Nucleon decay via dimension-6 operators in anomalous $U(1)_A$ SUSY GUT models and $E_6 \times SU(2)_F$ SUSY GUT model

PASCOS 2013 @ NTU

based on arXiv:1307.7529 [hep-ph] and more

Yu Muramatsu(Nagoya university)

Collaborator:

Nobuhiro Maekawa(Nagoya univesity, KMI)

1. Introduction and previous work
2. $E_6 \times SU(2)_F$ Model

Grand Unified Theory

many advantages and several realistic models

How do we identify models as “the” grand unified theory?

Model identification

$$\Lambda_{GUT} = 10^{12-16} GeV \gg \Lambda_{LHC} = 10^{3-4} GeV$$

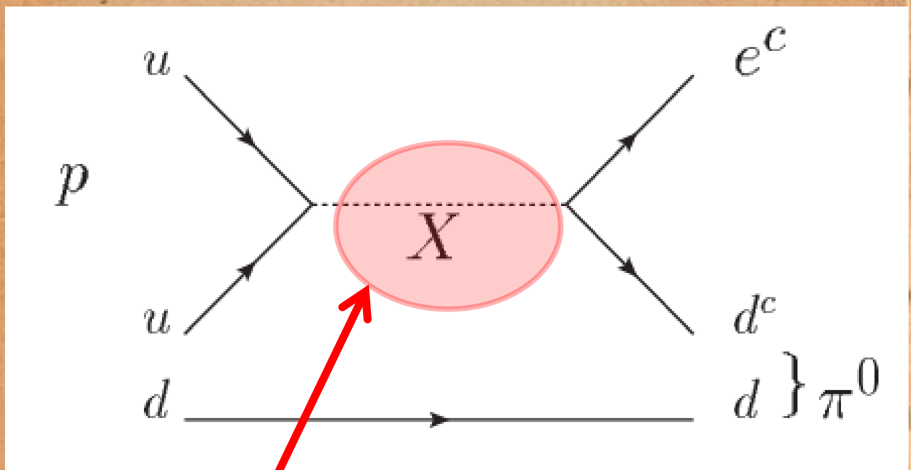
It is hard to identify models by accelerator.

In this work, we try GUT model identification by “the nucleon decay” (arXiv:1307.7529 [hep-ph]).

- phenomenon from GUT(bSM)
- expected to be observed in the near future

The nucleon decay in SUSY GUT models

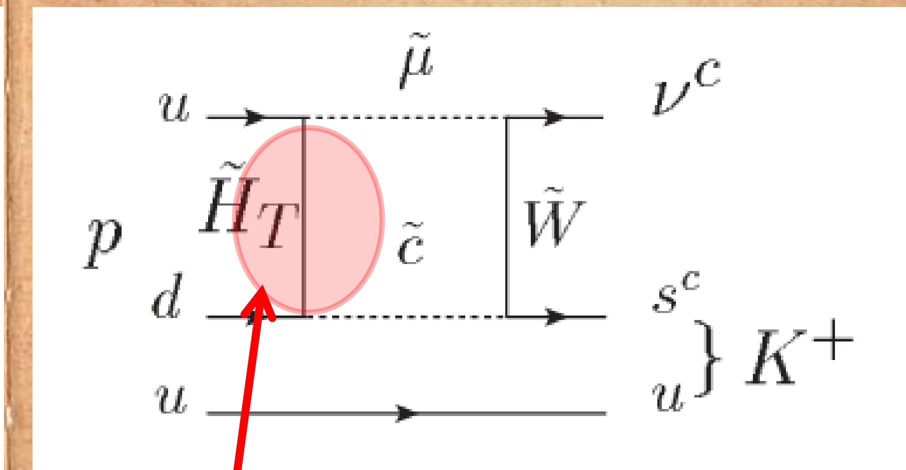
via dimension-6 operators
the main decay mode



X-type(X(3,2)) gauge boson

$$p \longrightarrow \pi^0 + e^c$$

via diemnsion-5 operators
the main decay mode



triplet(colored) Higgsino

$$p \longrightarrow K^+ + \nu^c$$

SUSY GUT	$\Lambda_{SUSY\ GUT} \sim 2 \times 10^{16}$ GeV $\tau_N \sim 10^{36}$years$(\propto \Lambda^4_{SUSY\ GUT})$	weake suppression

significant interaction

$\tau_{p \to \pi^0 + e^c} \geq 1.3 \times 10^{34}$@Super-Kamiokande

Anomalous $U(1)_A$ SUSY GUT

constructed under “natural assumptions”

- consider all operators which are allowed by symmetries
- consider effects of all higher-order operators
- operators’ coefficients are order 1

Anomalous $U(1)_A$ SUSY GUT models realize many features.

- doublet-triplet splitting
- gauge coupling unification
- realistic quark and lepton masses and mixings etc.

Nucleon decay is one of the most interesting predictions.

via dimension-6 operators

enhanced

Cabibbo angle

$\Lambda_A \sim \lambda^{-a} \Lambda_{SUSY\ GUT} < \Lambda_{SUSY\ GUT}$

GUT scale in anomalous $U(1)_A$ SUSY GUT models

$\Lambda_A \sim \lambda^{0.5} \Lambda_{SUSY\ GUT} = 10^{16}$ GeV

The nucleon decay via dimension-6 operators is significant.

via dimension-5 operators

Natural realization of doublet-triplet splitting suppresses the nucleon decay via dimension-5 operators.

We study the nucleon decay via dimension-6 operators.

Diagonalizing Matrix

$$\psi_{Li} Y_{ij} \psi^c_{Rj} = (L^\dagger_\psi \psi_L)_i (L^T_\psi Y R_\psi)_{ij} (R^\dagger_\psi \psi^c_R)_j$$
$$= \psi'_{Li} Y_{diag\ ij} \psi'^c_{Rj}$$

L_ψ, R_ψ : diagonalizing matrix

In the Standard Model (weak interaction)

$$U_{CKM} = L^\dagger_u L_d,\ U_{MNS} = L^\dagger_\nu L_e$$

In nucleon decay operators (X type gauge int.)

Diagonalizing matrices appear directly.

Experimentally,

We cannot measure diagonalizing matrices directly.

Theoretically,

For example in the minimal SU(5) GUT model,

Yukawa matrices have few degrees of freedom.

→ Diagonalizing matrices are strongly restricted.

But, $Y_d = Y_e^T$

To realize realistic quark and lepton masses and mixings,

we introduce additional interactions.

→ additional degrees of freedom

→ Diagonalizing matrices have uncertainties.

In the previous work (arXiv:1307.7529 [hep-ph]), we try to identify GUT models by nucleon decay.

two important ratios

$$R_1 \equiv \frac{\Gamma_{n\to\pi^0+\nu^c}}{\Gamma_{p\to\pi^0+e^c}}$$

To identify grand unification group

$$R_2 \equiv \frac{\Gamma_{p\to K^0+\mu^c}}{\Gamma_{p\to\pi^0+e^c}}$$

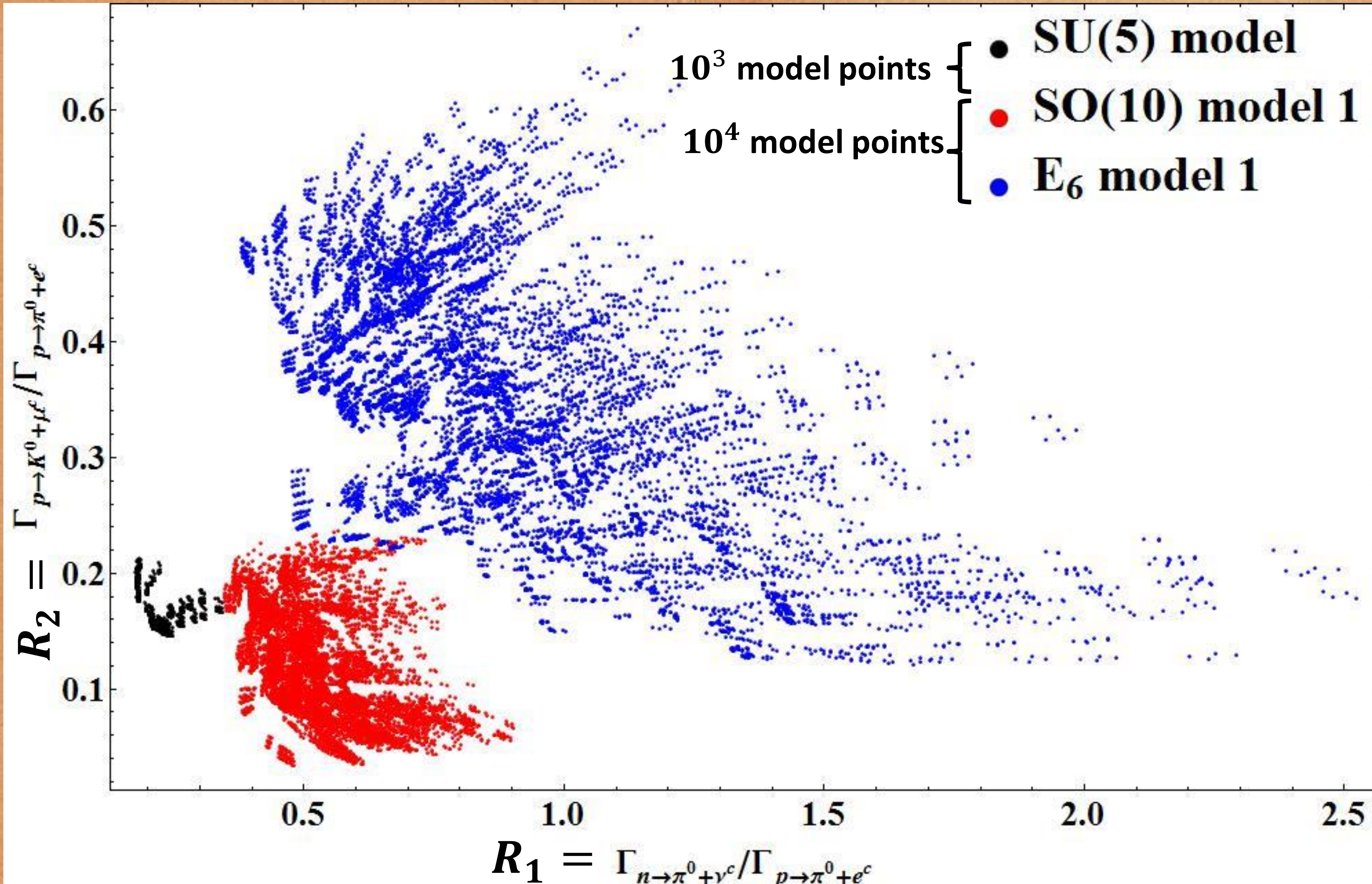
To identify Yukawa structure

$$\begin{aligned}
\mathcal{L}_{eff} \;=\; & \frac{g_{GUT}^2}{M_X^2}\{(\overline{e^c_{Ri}}u_{Rj})(\overline{u^c_{Lj}}d_{Li}) + (\overline{e^c_{Ri}}u_{Rj})(\overline{u^c_{Li}}d_{Lj}) \\
& + (\overline{e^c_{Li}}u_{Lj})(\overline{u^c_{Rj}}d_{Ri}) - (\overline{\nu^c_{Li}}d_{Lj})(\overline{u^c_{Rj}}d_{Ri})\} \\
& + \frac{g_{GUT}^2}{M_{X'}^2}\{(\overline{e^c_{Li}}u_{Lj})(\overline{u^c_{Ri}}d_{Rj}) - (\overline{\nu^c_{Li}}d_{Lj})(\overline{u^c_{Ri}}d_{Rj})\} \\
& + \frac{g_{GUT}^2}{M_{X''}^2}\{(\overline{E^c_{Li}}u_{Lj})(\overline{u^c_{Ri}}D_{Rj}) - (\overline{N^c_{Li}}d_{Lj})(\overline{u^c_{Ri}}D_{Rj})\}
\end{aligned}$$

SU(5) GUT

SO(10) GUT

E_6 GUT


SU(5) model
10^3 model points
SO(10) model 1
10^4 model points
E_6 model 1
0.6
0.5
0.4
0.3
0.2
0.1
$R_2 = \Gamma_{p\to K^0+\mu^c}/\Gamma_{p\to\pi^0+e^c}$
0.5
1.0
1.5
2.0
2.5
$R_1 = \Gamma_{n\to\pi^0+\nu^c}/\Gamma_{p\to\pi^0+e^c}$

1. Introduction and previous work
2. $E_6 \times SU(2)_F$ Model

$E_6 \times SU(2)_F$ Model

Yukawa structure at GUT scale is restricted.

27 dimensional representation for matter : Ψ

$\Psi_a (a = 1,2) : SU(2)_F$ doublet for first- and second-generation matters

$\Psi_3 : SU(2)_F$ singlet for third-generation matters

Features

- Realize realistic quark and lepton masses and mixings within restricted Yukawa structure
- Solve SUSY CP problem (Chromo-EDM constraint) by spontaneous CP violation mechanism
- Suppress Flavor Changing Neutral Current processes

in previous work

$$Y_u = \begin{pmatrix} y_{u11}\lambda^6 & y_{u12}\lambda^5 & y_{u13}\lambda^3 \\ y_{u21}\lambda^5 & y_{u22}\lambda^4 & y_{u23}\lambda^2 \\ y_{u31}\lambda^3 & y_{u32}\lambda^2 & y_{u33} \end{pmatrix}$$

$$Y_d = \begin{pmatrix} y_{d11}\lambda^6 & y_{d12}\lambda^{5.5} & y_{d13}\lambda^5 \\ y_{d21}\lambda^5 & y_{d22}\lambda^{4.5} & y_{d23}\lambda^4 \\ y_{d31}\lambda^3 & y_{d32}\lambda^{2.5} & y_{d33}\lambda^2 \end{pmatrix}$$

$$Y_e = \begin{pmatrix} y_{e11}\lambda^6 & y_{e12}\lambda^5 & y_{e13}\lambda^3 \\ y_{e21}\lambda^{5.5} & y_{e22}\lambda^{4.5} & y_{e23}\lambda^{2.5} \\ y_{e31}\lambda^5 & y_{e32}\lambda^4 & y_{e33}\lambda^2 \end{pmatrix}$$

$9 \times 3 = 27\ O(1)$ parameters for masses and mixings

in $E_6 \times SU(2)_F$ Model

$$Y_u = \begin{pmatrix} 0 & \frac{1}{3}y_{u12}\lambda^5 & 0 \\ -\frac{1}{3}y_{u12}\lambda^5 & y_{u22}\lambda^4 & y_{u23}\lambda^2 \\ 0 & y_{u23}\lambda^2 & y_{u33} \end{pmatrix}$$

$$Y_d = \begin{pmatrix} y_{d11}\lambda^6 & y_{d12}\lambda^{5.5} & \frac{1}{3}y_{d13}\lambda^5 \\ y_{d21}\lambda^5 & y_{d22}\lambda^{4.5} & y_{d23}\lambda^4 \\ y_{d31}\lambda^3 & y_{d32}\lambda^{2.5} & y_{d33}\lambda^2 \end{pmatrix}$$

$$Y_e = \begin{pmatrix} y_{d11}\lambda^6 & y_{e12}\lambda^5 & 0 \\ 0 & y_{e22}\lambda^{4.5} & y_{e23}\lambda^{2.5} \\ -y_{e12}\lambda^5 & y_{d23}\lambda^4 & y_{d33}\lambda^2 \end{pmatrix}$$

$4 + 9 + 3 = 16\ O(1)$ parameters for masses and mixings

$\theta_{ij}^{\psi L,R}$:mixing angle for diagonalizing matrix of $\psi_{L,R}$

$$L_\Psi, R_\Psi \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23}^{\Psi L,R} & s_{23}^{\Psi L,R} \\ 0 & -s_{23}^{\Psi L,R} & c_{23}^{\Psi L,R} \end{pmatrix} \begin{pmatrix} c_{13}^{\Psi L,R} & 0 & s_{13}^{\Psi L,R} \\ 0 & 1 & 0 \\ -s_{13}^{\Psi L,R} & 0 & c_{13}^{\Psi L,R} \end{pmatrix} \begin{pmatrix} c_{12}^{\Psi L,R} & s_{12}^{\Psi L,R} & 0 \\ -s_{12}^{\Psi L,R} & c_{12}^{\Psi L,R} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$s_{ij}^{\Psi L,R} \sim \theta_{ij}^{\Psi L,R}, c_{ij}^{\Psi L,R} \sim 1$ (main order)

$$\theta_{13}^{uL} = 0 \quad \theta_{13}^{uR} = 0 \quad \theta_{13}^{eL} = 0$$

$$\theta_{23}^{uL} = \theta_{23}^{uR} \quad \theta_{23}^{dL} = \theta_{23}^{eR} \quad \theta_{12}^{eR} = \theta_{23}^{eL}\theta_{12}^{eL}$$

$$|\theta_{12}^{uL}| = |\theta_{12}^{uR}| = \sqrt{m_u/m_c} \quad \frac{m_\mu}{m_\tau} = -\frac{\theta_{13}^{eR}}{\theta_{12}^{eL}}$$

$$\frac{\theta_{13}^{eL}\theta_{13}^{eR}m_\tau - \theta_{13}^{dL}\theta_{13}^{dR}m_b + \theta_{12}^{eL}\theta_{12}^{eR}m_\mu - \theta_{12}^{dL}\theta_{12}^{dR}m_s}{m_d - m_e} = 1$$

$$m_b = m_\tau$$

11 conditions @ GUT scale

Yukawa matrix 1-loop renormalization group equation in MSSM

$$\frac{d}{dt}\mathbf{Y}_{u,d,e} = \frac{1}{16\pi^2}\beta^{(1)}_{\mathbf{Y}_{u,d,e}}$$

$$\beta^{(1)}_{\mathbf{Y}_u} = \mathbf{Y}_u\left\{3\mathrm{Tr}(\mathbf{Y}_u\mathbf{Y}_u^\dagger) + 3\mathbf{Y}_u^\dagger\mathbf{Y}_u + \mathbf{Y}_d^\dagger\mathbf{Y}_d - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right\}$$

$$\beta^{(1)}_{\mathbf{Y}_d} = \mathbf{Y}_d\left\{\mathrm{Tr}(3\mathbf{Y}_d\mathbf{Y}_d^\dagger + \mathbf{Y}_e\mathbf{Y}_e^\dagger) + 3\mathbf{Y}_d^\dagger\mathbf{Y}_d + \mathbf{Y}_u^\dagger\mathbf{Y}_u - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{7}{15}g_1^2\right\}$$

$$\beta^{(1)}_{\mathbf{Y}_e} = \mathbf{Y}_e\left\{\mathrm{Tr}(3\mathbf{Y}_d\mathbf{Y}_d^\dagger + \mathbf{Y}_e\mathbf{Y}_e^\dagger) + 3\mathbf{Y}_e^\dagger\mathbf{Y}_e - 3g_2^2 - \frac{9}{5}g_1^2\right\}$$

$$\theta^{uL}_{13} = \text{negligible} \quad \theta^{uR}_{13} = \text{negligible} \quad \theta^{eL}_{13} = \text{negligible}$$

$$\theta^{uL}_{23} = \theta^{uR}_{23} \quad \theta^{dL}_{23} = \theta^{eR}_{23} \quad \theta^{eR}_{12} = \theta^{eL}_{23}\theta^{eL}_{12}$$

$$|\theta^{uL}_{12}| = |\theta^{uR}_{12}| = \sqrt{m_u/m_c} \qquad \frac{m_\mu}{m_\tau} = -\frac{\theta^{eR}_{13}}{\theta^{eL}_{12}}$$

$$\frac{\theta^{eL}_{13}\theta^{eR}_{13}m_\tau - \theta^{dL}_{13}\theta^{dR}_{13}m_b + \theta^{eL}_{12}\theta^{eR}_{12}m_\mu - \theta^{dL}_{12}\theta^{dR}_{12}m_s}{m_d - m_e} = 1$$

9 conditions for mixing angles @ low energy scale

Parameters for real diagonalizing matrix :

3 prameters (mixing angle) for each matrix

7 diagonalizing matrices : $L_u, L_d, L_e, L_\nu, R_u, R_d, R_e$

➡ 21 parameters

To realize

$$U_{CKM} = L_u^\dagger L_d, U_{MNS} = L_\nu^\dagger L_e$$

we use 6 parameters.

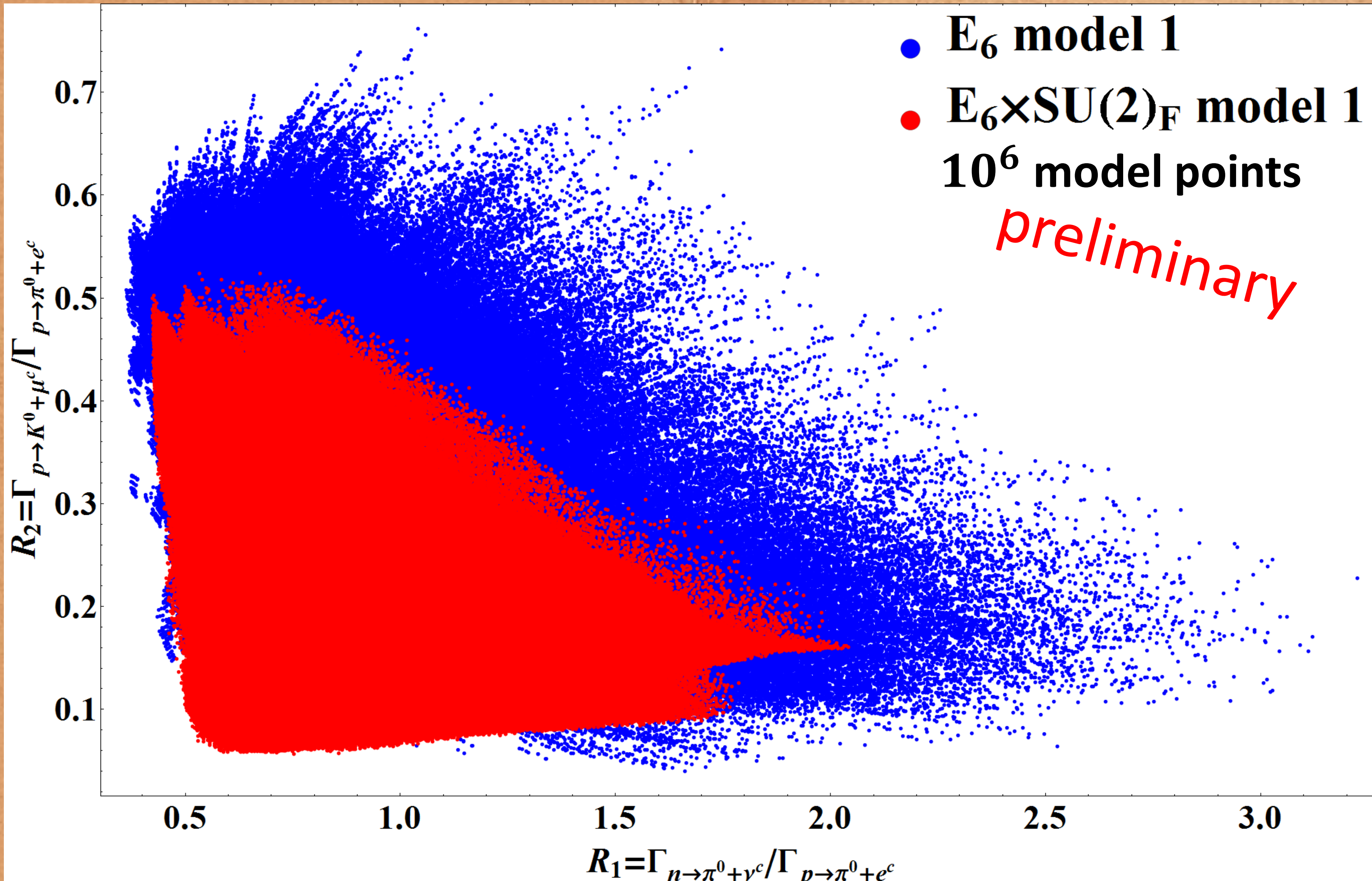
E_6 GUT model in previous work :

21 – 6 = 15 parameters

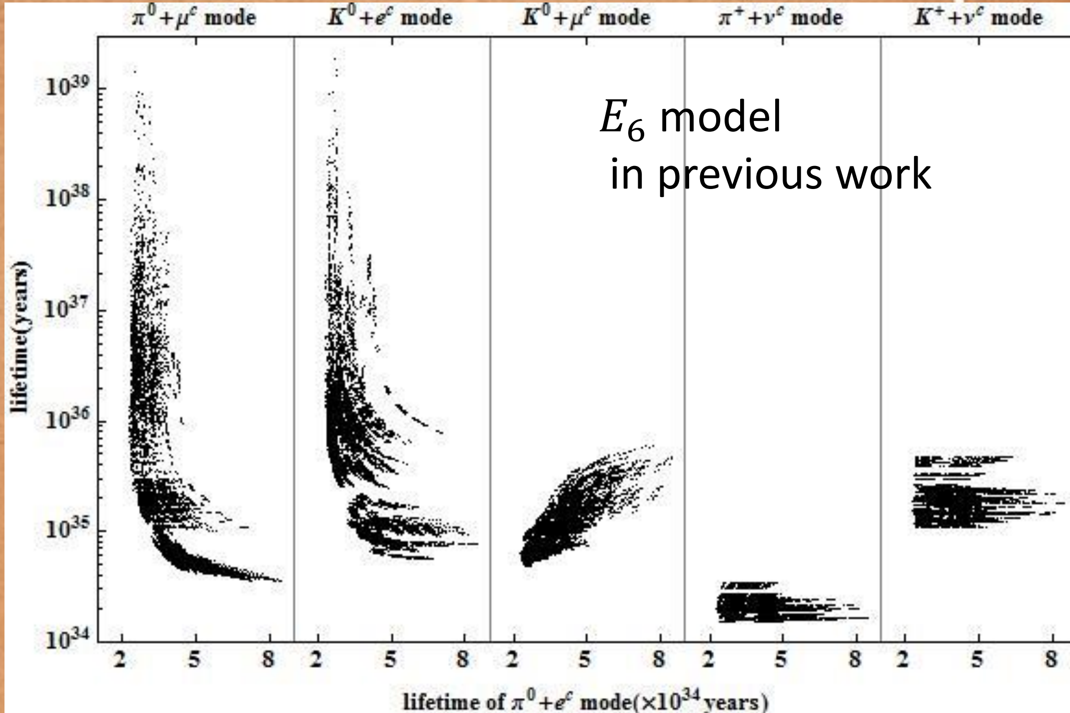
In this work we use 9 conditions.

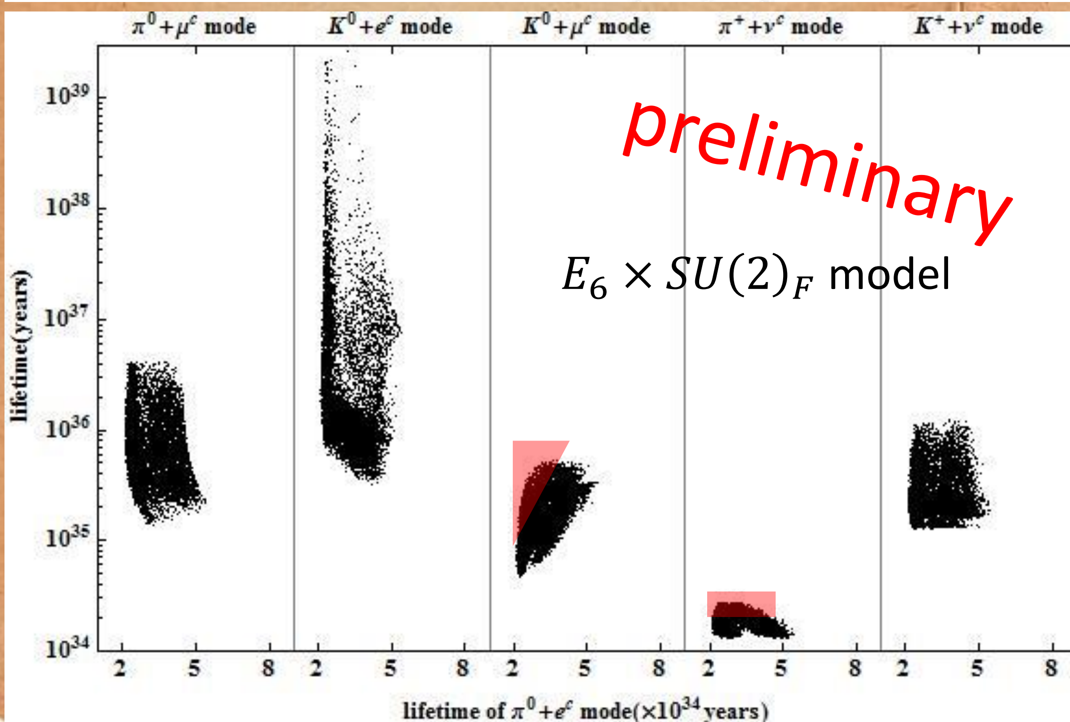
$E_6 \times SU(2)_F$ GUT model :

21 – 6 - 9 = 6 parameters (+ 1 sign)



E_6 model 1
$E_6 \times SU(2)_F$ model 1
10^6 model points
preliminary
0.7
0.6
0.5
0.4
0.3
0.2
0.1
$R_2 = \Gamma_{p \to K^0 + \mu^c} / \Gamma_{p \to \pi^0 + e^c}$
0.5
1.0
1.5
2.0
2.5
3.0
$R_1 = \Gamma_{n \to \pi^0 + \nu^c} / \Gamma_{p \to \pi^0 + e^c}$





In previous E_6 model

$L_{e12} \sim \lambda^{0.5} \sim 0.5,$

$L_{e13} \sim \lambda^3 \sim 0.01$

In $E_6 \times SU(2)_F$ model

$L_{e12} \sim 0.39 < \lambda^{0.5}, L_{e13} = 0$

Small mixing from first-generation charged lepton

$\tau_{p \to \pi^0 + e^c} \geq 1.3 \times 10^{34}$years

@Super-Kamiokande

$\tau_{p \to \pi^0 + e^c} \geq 1.3 \times 10^{35}$years

@Hyper-Kamiokande(planning)

Summary

- We calculate nucleon lifetimes.

  Especially, we pay attention to uncertainties of diagonalizing matrices.
- Flavor symmetry restrict Yukawa structure and diagonalizing matrices, therefore we can reduce uncertainties of diagonalizing matrices.
- In many model points R_1 and R_2 tend to be smaller than these in the E_6 model of previous work by conditions for mixing angles .


Thank you for your attention.

Back up slide

Why do we use $n \to \pi^0 + \nu^c$?

$$\Gamma_{n\to\pi^0+\nu^c}/\Gamma_{p\to\pi^0+e^c}$$

not $p \to \pi^+ + \nu^c$?

- sensitivity

	Partial mean life (10^{30} years)
$N \to \nu\pi$	> 112 (n), > 25 (p)

PDG(2012)

- form factor

$$\langle\pi^0|(ud)_\Gamma u_{\Gamma'}|p\rangle = \langle\pi^0|(du)_\Gamma d_{\Gamma'}|n\rangle$$

We can cancel form factor and uncertainty of that!!

$\bar{5}$ rep. mixing

In the minimal SO(10) GUT model, all SM matters and ν_R in each generation belong to only 16 rep.

⇒ Diagonalizing matrices for each matter are same at the GUT scale.

⇒ It is hard to realize realistic fermion masses and mixings in the minimal SO(10) GUT model.

SO(10) GUT with 10 rep.

$$\begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

diagonalizing matrix for each matter that belong to 16 rep. in SO(10).

⇒ for $\bar{5}$ rep.

$$\begin{pmatrix} \bar{5}_{\psi_1} \\ \bar{5}_{\psi_2} \\ \bar{5}_{\psi_3} \\ \bar{5}_T \end{pmatrix}$$

belong to 16 rep. ($\bar{5}_{\psi_1}, \bar{5}_{\psi_2}, \bar{5}_{\psi_3}$)

belong to 10 rep. ($\bar{5}_T$)

mixed

⇓ for 10 rep.

$$\begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

diagonalizing matrix for each matter that belong to 10 rep. in SU(5).

CKM type

⇓

$$\begin{pmatrix} 1 & \lambda^{0.5} & \lambda \\ \lambda^{0.5} & 1 & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix}$$

diagonalizing matrix for each matter that belong to $\bar{5}$ rep. in SU(5).

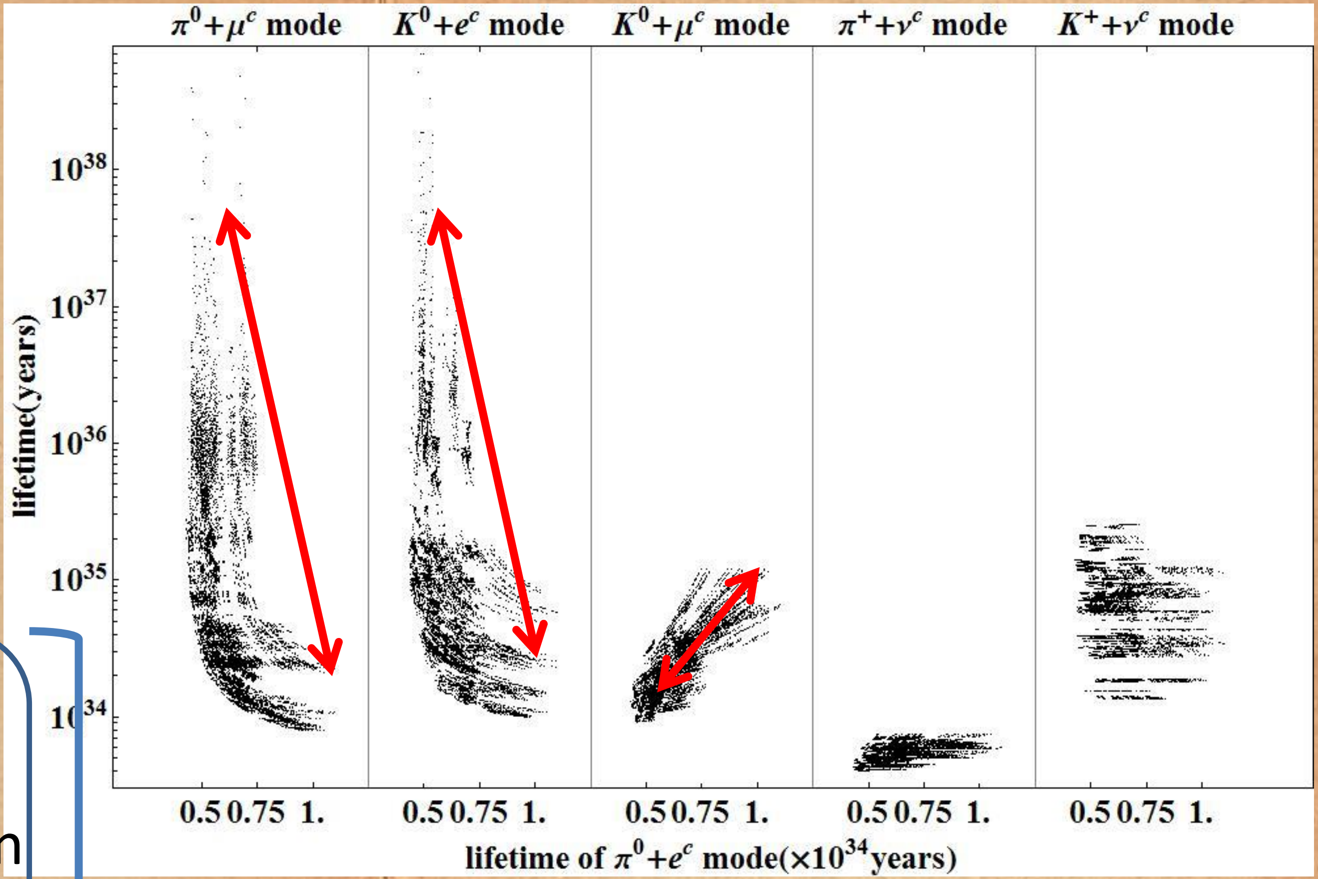
MNS type

dependence for anti-electron mode

$$\begin{pmatrix} A_{11} & A_{12}\lambda \\ A_{21}\lambda & A_{22} \end{pmatrix}$$

A_{ij}:order 1

uncertainty



large off diagonal element

unitary condition

small diagonal element

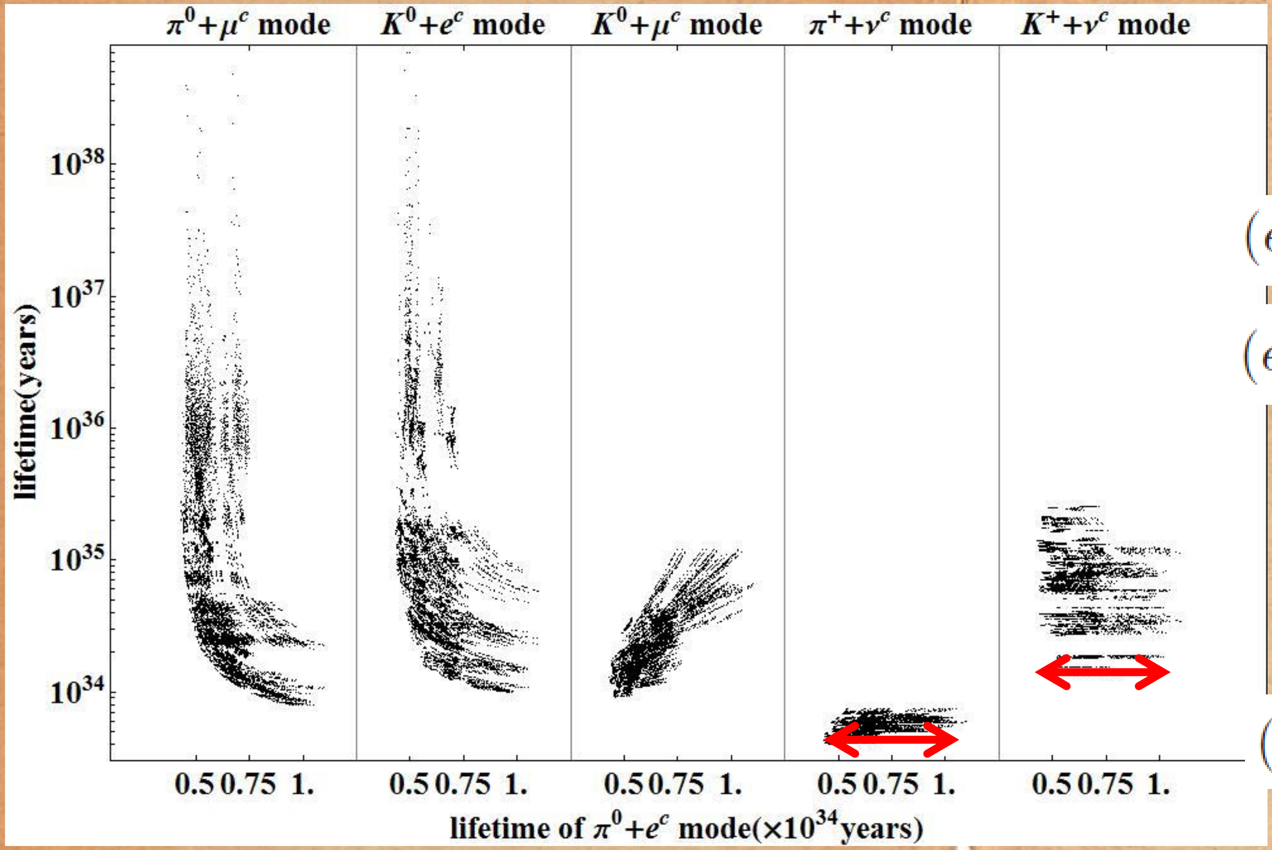
= large mixing

Lifetime of $p \to \pi^0 + e^c, K^0 + \mu^c$ mode become long.

⇕

Lifetime of $p \to \pi^0 + \mu^c, K^0 + e^c$ mode become short.

dependence for anti-neutrino mode



nucleon to
anti-electron operator

$$(\epsilon^{\alpha\beta\gamma}\bar{u}^c_{R\gamma}\gamma^\mu u_{L\beta})(\bar{e}^+_R\gamma_\mu d_{L\alpha})$$

$$(\epsilon^{\alpha\beta\gamma}\bar{u}^c_{R\gamma}\gamma^\mu u_{L\beta})(\bar{e}^+_L\gamma_\mu d_{R\alpha})$$

L_u, R_e, L_e, L_d, R_d

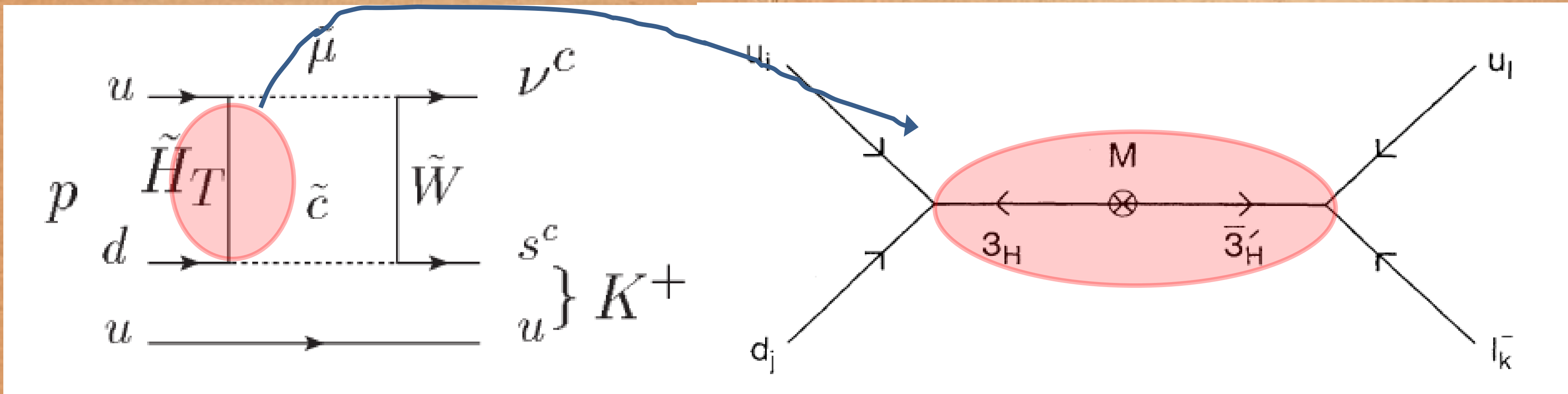
nucleon to
anti-neutrino operator

$$(\epsilon^{\alpha\beta\gamma}\bar{u}^c_{R\gamma}\gamma^\mu d_{L\beta})(\bar{\nu}^c_L\gamma_\mu d_{R\alpha})$$

L_ν, L_d, R_d

$R_u = 1_{3\times 3}$

suppression of dim 5 effective int.



mass matrix of triple Higgs

forbidden

$$(3_H \quad 3_{H'}) \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \begin{pmatrix} \bar{3}_H \\ \bar{3}_{H'} \end{pmatrix}$$

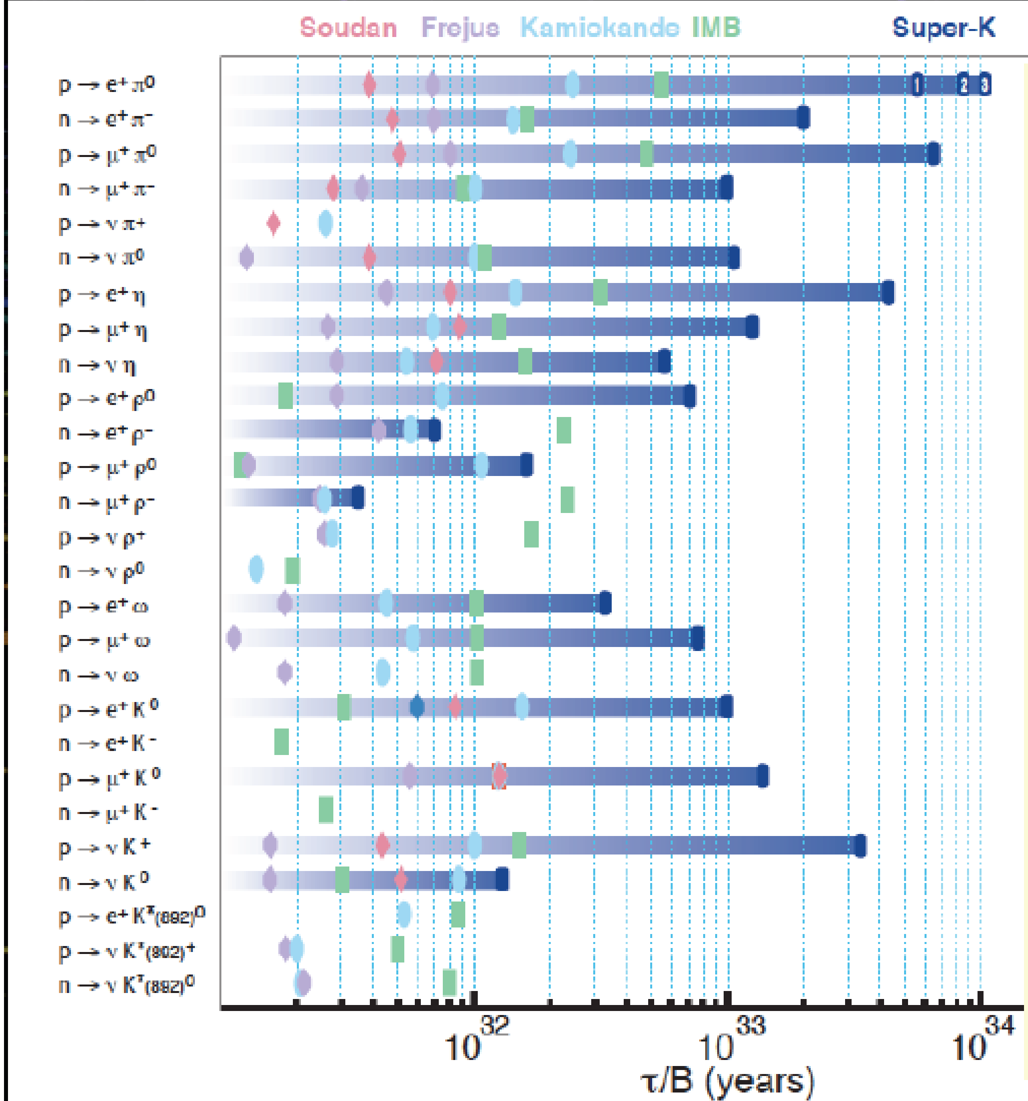
effective colored Higgs mass

$$m_c^{eff} \sim m^2/M$$

In anomalous $U(1)_A$ SUSY GUT models,

we can realize $m_c^{eff} > 10^{18} GeV$. ➡ strongly suppressed

lower limit of nucleon lifetime



- $p \rightarrow e + \pi^0$
  - just reaching to 10^{34} yrs
- $p,n \rightarrow (e^+$ or $\mu^+) + (\pi,\eta,\rho,\omega)$
  - many modes updated
- SUSY favored $p \rightarrow \nu K^+$ 3.3×10^{33} yrs
- K^0 modes, $\nu\pi 0$, $\nu\pi +$ to be updated
- Super-K has searched only for favored modes and got most stringent limits of $O(10^{32})$~$O(10^{34})$ years
- It is important to test many decay modes
  - radiative decays
    - $p \rightarrow (e^+,\mu^+)+\gamma$
  - invisible decays
    - $n \rightarrow \nu\nu\nu$
  - neutron-antineutron oscillation
  - di-nucleon decay ($|\Delta B|=2$)
    - pp→?
    - pn→?
    - nn→?

Siozawa @ KMI seminar 2012

future lower limit of nucleon lifetime @ Hyper-Kamiokande（10years running）

Mode	Sensitivity (90% CL)	Current limit
$p \to e^+\pi^0$	13×10^{34} years	1.3×10^{34} years
$p \to \mu^+\pi^0$	9.0×10^{34}	1.1×10^{34}
$p \to e^+\eta^0$	5.0×10^{34}	0.42×10^{34}
$p \to \mu^+\eta^0$	3.0×10^{34}	0.13×10^{34}
$p \to e^+\rho^0$	1.0×10^{34}	0.07×10^{34}
$p \to \mu^+\rho^0$	0.37×10^{34}	0.02×10^{34}
$p \to e^+\omega^0$	0.84×10^{34}	0.03×10^{34}
$p \to \mu^+\omega^0$	0.88×10^{34}	0.08×10^{34}
$n \to e^+\pi^-$	3.8×10^{34}	0.20×10^{34}
$n \to \mu^+\pi^-$	2.9×10^{34}	0.10×10^{34}
$p \to \overline{\nu}K^+$	2.5×10^{34}	0.40×10^{34}

arXiv:1109.3262 [hep-ex]

$$Y_u = \begin{pmatrix} 0 & \frac{1}{3} y_{u12} \lambda^5 & 0 \\ -\frac{1}{3} y_{u12} \lambda^5 & y_{u22} \lambda^4 & y_{u23} \lambda^2 \\ 0 & y_{u23} \lambda^2 & y_{u33} \end{pmatrix}$$

origin of $\frac{1}{3}$

$$\Psi^a A \Psi_a H$$

H: fundamental representation Higgs

A: adjoint Higgs $\langle A \rangle \propto Q_{B-L}$

$\frac{1}{3}$ is B-L charge of quarks.