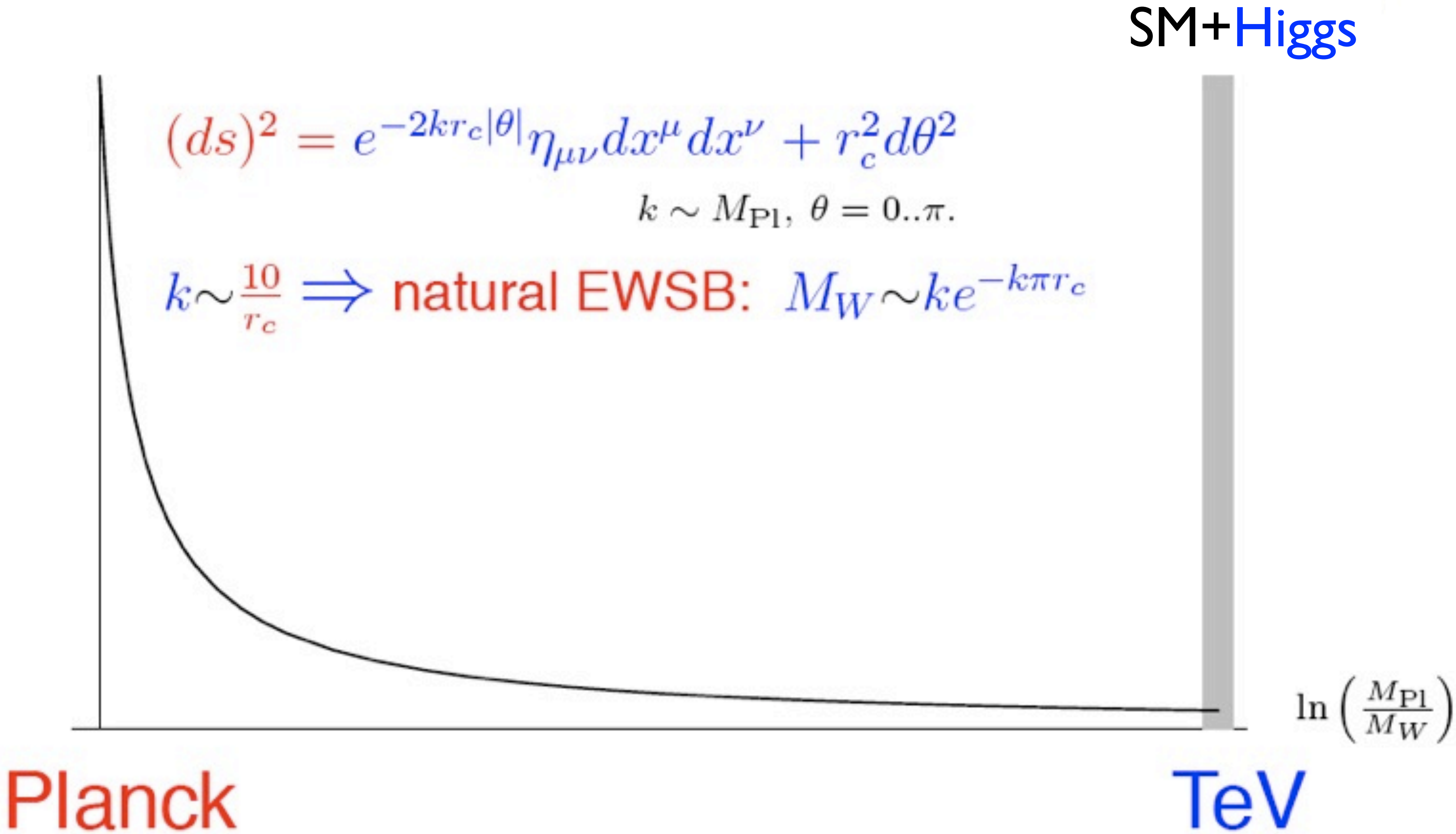
RS1 & the Hierarchy Problem

Randall-Sundrum, PRL (99)

$$(ds)^2 = e^{-2kr_c|\theta|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\theta^2$$

$k \sim M_{\rm Pl},\ \theta = 0..\pi.$

$k \sim \frac{10}{r_c} \Rightarrow$ natural EWSB: $M_W \sim k e^{-k\pi r_c}$



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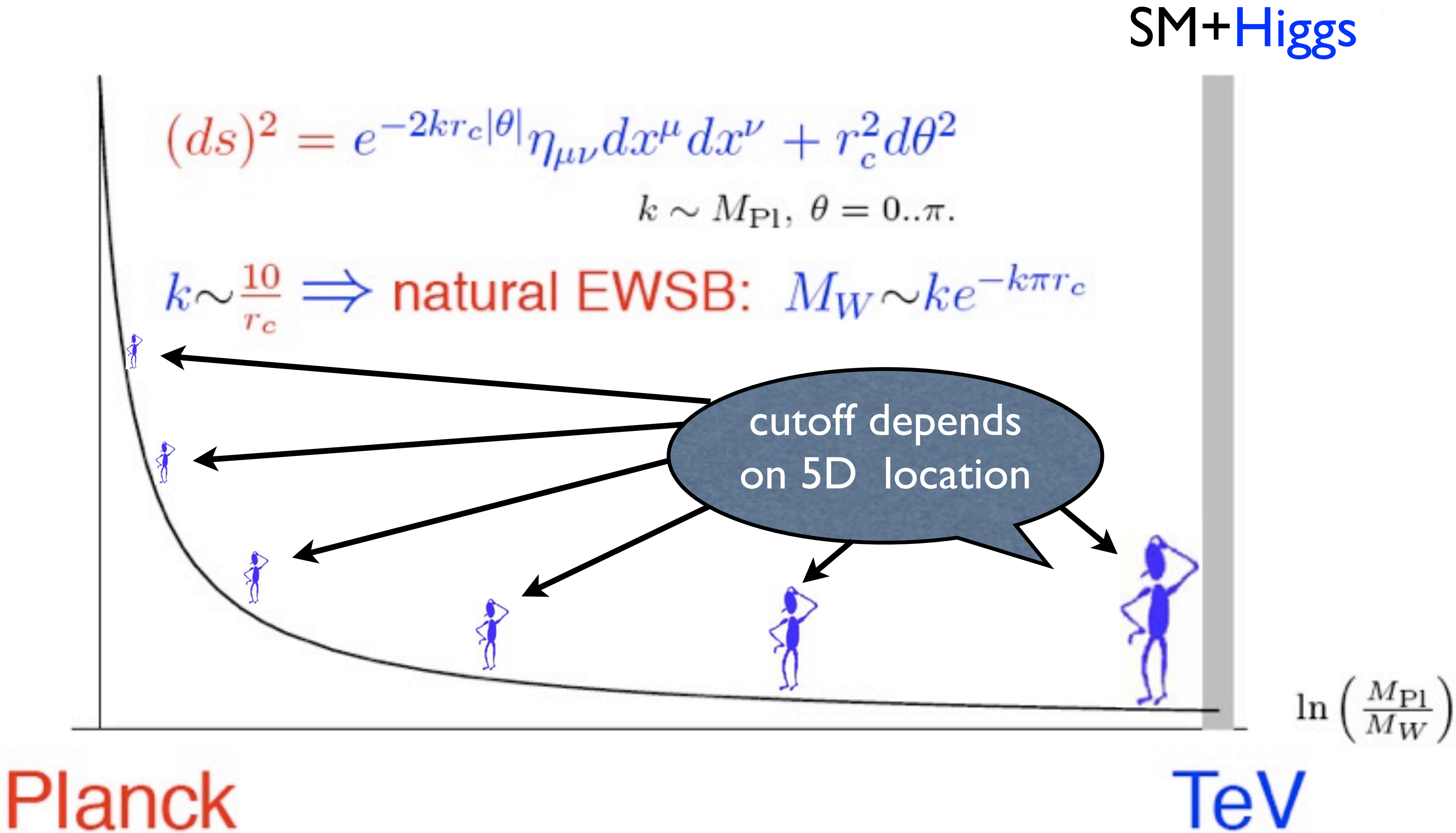
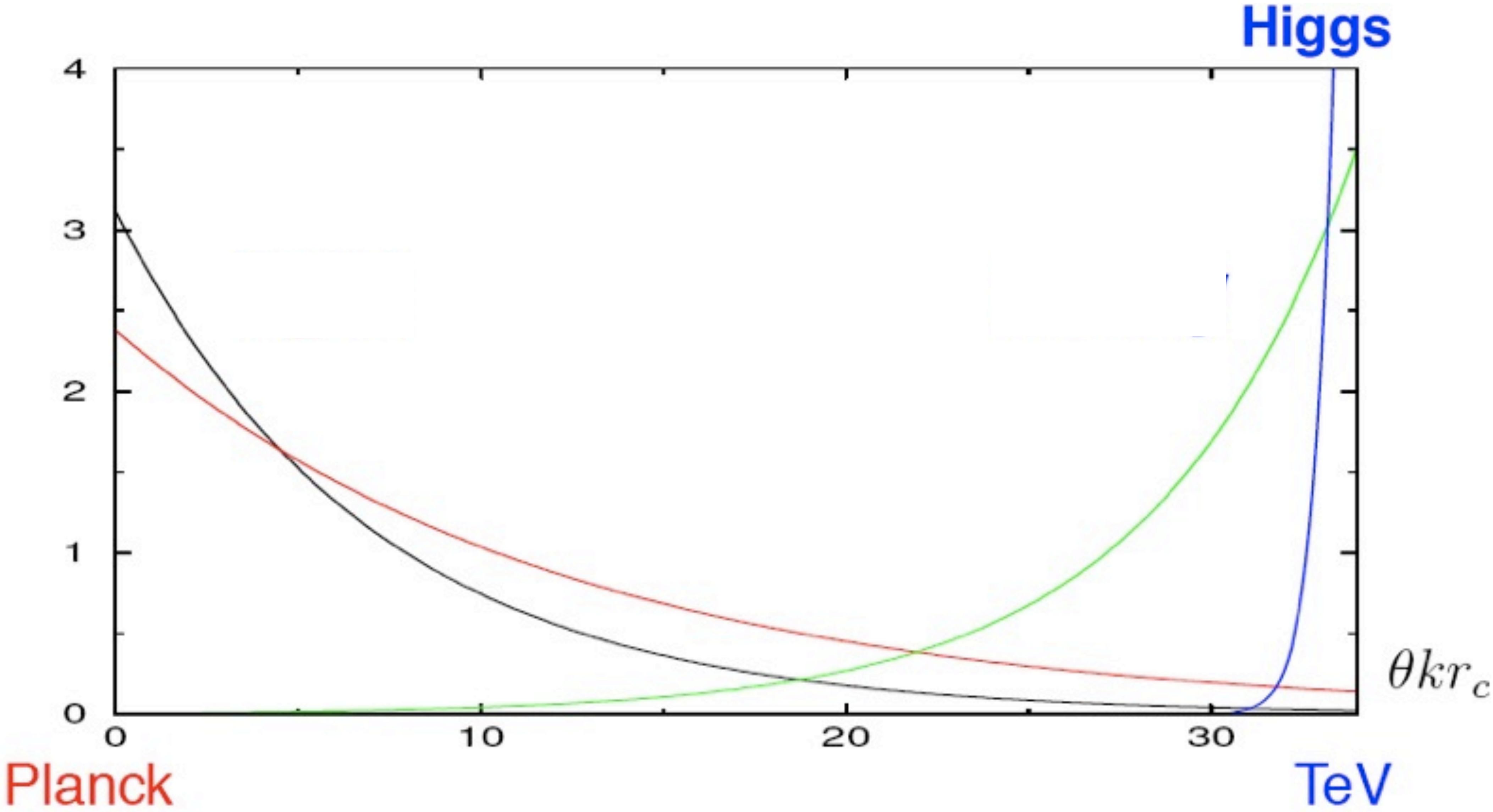


Fields (quarks) => bulk



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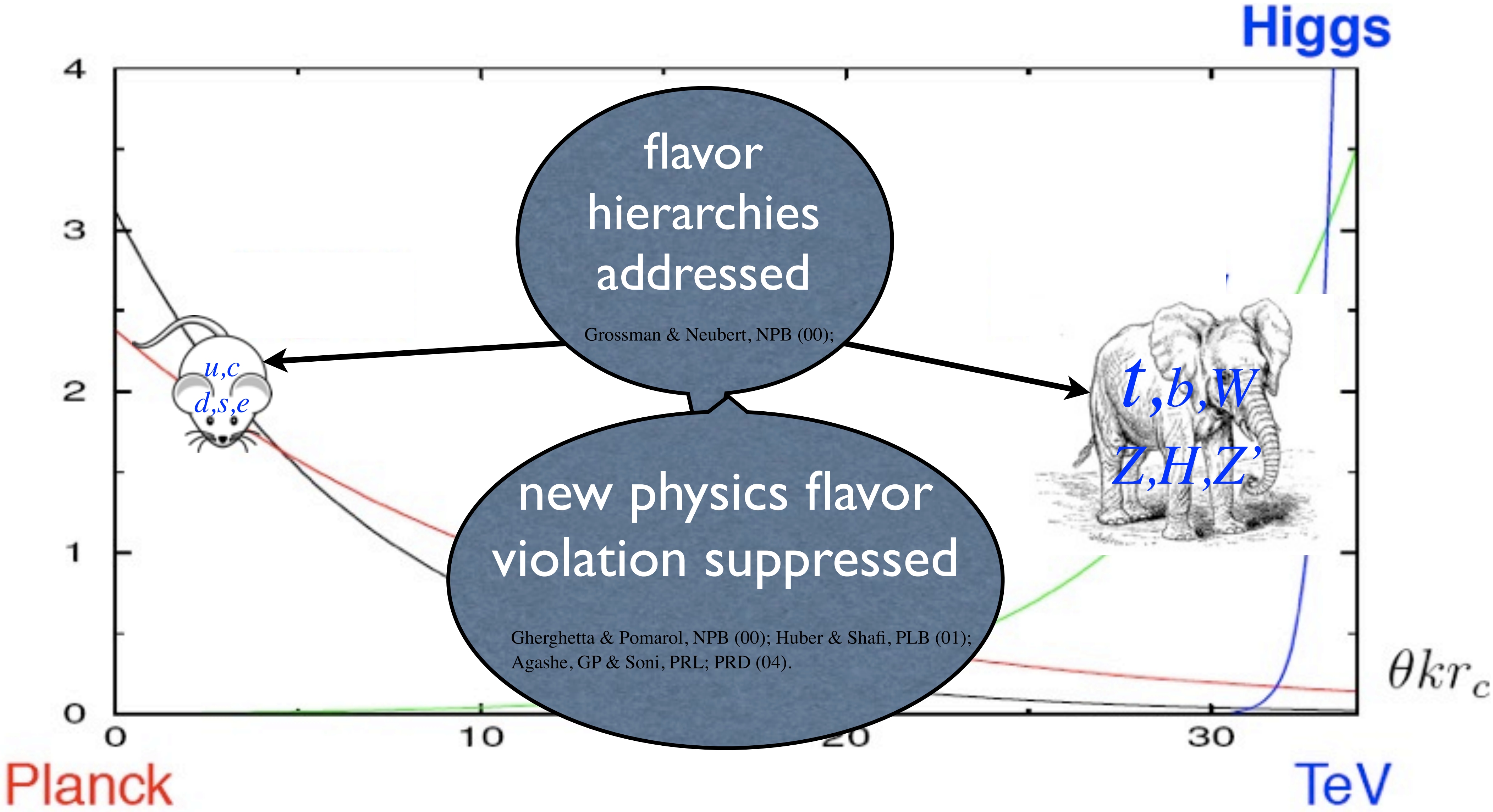

The RS "little" CP problem

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

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

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

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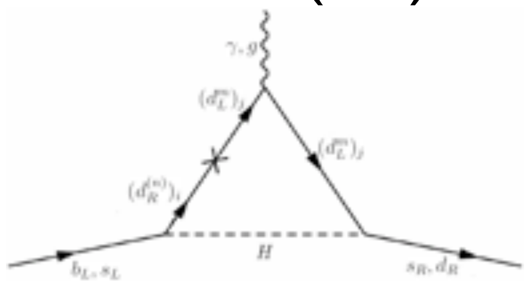

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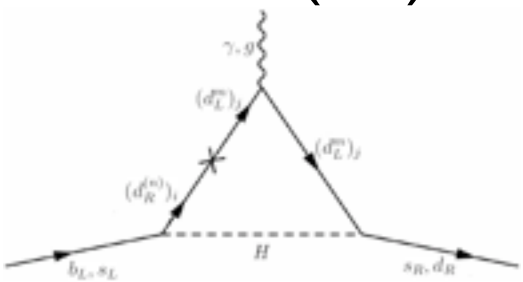
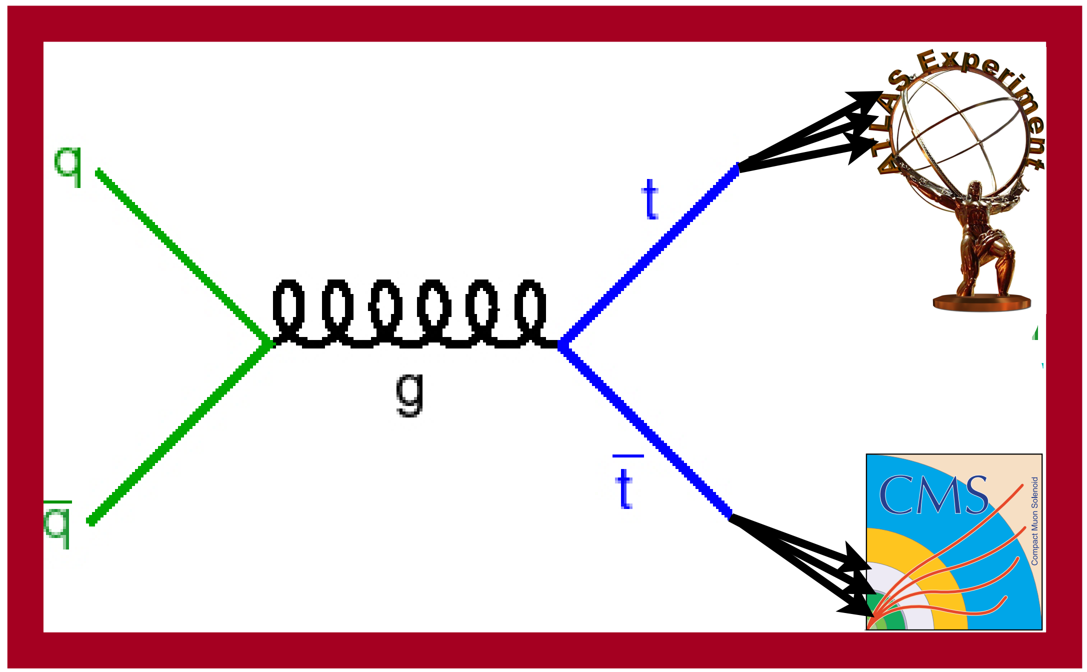


Severe tuning problem or fine tuning problem & null LHC pheno'.

Ultra natural warped model from flavor triviality
or
Sweet spot RS

C. Delaunay, O. Gedalia, S.J. Lee & GP (10)



5D MFV & Shining

What if we give up on solving the flavor puzzle?

Rattazzi & Zaffaroni (00), Cacciapaglia, Csaki, Galloway, Marandella, Terning & Weiler (07)

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◆ Rattazzi-Zaffaroni's (RZ) model: excellent & elegant protection but no solution for the little hierarchy problem?

Solution: Hierarchic 5D MFV (bulk RZ)

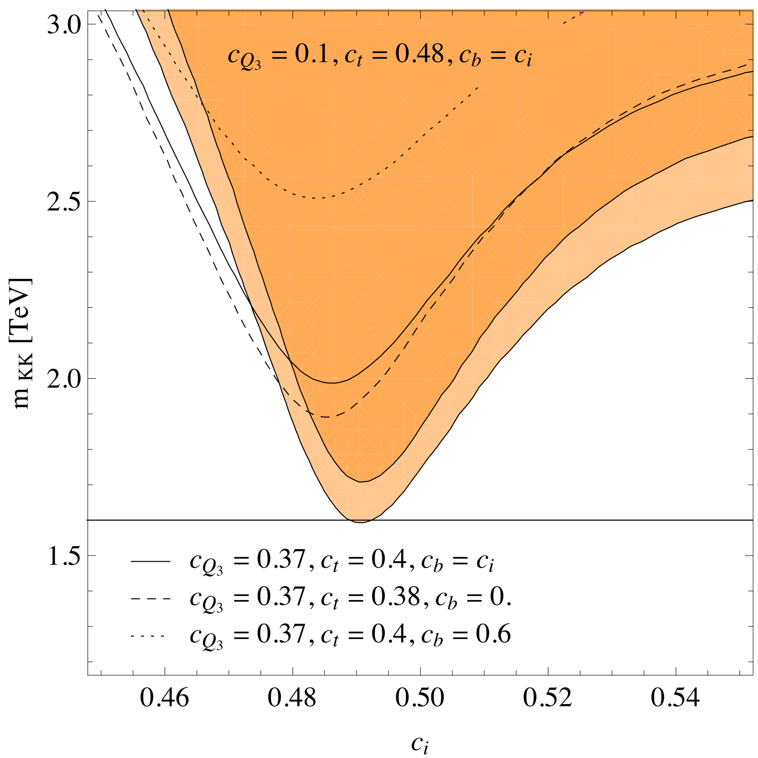
◆ $Y_{u,d}$ => 5D Yukawa the only source of flavor breaking.

Fitzpatrick, GP & Randall (07)
Csaki, et al. (09)

◆ Also, bulk masses are functions of same spurions:

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

Ultra naturalness is observed



Result of global fit to EWPT;
Delaunay, Gedalia, Lee & GP (10)

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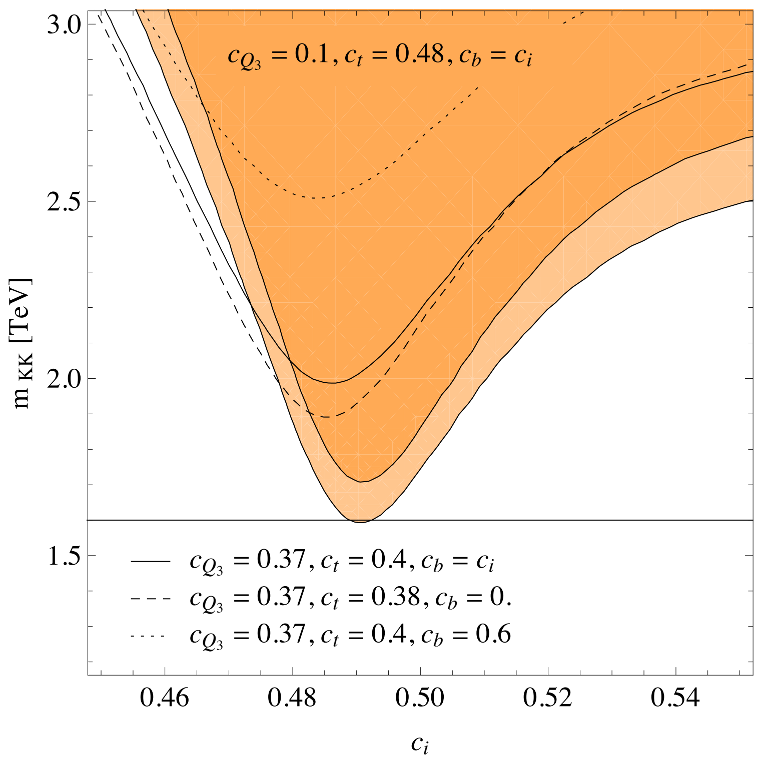

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Delaunay, Gedalia, Lee & GP (10)

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

Csaki, Lee, GP, Weiler, in progress.

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→ O_1 & O_4 decouple.
Interpolate:
(i) no NP
(ii) Universal one
(iii) B_s dominated!

C. Delaunay, O. Gedalia, S.J. Lee & GP (10)

Summary

♦ Assuming no direct CPV, data robustly tests SM prediction, almost no assumptions on long dist' QCD are made (exp' test).

♦ Data is consistent with NP interpretation favors large Bs contributions but not robustly.

♦ Can be accounted for by MFV.

♦ Ultra natural warped models => GMFV => can explain the data via KK gluon exchange, via LLRR operators.

♦ Low KK scale => soon tested @ LHC+flavor gauge bosons.