The $B \to X_s \gamma$ decay beyond the Standard Model

Diego Guadagnoli
Technical University Munich

Outline

- ☑ General remarks in the light of exp. vs. SM figures
- ☑ $B \to X_s \gamma$ in the general MSSM
  - ➘ Short parenthesis on model-independent phenomenological studies
- ☑ $B \to X_s \gamma$ in other specific (classes of) models

CKM 08, Sep 8 – 13, 2008

Introductory remarks

SM vs. exp

$$\mathrm{BR}[B \to X_s \gamma]_{exp} = (3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$$ **exp. average [HFAG]**

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

(Results refer to a photon energy cut $E_\gamma > 1.6$ GeV)

☑ Results agree within ~ 1 σ of the combined error (adding errors in quadrature)

Therefore, in beyond-the-SM studies, $B \to X_s \gamma$ plays (at the moment) a role similar to "null tests": new effects should be within the combined error

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Beyond-the-SM calculations and analyses

SUSY: the leading order and much of the next-to-leading corrections are known

Non-SUSY: much less explored.

In some classes of models, a nearby (unknown) UV completion implies sensitivity of the BR-calculation to the UV scale [difficulty absent in the MSSM]

Model-independent analyses: constrain directly the couplings of the effective Hamiltonian, independently of the dynamics responsible for the couplings themselves

$B \to X_s \gamma$ in SUSY

“**Impossibility of writing the magnetic-moment *effective* interaction in a SUSY-invariant way**”

⇒ In the limit of exact SUSY, BR[$B \to X_s \gamma$] = 0

[Ferrara-Remiddi 74]

[Barbieri-Giudice 93]

- **In the real world, SUSY is (badly) broken.**
  What is the generic expectation for BR[$B \to X_s \gamma$] in this case?

In the MSSM, there are 5 sets of graphs entering at leading order.
They all induce (at the scale μ_b) the magnetic operator $O_7 \equiv m_b (\bar{s}\, \sigma^{\mu\nu} P_R\, b) F_{\mu\nu}$

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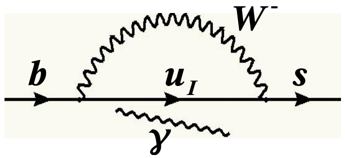

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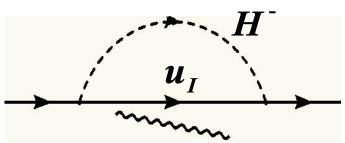
H^+



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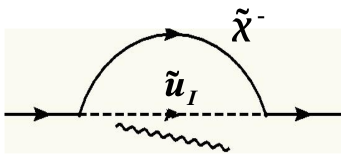

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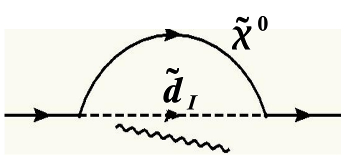
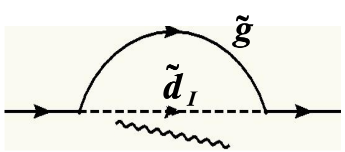


[negligible in all generality]

$\tilde{g}$



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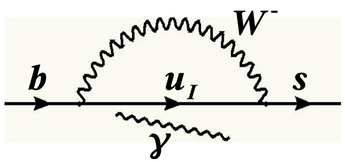

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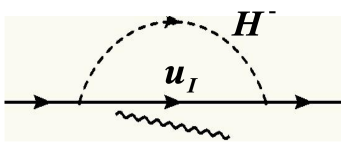

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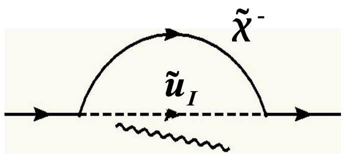

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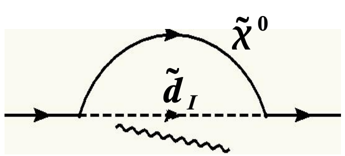

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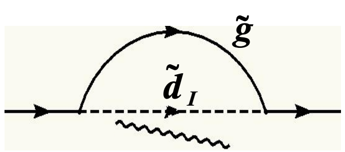

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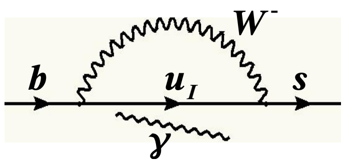

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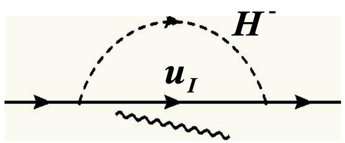

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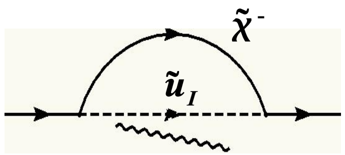

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- **$M_{\rm SUSY}$: "typical" SUSY mass running in the loop**

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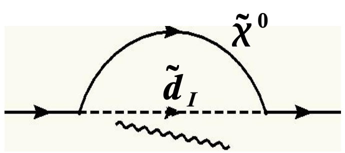

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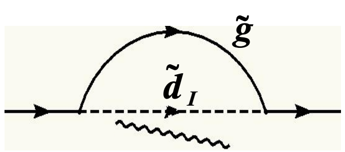

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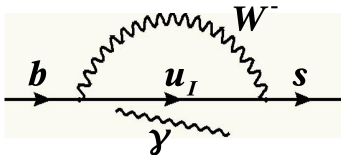

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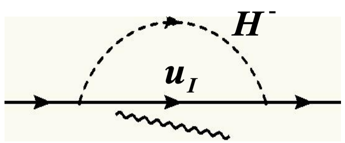

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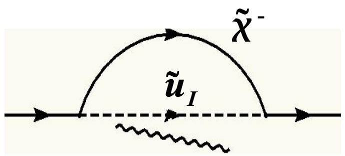

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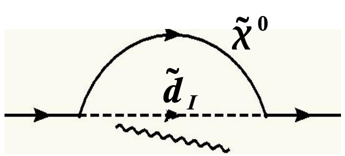

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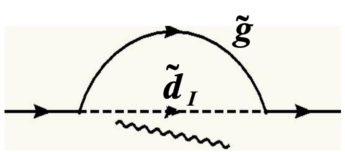

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No "hard" (= powerlike) GIM in the SM, because $m_t > M_W$

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(Potential) hard GIM at work in SUSY

- **M_{SUSY}: "typical" SUSY mass running in the loop**

- **Gluinos are the only contrib's where hard GIM is compensated by coupling enhancement**
- **Size of corrections crucially depends on the mechanism of SUSY breaking (= modeling of soft terms)**

The "flavor problem" enters here

Thorough discussion of SUSY LO: Bertolini, Borzumati, Masiero, Ridolfi, 91

More on gluino contrib's:

For general flavor violation, gluino-down squark contrib's are typically dominant

How should acceptable down-squark mass matrix entries look like?

$[\delta_{XY}]_{ij}$ = (normalized) off-diagonal entries in chirality *(X,Y)* and/or flavor *(i,j)*

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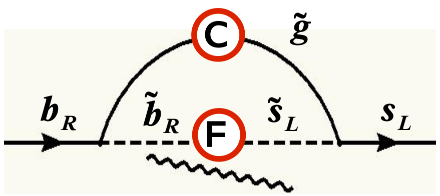
For gluino diagrams, (C) can occur:

in the internal gluino propagator



contrib: $\delta C_7^{\tilde{g},\tilde{g}} \propto m_{\tilde{g}}$

(F) $= [\delta_{LR}]_{23}$,
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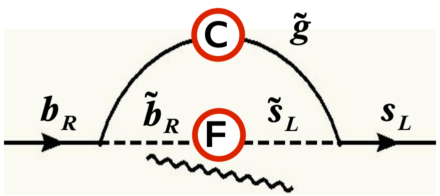

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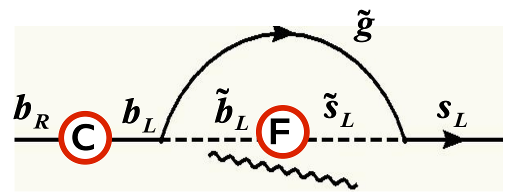
OR in the external b-quark propagator



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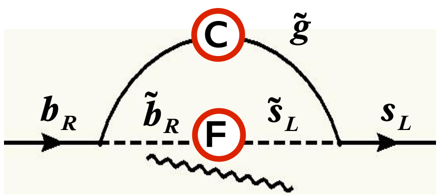

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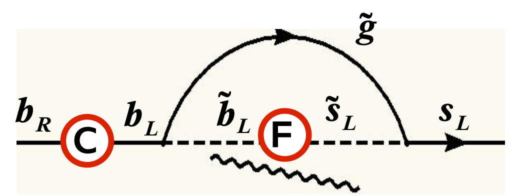

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Besmer, Greub, Hurth, 01
See also:
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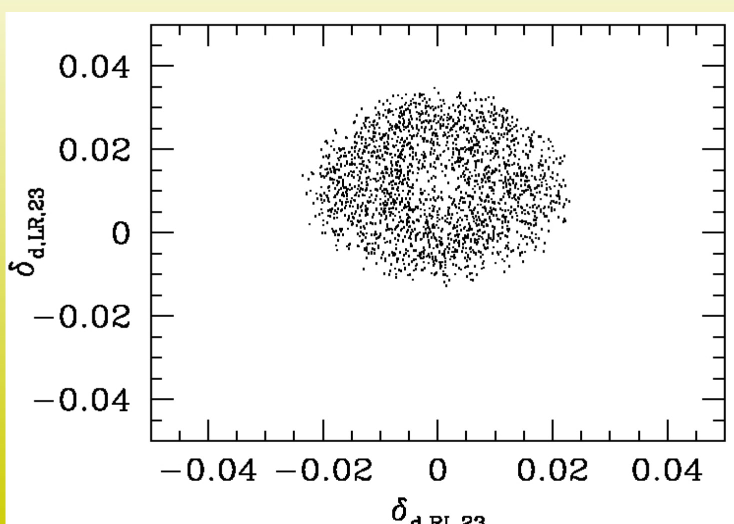

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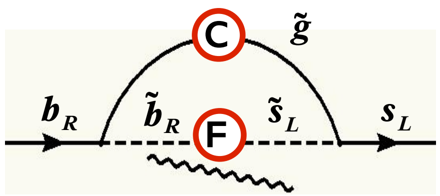

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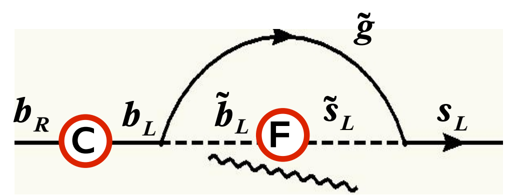

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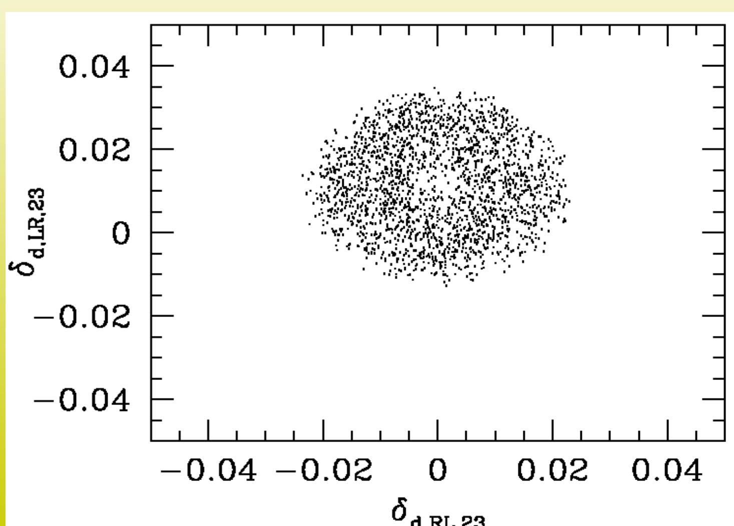

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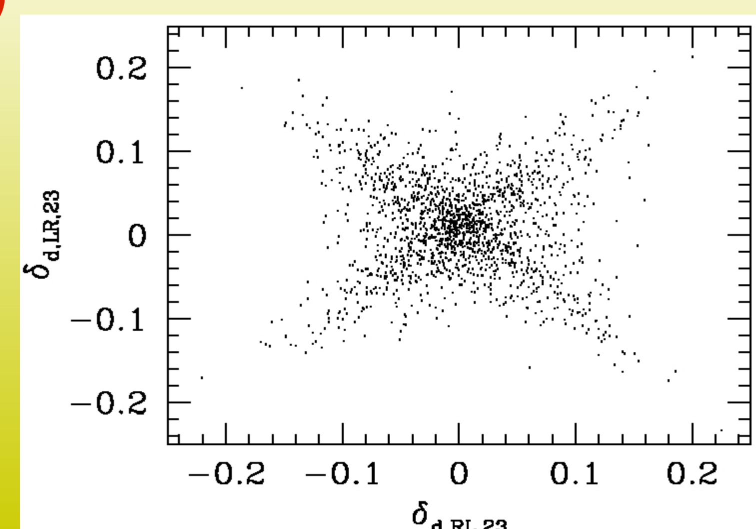
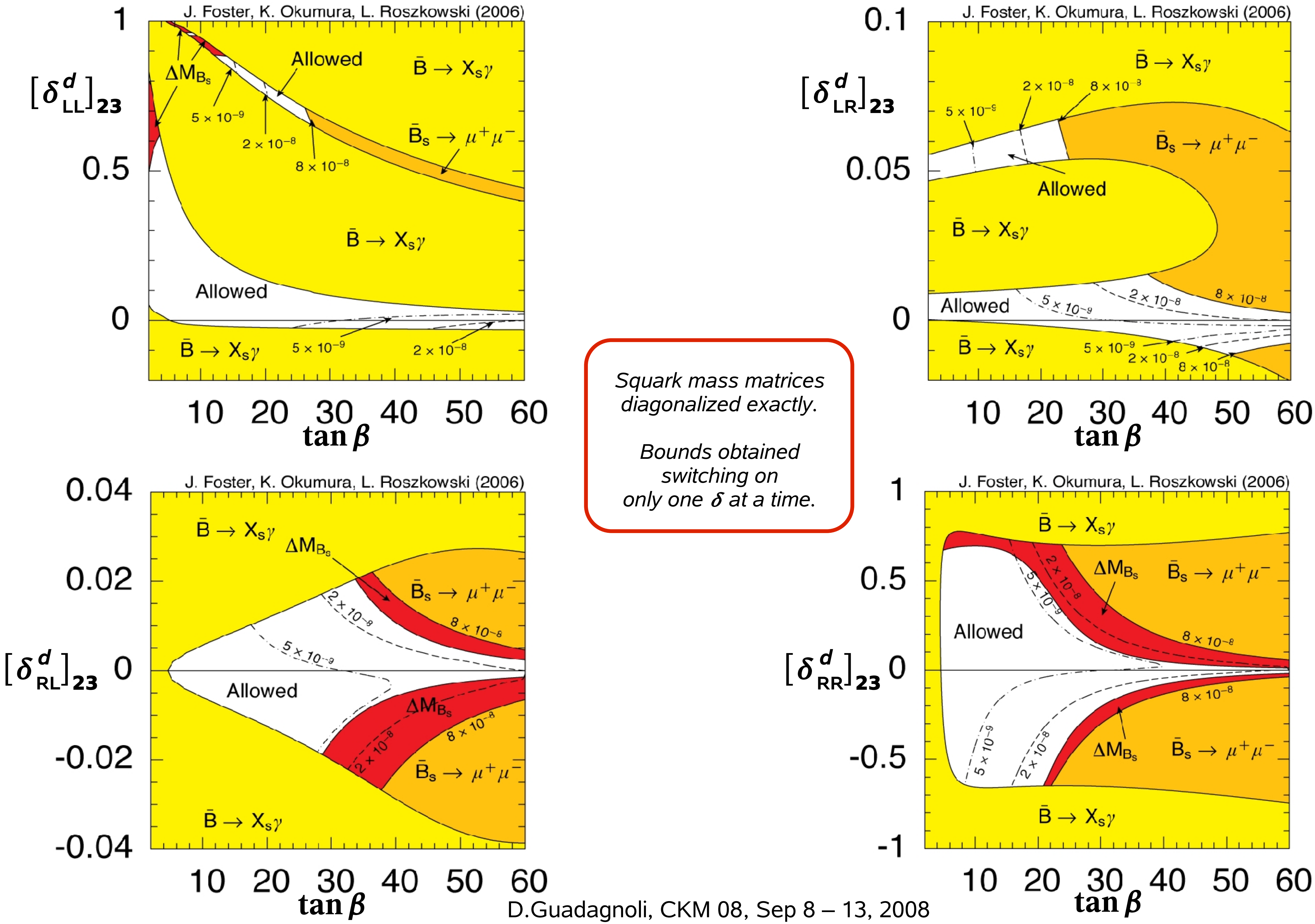
Beyond the single-insertion approx. (MIA), one can efficiently constrain only special combinations of the δ's

However, switching on simultaneously all possible (F)-insertions, the previous constraints get weaker:



General flavor mixing: $B \to X_s \gamma$ vs. other FCNCs

For previous, single-insertion analyses, see:
Gabbiani *et al.*, 96; Everett et al., 01; Ciuchini et al., 02



Squark mass matrices diagonalized exactly.

Bounds obtained switching on only one δ at a time.

Overview of NLO MSSM calculations

A complete calculation of NLO (SUSY-QCD) corrections to the LO coeff's in the MSSM is missing to date.

NLO MSSM calculations exist "only" in *scenarios*

NLO MSSM: formidable task

- Many scales in the game
- Bulky expressions if general flavor mixing is assumed

Scenario	Calculation / Remarks	References
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❷ MSSM	Gluonic corrections (calculation also in many other SM extensions)	Bobeth, Misiak, Urban, 98
❸ **MSSM** with no flavor violation in gluino vertices	Assumes the following mass hierarchy: $M_W \approx M_{H^\pm} \approx m_{\tilde{\chi}^\pm} \approx M_{\tilde{t}_R} \ll M[\text{other SUSY}]$	Ciuchini, Degrassi, Gambino, Giudice, 98
	General discussion of possibly large effects at NLO: large *tan*β and large *logs[*M_{SUSY} / M_W*]*	Degrassi, Gambino, Giudice, 00
	All-order resummation of large-*tan*β SUSY-QCD corrections	Carena, Garcia, Nierste, Wagner, 00
	Inclusion of neutral Higgs & of (higher order in) H^+	D'Ambrosio, Giudice, Isidori, Strumia, 02
	Removal of assumptions on charged Higgs masses	Borzumati, Greub, Yamada, 03
	General NLO corrections Recently FORTRAN-coded in **SusyBSG**	Degrassi, Gambino, Slavich, 06

SM vs. SUSY: further remarks

Bertolini *et al.*, 87
Deshpande *et al.*, 87

Besides absence of hard GIM,
the SM enjoys further enhancement after inclusion of leading QCD logs(M_W / μ_b)

$$C_7^{eff,\,SM}(\mu_b) / C_7^{SM}(M_W) \approx 1.65 \quad \Rightarrow$$

Enhancement over the purely e.w. BR of approx. $1.65^2 = 2.7$

NOTE: in SUSY an "opposite" effect seems to be at work.

Okumura, Roszkowski, 04

Namely, taking into account:

- ☑ RGE evolution between $\mu_{SUSY} \sim 1$ TeV and μ_W
- ☑ "correlated" flavor-violating corrections between $b \to s \gamma$ and m_b

reduces SUSY contributions (especially gluino's) wrt the "naive" $C_{7,\,SUSY}^{LO}(\mu_W)$

SM vs. SUSY: further remarks

Bertolini et al., 87
Deshpande et al., 87

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- **Besides (potential) suppression due to hard GIM,**
  charginos and Higgses tend to compensate each other in "half" of the SUSY parameter space, depending on sign($A_t\ \mu$)

Complex A_t, μ ?
Check effects in EDMs...

☑ **Gluino contributions are (the only ones) potentially catastrophic.**
Pattern of soft terms must be highly non-generic

This calls for an "organizing principle"

The scale at which the flavor group is broken may be much above the scale of SUSY-breaking M_{SUSY}

Then every flavor structure at or below M_{SUSY} would inherit from just the SM Yukawa couplings...

... resulting in a natural mechanism of SM-like near-flavor-conservation: **Minimal Flavor Violation**

On the sign of the $B \to X_s \gamma$ amplitude

To good approximation, one can write

$$BR[B \to X_s \gamma] \propto |C_7^{\text{eff}}(\mu_b)|^2$$

"effective" *low-energy* coupling to the operator
$O_7 \equiv m_b (\bar{s} \sigma^{\mu\nu} P_R b) F_{\mu\nu}$

Therefore, $B \to X_s \gamma$ is not sensitive to the sign of $C_7^{\text{eff}}(\mu_b)$

New-physics models such that $C_7^{\text{eff,new}}(\mu_b) \approx -2 C_7^{\text{eff,SM}}(\mu_b)$ escape the $B \to X_s \gamma$ constraint.

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- However, sensitive to the sign flip is $B \to X_s l^+ l^-$:
  - ☑ This decay is sensitive also to the coefficients of the operators
  $$\begin{cases} O_9 \equiv (\bar{s}_L \gamma_\alpha b_L)(\bar{l} \gamma^\alpha l) \\ O_{10} \equiv (\bar{s}_L \gamma_\alpha b_L)(\bar{l} \gamma^\alpha \gamma_5 l) \end{cases}$$
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☑ *" Extensions of the SM with flipped C_7 and with C_9, C_{10} not affected by large corrections are disfavored "*

In fact, take *e.g.* the range $q^2 \in [1, 6]$ GeV^2

BR[$B \to X_s l^+ l^-$] [10^{-6}]		
exp	**SM**	**flipped C_7**
1.60 ± 0.51	**1.57 ± 0.16**	**3.30 ± 0.25**

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☑ Corrections to C_9 and / or C_{10} need to be O(1) with respect to the corresponding SM values.

Such large corrections are very hard to obtain in concrete models. Especially, but not only, in MFV

Note, however, that on a model-independent basis, a flipped C_7 is not (yet) excluded.

For global analyses in MFV frameworks, see:
Bobeth *et al.*, 05; Hurth, Isidori, Kamenik, Mescia, 08

SUSY GUTs with Yukawa Unification and GUT-scale universalities

Generic features of these models:
$\tan\beta$ = O(50), large trilinear coupling A_t

$B \to X_s \gamma$ **is one of the key observables in assessing their viability**

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Interplay among observables

- $B \to X_s \gamma$ would need a cancellation between Higgs and chargino contributions, however Higgses are suppressed because of the $B_s \to \mu^+ \mu^-$ bound

Albrecht, Altmannshofer, Buras, DG, Straub, 07

The combined information from FCNCs (mostly, $B \to X_s \gamma$ and $B_s \to \mu^+ \mu^-$) favors <u>lower values of tanβ</u> (or else, pushes the squark scale to decoupling values)

- Conversely, it is known [e.g. Carena, Pokorski, Wagner, 93] that m_b prefers $\tan\beta$ O(50) (or else, $\tan\beta$ close to 1, excluded by lightest Higgs LEP bound)

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- ☑ Is the above tension among FCNCs for $\tan\beta$ O(50) a <u>general feature</u> of SUSY GUTs with YU and universal GUT-scale soft terms ?

- ☑ Is this tension relieved if $\tan\beta$ is below 50 (not too much in order not to spoil m_b) ?

Lowering $\tan\beta$:

Complete YU $\xrightarrow{\text{relaxed to}}$ $Y_t \simeq Y_\nu$ and $Y_b \simeq Y_\tau$

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Yes:
Independently from the assumed flavor textures, agreement among FCNCs is only achieved at the price of decoupling in the scalar sector

☑ Is this tension relieved if $\tan\beta$ is below 50 (not too much in order not to spoil m_b) ?

Yes:
A region of successful fits exists for $46 \le \tan\beta \le 48$

- ☑ (moderate) breaking of $t - b$ unification
- ☑ BR[$B \to X_s \gamma$] $\approx 2.9 \times 10^{-4}$
- ☑ (light part of) SUSY spectrum basically *fixed* by the interplay among constraints

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Complete YU $\xrightarrow{\text{relaxed to}}$ $Y_t \simeq Y_\nu$ and $Y_b \simeq Y_\tau$

SUSY GUTs without Yukawa Unification

Global fits within the constrained MSSM

(the MSSM resulting from universal soft-breaking terms at the GUT scale)

$B \to X_s \gamma$ is included, and plays an important role

However, the preferred region in the parameter space is still not fully agreed upon between different analyses

Parameters
m_0: univ. scalar mass
$m_{1/2}$: univ. gaugino mass
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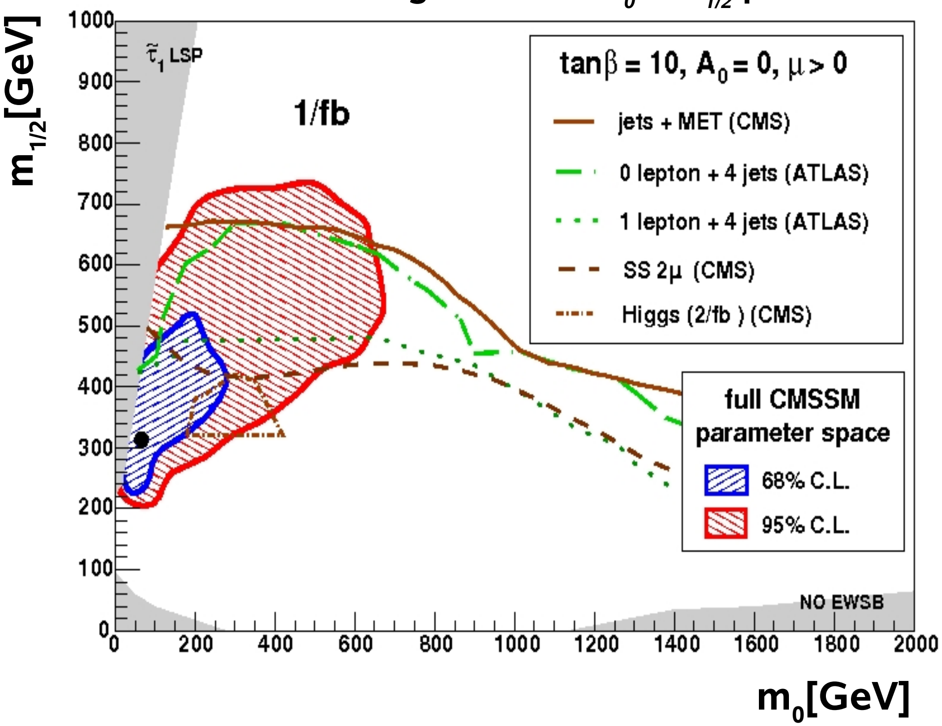
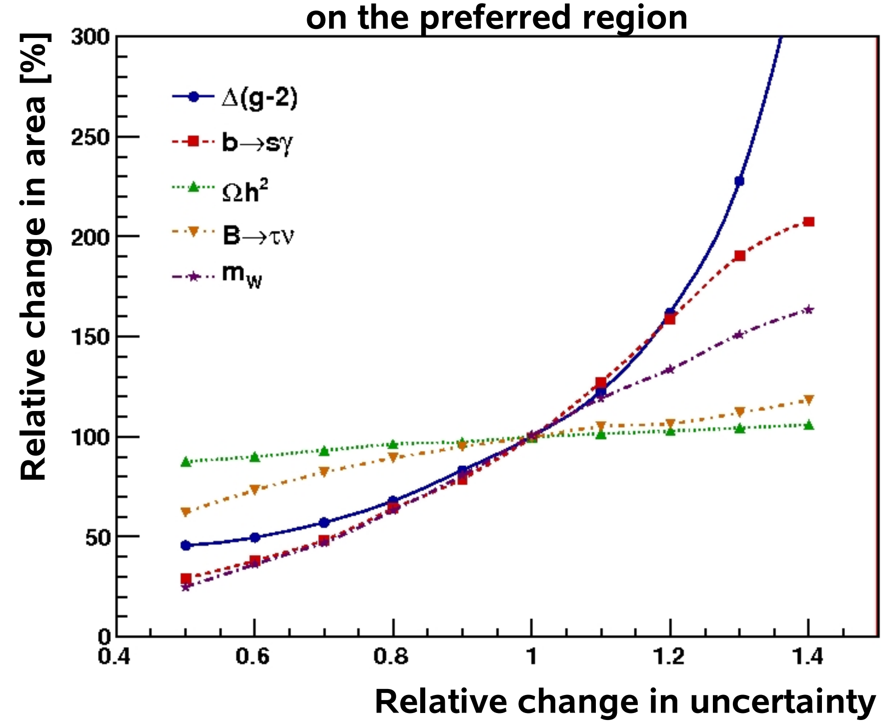
Buchmueller *et al.*, 08

Preferred region in the $m_0 - m_{1/2}$ plane



Impact of the various constraints on the preferred region



Low SUSY scale: Ruled by $(g-2)_\mu$?

$B \to X_s \gamma$ in Universal Extra Dimensions (UED)

Appelquist, Cheng, Dobrescu, 00 [ACD]

"Universal" ED: ED accessible to all SM fields

Corrections to EW observables (and FCNCs) arise only at the loop-level

Agashe, Deshpande, Wu, 01

Study the impact of $B \to X_s \gamma$

☑ In the simplest case (UED5 w/ 1 Higgs doublet) $B \to X_s \gamma$ is suppressed

⇨ **Bound on compactification radius:** $R^{-1} \geq$ 280 GeV

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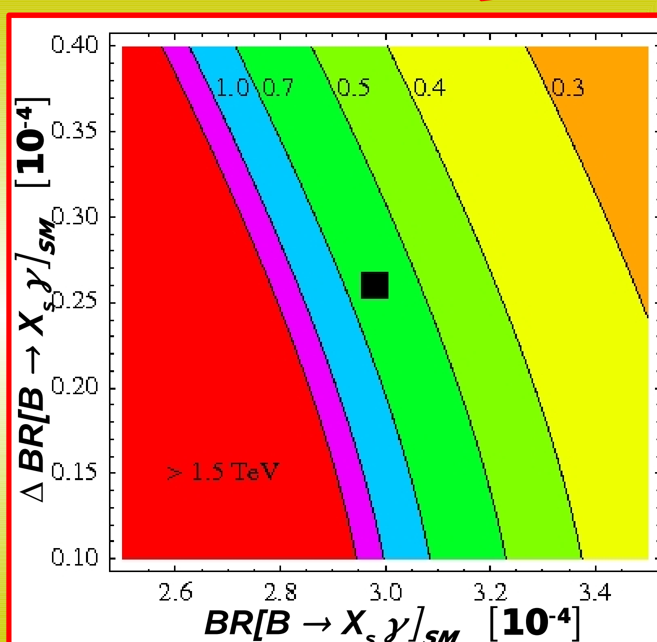
Haisch, Weiler, 07

☑ **Bound in UED5:**

$R^{-1} \geq$ *600 GeV*

from $B \to X_s \gamma$



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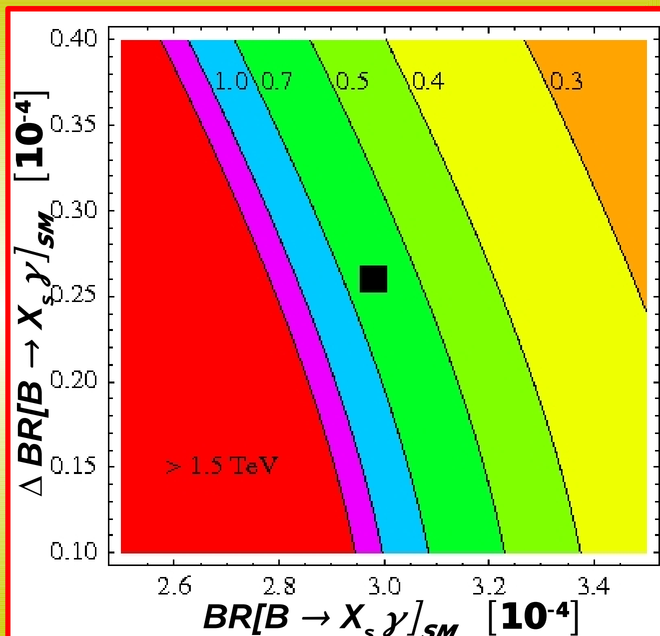

Freitas, Haisch, 08

$B \to X_s \gamma$ study in UED6

- ☑ Interesting issue, because dark matter constraint prefers $R^{-1} \leq 600$ GeV
- ☑ Conversely, **$B \to X_s \gamma$ imposes:**

$R^{-1} \geq 650$ GeV

Other places where $B \to X_s \gamma$ has been considered

Little(st) Higgs without or with T-parity

LH: Huo, Zhu, 03; Buras, Poschenrieder, Uhlig, Bardeen, 06

LHT: Blanke *et al.*, 06

$B \to X_s \gamma$ effects are typically well below the current theoretical error.

Models with warped extra dimensions

Kim, Kim, Song, 03;

Agashe, Perez, Soni, 04-05

Sizable $B \to X_s \gamma$ effects can generally be expected. However, precise answer is highly model-dependent: assumed setup, scale of KK modes, ...

Models with an additional Z' boson

"3-3-1 Model": Extended Higgs and gauge sectors.

Agrawal, Frampton, Liu, 96

Promberger, Schatt, Schwab, Uhlig, 08

Higgs sector contributions vastly dominant over those from gauge sector.

$B \to X_s \gamma$ effects basically indistinguishable with respect to a 2HDM II.

My Conclusions

- ☑ *BR[$B \to X_s \gamma$] belongs to the set of observables which are crucial in any new physics study, within and outside the flavor sector.*

- ☑ *By now $B \to X_s \gamma$ is a well-understood decay, also in various extensions of the SM.*

- ☑ *A major trigger to further progress in beyond-the-SM calculations and analyses will be further progress in the exp and SM errors.*