University of Sarajevo
Faculty for Mechanical Engineering Sarajevo
Department of Mathematics and Physics

TWO-BODY PROTON DECAY PREDICTIONS IN MINIMAL SU(5) MODEL FOR TEN YEAR PERIOD

dr. sc. Emina Džaferović-Mašić, mag. phys.

International Symposium on High Energy Physics (ISHEP-2024)
October 18-21 2024

AN OVERVIEW OF THE PRESENTATION

1. Introduction
   a) Standard Model & Beyond the Standard Model
2. SU(5) – Georgi-Glashow model
3. Proton decay (in SU(5))
4. Specific SU(5) Model
5. Correlation
   a) Numerical analysis (Gauge coupling unification generation, Yukawa coupling RGE running, Fermion mass fit, Proton decay signatures)
6. Conclusion

LET'S START

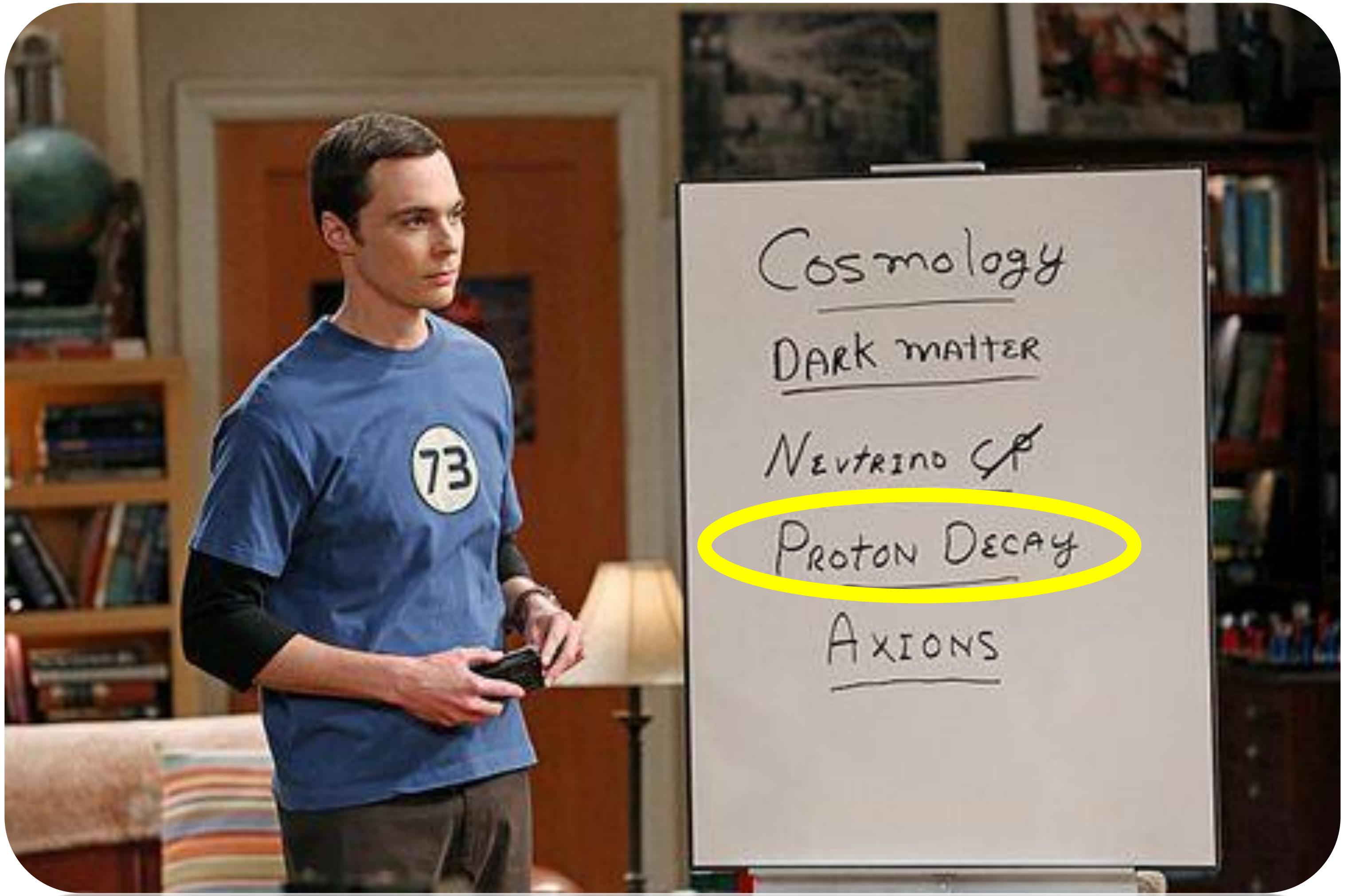


Figure 1.

STANDARD MODEL

Table 2.1: Standard Model particles

FERMIONS				BOSONS	
	families			SPIN	SPIN
	1st	2nd	3rd	1	0
quarks	u	c	t	gluons	H
	d	s	b	g	
leptons	e	μ	τ	$W^{\pm}$	
	ν_e	ν_μ	ν_τ	Z	

PROBLEMS WITH THE STANDARD MODEL

Fermionic Mass Hierarchy and Flavor Problem

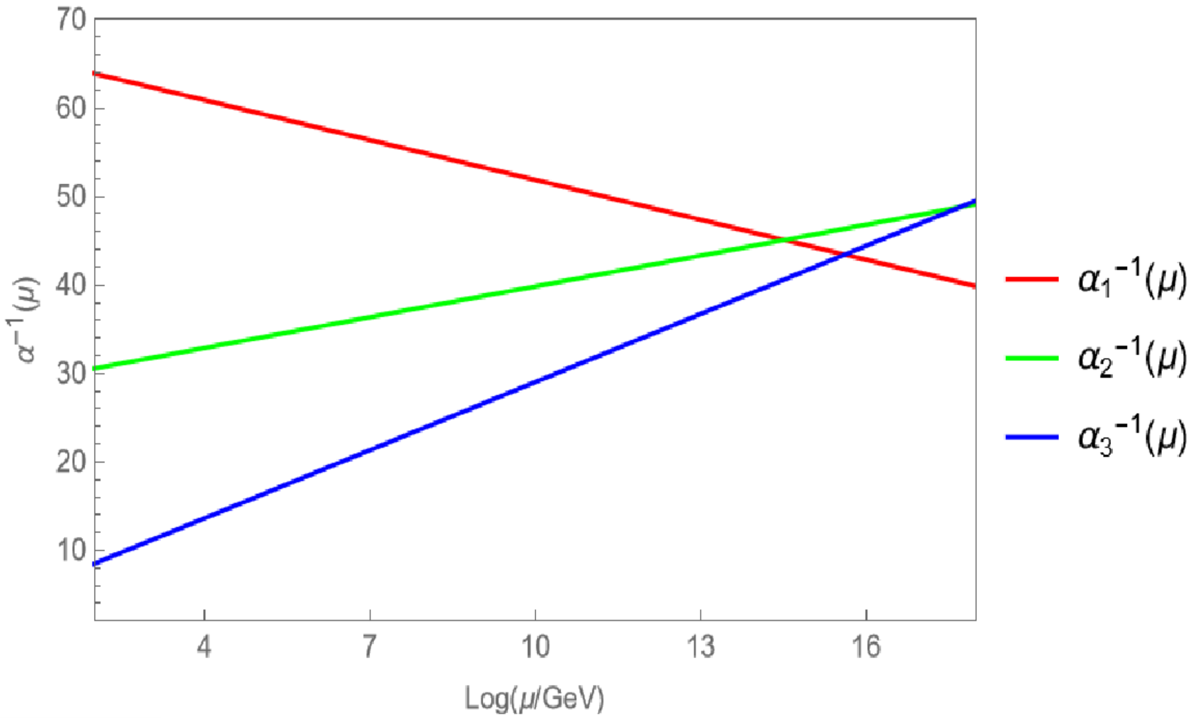
$$m_u^{\text{diag}} = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} \sim \begin{pmatrix} 2.16\,\text{MeV} & 0 & 0 \\ 0 & 1.27\,\text{GeV} & 0 \\ 0 & 0 & 172.4\,\text{GeV} \end{pmatrix}$$

$$m_d^{\text{diag}} = \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix} \sim \begin{pmatrix} 4.67\,\text{MeV} & 0 & 0 \\ 0 & 0.093\,\text{GeV} & 0 \\ 0 & 0 & 4.18\,\text{GeV} \end{pmatrix}$$

$$m_e^{\text{diag}} = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \sim \begin{pmatrix} 0.511\,\text{MeV} & 0 & 0 \\ 0 & 0.106\,\text{GeV} & 0 \\ 0 & 0 & 1.777\,\text{GeV} \end{pmatrix}$$

Gauge Coupling Unification

These three gauge couplings do not **meet** at any energy scale within the Standard Model framework.



SU(5)

- SU(5) Georgi-Glashow model [9]

Table 4.1: Fermions' quantum numbers

States	$SU(3)$ irrep	$SU(2)$ irrep	$U(1)$ Hypercharge Y	Charge Q	Weak isospin T_3	Color
d^c_{Ri}	$\bar{3}$	1	$+\frac{1}{3}$	$+\frac{1}{3}$	0	$i = 1, 2, 3$
u^c_{Ri}	$\bar{3}$	1	$-\frac{2}{3}$	$-\frac{2}{3}$	0	$i = 1, 2, 3$
d_{Li}	3	2	$+\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$	$i = 1, 2, 3$
u_{Li}	3	2	$+\frac{1}{6}$	$+\frac{2}{3}$	$+\frac{1}{2}$	$i = 1, 2, 3$
e^c_R	1	1	$+1$	$+1$	0	-
e_L	1	2	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	-
ν_{eL}	1	2	$-\frac{1}{2}$	0	$+\frac{1}{2}$	-

SU(5)

- SU(5) Georgi-Glashow model [9]

$$\psi_\alpha = \bar{5} = \begin{pmatrix} d^c_{R1} \\ d^c_{R2} \\ d^c_{R3} \\ e_L \\ -\nu_{eL} \end{pmatrix} = (\bar{3}, 1, 1/3) \oplus (1, 2, -1/2)$$

$$10 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u^c_3 & -u^c_2 & u_1 & d_1 \\ -u^c_3 & 0 & u^c_1 & u_2 & d_2 \\ u^c_2 & -u^c_1 & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix}$$

SU(5)

PROBLEMS with Georgi-Glashow model:

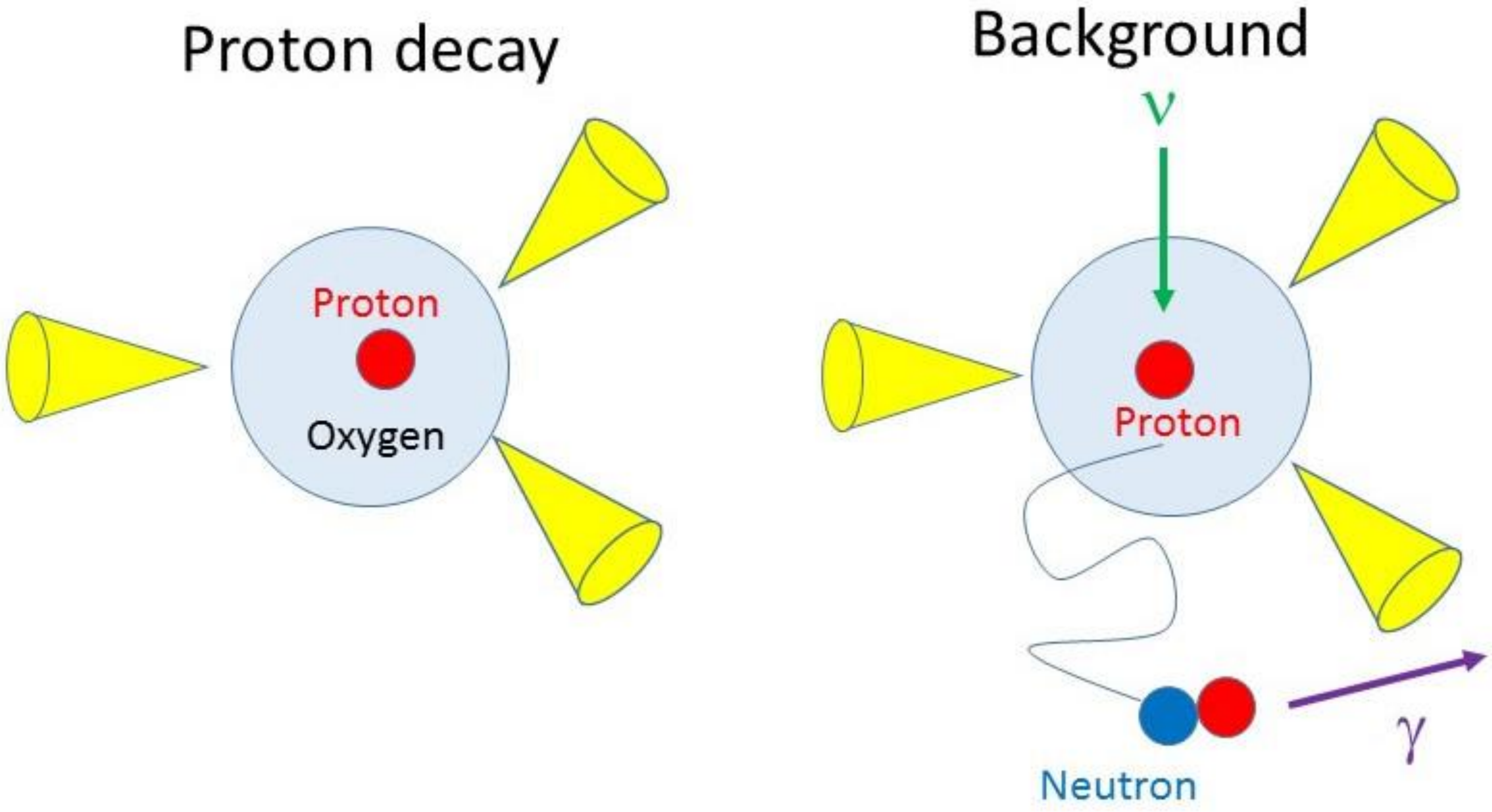
- massless neutrinos
- degeneracy in mass for down-type quarks and charged leptons

$$m_d = m_e \quad m_s = m_\mu \quad m_b = m_\tau$$

PROTON DECAY

- Andrei Sakharov – idea of proton decay
- baryon asymmetry problem
- time for GUT – reviving idea of proton decay
- SU(5) as one of GUT theories
- proton lifetime
- The Georgi-Glashow model - minimal SU (5)
- it has fewest number of adjustable parameters
- the mass $M_{X,Y}$ corresponds to the energy scale at which three out of four fundamental forces in nature come together and become indistinguishable.
- SU (5) should be able to predict scale associated with proton decay

$$\tau \propto \frac{M_{X,Y}^4}{m_p^5}$$



PROTON DECAY

- baryon number violated – proton decay happens
  - operators of dimension 6 and greater
  - lower do not violate baryon number
- 2 mediators of proton decay: gauge bosons & scalar leptoquark
  - conservation of B-L number

PROTON DECAY

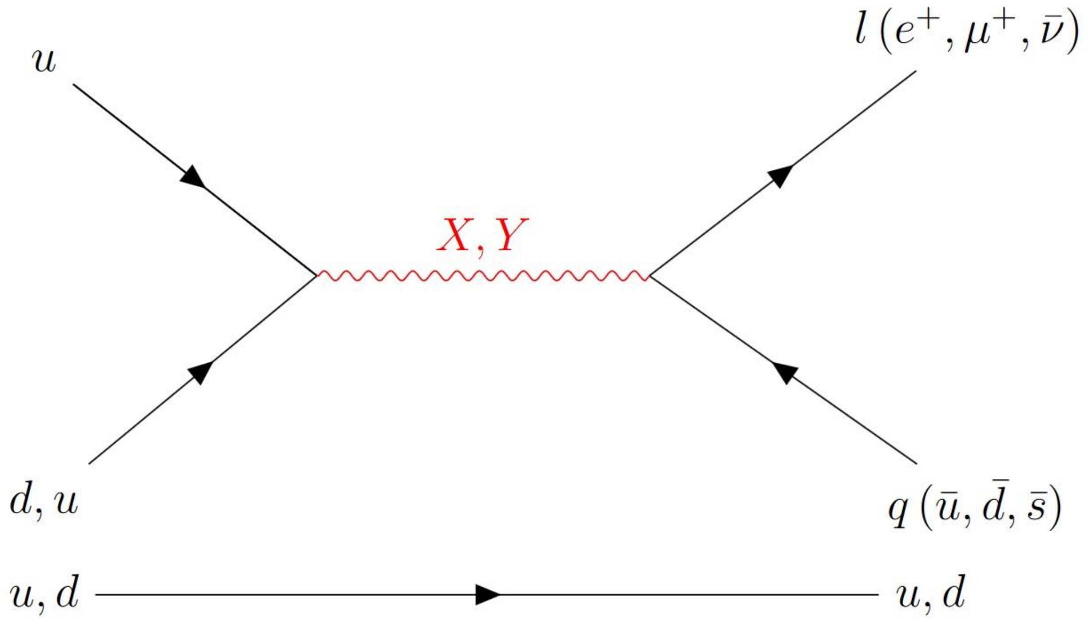


Figure 5.1:
Proton decay via the gauge boson mediation

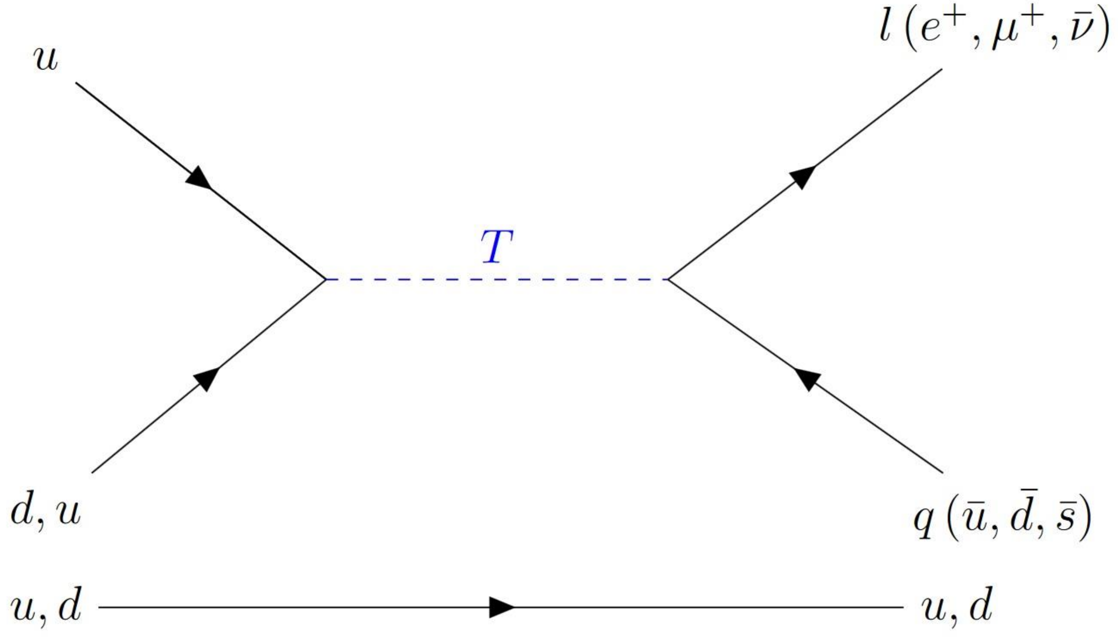


Figure 5.2:
Proton decay via the scalar leptoquark mediation

PROTON DECAY

IDEA:
finding the dominant channels in both proton decay through gauge bosons and through scalar leptoquark within well defined GUT model

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

$$p \to \pi^0 \mu^+$$

$$p \to \eta^0 e^+$$

$$p \to \eta^0 \mu^+$$

$$p \to K^0 e^+$$

$$p \to K^0 \mu^+$$

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

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

Table 5.1: Conservation of $B - L$ in two-body proton decays

decay channel	baryon number B	lepton number L	$B - L$
$p \to \pi^0 e^+$	$1 \neq 0 + 0$	$0 \neq -1 + 0$	$1 = 0 - (-1)$
$p \to \pi^0 \mu^+$	$1 \neq 0 + 0$	$0 \neq 0 + (-1)$	$1 = 0 - (-1)$
$p \to \eta^0 e^+$	$1 \neq 0 + 0$	$0 \neq 0 + (-1)$	$1 = 0 - (-1)$
$p \to \eta^0 \mu^+$	$1 \neq 0 + 0$	$0 \neq 0 + (-1)$	$1 = 0 - (-1)$
$p \to K^0 e^+$	$1 \neq 0 + 0$	$0 \neq 0 + (-1)$	$1 = 0 - (-1)$
$p \to K^0 \mu^+$	$1 \neq 0 + 0$	$0 \neq 0 + (-1)$	$1 = 0 - (-1)$
$p \to \pi^+ \overline{\nu}$	$1 \neq 0 + 0$	$0 \neq 0 + (-1)$	$1 = 0 - (-1)$
$p \to K^+ \overline{\nu}$	$1 \neq 0 + 0$	$0 \neq 0 + (-1)$	$1 = 0 - (-1)$

PROTON DECAY VIA SCALAR LEPTOQUARK

- Only one scalar leptoquark mediates proton decay – S_1

Table 5.2: Scalar leptoquarks' quantum numbers

LQ	Spin	$SU(3)$	$SU(2)$	$U(1)$	Allowed Coupling
S_1	0	3	1	-1/3	$\bar{q}_L^c l_L$ & $\bar{u}_R^c e_R$ & $\bar{q}_L^c q_L$ & $\bar{u}_R^c d_R$
$\tilde{S}_1$	0	3	1	-4/3	$\bar{d}_R^c e_R$ & $\bar{u}_R^c u_R$
S_3	0	$\bar{3}$	3	1/3	$\bar{q}_L^c l_L$ & $\bar{q}_L^c q_L$
R_2	0	3	2	7/6	$\bar{q}_L e_R$ & $\bar{u}_R l_L$
$\tilde{R}_2$	0	3	2	1/6	$\bar{d}_R l_L$

PROTON DECAY

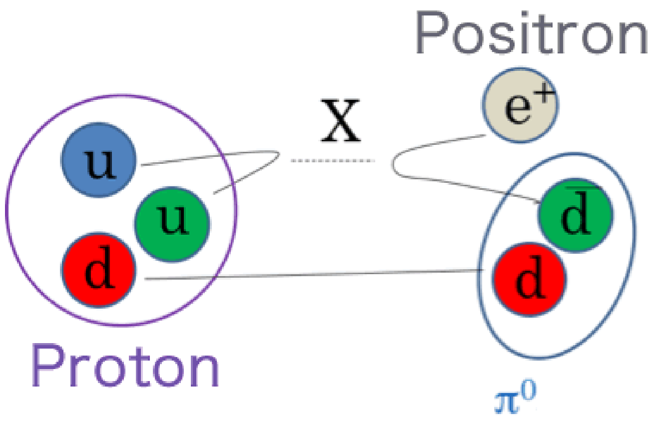
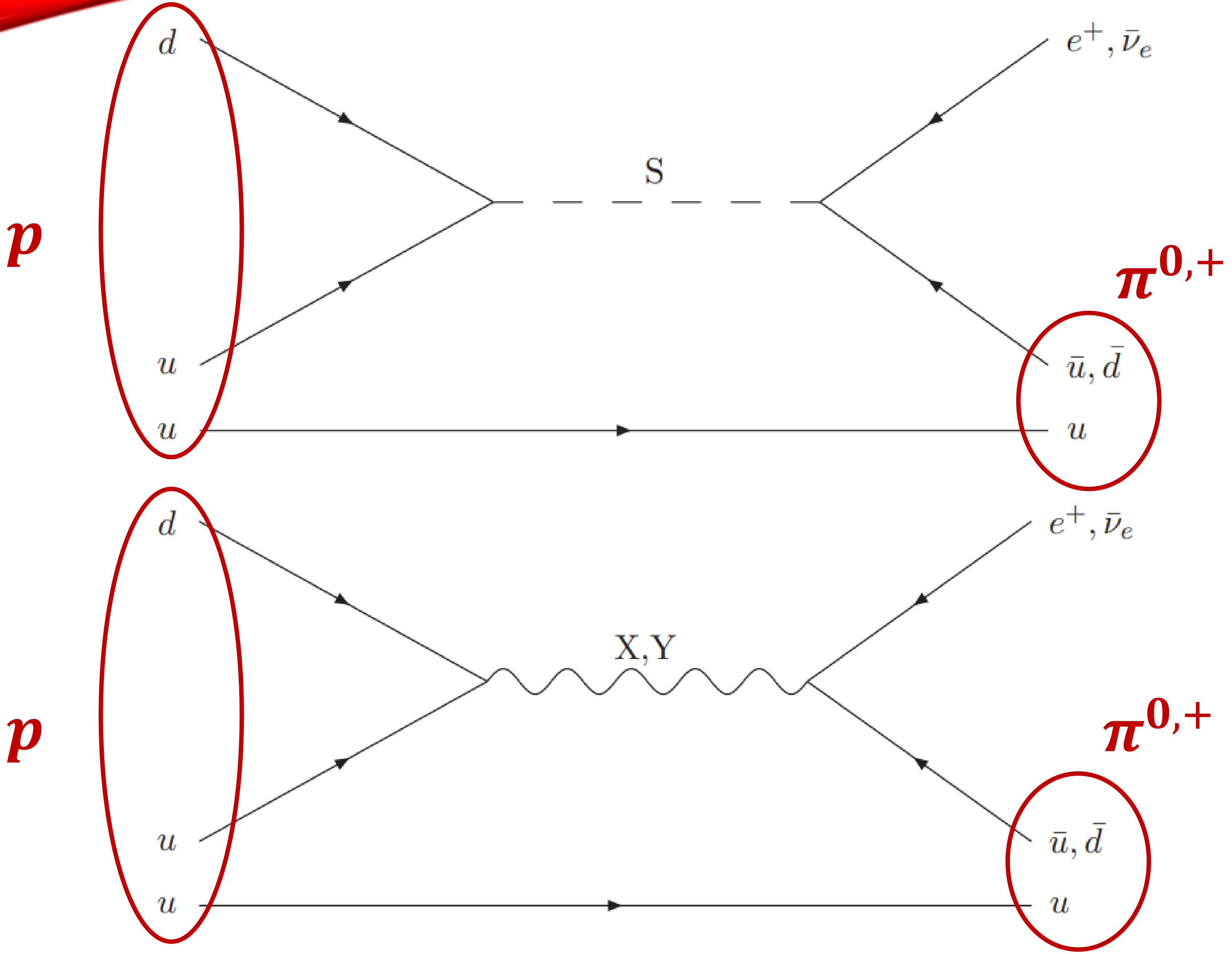
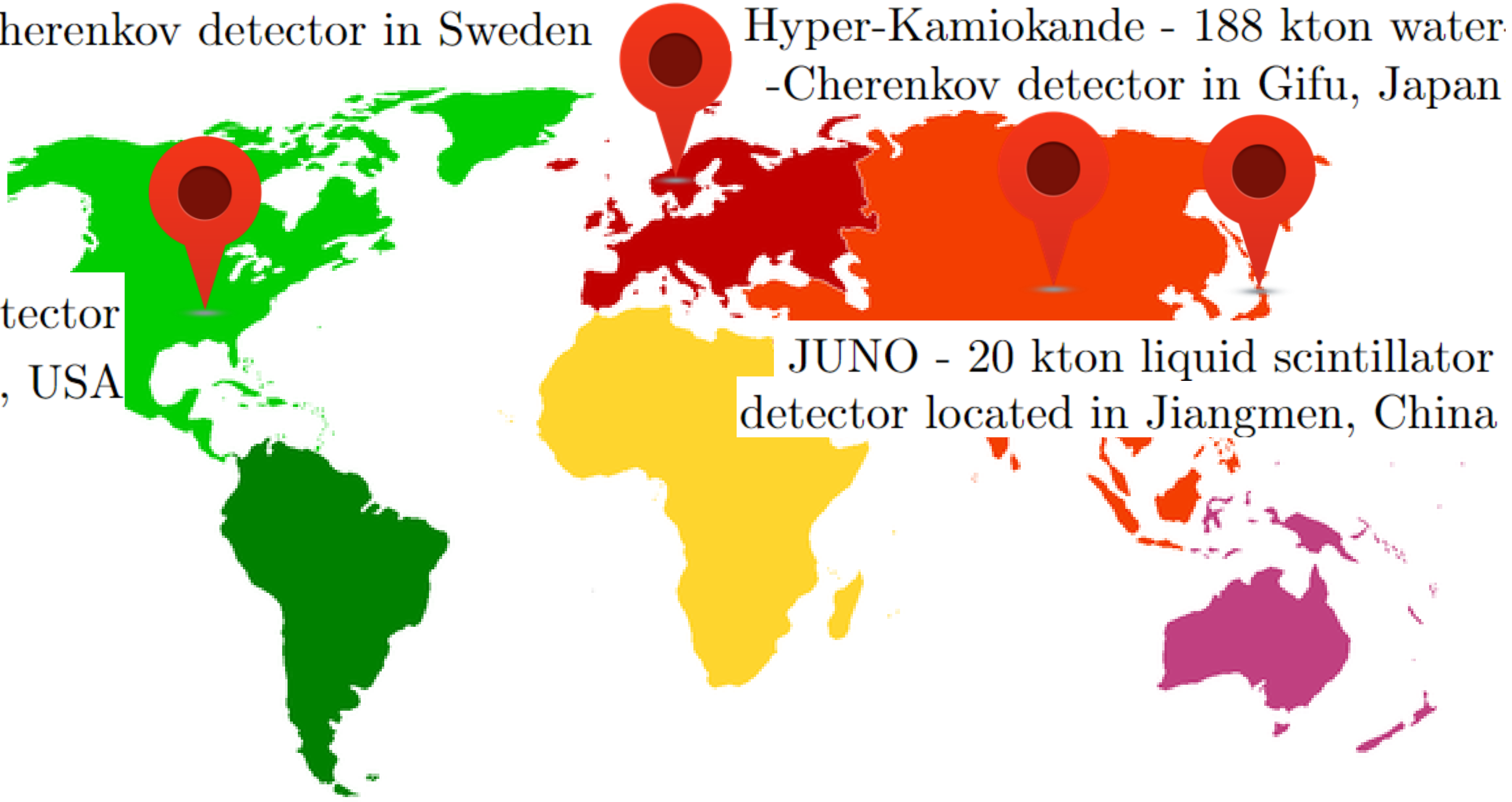


Figure 3.



EXPERIMENTS



EXPERIMENTS

Table 6.1: Experimental lower bounds on partial proton decay lifetimes at 90 % C.L.

PROTON DECAY CHANNELS	Proton lifetime bound at 90% C.L.
$p \to \pi^0 e^+$	2.4×10^{34} years [9]
$p \to \pi^0 \mu^+$	1.6×10^{34} years [9]
$p \to \pi^+ \overline{\nu}$	3.9×10^{32} years [89]
$p \to \eta^0 e^+$	1.0×10^{34} years [90]
$p \to \eta^0 \mu^+$	4.7×10^{33} years [90]
$p \to K^0 e^+$	1.1×10^{33} years [90]
$p \to K^0 \mu^+$	3.5×10^{33} years [13]
$p \to K^+ \overline{\nu}$	6.6×10^{33} years [89]

EXPERIMENTS

Table 6.2: Future expectations for a ten-year period of data taking

decay channel	current bound τ_p [years]	future sensitivity τ_p [years]
$p \to \pi^0 e^+$	2.4×10^{34} [9]	7.8×10^{34} [10]
$p \to \pi^0 \mu^+$	1.6×10^{34} [9]	7.7×10^{34} [10]
$p \to \eta^0 e^+$	1.0×10^{34} [11]	4.3×10^{34} [10]
$p \to \eta^0 \mu^+$	4.7×10^{33} [11]	4.9×10^{34} [10]
$p \to K^0 e^+$	1.1×10^{33} [12]	-
$p \to K^0 \mu^+$	3.6×10^{33} [13]	-
$p \to \pi^+ \overline{\nu}$	3.9×10^{32} [14]	-
$p \to K^+ \overline{\nu}$	6.6×10^{33} [15]	9.6×10^{33} [16] & 3.2×10^{34} [10]

SPECIFIC SU(5)

The model is built on eight representations:

$$5_H,\ 24_H,\ 35_H,\ \bar{5}_{Fi},\ 10_{Fi},\ 15_F,\ \overline{15}_F,\ \text{and}\ 24_V.$$

- **extension of the original Georgi-Glashow (GG) model**
- Scalar sector: 5, 24 & 35
- $5_H \equiv \Lambda = \Lambda_1\left(1, 2, \frac{1}{2}\right) + \Lambda_3(3, 1, -\frac{1}{3})$
- $24_H \equiv \phi$
- $35_H \equiv \Phi$
- VEV: $\langle 24_H \rangle \equiv \langle \phi \rangle = \frac{v_{24}}{\sqrt{15}} diag(-1, -1, -1, \frac{3}{2}, \frac{3}{2})$
- $\langle 5_H \rangle = v_H = 174\ GeV$

Table 7.1: Particle content of a specific $SU(5)$ model and associated β-function coefficients

Type of representations	$SU(5)$ state	Standard Model $(SU(3), SU(2), U(1))$	β-function coefficients (b_3, b_2, b_1)
scalar	$5_H \equiv \Lambda$	$\Lambda_1\,(1, 2, \frac{1}{2})$	$(0, \frac{1}{6}, \frac{1}{10})$
		$\Lambda_3\,(3, 1 - \frac{1}{3})$	$(\frac{1}{6}, 0, \frac{1}{15})$
	$24_H \equiv \phi$	$\phi_0\,(0, 0, 0)$	$(0, 0, 0)$
		$\phi_1\,(1, 3, 0)$	$(0, \frac{1}{3}, 0)$
		$\phi_3\,(3, 2, -\frac{5}{6})$	$(\frac{1}{6}, \frac{1}{4}, \frac{5}{12})$
		$\phi_{\overline{3}}\,(\overline{3}, 2, \frac{5}{6})$	$(\frac{1}{6}, \frac{1}{4}, \frac{5}{12})$
		$\phi_8\,(8, 1, 0)$	$(\frac{1}{2}, 0, 0)$
	$35_H \equiv \Phi$	$\Phi_1\,(1, 4, -\frac{3}{2})$	$(0, \frac{5}{3}, \frac{9}{5})$
		$\Phi_3\,(\overline{3}, 3, -\frac{2}{3})$	$(\frac{1}{2}, 2, \frac{4}{5})$
		$\Phi_6\,(\overline{6}, 2, \frac{1}{6})$	$(\frac{5}{3}, 1, \frac{1}{15})$
		$\Phi_{10}\,(\overline{10}, 1, 1)$	$(\frac{5}{2}, 0, 2)$
fermion	$\overline{5}_{Fi} \equiv F_i$	$L_i\,(1, 2, -\frac{1}{2})$	$(0, 1, \frac{3}{5})$
		$d_i^C\,(\overline{3}, 1, \frac{1}{3})$	$(1, 0, \frac{2}{5})$
	$10_{Fi} \equiv T_i$	$Q_i\,(3, 2, \frac{1}{6})$	$(2, 3, \frac{1}{5})$
		$u_i^C\,(\overline{3}, 1, -\frac{2}{3})$	$(1, 0, \frac{8}{5})$
		$e_i^C\,(1, 1, 1)$	$(0, 0, \frac{6}{5})$
	$15_F \equiv \Sigma$	$\Sigma_1\,(1, 3, 1)$	$(0, \frac{4}{3}, \frac{6}{5})$
		$\Sigma_3\,(3, 2, \frac{1}{6})$	$(\frac{2}{3}, 1, \frac{1}{15})$
		$\Sigma_6\,(6, 1, -\frac{2}{3})$	$(\frac{5}{3}, 0, \frac{16}{15})$
	$\overline{15}_F \equiv \overline{\Sigma}$	$\overline{\Sigma}_1\,(1, 3, -1)$	$(0, \frac{4}{3}, \frac{6}{5})$
		$\overline{\Sigma}_3\,(\overline{3}, 2, -\frac{1}{6})$	$(\frac{2}{3}, 1, \frac{1}{15})$
		$\overline{\Sigma}_6\,(\overline{6}, 1, \frac{2}{3})$	$(\frac{5}{3}, 0, \frac{16}{15})$

SPECIFIC SU(5)

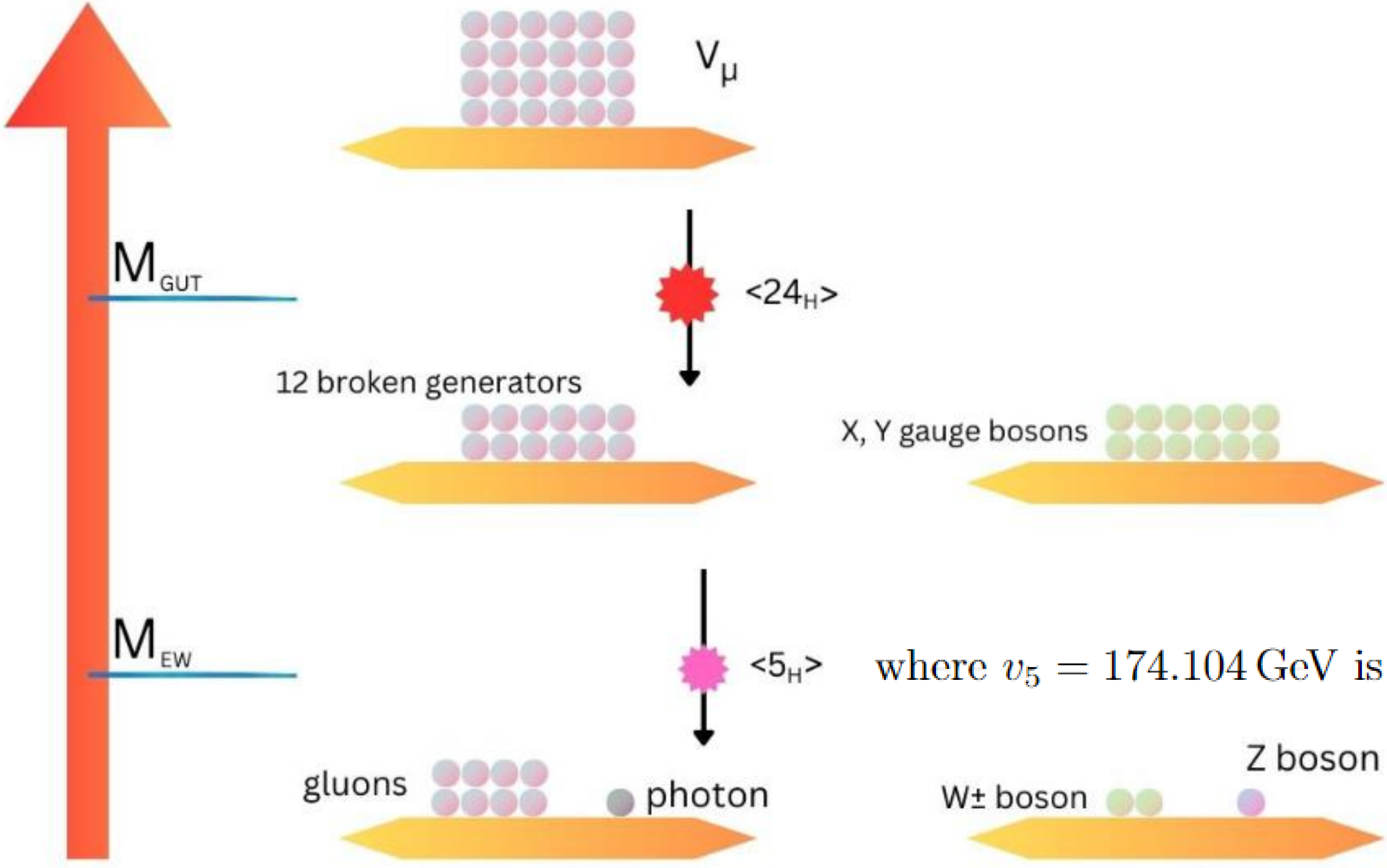
There are couple of specific predictions of this model. Neutrinos are Majorana particles with mass ordering corresponding to the normal hierarchy. And, one of the neutrinos is massless particle. Also, the model provides firm predictions for partial proton decay lifetimes thus establishing the link between experimental bounds on matter stability and a lower bound on the associated mass scales of new physics.

In comparison with the original Georgi-Glashow model, this model is extended with one additional scalar representation 35_H and an additional vector-like fermion generation represented with 15_F and $\overline{15}_F$. These additions are important in order to create an experimentally observed mismatch between the masses of the down-type quarks and charged leptons, generate realistic neutrino masses, and provide gauge coupling unification.

SPECIFIC SU(5)

SYMMETRY BREAKING

$$SU(5) \xrightarrow{\langle 24_H \rangle} SU(3) \times SU(2) \times U(1) \xrightarrow{\langle 5_H \rangle} SU(3) \times U(1)_{\text{em}}$$



$$\langle 5_H \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ v_5 \end{pmatrix} \qquad \langle 24_H \rangle = \frac{v_{24}}{\sqrt{15}} \begin{pmatrix} 1 & & & & \\ & 1 & & & \\ & & 1 & & \\ & & & -\frac{3}{2} & \\ & & & & -\frac{3}{2} \end{pmatrix}$$

where $v_5 = 174.104\,\text{GeV}$ is the Standard Model VEV.

SPECIFIC SU(5)

$$\mathcal{L} \supset \Big\{ +Y^u_{ij}\, T^{\alpha\beta}_i T^{\gamma\delta}_j \Lambda^\rho_{\epsilon_{\alpha\beta\gamma\delta\rho}} + Y^d_{ij}\, T^{\alpha\beta}_i F_{\alpha j}\Lambda^*_\beta + Y^a_i \Sigma^{\alpha\beta} F_{\alpha i}\Lambda^*_\beta + Y^b_i \overline{\Sigma}_{\beta\gamma} F_{\alpha i}\Phi^{*\alpha\beta\gamma}$$

$$+ Y^c_i\, T^{\alpha\beta}_i \overline{\Sigma}_{\beta\gamma}\phi^\gamma_\alpha + \text{h.c.} \Big\} + M_\Sigma \overline{\Sigma}_{\alpha\beta}\Sigma^{\alpha\beta} + y\overline{\Sigma}_{\alpha\beta}\Sigma^{\beta\gamma}\phi^\alpha_\gamma -$$

$$- \mu^2_\Lambda(\Lambda^*_\alpha\Lambda^\alpha) + \lambda^\Lambda_0\,(\Lambda^*_\alpha\Lambda^\alpha)^2 + \mu_1\Lambda^*_\alpha\Lambda^\beta\phi^\alpha_\beta + \lambda^\Lambda_1\,(\Lambda^*_\alpha\Lambda^\alpha)(\phi^\beta_\gamma\phi^\gamma_\beta) + \lambda^\Lambda_2\Lambda^*_\alpha\Lambda^\beta\phi^\gamma_\beta\phi^\alpha_\gamma -$$

$$- \mu^2_\phi(\phi^\beta_\gamma\phi^\gamma_\beta) + \mu_2\phi^\alpha_\beta\phi^\beta_\gamma\phi^\gamma_\alpha + \lambda^\phi_0\,(\phi^\beta_\gamma\phi^\gamma_\beta)^2 + \lambda^\phi_1\,\phi^\alpha_\beta\phi^\beta_\gamma\phi^\gamma_\delta\phi^\delta_\alpha + \mu^2_\Phi\,(\Phi^{*\alpha\beta\gamma}\Phi_{\alpha\beta\gamma}) +$$

$$+ \lambda^\Phi_0\,\Phi^{*\alpha\beta\gamma}\Phi_{\alpha\beta\gamma}(\Lambda^*_\rho\Lambda^\rho) + \lambda''_0\Phi^{*\alpha\beta\gamma}\Phi_{\beta\gamma\delta}\Lambda^\delta\Lambda^*_\alpha + \mu_3\Phi^{*\alpha\beta\gamma}\Phi_{\beta\gamma\delta}\phi^\delta_\alpha +$$

$$+ \lambda_1\,\Phi^{*\alpha\beta\gamma}\Phi_{\alpha\delta\rho}\phi^\delta_\beta\phi^\rho_\gamma + \lambda_2\,\Phi^{*\alpha\beta\rho}\Phi_{\alpha\beta\delta}\phi^\gamma_\rho\phi^\delta_\gamma + \Big\{\lambda'\,\Lambda^\alpha\Lambda^\beta\Lambda^\gamma\Phi_{\alpha\beta\gamma} + \text{h.c.}\Big\}$$

$$M_{\Sigma_6} = 2M_{\Sigma_3} - M_{\Sigma_1}$$

$$M^2_{\Phi_{10}} = M^2_{\Phi_1} - 3M^2_{\Phi_3} + 3M^2_{\Phi_6}$$

SPECIFIC SU(5) MODEL [16]

$SU(5)$	$SU(3)\times SU(2)\times U(1)$	$SU(5)$	$SU(3)\times SU(2)\times U(1)$
$5_H \equiv \Lambda$	$\Lambda_1\,(1,2,\frac{1}{2})$ $\Lambda_3\,(3,1,-\frac{1}{3})$	$\overline{5}_{Fi} \equiv F_i$	$L_i\,(1,2,-\frac{1}{2})$ $d_i^c\,(\overline{3},1,\frac{1}{3})$
$24_H \equiv \phi$	$\phi_0\,(1,1,0)$ $\phi_1\,(1,3,0)$ $\phi_3\,(3,2,-\frac{5}{6})$ $\phi_{\overline{3}}\,(\overline{3},2,\frac{5}{6})$ $\phi_8\,(8,1,0)$	$10_{Fi} \equiv T_i$	$Q_i\,(3,2,\frac{1}{6})$ $u_i^c\,(\overline{3},1,-\frac{2}{3})$ $e_i^c\,(1,1,1)$
		$15_F \equiv \Sigma$	$\Sigma_1(1,3,1)$ $\Sigma_3\,(3,2,\frac{1}{6})$ $\Sigma_6\,(6,1,-\frac{2}{3})$
$35_H \equiv \Phi$	$\Phi_1\,(1,4,-\frac{3}{2})$ $\Phi_3\,(\overline{3},3,-\frac{2}{3})$ $\Phi_6\,(\overline{6},2,\frac{1}{6})$ $\Phi_{10}\,(\overline{10},1,1)$	$\overline{15}_F \equiv \overline{\Sigma}$	$\overline{\Sigma}_1\,(1,3,-1)$ $\overline{\Sigma}_3\,(\overline{3},2,-\frac{1}{6})$ $\overline{\Sigma}_6\,(\overline{6},1,\frac{2}{3})$

- Fermion sector: $\overline{5}_i$ & 10_i, $i = 1,2,3$
- Additional fermions: 15_F & $\overline{15}_F$
- $15_F \equiv \Sigma = \Sigma_1(1,3,1) + \Sigma_3\left(3,2,\frac{1}{6}\right) + \Sigma_6\left(6,1,-\frac{2}{3}\right)$
- **Reason: SM multiplets in 24_H and 5_H cannot produce viable unification on their own**

SPECIFIC SU(5) MODEL [16]

$SU(5)$	$SU(3)\times SU(2)\times U(1)$	$SU(5)$	$SU(3)\times SU(2)\times U(1)$
$5_H \equiv \Lambda$	$\Lambda_1\,(1,2,\frac{1}{2})$	$\overline{5}_{F\,i} \equiv F_i$	$L_i\,(1,2,-\frac{1}{2})$
	$\Lambda_3\,(3,1,-\frac{1}{3})$		$d_i^c\,(\overline{3},1,\frac{1}{3})$
$24_H \equiv \phi$	$\phi_0\,(1,1,0)$	$10_{F\,i} \equiv T_i$	$Q_i\,(3,2,\frac{1}{6})$
	$\phi_1\,(1,3,0)$		$u_i^c\,(\overline{3},1,-\frac{2}{3})$
	$\phi_3\,(3,2,-\frac{5}{6})$		$e_i^c\,(1,1,1)$
	$\phi_{\overline{3}}\,(\overline{3},2,\frac{5}{6})$	$15_F \equiv \Sigma$	$\Sigma_1(1,3,1)$
	$\phi_8\,(8,1,0)$		$\Sigma_3\,(3,2,\frac{1}{6})$
$35_H \equiv \Phi$	$\Phi_1\,(1,4,-\frac{3}{2})$		$\Sigma_6\,(6,1,-\frac{2}{3})$
	$\Phi_3\,(\overline{3},3,-\frac{2}{3})$	$\overline{15}_F \equiv \overline{\Sigma}$	$\overline{\Sigma}_1\,(1,3,-1)$
	$\Phi_6\,(\overline{6},2,\frac{1}{6})$		$\overline{\Sigma}_3\,(\overline{3},2,-\frac{1}{6})$
	$\Phi_{10}\,(\overline{10},1,1)$		$\overline{\Sigma}_6\,(\overline{6},1,\frac{2}{3})$

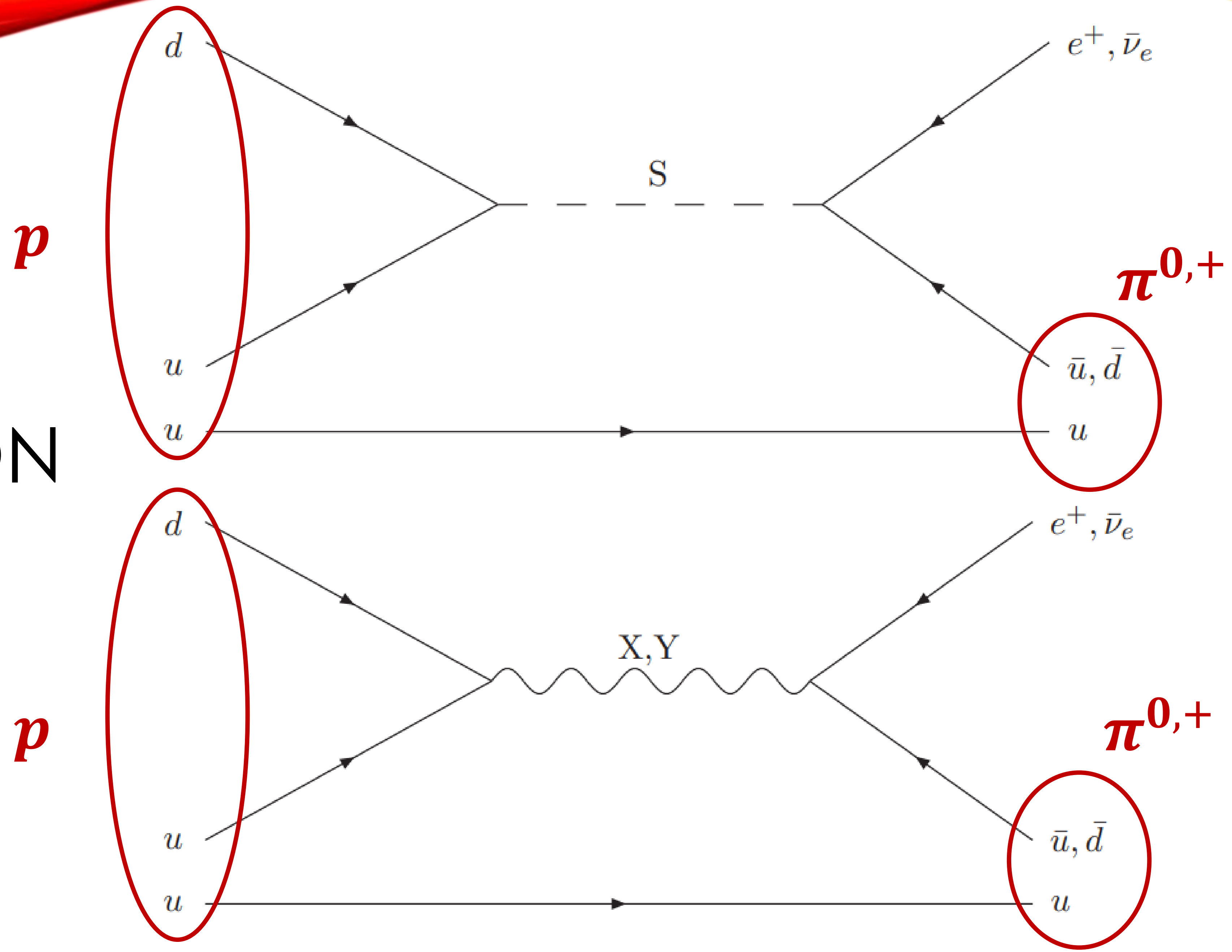
- TWO NEUTRINOS BECOME MASSIVE

SPECIFIC SU(5) MODEL [16]

$SU(5)$	$SU(3)\times SU(2)\times U(1)$	$SU(5)$	$SU(3)\times SU(2)\times U(1)$
$5_H \equiv \Lambda$	$\Lambda_1\,(1,2,\frac{1}{2})$ S_1: $\Lambda_3\,(3,1,-\frac{1}{3})$	$\overline{5}_{F\,i} \equiv F_i$	$L_i\,(1,2,-\frac{1}{2})$ $d_i^c\,(\overline{3},1,\frac{1}{3})$
$24_H \equiv \phi$	$\phi_0\,(1,1,0)$ $\phi_1\,(1,3,0)$ V_2: $\phi_3\,(3,2,-\frac{5}{6})$ $\phi_{\overline{3}}\,(\overline{3},2,\frac{5}{6})$ $\phi_8\,(8,1,0)$	$10_{F\,i} \equiv T_i$	$Q_i\,(3,2,\frac{1}{6})$ $u_i^c\,(\overline{3},1,-\frac{2}{3})$ $e_i^c\,(1,1,1)$
		$15_F \equiv \Sigma$	$\Sigma_1(1,3,1)$ $\Sigma_3\,(3,2,\frac{1}{6})$ $\Sigma_6\,(6,1,-\frac{2}{3})$
$35_H \equiv \Phi$	$\Phi_1\,(1,4,-\frac{3}{2})$ $\Phi_3\,(\overline{3},3,-\frac{2}{3})$ $\Phi_6\,(\overline{6},2,\frac{1}{6})$ $\Phi_{10}\,(\overline{10},1,1)$	$\overline{15}_F \equiv \overline{\Sigma}$	$\overline{\Sigma}_1\,(1,3,-1)$ $\overline{\Sigma}_3\,(\overline{3},2,-\frac{1}{6})$ $\overline{\Sigma}_6\,(\overline{6},1,\frac{2}{3})$

- PROTON DECAY SIGNATURES CAN BE PREDICTED.

CORRELATION



CORRELATION

- neutrino mass scale depends only on masses of two fields Σ_1 and Φ_1
- parameter space spanned in this plane M_{Φ_1}-M_{Σ_1}

$$(M_N)_{ij} \approx \frac{\lambda' v_5^2}{8\pi^2}(Y_i^a Y_j^b + Y_i^b Y_j^a)\frac{M_{\Sigma_1}}{M_{\Sigma_1}^2 - M_{\Phi_1}^2}\ln\left(\frac{M_{\Sigma_1}^2}{M_{\Phi_1}^2}\right) = m_0(Y_i^a Y_j^b + Y_i^b Y_j^a)$$

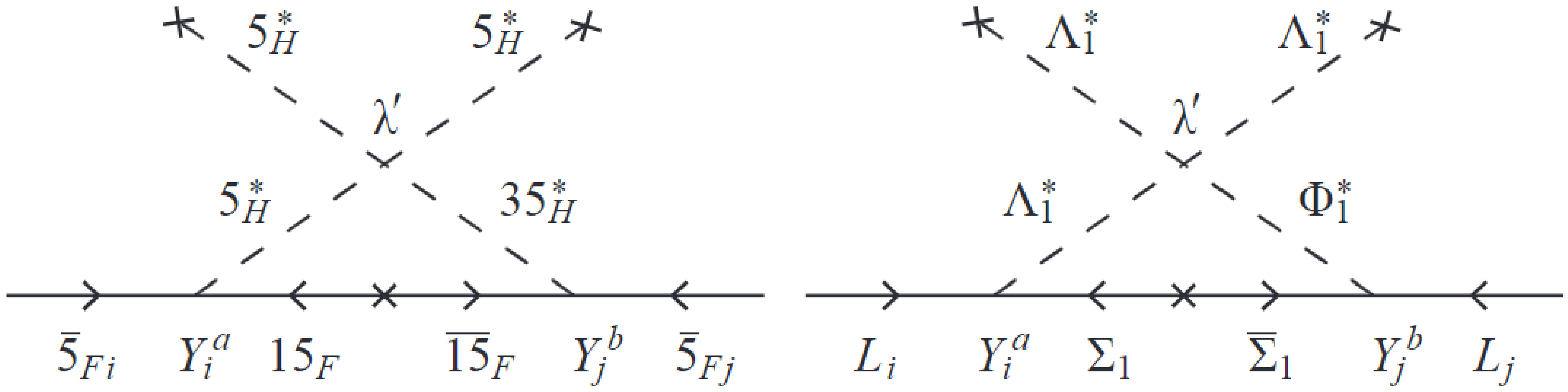
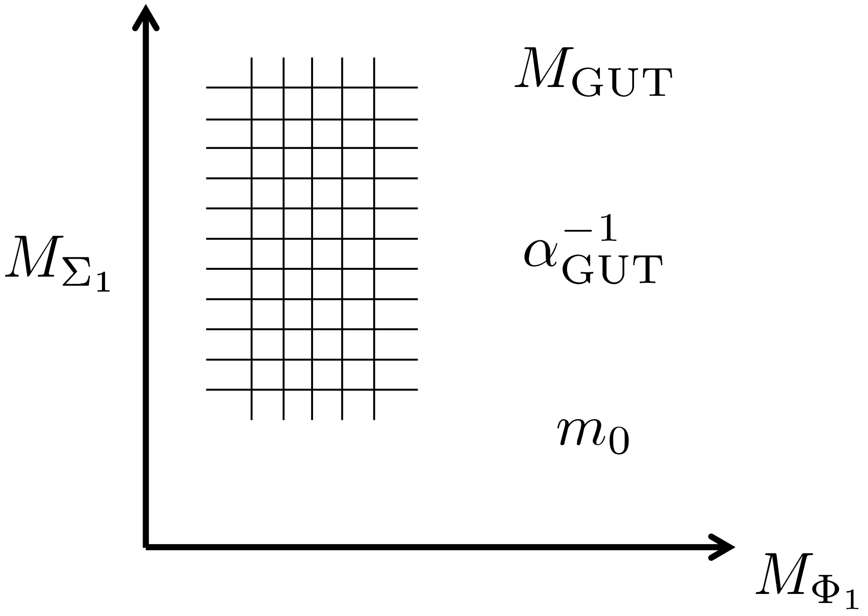


Figure 7.2: The Feynman diagrams of the leading order contribution towards Majorana neutrino masses at the $SU(5)$ (left panel) and the Standard Model (right panel) levels.

CORRELATION*

- GAUGE COUPLING UNIFICATION ($\max(M_{\mathrm{GUT}})$)

$$M \equiv \min(M_J), \qquad J = \Phi_1, \Phi_3, \Phi_6, \Phi_{10}, \Sigma_1, \Sigma_3, \Sigma_6, \phi_1, \phi_8, \Lambda_3$$



$$\Sigma_1\ (1,3,1)$$

$$\Phi_1 \left(1, 4, -\frac{3}{2}\right)$$

- MASS RELATION(S)

$$M_{\Sigma_6} + M_{\Sigma_1} = 2M_{\Sigma_3}$$

SCENARIO (*a*):

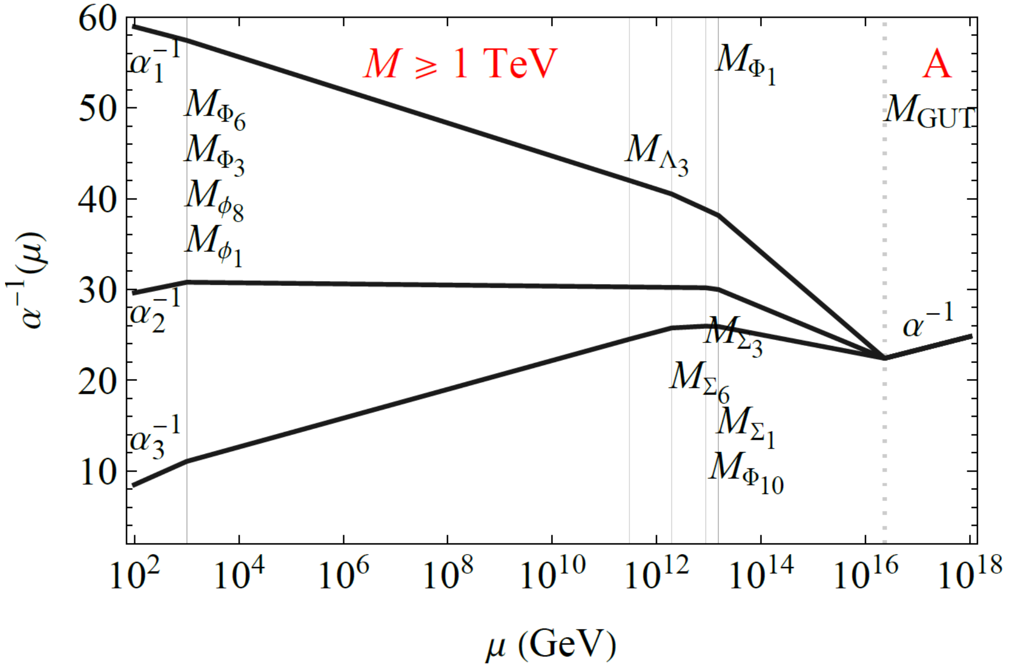
$$M_{\Sigma_6} \approx M_{\Sigma_1} \approx M_{\Sigma_3}$$

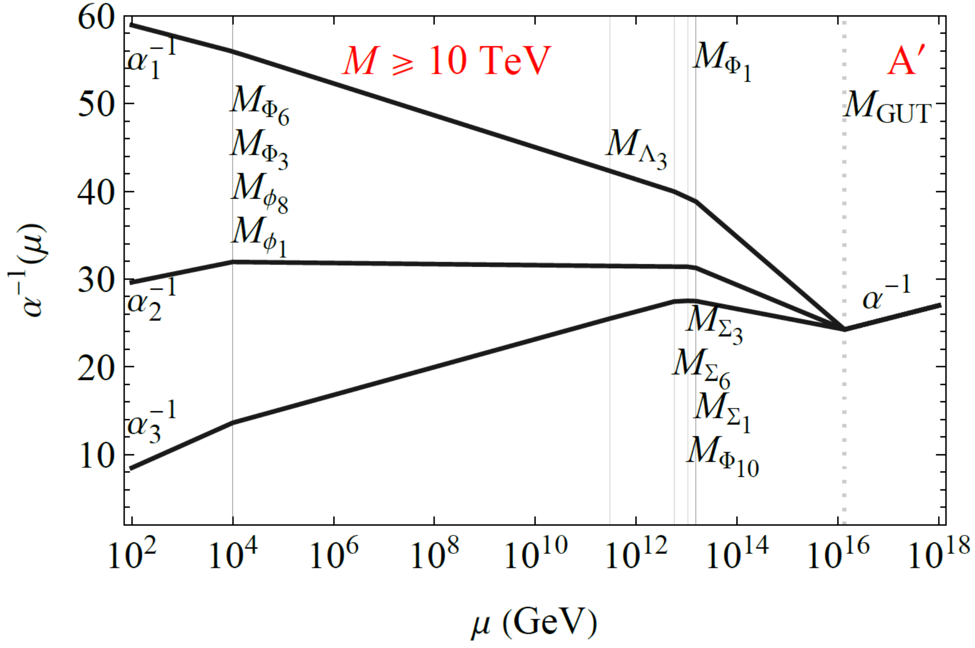
SCENARIO (*b*):

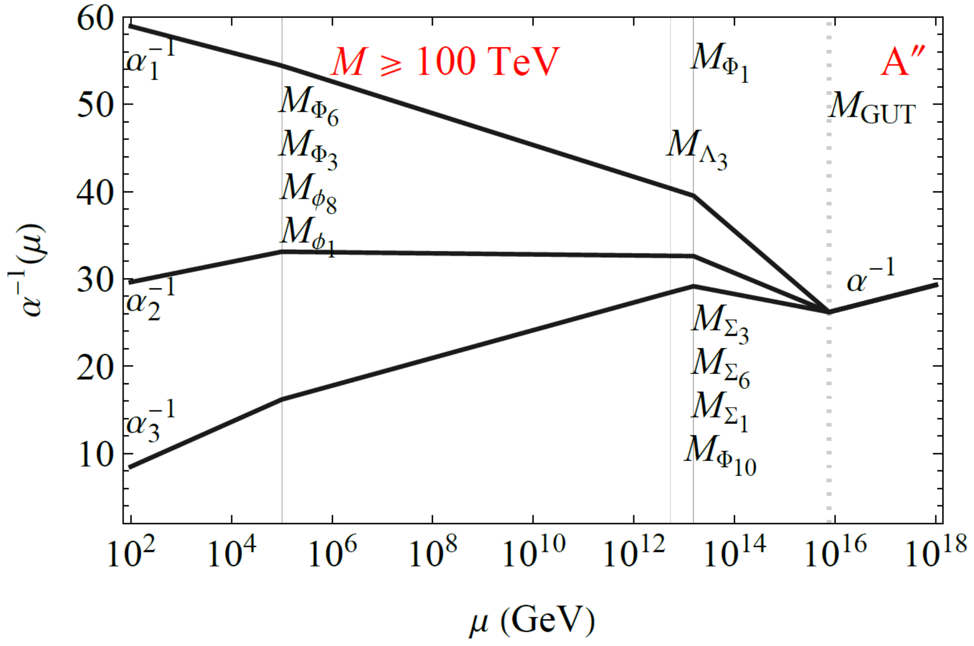
$$M_{\Sigma_6} = -M_{\Sigma_1}$$

*I.D., Emina Džaferović-Mašić, and Shaikh Saad, Phys.Rev.D 104 (2021) 1, 015023, arXiv:2105.01678.

- GAUGE COUPLING UNIFICATION







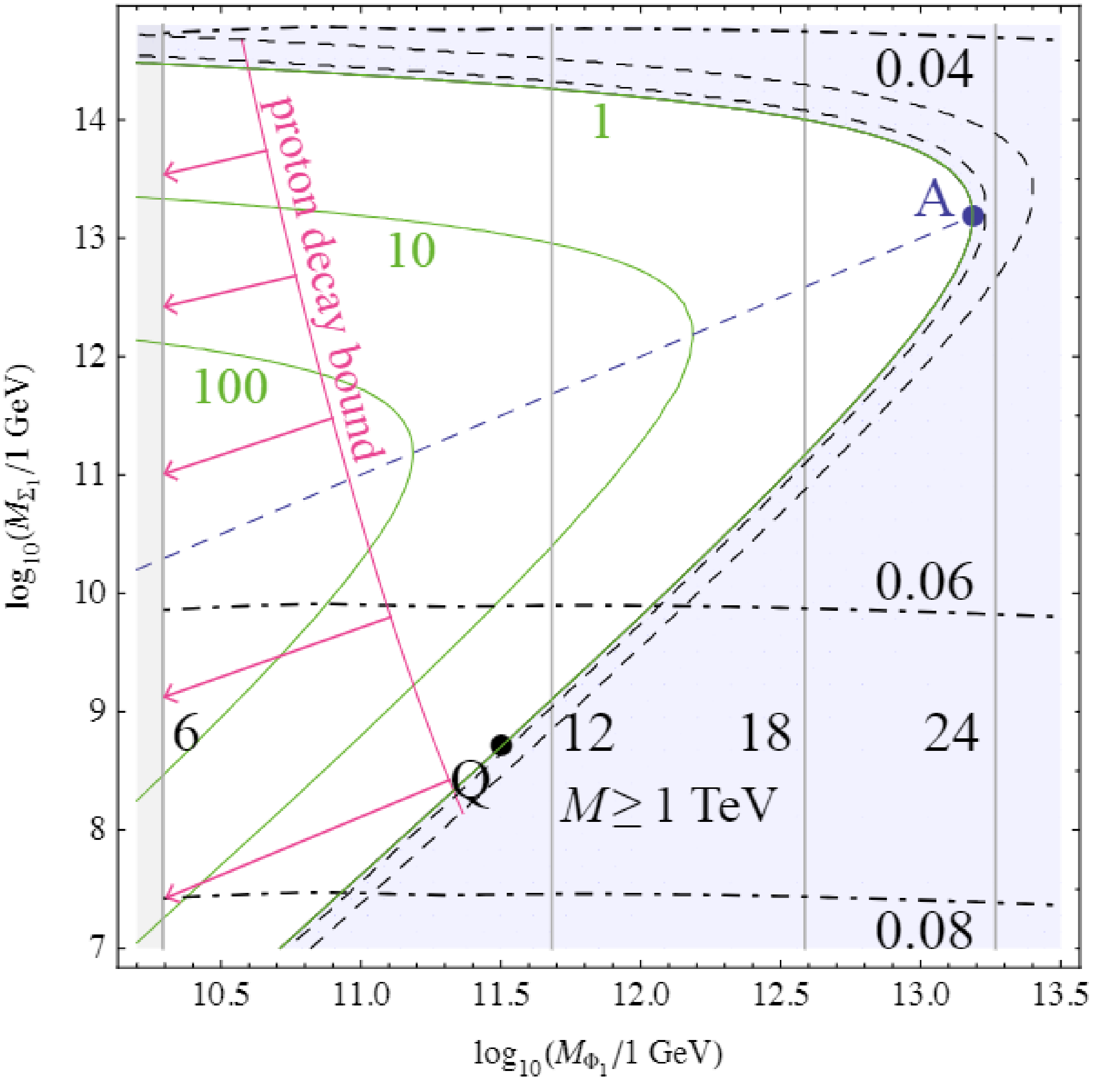
CORRELATION

The contours for M_{GUT} are given in units of 10^{15} GeV and are shown as the vertical solid lines while the contours for α_{GUT} are given as dot-dashed lines that run horizontally.

The parameter space that corresponds to $M_{GUT} \leq 6 \times 10^{15}$ GeV is discarded in this numerical study in all three instances due to the fact that such a low M_{GUT} is a priori not realistic with regard to the experimental input on the proton decay lifetimes.

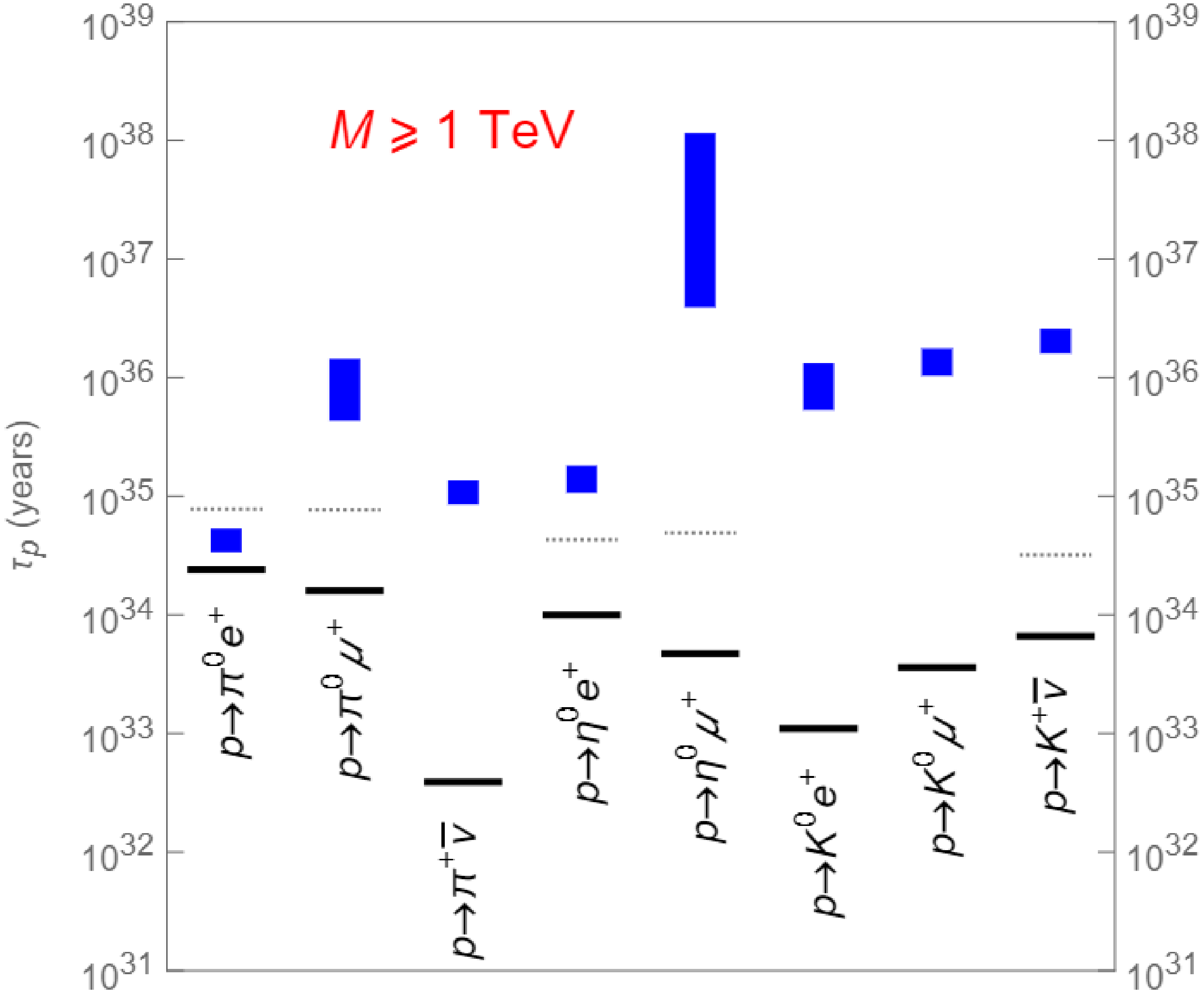
Green solid contours are used to mark the naive bound on the correct neutrino mass scale.

$2m_0/\sqrt{\Delta m_{31}^2}$ = 1, 10, 100

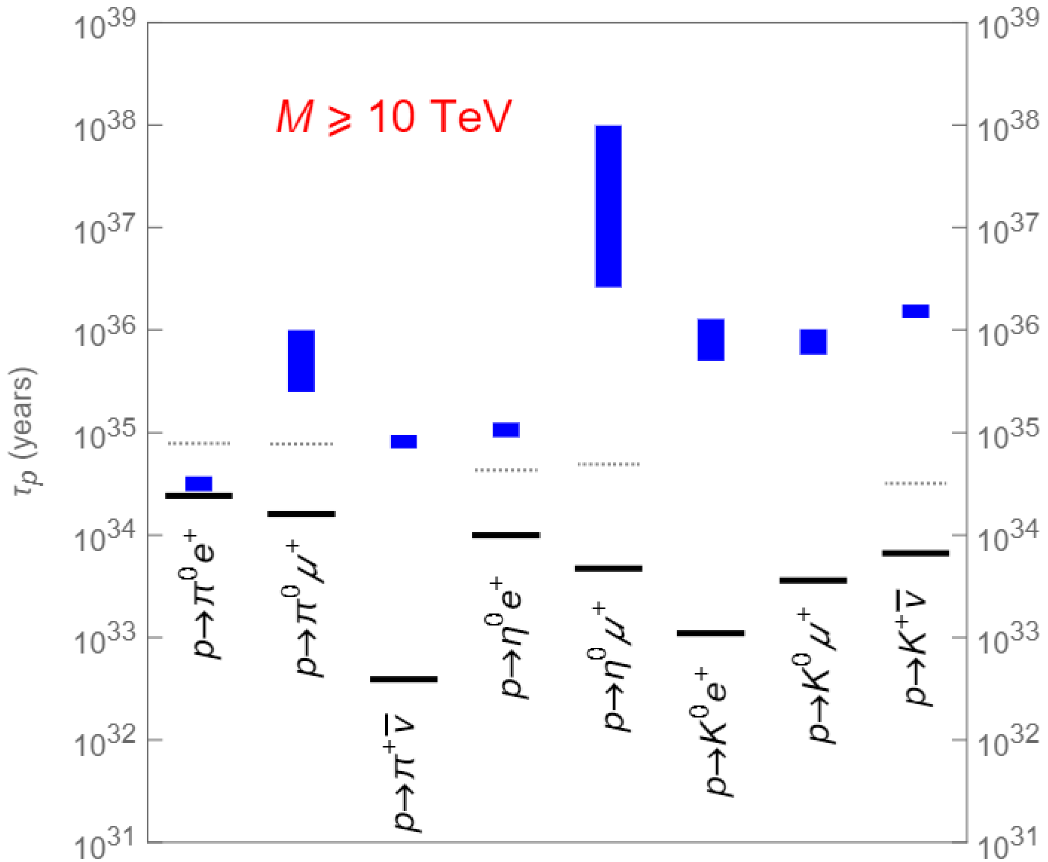


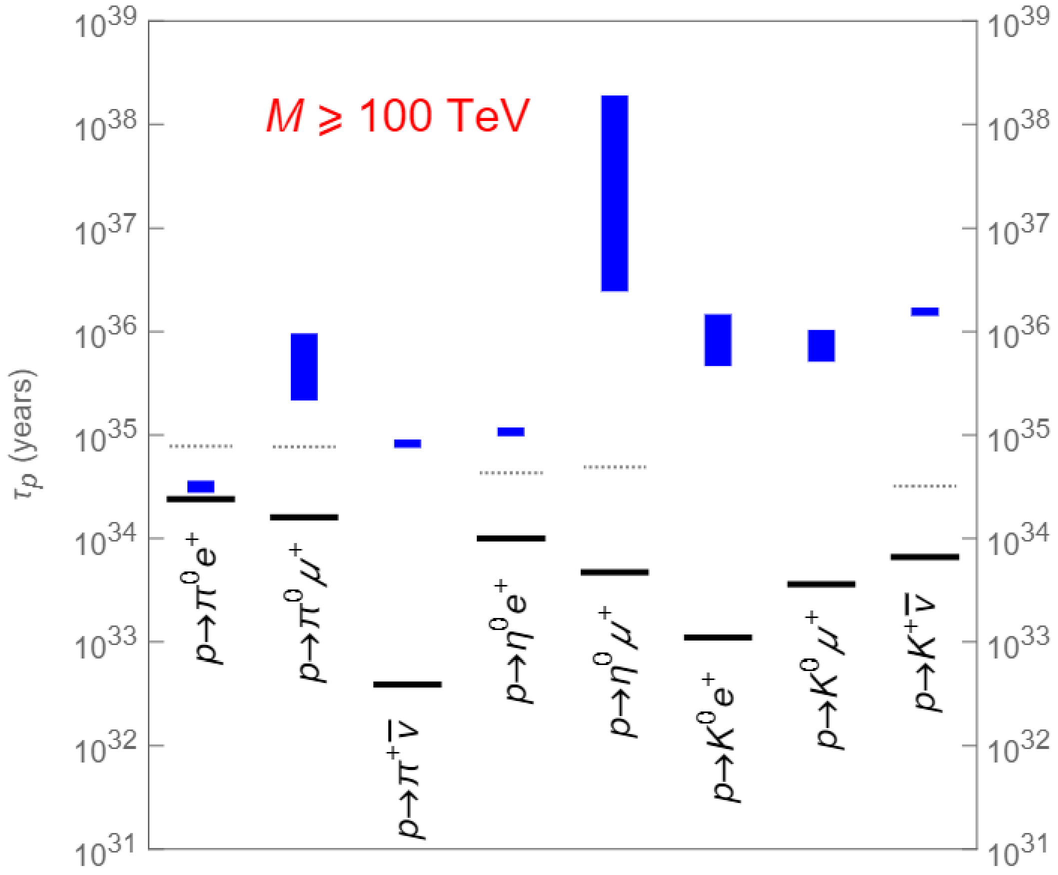
CORRELATION

Proton decay channels via gauge boson mediation within M ≥ 1 TeV scenario, where thin black horizontal lines represent current experimental limits, blue vertical bars stand for expected ranges within the model under consideration, and horizontal grey dashed lines represent future experimental sensitivities after ten-year period of data taking at 90 % C.L



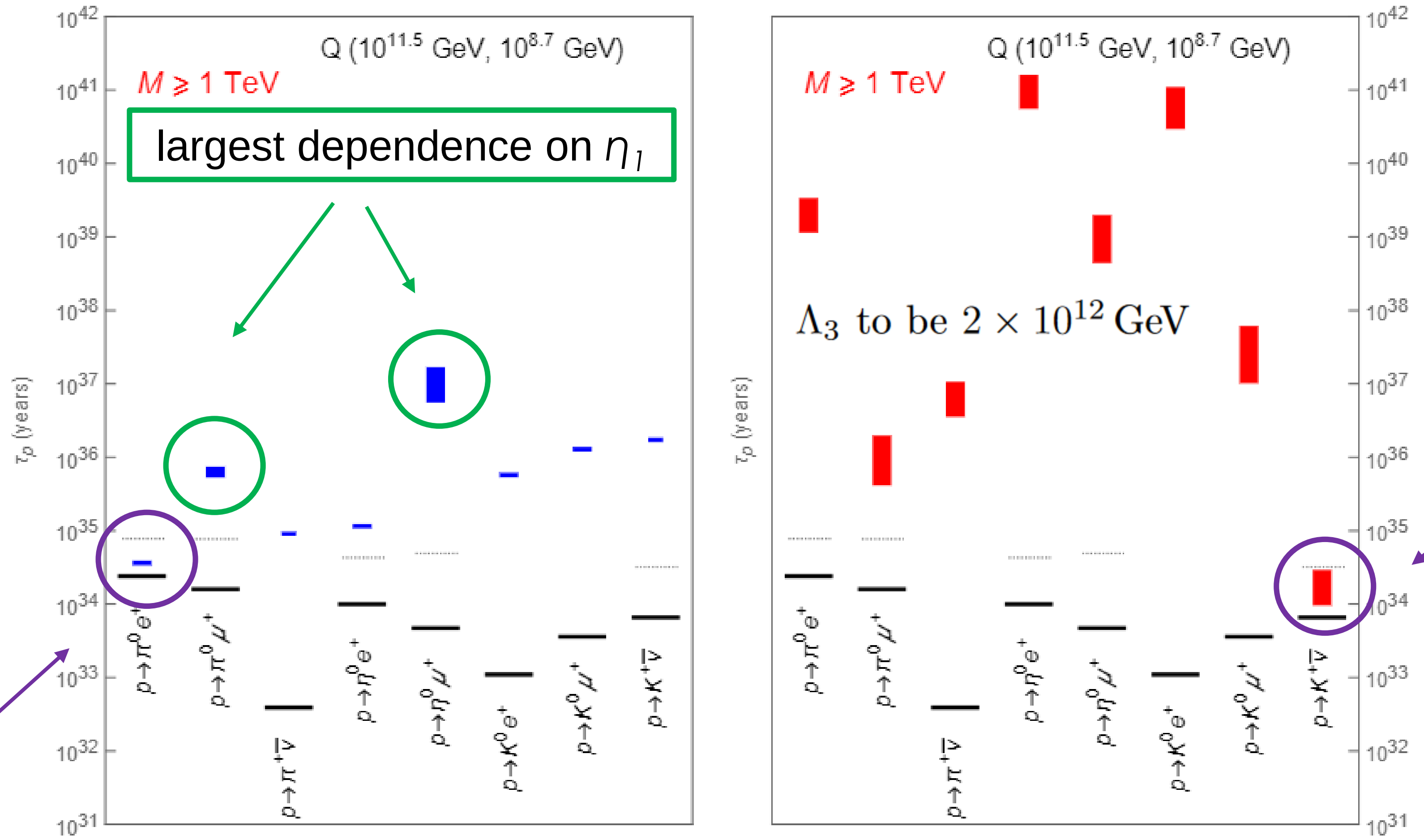
CORRELATION





CORRELATION

due to the fact that various contributions towards their decay widths are of approximately same magnitudes that even the smallest change in a single phase induces a large effect



(a) gauge boson mediation

(b) scalar leptoquark mediation

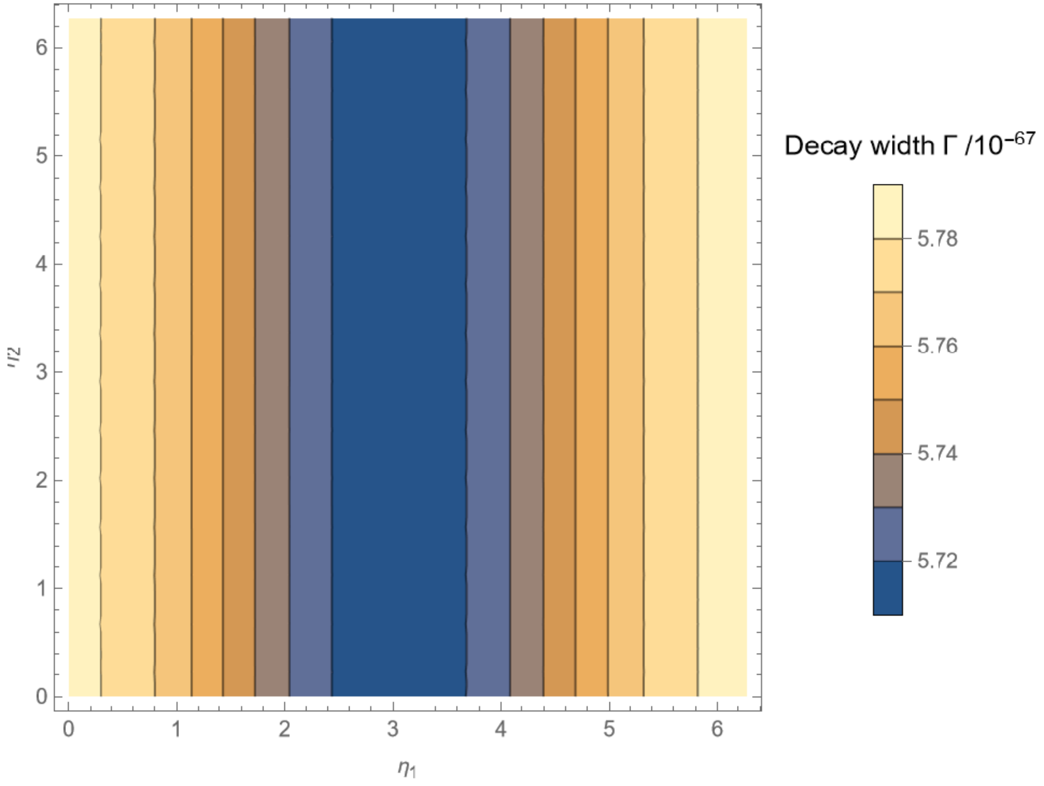
to be observed

to be observed

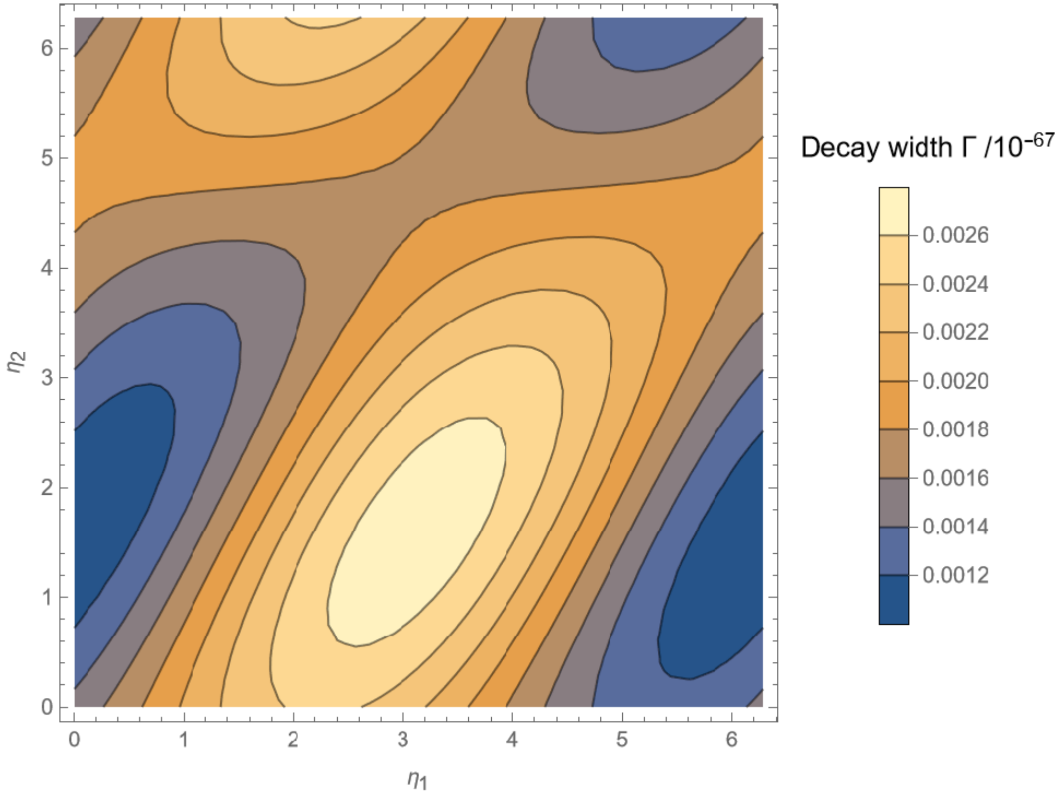
dependence not just on unitary transformations but on Yukawa coupling matrix entries as well

Figure 8.4: Proton decay widths for eight decay channels via **(a)** gauge boson and **(b)** scalar leptoquark mediations for point Q with coordinates of $M_{\Phi_1} = 10^{11.5}$ GeV and $M_{\Sigma_1} = 10^{8.7}$ GeV within $M \geq 1$ TeV scenario.

CORRELATION

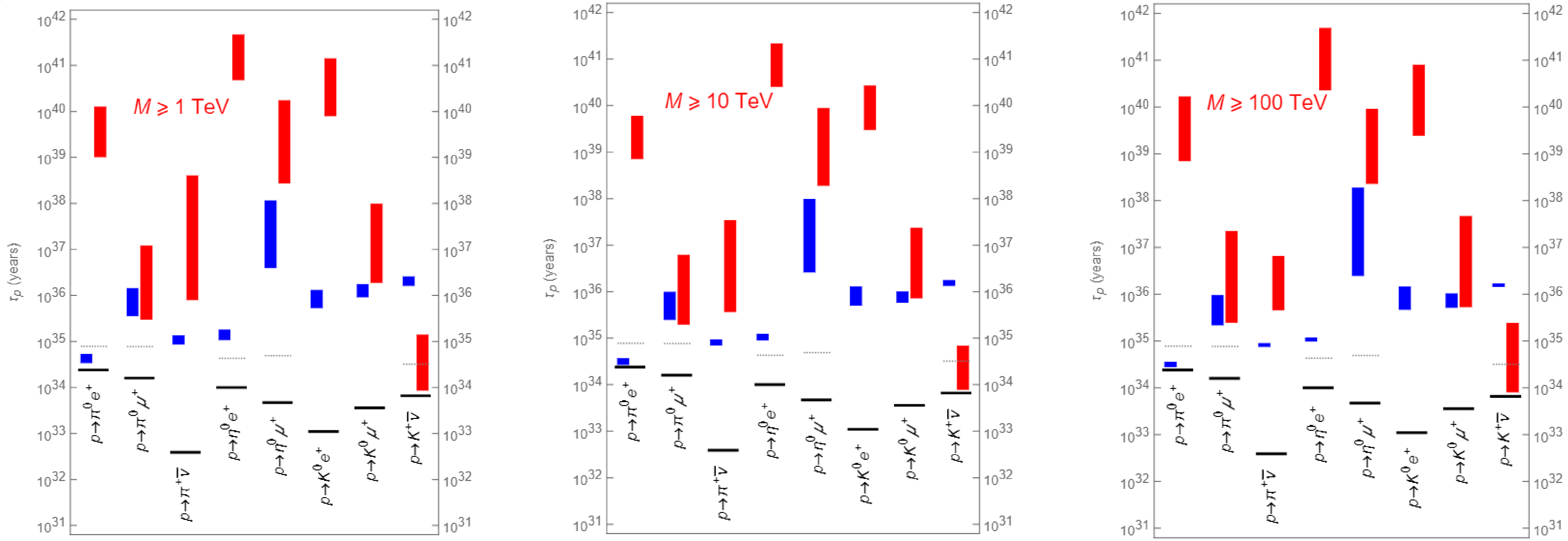


(a) $p \to \pi^0 e^+$ via gauge boson



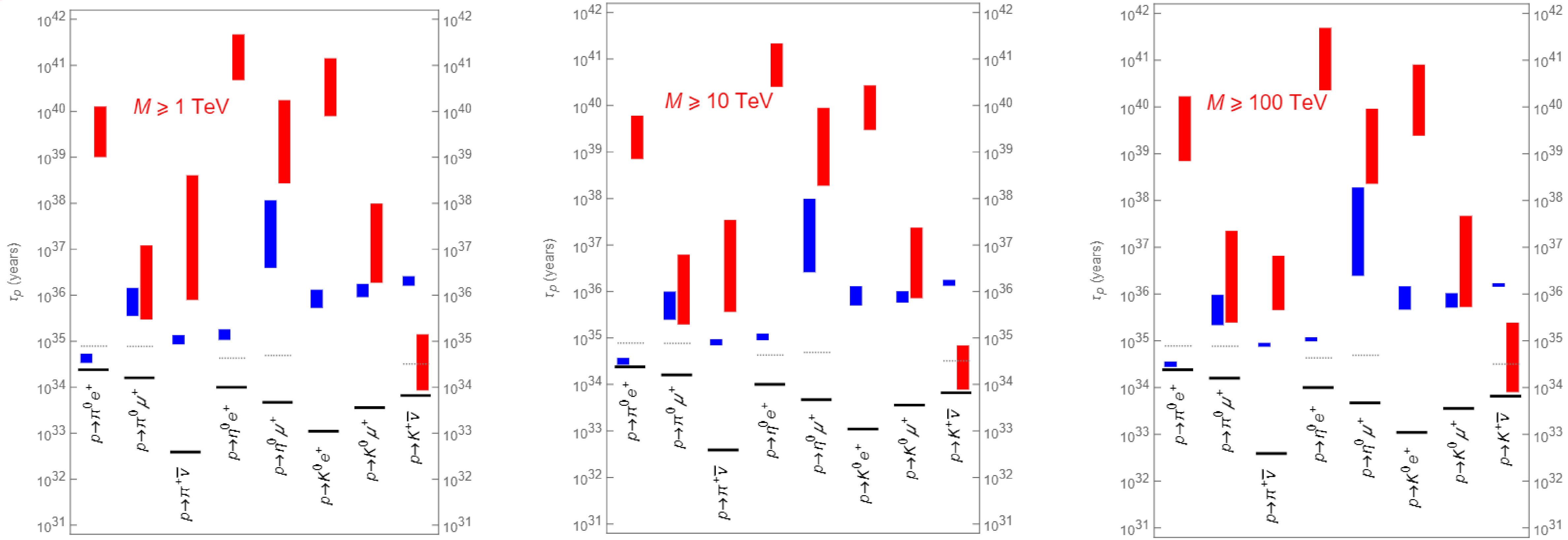
(b) $p \to \pi^0 e^+$ via scalar leptoquark

CORRELATION



Correlation of proton decay signatures via gauge boson and scalar leptoquark mediation within M ≥ 1 TeV, M ≥ 10 TeV, and M ≥ 100 TeV scenarios. Thin black lines represent current experimental limits, blue vertical bars are predictions for gauge boson mediation signatures, red vertical bars are corresponding predictions for scalar leptoquark mediations and grey dashed lines represent future experimental sensitivities after ten-year period of data taking at 90 % C.L.

CORRELATION



Gauge boson mediation uncertainties: ratio varies from point to point, unitary transformations and 2 unknown phases.
Scalar leptoquark mediation uncertainties: fermion mass fit varies from point to point, 2 unknown phases, decay widths are proportional to the products of Yukawa couplings.

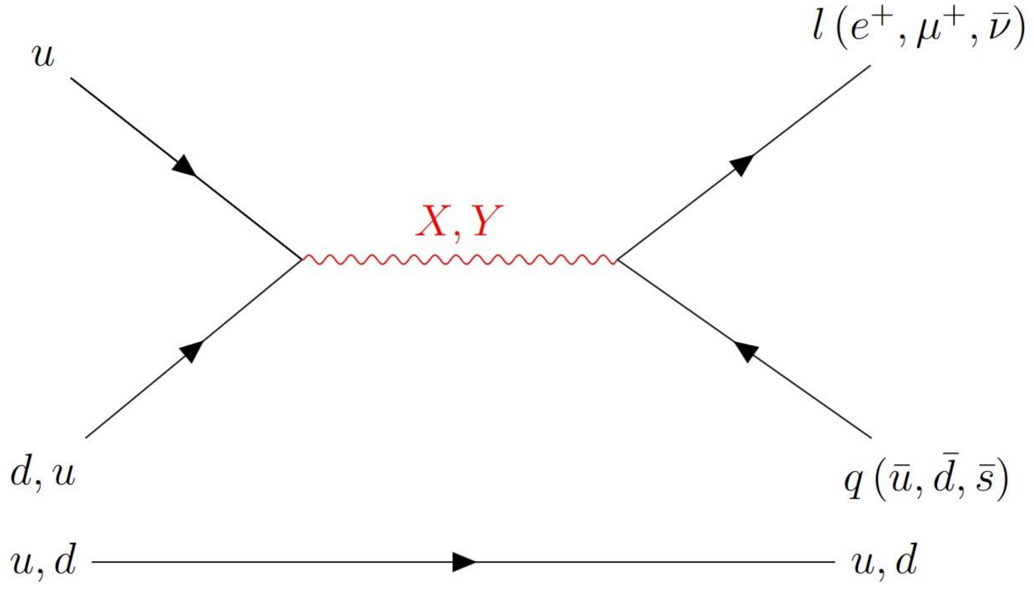
CONCLUSIONS

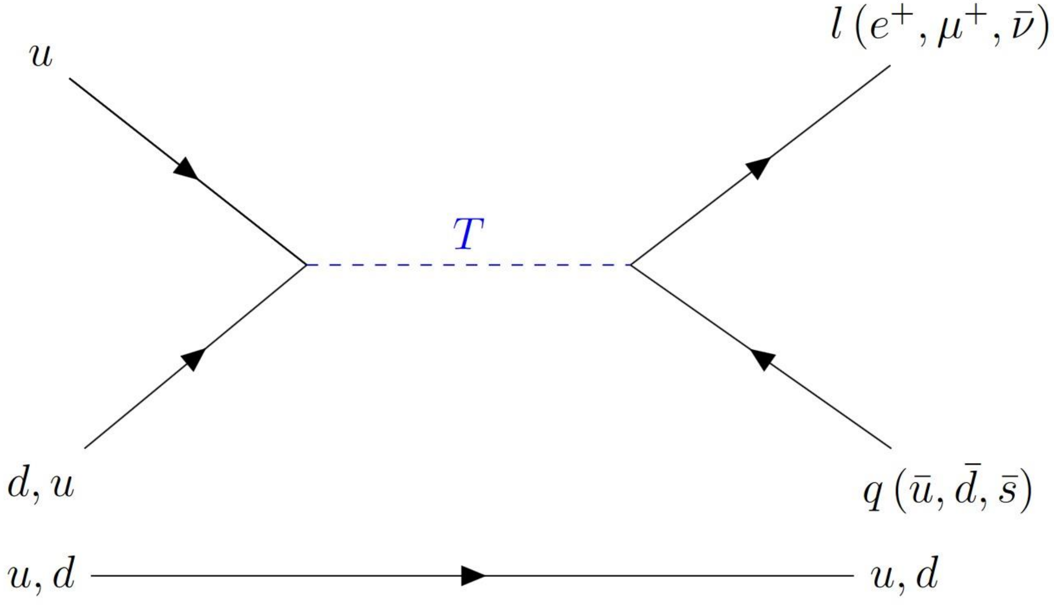
There are only two possible types of mediators of proton decay within the model in question. The anticipated experimental signal of these decay processes can, hence, originate solely from gauge boson mediation, or entirely from scalar leptoquark mediation, or from combination of the two. Our analysis stipulates that we can conclude with certainty that if in experiments proton is observed to decay to:

$p \to \pi^0 e^+$	the decay is mediated via gauge boson
$p \to K^+ \bar{\nu}$	the decay is mediated via scalar leptoquark
$p \to \pi^0 \mu^+$	combination of the two

CONCLUSIONS

- The fact that the proton decay signatures from two different sources of new physics can be predicted at this level of accuracy has not been observed in other models of SU (5) unification.
- There does not exist a single correlation study of proton decay signatures via two different sources of new physics in the literature.





REFERENCES

- [1] R. Brock, C. K. Jung & C.E.M. Wagner et al. "Proton Decay", *Workshop on Fundamental Physics at the Intensity Frontier*, 111-130, May 2012
- [2] T. Hambye & J. Heeck, "Proton decay into charged leptons", *Phys.Rev.Lett*.120, 171801, 24th April 2018
- [3] S.Weinberg, "The Decay of the Proton", *Scientific American*, June 1981
- [4] P. Nath & P. Fileviez Perez, "Proton stability in grand unified theories, in strings and in branes", *Phys. Rept*. 441, 191-317, 2007
- [5] M. Tanaka et al, "Search for proton decay into three charged leptons in 0.37 megaton-years exposure of the Super-Kamiokande", *Phys. Rev. D* 101, 052011, 2020
- [6] J. S. Yoo, Y. Aoki, T. Izubuchi and S. Syritsyn, "Proton decay matrix elements on the lattice", PoS LATTICE 2013 (2014)
- [7] F. Wilczek & A. Zee, "Operator Analysis of Nucleon Decay", Phys.Rev.Lett. 43, 21, 1571-1573, 19th November 1979
- [8] J. S. Yoo, Y. Aoki, T. Izubuchi and S. Syritsyn, "Proton decay matrix elements on the lattice with physical pion mass", *PoS LATTICE* 2018 (2019)
- [9] H. Georgi and S. L. Glashow, "Unity of All Elementary-Particle Forces", *Phys. Rev. Lett*.32, 438 (1974)

REFERENCES

- [10] Yorikiyo Nagashima, "Beyond the Standard Model of Elementary Particle Physics", ISBN: 978-3-527-41177-1, Wiley-VCH Verlag GmbH&Co. KGaA, Boschstr.12, 69469 Weinheim, Germany, 2014
- [11] Doršner and I. Mocioiu, "Predictions from type II see-saw mechanism in SU(5)", *Nucl. Phys. B* 796, 123 (2008)
- [12] J. Schechter & J. W. F. Valle, "Neutrino masses in SU(2)×U(1) theories", *Phys. Rev. D* 22, 9, 1st November 1980
- [13] G. Lazarides & Q. Shafi, "Proton lifetime and fermion masses in an SO(10) model", *Nucl. Phys. B* 181, 287-300 (1981)
- [14] Rabindra N. Mohapatra, "Neutrino masses and mixings in gauge models with spontaneous parity violation", *Phys. Rev. D* 23, 1, 1st January 1981
- [15] P. Fileviez Perez, "Fermion mixings vs d=6 proton decay", *Phys. Lett. B* 595, 476, (2004)
- [16] Doršner and S. Saad, "Towards Minimal SU(5)", *Phys. Rev. D* 101, 015009 (2020)
- [17] K. Kumerički, T. Mede and I. Picek, "Renormalizable SU(5) completions of a Zee-type neutrino mass model", *Phys. Rev. D* 97, no. 5, 055012 (2018)

REFERENCES (FIGURES)

- [Figure 1] www.digitalspy.com/tv/ustv/a649499/bazinga-21-awesome-facts-you-might-not-know-about-the-big-bang-theory
- [Figure 2] https://universe-review.ca/F15-particle03.htm
- [Figure 3] http://www.hyper-k.org/en/physics/phys-protondecay.html
- [Figure 4] https://indico.cern.ch/event/129268/contributions/1348781/attachments/88197/126257/Hayato_20110607_ProtonDecaySearch.pdf
- [Figure 5] https://indico.cern.ch/event/129268/contributions/1348781/attachments/88197/126257/Hayato_20110607_ProtonDecaySearch.pdf
- [Figure 6] https://phys.org/news/2016-11-super-kamiokande-detector-awaits-neutrinos-supernova.html

$$\begin{pmatrix} T & 0 & 0 & 0 & 0 \\ 0 & H & 0 & 0 & 0 \\ 0 & 0 & A & 0 & 0 \\ 0 & 0 & 0 & N & 0 \\ 0 & 0 & 0 & 0 & K \end{pmatrix}$$

$$\begin{pmatrix} Y & O & U \\ F & O & R \end{pmatrix}$$

$$\begin{pmatrix} Y & 0 & 0 & 0 \\ 0 & O & 0 & 0 \\ 0 & 0 & U & 0 \\ 0 & 0 & 0 & R \end{pmatrix}$$

$$\begin{pmatrix} A & 0 & 0 & 0 & 0 \\ 0 & T & 0 & 0 & 0 \\ 0 & I & T & 0 & 0 \\ 0 & O & 0 & E & 0 \\ 0 & N & 0 & 0 & N \end{pmatrix}$$