Proton Decay: Theory

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Prospects of Neutrino Physics
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Goal of the talk

- Given the null result of BSM searches @ LHC
  - Minimal GUT with high-scale SUSY
  - Non-SUSY SO(10) GUTs

  have been reconsidered.

- These scenarios predict rich signals in future proton decay experiments.

Grand Unified Theories (GUTs)

H. Georgi and S.L. Glashow, Phys .Rev. Lett. **32**, 438 (1974).

- Unification of quarks and leptons

$$\bar{\mathbf{5}} = \begin{pmatrix} \bar{D}_1 \\ \bar{D}_2 \\ \bar{D}_3 \\ E \\ -N \end{pmatrix} \qquad \mathbf{10} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \bar{U}_3 & -\bar{U}_2 & U^1 & D^1 \\ -\bar{U}_3 & 0 & \bar{U}_1 & U^2 & D^2 \\ \bar{U}_2 & -\bar{U}_1 & 0 & U^3 & D^3 \\ -U^1 & -U^2 & -U^3 & 0 & \bar{E} \\ -D^1 & -D^2 & -D^3 & -\bar{E} & 0 \end{pmatrix}$$

- Coupling unification

$$g_1(M_{\mathrm{GUT}}) = g_2(M_{\mathrm{GUT}}) = g_3(M_{\mathrm{GUT}})$$

Gauge coupling unification

\+ Yukawa unification

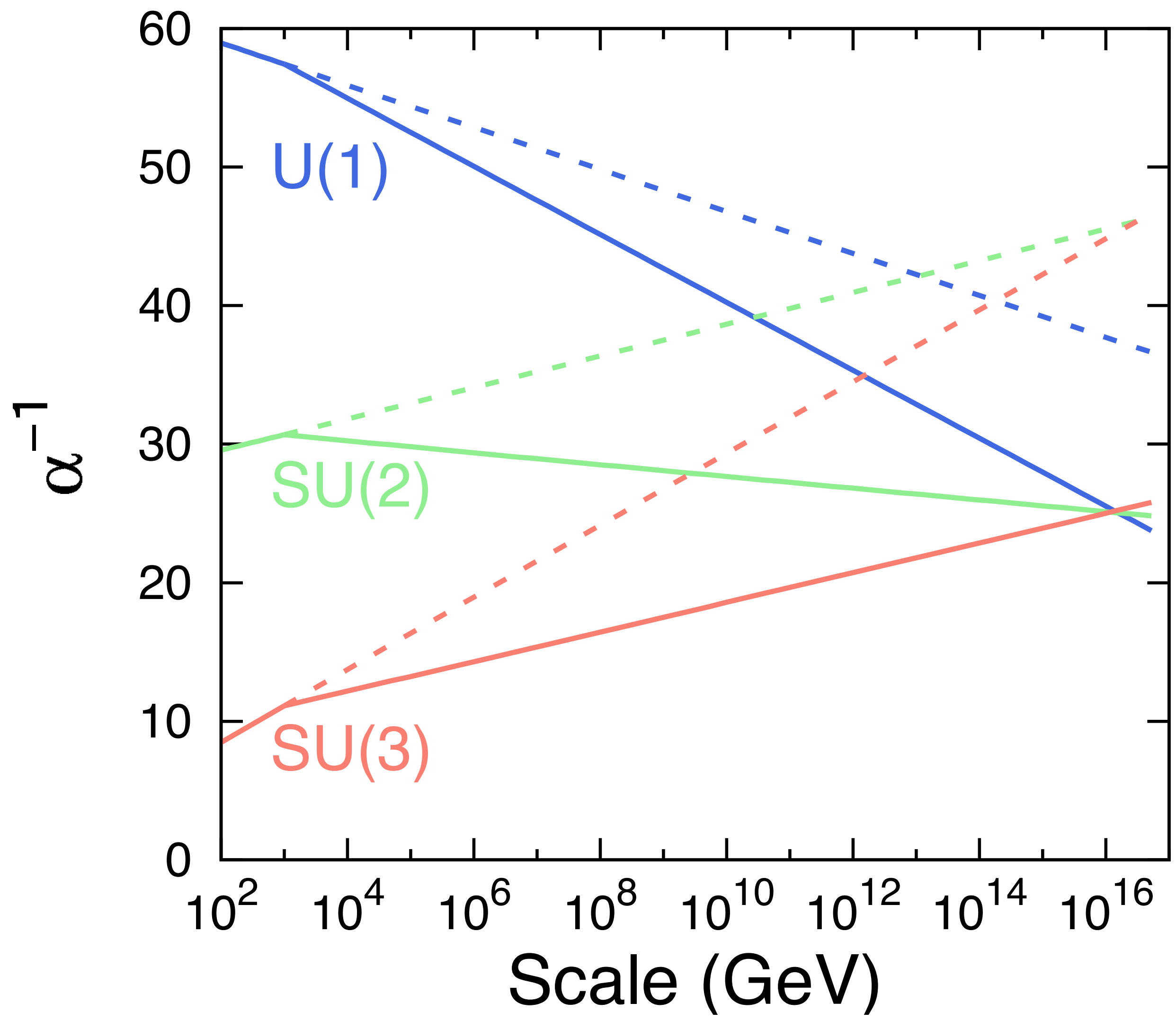
- Explain charge quantization, anomaly cancellation, etc.

SUSY GUTs

S. Dimopoulos and H. Georgi, Nucl. Phys. B**193**, 150 (1981);
N. Sakai, Z. Phys. C**11**, 153 (1981).

Supersymmetry (SUSY) and GUTs go well together.

- Gauge hierarchy problem
- Gauge coupling unification



Solid : SM
Dashed : MSSM

(SUSY scale: 1 TeV)

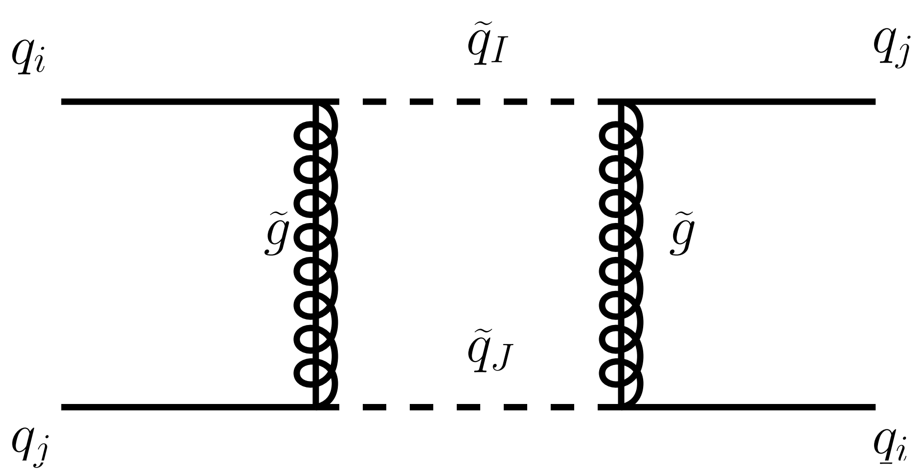
Problems in SUSY GUTs

Even before the LHC, some problems were know in SUSY GUTs.

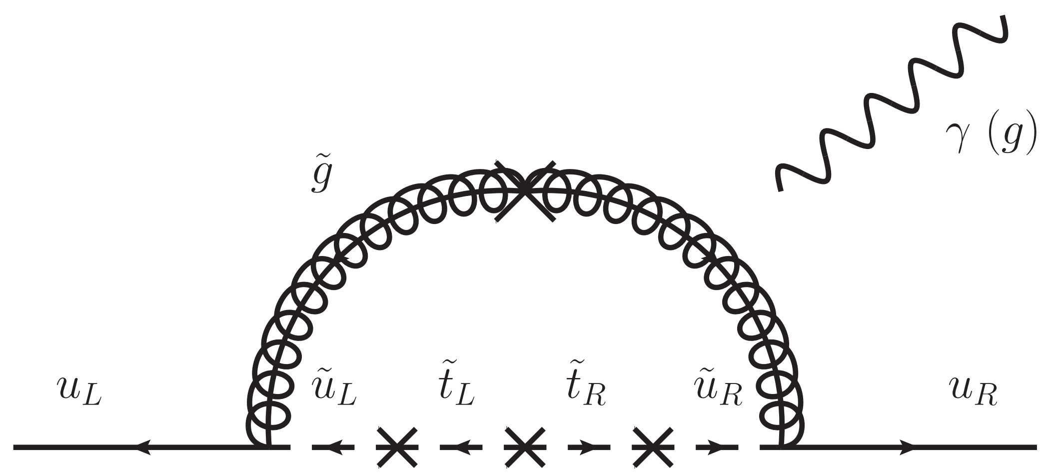
- SUSY flavor/CP problem

TeV-scale SUSY induces large FCNC processes and EDMs.

Meson oscillations



EDMs

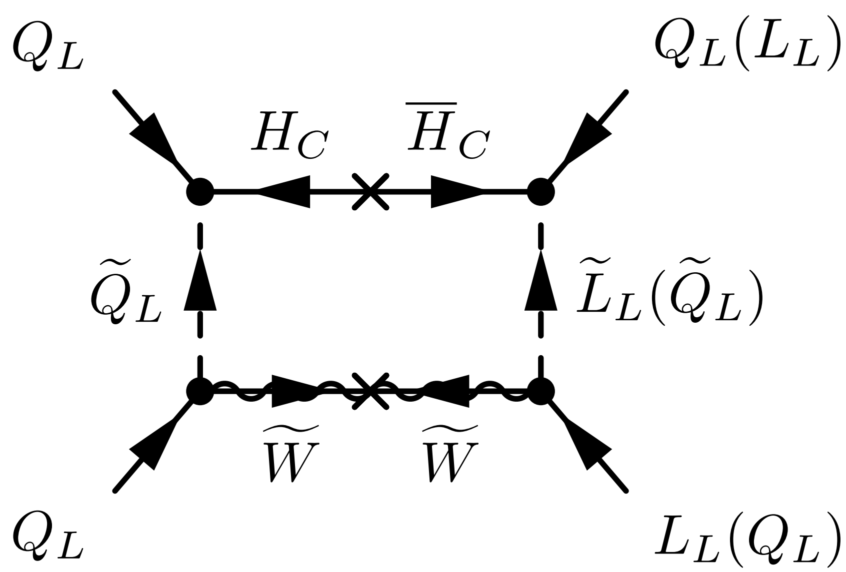


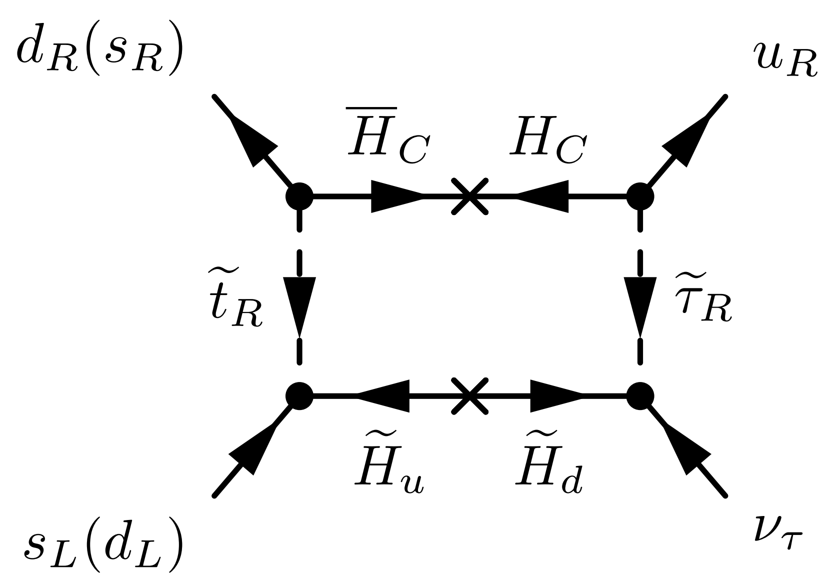
- Proton decay problem

N. Sakai and T. Yanagida, Nucl. Phys. B**197**, 533 (1982);
S. Weinberg, Phys. Rev. D**26**, 287 (1982).

Proton decay Problem in SUSY GUTs

In SUSY GUTs, proton decay is induced by the exchange of color-triplet Higgs field.





$$\propto \frac{1}{M_{\mathrm{GUT}} M_S}$$

Higgs multiplet

$$H = \begin{pmatrix} H_C^1 \\ H_C^2 \\ H_C^3 \\ H_u^+ \\ H_u^0 \end{pmatrix}, \quad \overline{H} = \begin{pmatrix} \overline{H}_{C1} \\ \overline{H}_{C2} \\ \overline{H}_{C3} \\ H_d^- \\ -H_d^0 \end{pmatrix},$$

In the minimal SUSY GUT with the TeV-scale SUSY, proton lifetime turns out to be too short.

H. Murayama and A. Pierce (2002).

Color-triplet Higgs MSSM Higgs

Suppression mechanism?

From Tanaka-san’s slide

Nucleon Decay

- Nucleon decay can occur via a direct transition from quark into lepto
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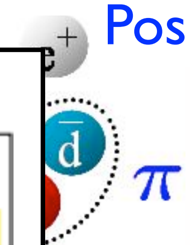
  - Ma pre de

$p \to e^+\pi^0$ decay mode



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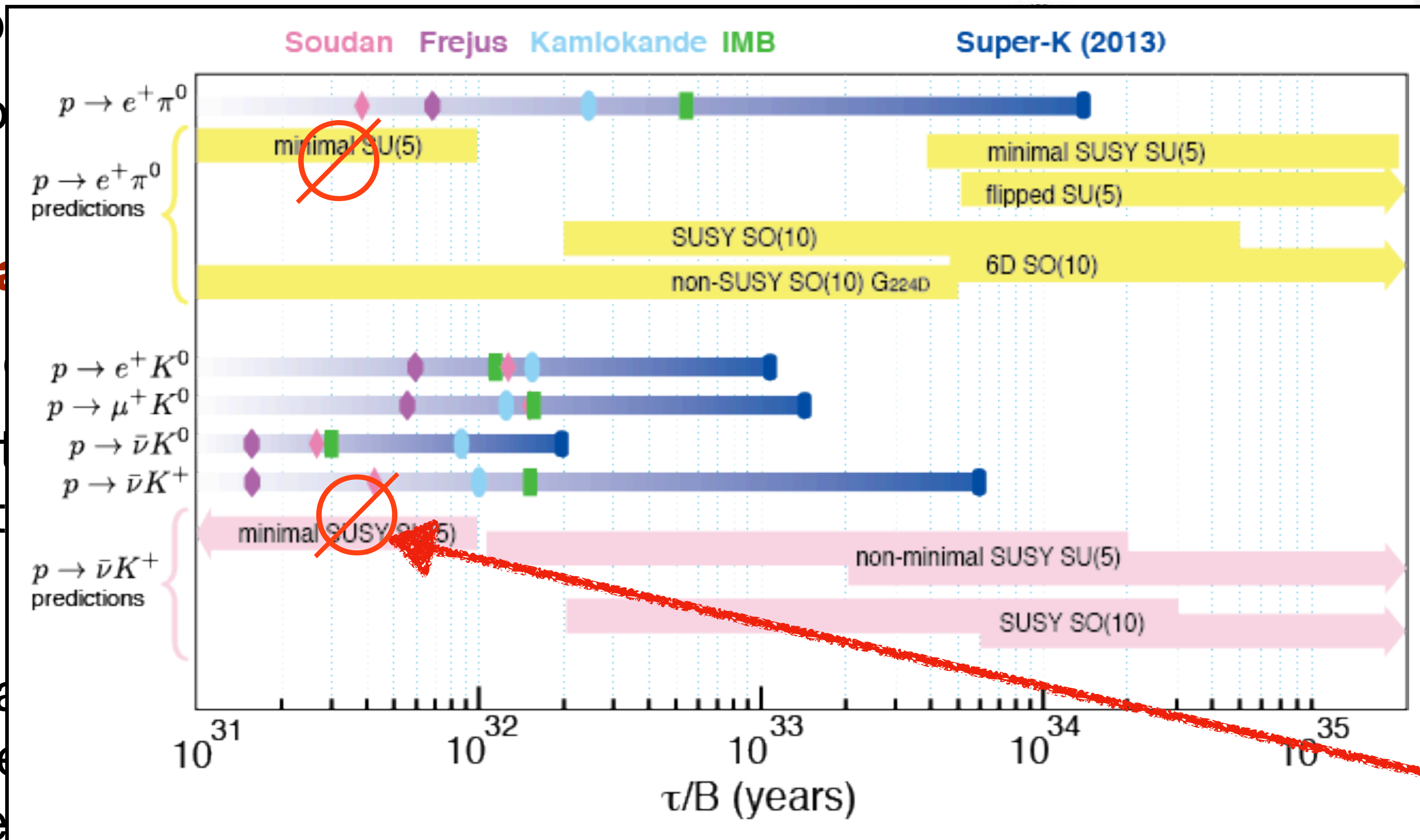

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SOFTSUSY 3.6.2

0

0 5 10 15

$\log_{10}(Q/GeV)$

- Nucleon decay search an unique prove for GUT and physics in very high energy

SUSY after the LHC

The LHC results, *i.e.*,

- Bound on SUSY particles
- 125 GeV Higgs mass

➡ SUSY particles are heavier than expected.

Implications for GUTs?

GUTs after the LHC

The following scenarios have been reconsidered.

Minimal SU(5) GUT with high-scale SUSY

- Flavor/CP problems solved.
- 125 GeV Higgs boson obtained.
- Gauge coupling unification maintained.
- Dark matter

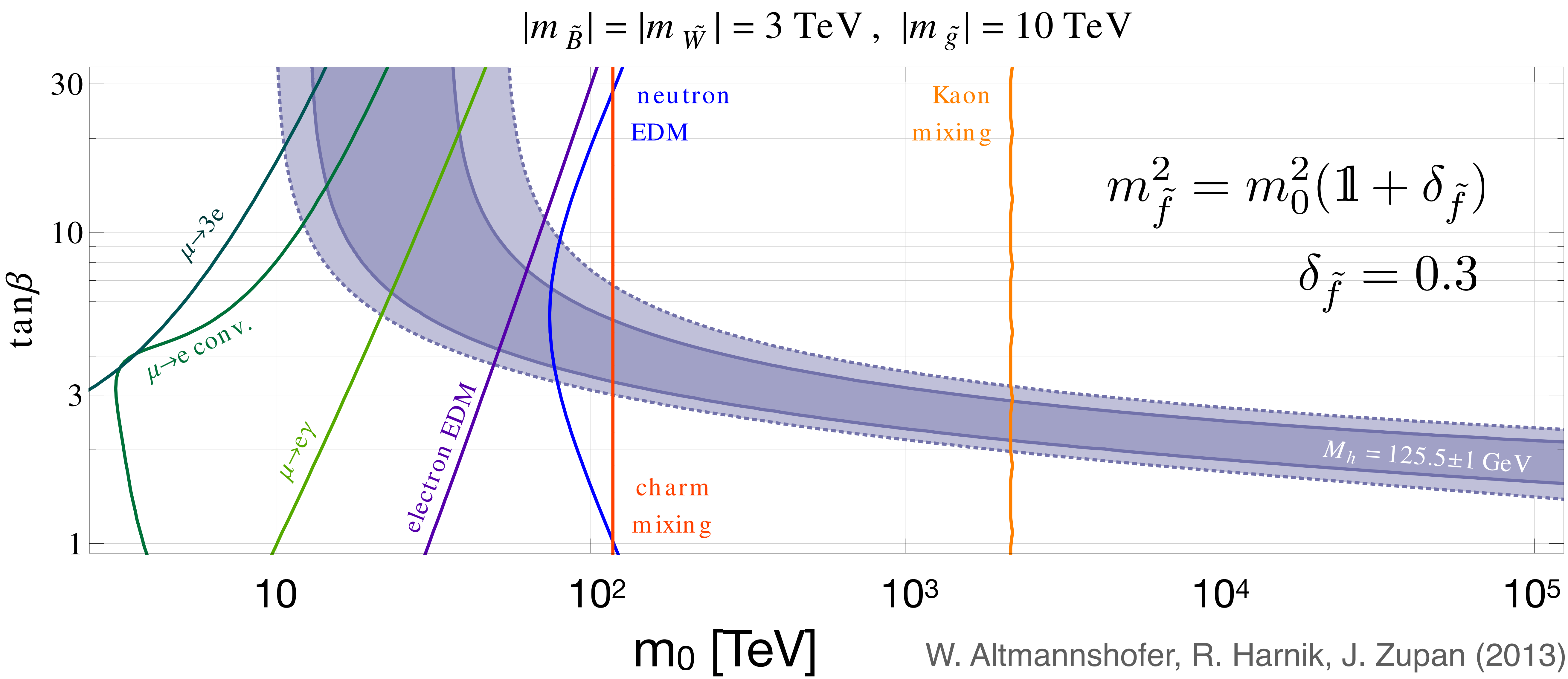
Non-SUSY SO(10) GUTs

- Gauge coupling unification.
- Right-handed neutrinos.
- Intermediate scales.

K. Harigaya's talk

Implications for proton decay?

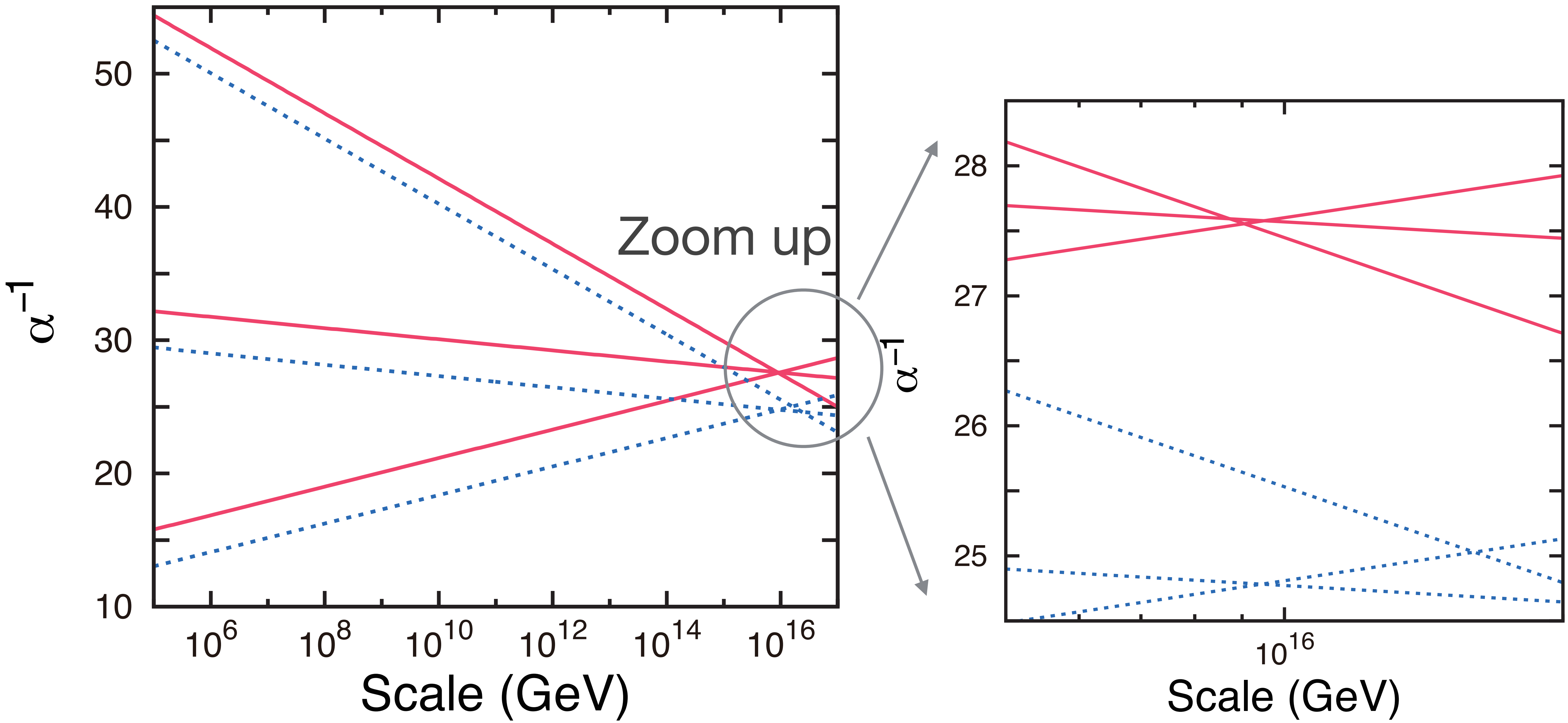
Flavor/CP in high-scale SUSY



W. Altmannshofer, R. Harnik, J. Zupan (2013).

- Limits from flavor physics/EDMs can be evaded for the multi-TeV scale SUSY.
- 125 GeV Higgs mass can be obtained.

Gauge coupling unification



Gauge coupling unification is maintained.

<u>High-scale</u>

$M_S = 10^2$ TeV

$M_2 = 3$ TeV

$M_3/M_2 = 9$

<u>Low-scale</u>

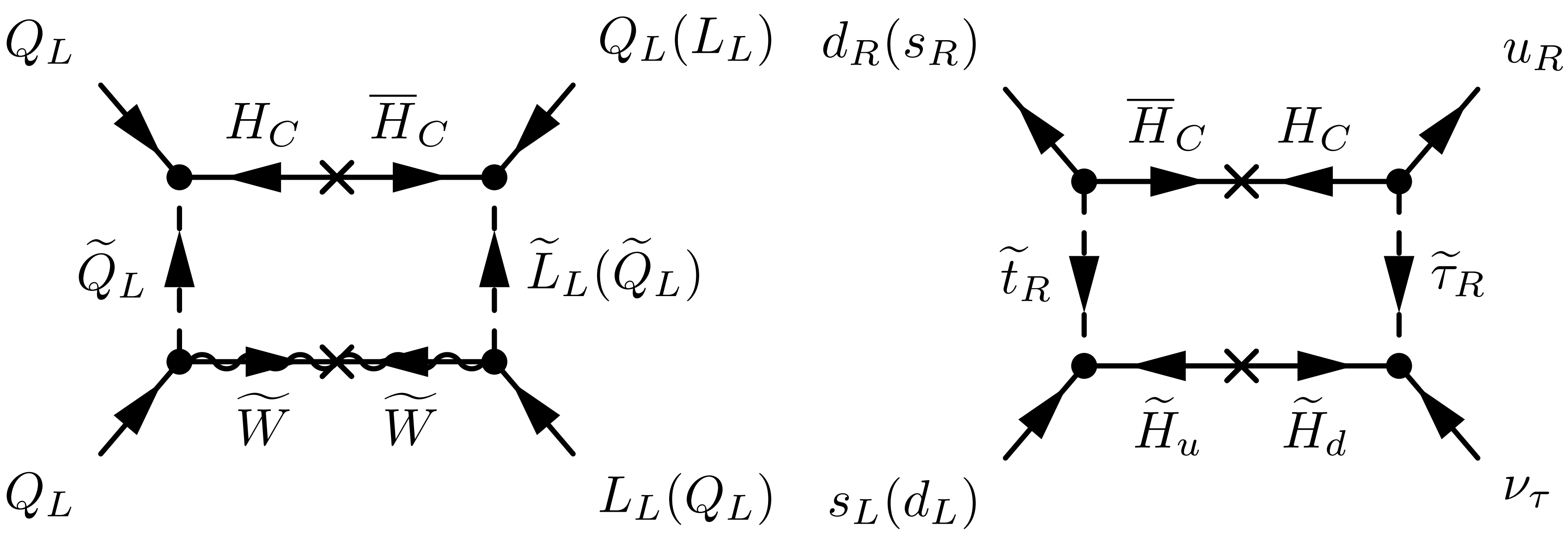
$M_S = 1$ TeV

$M_2 = 200$ GeV

$M_3/M_2 = 3.5$

Proton decay in SUSY GUTs

In SUSY GUTs, proton decay is induced by the exchange of color-triplet Higgs field.



$$\propto \frac{1}{M_{\rm GUT} M_S}$$

$$p \to K^+ \bar{\nu}$$

If the SUSY scale is high enough, the proton decay limit can be evaded.

J. Hisano, D. Kobayashi, T. Kuwahara, N. Nagata, JHEP **1307**, 038 (2013).

$$\tau(p \to K^+ \bar{\nu}) > 8.2 \times 10^{33} \ \text{yrs}$$

H. Tanaka's talk

Constrained MSSM (CMSSM)

Constrained MSSM (CMSSM)

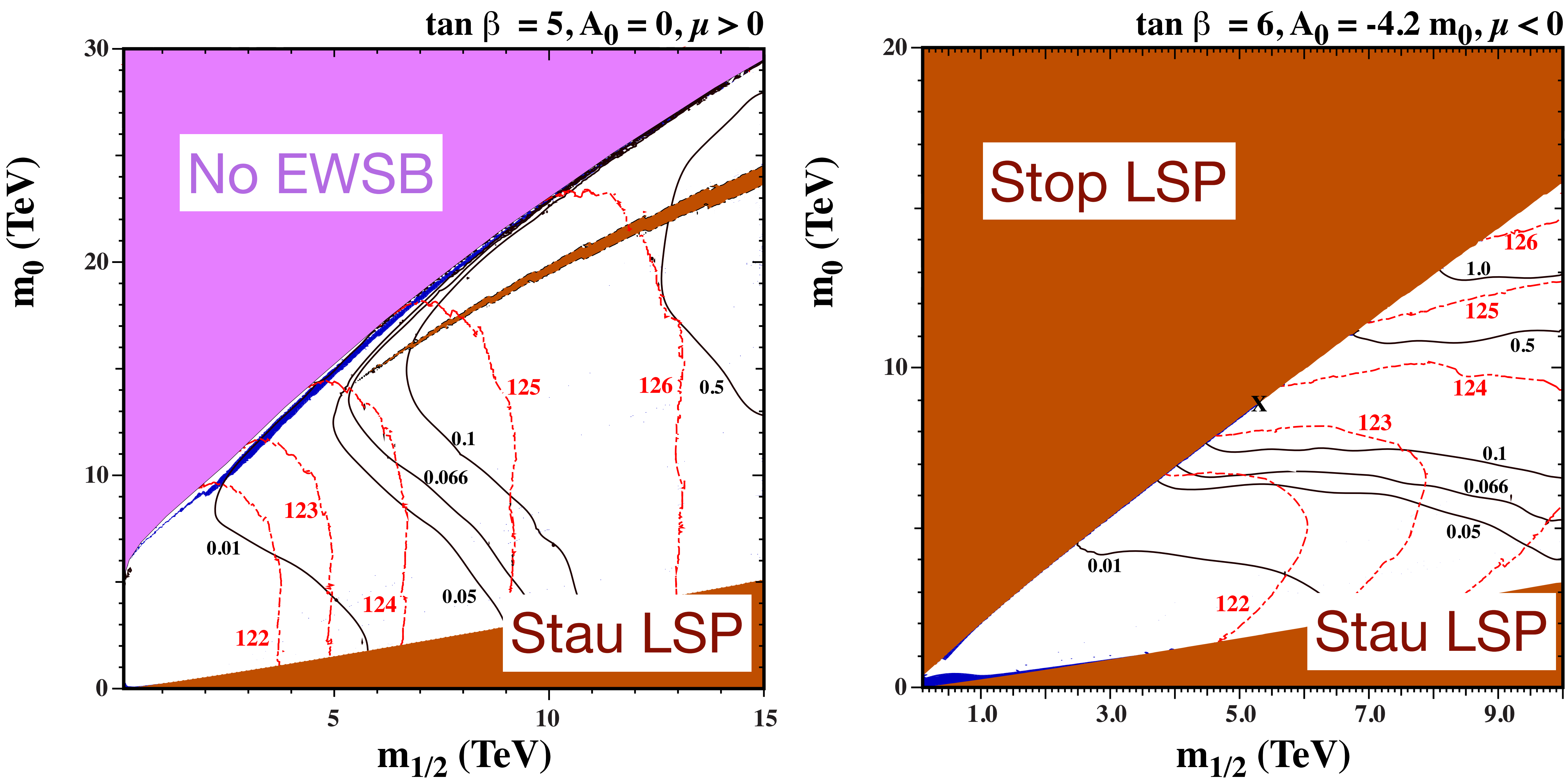
- Traditional benchmark model
- Impose universality conditions at the GUT scale.

Input parameters

$$m_0, \quad m_{1/2}, \quad A_0, \quad \tan\beta, \quad \mathrm{sign}(\mu)$$

Soft parameters at low energies are obtained by using renormalization group equations.

Proton decay in CMSSM



- Proton decay bound can be evaded.
- $p \to K^{+}\nu$ decay may be observed in future experiments.

J. Ellis, J. L. Evans, A. Mustafayev, N. Nagata, K. A. Olive, Eur. Phys. J. **C76**, 592 (2016).

High-scale SUSY GUTs

If SUSY scale is high,

- Large flavor violation in sfermion mass matrices is allowed.

- Minimal SUSY SU(5) can be consistent with the current proton decay bound.

No suppression mechanism.

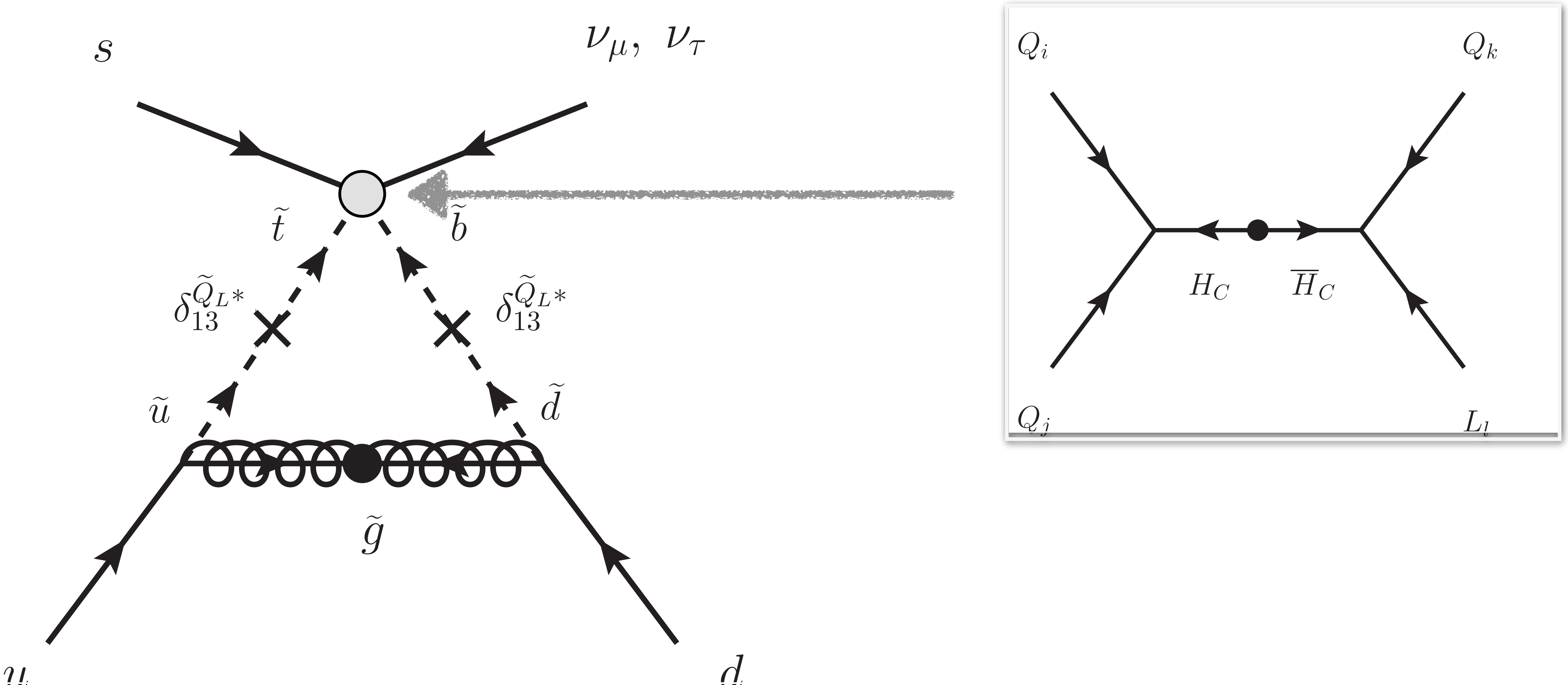
Minimal SU(5) + Non-trivial flavor structure in sfermion mass matrices

➡ Various proton decay channels may be observed in future.

Sfermion flavor and proton decay

If there is flavor mixing among sfermions;

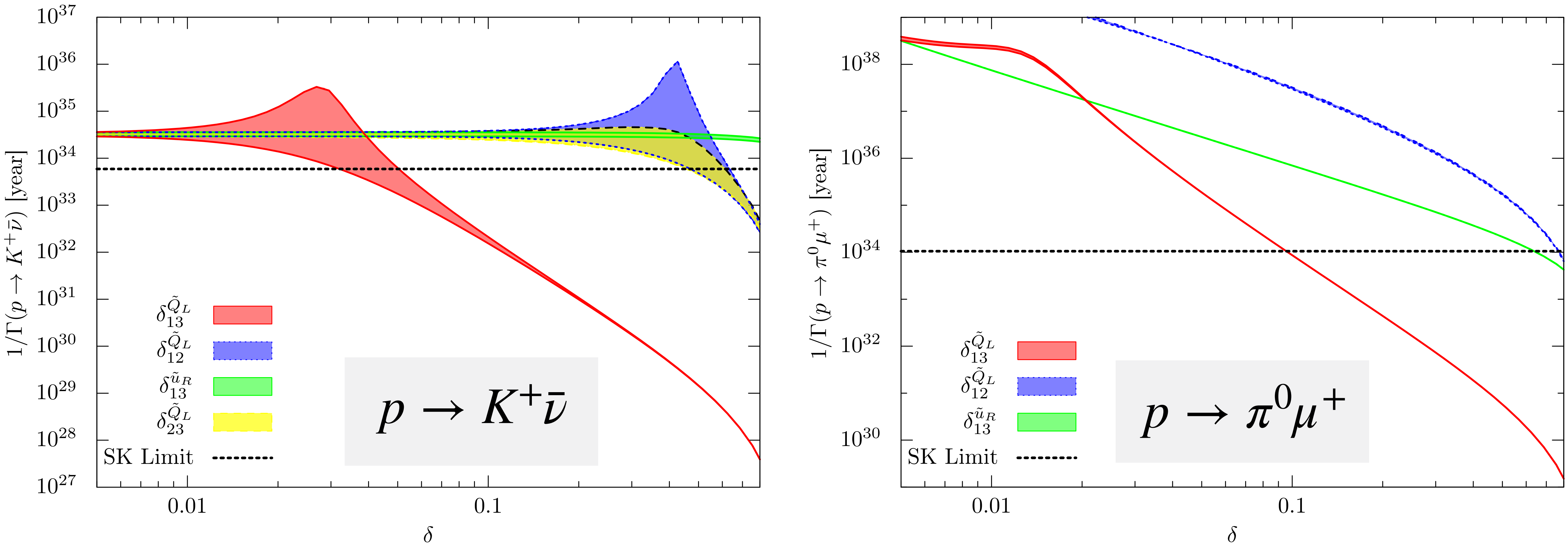
- Various decay channels are allowed.
- Gluino exchange becomes important.



Predictions for proton decay rates are significantly modified.

Sfermion flavor and proton decay

$M_{H_C} = 10^{16}$ GeV $\quad m^2_{\tilde{f}} = m_0^2(\mathbb{1} + \delta_{\tilde{f}})$ $\quad m_0 = 100$ TeV $\quad \tan\beta = 5$



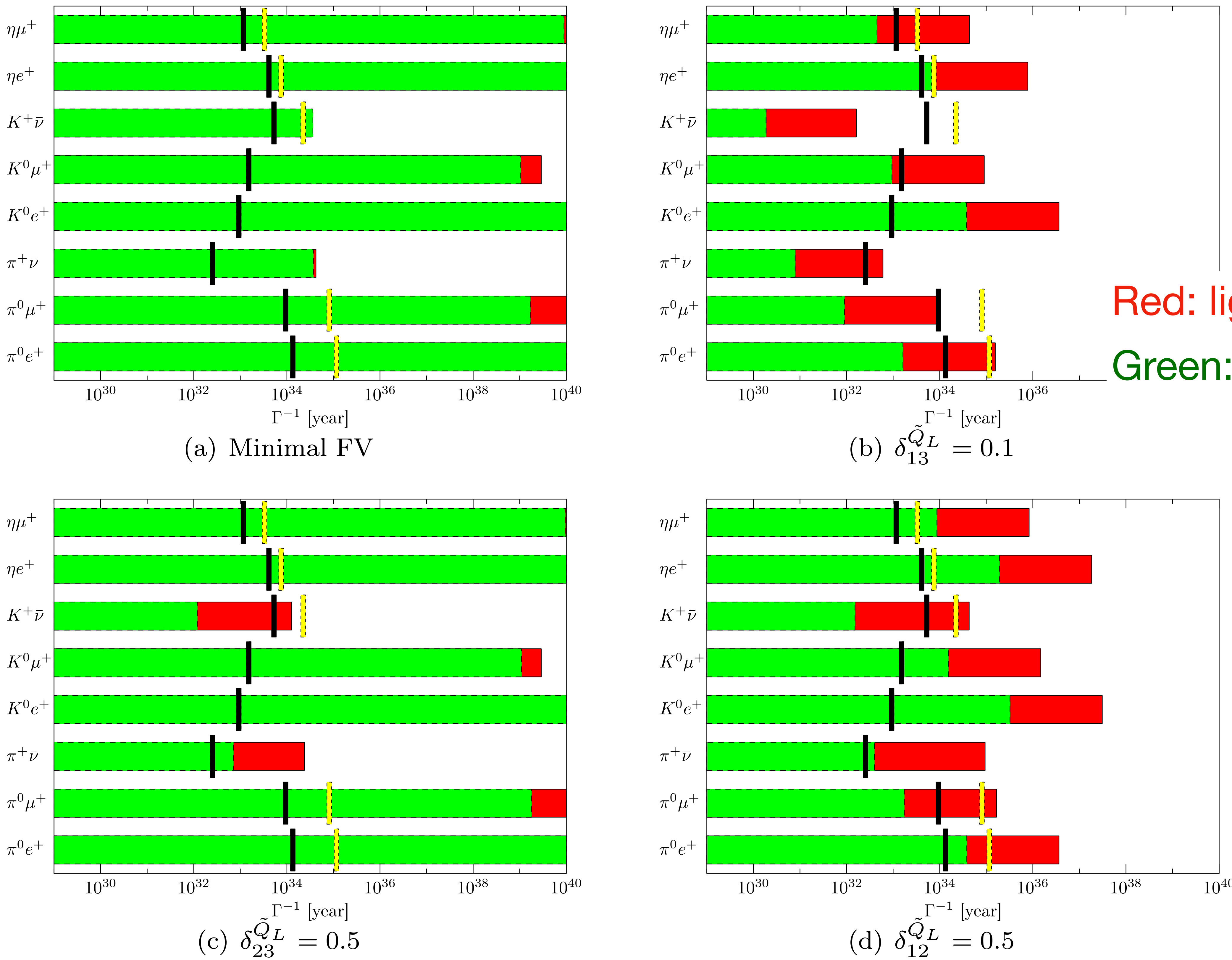
Line width: uncertainty from GUT Yukawa phases.

In the presence of sfermion mixing

- Proton decay rates are enhanced due to gluino contribution.
- Various decay channels become accessible.

N. Nagata and S. Shirai, JHEP **1403**, 049 (2014).

Sfermion flavor and proton decay

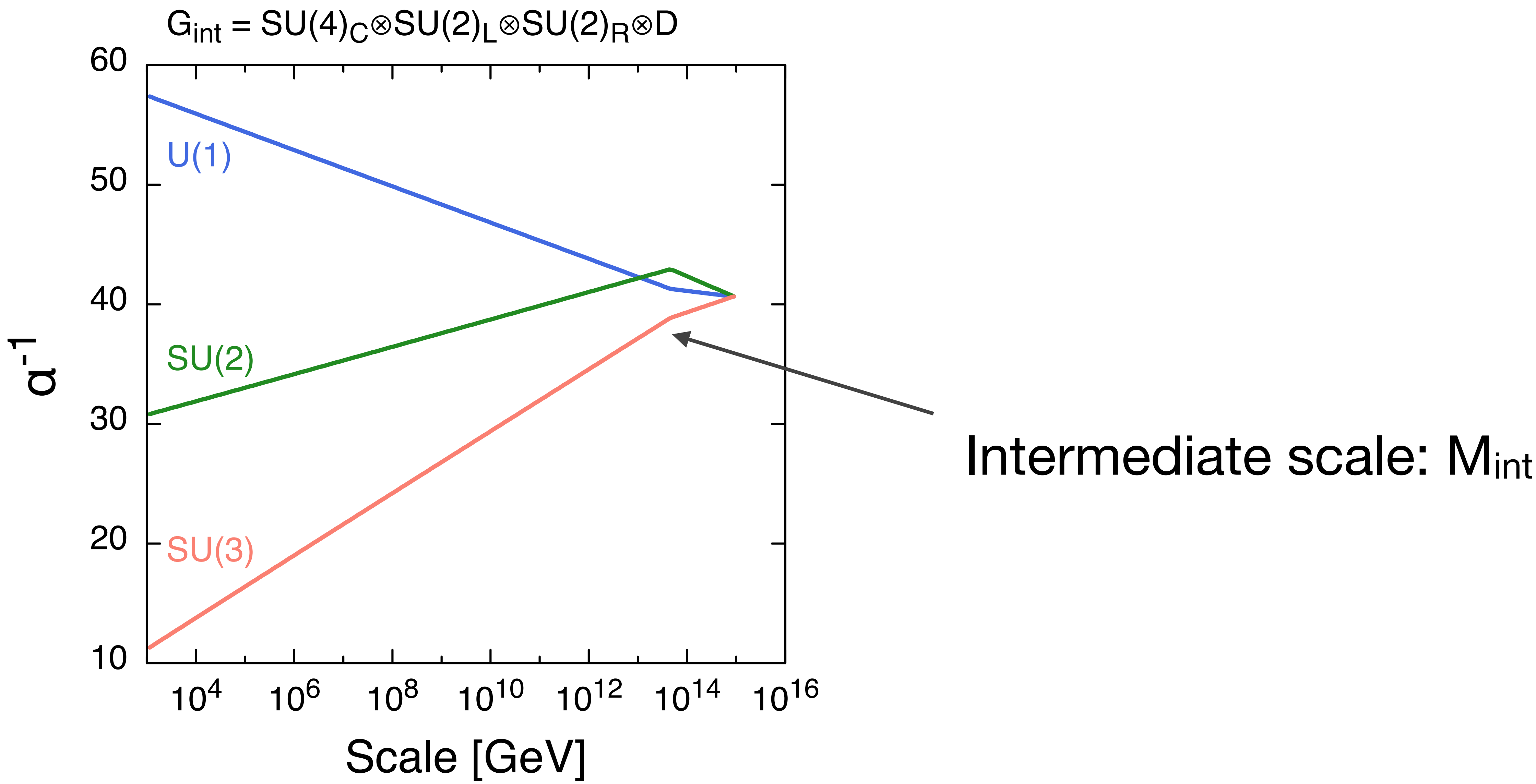


Red: light gaugino

Green: heavy gaugino

N. Nagata and S. Shirai, JHEP **1403**, 049 (2014).

Non-SUSY SO(10)



- Gauge coupling unification is realized with an intermediate gauge symmetry.
- $p \to e^+ \pi^0$ decay may be accessible.

K. Harigaya's talk

Summary

- We revisited
  - Minimal SU(5) GUT with high-scale SUSY
    - No flavor violation: $p \to K^+ \bar{\nu}$
    - Sfermion flavor violation: various channels

      e.g. $p \to \pi^0 \mu^+$
  - Non-SUSY SO(10) GUTs

    $p \to \pi^0 e^+$
- Future proton decay experiments can test these scenarios.

Backup

Discrete symmetry in SO(10)

In SO(10) GUTs, the extra U(1) is broken at M_{int}

By appropriately choosing the intermediate Higgs field, we can obtain

$$SO(10) \rightarrow G_{int} \rightarrow G_{SM} \times Z_N$$

<u>Group analysis</u> M. De Montigny and M. Masip (1994)

Higgs	126	672	…
Symmetr	Z_2	Z_3	…

Equivalent to "matter parity"

$$(-1)^{3(B-L)}$$

SO(10) contains $U(1)_{B-L}$

If we focus on rather small representations, Z_2 is the only possibility.

SO(10) can explain the stability of DM!

M. Kadastik, K. Kannike and M. Raidal (2009)
M. Frigerio and T. Hambye (2009)

Roles of 126

Breaks SO(10) into SM + matter parity at M_{int}

- SM fermion: Z_2-odd
- SM Higgs: Z_2-even

→

- Scalar DM: Z_2-odd
- Fermion DM: Z_2-even

Generate masses for right-handed neutrinos of $O(M_{int})$.

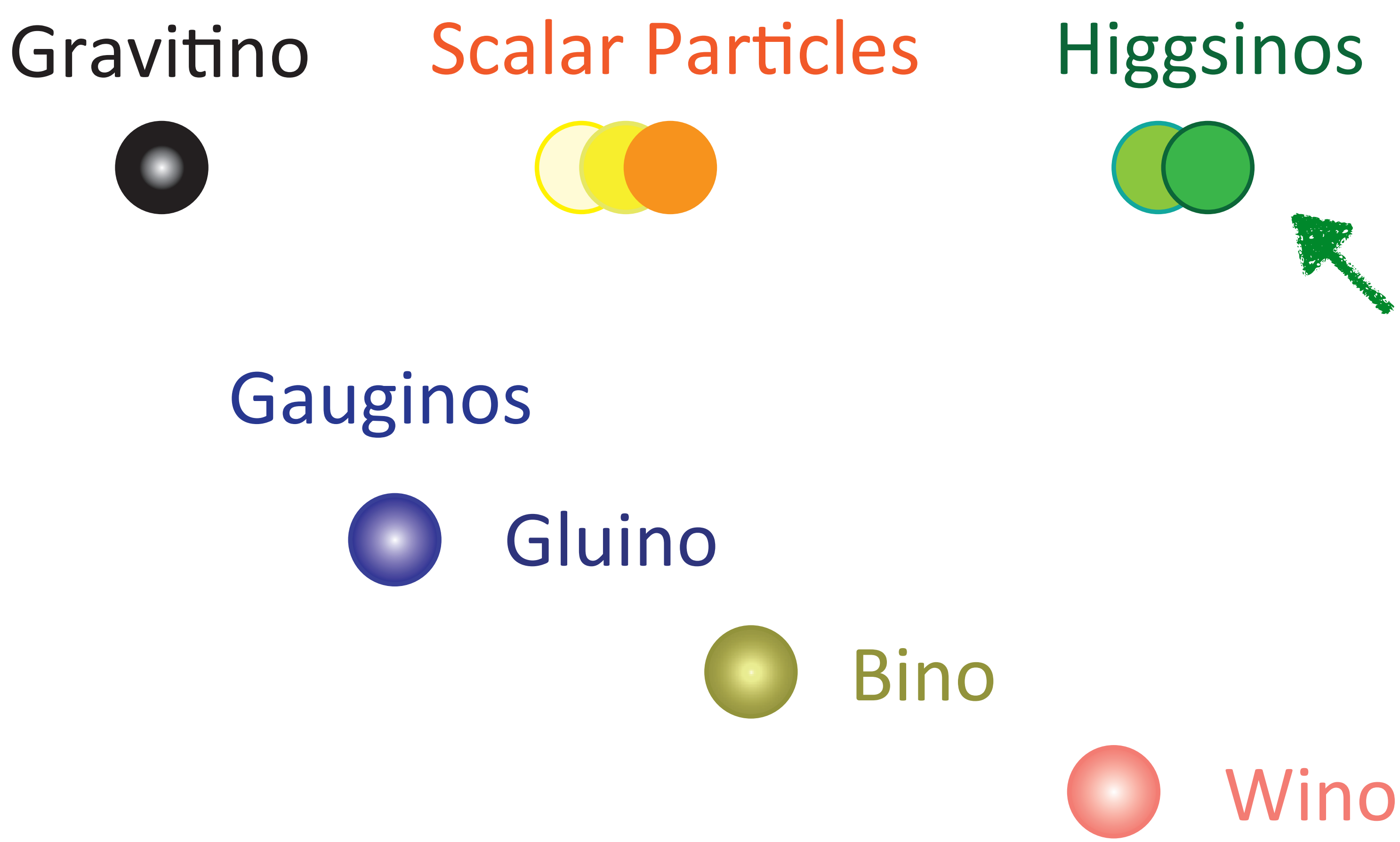
126 • 16 • 16 → $\langle \mathbf{126} \rangle \nu_R^c \nu_R^c$

B-L is spontaneously broken.

High-scale SUSY

L. J. Hall, Y. Nomura, S. Shirai (2012)
M. Ibe, S. Matsumoto, T. T. Yanagida (2012)
A. Arvanitaki, N. Craig, S. Dimopoulos, G. Villadoro (2012)
N. Arkani-Hamed, A. Gupta, D. E. Kaplan, N. Weiner, and T. Zorawski (2012)

Suppose that the SUSY-breaking field is not a singlet:



Higgsinos can be light if there is an additional symmetry.

Gaugino masses are induced at loop level.

e.g.) Anomaly mediation

L. Randall and R. Sundrum (1998)
G. F. Giudice, M. A. Luty, H. Murayama, and R. Rattazzi (1998)

High-scale SUSY

L. J. Hall, Y. Nomura, S. Shirai (2012)
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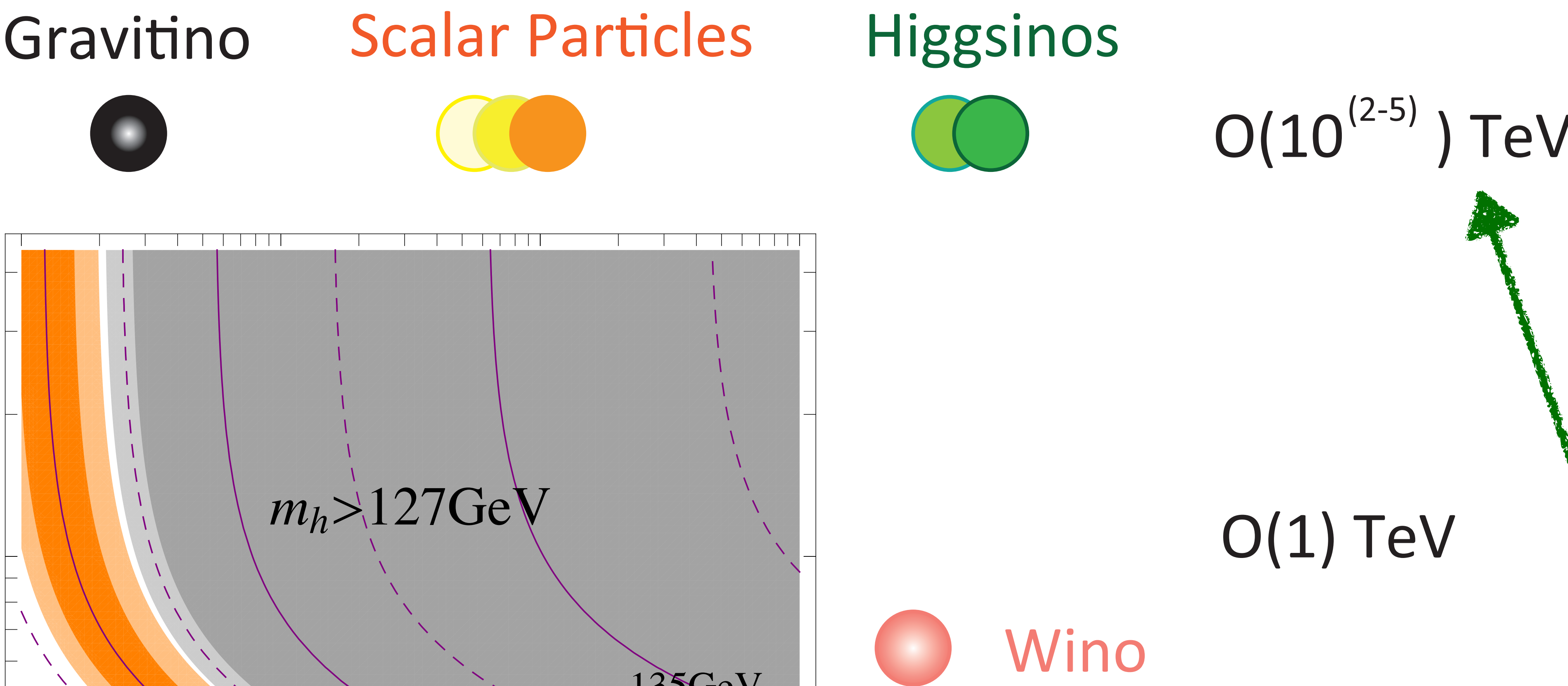

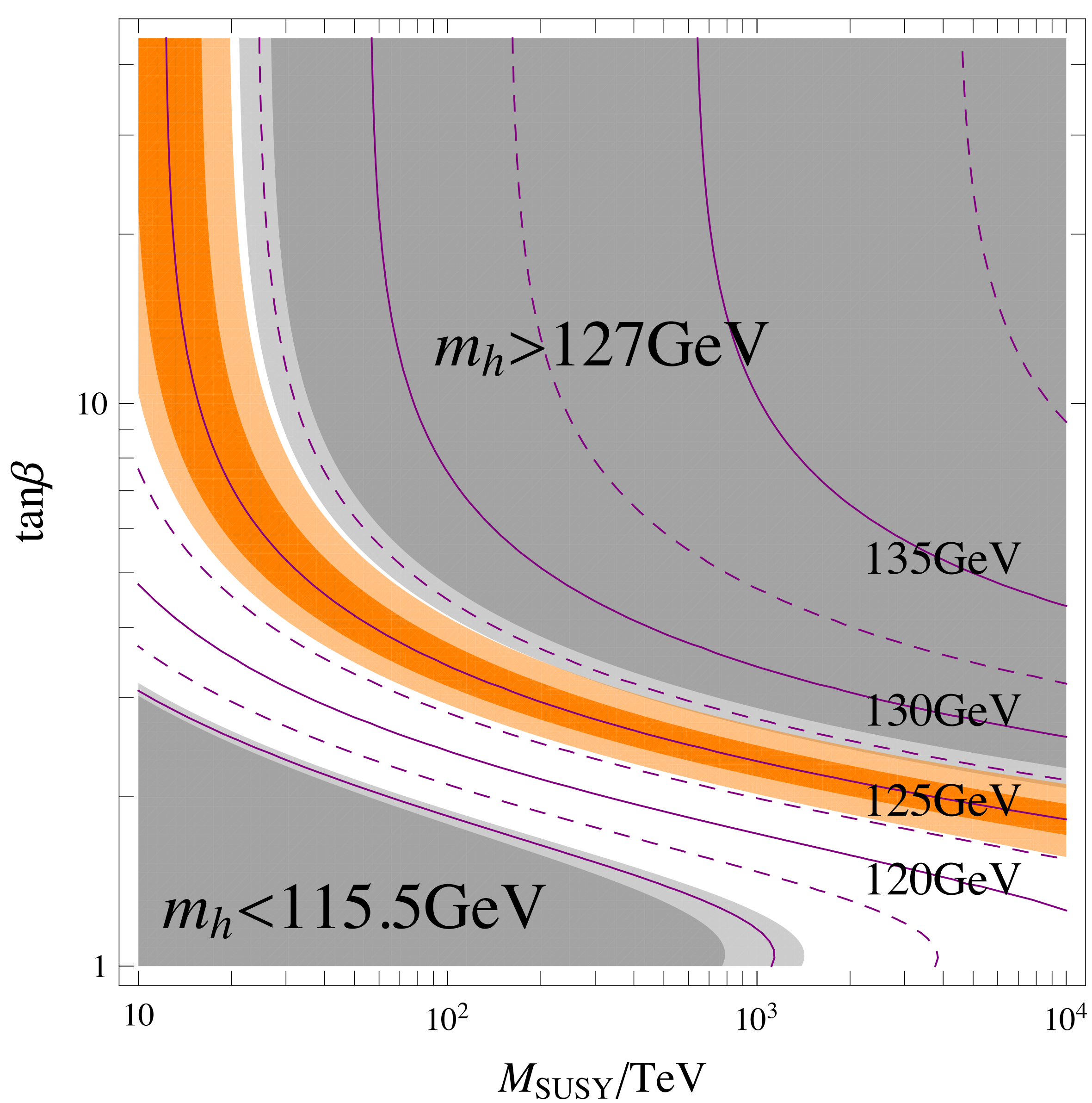

$m_h = 125$ GeV

High SUSY-breaking scale.

M. Ibe, S. Matsumoto, T. T. Yanagida (2012).

High-scale SUSY

L. J. Hall, Y. Nomura, S. Shirai (2012)
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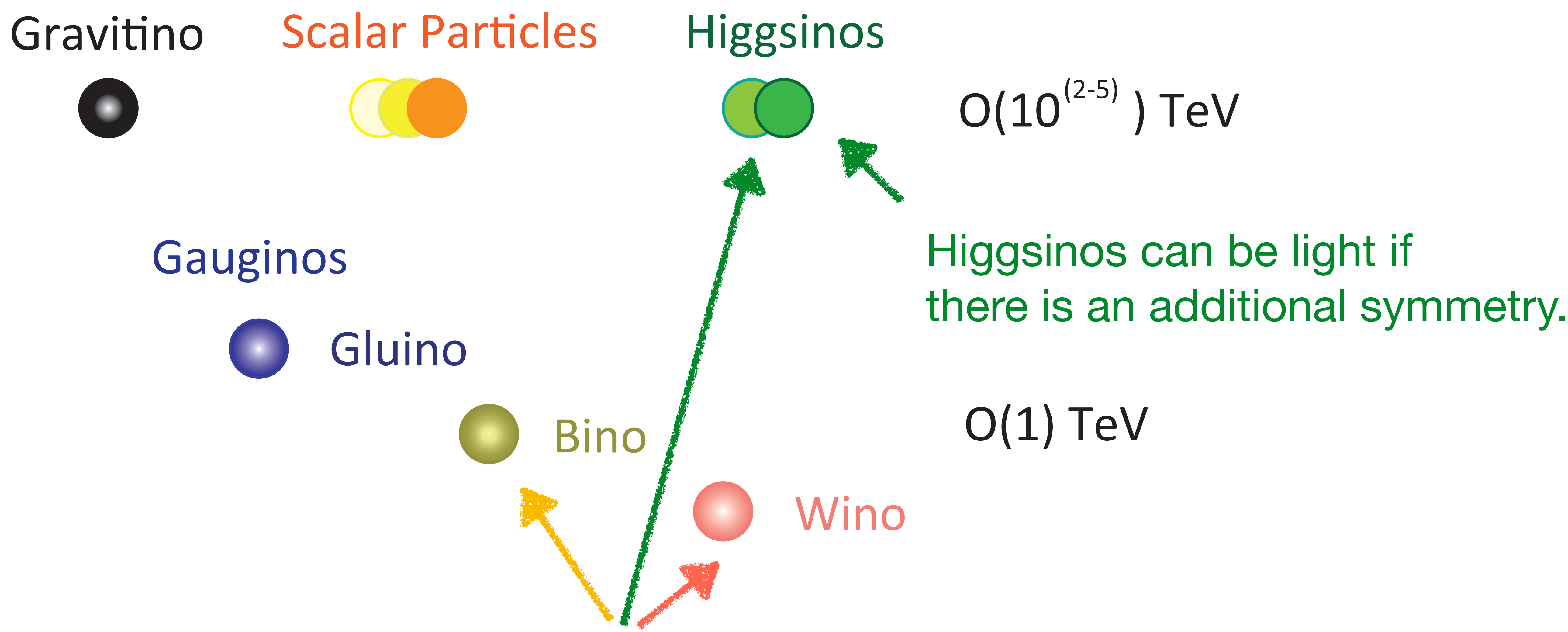
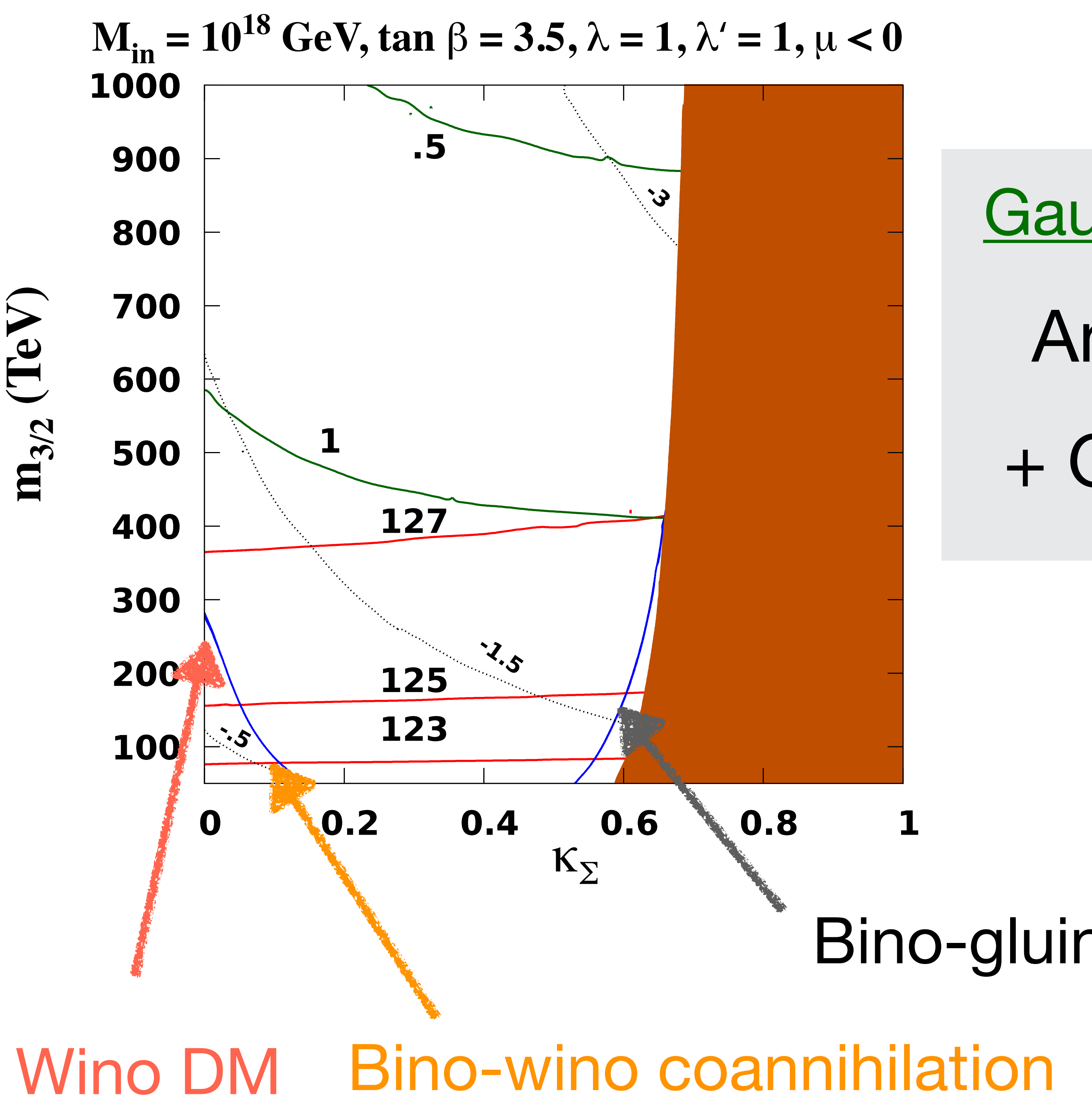


Dark matter candidates in this setup.

An example

Parameter space in SU(5) SuperGUT PGM.



Gaugino mass contribution

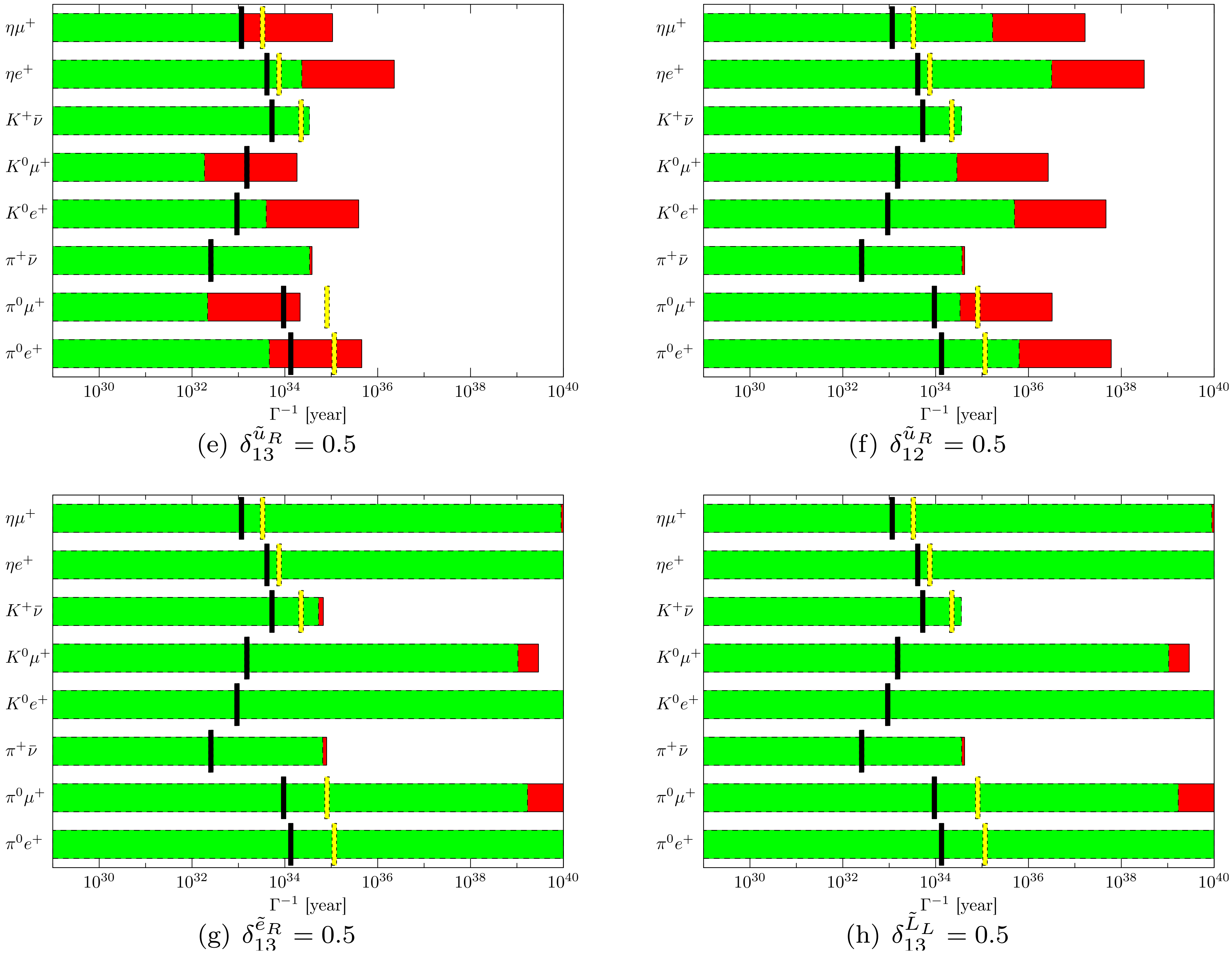
Anomaly mediation

+ GUT threshold corrections.

with $\frac{\kappa_\Sigma}{\sqrt{3}M_P}(Z+Z^*)|\Sigma|^2$

J. L. Evans, N. Nagata, K. A. Olive, 1902.09084.

Sfermion flavor and proton decay



N. Nagata and S. Shirai, JHEP **1403**, 049 (2014).