Flavor Physics in the LHC Era - Theory

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Plan

i) Prologue, Intro': flavor phys. & the standard model (SM).
ii) SM, global symmetry structure.
iii) Effective field theory for flavor phys. (model independent)
& minimal flavor violation.
iv) Flavor @ the LHC era, ex.: alignment.

Refs.:

Nir, ph/0109090; 0708.1872;

Gedalia & Perez, 1005.3106;

Isidori, Nir & Perez, 1002.0900.

Gedalia, Mannelli & Perez, 1003.3869;

Gedalia, Kamenik, Ligeti & Perez, 1202.5038.

Textbooks: CP Violation: Branco, Lavoura, Silva.

Prologue, current status of Supersymmetry

Putting stops aside, what are the bounds on first 2-generation "light" squarks?

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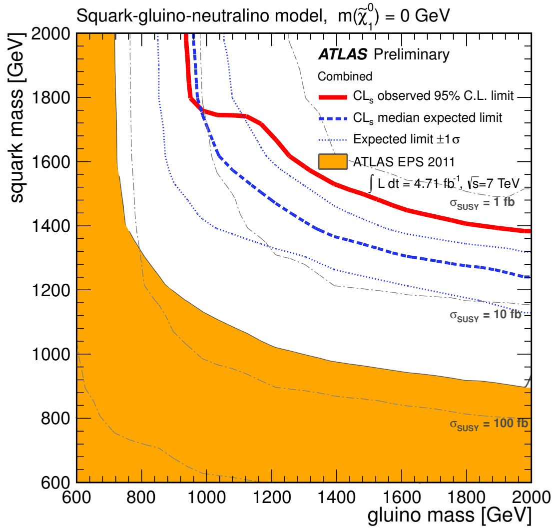

Light squarks > 1.4 TeV?

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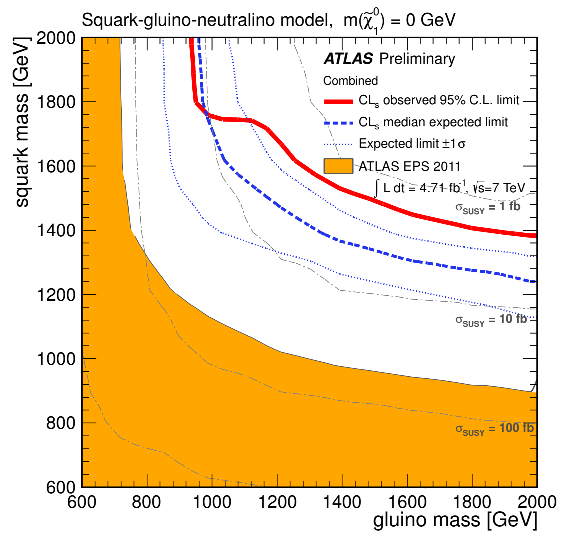


Light squarks > 1.4 TeV?

3rd lecture: big loop hole, because of misinterpretation of flavor constraints.
Some light squarks can be as light as few 100GeV !

Introduction (uniqueness of SM)

- SM fermions: 3 x $Q^I_{Li}(3,2)_{+1/6}$, $U^I_{Ri}(3,1)_{+2/3}$, $D^I_{Ri}(3,1)_{-1/3}$, $L^I_{Li}(1,2)_{-1/2}$, $E^I_{Ri}(1,1)_{-1}$
- This brings with it a whole kind of phys. called flavor/gen' phys.;
- It has a unique structure & thus comes with sharp predictions:
- Kobayashi-Maskawa Mechanism: 1 CP violating (CPV) phase;
- Mixings is controlled by only 3 real parameters (CKM angles).

Introduction (uniqueness of SM)

- Flavor is violated dominantly via charged current interactions (int's);
- Flavor violation, @leading order, only via left-handed (LH) currents;
- Dominantly, flavor violation is controlled by the top int's;
- Flavor sector posses an approximate $U(2)_Q$ x $U(2)_U$ x $U(3)_D$ symmetry;
- SM lepton sector which posses a global a $U(1)_l^3$ (beyond our scope).

SM Kobayashi-Maskawa (KM) Mechanism of Flavor & CP Violation

(2008 Nobel Prize)

- We now have an experimental (exp') support that the KM picture described nature (up to possibly small corrections):

- Based on several exp' observation (started in 64 many came in the last 10 years or so).

- CPV in the Kaon and *B* system => within the SM correlated => consistent with SM.

- Flavor conversion => precision data confirmed the SM.

- New bounds on CPV in the *D* mixing also confirms SM picture.

This implies: Severe bounds on non-SM flavor physics.

Is this the end of the story?

- Baryogenesis => SM cannot be the only source of CPV (otherwise, rapid proton-antip-protons annihilation of yield baryon asym' of < 10^{-18})

- Almost any SM extension give new sources of flavor and CPV.

- What about the up frontier (charm "anomaly")?

- Integrating out new phys.=> dim. 6 Ops.: $(\bar{d}_i d_j)^2/\Lambda_{NP}^2$

- Precision measurements=> $\Lambda_{NP} \gtrsim 10^4\text{TeV} \gg M_W$

$$\Downarrow$$

The flavor NP hierachy "problem" (puzzle not a problem)

What is flavor phys, in the int’ basis?

- The SM fermions appear in 3 generations.
- Flavor phys. describes int’ that distinguish between the generations.
- The fermions experience 2 types of int’:
- gauge int’, where two fermions couple to a gauge boson, & Yukawa interactions, where 2 fermions couple to a scalar.
- canonical basis: no gauge couplings between fermions of different generations => int’ basis
- Yuakawa interactions are complicated in the int’ basis, inter-gen’ couplings.
- But masses are from the Yukawa int’.
- Thus, int’ eigenstates do not have well-defined masses
- Flavor Phys. refers to the part of the SM that depends on Yukawa couplings.

What is flavor phys, mass basis?

- In the mass basis, Yukawa interactions are, simple, diagonal (not universal/degenerate).
- Eigenstates have, well-defined masses.
- Gauge interactions related to spontaneously broken symmetries can be quite complicated!
- the $SU(2)_L$ gauge couplings are not diagonal, they mix quarks of different generations.
- Flavor physics refers to fermion masses (Yukawa) and mixings (gauge).

The SM quark flavor sector, int' basis

Int' basis, the gauge part is trivial:

$$\bar{q}_i^I \, \not{D} q_j^I \, \delta^{ij}, \quad q \in Q, U, D \longrightarrow q_i \to U_{ij}^{(3\times 3)} q_j$$

global sym': $U(3)_Q \times U(3)_U \times U(3)_D$

Yukawa sector is interesting:

The quark Yukawa interactions are given by

$$-\mathcal{L}_{\rm Yukawa}^{\rm quarks} = Y_{ij}^d \overline{Q_{Li}^I} \phi D_{Rj}^I + Y_{ij}^u \overline{Q_{Li}^I} \tilde{\phi} U_{Rj}^I + {\rm h.c.}.$$

global sym': $U(1)_D^3 \times U(1)_U^3 \to U(1)_B$ (see later)

End of the 1st part

How many flavor parameters in the SM?

Do the counting in 2 ways, int' basis (sym' oriented) and mass basis (explicit).

Counting flavor parameters, int' basis

How many independent CP violating parameters are there in $\mathcal{L}^{\rm quarks}_{\rm Yukawa}$? Each of the two Yukawa matrices Y^q $(q = u, d)$ is 3×3 and complex. Consequently, there are 18 real and 18 imaginary parameters in these matrices.

The int' basis is not unique !

Ex.: can use flavor sym' to rotate the fields and get different form of Yukawa matrices; for ex. we can bring one of them to a diag' form.
=> mass basis for up or down quarks. (very useful for neutrino experimental physics, this is called the neutrino flavor basis where the charged lepton are brought to their mass eigenstate)

How many flavor para (Int' basis)?

Can use the freedom to eliminate unphysical parameters and count the physical ones:

SM flavor sym' breaking- $U(3)_Q \times U(3)_U \times U(3)_D \to \; U(1)_B$

Remove: 3U(3)=3(3Re+6Im)=>9Re +(18Im- $1_{U(1)_B}$) parameters

Thus altogether: (18-9)Re+(18-17)Im

6 masses + 3mixings +1CPVphase

Counting flavor parameters, mass basis

Setting the Higgs field to its vev, $\langle\phi^0\rangle = v/\sqrt{2}$ we find:

$$-\mathcal{L}_M^q = (M_d)_{ij}\overline{D_{Li}^I}D_{Rj}^I + (M_u)_{ij}\overline{U_{Li}^I}U_{Rj}^I + \text{h.c.}, \quad M_q = \frac{v}{\sqrt{2}}Y^q,$$

we decomposed the $SU(2)_{\mathrm{L}}$ quark doublets into their components:

$$Q_{Li}^I = \begin{pmatrix} U_{Li}^I \\ D_{Li}^I \end{pmatrix}.$$

The mass basis corresponds, by definition, to diagonal mass matrices. We can always find unitary matrices V_{qL} and V_{qR} such that

$$V_{qL}M_qV_{qR}^\dagger = M_q^{\text{diag}} \quad (q = u, d),$$

The quark mass eigenstates are then identified

$$q_{Li} = (V_{qL})_{ij}q_{Lj}^I, \quad q_{Ri} = (V_{qR})_{ij}q_{Rj}^I \quad (q = u, d).$$

flavor in weak int'(charged current), mass basis

The quarks-W^{+-} couplings are now complicated:

$$-\mathcal{L}^q_{W^\pm} = \frac{g}{\sqrt{2}}\overline{u_{Li}}\gamma^\mu (V_{uL}V^\dagger_{dL})_{ij} d_{Lj} W^+_\mu + \text{h.c.}.$$

The unitary 3×3 matrix,

$$V_{\rm CKM} = V_{uL}V^\dagger_{dL}, \quad (V_{\rm CKM}V^\dagger_{\rm CKM} = 1),$$

is the Cabibbo-Kobayashi-Maskawa (CKM) *mixing matrix*

The form of the CKM matrix *(i)*

The form of the matrix is not unique:

(i) There is freedom in defining V_{CKM} in that we can permute between the various generations. This freedom is fixed by ordering the up quarks and the down quarks by their masses, *i.e.* $(u_1, u_2, u_3) \to (u, c, t)$ and $(d_1, d_2, d_3) \to (d, s, b)$. The elements of V_{CKM} are written as follows:

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} .$$

The form of the CKM matrix *(ii)*

(ii) There is further freedom in the phase structure of $V_{\rm CKM}$. Let us define P_q $(q = u, d)$ to be diagonal unitary (phase) matrices. Then, if instead of using V_{qL} and V_{qR} for the rotation to the mass basis we use $\tilde{V}_{qL}$ and $\tilde{V}_{qR}$, defined by $\tilde{V}_{qL} = P_q V_{qL}$ and $\tilde{V}_{qR} = P_q V_{qR}$, we still maintain a legitimate mass basis since $M_q^{\rm diag}$ remains unchanged by such transformations. However, $V_{\rm CKM}$ does change:

$$V_{\rm CKM} \to P_u V_{\rm CKM} P_d^* .$$

The minimal form of the CKM matrix

$$V_{\rm CKM} \to P_u V_{\rm CKM} P_d^* .$$

remove 6 phases - $1_{U(1)_B} \Rightarrow V_{\rm CKM}$ contains 3 real mixing angles

& 1 CP violating (CPV) phase

SM: weak int' is only source of flavor and effectively CPV

(θ_{QCD} aside)

i) Only in charged current; ii) Dominantly via LH quarks.

The SM flavor parameters

masses in GeV <=> m_u=0.001-3; m_d=0.003-7; m_s=0.1; m_c=1.3; m_b=4.2; m_t=170; m_e=.00055; m_μ=0.11; m_τ=1.8.

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$. The three $\sin\theta_{ij}$ are the three real mixing parameters while δ is the Kobayashi-Maskawa phase.

$$\simeq \begin{pmatrix} 0.97 & 0.23 & 4.3\times10^{-3} \\ 0.23 & 0.96 & 4.2\times10^{-2} \\ 7.4\times10^{-3}\,(\text{indirect}) & 4.1\times10^{-2}\,(\text{indirect}) & 0.99\,(\text{indirect}) \end{pmatrix} \sim \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$\lambda \sim 0.23$ and $A, \rho, \eta \sim 0.8, 0.2, 0.3$

The flavor puzzle, small & hierarchical parameters

$$\mathrm{Im}[V_{ij}V_{kl}V_{il}^*V_{kj}^*] = J_{\mathrm{CKM}} \sum_{m,n=1}^{3} \epsilon_{ikm}\epsilon_{jln}, \quad (i,j,k,l = 1,2,3).$$

$$J_{\mathrm{CKM}} = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta \simeq \lambda^6 A^2 \eta = \mathcal{O}(10^{-5})$$

$$\mathcal{J} = \det[Y_U Y_U^\dagger, Y_D Y_D^\dagger] = \frac{1}{v^{12}} \Delta m_{tc}^2 \Delta m_{tu}^2 \Delta m_{cu}^2 \Delta m_{bs}^2 \Delta m_{bd}^2 \Delta m_{sd}^2 J_{\mathrm{CKM}} = \mathcal{O}\big(10^{-22}\big)$$

The flavor parameters span many order magnitudes and have a clear hierarchy, why (is it natural)?

End of the 2nd part

SM Flavor Structure, Spurion (sym') Analysis

The maximal global sym' consistent \w SM gauge sym' is:

$$U(3)_Q \times U(3)_U \times U(3)_D$$

Under SM flavor group: $Q(\mathbf{3},\mathbf{1},\mathbf{1})$,$U(\mathbf{1},\mathbf{3},\mathbf{1})$,$D(\mathbf{1},\mathbf{1},\mathbf{3})$

We promote $Y_{U,D}$ to spurions, transform under the flavor group $\Rightarrow$ flavor invariant $\mathcal{L}^{\mathrm{SM}}$.

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

$$Y_U(\mathbf{3},\bar{\mathbf{3}},1)\,, \qquad Y_D(\mathbf{3},1,\bar{\mathbf{3}})$$

MFV (minimal flavor violation) theories defined as an effective theory where only source of flavor breaking is given by powers of $Y_{U,D}$.

SM Flavor Structure, Spurion (sym') Analysis

More precisely, in heavy W limit flavor group is enhanced:

$$\mathcal{G}^{\rm SM} = U(3)_{Q^u} \times U(3)_{Q^d} \times U(3)_U \times U(3)_D$$

With the following spurions:

$$\text{Fields}: \; U_L(\mathbf{3},1,1,1), D_L(1,\mathbf{3},1,1), U(1,1,\mathbf{3},1), D(1,1,1,\mathbf{3})$$

$$\text{Spurions}: \; g_2(\mathbf{3},\bar{\mathbf{3}},1,1), Y_U(\mathbf{3},1,\bar{\mathbf{3}},1), Y_D(1,\mathbf{3},1,\bar{\mathbf{3}})$$

There's a 2-tale story for the quark singlets & doublets.

Since there's no flavor conversion involving RH currents => quark singlet flavor structure is simpler.

SM Flavor Structure, Quarks Singlets (RH)

$$\text{Fields}: \; U_L(\mathbf{3},1,1,1), D_L(1,\mathbf{3},1,1), \overbrace{U(1,1,\mathbf{3},1), D(1,1,1,\mathbf{3})}$$

$$\text{Spurions}: \; g_2^{\pm}(\mathbf{3},\bar{\mathbf{3}},1,1), \underbrace{Y_U(\mathbf{3},1,\bar{\mathbf{3}},1), Y_D(1,\mathbf{3},1,\bar{\mathbf{3}})}$$

$$U(3)_U \overset{Y_U^\dagger Y_U}{\Rightarrow} U(1)_U^3 \qquad\qquad U(3)_D \overset{Y_D^\dagger Y_D}{\Rightarrow} U(1)_D^3$$

Next, LH flavor sym' structure is more involved

(collective breaking)

SM Flavor Structure, Quarks Doublets (LH)

$$\text{Fields}: U_L(\mathbf{3},1,1,1), D_L(1,\mathbf{3},1,1), U(1,1,\mathbf{3},1), D(1,1,1,\mathbf{3})$$

$$\text{Spurions}: g_2^\pm(\mathbf{3},\bar{\mathbf{3}},1,1), Y_U(\mathbf{3},1,\bar{\mathbf{3}},1), Y_D(1,\mathbf{3},1,\bar{\mathbf{3}})$$

$$\begin{tikzcd}
 & & U(3)_Q\,(\text{diag.}) \arrow[dd, leftrightarrow, "g_2^\pm"] & & \\
 & & & & \\
U(3)_{Q^u} \arrow[uurr] \arrow[r, Rightarrow, "Y_U Y_U^\dagger"] & U(1)^3_{Q^u} \arrow[r, Rightarrow] & U(1)_B & U(1)^3_{Q^d} \arrow[l, Rightarrow] & U(3)_{Q^d} \arrow[l, Rightarrow, "Y_D Y_D^\dagger"'] \arrow[uull] \\
 & & V_{\mathrm{CKM}} \arrow[ul, leftrightarrow] \arrow[u, leftrightarrow] \arrow[ur, leftrightarrow] & &
\end{tikzcd}$$

End of 3rd Part

CPV (Kobayashi-Maskawa)

Note: C, P change the Lorentz rep from $SU(2)_L$ to $SU(2)_R$ but not CP

$$C\psi C^{-1} = i\eta_c(\bar{\psi}\gamma^0\gamma^2)^T\,, \quad P\psi(t,x)P^{-1} = \eta_p\gamma^0\psi(t,-x)$$

An intuitive explanation of why CP violation is related to *complex* Yukawa couplings goes as follows. The hermiticity of the Lagrangian implies that $\mathcal{L}_{\text{Yukawa}}$ has its terms in pairs of the form

$$Y_{ij}\overline{\psi_{Li}}\phi\psi_{Rj} + Y_{ij}^*\overline{\psi_{Rj}}\phi^\dagger\psi_{Li}. \tag{17}$$

A CP transformation exchanges the operators

$$\overline{\psi_{Li}}\phi\psi_{Rj} \leftrightarrow \overline{\psi_{Rj}}\phi^\dagger\psi_{Li}, \tag{18}$$

but leaves their coefficients, Y_{ij} and Y_{ij}^*, unchanged. This means that CP is a symmetry of $\mathcal{L}_{\text{Yukawa}}$ if $Y_{ij} = Y_{ij}^*$.

If field redef' yield basis in where *Y*'s are real => no CPV!

In the SM 3 gen => explicit CP breaking!
Any CPV obser' requires going through 3 gen'

How is CP broken in the SM (flavor sector)?

We can ignore the RH flavor sector (unbroken $U(1)^3_{q_R}$).

Can construct to adjoint of the *U(3)$_Q$* flavor group:

$$Y_U Y_U^\dagger \;\;\&\;\; Y_D Y_D^\dagger$$

CP violation is due to missalignment between the two (recall each breaks to $U(1)^3_Q$).

Also CPV requires complex flavor parameters, in term of reparameterization invariant:

$$Im(\mathcal{J}) = Im\{\det[Y_U Y_U^\dagger, Y_D Y_D^\dagger]\}$$

We saw that $\mathcal{J}$ is tiny so even though the phase is large the SM cannot yield baryogenesis.

Theory of meson decay and mixings

All the above is obscured by QCD!

We need effective description + identify clean obser' (ratios are better)

We define decay amplitudes of a pseudoscalar meson P (which could be charged or neutral) and its CP conjugate $\overline{P}$ to a multi-particle final state f and its CP conjugate $\overline{f}$ as

$$A_f = \langle f|\mathcal{H}|P\rangle \quad , \quad \overline{A}_f = \langle f|\mathcal{H}|\overline{P}\rangle \quad , \quad A_{\overline{f}} = \langle \overline{f}|\mathcal{H}|P\rangle \quad , \quad \overline{A}_{\overline{f}} = \langle \overline{f}|\mathcal{H}|\overline{P}\rangle \ ,$$

where $\mathcal{H}$ is the Hamiltonian governing weak interactions. The action of CP on these states introduces phases ξ_P and ξ_f that depend on their flavor content, according to

$$\begin{aligned} \mathrm{CP}|P\rangle &= e^{+i\xi_P}\,|\overline{P}\rangle \quad , \quad \mathrm{CP}|f\rangle = e^{+i\xi_f}\,|\overline{f}\rangle \ , \\ \mathrm{CP}|\overline{P}\rangle &= e^{-i\xi_P}\,|P\rangle \quad , \quad \mathrm{CP}|\overline{f}\rangle = e^{-i\xi_f}\,|f\rangle \ , \end{aligned}$$

so that $(\mathrm{CP})^2 = 1$. The phases ξ_P and ξ_f are arbitrary and unphysical because of the flavor symmetry of the strong interaction. If CP is conserved by the dynamics, $[\mathrm{CP}, \mathcal{H}] = 0$, then A_f and $\overline{A}_{\overline{f}}$ have the same magnitude and an arbitrary unphysical relative phase

$$\overline{A}_{\overline{f}} = e^{i(\xi_f - \xi_P)}\,A_f \ .$$

Theory of neutral meson decay and mixings

$$|\psi(0)\rangle = a(0)|P^0\rangle + b(0)|\overline{P}^0\rangle \, ,$$

$$|\psi(t)\rangle = a(t)|P^0\rangle + b(t)|\overline{P}^0\rangle + c_1(t)|f_1\rangle + c_2(t)|f_2\rangle + \cdots \, .$$

by a 2×2 effective Hamiltonian $\mathcal{H}$ that is not Hermitian, since otherwise the mesons would only oscillate and not decay. Any complex matrix, such as $\mathcal{H}$, can be written in terms of Hermitian matrices M and Γ as

$$\mathcal{H} = M - \frac{i}{2}\Gamma \, .$$

M and Γ are associated with $(P^0, \overline{P}^0) \leftrightarrow (P^0, \overline{P}^0)$ transitions via off-shell (dispersive) and on-shell (absorptive) intermediate states, respectively. Di-

The eigenvectors of $\mathcal{H}$ have well defined masses and decay widths. We introduce complex parameters $p_{L,H}$ and $q_{L,H}$ to specify the components of the strong interaction eigenstates, P^0 and $\overline{P}^0$, in the light (P_L) and heavy (P_H) mass eigenstates:

$$|P_{L,H}\rangle = p_{L,H}|P^0\rangle \pm q_{L,H}|\overline{P}^0\rangle$$

with the normalization $|p_{L,H}|^2 + |q_{L,H}|^2 = 1$. (Another possible choice, which is in standard usage for K mesons, defines the mass eigenstates according to their lifetimes: K_S for the short-lived and K_L for the long-lived state. The K_L is experimentally found to be the heavier state.) If either CP or CPT is a symmetry of $\mathcal{H}$ (independently of whether T is conserved or violated) then $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$, and solving the eigenvalue problem for $\mathcal{H}$ yields $p_L = p_H \equiv p$ and $q_L = q_H \equiv q$ with

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

Theory of neutral meson decay and mixings

If either CP or T is a symmetry of $\mathcal{H}$ (independently of whether CPT is conserved or violated), then M_{12} and Γ_{12} are relatively real, leading to

$$\left(\frac{q}{p}\right)^2 = e^{2i\xi_P} \quad \Rightarrow \quad \left|\frac{q}{p}\right| = 1 \, ,$$

only if, CP is a symmetry of $\mathcal{H}$ (independently of CPT and T) then bot of the above conditions hold, with the result that the mass eigenstates ar orthogonal

$$\langle P_H | P_L \rangle = |p|^2 - |q|^2 = 0 \, .$$

The real and imaginary parts of the eigenvalues of $\mathcal{H}$ corresponding to $|P_{L,H}\rangle$ represent their masses and decay-widths, respectively. The mass difference Δm and the width difference $\Delta\Gamma$ are defined as follows:

$$\Delta m \equiv M_H - M_L, \quad \Delta\Gamma \equiv \Gamma_H - \Gamma_L.$$

Theory of neutral meson decay and mixings

mass and width are given by

$$m \equiv \frac{M_H + M_L}{2}, \quad \Gamma \equiv \frac{\Gamma_H + \Gamma_L}{2}.$$

It is useful to define dimensionless ratios x and y:

$$x \equiv \frac{\Delta m}{\Gamma}, \quad y \equiv \frac{\Delta \Gamma}{2\Gamma}.$$

Solving the eigenvalue equation gives

$$(\Delta m)^2 - \frac{1}{4}(\Delta \Gamma)^2 = (4|M_{12}|^2 - |\Gamma_{12}|^2), \quad \Delta m \Delta \Gamma = 4 \mathrm{Re} M_{12} \Gamma_{12}^*.$$

CPV

All CP-violating observables in P and $\overline{P}$ decays to final states f and $\overline{f}$ can be expressed in terms of phase-convention-independent combinations of A_f, $\overline{A}_f$, $A_{\overline{f}}$ and $\overline{A}_{\overline{f}}$, together with, for neutral-meson decays only, q/p. CP violation in charged-meson decays depends only on the combination $|\overline{A}_{\overline{f}}/A_f|$, while CP violation in neutral-meson decays is complicated by $P^0 \leftrightarrow \overline{P}^0$ oscillations and depends, additionally, on $|q/p|$ and on $\lambda_f \equiv (q/p)(\overline{A}_f/A_f)$.

Using the effective Hamiltonian approximation, we obtain

$$\begin{aligned} |P^0_{\rm phys}(t)\rangle &= g_+(t)\,|P^0\rangle - (q/p)\; g_-(t)|\overline{P}^0\rangle, \\ |\overline{P}^0_{\rm phys}(t)\rangle &= g_+(t)\,|\overline{P}^0\rangle - (p/q)\; g_-(t)|P^0\rangle\ , \end{aligned}$$

where

$$g_\pm(t) \equiv \frac{1}{2}\left(e^{-im_H t - \frac{1}{2}\Gamma_H t} \pm e^{-im_L t - \frac{1}{2}\Gamma_L t}\right).$$

One obtains the following time-dependent decay rates:

$$\begin{aligned} \frac{d\Gamma[P^0_{\rm phys}(t)\to f]/dt}{e^{-\Gamma t}\mathcal{N}_f} &= \left(|A_f|^2 + |(q/p)\overline{A}_f|^2\right)\cosh(y\Gamma t) + \left(|A_f|^2 - |(q/p)\overline{A}_f|^2\right)\cos(x\Gamma t) \\ &+ 2\,{\rm Re}(q/p)A_f^*\overline{A}_f \sinh(y\Gamma t) - 2\,{\rm Im}(q/p)A_f^*\overline{A}_f\sin(x\Gamma t)\ , \\ \frac{d\Gamma[\overline{P}^0_{\rm phys}(t)\to f]/dt}{e^{-\Gamma t}\mathcal{N}_f} &= \left(|(p/q)A_f|^2 + |\overline{A}_f|^2\right)\cosh(y\Gamma t) - \left(|(p/q)A_f|^2 - |\overline{A}_f|^2\right)\cos(x\Gamma t) \\ & 2\,{\rm Re}(p/q)A_f\overline{A}_f^* \sinh(y\Gamma t) - 2\,{\rm Im}(p/q)A_f\overline{A}_f^*\sin(x\Gamma t)\ , \end{aligned}$$

$\mathcal{N}_f$ is a time-independnet normalization factor.

Three types of CPV

[I] **CP violation in decay** is defined by

$$|\overline{A}_{\overline{f}}/A_f| \neq 1 \,.$$

In charged meson decays, where mixing effects are absent, this is the only possible source of CP asymmetries:

$$\mathcal{A}_{f^\pm} \equiv \frac{\Gamma(P^- \to f^-) - \Gamma(P^+ \to f^+)}{\Gamma(P^- \to f^-) + \Gamma(P^+ \to f^+)} = \frac{|\overline{A}_{f^-}/A_{f^+}|^2 - 1}{|\overline{A}_{f^-}/A_{f^+}|^2 + 1} \,.$$

[II] **CP violation in mixing** is defined by

$$|q/p| \neq 1 \,.$$

In charged-current semileptonic neutral meson decays $P, \overline{P} \to \ell^\pm X$ (taking $|A_{\ell^+X}| = |\overline{A}_{\ell^-X}|$ and $A_{\ell^-X} = \overline{A}_{\ell^+X} = 0$, as is the case in the Standard Model, to lowest order in G_F, and in most of its reasonable extensions), this is the only source of CP violation, and can be measured via the asymmetry of "wrong-sign" decays induced by oscillations:

$$\mathcal{A}_{\rm SL}(t) \equiv \frac{d\Gamma/dt[\overline{P}^0_{\rm phys}(t) \to \ell^+ X] - d\Gamma/dt[P^0_{\rm phys}(t) \to \ell^- X]}{d\Gamma/dt[\overline{P}^0_{\rm phys}(t) \to \ell^+ X] + d\Gamma/dt[P^0_{\rm phys}(t) \to \ell^- X]} = \frac{1 - |q/p|^4}{1 + |q/p|^4} .$$

Note that this asymmetry of time-dependent decay rates is actually time independent.

Three types of CPV

[III] CPV in interference between mixing & decay. (occur when both B and $\bar{B}$ decay to a common CP final state).

$$\mathrm{Im}\lambda_f \neq 0\,,$$

with

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}\,.$$

This form of CP violation can be observed, for example, using the asymmetry of neutral meson decays into final CP eigenstates f_{CP}

$$\mathcal{A}_{f_{\mathrm{CP}}}(t) \equiv \frac{d\Gamma/dt[\overline{P}^0_{\mathrm{phys}}(t) \to f_{\mathrm{CP}}] - d\Gamma/dt[P^0_{\mathrm{phys}}(t) \to f_{\mathrm{CP}}]}{d\Gamma/dt[\overline{P}^0_{\mathrm{phys}}(t) \to f_{\mathrm{CP}}] + d\Gamma/dt[P^0_{\mathrm{phys}}(t) \to f_{\mathrm{CP}}]}\,.$$

Three types of CPV

If $\Delta\Gamma = 0$ and $|q/p| = 1$, as expected to a good approximation for B mesons but not for K mesons, then $\mathcal{A}_{f_{\rm CP}}$ has a particularly simple

$$\begin{aligned} \mathcal{A}_f(t) &= S_f \sin(\Delta m t) - C_f \cos(\Delta m t), \\ S_f &\equiv \frac{2\,{\rm Im}\lambda_f}{1+|\lambda_f|^2}, \quad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\,, \end{aligned}$$

If, in addition, the decay amplitudes fulfill $|\overline{A}_{f_{\rm CP}}| = |A_{f_{\rm CP}}|$, the interference between decays with and without mixing is the only source of the asymmetry and

$$\mathcal{A}_{f_{\rm CP}}(t) = {\rm Im}\lambda_{f_{\rm CP}} \sin(x\Gamma t).$$

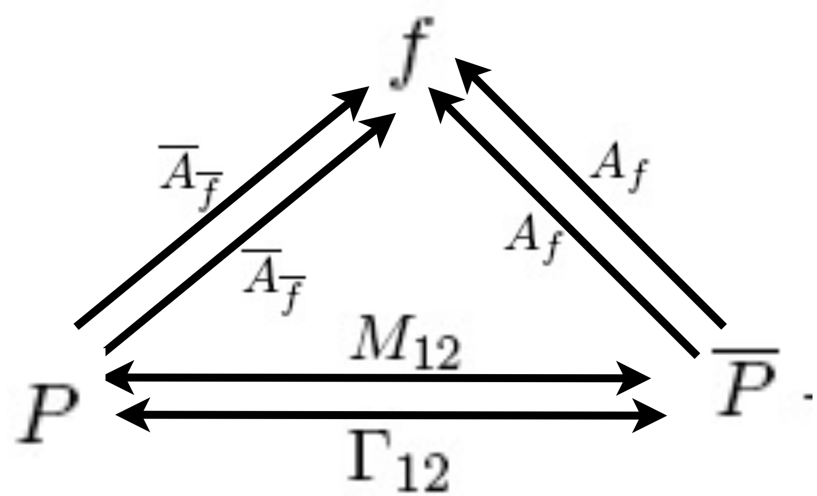
Three types of CPV

Tale of 2 phases:

$$
\begin{aligned}
A_f &= |a_1|e^{i(\delta_1+\phi_1)} + |a_2|e^{i(\delta_2+\phi_2)}, \\
\overline{A}_{\overline{f}} &= |a_1|e^{i(\delta_1-\phi_1)} + |a_2|e^{i(\delta_2-\phi_2)}.
\end{aligned}
$$

ral meson decays, it is useful to write

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

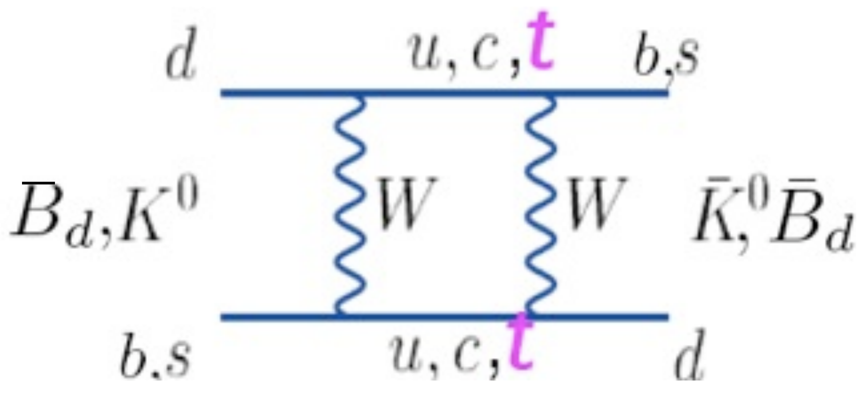


Case study: 3rd type CPV in $B \to \psi K_S$

$$\lambda_f = e^{-i\phi_B}(\overline{A}_f/A_f) \ ,$$

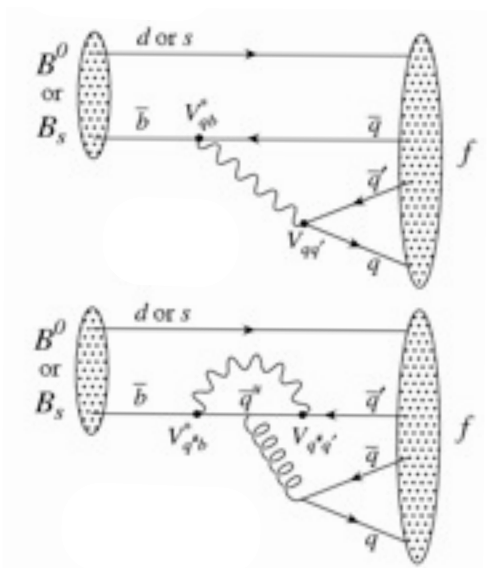
ϕ_B is the phase of M_{12}
the $B_d - \bar{B}_d$ mixing amplitude;

$$e^{-i\phi_B} = (V_{tb}^* V_{td})/(V_{tb} V_{td}^*) \ .$$



For $f = J/\psi K$, which proceeds via $\bar{b} \to \bar{c}c\bar{s}$ transition,

$$A_{\psi K} = (V_{cb}^* V_{cs})\, T_{\psi K} + (V_{ub}^* V_{us})\, P_{\psi K}^u ,$$



tiny smaller by a loop factor
& λ_C^2 factor, $\lambda_C^2 \sim 5\%$.

Case study: 3rd type CPV in $B \to \psi K_S$

this decay that is related to the fact that B^0 decays into $J/\psi K^0$ while $\overline{B}^0$ decays into $J/\psi \overline{K}^0$. A common final state, e.g. $J/\psi K_S$, is reached only via $K^0 - \overline{K}^0$ mixing. Consequently, the phase factor corresponding to neutral K mixing, $e^{-i\phi_K} = (V_{cd}^* V_{cs})/(V_{cd} V_{cs}^*)$, plays a role:

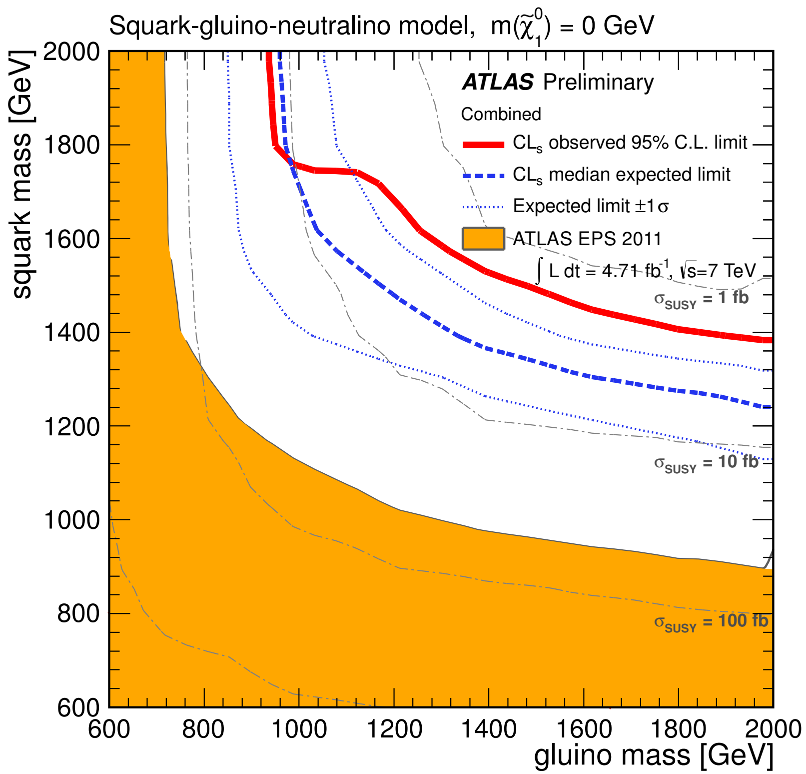
$$\frac{\overline{A}_{\psi K_S}}{A_{\psi K_S}} = -\frac{(V_{cb} V_{cs}^*)\, T_{\psi K} + (V_{ub} V_{us}^*)\, P_{\psi K}^u}{(V_{cb}^* V_{cs})\, T_{\psi K} + (V_{ub}^* V_{us})\, P_{\psi K}^u} \times \frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}.$$

$$\lambda_{\psi K_S} = -e^{-2i\beta} \;\Rightarrow\; S_{\psi K_S} = \sin 2\beta, \qquad \left\{ e^{i2\beta} = \frac{V_{tb}^* V_{td} V_{cb} V_{cd}^*}{V_{tb} V_{td}^* V_{cb}^* V_{cd}},\ \beta = arg\left[\frac{V_{tb}^* V_{td}]}{V_{cb}^* V_{cd}}\right] \right\}$$

$$\mathcal{A}_{f_{\rm CP}}(t) = {\rm Im}\lambda_f \;\sin(\Delta m t) \;\; \text{with} \;\; {\rm Im}\lambda_f = \eta_f \sin(\phi_M + 2\phi_f).$$

End of the 4th Part

1st & 2nd geneneration squark limits



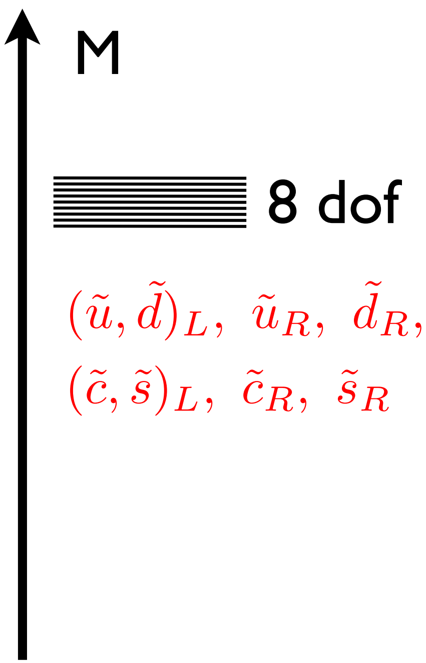
Light squarks > 1.4 TeV?

Why really should the first 2 generation squark need to be degenerate?

Blum, Grossman, Nir and GP (09);

Gedalia, Grossman, Nir and GP (09);

Gedalia, Kamenik, Ligeti & Perez (12).



Everything degenerate

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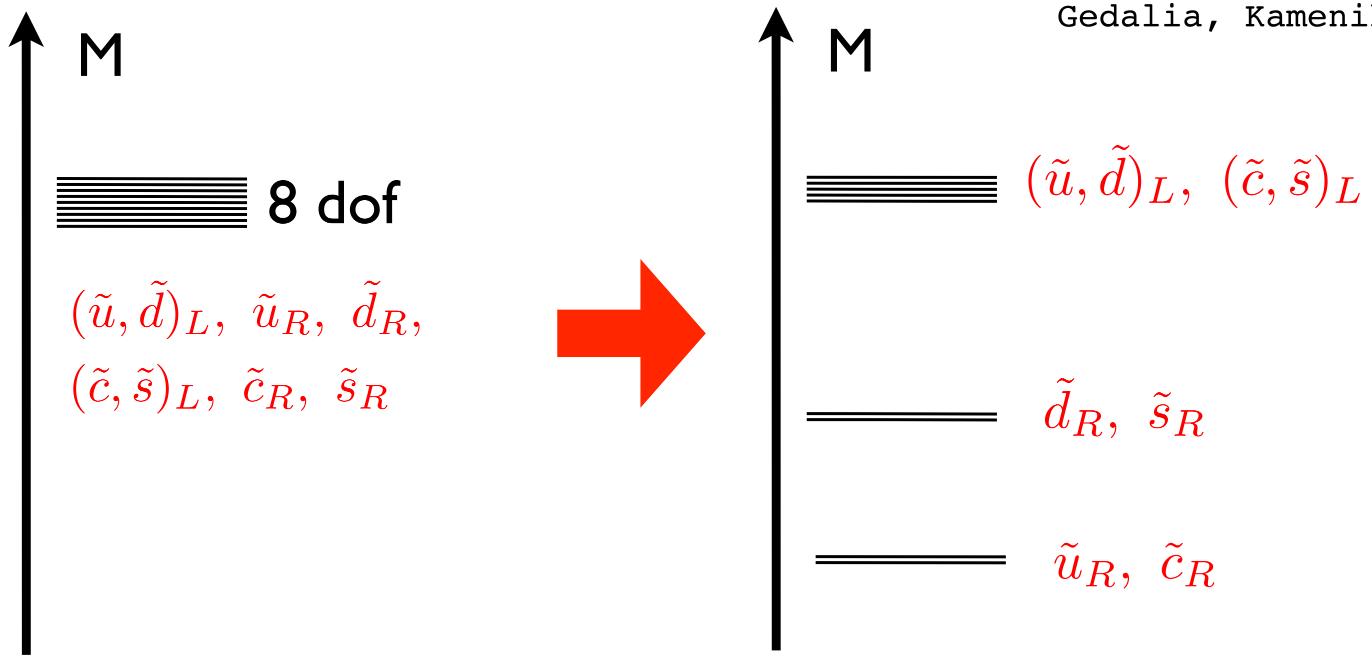

Everything degenerate

Split, but MFV !

What if they are not degenerate?

Mahbubani, Papucci, GP, Ruderman & Weiler, to appear.

Effective Field Theory (EFT) Model independent approach

microscopic dynamics above few *x 100* GeV is unknown.

Can parameterize our ignorance by set of higher dim' operators suppressed by the scale of new physics (NP).

$$\mathcal{H}_{\rm eff}^{\Delta S,C,B=2} = \sum_{i=1}^{5} \left(O_i^{sd}/\Lambda^2 + O_i^{cu}/\Lambda^2 + O_i^{b,sd}/\Lambda^2 \right)$$

(see e.g.: UTFit, 0707.03535)

$$Q_1^{q_iq_j} = \bar{q}_{jL}^{\alpha}\gamma_\mu q_{iL}^{\alpha}\bar{q}_{jL}^{\beta}\gamma^\mu q_{iL}^{\beta}\,, \quad Q_3^{q_iq_j} = \bar{q}_{jR}^{\alpha}q_{iL}^{\beta}\bar{q}_{jR}^{\beta}q_{iL}^{\alpha}\,, \quad Q_5^{q_iq_j} = \bar{q}_{jR}^{\alpha}q_{iL}^{\beta}\bar{q}_{jL}^{\beta}q_{iR}^{\alpha}\,.$$

$$Q_2^{q_iq_j} = \bar{q}_{jR}^{\alpha}q_{iL}^{\alpha}\bar{q}_{jR}^{\beta}q_{iL}^{\beta}\,, \quad Q_4^{q_iq_j} = \bar{q}_{jR}^{\alpha}q_{iL}^{\alpha}\bar{q}_{jL}^{\beta}q_{iR}^{\beta}\,,$$

Almost any NP model can be described at low *E* by this set of operators (above Op' are most dangerous & yet clean).

$\Delta F = 2$ 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	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}
$(\bar{t}_L \gamma^\mu u_L)^2$					same sign t's

$\Delta F = 2$ status

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

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}	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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$(\bar{t}_L \gamma^\mu u_L)^2$					sign t's

Probably bound already exists due to LHCb, CMS indep' confirmation?

Adding Leptons?

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}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
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$(\bar{b}_R\,d_L)(\bar{b}_L d_R)$	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}
$(\bar{t}_L\gamma^\mu u_L)^2$					same sign t's

$\bar{L}_i\sigma^{\mu\nu}e_{Rj}HF_{\mu\nu}$	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			$\frac{\sigma(\mu^- Ti\to e^- Ti)}{\sigma(\mu^- Ti\to capture)}$

Adding Leptons?

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$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2				
$(\bar{t}_L\gamma^\mu u_L)^2$					

Very very strong ...

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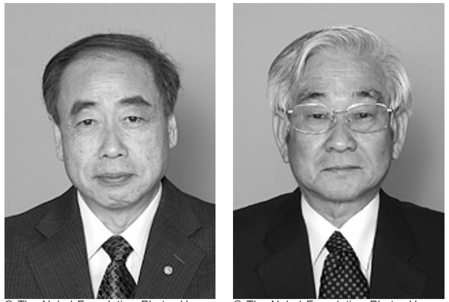
$(\bar{\mu}\gamma^\mu P_L e)\,(\bar{u}\gamma_\mu P_L u)$	1.9×10^2			$\frac{\sigma(\mu^- Ti\to e^- Ti)}{\sigma(\mu^- Ti\to capture)}$

What do we conclude ?

◆ SM mechanism to induce flavor & CPV is successful.

The Nobel Prize in Physics



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Makoto Kobayashi

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Toshihide Maskawa

$\Delta F = 2$ status

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

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- SM mechanism to induce flavor & CPV

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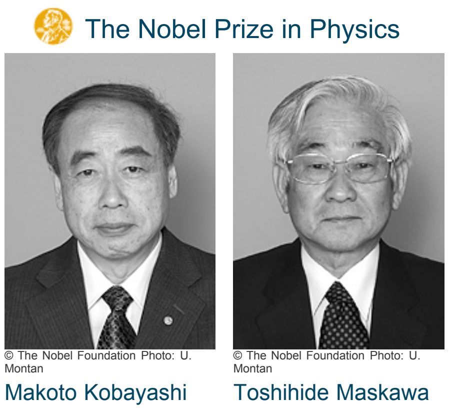

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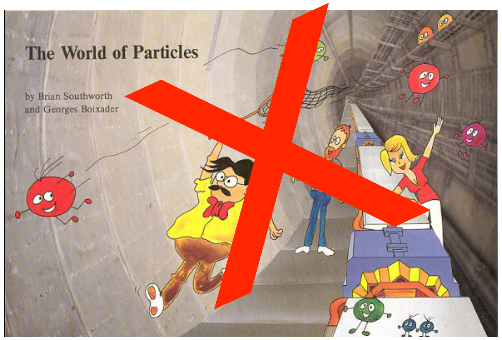
$(\bar{t}_L\gamma^\mu u_L)^2$					

- Bounds are too strong to allow for NP to be directly probed.



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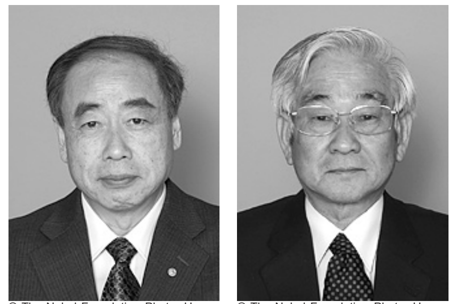

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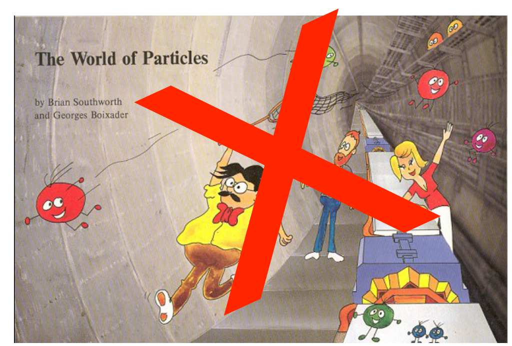
$(\bar{t}_L\gamma^\mu u_L)^2$					

♦ Bounds are too strong to allow for NP to be directly probed.



♦ Hint for underlying structure of microscopic laws of nature.

Alternatively, assume $1\mathrm{TeV}$ & bound coefficients

$$\begin{aligned}\mathcal{L}_{\Delta F=2} &= \frac{z_{sd}}{(1\,\mathrm{TeV})^2}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{(1\,\mathrm{TeV})^2}(\overline{c_L}\gamma_\mu u_L)^2 \\ &+ \frac{z_{sd}^4}{(1\,\mathrm{TeV})^2}(\overline{d_L}s_R)(\overline{d_R}s_L) + \frac{z_{cu}^4}{(1\,\mathrm{TeV})^2}(\overline{u_L}c_R)(\overline{u_R}c_L).\end{aligned}$$

$$\mathcal{I}m(z_{sd}, z_{sd}^4) \lesssim (3.4\times10^{-9}, 2.6\times10^{-11})\,(\Lambda_{\mathrm{NP}}/\mathrm{TeV})^2,$$

$$\mathcal{I}m(z_{cu}, z_{cu}^4) \lesssim (1.0\times10^{-7}, 1.1\times10^{-8})\,(\Lambda_{\mathrm{NP}}/\mathrm{TeV})^2,$$

recent, will be further improved

Flavor structure of TeV NP is highly non-generic!

What kind of NP survives?

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

(spoiled by RGE)

What kind of NP survives?

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

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- NP flavor structure is controlled by SM one, effective minimal flavor violation (MFV) => more exciting than guessed, see later ...

What kind of NP survives?

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

(spoiled by RGE)

- NP flavor structure is controlled by SM one, effective minimal flavor violation (MFV) => more exciting than guessed, see later ...

- Maybe NP is anarchic but aligned.

Nir-Seiberg (92); Fitzpatrick-Perez-Randall (07); Csaki-Surujon-Perez-Weiler (09).

Aligning away NP & the power of the D system

The bounds from $z^4_{sd,cu}$ are much more severe.

However, $z^4_{sd} \subset (1, \mathbf{8}, 1, \mathbf{8})$, $z^4_{cu} \subset (\mathbf{8}, 1, \mathbf{8}, 1)$

Have singlet part which can be aligned with SM, $Y_U^\dagger Y_U$, $Y_D^\dagger Y_D$.

On the other hand assuming $SU(2)_L$ $z_{sd,cu}$ expected to have a common origin, z_Q .

Cannot align z_Q simultaneously with both $Y_U Y_U^\dagger$ & $Y_D Y_D^\dagger$.

Nir (07); Blum, Grossman, Nir, GP (09)

Two generation covariance description

X_Q is 2x2 Hermitian matrix, can be described as a vector in SU(2) 3D flavor space.

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

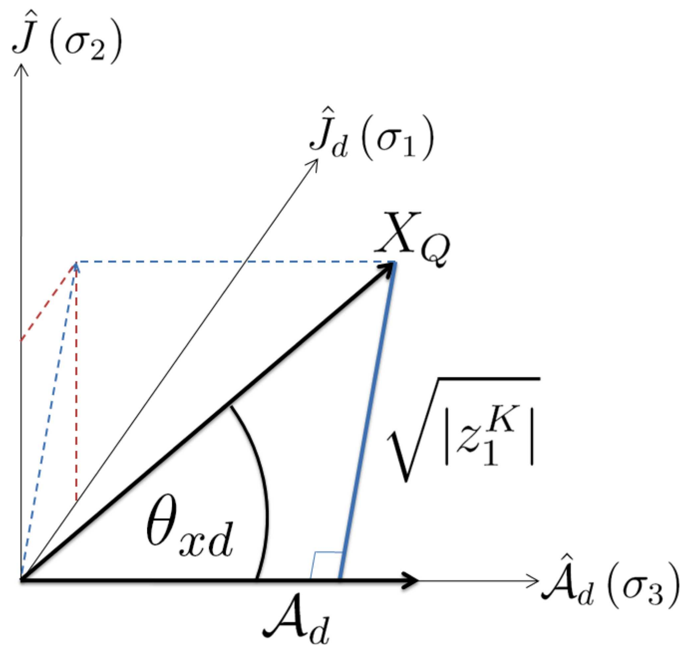
$$\cos(\theta_{AB}) \equiv \frac{\vec{A}\cdot\vec{B}}{|\vec{A}||\vec{B}|} = \frac{\mathrm{tr}(A\,B)}{\sqrt{\mathrm{tr}(A^2)\mathrm{tr}(B^2)}}\,.$$

The space can be span by using the SM Yukawas (very useful for CPV, see later):

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

Two generation covariance description, cont’

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



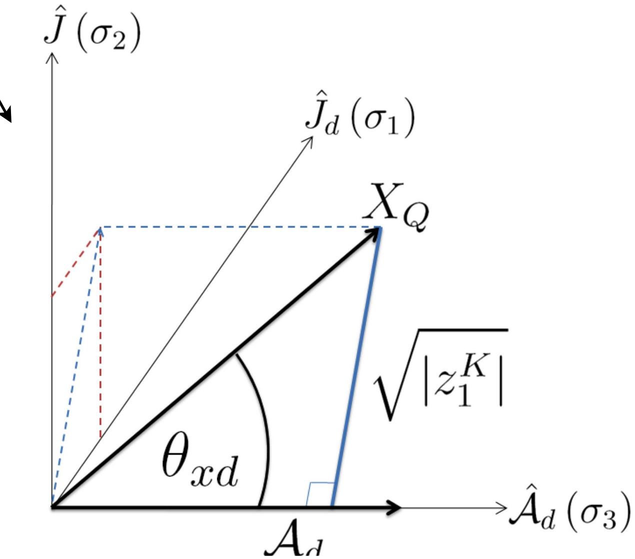
: The contribution of X_Q to $K^0 - \overline{K^0}$ mixing, Δm_K, given by the solid blue line. In the down mass basis, $\hat{\mathcal{A}}_d$ corresponds to σ_3, $\hat{J}$ is σ_2 and $\hat{J}_d$ is σ_1.

Combining $K^0 - \overline{K^0}$ mixing and $D^0 - \overline{D^0}$ mixing to constrain the flavor structure of new physics

Notice that:

A 2-gen' case, 3 adjoints yield CPV: $J = \mathrm{Tr}\left\{X\left[Y_D Y_D^\dagger, Y_U Y_U^\dagger\right]\right\}$

Projection of X_Q onto $\hat{J}$ is measuring the physical CPV phase.

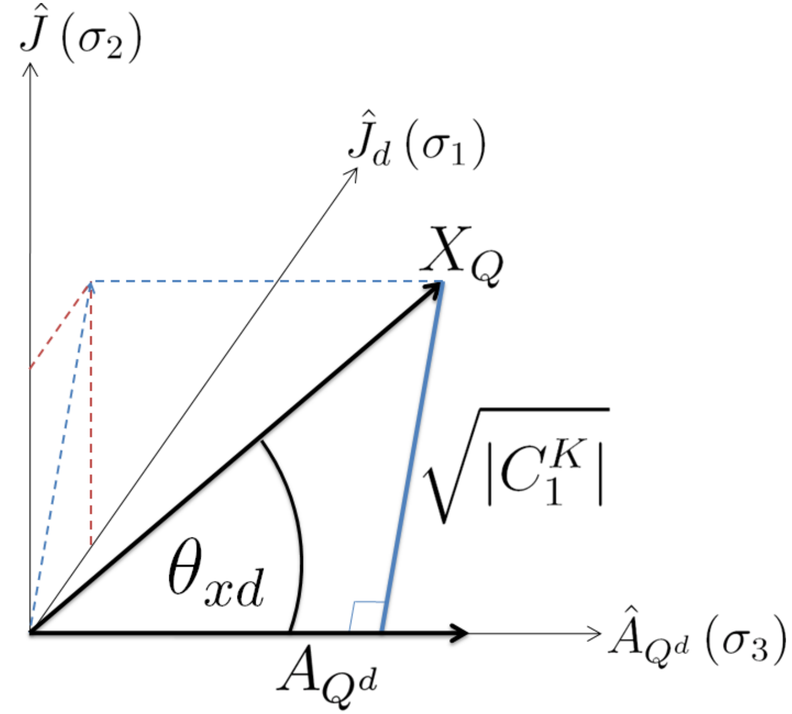


Assuming $SU(2)_L$: $\frac{1}{\Lambda_{\mathrm{NP}}^2}(\overline{Q_{Li}}(X_Q)_{ij}\gamma_\mu Q_{Lj})(\overline{Q_{Li}}(X_Q)_{ij}\gamma^\mu Q_{Lj}),$

Combining $K^0 - \overline{K^0}$ mixing and $D^0 - \overline{D^0}$ mixing to constrain the flavor structure of new physics

$$\frac{C_1}{\Lambda_{\mathrm{NP}}^2} O_1 = \frac{1}{\Lambda_{\mathrm{NP}}^2} \left[\overline{Q}_i (X_Q)_{ij} \gamma_\mu Q_j\right] \left[\overline{Q}_i (X_Q)_{ij} \gamma^\mu Q_j\right] ,$$

$$\left| C_1^{D,K} \right| = \left| X_Q \times \hat{A}_{Q^u,Q^d} \right|^2 \qquad \text{(Sorry } \mathcal{A}_{u,d} \equiv A_{Q^u,Q^d}\text{)}$$



$$\mathrm{Im}\left(C_1^{K,D}\right) = 2\left(X_Q \cdot \hat{J}\right)\left(X_Q \cdot \hat{J}_{u,d}\right) .$$

Finding the weakest robust bound

The covariant expansion of the new physics:

$$X_Q = L\left(X^{u,d}\hat{A}_{Q^u,Q^d} + X^J\hat{J} + X^{J_{u,d}}\hat{J}_{u,d}\right) ,$$

and the two bases are related through

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

while X^J remains invariant. We choose the X^i coefficients to be normalized,

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

such that L signifies the "length" of X_Q

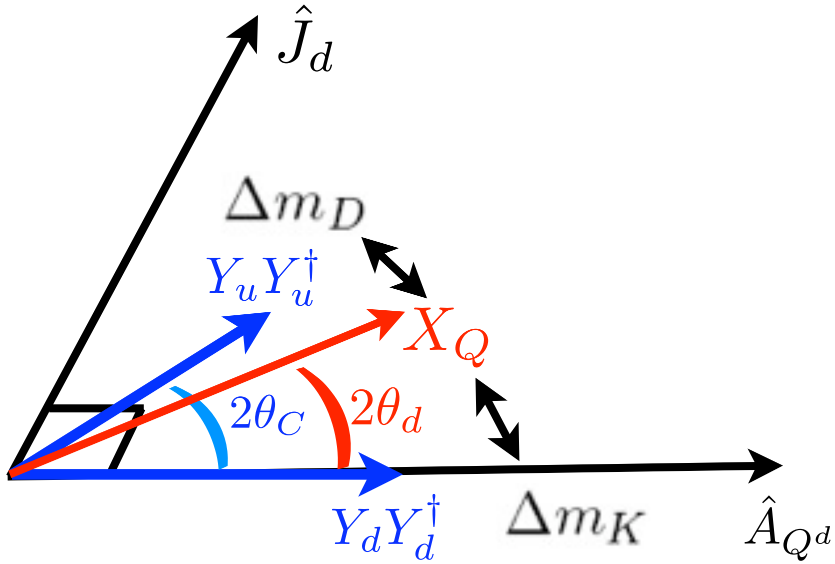
$$L = |X_Q| = \left(X_Q^2 - X_Q^1\right)/2 ,$$

where $X_Q^{1,2}$ are the eigenvalues of X_Q before removing the trace.

Finding the weakest robust bound, no CPV

$$C_1^K = L^2 \left[\left(X^J\right)^2 + \left(X^{J_d}\right)^2 \right] ,$$

$$C_1^D = \frac{L^2}{2} \left[2\left(X^J\right)^2 + \left(X^d\right)^2 + \left(X^{J_d}\right)^2 + \left(\left(X^{J_d}\right)^2 - \left(X^d\right)^2 \right) \cos(4\theta_{\rm C}) + 2X^d X^{J_d} \sin(4\theta_{\rm C}) \right] .$$



In order to minimize both contributions, we first need to set $X^J = 0$. Next we define

$$\tan\alpha \equiv \frac{X^{J_d}}{X^d} , \qquad r_{KD} \equiv \sqrt{\frac{\left(C_1^K\right)_{\rm exp}}{\left(C_1^D\right)_{\rm exp}}} ,$$

Finding the weakest robust bound, no CPV

Then the weakest bound is obtained for

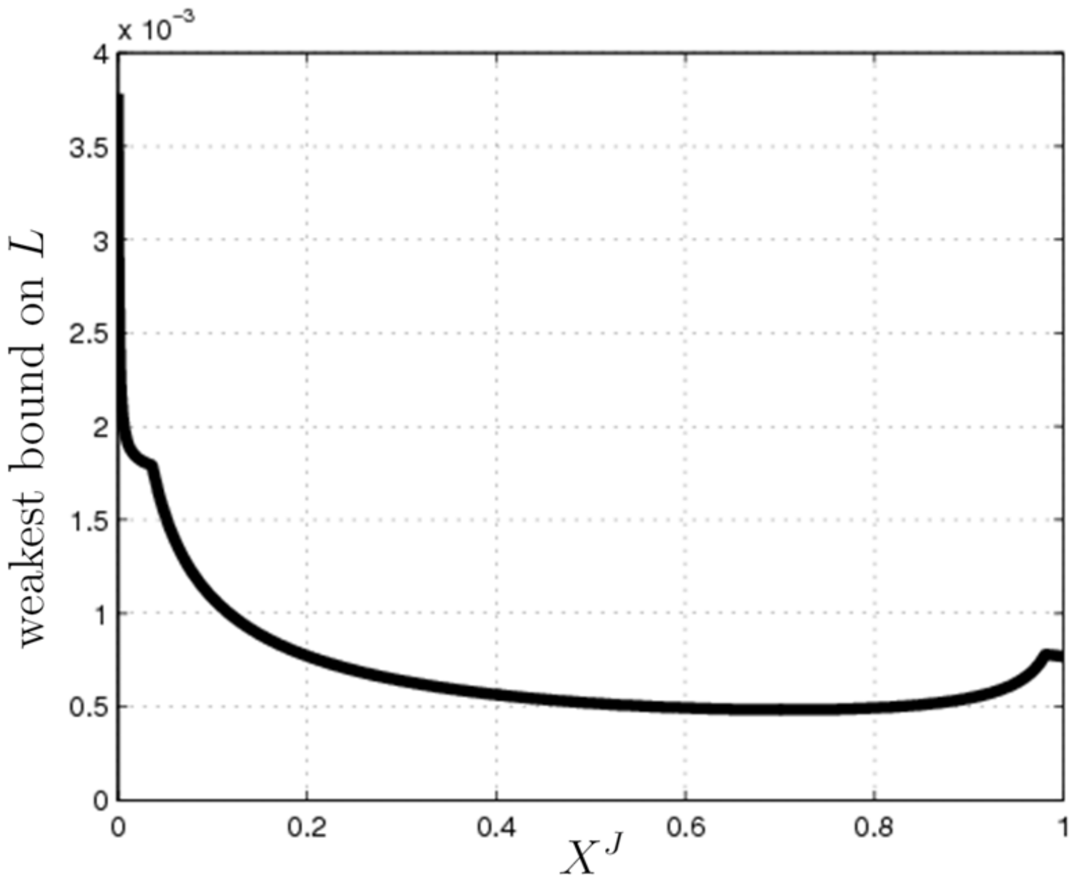
$$\tan\alpha = \frac{r_{KD}\sin(2\theta_{\mathrm{C}})}{1 + r_{KD}\cos(2\theta_{\mathrm{C}})}\,,$$

and is given by

$$L \leq 3.8\times 10^{-3}\left(\frac{\Lambda_{\mathrm{NP}}}{1\,\mathrm{TeV}}\right)\,.$$

Finding the weakest robust bound, with CPV

$$L \leq \frac{3.4 \times 10^{-4}}{\left[(X^J)^2 - (X^J)^4 \right]^{1/4}} \left(\frac{\Lambda_{\rm NP}}{1\,\rm TeV} \right)$$



Blum-Grossman-Nir-Perez (09)

The weakest upper bound on L coming from flavor and CPV in the K and D systems, as a function of the CP violating parameter X^J, assuming $\Lambda_{\rm NP} = 1$ TeV.

SUSY implications, naively looks like alignment is dead!!

What is X_Q in the SUSY case?

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

(squark doublets, 1TeV)

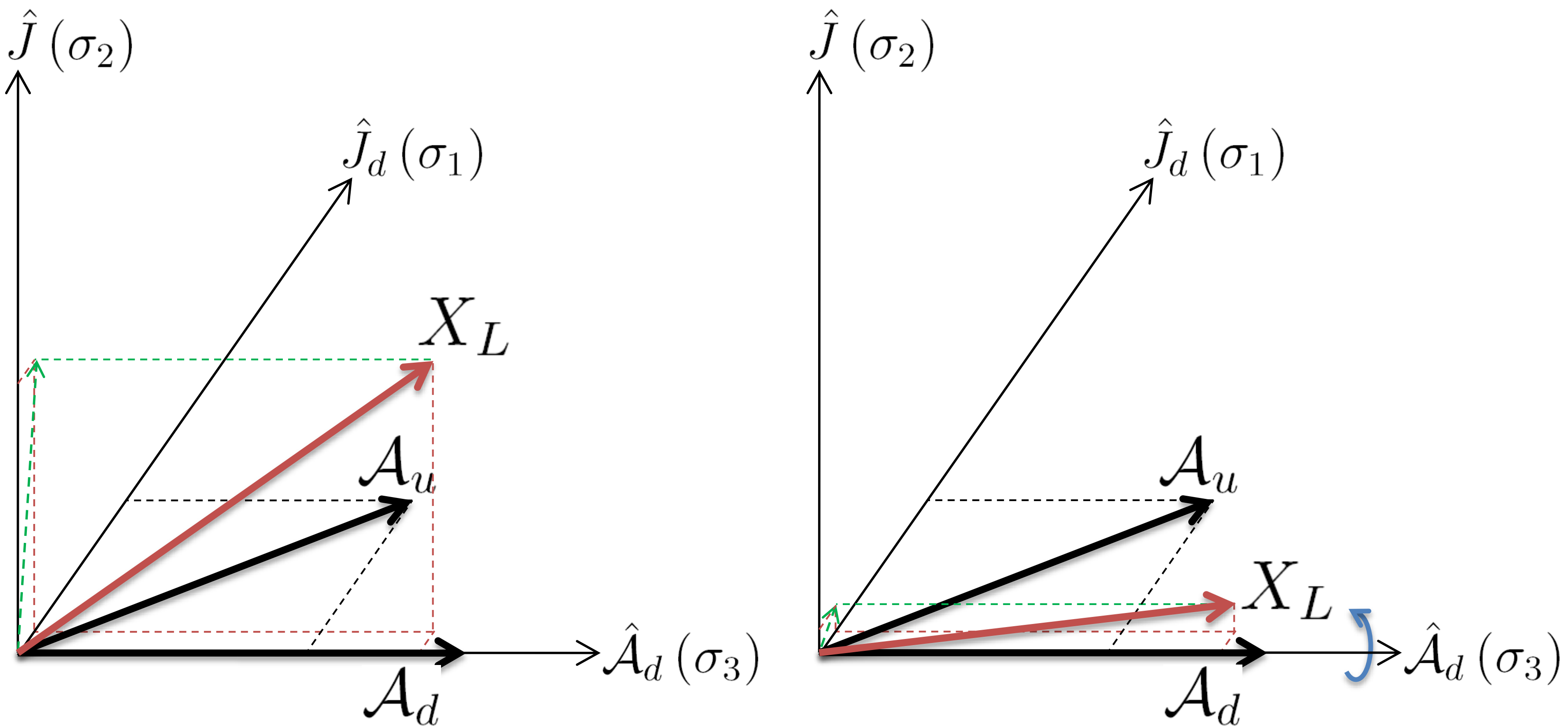
K. Blum, Y. Grossman, Y. Nir and G. Perez, PRL (2009)

With phases, first 2 gen' squark need to have almost equal masses.
Looks like squark anarchy/alignment is dead!

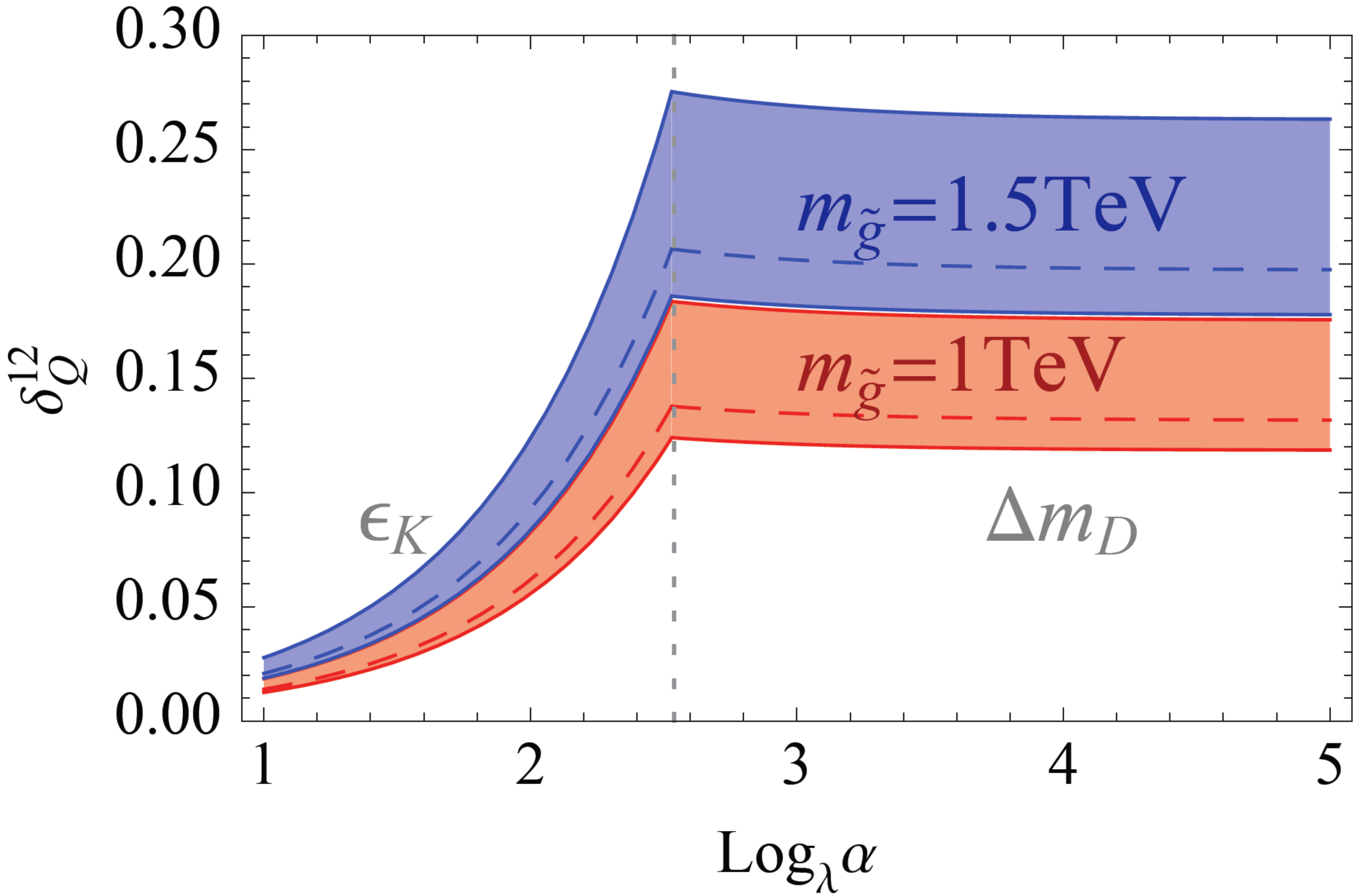
However ...

How alignment models work?

- The maximal phase case does not correspond to an alignment model.
- Alignment makes both real and imaginary parts small.



Degeneracy of Squarks

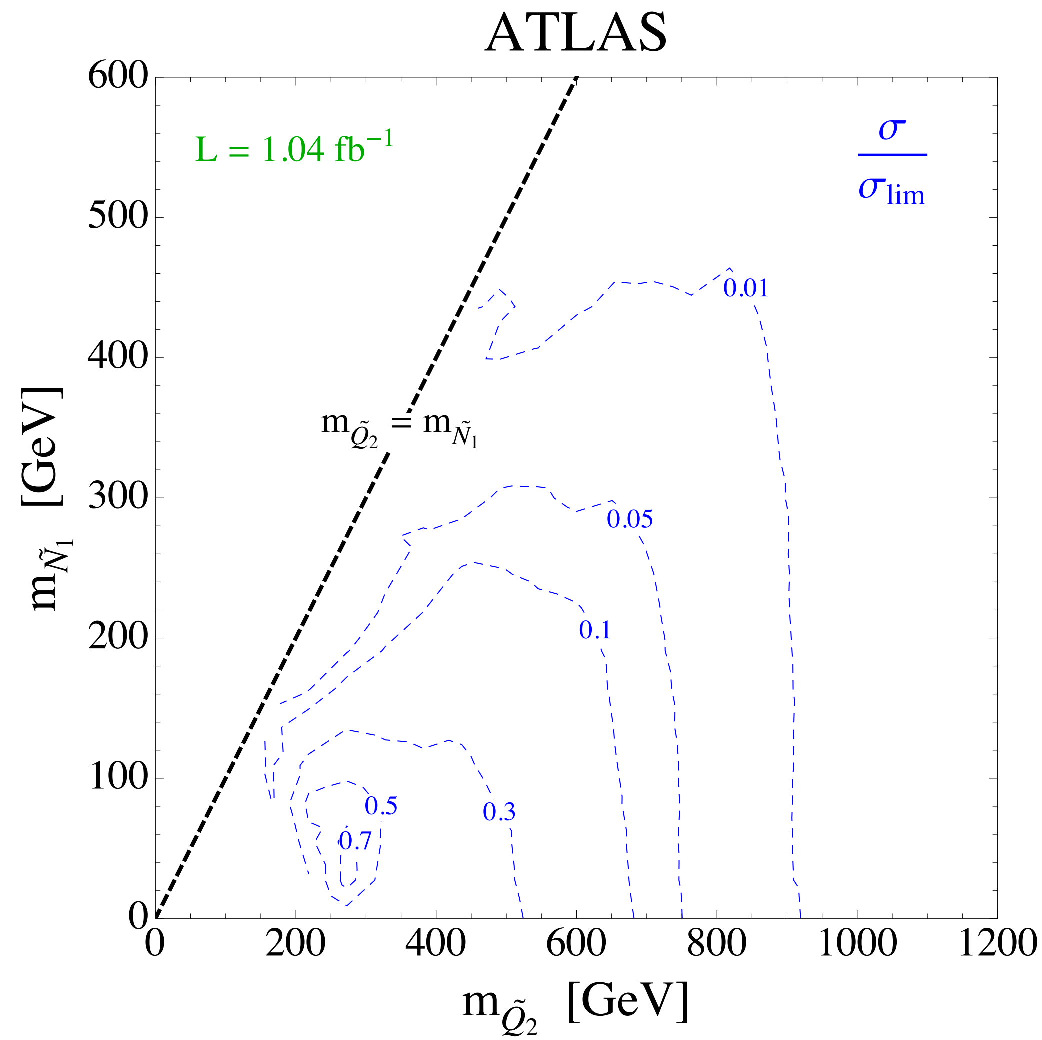


Degeneracy of Squarks

- No strong degeneracy required!
- Ex.: $m_{\tilde{g}}$=1.3 TeV, $m_{\tilde{Q}_1}$=550 GeV, $m_{\tilde{Q}_2}$=950 GeV
- This can be generated by*:
  - Anarchy at the SUSY breaking mediation scale
  - SUSY renormalization group flow to the TeV scale
  - Can lead to modest level of degeneracy

* Y. Nir and G. Raz, PRD **66**, 035007 (2002) [hep-ph/0206064]

No limit on LH 2nd gen' squark



Is there a 300 GeV squark hiding in the data?

Papucci, Ruderman, Perez, Mahbubani, Perez & Weiler, to appear.

End of the 5th Part And probably of these lectures...

SM Flavor Structure, is it fine tuned by itself?

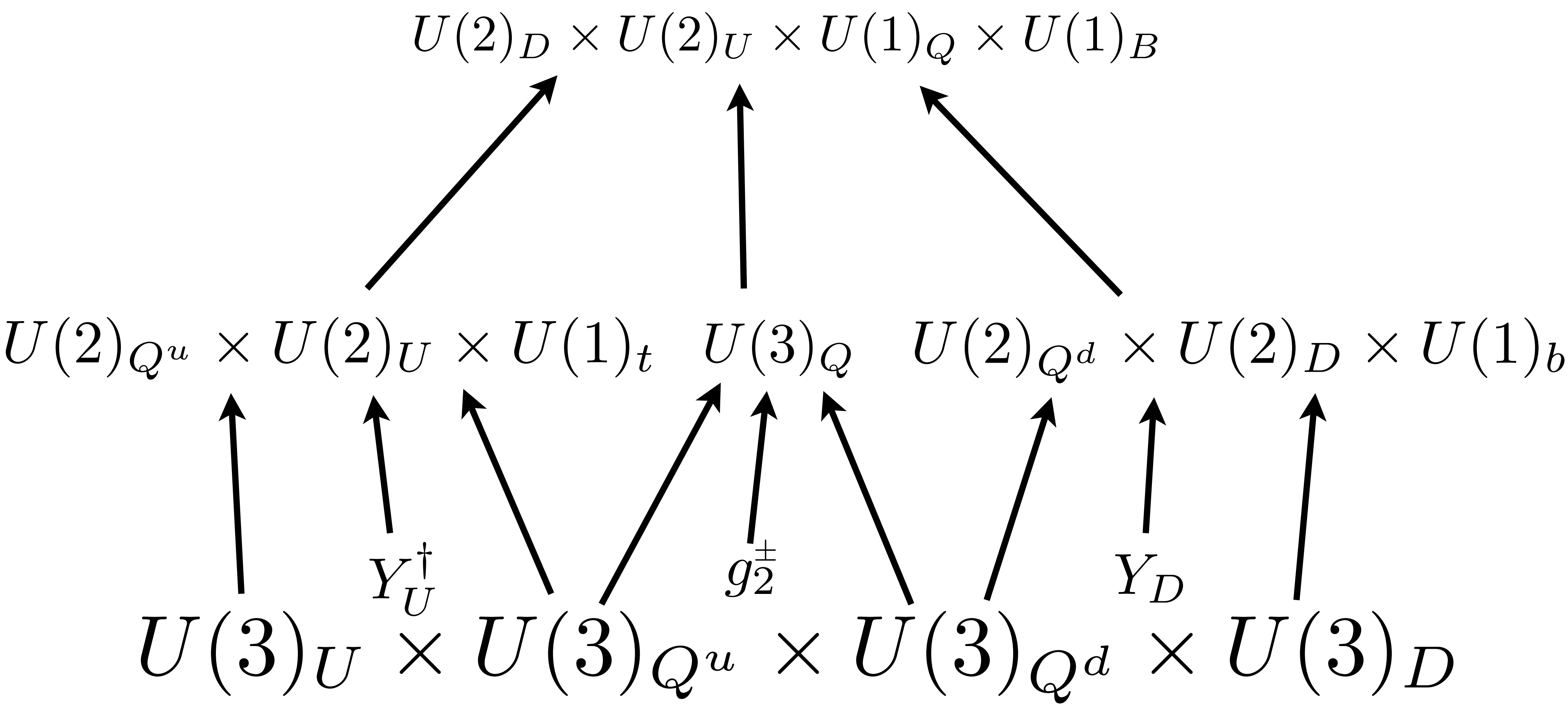
$$
\begin{tikzcd}
 & & & U(1)_B & & & \\
 & & U(1)^3_{Y_D \to 0} \arrow[urr] \arrow[rr, leftrightarrow, "V_{\mathrm{CKM}}"] & & U(1)^3_{Y_U \to 0} \arrow[ull] & & \\
 & U(1)^3_U \arrow[ur] & & U(3)_Q \arrow[ul] \arrow[ur] & & U(1)^3_D \arrow[ul] & \\
U(3)_U \arrow[ur] & \times \arrow[u, "Y_U^\dagger"] & U(3)_{Q^u} \arrow[ul] \arrow[ur] & \times \arrow[u, "g_2^\pm"] & U(3)_{Q^d} \arrow[ul] \arrow[ur] & \times \arrow[u, "Y_D"] & U(3)_D \arrow[ul]
\end{tikzcd}
$$

What is the flavor puzzle *(1st ingredient)*?

The flavor puzzle is of 2 ingredients:

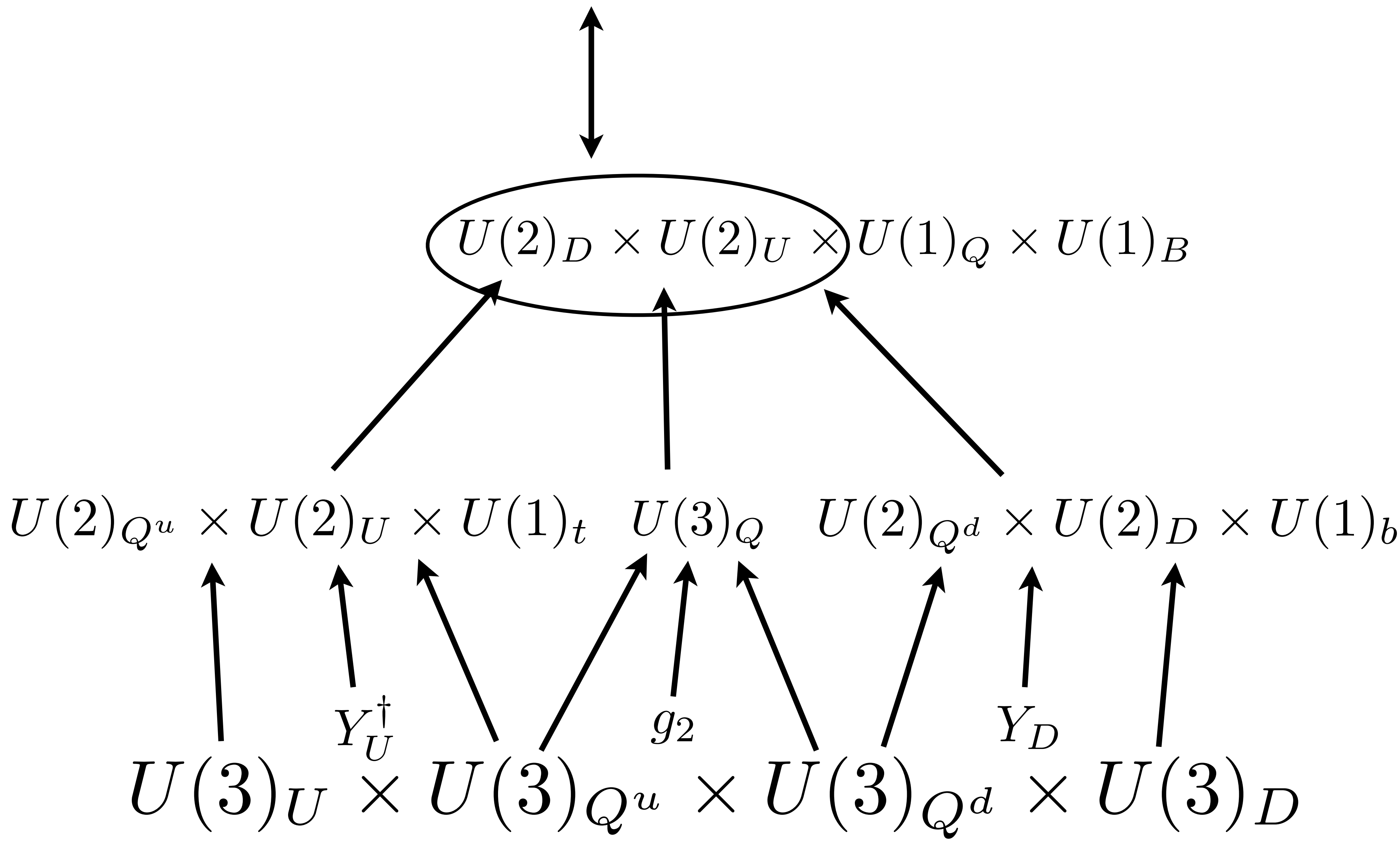
(i) Smallness of eigenvalues of Y_U & Y_D -

$$Y_u \sim \mathrm{diag}\,(0,0,y_t) \text{ and } Y_d \sim \mathrm{diag}\,(0,0,y_b).$$



Light quarks RH flavor group ~ conserved

RH currents involves the first 2 gen' are very small!
(within the SM even ones involve b are small)



What is the flavor puzzle *(2nd ingredient)*?

(ii) Smallness of the CKM mixing angles ($Y_{u,d}$ quasi-alignment) -

$$[Y_U Y_U^\dagger, Y_D Y_D^\dagger] \sim 0$$

In diagonal basis can expand Y's via Gel-Mann matrices:

$$\lambda_{3,8} = \frac{1}{\sqrt{2}}\,\mathrm{diag}(1,-1,0), \frac{1}{\sqrt{6}}\,\mathrm{diag}(1,1,-2)$$

$$Y_U Y_U^\dagger, Y_D Y_D^\dagger \sim \frac{y_{t,b}^2}{\sqrt{3}}\left[\frac{1}{\sqrt{3}}\,1_3 - \sqrt{\frac{1}{2}}\left(2 - \frac{m_{c,s}^2}{m_{t,b}^2}\right)\lambda_8 - \sqrt{\frac{3}{2}}\frac{m_{c,s}^2}{m_{t,b}^2}\,\lambda_3\right]$$

To leading order only the rotation in the *(13) & (23)* matters, hence, say in the down mass basis we find:

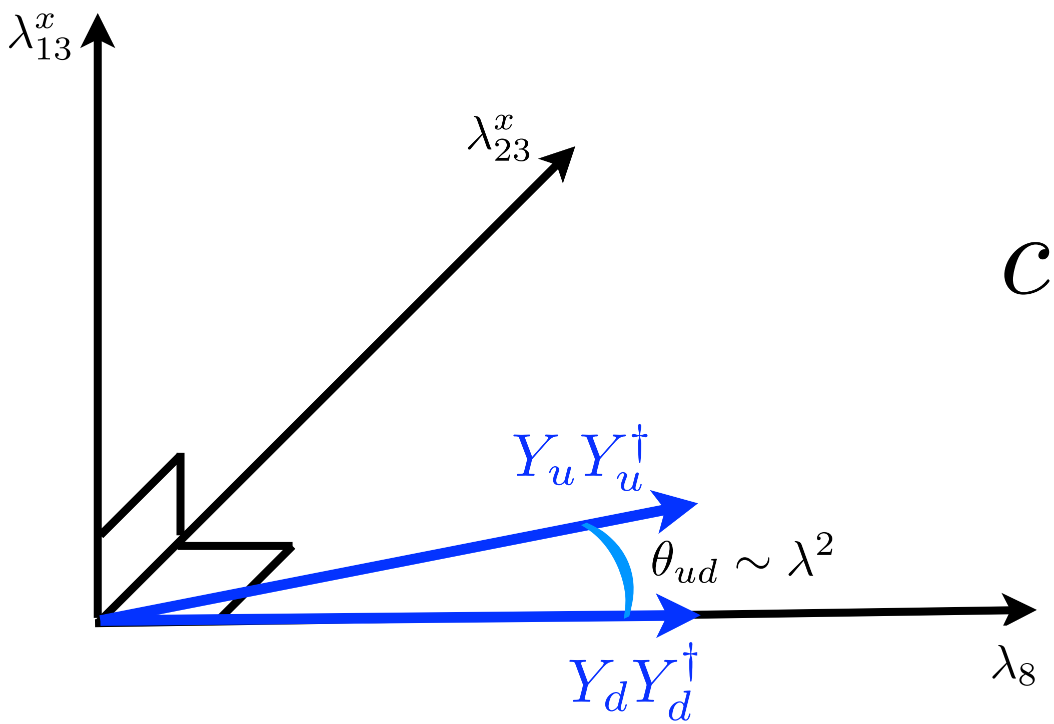
$$\begin{aligned}(Y_U Y_U^\dagger)_{\mathrm{down}} &= V_{\mathrm{CKM}}^\dagger (Y_U Y_U^\dagger)_{\mathrm{diag}} V_{\mathrm{CKM}} \sim y_t^2 V_{\mathrm{CKM}}^{ti} V_{\mathrm{CKM}}^{*\,tj} \\ &\sim \frac{y_t^2}{\sqrt{3}}\left[\frac{1}{\sqrt{3}}\,1_3 - \sqrt{2}\,\lambda_8 + c_{13}\,\lambda_{13}^x + c_{23}\,\lambda_{23}^x\right]\end{aligned}$$

$$\lambda_{23,13}^x = \frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&0&1\\0&1&0\end{pmatrix}, \frac{1}{\sqrt{2}}\begin{pmatrix}0&0&1\\0&0&0\\1&0&0\end{pmatrix}$$

CKM & Quasi alignment

The amount of alignment can be extracted from the scalar product of two vectors (in any flavor basis):

$$\cos\theta_{ud} \equiv \frac{\vec{A}\cdot\vec{B}}{|\vec{A}|\,|\vec{B}|} = \frac{\mathrm{tr}\left[\left(Y_U Y_U^\dagger\right)_{\not{\mathrm{tr}}}\left(Y_D Y_D^\dagger\right)_{\not{\mathrm{tr}}}\right]}{\sqrt{\mathrm{tr}\left[\left(Y_U Y_U^\dagger\right)_{\not{\mathrm{tr}}}^2\right]\mathrm{tr}\left[\left(Y_D Y_D^\dagger\right)_{\not{\mathrm{tr}}}^2\right]}} \sim 1 - c\,\lambda^4 \Rightarrow \theta_{ud} = \mathcal{O}(\lambda^2)$$



$$c_{23,13} = \mathcal{O}(\lambda^{2,3})$$

The flavor puzzle, breaking & naturalness

Flavor puzzle: The parameters' are small and hierarchical!

Is the flavor sector fine tuned?

'**t Hooft** definition of technical naturallness: a parameter is natural if when it's set to 0 there's an enhanced sym'.

Light masses are protected by residual $U(2)_D \times U(2)_U$ sym'.

Mixing angles are protected by $U(1)^3_Q$ sym'.

Flavor puzzles => tuning not fine tuning (nothing unnatural)!

Back to the bounds from flavor precision

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		
$(\bar{t}_L\gamma^\mu u_L)^2$					

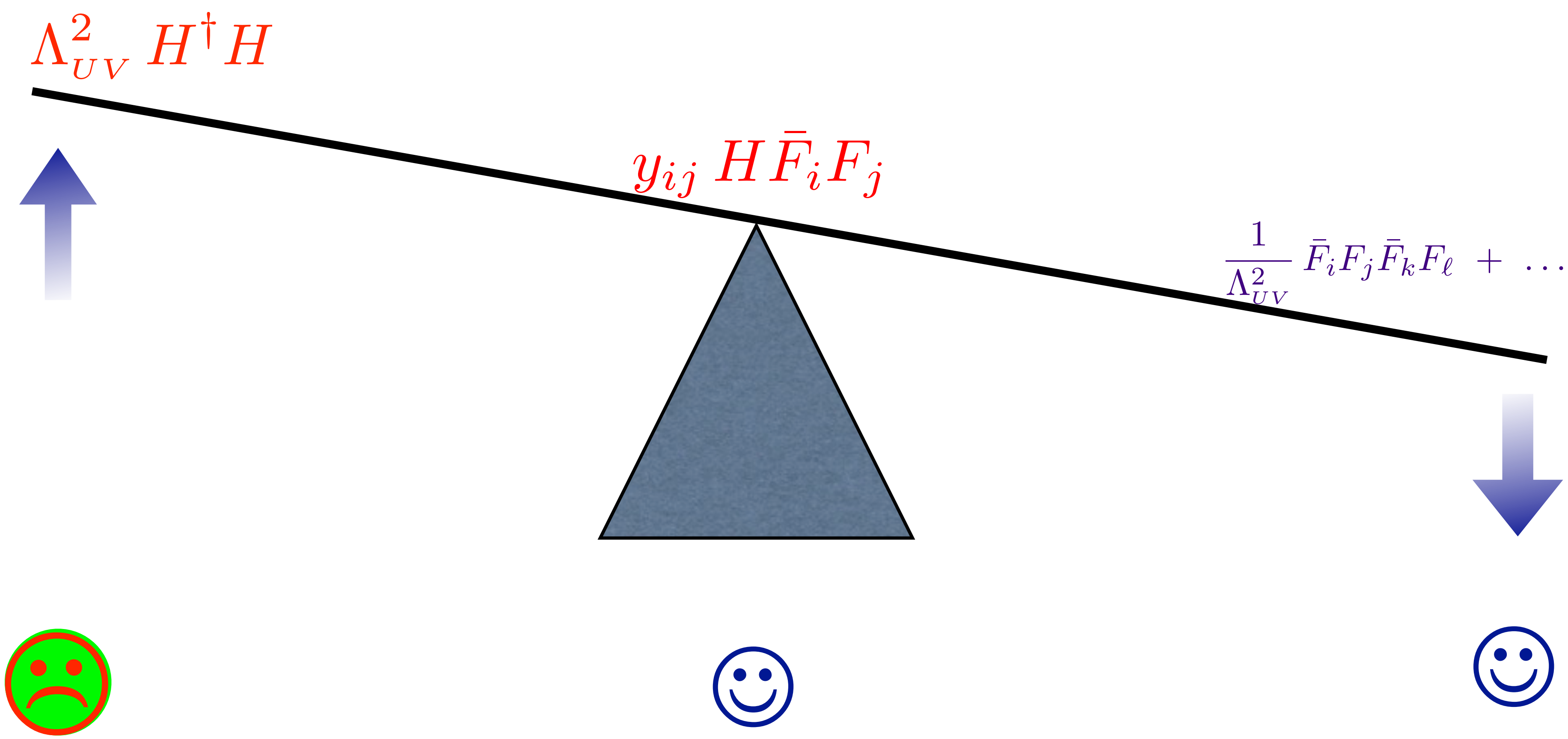
$\bar{L}_i\sigma^{\mu\nu}e_{Rj}HF_{\mu\nu}$	1.7×10^4			$Br\,(\mu\to e\gamma)$
	3.3×10^2			$Br\,(\tau\to\mu\gamma)$
	2.6×10^2			$Br\,(\tau\to e\gamma)$
$(\bar{\mu}\gamma^\mu P_L e)\,(\bar{u}\gamma_\mu P_L u)$	1.9×10^2			$\frac{\sigma(\mu^- Ti\to e^- Ti)}{\sigma(\mu^- Ti\to capture)}$

Very very strong ...

With new physics new flavor problem arises

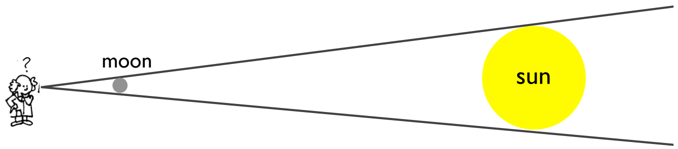
Hierarchy see-saw

Standard Model up to some $\Lambda^2_{UV} \gg 1\,\mathrm{TeV}$

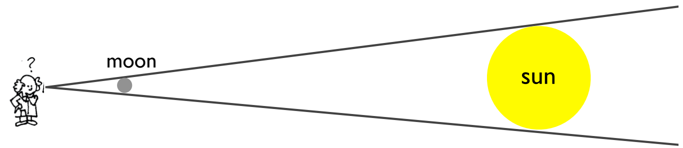


Rattazzi (12)

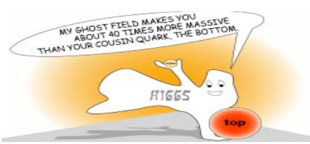
What about the fine tuning problem ?

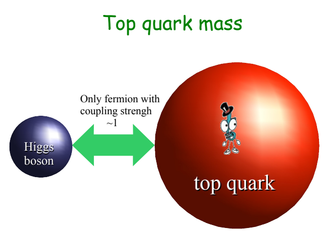


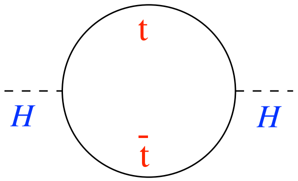
What about the fine tuning problem ?



- The most severe problem is due to top coupling:







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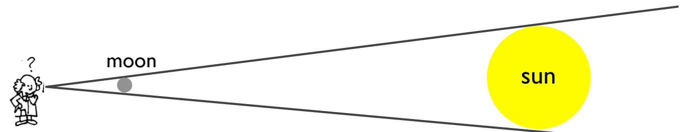

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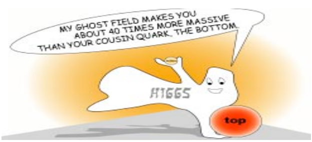

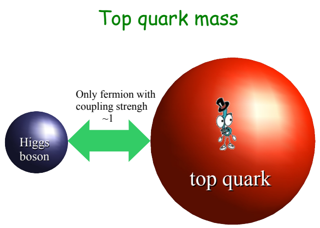

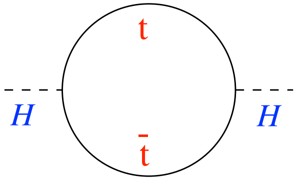

$$\text{Assume cutoff } \Lambda = 7\,\text{TeV};\ \delta_t m_h^2 = \frac{3}{8\pi^2} y_t^2 \Lambda^2 \sim 1.4\text{TeV}^2$$

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

fine tuning of worse than 1:100 !

However little is known on tFCNC

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}	$\Delta m_K;\ \epsilon_K$
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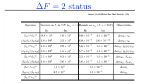
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p \rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	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}
$(\bar{t}_L \gamma^\mu u_L)^2$					same sign t's



However little is known on tFCNC

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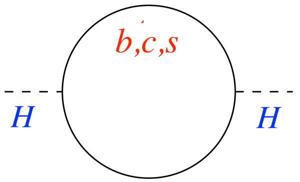
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	[illegible]	[illegible]	[illegible]
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		[illegible]	[illegible]	[illegible]
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		[illegible]	[illegible]	[illegible]
$(\bar{t}_L \gamma^\mu u_L)^2$			[illegible]	[illegible]	[illegible]

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 ($c_{ij} = 1$)	
	Re	Im
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5
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$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4
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	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 $1{:}100$?

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

$$c: \ \Rightarrow \Lambda_c \lesssim 2\times 10^3\ \text{TeV}$$

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$\ldots\gamma^\mu s_L)^2$	1.1×10^2	
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B system: only case with tension with LLLL operators; Improvement in Bs will get us there as well.

MFV & quick way to estimate SM strength of FCNC & constraints

As we saw, flavor structure of NP not generic, similar to SM.

Extra protection is obtained if the NP flavor structure
is controlled by same parameters as the SM
(also, a quick, effortless, way to estimate SM contributions).

promote $Y_{U,D}$ to spurions, transform under the flavor group $\Rightarrow$ flavor invariant $\mathcal{L}^{\rm SM}$.

D'Ambrosio et. al (02).

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

$$Y_U(\mathbf{3},\bar{\mathbf{3}},1)\,, \qquad Y_D(\mathbf{3},1,\bar{\mathbf{3}})$$

Allow higher dim' flavor invariant new op's.

GIM mechanism (Glashow-Iliopoulos-Maiani, 70) suppression of neutral currents

So far -> Flavor violation (FV) only in CC. What about NC?

Unitarity of CKM implies cancellation of divergencies & absence of flavor changing neutral currents (FCNC).

Gluon & photon protected by gauge univ'; *Z* ??

Defining $\tan\theta_W \equiv g'/g$, the Standard Model gives

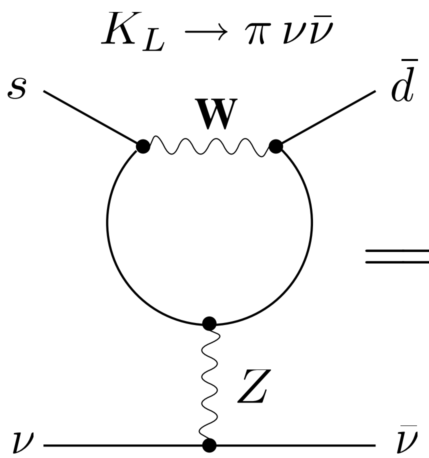
$$Z^\mu = \cos\theta_W W_3^\mu - \sin\theta_W B^\mu .$$

Let us examine, for example, the Z-interactions with d_L in the mass basis:

$$\begin{aligned} -\mathcal{L}_Z &= \frac{g}{\cos\theta_W}\left(-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W\right)\overline{d_{Li}}\gamma^\mu (V_{dL}^\dagger V_{dL})_{ij} d_{Lj} Z_\mu \\ &= \frac{g}{\cos\theta_W}\left(-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W\right)\overline{d_{Li}}\gamma^\mu d_{Li} Z_\mu . \end{aligned}$$

We learn that the neutral current interactions remain universal

GIM mechanism, SM 1-loop example



$$\Longrightarrow \quad V_{is} \left[\int d^4 k \, \frac{k^2}{(k^2 - m_i^2)^2} \frac{1}{k^2 - M_W^2} \right] V_{id}^* = \left(V^\dagger \, \mathrm{diag}[f(m_i^2)] \, V \right)_{12}$$

(i) Div' part is m_i indep' $\Rightarrow 0$

(ii) Hard GIM: leading contribution suppressed by $V_{is} V_{id}^* \Delta m_{ij}^2$

We learn that the neutral current interactions remain universal in the mass basis and there are no additional flavor parameters in their description. This situation goes beyond the Standard Model to all models where all left-handed quarks are in $SU(2)_{\mathrm{L}}$ doublets and all right-handed ones in singlets.

MFV & GIM

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Allow higher dim’ flavor invariant new op’s.

Effective field theory of MFV

The only source of flavor & CPV is due to the SM Yukawas.

$Y_U Y_U^\dagger$ & $Y_D Y_D^\dagger$ transform as $\mathbf{8+1}$ of the $U(3)_Q$ flavor group

and $Q_L^i(\mathbf{3},1,1)$, $U_R^i(1,\mathbf{3},1)$, $D_R^i(1,1,\mathbf{3})$.

After symm' breaking useful to consider the approx' limit

$$\mathcal{G}^{\rm SM} = U(3)_{Q^u} \times U(3)_{Q^d} \times U(3)_U \times U(3)_D$$

$$\text{Fields}: \ U_L(\mathbf{3},1,1,1), D_L(1,\mathbf{3},1,1), U(1,1,\mathbf{3},1), D(1,1,1,\mathbf{3})$$

$$\text{Spurions}: \quad (\mathbf{3},\bar{\mathbf{3}},1,1), Y_U(\mathbf{3},1,\bar{\mathbf{3}},1), Y_D(1,\mathbf{3},1,\bar{\mathbf{3}})$$

GIM mechanism & $SU(3)_{Qu}$ x $SU(3)_{Qd}$

In term of spurions, $\bar{d}_L^i\,(g_2^Z)^2_{ij}\,d_L^j$ is flavor trivial.

Leading contributions to neutral currents (NCs)

$$\bar{d}_L^i\, g_2^{ij} \left(Y_U Y_U^\dagger\right)_{jl} g_2^{lk}\, d_L^k$$

Highly suppressed, at LO need to go through the 3rd gen'. ($y_t^2 V_{\rm CKM}^{ti} V_{\rm CKM}^{*\,tj}$)

Within the SM flavor changing NCs (FCNCs) are highly suppressed => good probe of new physics (NP).

Effective field theory of MFV

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$Y_U Y_U^\dagger$ & $Y_D Y_D^\dagger$ transform as **8+1** of the $U(3)_Q$ flavor group and $Q_L^i(\mathbf{3},1,1)$, $U_R^i(1,\mathbf{3},1)$, $D_R^i(1,1,\mathbf{3})$.

Thus $O_1^{ij} = [\bar{Q}_L^i[a(Y_U Y_U^\dagger)_{ij} + b(Y_D Y_D^\dagger)_{ij}]Q_L^j]^2$ is $U(3)_Q$ invariant.

The amount of flavor violation is calculated via setting the Y's to their observed "background" value.

Down quark flavor violation is described in their mass basis:

$$O_1^{ij,d} = \{\bar{D}_L^i[\tfrac{a}{v^2} V_{\mathrm{CKM}}\,\mathrm{diag}(m_{u^i}^2) V_{\mathrm{CKM}}^\dagger]_{ij} + \tfrac{b}{v^2}\mathrm{diag}(m_{d^i}^2)]D_L^j\}^2$$

CKM controls flavor & CPV

no flavor conversion.

MFV, estimation of amplitudes, SM approx' sym'

$$O_1^{ij,d} = \{\bar{D}_L^i[\tfrac{a}{v^2} V_{\rm CKM}\,{\rm diag}(m^2_{u^i}) V^\dagger_{\rm CKM}]_{ij} + \tfrac{b}{v^2}\cancel{{\rm diag}}(m^2_{d^i})]D_L^j\}^2$$

In most cases we can use $m^2_{u^i,d^i} \sim (0,0,m^2_{t,b})$

Thus, $[V_{\rm CKM}\,{\rm diag}(m^2_{u^i}/v^2)V^\dagger_{\rm CKM}]_{ij} \sim y_t^2 V_{ti} V^*_{tj}$

For $B_{d,s}$ system: $\left(\mathcal{H}_{\rm eff}^{\Delta B=2}\right)^{\rm MFV}_{O_1^{bd,s}} \sim (\bar{b}_L\gamma^\mu d_L, s_L)^2 (V_{tb}V^*_{td,s})^2/\Lambda^2_{\rm MFV}$

Ex. $B_{d,s}$ mass difference, $\Delta m_{d,s}$: $x_{d,s} \equiv \dfrac{(\Delta M)_{B_{d,s}}}{\Gamma_{B_{d,s}}} = \dfrac{2|M_{12}|_{B_{d,s}}}{\Gamma_{B_{d,s}}}$

$$2m_B|M_{12}| = |\langle \bar{B}^0|\left(\mathcal{H}_{\rm eff}^{\Delta B=2}\right)^{\rm MFV}_{O_1^{bd}}|B^0\rangle| = \frac{2}{3}B_B(\mu)F_B^2 m_B^2 \times |V_{tb}V^*_{td}|^2/\Lambda^2_{\rm MFV}$$

Homework: write the leading RR & LR up type flavor violating higher dim' operators, within MFV.

MFV, connection with SM

Can use same method to estimate SM contributions!

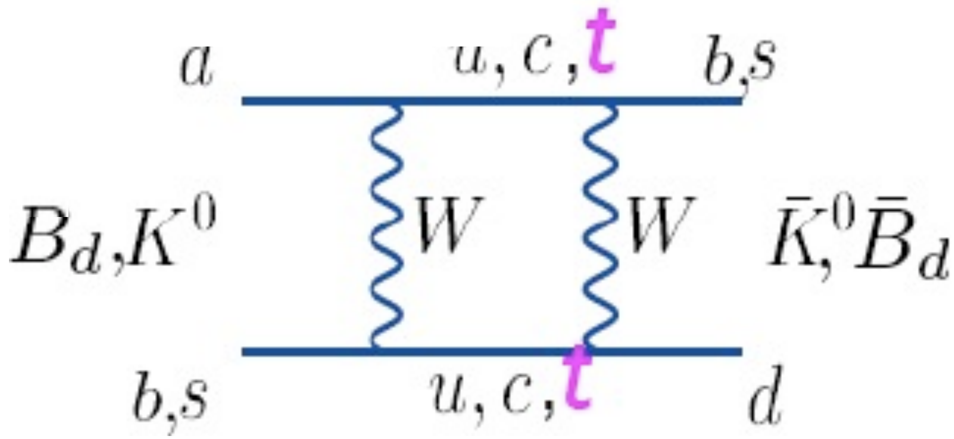
The SM structure is identical,

say for $B_{d,s}$ system: $\left(\mathcal{H}_{\text{eff}}^{\Delta B=2}\right)_{O_1^{bd,s}}^{\text{SM}} \sim (\bar{b}_L \gamma^\mu d_L, s_L)^2 (V_{tb} V_{td,s}^*)^2 / \Lambda_{\text{SM}}^2$

What is Λ_{SM}^2?

Can "guesstimate":

$$\frac{1}{\Lambda_{\Delta\text{F}=2}^2} \approx \frac{M_W^2 G_F^2}{16\pi^2}$$



Factor of 2 smaller than the LO result, $\Lambda_{\text{SM}}^{\Delta F=2} \approx 4.4\,\text{TeV}$

MFV & the SM contributions

Similarly can be applied to CPV in Kaon system, ϵ_K:

$$\left(\mathcal{H}_{\rm eff}^{\Delta s=2}\right)_{O_1^{sd}} = \left(\bar{s}_L \gamma^\mu d\right)^2 \left(V_{ts} V_{td}^*\right)^2 / \Lambda_{\rm MFV}^2$$

Agreement between Exp' data & SM implies: $\Lambda^{\rm SM}_{\Delta \rm F=2} \lesssim \Lambda^{\rm MFV}_{\Delta \rm F=2}$

So we can estimate bounds for CP conserving [CPV] $(LL)^2, (RR)^2$ operators via $\Lambda^{K,B_{d,s}} \gtrsim \Lambda_{\rm SM} \times (0.1\lambda^{-5}, \lambda^{-3}, \lambda^{-2})\, [(2\lambda^{-5}, 4\lambda^{-3}, \lambda^{-2})]$

Thus, MFV protection is mostly due to "CKM" suppression.

For some $LLRR$, $\Delta B, S = 2$, operators $\mathcal{O}(10, 100)$ enhancement is obtained!

General MFV, non-linear MFV (NLMFV)

Kagan, GP, Volansky & Zupan (09).

If time permit we shall answer last 2 questions.

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

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

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

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 from large eigenvalues, expand linearly (non-linearly) the small (large) flavor breaking.

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

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

broken generators

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

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

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

The formalism

Magic, 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 $\mathcal{H}^{\rm SM}$.

NLMFV described via requiring solely $\mathcal{H}^{\rm SM}$-invariance!

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

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

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

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

Predictions

LO flavor violation come from the following operators:

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 $\overline{\tilde{d}_R^{(2)}}\phi_d^\dagger\chi\tilde{b}_R.$

Kaon phys.: $\overline{\tilde{d}_L^{(2)}}\phi_u\phi_u^\dagger\tilde{d}_L^{(2)}, \quad \overline{\tilde{d}_L^{(2)}}\chi\chi^\dagger\tilde{d}_L^{(2)}.$

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

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

Kaon: contributions from charm & top are decorrelated.

Generically, CPV in B_s bounds on in B_d system .

(without light RH currents they are fully correlated)

Generically, large CPV in D & top FCNC (also in LMFV).

(more in the homework)

Flavor Diagonal Information

Flavor at the LHC

If no NP probed t-FCNC & D mixing could be at the frontier, we have just entered the isospin up flavor precision era.

However, what if new particles which couple SM fermions discovered ?
These may carry microscopical info' flavor dynamics.

We can look at two entities:
(i) Spectrum or strength of flavor diagonal couplings.
(ii) Flavor conversion info'.

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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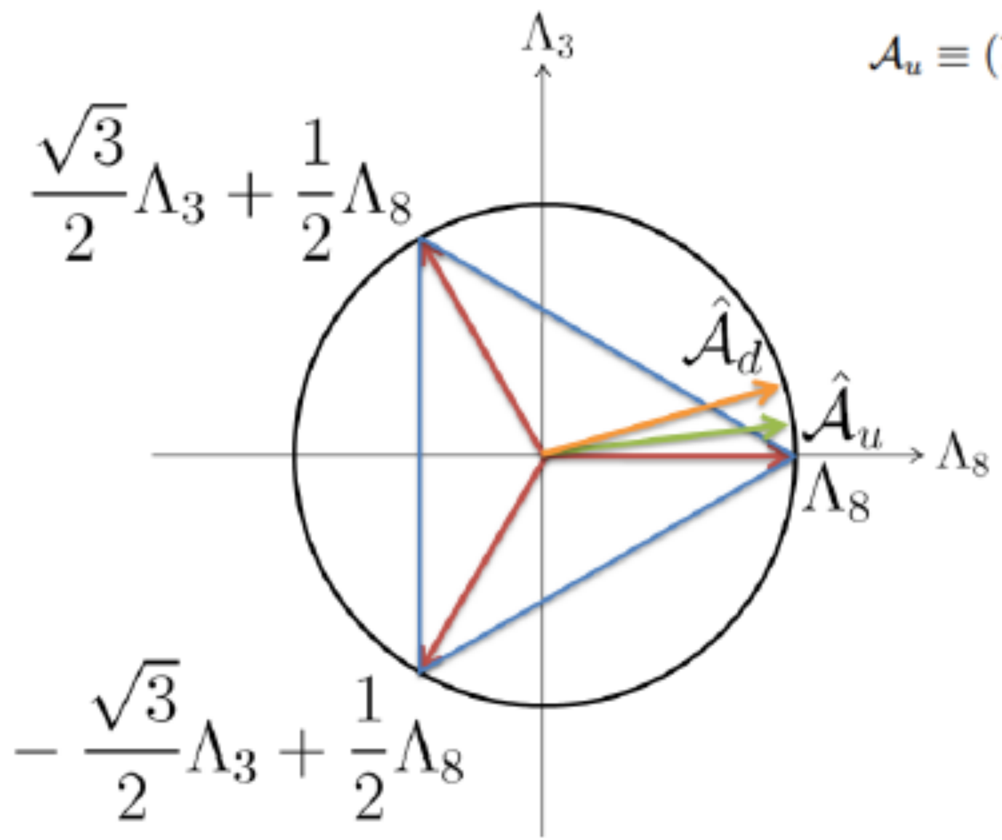

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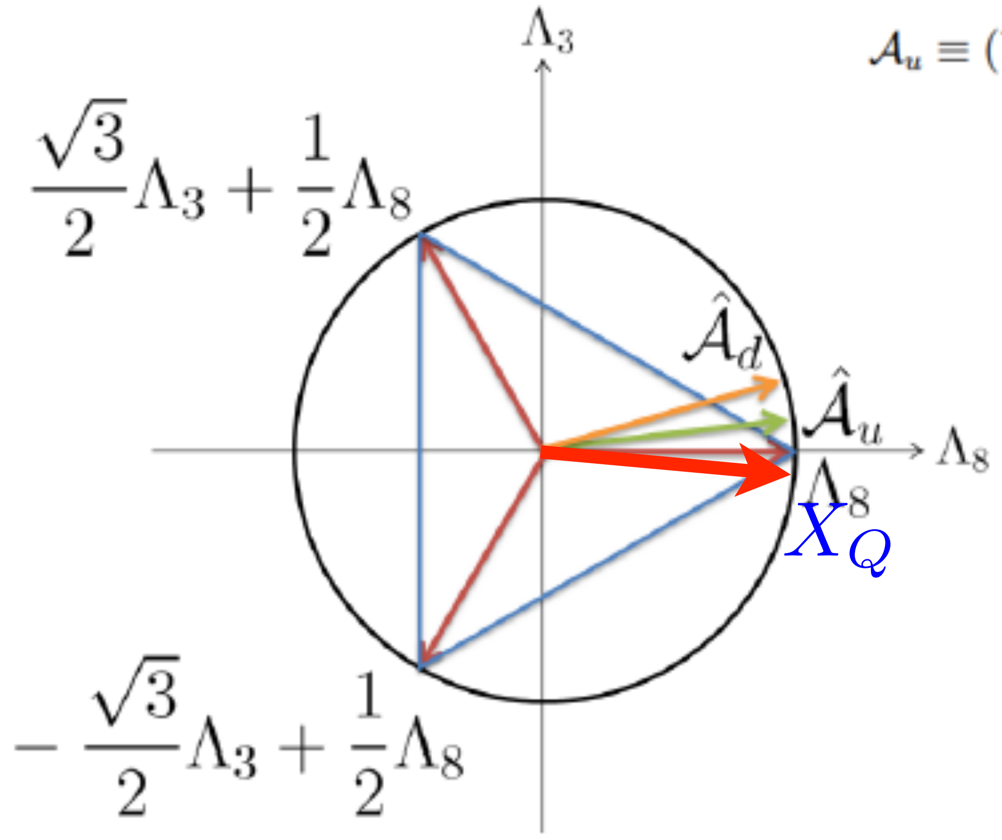

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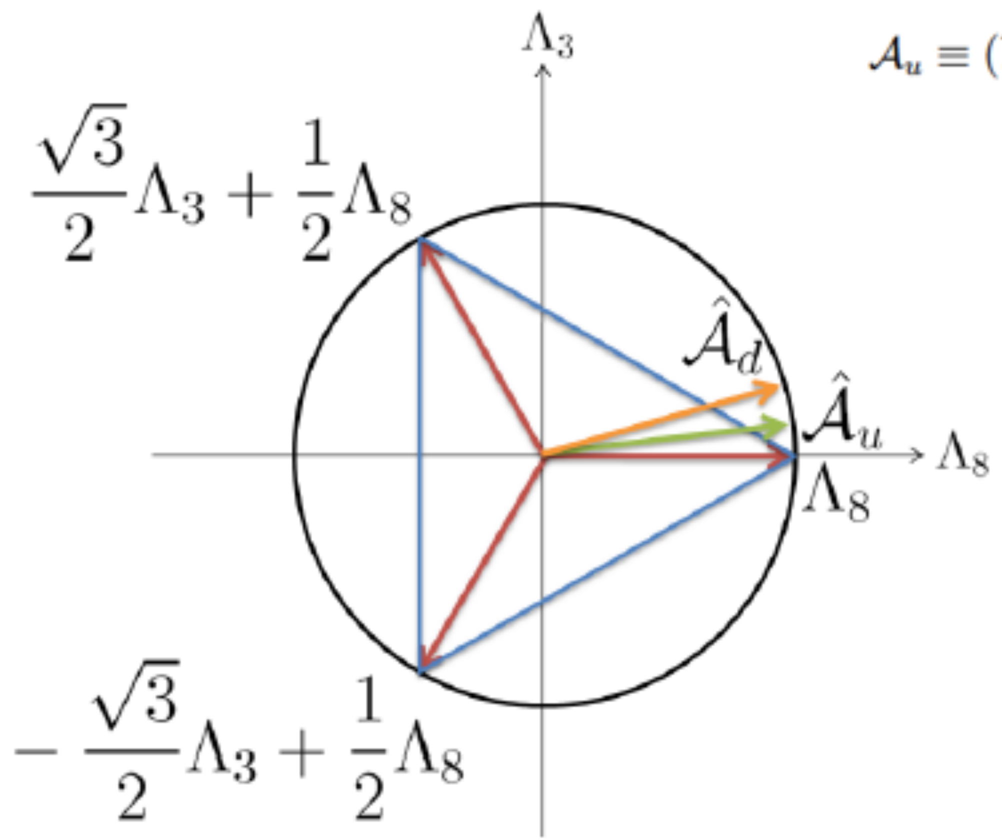

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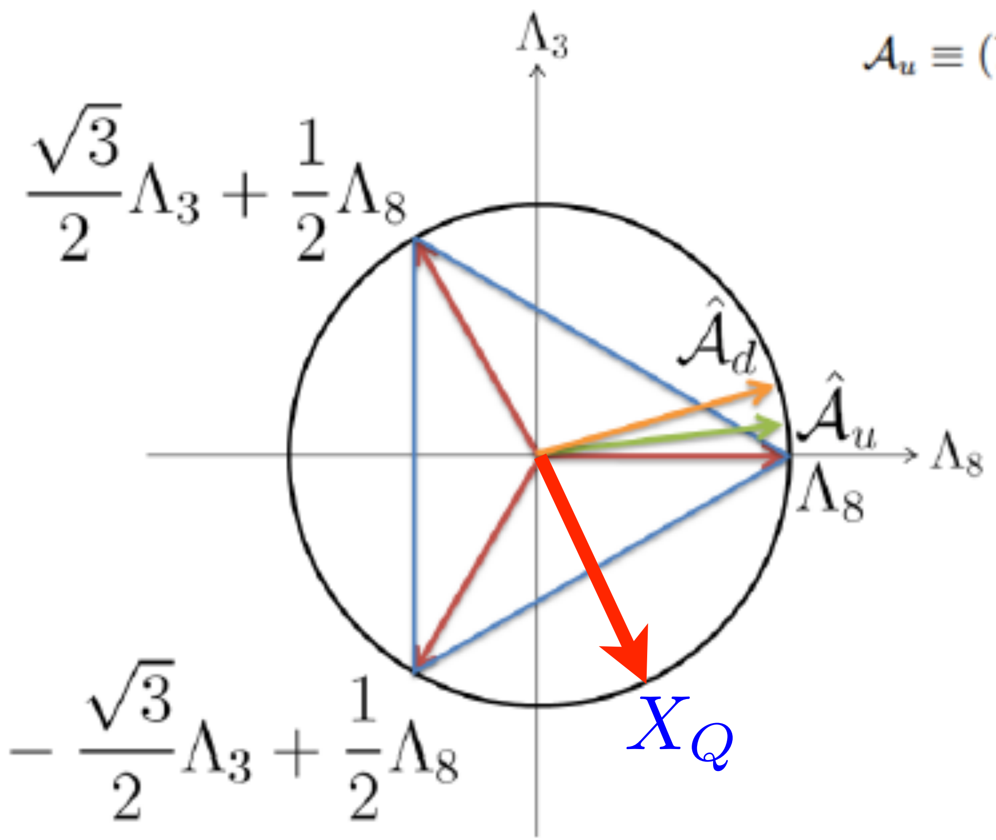

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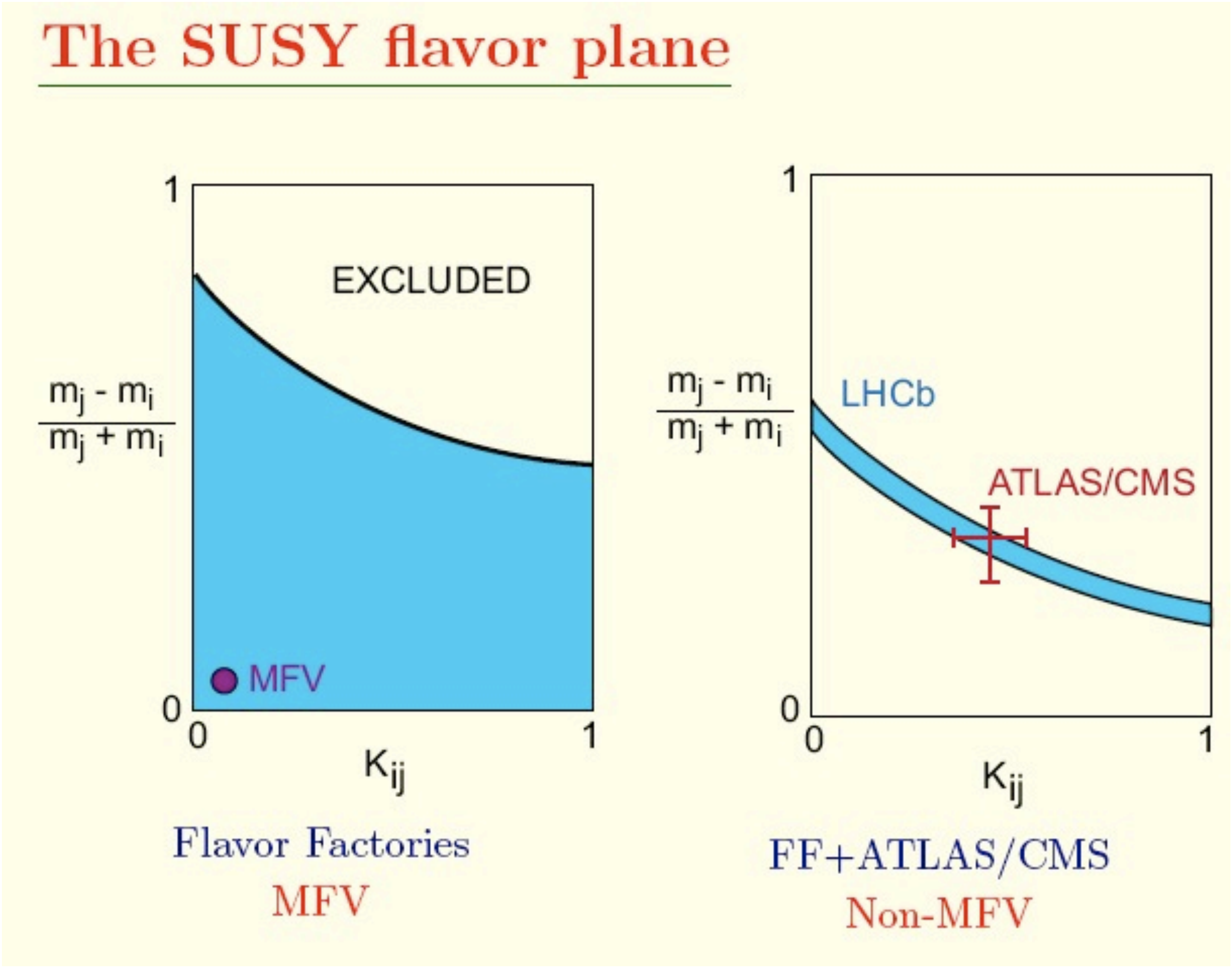
$$\Lambda_3 = \frac{1}{\sqrt{2}}\mathrm{diag}(1,-1,0),$$

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

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

Illustration



Nir, Planck 2009

Summary

The SM flavor sector is unique

Yields sharp predictions

All so far were verified

Unless NP is ~ MFV or maybe aligned?

Up type FCNC measurements could hold the key

Electroweak & flavor precision tests => NP has non-generic structure

Cannot be the end of the story => baryogenesis

Probably not the end of the story => hierarchy problem

End of the 5th lecture