Gauge Mediation beyond MFV

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

Overview

- Modification of minimal Gauge Mediation with new messenger-matter couplings controlled by same flavor dynamics as Yukuwas

- Due to large A-terms, one can easily accommodate a 125 GeV Higgs for light and predictive SUSY spectrum (one additional parameter wrt GMSB)

- New sources of flavor violation depending on underlying flavor model, but built-in suppression due to loop origin of soft terms

The Status of Gauge Mediation

- Gauge Mediation elegant and predictive

- In minimal GM difficult to get large Higgs mass (A-terms are small)

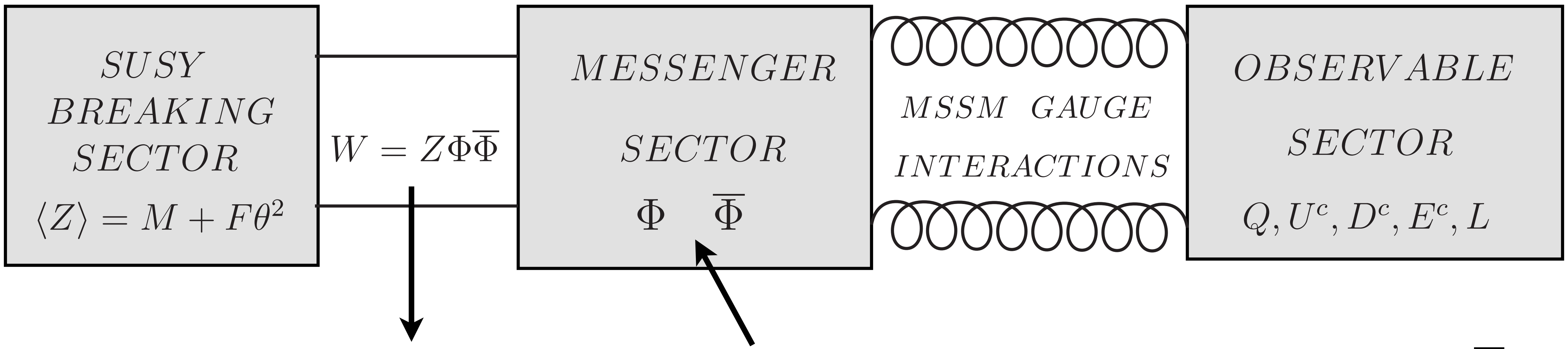
$$\Delta m_h^2 \approx \frac{3m_t^2}{8\pi^2 v^2}\left(\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

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

→ would need very large stop masses → all SUSY particles very heavy

Go beyond minimal GM for large A-terms

The Structure of Minimal GMSB



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

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

1-loop gaugino masses $\quad M_a = N \frac{\alpha_a}{4\pi} \Lambda$

2-loop flavor-universal sfermion masses $\quad \tilde{m}_Q^2 = 2NC_a \left(\frac{\alpha_a}{4\pi} \Lambda \right)^2$

Vanishing A-terms $\quad A = 0$

$\Lambda \equiv F/M$

Generating large A-terms in GM

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

$$\Delta W = \begin{cases} U\overline{\Phi}_{\overline{5}}\,\overline{\Phi}_{\overline{5}} \\ QU\Phi_5 \\ H_u\Phi_{10}\Phi_{10} \\ \cdots \end{cases}$$

Evans, Ibe, Yanagida '11,'12 Craig, Knapen, Shih, Zhao '12

Albeid, Babu '12 Byakti, Ray '13 Evans, Shih '13 Jelinski '13

...

- Also new contributions to sfermion masses

  → need to take care of flavor structure!

new couplings proportional to Yukawas **OR** new couplings suppressed as Yukawas

Flavored GM

Shadmi, Szabo '11

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

$$\Delta W = \lambda^U_{ij} Q_i U_j \Phi_{H_u} + \lambda^D_{ij} Q_i D_j \overline{\Phi}_{H_d}$$

- Assume that couplings are controlled by same underlying flavor dynamics as Yukawas

  (flavor symmetries, partial compositeness...)

- Simplest scenario: flavor only from matter fields

$$\Phi, \overline{\Phi} \sim H_u, H_d \quad \longrightarrow \quad \boxed{\lambda^{U,D} \sim y^{U,D}}$$

e.g. not charged under flavor symmetry

The Setup

- Messengers and Higgs distinguished by symmetry that forbids mu-term: H chiral, Φ vector-like

→ for N=1 only one messenger can mix with H

e.g.

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

- Final setup

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

$\lambda^U_{ij} \sim y^U_{ij}$ ⟶ **only** λ^U_{33} **relevant for SUSY spectrum**

High-energy Spectrum

Evans, Shih '13

- Non-zero squark A-terms

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

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

$$\Delta m^2_{Q(U)} \sim \frac{\Lambda^2}{256\pi^4}\left(\lambda_U \lambda_U^\dagger - g_3^2\right)\lambda_U \lambda_U^\dagger \qquad \Delta m^2_D \sim \frac{\Lambda^2}{256\pi^4} y_D^\dagger \lambda_U \lambda_U^\dagger y_D$$

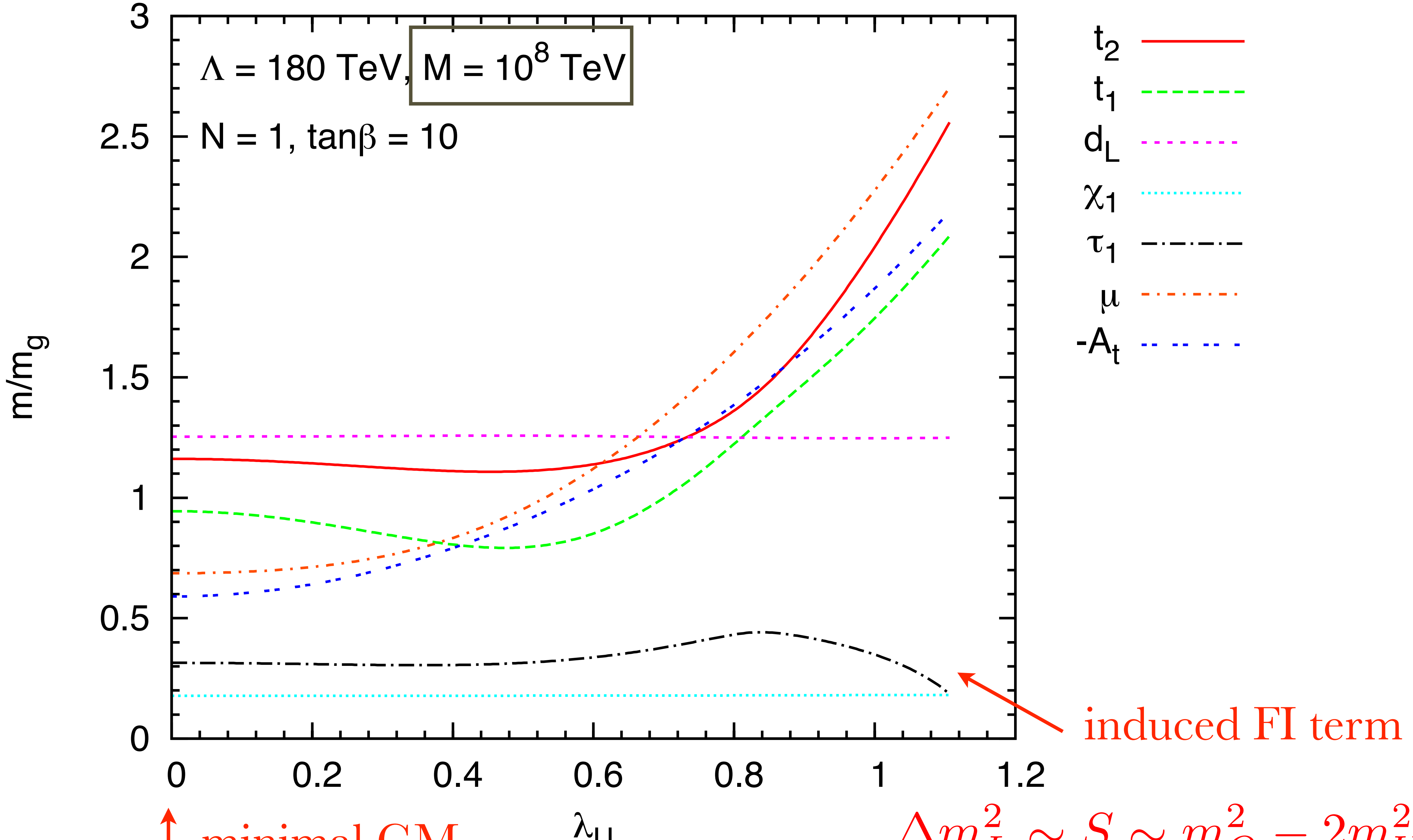
$$\Delta m^2_{H_u} \sim -\frac{\Lambda^2}{256\pi^4}\mathrm{Tr}\, y_U^\dagger \lambda_U \lambda_U^\dagger y_U \qquad \Delta m^2_{H_d} \sim -\frac{\Lambda^2}{256\pi^4}\mathrm{Tr}\, y_D^\dagger \lambda_U \lambda_U^\dagger y_D$$

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

Low-energy Spectrum

$\lambda^U_{33} \equiv \lambda_U$

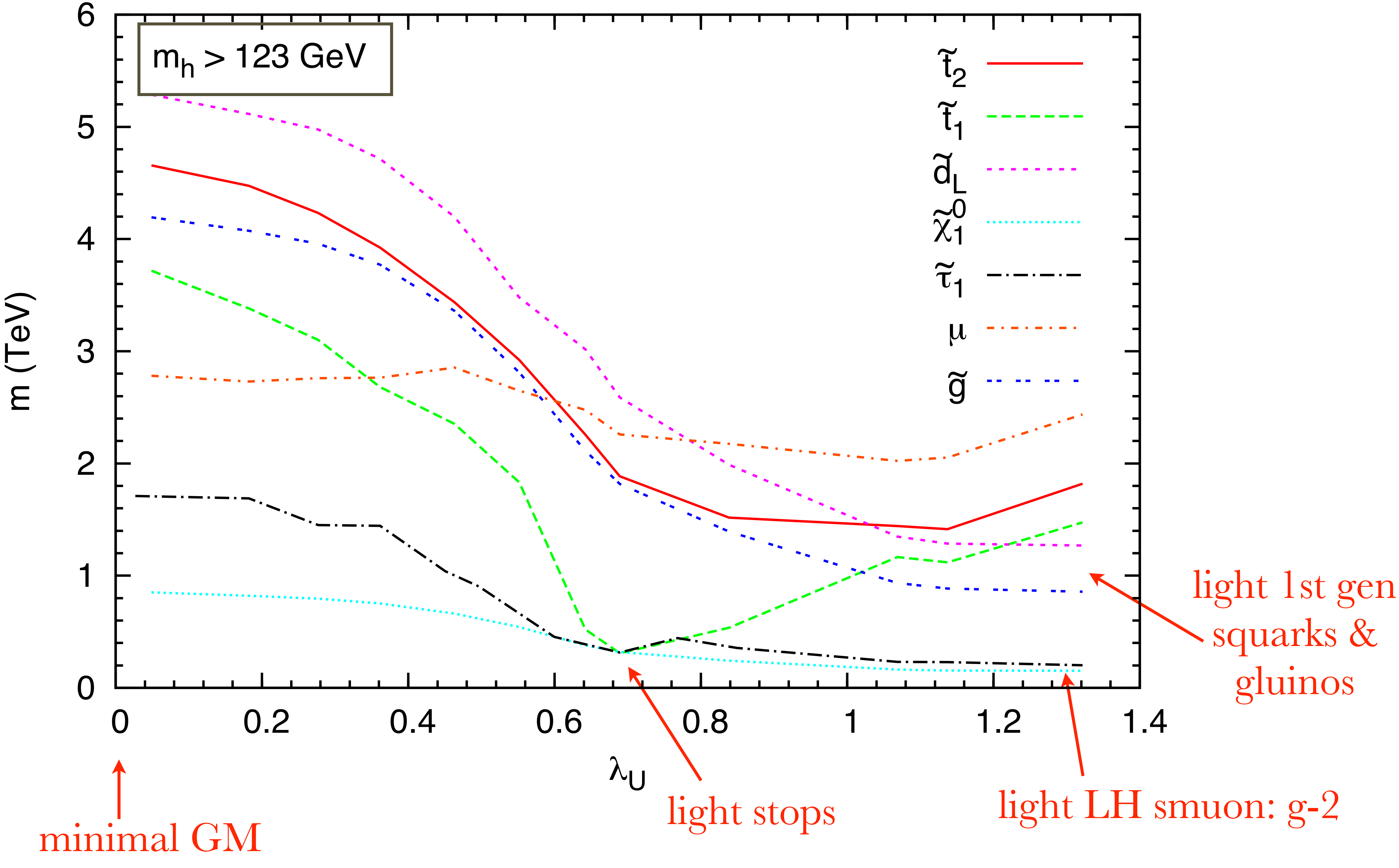
Evans, Ibe, Yanagida '11,'12



↑ minimal GM

$\Delta m_L^2 \sim S \sim m_Q^2 - 2m_U^2$

Low-energy Spectrum



Sflavor Structure

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

$$(\delta^u_{LL})_{ij} \sim (\lambda_U)_{i3}(\lambda^*_U)_{j3} \qquad (\delta^d_{LL})_{ij} \sim V^*_{3i}V_{3j},$$

$$(\delta^u_{RR})_{ij} \sim (\lambda^*_U)_{3i}(\lambda_U)_{3j} \qquad (\delta^d_{RR})_{ij} \sim y^D_i y^D_j V^*_{3i}V_{3j}$$

Possibly sizable Light Yukawa suppression

$$(\delta^u_{LR})_{ij} \sim (\lambda_U)_{i3}(\lambda_U)_{3j} \qquad (\delta^d_{LR})_{ij} \sim V^*_{3i}V_{3j}y^D_j$$

Possibly sizable Additional CKM suppression

Flavor constraints

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

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

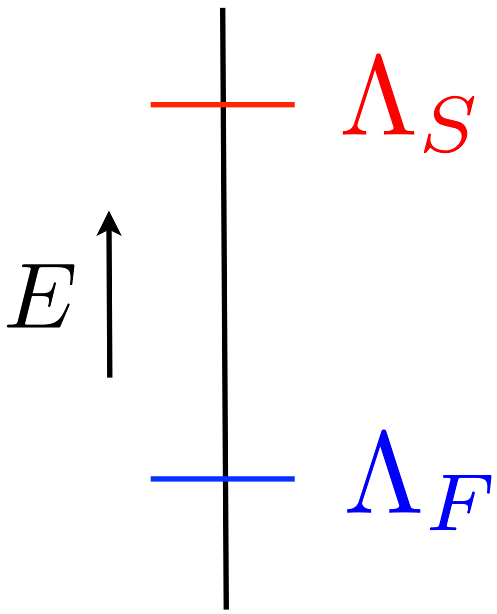
$D - \overline{D}$ mixing

$$(\delta^u_{RR})_{12} \sim (\lambda^*_U)_{31}(\lambda_U)_{32}$$

Neutron EDM

$$(\delta^u_{LR})_{11} \sim (\lambda_U)_{13}(\lambda_U)_{31}$$

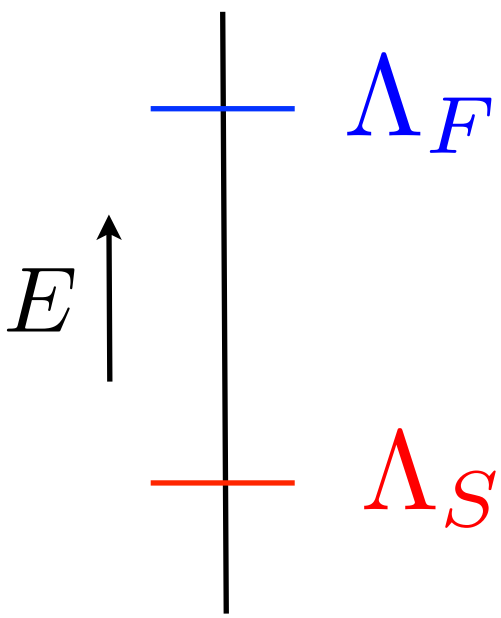
Comparison to other Sflavor Models



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	$U(1)$	$\text{FGM}_{U,D} + U(1)$	$\text{FGM}_U + U(1)$
$(\delta^u_{LL})_{ij}$	$V_{i3}V^*_{j3}y_b^2$	$(\epsilon^q_3)^2 V_{i3}V^*_{j3}$	$\frac{V_{i3}}{V_{j3}}\vert_{i\leq j}$	$V_{i3}V^*_{j3}y_t^2$	$V_{i3}V^*_{j3}y_t^2$
$(\delta^d_{LL})_{ij}$	$V^*_{3i}V_{3j}y_t^2$	$(\epsilon^q_3)^2 V_{i3}V^*_{j3}$	$\frac{V_{i3}}{V_{j3}}\vert_{i\leq j}$	$V^*_{3i}V_{3j}y_t^2$	$V^*_{3i}V_{3j}y_t^2$
$(\delta^u_{RR})_{ij}$	$y^U_i y^U_j V_{i3}V^*_{j3}y_b^2$	$\frac{y^U_i y^U_j}{V_{i3}V^*_{j3}} \frac{(\epsilon^u_3)^2}{y_t^2}$	$\frac{y^U_i V_{j3}}{y^U_j V_{i3}}\vert_{i\leq j}$	$\frac{y^U_i y^U_j}{V_{i3}V^*_{j3}}$	$\frac{y^U_i y^U_j}{V_{i3}V^*_{j3}}$
$(\delta^d_{RR})_{ij}$	$y^D_i y^D_j V^*_{3i}V_{3j}y_t^2$	$\frac{y^D_i y^D_j}{V_{i3}V^*_{j3}} \frac{(\epsilon^u_3)^2}{y_t^2}$	$\frac{y^D_i V_{j3}}{y^D_j V_{i3}}\vert_{i\leq j}$	$\frac{y^D_i y^D_j}{V_{i3}V^*_{j3}}$	$y^D_i y^D_j V^*_{3i}V_{3j}y_t^2$
$(\delta^u_{LR})_{ij}$	$y^U_j V_{i3}V^*_{j3}y_b^2$	$y^U_j \frac{V_{i3}}{V^*_{j3}}$	$y^U_j \frac{V_{i3}}{V^*_{j3}}$	$y^U_j V_{i3}V^*_{j3}y_t^2 + y^U_i \frac{y^U_i y^U_j}{V_{i3}V^*_{j3}}$ $y^U_j \frac{V_{i3}}{V^*_{j3}} y_t^6$	$y^U_j V_{i3}V^*_{j3}y_t^2 + y^U_i \frac{y^U_i y^U_j}{V_{i3}V^*_{j3}}$ $y^U_j \frac{V_{i3}}{V^*_{j3}} y_t^6$
$(\delta^d_{LR})_{ij}$	$y^D_j V^*_{3i}V_{3j}y_t^2$	$y^D_j \frac{V_{i3}}{V^*_{j3}}$	$y^D_j \frac{V_{i3}}{V^*_{j3}}$	$y^D_j V^*_{3i}V_{3j}y_t^2 + y^D_i \frac{y^D_i y^D_j}{V_{i3}V^*_{j3}}$ $y^D_j \frac{V^*_{3i}}{V_{3j}} y_t^4 y_b^2$	$y^D_j V^*_{3i}V_{3j}y_t^2$

Despite weak U(1) suppression FGM looks like PC

Application: SUSY ΔA_{CP}

- Evidence (?) for direct CPV in charm decays

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = -(0.67 \pm 0.16)\%$$

Latest LHCb result:

Naïve average*

ΔA_{CP} = (−0.33 ± 0.12)%

- Unclear whether need new Physics

SM needs largish hadronic enhancement:

$$\mathcal{O}\left(\frac{V_{cb}V_{ub}}{V_{cs}V_{us}}\frac{\alpha_s}{\pi}\right) \sim 10^{-4}$$

- Can be generated in SUSY from LR transition

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

Giudice, Isidori, Paradisi '12

no way in MFV $\quad (\delta^u_{LR})_{12} \sim 10^{-7}$

SUSY ΔA_{CP} in FGM

- Constraints on underlying flavor model

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

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

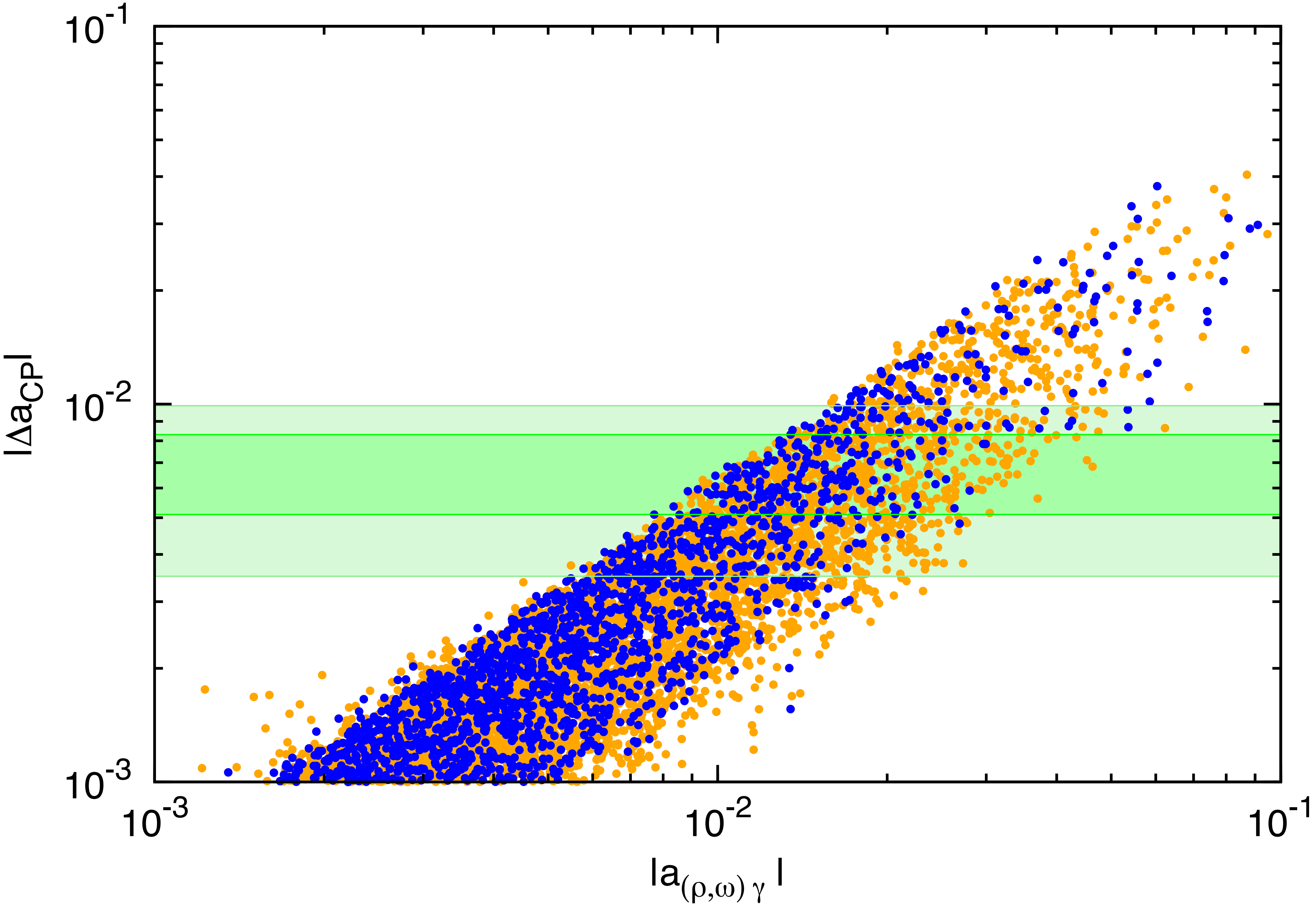
- ΔA_{CP} depends on different combination λ_U entries

$$(\delta^u_{LR})^{eff}_{12} \sim (\lambda_U)_{13}(\lambda_U)_{32}$$

Large ΔA_{CP} possible for suitable flavor model

Testable with ΔA_{CP} vs. $D \to V\gamma$

Isidori, Kamenik '12



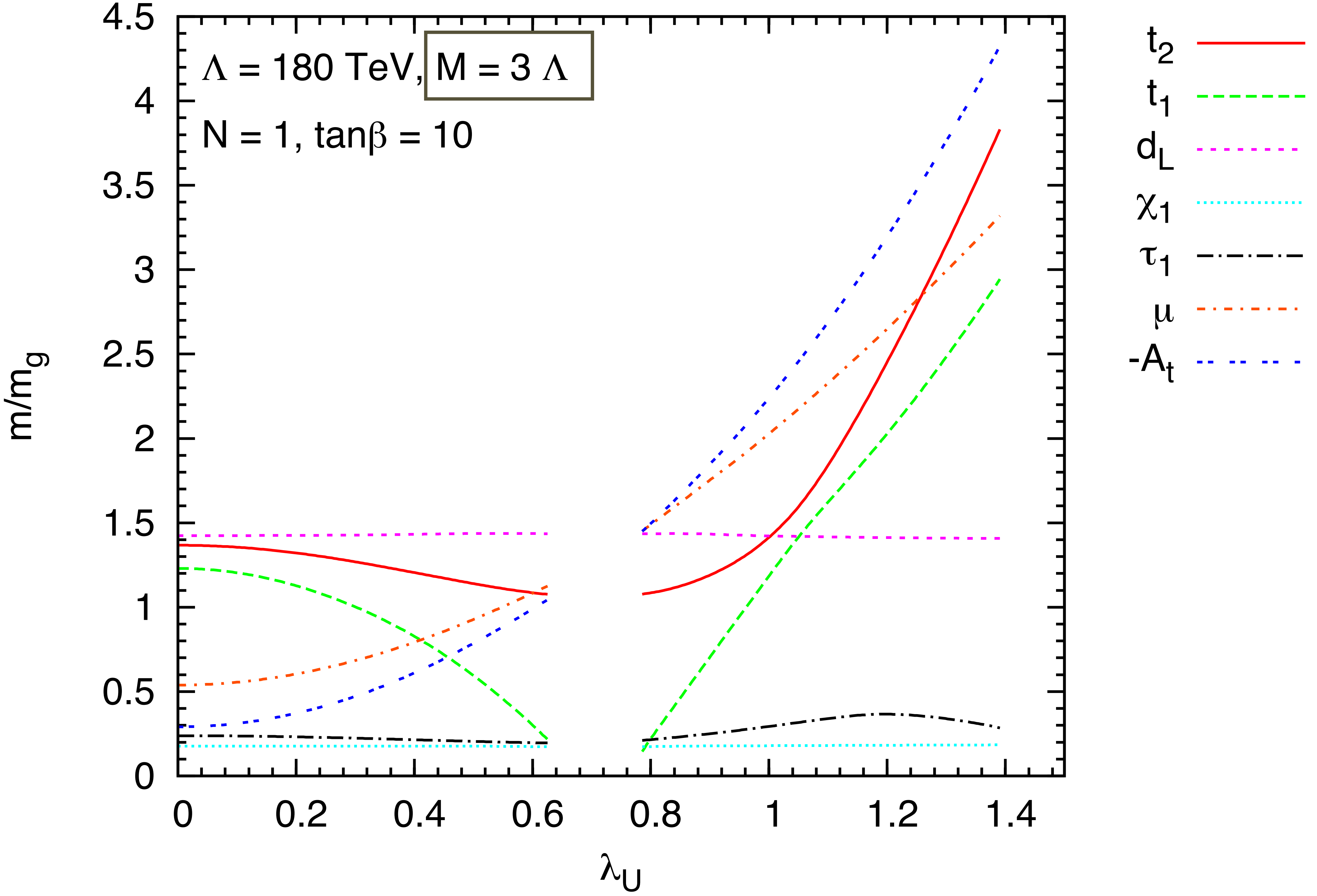
>123 GeV Higgs

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
- Perfect framework to address direct CPV in charm

Backup

Low-energy Spectrum



NMSSM for mu-term

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

add S and break U(1) to Z3

	Φ_{H_u}	$\overline{\Phi}_{H_d}$	H_u	H_d	X	Q, U, D, E, L	S
Z_3	1	-1	1	1	0	1	1

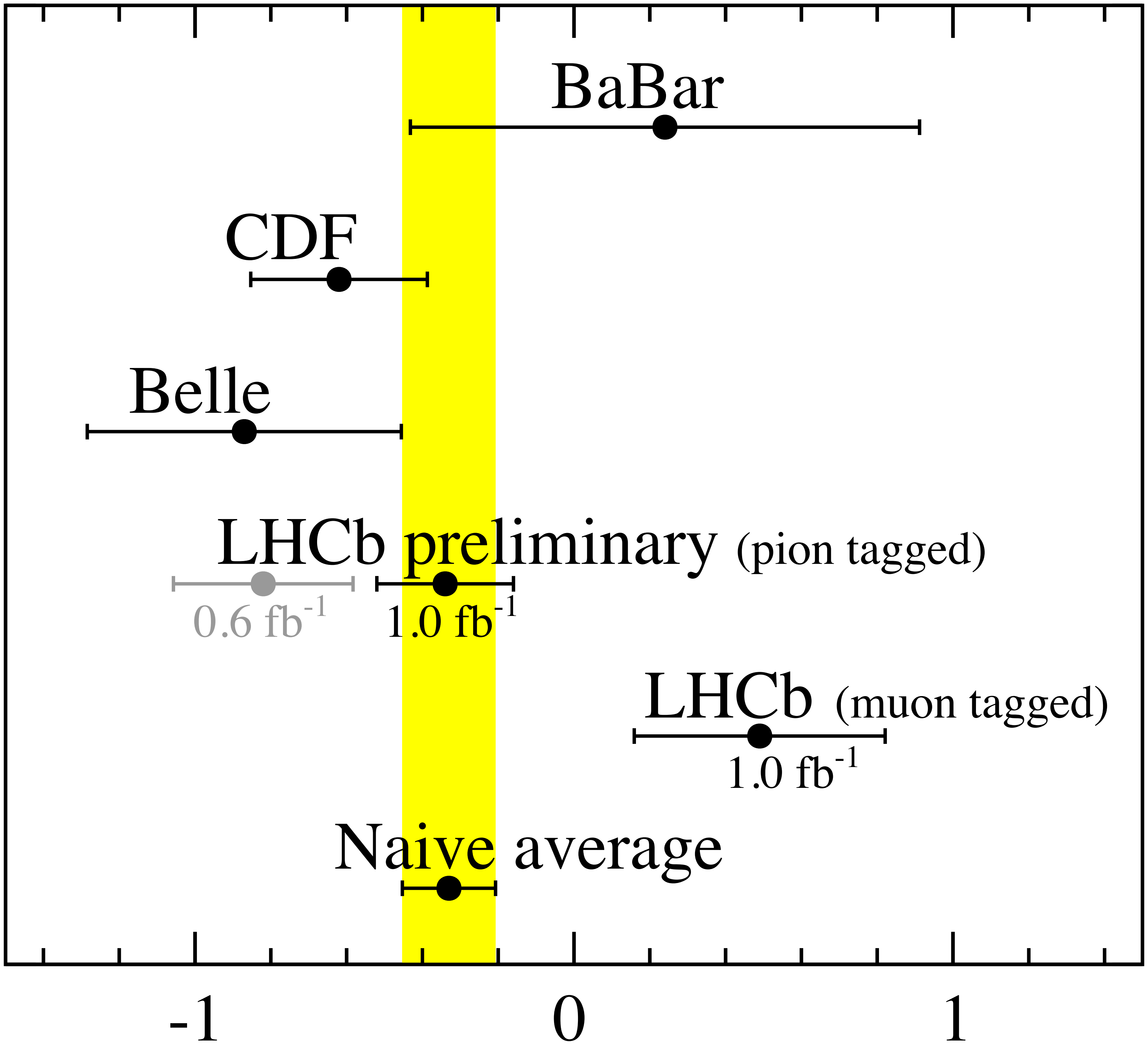
$$W \sim X\overline{\Phi}_{H_d}\left(\Phi_{H_u} + H_u\right) + QU\left(\Phi_{H_u} + H_u\right) + SH_d\left(\Phi_{H_u} + H_u\right) + S^3$$

Φ'_{H_u}

$\mu -$ term

helps to get negative m_S^2

Experimental situation



Naïve average*

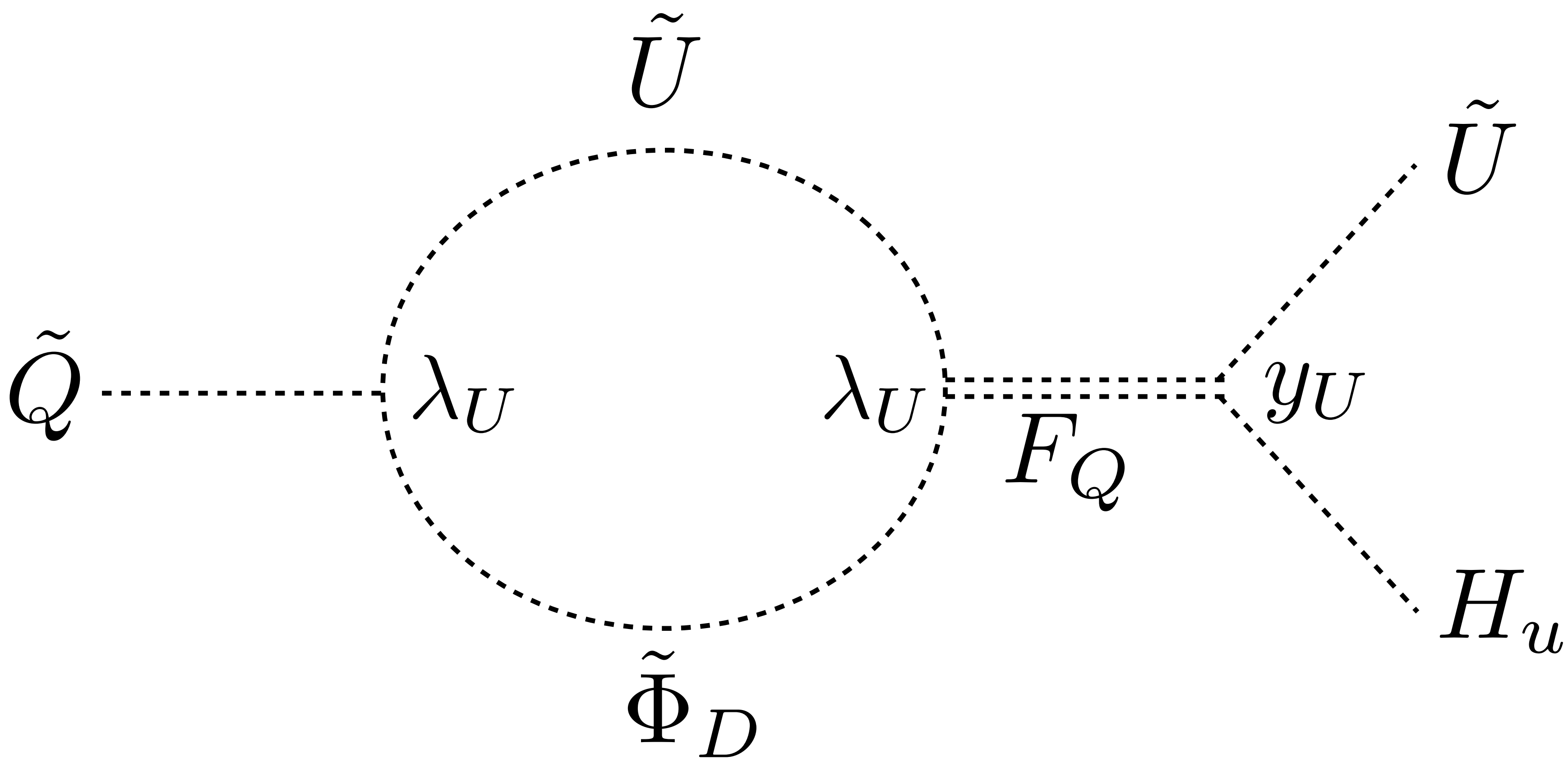
$\Delta A_{CP} = (-0.33 \pm 0.12)\%$

*) Does not account for indirect CP violation.
No scaling of errors.

CERN-LHC seminar, 12 March 2013

Jeroen van Tilburg

A-terms



1-loop contributions

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

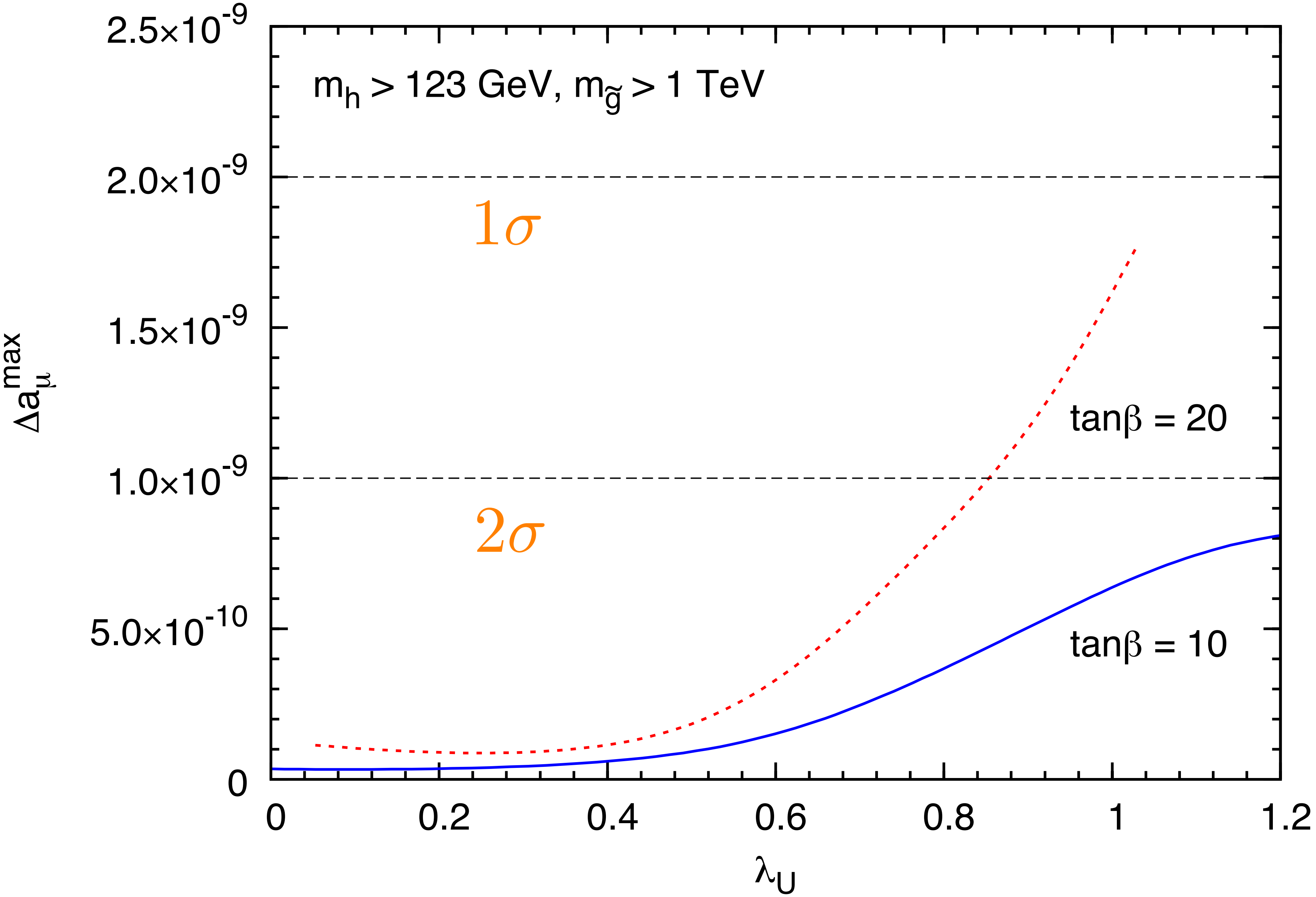
$$\Delta m^2_{U,1-loop} \sim -\frac{\Lambda^2}{16\pi^2}\frac{\Lambda^2}{M^2}\lambda_U^\dagger \lambda_U$$

Tree-level contributions

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

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

Muon g-2



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

Evans, Ibe, Shirai, Yanagida '12

SU(5) invariant charge assignment

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

$$\Delta W = (\lambda_{QQ})_{ij} Q_i Q_j \Phi_T + (\lambda_{UE})_{ij} U_i E_j \Phi_T$$

with $\lambda_{QQ} \sim \lambda_{UE} \sim \lambda_U \sim y_U$

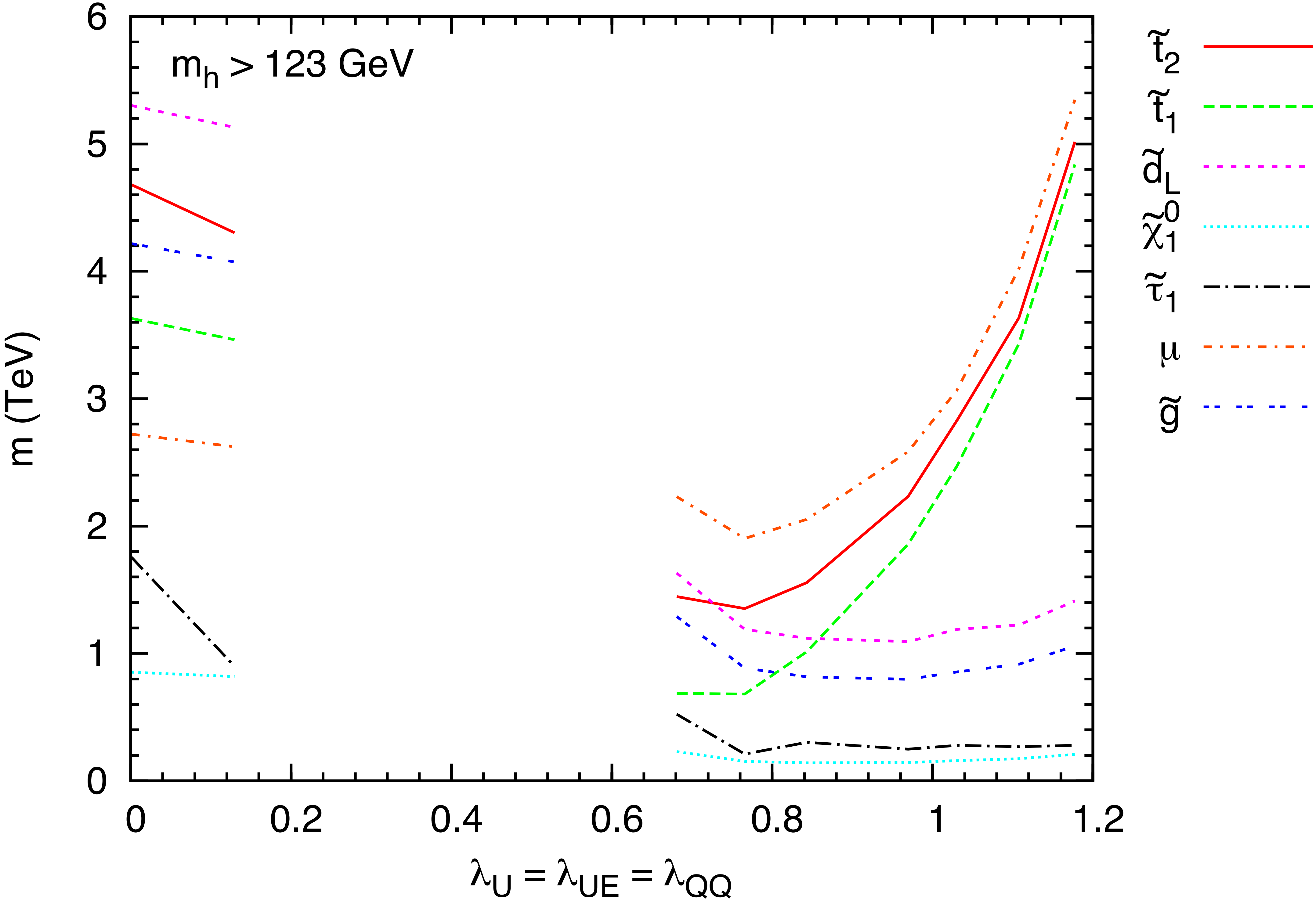
no dim 5 proton decay operators

$$K_{eff} \sim \underbrace{\frac{(\lambda_{QQ})_{11}(\lambda_{UE})_{11}}{M^2}}_{1/M_{eff}^2} Q_1^\dagger Q_1^\dagger U_1 E_1$$

$M_{eff} \gtrsim 10^{15}\mathrm{GeV}$

⇒ $M \gtrsim 10^{10}\mathrm{GeV}$

SU(5) invariant charge assignment



ΔA_{CP} in U(1) Flavor Models

maximal effect bounded from EDM constraint

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

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

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

need indeed $5 \times 10^{-4} \frac{\tilde{m}}{\text{TeV}}$

better situation than Gravity Mediation + U(1)

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

Hiller, Nir '12