Gauge Mediation beyond MFV

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based on arXiv:1304.1453
with L. Calibbi & P. Paradisi

Overview

- Modification of GMSB with new messenger-matter couplings controlled by same flavor dynamics as Yukuwas Shadmi, Szabo '11

- Can easily accommodate 125 GeV Higgs for light and predictive SUSY spectrum

- Flavor violation depends on underlying flavor model, but built-in suppression of $\Delta F=2$ effects and main source δ^u_{LR}

The Status of SUSY

- SUSY most appealing solution to hierarchy problem

- Yet no signals at the LHC

$$m_{\tilde{q}_{1,2}} \sim m_{\tilde{g}} \gtrsim 1\,\text{TeV} \qquad m_{\tilde{q}_3} \sim m_{\tilde{\chi}} \gtrsim 300\,\text{GeV}$$

- Moderately light Higgs no problem

$m_h \sim 125\,\text{GeV}$ → MSSM with $A_t \sim \sqrt{6} M_S$

$m_h \sim 125\,\text{GeV}$ → NMSSM, new D-terms

The Status of Gauge Mediation

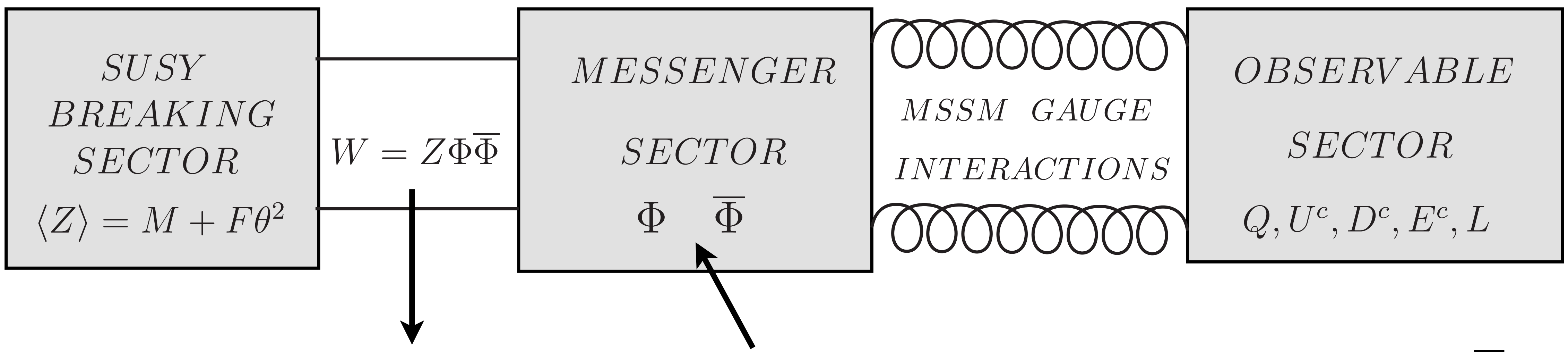
- Gauge Mediation very elegant and predictive scenario of SUSY breaking

- Difficult to get large A-terms in minimal GM

A-terms vanish at messenger scale, generated only by RG evolution ➡ $A_t \sim 0.5\, M_S$

- Go beyond minimal GM for non-vanishing A

The structure of 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 $\qquad M_a = N \dfrac{\alpha_a}{4\pi}\Lambda$

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

Vanishing A-terms $\qquad \Lambda \equiv F/M$

Generating A in GMSB

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

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

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

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

- Generate also new contributions to sfermion masses: take care of flavor structure

- Indeed most models preserve MFV structure of minimal GMSB

Flavored GMSB

Shadmi, Szabo '11

- $\mathbf{5}, \overline{\mathbf{5}}$ Messengers same QN's as MSSM Higgs

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

for $\lambda^{U,D} \sim \mathcal{O}(1)$ flavor structure sfermions completely spoiled

- Suggestive to assume same parametric suppression as Yukawas

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

- New source of FV that is small but not MFV

Why go beyond MFV?

- MFV very restrictive, new FV extremely small

- 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*

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

- Unclear whether need new Physics

SM needs large hadronic enhancement: $\mathcal{O}(\frac{V_{cb}V_{ub}}{V_{cs}V_{us}}\frac{\alpha_s}{\pi}) \sim 10^{-4}$

ΔA_{CP} in SUSY

- Can be generated in SUSY with "misaligned A-terms"

Giudice, Isidori, Paradisi '12

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

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

- No way in MFV

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

Setup

- General FGM setup

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

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

- Motivation

$\Phi, \overline{\Phi} \sim H_u, H_d$ under any dynamics explaining flavor (flavor symmetries, partial compositeness...)

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

for N=1 only one messenger can couple to matter

- Forbid mu-term with U(1) (discrete subgroup)

	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	$-1/2$

$$\begin{array}{c} \\ H_u \\ \Phi_{H_u} \end{array}\begin{array}{c} \begin{array}{cc} H_d & \overline{\Phi}_{H_d} \end{array} \\ \begin{pmatrix} 0 & X \\ 0 & X \end{pmatrix} \end{array} \xrightarrow{\text{redefine}} \begin{array}{c} \\ H'_u \\ \Phi'_{H_u} \end{array}\begin{array}{c} \begin{array}{cc} H_d & \overline{\Phi}'_{H_d} \end{array} \\ \begin{pmatrix} 0 & 0 \\ 0 & X \end{pmatrix} \end{array}$$

- Most general superpotential

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

$\lambda^U_{ij} \sim y^U_{ij}$ $\longrightarrow$ **only** $\lambda^U_{33} \equiv \lambda_U$ **relevant for SUSY spectrum**

High-energy Spectrum

Evans, Shih '13

- Non-zero quark 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 masses

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

- New contribs to 2-loop soft Higgs masses

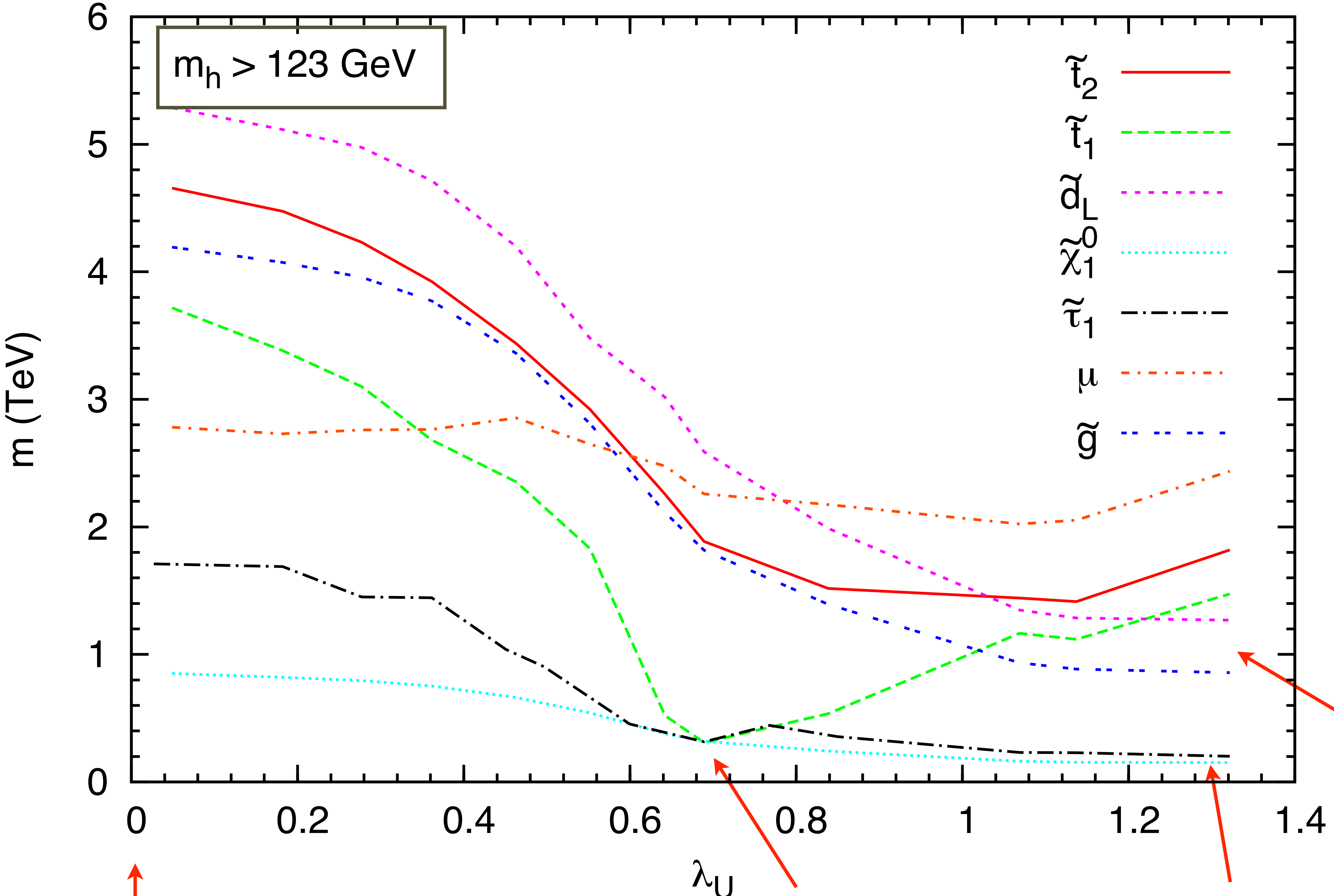
$$\Delta m^2_{H_u} \sim -\frac{\Lambda^2}{256\pi^4}\mathrm{Tr}\, y_U^\dagger \lambda_U \lambda_U^\dagger y_U \qquad \Delta m^2_{H_d} \sim -\frac{\Lambda^2}{256\pi^4}\mathrm{Tr}\, y_D^\dagger \lambda_U \lambda_U^\dagger y_D$$

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

Low-energy Spectrum

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

Evans, Ibe, Yanagida '11,'12



light 1st gen squarks & gluinos

light stops

light LH smuon: g-2

minimal GM

Sfermion Flavor Structure: LL/RR

$$(\delta^u_{LL})_{ij} \sim (\lambda_U)_{i3}(\lambda^*_U)_{j3}$$
$$(\delta^u_{RR})_{ij} \sim (\lambda^*_U)_{3i}(\lambda_U)_{3j}$$

$$(\delta^d_{LL})_{ij} \sim V^*_{3i}V_{3j},$$
$$(\delta^d_{RR})_{ij} \sim y^D_i y^D_j V^*_{3i}V_{3j}$$

D_RR has light Yukawa suppression

$(\lambda_U)_{ij} \sim y^U_{ij}$ → $(\lambda_U)_{23} \lesssim V_{cb}$ $(\lambda_U)_{13} \lesssim V_{ub}$

LL has CKM suppression

only U_RR can be sizable

Sfermion Flavor Structure: LR

$$(\delta^u_{LR})_{ij} \sim (\lambda_U)_{i3}(\lambda^*_U)_{j3} y^U_j + (\lambda^*_U)_{3i}(\lambda_U)_{3j} y^U_i$$

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

U_LR and D_LR have additional CKM suppression

$$(\delta_{LR})^{eff}_{ij} = (\delta_{LL})_{ik}(\delta_{LR})_{kl}(\delta_{RR})_{lj}$$

$$(\delta^u_{LR})^{eff}_{ij} \sim (\lambda_U)_{i3}(\lambda_U)_{j3} \qquad (\delta^d_{LR})^{eff}_{ij} \lesssim (\delta^d_{LR})_{ij}$$

only (effective) U_LR can be sizable

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

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

SUSY ΔA_{CP}

- Constraints on λ_U / y_U

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

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

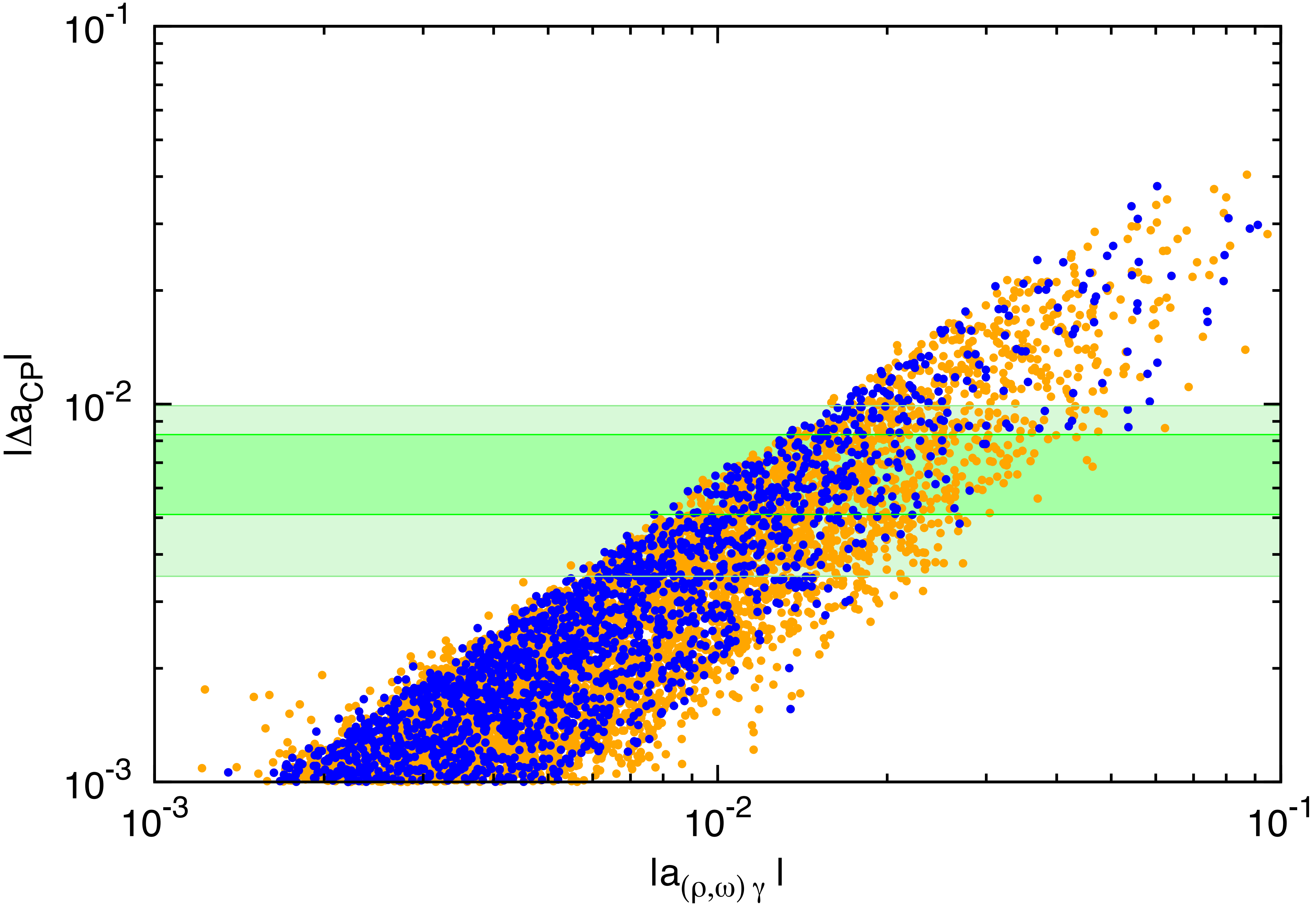
- ΔA_{CP} depends on different combination λ_U entries

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

large ΔA_{CP} possible for suitable flavor model

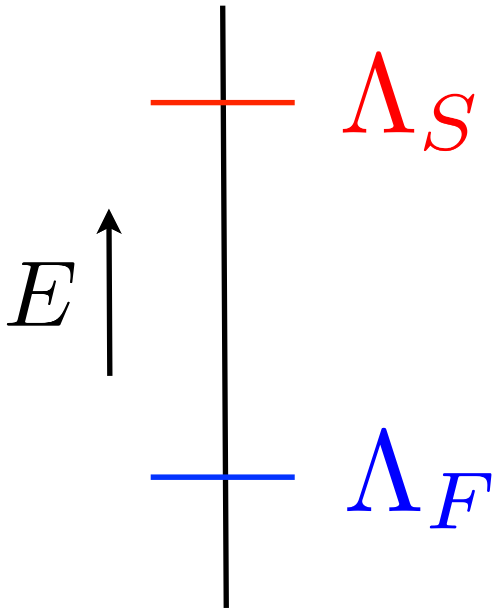
Testable with ΔA_{CP} vs. $D \to V\gamma$

Isidori, Kamenik '12



- >123 GeV Higgs

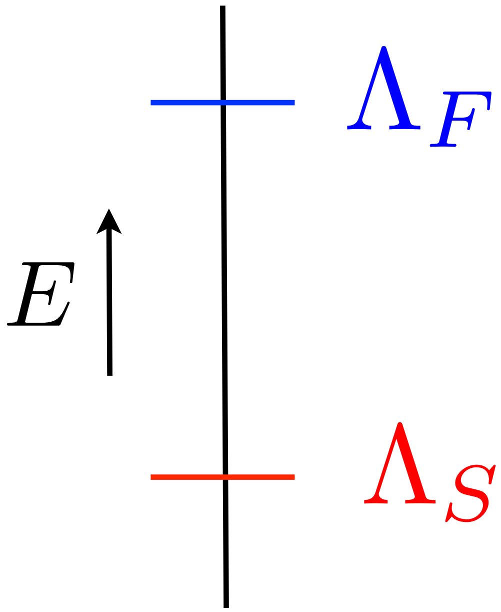
Comparison to other Flavor Structures



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

Despite weak U(1) suppression FGM looks like PC

Summary

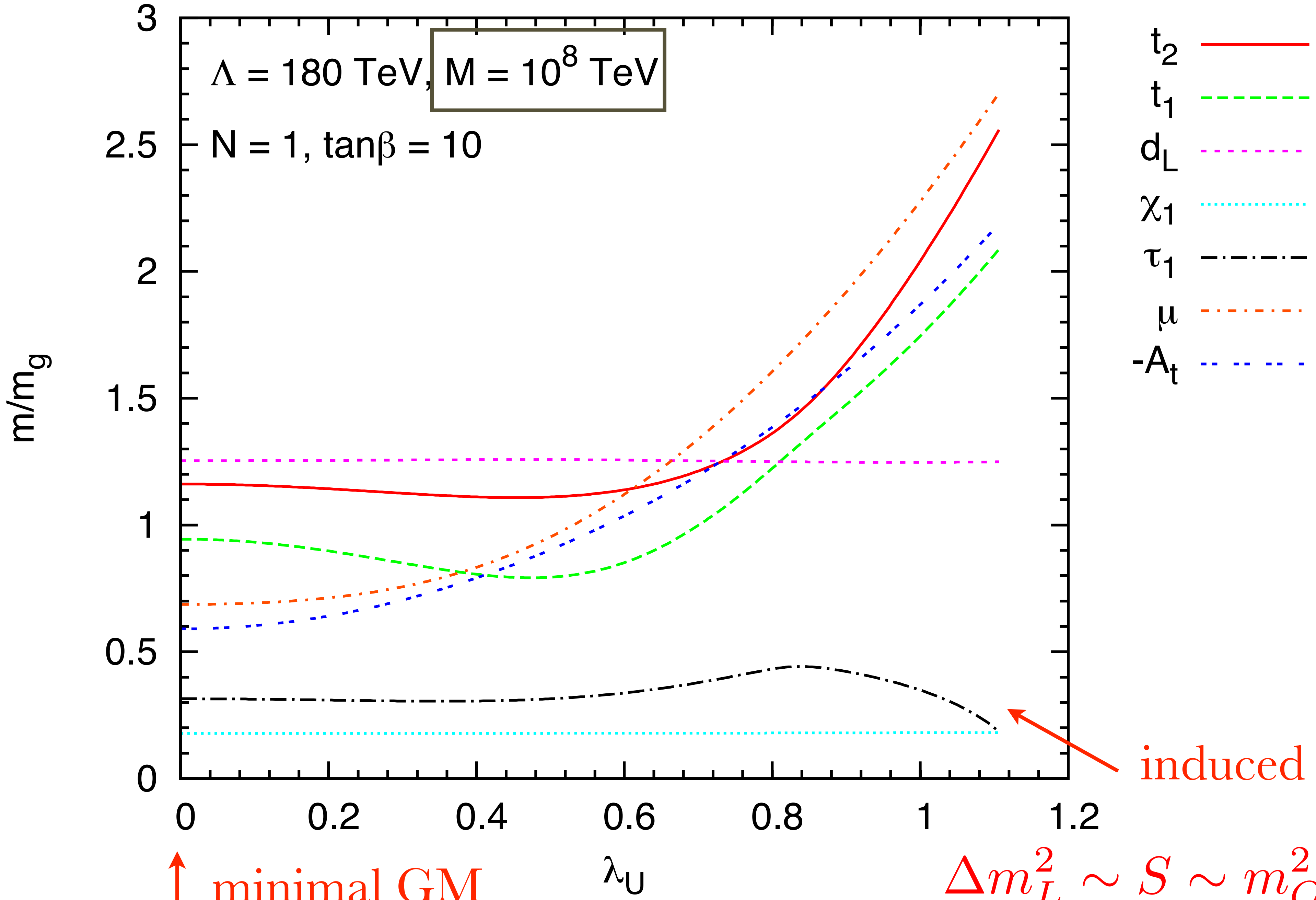
- Consider couplings of GM messenger to MSSM that are parametrically small as Yuks
- Leads to large misaligned A-terms
- Can get large m_h with light, calculable spectrum
- Flavor pheno non-MFV, depends on flavor model
- $\Delta F=2$ small, dominant effects from U_LR
- Can account for ΔA_{CP}

Backup

Low-energy Spectrum

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

Evans, Ibe, Yanagida '11,'12

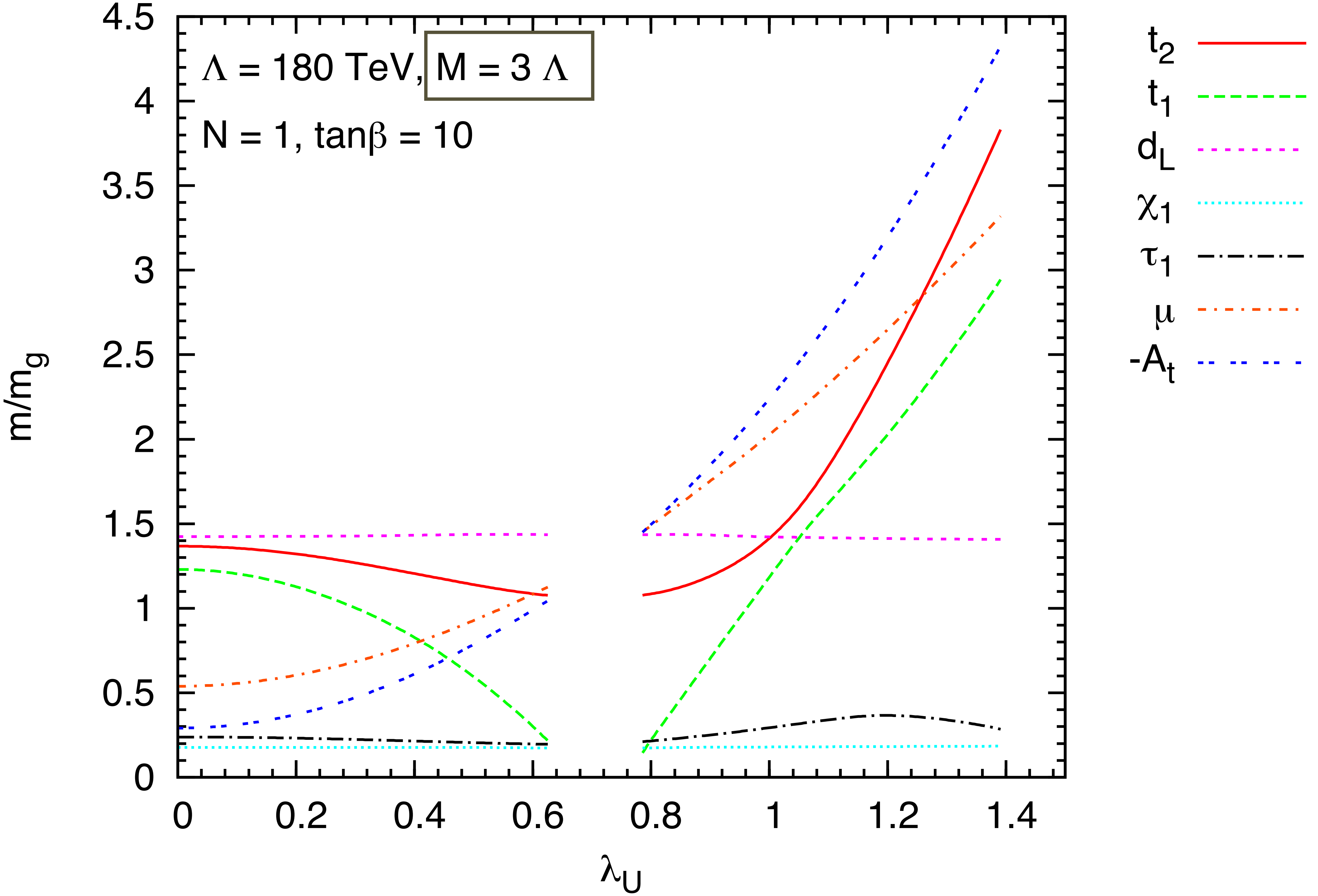


induced FI term

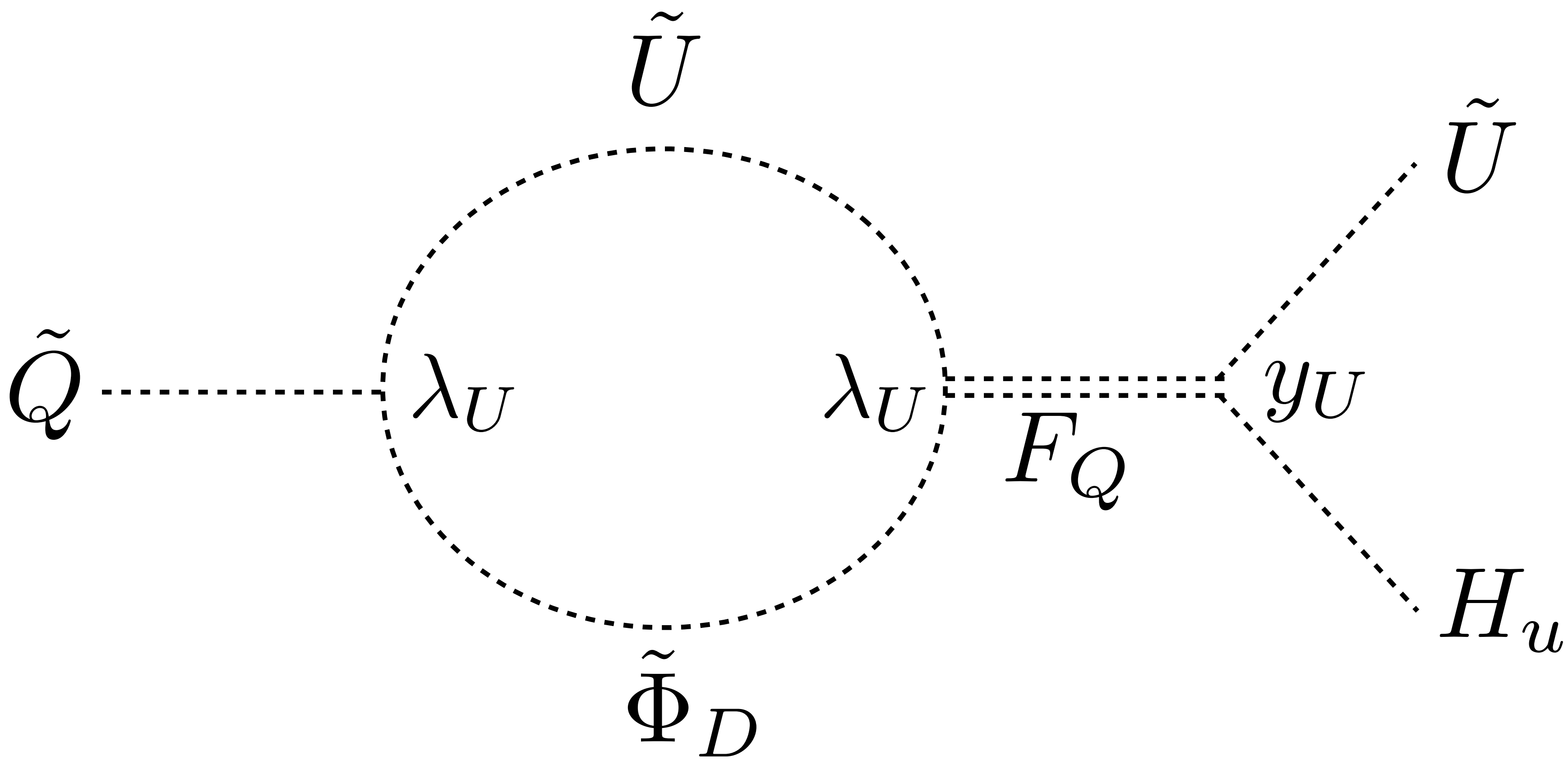
minimal GM

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

Low-energy Spectrum



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

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

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

1-loop contributions to Higgs mass

$$\Delta m_h^2 = \frac{3m_t^4}{8\pi^2 v^2}\left(\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

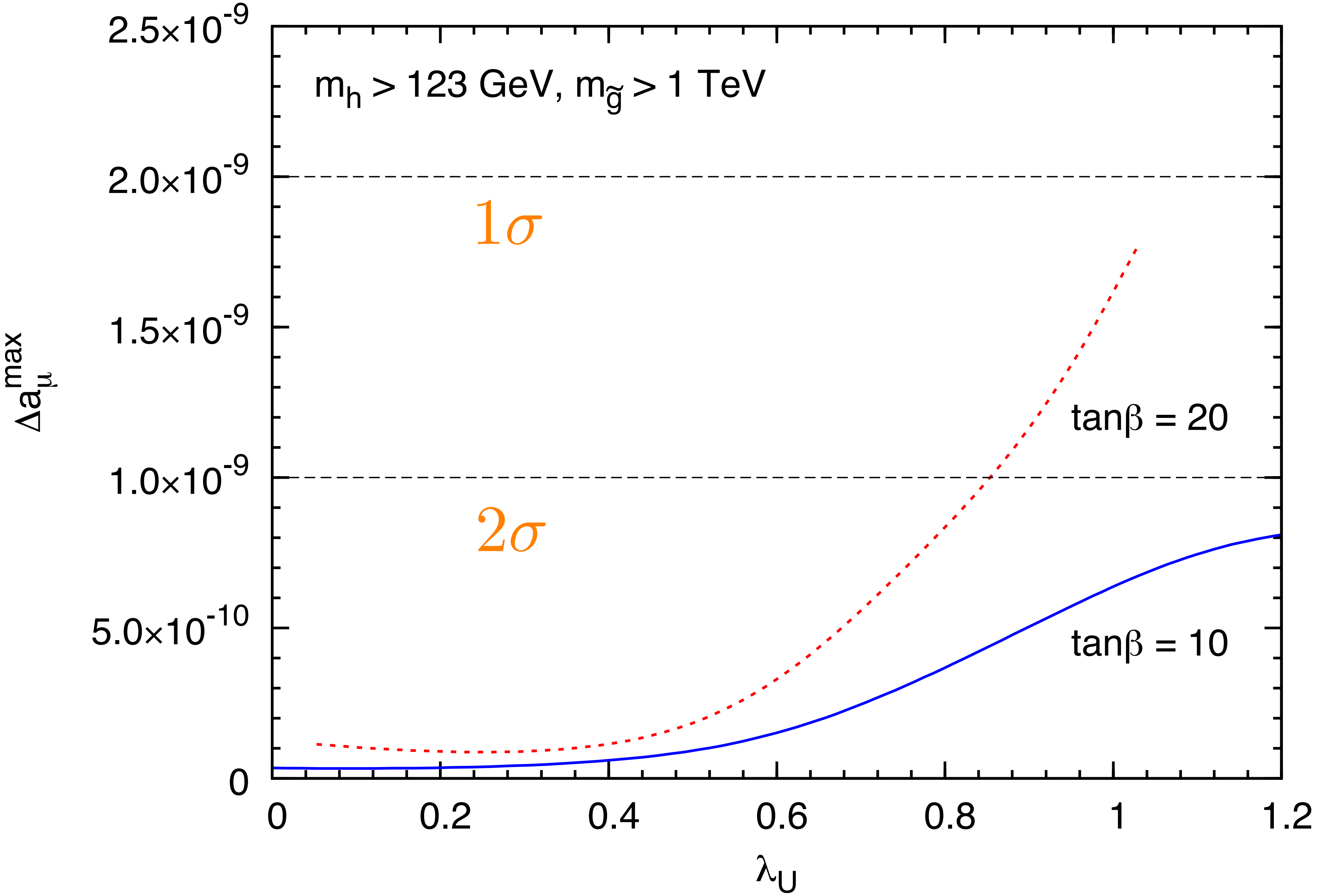
$$M_S = \left(m_{\tilde{t}_1} m_{\tilde{t}_2}\right)^{1/2}$$

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

maximized for

$$X_t = \pm\sqrt{6}M_S \sim 2.4\, M_S$$

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

Generating mu in the NMSSM

Field	$(\Phi_D)_1$	$(\overline{\Phi}_D)_1$	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

$$W \sim X\overline{\Phi}_D(\underbrace{H_u + \Phi_D}_{\Phi'_D}) + QU(H_u + \Phi_D) + SH_d(H_u + \Phi_D) + S^3$$

$\mu -$ term

helps to get negative m_S^2

ΔA_{CP} in U(1) Flavor Models

maximal effect bounded from EDM constraint

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

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

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

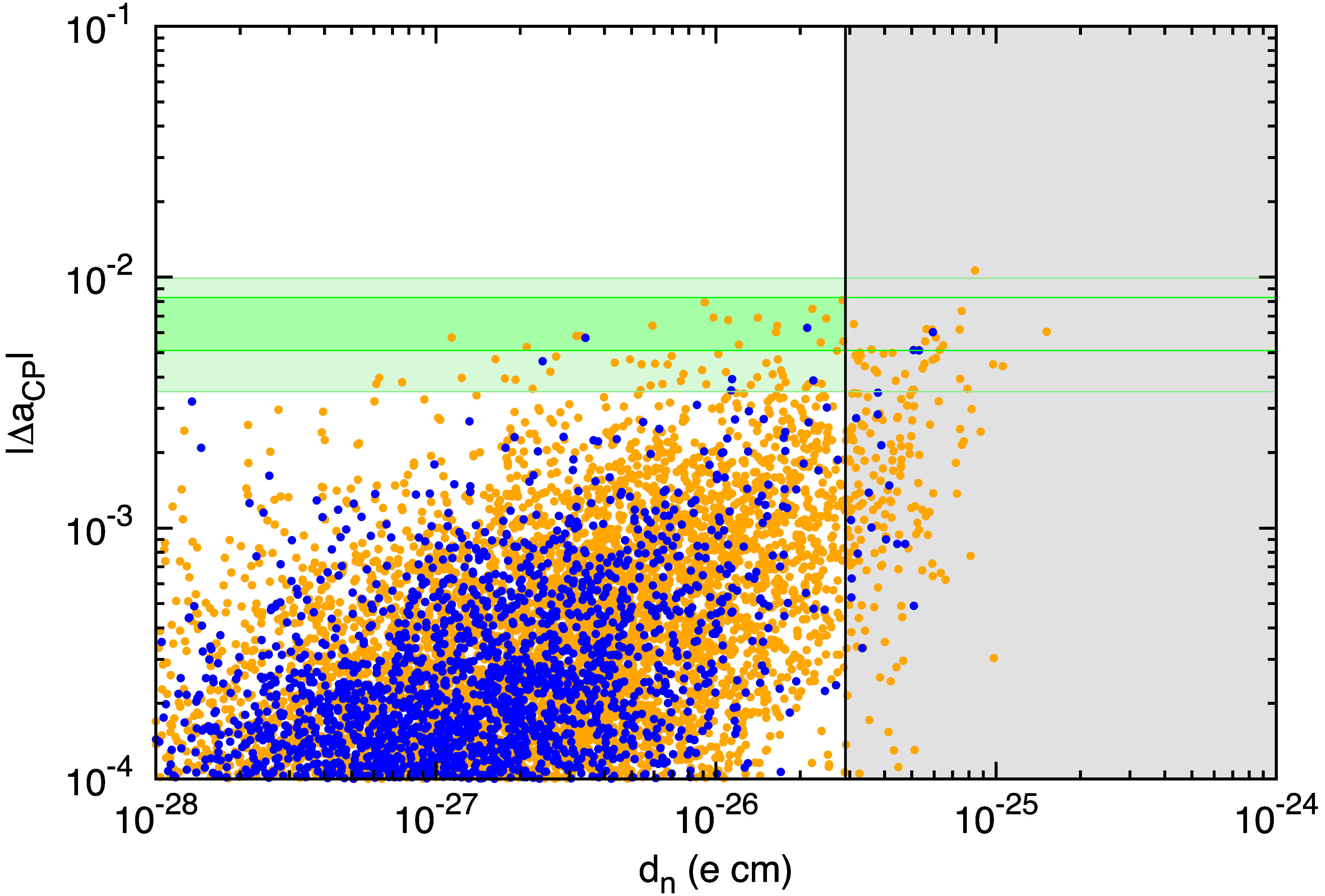
still fine due to order(1) coefficients!

slightly better situation than Gravity Mediation + U(1)

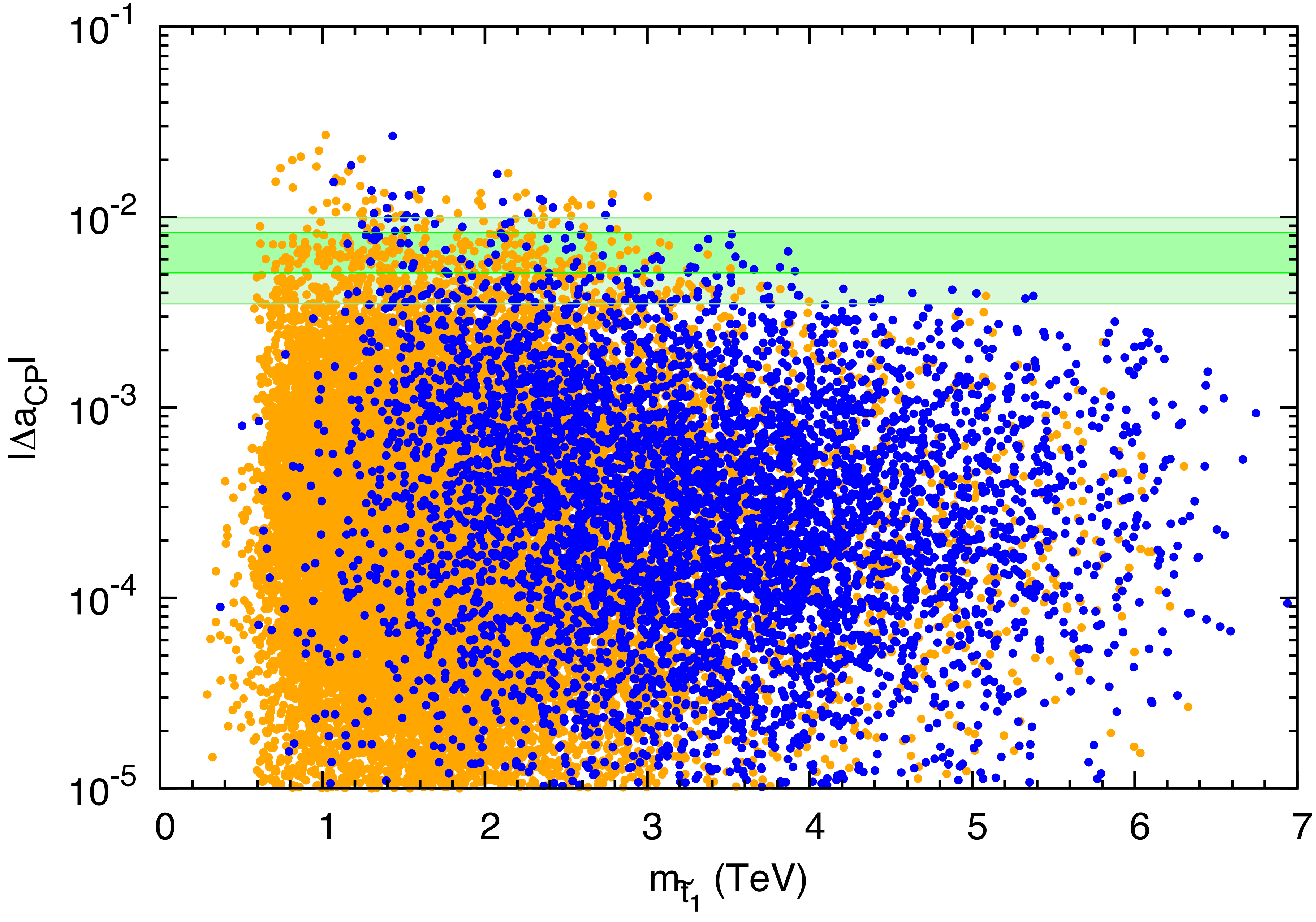
$$(\delta^u_{LR})_{12} \lesssim 8 \times 10^{-5} \frac{\tilde{m}}{\text{TeV}}$$

Hiller, Nir '12

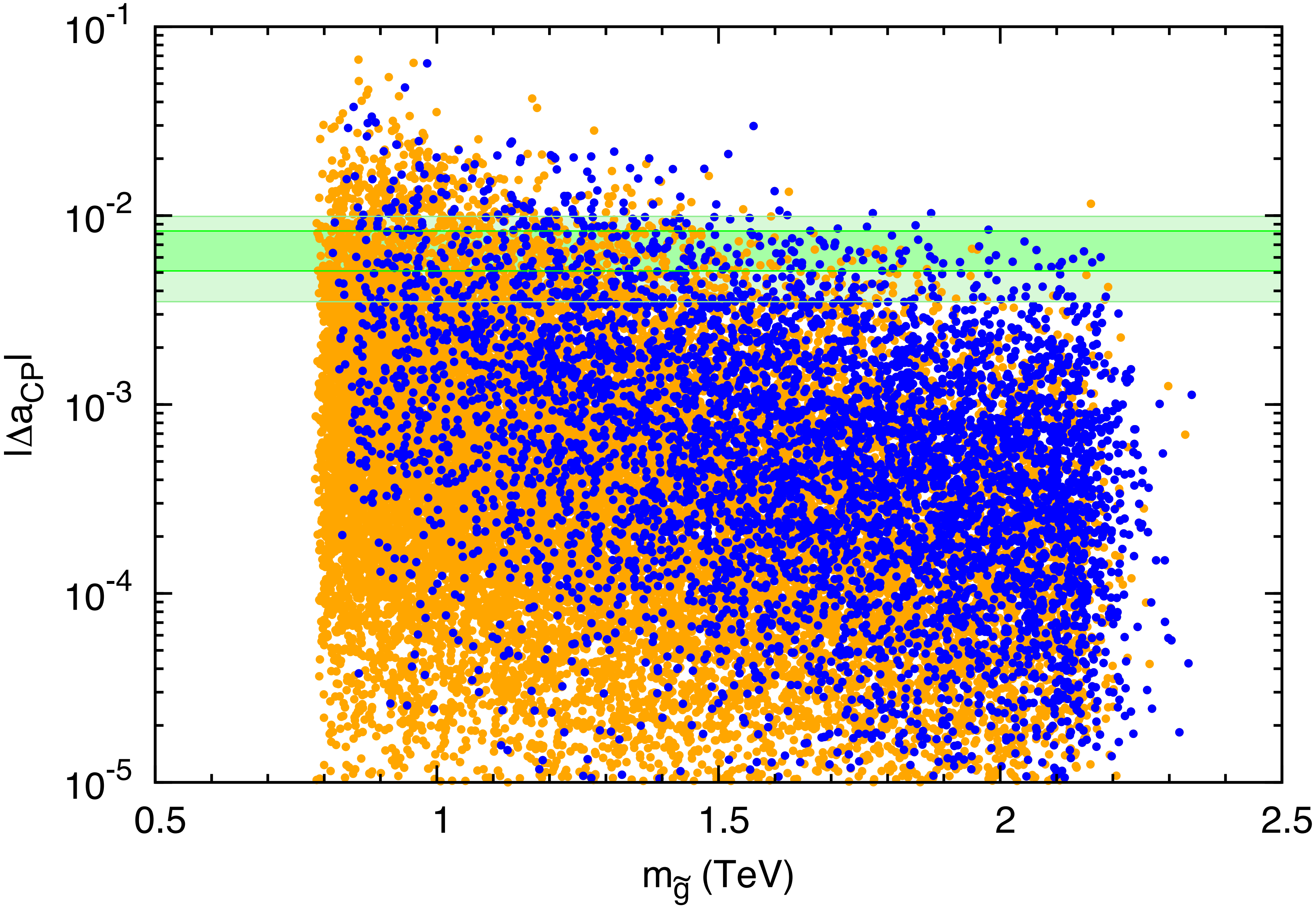
ΔA_{CP} in U(1) Flavor Models



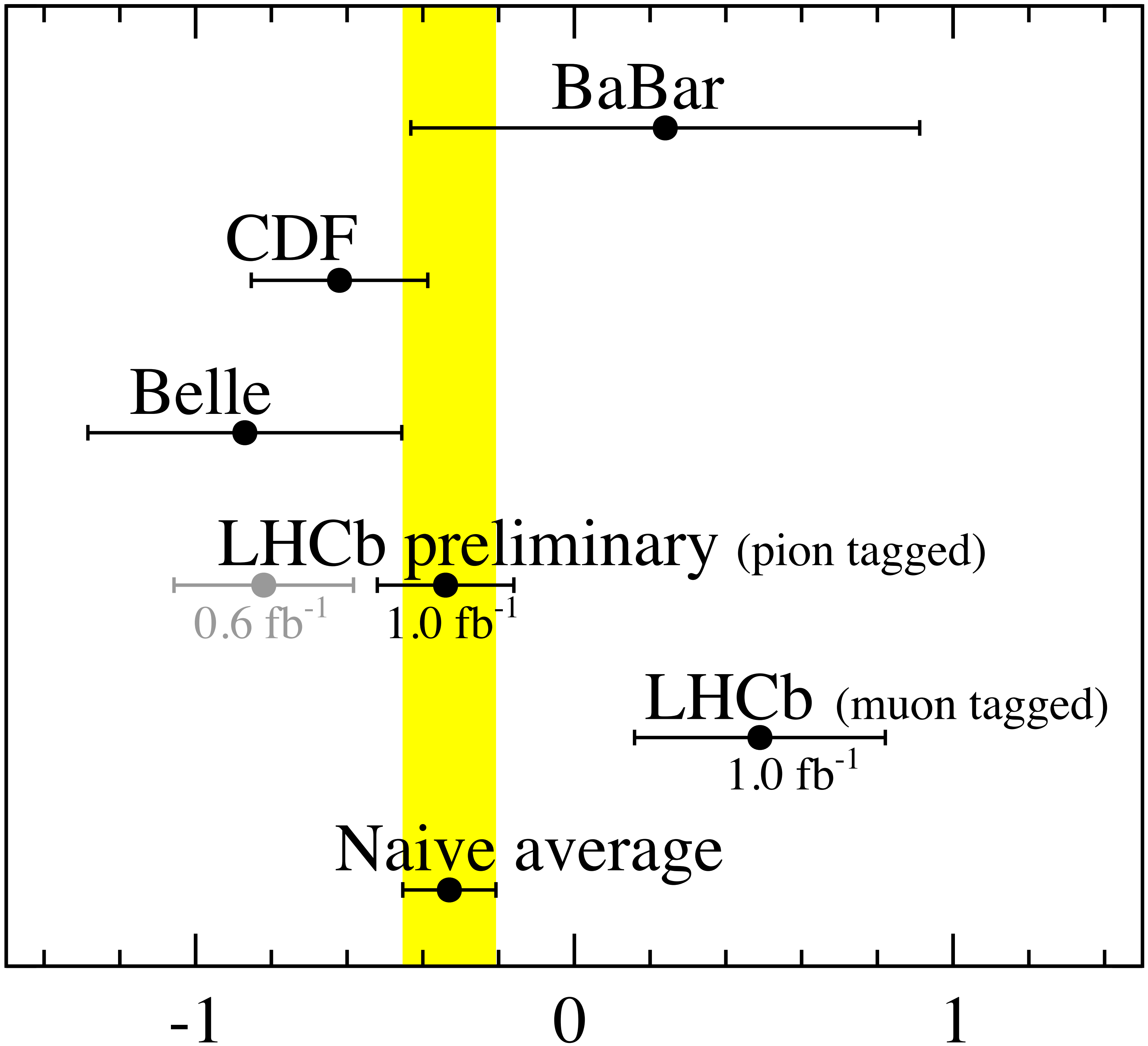
ΔA_{CP} vs m_stop



ΔA_{CP} vs m_gluino



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