Effects of SUSY, Little Higgs, etc on B decay

Benjamin Grinstein

FPCP 2009

Lake Placid, NY

Flavor physics in not the Standard Model (in not Five Dimensions)

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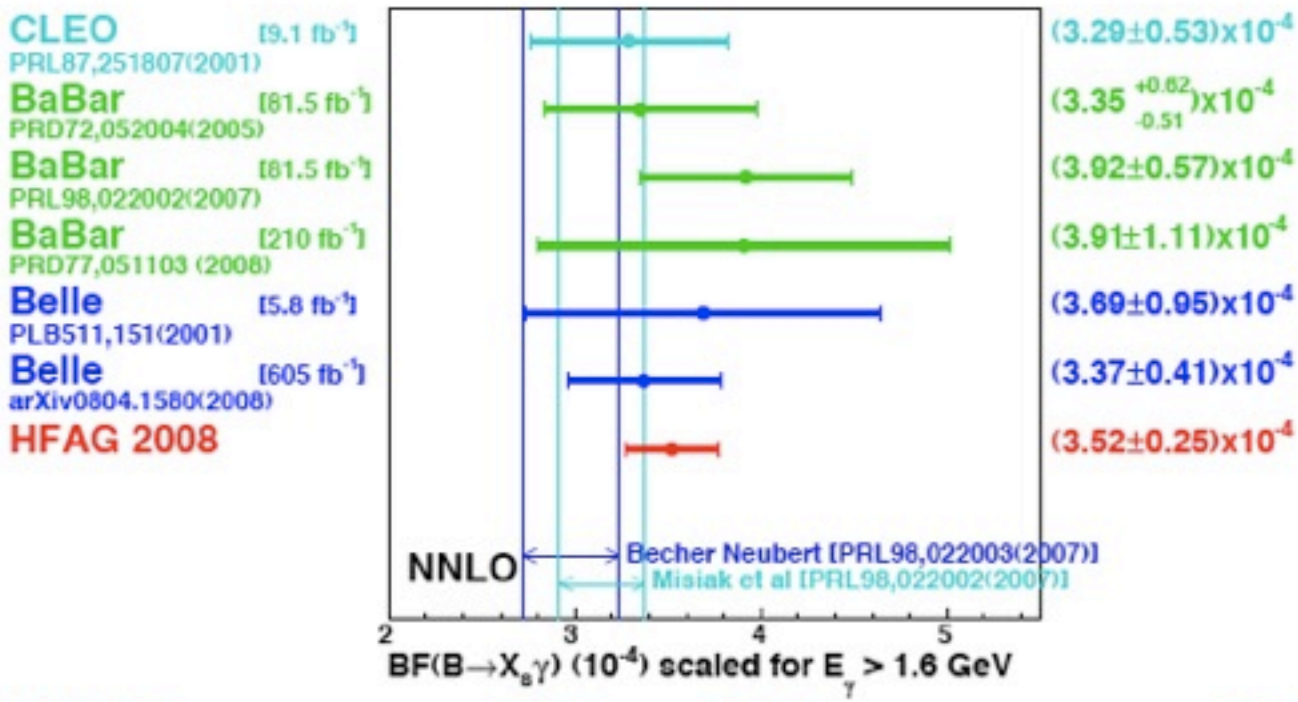

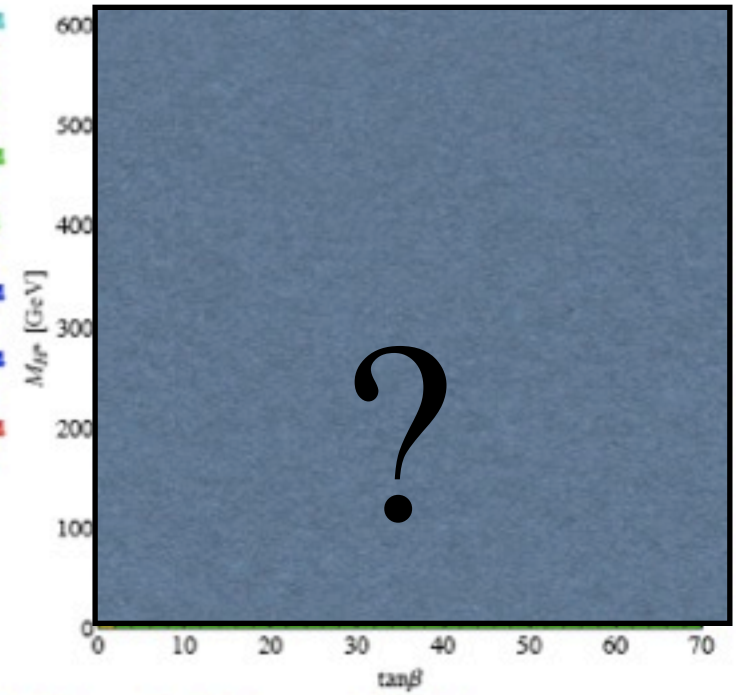

HFAG average: $\mathcal{B}(B \to X_s\gamma)_{E_\gamma>1.6\ \text{GeV}} = (3.52 \pm 0.25) \times 10^{-4}$

(scaling down to 1.6 GeV may be controvertial — motivation to lower E_γ)

- Agreement with latest NNLO calculation
- Strong constraints on generic 2HDM charged Higgs
  (MSSM charged Higgs case is more complicated due to possible destructive interference)
- Also strong constraints on various new physics scenarios
  (but bigger room than before as data $\mathcal{B}$ is now higher than SM)

Bottom-up approach

Assume New Physics (NP) at short distances

NP not directly accessible to experiment (yet): effects appear indirectly as modifications to interactions among SM particles

Supplement SM lagrangian with terms of dimension higher than four ("higher dimension operators") as allowed by Lorentz Invariance and gauge symmetries.

A term of dimension n>4 appears in the lagrangian with coefficient $c/\Lambda_{\rm NP}^{n-4}$ (with $c \sim 1$)
Hence low energy effects are suppressed by powers of $\Lambda_{\rm NP}$

Advantages of bottom-up approach:
- fairly general, encompasses many (all?) realistic extensions of SM (model independent)
- few parameters

Disadvantages:
- no clear correlation between long (GeV^{-1}) and very short (TeV^{-1}) distances

Top-down approach

Assume specific model of New Physics (NP)

Lagrangian contains new d.o.f

If motivation is hierarchy problem, new particles of mass $\sim$ TeV expected
(hence $\Lambda_{\rm NP}$ order a TeV in bottom-up approach;
if new particles of mass M only in loops or long distance processes then $\Lambda_{\rm NP} \sim 4\pi M$)

At long distances can replace by EFT by integrating out new d.o.f.
get lagrangian of bottom-up approach with specific coefficients for higher dimension terms

Advantages of top-down approach:
- specific correlations between long and short distance effects
- specific correlations between long distance effects

Disadvantages:
- many new parameters
- limited by our imagination and prejudice
- unwieldy (eg, number of variants of SUSY models and corresponding number of publications)

Flavor problem

The EFT (either approach) generically contains terms that mediate $\Delta F = 2$ or FCNC decays at tree level and suppressed only by $c/\Lambda_{\rm NP}^{n-4}$ (with $c \sim 1$)

with $n - 4 = 2$ this requires $\Lambda_{\rm NP}$ in excess of 10^4 TeV from, *e.g.*, K-mixing

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$$\frac{1}{\Lambda_{\rm NP}^2}\left[z_1^K(\overline{d_L}\gamma_\mu s_L)(\overline{d_L}\gamma^\mu s_L) + z_1^D(\overline{u_L}\gamma_\mu c_L)(\overline{u_L}\gamma^\mu c_L) + z_4^D(\overline{u_L}c_R)(\overline{u_R}c_L)\right]$$

$$|z_1^K| \leq z_{\rm exp}^K = 8.8\times 10^{-7}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

$$|z_1^D| \leq z_{\rm exp}^D = 5.9\times 10^{-7}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

$$\mathcal{I}m(z_1^K) \leq z_{\rm exp}^{IK} = 3.3\times 10^{-9}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

$$\mathcal{I}m(z_1^D) \leq z_{\rm exp}^{ID} = 1.0\times 10^{-7}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

(Nir, Perez, Weiler, talks Planck2009)

bottom-up

Minimal Flavor Violation (MFV)

Buras et al (several)
D'Ambrosio etal
Haisch & Weiler
Lunghi et al

In SM only the Yukawa couplings break the flavor symmetry

$$\mathscr{L} = \bar{Q}_L Y_D D_R H + \bar{Q}_L Y_U U_R H_c + \bar{L}_L Y_E E_R H \ + \ \text{h.c.}$$

Assume this is only source of flavor symmetry breaking.
Extend SM (same fields) by tower of higher dim operators (keep only dim 5-6).
Yukawas as spurions, eg, $\bar{Q}_L Y_U Y_U^\dagger Q_L \,, \quad \bar{D}_R Y_D^\dagger Y_U Y_U^\dagger Q_L \,, \quad \bar{D}_R Y_D^\dagger Y_U Y_U^\dagger Y_D D_R \,.$

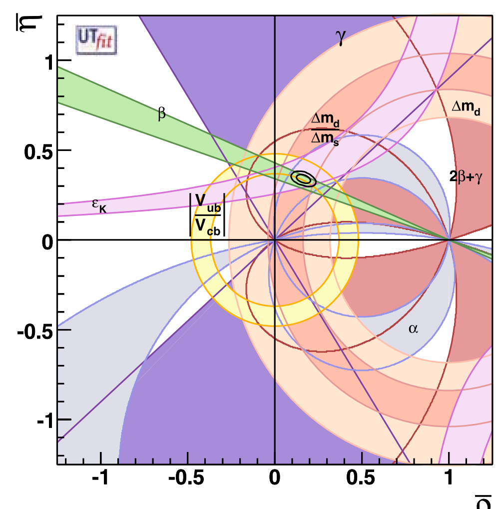
Classify operators of interest. Bound.

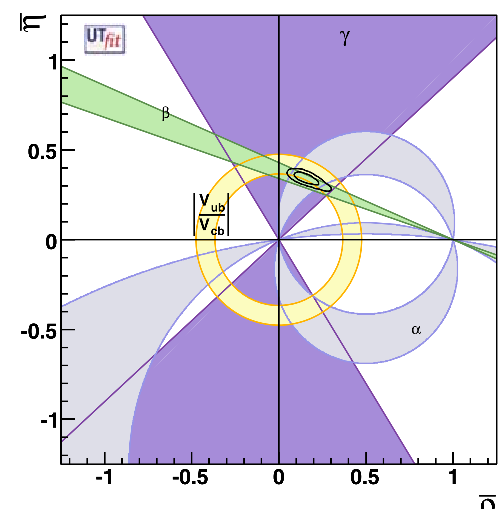
Minimally flavour violating dimension six operator	main observables	Λ [TeV] −	Λ [TeV] +		update −	update +
$\mathcal{O}_0 = \frac{1}{2}(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)^2$	$\epsilon_K, \quad \Delta m_{B_d}$	6.4	5.0		8.8	5.9
$\mathcal{O}_{F1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$B \to X_s \gamma$	9.3	12.4		9.0	5.0
$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.6	3.5			
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7	*	3.2	3.7
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0	*		
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6	*	2.0	2.0
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi, \quad \epsilon'/\epsilon, \ldots$	~ 1				

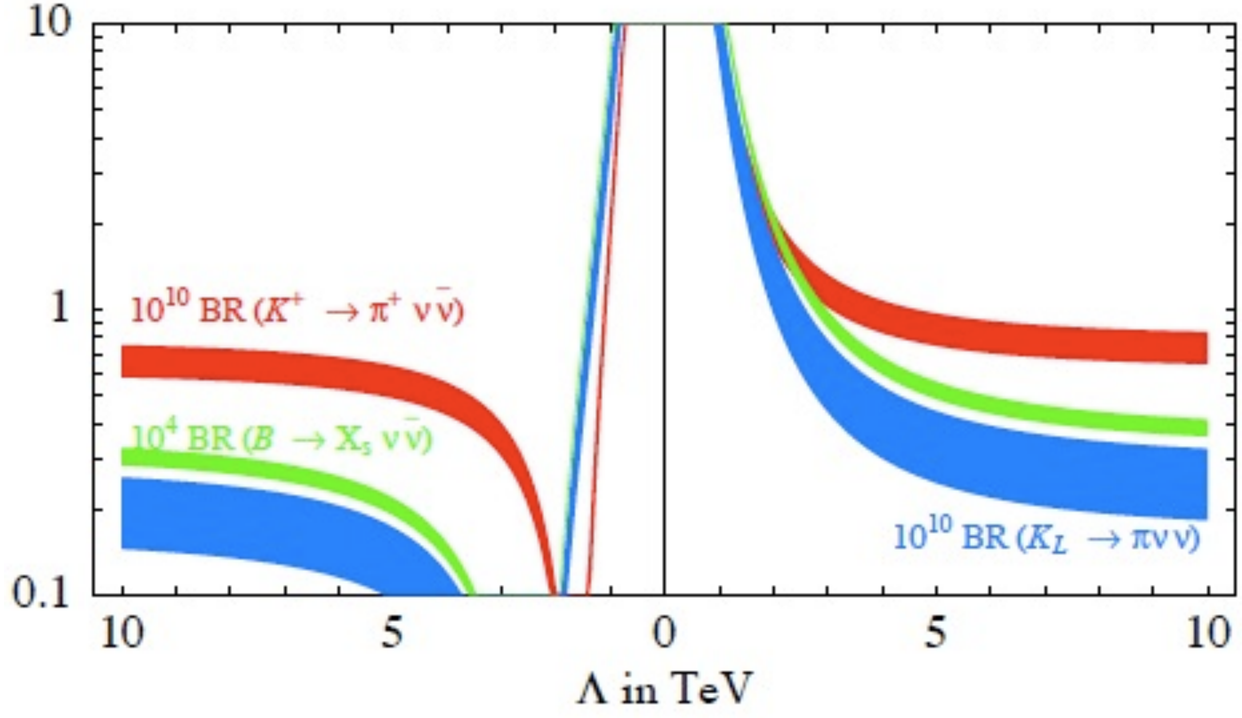
$$Y_D = \lambda_d \,, \qquad Y_L = \lambda_\ell \,, \qquad Y_U = V^\dagger \lambda_u \,, \qquad (\lambda_{\rm FC})_{ij} = \begin{cases} \left(Y_U Y_U^\dagger\right)_{ij} \approx \lambda_t^2 V_{3i}^* V_{3j} & i \neq j \,, \\ 0 & i = j \,. \end{cases}$$

comments

- Many specific models covered by the MFV analysis, among them
    - two-Higgs-doublet model (2HDM) types I and II, for small tanβ
    - the minimal-supersymmetric SM (MSSM) with MFV, for small tanβ
        - MSSM with gauge mediation SUSY breaking
    - minimal universal extra dimension (mUED) model
    - littlest Higgs model with T-parity (LHT)
    - littlest Higgs model with degenerate mirror fermions
- With two H doublets, at large tanβ, additional operators relevant.
  Single H case is “constrained” MFV (CMFV)
- Not enough CP for baryogenesis. Additional CP in lepton extension “MLFV,” sufficient leptogenesis
- General analysis of CMFV:
  11 parameters (= 4 CKM + 7 C_i’s)
  (tree level γ and V_{ub} always unaffected,
  now also β and α).



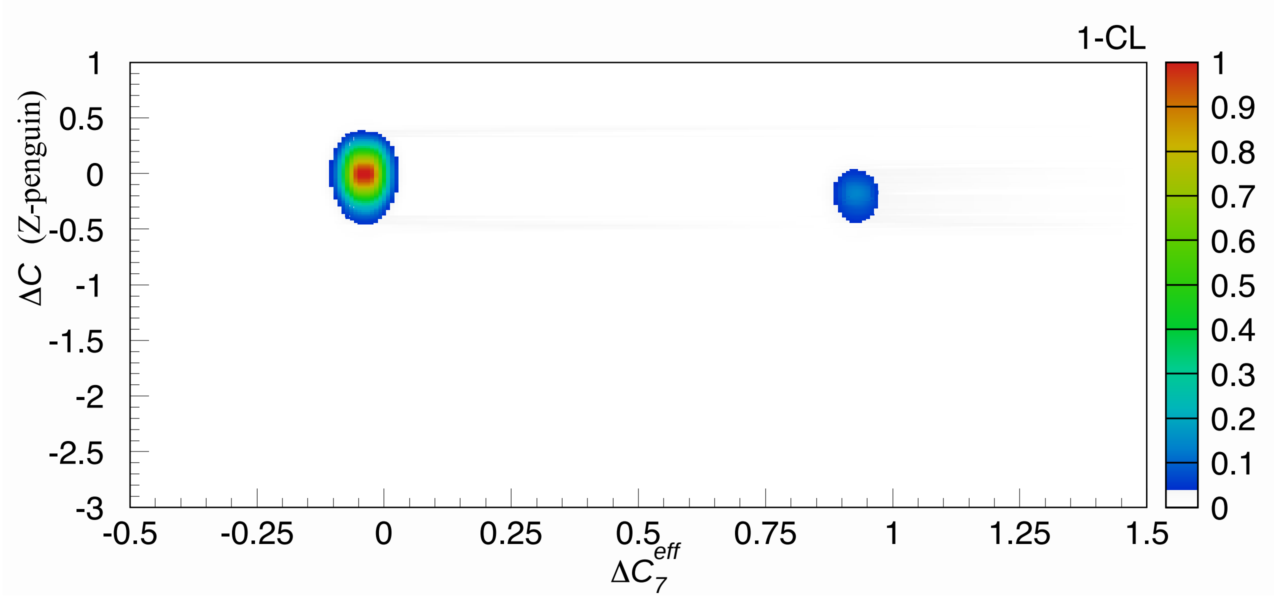




old fashioned

D'Ambrosio etal

new...



Haisch & Weiler

technology change

2HDM & MFV at large $\tan\beta$

2HDM = 2 Higgs doublet model

- minimalistic extension of SM (not really NP, it does not solve anything).
- possible limit (or component) of real NP (eg, SUSY)

spectrum $h^\pm, H^0, h^0, a^0$ (8 fields - 3 eaten = 5 particles)

- flavor problem: huge FCNC's (tree level) from FC couplings of neutral scalars
- solution: restrict couplings to quarks (& leptons) Glashow & Weinberg '77ish

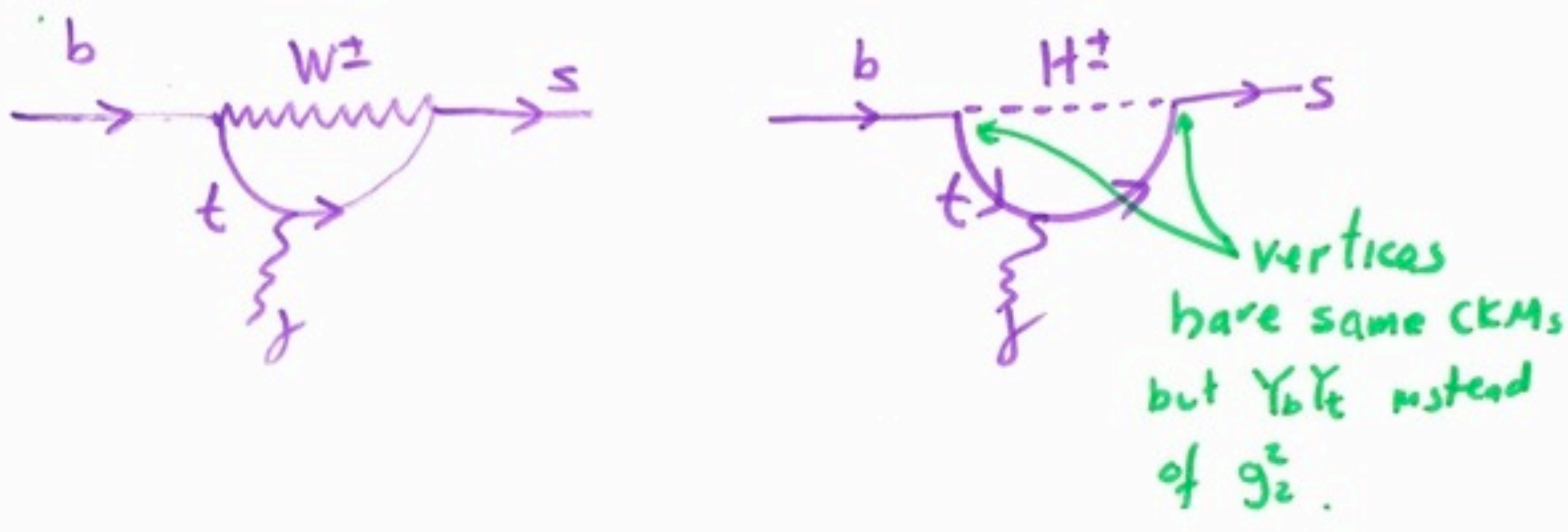
$$\mathcal{L}_Y = \bar{Q}_L Y_D D_R H_D + \bar{Q}_L Y_U U_R H_U + \bar{L}_L Y_E E_R H_D \text{ h.c.}$$

(alternatively, couple all ψ's to one H, none to the other H').

- $\mathcal{L}_Y$ has additional PQ symmetry (must break in V(H)).
- New parameter $\tan\beta \equiv \frac{\langle H_U \rangle}{\langle H_D \rangle} = \frac{v_U}{v_D}$

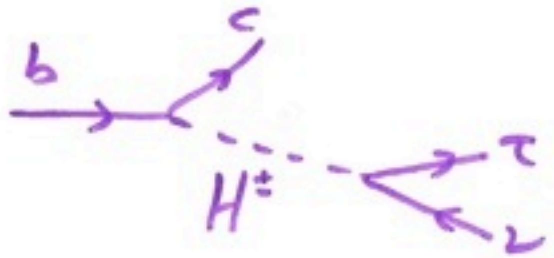
- normalization of $Y_{U,D,E}$ controlled by $v = \sqrt{v_U^2 + v_D^2}$ and $\tan\beta$
- at (large) $\tan\beta \gg 1$ m_b/m_t is small because $1/\tan\beta \ll 1$, while $Y_b \sim Y_t \sim 1$.

→ effects significant in processes that are 1-loop in SM (ie, $H^\pm$ exchange competes with $W^\pm$ exchange, no longer suppressed by $Y_b \sim \frac{m_b}{M_W}$)



Hou, '93
Isidori, '93

Sometimes even at tree level !



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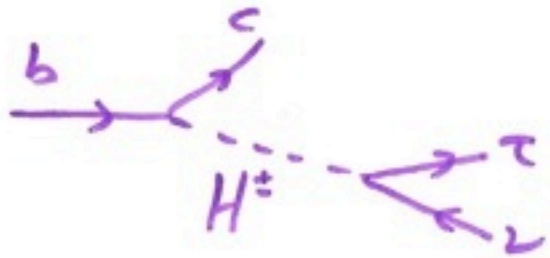

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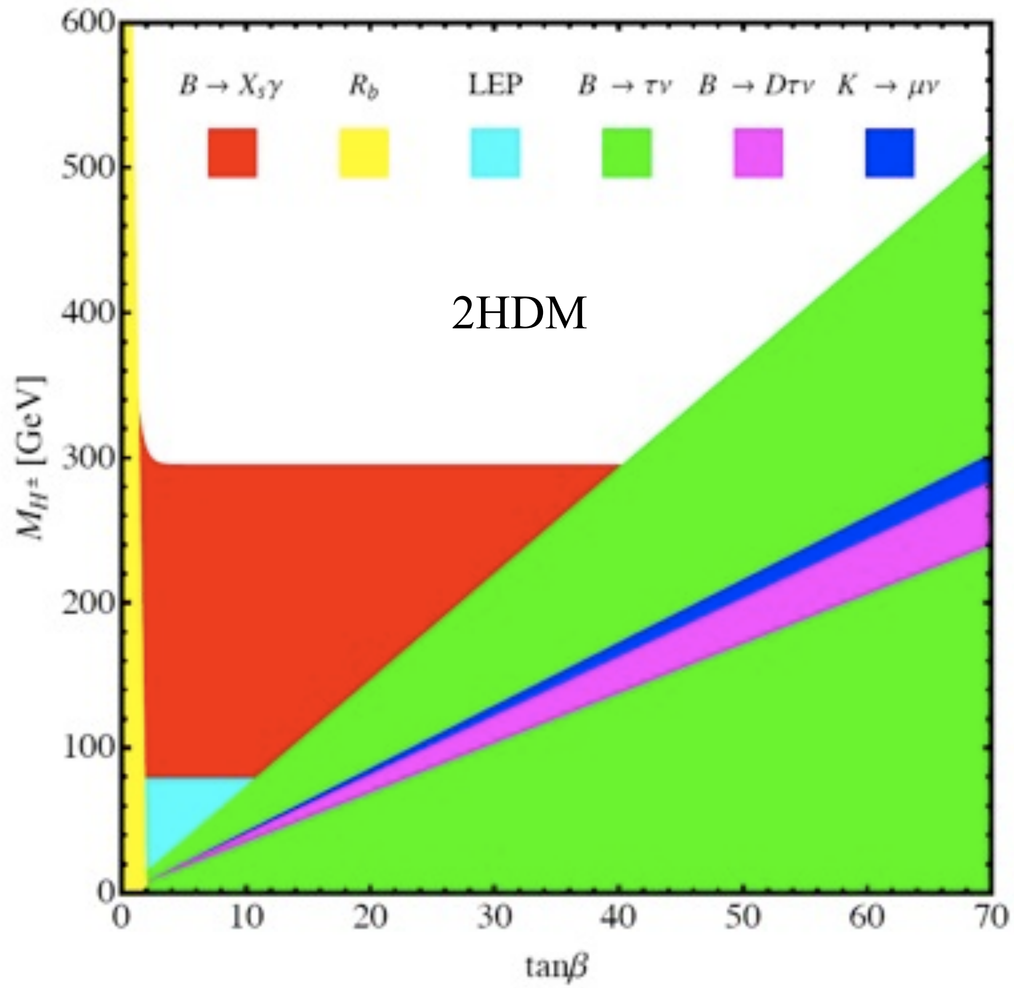


MFV @ $\tan\beta \gg 1$

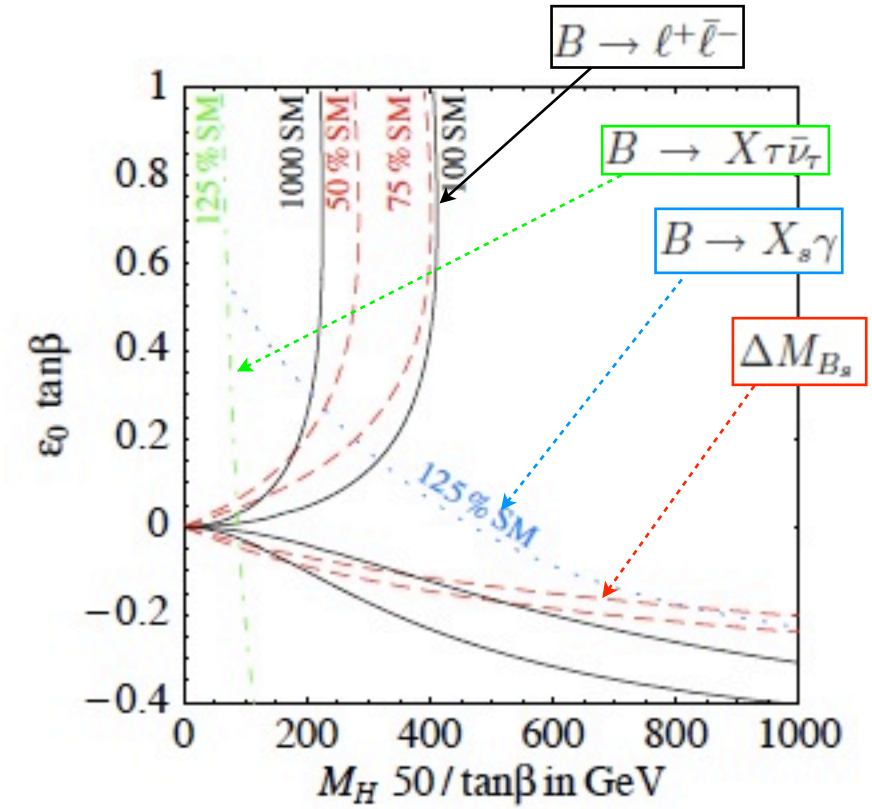
- Same construction (list operators, use symmetries, $Y_{U,D}$ as spurions) but now
  - include $H_{u,D}$ (with PQ sym?)
  - Y_D is not negligible

$\Rightarrow$ enlarged basis of significant terms

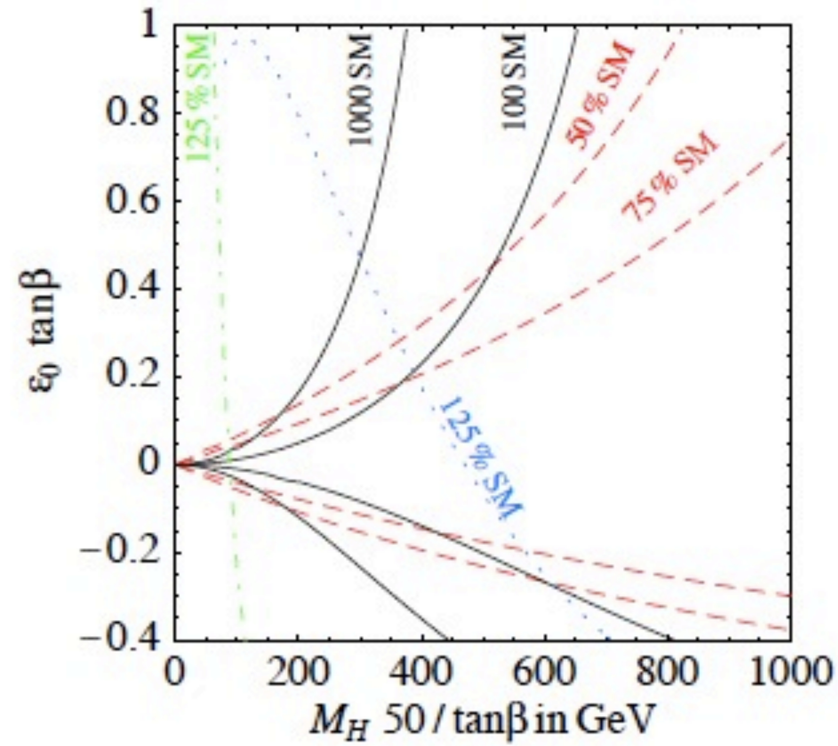
$\Rightarrow$ substantial connection between K & B amplitudes in 1H-MFV destroyed (weakened)

- $Y_b \sim 1$ $\rightarrow$ affects helicity suppressed observables in B physics

- $Br(B^- \to \ell^- \nu)$ suppressed (rel SM) by $\left(1 - \frac{m_b^2}{m_{H^\pm}^2}\tan^2\beta\right)^2 \sim 10\%-50\%$
- $B \to X_s \gamma$, ΔM_{B_s} $\sim$ 10-30 % effects
- $B \to \ell^+ \ell^-$ huge!



$\epsilon_2 = \epsilon_0$



$\epsilon_2 = -\epsilon_0$

D'Ambrosio etal

here used PQ breaking in Yukawa terms, with small parameters:

$$\mathscr{L}_{\epsilon Y_D} = \bar{Q}_L \left(\epsilon_0 + \epsilon_1 \Delta + \epsilon_2 \hat{\lambda}_{\rm FC} + \epsilon_3 \hat{\lambda}_{\rm FC} \Delta + \epsilon_4 \Delta \hat{\lambda}_{\rm FC}\right) \hat{\lambda}_d D_R (H_U)^c \ + \ \text{h.c.},$$

SMOKING GUN FOR MFV @ $\tan\beta \gg 1$

An enhancement of both

$$B_s \to \ell^+\ell^- \quad \text{and} \quad B_d \to \ell^+\ell^-$$

with

$$\frac{\Gamma(B_s \to \ell^+\ell^-)}{\Gamma(B_d \to \ell^+\ell^-)} \approx \left|\frac{V_{ts}}{V_{td}}\right|^2$$

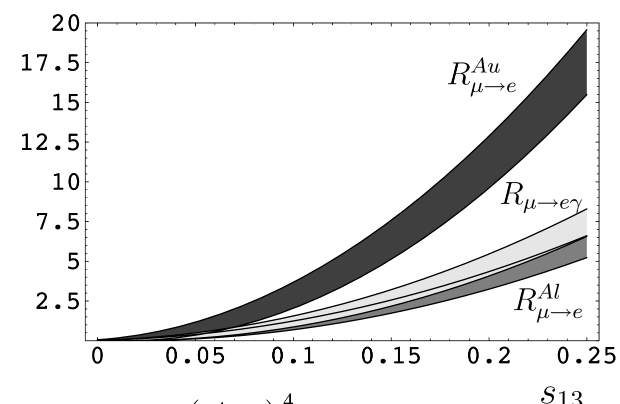
B,D and K Decays, Buchalla et al, Eur. Phys. J. C (2008) 57: 309–492

More correlations → MFV w. GUTs $b \to s\gamma$ … $\mu \to e\gamma$

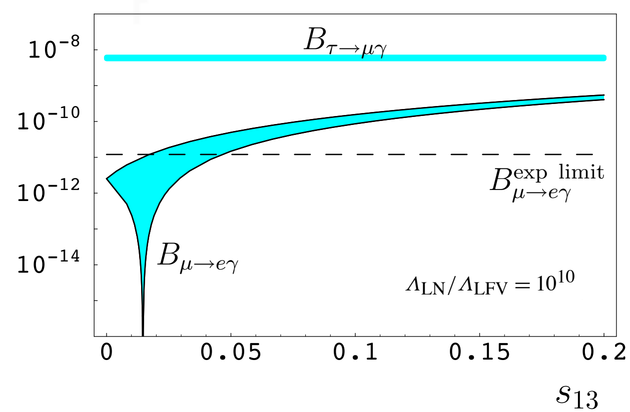
→ specific models… top-down approach

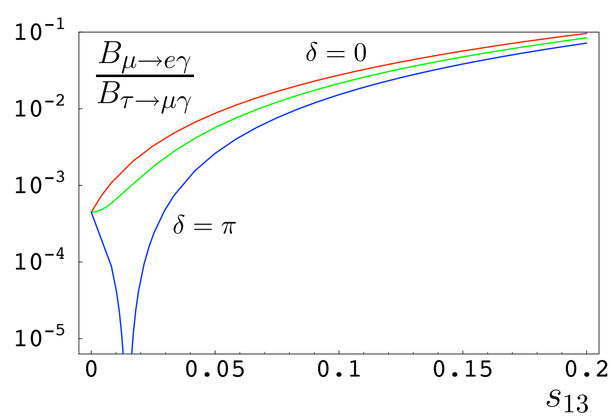
↓

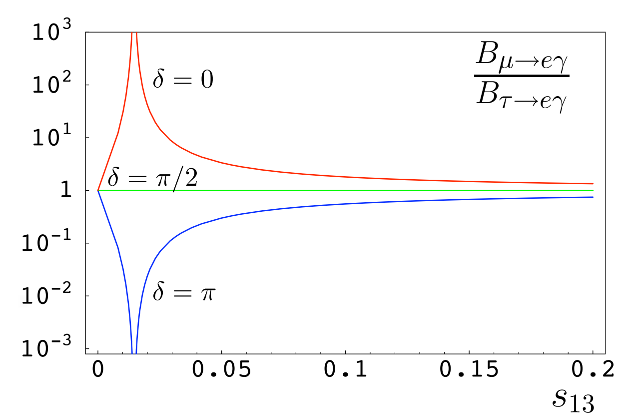
let's talk SUSY



$$B_{\ell_i\to\ell_j(\gamma)} = 10^{-50}\left(\frac{\Lambda_{\rm LN}}{\Lambda_{\rm LFV}}\right)^4 R_{\ell_i\to\ell_j(\gamma)}(s_{13},\delta;c^{(i)})$$







(quark mass/mixing induced terms neglected)

Cirigliano et al

Top-down

Top-Down Approach

- flavor problem imposes severe constraints on most models
- hence, models often built to naturally exhibit MFV
  (and sometimes not so naturally)
- not all flavor-safe models incorporate MFV hypothesis
  - generic* SUSY/MSSM (with or without R parity) ☹

  vs

  - Lee-Wick SM ☺

* $m_{1/2}, m_0$ large?

SUSY

Gazillion versions....

To begin to specify a bit, consider only

$$G_{gauge} = SU(3)_C \times SU(2)_W \times U(1)_Y$$

Def: MSSM particle (field) content

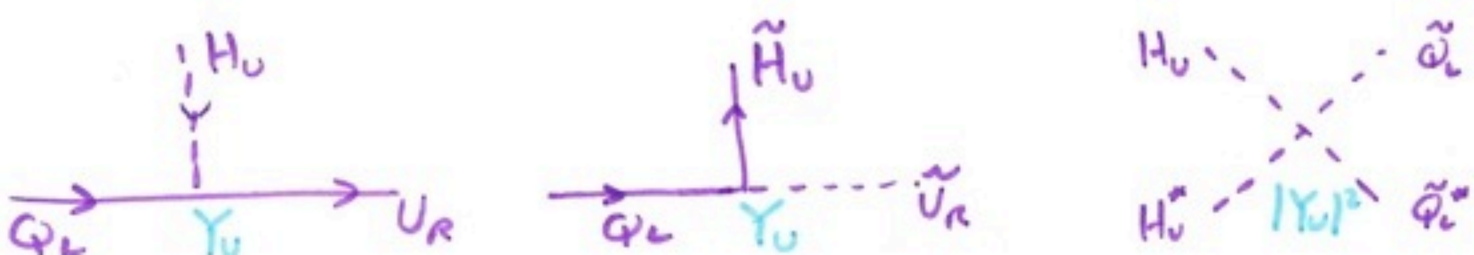
ψ (spin-1/2)	Q_L	U_R	D_R	L_L	E_R	$\tilde{H}_U$	$\tilde{H}_D$
ϕ (spin-0)	$\tilde{Q}_L$	$\tilde{U}_R$	$\tilde{D}_R$	$\tilde{L}_L$	$\tilde{E}_R$	H_U	H_D

"$\widetilde{\text{gauge}}$"

— content of 2HDM

$\sim$ Δspin = 1/2 partners

\+ Interactions with dimensionless couplings (dim = 4 terms in $\mathcal{L}$) constrained by SUSY, eg



+ one (unique) set of SUSY interactions with couplings with mass dimension, "μ-term"

$$W = \mu\, \Phi_{H_U} \Phi_{H_D} \leftrightarrow V = \mu\, \bar{\tilde{H}}_U \tilde{H}_D + \mu^2 (H_U^\dagger H_U + H_D^\dagger H_D)$$

+ arbitrary "soft-SUSY-breaking" interactions

- masses, eg, $\hat{m}^2_{Q_L} |\tilde{Q}_L|^2$, $m_{1/2} \bar{\Psi}_g \Psi_g$ (gluino)
- cubic (must be after Yukawa terms): eg, $m_0 A\, \tilde{Q}_L^* H_U U_R$

The minimal in MSSM refers to particle content.

Motivated by $N=1$ supergravity mediated breaking with radiative EW breaking.

- MSSM is a flavor disaster

Ellis et al, '82
Dugan et al '85
Barbieri et al, '82

- semi bottom-up approach: assume MSSM with MFV

susy terms are already ok. susy bkg:

$$\Rightarrow \quad \tilde{m}^2_{Q_L} = \tilde{m}_0^2 \left(a_1 \mathbb{1} + b_1 Y_U Y_U^\dagger + b_1' Y_D Y_D^\dagger + \cdots \right)$$

$$\tilde{m}_{U_R} = \tilde{m}_0^2 \left(a_2 \mathbb{1} + b_2 Y_U^\dagger Y_U + \cdots \right)$$

$$\tilde{m}_{D_R} = \tilde{m}_0^2 \left(a_3 \mathbb{1} + b_3 Y_D^\dagger Y_D + \cdots \right)$$

$$A_U = A \tilde{m}_0 \left(a_4 Y_U + b_4 Y_D Y_D^\dagger Y_U + \cdots \right)$$

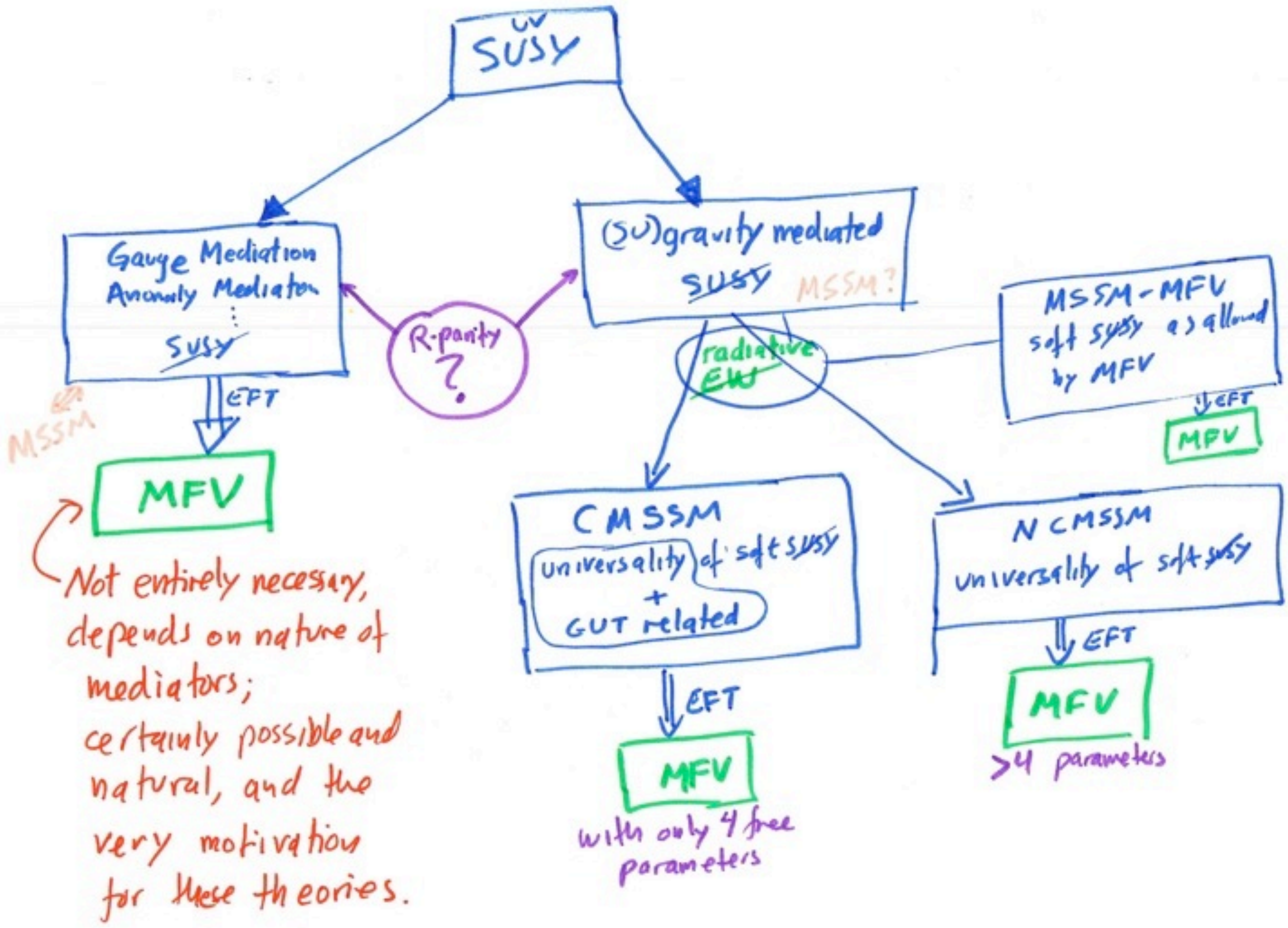
$$A_D = A \tilde{m}_0 \left(a_5 Y_D + b_5 Y_U Y_U^\dagger Y_D + \cdots \right)$$

- get EFT integrating out susy partners* $\Rightarrow$
  - moderate $\tan\beta$ is GMFV with
  - $\tan\beta \gg 1$ is MFV large $\tan\beta$ with

  $\Lambda \approx 4\pi \tilde{m}_0$

$\Rightarrow$ given bounds from MFV, this is ok provided $\tilde{m}_0 \gtrsim \frac{(\text{few TeV})}{4\pi}$

* except, perhaps, LSP


UV SUSY
Gauge Mediation
Anomaly Mediation
SUSY
(SU)gravity mediated
SUSY
MSSM?
R-parity ?
EFT
MSSM
MFV
radiative EW
MSSM-MFV
soft susy as allowed by MFV
EFT
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CMSSM
universality of soft susy + GUT related
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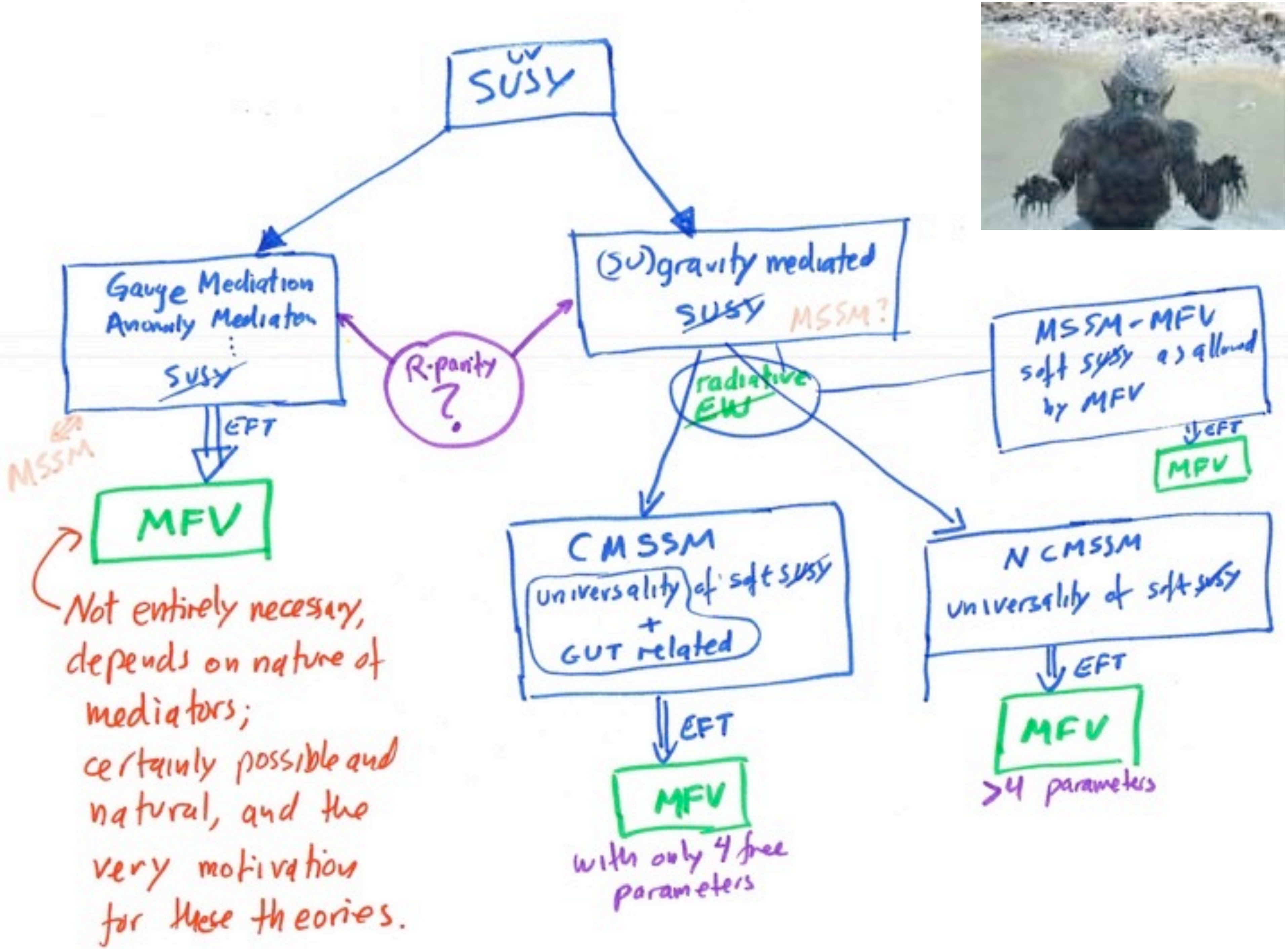
>4 parameters
EFT
MFV
with only 4 free parameters
Not entirely necessary, depends on nature of mediators; certainly possible and natural, and the very motivation for these theories.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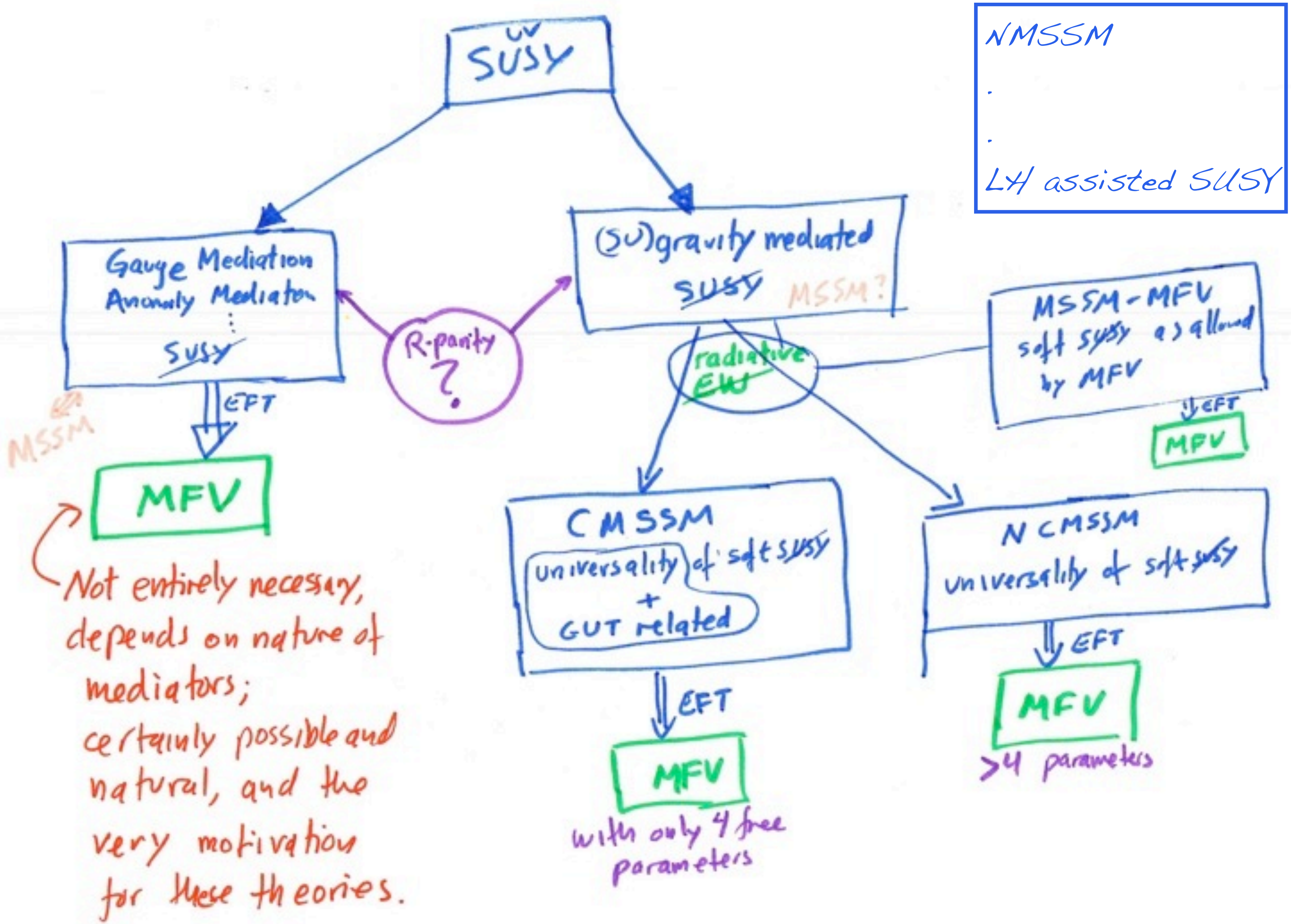
UV
SUSY
NMSSM
.
.
LH assisted SUSY
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R-parity breaking

$$W = h^U Q H_U u^c + h^D Q H_D d^c + h^L L H_D e^c + \mu H_U H_D$$
$$+ \mu' H_U L + \lambda''_{ijk} u_i^c d_j^c d_k^c + \lambda'_{ijk} Q_i L_j d_k^c$$
$$+ \lambda_{ijk} L_i L_j e_k^c,$$

B-violation... Proton decay

Even if λ taken arbitrarily to vanish for first generation $\lambda' \times \lambda'' < 10^{-7}$

Can set $\lambda'' = 0$ by B-parity.

Produce significant FC effects.

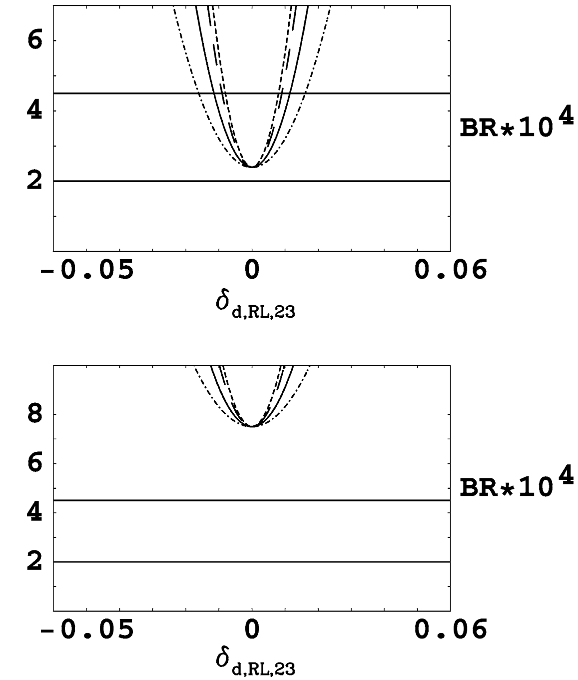
Loss of correlations (both to CKM and among FCNC processes)

General MSSM

Ruled out unless squarks almost degenerate
Assume small

$$\delta = \frac{\Delta m^2}{\bar{m}^2}$$

and bound



Besmer et al, NPB609:359,2001

Table 3 95% probability bounds on $|(\delta^q_{ij})_{AB}|$ obtained for squark and gluino masses of 350 GeV. See the text for details

BDK-review

$\lvert(\delta^d_{12})_{LL,RR}\rvert$	$\lvert(\delta^d_{12})_{LL=RR}\rvert$	$\lvert(\delta^d_{12})_{LR}\rvert$	$\lvert(\delta^d_{12})_{RL}\rvert$
1×10^{-2}	2×10^{-4}	5×10^{-4}	5×10^{-4}
$\lvert(\delta^u_{12})_{LL,RR}\rvert$	$\lvert(\delta^u_{12})_{LL=RR}\rvert$	$\lvert(\delta^u_{12})_{LR}\rvert$	$\lvert(\delta^u_{12})_{RL}\rvert$
3×10^{-2}	2×10^{-3}	6×10^{-3}	6×10^{-3}
$\lvert(\delta^d_{13})_{LL,RR}\rvert$	$\lvert(\delta^d_{13})_{LL=RR}\rvert$	$\lvert(\delta^d_{13})_{LR}\rvert$	$\lvert(\delta^d_{13})_{RL}\rvert$
7×10^{-2}	5×10^{-3}	1×10^{-2}	1×10^{-2}
$\lvert(\delta^d_{23})_{LL}\rvert$	$\lvert(\delta^d_{23})_{RR}\rvert$	$\lvert(\delta^d_{23})_{LL=RR}\rvert$	$\lvert(\delta^d_{23})_{LR,RL}\rvert$
2×10^{-1}	7×10^{-1}	5×10^{-2}	5×10^{-3}

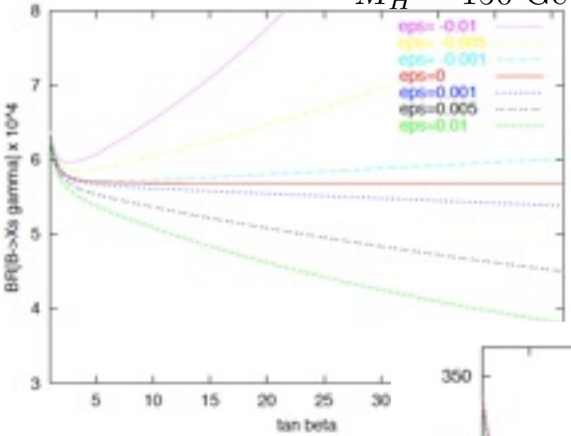
CMSSM (at large tan β, possibly)

$\tan\beta \sim 1$ charged Higgs and chargino exchanges dominant

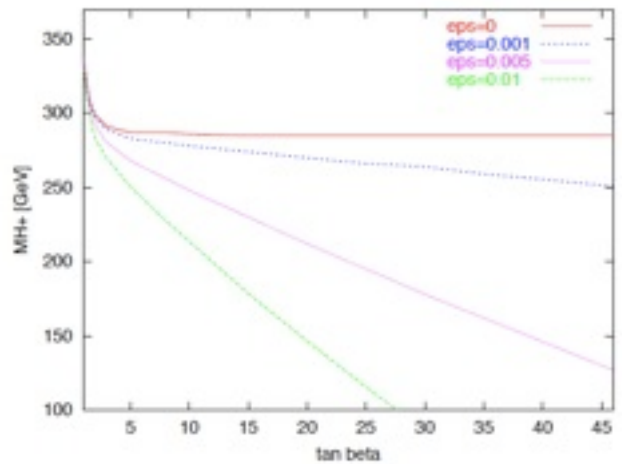
$\tan\beta \gg 1$ Higgs exchange dominant

five new (beyond SM) parameters

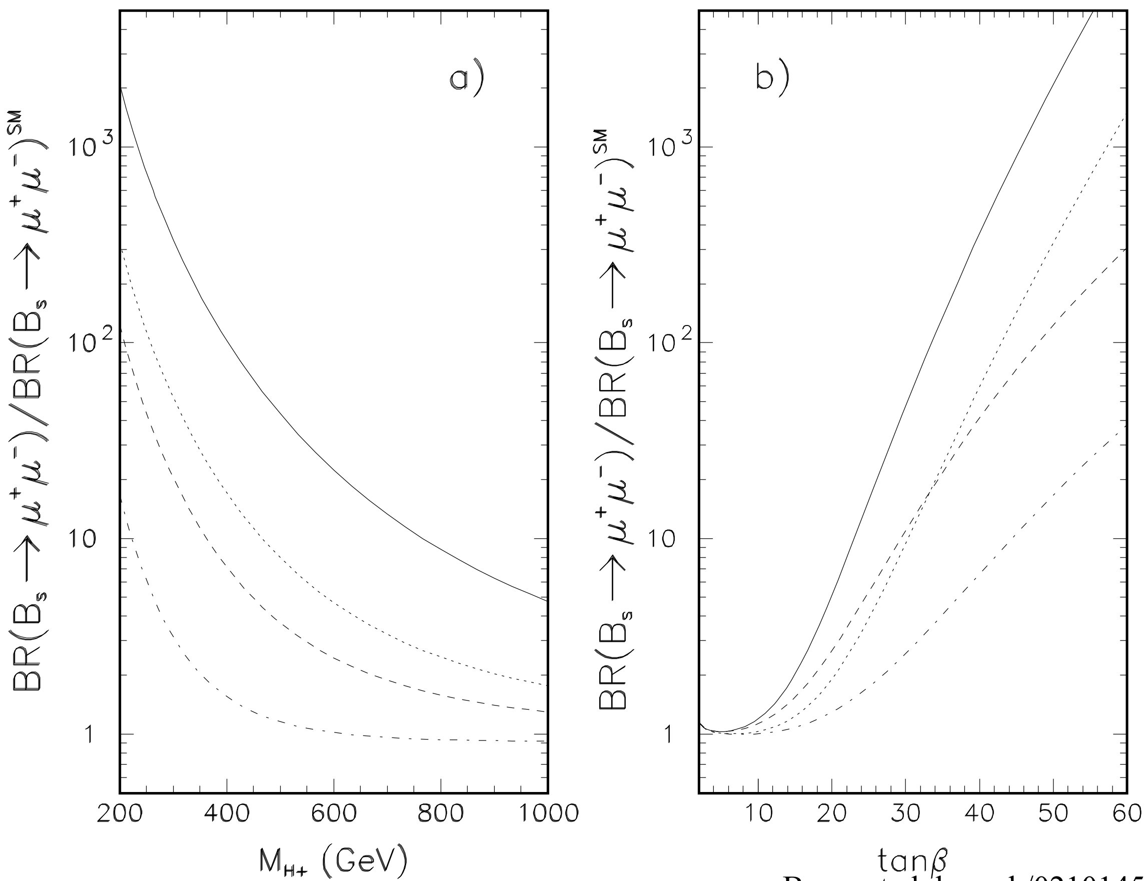
$M_H = 150$ GeV



Degrassi et al, hep-ph/0009337

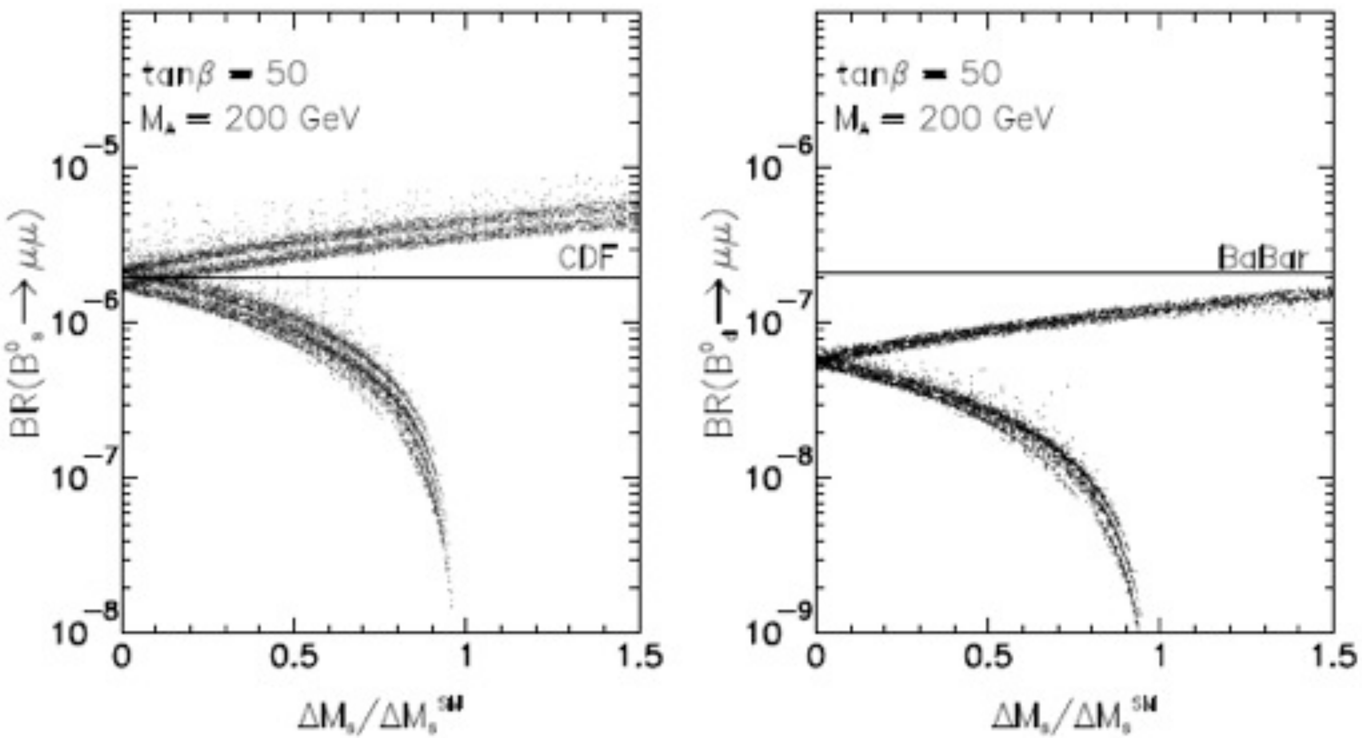


$$m_b = \sqrt{2} M_W \, \frac{y_b}{g} \, \cos\beta \, (1 + \epsilon_b \tan\beta) \, .$$



Buras et al, hep-ph/0210145

correlations ...



Buras et al, hep-ph/0207241

(branches: sign of 1+f_s)

$$\Delta M_{s,d}/(\Delta M_{s,d})^{\rm SM} \equiv |1+f_{s,d}|$$

The End

Flavor Physics imposes strong restrictions on New Physics

Evaded by MFV and any NP that reduces to that at long distances

Evaded also by extensions of MFV or even some other NP (so cannot conclude MFV is necessary)

Correlations are predicted, how much depends on assumptions

SUSY mush (how predictive depends on assumptions), but often just like 2HDM