ANARCHY vs. STRUCTURE

(flavor in supersymmetry)

based on GH, Y. Hochberg and Y. Nir, 0812.0511 [hep-ph], JHEP03(2009)115, and 1001.asap.

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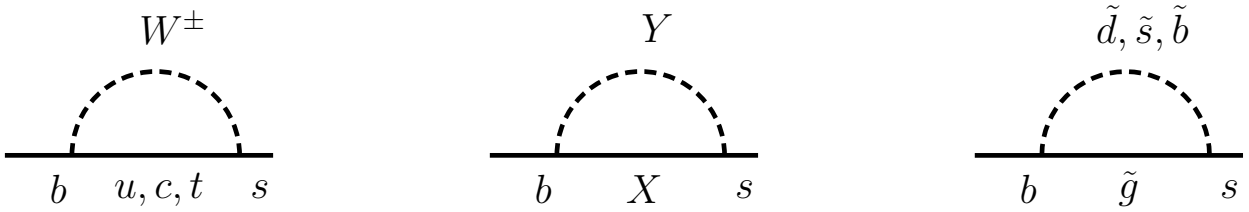
6.1.2010



The absence of O(1) New Physics observations in FCNC-processes implies that physics at theTeV-scale has non-generic flavor properties.

In particular, suppression mechanisms of similar power as CKM and GIM, which are built-in in the SM, need to be at work.

Minimal Flavor Violation (MFV)

A model-independent framework, which passes all current flavor-tests, is to assume that flavor is broken only through the Yukawa matrices, as in the SM.

This is termed minimal flavor violation.

Chivukula, Georgi '87; d'Ambrosio et al '02 non-symmetry based definitions: Ali,London '99; Buras^2 '00

Very predictive framework.

As in the SM, the origin of flavor is not addressed.

Yukawa Matrices

$$Y_u \sim \begin{pmatrix} 10^{-5} & -0.002 & 0.008 + i\,0.003 \\ 10^{-6} & 0.007 & -0.04 \\ 10^{-8} + i\,10^{-7} & 0.0003 & 0.94 \end{pmatrix}$$

$$Y_d \sim \mathrm{diag}\left(10^{-5}, 5 \cdot 10^{-4}, 0.025\right) \quad (\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle})$$

$$Y_e \sim \mathrm{diag}\left(10^{-6}, 6 \cdot 10^{-4}, 0.01\right) \quad (\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle})$$

Very peculiar pattern.

* The superpotential ($N = 1$, unbroken R-parity) is MFV.

$$W_{MSSM} = Q Y_u H_u U + Q Y_d H_d D + L Y_e H_d E + \mu H_d H_u$$

* Squark flavor-mixing within MFV expressed through quark-Yukawas

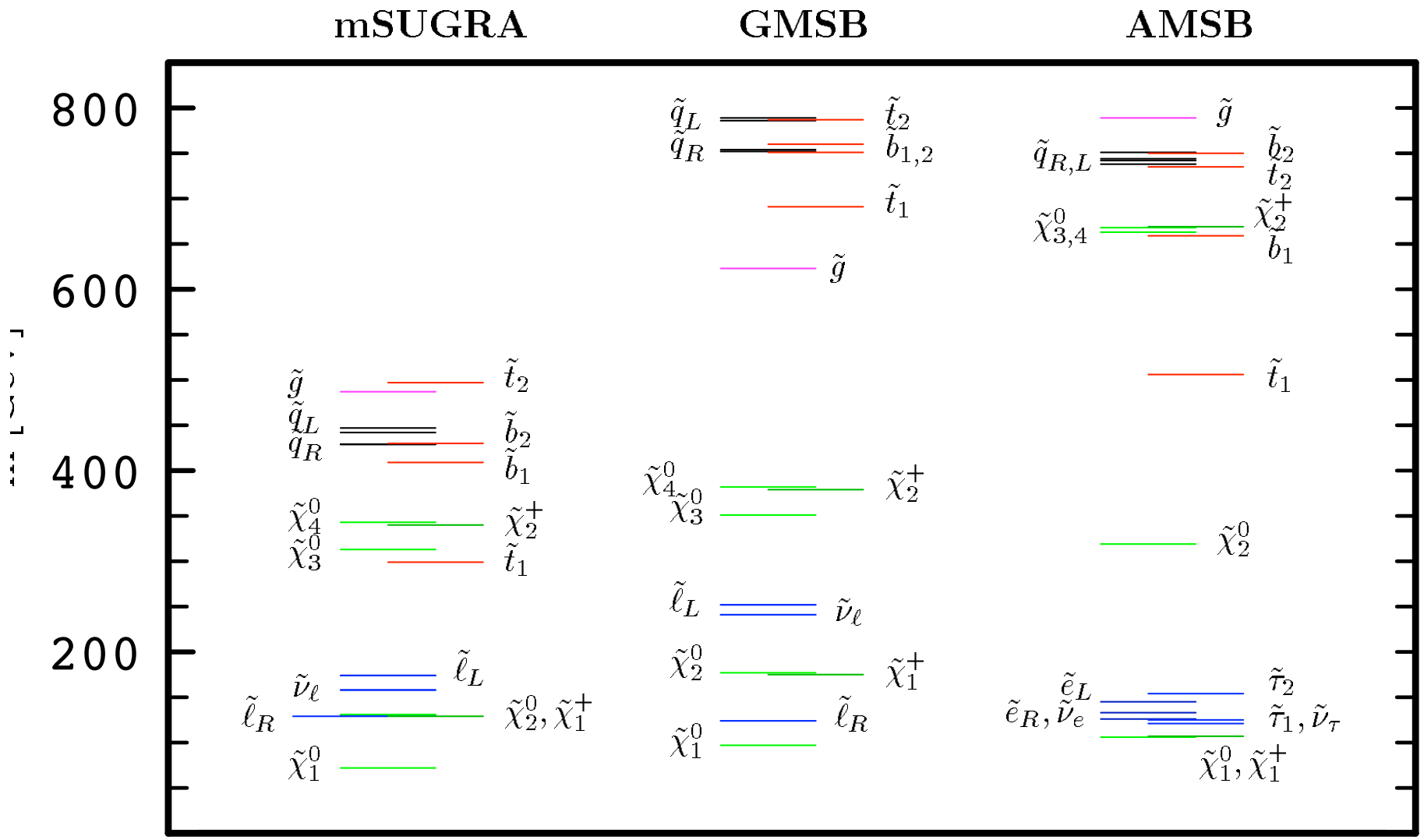
$$\tilde{M}_Q^2 \;=\; \tilde{m}^2 (a_1 \mathbf{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger) \quad \text{etc.}$$

Controlled departure from flavor-blind SUSY breaking.

* Anomaly mediation, gauge mediation and CMSSM/mSUGRA (by construction) are MFV.

* Generic feature of such models are highly degenerate first and second generation squarks.

MFV MSSM Spectra



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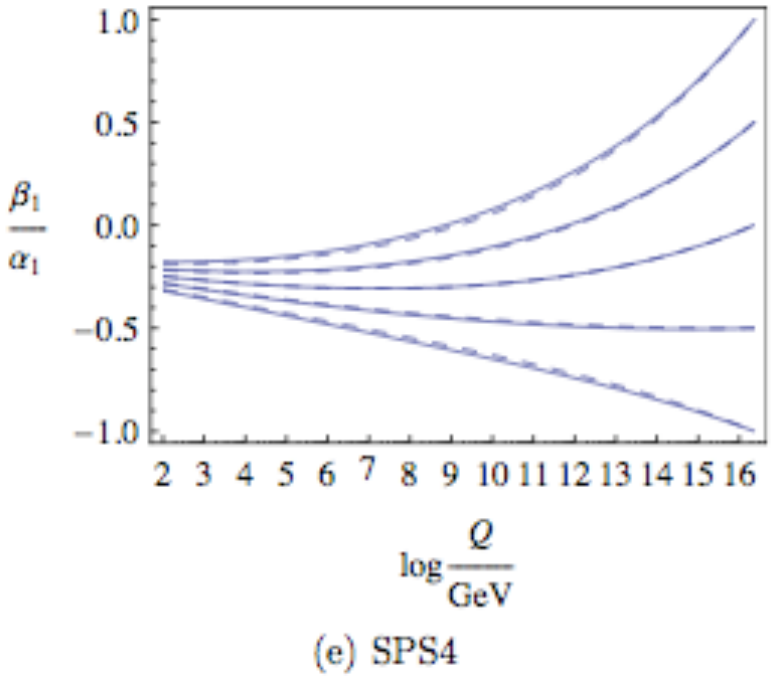
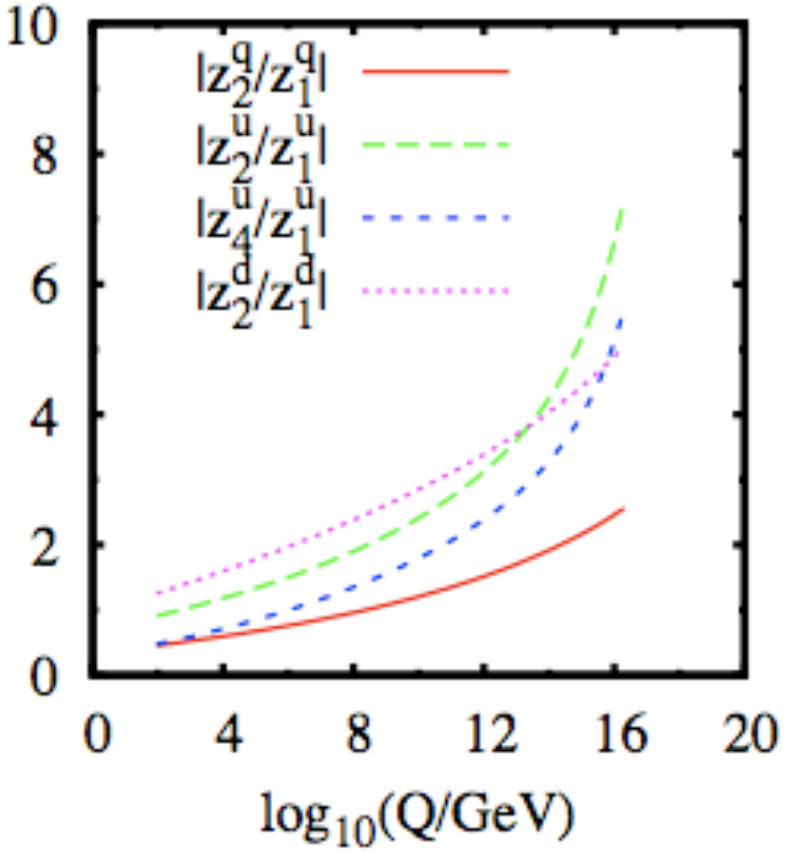
Running MFV Coefficients b_i/a_j

$$\tilde{M}_Q^2 = \tilde{m}^2(a_1 \mathbf{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger)$$

left Fig.: 0805.3989 [hep-ph], right: AMSB 0902.4880 [hep-ph]



(e) SPS4



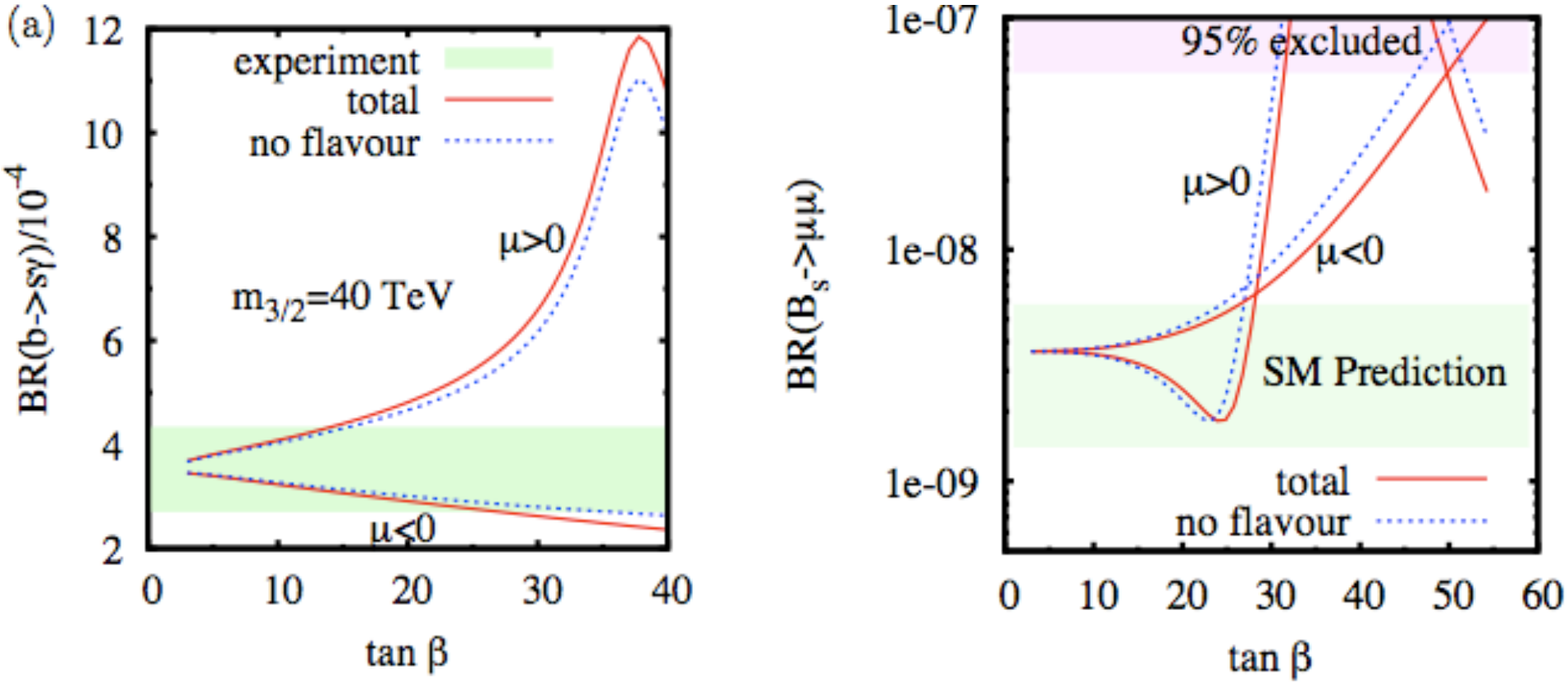
RG-running suppresses flavor violation towards the weak scale.

For low $\tan\beta$, (minimal) anomaly mediation becomes exactly flavor blind in the QIR-fixed point limit of the top-Yukawa.

Predictivity and large effects in FCNC loops

* Predictive $\mathcal{O}(1)$ effects within MFV models if $\tan\beta$ largish. many works

Here, AMSB ($m_{3/2} = 40$ TeV) Figs from Allanach et al 0902.4880

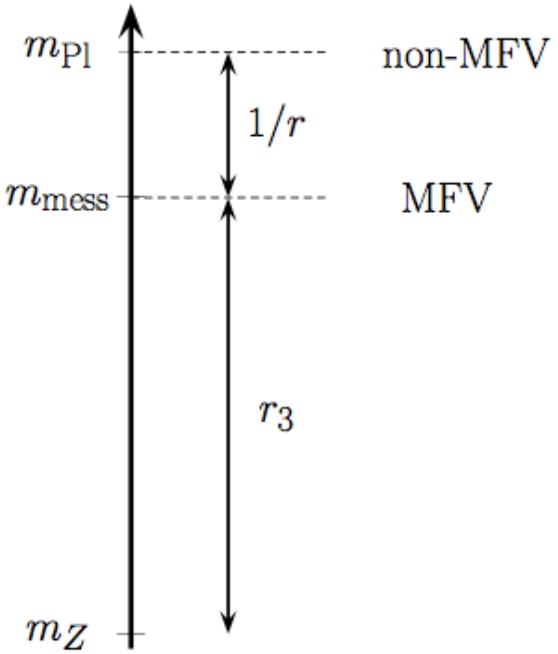


Analytical expressions for the full flavor structure, that is, a_i, b_j or $(\delta^q)_{ij}$, within mAMSB 0902.4880 .

A viable non-MFV model ?

* realistic, viable
* at which level do non-MFV effects in which observables appear?
* access structure of flavor breaking thru non-MFV: anarchy vs symmetry

Framework Hybrid Gauge Gravity Mediation

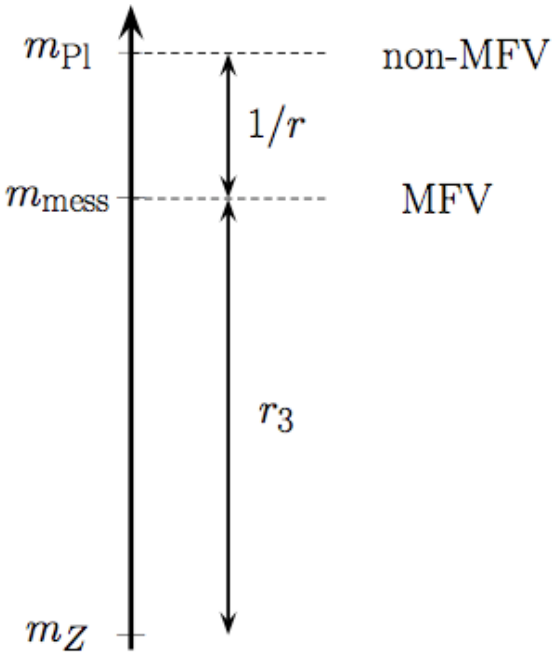


Consider gauge mediation, which is MFV, in the background of gravity mediation. related works (sleptons): Feng et al, 0712.0674; Nomura et al, 0712.2074, 0802.2582

* Can we probe the (always present) effects from gravity mediation with gauge mediation being the dominant effect of SUSY-breaking ?

* Is the model viable, or, what are the current flavor constraints?

Hybrid Gauge-Gravity Mediation:Intro

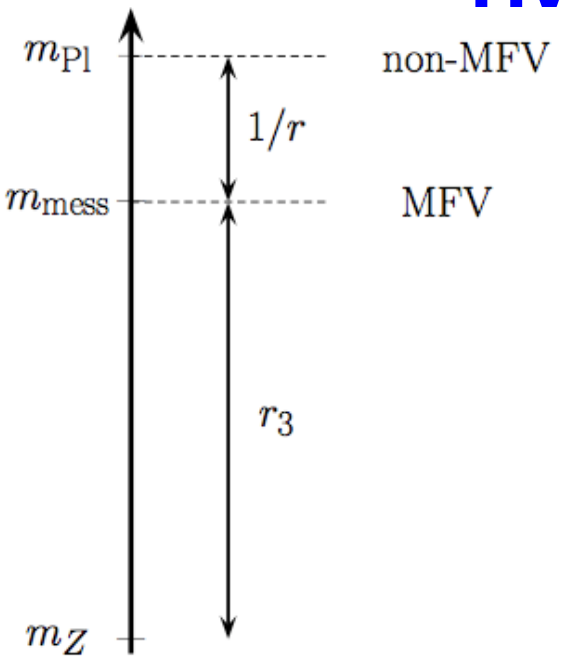


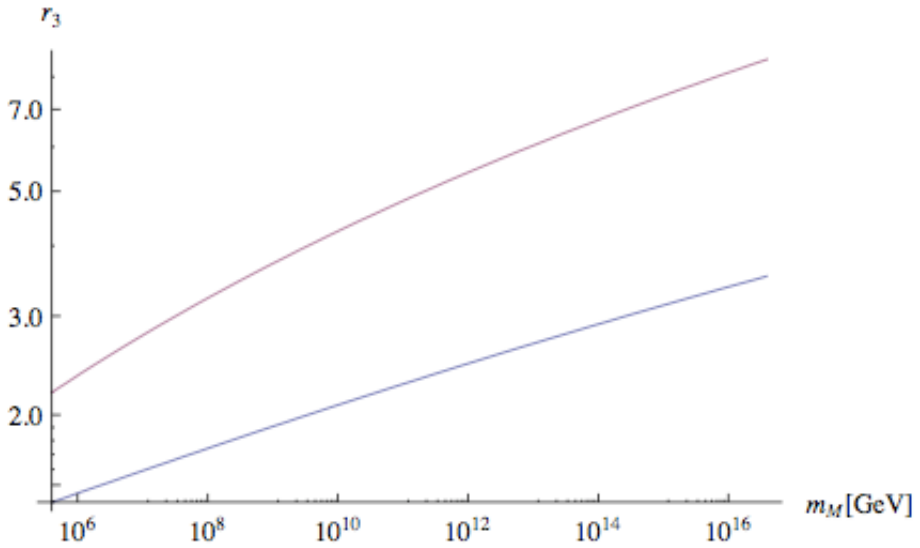
Let X_{Q_L} be the flavor structure of gravity-mediated squark masses:

$$M^2_{\tilde{Q}}(m_Z) \sim \tilde{m}^2_Q(r_3\mathbf{1} + c_u Y_u Y_u^\dagger + c_d Y_d Y_d^\dagger + r X_{Q_L})$$

Flavor observables probe off-diagonals $\sim r/r_3 X_{Q_L}$, i.e., the flavor structure and the separation between the Planck and the messenger scale.

Hvbrid Gauge-Gravity Mediation: Scales





* MSSM-RGE-factor for soft squark masses $\tilde{m}^2(m_Z) = r_3 \tilde{m}^2(m_{mess})$

$r_3 = r_3(m_M) = 1 + \frac{8}{3\pi}\left(\int_{\ln(m_Z)}^{\ln(m_M)} dt \frac{\alpha_3^3(t)}{\alpha_3^2(m_M)}\right) \frac{M_3^2(m_M)}{\tilde{m}^2(m_M)};$

$\frac{M_3^2(m_M)}{\tilde{m}_{12}^2(m_M)} = \frac{3}{8} N_M + \mathcal{O}\left[\left(\frac{\alpha_i}{\alpha_3}\right)^2\right], i = 1,2, \quad \text{for} \quad q = Q, U, D \qquad r_3 \gtrsim 1$ (mGMSB)

* Ratio of soft masses $r = \tilde{m}^2_{gravity} / \tilde{m}^2_{gauge}$

$r \sim \left(\frac{m_M}{m_{\rm Pl}}\right)^2 \left(\frac{4\pi}{\alpha_3(m_M)}\right)^2 \frac{3}{8} \frac{1}{N_M}$ (mGMSB; highest F-term couples to gauge mediation)

* Soft terms with flavor at the messenger scale m_M:

Squark mass-squared terms:

$$\begin{aligned} M^2_{\tilde{Q}_L}(m_M) &= \tilde{m}^2(\mathbf{1} + rX_{Q_L}), \\ M^2_{\tilde{D}_R}(m_M) &= \tilde{m}^2(\mathbf{1} + rX_{D_R}), \\ M^2_{\tilde{U}_R}(m_M) &= \tilde{m}^2(\mathbf{1} + rX_{U_R}). \end{aligned}$$

A-terms:

$$\begin{aligned} A^u(m_M) &= \tilde{m}\sqrt{r}\; Z_{A_u}, \\ A^d(m_M) &= \tilde{m}\sqrt{r}\; Z_{A_d}. \end{aligned}$$

Flavor structure of gravity-mediation: X, Z

$$M^2(m_M) = \tilde{m}^2(\mathbf{1} + rX), \qquad A(m_M) \;=\; \tilde{m}\sqrt{r}\; Z.$$

anarchy (An): $X_{ij} \sim \mathcal{O}(1)$ (no accidental cancellations)

structure (FN): Froggatt-Nielsen flavor symmetry; responsible also for the Yukawas.

X	Z	observable 1	observable 2	...
FN	FN			
An	FN			
An	An			

* Froggatt-Nielson-terms with V_{ij}: CKM, m_{q_i}: quark masses

$$(X_{q_{L,R}})_{ii} \sim 1, \quad (X_{q_L})_{ij} \sim |V_{ij}|, \quad (X_{q_R})_{ij} \sim \frac{m_{q_i}/m_{q_j}}{|V_{ij}|} \quad (i<j), \;\; q = U, D.$$

A-terms:

$$(Z_{A_q})_{ij} \sim Y^q_{ij} \sim V_{ij} m_{q_j}/v_q.$$

As in anarchy, soft terms fixed up to order one, in general complex numbers.

Hybrid Gauge-Gravity Mediation, at m_Z

Analytical solution to MSSM-RG up to order one numbers

(in flavor basis)

$$M^2_{\tilde{Q}_L}(m_Z) \sim \tilde{m}^2(r_3\mathbf{1} + c_u Y_u Y_u^\dagger + c_d Y_d Y_d^\dagger + r X_{Q_L} + r Z_{A_u} Z_{A_u}^\dagger + r Z_{A_d} Z_{A_d}^\dagger),$$

(in basis with diagonal quark mass matrices and gluino couplings)

$$(\delta^d_{i3})_{LL} \sim \frac{1}{r_3}\max\{r(X_{d_L} + Z_{A_u} Z_{A_u}^\dagger + Z_{A_d} Z_{A_d}^\dagger)_{i3}, c_u y_t^2 |V_{tb} V_{ti}^*|\},$$

$$(\delta^u_{ij})_{LR} \sim (Z_{A_u})_{ij}\sqrt{r} v_u/(r_3 \tilde{m}). \qquad \text{etc.}$$

Ready for phenomenology!

The model parameters are: scale separation r/r_3 and flavor factors X, Z

(+GMSB)

I. Both X,Z follow the FN symmetry

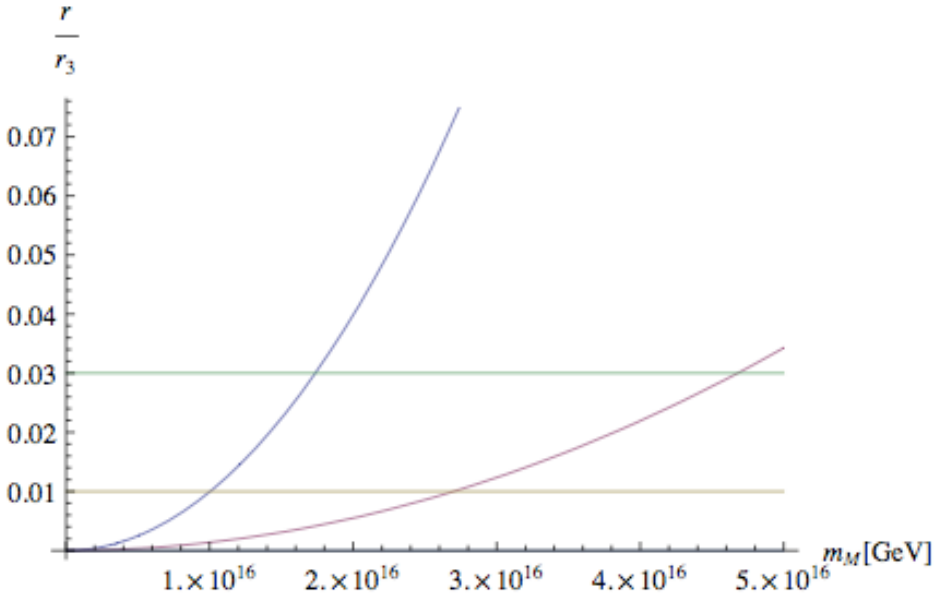
Strongest bound from $K - \bar{K}$-mixing: $\langle \delta^d_{12} \rangle \sim r/r_3 \sqrt{m_d/m_s}$

$r/r_3 \lesssim 0.01 - 0.03$.

Charm mixing suppressed: $\langle \delta^u_{12} \rangle \sim r/r_3 \sqrt{m_u/m_c}$

Both X,Z follow the FN symmetry; Predictions

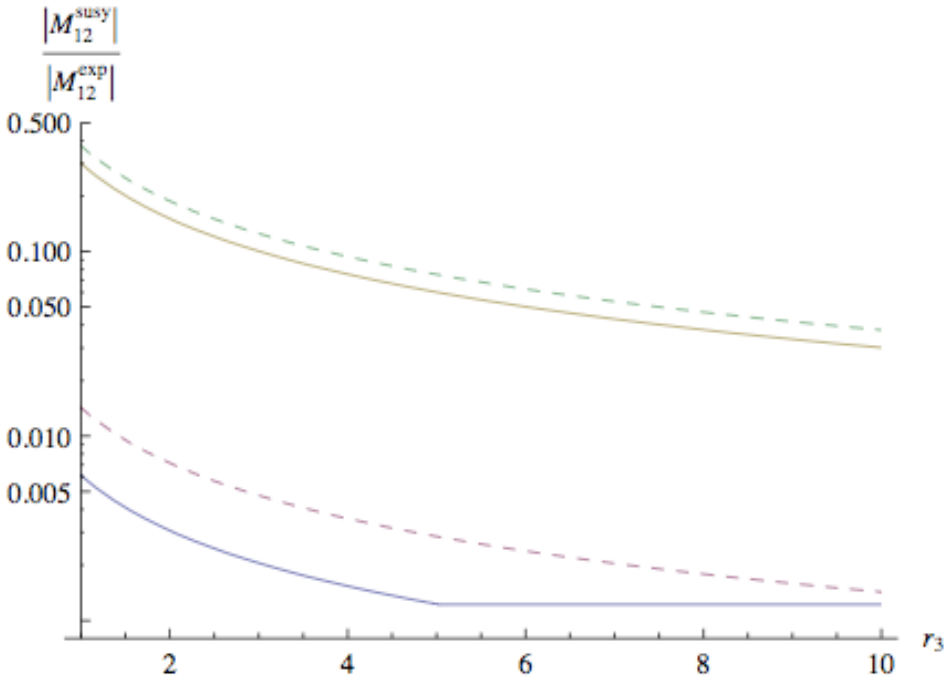
* Strongest bound from $K - \bar{K}$-mixing: $r/r_3 \lesssim 0.01 - 0.03$.



For number of messenger $N_M = 1$ (upper) and $N_M = 3$ (lower curve).

* $m_M \lesssim m_{Pl}/10^3$ for $N_M = 1$ (mGMSB; highest F-term couples to gauge mediation).

Both X,Z follow the FN symmetry;B, D-mixing



Upper two curves for $\tan\beta = 30$ and $m_{A^0} = 200$ GeV.

* B_d (solid), B_s (dashed): Effects in mixing of order ten percent if $\tan\beta$ is large, otherwise one percent.

* D-mixing: $|M_{12}^{\rm susy}/M_{12}^{\rm exp}| \lesssim 5\%$ (order 1 in different flavor model possible).

The model parameters are: scale separation r/r_3 and flavor factors X, Z

(+GMSB)

II. X $\sim O(1)$anarchical, Z (A-terms) follow FN symmetry

Strongest bound from $K - \bar{K}$-mixing: $\langle \delta^d_{12} \rangle \sim r/r_3$

$r/r_3 \lesssim 0.002 - 0.006$.

Charm mixing order one: $\langle \delta^u_{12} \rangle \sim r/r_3$

The model parameters are: scale separation r/r_3 and flavor factors X, Z

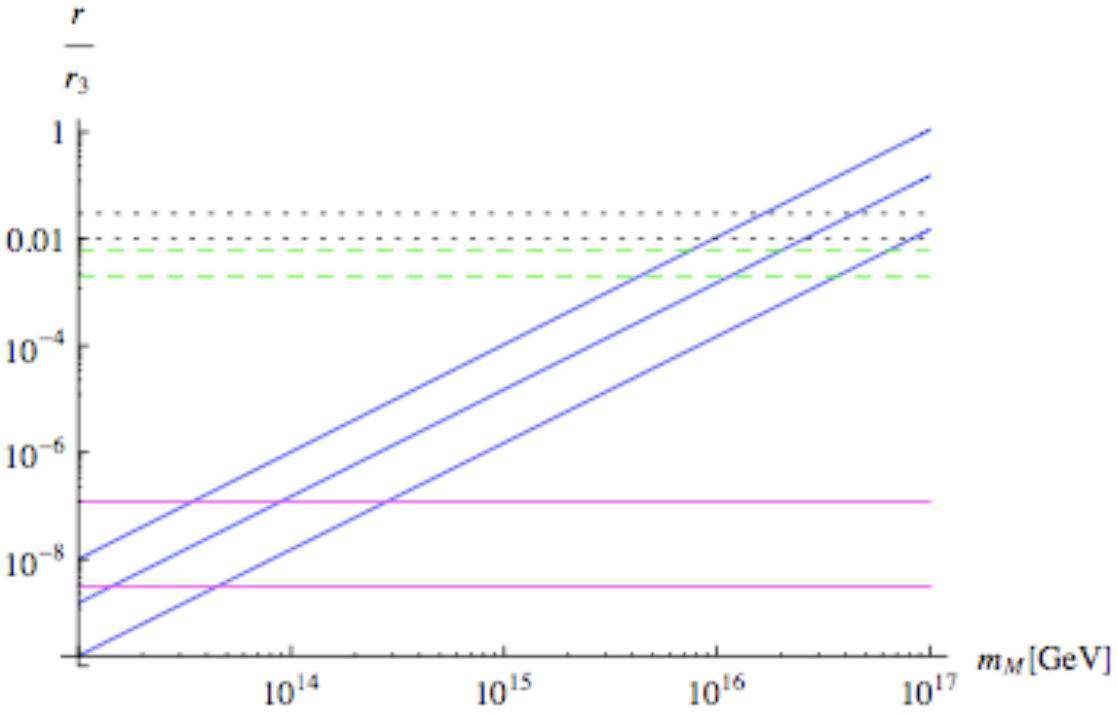
(+GMSB)

III. Full anarchy $X, Z \sim O(1)$anarchical

Strongest bound from neutron EDM: $(\delta^u_{11})_{LR} \sim \sqrt{r} v \sin\beta/(r_3 \tilde{m})$
$r/r_3 \lesssim 10^{-7}$.

Flavor physics quasi MFV-like.

Summary: Scales, viability



For number of messengers $N_M = 1$ (upper) and $N_M = 3$ (middle) and $N_M = 10$ (lower curve);

(mGMSB; highest F-term couples to gauge mediation).

* black (FN), green (X: An, Z:FN) $m_M \lesssim m_{Pl}/10^3$ for $N_M = 1$.
* pink (full anarchy/no structure) $m_M \lesssim m_{Pl}/10^5$ for $N_M = 1$.

Summary: Flavor and CP

The maximal size of possible effects in the mixing of B_d, B_s and D^0 for low $\tan\beta$ (large $\tan\beta$) and the neutron EDM:

X	Z	B_d	B_s	D^0	d_n
FN	FN	0.002 (0.10)	0.005 (0.13)	0.03	0.02
An	FN	0.007 (0.36)	0.002 (0.05)	$\mathcal{O}(1)$	0.01
An	An	$2 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$\mathcal{O}(10^{-10})$	1

Summary

- We considered the effects of gravity-induced SUSY-breaking within gauge mediation. The model is a viable non-MFV scenario if the separation between the Planck and the messenger scale is sufficiently large.
- Given a model of flavor at the Planck scale, the hybrid gauge-gravity model is predictive, and can be tested with precision flavor and CP experiments.
- The different flavor realizations lead to distinct pattern.

... of new, rare and possibly beautiful, perhaps strange and eventually charming physics ...

HAPPY BIRTHDAY DANIEL