Lepton Flavor Violation in high-scale SUSY with right-handed neutrinos

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- Phys.Lett. B723 (2013) 107-112
- arXiv:1305.7357 (to be published in PLB)

8 Dec, 2013 「ニュートリノフロンティア」研究会 @クロス・ウェーブ府中

今日の話のまとめ

（重い）SUSY model

＋

重い右巻きニュートリノ

‖

大きな Lepton Flavor Violation！？

LFV in the SM with massive neutrinos

- Neutrino oscillations ⟵ Massive neutrinos

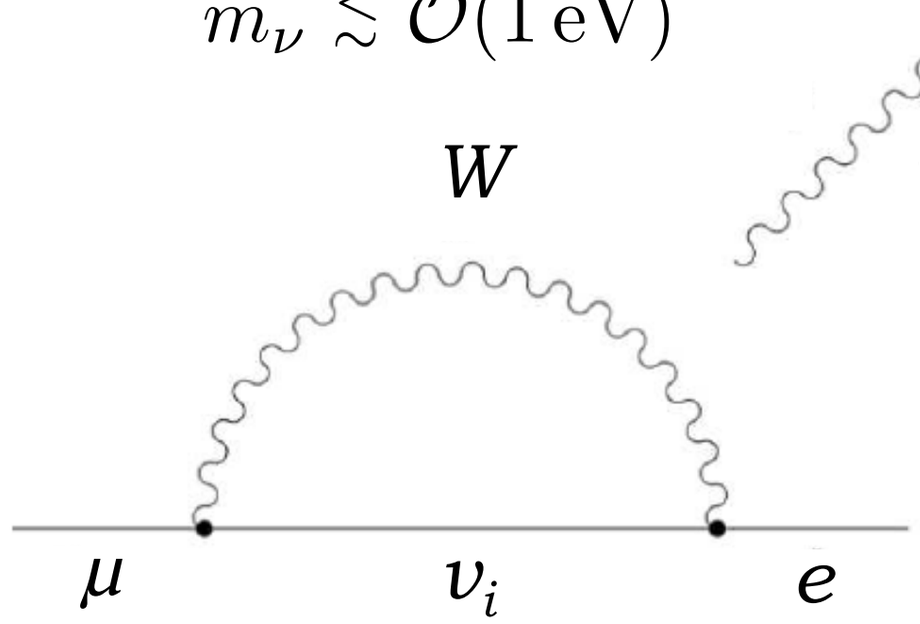
Dirac? Majorana (see-saw)?

$$m_\nu \lesssim \mathcal{O}(1\,\mathrm{eV})$$

Lepton Flavor is not conserved

$$\mathrm{Br}(\mu \to e\gamma) \sim \left| \sum_i U_{\mu i} U_{ei} \frac{m_{\nu_i}^2}{M_W^2} \right|^2$$

$$\lesssim \mathcal{O}(10^{-50})$$



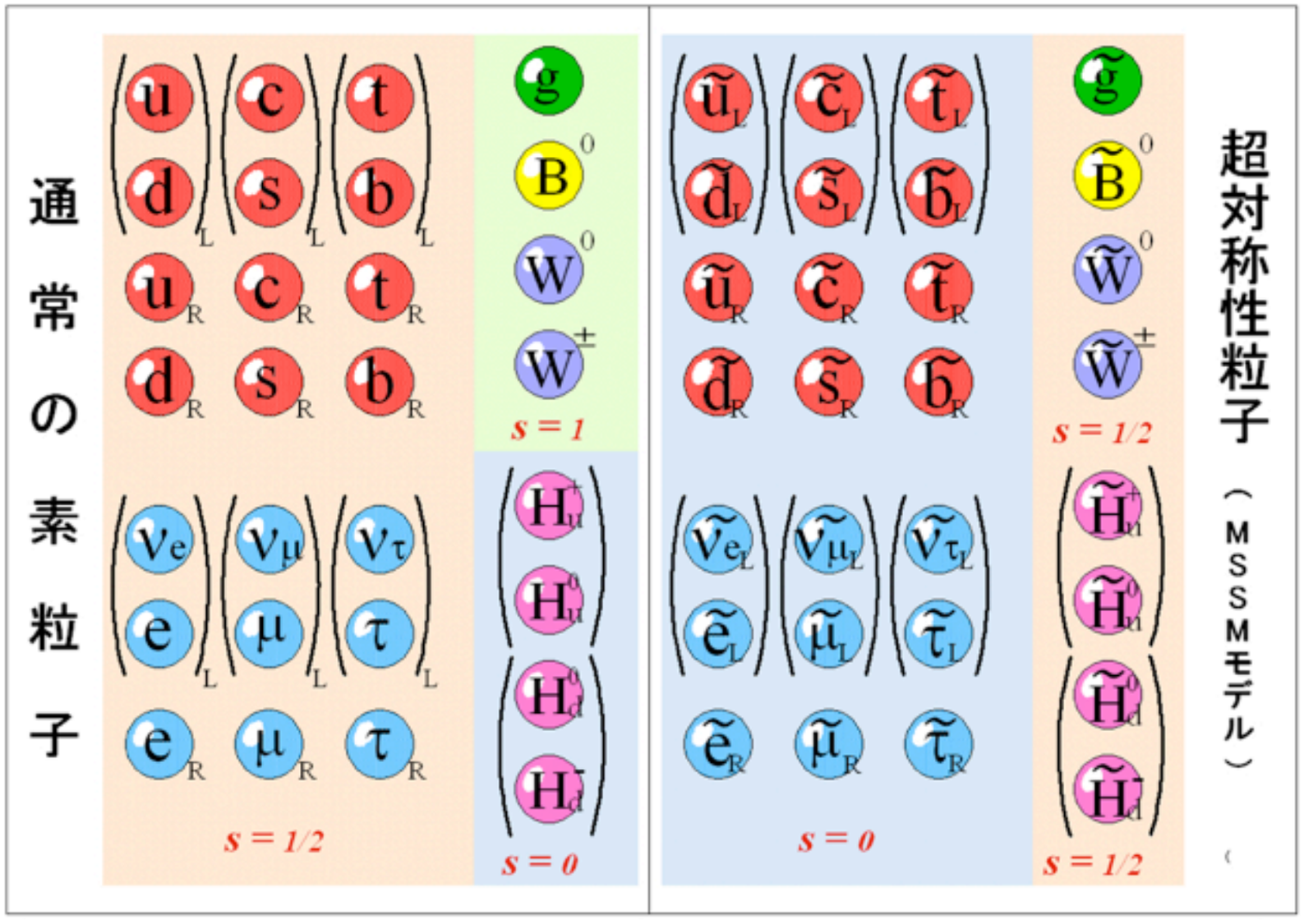
Any LFV observations in the near future experiments implies the existence of physics beyond the SM

massive neutrino + New Physics = Large LFV ?

最小超対称標準模型

(Minimal Supersymmetric Standard Model)

超対称性 (SUSY) ＝ ボゾンとフェルミオンの対称性



Squark
Slepton
Gluino
Bino
Wino
Higgsino

電弱対称性の破れ

→ Neutralino
→ Chargino

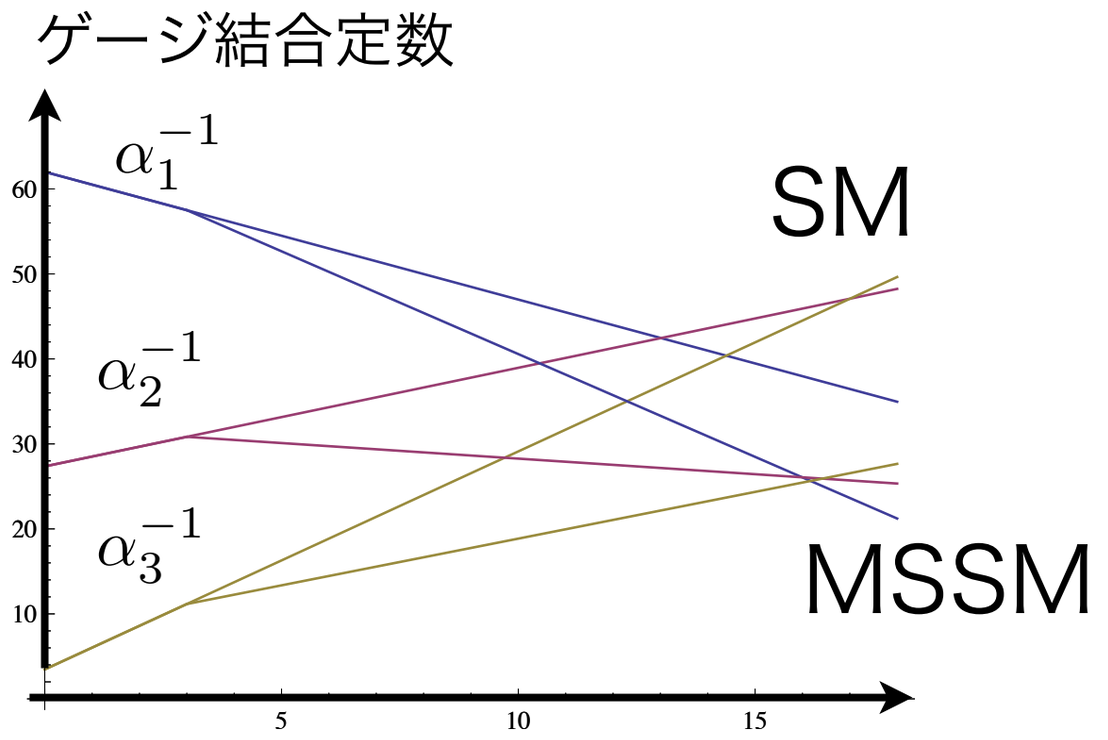
Higgs２重項（２HDM） → h, H, A, H^+

$$\langle H_d \rangle^2 + \langle H_u \rangle^2 = \frac{v^2}{2}$$

$$\tan\beta = \langle H_u \rangle / \langle H_d \rangle$$

どうして超対称性模型？

- 弦理論では超対称性は必須
- 大統一理論への示唆
- Hierarchy Problem (HP)
  (m_{EW}^2とm_{SUSY}^2の微調整)
- 暗黒物質(DM)の候補が存在
  (neutralino, gravitino, ...)
- 軽いヒッグスを予言
  (Higgs の４点結合がゲージ結合定数で与えられる)
- ミューオンの異常磁気能率を説明できる数少ない模型

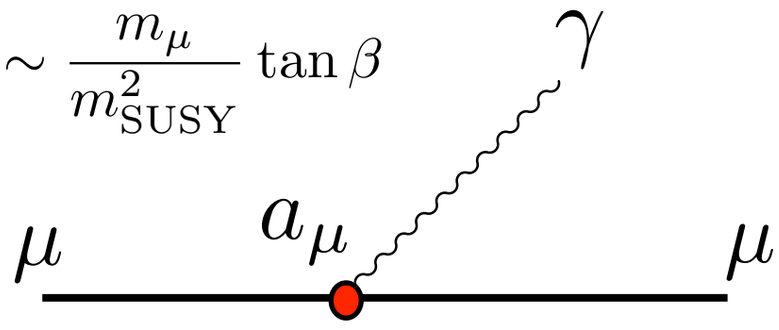


$$m_h^2 = m_Z^2 \cos^2 2\beta + \text{輻射補正項}$$

tree　　loop

$$a_\mu^{\mathrm{SUSY}} \sim \frac{m_\mu}{m_{\mathrm{SUSY}}^2} \tan\beta$$

$$\left(y_\mu \sim \frac{m_\mu}{v} \tan\beta\right)$$



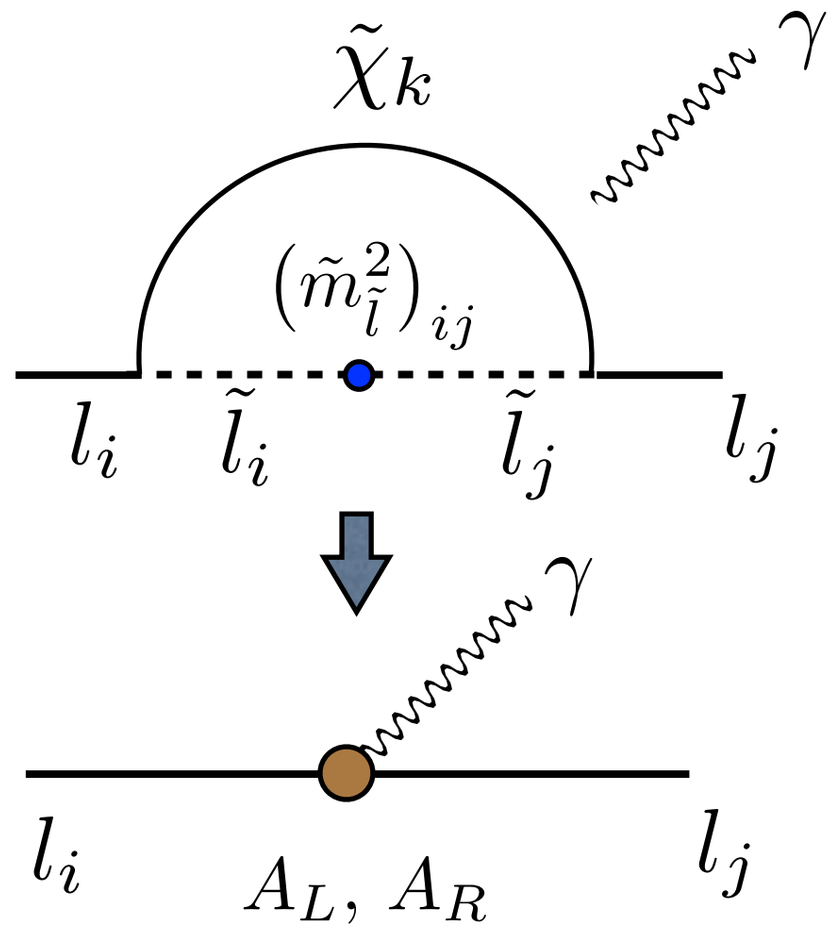
LFV in SUSY models

[Hisano et al '95]

Origin of flavor-violation

Off-diagonal components of slepton mass matrices

$$\left(\Delta_{\rm MI} \equiv \frac{(m^2_{\tilde{l}})_{ij}}{m^2_{\rm SUSY}}\right)$$



$$(m^2_{\tilde{l}})_{ij} \simeq \begin{bmatrix} m^2_{\tilde{L}} + m_e^\dagger m_e & a_e^\dagger v_d + m_e^\dagger \mu \tan\beta \\ a_e v_d + m_e \mu \tan\beta & m^2_{\tilde{E}} + m_e m_e^\dagger \end{bmatrix}$$

$$\mathcal{L} = \frac{e m_i}{2}\, \bar{l}_i F_{\mu\nu} \sigma^{\mu\nu} (A_L P_L + A_R P_R) l_j$$

where

$$A_L, A_R \sim \frac{\alpha_2}{4\pi} \frac{\Delta_{\rm MI}}{m^2_{\rm SUSY}} \tan\beta$$

$$\frac{Br(l_i \to l_j \gamma)}{Br(l_i \to l_j \nu_i \bar{\nu}_j)} = \frac{48\pi^2 e^2}{G_F^2} \left(|A_L|^2 + |A_R|^2\right) \quad \propto \frac{\Delta^2_{\rm MI}}{m^4_{\rm SUSY}} \tan^2\beta$$

- mass scale of SUSY particles
- Size of flavor-violation

LFV in SUSY models

SUSY scale

TeV-Scale

⇦

muon g-2 -- O(100)GeV sleptons & EW gauginos

Hierarchy Problem -- fine tuning btw m_W^2 & m_{SUSY}^2

Dark Matter -- thermal or non-thermal production?

GUT -- only light gauginos? log-dependence

Size of flavor violation

Off-diagonal components of slepton mass matrices

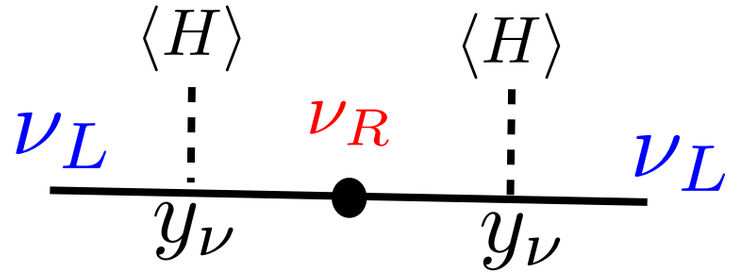
1. Arbitrary values (Anarchy) ⟶ too large LFV rates (SUSY flavor problem)

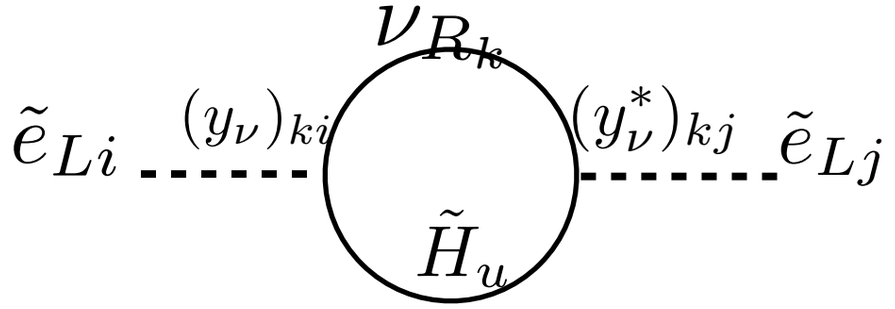
2. No flavour-mixing at tree-level (Universal) ⟶ Importance of radiative corrections

LFV in SUSY models with diagonal soft masses

- No LFV at tree-level $\quad m_{\tilde{l}}^2 \simeq m_0^2 \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}$
- Non-zero off-diagonal elements ⟸ Radiative Corrections

Ex) See-saw model





$$\mathcal{L}_{\rm eff} = \frac{1}{M_\nu}(l_L H_u)(l_L H_u) \qquad m_\nu = \frac{y_\nu^2 v^2}{M_\nu}$$

Same origin

$$(\tilde{m}_L^2)_{ij} \sim (y_\nu^\dagger)_{ik}(y_\nu)_{kj} \log \frac{M_X}{M_{\nu_k}}$$

$$y_\nu = \frac{1}{v_u}\sqrt{\hat{M}_N}\; R\; \sqrt{\hat{m}_\nu}\; U_{\rm MNS}^\dagger$$

[Casas, Ibarra '01]

$y_\nu \sim 1 \quad \text{for} \quad M_N \sim 10^{15}\,\text{GeV}$

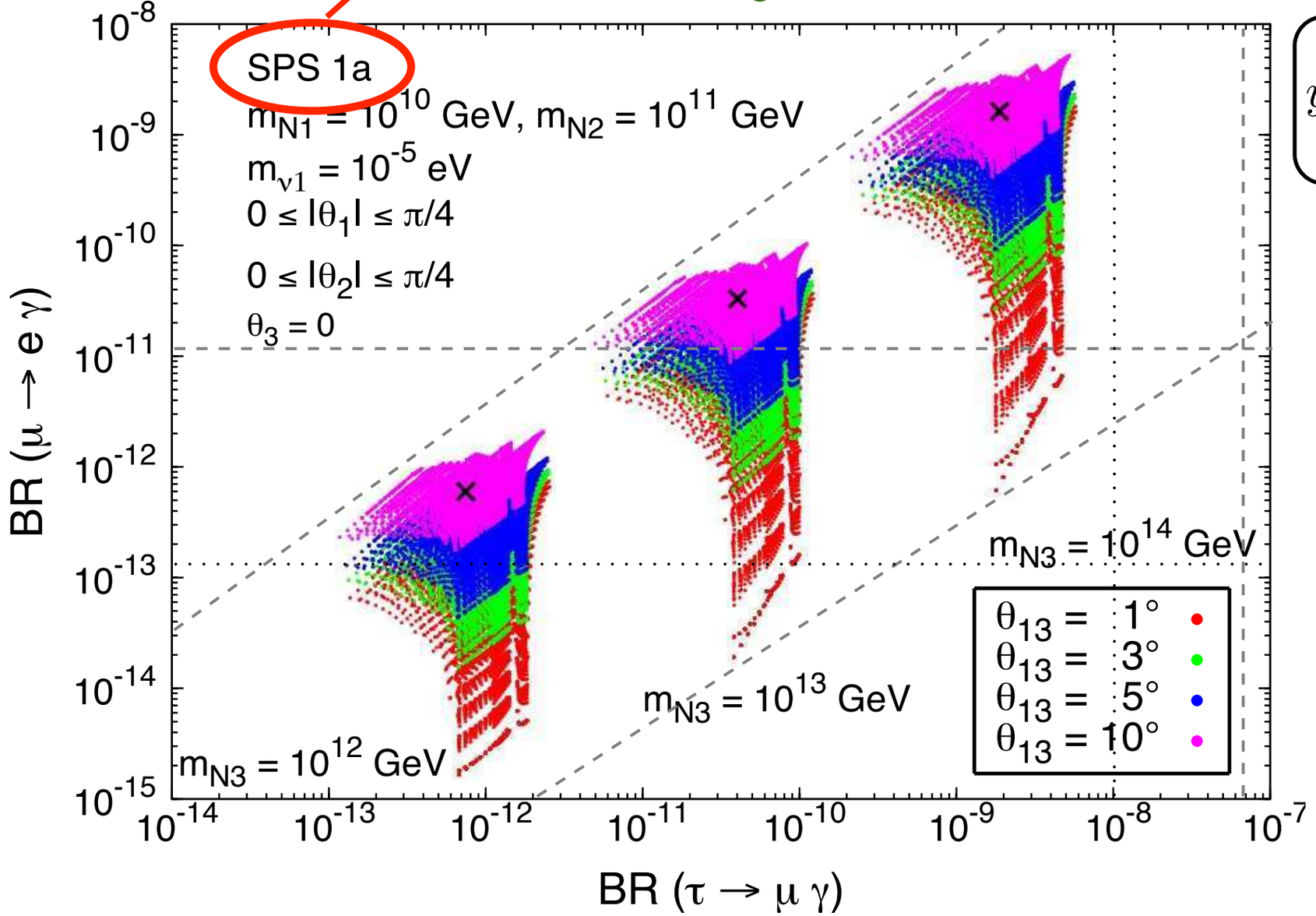
cf. SO(10) GUT: 16=6+3+3+2+1+1

$q_L\; d_R\; u_R\; l_L\; e_R\; \nu_R$

LFV in SUSY models with RNs

$$m_{\tilde{l}} \sim 200\,\mathrm{GeV}, \quad M_{\tilde{W}} \sim 180\,\mathrm{GeV}$$

[Antusch, Arganda, Herrero, Teixeira '06]

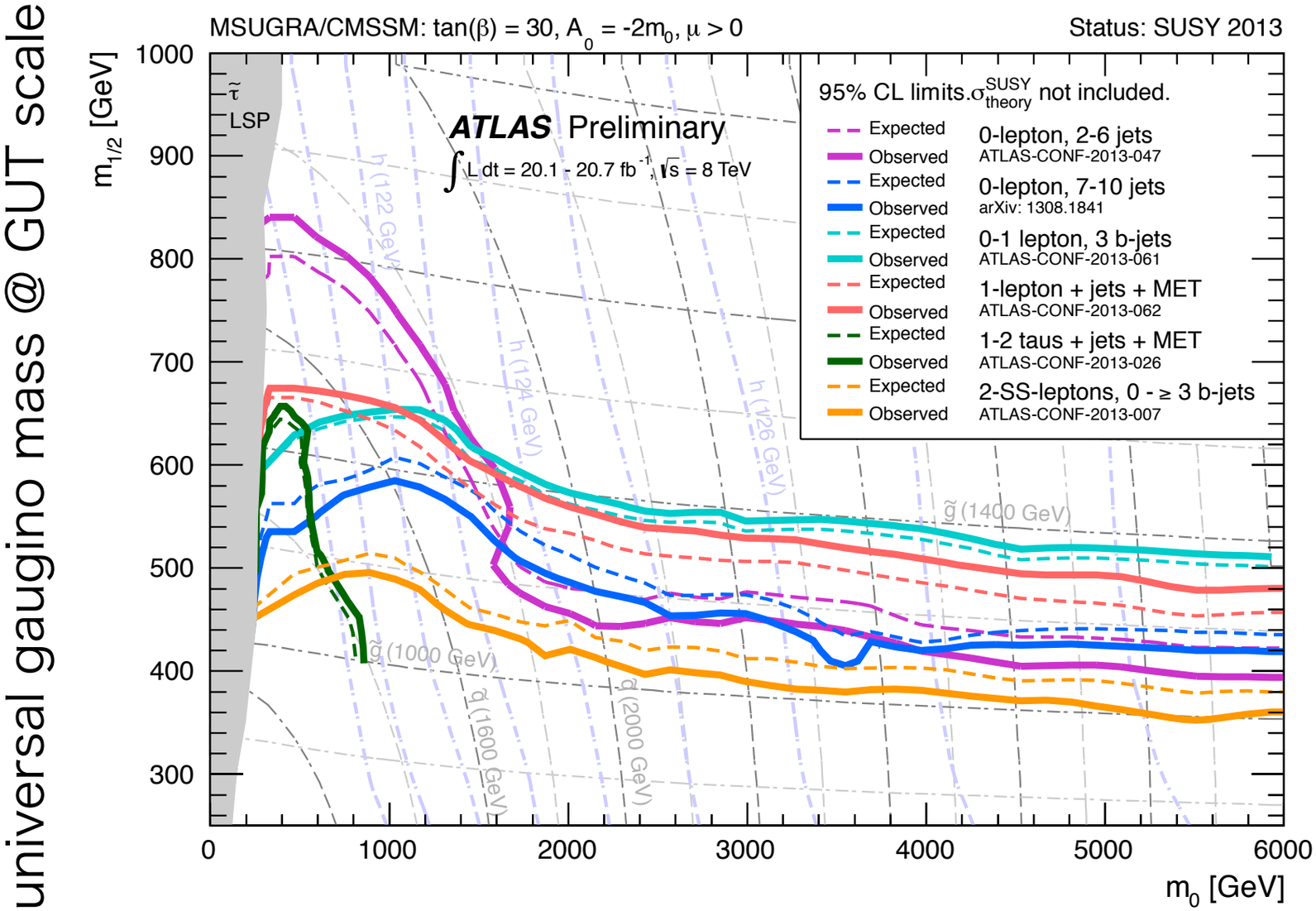


$$y_\nu = \frac{1}{v_u}\sqrt{\hat{M}_R}\,R\,\sqrt{\hat{m}_\nu}\,U^\dagger_{MNS}$$

Large Br
for larger M_N

LHC7+8

- Poor News : Non-observation of NP particles



In a SUSY model

$$m_{\tilde{q}} \gtrsim 1.8\,\mathrm{TeV}$$

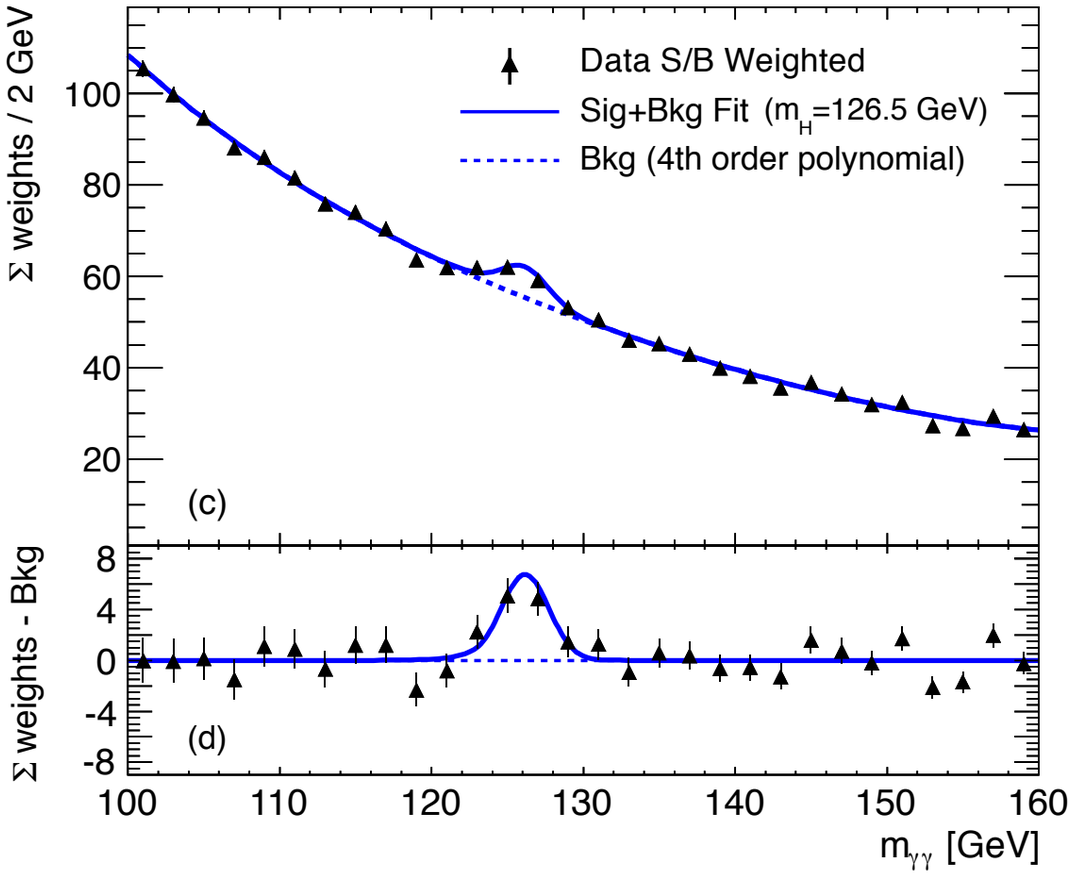
$$M_{\tilde{g}} \gtrsim 1.4\,\mathrm{TeV}$$

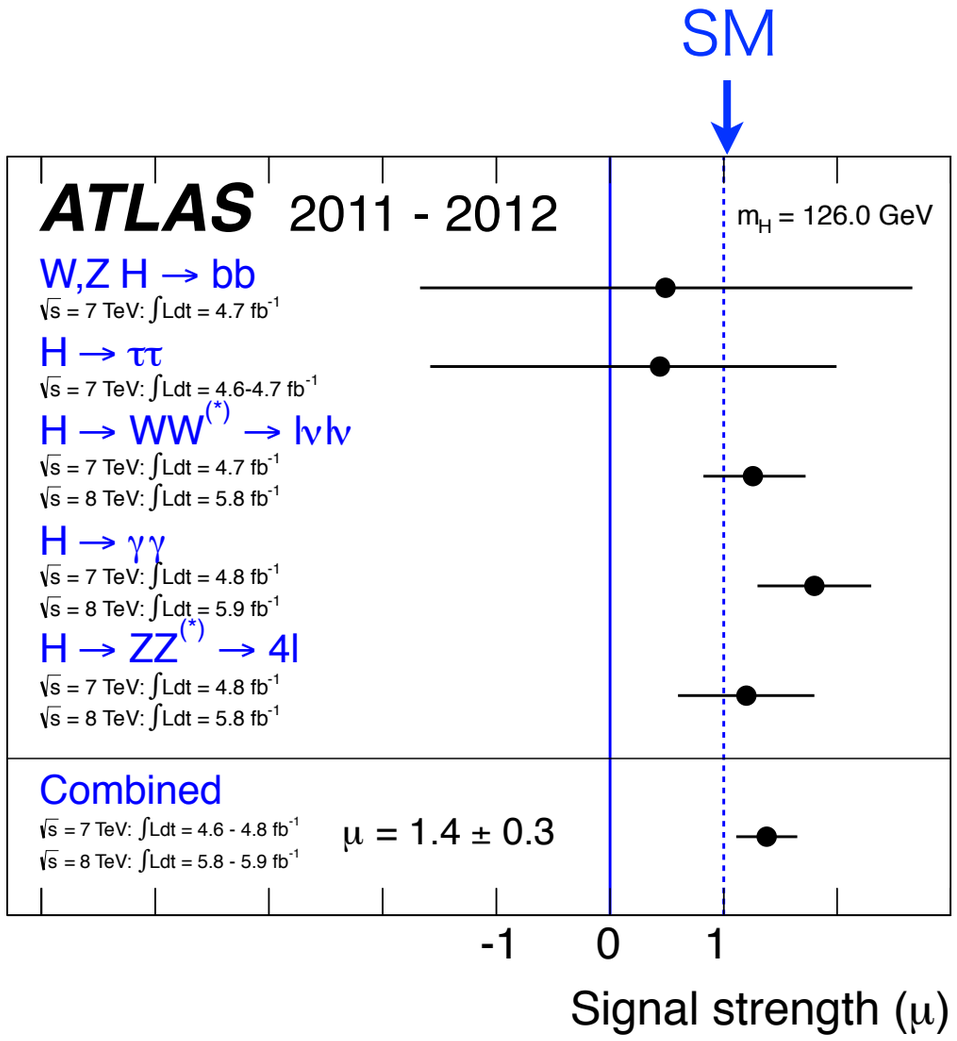
masses of colored particles are highly constrained

Note, LFV is probably induced by non-colored particles, which might escape from LHC search

LHC7+8

- Great News : Discovery of Higgs boson





$$m_h \sim 126\mathrm{GeV}$$

- Multi-channel
- Consistent with SM

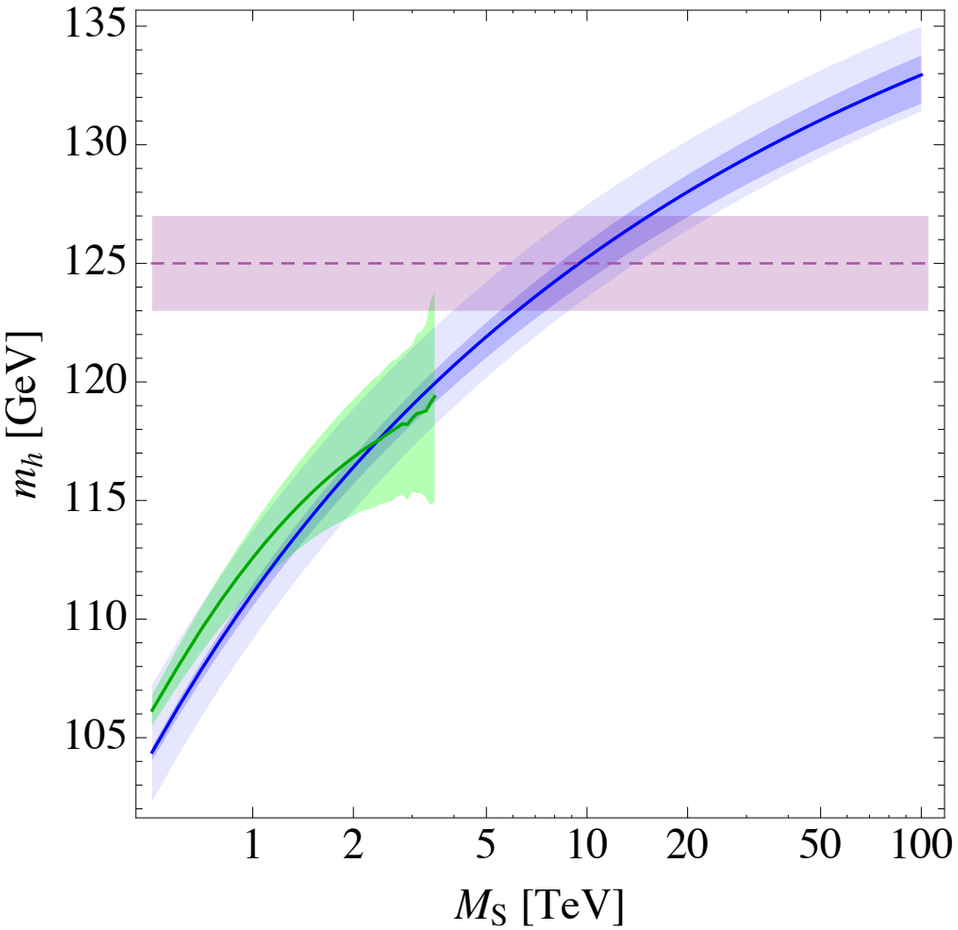
Implication of Higgs mass on SUSY models

"Higgs mass = 126 GeV" ⇒ constraints on SUSY parameters

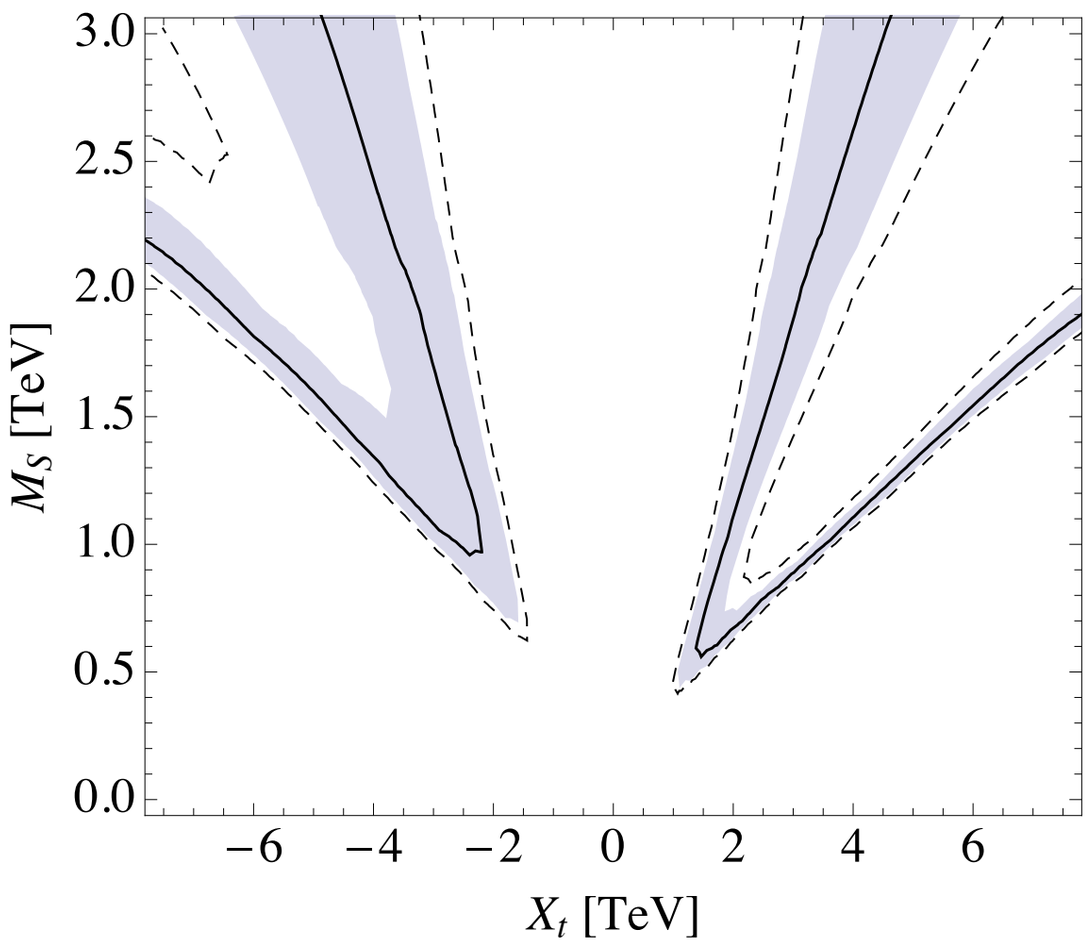
$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left[\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{A_t^2}{M_S^2}\left(1 - \frac{A_t^2}{12M_S^2}\right)\right]$$

$(126\,\mathrm{GeV})^2$ $(91\,\mathrm{GeV})^2$

[Draper, Meade, Reece, Shih '11]



$m_{\tilde{t}} \sim \mathcal{O}(10\,\mathrm{TeV})$



large A term

LFV in High-scale SUSY models

126 GeV Higgs boson + Null result of SUSY search

SUSY scale

O(10-100)TeV sfermions

~~muon g-2~~, ~~HP~~?, DM, GUT

OK for 2) OK

1) gaugino mass ~ sfermion mass (gravity-med.)

2) gaugino mass << sfermion mass (anomaly-med.)

Size of flavor violation

Off-diagonal components of slepton mass matrices

1. Arbitrary values (Anarchy) ← The simplest and the most natural case.

2. No flavour-mixing at tree-level (Universal)

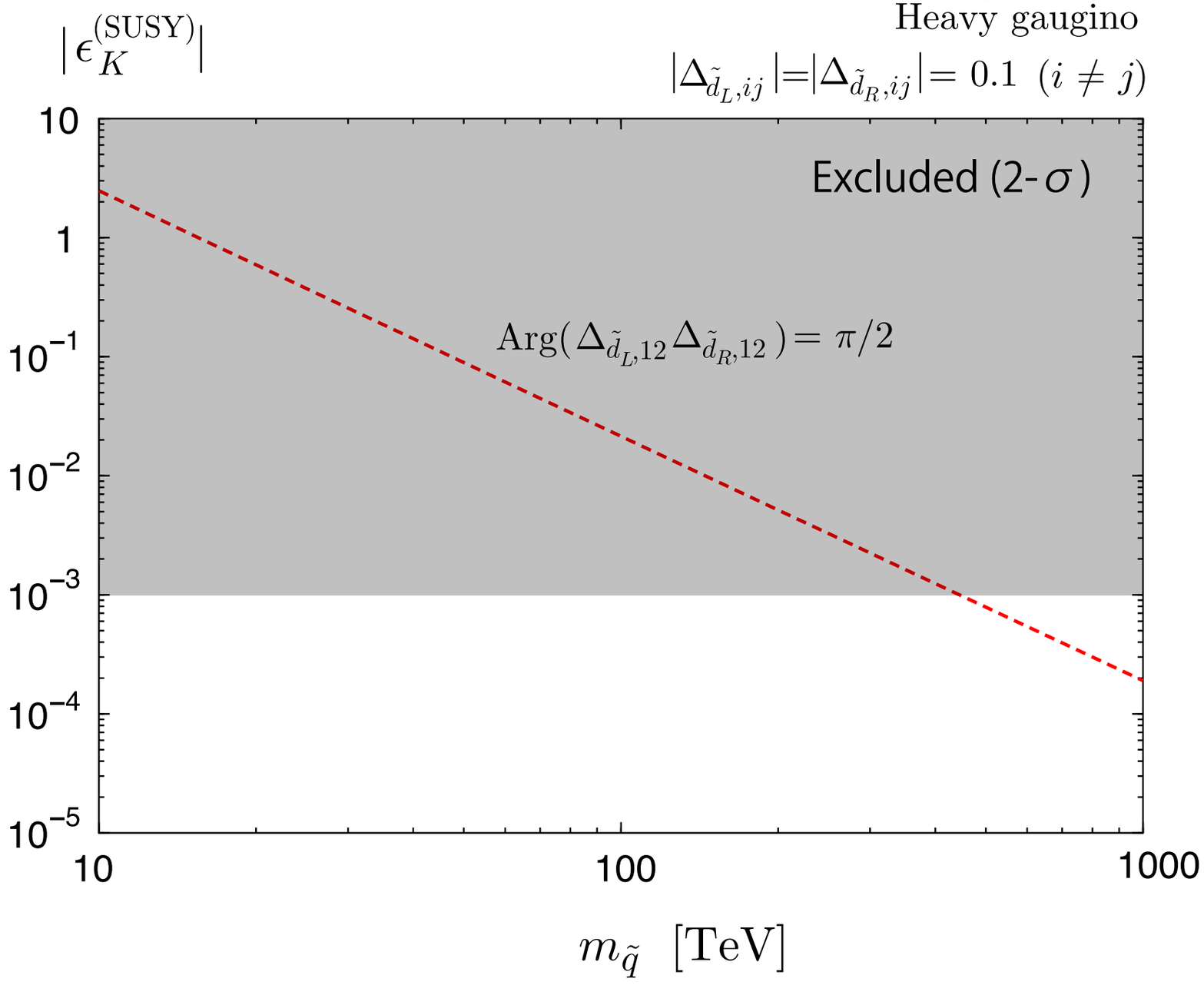
↑ The strongest constraint comes from Kaon-mixing

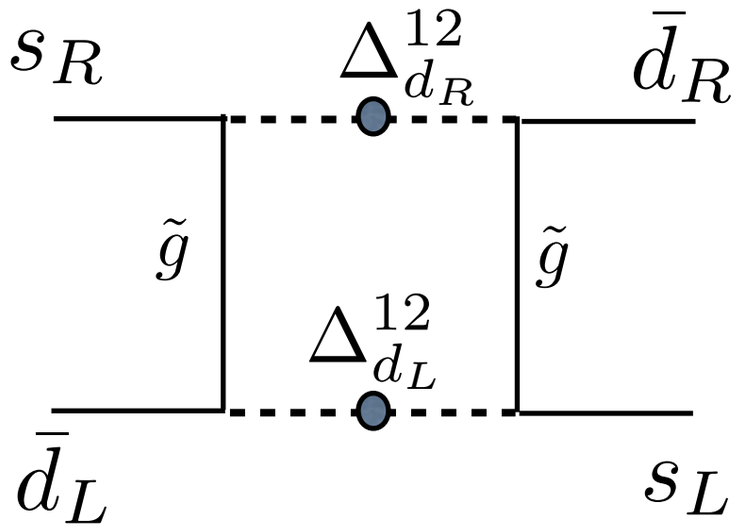
Kaon mixing parameter

$|\Delta_{ij}| = 0.1$

[Moroi, MN (2013)]

maximal phase





$$\epsilon_K \propto \frac{\mathrm{Im}[\Delta^{12}_{d_R}\Delta^{12}_{d_L}]}{m^2_{\mathrm{SUSY}}}$$

Suppressed If the phases are cancelled

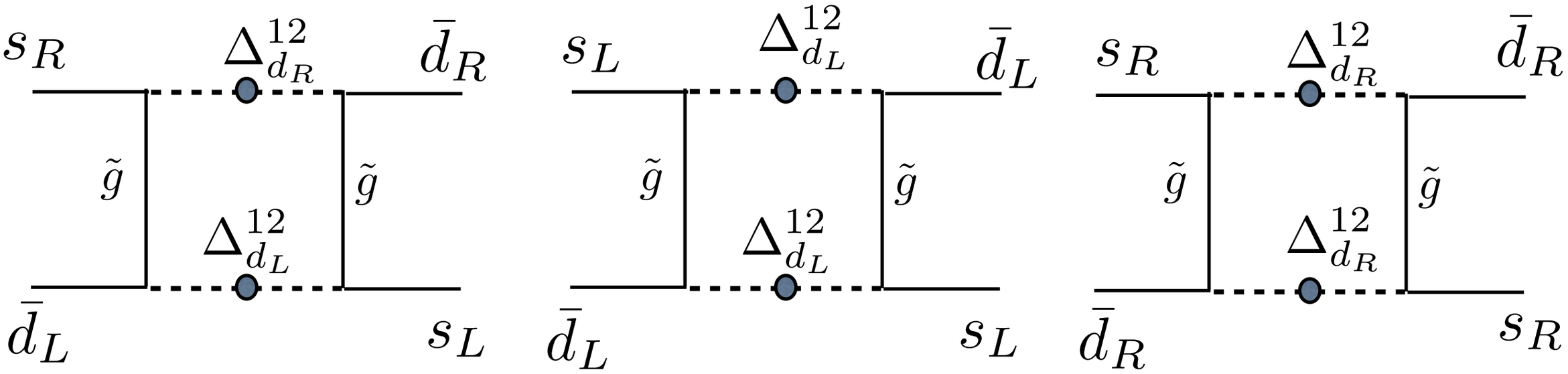
symmetry?

SO(10) relation and C-invariance

$$m^2_{\tilde{d}_L,ij} = m^{2*}_{\tilde{d}_R,ij}$$

⟵ C-inv. : $d_L \leftrightarrow d^c_R$

⇨ $\epsilon_K^{\rm SUSY}$ is suppressed



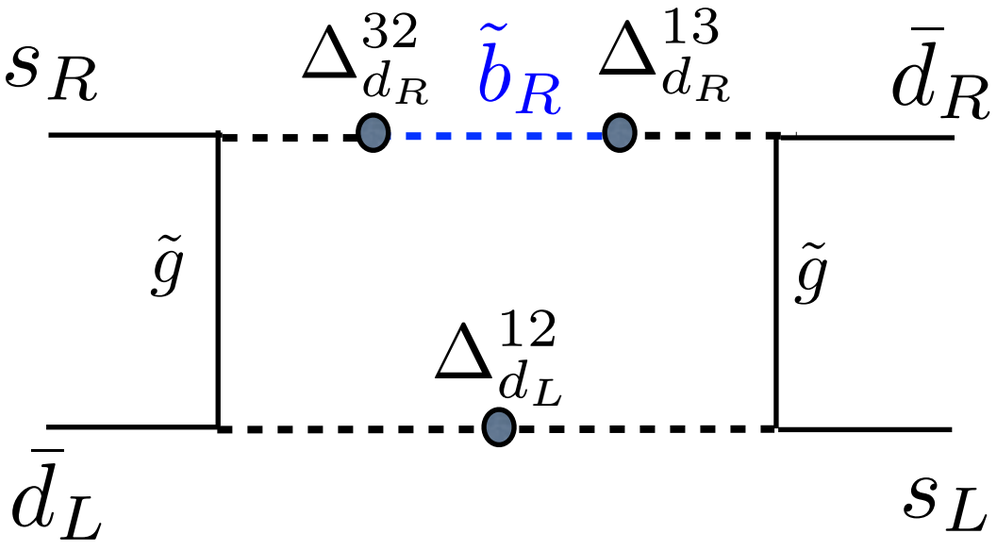
$$\mathrm{Im}[\Delta^{12}_{d_R}\Delta^{12}_{d_L}] = 0 \qquad \mathrm{Im}[\Delta^{12}_{d_L}\Delta^{12}_{d_L}] = -\mathrm{Im}[\Delta^{12}_{d_R}\Delta^{12}_{d_R}]$$

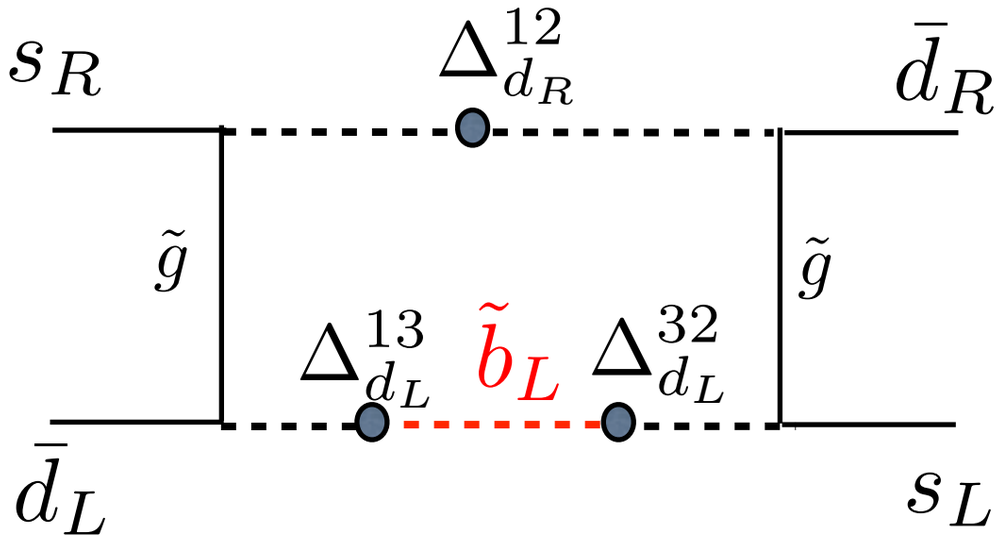
Breaking of C-inv. : EW & Yukawa interactions

Breaking of SO(10) relation

Dominant SUSY contribution comes from

$$m^2_{\tilde{d}_L,33} \neq m^{2*}_{\tilde{d}_R,33}$$ (RG effect through top Yukawa)



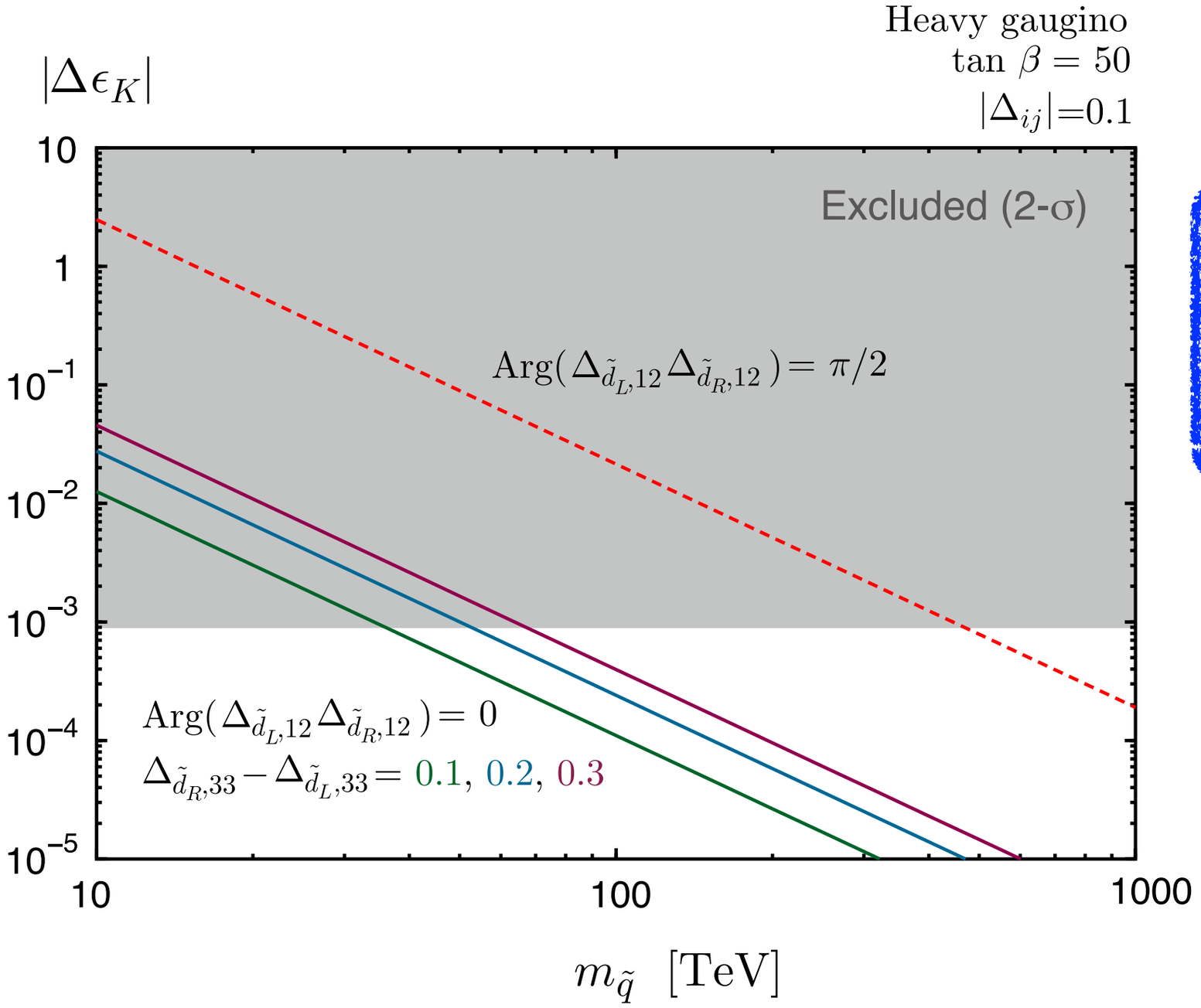


$$\epsilon_K^{\rm SUSY} \sim \frac{{\rm Im}[\Delta^{13}_{d_R}\Delta^{32}_{d_R}\Delta^{12}_{d_L}]}{m^2_{\rm SUSY}} \frac{m^2_{\tilde{b}_L} - m^2_{\tilde{b}_R}}{m^2_{\rm SUSY}}$$

$\tan\beta$	$\Delta_{d_L,33}$	$\Delta_{d_R,33}$
10	0.7	1
30	0.7	0.8
50	0.5	0.5

Kaon mixing parameter

$|\Delta_{ij}| = 0.1$ maximal phase

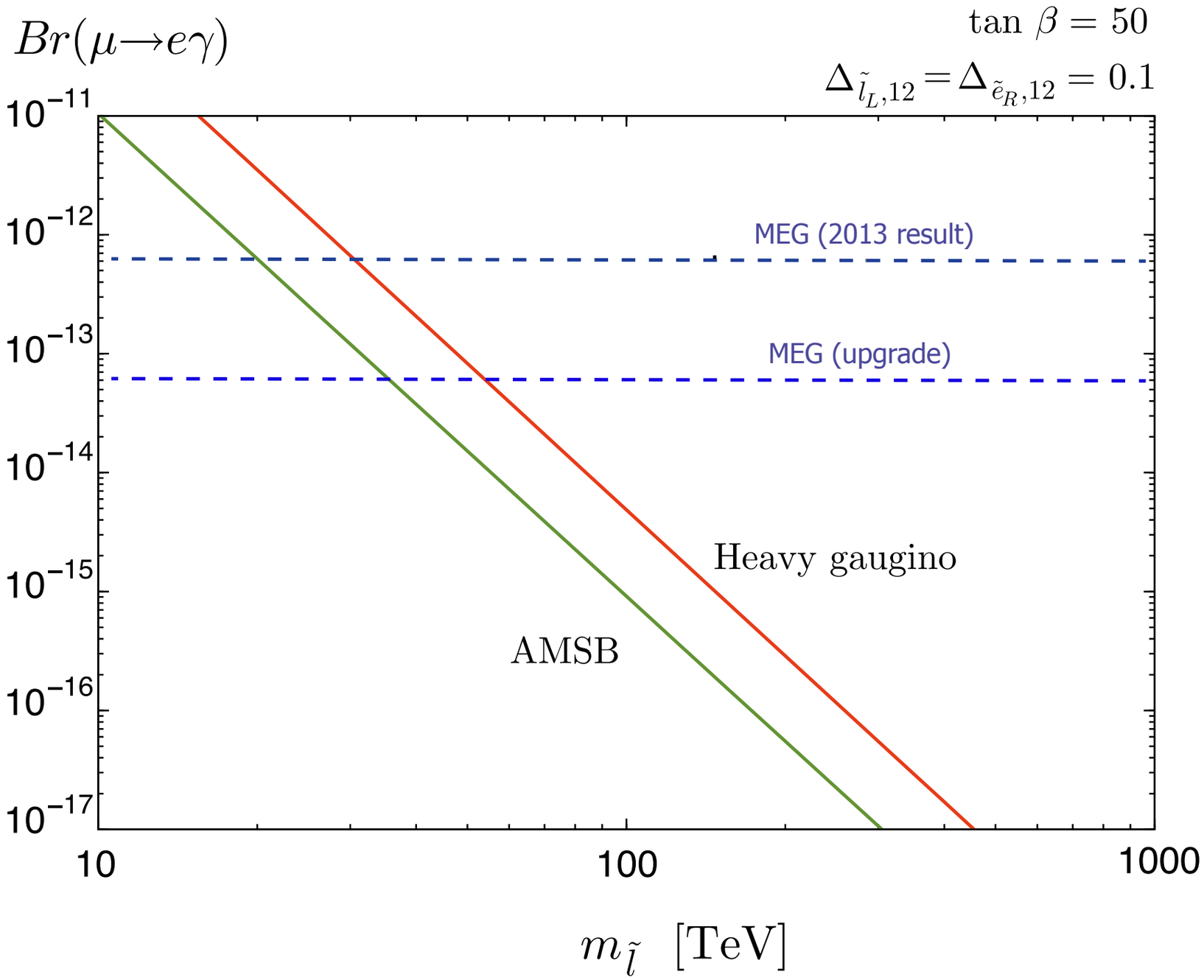


With SO(10) relation, $\epsilon_K^{\rm SUSY}$ is significantly reduced

Enough? Yes → Anarchy; No → Universal

LFV in High-scale SUSY models (Anarchy)

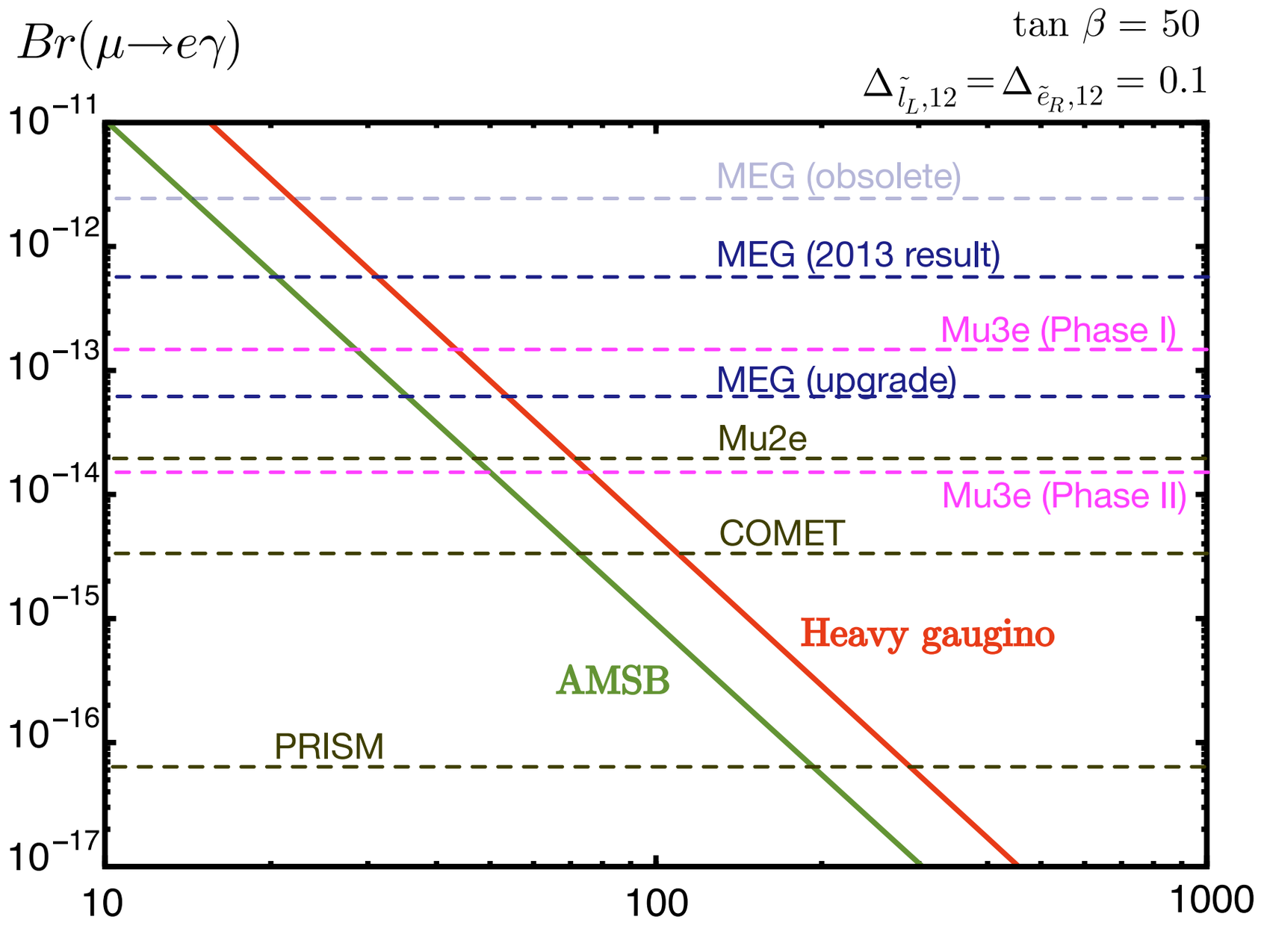
- Anarchy … large off-diagonal elements are given at tree-level



LFV in High-scale SUSY models (Anarchy)

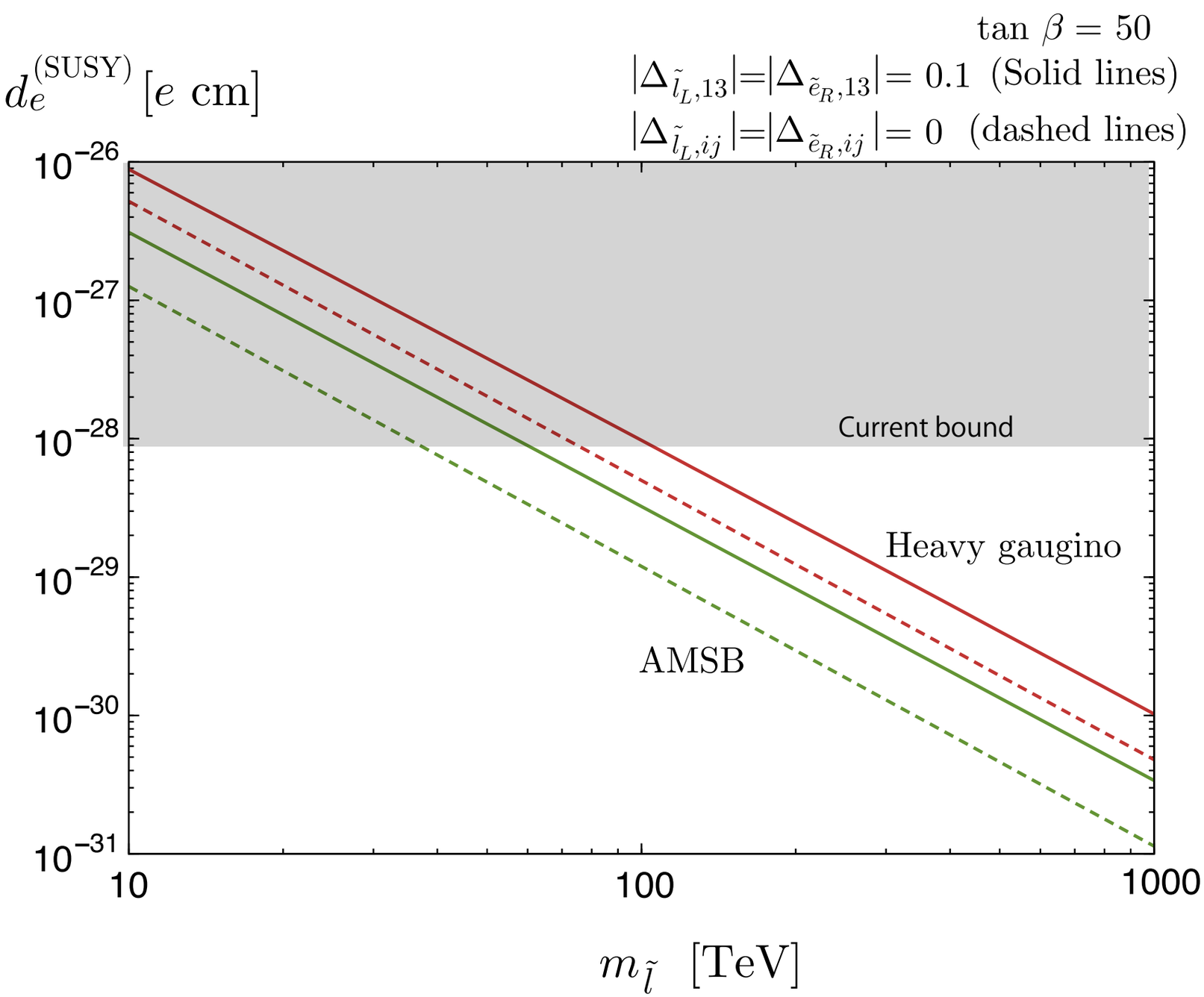
In SUSY models, there is strong correlations btw Br($\mu \to$e γ), Br($\mu \to$eee) and $R_{\mu e}$

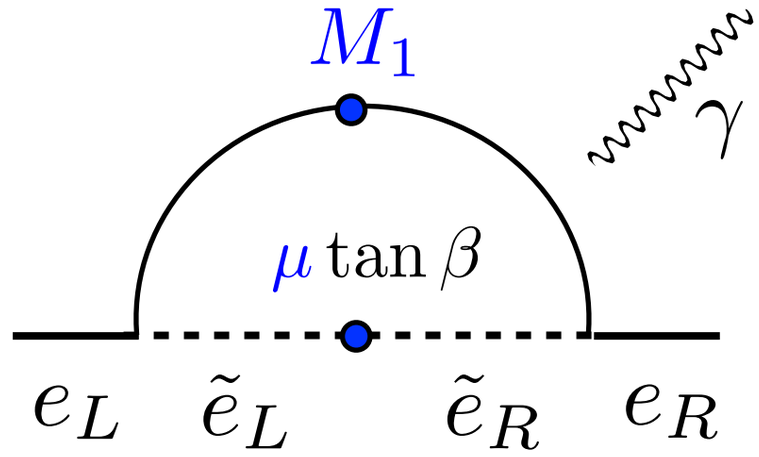
Future experimental limits can be converted to that of $\mathrm{Br}(\mu \to e\gamma)$

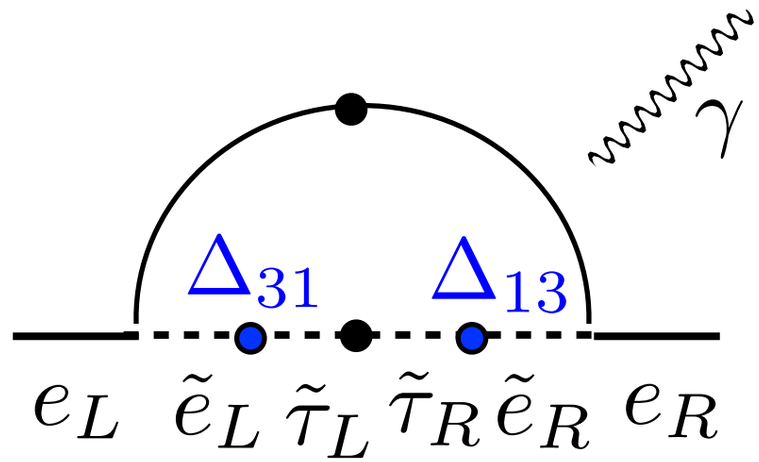


$$Br \propto \frac{\Delta^2}{m_{\mathrm{SUSY}}^4}$$

Electron EDM in High-scale SUSY models







$$d_e \propto \frac{\Delta^2}{m^2_{\mathrm{SUSY}}}$$

New Limit: $d_e < 8.7 \times 10^{-29}$

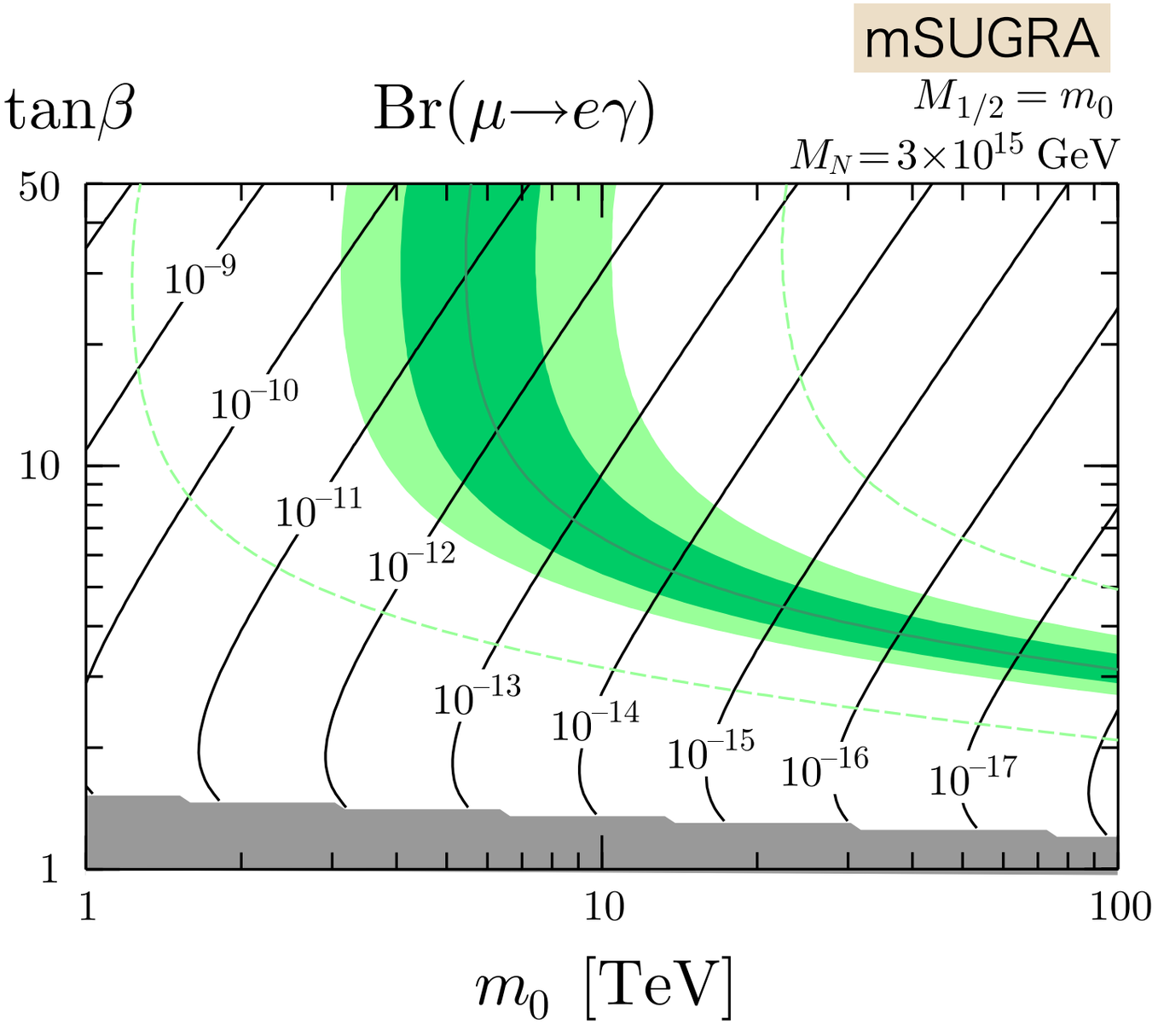
ACME colaboration (2013)

LFV in high scale SUSY models (universal)

[Moroi, MN, Ynagida (2013)]

- Universal ... off-diagonal elements are generated by radiative corrections

In the see-saw model, with keeping the explanation of Higgs mass, is it possible to detect the LFV signals?



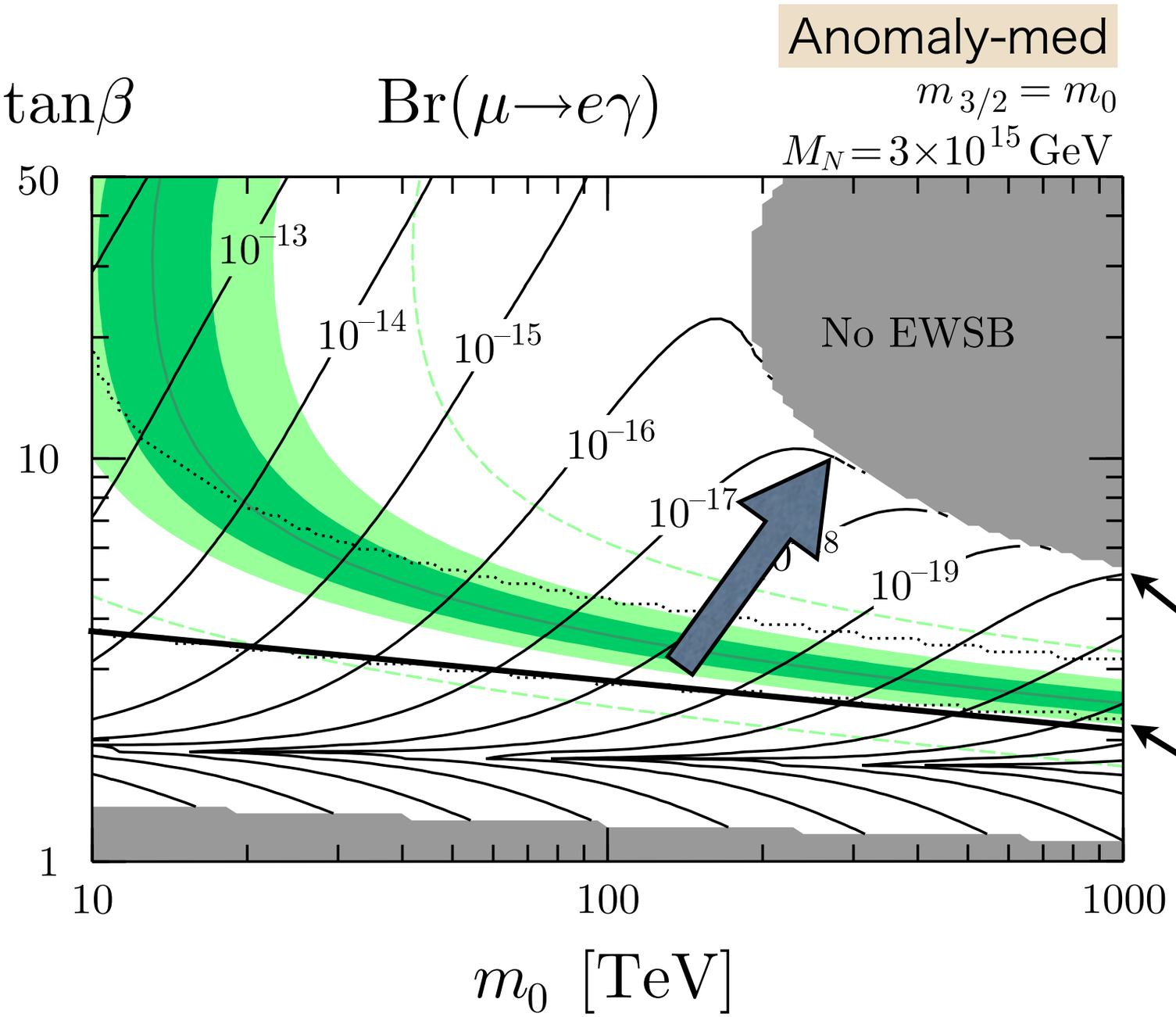
$m_h \simeq 126\,\mathrm{GeV}$

$M_R \sim M_{\mathrm{GUT}}$ $(y_\nu \sim 1)$

⇒ measurable LFV rates

LFV in high scale SUSY models (universal)

- Large neutrino Yukawa coupling is also useful to enlarge the parameter spaces with successful EWSB



For $M_i \ll m_0$, it becomes difficult to achieve successful EWSB

cf. focus point

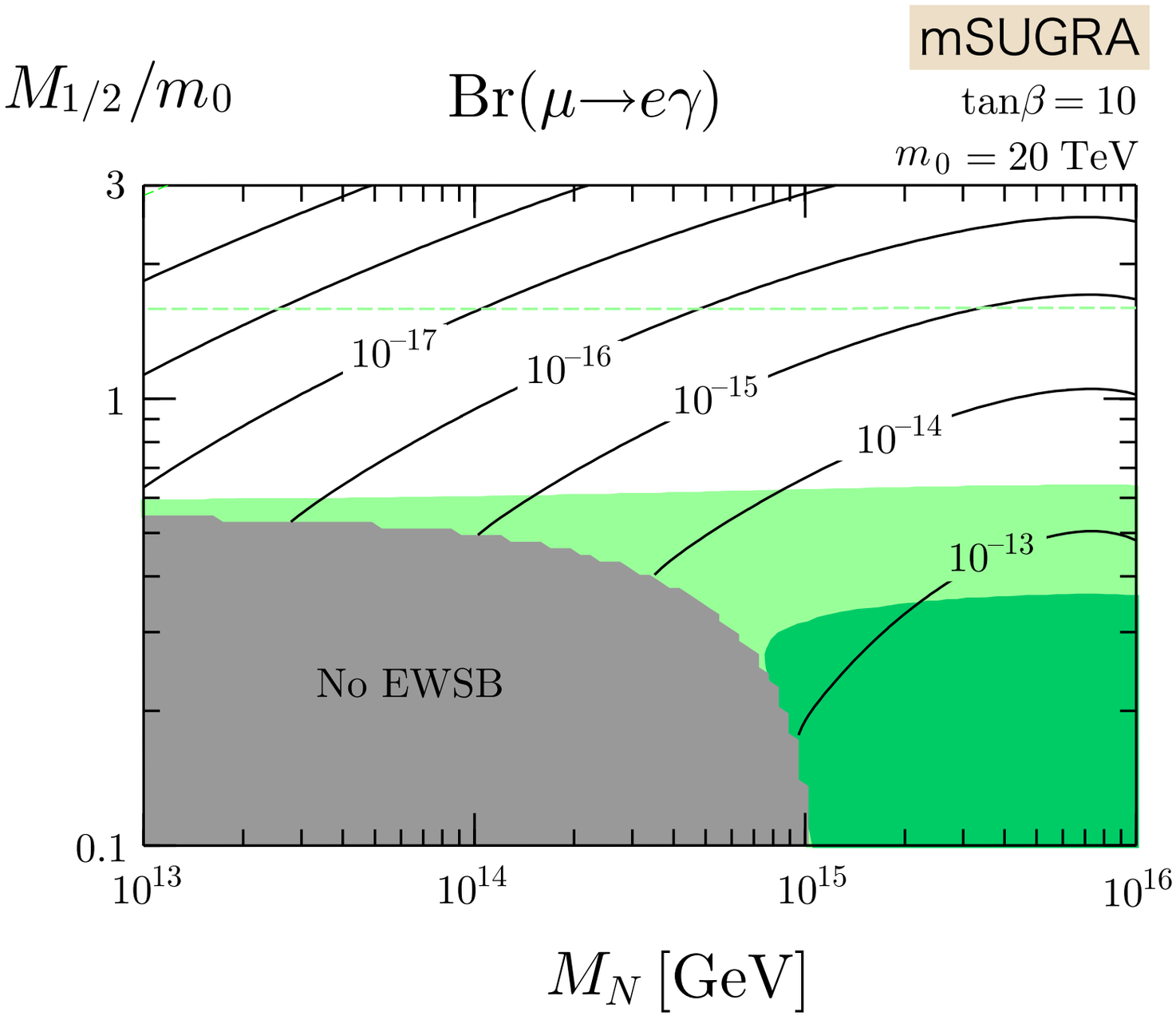
$y_\nu \nearrow \Rightarrow m^2_{H_u} \searrow$

$M_N = 3\times10^{15}\,\mathrm{GeV}$

$M_N = 10^{11}\,\mathrm{GeV}$

LFV in high scale SUSY models (universal)

- Large neutrino Yukawa coupling is also useful to enlarge the parameter spaces with successful EWSB



$m_h \simeq 126\,\mathrm{GeV}$

For smaller gaugino masses, large neutrino Yukawa is required

Summary

✓ 近年のLHC実験の結果(ヒッグスの質量、SUSY粒子の未発見)を踏まえると、O(10) TeV の重いSUSY模型が興味深い

✓ ニュートリノ振動はレプトンフレーバーの破れの証拠であり、重いSUSY模型でもニュートリノ湯川結合を通して観測可能な荷電レプトンフレーバの破れが生じうる

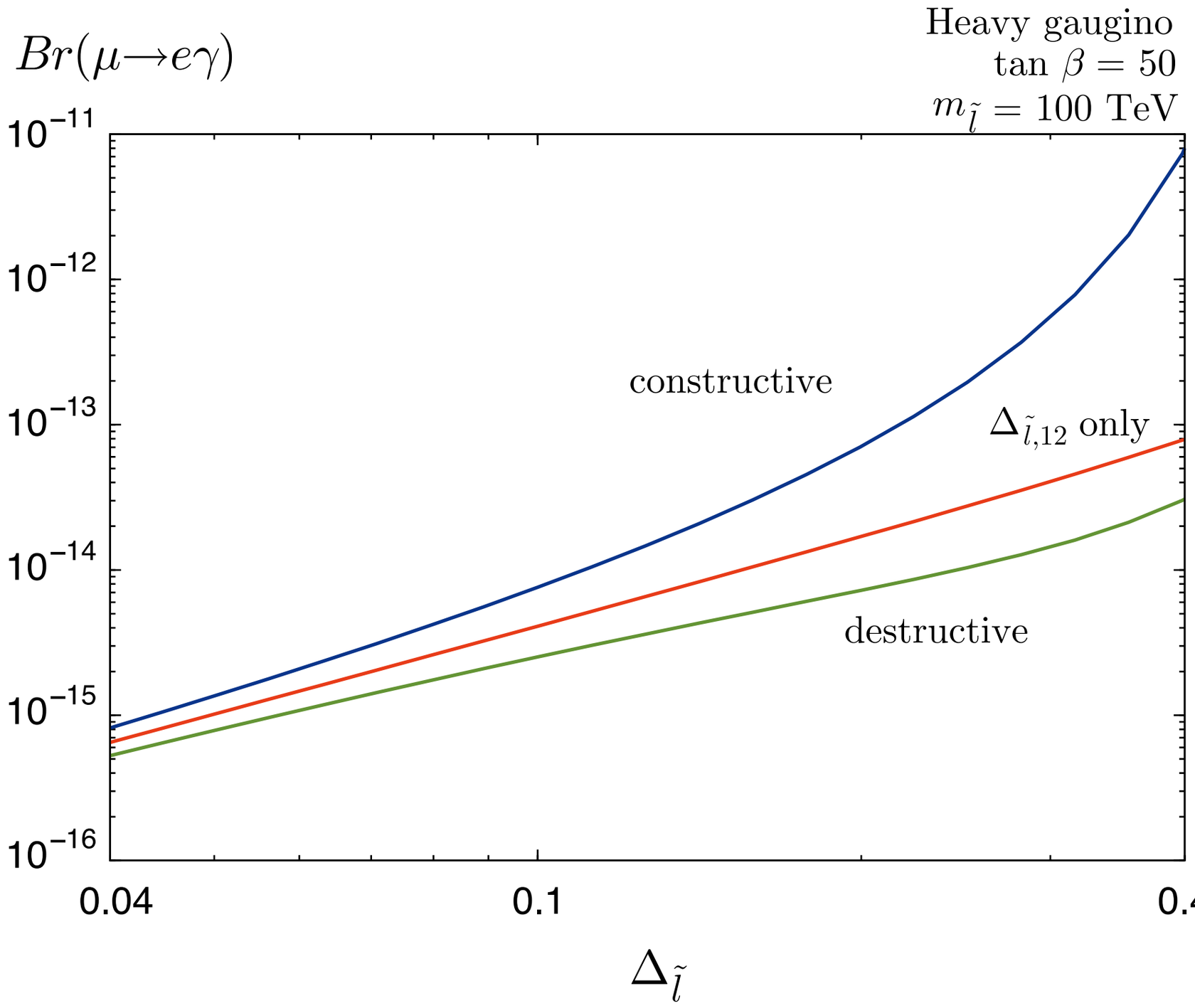
✓ SO(10) relation があると Kaon mixing の制限を緩める

✓ EDMの実験が面白い

✓ 大きなニュートリノ湯川結合はEWSBを助けるのにも役立つ

Back up

Importance of double-mass insertion in high-scale SUSY models (Anarchy)



$\alpha_2 \Delta^{12}_{e_L}$

vs

$\alpha_Y \Delta^{13}_{e_L} \Delta^{32}_{e_R} \, m_\tau / m_\mu$

single mass insertion

$$Br \propto \frac{\Delta^2}{m^4_{\rm SUSY}}$$

double mass insertion

$$Br \propto \frac{\Delta^4}{m^4_{\rm SUSY}}$$