

Revisiting Flavor and CP Violation in Supersymmetric SU(5) with Right-handed Neutrinos

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Based on

arXiv:1807.08234 with J.L.Evans (KIAS) and K.Kadota (ibs-CTPU)

SUSY SU(5) GUTs

- Minimal models of Supersymmetric Grand Unified Theories
- Each generations unified into $\bar{5}+10(+1)$ in SU(5)

SUSY SU(5) w/ 3 N_{RS}

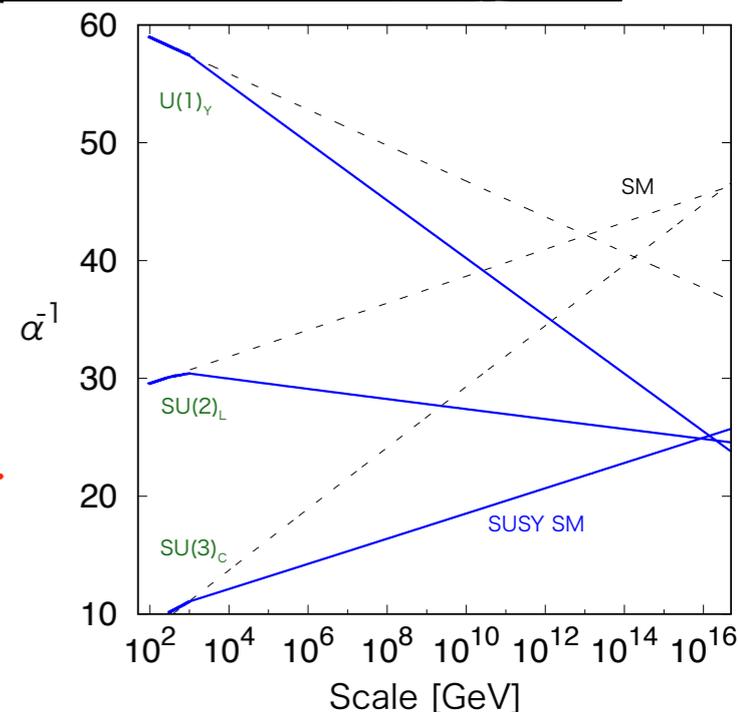
Matter Contents

$$\Psi_i = (Q_i, \bar{U}_i, \bar{E}_i), \quad \Phi_i = (\bar{D}_i, L_i), \quad \bar{N}_i$$

- Neutrino Mass: Right-handed Neutrinos & (type-I) Seesaw mechanism

Higgs Contents

$$H = (H_u, H_C), \quad \bar{H} = (H_d, \bar{H}_C), \quad \Sigma$$



Superpotential

$$W = \frac{f_{ij}^u}{4} \Psi_i \Psi_j H + \sqrt{2} f_{ij}^d \Psi_i \Phi_j \bar{H} + f_{ij}^\nu \Phi_i \bar{N}_j H + \frac{1}{2} (M_R)_{ij} \bar{N}_i \bar{N}_j + W_{\text{GUT}} + W_{\text{Pl}}$$

$$W_{\text{GUT}} = \mu_H \bar{H} H + \lambda \bar{H} \Sigma H + \frac{\mu_\Sigma}{2} \text{Tr} \Sigma^2 + \frac{\lambda_\Sigma}{3} \text{Tr} \Sigma^3$$

$$W_{\text{Pl}} = \frac{c}{M_{\text{Pl}}} \text{Tr}[\Sigma \mathcal{W} \mathcal{W}] + \dots$$

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Using field rotation, Yukawa matrices in mass basis are given by

$$f_{ij}^u = f_i^u e^{i\varphi_{u_i}} \delta_{ij},$$

$$f_{ij}^d = f_i^d V_{ij}^*,$$

$$f_{ij}^\nu = f_j^\nu e^{i\varphi_{d_i}} U_{ij}^*,$$

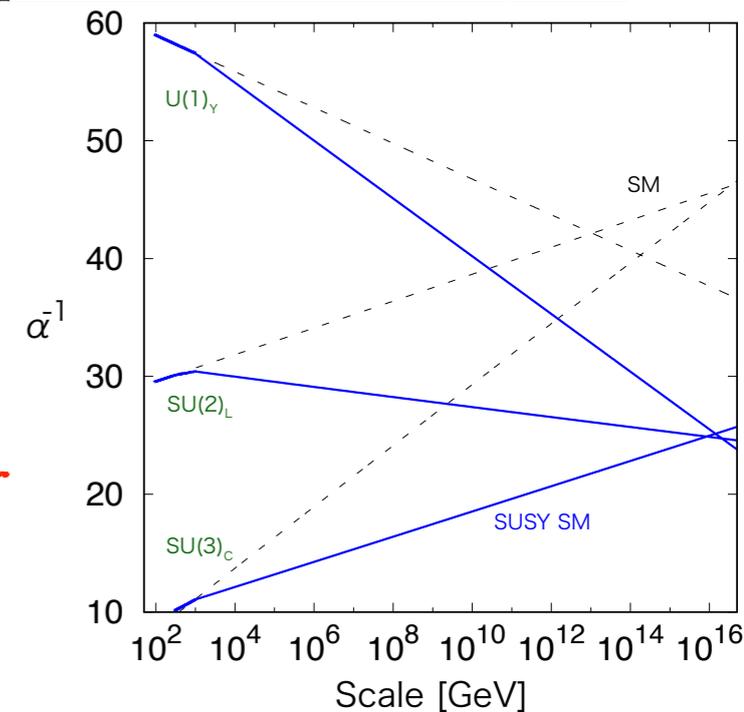
$$(M_R)_{ij} = e^{i\varphi_{\nu_i}} W_{ik} (M_R^D)_k e^{2i\varphi_{\nu_k}} W_{jk} e^{i\varphi_{\nu_j}} \rightarrow M_R \delta_{ij},$$

Additional GUT-scale phases appear.

$$\sum_i \varphi_{f_i} = 0 \quad (f = u, d, \nu)$$

Model Parameters (from SU(5) with RNs)

$$M_R, \varphi_{u_i}, \varphi_{d_i}$$



Universality

A way avoiding dangerous flavor and/or CP violating phenomena.

$$\begin{aligned}
 -\mathcal{L}_{\text{soft}} = & (m_{10}^2)_i^j \tilde{\psi}^{*i} \tilde{\psi}_j + (m_{\bar{5}}^2)_i^j \tilde{\phi}^{*i} \tilde{\phi}_j + (m_N^2)_i^j \tilde{n}^{*i} \tilde{n}_j + m_H^2 H^\dagger H + m_{\bar{H}}^2 \bar{H}^\dagger \bar{H} + m_\Sigma^2 \Sigma^\dagger \Sigma \\
 & + \left(\frac{(A_{10})_{ij}}{4} \tilde{\psi}_i \tilde{\psi}_j H + \sqrt{2} (A_{\bar{5}})_{ij} \tilde{\psi}_i \tilde{\phi}_j \bar{H} + (A_N)_{ij} \tilde{\phi}_i \tilde{n}_j H + (B_N)_{ij} \tilde{n}_i \tilde{n}_j + \text{h.c.} \right) \\
 & + \left(\frac{1}{2} M_5 \lambda^a \lambda^a + B_H \bar{H} H + A_\lambda \bar{H} \Sigma H + \frac{B_\Sigma}{2} \text{Tr} \Sigma^2 + \frac{A_\Sigma}{3} \text{Tr} \Sigma^3 + \text{h.c.} \right)
 \end{aligned}$$

- **Scalar Masses Universality** $(m_{\text{sfermions}}^2)_i^j = m_0^2 \delta_i^j$, $m_{\text{Higgses}}^2 = m_0^2$
- **A-term Universality** $A_Y = A_0 f_Y$
- **Gaugino masses** $M_5 = M_{1/2}$

This universality is assumed at the input scale M_{in} :

- $M_{\text{in}} = \text{GUT Scale } (2 \times 10^{16} \text{ GeV})$: “CMSSM”
- $M_{\text{in}} = \text{GUT Scale} \sim \text{Planck Scale}$: “**super-GUT scenarios**”
- $M_{\text{in}} = \text{below GUT Scale}$: “sub-GUT scenarios”

of parameters in the models where CMSSM-like boundary conditions are assumed

$$m_0, M_{1/2}, A_0, \tan \beta, \text{sgn}(\mu), M_{\text{in}}$$

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 \end{aligned}$$

μ and $B\mu$ terms are determined to satisfy EWSB conditions as usual CMSSM case

$$|\mu|^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta + \frac{1}{2} m_Z^2 (1 - \tan^2 \beta) + \Delta_\mu^{(1)}}{\tan^2 \beta - 1 + \Delta_\mu^{(2)}} \quad @ \text{ SUSY scale}$$

$$B\mu = -\frac{1}{2} (m_{H_u}^2 + m_{H_d}^2 + 2\mu^2) \sin 2\beta + \Delta_B$$

A non-trivial constraint on the soft SUSY breaking parameters in super-GUT models

$$\text{B-condition} \quad \left(\frac{A_\Sigma}{\lambda_\Sigma} \right)^2 \gtrsim 8m_\Sigma^2 \quad @ \text{ GUT scale}$$

[Ellis, Evans, Mustafayev, Nagata, Olive '16]

if universal soft parameters are assumed to be real at input scale.

CP phases in soft SUSY parameters @ M_{in} set to be zero

Flavor & CPV Physics

In the minimal SU(5), if CMSSM-like boundary conditions (real) are assumed at M_{in}
Flavor violation / CP violation arises only from CKM angles / phase

In the SUSY SU(5) w/ RNs

Large mixing and phases in the neutrino sector

PMNS mixing angles and Dirac CP phase (central values in PDG)

$$\sin^2 \theta_{12} = 0.297, \quad \sin^2 \theta_{23} = 0.425, \quad \sin^2 \theta_{31} = 0.0214, \quad \delta_{CP} = 1.38\pi.$$

RGEs b/w M_{in} and $M_{\text{GUT}}/M_{\text{R}}$

FV & CPV in right-handed sdown and charged slepton sector arise

$$\begin{aligned} (m_{\tilde{d}}^2)_{ij} &\simeq -\frac{1}{8\pi^2} e^{i(\varphi_{d_i} - \varphi_{d_j})} U_{ik} (f_k^\nu)^2 U_{jk}^* (3m_0^2 + A_0^2) \ln \frac{M_{\text{in}}}{M_{\text{GUT}}} \\ (m_{\tilde{L}}^2)_{ij} &\simeq -\frac{1}{8\pi^2} e^{i(\varphi_{d_i} - \varphi_{d_j})} U_{ik} (f_k^\nu)^2 U_{jk}^* (3m_0^2 + A_0^2) \ln \frac{M_{\text{in}}}{(M_{\text{R}}^D)_k} \end{aligned} \quad (i \neq j)$$

Assuming diagonal Majorana mass matrices M_{R}

We focus on FV: **PMNS mixing angles**
 CPV: **PMNS phases** and **GUT scale phases** in this study.

FV & CPV constraints

- Meson Oscillation (Kaon mixing)

SUSY contributions w/ mass insertion approx.

$$\mathcal{H}_{\text{eff.}}^{\Delta S=2} \simeq -\frac{\alpha_S^2}{36m_{\tilde{q}}^2} \left(\Delta_{12}^{(R)}\right)^2 F_1 \left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right) \bar{d}_R^\alpha \gamma_\mu s_R^\alpha \bar{d}_R^\beta \gamma^\mu s_R^\beta - \frac{\alpha_S^2}{3m_{\tilde{q}}^2} \Delta_{12}^{(L)} \Delta_{12}^{(R)} F_2 \left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right) \bar{d}_L^\alpha s_R^\alpha \bar{d}_R^\beta s_R^\beta$$

$$- \frac{\alpha_S^2}{9m_{\tilde{q}}^2} \Delta_{12}^{(L)} \Delta_{12}^{(R)} F_3 \left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right) \bar{d}_L^\alpha s_R^\beta \bar{d}_R^\beta s_R^\alpha$$

$$(m_{\tilde{d}}^2)_{12} \simeq -\frac{1}{8\pi^2} e^{i(\varphi_{d_1} - \varphi_{d_2})} U_{1k} (f_k^\nu)^2 U_{2k}^* (3m_0^2 + A_0^2) \ln \frac{M_{\text{in}}}{M_{\text{GUT}}}$$

SUSY contributions

$$\Delta m_K^{\text{SUSY}} = 2\text{Re} \left\langle \bar{K}^0 \left| \mathcal{H}_{\text{eff.}}^{\Delta S=2} \right| K^0 \right\rangle ,$$

$$\epsilon_K^{\text{SUSY}} = \frac{1}{\sqrt{2}\Delta m_K} \text{Im} \left\langle \bar{K}^0 \left| \mathcal{H}_{\text{eff.}}^{\Delta S=2} \right| K^0 \right\rangle$$

Hadron matrix elements:

SM op.: [FLAG average '16]

BSM ops.: [SWME collaboration '15]

Constraints on FV and CPV

Experimental values

$$\Delta m_K|_{\text{exp}} = (3.484 \pm 0.006) \times 10^{-12} \text{ MeV}$$

$$|\epsilon_K|_{\text{exp}} = (2.228 \pm 0.011) \times 10^{-3}$$

SM predictions

$$\Delta m_K|_{\text{SM}} = 3.19(41)(96) \times 10^{-12} \text{ MeV} \quad [\text{Bai, Christ, Izubuchi, Sachrajda, Soni, Yu '15}]$$

$$|\epsilon_K|_{\text{SM}} = 2.24(19) \times 10^{-3} \quad [\text{Ligeti, Sala '16}]$$

Constraints on model

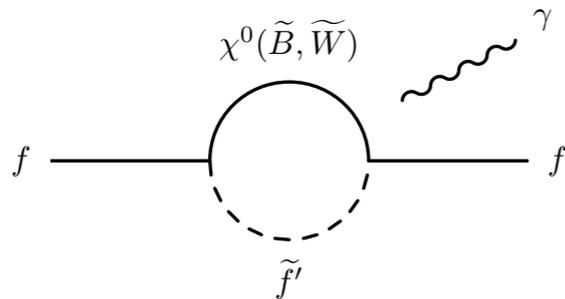
$$* \quad |\epsilon_K|_{\text{SUSY}} \lesssim 0.31 |\epsilon_K|_{\text{SM}} \simeq 0.69 \times 10^{-3}$$

[Ligeti, Sala '16]

- * Δm_K should be less than exp. and th. errors

FV & CPV constraints

- Electric Dipole Moments (EDMs)



SUSY Contributions

1-loop: neutralino-sfermion diagrams

2-loop: Barr-Zee contributions

Main contribution: 1-loop w/ FV

$$\frac{d_e}{e} \sim \frac{g_Y^2}{32\pi^2} \frac{m_\tau}{m_{\tilde{l}}^2} \frac{\mu M_1}{m_{\tilde{l}}^2} \text{Im}[(\Delta_l^{(L)})_{13} (\Delta_l^{(R)})_{31}] f(x)$$

[Hisano, Nagai, Paradice '07]

$$(m_{\tilde{L}}^2)_{13} \simeq -\frac{1}{8\pi^2} e^{i(\varphi_{d_1} - \varphi_{d_3})} \sum_k U_{1k} (f_k^\nu)^2 U_{3k}^* (3m_0^2 + A_0^2) \ln \frac{M_{\text{in}}}{(M_R^D)_k}$$

Recent Constraint on EDM

$$|d_e| \lesssim 9.3 \times 10^{-29} \text{ e cm} \quad [\text{ACME collaboration '16}]$$

Neutron EDM, other atomic EDMs: weak constraints on our model

- Determination of GUT-scale phases

$$\varphi_{d_1} - \varphi_{d_2}$$

ϵ_K maximized

$$\varphi_{d_1} - \varphi_{d_3}$$

d_e maximized (or we choose moderate value)

to see aggressive bounds

FV & CPV constraints

- Proton Decay

is also challenging in the SUSY SU(5)

$$M_{HC} \gtrsim 10^{17} \text{ GeV}$$

Proton decay constraint ($M_s \sim 10 \text{ TeV}$)

$$\tau(p \rightarrow K^+ \bar{\nu}) \gtrsim 6.6 \times 10^{33} \text{ years}$$

$$M_{HC} \simeq 10^{15} \text{ GeV}$$

Gauge coupling unification

in minimal SU(5)

Unification constraint is relaxed by the M_{Pl} suppressed operator

$$\frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} - \frac{1}{g_1^2(Q)} = \frac{1}{2\pi^2} \frac{3}{5} \ln \frac{M_{HC}}{Q} - 12 \frac{8cv}{M_{\text{Pl}}}$$

$$\frac{5}{g_1^2(Q)} - \frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} = \frac{3}{2\pi^2} \ln \frac{M_X^2 M_\Sigma}{Q^3}$$

$$W_{\text{Pl}} = \frac{c}{M_{\text{Pl}}} \text{Tr}[\Sigma \mathcal{W} \mathcal{W}] + \dots$$

[Tobe, Wells '03]

M_{HC} : function of Yukawa couplings among GUT-Higgses

($\rightarrow \lambda \sim O(1)$, $\lambda_\Sigma \ll 1$ are required)

$$M_{HC} = \lambda \left(\frac{M_X^2 M_\Sigma}{g_5^2 \lambda_\Sigma} \right)^{1/3}$$

$\tan \beta$: small value is preferred (assume to be 6 in numerical studies)

$$\lambda = 0.5, \quad \lambda_\Sigma = 10^{-4}$$

φ_{u_i} : are assumed to ensure the longevity of protons

Wilson coefficients for D=5 proton decay

$$C_{5L}^{ijkl} = -\frac{1}{M_{HC}} f_i^u e^{i\varphi_{u_i}} \delta^{ij} V_{kl}^* f_l^d$$

$$C_{5R}^{ijkl} = -\frac{1}{M_{HC}} f_i^u V_{ij} V_{kl}^* f_l^d e^{-i\varphi_{u_k}}$$

Recall free parameters

Fixed to ensure proton long lifetime

$$\lambda = 0.5, \quad \lambda_\Sigma = 10^{-4}$$

$$\tan \beta = 6$$

$m_0^2, M_{1/2}, A_0, \tan \beta, \text{sgn}(\mu), M_{\text{in}}, M_R, \lambda, \lambda_\Sigma, \varphi_{u_i}, \varphi_{d_i}$

finite A_0 is preferred

- Higgs mass
- B-condition

$$\left(\frac{A_\Sigma}{\lambda_\Sigma} \right)^2 \gtrsim 8m_\Sigma^2$$

Fixed to see the most aggressive constraints

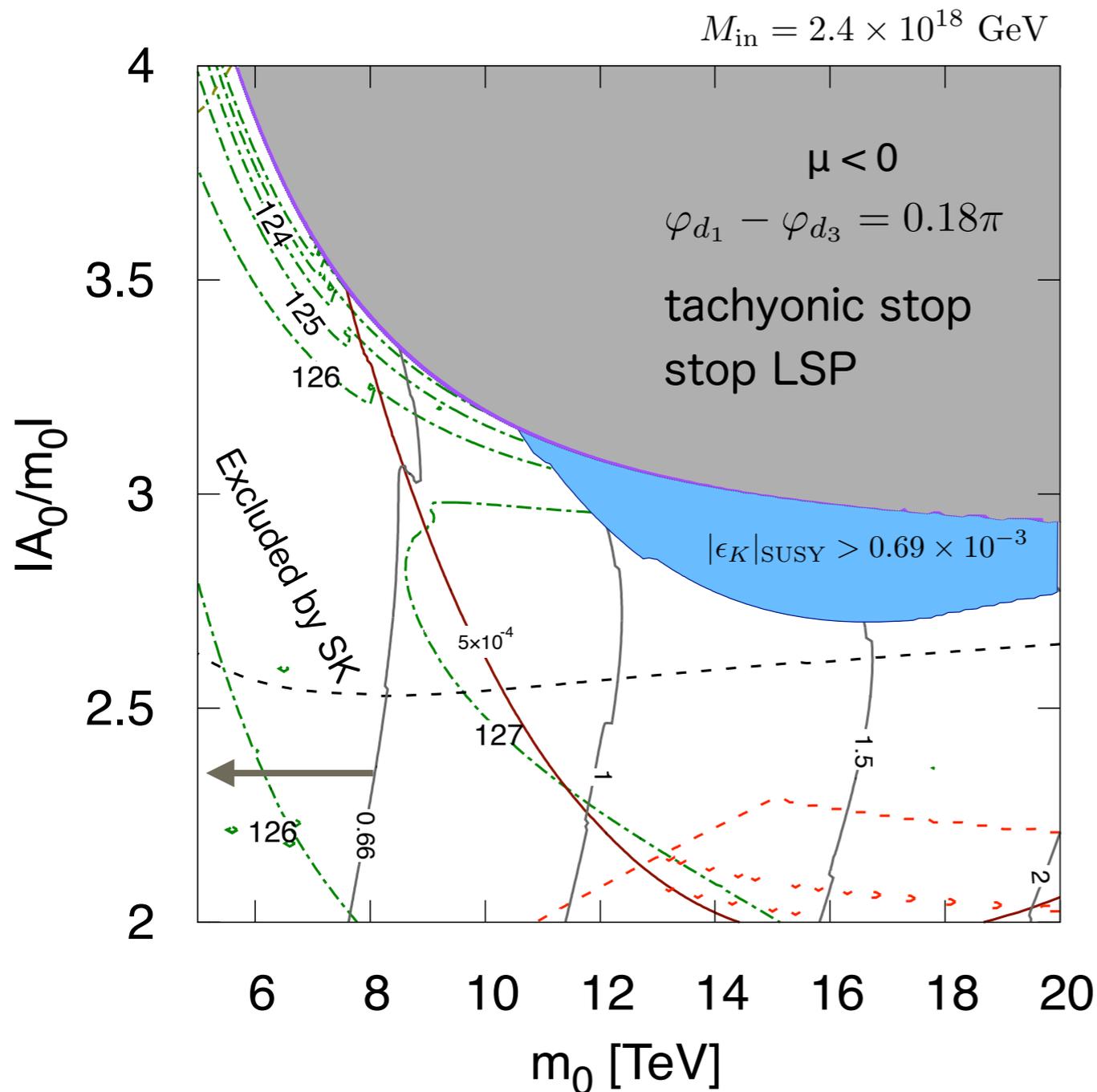
$$M_{\text{in}} = M_{\text{Pl}} = 2.4 \times 10^{18} \text{ GeV}$$

$$M_R = 10^{15} \text{ GeV} \quad \text{and diagonalized structure}$$

$$\varphi_{d_1} - \varphi_{d_2} \quad \varepsilon_\kappa \text{ maximized}$$

$$\varphi_{d_1} - \varphi_{d_3} \quad d_e \text{ maximized (or we choose moderate value)}$$

Results



Model Parameters:

$$M_{N_R} = 10^{15} \text{ GeV}$$

$$\lambda = 0.5, \quad \lambda_\Sigma = 10^{-4}$$

φ_{u_i} : maximize proton lifetime

$\varphi_{d_1} - \varphi_{d_2} = 0.18\pi$: maximize ϵ_K

$$M_{1/2} = 4.5 \text{ TeV}, \quad \tan \beta = 6$$

Mass Spectrum: FeynHiggs 2.14.2

blue shaded: excluded by ϵ_K constraint
 green dotted: Higgs mass
 above black dotted: B-condition is satisfied

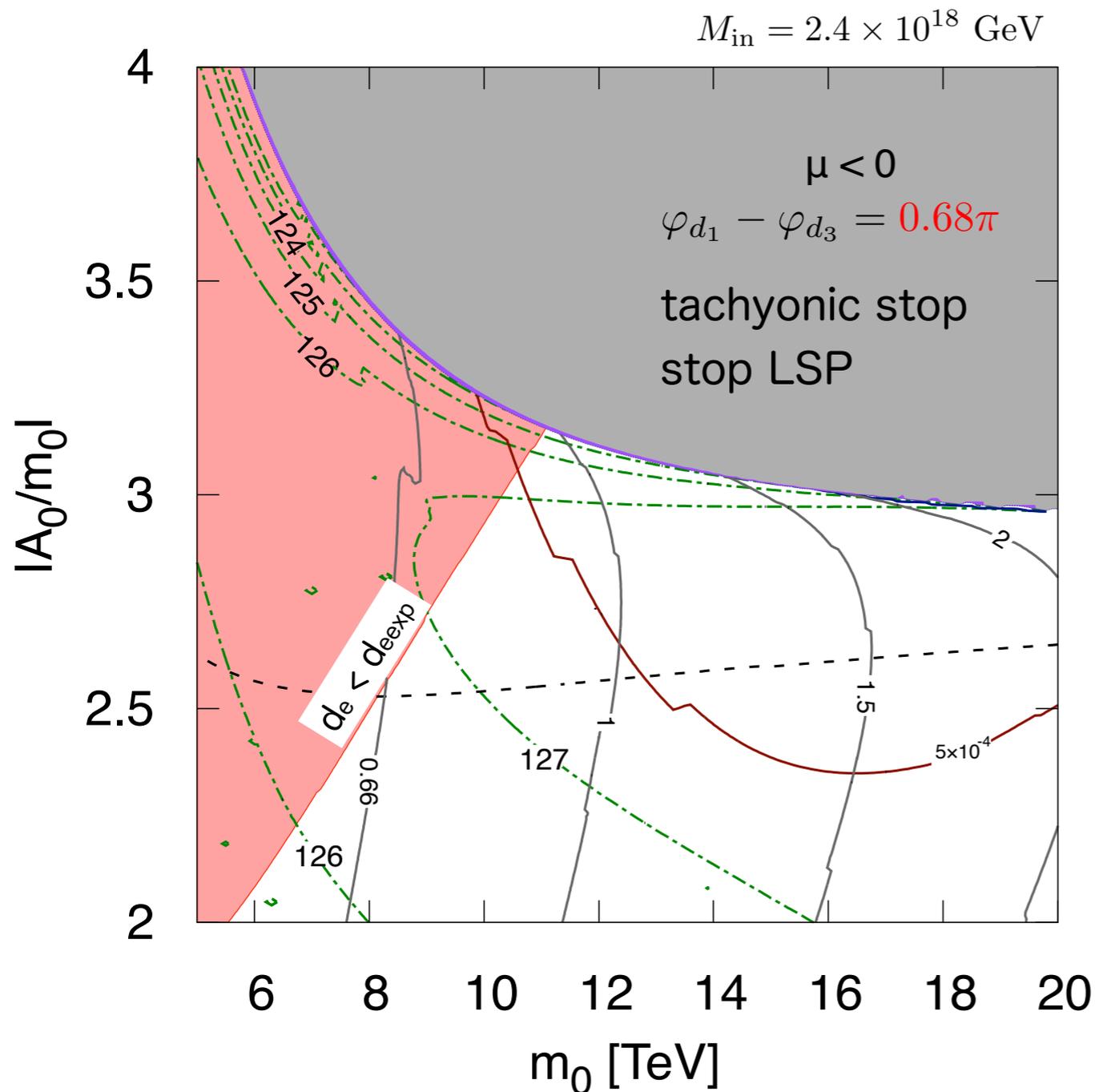
$$m_{\tilde{t}_1} - m_{\chi_1^0} \lesssim 100 \text{ GeV}$$

near boundary (purple)

Inside red-dotted island @ high m_0 :

$$\text{beyond final goal of ACME-II} \quad |d_e| \lesssim 10^{-31} e \text{ cm}$$

Results



GUT-scale phases to maximize eEDM

Model Parameters:

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Red shaded region:

predicted eEDM exceeds current constraint

$$|d_e| < 9.3 \times 10^{-29} [e \text{ cm}]$$

above black dotted: B-condition is satisfied

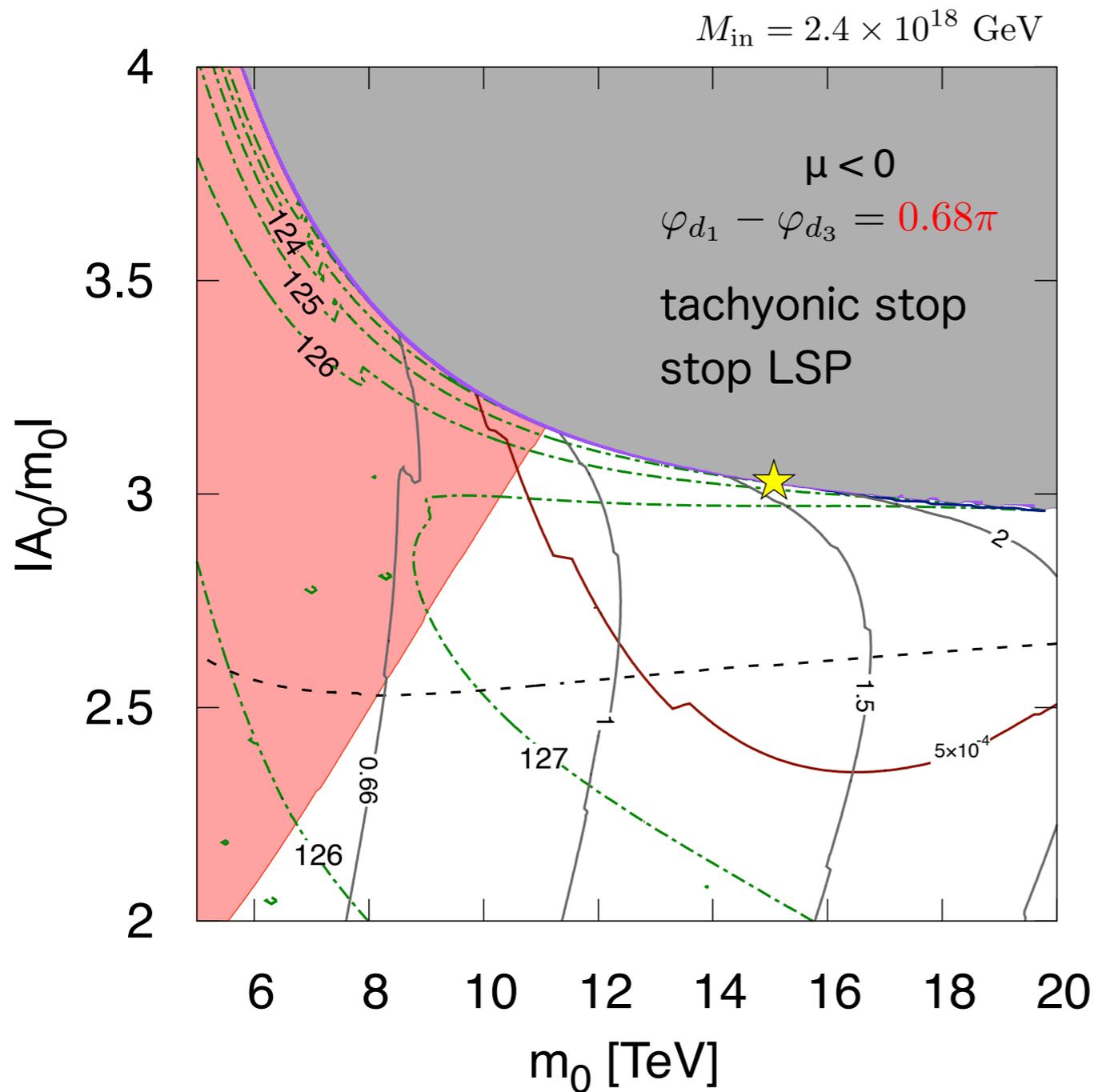
$$m_{\tilde{t}_1} - m_{\chi_1^0} \lesssim 100 \text{ GeV}$$

near boundary (purple)

A whole parameter region is accessible to the ACME-II sensitivity on eEDM:

$$|d_e| \simeq 10^{-31} e \text{ cm}$$

Results



Sparticle mass spectrum @ ref.

Particle	Mass
h	125.2 [GeV]
H, A, H^\pm	23.0 [TeV]
$(\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0)$	(2.56 , 4.14, 19.2, 19.2) [TeV]
\tilde{g}	8.70 [TeV]
$(\tilde{\tau}_1, \tilde{\tau}_2)$	(10.4, 13.1) [TeV]
$(\tilde{t}_1, \tilde{t}_2)$	(2.61 , 10.9) [TeV]
$(\tilde{b}_1, \tilde{b}_2)$	(10.9, 12.6) [TeV]

$m_{\tilde{t}_1} - m_{\chi_1^0} \lesssim 100 \text{ GeV}$
 near boundary (purple)

DM: bino-stop coannihilation
 near the boundary
 [Ellis, Evans, Luo, Olive, Zheng '18]

Glueballs below 10TeV @ 100TeV Collider
 [Ellis, Zheng '15]

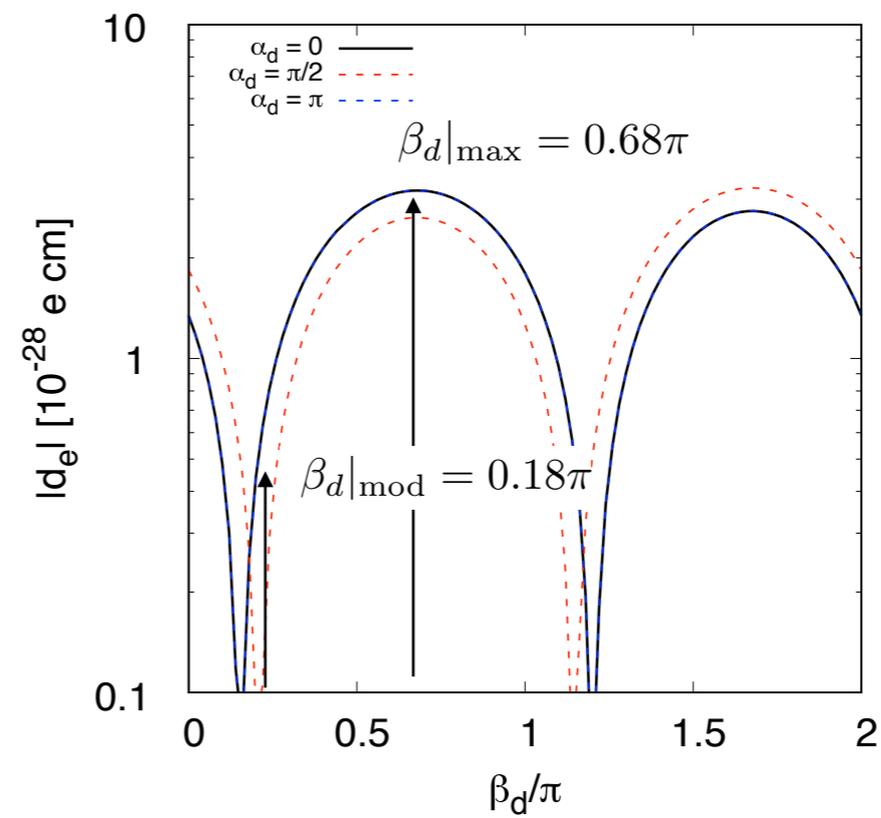
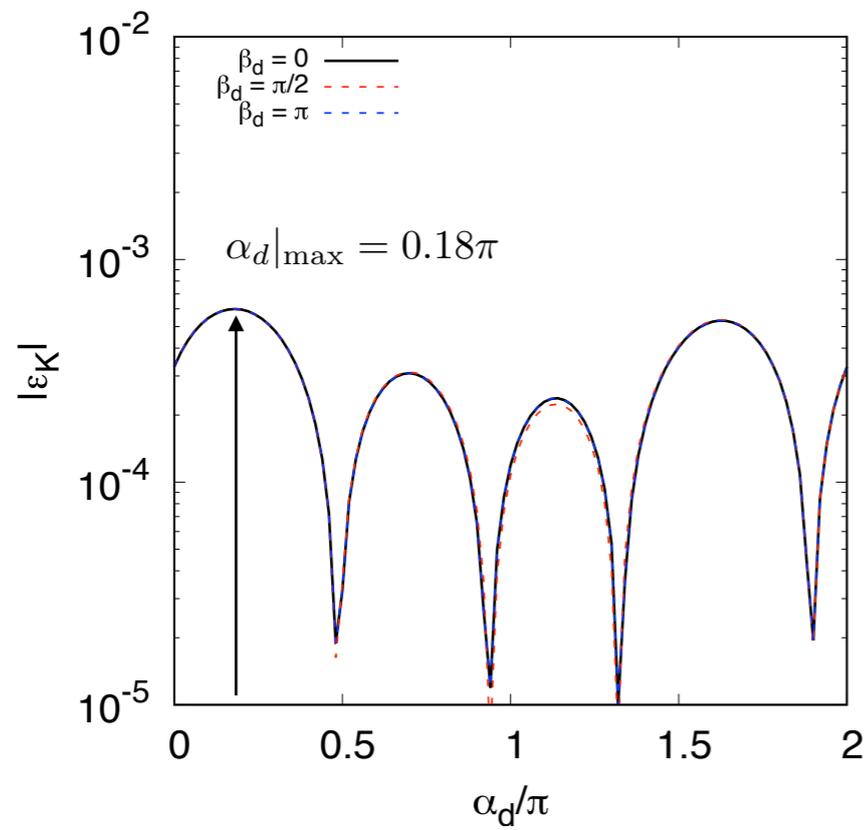
Summary and Discussion

- ✓ We reexamined the SUSY SU(5) GUT with Right-handed neutrinos and with input scale for soft-SUSY breaking parameters above the GUT scale (super-GUT scenario)
- ✓ Due to **PMNS matrix and GUT-scale additional phases**, flavor and CPV processes mainly constrains on this model
- ✓ $A_0 \neq 0$ case: we found the region is compatible with all constraints (Higgs mass, Proton stability, and flavor and CPV processes)
LSP: bino (coannihilation with stops)
- ✓ Electron EDM gives a strong constraint on this model; future sensitivity by ACME-II exp may cover the broad parameter region.

Backup

Phase determination

$$\tan \beta = 6, \quad M_{1/2} = 1 \text{ TeV}, \quad A_0 = 0, \quad \mu > 0, \quad M_{\text{in}} = M_{\text{Pl}}$$



$$\alpha_d = \varphi_{d_1} - \varphi_{d_2}$$

$$\beta_d = \varphi_{d_1} - \varphi_{d_3}$$

B-matching Condition in detail

soft-supersymmetry breaking parameters above M_{GUT}

$$-\mathcal{L}_{\text{soft}} = \left(B_H \mu_H \bar{H} H + A_\lambda \lambda \bar{H} \Sigma H + \frac{B_\Sigma \mu_\Sigma}{2} \text{Tr} \Sigma^2 + \frac{A_\Sigma \lambda_\Sigma}{3} \text{Tr} \Sigma^3 + \text{h.c.} \right) + \dots$$

soft-supersymmetry breaking parameters below M_{GUT}

$$-\mathcal{L}_{\text{soft}} = (B \mu H_u H_d + \text{h.c.}) + \dots$$

Matching conditions including F-term VEV of Σ

$$\langle \Sigma \rangle = v [1 + (A_\Sigma - B_\Sigma) \theta^2] \text{diag}(2, 2, 2, -3, -3)$$

$$\mu = \mu_H - 3\lambda v \left(1 + \frac{A_\Sigma - B_\Sigma}{2\mu_\Sigma} \right)$$

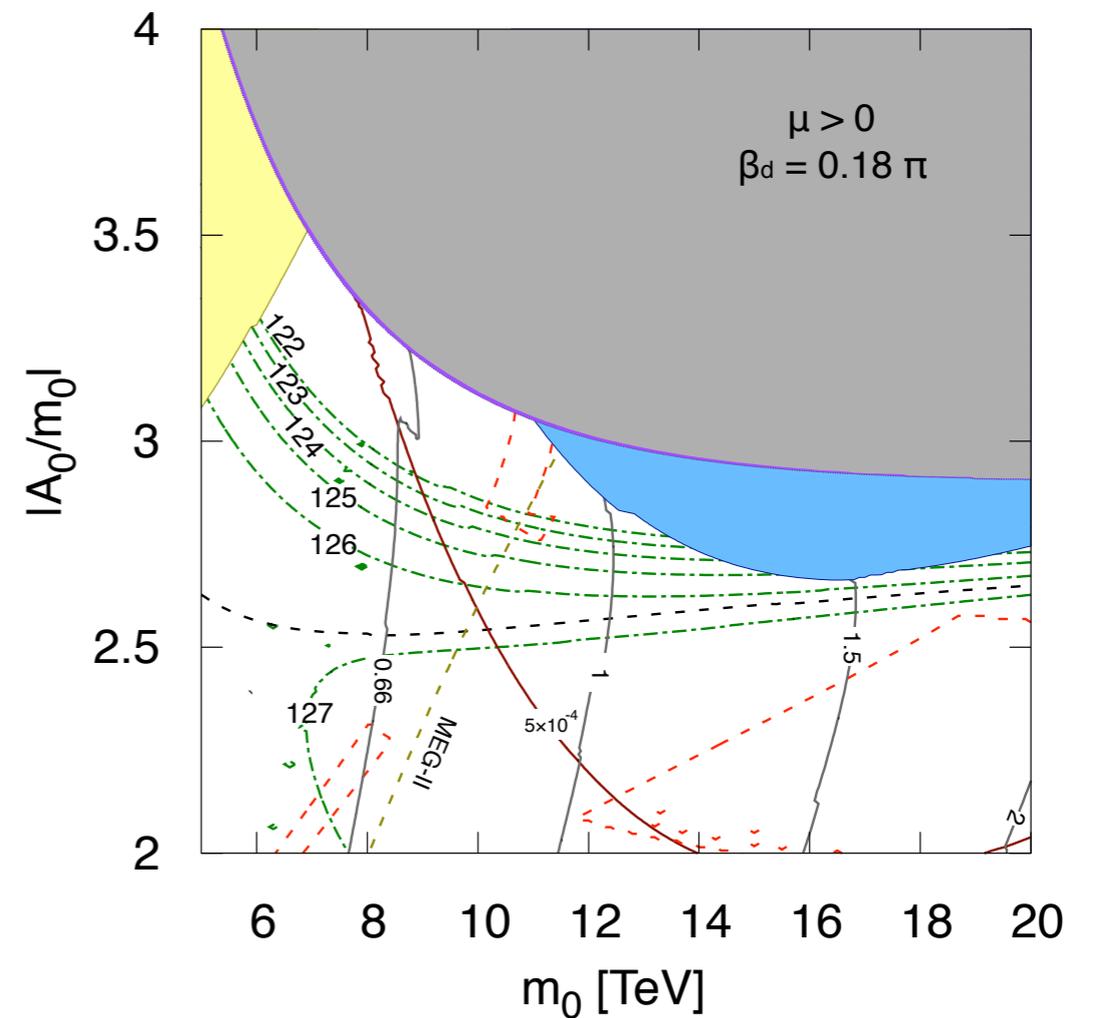
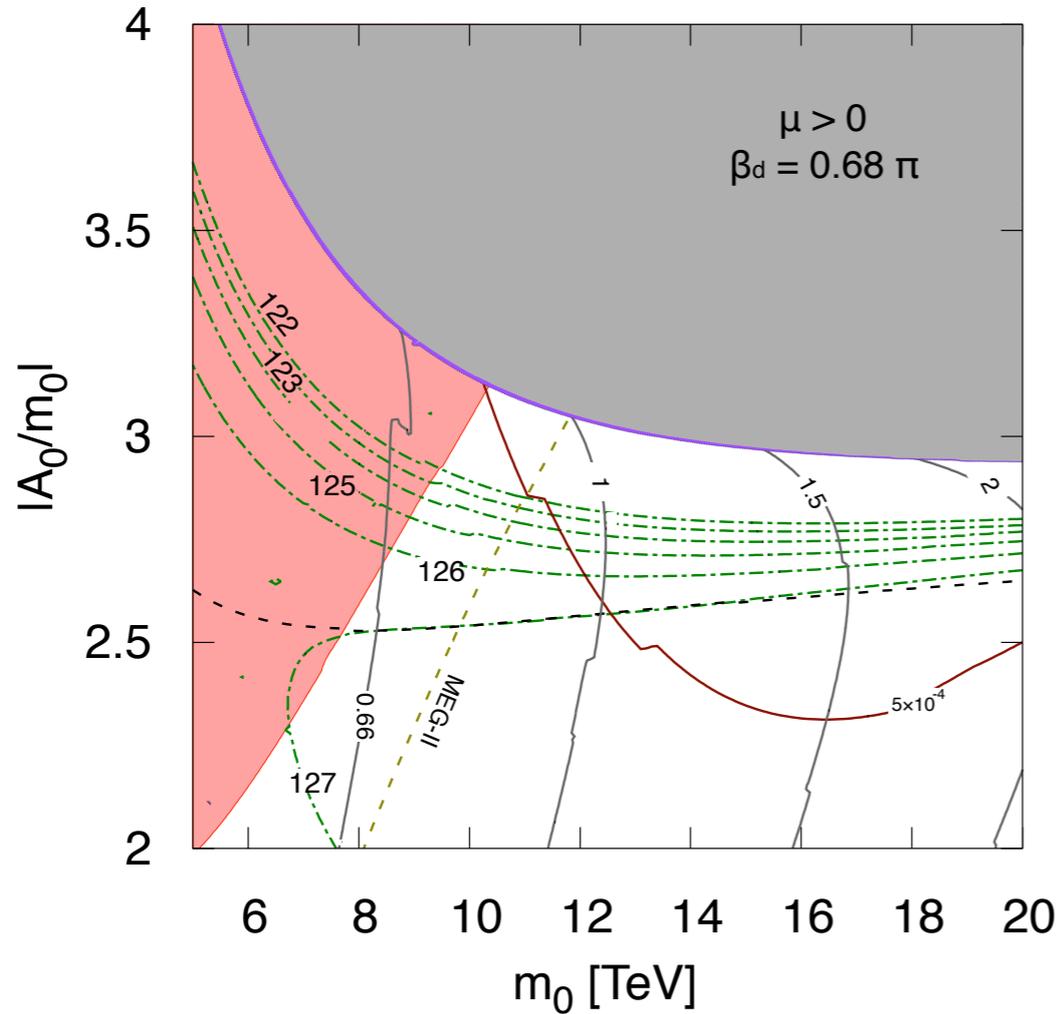
$$\Delta_A = A_\Sigma - B_\Sigma - A_\lambda + B_H \simeq 0$$

$$B = B_H + \frac{3\lambda v \Delta_A}{\mu} + \frac{6\lambda}{\lambda_\Sigma \mu} [(A_\Sigma - B_\Sigma)(2B_\Sigma - A_\Sigma + \Delta_A) - m_\Sigma^2]$$

Removing B_H and assuming that B_Σ has real solutions,

$$A_\Sigma^2 - \frac{\lambda_\Sigma \mu}{3\lambda} (A_\Sigma - 4A_\lambda + 4B) + \left(\frac{\lambda_\Sigma \mu}{6\lambda} \right)^2 \geq 8m_\Sigma^2,$$

sign(mu) dependence



Difficult to realize both the observed Higgs mass and bino-stop coannihilation.

mu e gamma process depends on sign of mu (positive mu has the right sign to add)

$$\mathcal{M}(l_i \rightarrow l_j + \gamma) = (C_{LL} + C_{LR})_{ji} \bar{l}_j P_R [l_i]$$

$$(C_{LL})_{ji} = \frac{e}{16\pi^2} m_{l_i} \left[\frac{(m_L^2)_{ij}}{m_e^4} \sum_{i=1,2} g_i^2 S_e(x_{ei}) + \frac{(m_L^2)_{ij}}{m_\nu^4} g_2^2 S_\nu(x_{\nu 2}) \right]$$

$$(C_{LR})_{ji} = \frac{eg_1^2}{16\pi^2} M_1 \sum_A U_{jA} U_{i+3A}^* \frac{1}{m_{\tilde{e},A}} S_{LR}(x_{e1})$$