フレーバーからテラスケールへ
（さらに、テラスケールからフレーバーへ）

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新学術領域研究
先端加速器LHCが切り拓くテラスケールの素粒子物理学
～真空と時空への新たな挑戦～
研究会
２０１３年５月２３日～２５日

今日の話題

1. テラスケール新物理への期待
2. ヒッグス粒子の相互作用へのフレーバーからの制限
3. テラスケール新物理へのフレーバーの物理からのアプローチ

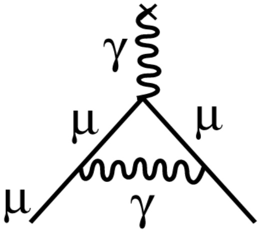
テラスケール新物理への期待

テラスケール新物理の存在を示唆するもの

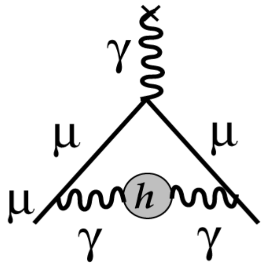
1. ミューオン g-2
2. 暗黒物質
3. 電弱バリオン数生成
4. ニュートリノ質量
5. ヒッグス質量自然さの問題
6.

Muon g-2

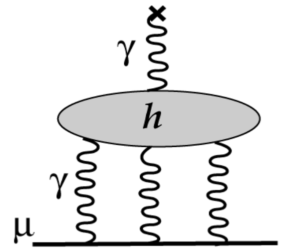
Various contribution to muon g-2 :



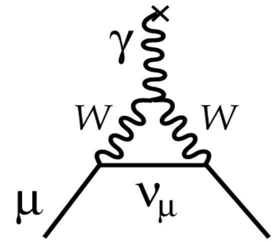
QED
Up to 5-loop leading
Kinoshita et al



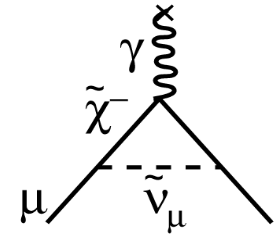
Hadronic vacuum polarization (HVP)



Light-by-light scattering (LBL)



Electroweak at two-loop level



Beyond SM

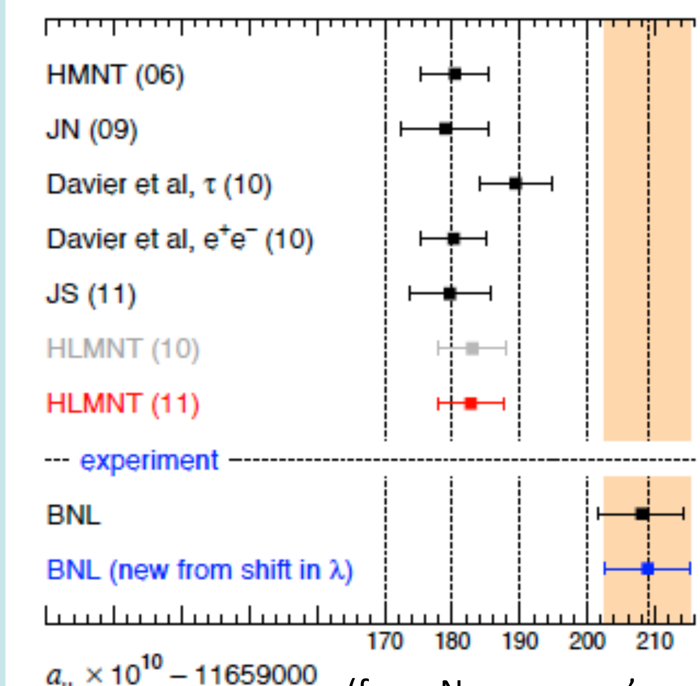
3 sigma deviation from the SM prediction

$$\delta a_\mu \sim 3 \times 10^{-9}$$

which is twice larger than weak boson contribution.

2 (or 3) possibilities:

- Uncertainties com from HVP and LBL
- New contribution from BSM
-



(from Nomura-san's paper)

Muon g-2

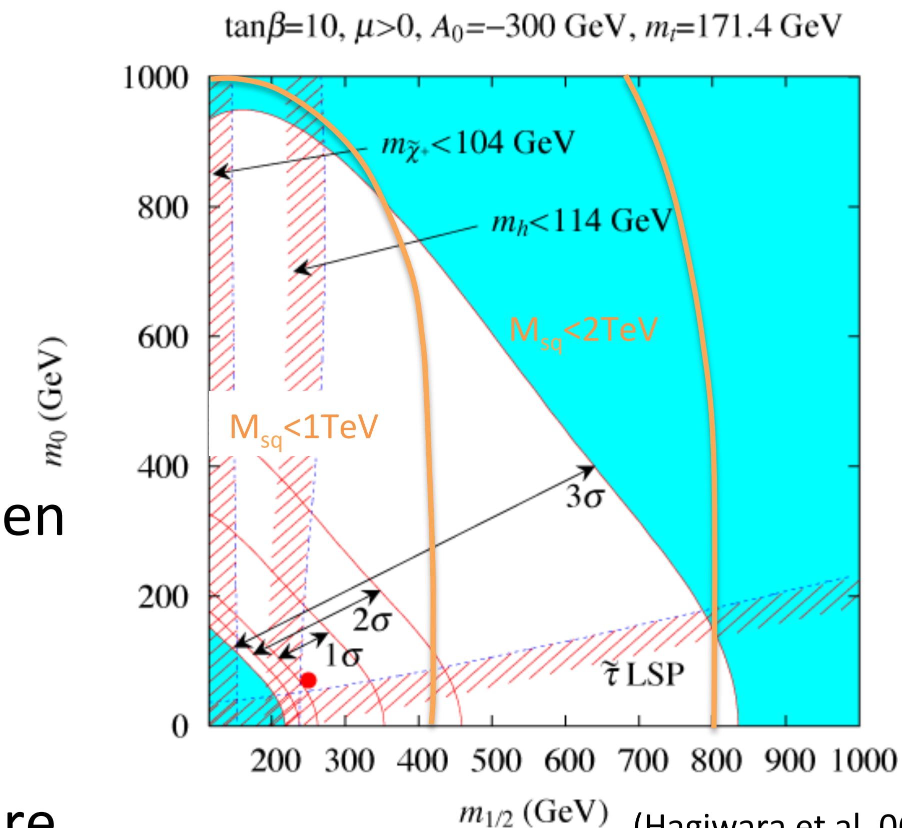
Contribution from SUSY SM:

Since SUSY SM has two Higgs doublets, muon g-2 has a contribution proportional to $\tan\beta \equiv \langle H_2 \rangle / \langle H_1 \rangle$.

$$\delta a_\mu \sim \frac{5\alpha_2 + \alpha_Y}{48\pi} \frac{m_\mu^2}{M_{\rm SUSY}^2} \tan\beta$$

$$= 3 \times 10^{-9} \left(\frac{\tan\beta}{10} \right) \left(\frac{M_{\rm SUSY}}{200{\rm GeV}} \right)^{-2}$$

CMSSM (Constrained MSSM) has been constrained by null results in SUSY searches. If we give up the GUT relation, we may get light EW SUSY particles, while squarks and gluino are heavy enough.

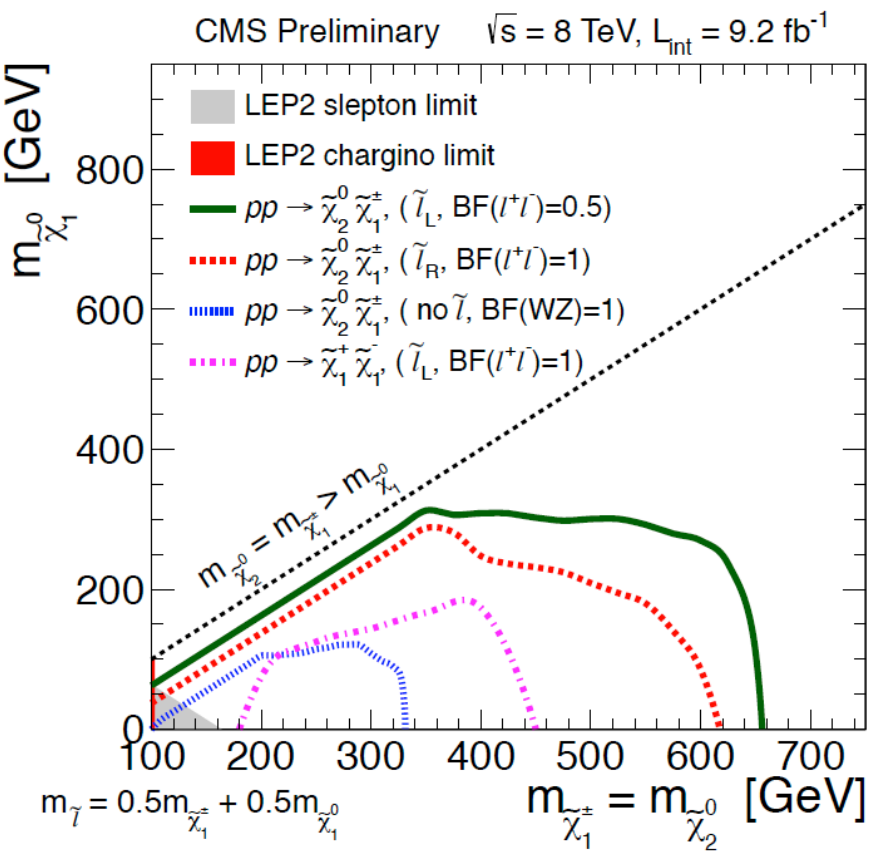


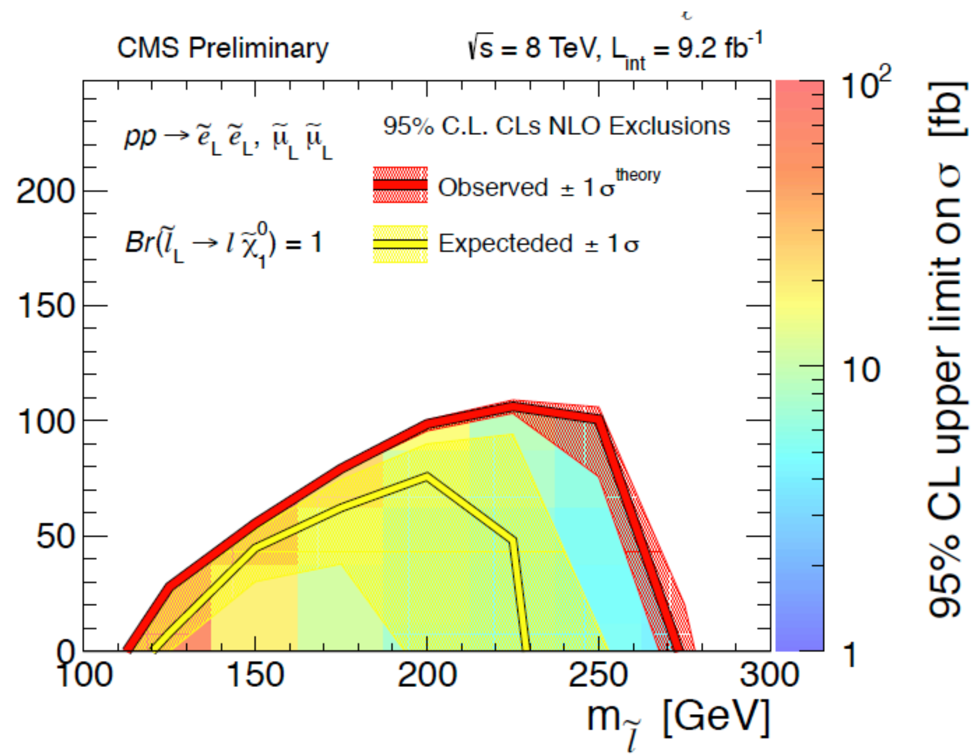
(Hagiwara et al, 06)

Muon g-2

Direct searches for chargino/neutralino and slepton by CMS.

When chargino/neutralino can decay into sleptons, the constraints on the masses are stronger.





Muon g-2

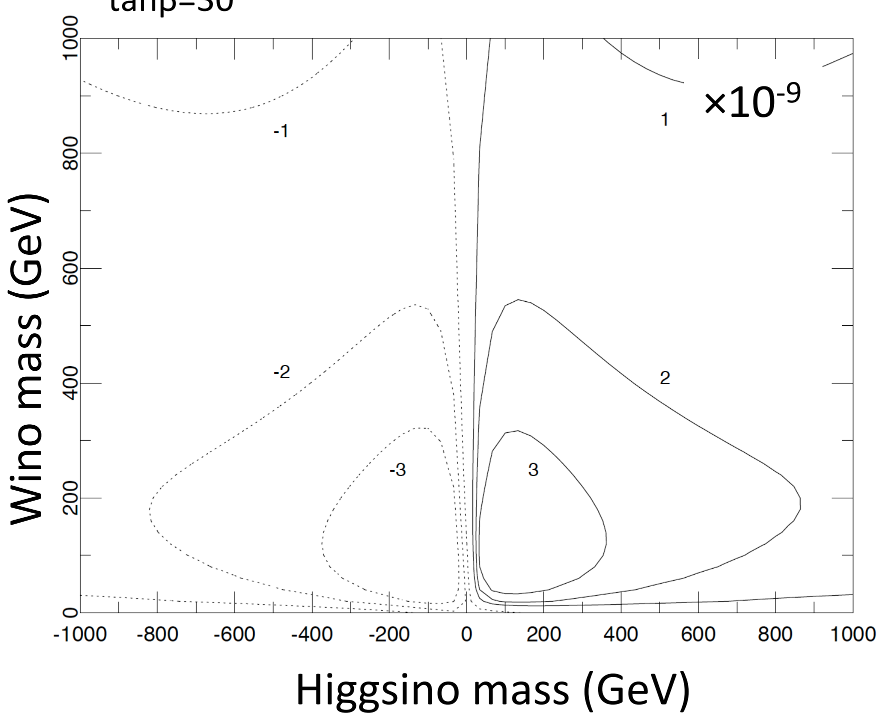
Anatomy of SUSY contribution Δa_μ :

Case1 (compact spectrum): chargino-sneutrino diagram.

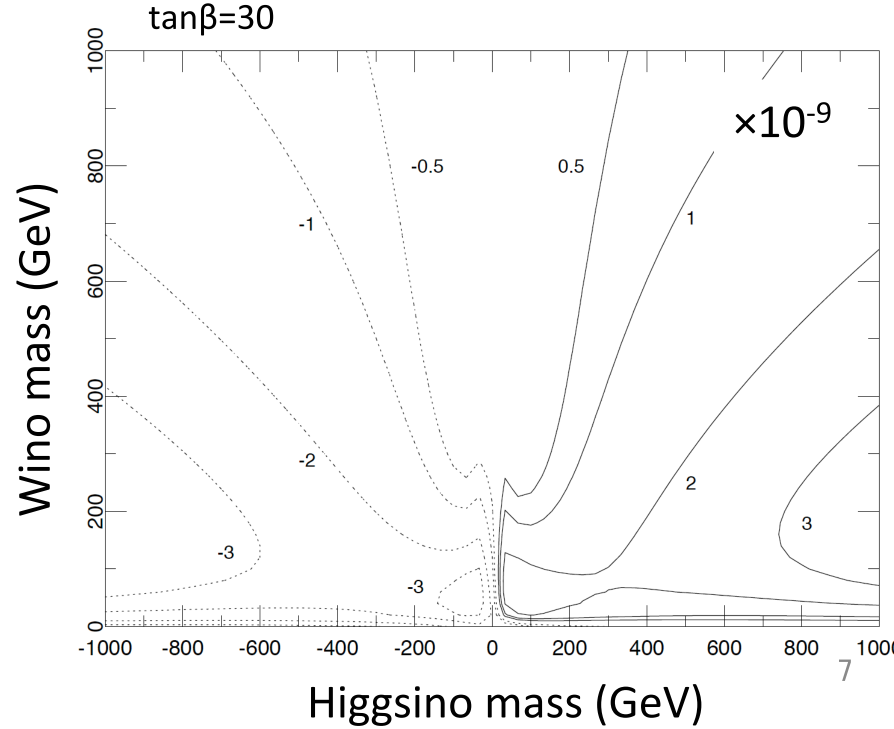
Case2 (large higgsino mass): bino-like neutralino-slepton diagram (enhanced left-right mixing proportional to higgsino mass)

(Moroi (95))

Left and right-handed smuons, 500 and 1000 GeV
tanβ=30



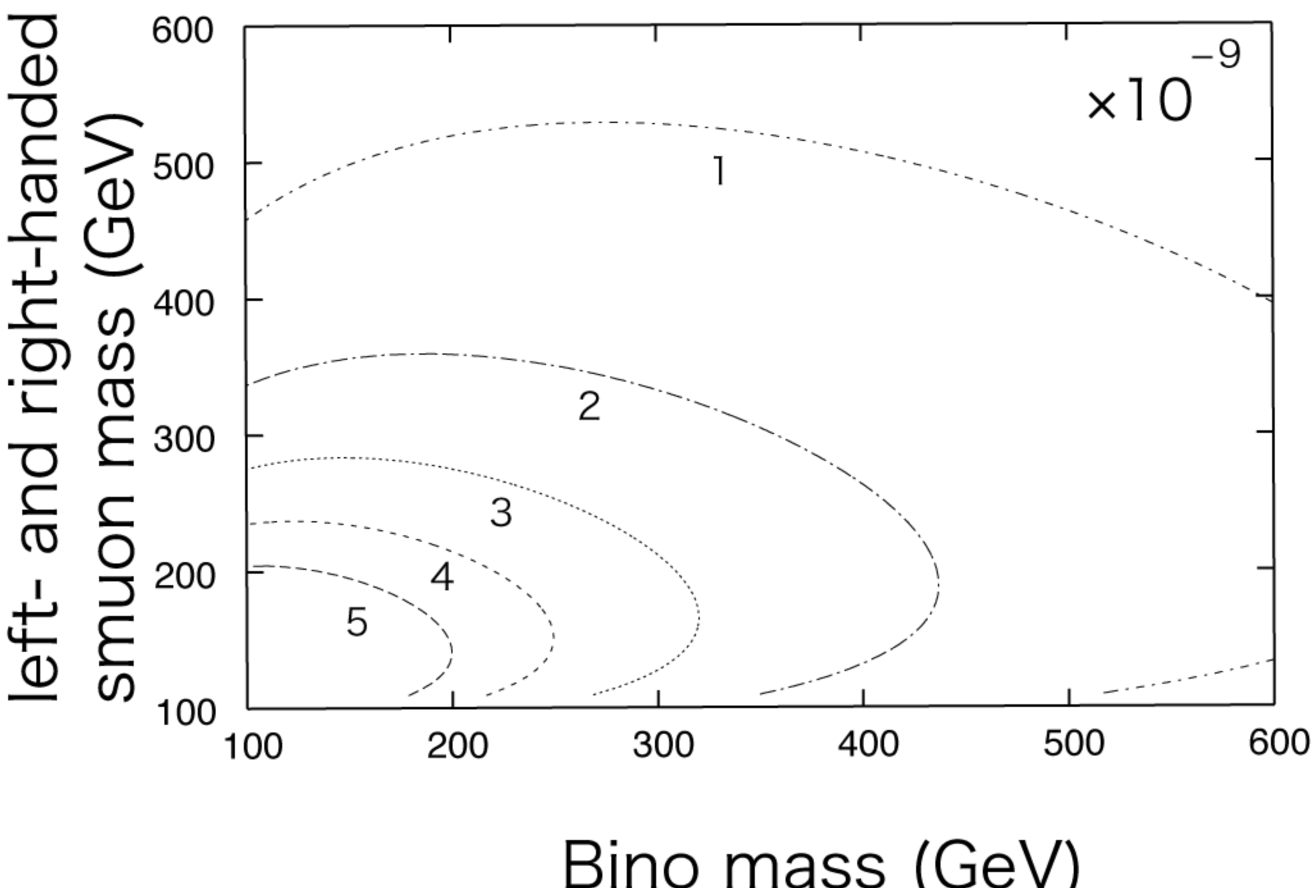
Left and right-handed smuons, 500 and 100 GeV
tanβ=30



Muon g-2

Case2 (one light slepton and large higgsino mass):

Large higgsino mass is constrained from vacuum (meta)stability for stau direction. Assuming stau is lighter than smuon, we derive upperbound on SUSY contribution to muon g-2.



Electroweak baryogenesis

Sakharov's three conditions for baryogenesis

1. Baryon number violation (Sphaleron)
2. C and CP violations (CKM or new phase)
3. Out of equilibrium (1^{st} order EW phase transition)

EWBG in SM

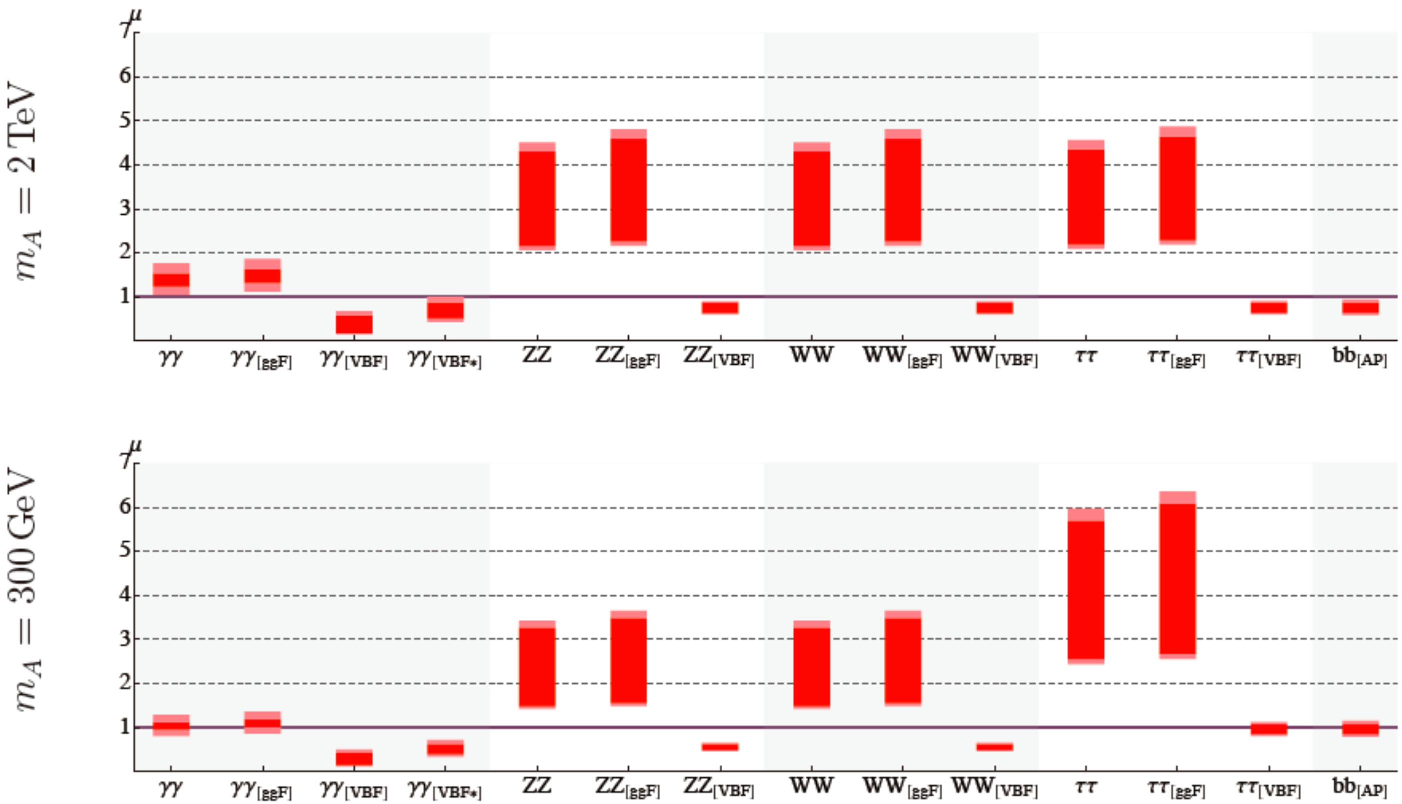
- 1^{st} order EWPT may be possible for mh smaller than ~70 GeV.
- CP violation in CKM is too small.

EWBG in MSSM (stop lighter top)

- 1^{st} order EWPT may be possible when stop mass is smaller than ~115GeV.
- CP violation comes from SUSY breaking.

Electroweak baryogenesis

Stop mass is smaller than 115GeV is ruled out at 97% CL and 98%CL for mA= 300 GeV and 2TeV, respectively. (Curtin et al (12))



Electroweak baryogenesis

New possibility: Higgs coupled with strongly-interacting sector

$$V(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

Boson loop

Introduction of new strongly-interacting boson coupled with Higgs boson leads Landau pole around O(10) TeV, above which the description should be changed.

Kanemura-Shindou-Yamada model

Symmetries: SUSY $SU(2)_H \times SU(2)_L \times U(1)_Y \times Z_2$

Matter contents: Nf=Nc+1 (confiment)

Particle contents below the cutoff scale:

2doublets (MSSM-like Higgs)

2doublets+charged singlets+neutral singlets

New particles affects hhh, hγγ couplings.

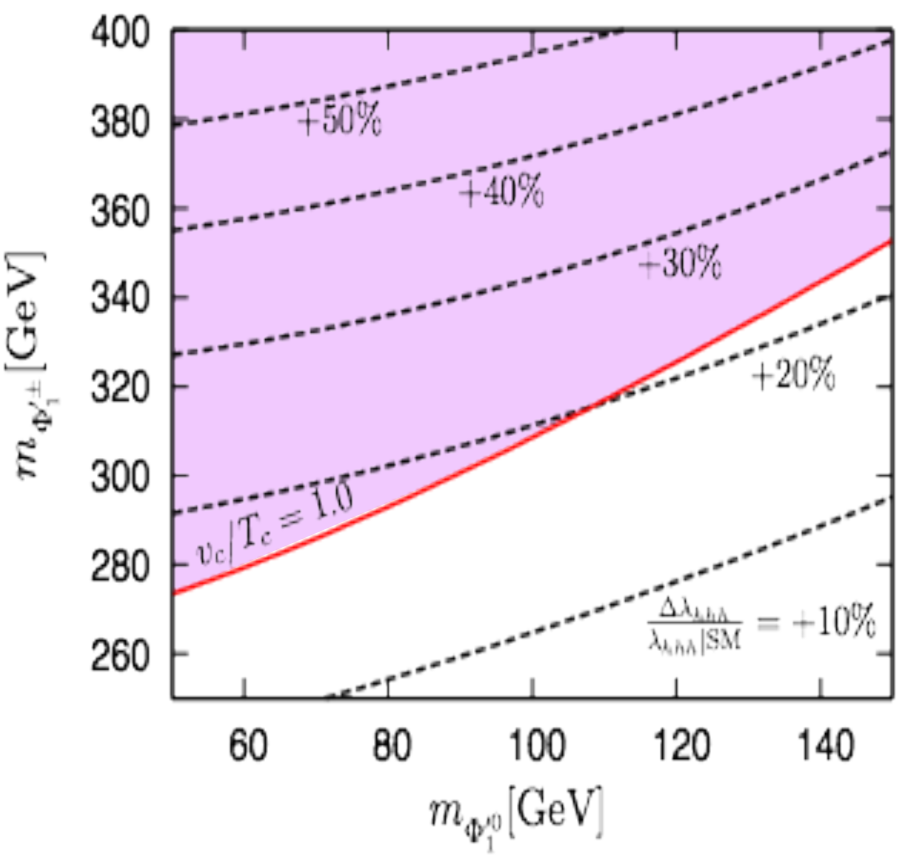
Fields	$SU(2)_L$	$U(1)_Y$	Z_2
$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$	2	0	+
T_3	1	+1/2	+
T_4	1	−1/2	+
T_5	1	+1/2	−
T_6	1	−1/2	−

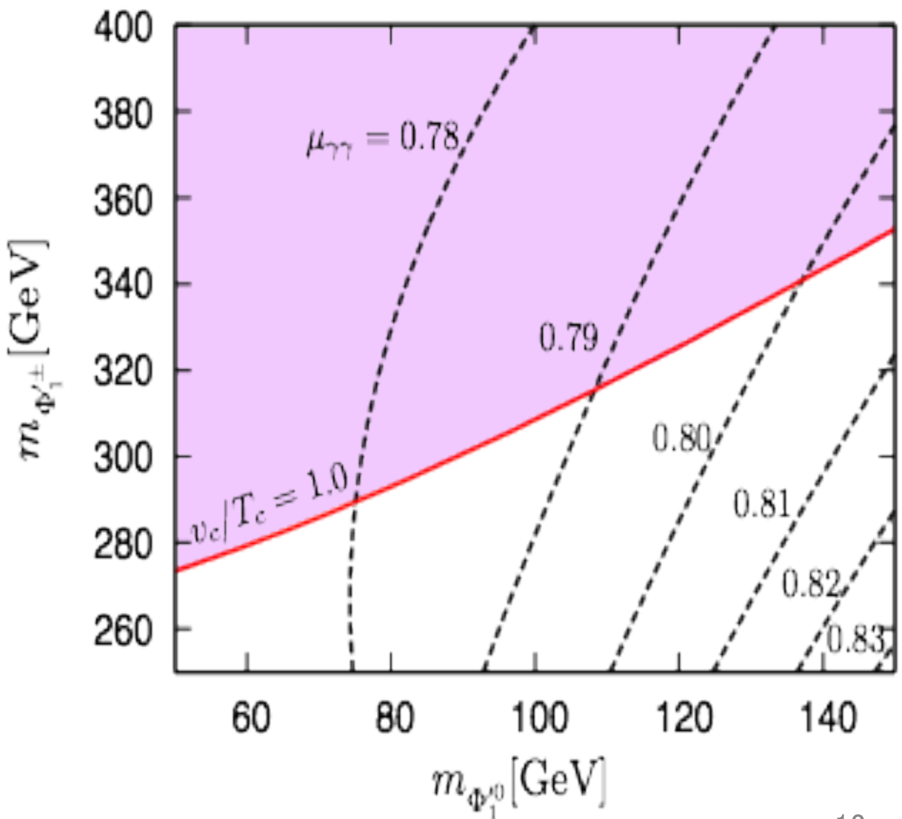
Electroweak baryogenesis

Kanemura-Shindou-Yamada model:

Couplings hhh and hγγ may be deviated from the SM prediction.

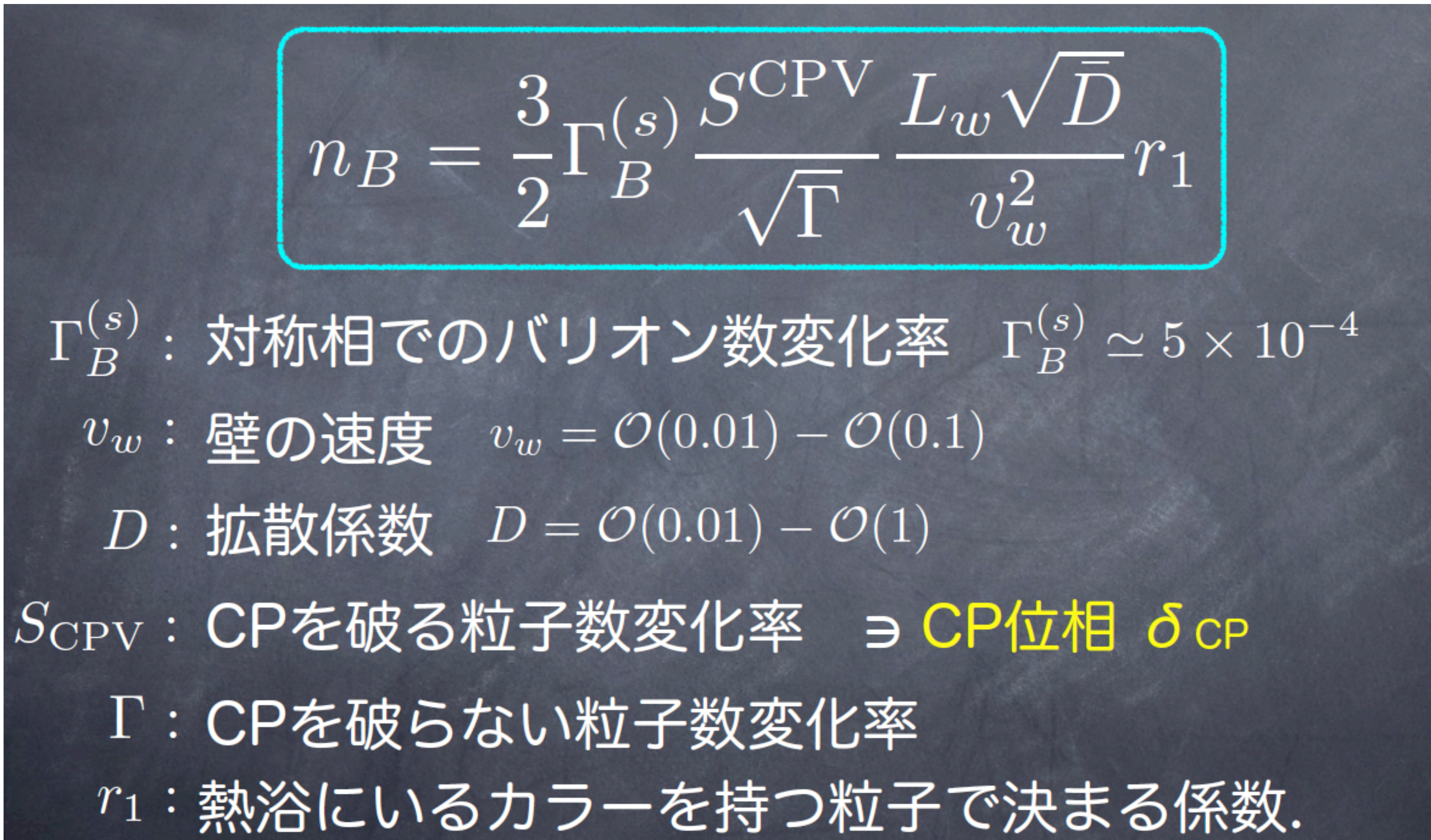
(Kanemura, Senaha,Shindou and Yamada (1211.5883))





Electroweak baryogenesis

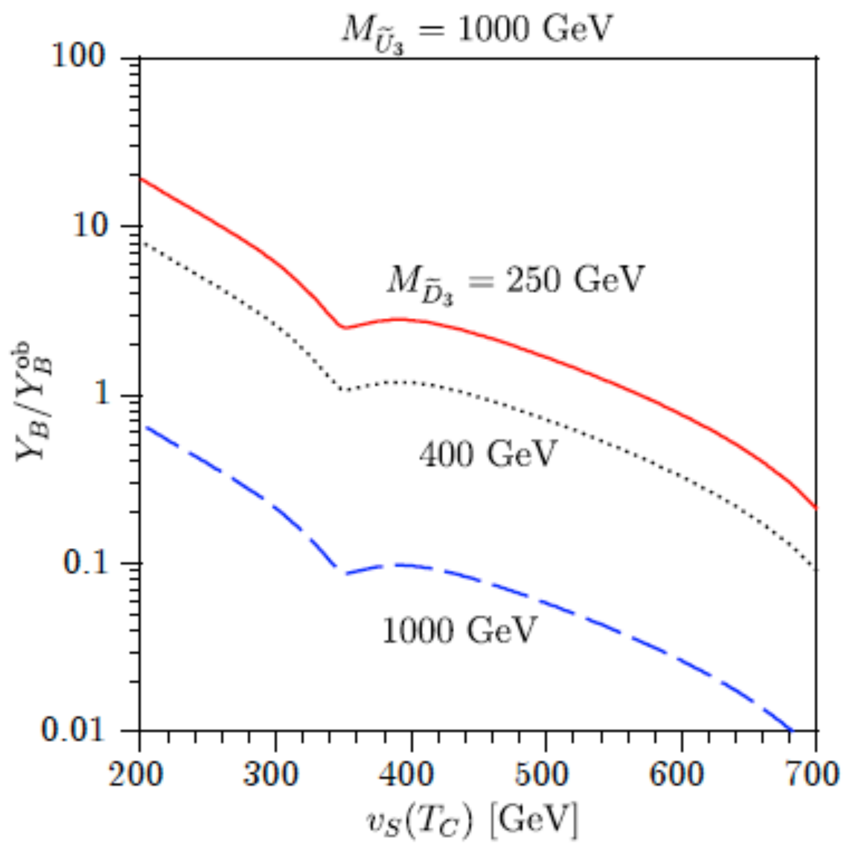
Generated baryon number in SUSY SM is sensitive to SUSY particle masses.



(Seneha-san's presentation)

Electroweak baryogenesis

Generated baryon number in SUSY SM is sensitive to SUSY particle masses. For example, existence of lighter colored particles suppress the strong sphaleron (comes from QCD anomaly) so that generated baryon number is increased.



Electrobaryongesis in a scenario based in NMSSM (Senaha et al (12))

ヒッグス粒子の相互作用へのフレーバーからの制限

1. CP violating Higgs coupling
2. Lepton-flavor violating Higgs coupling

New physics contribution to odd hγγ and hgg

Low-energy theorem:

New fermions with mass terms dependent on Higgs VEV are integrated out ($\mathcal{L}_M = -\mathcal{M}_{i,j}(v)\,(\overline{\psi}_{iL}\psi_{jR}) + h.c.$) so that

$$\mathcal{L}_{h\gamma\gamma} = \frac{\alpha}{4\pi}\,Q_e^2\,\frac{h}{v}\left\{\frac{1}{3}\,F^{\mu\nu}F_{\mu\nu}\,v\frac{\partial}{\partial v}\log\mathrm{Det}\left[\mathcal{M}^\dagger\mathcal{M}\right] + F^{\mu\nu}\tilde{F}_{\mu\nu}v\frac{\partial}{\partial v}\arg\left[\mathrm{Det}\mathcal{M}\right]\right\}$$

CP-even hγγ coupling

CP-odd hγγ coupling (No bosonic contribution)

One example is 4th generation with SU(2)*U(1) inv. Dirac mass terms.

$$v\frac{\partial}{\partial v}\log\mathrm{Det}\left[\mathcal{M}^\dagger\mathcal{M}\right] \simeq -4v^2\frac{\mathrm{Re}[M_1M_2y_{12}y_{21}]}{|M_1M_2|^2}$$

(M_1, M_2 : Dirac masses)

$$v\frac{\partial}{\partial v}\arg\left[\mathrm{Det}\mathcal{M}\right] \simeq -2v^2\frac{\mathrm{Im}[M_1M_2y_{12}y_{21}]}{|M_1M_2|^2}$$

(y_{12}, y_{21} : Yukawa coupling)

If CP phase is O(1), CP-odd coupling is not negligible.

CP-odd hgg coupling is also generated when new fermions have color.

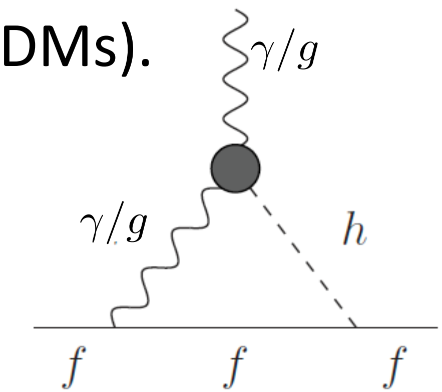
New physics contribution to odd hγγ and hgg

Higgs coupling to 2 γs and 2gs:

$$\mathcal{L} = c_{\rm SM}^{\gamma\gamma}\frac{\alpha}{4\pi}\frac{h}{v}\left\{r_\gamma F^{\mu\nu}F_{\mu\nu} + s_\gamma F^{\mu\nu}\tilde{F}_{\mu\nu}\right\} + c_{\rm SM}^{gg}\frac{\alpha}{12\pi}\frac{h}{v}\left\{r_g G^{a\mu\nu}G^a_{\mu\nu} + s_g G^{a\mu\nu}\tilde{G}^a_{\mu\nu}\right\}$$

$$Br_{h\to\gamma\gamma(gg)} = Br_{h\to\gamma\gamma(gg)}|_{\rm SM}\times(\gamma^2_{\gamma(g)} + s^2_{\gamma(g)})$$

Barr-Zee diagrams generate EDMs and CEDMs (color EDMs).



$$|d_e/e| \sim 8\times 10^{-27}{\rm cm}\times s_\gamma L$$

$$|d_q/e| \sim 2\times 10^{-26}{\rm cm}\times Q_q m_q({\rm MeV})\times s_\gamma L$$

$$|d_q^c| \sim 3\times 10^{-26}{\rm cm}\times m_q({\rm MeV})\times s_g L$$

where $L = \log(\Lambda^2/m_h^2)$.

From $|d_e/e| < 1.0\times 10^{-27}{\rm cm}$, $|d_n/e| < 2.9\times 10^{-26}{\rm cm}$, $s_\gamma L < \tilde{1}0\%,\ s_g L < \tilde{1}.$

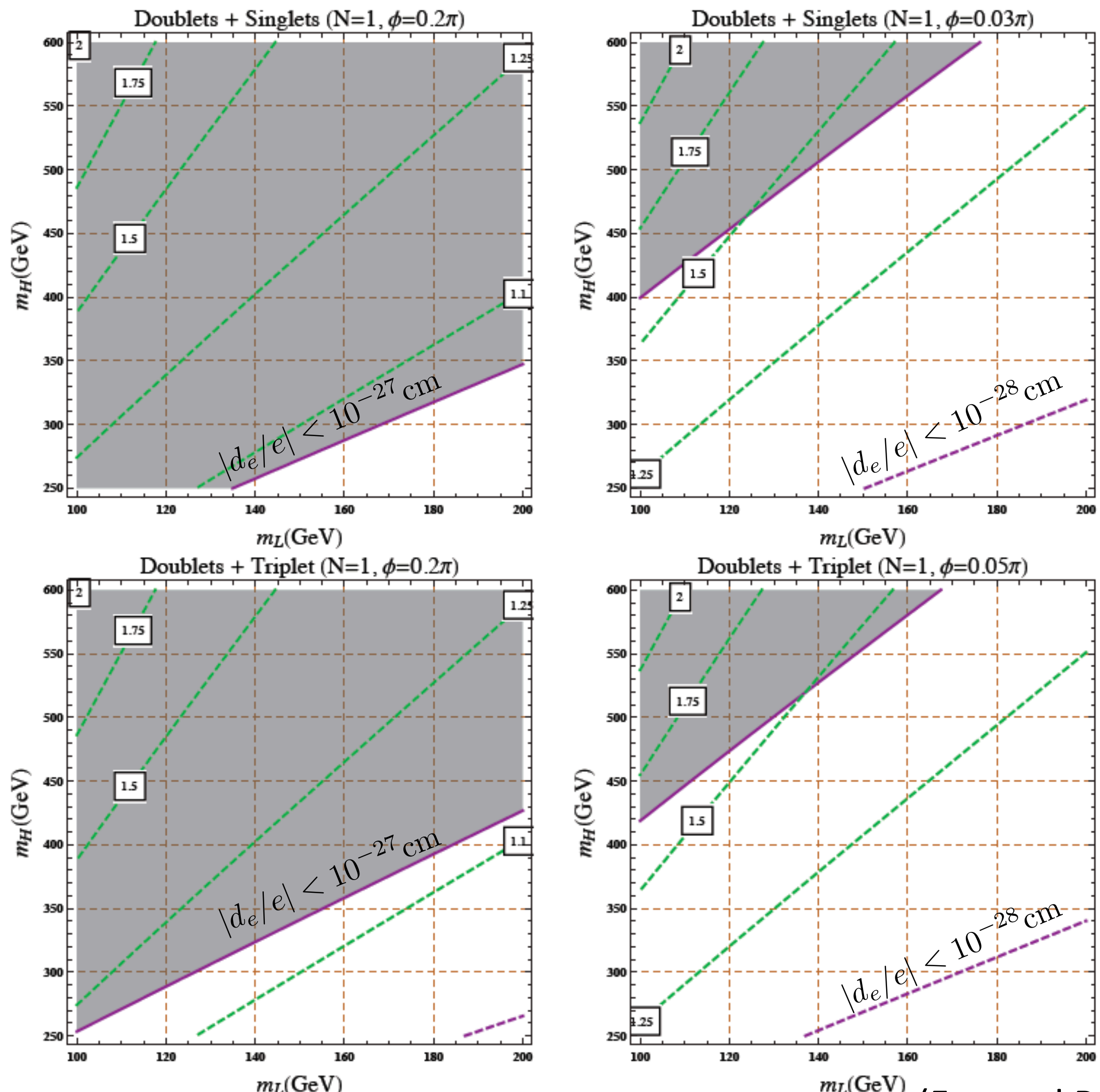
Higgs decay to 2 γs and 2gs is mildly constrained, if O(1) CP phase is in new contribution.

New physics contribution to odd hγγ and hgg

Signal strength for γγ mode constrained from electron EDM

SU(2) doublet and singlet with Dirac masses

SU(2) doublet and triplet with Dirac and Majorana Masses.



(Fan and Reece (13))

New physics contribution to odd hγγ and hgg

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SU(2) doublet and singlet with Dirac masses

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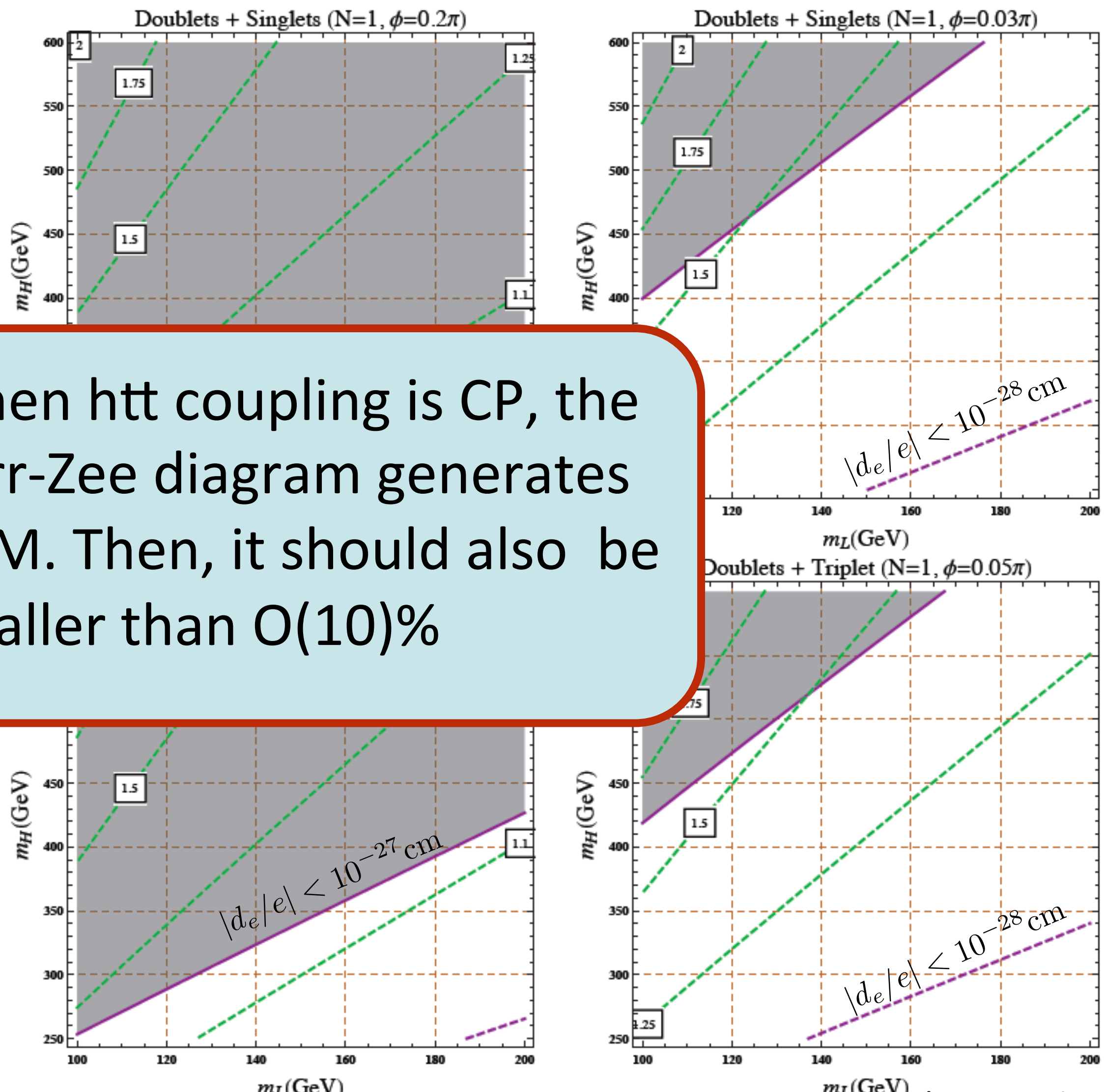


When htt coupling is CP, the Barr-Zee diagram generates EDM. Then, it should also be smaller than O(10)%

(Fan and Reece (13))

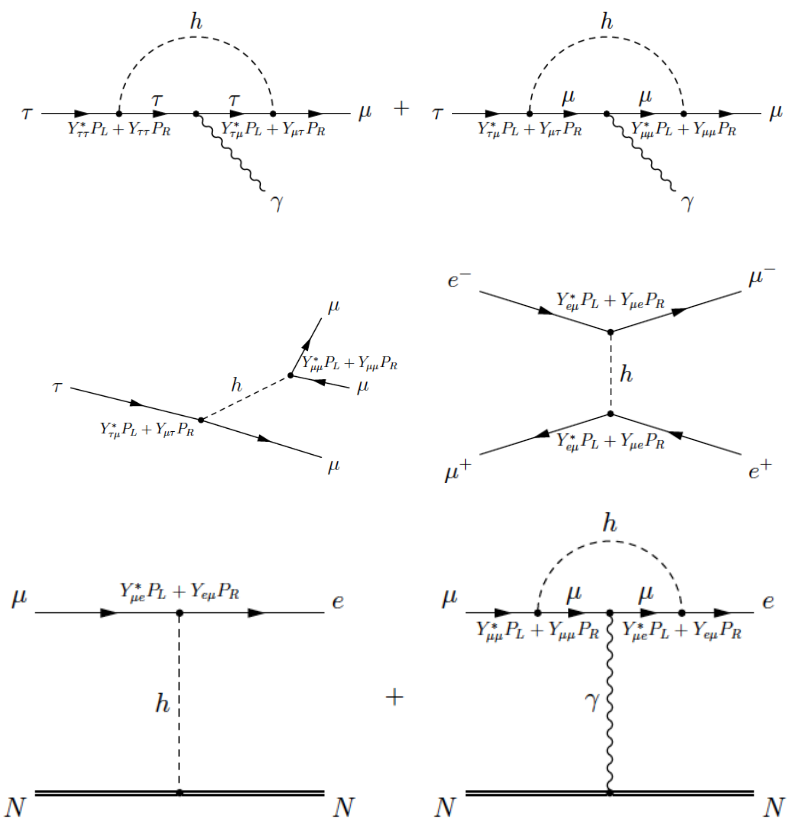
Lepton-flavor violating Higgs coupling

Discovered Higgs(-like) boson is in the standard model?

$$-\mathcal{L}_{\rm Yukawa} = \lambda_{ij}\bar{f}^i_L f^j_R H + \lambda'_{ij}\bar{f}^i_L f^j_R H \frac{H^\dagger H}{\Lambda^2} + {\rm h.c.}$$

$$= m_i \bar{f}^i_L f^i_R + Y_{ij}\bar{f}^i_L f^j_R h^0 + {\rm h.c.}$$

Flavor-violating Higgs(-like) coupling

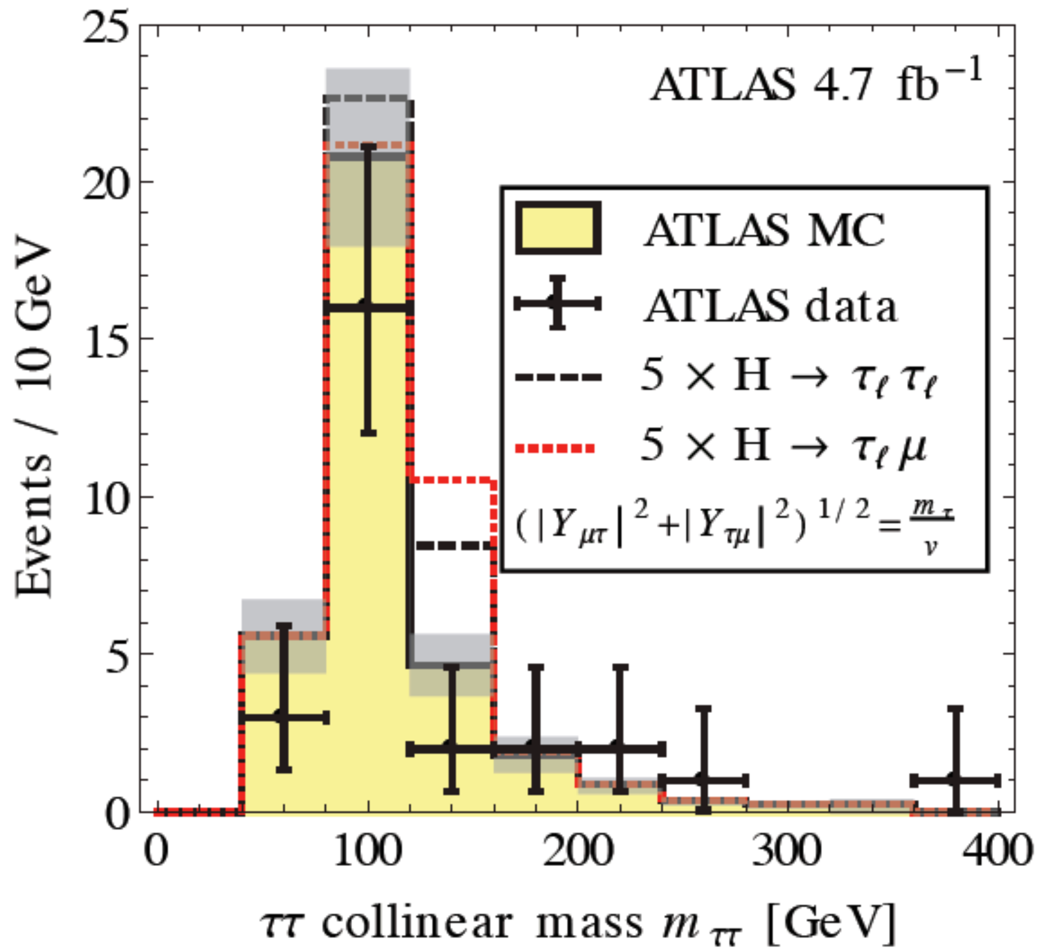


Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	< 0.31
electron $g-2$	$\mathrm{Re}(Y_{e\mu}Y_{\mu e})$	$-0.019 \dots 0.026$
electron EDM	$\lvert\mathrm{Im}(Y_{e\mu}Y_{\mu e})\rvert$	$< 9.8 \times 10^{-8}$
$\mu \to e$ conversion	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 4.6 \times 10^{-5}$
M-$\bar{M}$ oscillations	$\lvert Y_{\mu e} + Y^*_{e\mu}\rvert$	< 0.079
$\tau \to e\gamma$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to e\mu\mu$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.66
electron $g-2$	$\mathrm{Re}(Y_{e\tau}Y_{\tau e})$	$[-2.1 \dots 2.9] \times 10^{-3}$
electron EDM	$\lvert\mathrm{Im}(Y_{e\tau}Y_{\tau e})\rvert$	$< 1.1 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	$< 1.6 \times 10^{-2}$
$\tau \to 3\mu$	$\sqrt{\lvert Y^2_{\tau\mu} + \lvert Y_{\mu\tau}\rvert^2}$	< 0.52
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau}Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau}Y_{\tau\mu})$	$-0.8 \dots 1.0$
$\mu \to e\gamma$	$(\lvert Y_{\tau\mu}Y_{\tau e}\rvert^2 + \lvert Y_{\mu\tau}Y_{e\tau}\rvert^2)^{1/4}$	$< 3.4 \times 10^{-4}$

(Harnik, Kopp, Zupan, (12))

Lepton-flavor violating Higgs coupling

(Harnik, Kopp, Zupan (13))

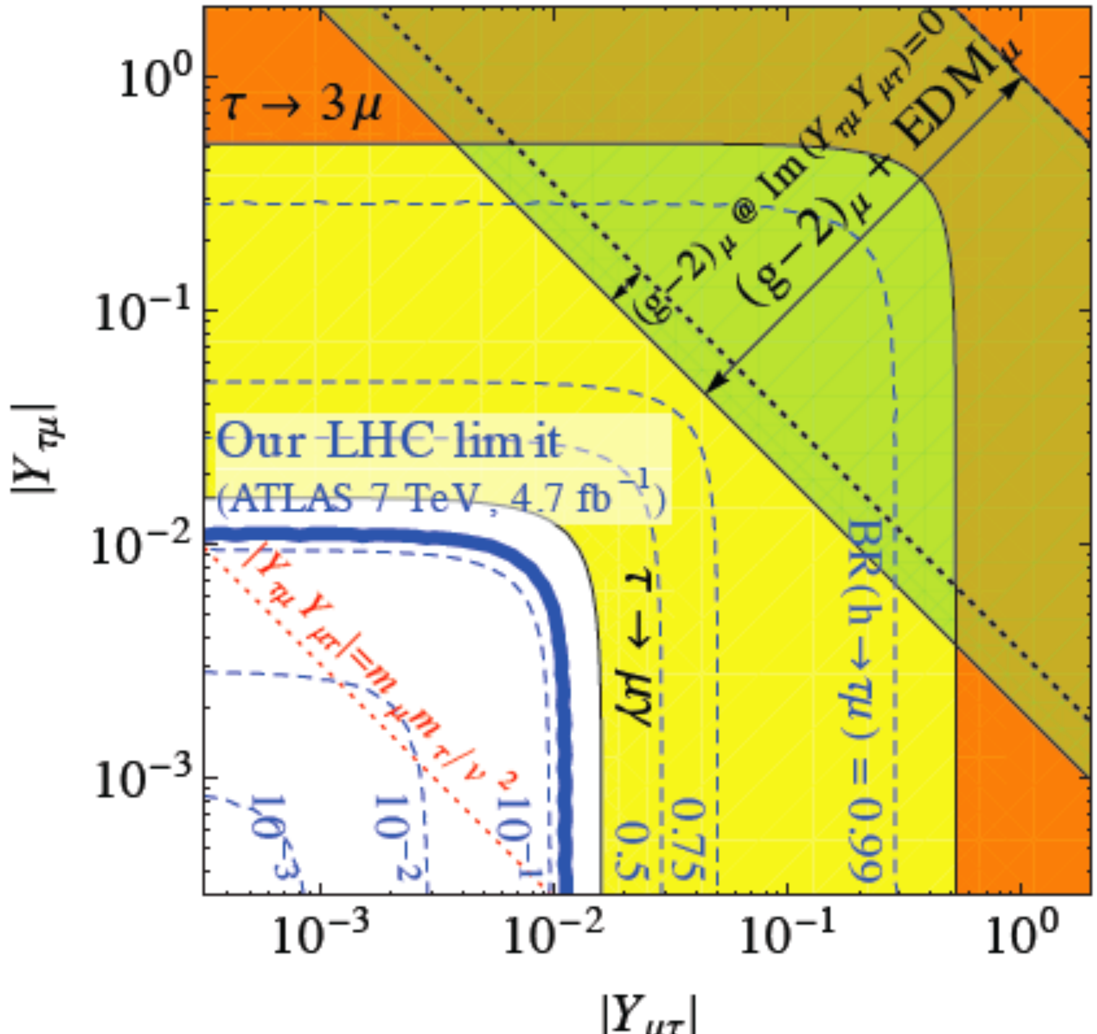


The LFV Higgs decay is already constrained

$$\mathrm{Br}(h \to \tau\mu(\tau e)) <\sim 0.1$$

Lepton-flavor violating Higgs coupling

(Harnik, Kopp, Zupan (13))



LFV Higgs decay search at LHC and LFV tau decay searches at B factories are competitive.

テラスケール新物理への
フレーバーの物理からのアプローチ

1. Flavor constraints on MSSM with extra matter
2. How to access high-scale SUSY

Flavor constraints on MSSM with extra matter

Introduction of extra matter to MSSM

- Radiative correction to Higgs boson mass
- New flavor violation

Problem: How to construct more realistic model(s)

- How to control flavor violation
- Origin of mass for extra matter

MSSM with extra matter (SU(5) 10+10* dim multiplets)

under U(1) flavor and U(1) Peccei-Quinn symmetries.

	$U(1)_{\rm flavor}$	$U(1)_{\rm PQ}$		$(1)_{\rm flavor}$	$U(1)_{\rm PQ}$
10_1	2	1	$5^\star_1$	1	1
10_2	1	1	$5^\star_2$	1	1
10_3	0	1	$5^\star_3$	1	1
10_4	0	1	$10^\star_5$	0	-5
H_1	0	-2	H_2	0	-2

Flavor constraints on MSSM with extra matter

Superpotential $(i = 1-4, a = 1-3)$:

$$W = \xi^{Q_i+Q_j} H_1 10_i 10_j + \xi^{Q_i+Q_a} H_2 10_i 5^\star_a + \xi^Q_i M 10_i 10^\star_5 + \mu H_1 H_2$$

U(1) flavor and U(1) Peccei-Quinn symmetries are broken by S and P.

$$\xi = \langle S \rangle / M_\star \sim 0.2 \qquad M \sim \mu \sim \langle P \rangle^2 / M_\star = O(100)\mathrm{GeV}$$

H1 is coupled with extra matter while H2 not.

(no excess hγγ, no Barr-Zee type EDM, and no reduction of Higgs mass)

Tree-level FCNC appears due to introduction of 10* in Z coupling

- μ→eγ/3e (left-handed lepton mixing)

$$\xi(v/M) <\sim 10^{-3}$$

- up quark (C)EDM due to left- and right-handed up quark mixing)

$$\xi^2(v/M) <\sim 10^{-(3-4)}$$

- Neutral Keon mixing (left-handed down quark mixing)

$$\xi(v/M) <\sim 10^{-2}$$

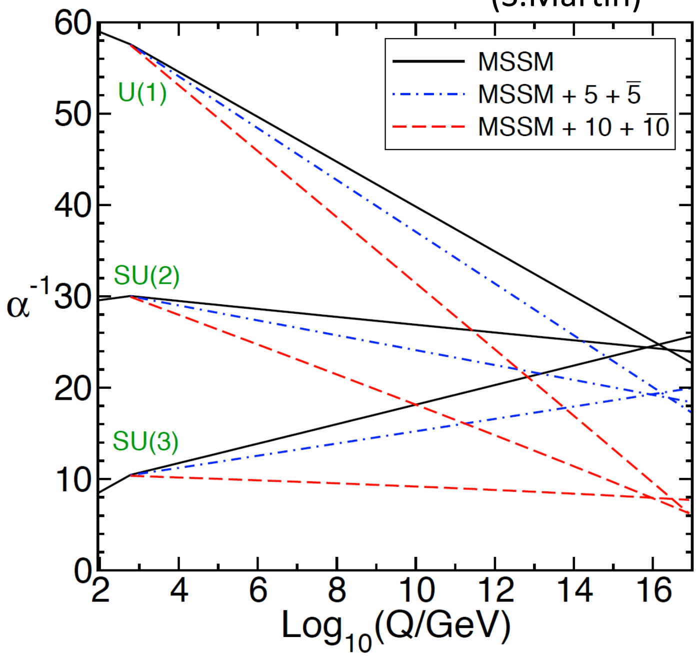
Proton decay in SUSY GUTs with extra matter

Introduction of extra matter makes gauge coupling at GUT scale larger.

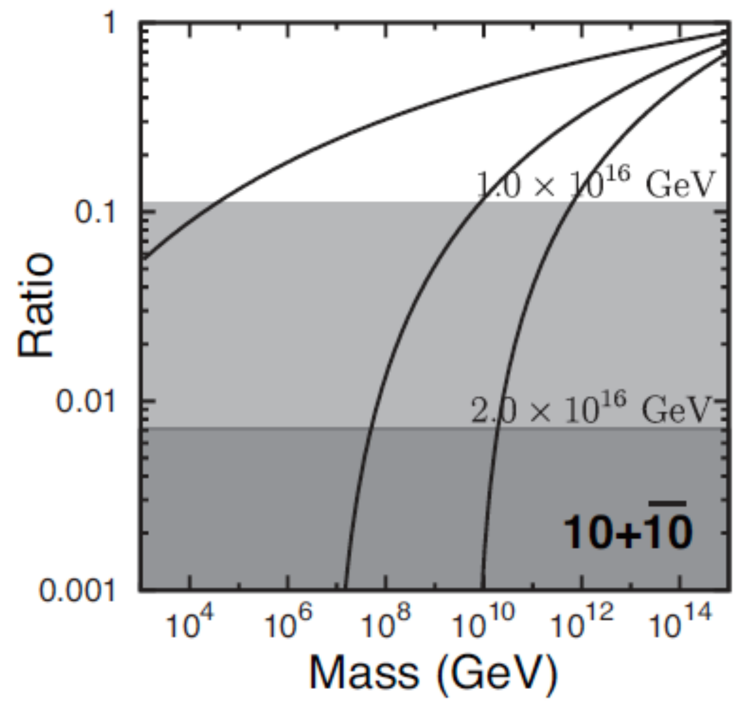
X boson proton decay rate is enhanced.

Gauge coupling unification
in MSSM with extra matter

(S.Martin)



Suppression factors for proton lifetime,
compared with the case without extra matters,
as functions of mass for extra matters.



(JH, Nagata, Kobayashi (12))

How to access high-scale SUSY

High-scale SUSY:

Gauginos : O(1) TeV

Sfermions and Higgsino: O(10^2)TeV.

1. larger radiative correction to Higgs mass
2. dark matter is wino (m< 2.7 TeV)
3. FCNC and CP problems are solved.
4. Gauge coupling unification is improved.

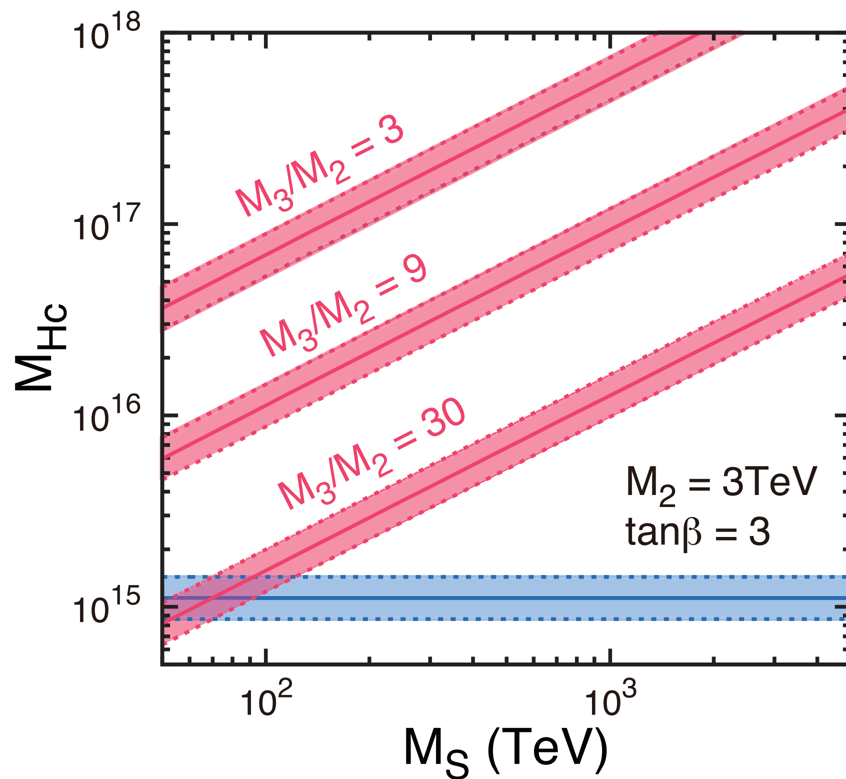
Gauge coupling unification in high-scale SUSY

. From gauge coupling unification, we can constrain GUT-particle mass spectrum, especially colored Higgs mass (MHc) in the minimal SUSY SU(5) GUT.

$$\frac{3}{\alpha_2(m_Z)} - \frac{2}{\alpha_3(m_Z)} - \frac{1}{\alpha_1(m_Z)} = \frac{1}{2\pi}\left[\frac{12}{5}\ln\left(\frac{M_{H_C}}{m_Z}\right) - 2\ln\left(\frac{M_S}{m_Z}\right) + 4\ln\left(\frac{M_3}{M_2}\right)\right]$$

Ms is sfermion and Higgsino masses and M3 and M2 are gluino and wino masses, respectively.

Low-energy SUSY predicts colored Higgs mass around 10^{15} GeV (blue bands in figs), while the gauge coupling unification can be improved in high-scale SUSY.



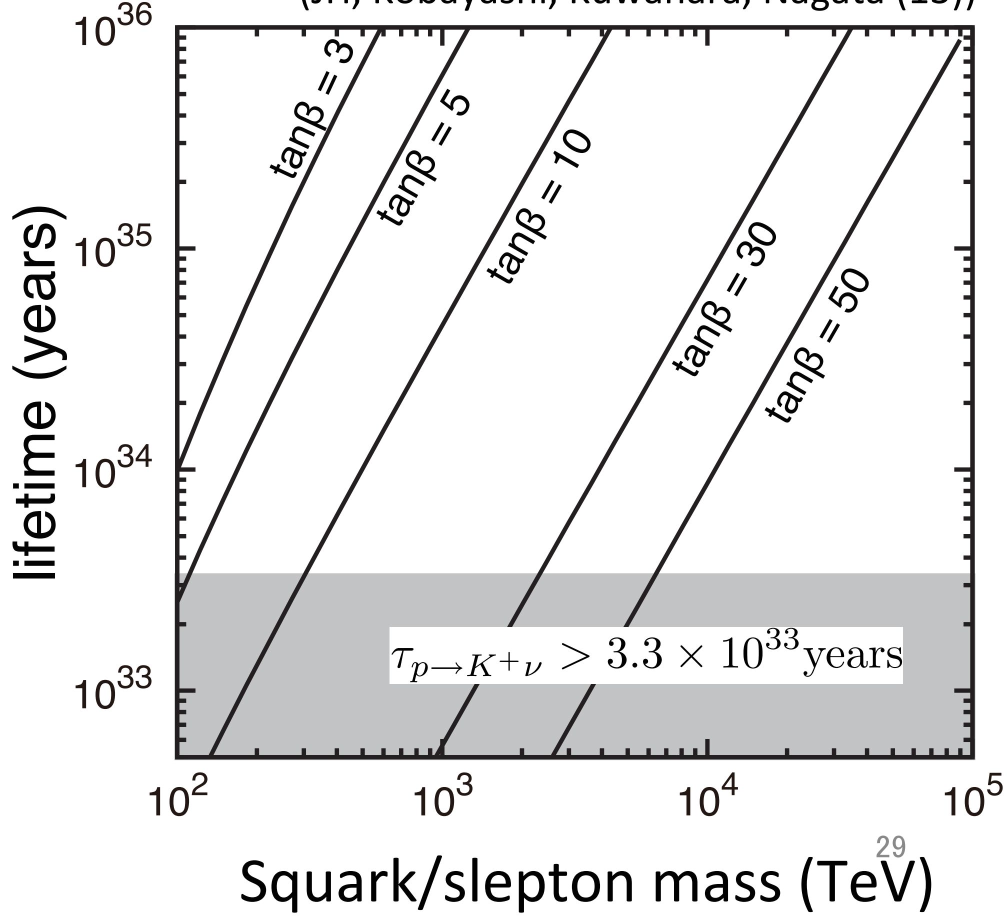
Colored Higgs proton decay

Proton decay induced by colored Higgs exchange killed the minimal SUSY SU(5) GUT with low-scale SUSY. In high-scale SUSY, the proton decay is suppressed so that the model is revived. In addition, future experiments may be accessible, depending on parameters.

(JH, Kobayashi, Kuwahara, Nagata (13))

Higgsino mass is equal to squark/slepton mass.
Wino mass is 3 TeV.

$M_{H_C} = 10^{16}$ GeV



Summary of my talk

- Muon g-2, EWBG, dark matter, and naturalness of Higgs mass motivates us to consider TeV-scale new physics. LHC may give us answers for them.
- Higgs boson properties are constrained from flavor physics. Constraints on EDMs gives bounds on (CP violating) $h\gamma\gamma$ and hgg. Constraints on tau LFV coupling of Higgs at LHC would be competitive to low-energy experiments.
- New ideas for TeV scale should be tested from flavor physics. A realistic extension of MSSM with extra matter has a tension with flavor physics. It is difficult to access high-scale SUSY models, though flavor physics may have windows to them, such as proton decay.