FLAVOR PHYSICS THEORY

–Flavor Physics: about, status

–Recent Flavor-TH developments (selection)

–Outlook

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Flavor physics originates from the generational structure of known fundamental matter $\psi \to \psi_i$, $i = 1, 2, 3$, with lives in the same representation of the SM gauge group:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$$

The Yukawa matrices $Y_{u,d,e}$ are the sole sources of flavor in the SM:

$$\mathcal{L}_{SM} = \sum_{\psi=Q,U,D,L,E} \bar{\psi}_i i \not{D} \psi_i$$

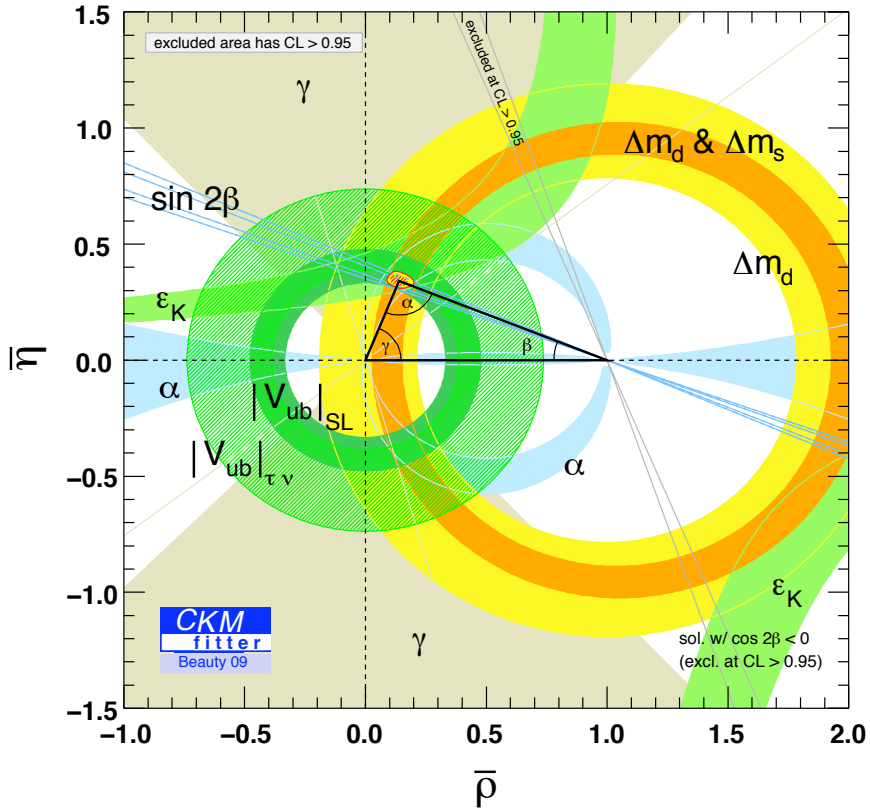
$$-\bar{Q}_i (Y_u)_{ij} \Phi^C U_j - \bar{Q}_i (Y_d)_{ij} \Phi D_j - \bar{L}_i (Y_e)_{ij} \Phi E_j$$

$$+\mathcal{L}_{higgs} + \mathcal{L}_{gauge}$$

This set-up predicts correlations and CP-violation.

The Flavor of the Quarks/CKM 2009

The CKM-picture of flavor and CP violation is currently consistent with all – and quite different – laboratory observations, although some tensions exist.



Modulo ”hints” all hadronic flavor changing data are currently ok with the SM within uncertainties.

Different sectors and different couplings probed:

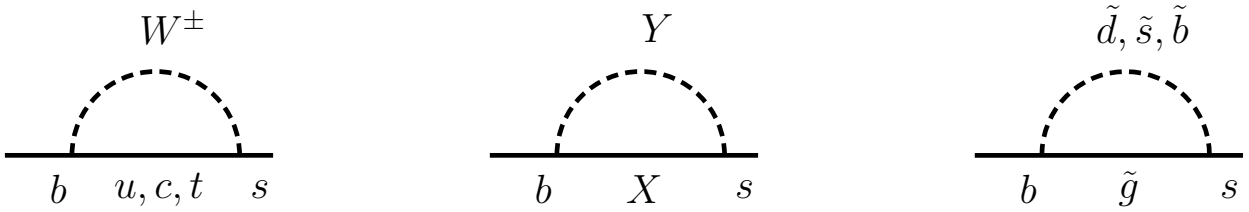
$s \to d$: $K^0 - \bar{K}^0$, $K \to \pi\nu\bar{\nu}$

$c \to u$: $D^0 - \bar{D}^0$ (first data on FCNC in up-sector)

$b \to d$: $B^0 - \bar{B}^0$, $B \to \rho\gamma$, $b \to d\gamma$ ($B \to \pi ll$ close)

$b \to s$: $B_s - \bar{B}_s$, $b \to s\gamma$, $B \to K_s\pi^0\gamma$, $b \to sll$, $B \to K^{(*)}ll$ (precision, angular observables starting), $B_s \to \mu\mu$ (bound improving)

$t \to c, u$: not observed



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.

Very predictive framework.

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

MFV model-independent: Chivukula, Georgi '87, Ali, London '99, Buras^2 '00

MFV-SUSY: d'Ambrosio, Giudice, Isidori, Strumia '02

MFV variants, extensions: Agashe, Papucci, Perez, Pirjol '05, Feldmann, Mannel '08, Kagan, Perez, Volansky, Zupan '09

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.

Recent Flavor-TH Developments & Directions

- Supersymmetric models with MFV and near-MFV

- Flavor physics at colliders

Minimal Flavor in Supersymmetry

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

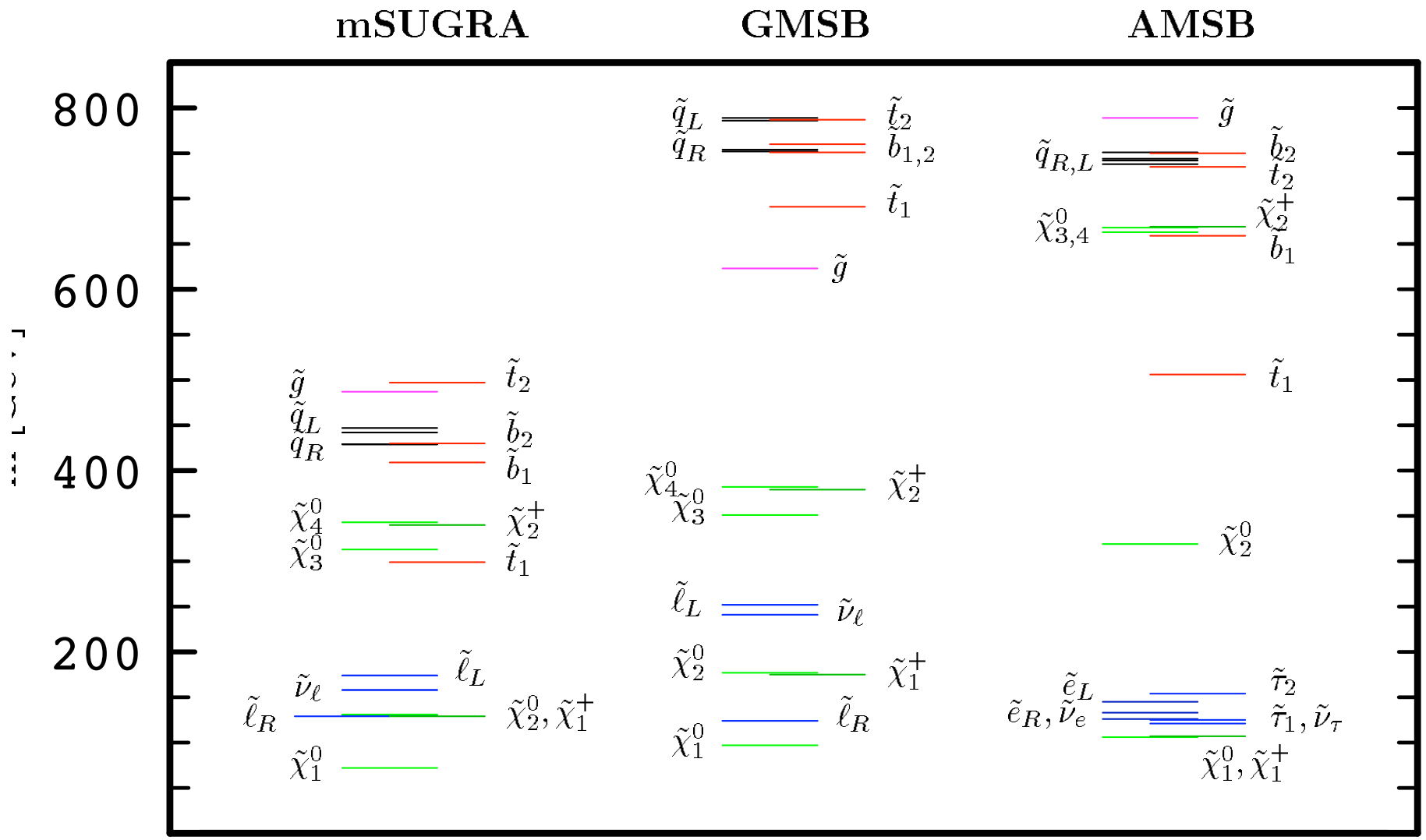
$$\tilde{M}_Q^2 \;=\; \tilde{m}^2 (a_1 \mathbf{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger) \quad \text{etc.}$$

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

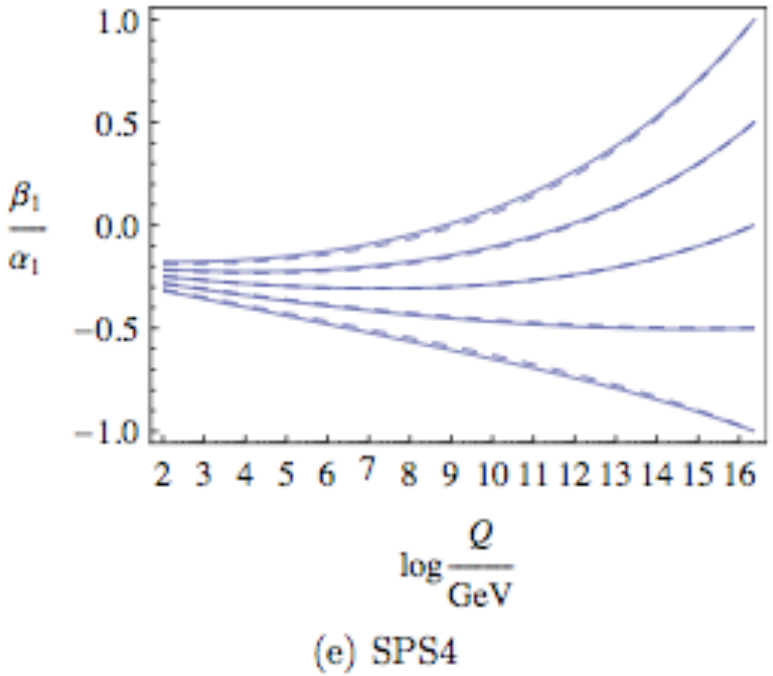


TESLA TDR Part III '01

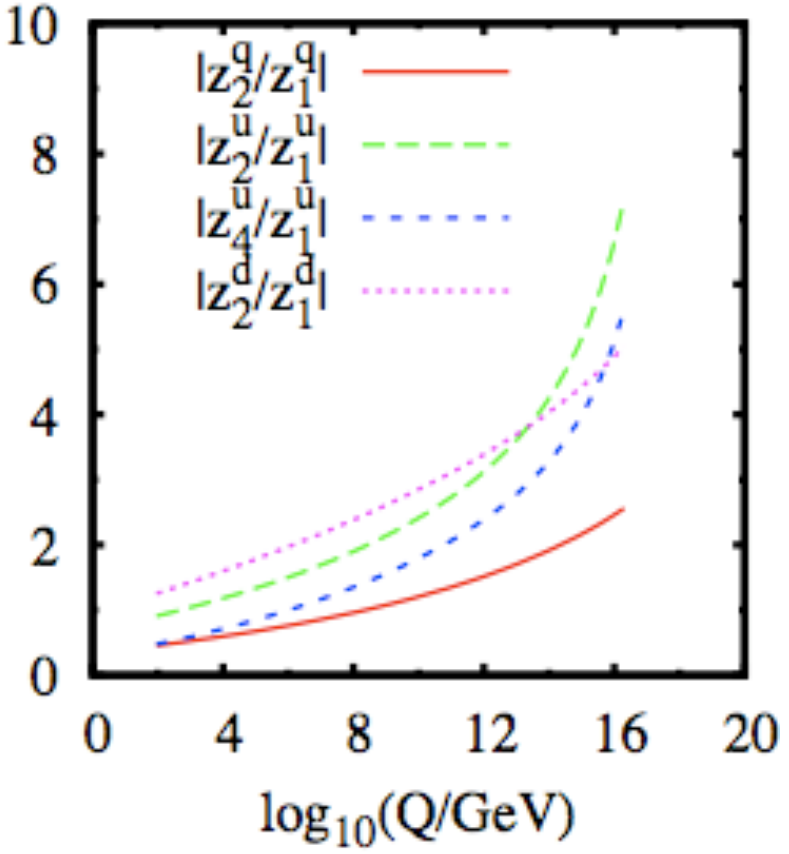
Running MFV Coefficients b_i/a_j

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

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



(e) SPS4



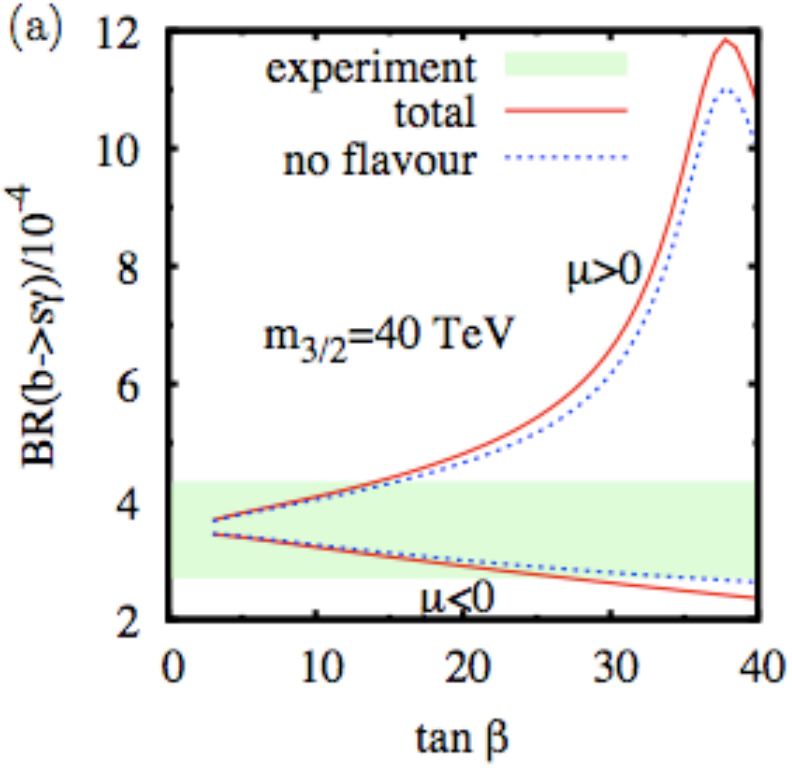
RG-running suppresses flavor violation towards the weak scale.

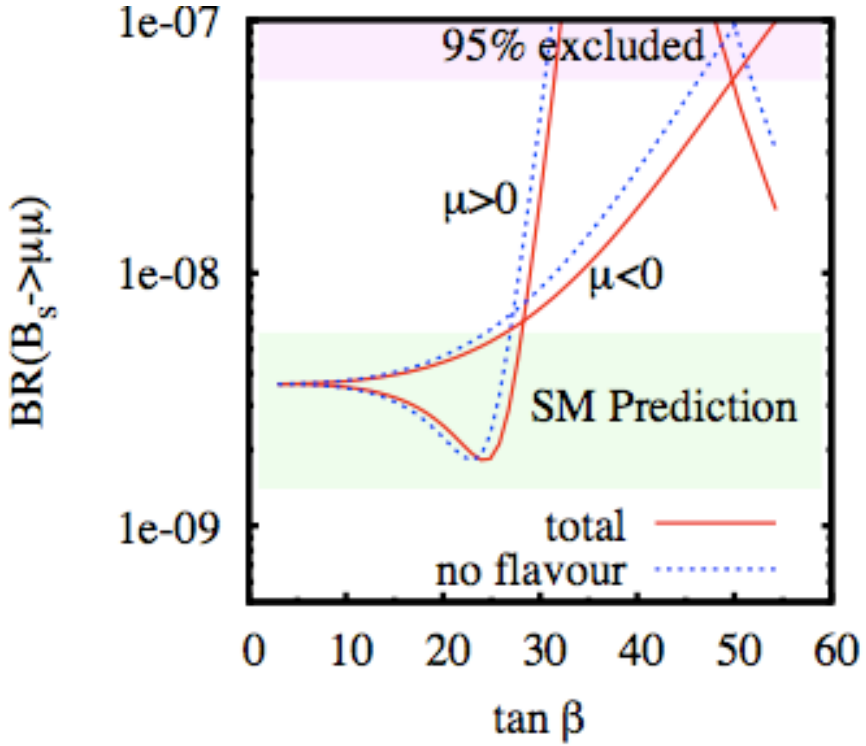
For low $\tan\beta$, (minimal) anomaly mediation becomes exactly flavor blind in the QIR-fixed point limit of the top-Yukawa.

Predictivity and large MFV effects in FCNC loops

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

Here, AMSB ($m_{3/2} = 40$ TeV) Figs from 0902.4880 [hep-ph]





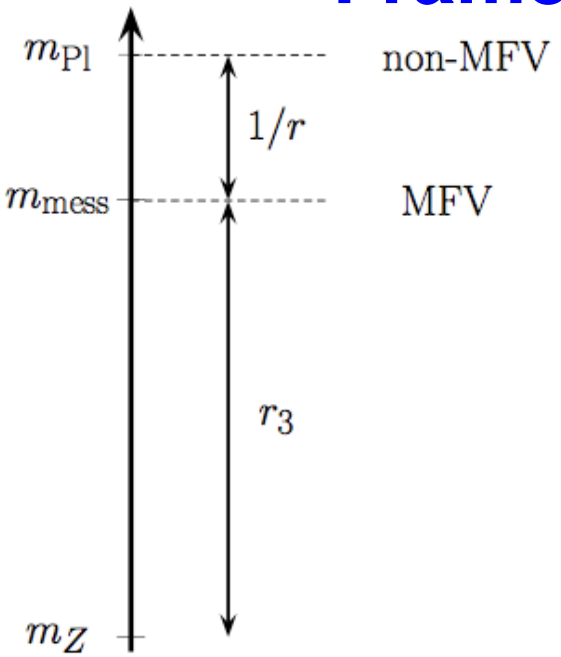
Analytical expressions for the full flavor structure, that is, a_i, b_j or $(\delta^q)_{ij}$, within mAMSB. Complementarity $b \to s\gamma$ vs. $B_s \to \mu\mu$.

Beyond MFV-SUSY

* Realistic, viable?
* At which level do non-MFV effects in which observables appear?
* Access structure of flavor breaking thru non-MFV: anarchy vs symmetry

Beyond MFV: hybrid Gauge-Gravity models with flavor $U(1)$: GH, Hochberg, Nir '09 (quarks), or with anarchy GH, Hochberg, Nir '10 (quarks). sleptons: Feng, Lester, Nir, Shadmi '07, Nomura, Papucci, Stolarki '07

Framework Hybrid Gauge-Gravity Mediation

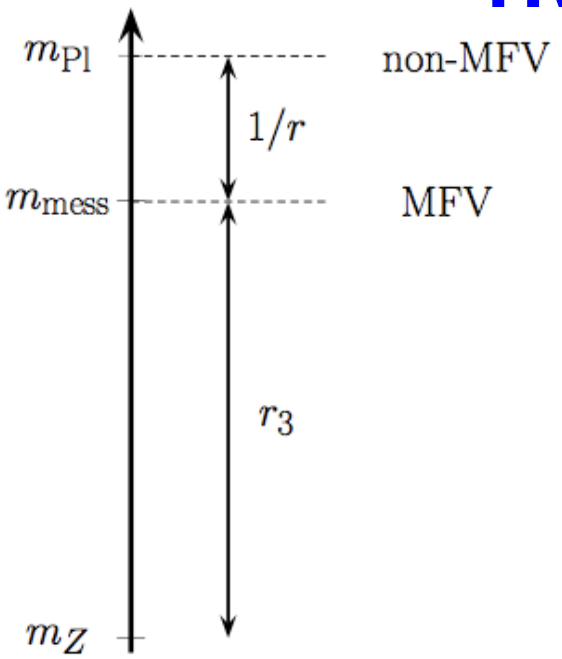


Consider gauge mediation, which is MFV, in the background of gravity mediation. Assume the flavor properties of the latter controlled by **symmetry or anarchy?** 1001.1513 [hep-ph]

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

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

Hybrid Gauge-Gravity Mediation: Flavor



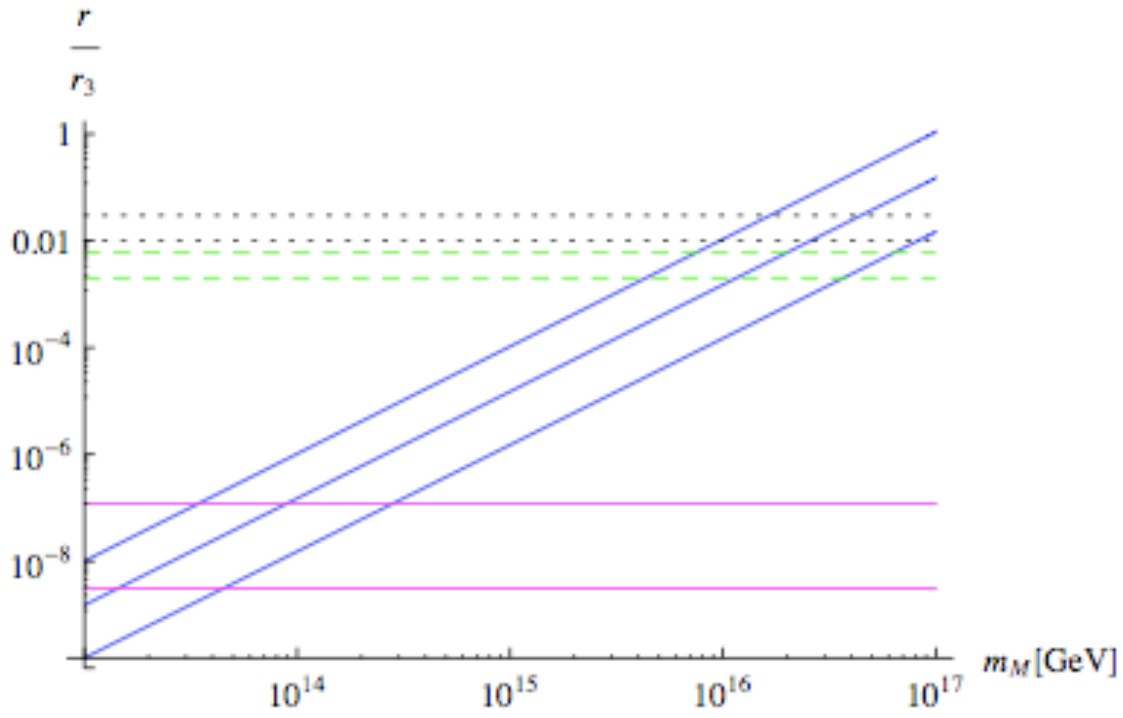
$$M^2_{\tilde{Q}}(m_Z) \sim \tilde{m}^2_Q(r_3\mathbf{1} + c_u Y_u Y_u^\dagger + c_d Y_d Y_d^\dagger + r X_{Q_L}) \qquad X_{Q_L}\text{: gravity med.}$$

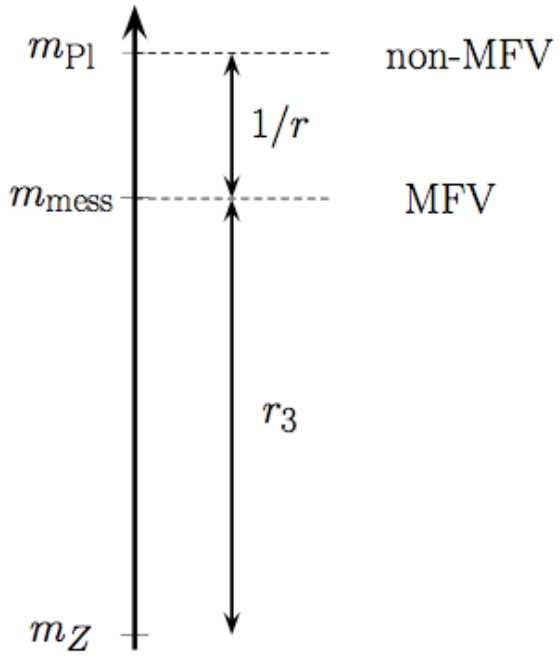
anarchy: $X_{ij} \sim \mathcal{O}(1)$ (no accidental cancellations)

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

Model parameters: scale separation r/r_3 and flavor factors X (+GMSB) $\rightarrow$ **Ready for phenomenology!**

Hybrid Gauge-Gravity Mediation: Constraints





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).

$K - \bar{K}$: black (FN), green (X: An, Z:FN) $m_M \lesssim m_{Pl}/10^3$ for $N_M = 1$.

nEDM: pink (full anarchy/no structure) $m_M \lesssim m_{Pl}/10^5$ for $N_M = 1$.

We get a bound from flavor on BSM-physics general properties.

Hybrid Gauge Gravity: Predictions

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

flavor	factors	B_d	B_s	D^0	d_n
FN-symmetry	$(A, \tilde{m}^2)$	0.002 (0.10)	0.005 (0.13)	0.03	0.02
$\tilde{m}^2$ anarchy	$A \sim Y$	0.007 (0.36)	0.002 (0.05)	$\mathcal{O}(1)$	0.01
full anarchy	$(A, \tilde{m}^2)$	$2 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$\mathcal{O}(10^{-10})$	1

distinguishable! full anarchy: MFV-like

With the additional non-MFV input from physics beyond the Standard Model, there is the opportunity to get a handle on the flavor puzzle.

Flavor Physics at Colliders

Collider and flavor: Squarks, gluinos: Hurth, Porod ’03, ’09,Bozzi, Fuks, Hermann, Klasen ’07;Charged Higgs: Diaz-Cruz, He,Yuan ’01,

Dittmaier, GH, Plehn, Spannowsky ’07;sleptons: Feng, Lester, Nir, Shadmi ’07, ’09, Nomura, Papucci, Stolarki ’07; Stop-decay length

MFV test @ LHC: GH, Nir ’08, GH, Kim, Sedello ’09.

Studies on selected processes available (Disquark-, Higgs production and decay, slepton mass splittings). Huge effects possible if flavor is broken non-minimally. For (S)quarks, the third generation needs to be involved.

Can we actually measure MFV SM-partner couplings?

Measuring MFV Mixing at Colliders

In MFV, mixing between third and other generations is suppressed:

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

$$(\tilde{M}_Q^2)_{23}/\tilde{m}^2 \sim \lambda_b^2 V_{cb} V_{tb}^* \sim 10^{-5} \tan\beta^2$$

Such a tiny coupling can indeed be probed if $\tilde{t} \to c\chi^0$ is the dominant decay & sufficiently suppressed rate. 0802.0916[hep-ph]

Then, the lifetime of the stop is long:

$$\tau_{\tilde{t}} \sim \text{ ps} \left(\frac{100 \text{ GeV}}{m_{\tilde{t}}}\right) \left(\frac{0.03}{\Delta m/m_{\tilde{t}}}\right)^2 \left(\frac{10^{-5}}{Y}\right)^2 \text{ where } \Delta m = m_{\tilde{t}} - m_{\chi^0},$$

$Y_{\text{MFV}} \sim \lambda_b^2 V_{cb}$.

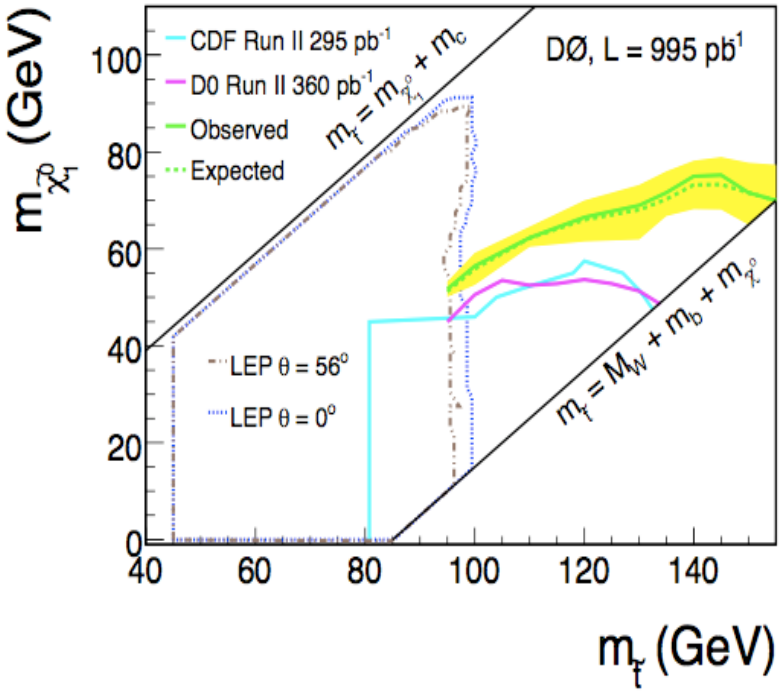
Yields a macroscopic decay length of a few hundred microns (or even larger), which is a way to "measure V_{cb}" with stops.

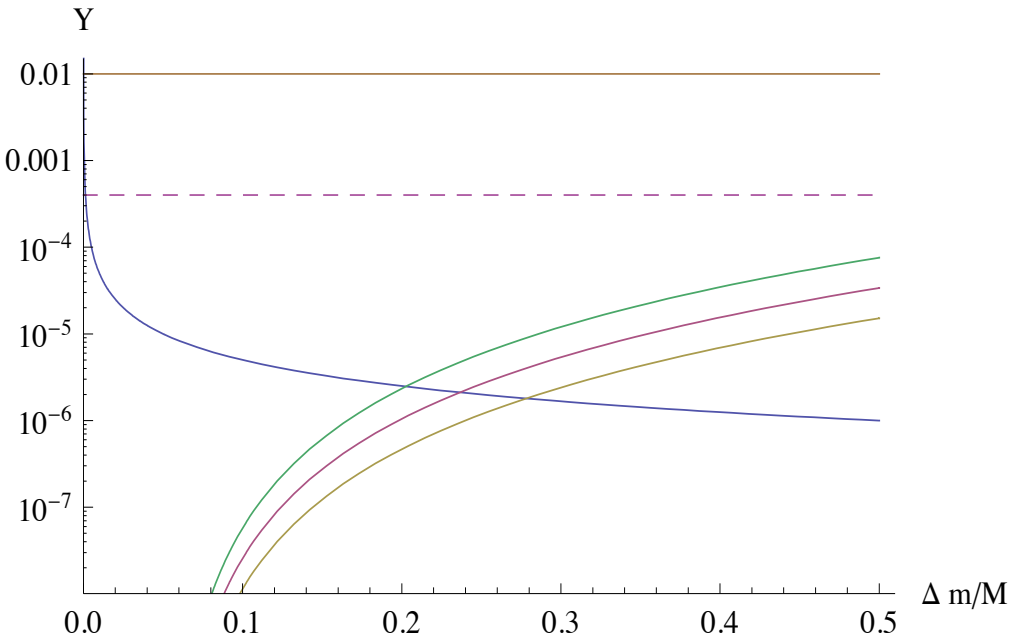
Long Live the Stop

$Y_{MFV} \sim \lambda_b^2 V_{cb} V_{tb}^* \sim 10^{-5} \tan\beta^2$; $Y \sim V_{cb}\lambda_c$ (alignement).

Works for $m_{\tilde{t}} - m_\chi$ smallish.

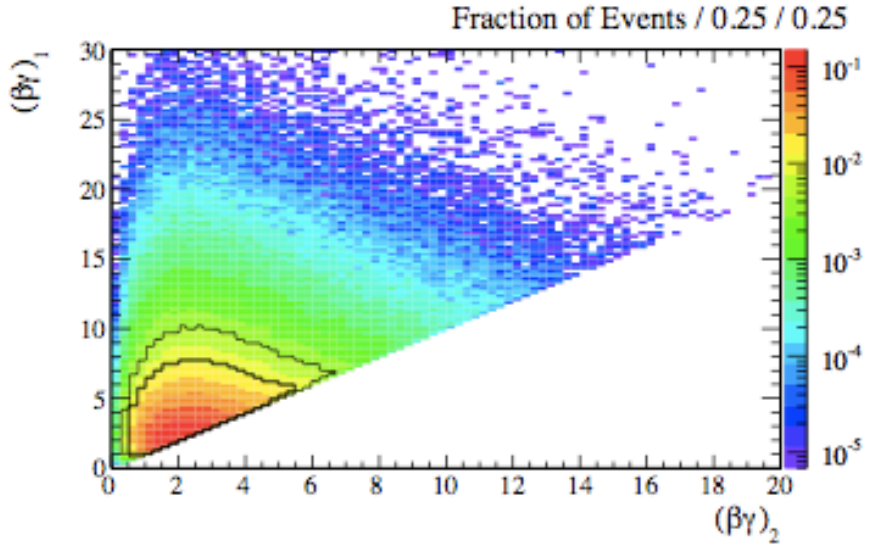
left: 0803.2263 [hep-ex], right: 0802.0916[hep-ph],0905.0327 [hep-ph]

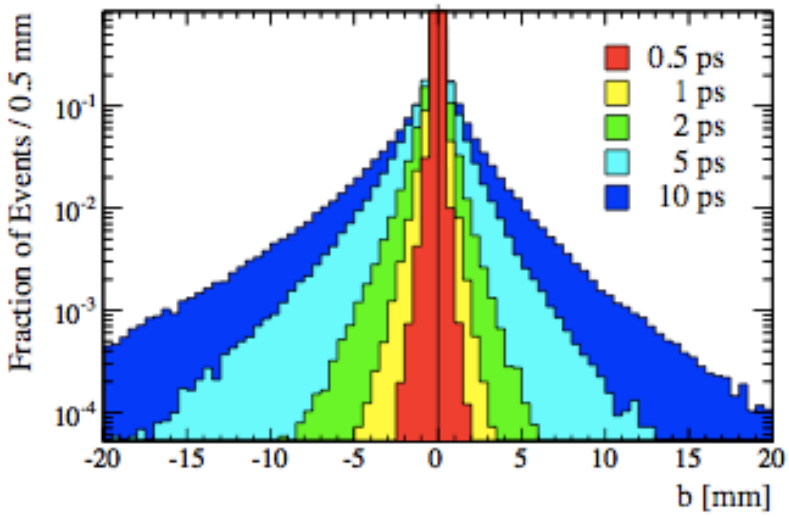




Far travel the Stop at the LHC; $\tilde{t} \to c\chi^0$

Light stops are produced with low BGD in association with like-sign tops $pp \to \tilde{t}^*\tilde{t}^*tt, \tilde{t}\tilde{t}\bar{t}\bar{t}$ Kraml, Raklev '05; $\sigma \sim \text{few pb}$ for 100 GeV stop and 500 GeV gluino.





$\gamma\beta \sim O(1)$, b: transverse impact parameter

0910.2124[hep-ph] Up to 10 events with 1 fb^{-1} (no detector effects, 14TeV).

Summary

- CKM fits and determinations: increasing high precision; (anomalies and clashes to be resolved.) Would like to have ultimately V_{CKM} from SM-dominated observables only.

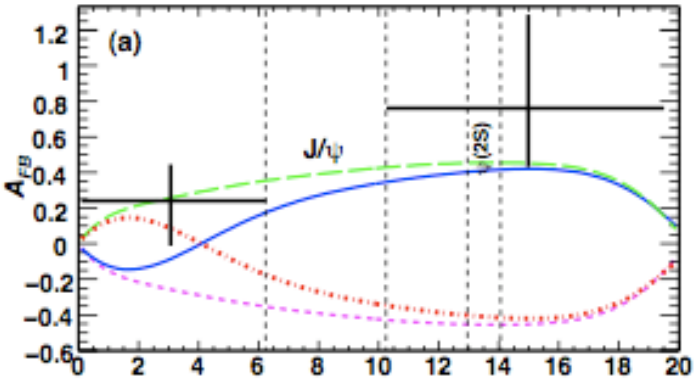
  desired: γ direct

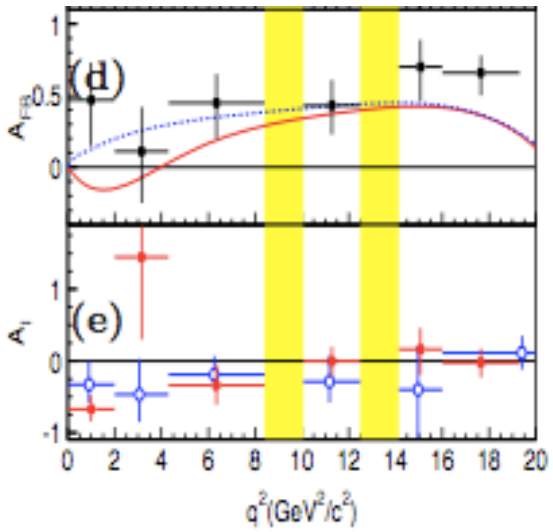
- Rare decays: start doing involved asymmetries and observables in exclusive $b \to sll, q\gamma$ modes; angular analysis promising for LHCb with muons; opportunity for electrons and neutrinos, also inclusive modes and if feasible taus, for a super flavor factory.

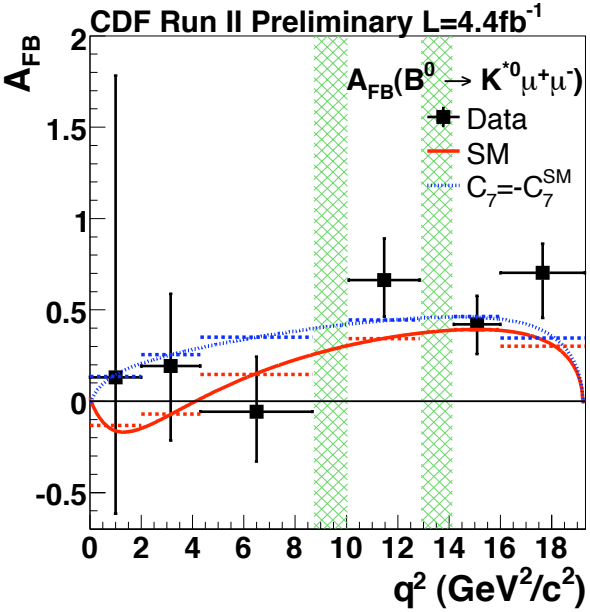
  nearer term: like to see $B_s \to \mu\mu$ (and $\mathcal{B}(B_s \to \mu\mu)/\mathcal{B}(B_d \to \mu\mu)$); $\arg(B_s - \bar{B}_s)$ mixing

Summary

left: BaBar: 0804.4412 [hep-ex], mid: Belle 0904.0770 [hep-ex], CDF Public note 09-11-12, see Sergey Burdins talk







sign/zero of $A_{\rm FB}$ at low dilepton mass?

sign of $A_{\rm FB}$ at large dilepton mass SM-like 0805.2525 [hep-ph]

Summary

- Flavor physics in the LHC-era: map out flavor quantum numbers of the SM-partners related to electroweak-symmetry breaking at the TeV-scale.
- Opportunities for indirect and direct measurements.
- Flavor constraints for model building: Large deviations from MFV require answer why we see (where we looked so far) at least predominantly SM-like flavor violation.
- The observation of non-MFV couplings could point towards the origin of generational mixing and hierarchies, i.e., flavor.

BACK-UP

Non-MFV Signals and Revenue

A powerful way to search for non-MFV contributions is to look for deviations from CKM-hierarchies.

$$R_{\mu\mu} = \frac{\mathcal{B}(B_s \to \mu^+\mu^-)}{\mathcal{B}(B_d \to \mu^+\mu^-)} \sim \frac{m_{B_s} f_{B_s}^2 \tau_{B_s}}{m_{B_d} f_{B_d}^2 \tau_{B_d}} r_{\rm ps} \times \begin{cases} \frac{|V_{ts}|^2}{|V_{td}|^2} & \text{for } (\text{MFV}, (\delta^d_{i3})_L) \\ \frac{|m_s V_{td}|^2}{|m_d V_{ts}|^2} & \text{for } ((\delta^d_{i3})_R) \\ \frac{m_s}{m_d} & \text{for } (\langle \delta^d_{i3} \rangle) \end{cases}$$

From top to bottom: 25 (MFV),14,19 (this FN-model);
$R_{\mu\mu}$ suppressed w.r.t. MFV/SM. Both Br's can be enhanced.

Right-handed FCNCs possibly even CP-violating are also indicative.

With the additional non-MFV input from physics beyond the Standard Model, there is the opportunity to get a handle on the flavor puzzle.