Journées jeunes chercheurs 2013:

La physique de la saveur dans le MSSM: Un tour d'horizon

Superviseurs:

- Fawzi Boudjema
- Björn Herrmann

Yannick STOLL

OUTLINE:

I. Flavor physics within the Standard model

II. Physic beyond the standard model: Motivations

III. Flavor violation within the MSSM

IV. A SU(5) footprint within the up squark sector

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What is Flavor exactly?

Standard model: Standard theory of Particle physics:

Based on the gauge group $U(1)_Y \times SU(2)_L \times SU(3)_C$

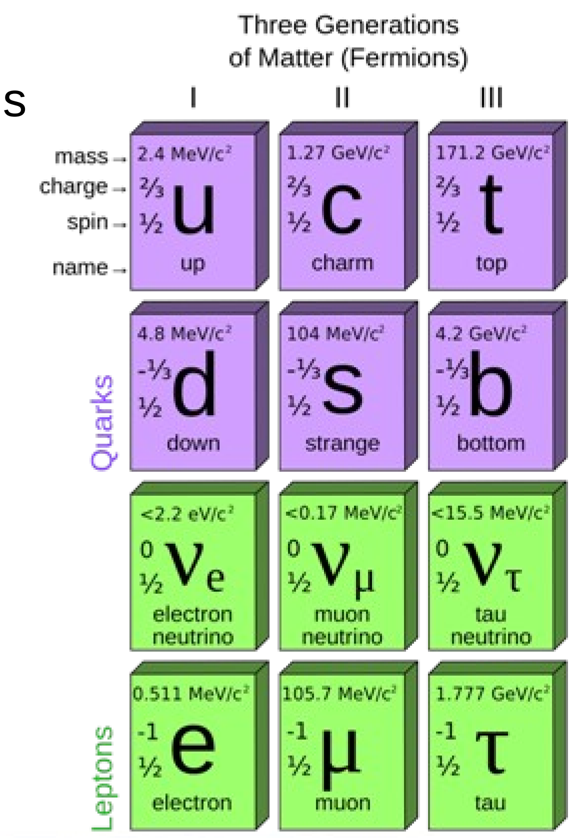
3 representations of the SM gauge group: $Q(3,2)_{\frac{1}{6}}, U(3,1)_{\frac{2}{3}}, D(3,1)_{-\frac{1}{3}}$

Flavors → 3 replications in the SM of these 3 representations

Flavor physics: Study of the interactions between these different families

Flavor dynamic described by Yukawas Interactions:

$$\mathcal{L}^{\mathrm{F}} = \overline{q^i} \not{D}\, q^j \delta_{ij} + (Y_U)_{ij} \overline{Q^i} U^j H_U + (Y_D)_{ij} \overline{Q^i} D^j H_D + \mathrm{h.c.}$$



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Flavor physics within the Standard model:

Two basis are used:

- Weak eigenstates
- Mass eigenstates: Yukawas diagonal

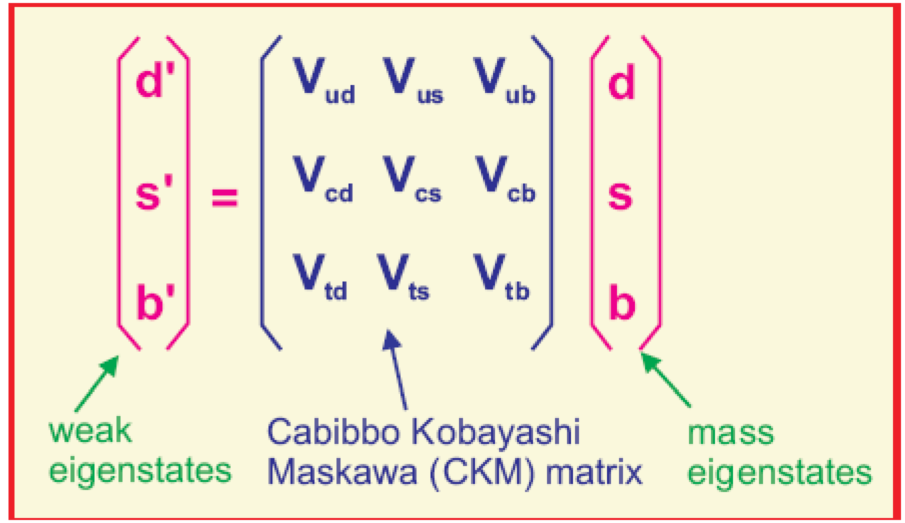
Two unitary transformations needed:

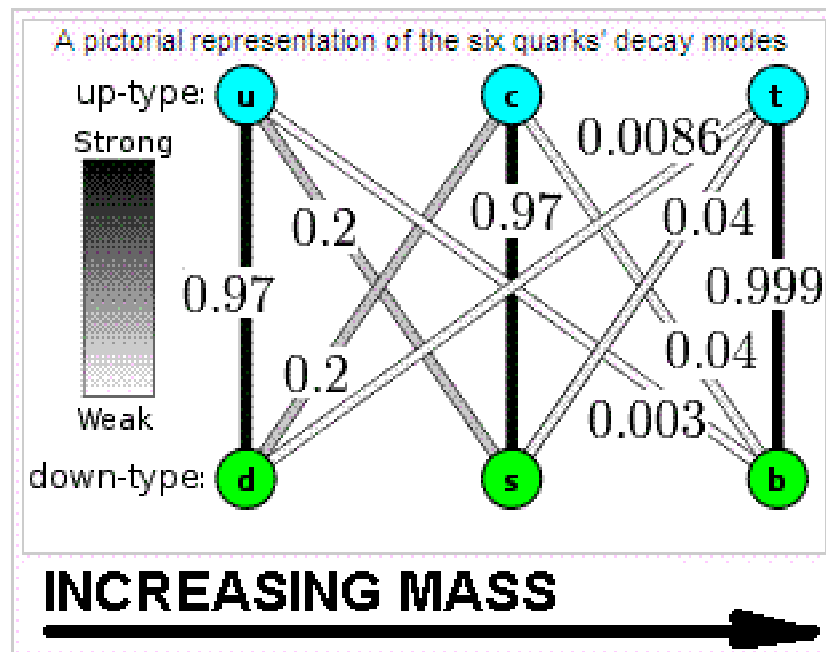
$$Y_U \to V_U Y_U V_U^\dagger \qquad Y_D \to V_D Y_D V_D^\dagger$$

CKM Matrix → Mismatch between V_U, V_D

$$V_{CKM} = V_U V_D^\dagger$$

- 3 mixing angles
- 1 CP violation phase
- Only source of flavor violation in the SM





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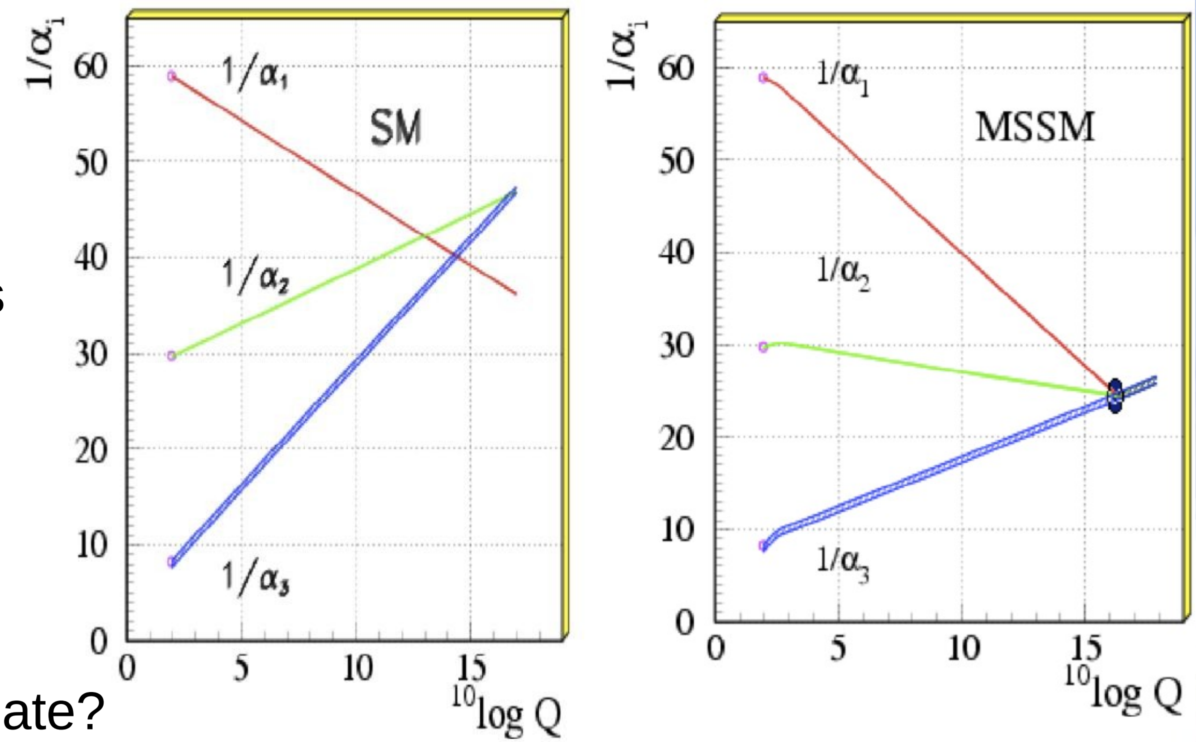
Beyond the SM: An Invitation 1/2:

The Standard Model:

- General Framework of particle physics since more than 30 years
- Theory well establish experimentally (EWPT: G_F, ρ...)

But several questions arise:

- The Gauge Hierarchy Problem
- What about a Dark Matter Candidate?
- Gauge coupling Unification
- Baryogenesis
- Flavor puzzle



One Example:

SM: $1/\alpha_1, 1/\alpha_2, 1/\alpha_3$ same order at high scale
In Reality they disagree by more than 7σ

MSSM: Quasi-Perfect Match at $\sim 10^{16}$GeV
Encourage the quest for a unified theory

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Beyond the SM: An Invitation 2/2:

The (SM) Flavor Puzzle:

$Y_t \sim 1, Y_c \sim 10^{-2}, Y_u \sim 10^{-5}$

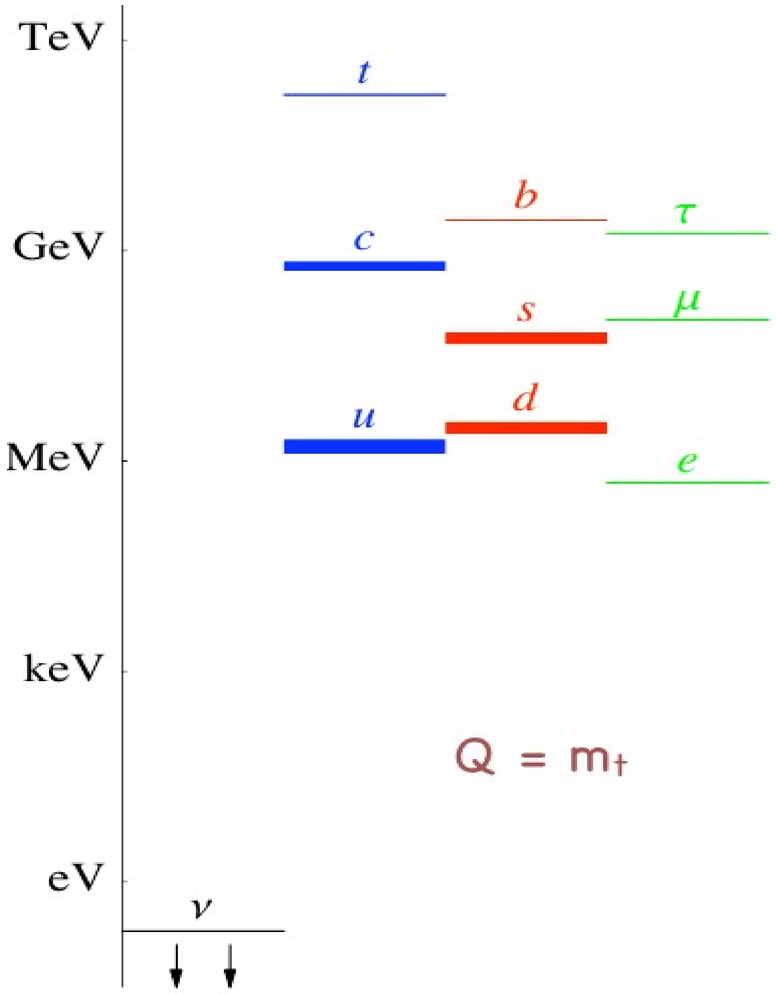
$Y_b \sim 10^{-2}, Y_s \sim 10^{-3}, Y_d \sim 10^{-4}$

$Y_\tau \sim 10^{-2}, Y_\mu \sim 10^{-3}, Y_e \sim 10^{-6}$

$|V_{us}| \sim 0.2, |V_{cb}| \sim 0.04, |V_{ub}| \sim 0.004, \delta_{KM} \sim 77°$

- For Comparison : $g_s \sim 1, g \sim 0.6, g' \sim 0.3, \lambda \sim 1$
- The SM flavors parameters have structure: smallness and hierarchy

Why ? : The SM flavor puzzle



All proposals are welcomed to:

stoll@lapth.cnrs.fr

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What is exactly SUSY?

- A Symmetry linking Bosons and Fermions:

Two New Spinorials Generators:

$$\left\{Q_a, Q_b^\dagger\right\} = (\sigma^\mu)_{ab} P_\mu$$

$$Q|boson> = |fermion>$$

- Introduce a new superpartner of same mass and of opposite statistic for each SM particle

- No Superpartner observed so far:

- If SUSY is realized in Nature, it has to be a broken symmetry at the EW scale
  Breaking spontaneously SUSY is NO easy task

► Explicit SB: Only via positive dimensions mass terms namely soft breaking

MSSM:

- Simplest SUSY extension of the SM
- At total (SM+MSSM), 124 free parameters

BUT

- True SUSY breaking mechanism unknown
- GUT theories reduces the number of free parameters

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MSSM: particle content:

SM Particles		Spin		Spin		Superpartners
Quarks	$(u_L \quad d_L)$	$1/2$	Q	0	$(\tilde{u}_L \quad \tilde{d}_L)$	Squarks
	$u_R^\dagger$	$1/2$	$\bar{u}$	0	$\tilde{u}_R^*$	
	$d_R^\dagger$	$1/2$	$\bar{d}$	0	$\tilde{d}_R^*$	
Leptons	$(\nu \quad e_L)$	$1/2$	L	0	$(\tilde{\nu} \quad \tilde{e}_L)$	Sleptons
	$e_R^\dagger$	$1/2$	$\bar{e}$	0	$\tilde{e}_R^*$	
Higgs	$(H_u^+ \quad H_u^0)$	0	H_u	$1/2$	$(\tilde{H}_u^+ \quad \tilde{H}_u^0)$	Higgsinos
	$(H_d^0 \quad H_d^-)$	0	H_d	$1/2$	$(\tilde{H}_d^0 \quad \tilde{H}_d^-)$	
Gluon	g	1		$1/2$	$\tilde{g}$	Gluino
W bosons	$W^0, W^\pm$	1		$1/2$	$\tilde{W}^0, \tilde{W}^\pm$	Winos
B boson	B^0	1		$1/2$	$\tilde{B}^0$	Bino
Graviton	G	2		$3/2$	$\tilde{G}$	Gravitino

The New physic flavor puzzle 1/2:

See Y Nir presentation:
Understanding flavor and CP violation

The SM must certainly be an Effective field theory:

We don't care about the UV dynamics:

- NP effects taking into account through NR operators (dim > 4)
- Introduce a new scale Λ_{NP} to which the SM is valid.

For example, we expect the dimension 6 operator:

$$\frac{z_{sd}}{\Lambda_{NP}^2}(\bar{d}_L\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{NP}^2}(\bar{c}_L\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{NP}^2}(\bar{d}_L\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{NP}^2}(\bar{s}_L\gamma_\mu b_L)^2$$

Will introduce new contribution to the neutral meson mixing:

$$\frac{\Delta m_B}{m_B} \sim \frac{f_B^2}{3} \times \frac{z_{bd}}{\Lambda_{NP}^2}$$

The New physic flavor puzzle 2/2:

For $z_{ij} \sim 1$:

$$\Lambda_{\rm NP} \gtrsim \begin{cases} 1 \times 10^4 \; TeV & \epsilon_K \\ 1 \times 10^3 \; TeV & \Delta m_K \\ 9 \times 10^2 \; TeV & \Delta m_D \\ 9 \times 10^2 \; TeV & S_{\psi K} \\ 4 \times 10^2 \; TeV & \Delta m_B \\ 7 \times 10^1 \; TeV & \Delta m_{B_s} \end{cases}$$

For $\Lambda_{NP} \sim 1\text{TeV}$:

$$\begin{array}{rcl} \mathcal{I}m(z_{sd}) & \lesssim & 6 \times 10^{-9} \\ z_{sd} & \lesssim & 8 \times 10^{-7} \\ z_{cu} & \lesssim & 1 \times 10^{-6} \\ \mathcal{I}m(z_{bd}) & \lesssim & 1 \times 10^{-6} \\ z_{bd} & \lesssim & 6 \times 10^{-6} \\ z_{bs} & \lesssim & 2 \times 10^{-4} \end{array}$$

The flavor structure of NP@TeV must be highly non generic:

→ New Physic flavor puzzle

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Flavour Violation: MSSM case

Arise as in the SM case from a mismatch between the rotation in the up and down squark sectors:

- Matter fields-->Weyl Spinors, need two 6X6 unitary matrix
- In the Up type-Sector:

$$\mathcal{M}^2_{\tilde{u}} = \begin{pmatrix} \mathcal{M}^2_{\tilde{u},LL} & \left(\mathcal{M}^2_{\tilde{u},RL}\right)^\dagger \\ \mathcal{M}^2_{\tilde{u},RL} & \mathcal{M}^2_{\tilde{u},RR} \end{pmatrix}$$

With for example:

Soft term

$$\left(M^2_{\tilde{u}LL}\right)_{\alpha\beta} = M^2_{Q_u\alpha\beta} + \left[\left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right)\cos 2\beta m_Z^2 + m^2_{u_\alpha}\right]\delta_{\alpha\beta}$$

Mass eigenstates given by:

$$diag\left(m^2_{\tilde{u}_1}, m^2_{\tilde{u}_2}, m^2_{\tilde{u}_3}, m^2_{\tilde{u}_4}, m^2_{\tilde{u}_5}, m^2_{\tilde{u}_6}\right) = \mathcal{R}^{\tilde{u}} \mathcal{M}^2_{\tilde{u}} \mathcal{R}^{\tilde{u}\dagger}$$

$$\left(\tilde{u}_1, \tilde{u}_2, \tilde{u}_3, \tilde{u}_4, \tilde{u}_5, \tilde{u}_6,\right)^T = \mathcal{R}^{\tilde{u}}\left(\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R\right)$$

6X6 unitary (up-type) rotation matrix

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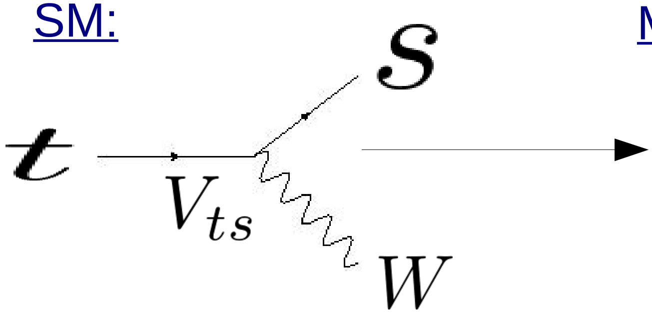
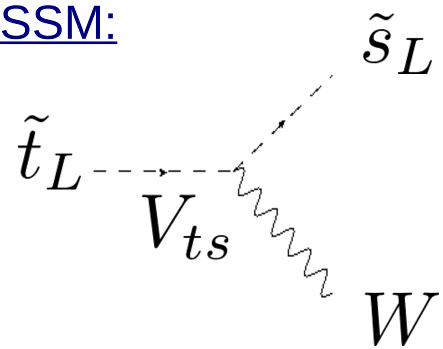
The Minimal flavor violation hypothesis:

The SM FCNC protected,
GIM Mechanism:

SM:



MSSM:



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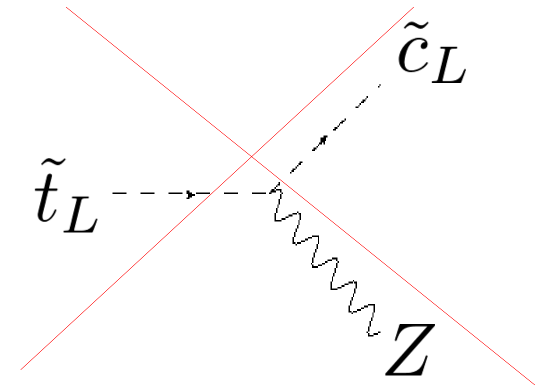

MFV hypothesis:

- All flavor violation comes from the Yukawas
- Practical way of dealing with flavor constraints
- All soft-breaking terms are diagonal
- Very popular hypothesis but pessimistic

Schematically:

$$M^2_{\tilde{u}} = \begin{pmatrix} V_{CKM} M^2_Q V^\dagger_{CKM} & (A^2_U)^\dagger \\ A^2_U & M^2_U \end{pmatrix}$$

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A SU(5) footprint in the up-sector 1/2 :

SU(5): Most simple extension of the SM gauge group

$$M^2_{\tilde{u}} = \begin{pmatrix} V_{CKM} M^2_Q V^\dagger_{CKM} & (A^2_U)^\dagger \\ A^2_U & M^2_U \end{pmatrix}$$

$$A_U \ : \ \text{Soft trilinear parameter}$$

If SU(5) holds at GUT or lower scale than: $A_U = A^t_U$ @ high scale

- This relations is not too much spoiled by RGE flow:
- Study mixing between the second and third generation

RGE induced asymmetry at the weak scale:

$$\Delta^{EW} a^{32}_u \equiv \frac{a^{32}_u - a^{23}_u}{\frac{1}{6}\sum_{i=1}^{6} m_{\tilde{u}_i}} = f(a^{32/23}_u, a^{32/23}_d @GUTscale)$$

Should be “small” in order to asses the SU(5) hypothesis

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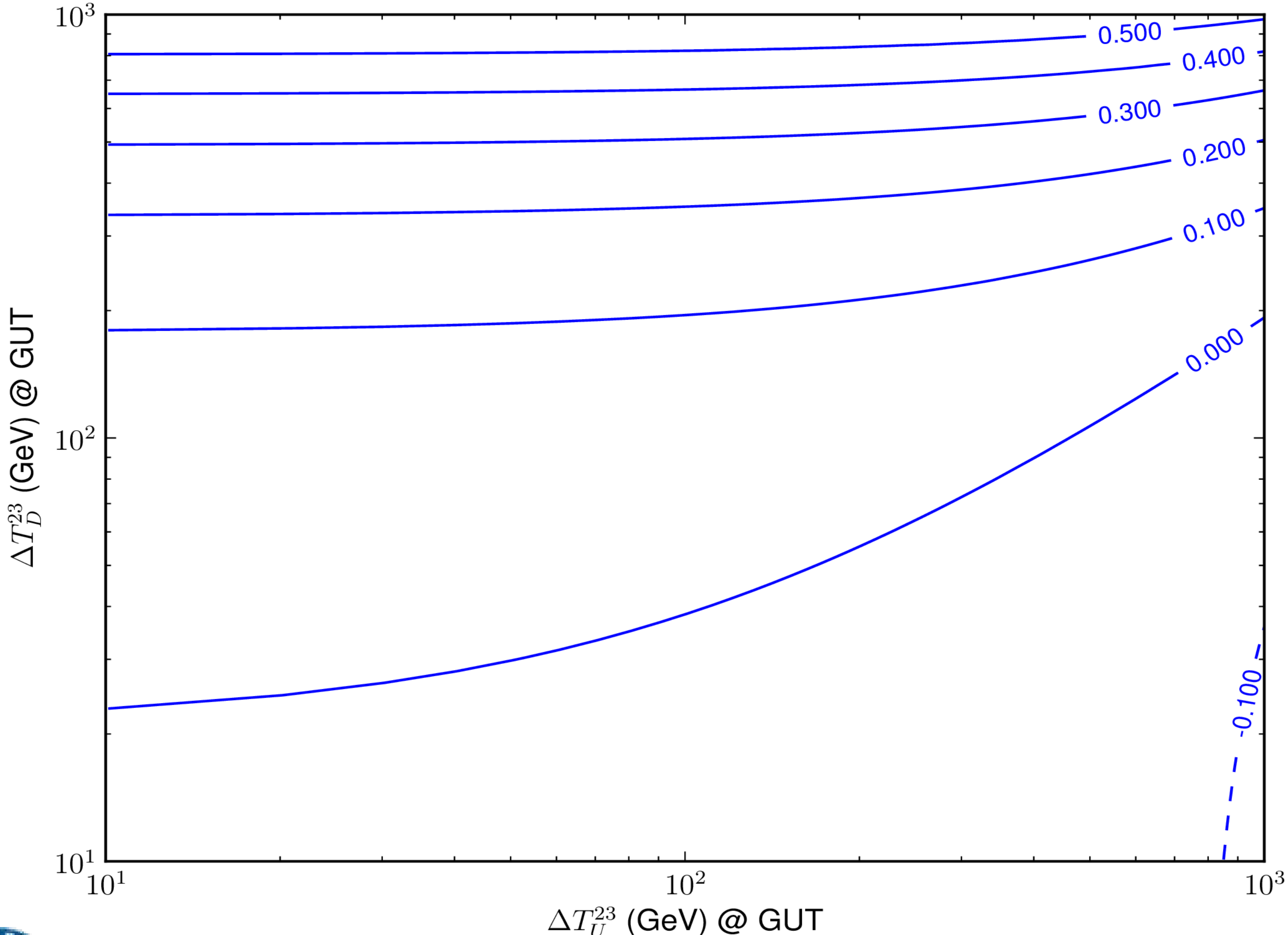
A SU(5) footprint in the up-sector 2/2 :



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- S Martin : A Supersymmetry Primer

Flavor physics:

- O Gedalia & G Perez : TASI 2009 Lectures – Flavor Physics
- Isidori *et al :* Minimal flavor violation: an effective field theory *approach*

NMFV:

- Herrmann *et al* : Flavour violating bosonic squark decays at LHC: arXiv:1212.468
- Calibbi *et al* : Gauge Mediation beyond Minimal Flavor Violation: arXiv: 1304.1453

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QUESTIONS?

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Non minimal flavor violation: General Idea:

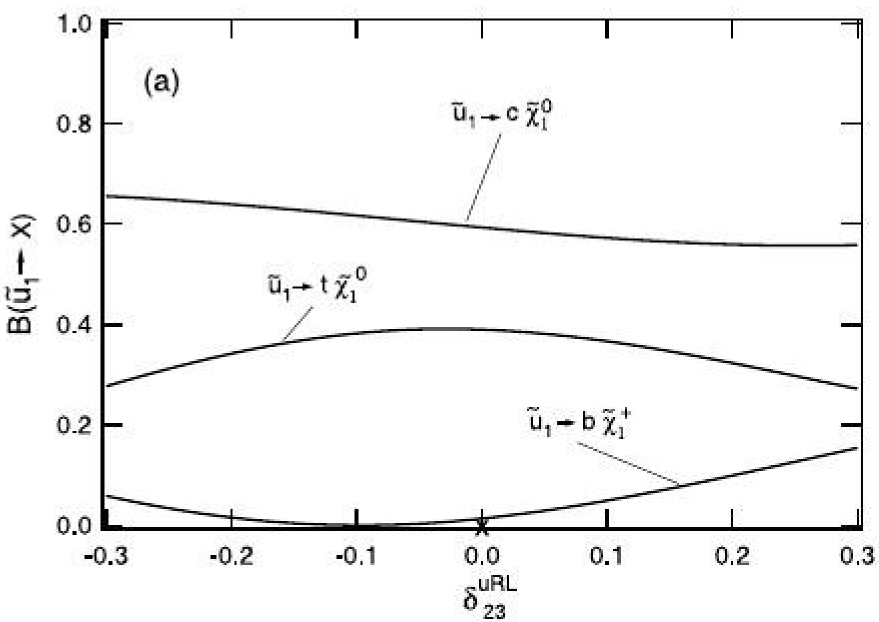
- Flavor violation beyond Yukawas couplings
- Opens up new sources of flavor violation
- Maybe relevant for LHC pheno and/or Dark matter searches

$$\mathcal{M}^2_{\tilde u} = \left(\begin{array}{ccc|ccc}
M^2_{\tilde L_u} & \Delta^{uc}_{\rm LL} & \Delta^{ut}_{\rm LL} & m_u X_u & \Delta^{uc}_{\rm LR} & \Delta^{ut}_{\rm LR} \\
\Delta^{cu*}_{\rm LL} & M^2_{\tilde L_c} & \Delta^{ct}_{\rm LL} & \Delta^{cu*}_{\rm RL} & m_c X_c & \Delta^{ct}_{\rm LR} \\
\Delta^{tu*}_{\rm LL} & \Delta^{tc*}_{\rm LL} & M^2_{\tilde L_t} & \Delta^{tu*}_{\rm RL} & \Delta^{tc*}_{\rm RL} & m_t X_t \\ \hline
m_u X^*_u & \Delta^{uc}_{\rm RL} & \Delta^{ut}_{\rm RL} & M^2_{\tilde R_u} & \Delta^{uc}_{\rm RR} & \Delta^{ut}_{\rm RR} \\
\Delta^{cu*}_{\rm LR} & m_c X^*_c & \Delta^{ct}_{\rm RL} & \Delta^{cu*}_{\rm RR} & M^2_{\tilde R_c} & \Delta^{ct}_{\rm RR} \\
\Delta^{tu*}_{\rm LR} & \Delta^{tc*}_{\rm LR} & m_t X^*_t & \Delta^{tu*}_{\rm RR} & \Delta^{tc*}_{\rm RR} & M^2_{\tilde R_t}
\end{array}\right)$$

A priori, controlled by 24 Independent parameters :

$$\delta^{uLL}_{\alpha\beta} = \frac{M^2_{Q_{\alpha\beta}}}{\sqrt{M^2_{Q_{\alpha\alpha}} M^2_{Q_{\beta\beta}}}}, \delta^{uRR}_{\alpha\beta} = \frac{M^2_{U_{\alpha\beta}}}{\sqrt{M^2_{U_{\alpha\alpha}} M^2_{U_{\beta\beta}}}},$$

$$\delta^{uRL}_{\alpha\beta} = \frac{\left(\frac{v_2}{\sqrt{2}}\right) T_{U\beta\alpha}}{\sqrt{M^2_{U_{\alpha\alpha}} M^2_{U_{\beta\beta}}}}$$



May originate from microscopic dynamics:

- GUT theories
- Flavor symmetries

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