Flavor symmetry and proton decay in high-scale supersymmetry

Keiichi Watanabe (ICRR, U Tokyo)

Work in progress

with M. Ibe (ICRR) and S. Shirai (IPMU)

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Today's goal

- Flavor symmetries (e.g. Froggatt-Nielsen mechanism) can explain flavor structures

- In grand unified theories, flavor structures of quarks and leptons can be understood uniformly

- Flavor symmetries can be verified using proton decay

Contents

1. Flavor structure and
   Grand Unified Theory (GUT)

2. Supersymmetry (SUSY)

3. Summary

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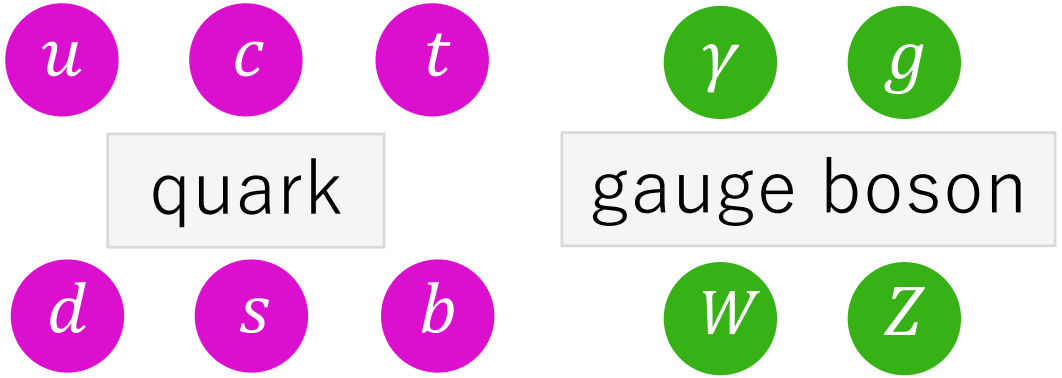
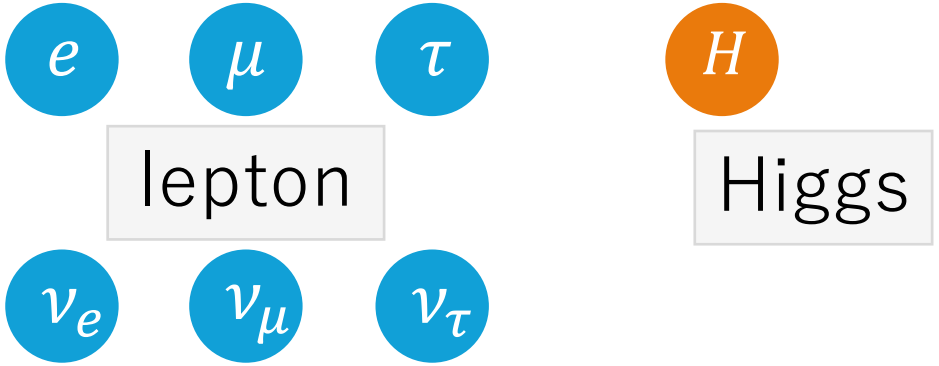
The standard model(SM)



- Very successful

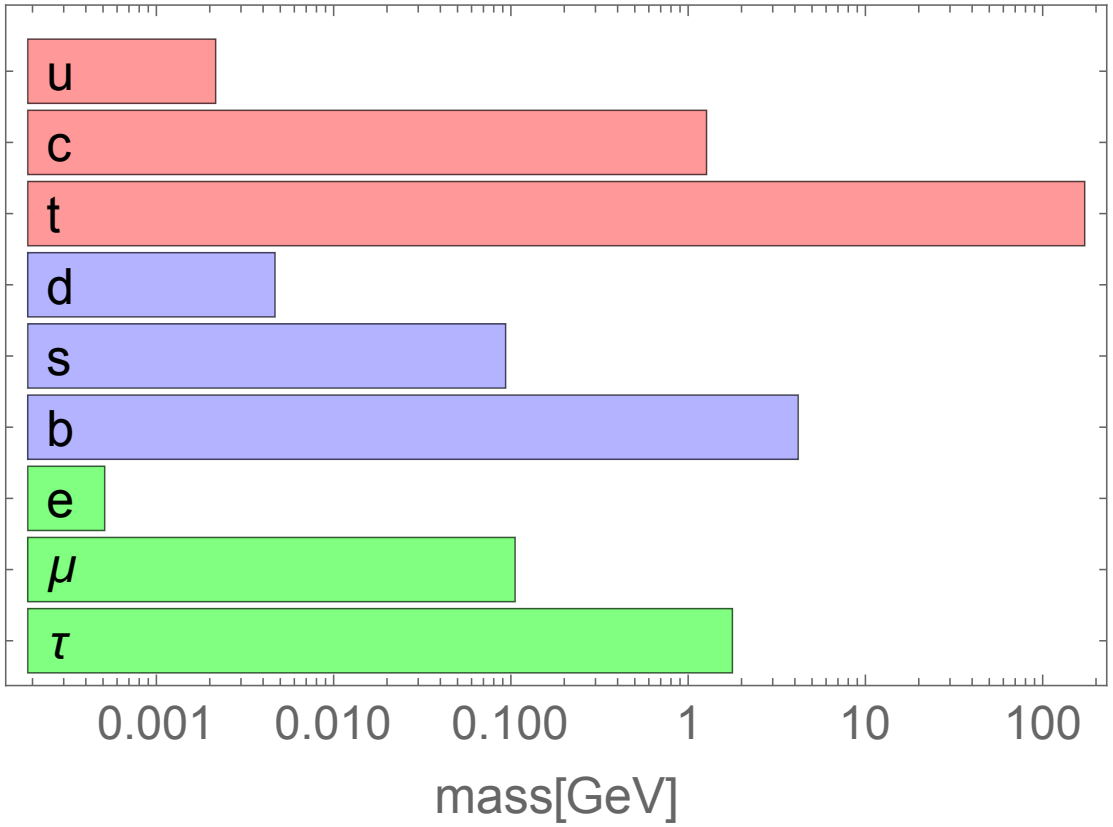


- Repetitive structure of quarks and leptons

Situation

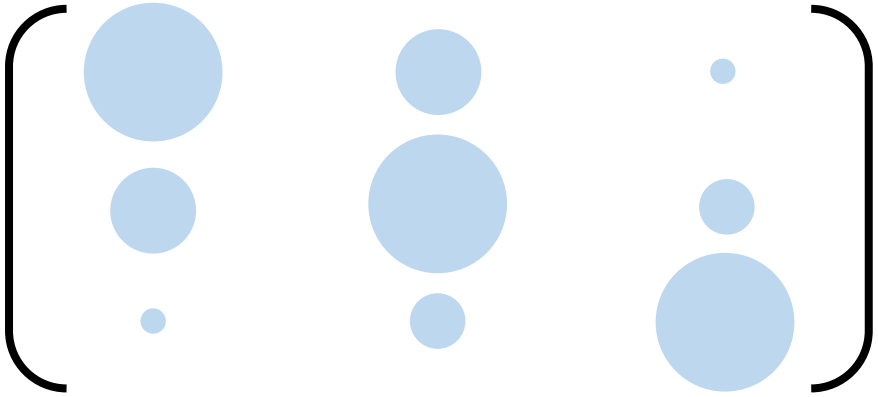
There exist flavor puzzles in the SM !

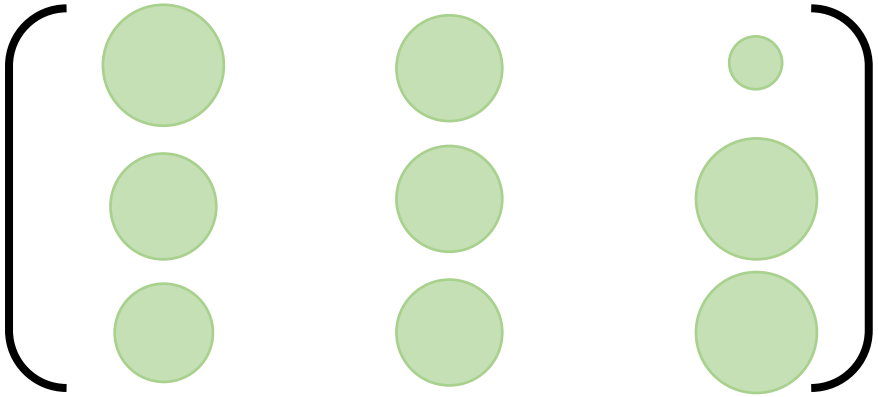
Fermion mass structure



There is hierarchical mass structure.

Structure of mixings

$|V_{\mathrm{CKM}}| =$  hierarchical

$|V_{\mathrm{PMNS}}| =$  anarchical

Mixing matrices have distinctive structures.

Froggatt-Nielsen (FN) mechanism

C.D.Froggatt and H.B.Nielsen, Nucl,Phys.B 147 (1979)

- Consider new U(1) symmetry

$$f_i : q(f_i), \qquad (\ i\text{: generation}\ )$$

- We cannot write ordinary Yukawa interactions

$$\cancel{f_i\, f_j\, H}$$

- If we introduce new scalar $S : -1$,

$$\kappa_{ij}\, f_i\, f_j\, H \times \left(\frac{S}{M_{\mathrm{Pl}}}\right)^{|q(f_i)+q(f_j)|}, \quad \kappa_{ij} = O(1)$$

FN mechanism

- If S obtains VEV,

$$\kappa_{ij}\, f_i\, f_j\, H \times \left(\frac{\langle S\rangle}{M_{\rm Pl}}\right)^{|q(f_i)+q(f_j)|} = \kappa_{ij}\, f_i\, f_j\, H \times \epsilon^{|q(f_i)+q(f_j)|},$$

$$y_{ij} = \kappa_{ij} \times \epsilon^{|q(f_i)+q(f_j)|}, \qquad \epsilon = \langle S\rangle / M_{\rm Pl} < 1$$

- **Flavor structure is realized naturally.**

SU(5) Grand Unified Theory (GUT)

- matter unification

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \; u_R^c, \; d_R^c, \; e_R^c$$

$$\bar{5} = \begin{pmatrix} d_{\mathrm{R}}^c \\ d_{\mathrm{G}}^c \\ d_{\mathrm{B}}^c \\ e \\ -\nu \end{pmatrix}, \qquad 10 = \begin{pmatrix} 0 & u_{\mathrm{B}}^c & -u_{\mathrm{G}}^c & u_{\mathrm{R}} & d_{\mathrm{R}} \\ -u_{\mathrm{B}}^c & 0 & u_{\mathrm{R}}^c & u_{\mathrm{G}} & d_{\mathrm{G}} \\ u_{\mathrm{G}}^c & -u_{\mathrm{R}}^c & 0 & u_{\mathrm{B}} & d_{\mathrm{B}} \\ -u_{\mathrm{R}} & -u_{\mathrm{G}} & -u_{\mathrm{B}} & 0 & e^c \\ -d_{\mathrm{R}} & -d_{\mathrm{G}} & -d_{\mathrm{B}} & -e^c & 0 \end{pmatrix}$$

SU(5) Grand Unified Theory (GUT)

- fermion

$$\bar{5} = \begin{pmatrix} d^c_{\mathrm{R}} \\ d^c_{\mathrm{G}} \\ d^c_{\mathrm{B}} \\ e \\ -\nu \end{pmatrix}, \qquad 10 = \begin{pmatrix} 0 & u^c_{\mathrm{B}} & -u^c_{\mathrm{G}} & u_{\mathrm{R}} & d_{\mathrm{R}} \\ -u^c_{\mathrm{B}} & 0 & u^c_{\mathrm{R}} & u_{\mathrm{G}} & d_{\mathrm{G}} \\ u^c_{\mathrm{G}} & -u^c_{\mathrm{R}} & 0 & u_{\mathrm{B}} & d_{\mathrm{B}} \\ -u_{\mathrm{R}} & -u_{\mathrm{G}} & -u_{\mathrm{B}} & 0 & e^c \\ -d_{\mathrm{R}} & -d_{\mathrm{G}} & -d_{\mathrm{B}} & -e^c & 0 \end{pmatrix},$$

- scalar

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \quad \Rightarrow \quad H_5 = \begin{pmatrix} H_{\mathrm{R}} \\ H_{\mathrm{G}} \\ H_{\mathrm{B}} \\ H^+ \\ H^0 \end{pmatrix}$$

SU(5) Grand Unified Theory (GUT)

$$\bar{5} = \begin{pmatrix} d^c_{\mathrm{R}} \\ d^c_{\mathrm{G}} \\ d^c_{\mathrm{B}} \\ e \\ -\nu \end{pmatrix}, \quad 10 = \begin{pmatrix} 0 & u^c_{\mathrm{B}} & -u^c_{\mathrm{G}} & u_{\mathrm{R}} & d_{\mathrm{R}} \\ -u^c_{\mathrm{B}} & 0 & u^c_{\mathrm{R}} & u_{\mathrm{G}} & d_{\mathrm{G}} \\ u^c_{\mathrm{G}} & -u^c_{\mathrm{R}} & 0 & u_{\mathrm{B}} & d_{\mathrm{B}} \\ -u_{\mathrm{R}} & -u_{\mathrm{G}} & -u_{\mathrm{B}} & 0 & e^c \\ -d_{\mathrm{R}} & -d_{\mathrm{G}} & -d_{\mathrm{B}} & -e^c & 0 \end{pmatrix}, \quad H_5 = \begin{pmatrix} H_{\mathrm{R}} \\ H_{\mathrm{G}} \\ H_{\mathrm{B}} \\ H^+ \\ H^0 \end{pmatrix}$$

Proton decay !

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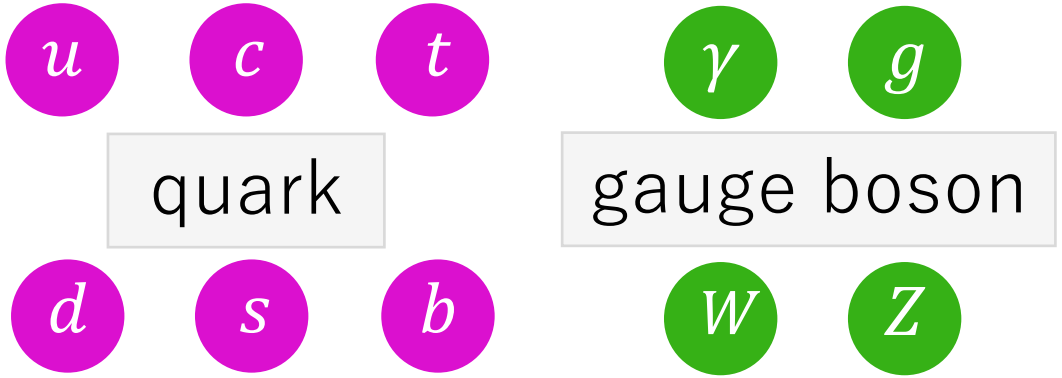
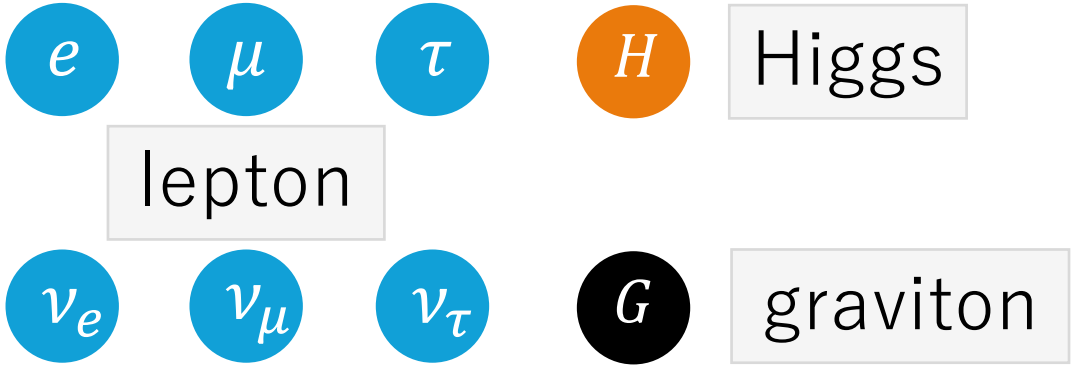
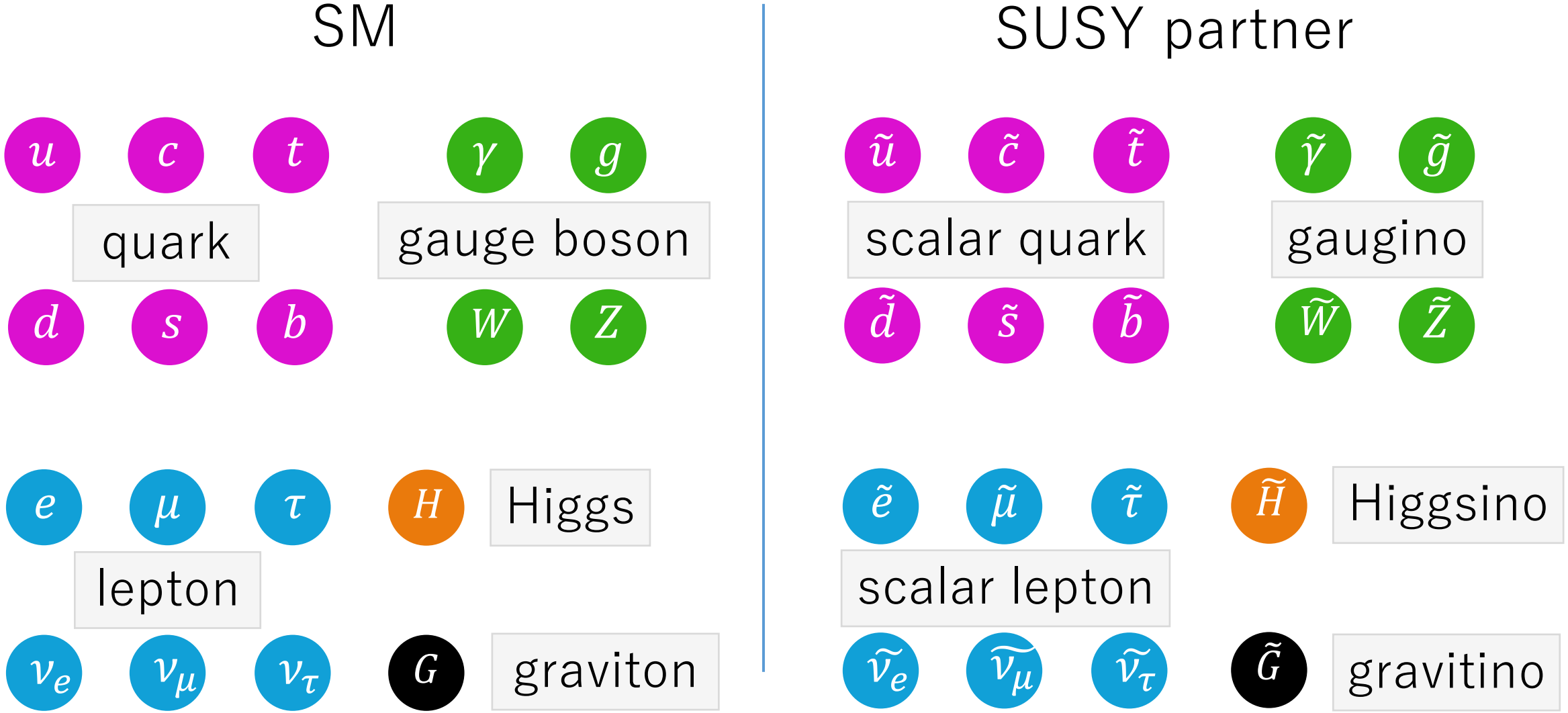
Minimal Supersymmetric SM (MSSM)



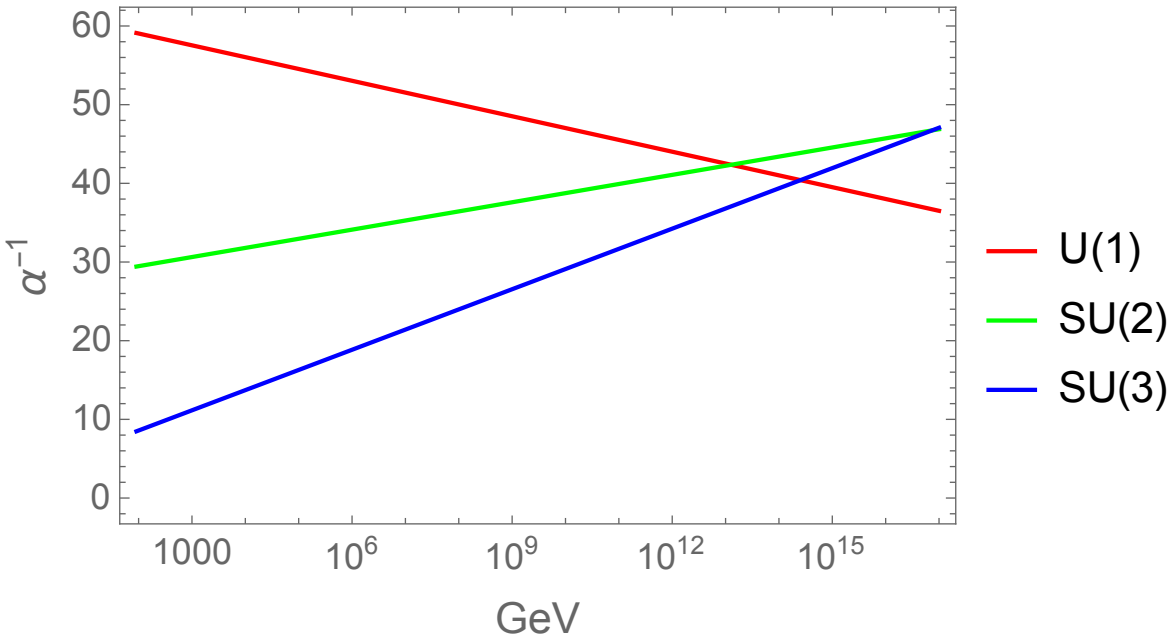


Minimal Supersymmetric SM (MSSM)

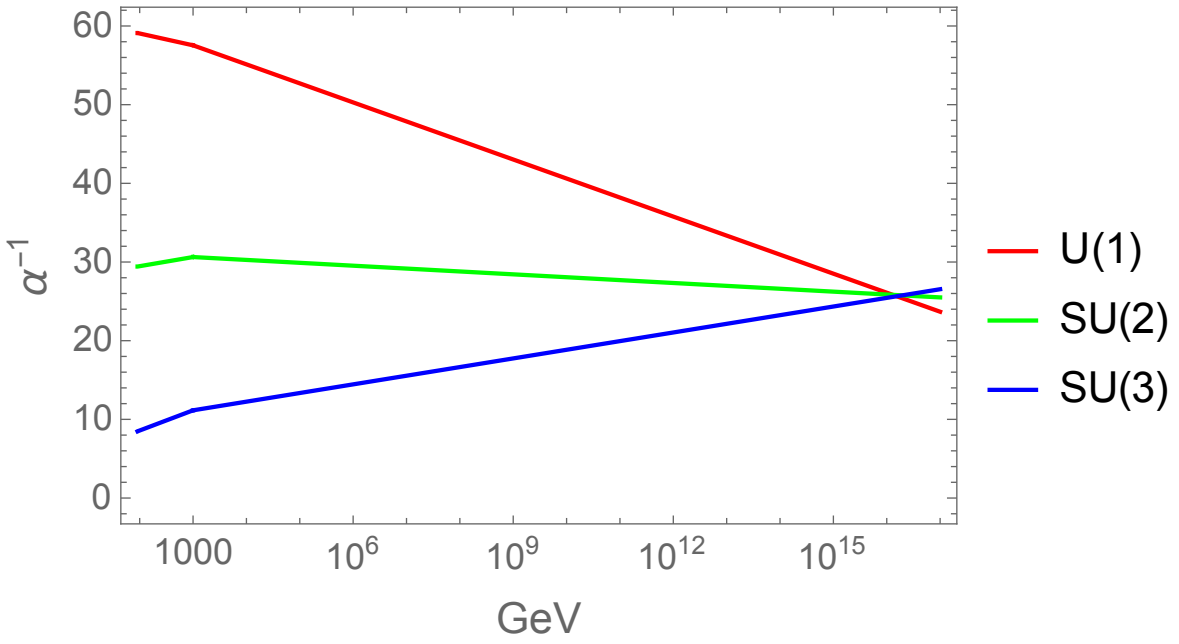


Gauge couplings

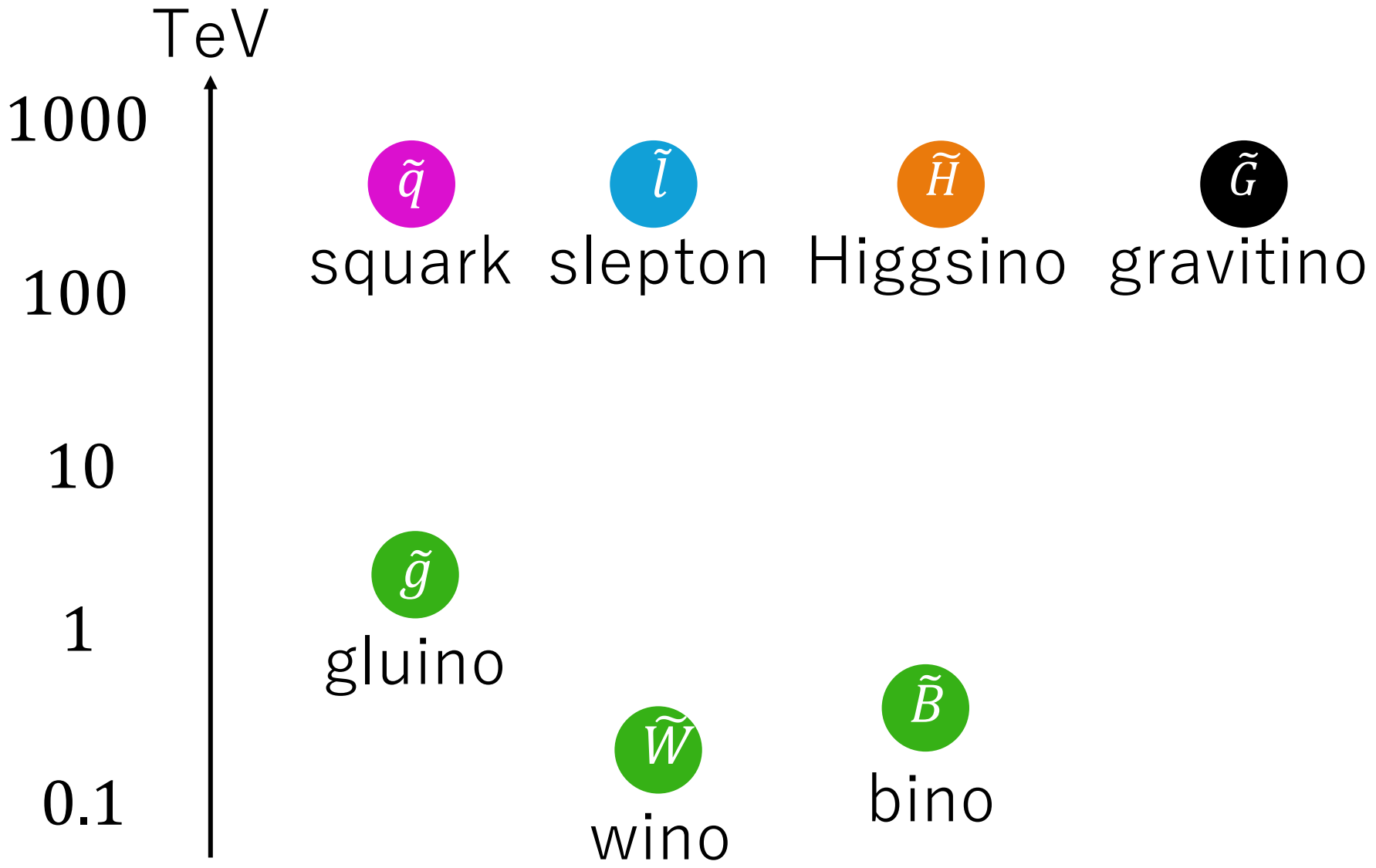
SM



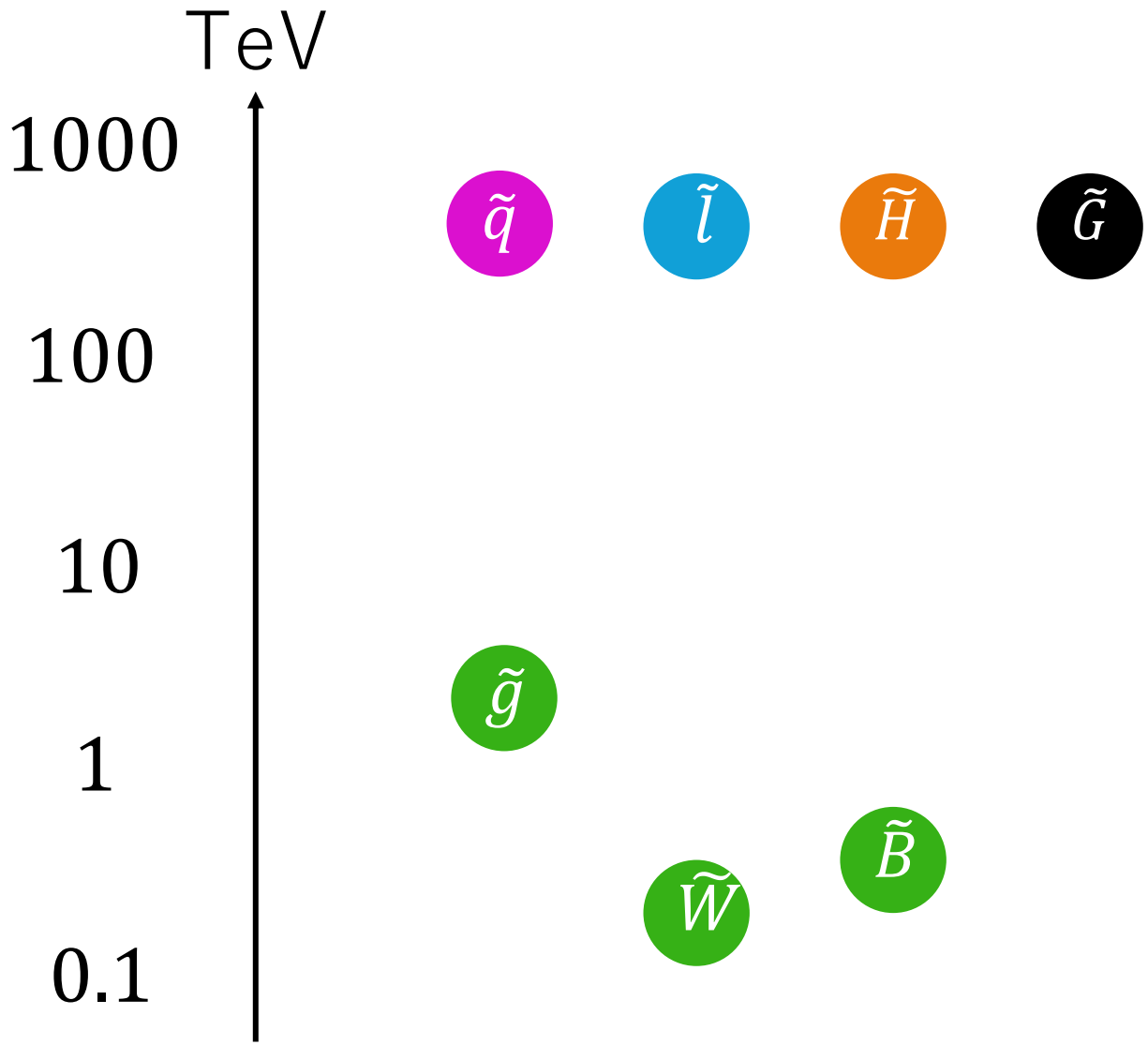
MSSM



High-scale SUSY



High-scale SUSY



$m_h = 125$ GeV

~~flavor problem~~

proton decay

dark matter

Flavor effect

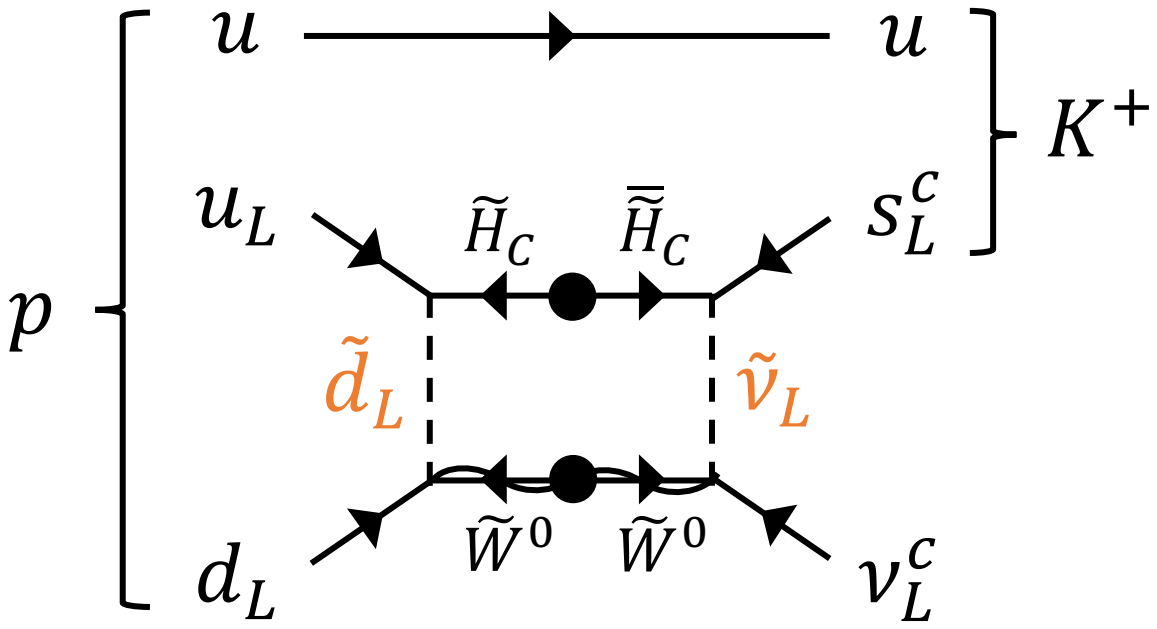
- fermion mass terms

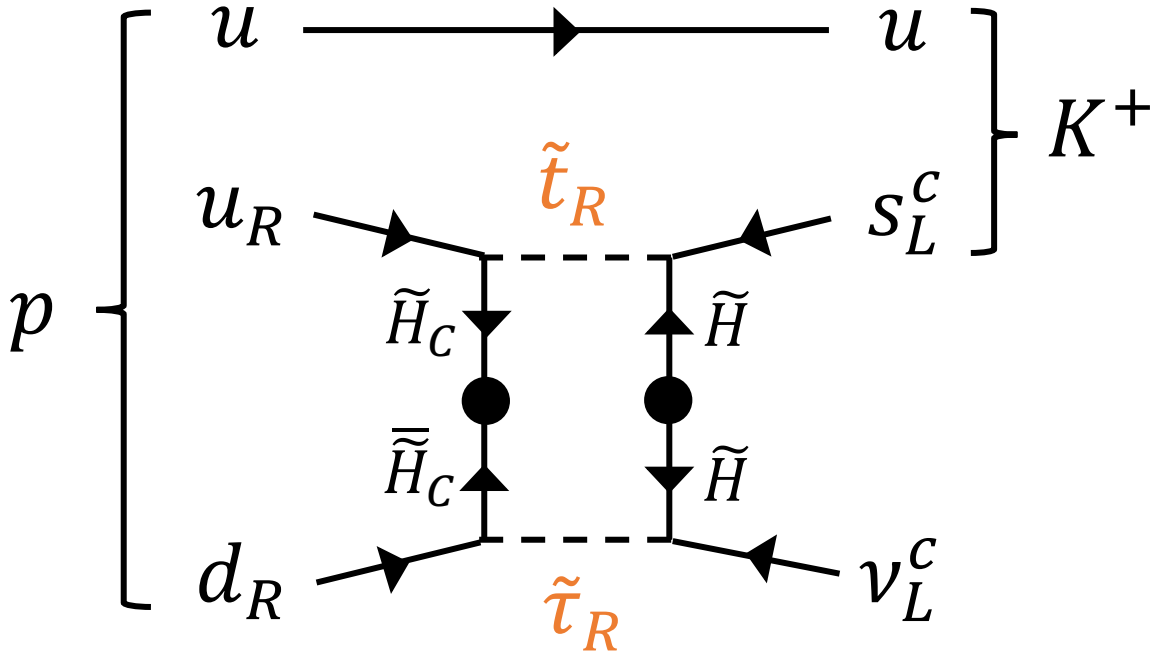
$$y_{ij}\,\langle H\rangle \times \bar{f}_i\, f_j \quad \Rightarrow \quad f_i \longrightarrow f_k$$

- sfermion mass terms

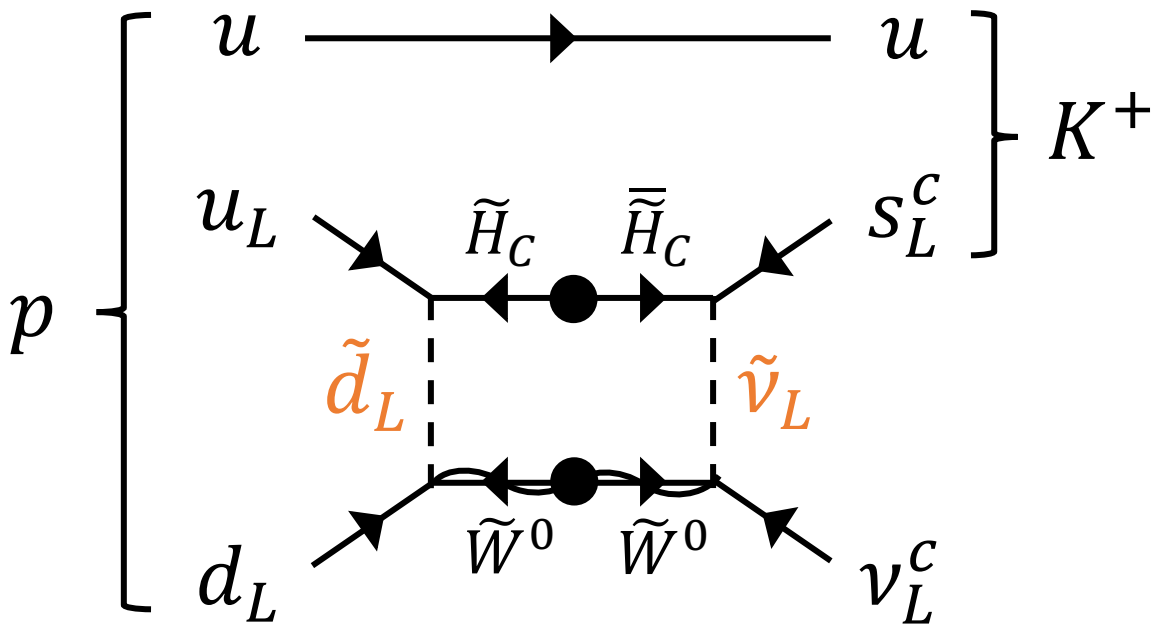
$$m_{ij}^2 \times \tilde{f}_i^{\dagger}\, \tilde{f}_j \quad \Rightarrow \quad \tilde{f}_i \longrightarrow \tilde{f}_k$$

Proton decay in SUSY GUT





Proton decay in SUSY GUT



$\tilde{H}_C$: colored Higgsino

$\tilde{W}^0$: neutral wino

$\tilde{d}_L, \tilde{\nu}_L$: sfermions

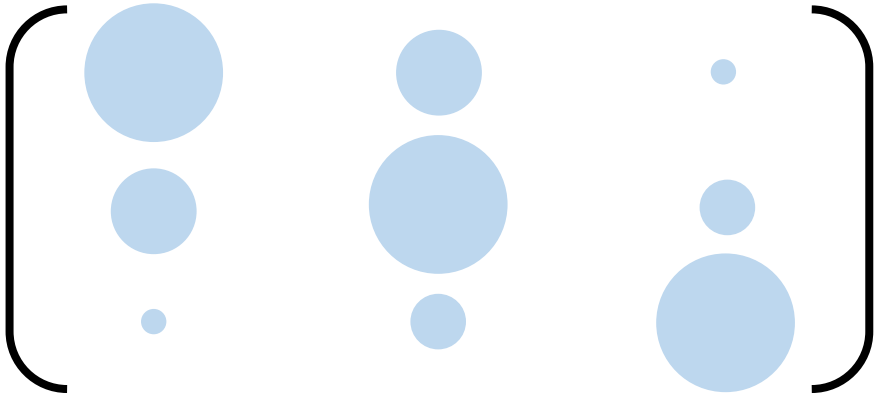
⟶ flavor mixings

We focus on SUSY GUT with FN mechanism.

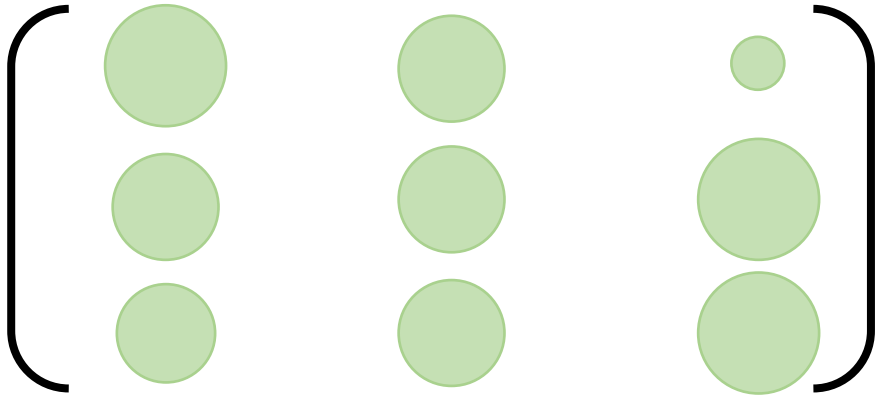
FN mechanism + SUSY GUT

- sfermion mass structure

$$\left|m^2_{\tilde{Q}_L,\tilde{u}_R,\tilde{e}_R}\right| \sim$$

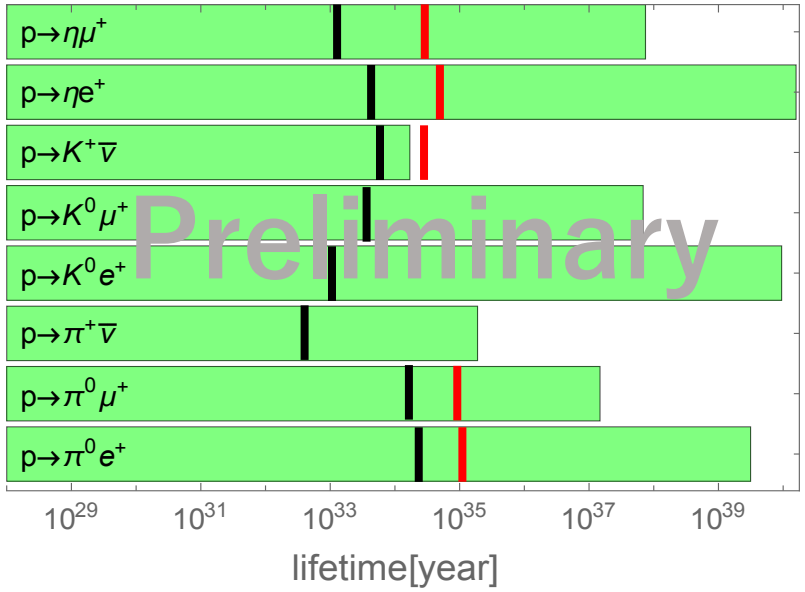


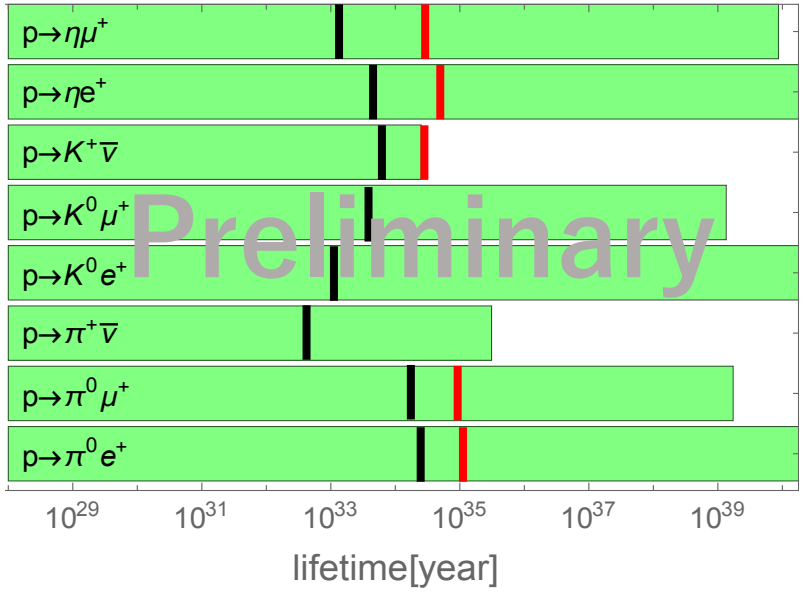
$$\left|m^2_{\tilde{L}_L,\tilde{d}_R}\right| \sim$$

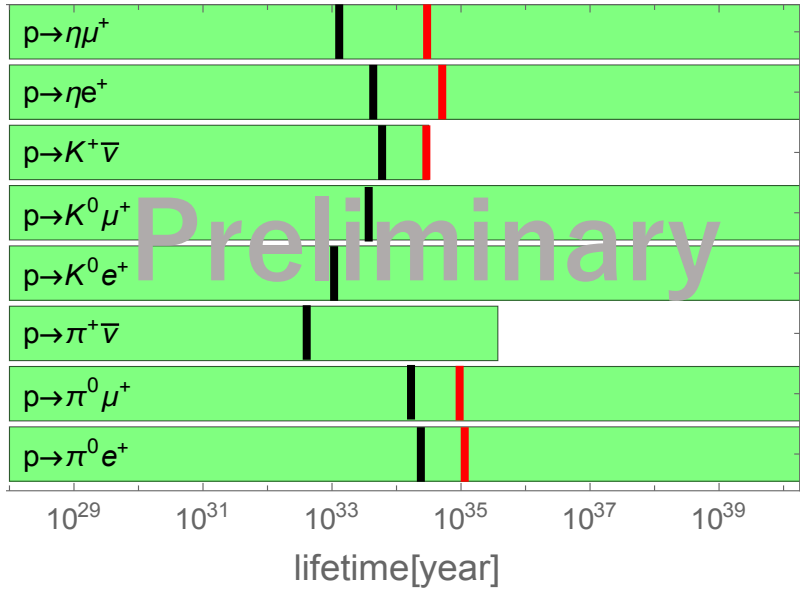


Results: $\mathbf{10} \ni (Q_L, u_R^c, e_R^c)$

$q(10) = (3, 2, 0)$ $(4, 2, 0)$ $(5, 2, 0)$

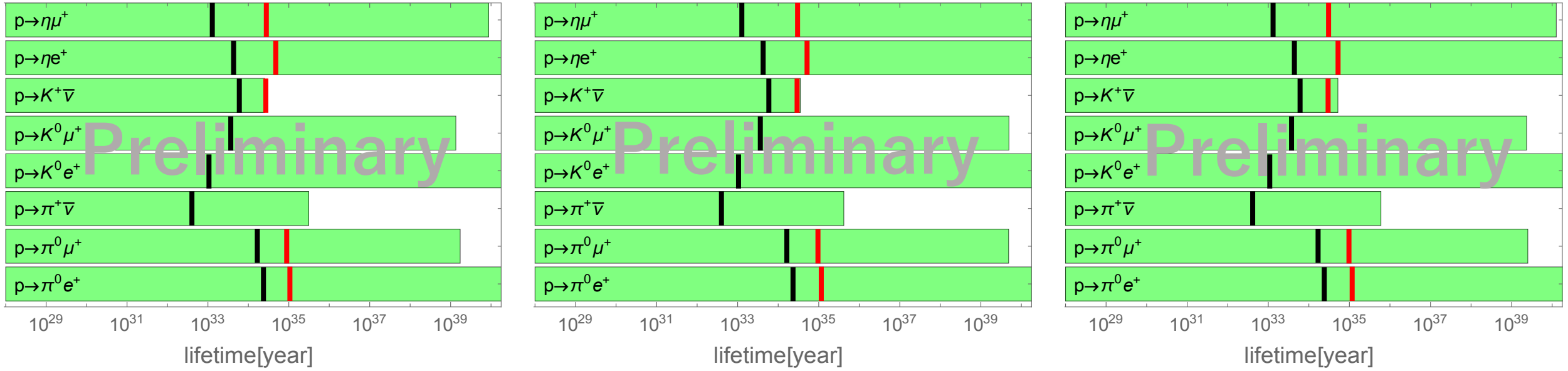






Results: $\bar{5} \ni (d_R^c, L_L)$

$q(\bar{5}) = (4, 4, 3)$ $(4, 3, 3)$ $(3, 3, 3)$



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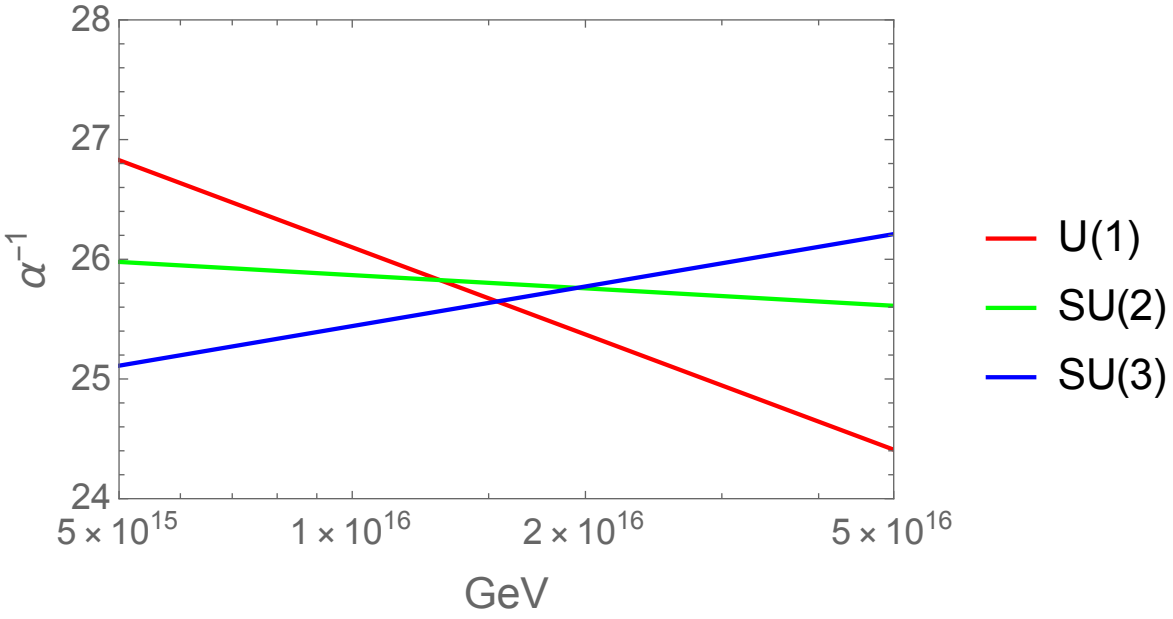
Summary

- Froggatt-Nielsen mechanism can explain flavor structures
- In grand unified theories, flavor structures of quarks and leptons can be understood uniformly
- Flavor symmetries can be verified using proton decay

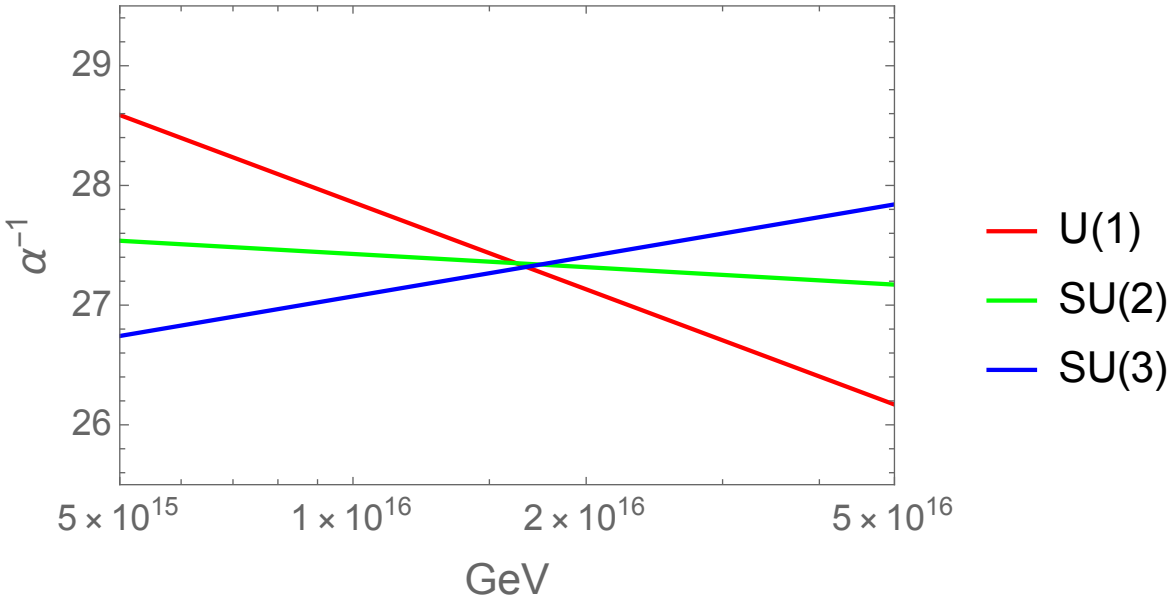
Backup

Gauge couplings

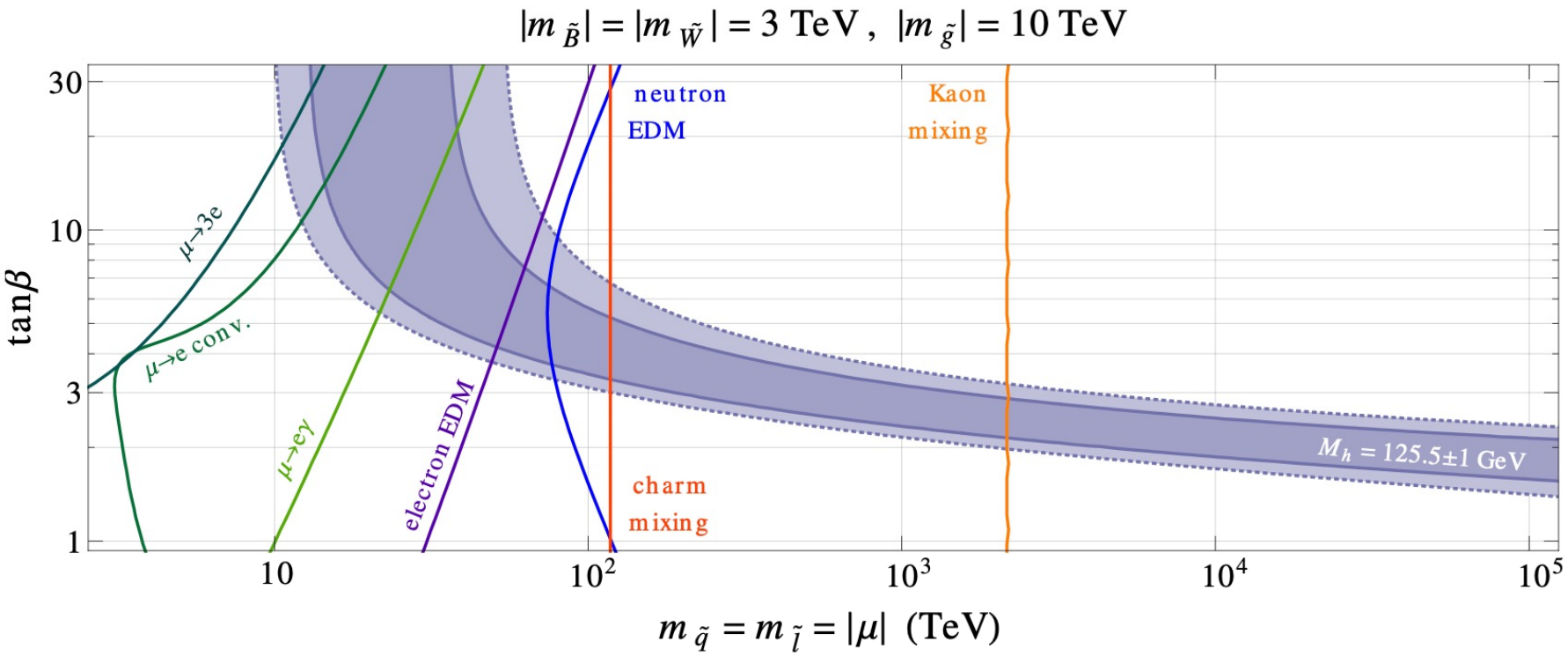
Low-scale SUSY



High-scale SUSY



Flavor problem on SUSY



W. Altmannshofer, R. Harnik and J. Zupan, JHEP 11 (2013) 202