

Gauge Mediation beyond MFV

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based on JHEP 1306 (2013)
with L. Calibbi & P. Paradisi

Overview

- Modification of GMSB with new messenger-matter couplings controlled by same flavor dynamics as Yukawas
- Due to large A-terms, one can easily accommodate 125 GeV Higgs for light and predictive SUSY spectrum
- New sources of flavor violation depending on underlying flavor model, but built-in suppression of LL&RR, so that main source LR

The Status of Gauge Mediation

- Gauge Mediation elegant and predictive
- In minimal GM difficult to get large Higgs mass (A-terms are small)

$$\Delta m_h^2 \approx \frac{3m_t^2}{8\pi^2 v^2} \left(\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12M_S^2} \right) \right)$$

$$X_t = A_t - \mu \cot \beta$$

- Need to go beyond minimal GM for large A-terms

→ see talk by D. Shih

Generating large A-terms in GM

- Need direct messenger-MSSM couplings
(usually forbidden by discrete symmetry)

$$\Delta W = \begin{cases} U \bar{\Phi}_5 \bar{\Phi}_5 & \text{Evans, Ibe, Yanagida '11,'12 \quad Craig, Knapen, Shih, Zhao '12} \\ QU \Phi_5 & \text{Albeid, Babu '12 \quad Byakti, Ray '13 \quad Evans, Shih '13 \quad Jelinski '13} \\ H_u \Phi_{10} \Phi_{10} & \dots \\ \dots & \dots \end{cases}$$

- Also new contributions to sfermion masses
→ need to take care of flavor structure!

new couplings
proportional to Yukawas

OR

new couplings
suppressed as Yukawas

- Take $5, \bar{5}$ messengers with positive R-parity

$$\Delta W = \lambda_{ij}^U Q_i U_j \Phi_{H_u} + \lambda_{ij}^D Q_i D_j \bar{\Phi}_{H_d}$$

- Assume that couplings are controlled by same underlying flavor dynamics as Yukawas (flavor symmetries, partial compositeness...)
- Simplest scenario: flavor only from matter fields

$$\Phi, \bar{\Phi} \sim H_u, H_d$$



$$\lambda^{U,D} \sim y^{U,D}$$

e.g. not charged under flavor symmetry

The Setup

- Messengers and Higgs distinguished by symmetry that forbids mu-term

H chiral

Φ vector-like

e.g.

$U(1)$	Φ_{H_u}	Φ_T	$\bar{\Phi}_{H_d}$	$\bar{\Phi}_T$	H_u	H_d	X	Q, U, D, E, L
	1	0	-1	0	1	1	0	-1/2

- Final setup

$$W = (y_U)_{ij} Q_i U_j H_u + (y_D)_{ij} Q_i D_j H_d + (y_E)_{ij} L_i E_j H_d + X (\bar{\Phi}_T \Phi_T + \bar{\Phi}_{H_d} \Phi_{H_u}) + (\lambda_U)_{ij} Q_i U_j \Phi_{H_u}$$

$$\lambda_{ij}^U \sim y_{ij}^U \longrightarrow \text{only } \lambda_{33}^U \text{ relevant for SUSY spectrum}$$

High-energy Spectrum

Evans, Shih '13

- Non-zero squark A-terms

$$A_U = -\frac{\Lambda}{16\pi^2} \left(\lambda_U \lambda_U^\dagger y_U + 2 y_U \lambda_U^\dagger \lambda_U \right) \quad A_D = -\frac{\Lambda}{16\pi^2} \lambda_U \lambda_U^\dagger y_D$$

- New contris to 2-loop squark and soft Higgs masses

$$\Delta m_{Q(U)}^2 \sim \frac{\Lambda^2}{256\pi^4} \left(\lambda_U \lambda_U^\dagger - g_3^2 \right) \lambda_U \lambda_U^\dagger \quad \Delta m_D^2 \sim \frac{\Lambda^2}{256\pi^4} y_D^\dagger \lambda_U \lambda_U^\dagger y_D \quad \downarrow$$

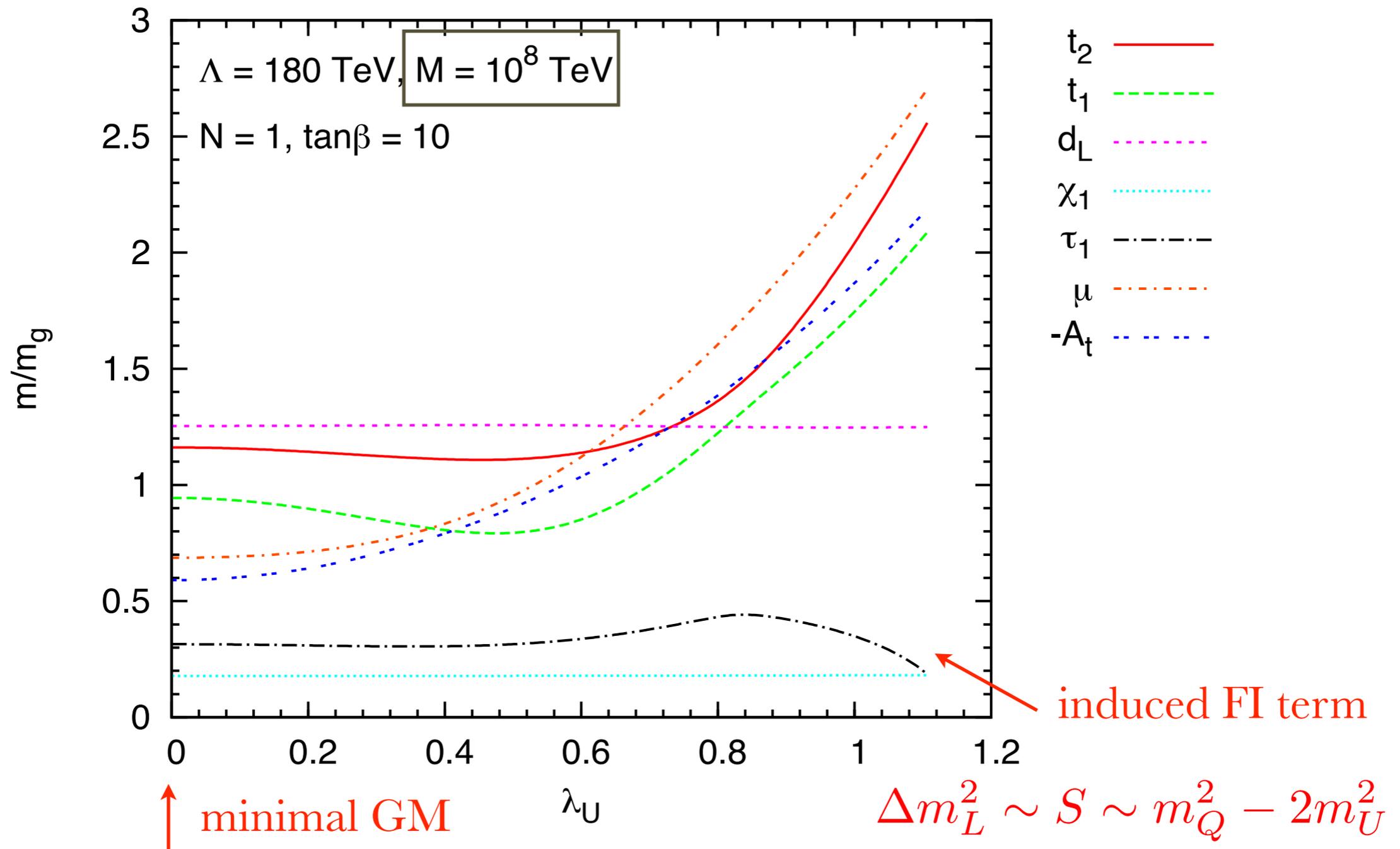
$$\Delta m_{H_u}^2 \sim -\frac{\Lambda^2}{256\pi^4} \text{Tr} y_U^\dagger \lambda_U \lambda_U^\dagger y_U \quad \Delta m_{H_d}^2 \sim -\frac{\Lambda^2}{256\pi^4} \text{Tr} y_D^\dagger \lambda_U \lambda_U^\dagger y_D \quad \downarrow$$

- Negative 1-loop squark masses (for low messenger scales)

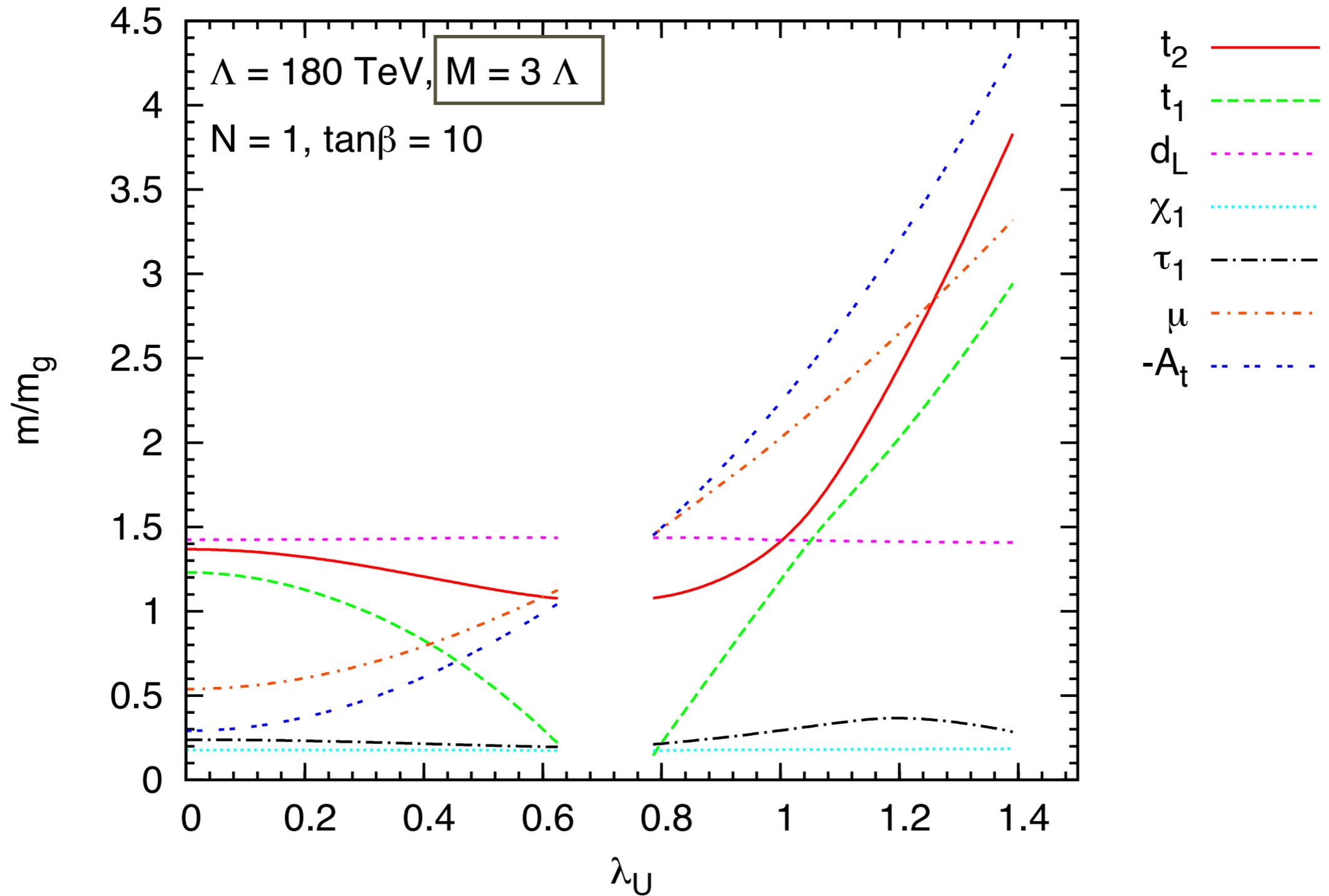
Low-energy Spectrum

$$\lambda_{33}^U \equiv \lambda_U$$

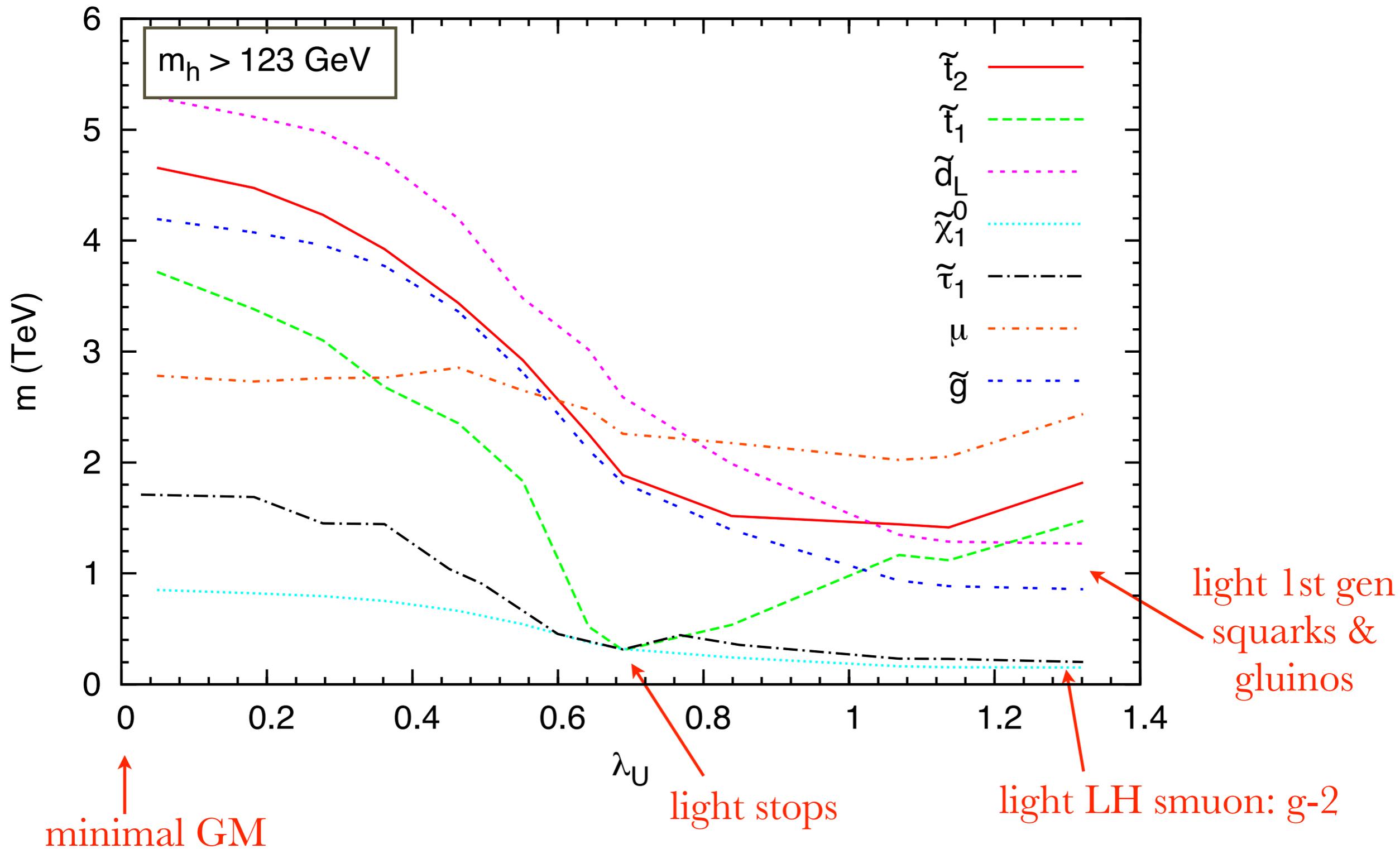
Evans, Ibe, Yanagida '11,'12



Low-energy Spectrum



Low-energy Spectrum



Sflavor Structure

CKM suppression $[(\lambda_U)_{i3} \lesssim V_{i3}]$

$$(\delta_{LL}^u)_{ij} \sim (\lambda_U)_{i3} (\lambda_U^*)_{j3}$$

$$(\delta_{RR}^u)_{ij} \sim (\lambda_U^*)_{3i} (\lambda_U)_{3j}$$

$$(\delta_{LL}^d)_{ij} \sim V_{3i}^* V_{3j},$$

$$(\delta_{RR}^d)_{ij} \sim y_i^D y_j^D V_{3i}^* V_{3j}$$

possibly sizable

light Yukawa suppression

$$(\delta_{LR}^u)_{ij} \sim (\lambda_U)_{i3} (\lambda_U)_{3j}$$

$$(\delta_{LR}^d)_{ij} \sim V_{3i}^* V_{3j} y_j^D$$

possibly sizable

additional CKM suppression

Flavor constraints

Most constraints automatically satisfied for $\tilde{m} \sim 1$ TeV

$(\delta_{XX}^D)_{12}$	9.2×10^{-2} [Re]	1.2×10^{-2} [Im]
$\langle \delta_{12}^D \rangle$	1.9×10^{-3} [Re]	2.6×10^{-4} [Im]
$(\delta_{LR}^D)_{12}$	5.6×10^{-3} [Re]	4.0×10^{-5} [Im]
$(\delta_{XX}^U)_{12}$	1.0×10^{-1} [Re]	6.0×10^{-2} [Im]
$\langle \delta_{12}^U \rangle$	6.2×10^{-3} [Re]	4.0×10^{-3} [Im]
$(\delta_{LR}^U)_{12}$	1.6×10^{-2} [Re]	1.6×10^{-2} [Im]
$(\delta_{XX}^D)_{13}$	2.8×10^{-1} [Re]	6.0×10^{-1} [Im]
$\langle \delta_{13}^D \rangle$	4.2×10^{-2} [Re]	1.8×10^{-2} [Im]
$(\delta_{LR}^D)_{13}$	6.6×10^{-2} [Re]	1.5×10^{-1} [Im]
$(\delta_{LR}^D)_{11}$	2.0×10^{-6}	
$(\delta_{LR}^U)_{11}$	4.0×10^{-6}	

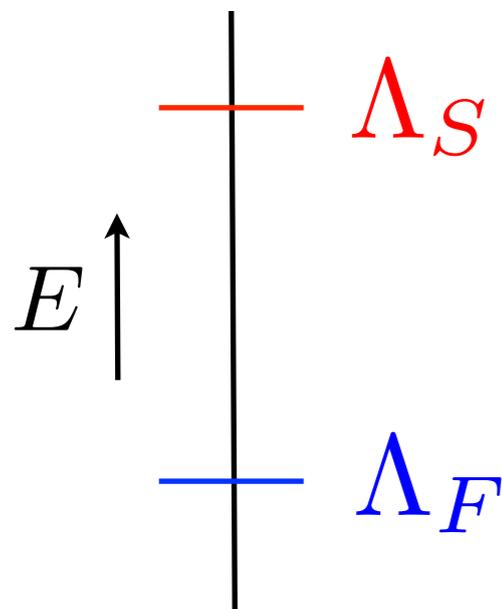
$D - \bar{D}$ mixing

$$(\delta_{RR}^u)_{12} \sim (\lambda_U^*)_{31} (\lambda_U)_{32}$$

Neutron EDM

$$(\delta_{LR}^u)_{11} \sim (\lambda_U)_{13} (\lambda_U)_{31}$$

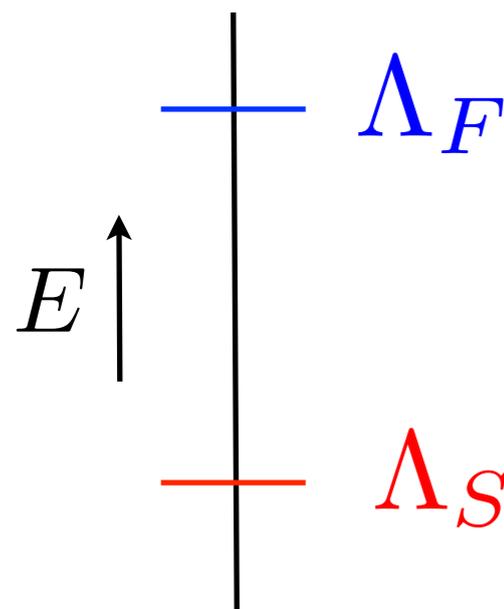
Comparison to other Sflavor Models



**e.g. Gravity Mediation + Flavor Model,
SUSY Partial Compositeness**

δ_{ij} controlled by flavor dynamics at Λ_F

→ SUSY spectrum not very predictive



Flavored Gauge Mediation + Flavor Model

δ_{ij} controlled by flavor dynamics at Λ_S

→ SUSY spectrum very predictive

→ extra suppression FV from loop structure

Comparison: FGM + U(1) model

	MFV	PC	U(1)	FGM _{U,D} + U(1)	FGM _U + U(1)
$(\delta_{LL}^u)_{ij}$	$V_{i3}V_{j3}^*y_b^2$	$(\epsilon_3^q)^2V_{i3}V_{j3}^*$	$\frac{V_{i3}}{V_{j3}} _{i \leq j}$	$V_{i3}V_{j3}^*y_t^2$	$V_{i3}V_{j3}^*y_t^2$
$(\delta_{LL}^d)_{ij}$	$V_{3i}^*V_{3j}y_t^2$	$(\epsilon_3^q)^2V_{i3}V_{j3}^*$	$\frac{V_{i3}}{V_{j3}} _{i \leq j}$	$V_{3i}^*V_{3j}y_t^2$	$V_{3i}^*V_{3j}y_t^2$
$(\delta_{RR}^u)_{ij}$	$y_i^U y_j^U V_{i3}V_{j3}^*y_b^2$	$\frac{y_i^U y_j^U}{V_{i3}V_{j3}^*} \frac{(\epsilon_3^u)^2}{y_t^2}$	$\frac{y_i^U V_{j3}}{y_j^U V_{i3}} _{i \leq j}$	$\frac{y_i^U y_j^U}{V_{i3}V_{j3}^*}$	$\frac{y_i^U y_j^U}{V_{i3}V_{j3}^*}$
$(\delta_{RR}^d)_{ij}$	$y_i^D y_j^D V_{3i}^*V_{3j}y_t^2$	$\frac{y_i^D y_j^D}{V_{i3}V_{j3}^*} \frac{(\epsilon_3^u)^2}{y_t^2}$	$\frac{y_i^D V_{j3}}{y_j^D V_{i3}} _{i \leq j}$	$\frac{y_i^D y_j^D}{V_{i3}V_{j3}^*}$	$y_i^D y_j^D V_{3i}^*V_{3j}y_t^2$
$(\delta_{LR}^u)_{ij}$	$y_j^U V_{i3}V_{j3}^*y_b^2$	$y_j^U \frac{V_{i3}}{V_{j3}^*}$	$y_j^U \frac{V_{i3}}{V_{j3}^*}$	$y_j^U V_{i3}V_{j3}^*y_t^2 + y_i^U \frac{y_i^U y_j^U}{V_{i3}V_{j3}^*}$ $y_j^U \frac{V_{i3}}{V_{j3}^*} y_t^6$	$y_j^U V_{i3}V_{j3}^*y_t^2 + y_i^U \frac{y_i^U y_j^U}{V_{i3}V_{j3}^*}$ $y_j^U \frac{V_{i3}}{V_{j3}^*} y_t^6$
$(\delta_{LR}^d)_{ij}$	$y_j^D V_{3i}^*V_{3j}y_t^2$	$y_j^D \frac{V_{i3}}{V_{j3}^*}$	$y_j^D \frac{V_{i3}}{V_{j3}^*}$	$y_j^D V_{3i}^*V_{3j}y_t^2 + y_i^D \frac{y_i^D y_j^D}{V_{i3}V_{j3}^*}$ $y_j^D \frac{V_{3i}^*}{V_{3j}} y_t^4 y_b^2$	$y_j^D V_{3i}^*V_{3j}y_t^2$

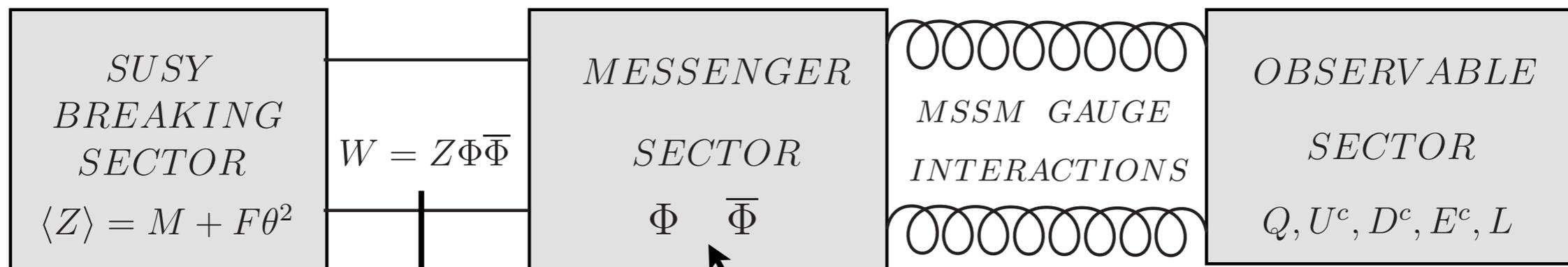
Despite weak U(1) suppression FGM looks like PC

Summary

- Consider couplings of GM messenger to MSSM that are parametrically small as Yukawas
- Leads to large misaligned A-terms
- Large Higgs mass with light, calculable spectrum
- Flavor pheno non-MFV, depends on flavor model
- LL&RR transitions small, dominant effects from LR
- Suitable for generating soft terms in Flavor Models

Backup

The structure of GMSB



$$M_F = M$$

$$(M_S^2)_{1,2} = M^2 \pm F$$

complete SU(5) multiplets: $N \times (\mathbf{5} + \bar{\mathbf{5}})$

1-loop Gaugino masses

$$M_a = N \frac{\alpha_a}{4\pi} \Lambda$$

2-loop **flavor-universal** Sfermion masses

$$\tilde{m}_Q^2 = 2N C_a \left(\frac{\alpha_a}{4\pi} \Lambda \right)^2$$

Vanishing A-terms

$$\Lambda \equiv F/M$$

ΔA_{CP} in SUSY

- Can be generated in SUSY with “misaligned A-terms”

Giudice, Isidori,
Paradisi '12

$$A_{ij}^U \sim y_{ij}^U \quad \text{but} \quad A_{ij}^U \not\propto y_{ij}^U$$

$$\Delta A_{CP}^{SUSY} \sim 0.6\% \frac{\text{Im}(\delta_{LR}^u)_{12}}{10^{-3}} \left(\frac{1\text{TeV}}{\tilde{m}} \right)$$

- No way in MFV

$$(\delta_{LR}^u)_{12} \sim 10^{-7}$$

SUSY ΔA_{CP} in FGM

- Constraints on λ_U / y_U

$$(\lambda_U)_{31}^* (\lambda_U)_{32} \lesssim 6.0 \times 10^{-2} \left(\frac{M_S}{1 \text{ TeV}} \right) \quad D - \bar{D}$$

$$(\lambda_U)_{13} (\lambda_U)_{31} \lesssim 1.7 \times 10^{-5} \left(\frac{M_S}{1 \text{ TeV}} \right) \left(\frac{M_S}{A} \right) \quad \text{EDM}$$

- ΔA_{CP} depends on different combination λ_U entries

$$(\delta_{LR}^u)^{eff}_{12} \sim (\lambda_U)_{13} (\lambda_U)_{32}$$

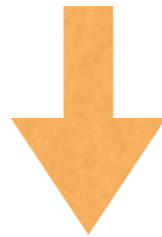
large ΔA_{CP} possible for suitable flavor model

ΔA_{CP} in U(1) Flavor Models

maximal effect bounded from EDM constraint

$$(\delta_{LR}^u)_{11} \lesssim 3 \times 10^{-6} \frac{\tilde{m}}{\text{TeV}}$$

$$(\delta_{LR}^u)_{12} \sim \frac{m_c}{m_u} V_{us} (\delta_{LR}^u)_{11}$$



$$(\delta_{LR}^u)_{12} \lesssim 3 \times 10^{-4} \frac{\tilde{m}}{\text{TeV}}$$

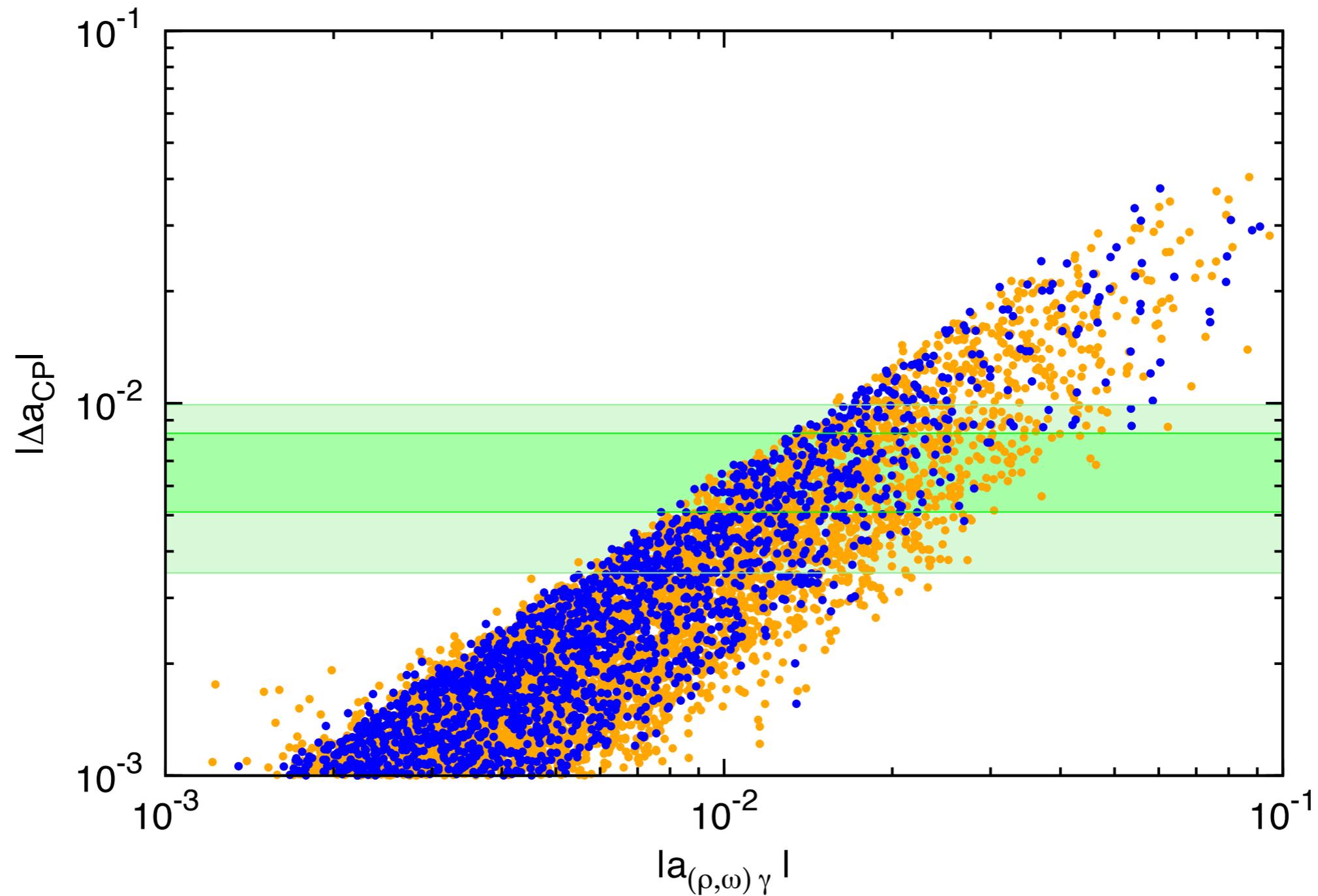
still fine due to order(1) coefficients!

slightly better situation than Gravity Mediation + U(1)

$$(\delta_{LR}^u)_{12} \lesssim 8 \times 10^{-5} \frac{\tilde{m}}{\text{TeV}}$$

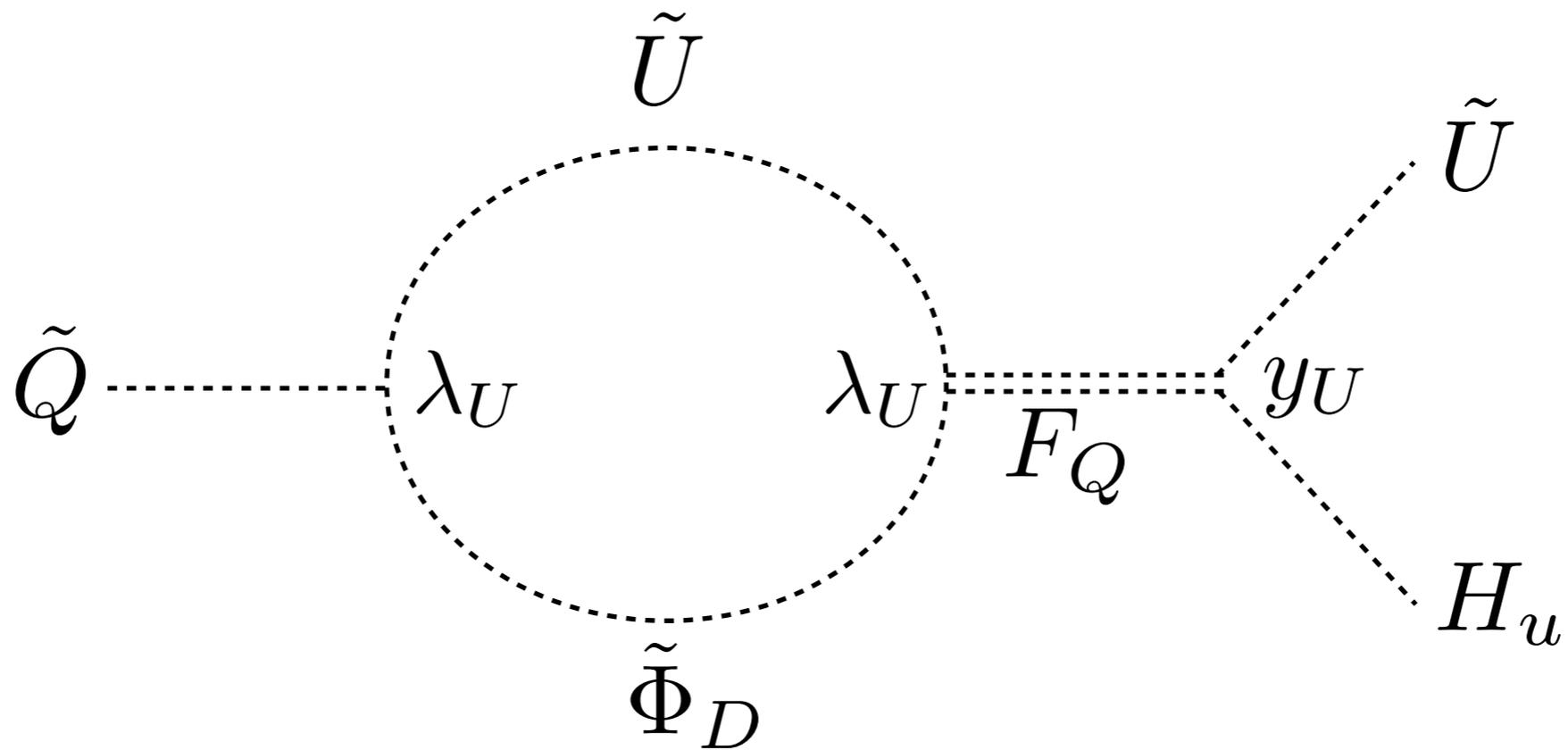
Hiller, Nir '12

Testable with ΔA_{CP} vs. $D \rightarrow V\gamma$ Isidori, Kamenik '12



● >123 GeV Higgs

A-terms



1-loop contributions

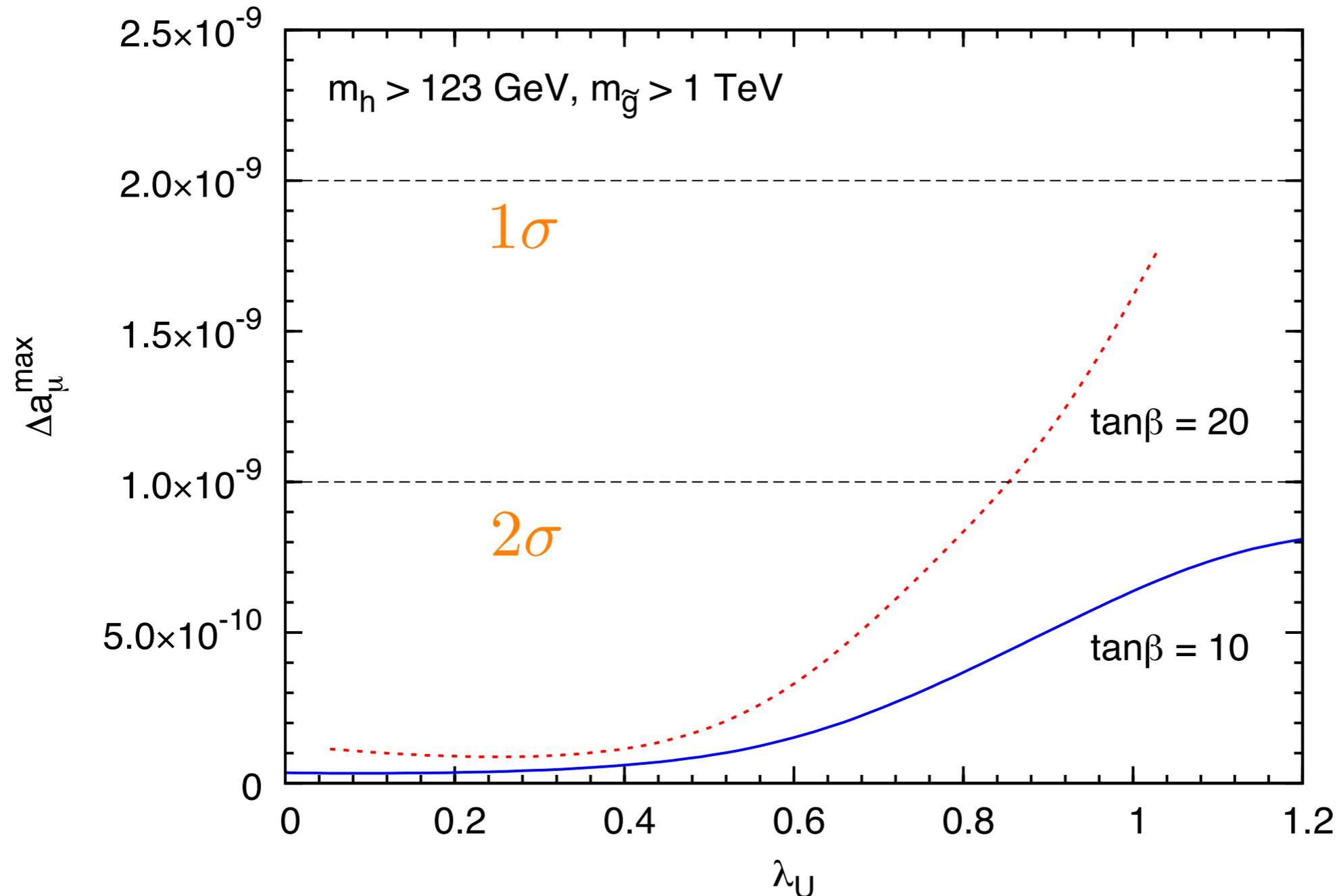
$$\Delta m_{Q,1-loop}^2 \sim -\frac{\Lambda^2}{16\pi^2} \frac{\Lambda^2}{M^2} \lambda_U \lambda_U^\dagger$$
$$\Delta m_{U,1-loop}^2 \sim -\frac{\Lambda^2}{16\pi^2} \frac{\Lambda^2}{M^2} \lambda_U^\dagger \lambda_U$$

Tree-level contributions

$$\Delta W = \mu H_u H_d + \mu' \Phi_{H_u} H_d$$

$$\Delta m_{H_d,tree}^2 = -\frac{\mu'^2}{M^2} \frac{\Lambda^2}{1 - \Lambda^2/M^2}$$

Muon g-2



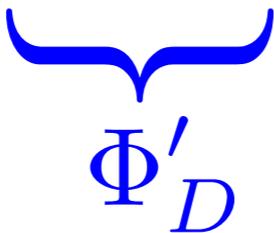
$$\Delta a_\mu \approx 1.3 \times 10^{-9} \left(\frac{\tan\beta}{10} \right) \left(\frac{500 \text{ GeV}}{\tilde{m}_{\mu_R}} \right)^2 \left(\frac{\mu/\tilde{m}_{\mu_L}}{10} \right)$$

Evans, Ibe, Shirai, Yanagida '12

Generating μ in the NMSSM

Field	$(\Phi_D)_1$	$(\bar{\Phi}_D)_1$	H_u	H_d	X	Q	S
U(1)	1	-1	1	1	0	-1/2	-2
Z_3	1	-1	1	1	0	1	1

$$W \sim X \bar{\Phi}_D (H_u + \Phi_D) + QU (H_u + \Phi_D) + SH_d (H_u + \Phi_D) + S^3$$





 $\mu - \text{term}$



helps to get negative m_S^2