TDLI-PKU BSM workshop 2022
TDLI institute, 8/3

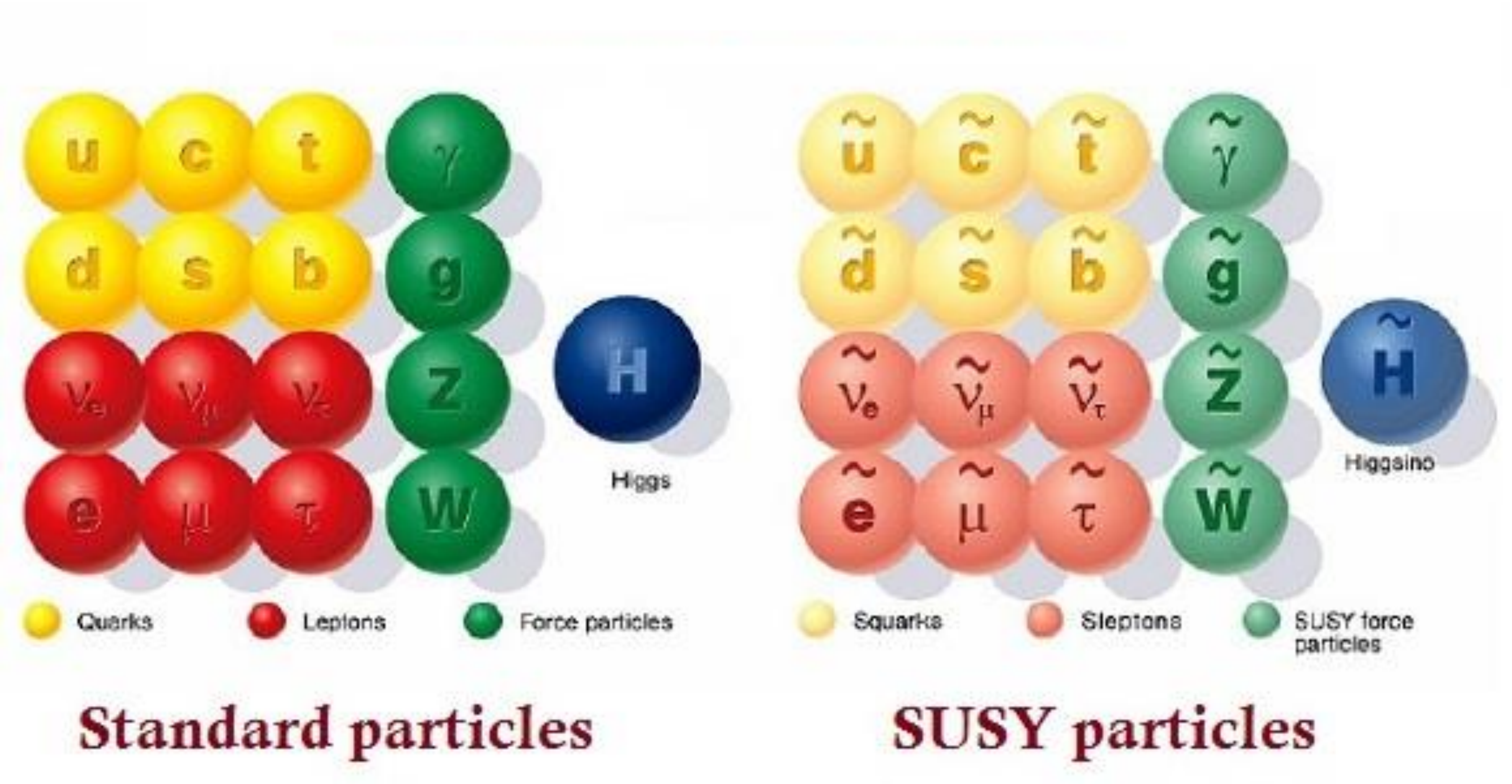
CP/flavor-safe SUSY model for light sleptons

- QCD axion multiplet as a SUSY breaking field -

Norimi Yokozaki (Zhejiang University)

Supersymmetry

- Exchange symmetry between bosons and fermions
- Stabilizing any large hierarchies
- Provide dark matter candidates
- Consistent with grand unified theories (potentially explain charge quantization)

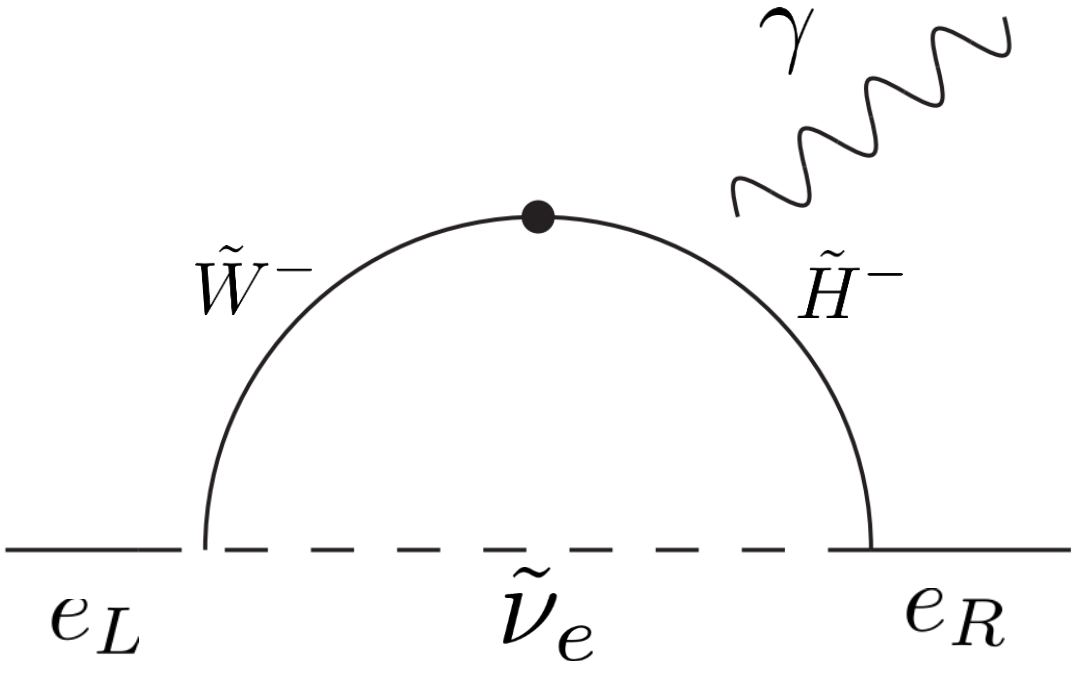


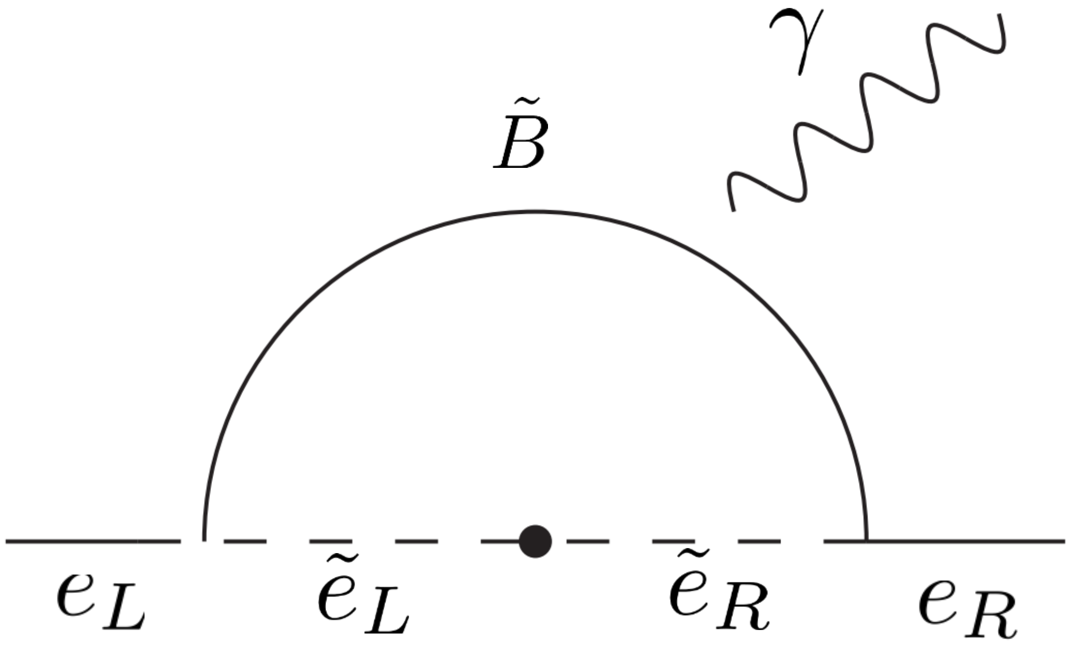
SUSY breaking

- Exact supersymmetry → fermion mass = boson mass, which is obviously inconsistent with collider and other experiments
- Need to introduce **soft SUSY breaking mass parameters**, which determine all the masses of the super-partners and interactions
- Some of the mass parameters have to take highly unnatural values (complex arguments, flavor mixings) otherwise experimental constraints can not be satisfied
- Ultraviolet (UV) model which explains these unnatural SUSY breaking mass parameters is required

Electric dipole moment

Focusing on the electron electric dipole moment (EDM), two leading contributions are





At ● , $\langle H_u \rangle$ is picked up. The diagrams $\propto m_e \tan\beta$

$(\tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle)$

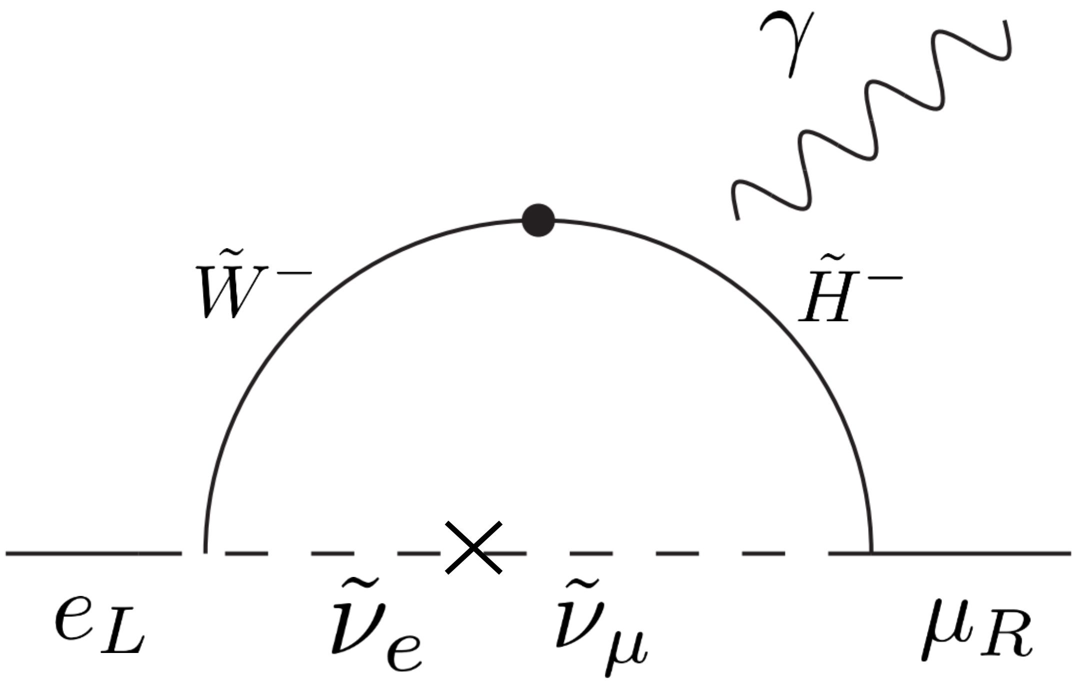
$|d_e| \lesssim 1.1 \times 10^{-29}\, e\,\mathrm{cm}$ → $m_{\mathrm{SUSY}} \gtrsim 50\,\mathrm{TeV}$ for $\tan\beta = 5$

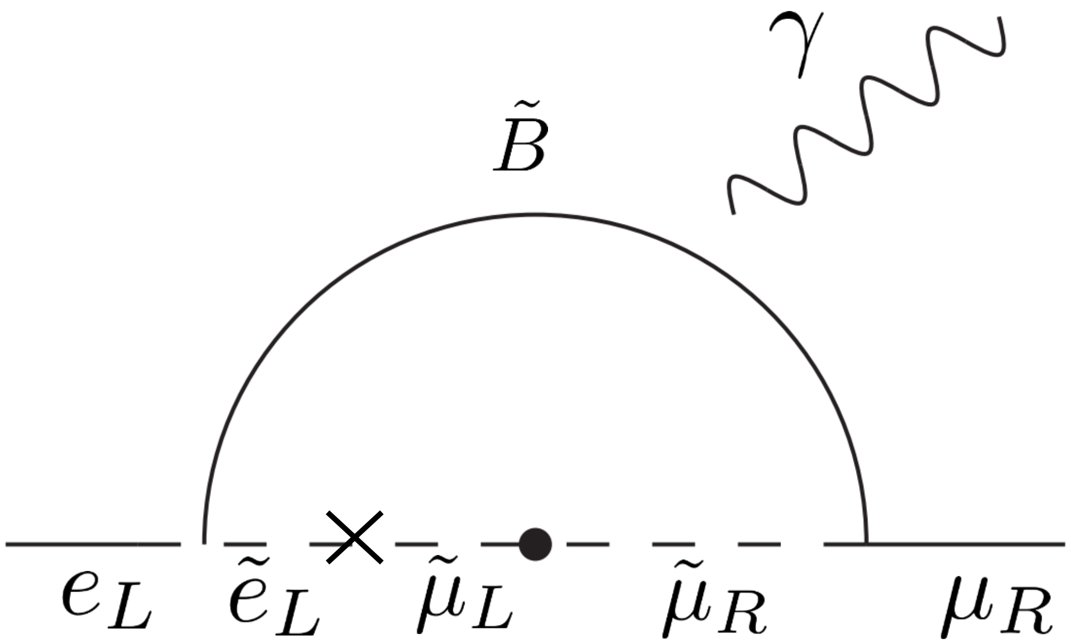
(ACME II)

If the CPV phase is π/2

Lepton flavor violation

Similarly, $\mathrm{Br}(\mu \to e\,\gamma)$ easily exceeds the experimental bound





diagrams $\propto m_\mu \tan\beta$

$\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ ➡ $m_{\mathrm{SUSY}} \gtrsim 20\,\mathrm{TeV}$ for $\tan\beta = 5$

(MEG experiment)

If $(\delta^l_{LL})_{12}$ is close to 1

$$\left((\delta^l_{LL})_{12} = \frac{(m^2_{\tilde{L}})_{12}}{m^2_{\tilde{L}}} \right)$$

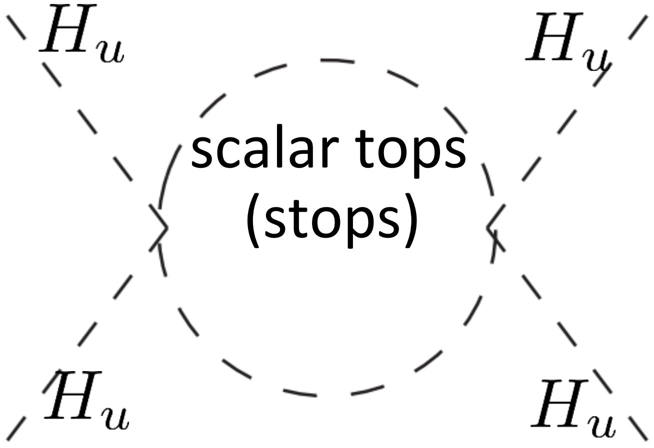
A future mu-e conversion experiment (PRISM/PRIME) is sensitive to the SUSY scale, which is one order of magnitude larger.

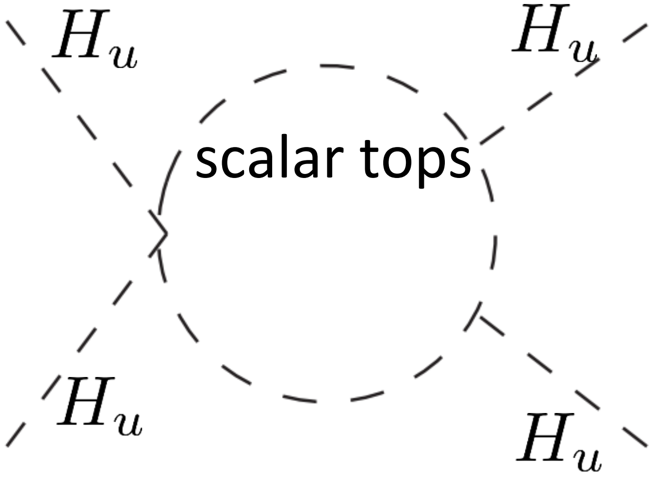
- CP and flavor problems are important for $m_{\rm SUSY} \lesssim \mathcal{O}(10)\,{\rm TeV}$

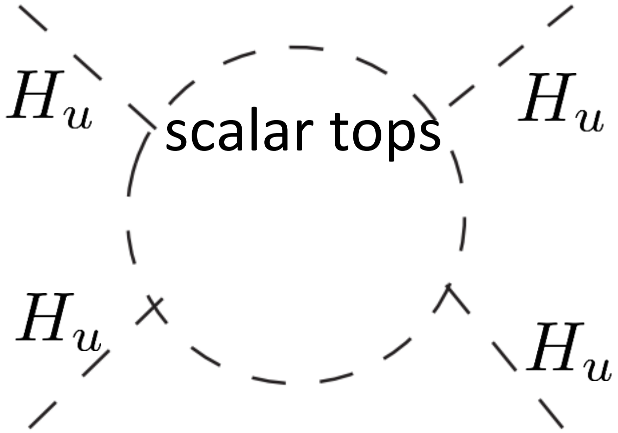
- We have a motivation to consider (partially) light SUSY particles of O(100) GeV, the muon g-2 anomaly (CP/flavor problems are so severe!)

- When the SUSY particles explain the muon g-2 anomaly, CP/flavor safe SUSY breaking becomes much more important

- The Higgs mass of 125 GeV always requires colored SUSY particles to be heavier than 3-10 TeV



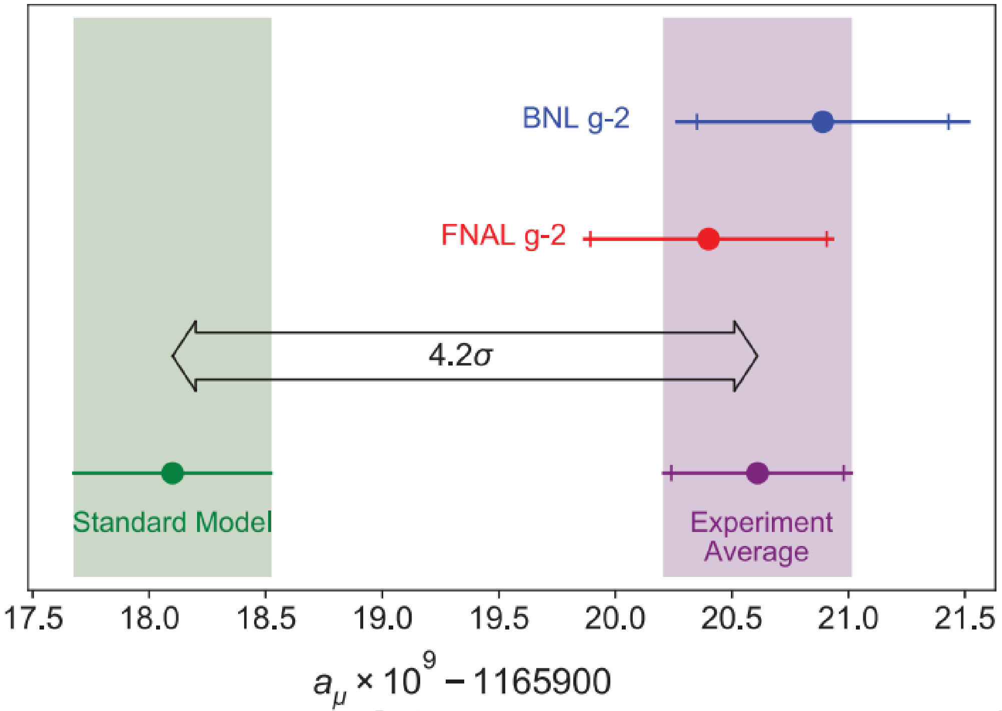




(decrease Higgs mass)

[Okada, Yamaguchi, Yanagida; Ellis, Ridolfi, Zwirner; Haber, Hempfling, 1991;
... Bahl, Hahn, Heinemeyer, Hollik, Paßehr, Rzehak, Weiglein, 2018]

Muon g-2 anomaly



[Phys. Rev. Lett. 126, 141801]

$$a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11},$$

NP contribution must be as large as the W boson contribution in SM

$$\text{c.f. } (a_\mu)_{\mathrm{SM,EW}} \approx 15.4 \times 10^{-10}$$

[from white paper]

For SUSY cases, EW SUSY particles of O(100) GeV can explain the anomaly with tanβ enhancement

SM prediction of the muon g-2?

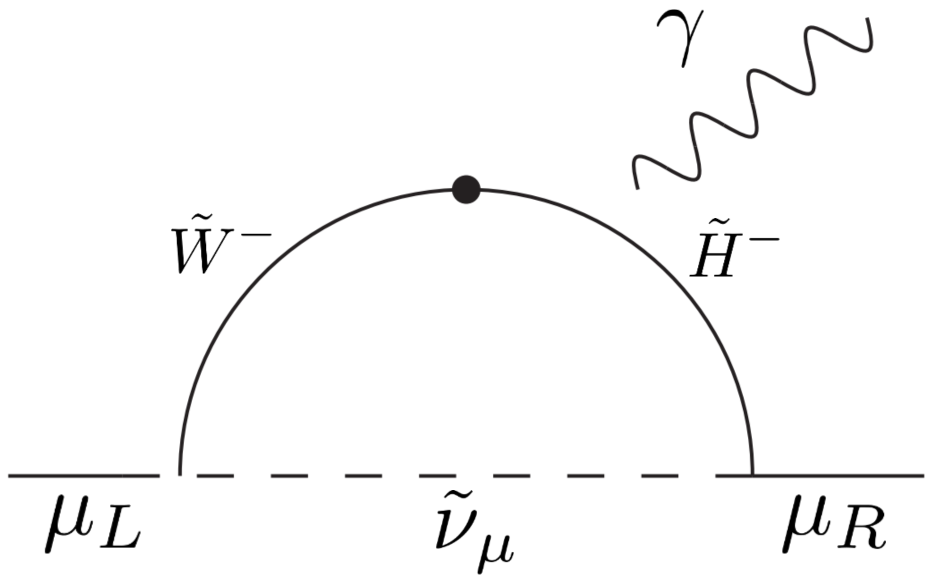
If the lattice calculations are correct, something may be happening in experimental data for $\sqrt{s} \lesssim 1\,\mathrm{GeV}$ (indication from EW fit) [PRD10Z2,033002]

In fact, the shot-distance contribution from the up-to-date lattice result is consistent with those from data-driven approaches [ETMC, 2206.15084]

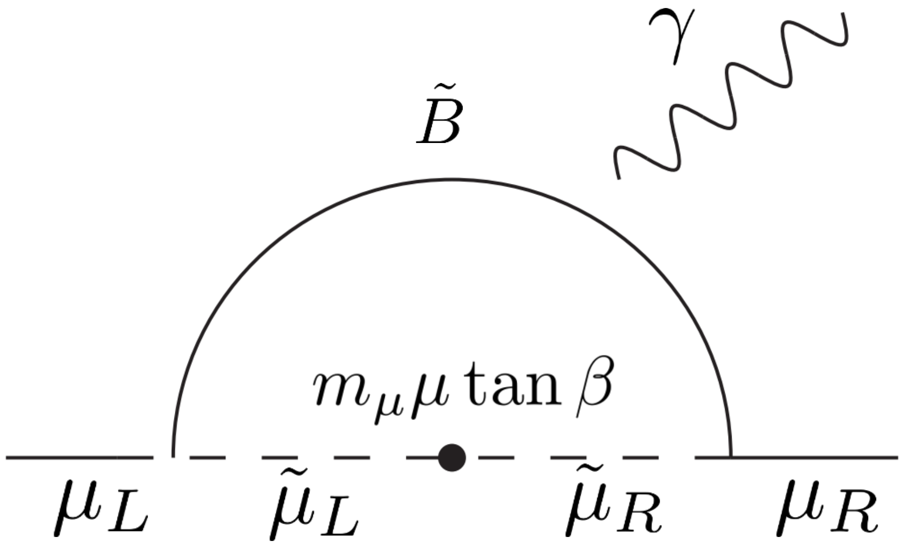
Two usual dominant contributions

SUSY contributes to the muon g-2 through similar diagrams to those of EDM and LFV

☐ For light higgsino



☐ For heavy higgsino



μ : higgsino mass parameter

EDM and LFV are inevitably enhanced

- Electron EDM

$$\theta_{\mathrm{CPV}} \lesssim 10^{-5} \times \left(\frac{(a_\mu)_{\mathrm{SUSY}}}{2.2 \times 10^{-9}} \right)^{-1} \left(\frac{|d_e/e|}{1.1 \times 10^{-29}\mathrm{cm}} \right)$$

- Lepton flavor violation

$$|(\delta^l_{LL})_{12}| \lesssim 5 \times 10^{-5} \left(\frac{(a_\mu)_{\mathrm{SUSY}}}{2.2 \times 10^{-9}} \right)^{-1} \left(\frac{\mathrm{Br}(\mu \to e\gamma)}{4.2 \times 10^{-13}} \right)^{1/2}$$

CPV and LFV need to be so small!

[see e.g., Hisano and Tobe, 2001]

A closer look at CP violation

Two important physical phases are

☐ For light higgsino

$\mathrm{Arg}(M_{\tilde{W}}(B_\mu/\mu)^*)$

☐ For heavy higgsino

$\mathrm{Arg}(M_{\tilde{B}}(B_\mu/\mu)^*)$

$$W \ni \mu H_u H_d$$

$$V(H_u, H_d) \ni B_\mu H_u H_d + h.c.$$

Renormalization group equations mix up the complex arguments

$$\frac{d(B_\mu/\mu)}{d\ln\mu_R} = \frac{1}{16\pi^2}\left(6A_tY_t^2 + 6A_bY_b^2 + 2A_\tau Y_\tau^2 + 6g_2^2 M_{\tilde{W}} + \frac{6}{5}g_1^2 M_{\tilde{B}}\right)$$

$$\frac{dA_{(t,b)}}{d\ln\mu_R} \ni \frac{1}{16\pi^2}\frac{32}{3}g_3^2 M_{\tilde{g}}$$

$$(\Delta(B_\mu/\mu))_{\mathrm{gluino}} \ni \frac{1}{8\pi^4}g_3^2(Y_t^2+Y_b^2)\left[\ln\frac{M_{\mathrm{UV}}}{m_{\mathrm{SUSY}}}\right]^2$$

Equally important

Almost all the SUSY breaking mass parameters must have an aligned phase

A closer look at CP violation

In supergravity, SUSY breaking mass parameters come from two sources

SUSY breaking field

$$Z \ni \langle F_Z \rangle \, \theta^2$$

Gravity multiplet

$$\langle F_\Phi \rangle$$

$|\langle F_Z \rangle| \sim |\langle F_\Phi \rangle M_{\rm PL}|$ ⬅ (almost) vanishing cosmological constant

But $\mathrm{Arg}\,\langle F_Z \rangle \neq \mathrm{Arg}\,\langle F_\Phi \rangle$

At the UV scale (say GUT scale), the soft SUSY breaking mass parameters are

$$M_{\tilde{B}} = k_1 \frac{\langle F_Z \rangle}{M_{\rm PL}} + \frac{33}{5} \frac{g_1^2}{16\pi^2} \langle F_\phi \rangle$$

$$M_{\tilde{W}} = k_2 \frac{\langle F_Z \rangle}{M_{\rm PL}} + \frac{g_2^2}{16\pi^2} \langle F_\phi \rangle$$

$$M_{\tilde{g}} = k_3 \frac{\langle F_Z \rangle}{M_{\rm PL}} - 3 \frac{g_3^2}{16\pi^2} \langle F_\phi \rangle$$

$$B_\mu / \mu = - \langle F_\Phi \rangle + k_H \frac{\langle F_Z \rangle}{M_{\rm PL}}$$

$$A_{t,b,\tau} = \frac{(\mathrm{coupling})^2}{16\pi^2} \langle F_\Phi \rangle + k_{t,b,\tau} \frac{\langle F_Z \rangle}{M_{\rm PL}}$$

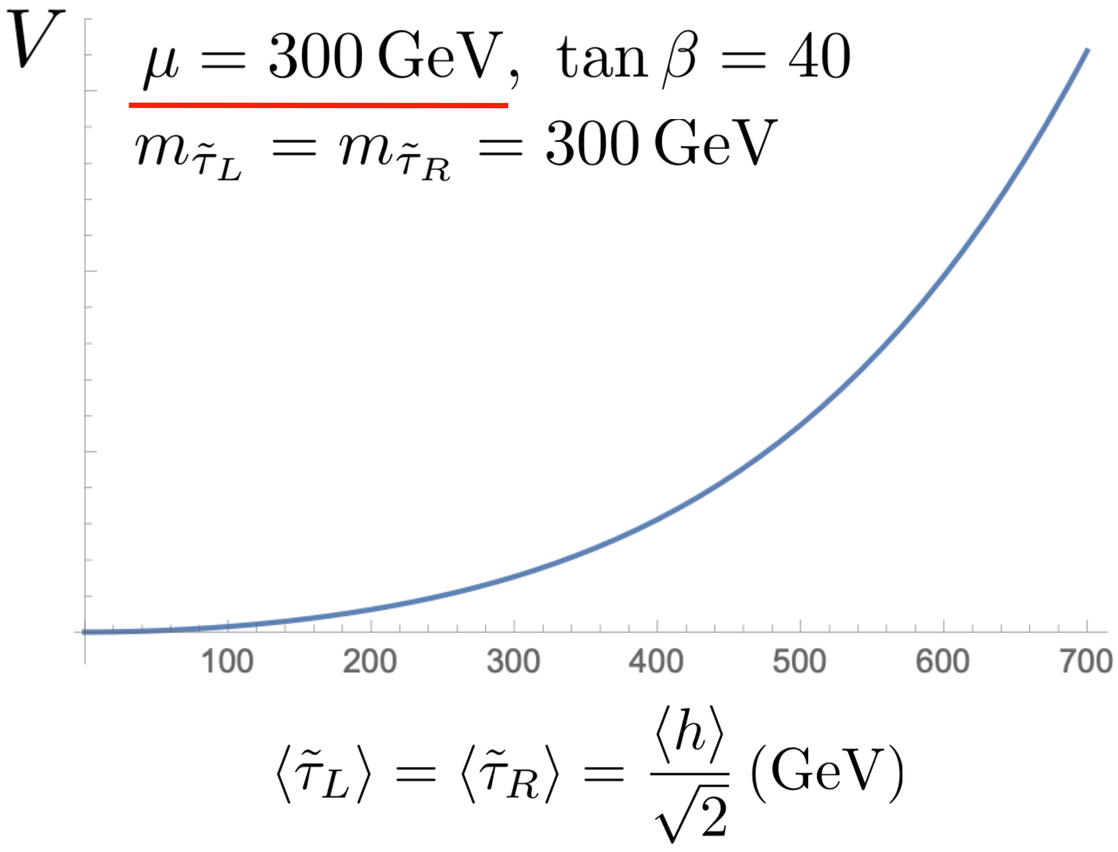
All k are independent complex coefficients

Very difficult to have the aligned phases up to 0.00001

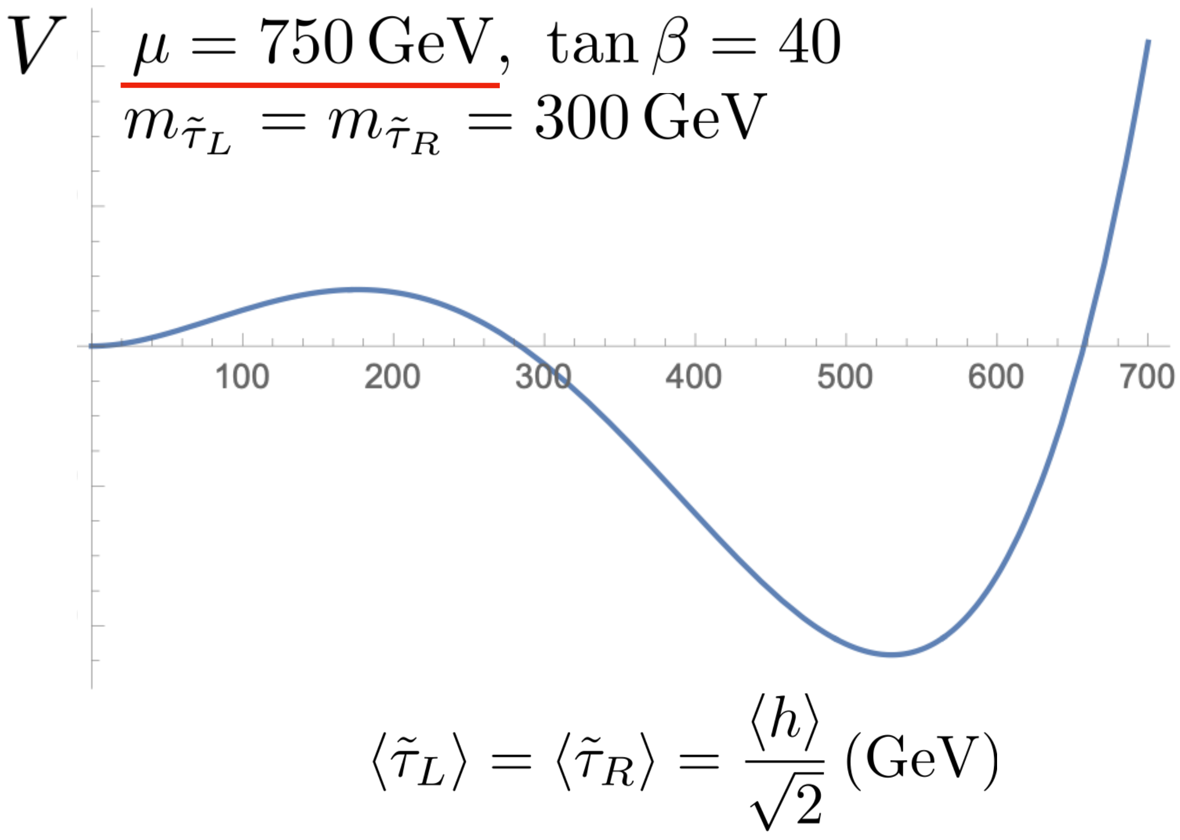
Vacuum stability

- The vacuum stability constraint is severe when the higgsino mass, μ, and tanβ are large → another obstacle for muon g-2 explanation
- Scalar trilinear interaction can generate a charge breaking global minimum

$$-\mathcal{L} \ni -\frac{m_\tau}{v}\boxed{\mu \tan\beta}\frac{h}{\sqrt{2}}\tilde{\tau}_L\tilde{\tau}_R^* + h.c.$$



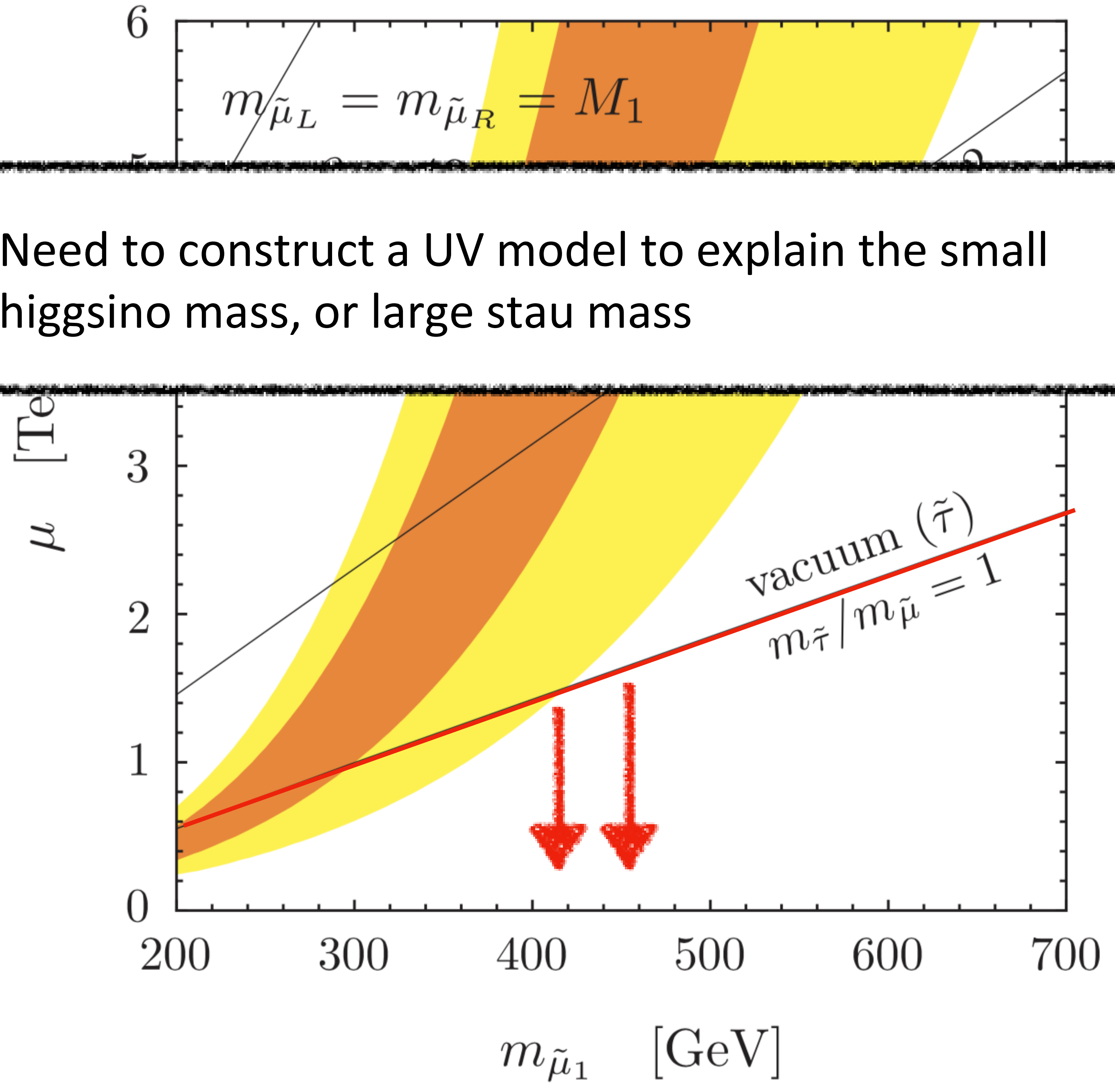
Stable EWSB minimum



Meta-stable EWSB minimum

Muon g-2 vs vacuum stability

- Smuons are O(100) GeV. But the staus are (much) lighter in many UV models, taking into account the renormalization group evolution



Need to construct a UV model to explain the small higgsino mass, or large stau mass

[Endo, Hamaguchi, Kitahara, Yoshinaga, 2013]

Requirements

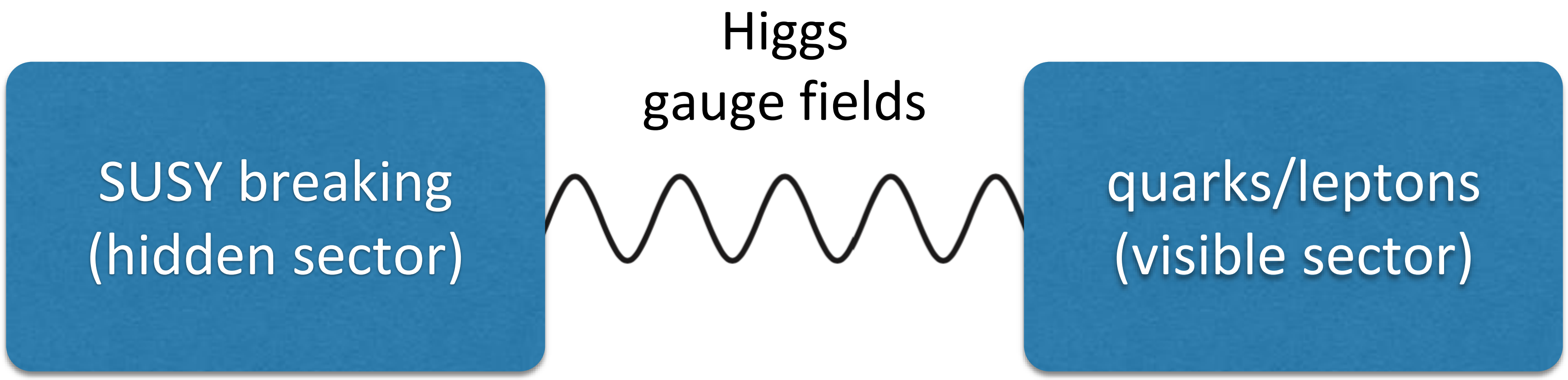
- Small enough flavor violations (in particular lepton flavor violations)
    - Superpartners of fermions (sleptons and squarks) obtain masses only through gauge and Yukawa interactions
- (meta-)stability of the EWSB minimum

  Severe when stau mass ~ smuon mass and $\mu \times \tan\beta$ is large

    - Non-zero SUSY breaking masses of Higgs doublets
        1. For $m_{H_u}^2 > 0$, the small higgsino mass parameter
        2. For $m_{H_u}^2 = m_{H_d}^2 < 0$, Yukawa interactions make the staus heavy
- No CP violating phase
    - Maybe related to the strong CP problem

Concrete setup

- Sleptons and squarks are massless at UV scale due to the separation between SUSY breaking field and lepton/quark multiplets
- This separation is explained in 5D setup or Nambu-Goldstone (NG) picture, where sleptons and squarks are NG bosons of some symmetry breaking
- Only Higgs doublets and gauge multiplets obtain non-zero soft SUSY breaking mass parameters at UV scale (tree level)
- Gauge and Yukawa interactions make sleptons and squarks massive through radiative corrections



Higgs
gauge fields

SUSY breaking
(hidden sector)

quarks/leptons
(visible sector)

[Brane separation: Randall and Sundrum, 1999; Agashe, Ekhterachian, Liu, Sundrum, 2022]
[Squarks and sleptons as NG bosons: Kugo and Yanagida, 1984; Harigaya, Yanagida, Yokozaki; 2015]

CP safe SUSY breaking

- SUSY CP as well the strong CP problem are solved if the SUSY breaking field is charged under a shift symmetry:

$$Z \to Z + i\mathcal{R} \ (\mathcal{R} \text{ is a real constant})$$

[Iwamoto, Yanagida, Yokozaki, 2015]

SUSY breaking field = QCD axion supermultiplet

(Shift symmetry = Peccei-Quinn symmetry)

- Concerning SUSY breaking, Z does not appear in the superpotential due to the shift symmetry. However, the SUSY is broken for vanishing cosmological constant

[Izawa, Kugo, Yanagida, 2011]

CP safe SUSY breaking

SUGRA Lagrangian with the shift symmetry takes

e.g., $M_* \approx M_{\rm PL}/3$

$$\mathcal{L}_{\rm SUGRA} \ni \int d^4\theta |\Phi|^2 \left[-3M_{\rm PL}^2 + M_*^2 g(x) + f_u(x)|H_u|^2 + f_d(x)|H_d|^2 \right]$$

$$+ \left[\int d^2\theta \Phi^3 \mathcal{C} + h.c. \right]$$

$$x = Z + Z^* \qquad \Phi = \phi(1 + F_\phi \theta) \qquad \phi = \left(1 - \frac{M_*^2 \langle g(x) \rangle}{3M_{\rm PL}^2} \right)^{-1/2}$$

$\mathcal{C} \approx m_{3/2} M_{\rm PL}^2$ (taken to be real without a loss of generality)

$g(x), f_u(x)$ and $f_d(x)$ are real functions → No CP violation

---

Equations of motion lead to $V = V(x) = -3\phi^3 F_\phi \mathcal{C}$

Vanishing cosmological constant

$\langle V \rangle = 0$ → $\langle F_\phi \rangle = 0$

No SUSY breaking masses
from the gravity multiplet

Equations of motion → $\langle F_Z \rangle \neq 0$

SUSY must be broken

CP safe SUSY breaking

- The shift symmetry prohibits the tree-level gaugino masses but they are generated by anomalies

e.g. $W = M' e^{-q_a Z} \Psi_a^{I_a} \bar{\Psi}_a^{I_a} \quad (a = U(1)_Y, SU(2)_L, SU(3)_c)$

- The gaugino masses are predicted to be real

canonically normalized $\langle F_Z \rangle = -\sqrt{3} m_{3/2} M_{\rm PL}$

$$\mathcal{L} \ni \frac{\sqrt{2}}{32\pi^2 f_a} \int d^2\theta Z (k_1 \mathcal{W}_1^2 + k_2 \mathcal{W}_2^2 + \mathcal{W}_3^2) + h.c.$$

$$\left(f_a \sim M_*^2 / M_{\rm PL}^2 \sim 10^{17}\,{\rm GeV},\ Z \ni i\frac{a(x)}{\sqrt{2}} \right)$$

real gaugino masses of O(1) TeV
(wino, bino and gluino masses)

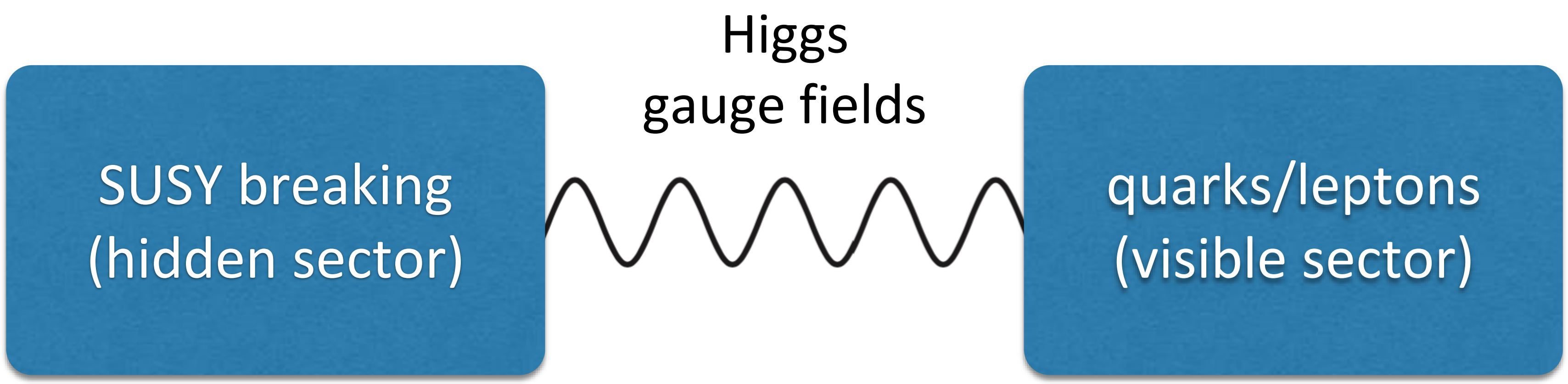
Solves the strong CP!

$$\mathcal{L} \ni \frac{a(x)}{64\pi^2 f_a} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

The gravitino mass m3/2 is taken as O(10) TeV (favored by cosmology)

[Harigaya, Yanagida, Yokozaki, 2017]

CP safe SUSY breaking



Higgs
gauge fields

SUSY breaking
(hidden sector)

quarks/leptons
(visible sector)

+

PQ symmetry: $Z \to Z + i\mathcal{R}$ ($\mathcal{R}$ is a real constant)

- Solves SUSY flavor/CP problem and the strong CP problem
- Squarks and sleptons are massless at the UV scale
- **Only three gaugino masses and soft SUSY breaking mass parameters related to the Higgs doublets are non-zero**
- Imaginary part of Z becomes QCD axion and can be dominant dark matter

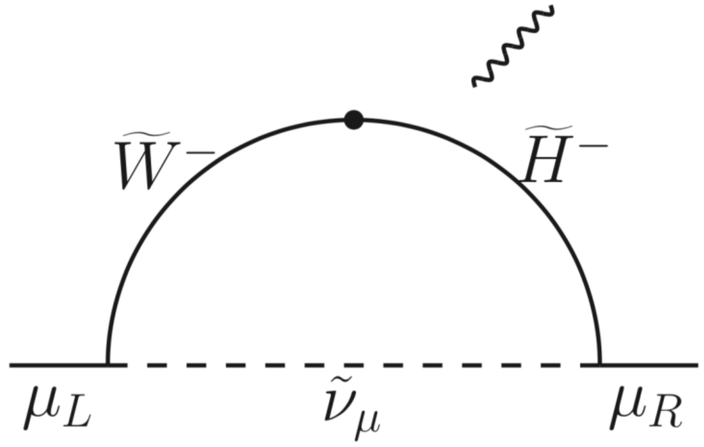
$$m_a \approx 5.7 \times 10^{-11}\,\mathrm{eV}\left(\frac{10^{17}\,\mathrm{GeV}}{f_a}\right)$$

$m_{3/2} = \mathcal{O}(10\,\mathrm{TeV})$ (favored by cosmology)

(How to realize the separation between the hidden sector and visible sector depends on the setup)

Light higgsino case

- With positive $m_{H_u}^2$, higgsino mass, μ, can be small
→ wino-higgsino loop dominant
- Sub-dominant wino-higgsino dark matter has a large cross section with nuclei



The higgsino mass parameter, μ, should be consistent with EWSB conditions

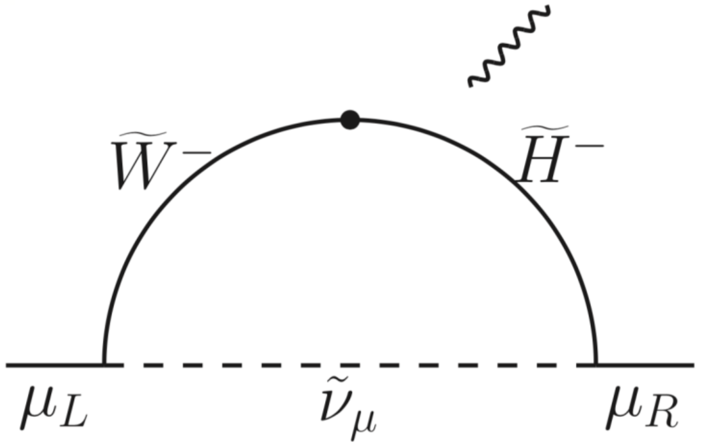
$$\frac{m_Z^2}{2} \approx \mu^2 + (m_{H_u}^2)_{\rm UV} + \underset{\uparrow}{\Delta_{\rm rad} m_{H_u}^2}$$

large and negative
(mainly from stop and gluino loops)

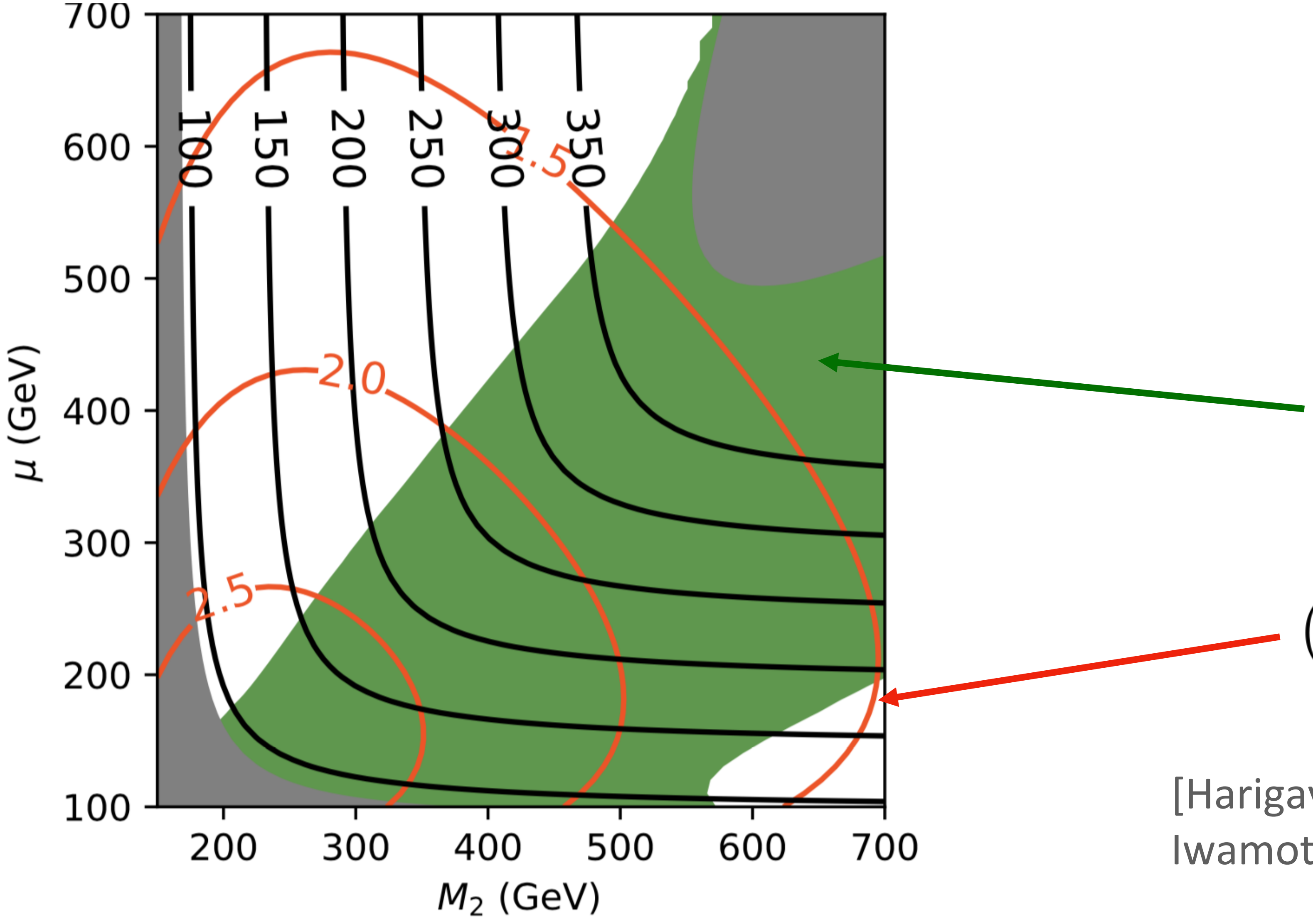
$(m_{H_u}^2)_{\rm UV} \sim (3\,{\rm TeV})^2$ is required

Light higgsino case

- With positive $m_{H_u}^2$, higgsino mass, μ, can be small
  → wino-higgsino loop dominant
- Sub-dominant wino-higgsino dark matter has a large cross section with nuclei



$(M_1, M_3, A_u, m_A) = (3800, 2500, -1000, 2000)$ GeV and $\tan\beta = 40$.



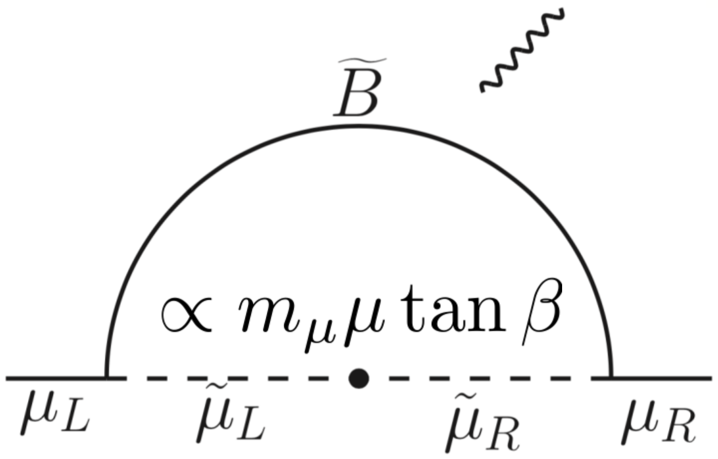
excluded by direct detection (XENON)

$(a_\mu)_{\rm SUSY} \times 10^9$

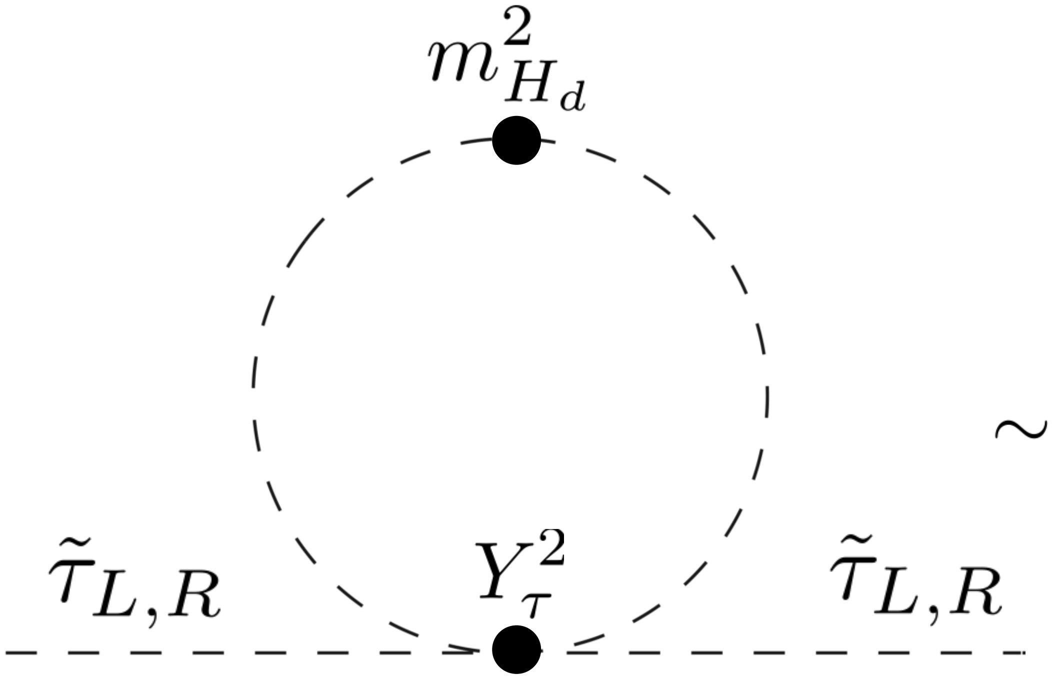
[Harigaya, Yanagida, Yokozaki, 2015; Iwamoto, Yanagida, Yokozaki, 2021]

Heavy higgsino case

- Bino-loop proportional to the higgsino mass parameter is dominant (wino-higgsino loop is suppressed)
- Bino can becomes a dominant or sub-dominant dark matter (with coannhilation mechanism)
- Vacuum stability constraint is avoided with heavy staus



Negative $m_{H_d}^2 \simeq m_{H_u}^2$ generate large stau mass



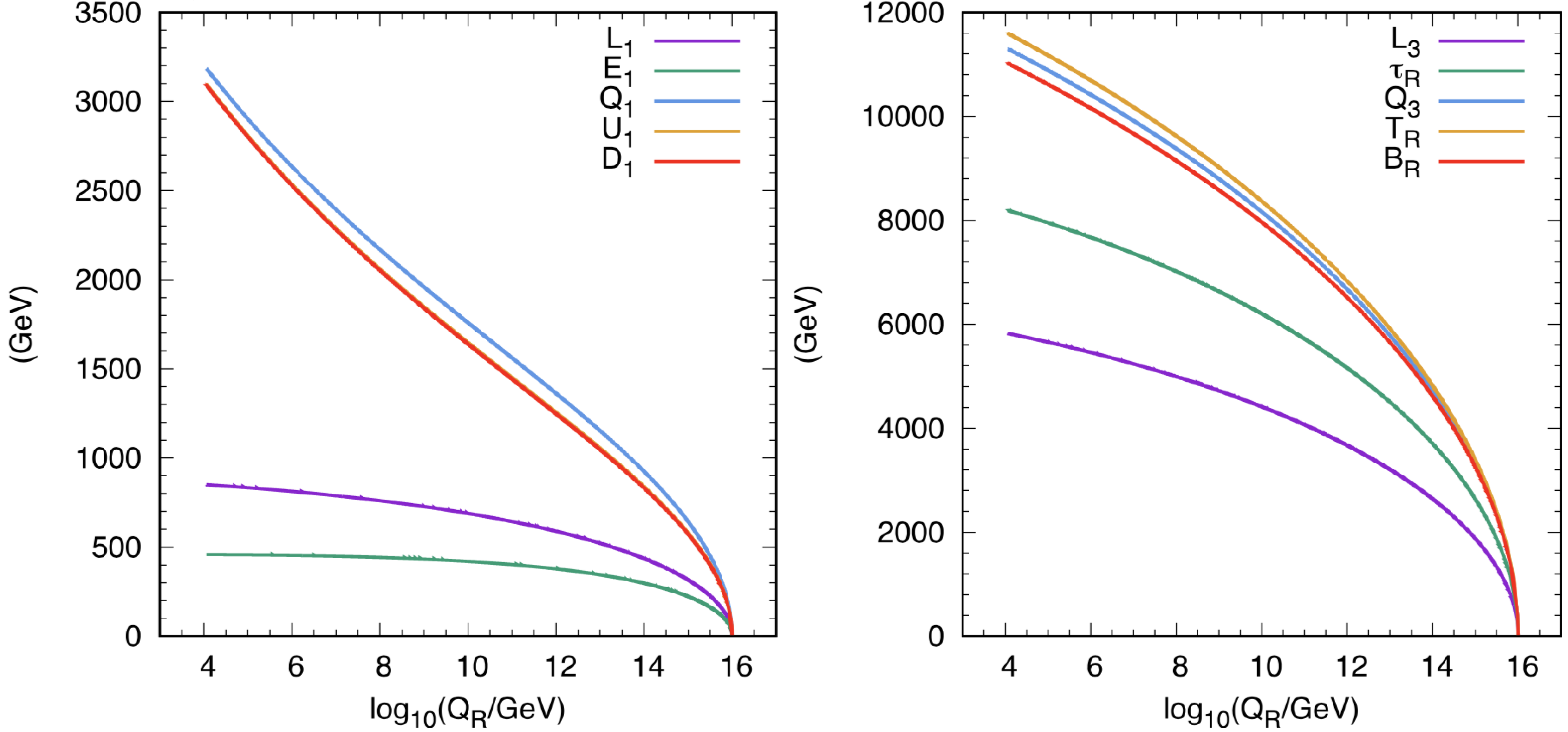
$$\sim \frac{Y_\tau^2}{8\pi^2}(-m_{H_d}^2)\ln\frac{M_{\rm GUT}}{m_{\rm SUSY}}$$

[Yamaguchi, Yin, 2016; Yin, Yokozaki, 2016]

Higgs loop effects

- Staus stops and sbottoms becomes heavy during renormalization group evolution
- Flavor violation only comes from CKM matrix

$$m^2_{H_{u/d}} = -7\times 10^8\,\mathrm{GeV}^2,\ \tan\beta = 40,\ (M_{\mathrm{bino}}, M_{\mathrm{wino}}, M_{\mathrm{gluino}}) = (440, 220, -2000)\,\mathrm{GeV}$$

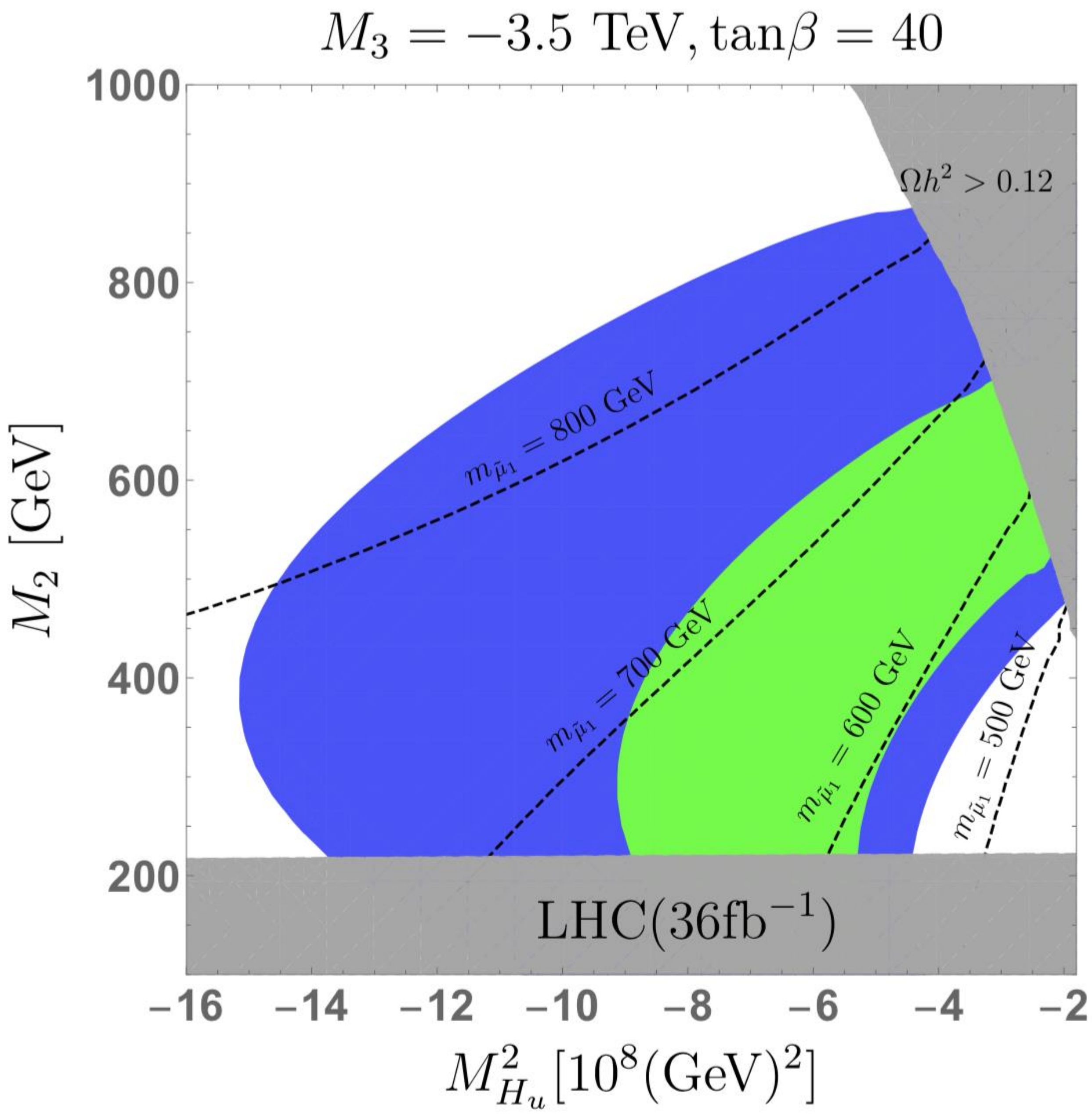


[Yin, Yokozaki, 2015; Cox, Han, Yanagida, Yokozaki, 2018]

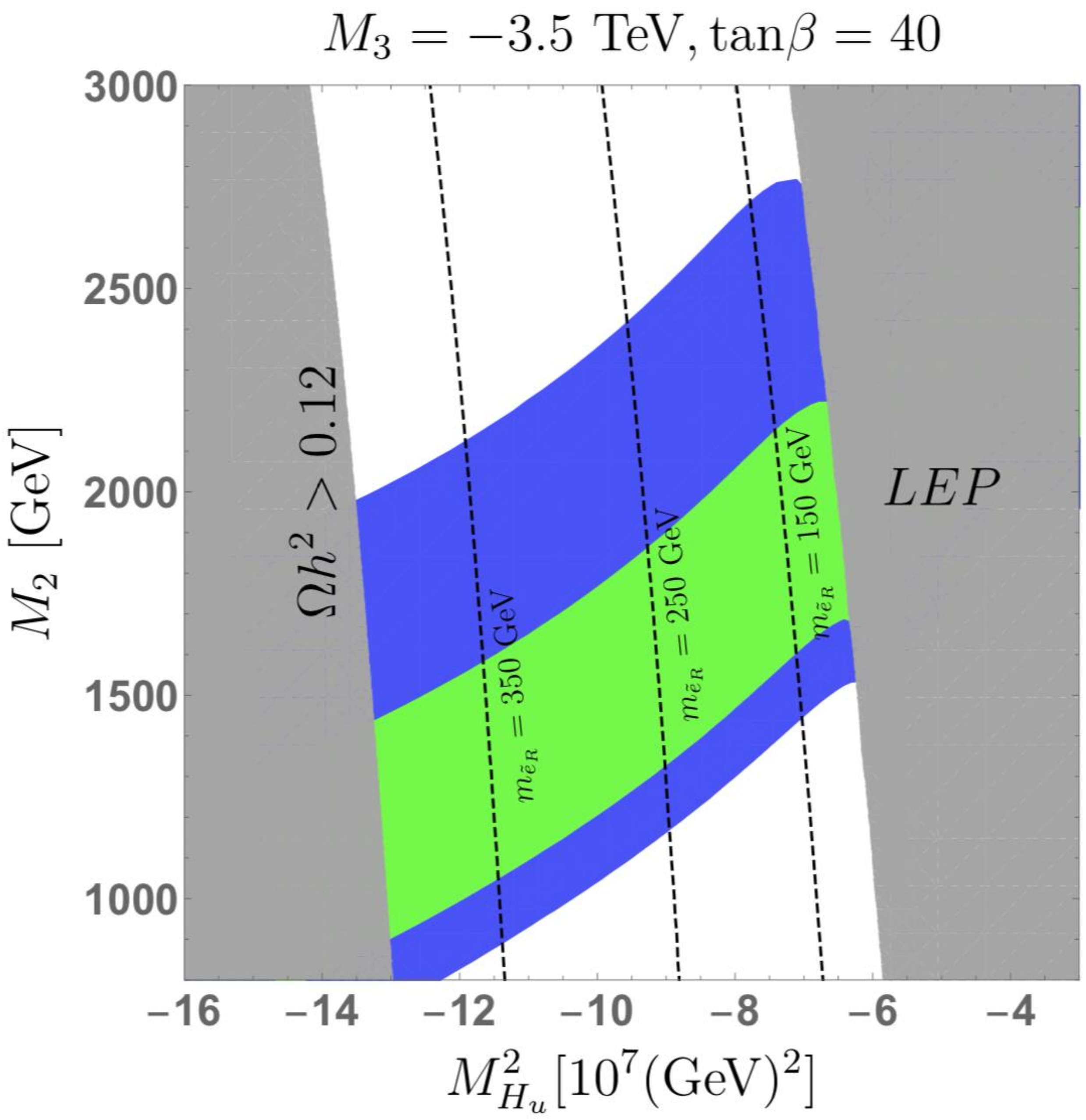
Muon g-2 and dark matter

Coannihilation is necessarily to sufficiently reduce the relic density of bino

Bino-wino coannihilation



Bino-slepton coannihilation



[Cox, Han, Yanagida, Yokozaki, 2018]

Conclusion

- CP/flavor issues are so severe for light slepton scenarios (in particular, CP problem is difficult to be solved)
- QCD axion multiplet can be origin of SUSY breaking, which predicted all the soft SUSY breaking mass parameters to be (essentially) real at the UV scale
- The muon g-2 anomaly is consistently explained
- Non-universal gaugino masses are consistent with some grand unified theory models (e.g. $SU(5) \times U(3)$ and $SU(5) \times U(2)$)

[PGU: Yanagida, 1994; Hotta, Izawa, Yanagida, 1995]
[Non-universal gaugino masses: Harigaya, Yanagida, Yokozaki, 2015]

Non-universal gaugino masses

As an example, consider SU(5) x U(3) product group unification model

$$
\begin{aligned}
g_1^{-2} &= g_5^{-2} + \mathcal{N}^{-1} g_{1H}^{-2} \,, \\
g_2^{-2} &= g_5^{-2} \,, \\
g_3^{-2} &= g_5^{-2} + g_{3H}^{-2} \,,
\end{aligned}
$$

approximate coupling unification

for $g_{1H}^2 , g_{3H}^2 \gg g_5^2$

$$
\begin{aligned}
\mathcal{L} = &\int d^2\theta \left(\frac{1}{4g_5^2} - \frac{k_5}{2M_P} Z \right) W_5 W_5 + h.c. \\
&+ \int d^2\theta \left(\frac{1}{4g_{3H}^2} - \frac{k_{3H}}{2M_P} Z \right) W_{3H} W_{3H} + h.c. \\
&+ \int d^2\theta \left(\frac{1}{4g_{1H}^2} - \frac{k_{1H}}{2M_P} Z \right) W_{1H} W_{1H} + h.c. \,,
\end{aligned}
$$

➡

$$
\begin{aligned}
M_1 &= (k_5 \mathcal{N} + k_{1H}) \frac{g_5^2 g_{1H}^2}{g_5^2 + \mathcal{N} g_{1H}^2} \frac{F_Z}{M_P} \,, \\
M_2 &= k_5 g_5^2 \frac{F_Z}{M_P} \,, \\
M_3 &= (k_5 + k_{3H}) \frac{g_5^2 g_{3H}^2}{g_5^2 + g_{3H}^2} \frac{F_Z}{M_P} \,,
\end{aligned}
$$