SO(10) SUSY GUTs with family symmetries: the test of FCNCs

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Outline

- **The DR Model:** an SO(10) SUSY GUT with D_3 family symmetry
  - ☺ Top-down approach to the MSSM+ν
  - ☺ Successful fit to quark & lepton masses, CKM & PMNS matrices
- **Including FCNCs:** the only way to test the pattern of SUSY particles' masses & mixings predicted by the model
- **Details on the analysis:** global fit to low-energy observables, FCNCs directly in the χ^2 function

The Model

The model by Dermíšek & Raby (DR) is

- *an SO(10) SUSY GUT*
- *with an additional* $D_3 \times [U(1) \times Z_2 \times Z_3]$ *family symmetry*

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Why SO(10)

- Complete quark-lepton unification: single **16** representation for each family
- Natural inclusion of ν_R in each **16**. See-saw mechanism easily incorporated.
- Can explain the pattern of quark/lepton masses and mixings, through family symmetries or (few) extra fermion multiplets

Dermíšek & Raby
Babu & Barr ('95)
many other authors

Why (discrete) family symmetries

- ✘ Global symmetries: are believed *not* to arise in string theory
- ✘ Local (i.e. gauge) symmetries: typically enhance FCNCs

⇒ Discrete symmetries can arise e.g.

- ☑ as the remnant of spontaneously broken gauge symmetries
- ☑ directly from compactifications in string theory

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Family symmetries: "isospin" example

❶ We know that in SO(10) the $\mathbf{16}_i$ contains the fermions of the *i*-th generation
Let $\{16_1 , 16_2\}$ transform as an *isospin doublet* and 16_3 as a singlet

❷ Then let us introduce:

- **"flavon" fields ϕ:** transform under the "family isospin", are SO(10) singlets
- **Froggatt-Nielsen fields χ:** transform under the "family isospin", are 16's of SO(10)

❸ Now one can build up the following interactions:

Yukawa unification only for 3rd generation fermions

$$\left(\mathbf{16}_{1,2} \cdot [\text{Higgs}] \cdot \chi \;, \quad \mathbf{16}_{1,2} \cdot \phi \cdot \chi \;, \quad \mathbf{16}_{1,2} \cdot \phi \cdot [\text{Higgs}] \cdot \chi \;, \quad \mathbf{16}_{3} \cdot [\text{Higgs}] \cdot \mathbf{16}_{3} \right)$$

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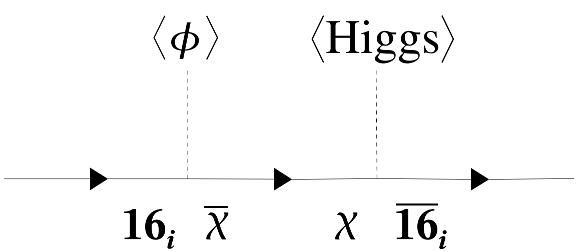
❹ One then **breaks spontaneously** the family symmetry through $\langle \phi \rangle$= vev and **integrates out** the χ, with $M_\chi \approx$GUT scale.

Mass terms for, say, quarks are generated through diagrams like:



$$\overline{q}\, M_q\, q \;\propto\; \overline{q}\, \frac{\langle \phi \rangle}{M_\chi} \langle \text{Higgs} \rangle\, q$$

- FN states implement a sort of "see-saw" mechanism to make quark masses $\ll$ GUT scale
- Quark mass hierarchies are understood in terms of the *sequential* breaking of the family symmetry through $\langle \phi \rangle$= vev

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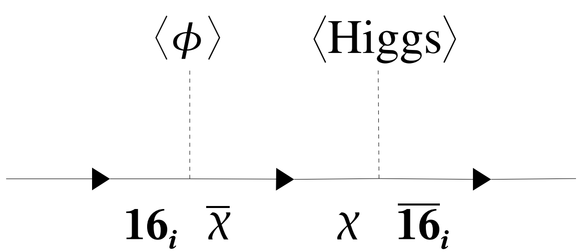

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- Quark mass hierarchies are understood in terms of the *sequential* breaking of the family symmetry through $\langle \phi \rangle$= vev

☑ The DR model realizes the above mechanism with the smallest (non-Abelian) *discrete analogue* of "isospin", i.e. the D_3 group.

With 11 family-symmetry (real) parameters, it successfully describes quark & lepton masses and mixings.

With a total of 24 parameters (less than in the SM+ν) the whole MSSM+ν parameter space is fixed.

It is worthwhile to perform a more detailed analysis of the DR model.

The aim is to *test* the SUSY mass spectrum and mixings predicted by the model.

The SUSY spectrum will affect flavor-changing neutral current (FCNC) processes.

Albrecht, Altmannshofer, Buras, D.G., Straub, JHEP '07

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One step back:
how a GUT-scale model is tested at the EW scale.

The DR model is specified in terms of

- coupling and unified scale: α_G , M_G
- soft SUSY-breaking params at M_G
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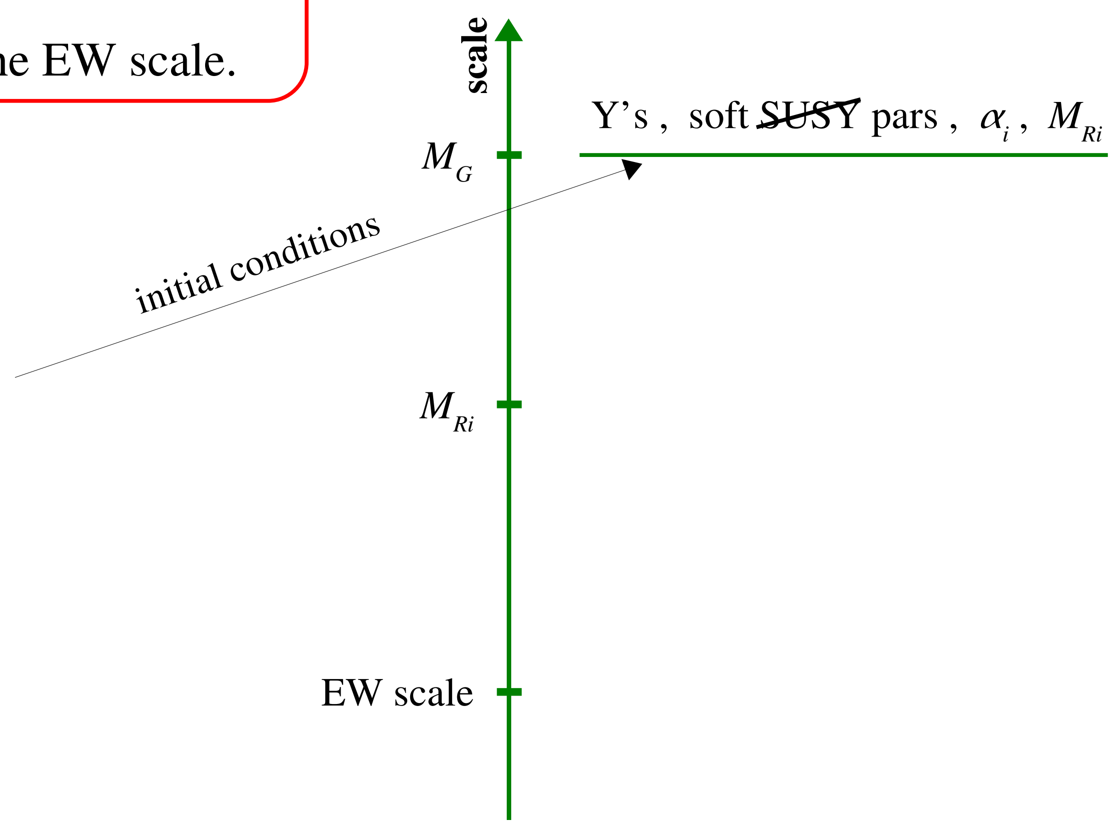

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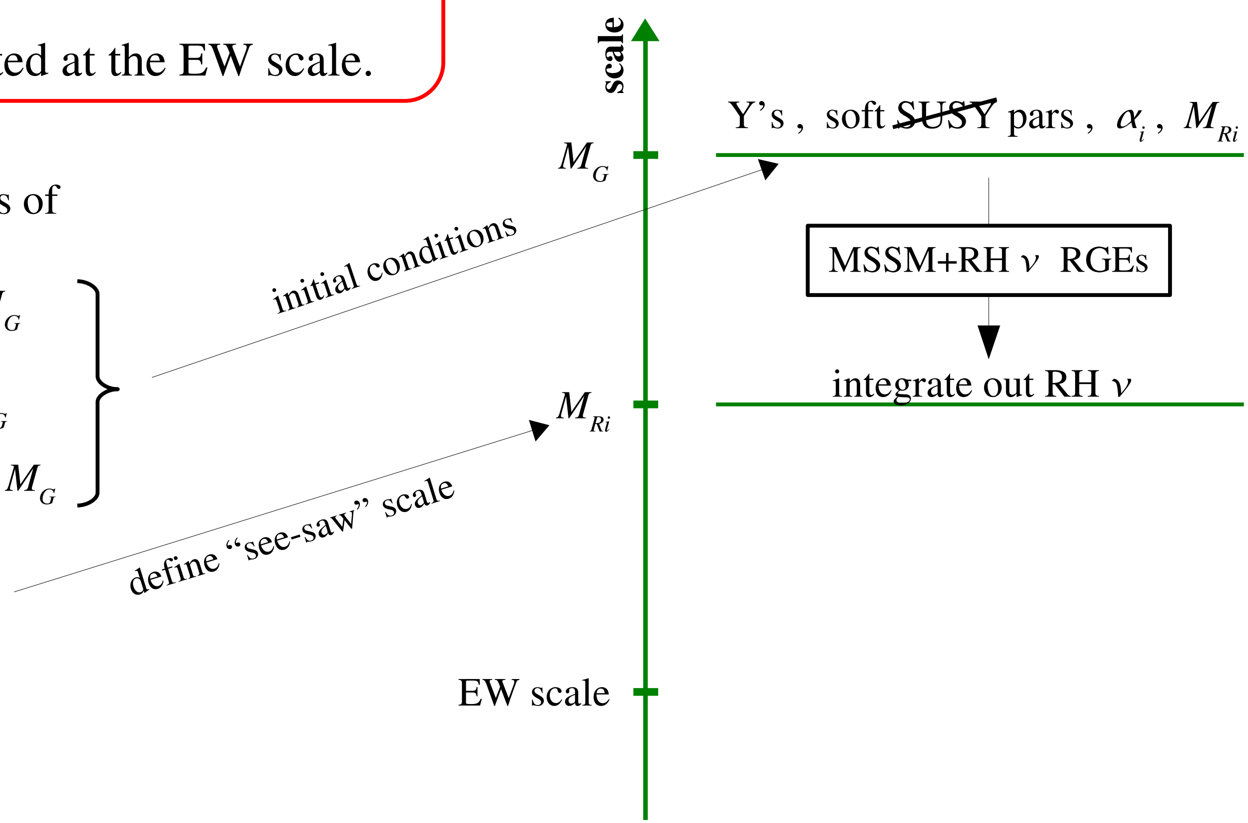

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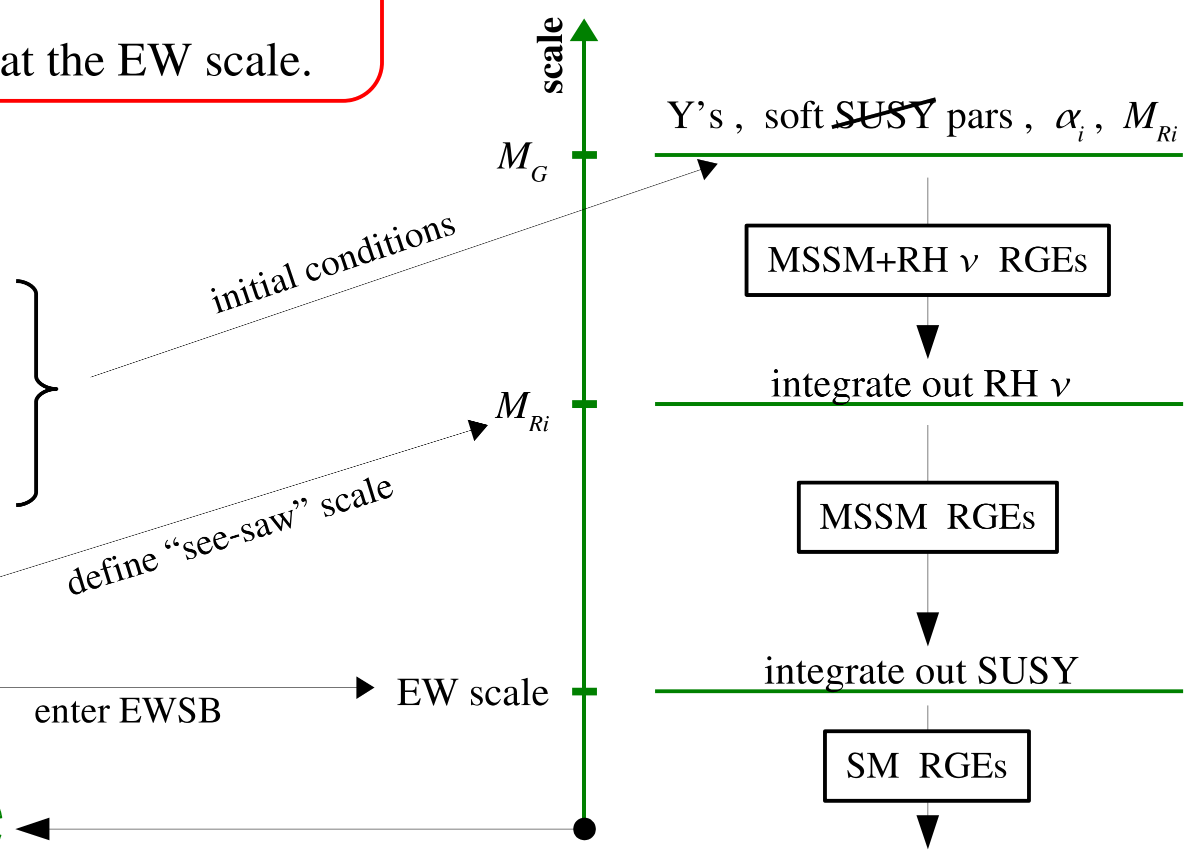

Compute observables

A closer look to the strategy

- We test the model, through the following observables O_i :

EW obs.	quark masses	lepton masses	CKM & PMNS
M_W	M_t	M_τ	$\lvert V_{us}\rvert$
M_Z	$m_b(m_b)$	M_μ	$\lvert V_{ub}\rvert$
G_F	$m_c(m_c)$	M_e	$\lvert V_{cb}\rvert$
$\alpha_{\text{e.m.}}$	$m_s(2\,\text{GeV})$	Δm^2_{31}	$\sin 2\beta$
$\alpha_s(M_Z)$	$m_d(2\,\text{GeV})$	Δm^2_{21}	$\sin^2 2\theta_{12}$
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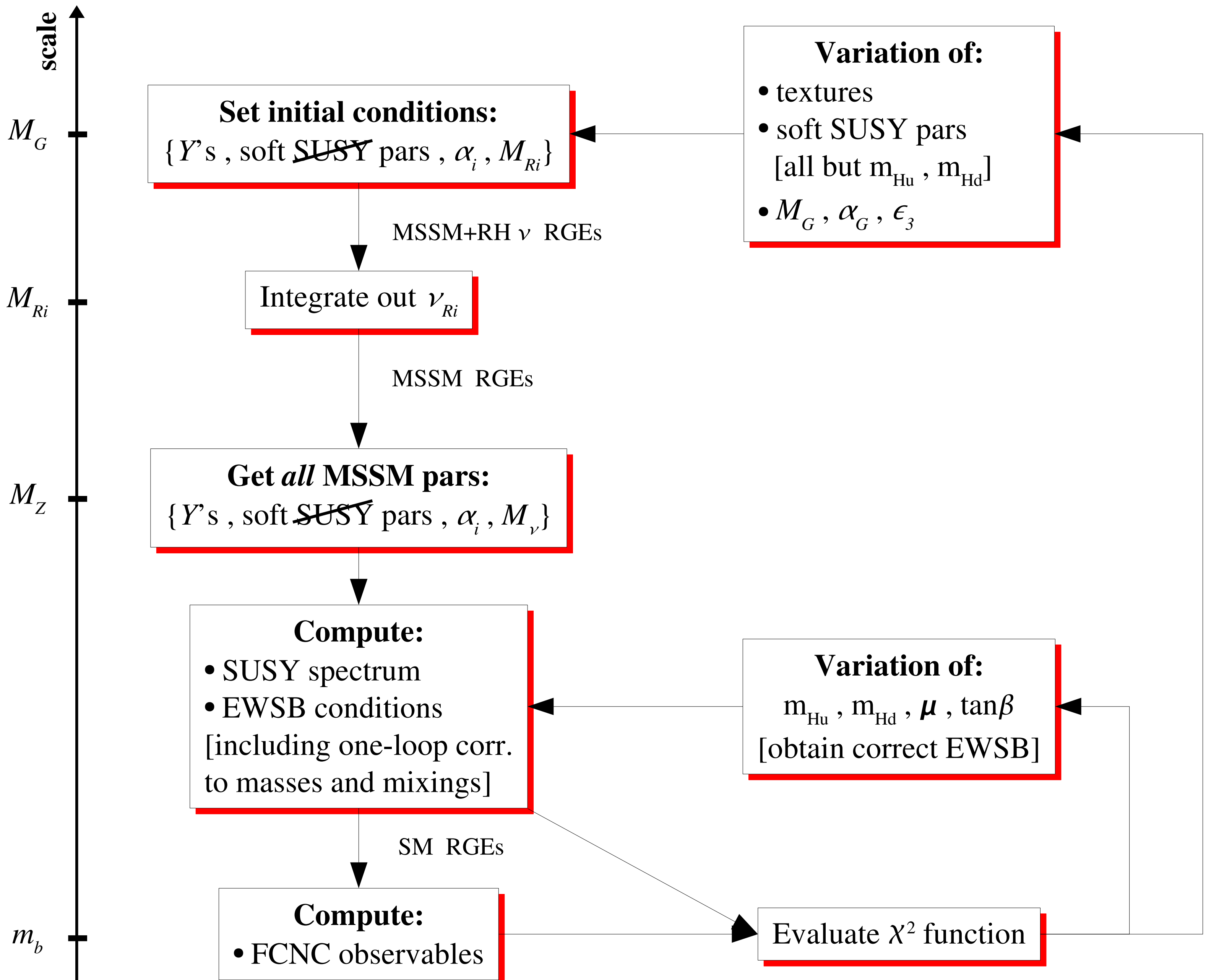
- These observables O_i enter a χ^2 function, defined as

$$\chi^2[\text{model pars}] \equiv \sum_{i=1}^{N_{\rm obs}} \frac{\left(f_i[\text{model pars}] - O_i\right)^2}{(\sigma_i^2)_{\rm exp} + (\sigma_i^2)_{\rm theo}}$$

f_i : model prediction for O_i

- The χ^2 function is then minimized upon variation of the model parameters.

Detailed chart of the fitting procedure



FCNCs considered in the analysis: Main features

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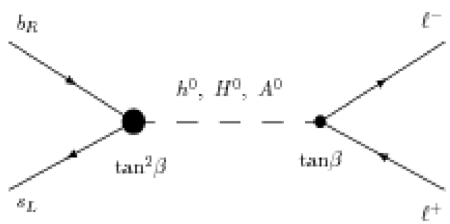

Enhancement going as:

$$\mathrm{BR}[B_s \to \mu^+ \mu^-] \propto A_t^2 \frac{\tan^6\beta}{M_A^4}$$

(Old) upper bound from CDF

$$\mathrm{BR}[B_s \to \mu^+ \mu^-]_{\mathrm{exp}} < 1.0 \times 10^{-7} \quad \Rightarrow \quad M_A > 450 \text{ GeV}$$

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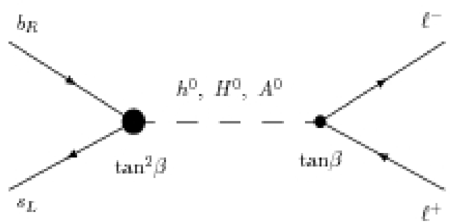

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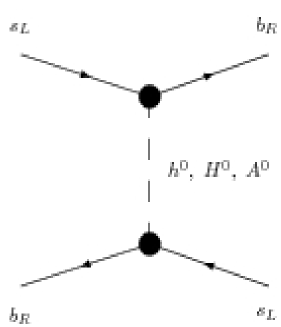
☑ ΔM_s

Again, double penguin dominance



\+ other external chiralities

Suppression going as:

$$\Delta M_s \propto -\frac{m_b m_s}{M_W^2} A_t^2 \frac{\tan^4\beta}{M_A^2}$$

Within the DR model, typical corrections to ΔM_s do not exceed –5%

☑ $\mathrm{BR}[\overline{B} \to X_s \gamma]$

$$\mathrm{BR}[\overline{B} \to X_s \gamma]^{\mathrm{exp}}_{E_\gamma > 1.6\,\mathrm{GeV}} = (3.55 \pm 0.26) \times 10^{-4}$$ { HFAG average }

$$\mathrm{BR}[\overline{B} \to X_s \gamma]^{\mathrm{SM}}_{E_\gamma > 1.6\,\mathrm{GeV}} = (3.15 \pm 0.23) \times 10^{-4}$$ { Misiak *et al.*, PRL '07 }

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Very rough $b \to s\,\gamma$ formula

$$\Gamma[\bar{B} \to X_s \gamma] \approx \frac{G_F^2 \alpha_{\mathrm{e.m.}}}{32\pi^4} |V_{ts}^* V_{tb}|^2 m_b^5 \left(|C_7^{\mathrm{eff}}(\mu_b)|^2 + \ldots \right)$$

Subleading corr's & contrib's negligible in the DR model

with $C_7^{\mathrm{eff}}(\mu_b) = C_{7,\mathrm{SM}}^{\mathrm{eff}}(\mu_b) + C_{7,\mathrm{DR}}(\mu_b)$

In order to end up with a "SM-like" prediction, one must have either

$$C_{7,\mathrm{DR}}(\mu_b) \ll C_{7,\mathrm{SM}}^{\mathrm{eff}}(\mu_b)$$

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Notes

- This solution is highly conspired
- SUSY is here *not* a "correction" to the SM result
- The theoretical control on the SUSY part should then be at least as good as in the SM
- In absence of it, we find e.g. a *strong* sensitivity to the SUSY matching scale

☑ $\mathrm{BR}[\overline{B} \to X_s \gamma]$ [continued]

Within the DR model, dominant NP contributions are from charginos and Higgses. Gluinos play a minor role.

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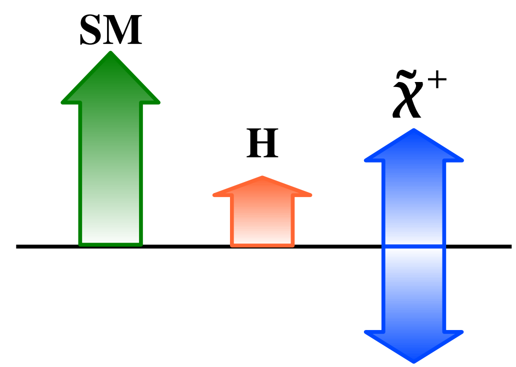
$$C_7^{\tilde{\chi}^+} \propto +\mu A_t \tan\beta \times \mathrm{sign}(C_7^{\mathrm{SM}})$$



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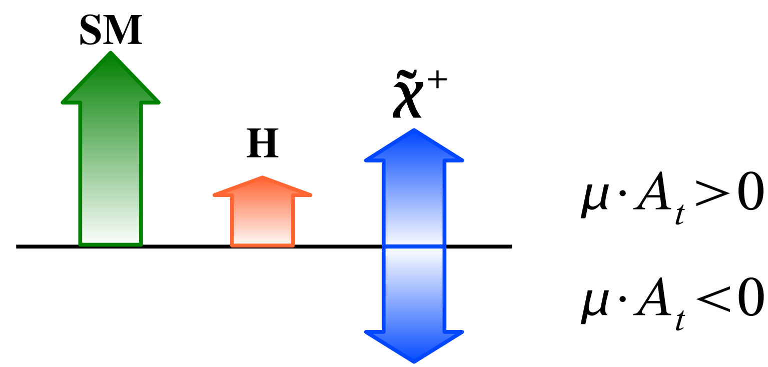
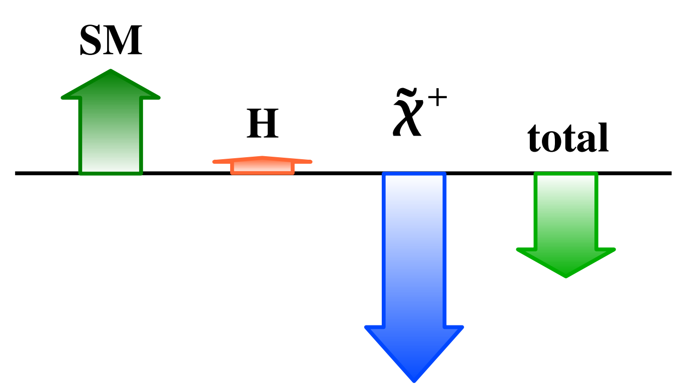


In the DR model, chargino contrib's can be very large. As a matter of fact:

$\mu \cdot A_t < 0$ "prefers" the fine-tuned case:



☑ $\mathrm{BR}[\overline{B} \to X_s l^+ l^-]$

At variance with $b \to s\, \gamma$, the decay $b \to s\, l^+ l^-$ is sensitive to the sign of C_7^{eff}

$$\hat{s} = (p_{\mu^+} + p_{\mu^-})^2 / m_b^2$$

$$\frac{d\Gamma[\overline{B} \to X_s l^+ l^-]}{d\hat{s}} \propto (1+2\hat{s})\left(|\tilde{C}_9^{\mathrm{eff}}(\hat{s})|^2 + |\tilde{C}_{10}^{\mathrm{eff}}(\hat{s})|^2\right) + 4\left(1+\frac{2}{\hat{s}}\right)|C_7^{\mathrm{eff}}|^2 + 12\, C_7^{\mathrm{eff}}\, \mathrm{Re}\left(\tilde{C}_9^{\mathrm{eff}}(\hat{s})\right)$$

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	BaBar & Belle average	**SM**	$\boldsymbol{C_7^{\rm eff} \to -C_7^{\rm eff}}$
$10^6 \times \mathrm{BR}[\bar{B}\to X_s l^+ l^-]^{\mathrm{low}-\hat{s}}_{\mathrm{exp}}$	$= 1.60 \pm 0.51$	1.57 ± 0.16	3.30 ± 0.25

Gambino, Haisch, Misiak, PRL '05

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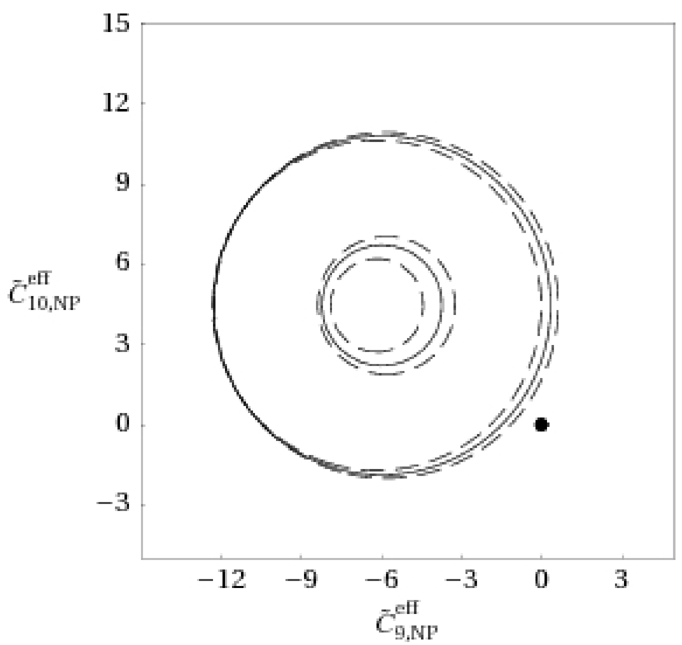
The sign of $C_7^{\rm eff}$ is the same as in the SM, unless C_9 and C_{10} are significantly affected by NP



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At variance with $b \to s\,\gamma$, the decay $b \to s\, l^+ l^-$ is sensitive to the sign of $C_7^{\rm eff}$

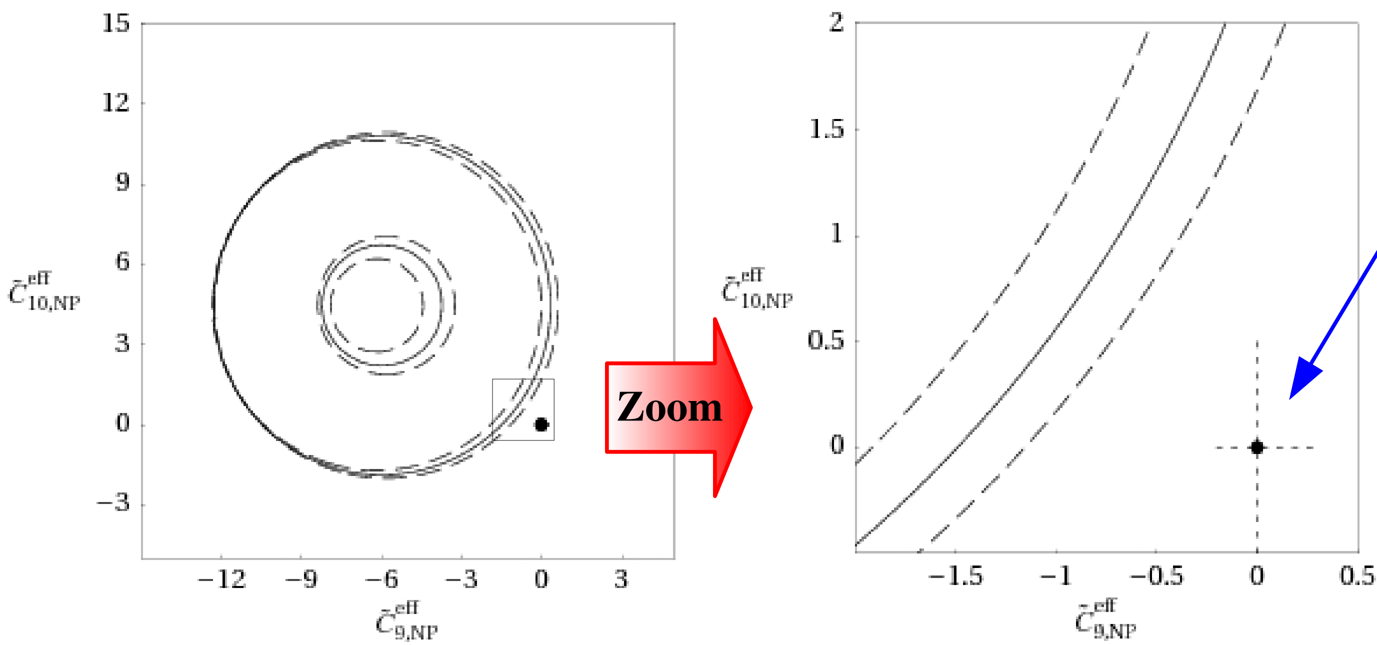
$\hat{s} = (p_{\mu^+} + p_{\mu^-})^2 / m_b^2$

$$\frac{d\Gamma[\bar{B}\to X_s l^+ l^-]}{d\hat{s}} \propto (1+2\hat{s})\left(|\tilde{C}_9^{\rm eff}(\hat{s})|^2 + |\tilde{C}_{10}^{\rm eff}(\hat{s})|^2\right) + 4\left(1+\frac{2}{\hat{s}}\right)|C_7^{\rm eff}|^2 + 12\, C_7^{\rm eff}\, \mathrm{Re}\left(\tilde{C}_9^{\rm eff}(\hat{s})\right)$$

	BaBar & Belle average	SM	$C_7^{\rm eff} \to -C_7^{\rm eff}$
$10^6 \times \mathrm{BR}[\bar{B}\to X_s l^+ l^-]_{\rm exp}^{{\rm low}-\hat{s}}$	$= 1.60 \pm 0.51$	1.57 ± 0.16	3.30 ± 0.25

Gambino, Haisch, Misiak, PRL '05

The sign of $C_7^{\rm eff}$ is the same as in the SM, unless C_9 and C_{10} are significantly affected by NP



Maximal ranges within the MFV MSSM (to which the low-energy DR model belongs)

Gambino, Haisch, Misiak, PRL '05

Ali, Lunghi, Greub, Hiller, PRD '02

Some "reference" fits

univ. scalar term $m_{16} = 4$ TeV,
univ. trilinear $A_0 \approx -2\, m_{16}$,
$\mu > 0$

The solution $A_0 \approx -2\, m_{16}$ helps 3rd generation Yukawa unification

To fit m_b, a cancellation between these terms is required: $|A_t| > m_{\tilde{g}}$

Helped by $A_0 \approx -2\, m_{16}$

$$m_b(M_Z) = m_b^{(0)}\left[1 + \mu \tan\beta \left(\frac{2\alpha_s}{3\pi}\frac{m_{\tilde{g}}}{m_{\tilde{b}}^2} + \frac{\lambda_t^2}{16\pi^2}\frac{A_t}{m_{\tilde{t}}^2}\right) + \Delta m_b^{\log}\right]$$

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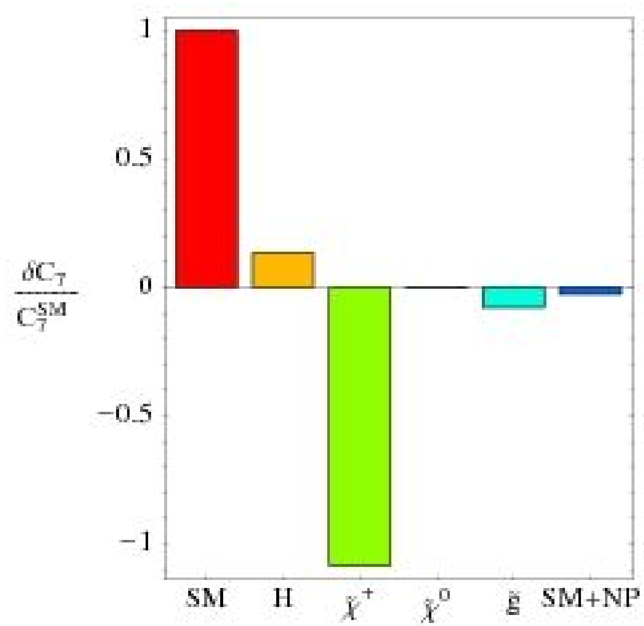
This solution prefers $C_7 = -2\, C_7^{SM}$.

Imposing $C_7 > 0$, one has:

$B_s \to \mu^+ \mu^-$ implies $M_A \geq 450$ GeV

$b \to s\, \gamma$ is chargino dominated



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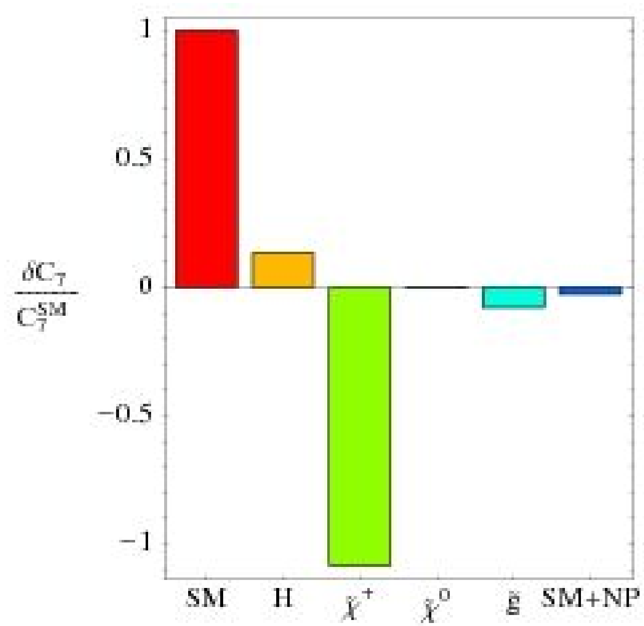

Only way-out: decoupling

$$m_{\tilde{t}} \geq 2\,\text{TeV}$$

Some “reference” fits: continued

$$m_{16} = 4\ \text{TeV},\ \ \mu \gtrless 0$$
$$|A_0| \neq 2\, m_{16}$$

In this case one has NO inverted mass hierarchy:

One typically finds solutions with both $m_{\tilde{t}}$, $m_{\tilde{b}}$ heavy, and A_t small

Easy to fit m_b, since in this case these two terms are both small

$$m_b(M_Z) = m_b^{(0)} \left[1 + \mu \tan\beta \left(\frac{2\alpha_s}{3\pi} \frac{m_{\tilde{g}}}{m_{\tilde{b}}^2} + \frac{\lambda_t^2}{16\pi^2} \frac{A_t}{m_{\tilde{t}}^2} \right) + \Delta m_b^{\log} \right]$$

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Now $b \to s\,\gamma$ is OK ☞ But typical masses are

$$m_{\tilde{t}} \geq 2.6\,\text{TeV}$$
$$M_A \geq 1.5\,\text{TeV}$$

In this case EWSB finds generically very large masses for heavy Higgses

The Big Picture

Fit strategy:
choose $m_{16} \in [4,10]$ TeV, then let the fit determine the other param's.

Dictionary
m_{16} = univ. soft scalar term
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Benchmark Cases

	Fit Details	Remarks	sign(C_7)	$m_{\tilde{t}}$ [GeV]	$b \to s \gamma$	$b \to s\, l^+ l^-$
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☑ $\mathrm{BR}[B_u \to \tau\,\nu]$: a possible additional problem

The DR model fits successfully quark & lepton masses and mixings.
However, among the predictions one gets:

$|V_{ub}^{\mathrm{DR}}| \simeq 3.26 \times 10^{-3}$ which is somehow "too small" ⇒ The $B_u \to \tau\,\nu$ mode is a way to display the problem

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In the SM

The $B_u \to \tau \nu$ decay is affected by a large error due to the poor knowledge of $F_{B^+} \approx F_{B_d}$ ⇒ One considers one of the "Ikado" ratios

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$$10^4 \times \mathrm{BR}(B_u \to \tau \nu)_{\mathrm{SM}} = \begin{cases} 0.87 \pm 0.11 \ , & \text{with} |V_{ub}|_{\mathrm{UTfit}} = 3.66(15) \times 10^{-3} \\ 1.31 \pm 0.23 \ , & \text{with} |V_{ub}|_{\mathrm{incl}} = 4.49(33) \times 10^{-3} \end{cases}$$

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Belle & BaBar average

In the DR model

$$\frac{{\rm BR}(B_u \to \tau_\nu)_{\rm DR}}{{\rm BR}(B_u \to \tau_\nu)_{\rm SM}} = \left[1 - \frac{m_{B^+}^2}{m_{H^+}^2} \frac{\tan^2\beta}{1 + \epsilon_0 \tan\beta}\right]^2 \left|\frac{V_{ub}^{\rm DR}}{V_{ub}^{\rm SM}}\right|^2$$

suppression: Hou; Akeroyd+Recksiegel; Isidori+Paradisi

further suppression

Typical prediction:

$$10^4 \times {\rm BR}(B_u \to \tau_\nu)_{\rm DR} \leq 0.6$$

Conclusions

- The DR model, an SO(10) SUSY GUT with a D_3 family symmetry, provides *detailed, testable* predictions for the low-energy MSSM.
  It successfully describes quark and lepton masses and mixings.

- The DR model is however challenged when probed against the *simultaneous* description of quark FCNC data.
  This test is accomplished through a global fit, with FCNCs appearing directly in the χ^2 function.

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- Work in progress in this direction. See David Straub's talk.