LHC時代におけるフレーバーの物理

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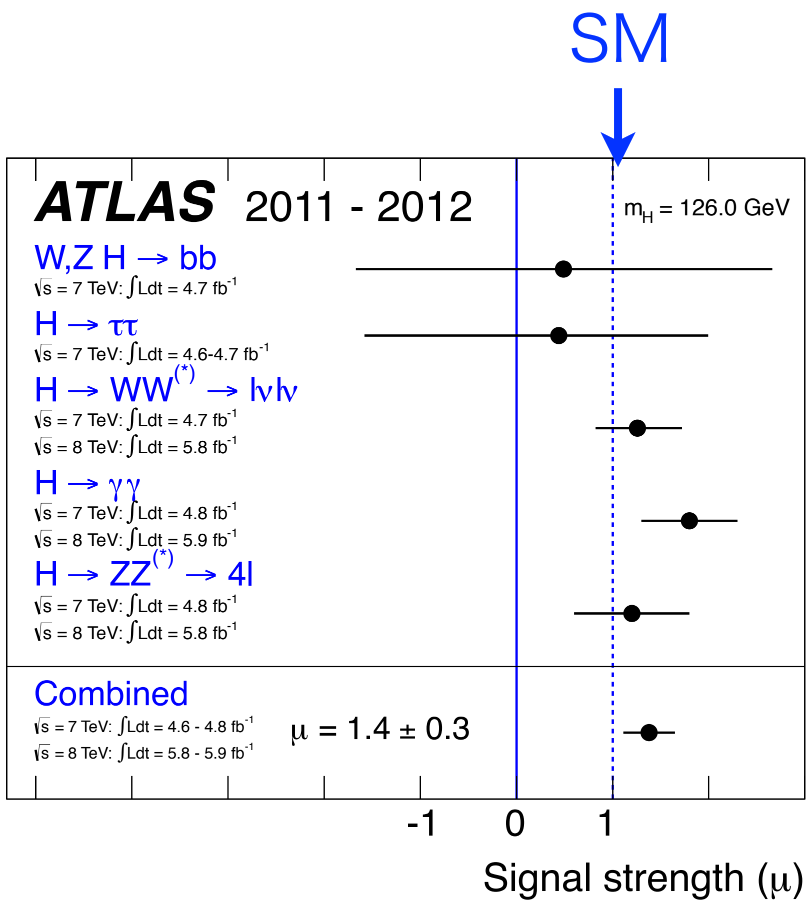
30 July, 2014　　基研研究会　素粒子物理学の進展２０１４

LHC7+8

- Discovery of 126 GeV Higgs

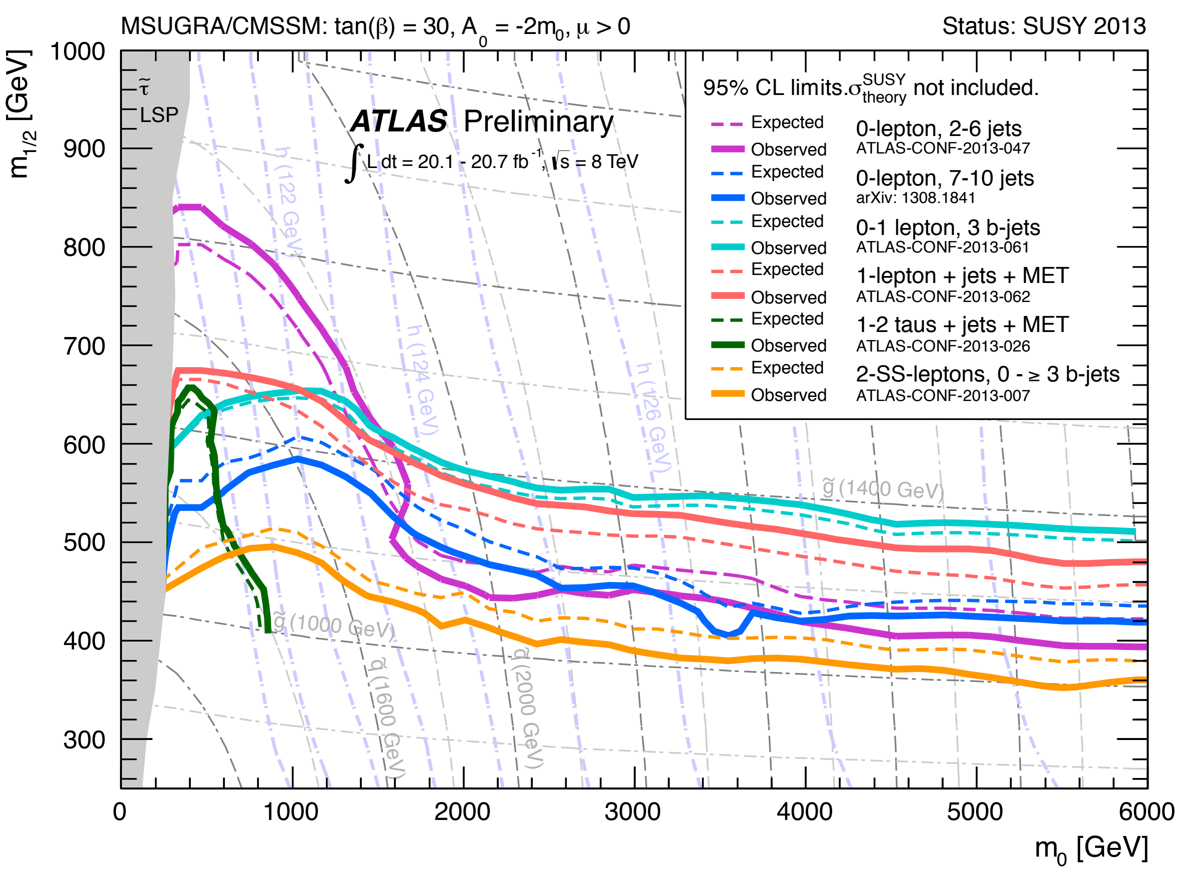
  The last missing piece of the Standard Model (SM)!



- Non-observation of NewPhysics (NP) signals

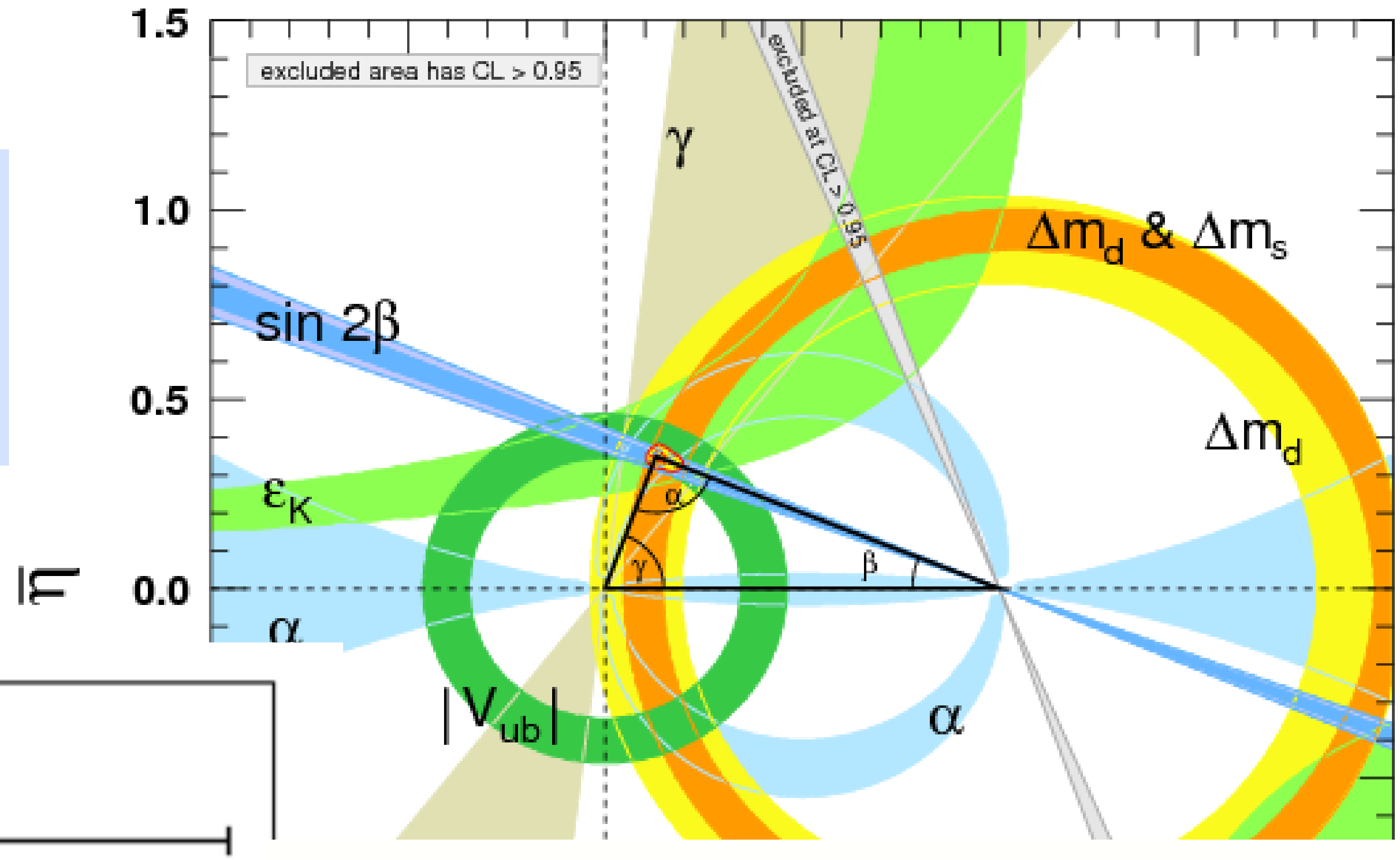
  ex) CMSSM

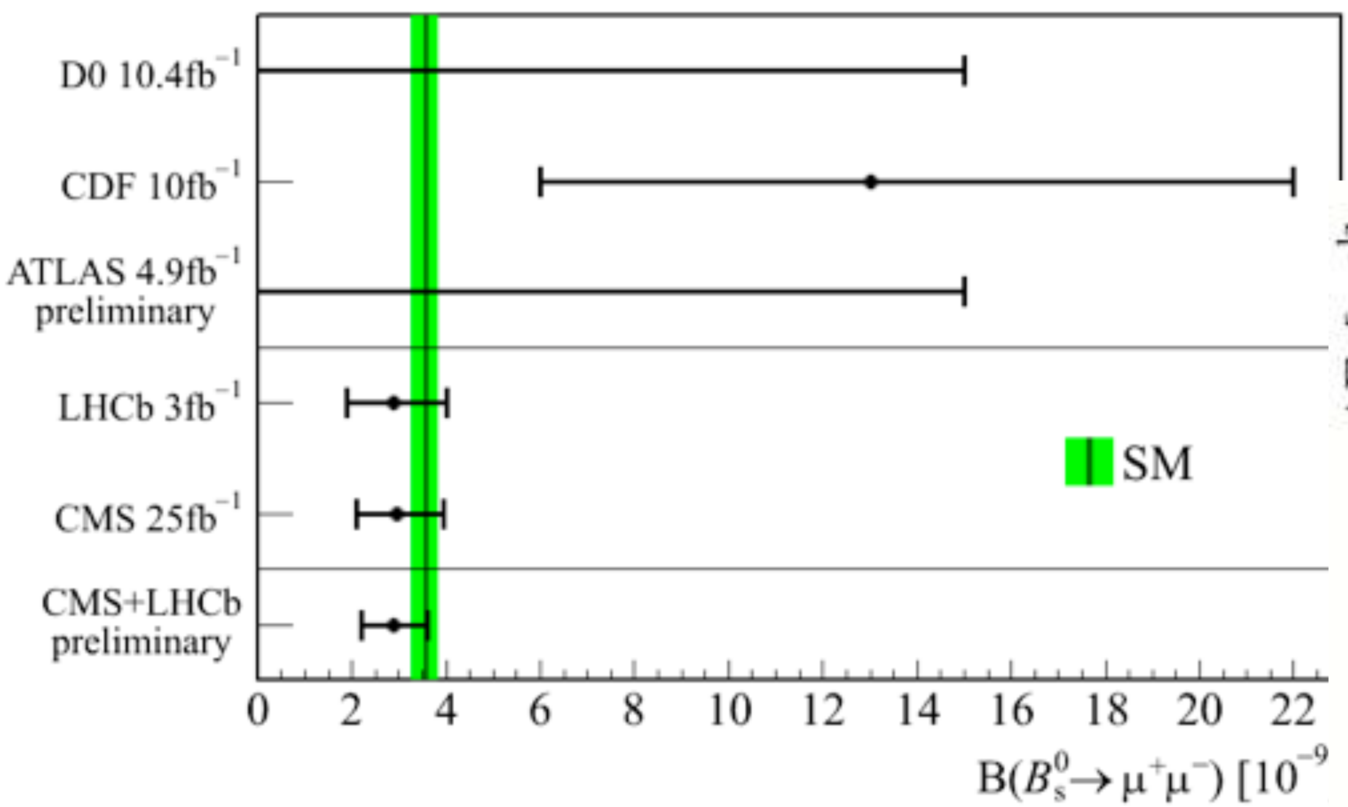
$$m_{\tilde{q}} \gtrsim 1.8\,\mathrm{TeV}$$
$$M_{\tilde{g}} \gtrsim 1.4\,\mathrm{TeV}$$

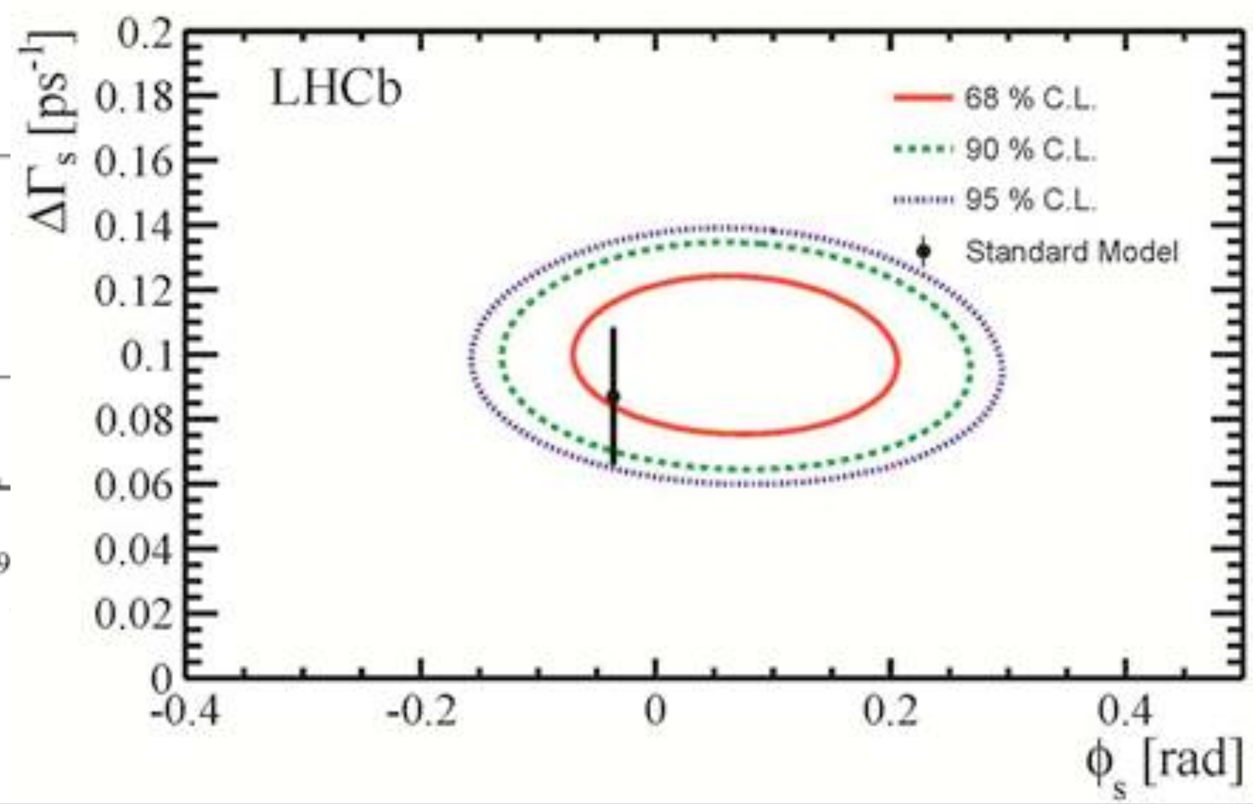


Great successes of the SM in the flavor sector

SM looks to work very well.







Why flavor factories?

- In present, LHC experiments have not found any signals of new physics (NP) in the high-energy frontier.
  - If LHC finds some NP, flavor experiments play complementary roles to probe the flavor sector of the NP.
  - If not, favor factories (and cosmology) may give the unique access to the NP in the high-luminosity frontier.

Why flavor factories?

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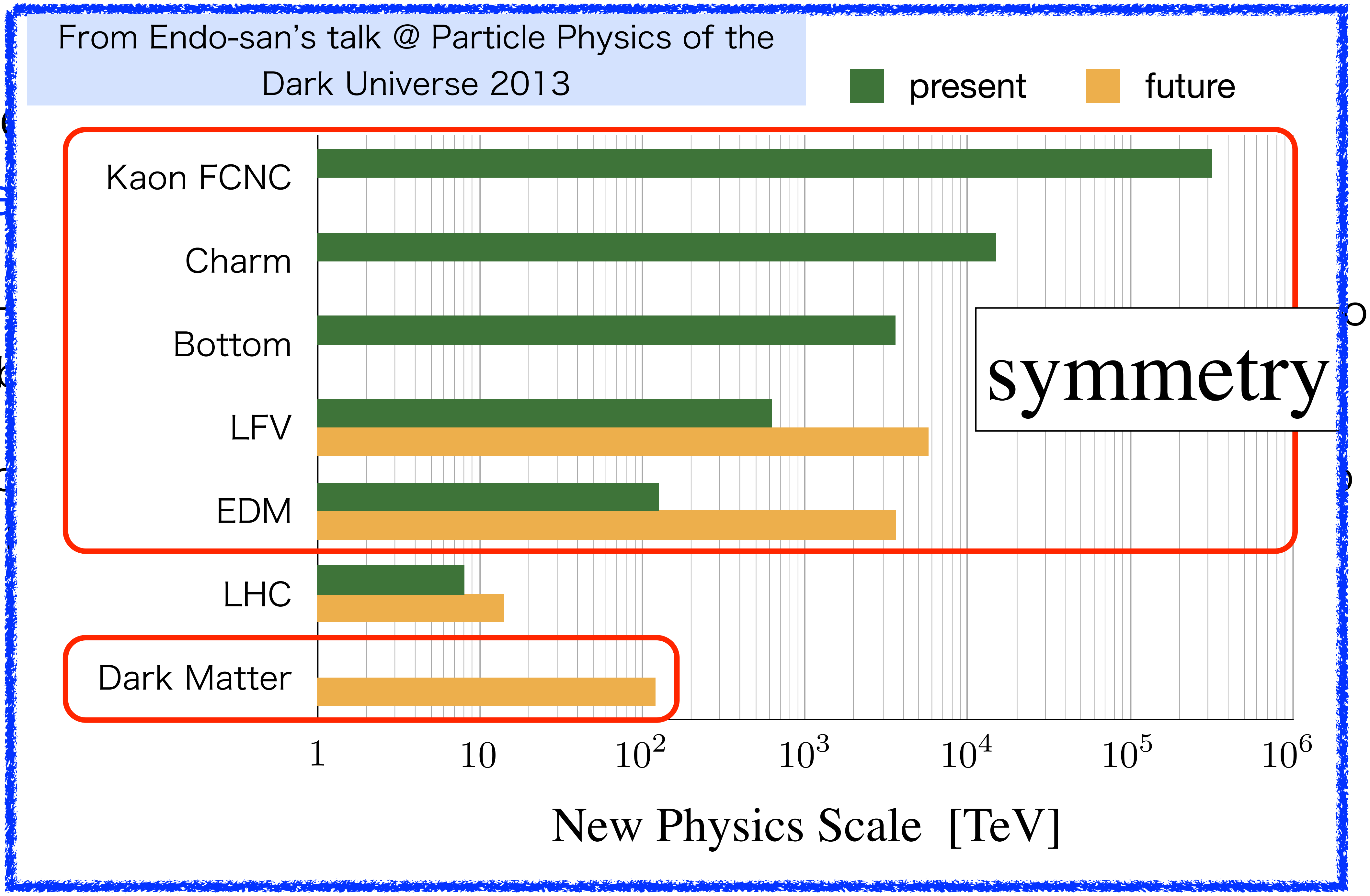
  of ne
  - If LH
    prob
  - If no
    the



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In both of the situations, we need more observables and more precision!

SuperKEKB, LHCb, LFV, g-2, EDM, K, neutrino, ...

NP search by the flavor observables

Strategies

- For hadronic observables that are SM consistent but still have a lot of room for NP, such as $B_q \to \mu^+\mu^-$, ΔM_q, $\Delta\Gamma_q$, a^q_{sl}, β_s and β, both experimental and theoretical efforts are required to pin down the existence of NP. (Correlation and global analyses may help)
- Resolving and understanding of remaining discrepancies: muon g-2, $B \to D^{(*)} \tau\nu$, dimuon asymmetry, V_{ub}, $B \to K^{(*)} \mu^+\mu^-$, β ....
- In the SM background free experiment, such as LFVs and EDMs, just FIND THE SIGANL.

Implications on NP models

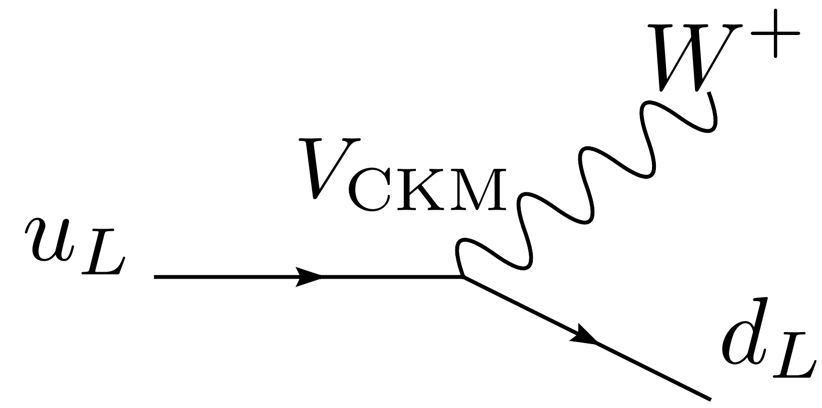
- Tendency of possible NP effects are constrained by precisely-measured flavor observables.
- Consider the NP models which explain existing anomalies.
- Consider (theoretically and/or experimentally) well-motivated models which predict flavor signals.

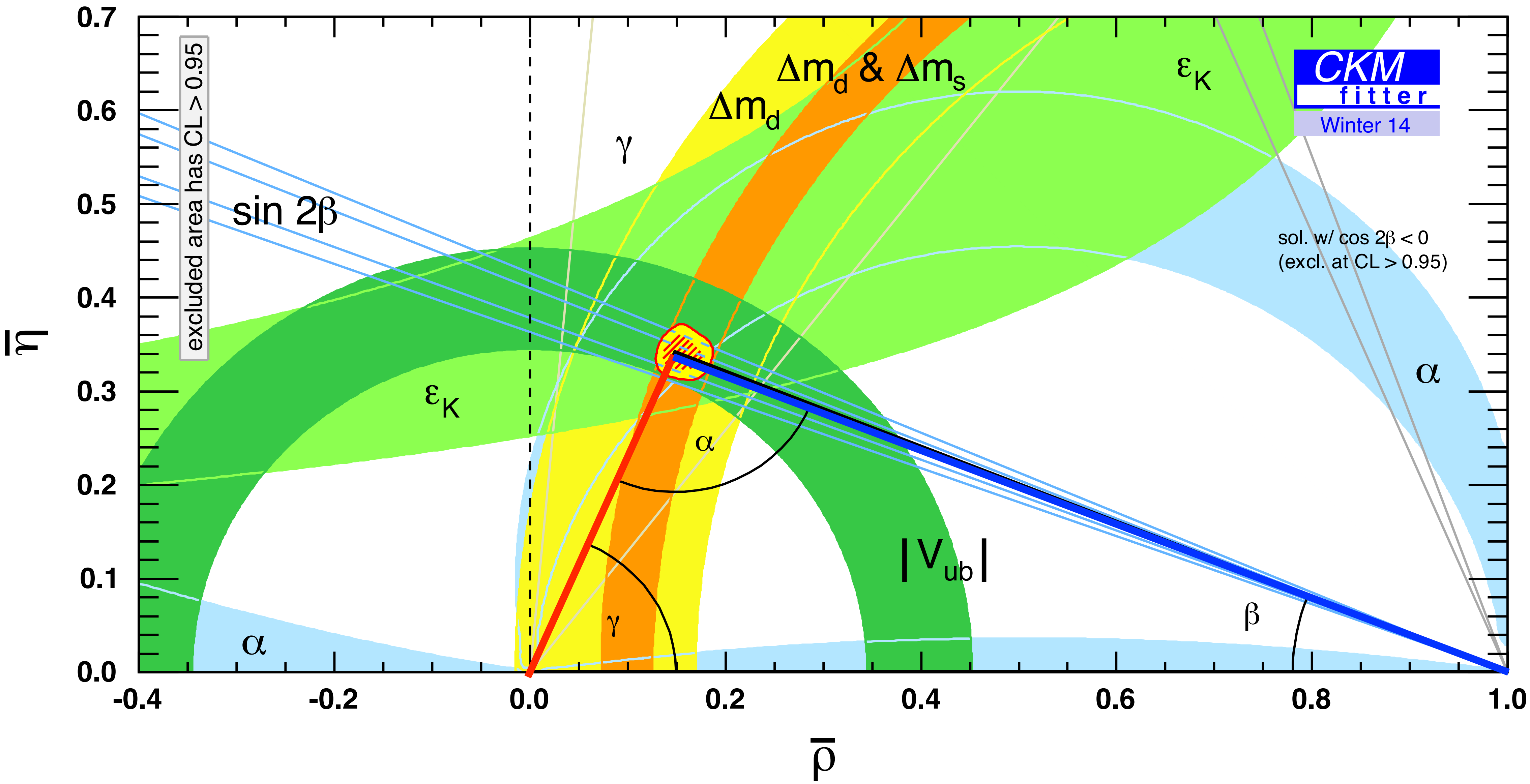
Outline

1. Introduction
2. Comparison of experimental results and SM predictions
    - Precise measurements and calculations in the flavor physics
    - Remaining anomalies(?)
3. LFVs and EDMs
    - Implications on SUSY search
4. Summary

まずはSMと実験がよく一致しているこれから

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$





Comparison btw SM and Exp (I)

- B meson mixing

$$\Delta M_d(\mathrm{SM}) = (0.543 \pm 0.091)\,\mathrm{ps}^{-1}$$

$$\Delta M_s(\mathrm{SM}) = (17.3 \pm 2.6)\,\mathrm{ps}^{-1}$$

$$\Delta M_d(\mathrm{Exp}) = (0.510 \pm 0.004)\,\mathrm{ps}^{-1}$$

$$\Delta M_s(\mathrm{Exp}) = (17.69 \pm 0.08)\,\mathrm{ps}^{-1}$$

$$\Delta\Gamma_s(\mathrm{HQE}) = (0.087 \pm 0.021)\ \mathrm{ps}^{-1}$$

$$\frac{\Delta\Gamma_d}{\Gamma_d}(\mathrm{HQE}) = (0.42 \pm 0.08)\ \%$$

$$\Delta\Gamma_s(\mathrm{Exp}) = (0.081 \pm 0.011)\ \mathrm{ps}^{-1}$$

$$\frac{\Delta\Gamma_d}{\Gamma_d}(\mathrm{HFAG}) = (1.5 \pm 1.8)\ \%$$

$$\frac{\Delta\Gamma_d}{\Gamma_d}(\mathrm{D0}) = (0.5 \pm 1.38)\ \%$$

$$\frac{\Delta\Gamma_d}{\Gamma_d}(\mathrm{LHCb}) = (-4.4 \pm 2.7)\ \%$$

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Lattice inputs

$$F_q\sqrt{\hat{B}_q} = 216(16),\ \ 266(18)\ \mathrm{MeV}$$

- central values
- errors

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Large NP room for $\Delta\,\Gamma_d$

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Comparison btw SM and Exp (II)

$$V_{ub}(\text{excl}) = 3.42(31) \times 10^{-3} \qquad V_{ub}(\text{incl}) = 4.40(25) \times 10^{-3}$$

Buras and Girrbach (2013)

$\lvert V_{ub}\rvert \times 10^3$	3.1	3.4	3.7	4.0	4.3	Experiment
$\lvert \varepsilon_K \rvert \times 10^3$	1.76	1.91	2.05	2.19	2.33	2.228(11)
$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) \times 10^4$	0.58	0.70	0.83	0.97	1.12	1.14(22)
$(\sin 2\beta)_{\text{true}}$	0.619	0.671	0.720	0.766	0.808	0.679(20)
$S_{\psi\phi}$	0.032	0.035	0.038	0.042	0.046	~~0.001(9)~~ $-(0.04^{+0.10}_{-0.13})$

SM predictions for $\gamma = 68^\circ$

- V_{ub}- ε_K-$S_{\psi K_S}$ tension is relaxed

$$V_{ub}(\text{excl}) : 3.1 \to 3.4 \quad \longleftarrow \quad V_{ub}(\text{Belle 2013}) : 3.52$$

$$\mathcal{B}(B \to \tau\nu)(\text{exp}) : 1.73 \to 1.14 \quad \longleftarrow \quad \mathcal{B}(B \to \tau\nu)(\text{Belle 2012}) : 0.72$$

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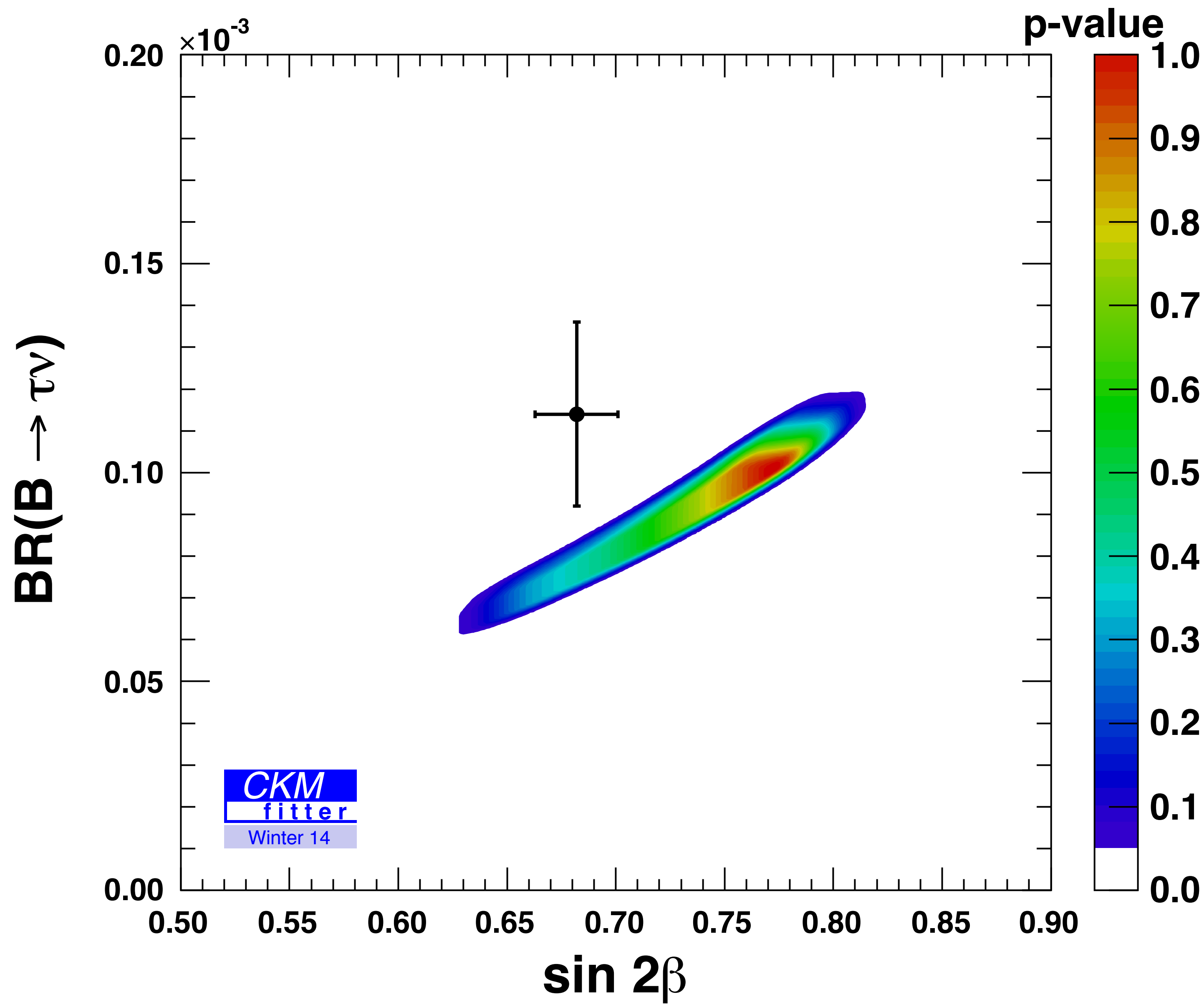
SM predictior



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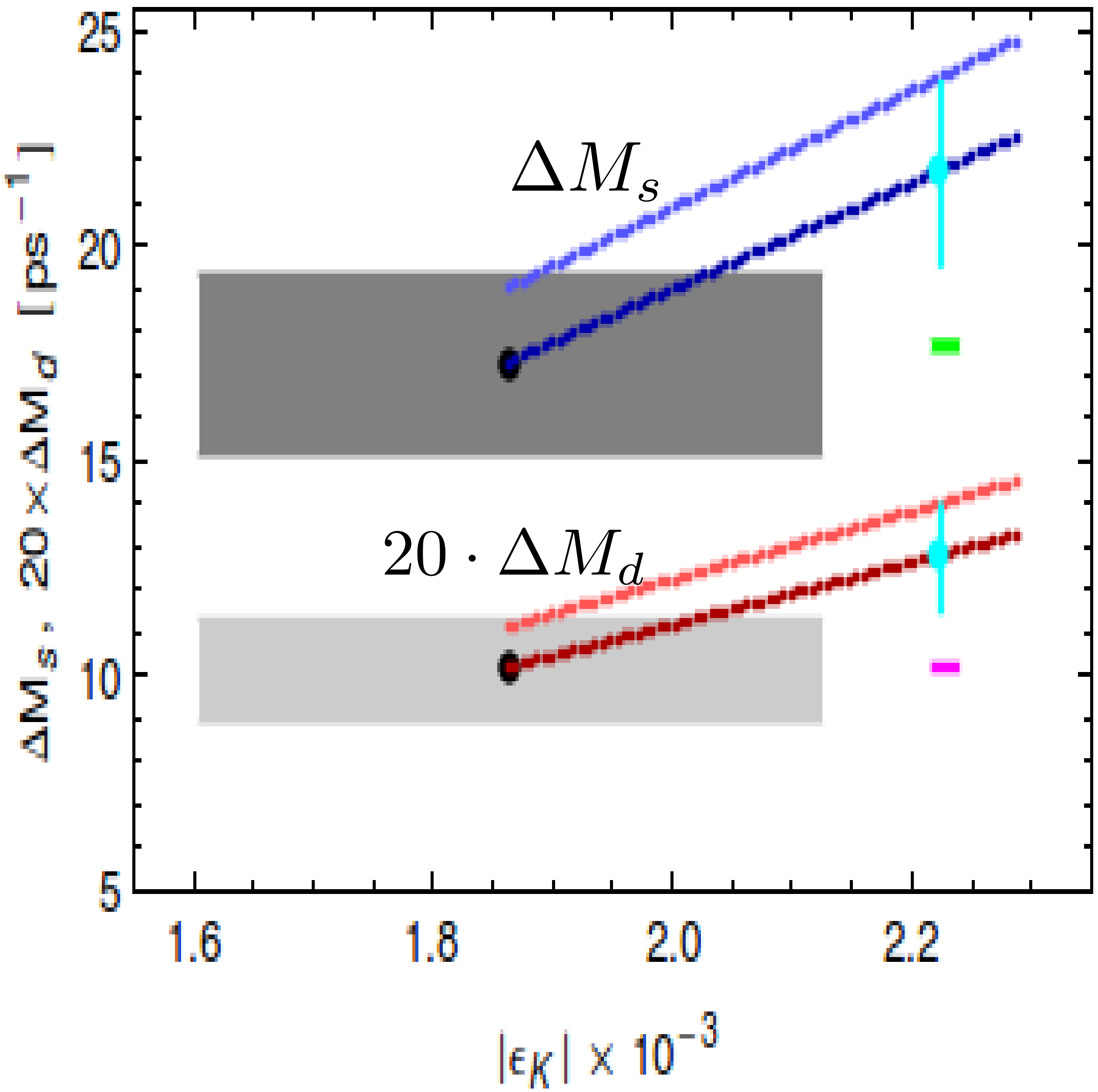
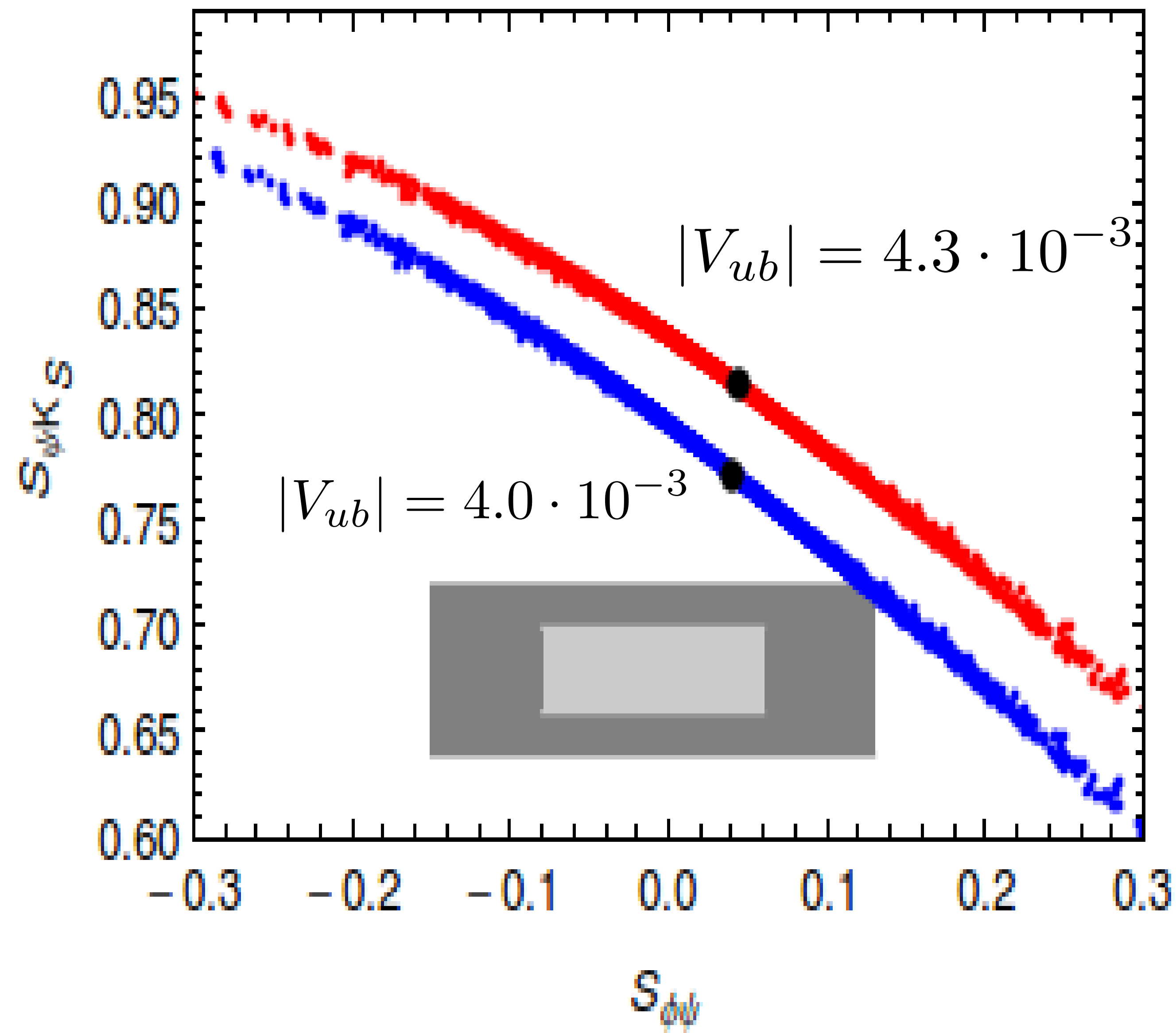
ε K(SM)がやや小さいのが気になる？

CMFV



$2\mathrm{HDM}_{\overline{\mathrm{MFV}}}$



See, Buras and Girrbach 1306.3775

Comparison btw SM and Exp (III)

$$\bar{\mathcal{B}}(B_s \to \mu^+\mu^-)(\mathrm{SM}) = (3.65 \pm 0.23) \times 10^{-9}$$

$$\bar{\mathcal{B}}(B_d \to \mu^+\mu^-)(\mathrm{SM}) = (1.06 \pm 0.09) \times 10^{-10}$$

$$\bar{\mathcal{B}}(B_s \to \mu^+\mu^-)(\mathrm{Exp}) = (2.9 \pm 0.7) \times 10^{-9}$$

$$\bar{\mathcal{B}}(B_d \to \mu^+\mu^-)(\mathrm{Exp}) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

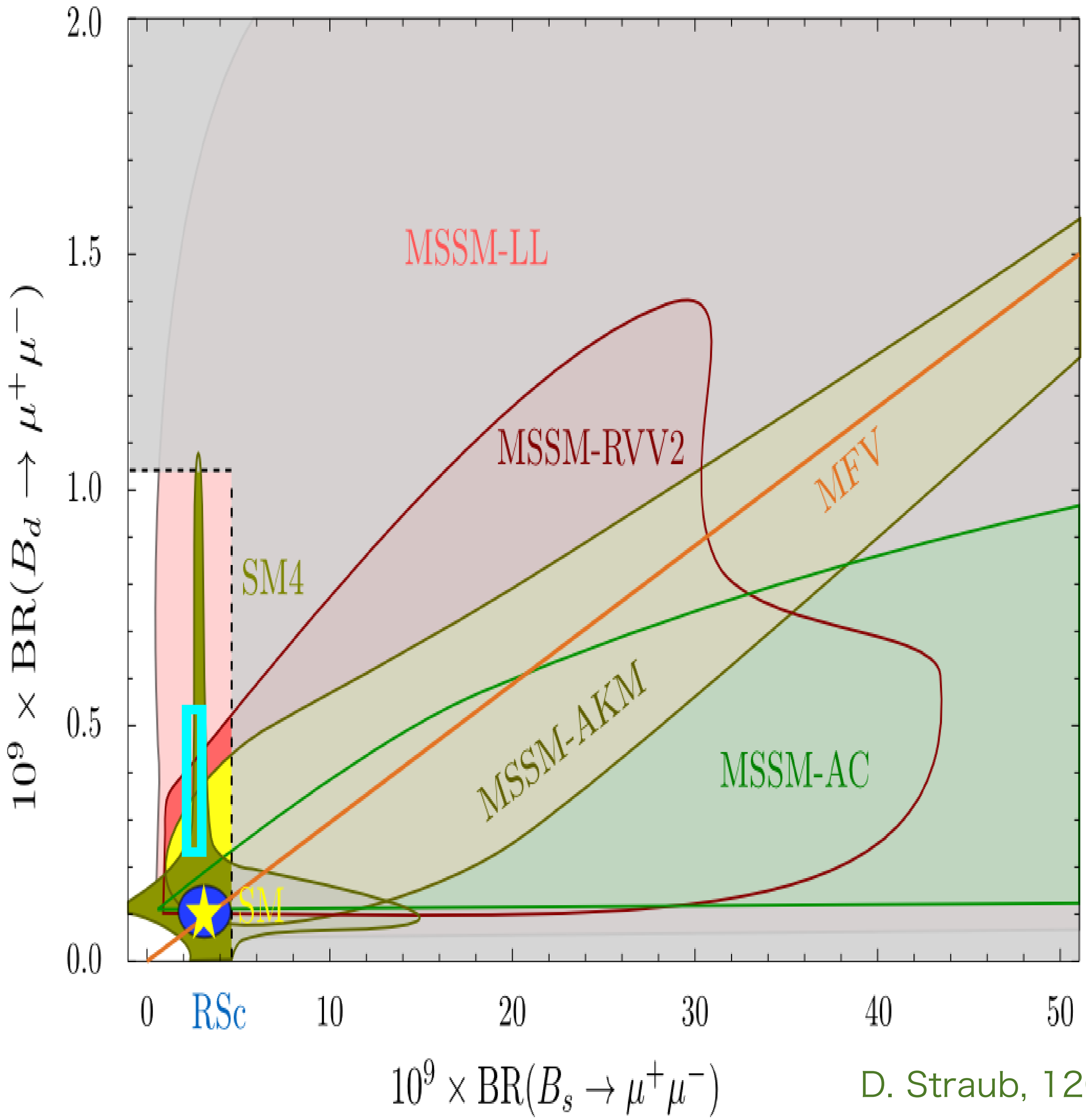
- NNLO-QCD & NLO EW corrections Bobeth et al (2014)
- Average time-integrated branching ratio de Bruyn et al (2012)

$$\bar{\mathcal{B}} = \frac{1 + A_q}{1 - y_q^2}\mathcal{B}^{[t=0]}$$

where $y_q = \frac{\Delta\Gamma_q}{2\Gamma_q}$ $A_q(\mathrm{SM}) = y_q$

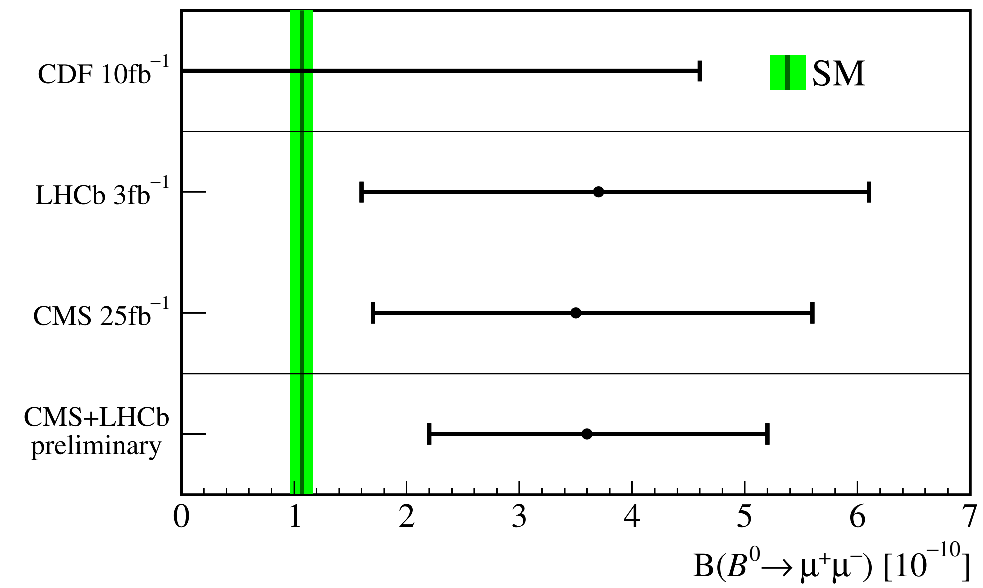
$$y_s = 0.088 \pm 0.014$$

Implications on NP models (I)



D. Straub, 1205.6094

$B_d \to \mu^+\mu^-$

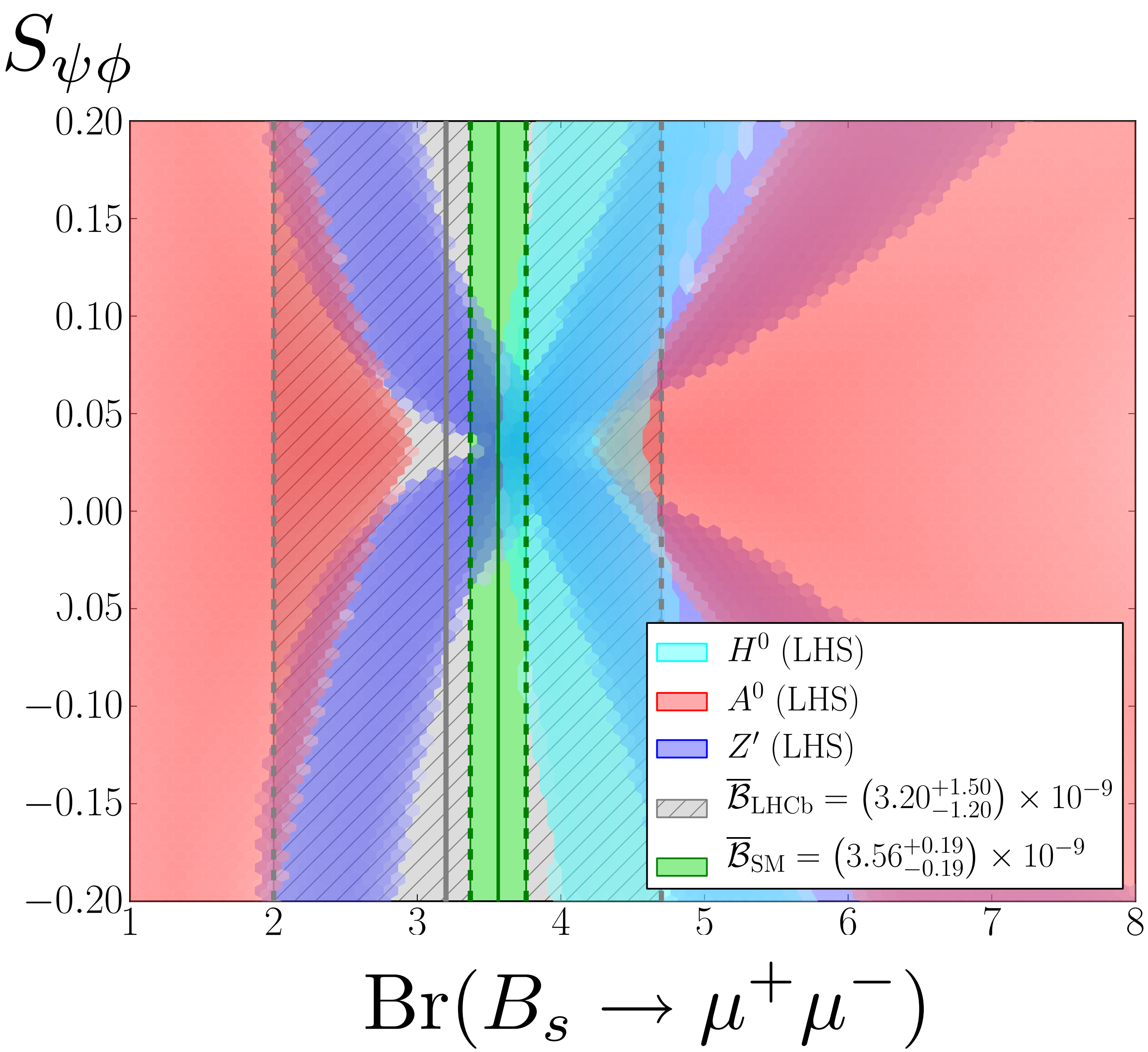


2.4 σ above 0

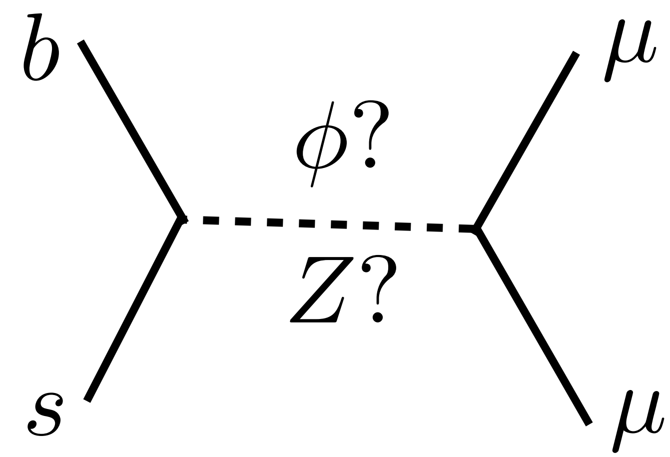
1.6 σ above the SM value

If confirmed,
proof of non-MFV

Implications on NP models (II)



[Buras, Fazio, Girrbach, Knegjens and MN (2013)]



$$\mathcal{B} \sim |A + P|^2 + |S|^2$$

To obtain Br< Br(SM), interference with SM amp. is required.

Note,

h_{SM} + FV b-s coupling

→ 8 % increase at most

+ P-scalar muon coupling

→ Br<Br(SM) is possible

Remaining anomalies (?)

- muon g-2
- $B \to D^{(*)} \tau \nu$
- Dimuon asymmetry
- $B \to K^{(*)} \mu^+ \mu^-$
- V_{ub}
- β

Like-sign dimuon asymmetry (~2012)

- D0 collaboration measured the like-sign dimuon asymmetry A_{CP}, which is interpreted as a CP-violating effect in B meson mixing.

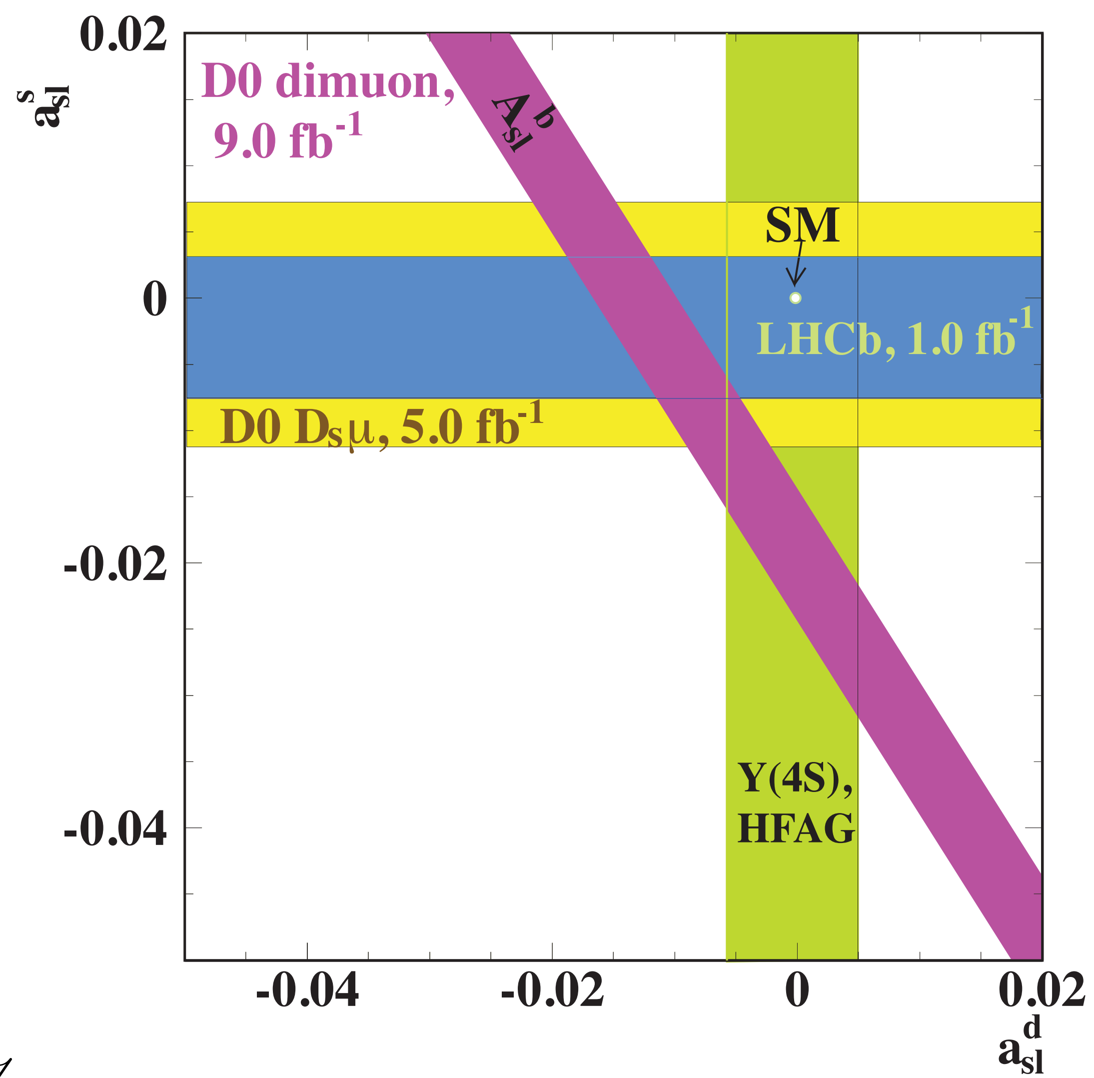
$$A_{\rm CP} \propto A^b_{sl} \equiv C_d a^d_{sl} + C_s a^s_{sl}$$

$$\begin{aligned} p\bar{p} &\rightarrow b\bar{b}X, \\ b &\rightarrow b \text{ hadron} \rightarrow \mu^- (\text{“right-sign” } \mu), \\ \bar{b} &\rightarrow B^0_{(s)} \rightarrow \bar{B}^0_{(s)} \rightarrow \mu^- (\text{“wrong-sign”} \mu); \end{aligned}$$

$$A^b_{sl}(\mathrm{D0}, 9\,\mathrm{fb}^{-1}) = (-0.787 \pm 0.172 \pm 0.093)\%$$

$$A^b_{sl}(SM) = (-0.028^{+0.005}_{-0.006})\%$$

3.9 σ



- LHCb confirmed SM consistent semi-leptonic asymmetry for B_s mesons.

Like-sign dimuon asymmetry (2013)

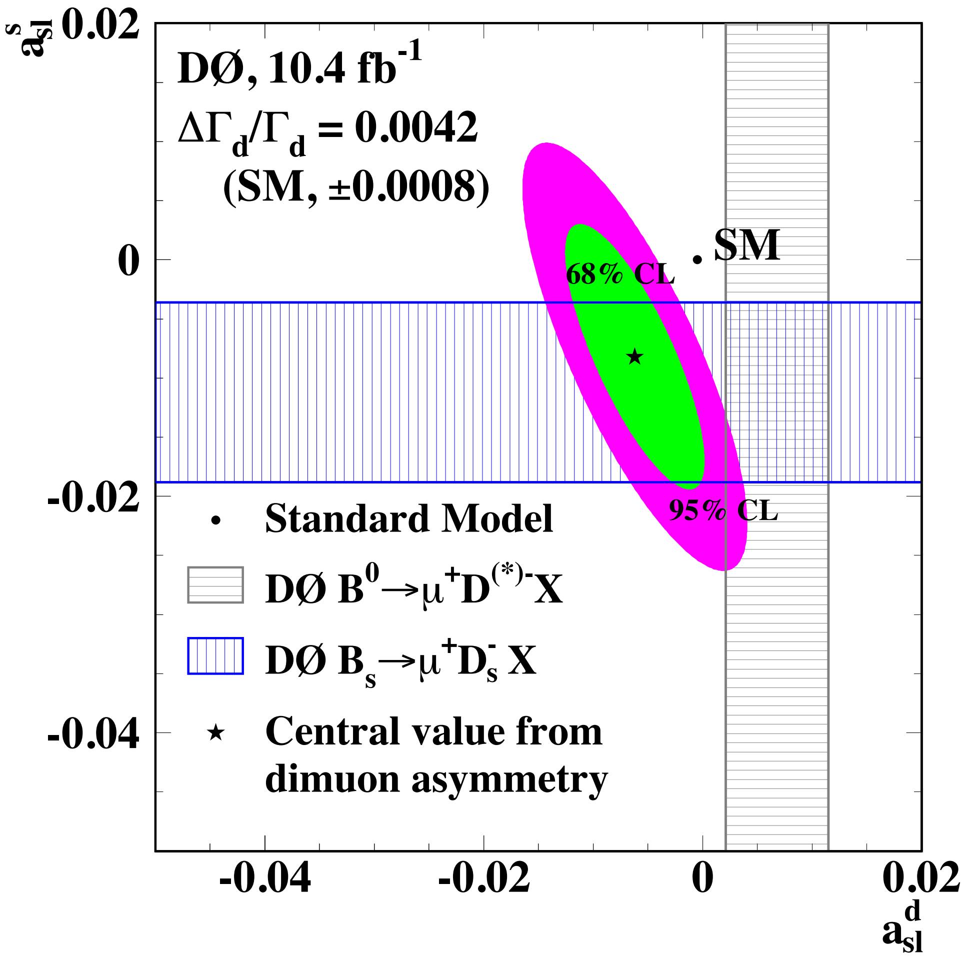
- New contributions proportional to decay rate differences were found.

$$A_{\rm CP} \propto A^b_{sl} + C_{\Gamma_d}\frac{\Delta\Gamma_d}{\Gamma_d} + C_{\Gamma_s}\frac{\Delta\Gamma_s}{\Gamma_s}$$

CP violation in the interference of B meson decay amplitude with and without mixing.

$$\begin{aligned} p\bar{p} &\to b\bar{b}X, \\ b &\to b\ \text{hadron} \to \mu^-(\text{“right-sign”}\mu), \\ \bar{b} &\to B^0(\to \bar{B}^0) \to D^+D^-, \\ D^- &\to \mu^-(\text{“wrong-sign”}\mu); \end{aligned}$$

Borissov and Hoeneisen (2013)



3.4 σ

D0 collaboration (2013)

Assuming SM decay rate diffrences,

$$A^b_{sl} = (-0.496 \pm 0.153 \pm 0.072)\%$$ 2.8 σ

Assuming SM semi-leptonic asymmetry,

$$\Delta\Gamma_d/\Gamma_d = (+2.63 \pm 0.66) \times 10^{-2}$$ 3.3 σ

New Physics in $\Delta\Gamma_d$

Bobeth, Haisch, Lenz, Pecjak, Tetlalmatzi-Xolocotzi (2013)

- D0 measurements may be explained by possible NP contributions to $\Delta\Gamma_d$.
  - The SM prediction of $\Delta\Gamma_s$ agrees quite well with the experimental value.
  - $\Delta\Gamma_d$ is triggered by the CKM-suppressed decay b→ccd (Br~1%). Thus, large modification of Γ(b→ccd) can be hidden in the uncertainties of Γ_{tot}.
  - The SM contribution to $\Delta\Gamma_d$ has a large cancellation between individual (charm and up) contributions. Then, NP effects can be easily enhanced compared to the SM one.

- Model-independent analysis:

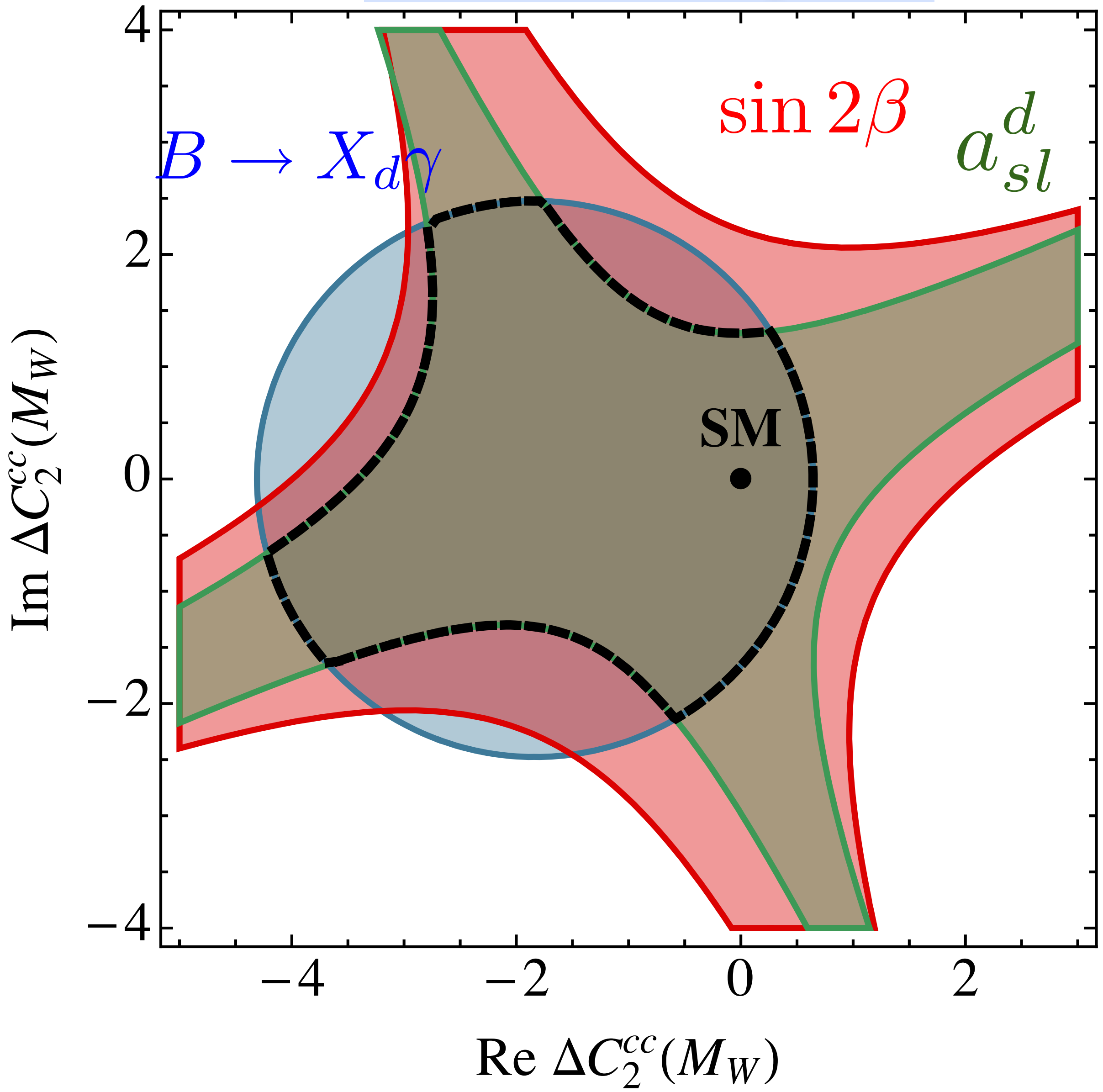
$$\mathcal{H} = \frac{4G_F}{\sqrt{2}} \sum_{p,p'=u,c} V_{pd}^* V_{p'b} (C_1^{pp'} Q_1^{pp'} + C_2^{pp'} Q_2^{pp'}) \qquad \left(C_i^{pp'} = C_i^{\rm SM} + \Delta C_i^{pp'}\right)$$

where

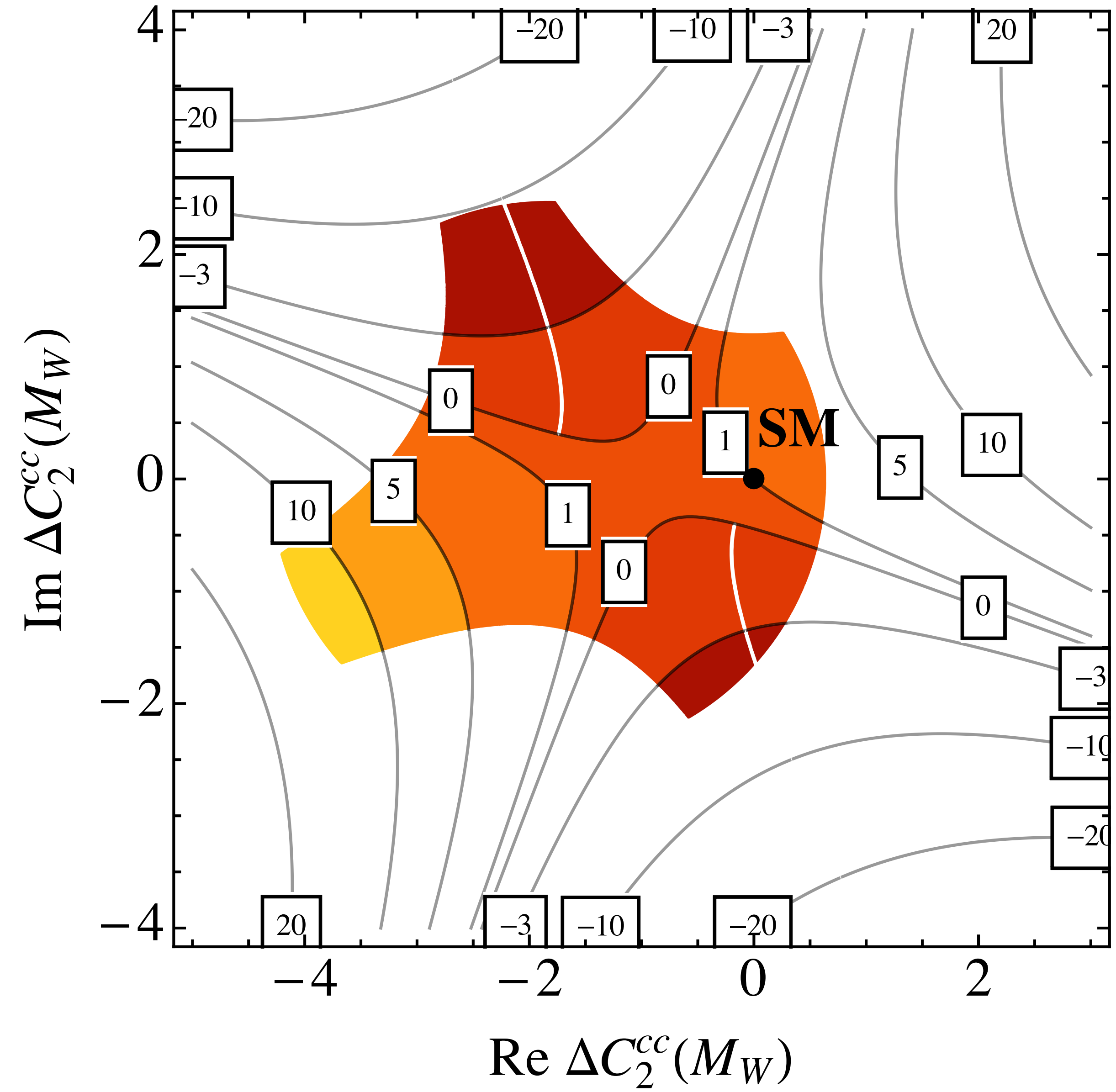
$$Q_1^{pp'} = \left(\bar{d}^\alpha \gamma^\mu P_L p^\beta\right) \left(\bar{p}'^\beta \gamma_\mu P_L b^\alpha\right)$$
$$Q_2^{pp'} = \left(\bar{d}^\alpha \gamma^\mu P_L p^\alpha\right) \left(\bar{p}'^\beta \gamma_\mu P_L b^\beta\right)$$

New Physics in Δ Γ d : b→ccd

Allowed region



$\Delta\Gamma_d/\Delta\Gamma_d^{SM}$

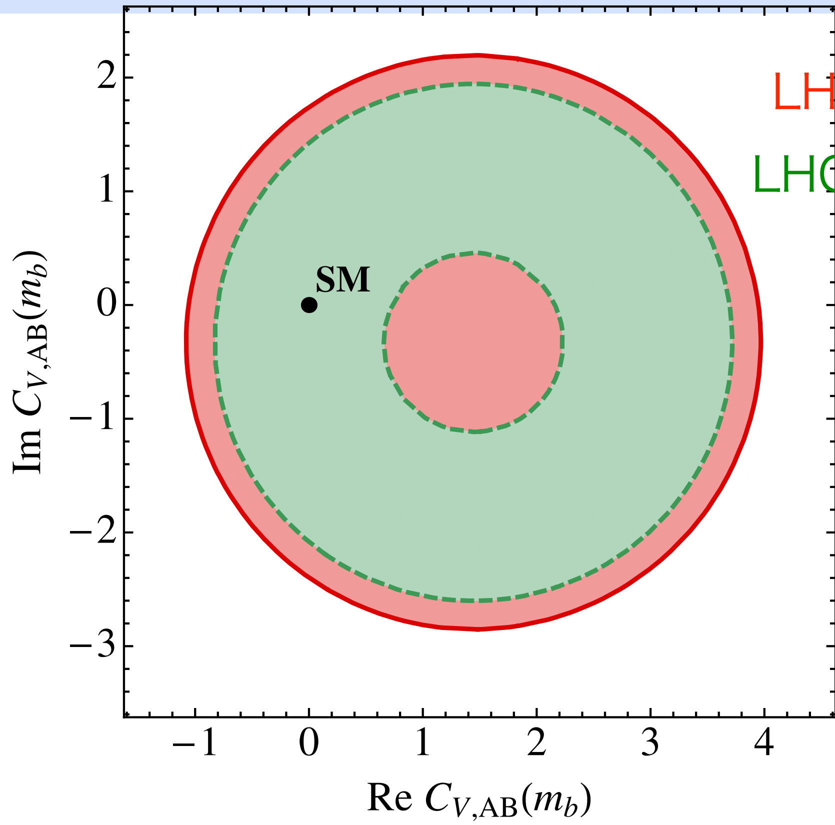


$\Delta\Gamma_d/\Delta\Gamma_d^{SM} \sim 5$ is possible

New Physics in Δ Γ$_d$: b→ τ τ d

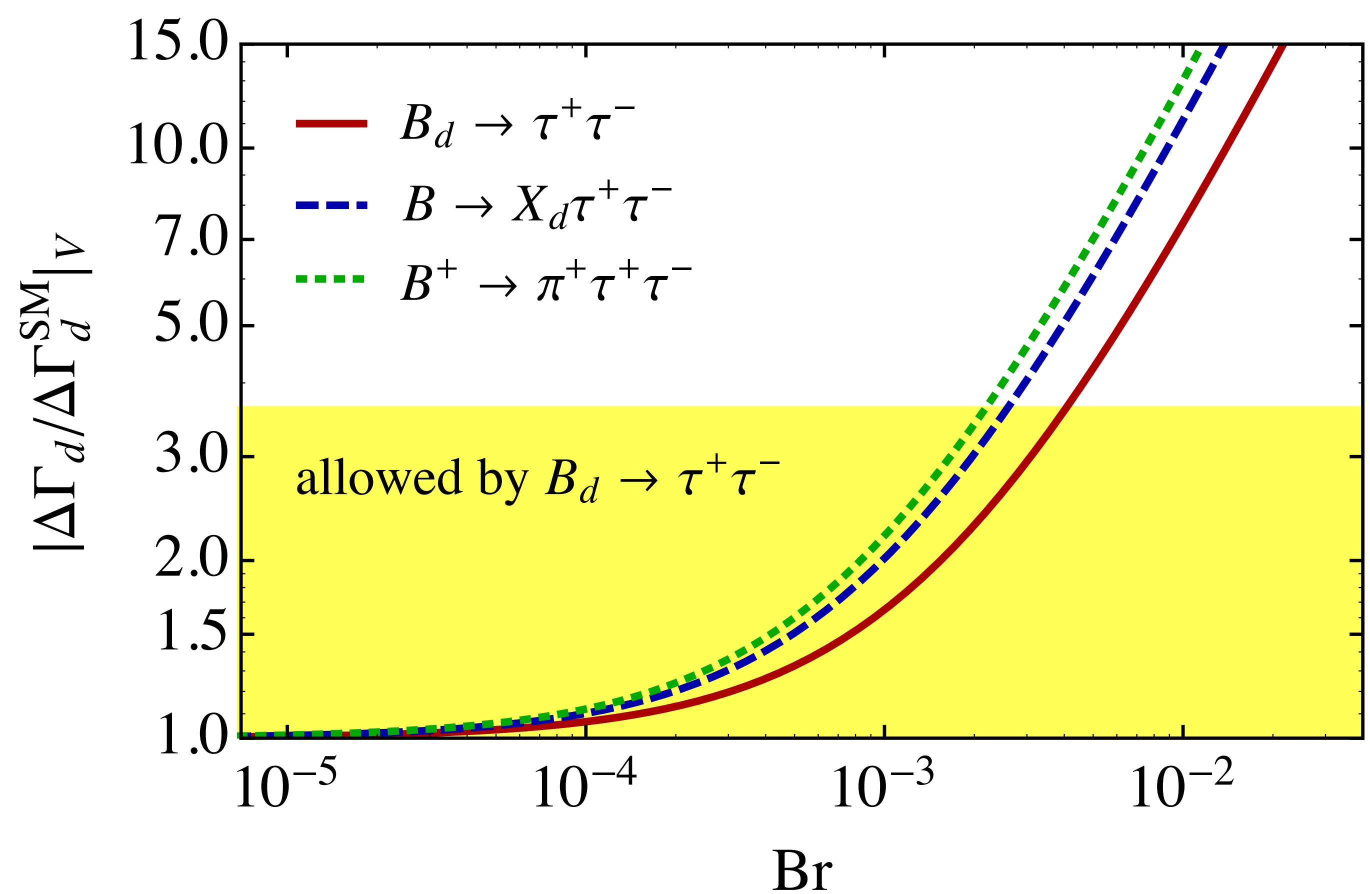
Constraint from $B^+ \to \pi^+\mu^+\mu^-$

(S, V, T operators)



Constraint	$\|C_{V,AB}(m_b)\|$
$\mathrm{Br}\,(B_d \to \tau^+\tau^-)$	2.2
$\mathrm{Br}\,(B \to X_d\tau^+\tau^-)$	5.3
$\mathrm{Br}\,(B^+ \to \pi^+\tau^+\tau^-)$	6.2
;	
$\mathrm{Br}\,(B \to X_d\gamma)$	—
$\mathrm{Br}\,(B^+ \to \pi^+\mu^+\mu^-)$	4.0

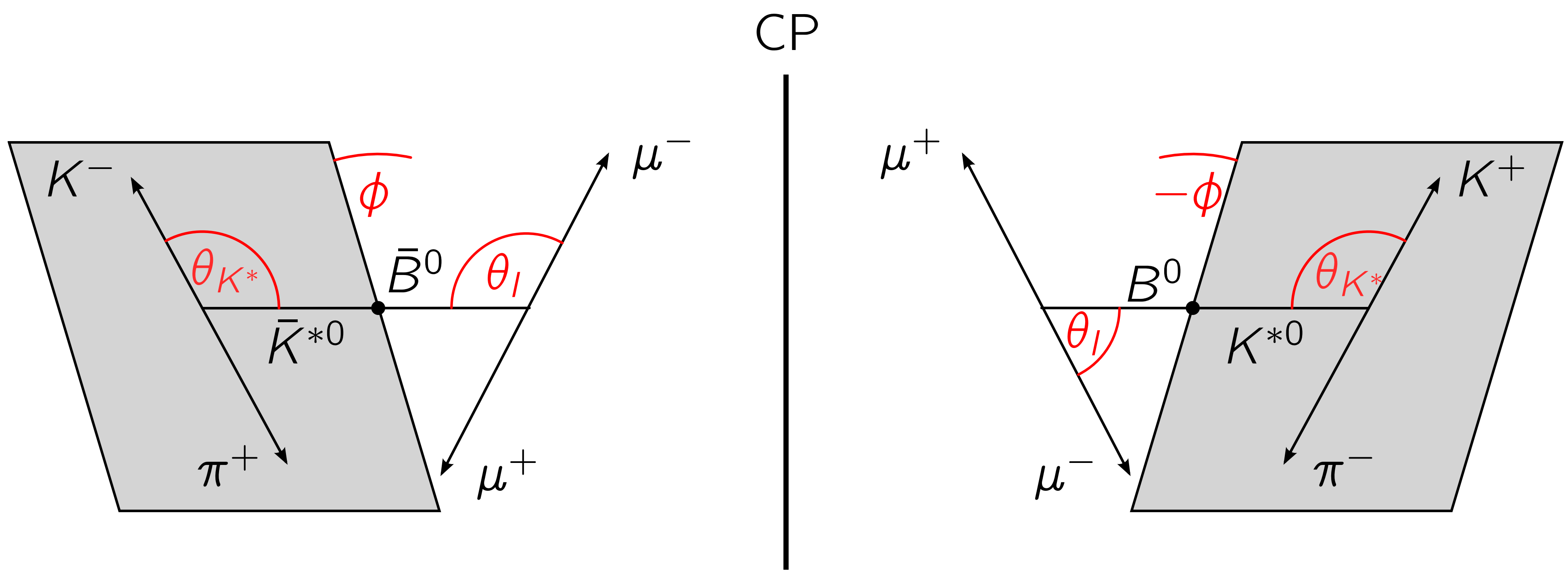
$\Delta\Gamma_d/\Delta\Gamma_d^{\mathrm{SM}}$



$\Delta\Gamma_d/\Delta\Gamma_d^{\mathrm{SM}} \sim 3$ is possible

From slides by D. Straub @ KEK-FF2014

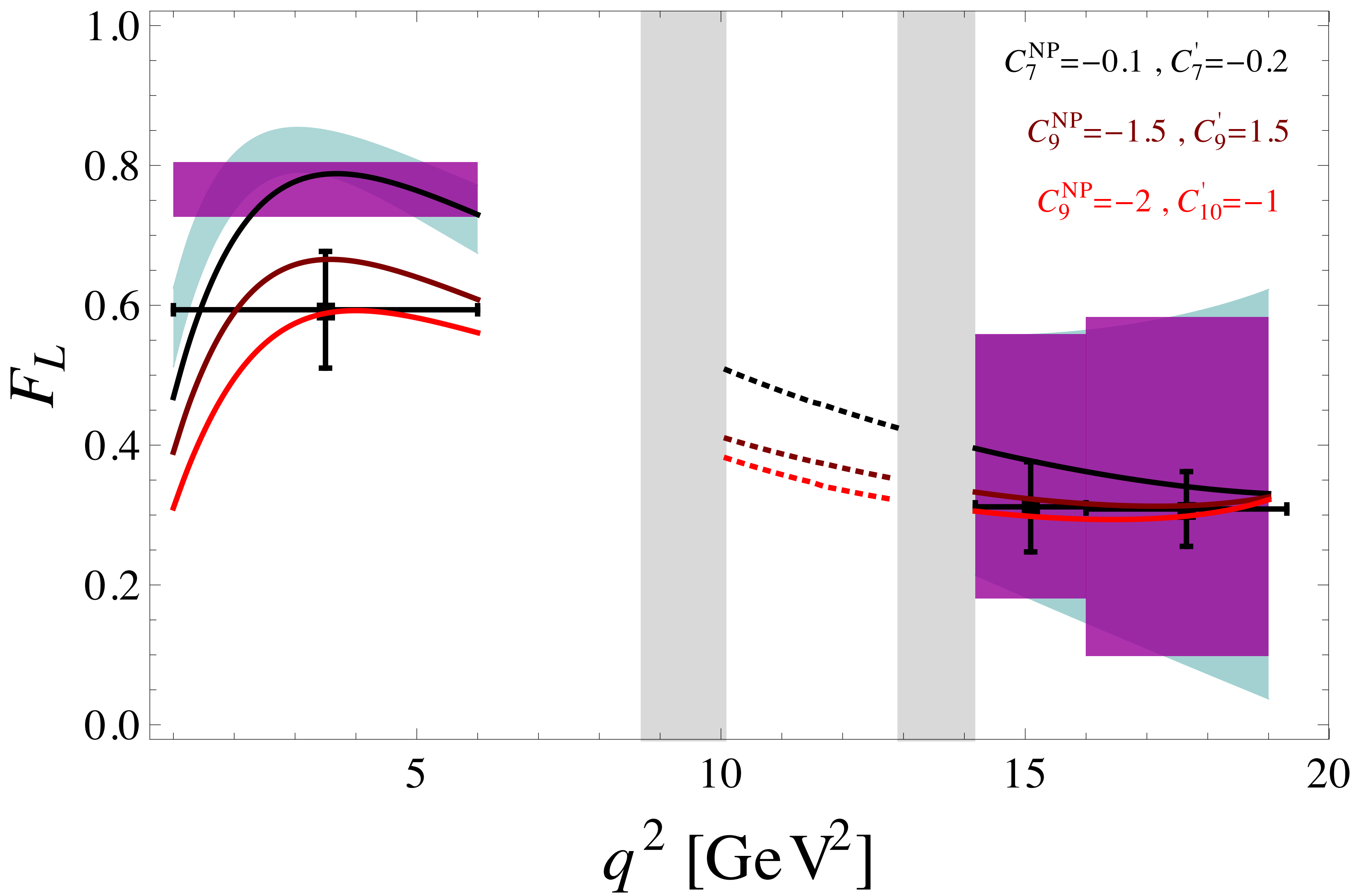
$B \to K^* \mu^+ \mu^-$ angular observables



$$\frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 \, d\cos\theta_l \, d\cos\theta_{K^*} \, d\phi} \sim \sum_i S_i(q^2) \, f_i(\theta_l, \theta_{K^*}, \phi)$$

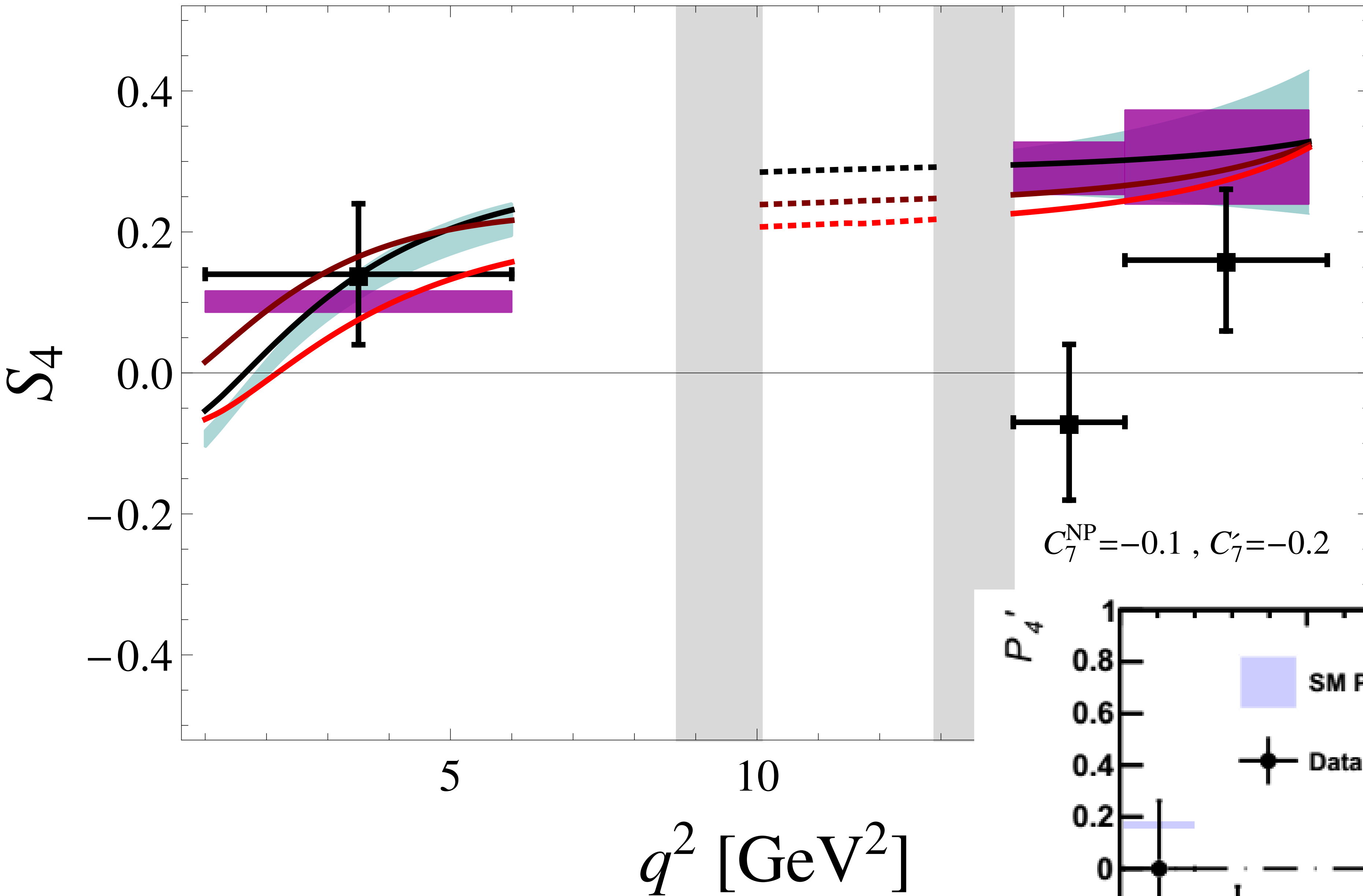
$$\frac{d^4(\Gamma - \bar{\Gamma})}{dq^2 \, d\cos\theta_l \, d\cos\theta_{K^*} \, d\phi} \sim \sum_i A_i(q^2) \, f_i(\theta_l, \theta_{K^*}, \phi)$$

SM vs. data: F_L [Altmannshofer and DS 1308.1501]

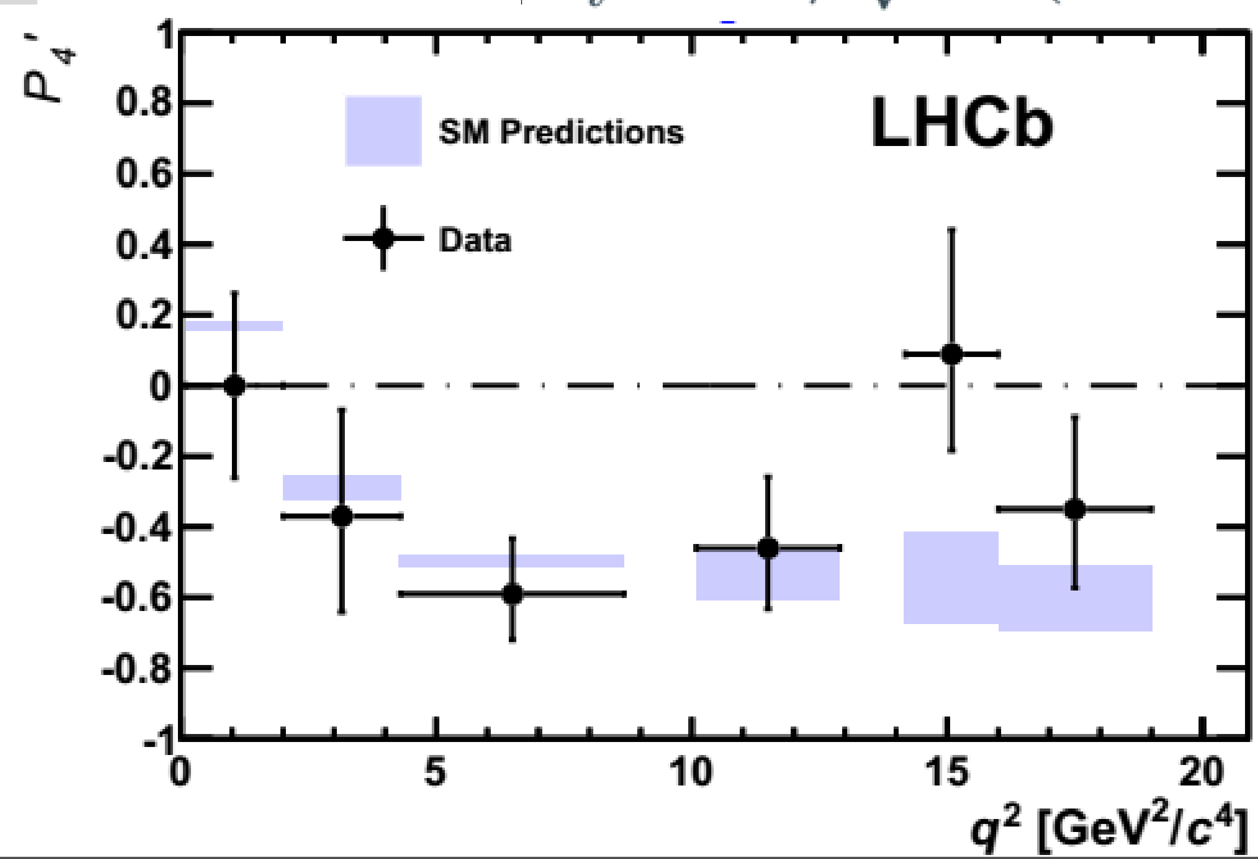


1.9σ tension at low q^2 (driven by ATLAS and BaBar data)

SM vs. data: S_4 [Altmannshofer and DS 1308.1501]

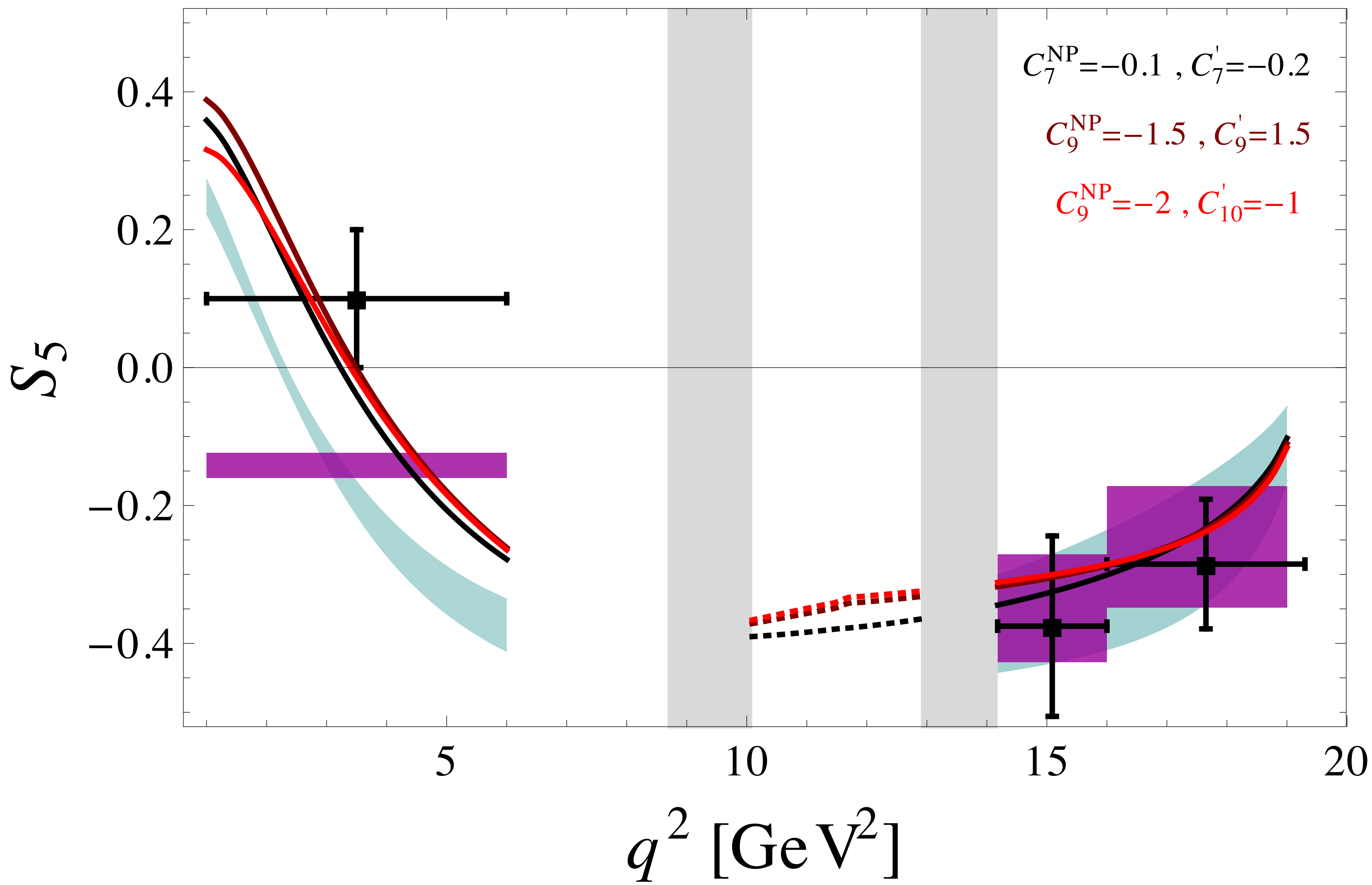


$$P_i' = S_i/\sqrt{F_L(1-F_L)}$$



2.8σ tension at high q^2

SM vs. data: S_5 [Altmannshofer and DS 1308.1501]

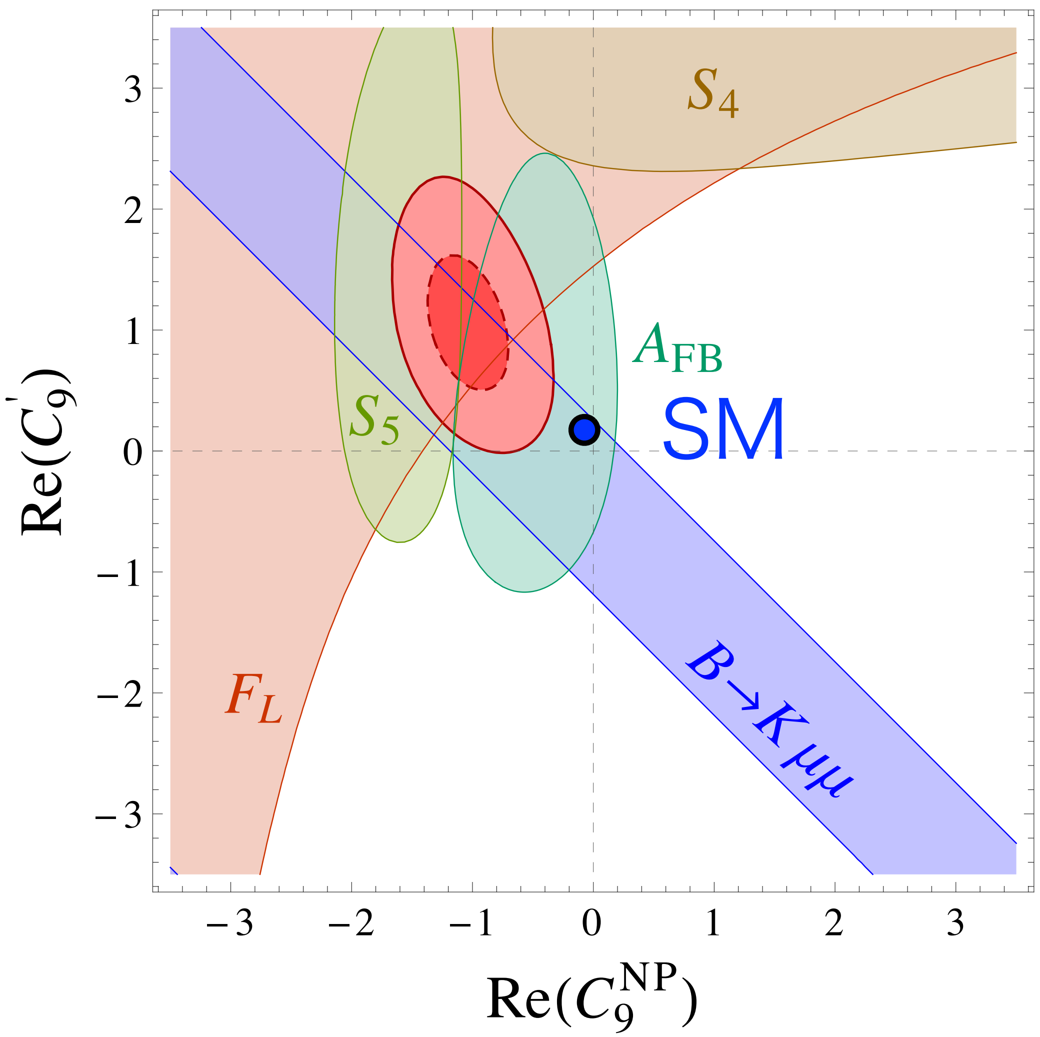


2.4σ tension at low q^2

The "$B \to K^*\mu\mu$ anomaly"

Fitting C_9 and $C'_{9,10}$

[Altmannshofer and DS 1308.1501]



The are 2–3σ tensions in the observables F_L, S_4, S_5. Possible explanation

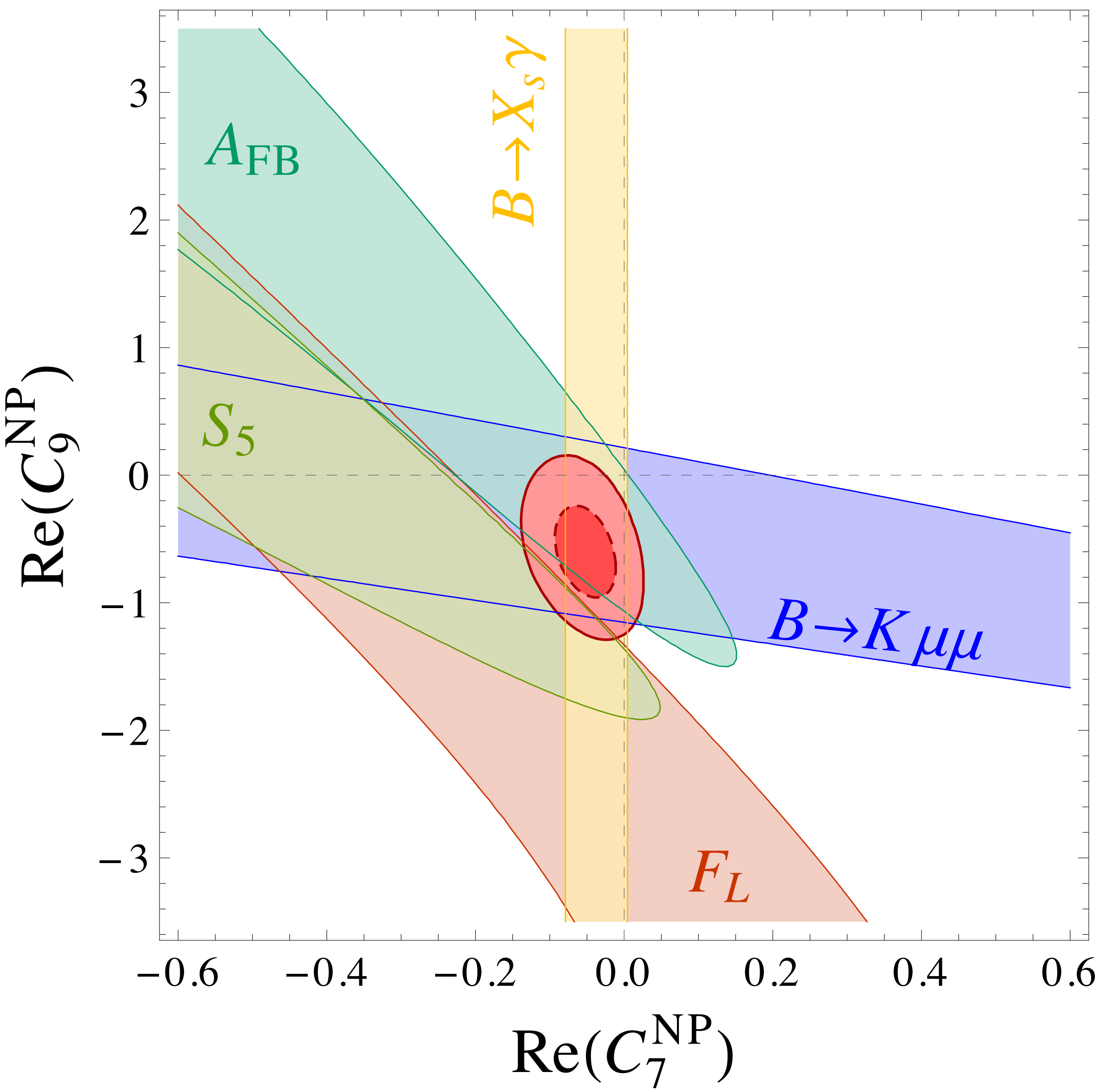
- Statistical fluctuation . . .
- Underestimated theory uncertainties ($\to$ see talk by Th. Feldmann!)
  - Non-factorizable corrections at low q^2
  - Violation of quark-hardon duality at low and high q^2
  - form factors
- New physics?
  - Can the tensions be removed by modifying C_i without upsetting other constraints?
  - The answer for the S_4 tension is clearly “no”. What about the S_5, F_L tensions?

- Simultaneous NP effect in C_9 and C'_9 gives the best fit to the data
- As yet, only proposed model that can accomodate the effect: flavour-violating Z'

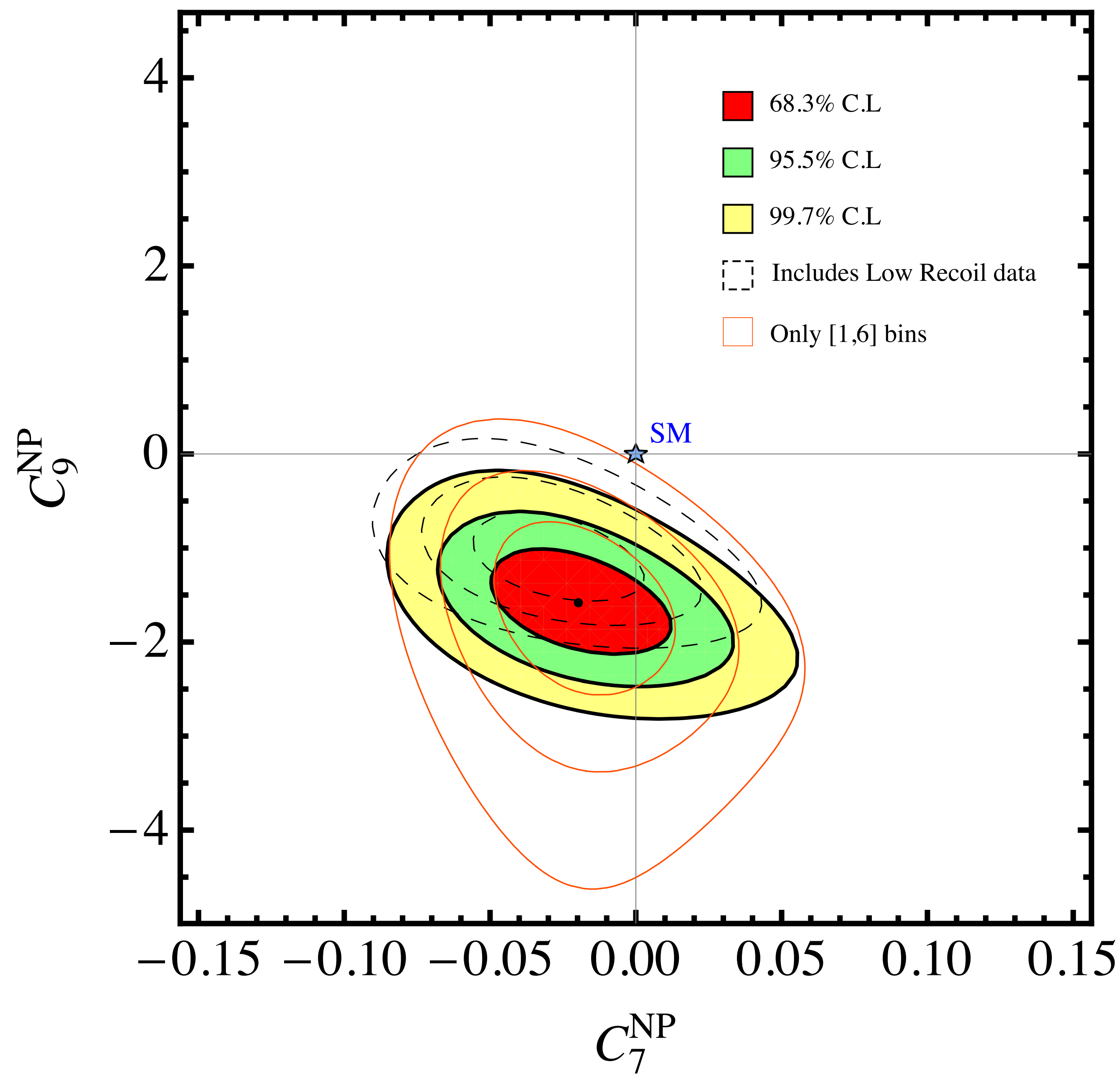
Fitting C_7 and C_9

$$\mathcal{O}_7 = e/(16\pi^2)\, m_b(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu},$$
$$\mathcal{O}_9 = e^2/(16\pi^2)\,(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell),$$
$$\mathcal{O}_{10} = e^2/(16\pi^2)\,(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell),$$

Altmannshofer and Straub (2013)



Descotes-Genon, Matias and Virto (2013)



R(D$^{(*)}$)

See, Hagiwara, nojiri and sakaki (2014) and references therein

Semi-leptonic decay

$$R(D^{(*)}) = \frac{\Gamma(B \to \bar{D}^{(*)}\tau^+\nu_\tau)}{\Gamma(B \to \bar{D}^{(*)}l^+\nu_l)}$$

$$R(D)_{\rm SM} = 0.305 \pm 0.012, \quad R(D^*)_{\rm SM} = 0.252 \pm 0.004.$$

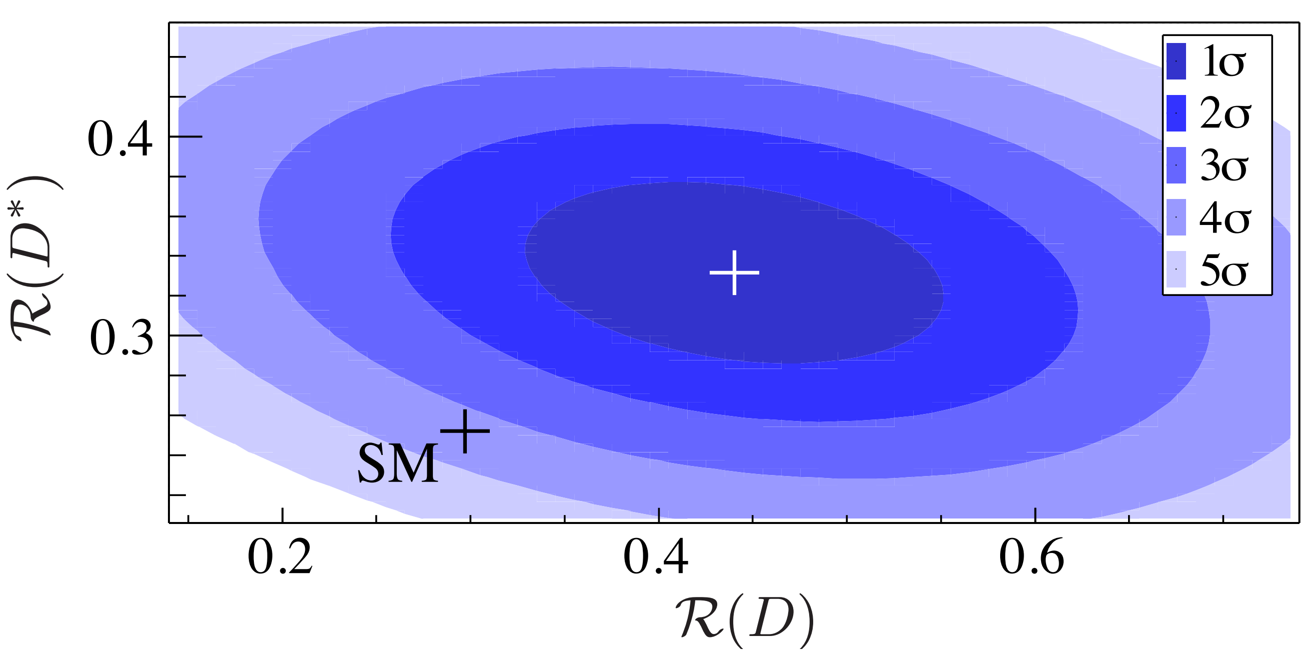
$$R(D)_{\rm BaBar} = 0.440 \pm 0.072, \quad R(D^*)_{\rm BaBar} = 0.332 \pm 0.030,$$

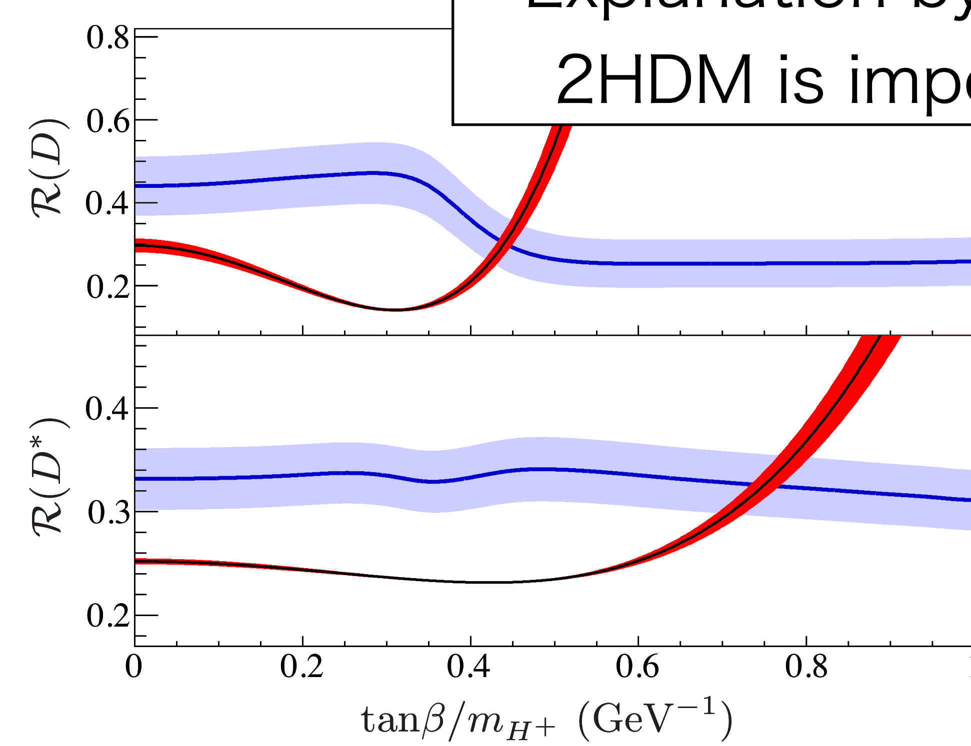
$$R(D)_{\rm Belle} = 0.34 \pm 0.12, \quad R(D^*)_{\rm Belle} = 0.43 \pm 0.08,$$

$$\Rightarrow \quad R(D)_{\rm exp} = 0.42 \pm 0.06, \quad R(D^*)_{\rm exp} = 0.34 \pm 0.03,$$

3.8 σ

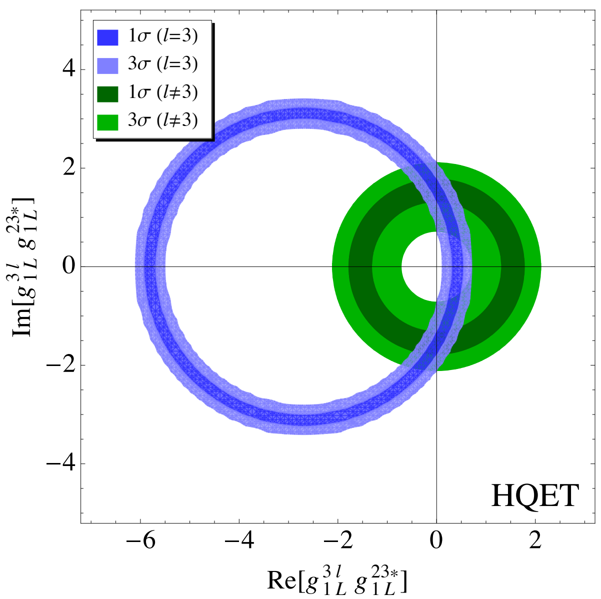
Explanation by Type-II 2HDM is impossible





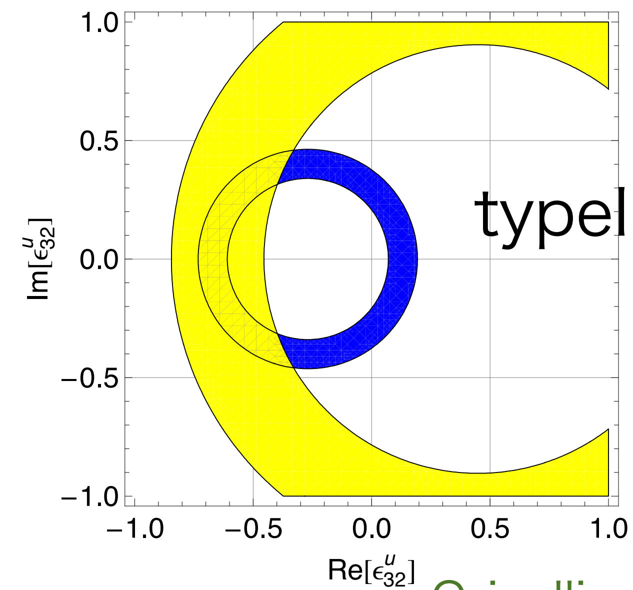
NP explanations

- Explanations by Type-III 2HDM, lepto-quark model are possible



lepto-quark

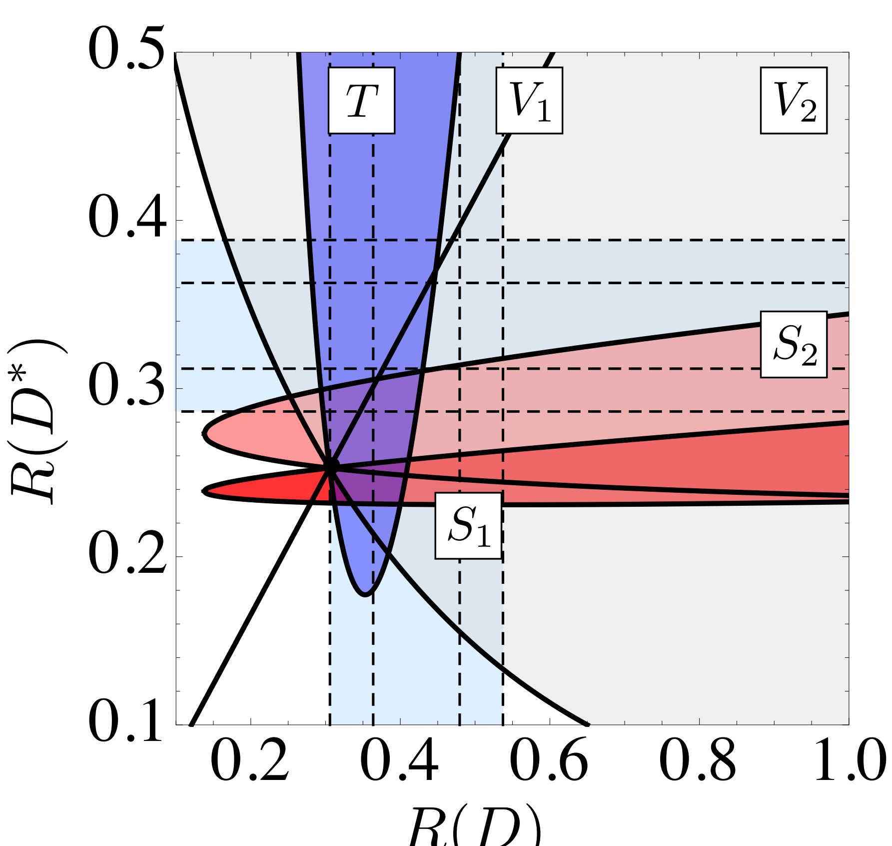
Sakaki et al (2013)



typeIII 2HDM

Crivellin et al (2012)

- Model-independent analysis



Tanaka et al (2012)

$$\mathcal{O}_{V_1} = (\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_{\tau L}),$$
$$\mathcal{O}_{V_2} = (\bar{c}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma_\mu\nu_{\tau L}),$$
$$\mathcal{O}_{S_1} = (\bar{c}_L b_R)(\bar{\tau}_R\nu_{\tau L}),$$
$$\mathcal{O}_{S_2} = (\bar{c}_R b_L)(\bar{\tau}_R\nu_{\tau L}),$$
$$\mathcal{O}_T = (\bar{c}_R\sigma^{\mu\nu} b_L)(\bar{\tau}_R\sigma_{\mu\nu}\nu_{\tau L}).$$

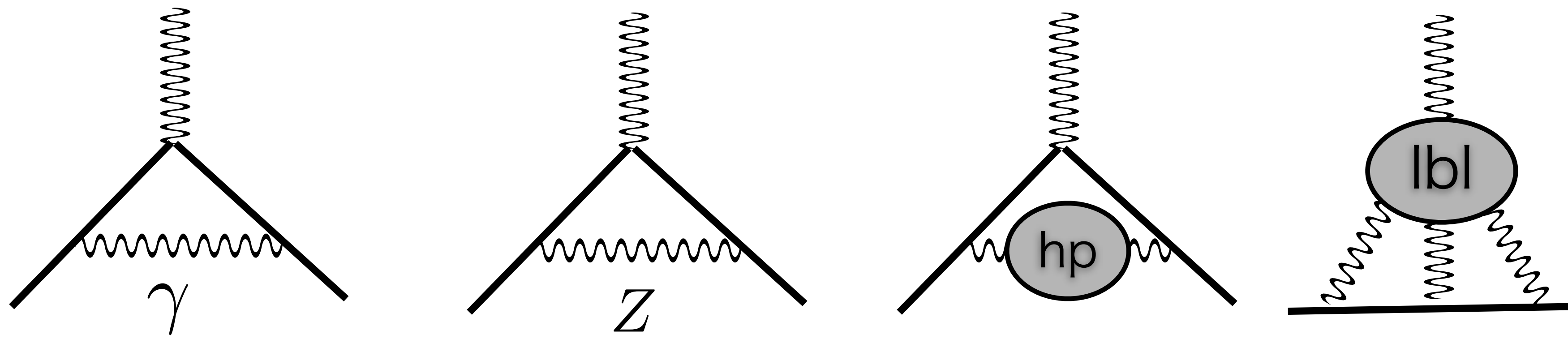
muon g-2

Magnetic Moment

$$\vec{\mu} = g_\mu \frac{e}{2m_\mu} \vec{S}$$

$$a_\mu \equiv \frac{g_\mu - 2}{2} \neq 0$$

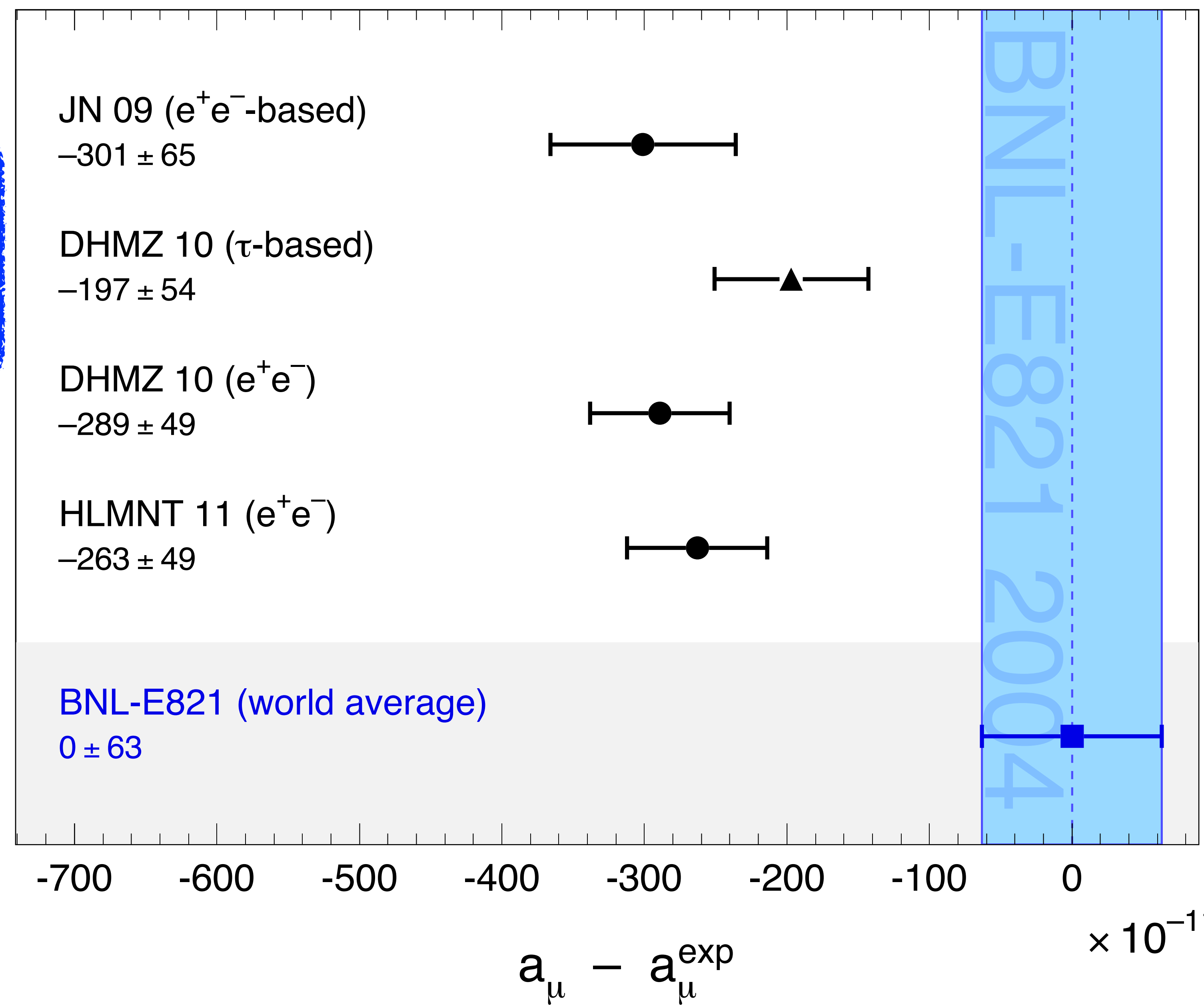
Radiative corrections



$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM}$$
$$= (28.8 \pm 80) \times 10^{-10}$$

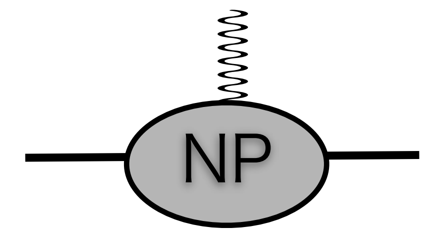
3.6 σ

$$a_\mu^{\rm EW} = 15.4 \times 10^{-10}$$

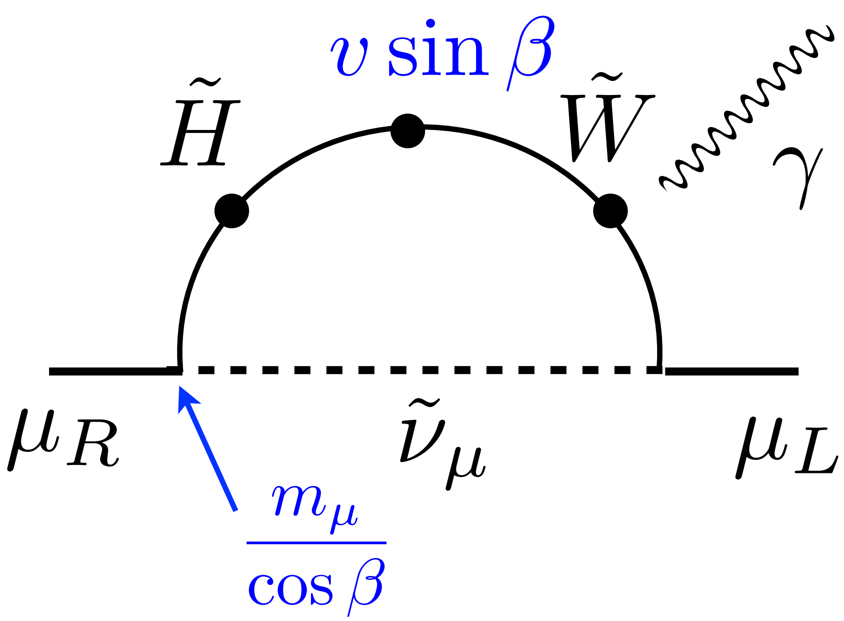


Implication on NP models

$$\Delta a_\mu \sim a_\mu^{\mathrm{EW}} \sim \alpha_2 \frac{m_\mu^2}{m_W^2}$$



- light new particle $\longrightarrow$ dark photon
- heavy (<O(100 GeV)) new particle
  + enhancement factor $\longrightarrow$ SUSY, RS ...



$$a_\mu^{\mathrm{SUSY}} \sim \alpha_2 \frac{m_\mu^2}{m_{\mathrm{SUSY}}^2} \tan\beta$$

Waiting for further experimental confirmations @Fermi and J-park.

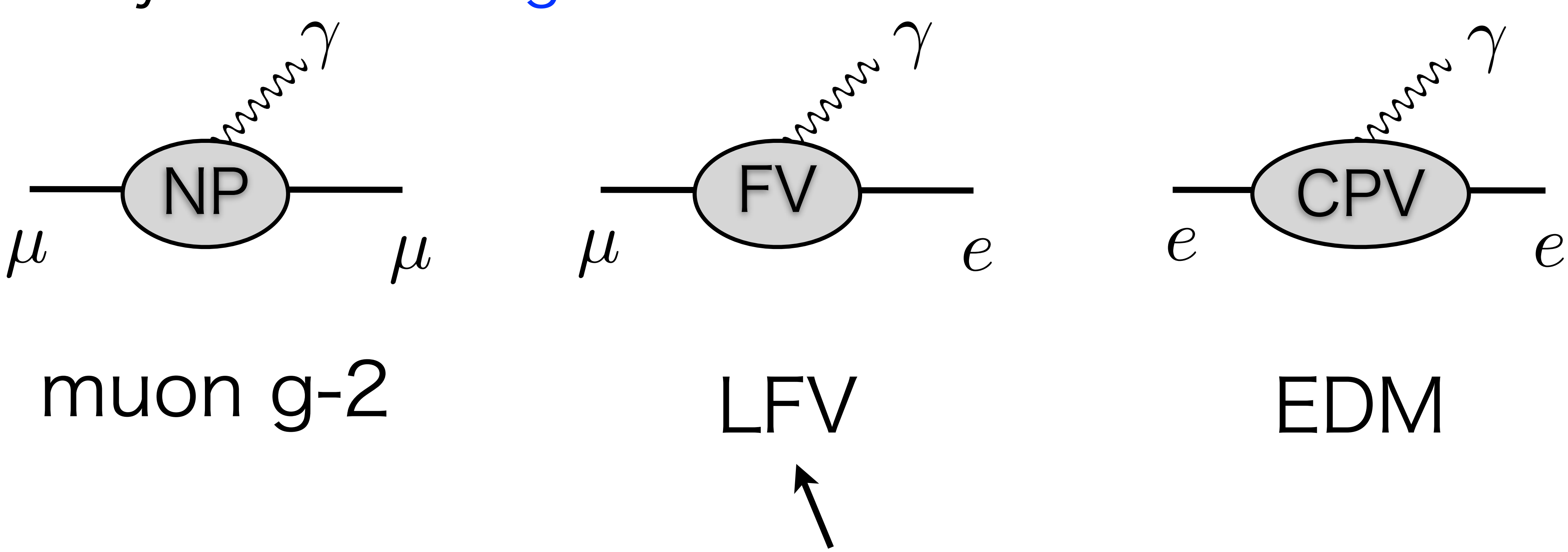
LFVs and EDMs

- SM predictions are highly suppressed

  $\rightarrow$ stringent constraints and/or strong tools to probe NP models

- Theoretically and/or Experimentally well-motivated models

Similarity with muon g-2

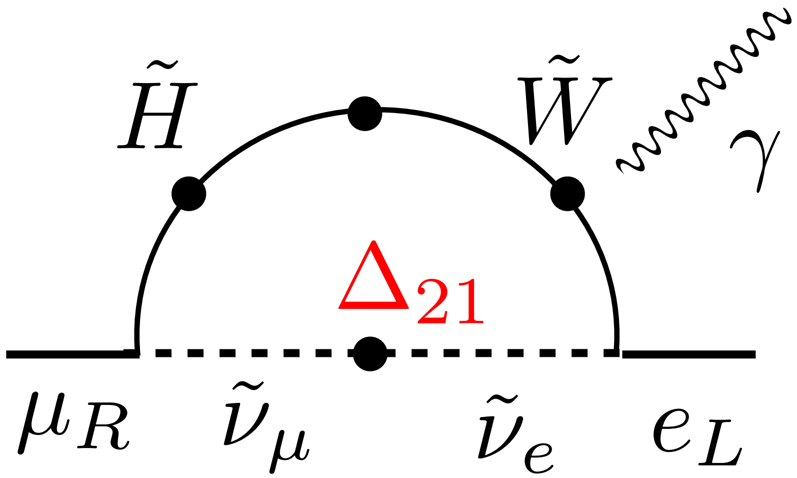


related with generation of ν masses?

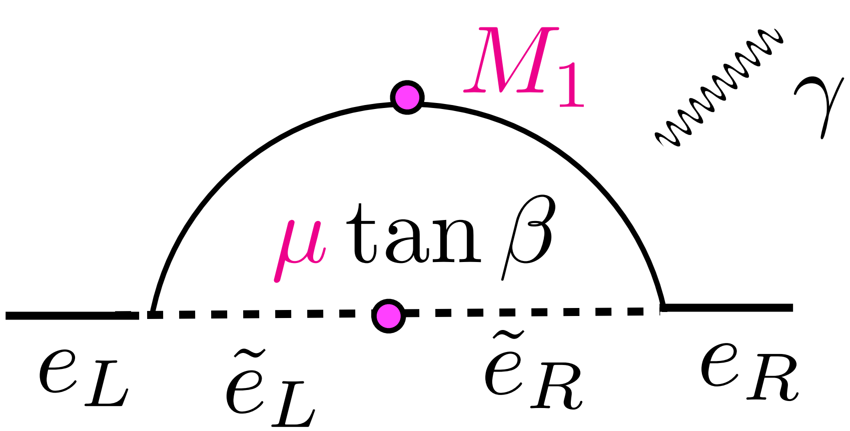
TeV-scale SUSY models

Before the LHC run, O(0.1-1)TeV SUSY particles are expected.

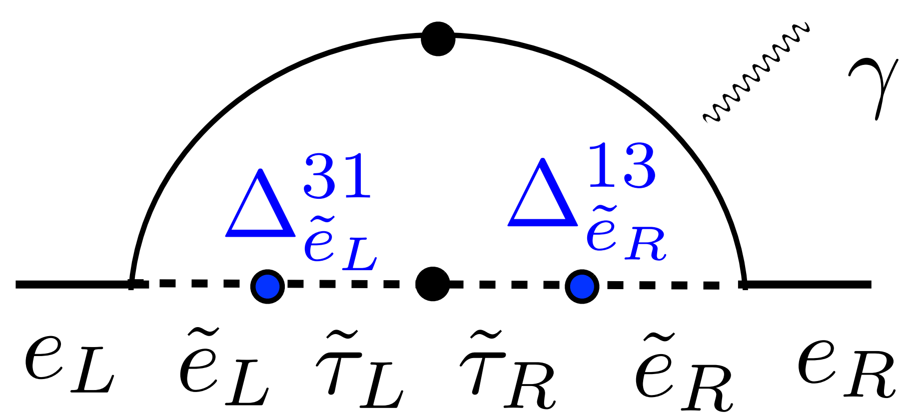
- GUT
- Flavor & CP problem
- Dark Matter
- Collider signatures
- Naturalness
- Muon g-2



LFVs



"flavor-blind EDM"



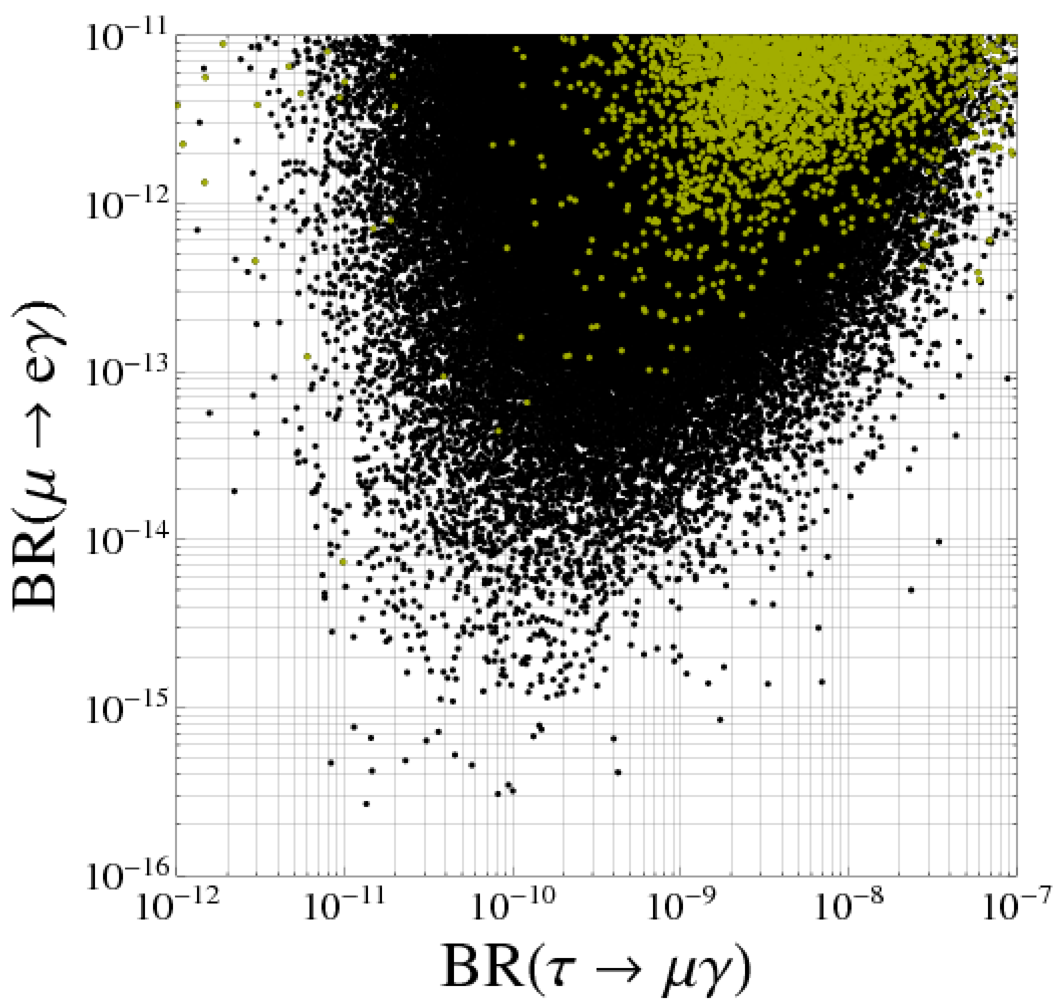
"flavored EDM"

LFV in SUSY flavor models

Lepton (& quark) flavor signals are discussed in some representative flavor models. [Altmannshofer, Buras, Gori, Paradisi, Straub '09]

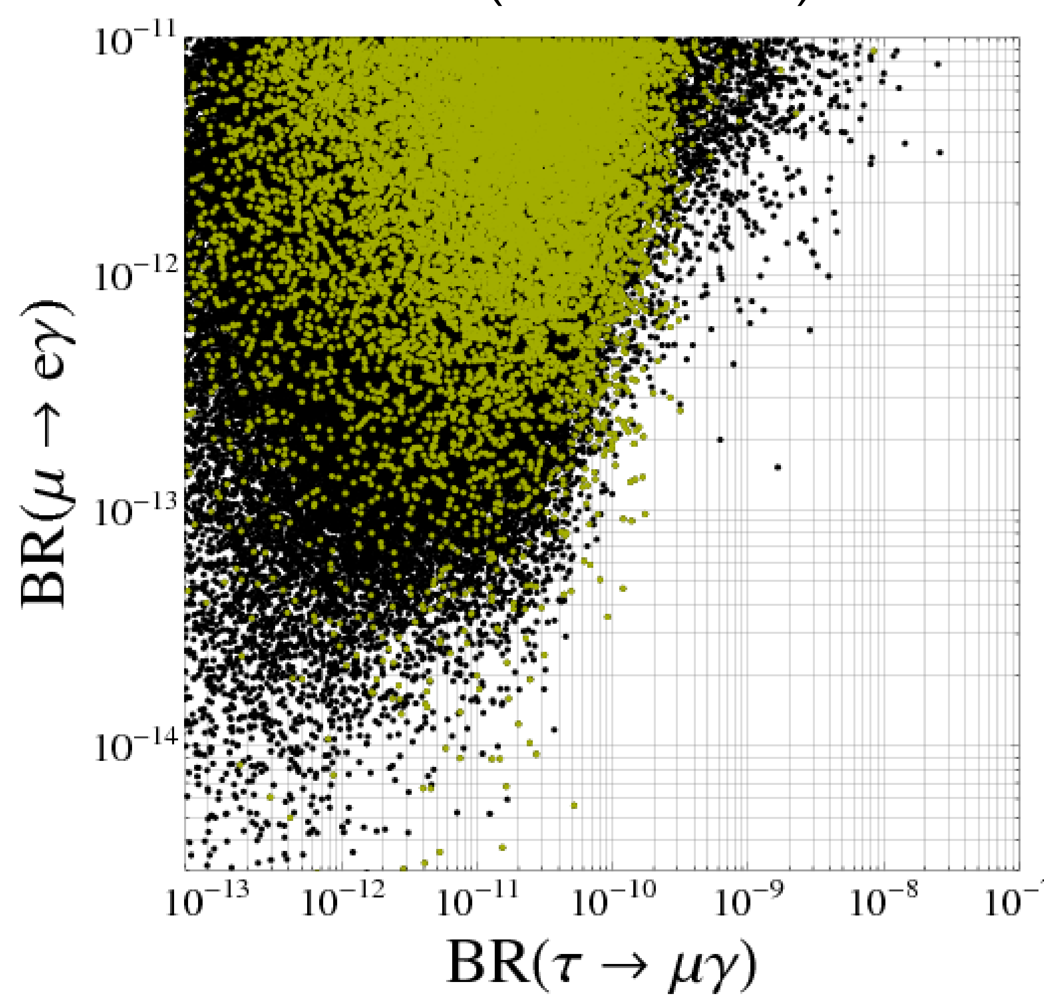
RVV2 model SU(3)
[Ross, Velasco-S, Vives]

$$\delta_e^{LL} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^2 \\ \lambda^3 & \cdot & \lambda \\ \lambda^2 & \lambda & \cdot \end{pmatrix} \quad \delta_e^{RR} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^2 \\ \lambda^3 & \cdot & \lambda \\ \lambda^2 & \lambda & \cdot \end{pmatrix}$$



AKM model SU(3)
[Antusch, King, Malinsky]

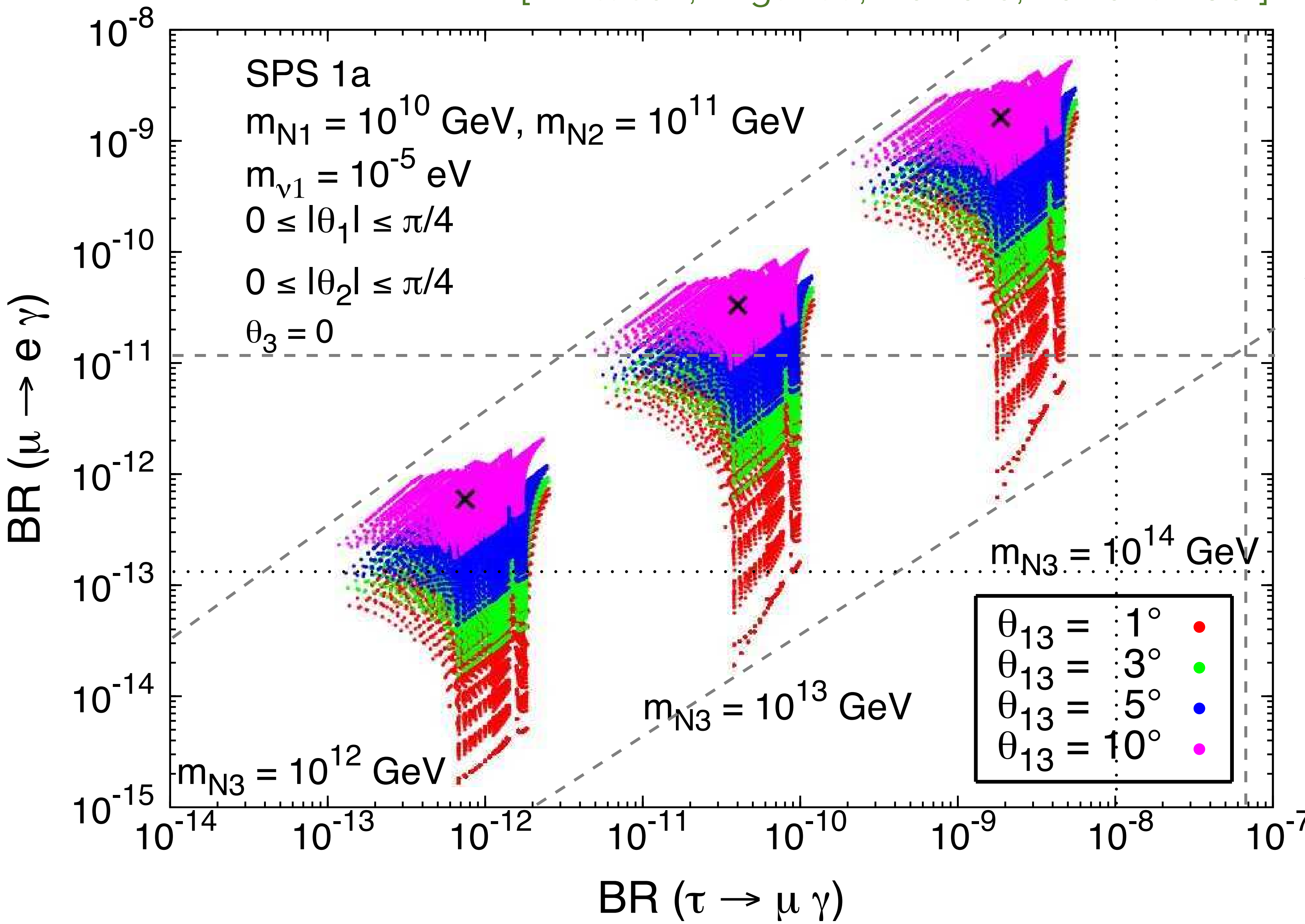
$$\delta_e^{LL} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & 0 \\ 0 & 0 & \cdot \end{pmatrix} \quad \delta_e^{RR} \sim \begin{pmatrix} \cdot & \lambda^4 & \lambda^4 \\ \lambda^4 & \cdot & \lambda^2 \\ \lambda^4 & \lambda^2 & \cdot \end{pmatrix}$$



$\Delta a_\mu > 10^{-9}$

LFV in SUSY models with RNs

[Antusch, Arganda, Herrero, Teixeira '06]



Slepton mixings are generated by neutrino Yukawa couplings

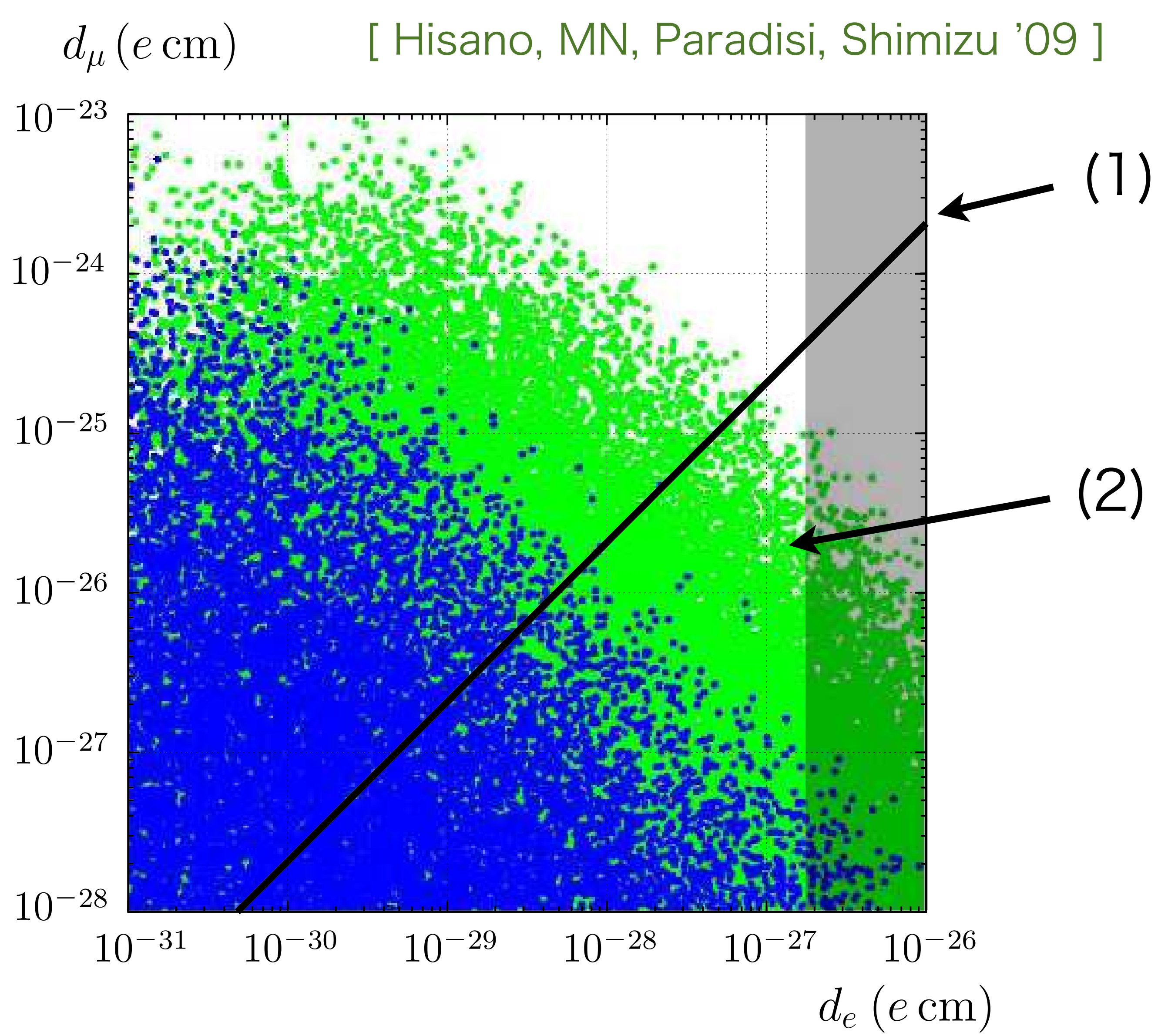
↑

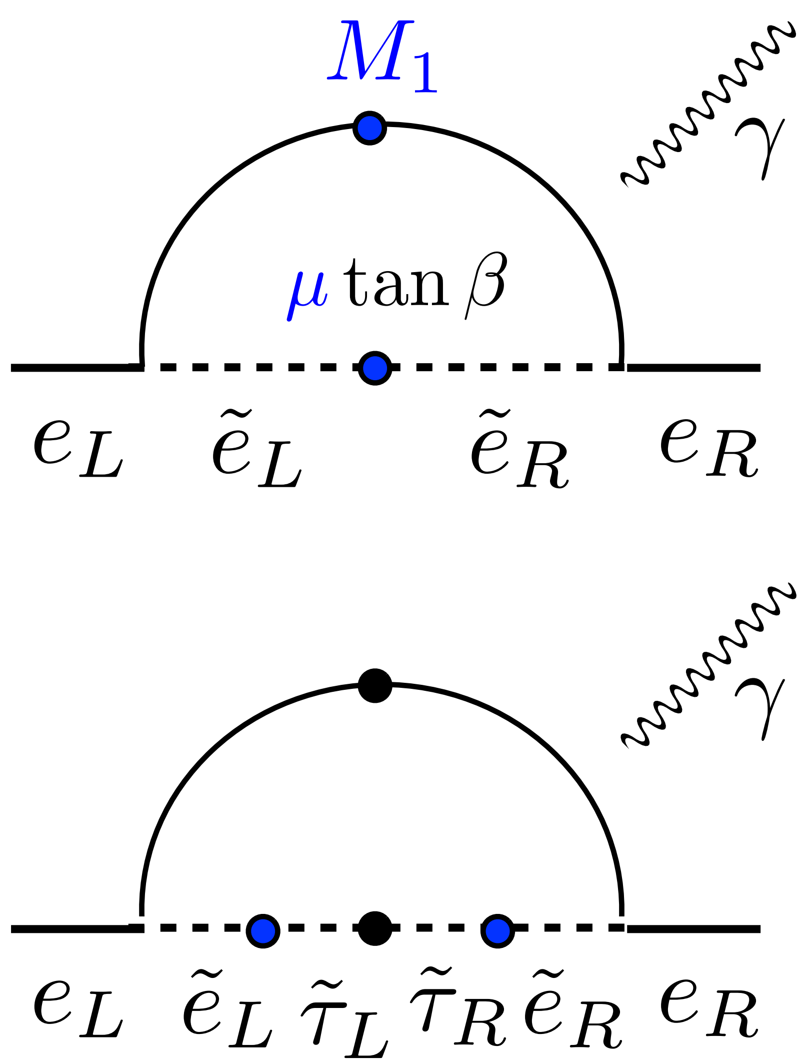
ν mass generation by see-saw mechanism

Correlation with leptonic EDMs

leptonic EDMs

CP violation comes from (1) gaugino masses and/or (2) slepton mixing terms





$\mathrm{Br}(\mu \to e\gamma) < 10^{-13}$

$\mathrm{Br}(\mu \to e\gamma) < 10^{-11}$

LFV, muon g-2 and eEDM

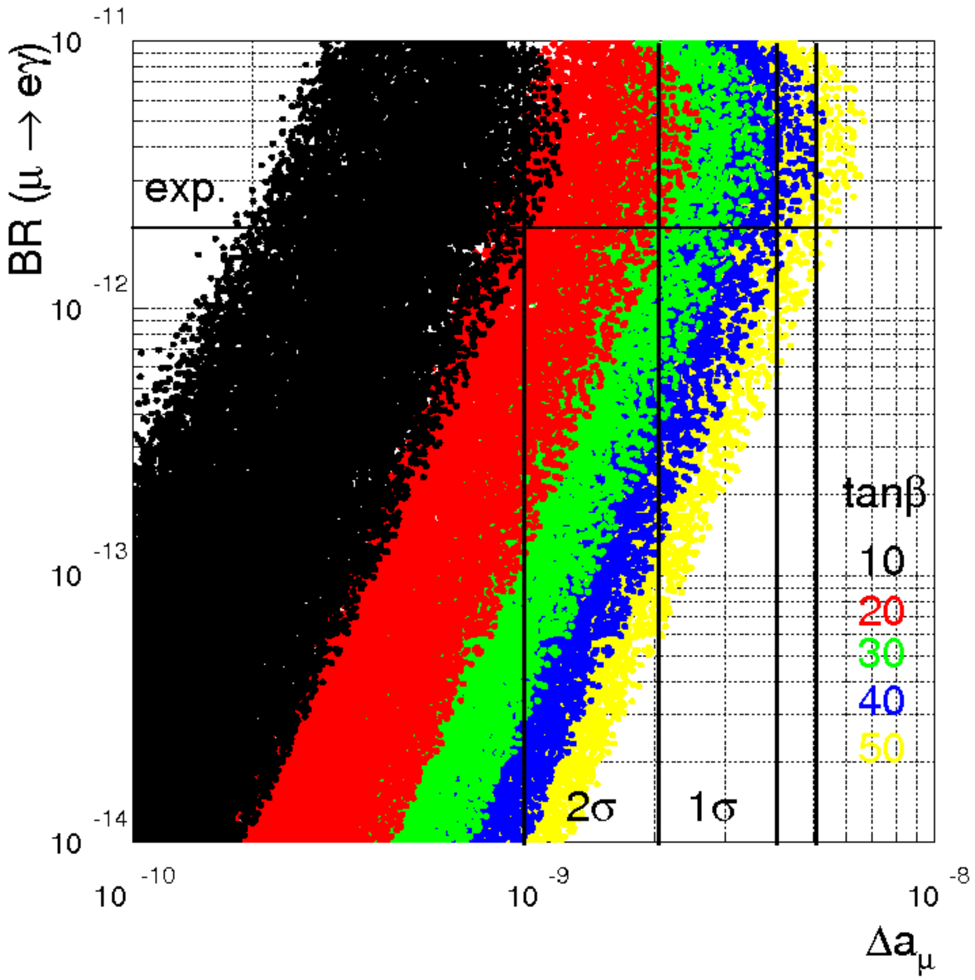
- Distorted A terms scenario [Giudice, Isidori, Paradisi '12]

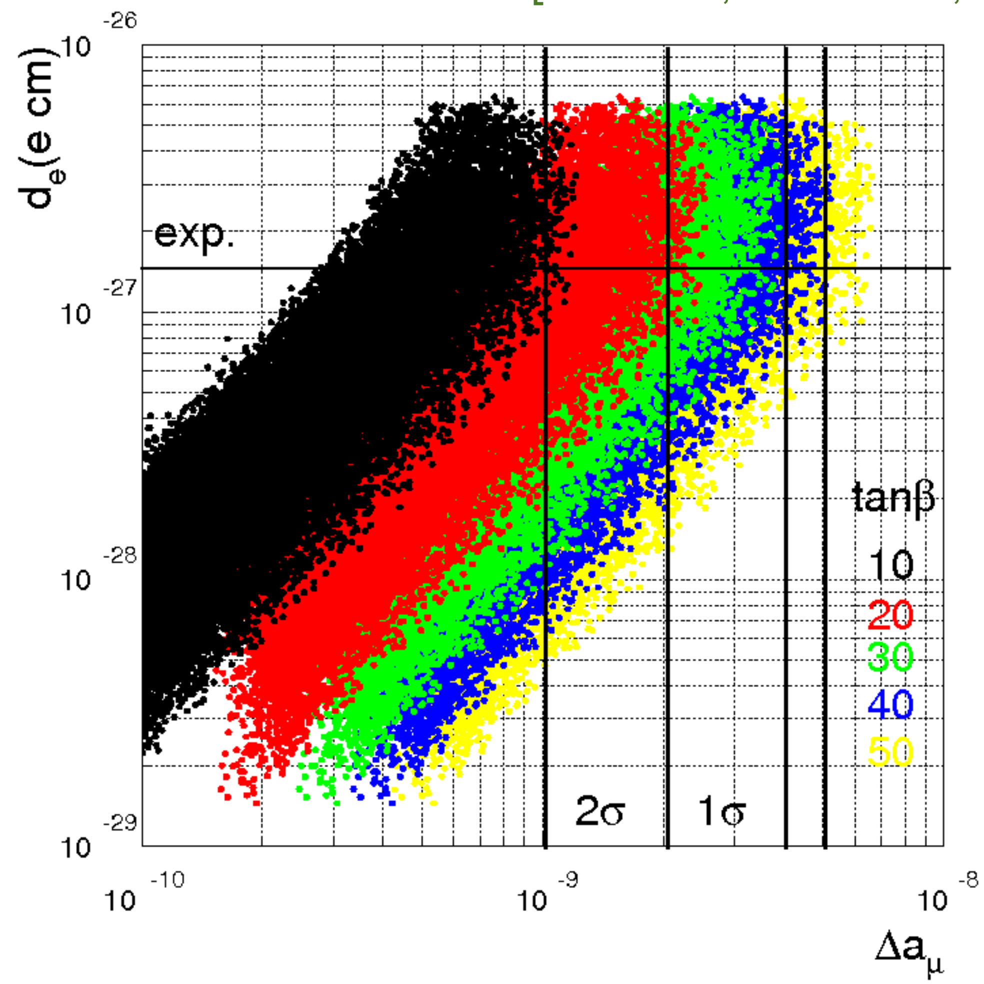
$$(\delta^f_{LR})_{ij} \sim \frac{A_f \theta_{ij} m_{f_j}}{m^2_{\tilde{f}}} \qquad f = u, d, e$$

Sources of flavor & CP violation

LFV, eEDM : U(1), no tanbeta
muon g-2 : SU(2), tanbeta enhancement

[Giudice, Paradisi, Passera '12]





$$\theta_{ij} = \sqrt{m_i/m_j}$$

LHC results pushed up SUSY scale!

- Non-observation of SUSY particles

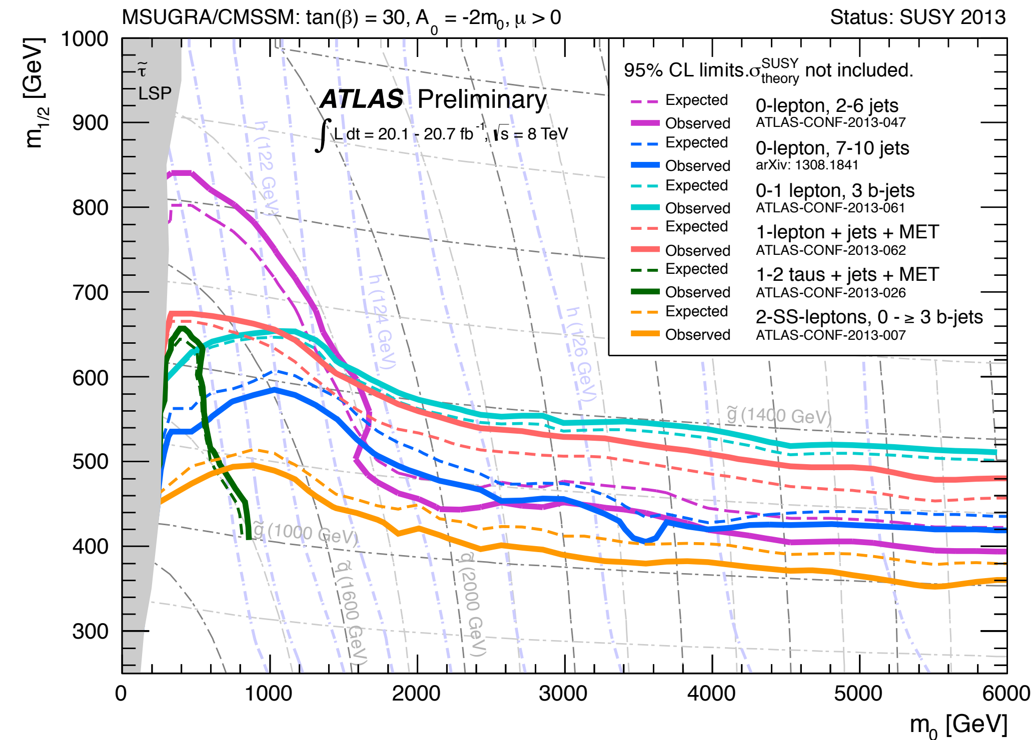
$$m_{\tilde{q}} \gtrsim 1.8\,\text{TeV} \quad M_{\tilde{g}} \gtrsim 1.4\,\text{TeV}$$

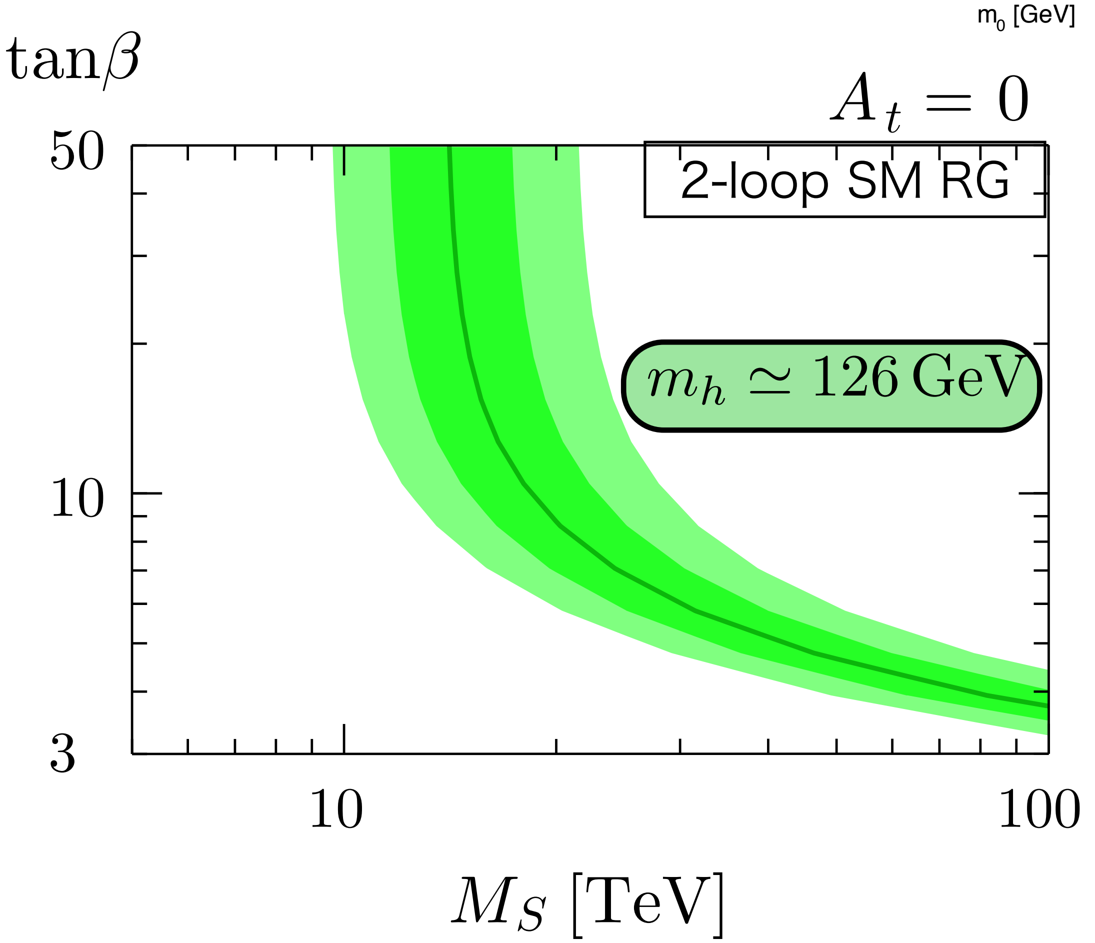
- Discovery of 126 GeV Higgs

<u>MSSM</u>

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

- Heavy stops (O(10-100)TeV)
- Large A term
- Vector-quarks, U(1)' ...
- NMSSM





High-scale SUSY models

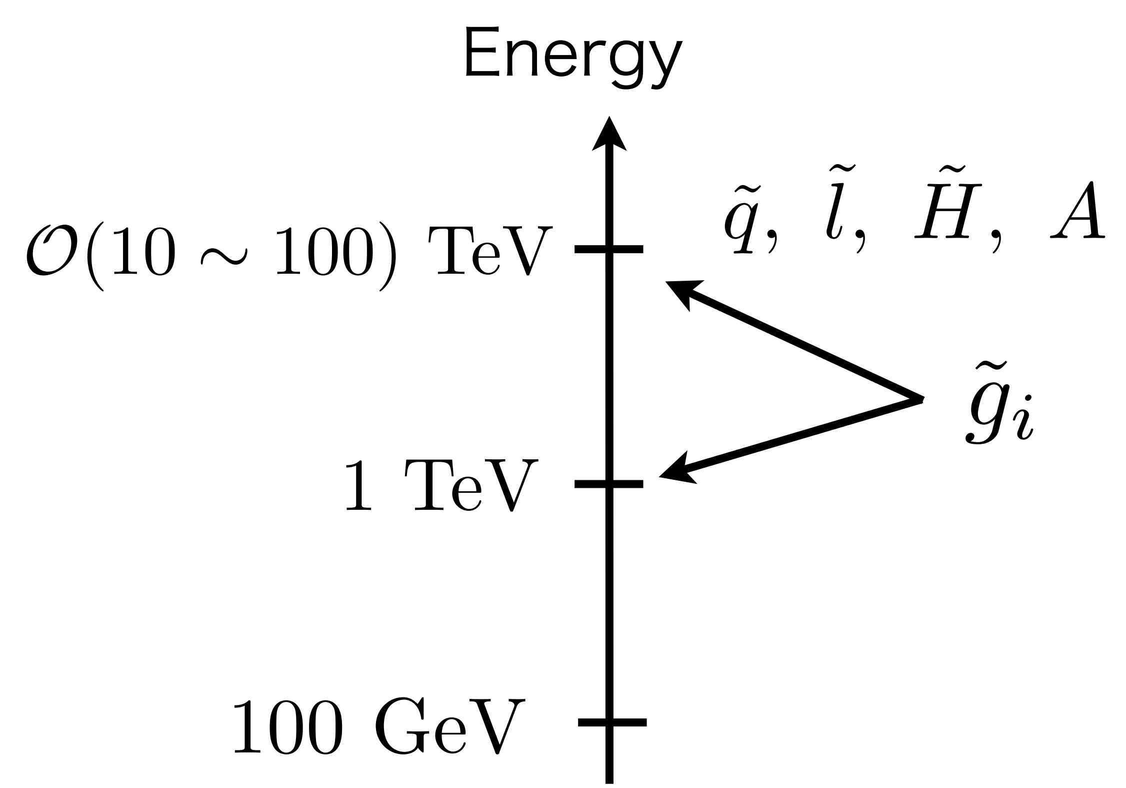
126 GeV Higgs boson + Null result of SUSY search

→ O(10-100)TeV sfermions

1) gaugino mass ~ sfermion mass — Heavy gaugino, mSUGRA

2) gaugino mass << sfermion mass — Anomaly-med

- GUT
- Flavor & CP problem
- Dark Matter
- Collider signatures
- Naturalness (0.1~0.001%) ?
- ~~Muon g-2~~



High-scale SUSY models

126 GeV Higgs boson + Null result of SUSY search

RA

Thanks to the automatic suppression by heavy masses, large flavor- and CP-violating parameters are allowed. In this situation, flavor observables are used to access such a high scale physics!

- GUT
- Flavor & CP ~~problem~~ probe
- Dark Matter
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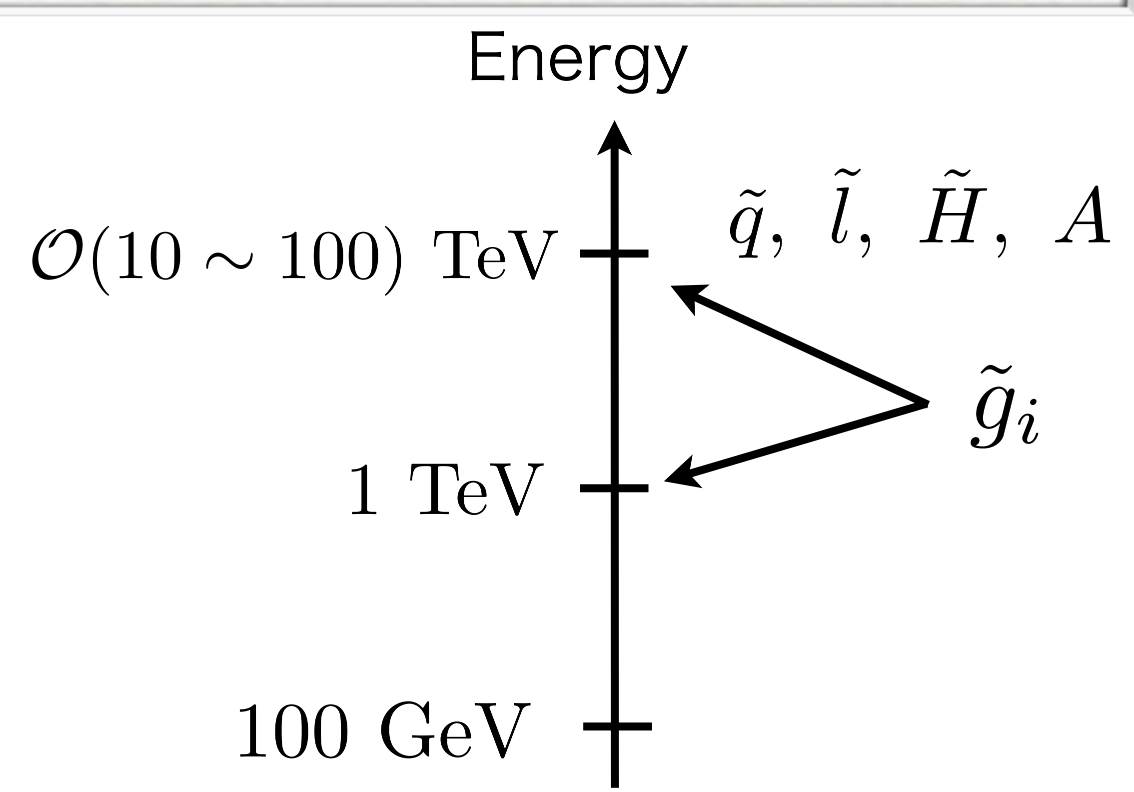

High-scale SUSY models

126 GeV Higgs boson + Null result of SUSY search

Thanks to the automatic suppression by heavy masses, large flavor- and CP-violating parameters are allowed. In this situation, flavor observables are used to access such a high scale physics!

- GUT
- Flavor & CP ~~problem~~ probe
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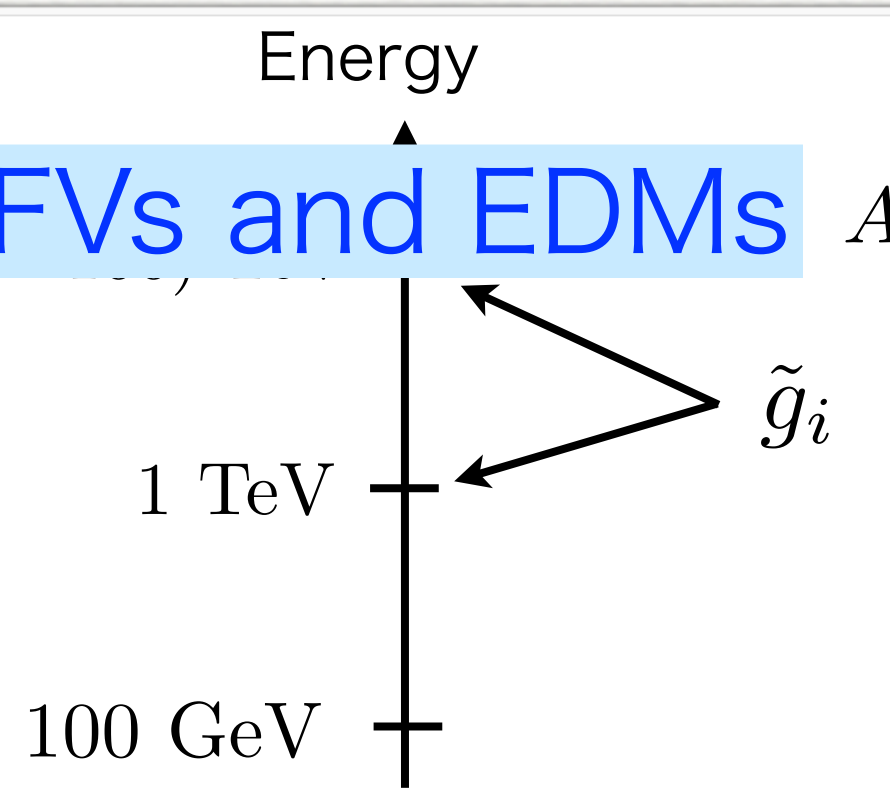
- ~~Muon g-2~~

ε_K, LFVs and EDMs



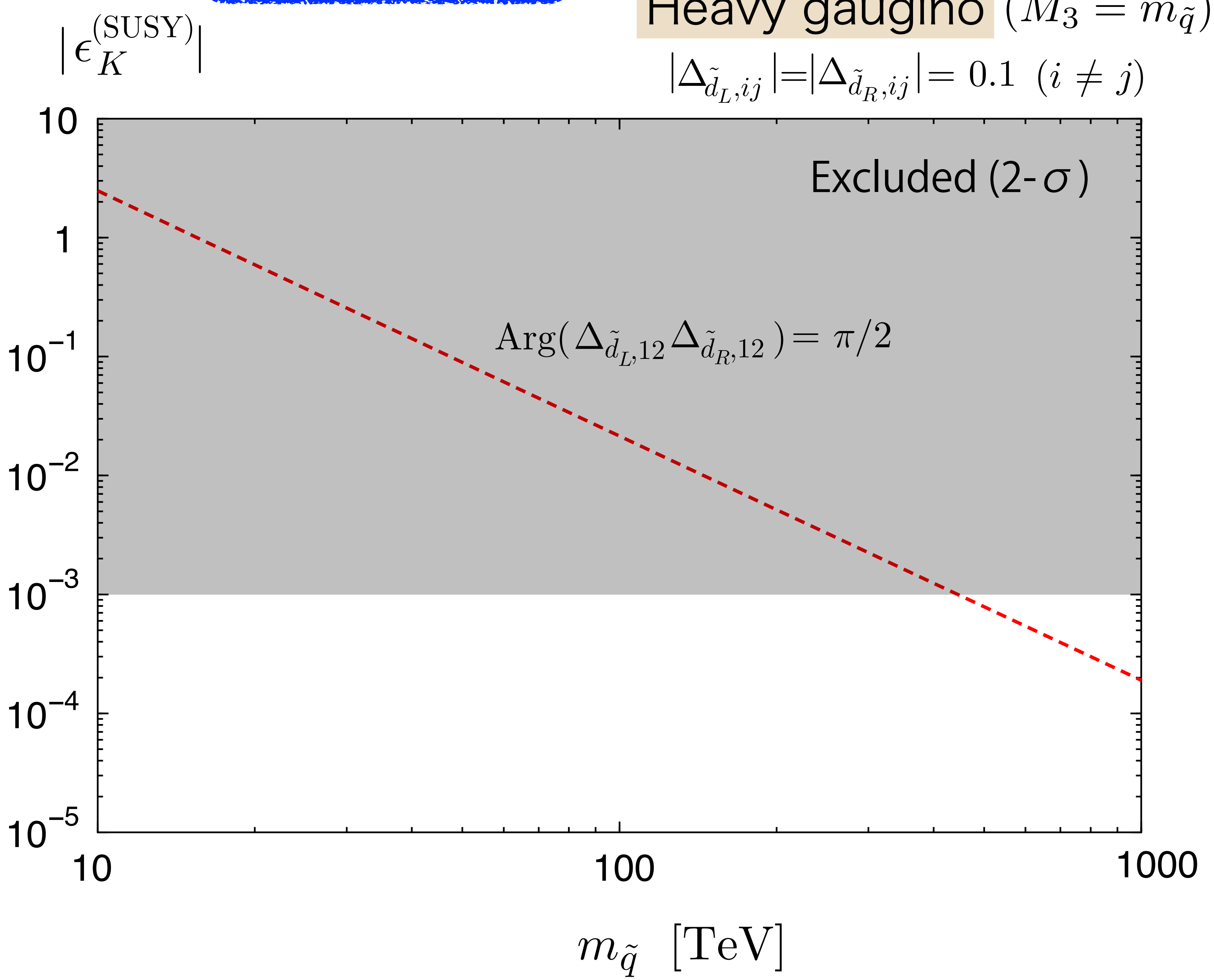
Kaon mixing parameter

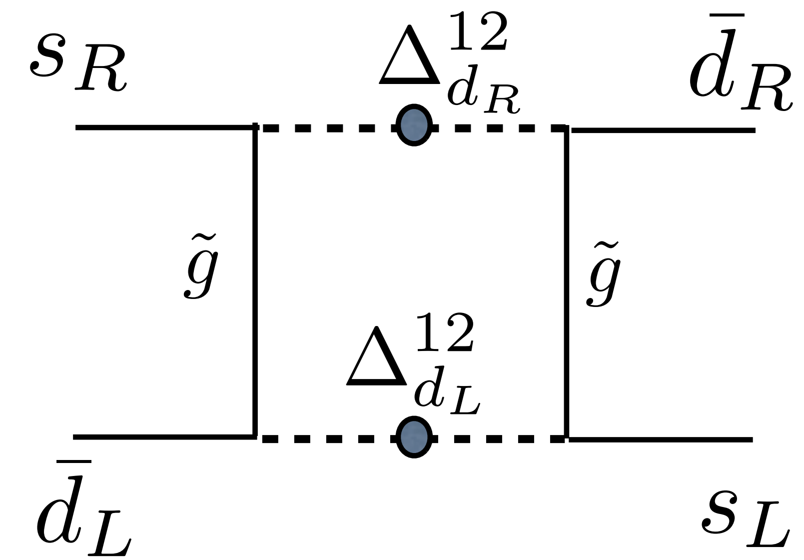
[Moroi and MN (2013)]

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

Heavy gaugino $(M_3 = m_{\tilde{q}})$

$|\Delta_{\tilde{d}_L,ij}| = |\Delta_{\tilde{d}_R,ij}| = 0.1 \quad (i \neq j)$





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

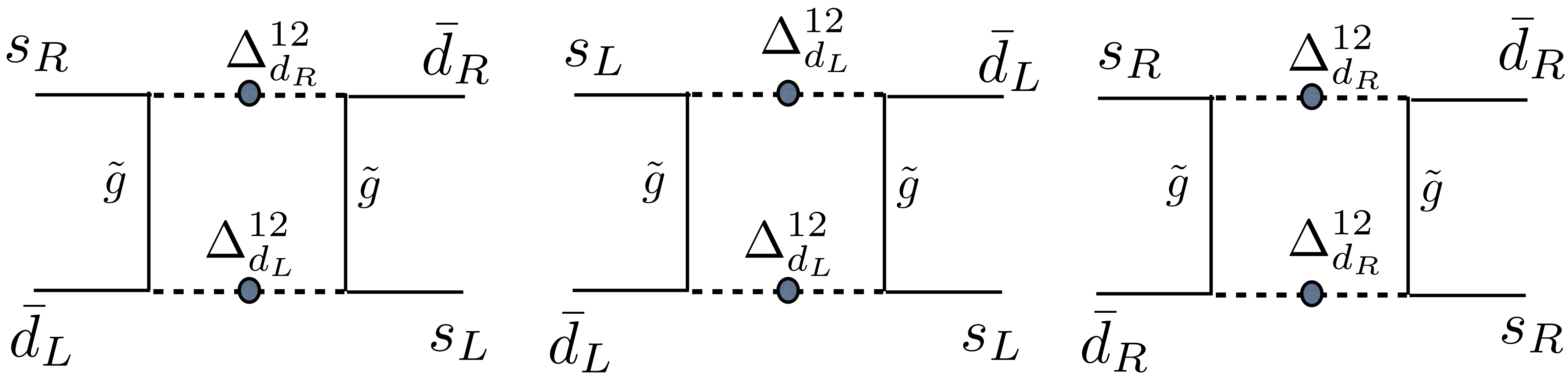
Suppressed If the phases are cancelled

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



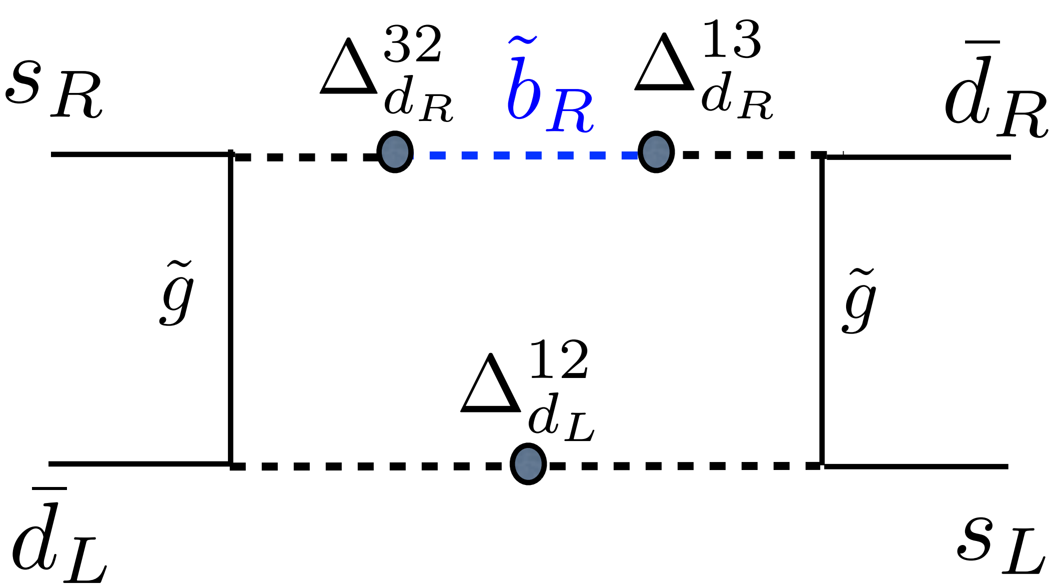
$${\rm Im}[\Delta^{12}_{d_R}\Delta^{12}_{d_L}] = 0 \qquad {\rm Im}[\Delta^{12}_{d_L}\Delta^{12}_{d_L}] = -{\rm Im}[\Delta^{12}_{d_R}\Delta^{12}_{d_R}]$$

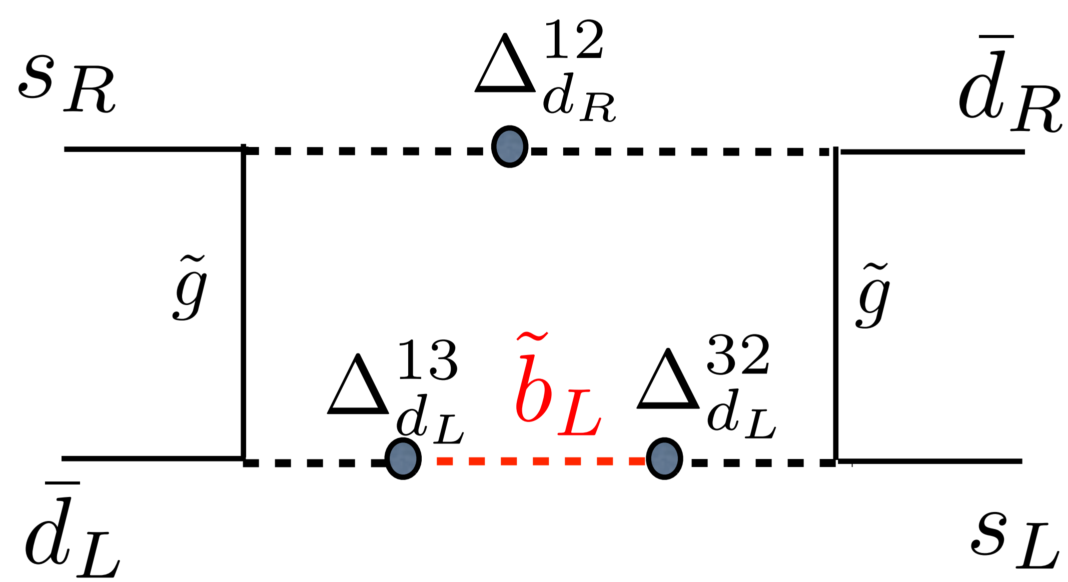
Breaking of C-inv. : EW & Yukawa interactions

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)





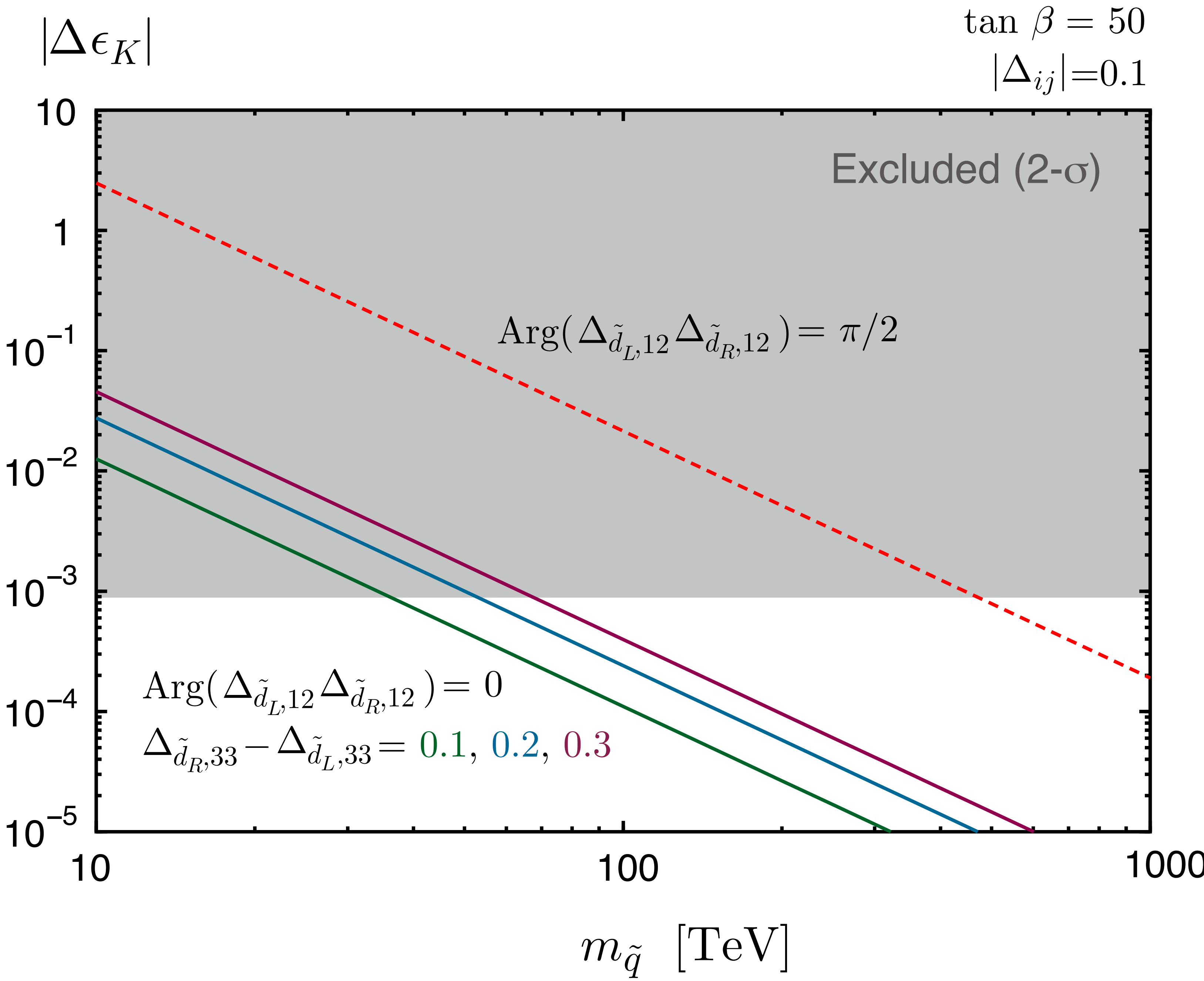
$$\epsilon_K^{SUSY} \sim \frac{\mathrm{Im}[\Delta^{13}_{d_R}\Delta^{32}_{d_R}\Delta^{12}_{d_L}]}{m^2_{SUSY}} \frac{m^2_{\tilde{b}_R} - m^2_{\tilde{b}_L}}{m^2_{SUSY}}$$

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

Kaon mixing parameter

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

Heavy gaugino



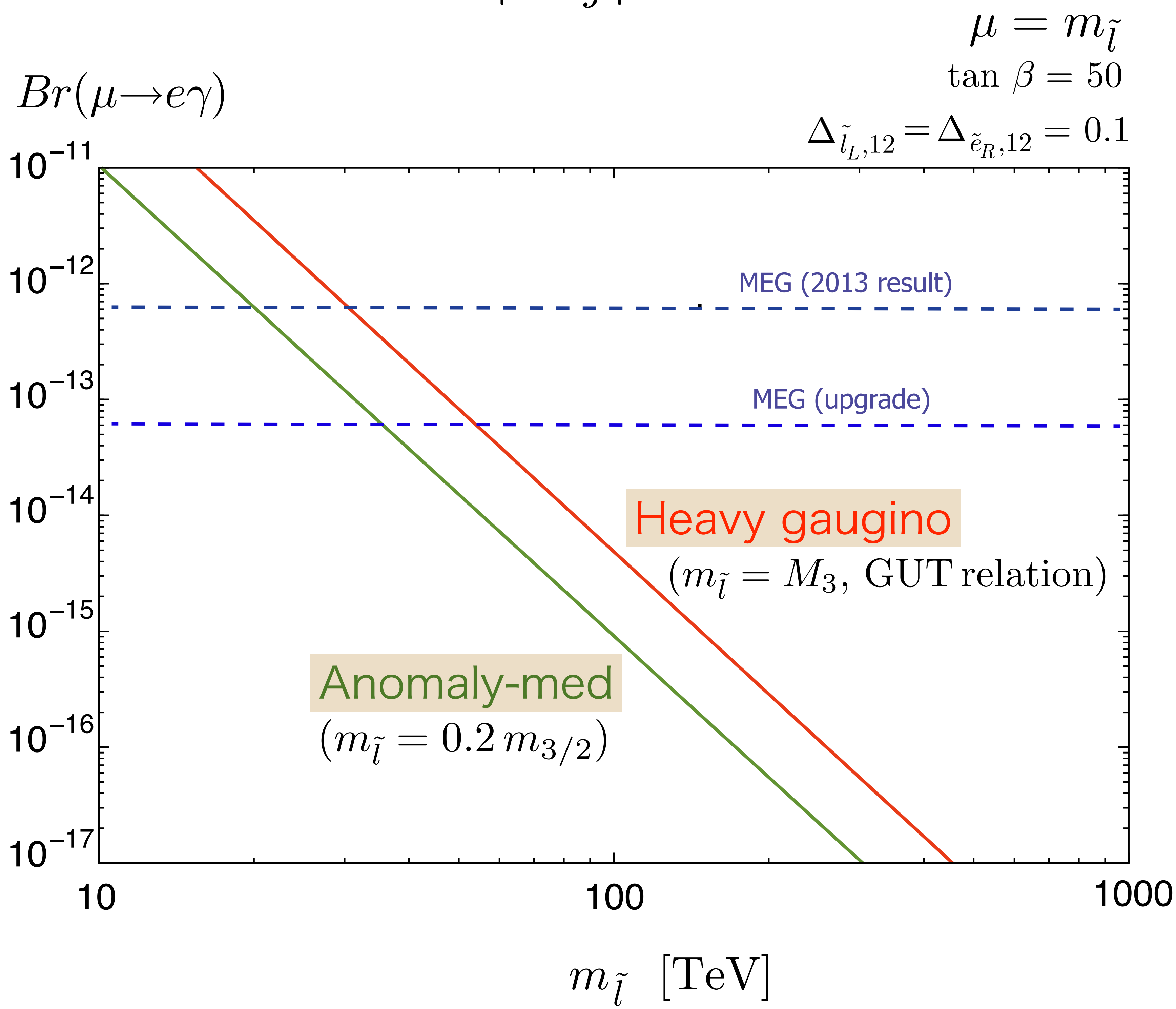
With SO(10) relation, $\epsilon_K^{\mathrm{SUSY}}$ is significantly reduced

$m_{\mathrm{SUSY}} > \mathcal{O}(10)$ TeV

Note,
$\Delta M_K,\ D^0\bar{D}^0$:$\sim$ 30TeV

LFV in High-scale SUSY models

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



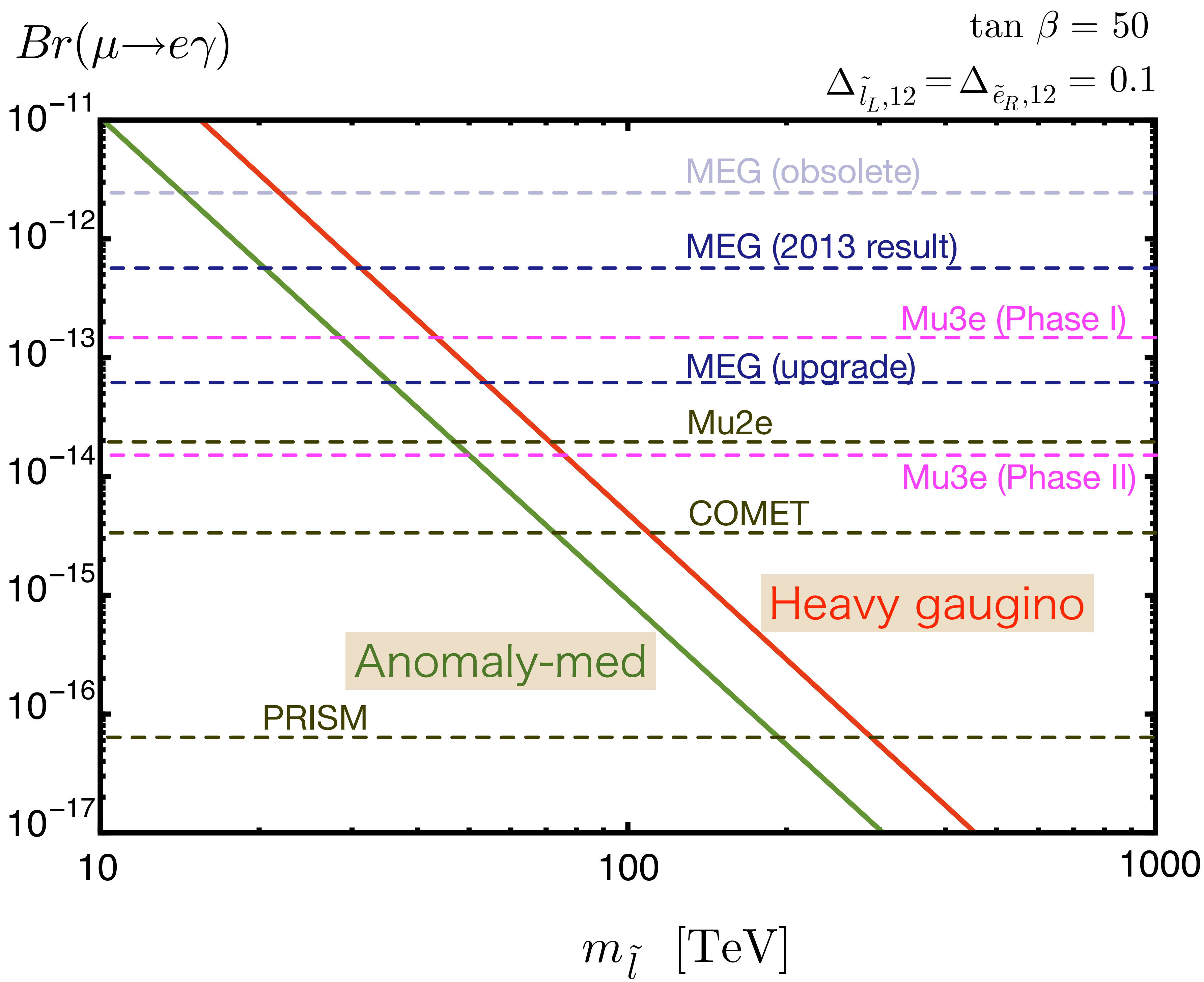
$$\mathrm{Br} \propto \frac{\Delta^2}{m_{\tilde{l}}^4} \left(\frac{M_2 \mu\ t_\beta}{m_{\tilde{l}}^2} \right)^2$$

14年7月30日水曜日

LFV in High-scale SUSY models

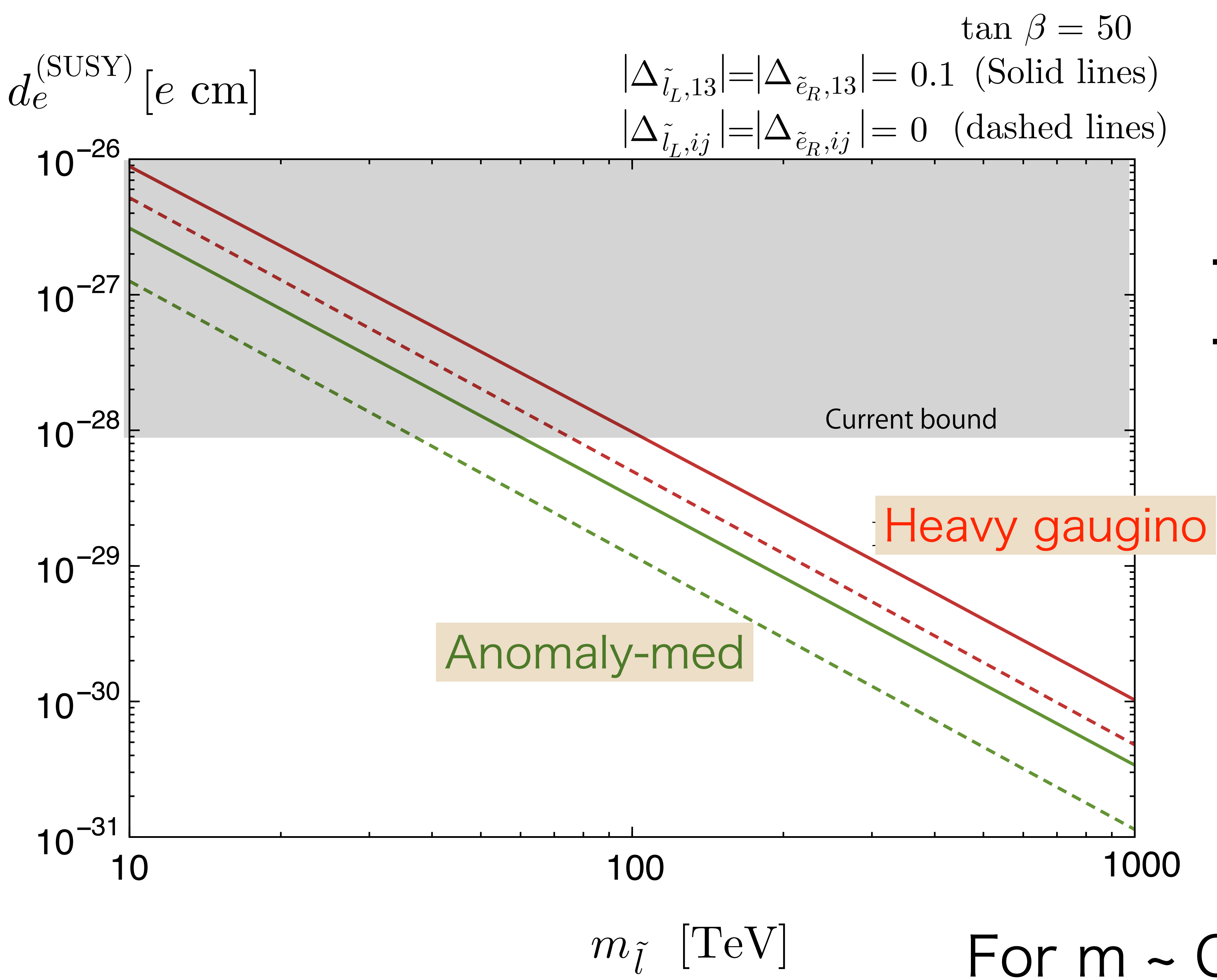
In SUSY models, there is strong correlations btw Br($\mu \to e\ \gamma$), Br($\mu \to eee$) and $R_{\mu e}$

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



—— : flavored EDM

- - - - : flavor-blind EDM

With Δ~O(1), flavored EDMs are much important because of the large enhancement by m_τ/m_e.

$$d_e \propto \frac{\Delta^2}{m_{\tilde{l}}^2} \frac{M_1 \mu}{m_{\tilde{l}}^2} t_\beta$$

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

ACME collaboration (2013)

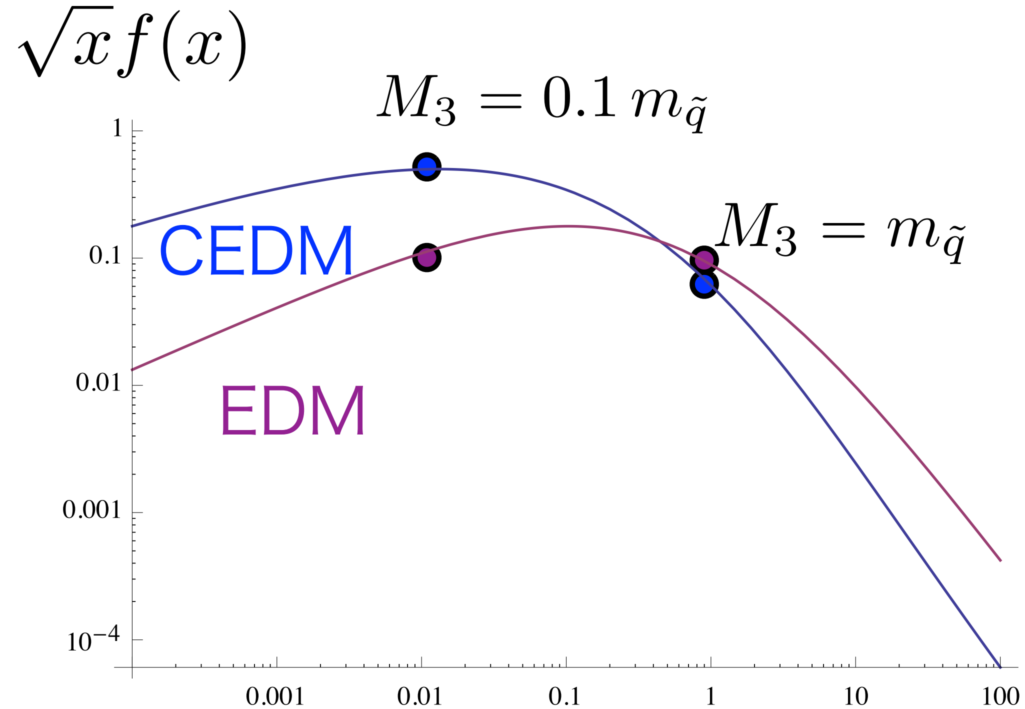
For m ~ O(10) TeV, we need some mechanism to suppress the CP phases .

Quark (C)EDMs

$$d_q^c \simeq \frac{\alpha_s}{4\pi}\frac{m_{q_3}}{m_{\tilde{q}}^2}\frac{M_3 X_q}{m_{\tilde{q}}^2}\mathrm{Im}[\Delta_{13}^R \Delta_{31}^L]\, f(M_3^2/m_{\tilde{q}}^2)$$

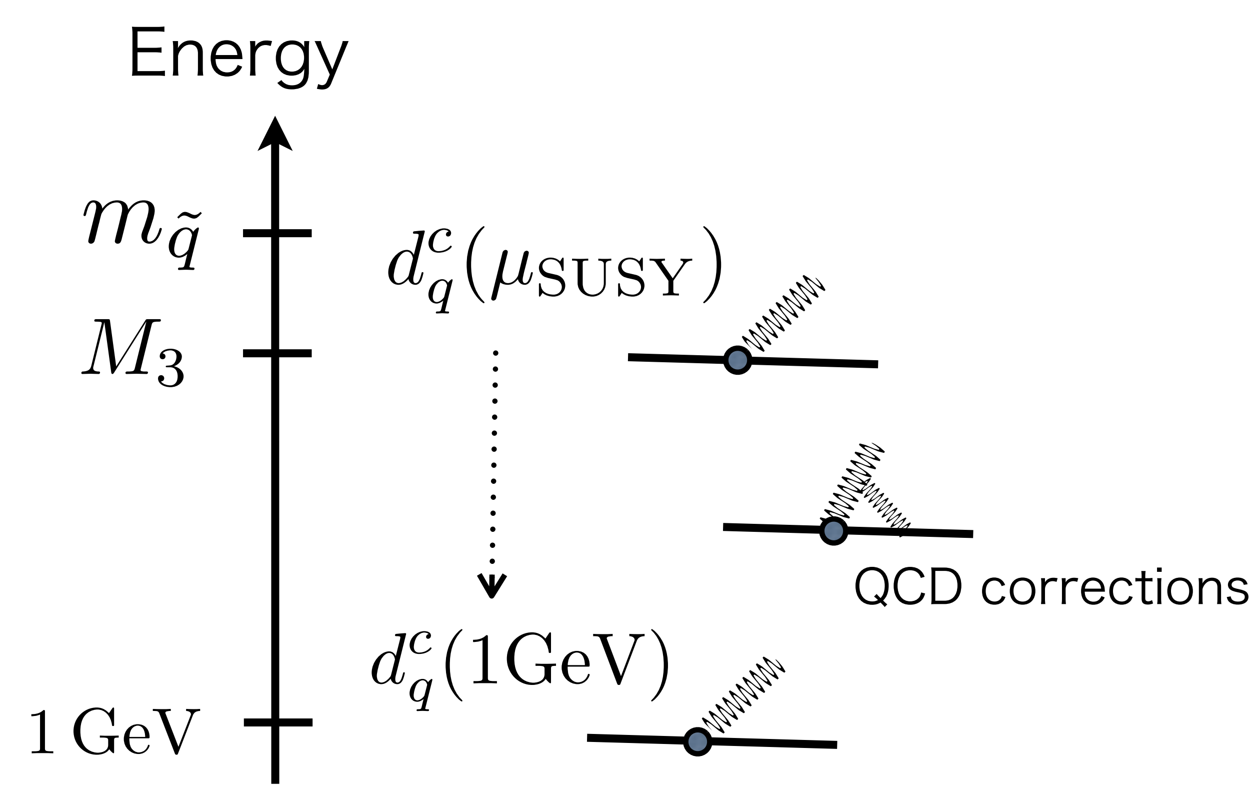
$$f(x) \sim 3\log x + \frac{59}{6} \quad (x \ll 1)$$

not suppressed so much even
for lighter gauginos



Matching scale μ_{SUSY}?

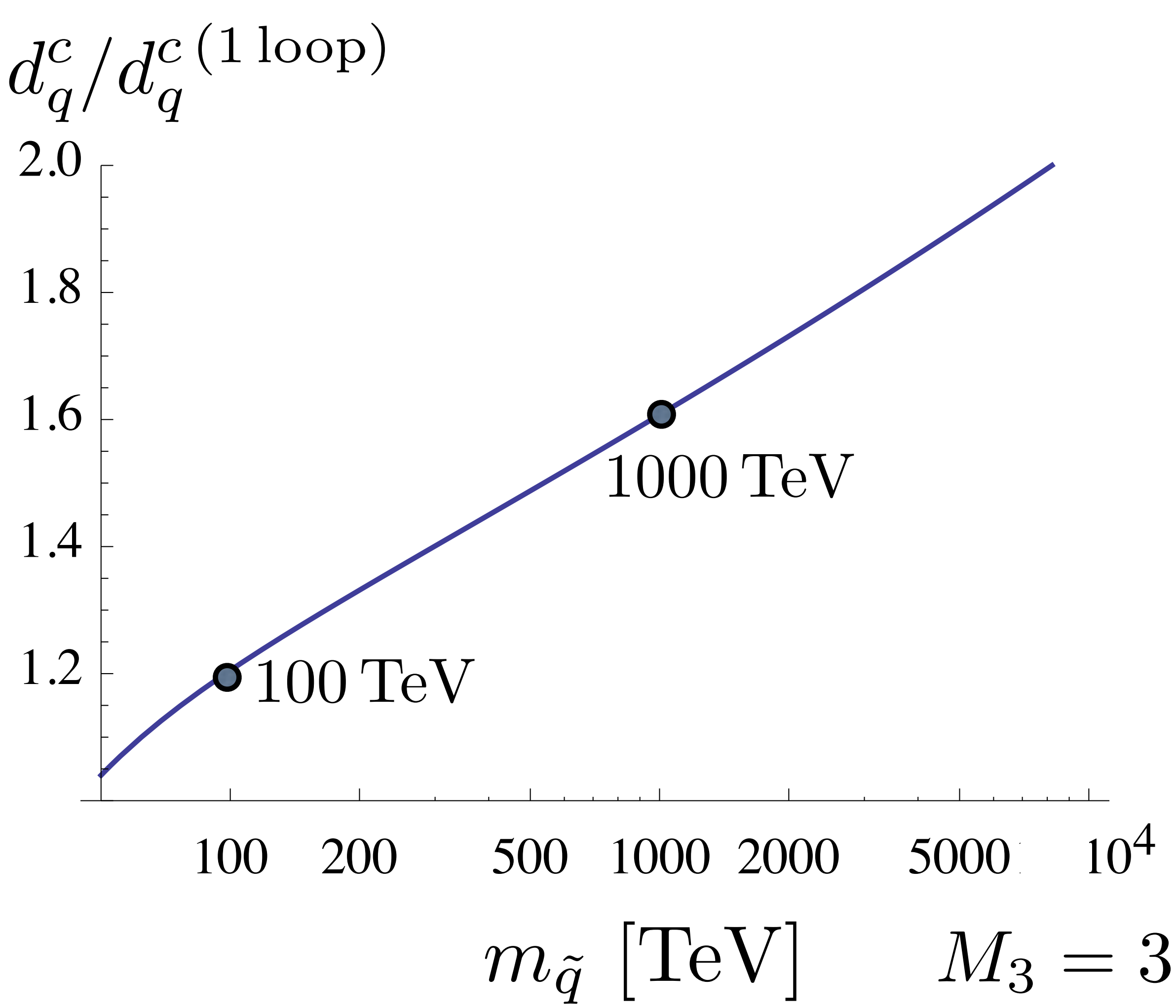
$$\alpha_s(100\mathrm{TeV})/\alpha_s(3\mathrm{TeV}) \sim 0.82$$
$$M_3(100\mathrm{TeV})/M_3(3\mathrm{TeV}) \sim 0.69$$
$$m_q(100\mathrm{TeV})/m_q(3\mathrm{TeV}) \sim 0.85$$



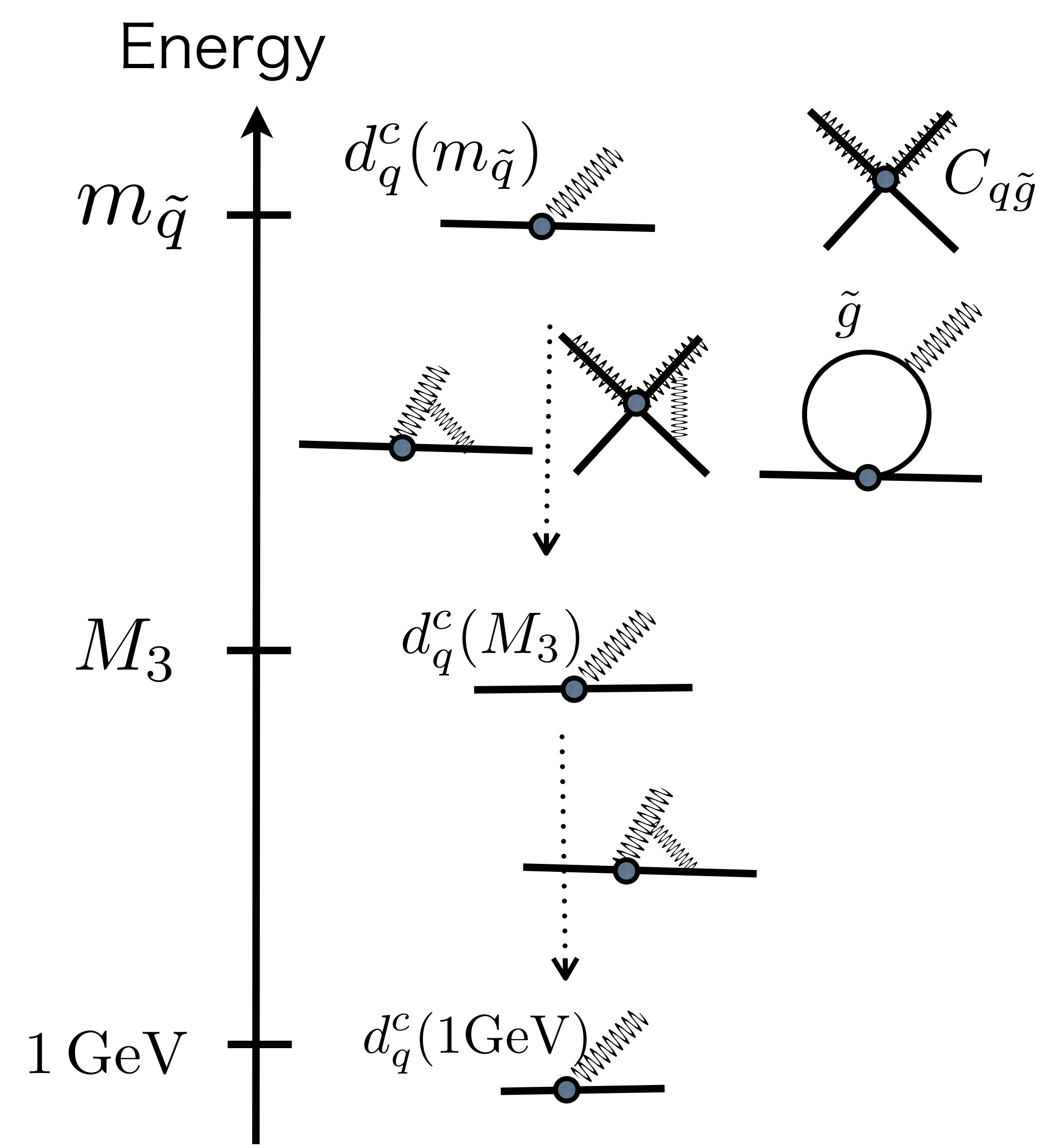
QCD corrections to Quark (C)EDMs in high scale SUSY models

Altmannshofer, Harnik, Zupan (2013), Fuyuto, Hisano, Nagata, Tsumura (2013)

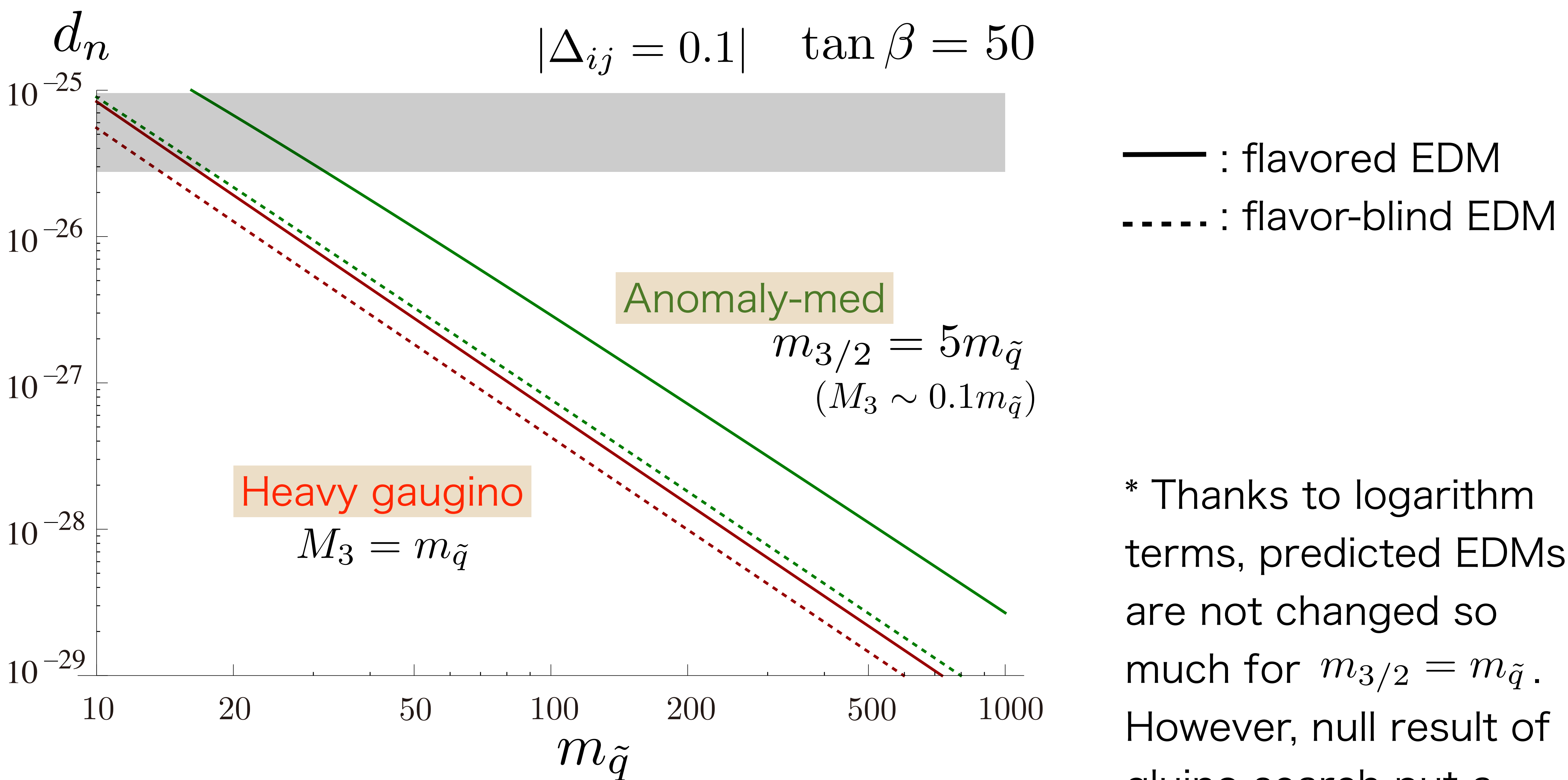
For $M_3 \ll m_{\tilde{q}}$, we need RG analysis to resum large logarithms.



$M_3 = 3\,\mathrm{TeV}$

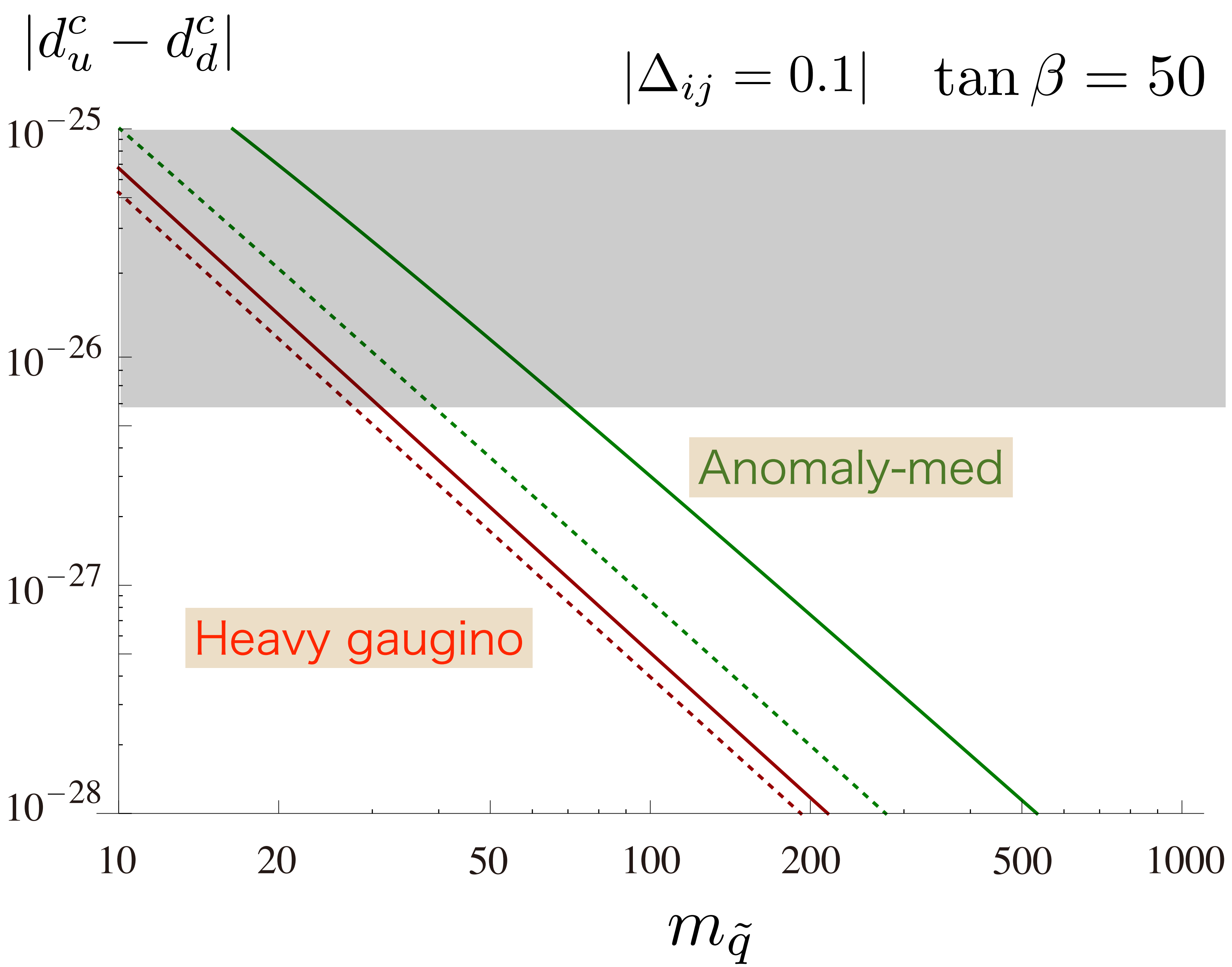


nEDM in high scale SUSY models



* Thanks to logarithm terms, predicted EDMs are not changed so much for $m_{3/2} = m_{\tilde{q}}$. However, null result of gluino search put a bound, $m_{\tilde{q}} > 40\,\mathrm{TeV}$, in that case.

HgEDM in high scale SUSY models



——— : flavored EDM

- - - - : flavor-blind EDM

$|d_u^c - d_d^c| \lesssim 6 \times 10^{-27}$

from mercury EDM

Hadronic EDMs are enhanced for lighter gluino

LFV in high-scale SUSY models with universal soft masses

[Moroi, MN, Ynagida (2013)]

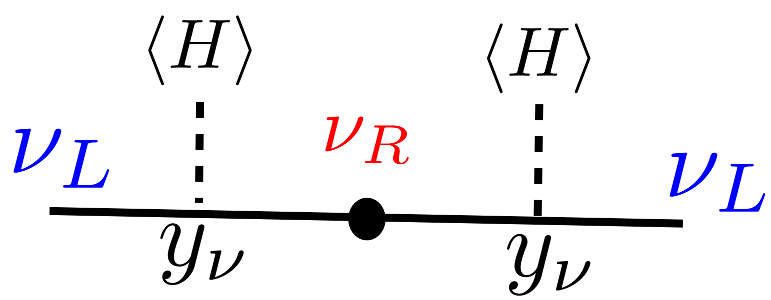
- Even with m ~ O(10-100) TeV, epsilonK and EDMs puts severe constraints on flavor- and CP-violating parameters.
- Sfermion mass matrices may have some universal (degenerate) structures at the tree-level to ameliorate these constraints even in high-scale SUSY models.

Can we expect some flavor signals?

- Yes, flavor-mixing might be generated by radiative corrections.

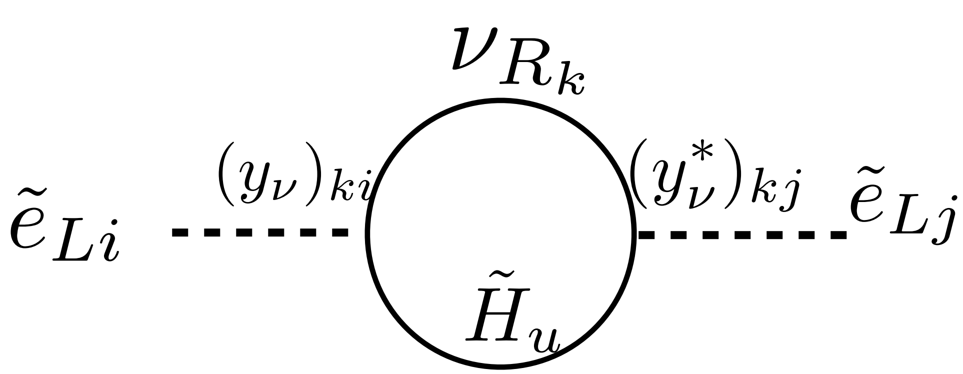
Type-I SUSY see-saw model

Type-I See-saw model ... Introduction of heavy right-handed neutrinos (RNs)



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

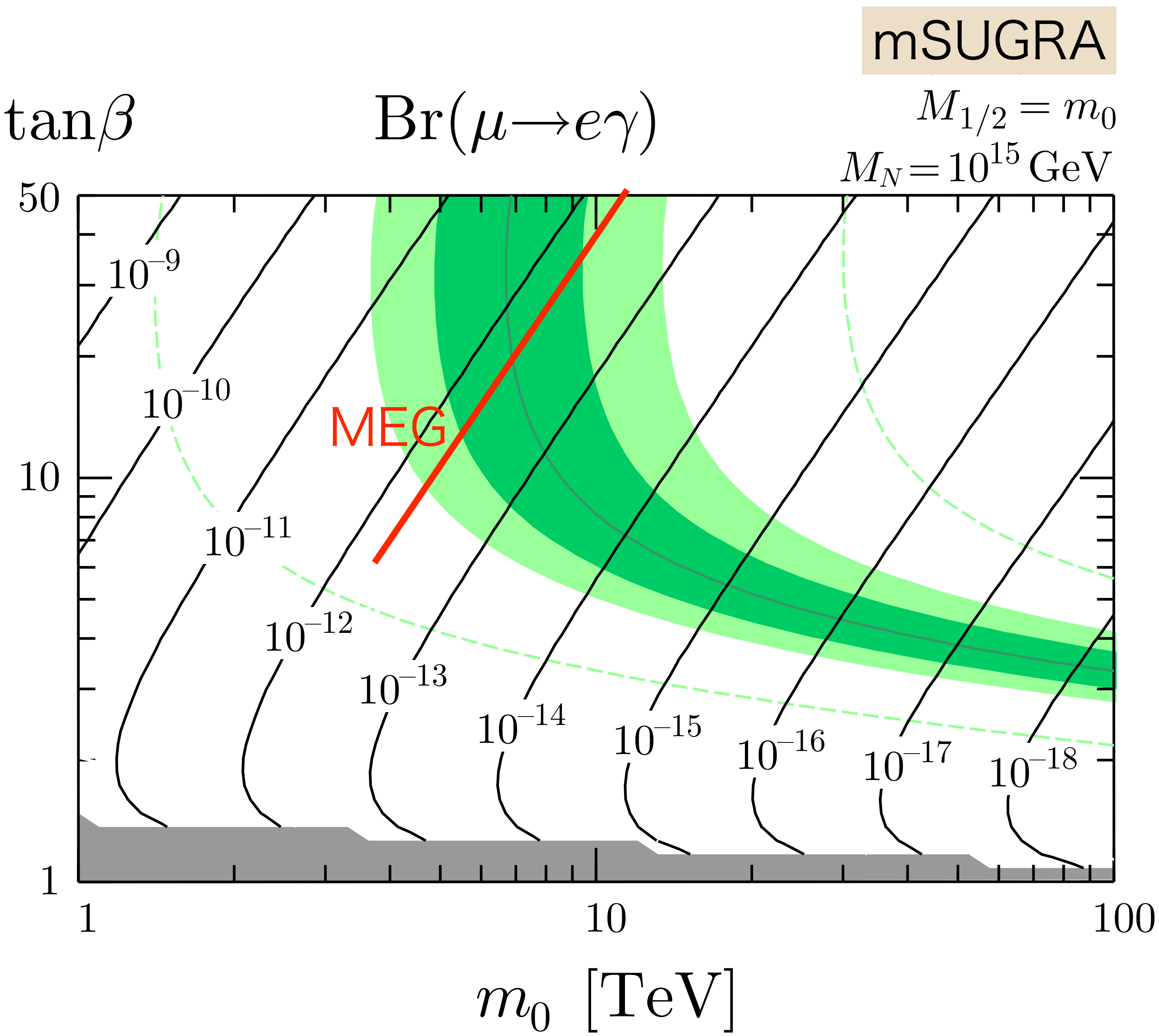
For $y_\nu \sim 1, \ M_N \sim 10^{15}\text{GeV}$



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

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

LFV in high scale SUSY models (universal)



$m_0,\ M_{1/2},\ \tan\beta,\ M_N(\text{or } y_\nu)$

$y_\nu \to \Delta_{\tilde{e}_L}$

Flavored EDMs and epsilonK constraints are absent

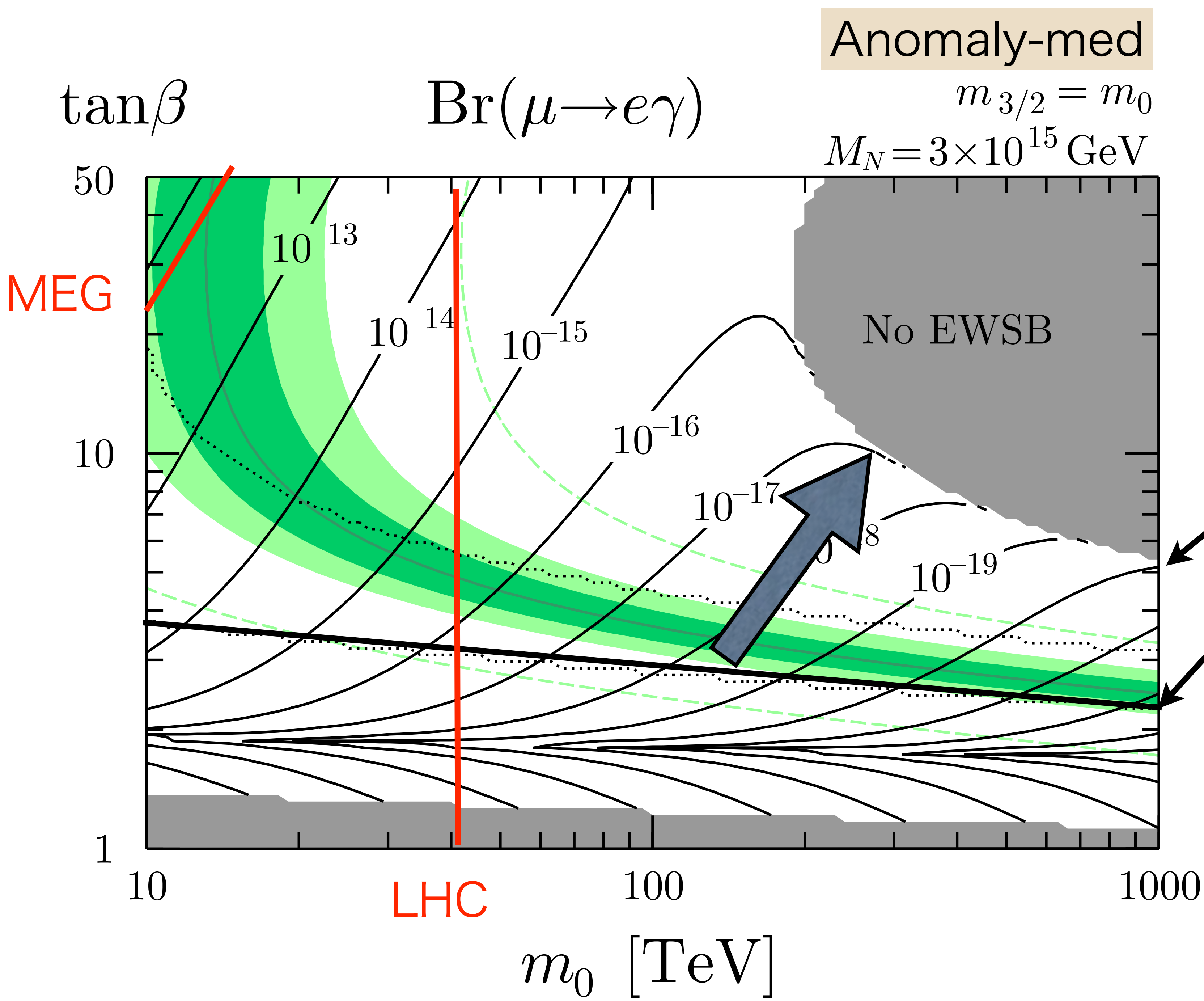
$m_h \simeq 126\,\mathrm{GeV}$

$M_N \sim 10^{15}\mathrm{GeV} \quad (y_\nu \sim 1)$

→ 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

$$y_\nu \nearrow \;\Rightarrow\; m_{H_u}^2 \searrow$$

$M_N = 3 \times 10^{15}$ GeV

$M_N = 10^{11}$ GeV

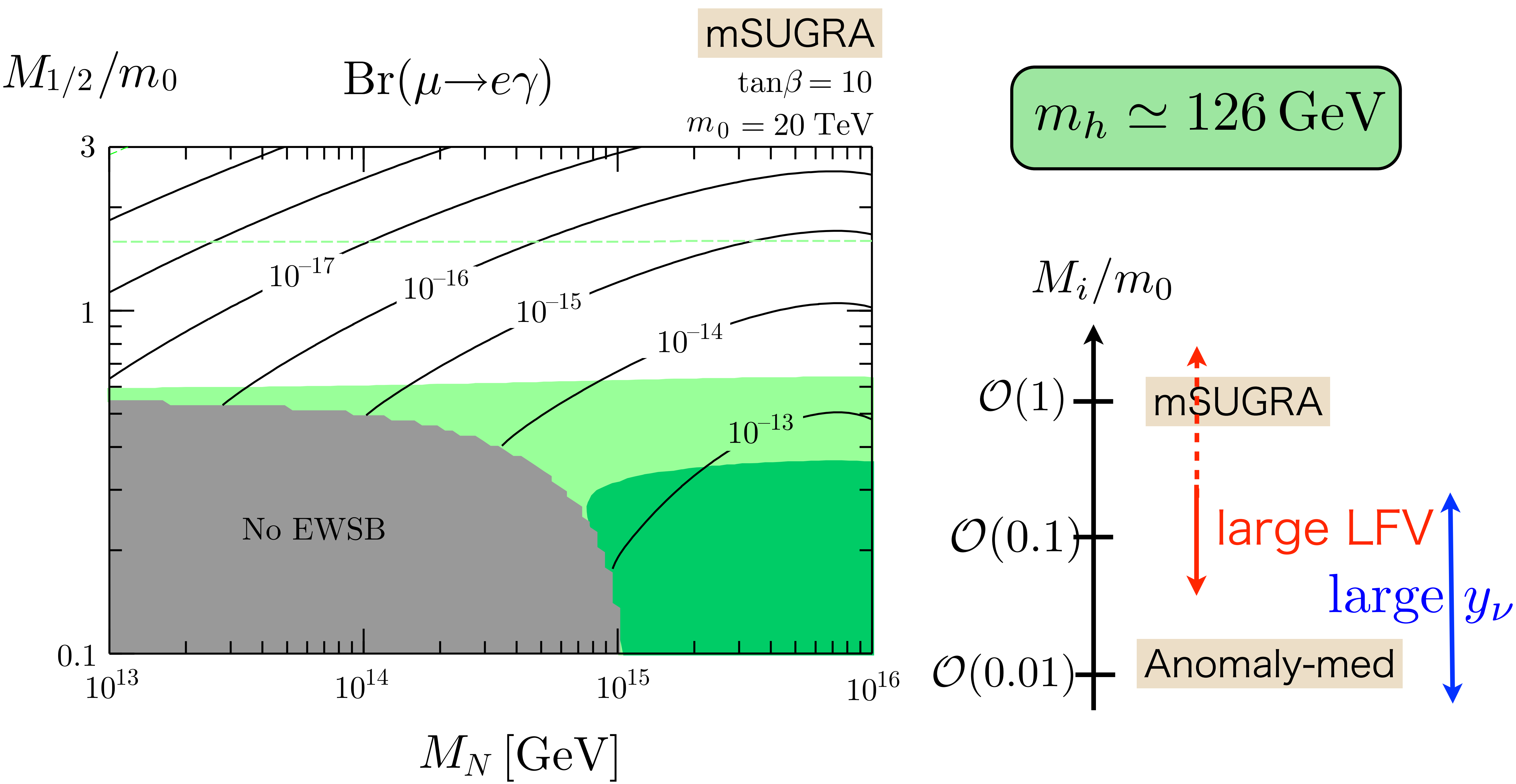
gluino mass bound: $m_{3/2} > 40$ TeV

challenging to detect LFV signals

loophole: small κ_{ij} ?

LFV in high scale SUSY models (universal)

- With lighter gaugino masse, a large neutrino Yukawa coupling is required, as long as universal soft masses are assumed.



まとめ

✓ フレーバーの物理による新物理探索のためには、標準模型の予言と実験結果の精密な比較検証が必要。

- 複数の観測量を考慮することにより現れる、新物理への示唆
- 残っているアノマリー(?)の現状

✓ フレーバー観測量はLHC実験では直接探索できない高いエネルギースケールの物理を探ることが可能。

- LFV & EDM による高エネルギー(10-100 TeV) 超対称模型の探索

宣伝

- KEK Theory Meeting on Particle Physics Phenomenology (KEK-PH 2014)

  10/21-10/24

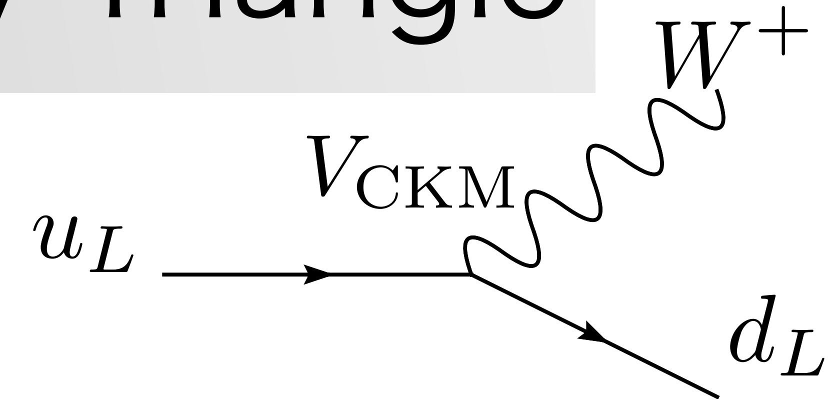
- KEK Flavor Factory Workshop (KEK-FF2014FALL)/ Belle II Theory Interface Platform (B2TiP) Meeting

  10/28-10/31

  http://kds.kek.jp/conferenceDisplay.py?confId=15873

Back Up

CKM matrix and Unitarity Triangle



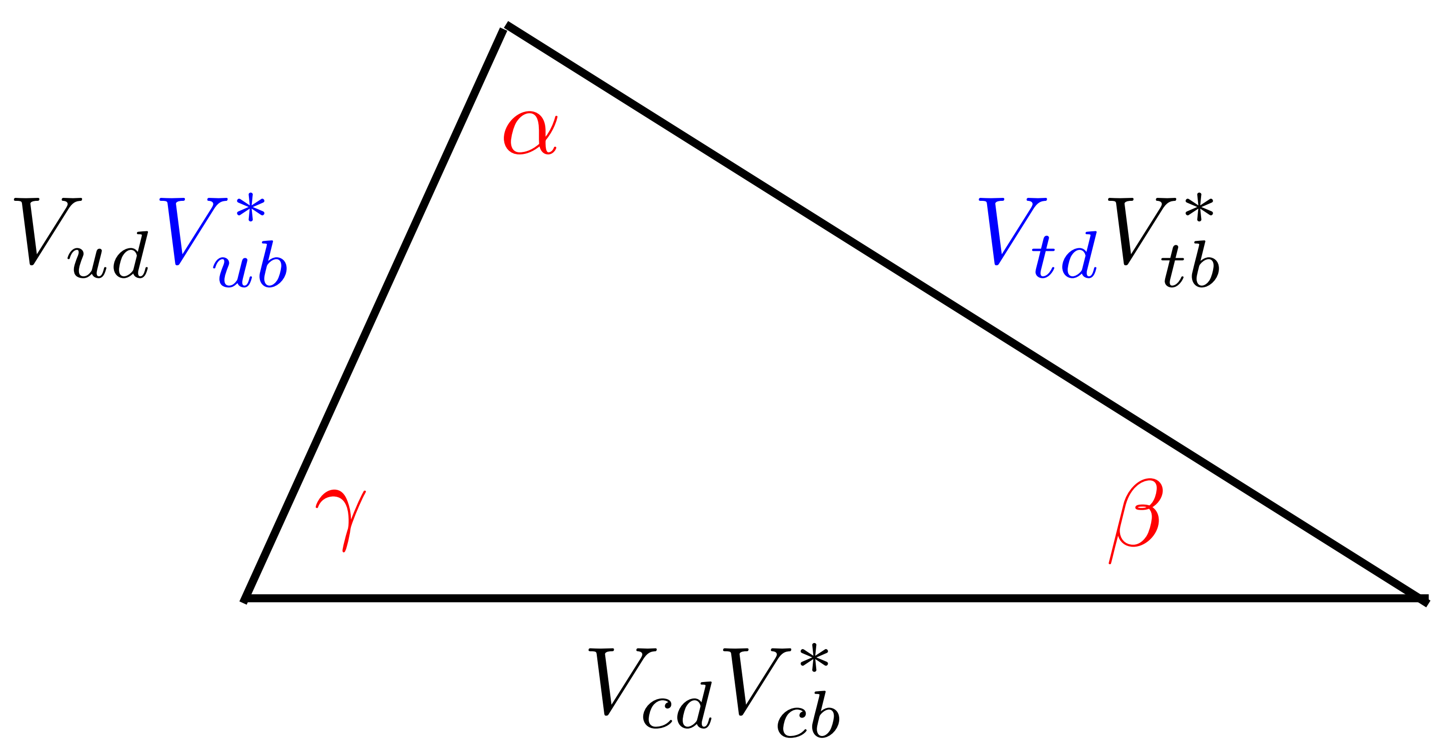
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Wolfenstein parametrization

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$|V_{us}| = 0.2252(9)$$

$$|V_{cb}| = (40.6 \pm 1.3) \times 10^{-3}$$

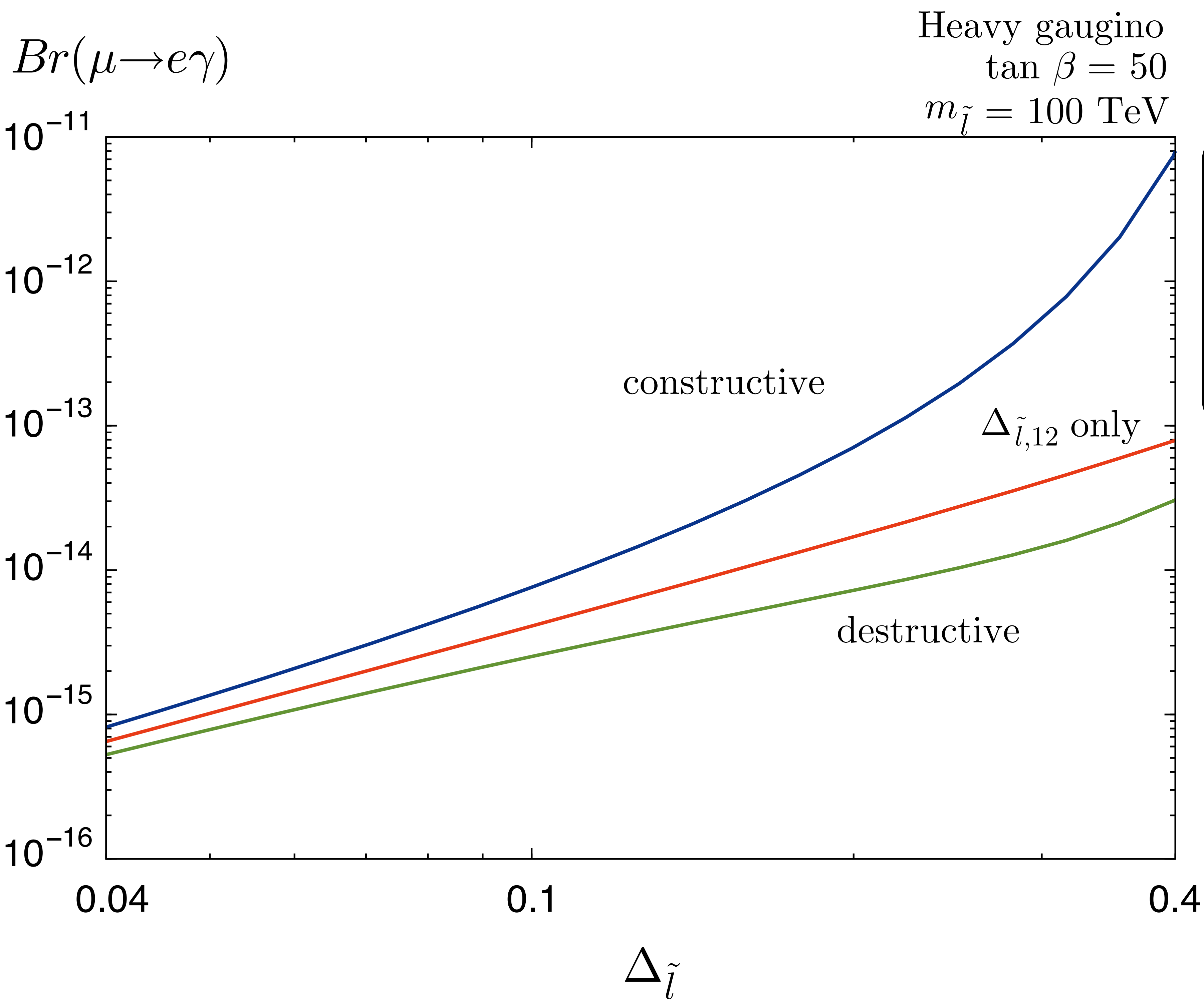


$$V_{td} = |V_{td}|e^{-i\beta}$$

$$V_{ub} = |V_{ub}|e^{-i\gamma}$$

$$V_{ts} = -|V_{ts}|e^{-i\beta_s}$$

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



$$\alpha_2 \Delta_{e_L}^{12}$$

vs

$$\alpha_Y \Delta_{e_L}^{13} \Delta_{e_R}^{32} m_\tau / m_\mu$$

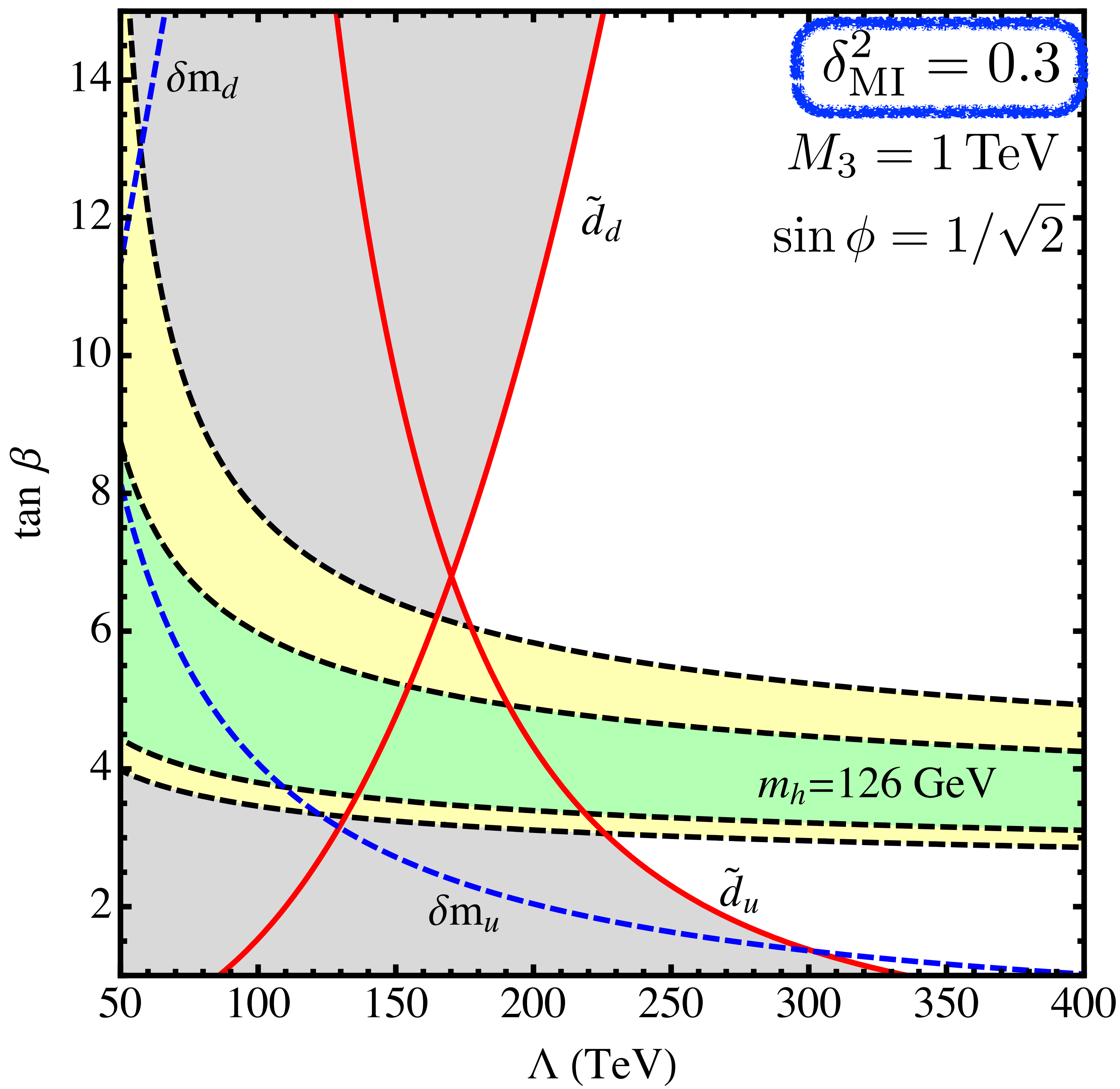
single mass insertion

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

double mass insertion

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

Summary of flavor constraints (i)



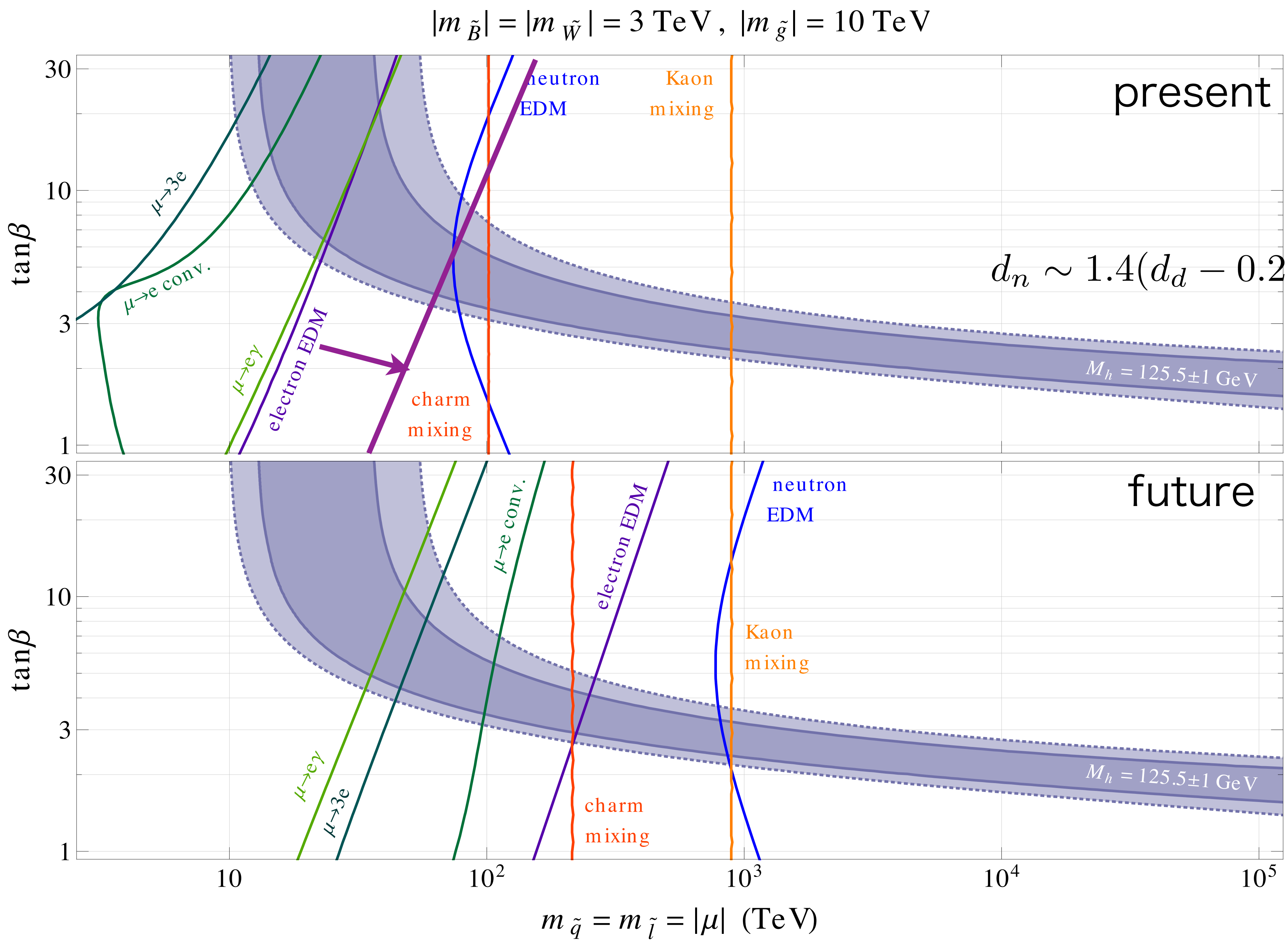
$$|\tilde{d}_u - \tilde{d}_d| < 6 \times 10^{-27}\,\text{cm}$$

from mercury EDM

McKeen,Pospelov and Ritz (2013)

Summary of flavor constraints (ii)

Altmannshofer, Harnik, Zupan (2013)

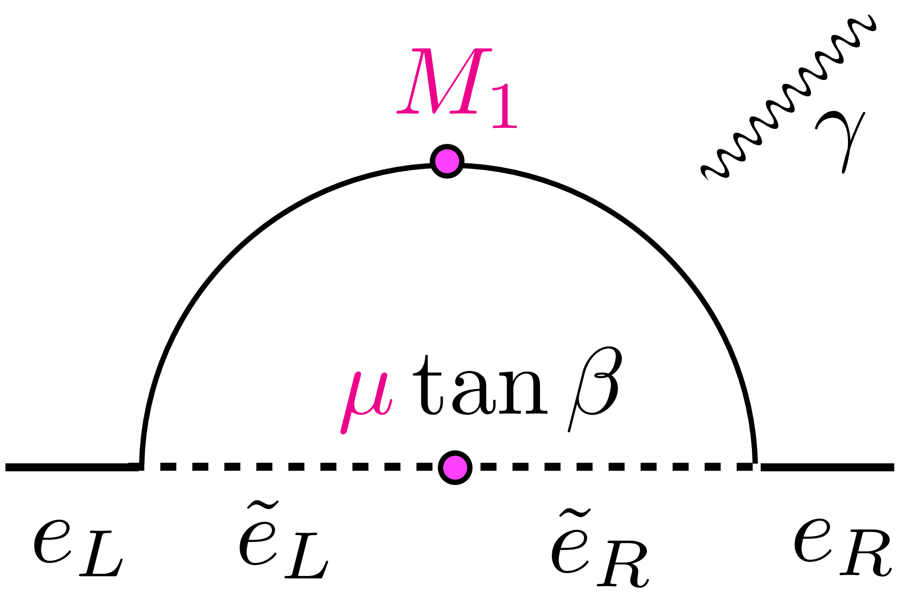


$\delta_{\rm MI} = 0.3$

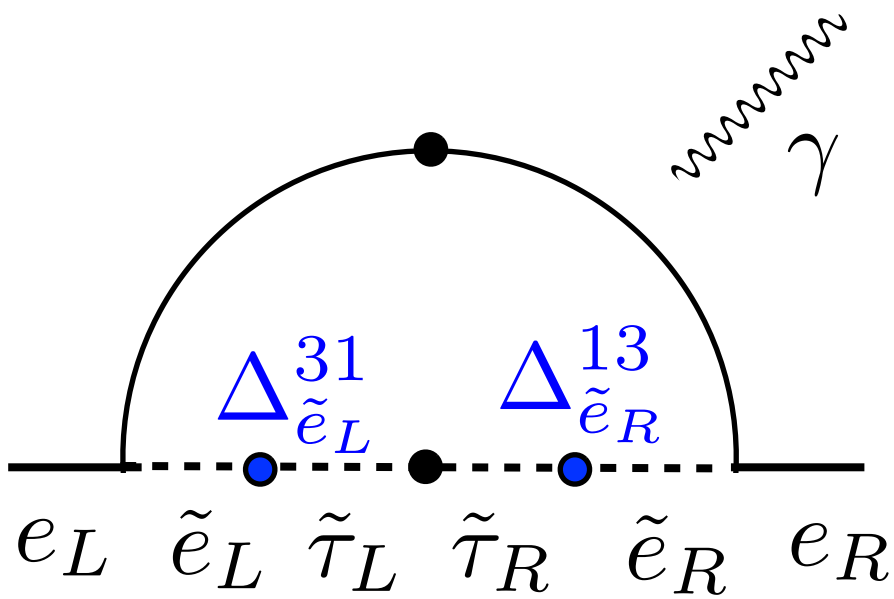
$$d_n \sim 1.4(d_d - 0.25 d_u) + 1.1\, e\, (d_d^c + 0.5 d_u^c)$$
$$< 2.9 \times 10^{-26} e\, cm$$

Electron EDM in SUSY models

CP violating phases can appear in flavor-blind and/or flavor-violating mass terms.



"flavor-blind EDM"



"flavored EDM"

For Δ~O(1), flavored EDMs are much important because of the large enhancement by m_τ/m_e .