Saitama University 埼玉大学

iTHEMS

RIKEN Center for Interdisciplinary Theoretical and Mathematical Sciences

HEP seminar

Phenomenological Constraints on the Leptophilic Zee Model

Presented by: Le Duc-Truyen

Collaboration: Prof. Chang We-Fu

Hi! I'm Le Duc Truyen (黎德傳)

from National Tsing Hua University

> “To move forward you need to leave something behind”
> Interstellar Quote inspired by Newton's third law

Where I am

What I Do During My Free Time

Things that keep me occupied usually on weekends

TRAVELING

READING BOOK

Philosophy, History, Math, Mythology, Tourism, Cooking

MUSICS

Listen and play musical instruments

BOARD GAME

Play, analyse and create a new board game

SPORT

Soccer, Baminton, Swimming, Ping pong, and any outdoor activities

WACHING MOVIE

Film criticism

What Topics Keep Me Interested

Reseach topics

HIGH ENERGY PHYSIC

• Building Beyond Standard Model
• Dark Matter and Anomalies
• Computational application for High Energy Physics

QUANTUM COMPUTATION AND QUANTUM INFORMATION

• Quantum algorithms and software, specifically applying for High Energy Physics
• Black Hole Quantum Information
• Quantum AI
• Quantum Optimization and Simulation

ALL THINGS EFT

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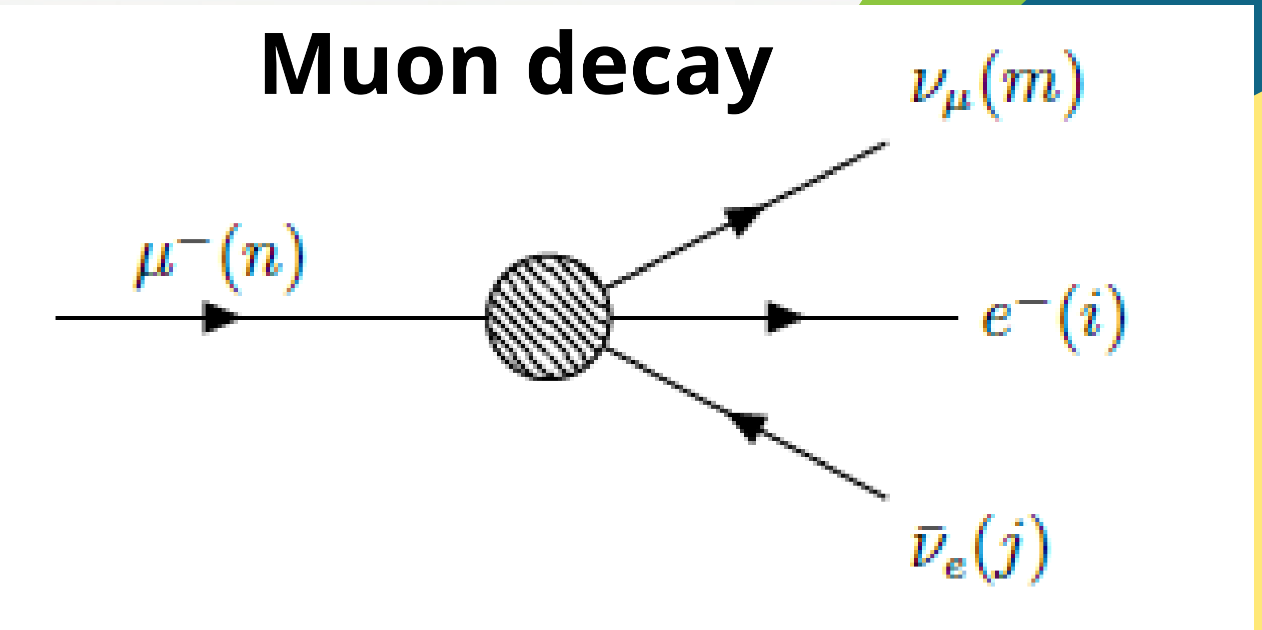
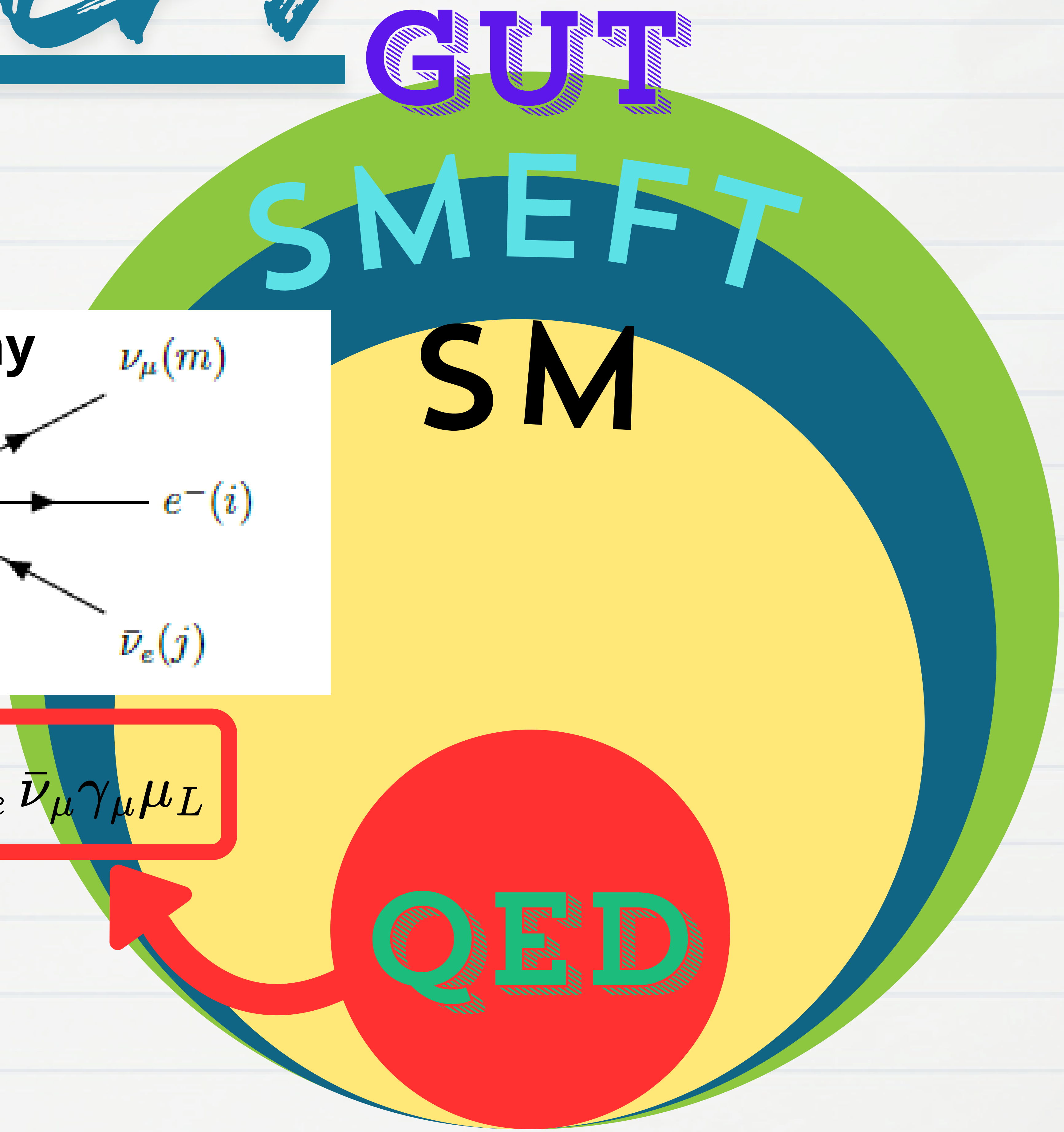


$$\mathcal{L}_{\text{Fermi}} = -2\sqrt{2}G_F\,\bar{e}_L\gamma^\mu\nu_e\,\bar{\nu}_\mu\gamma_\mu\mu_L$$



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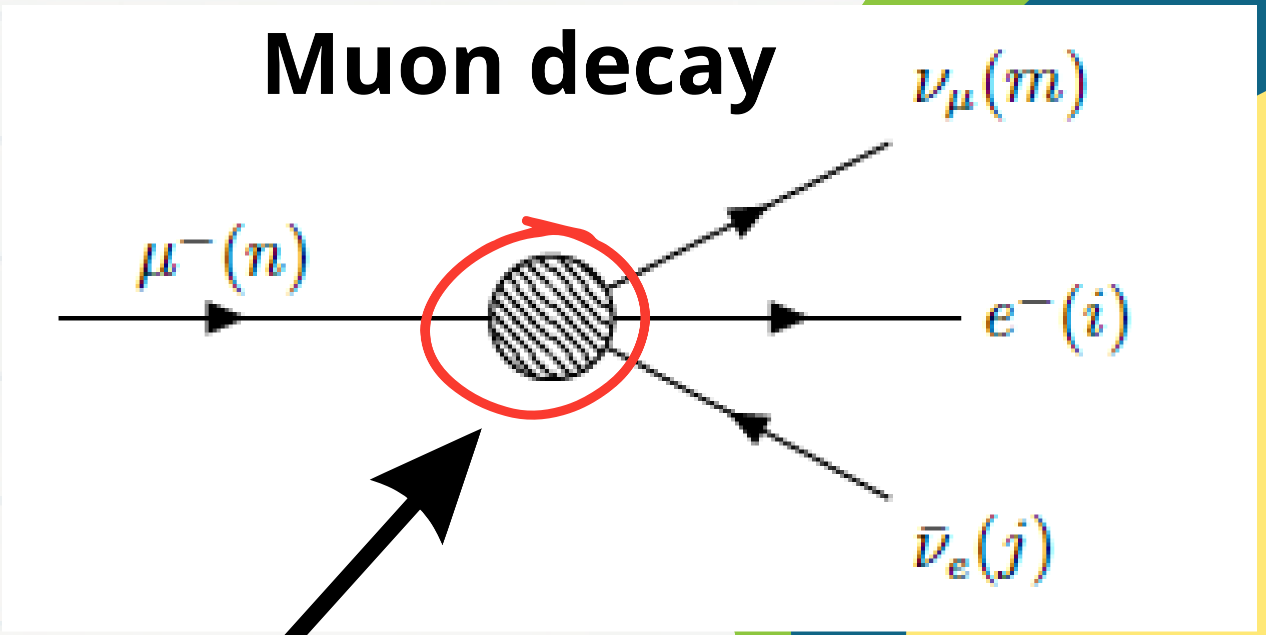

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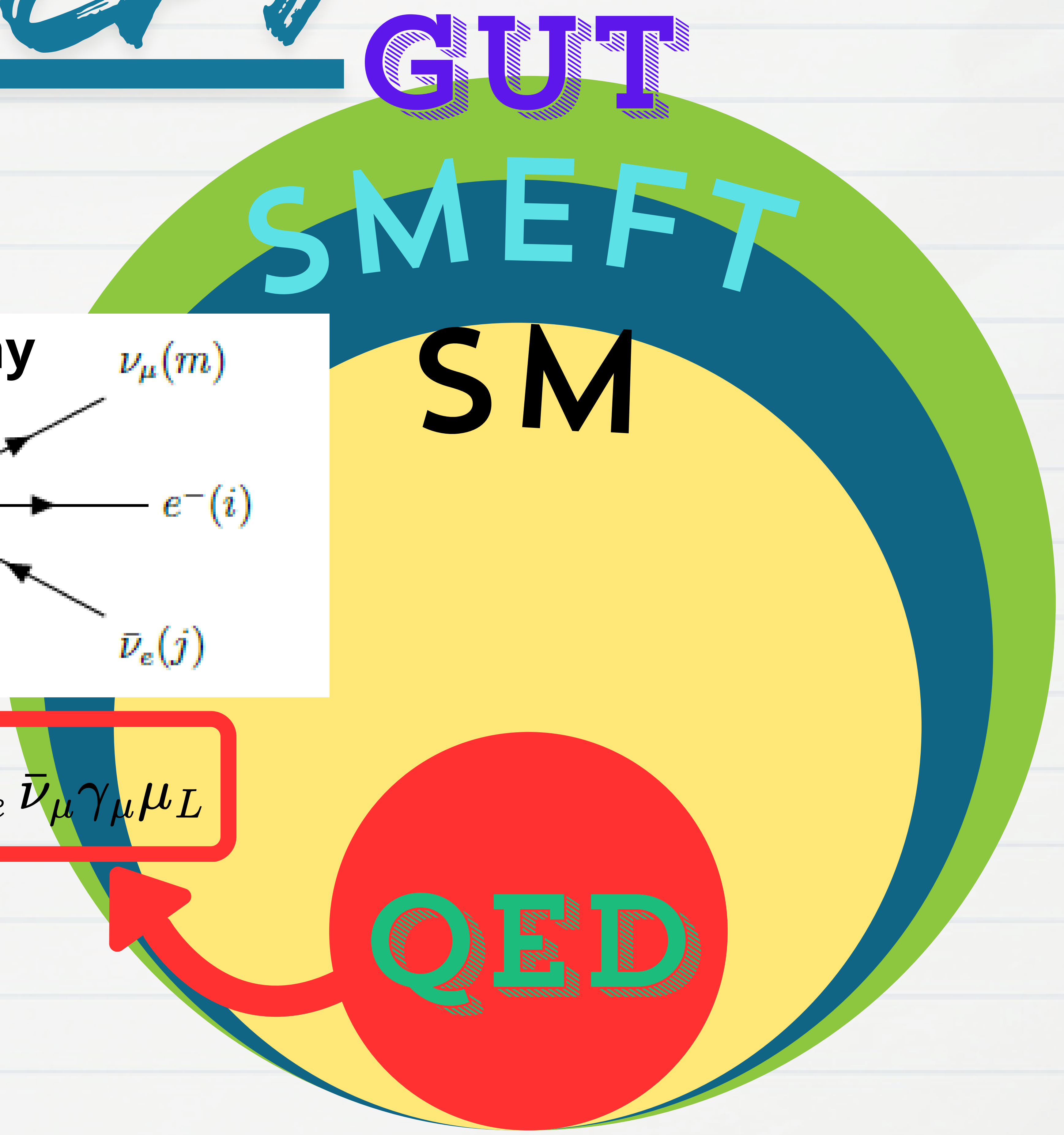

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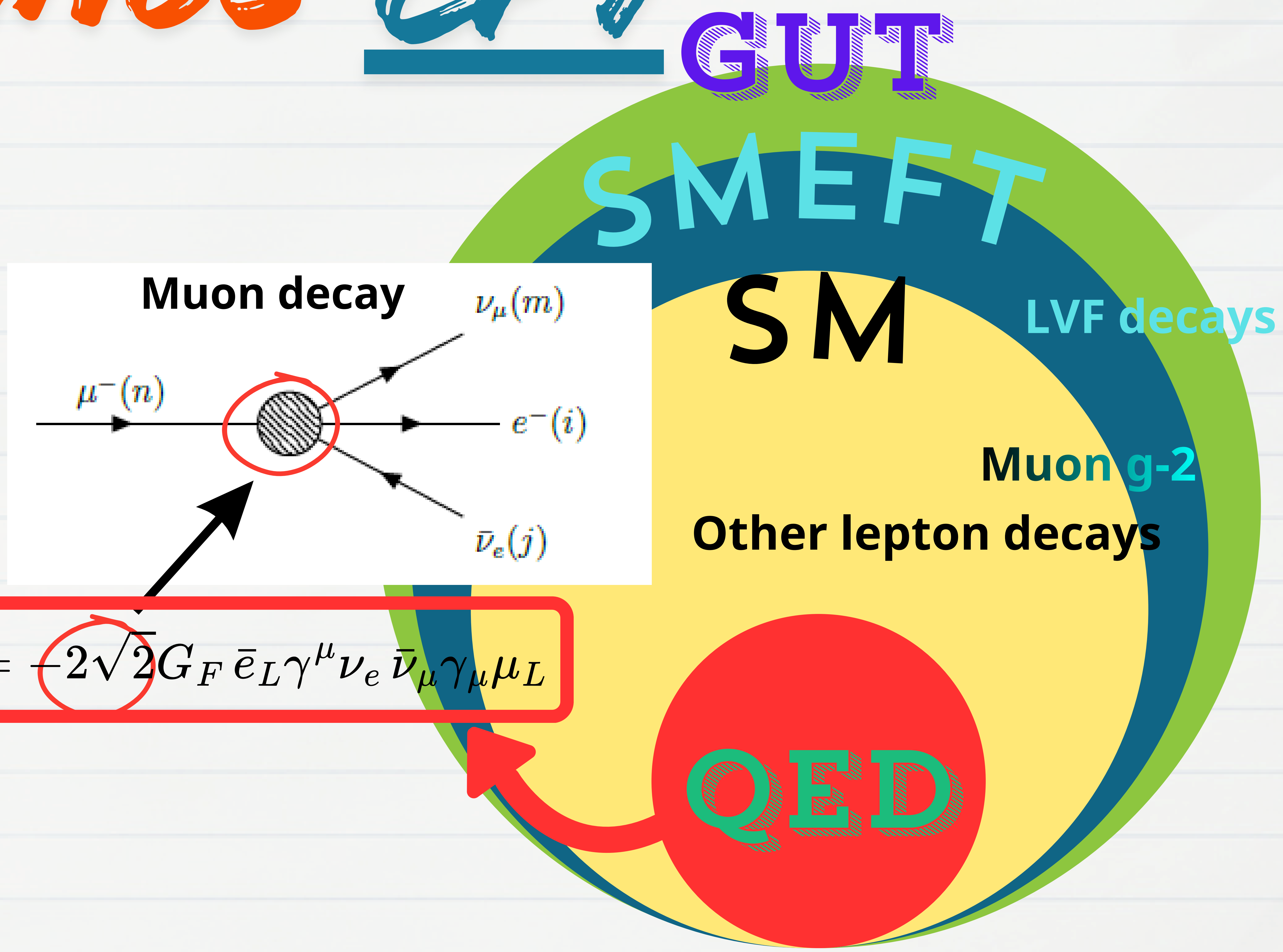

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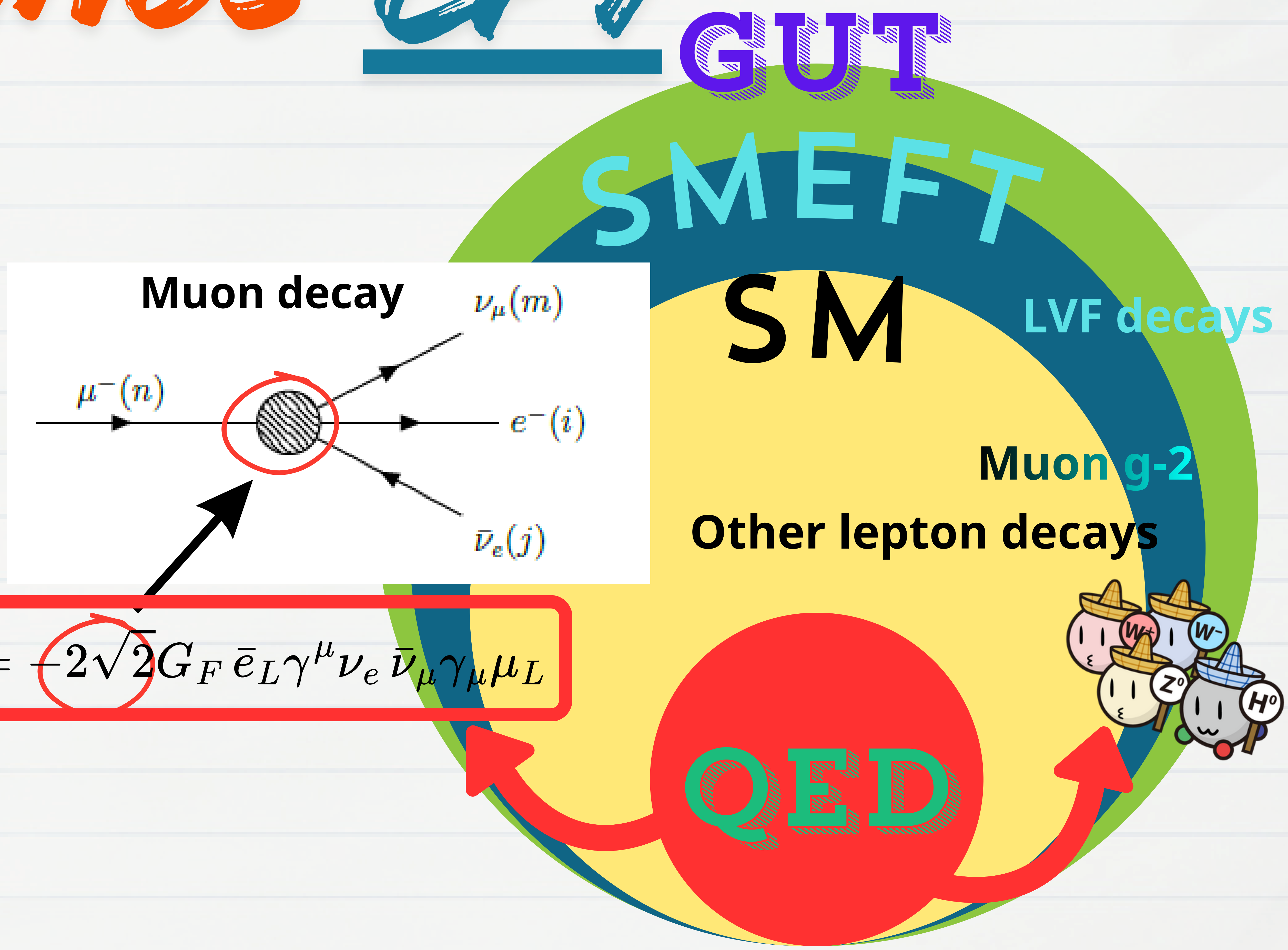

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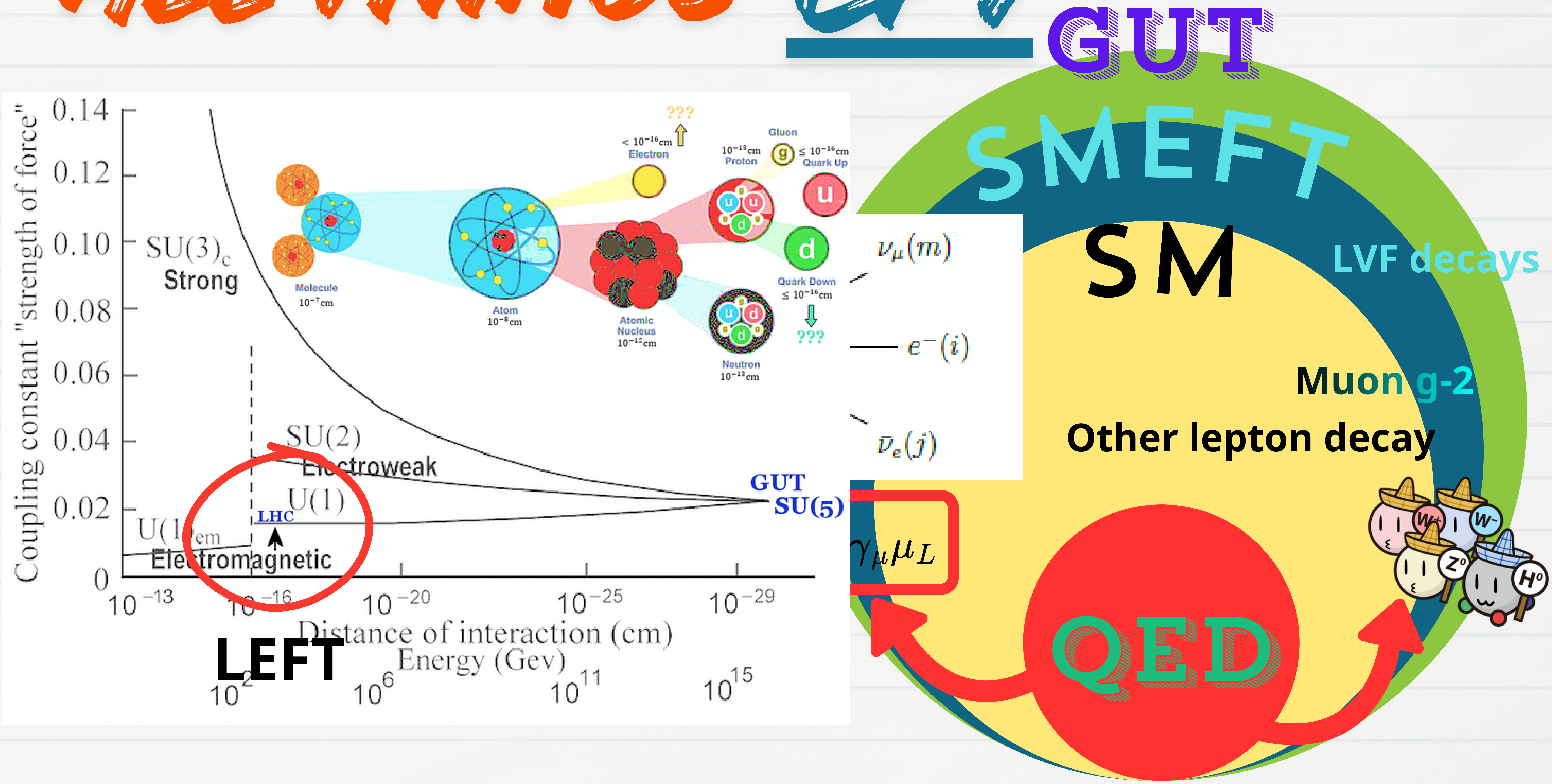


STANDARD Model

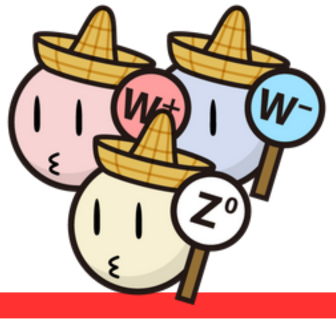
$$\mathcal{L}_{\mathrm{SM}} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \bar{\psi} i \gamma^\mu D_\mu \psi + |D_\mu \phi)|^2 - V(\phi) + \bar{\psi}_L \hat{Y} \phi \psi_R + \mathrm{h.c.}.$$

STANDARD Model

$$\mathcal{L}_{\rm SM} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \bar{\psi} i \gamma^\mu D_\mu \psi + |D_\mu \phi)|^2 - V(\phi) + \bar{\psi}_L \hat{Y} \phi \psi_R + \text{h.c.}.$$

Electroweak breaking

~ 246 GeV



$$\mathcal{L}_{\rm QED} = -\frac{1}{4} A_{\mu\nu} A^{\mu\nu} + \bar{\psi} i \gamma^\mu D_\mu \psi + m \bar{\psi} \psi$$

$$\mathcal{L}_{\rm Fermi}$$

$$\mathcal{L}_{WW\gamma} \sim A_{\mu\nu} W^{+\,\mu} W^{-\,\nu} + \ldots$$

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}} \bar{\nu}_l \gamma^\mu \ell^L \, W^+_\mu + h.\,c.$$

STANDARD Model

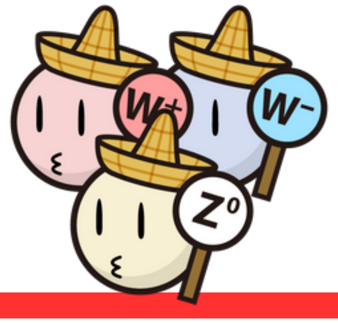
$$\mathcal{L}_{\text{SM}} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \bar{\psi} i \gamma^\mu D_\mu \psi + |D_\mu \phi)|^2 - V(\phi) + \bar{\psi}_L \hat{Y} \phi \psi_R + \text{h.c.}.$$

UV models

Electroweak breaking

~ 246 GeV

LVF decays



Muon g-2

$$\mathcal{L}_{\text{QED}} = -\frac{1}{4} A_{\mu\nu} A^{\mu\nu} + \bar{\psi} i \gamma^\mu D_\mu \psi + m \bar{\psi} \psi$$

$$\mathcal{L}_{\text{Fermi}}$$

Neutrino mass

$$\mathcal{L}_{WW\gamma} \sim A_{\mu\nu} W^{+\,\mu} W^{-\,\nu} + \ldots$$

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LOW-ENERGY EFT

$$\mathcal{L}_{\rm SM} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \bar{\psi} i \gamma^\mu D_\mu \psi + |D_\mu \phi)|^2 - V(\phi) + \bar{\psi}_L \hat{Y} \phi \psi_R + \text{h.c.}.$$

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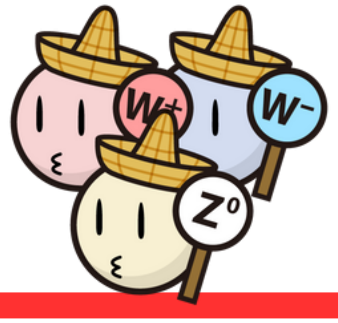

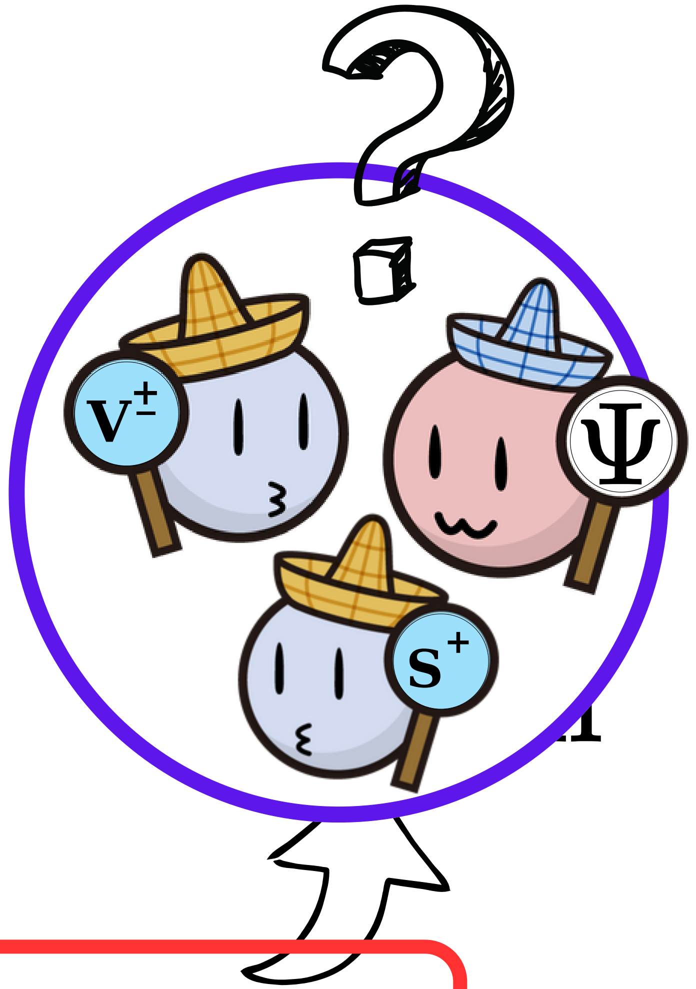

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LOW-ENERGY EFT

$$\mathcal{L}_S = a_\phi |D_\mu \phi|^2 - b_\phi m_\phi^2 \, |\phi|^2 \quad \mathcal{L}_{F\text{–}S} = \bar{\psi}_i \left(Y_{ij}^L \, \hat{L} + Y_{ij}^R \, \hat{R} \right) \psi_j \, \phi + \text{h.c.}$$

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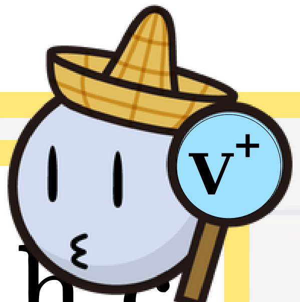
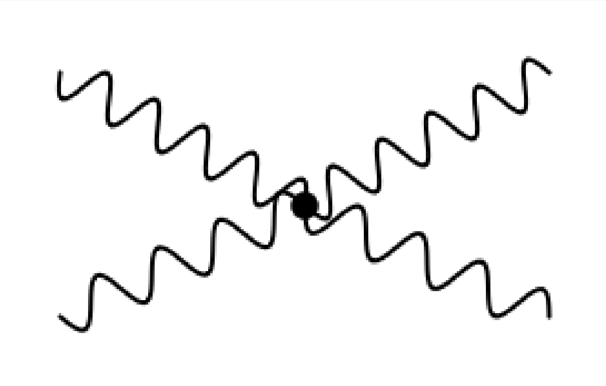
$$\mathcal{L}_{V_\pm} = -\frac{a_V}{2} \, \tilde{V}^+_{\mu\nu} \tilde{V}^{-\,\mu\nu} + b_V m_V^2 \, V^+_\mu V^{-\,\mu} + i c_V e Q_V \, A^{\mu\nu} V^+_\mu V^-_\nu$$



$$\mathcal{L}_{F\text{–}V^\pm} = \bar{\psi}_i \left(V^L_{ij} \, \hat{L} + V^R_{ij} \, \hat{R} \right) \gamma^\mu \psi_j \, V^\pm_\mu + \text{h.c.}$$

$$d_V |V^\pm_\mu|^4$$

$$\mathcal{L}_{\text{QED}} = -\frac{1}{4} \, A_{\mu\nu} A^{\mu\nu} + \bar{\psi} i \gamma^\mu D_\mu \psi + m \bar{\psi} \psi$$



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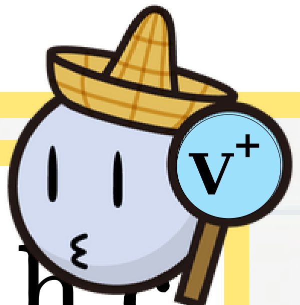

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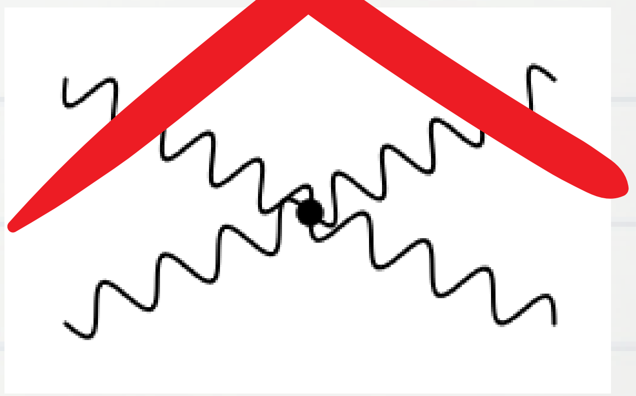

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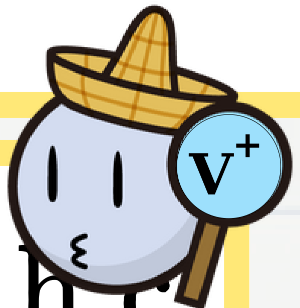

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Klein-Gordon Eq. $\longrightarrow$ $a_\phi = b_\phi = a_V = b_V = 1$

LOW-ENERGY EFT

$$\mathcal{L}_S = a_\phi |D_\mu \phi|^2 - b_\phi m_\phi^2 \, |\phi|^2 \quad \mathcal{L}_{F\text{–}S} = \bar{\psi}_i \left(Y_{ij}^L \, \hat{L} + Y_{ij}^R \, \hat{R} \right) \psi_j \, \phi + \text{h.c.}$$

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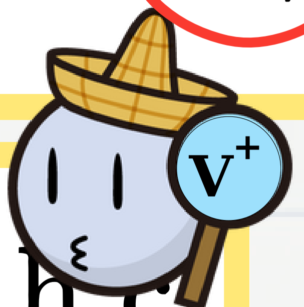

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$$\wr$$

$$\mathcal{L}_{WW\gamma} \sim A_{\mu\nu} W^{+\,\mu} W^{-\,\nu} + \ldots$$

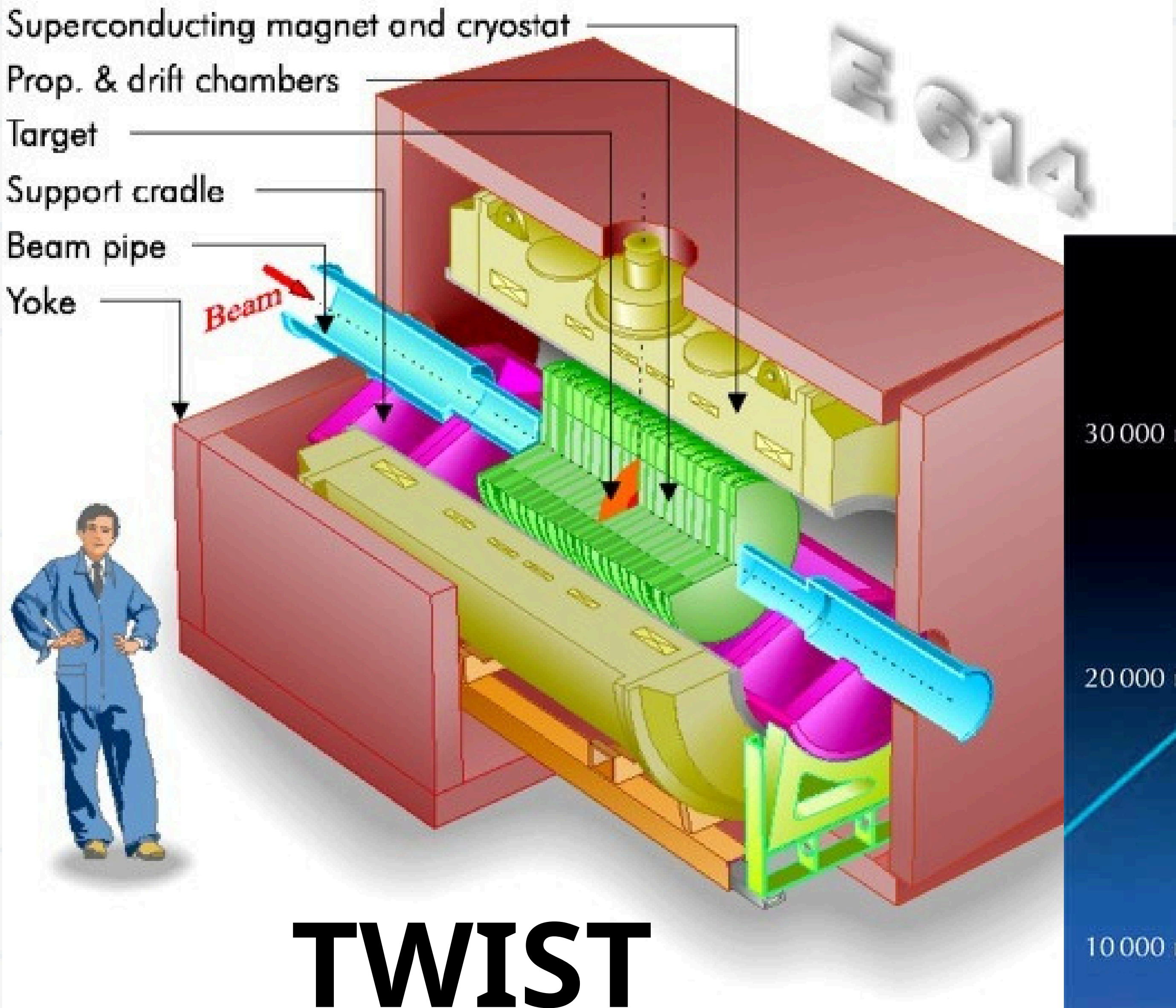
$$\mathcal{L}_{\text{QED}} = -\frac{1}{4} A_{\mu\nu} A^{\mu\nu} + \bar{\psi} i \gamma^\mu D_\mu \psi + m \bar{\psi} \psi$$

Fixed at one-loop level

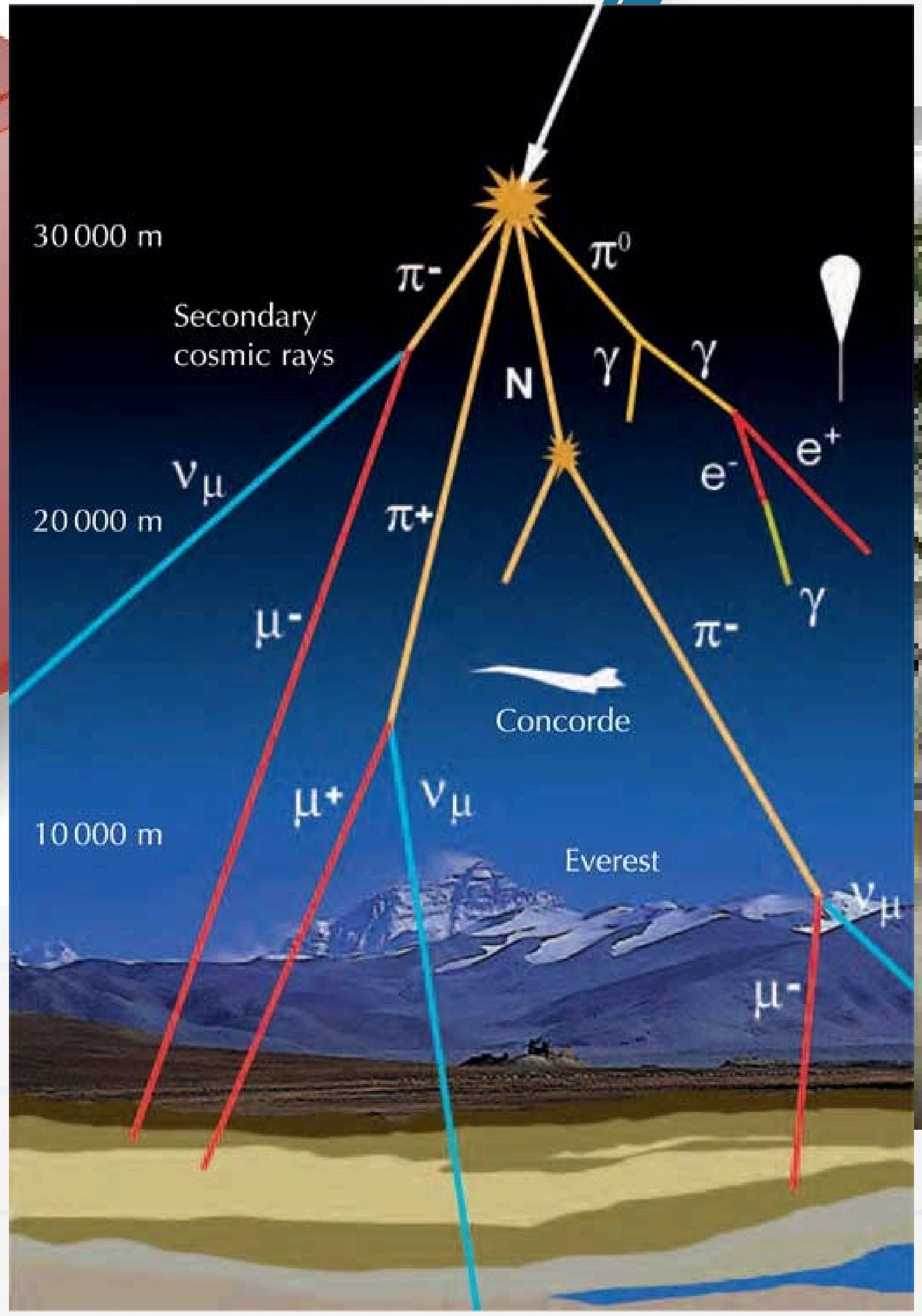
$$c_{V^\pm} = 1$$

Klein-Gordon Eq. $\longrightarrow$ $a_\phi = b_\phi = a_V = b_V = 1$

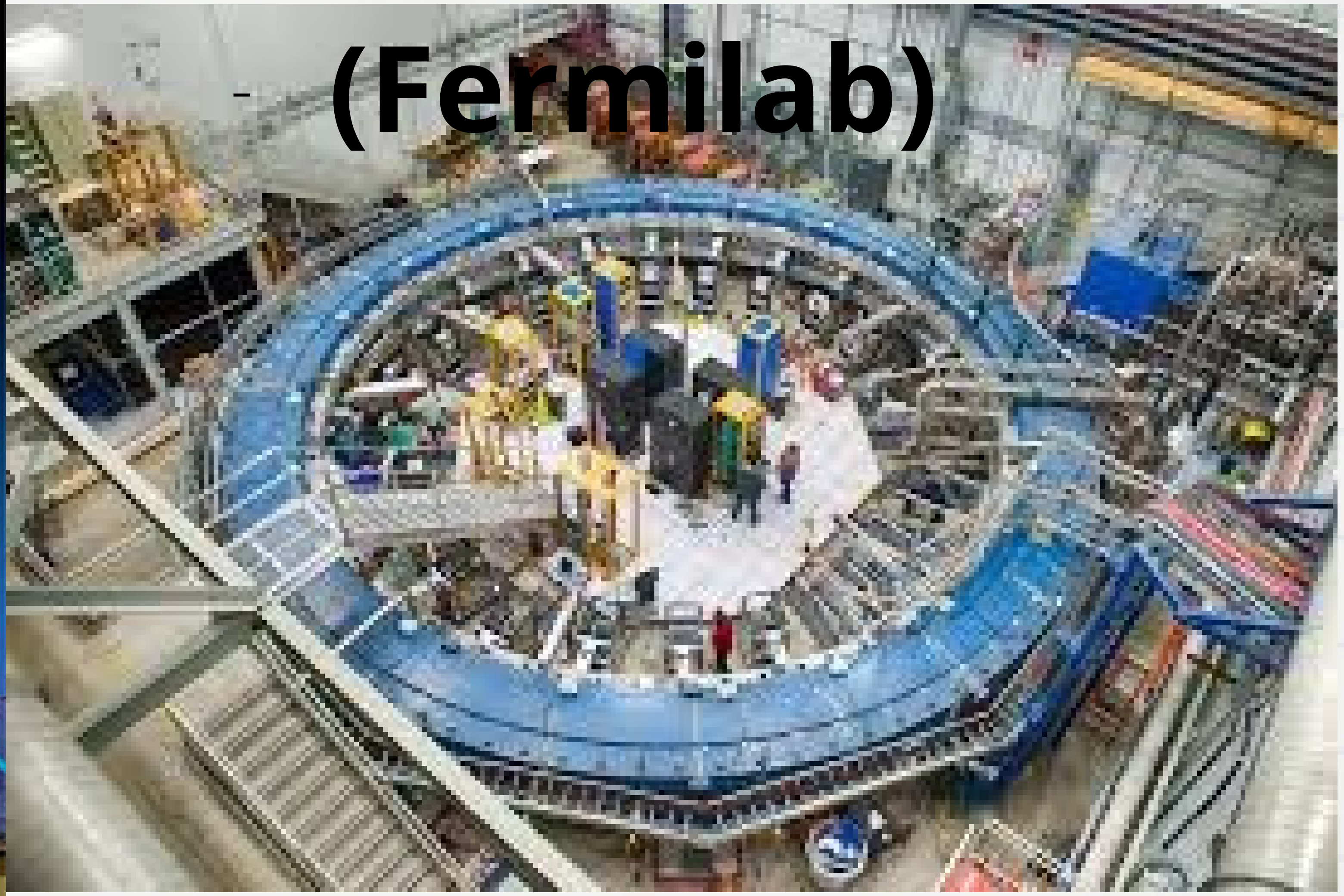
MUON Experiments



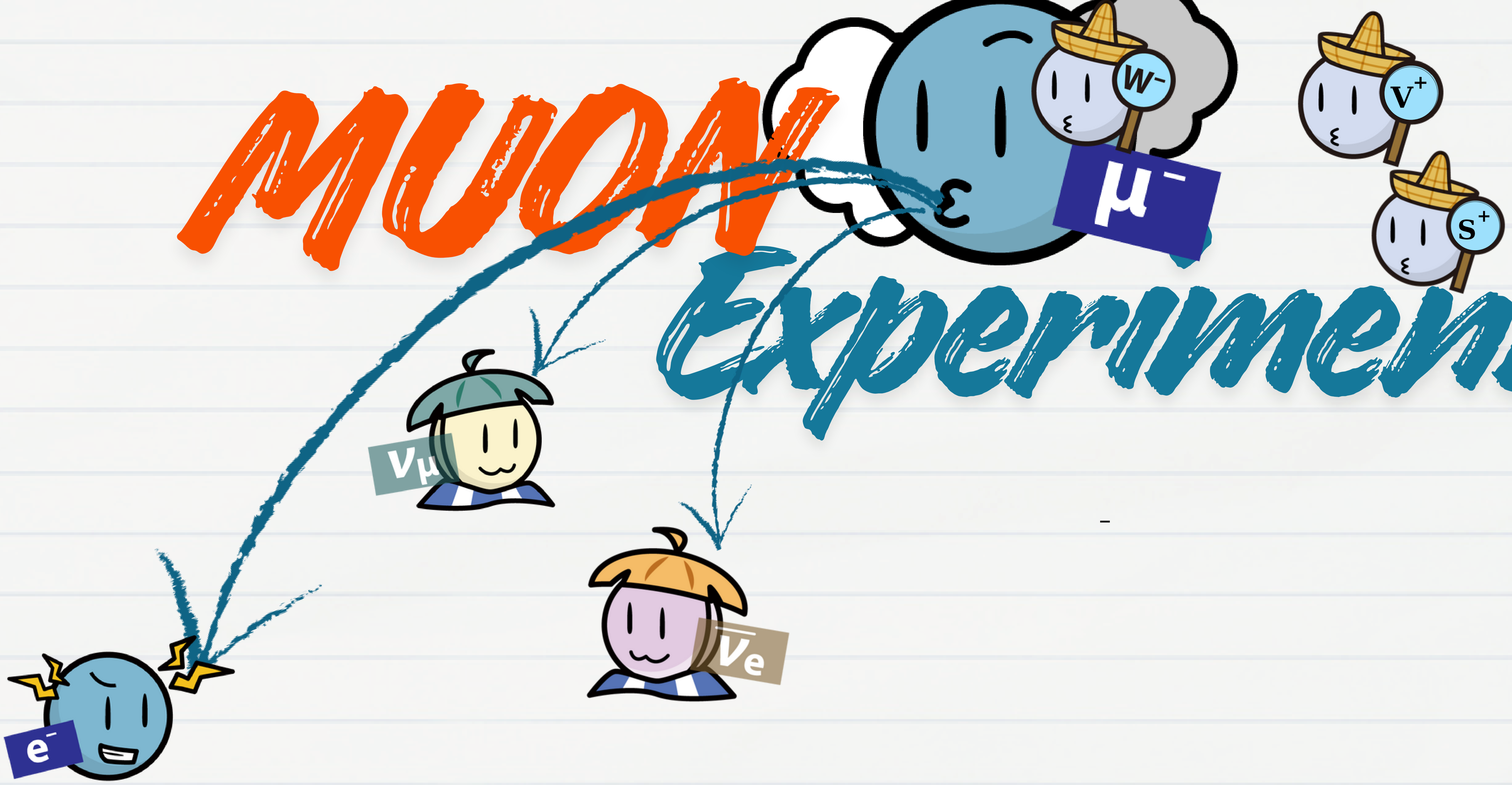
TWIST (TRIUMF)



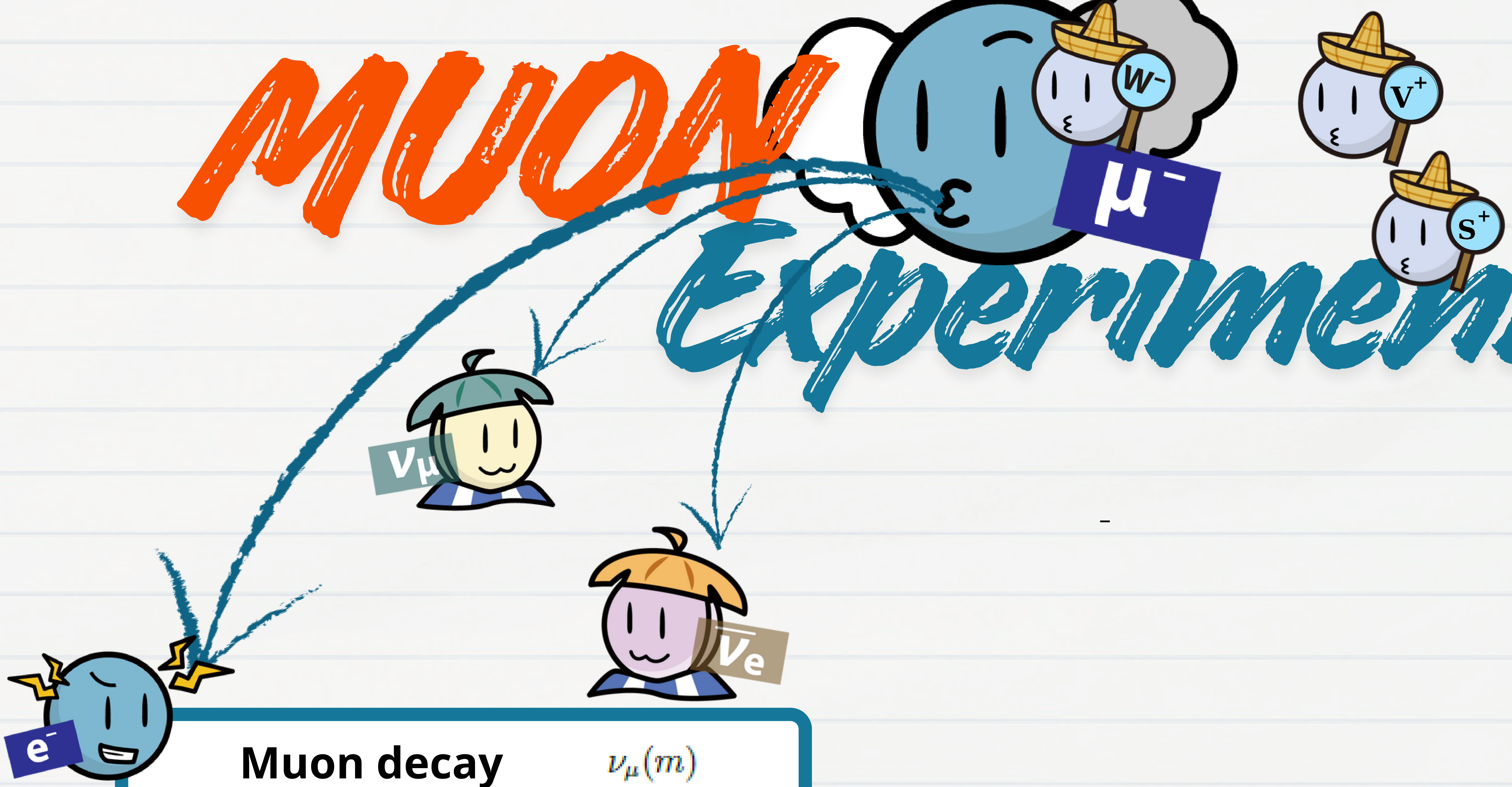
G-2 (Fermilab)



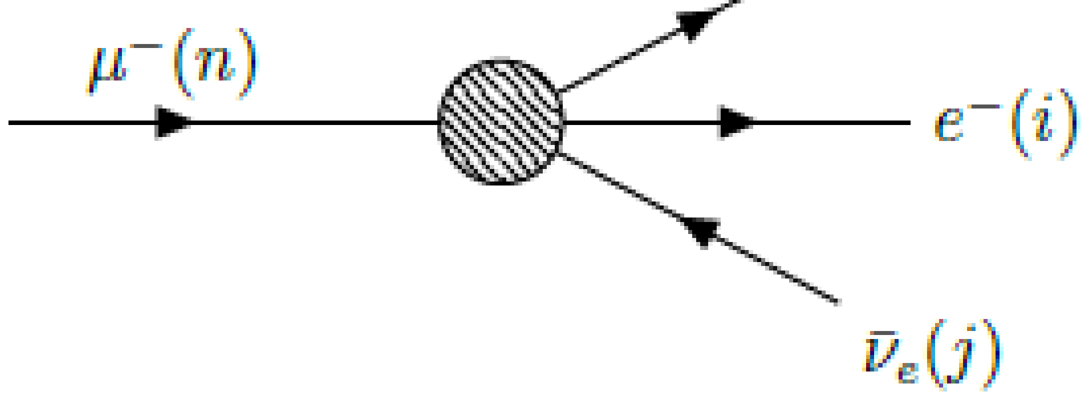
MUON Experiments



Muon Experiments

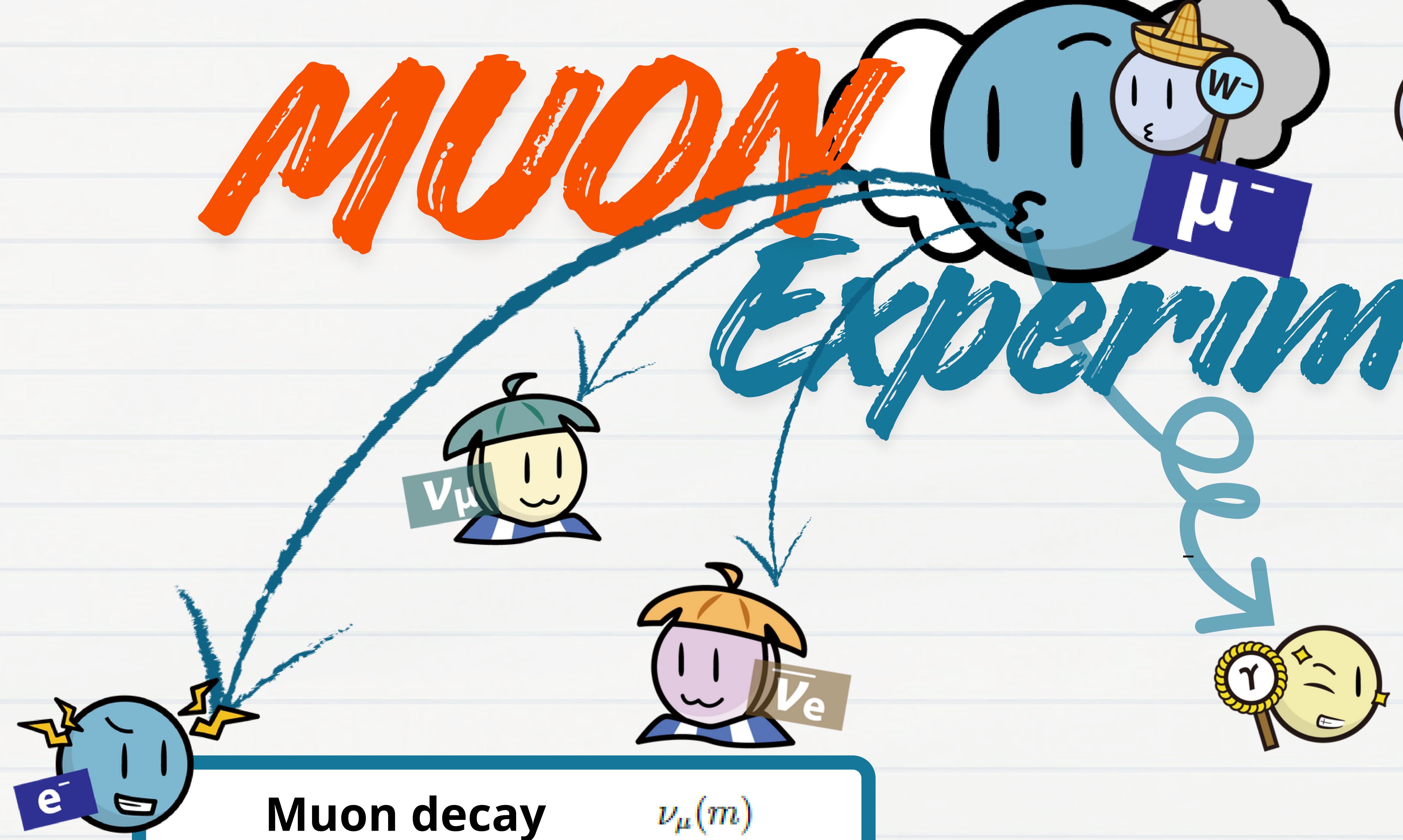


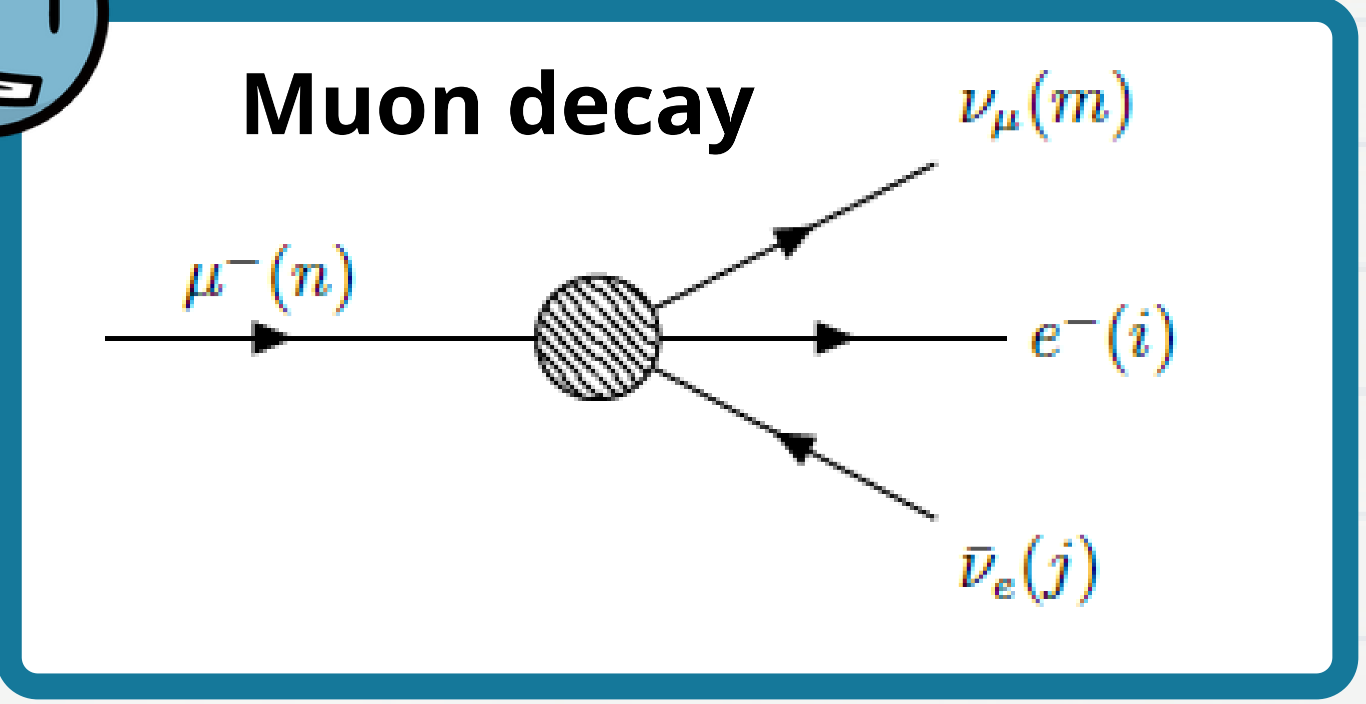
Muon decay

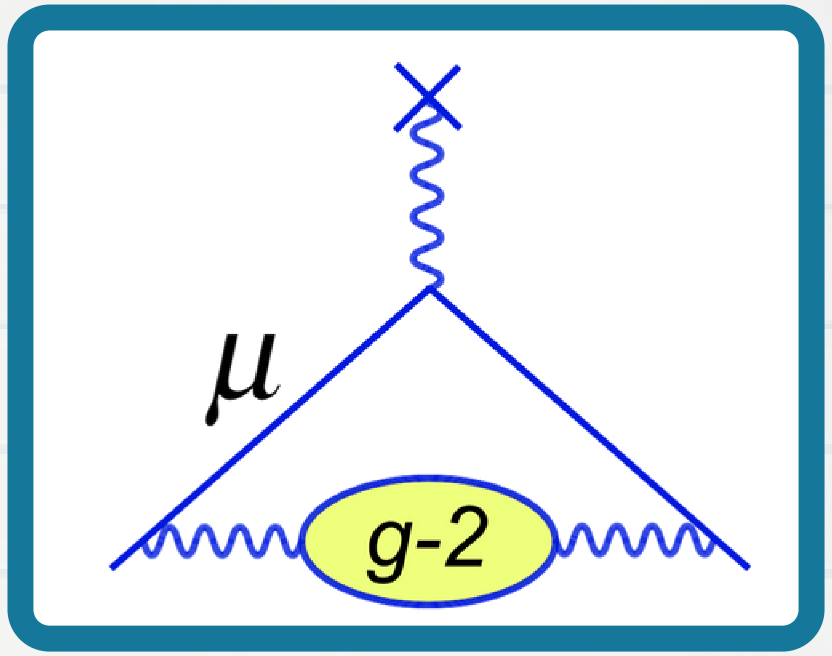


$$\frac{d\Gamma}{d\Omega} = \frac{m_\mu^5}{3\cdot 2^9\cdot \pi^4}(a+4b+6c)\left\{3(1-x)+2\rho\left(\frac{4}{3}x-1\right)\right.$$
$$\left. -\xi\cos\theta\left[(1-x)+2\delta\left(\frac{4}{3}x-1\right)\right]\right\}x^2\,dx$$

MUON Experiments







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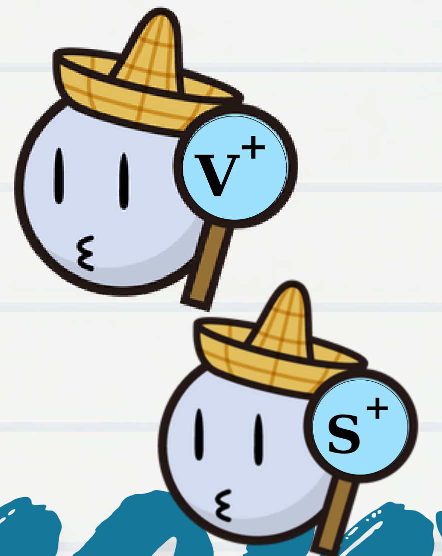
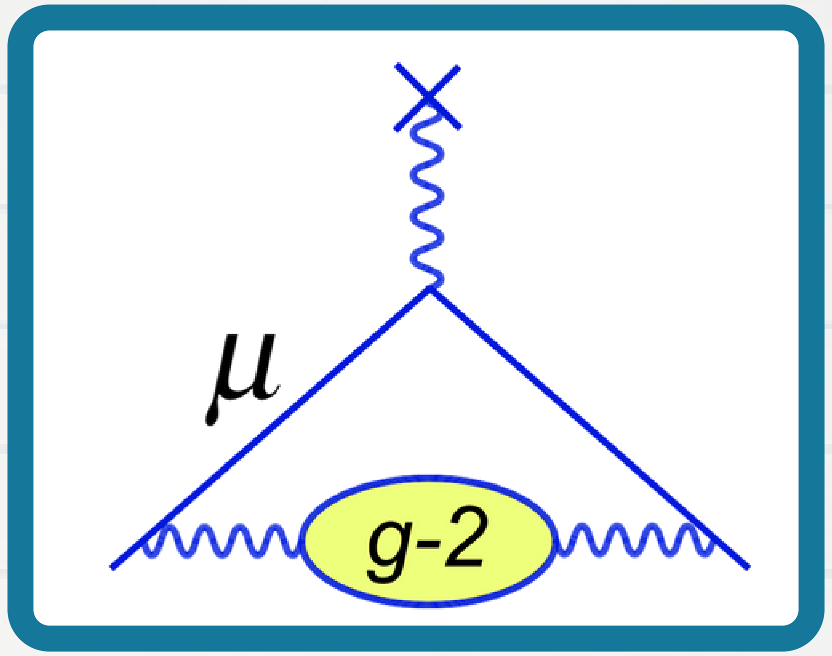
uon Experiments

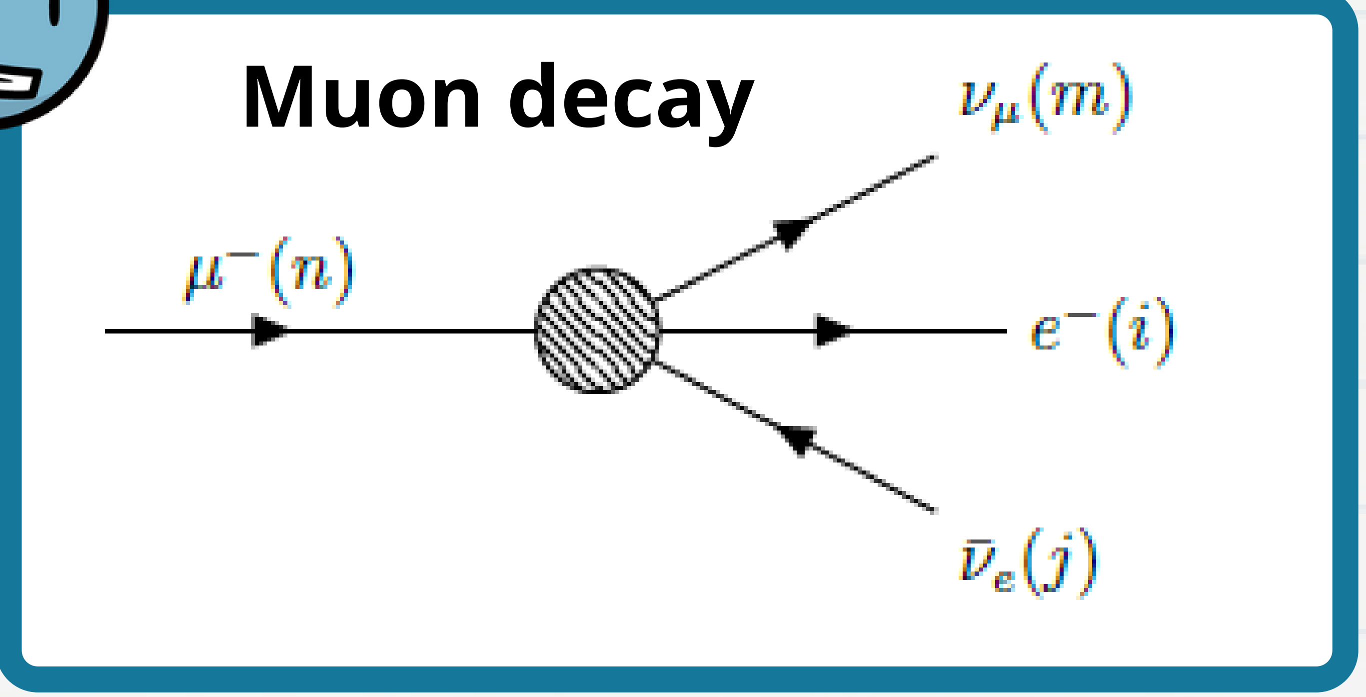
- $\rho = 0.74979(26)$
- $\delta = 0.75047(34)$
- $|\xi| = 1.0009^{+0.0016}_{-0.0007}$

$\Delta a_\mu = (2.74 \pm 0.73) \times 10^{-9}$ [5]

$\Delta a_e = (-88 \pm 36) \times 10^{-14}$ [12].







$$\frac{d\Gamma}{d\Omega} = \frac{m_\mu^5}{3 \cdot 2^9 \cdot \pi^4}(a + 4b + 6c)\left\{3(1-x) + 2\rho\left(\frac{4}{3}x - 1\right) - \xi \cos\theta \left[(1-x) + 2\delta\left(\frac{4}{3}x - 1\right)\right]\right\} x^2\, dx$$

1

3/4

EFT framework

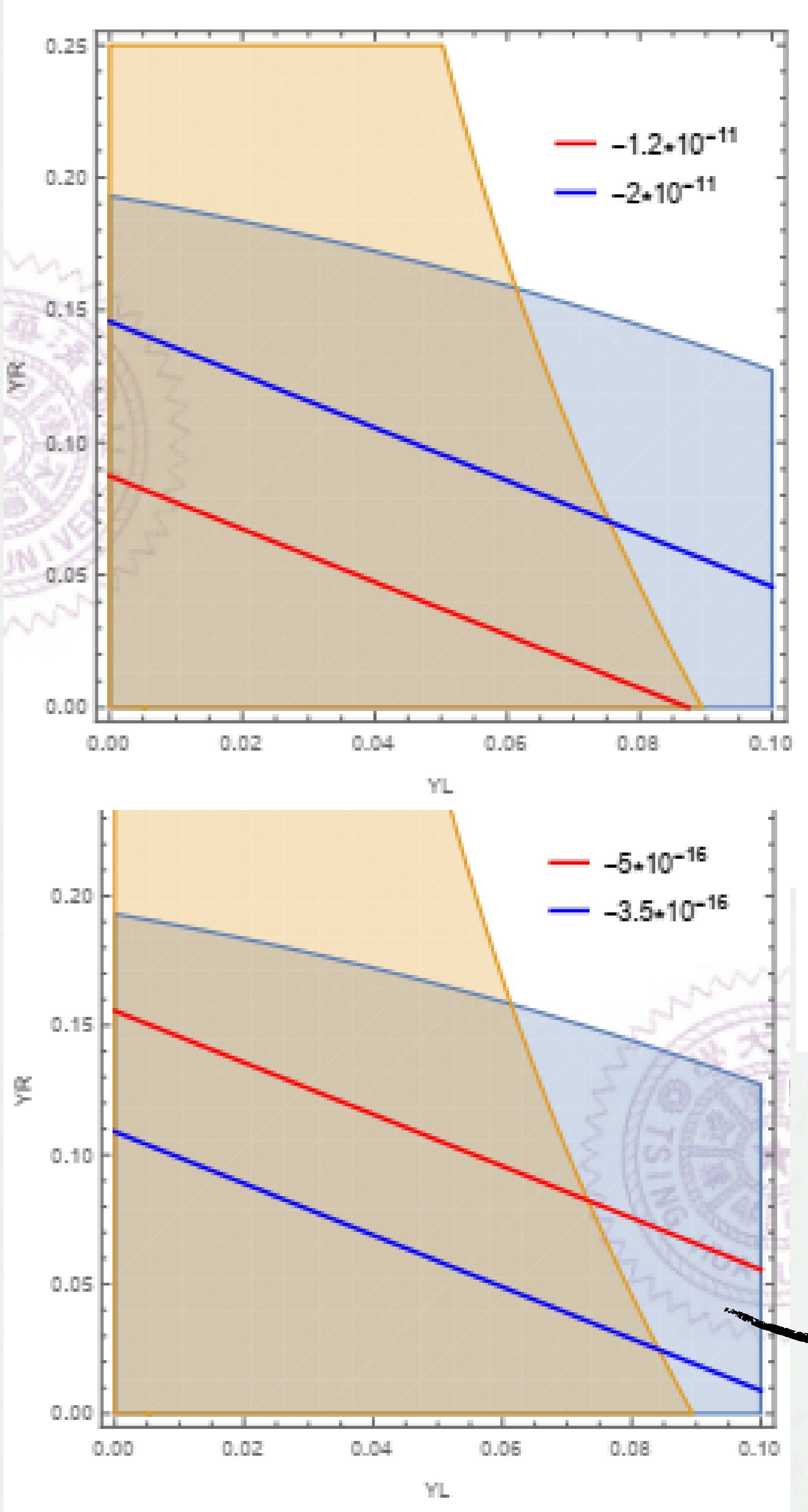
$$\mathcal{L}_S = |D_\mu\phi|^2 - m_\phi^2|\phi|^2,$$
$$\mathcal{L}_F = i\bar\psi \not{D}\psi - m_f^2\bar\psi\psi,$$
$$\mathcal{L}_{V^\pm} = -\frac{1}{2}\bar V^+_{\mu\nu}\bar V^{-\mu\nu} + m_V^2 V^+_\mu V^{-\mu} + ieQ_V a F^{\mu\nu}V^+_\mu V^-_\nu,$$
$$\mathcal{L}_{F\text{-}S} = \bar\psi_i\left(Y^L_{ij}\hat L + Y^R_{ij}\hat R\right)\psi_j\phi + \text{h.c},$$
$$\mathcal{L}_{F\text{-}V^\pm} = \bar\psi_i\left(V^L_{ij}\hat L + V^R_{ij}\hat R\right)\gamma^\mu\psi_j V^-_\mu + \text{h.c}$$

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm S} + \mathcal{L}_{\rm Y} + \mathcal{L}_{\text{F-}V^\pm} + \mathcal{L}_{V^\pm} + \mathcal{L}_\gamma,$$

Negative contribution

!! Possible solution comes from neutral boson with chiral enhancement

Charged Scalar

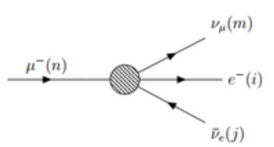


(b) Muon MDM

(a) Electron MDM

MUON DECAY

$$d\Gamma = \frac{m_\mu^5}{3*2^9*\pi^4}*(a+4b+6c)\left\{3(1-x)+2\rho\left(\frac{4}{3}x-1\right)\right.$$
$$\left.-\xi\cos\theta\left[(1-x)+2\delta\left(\frac{4}{3}x-1\right)\right]\right\}x^2dx,$$



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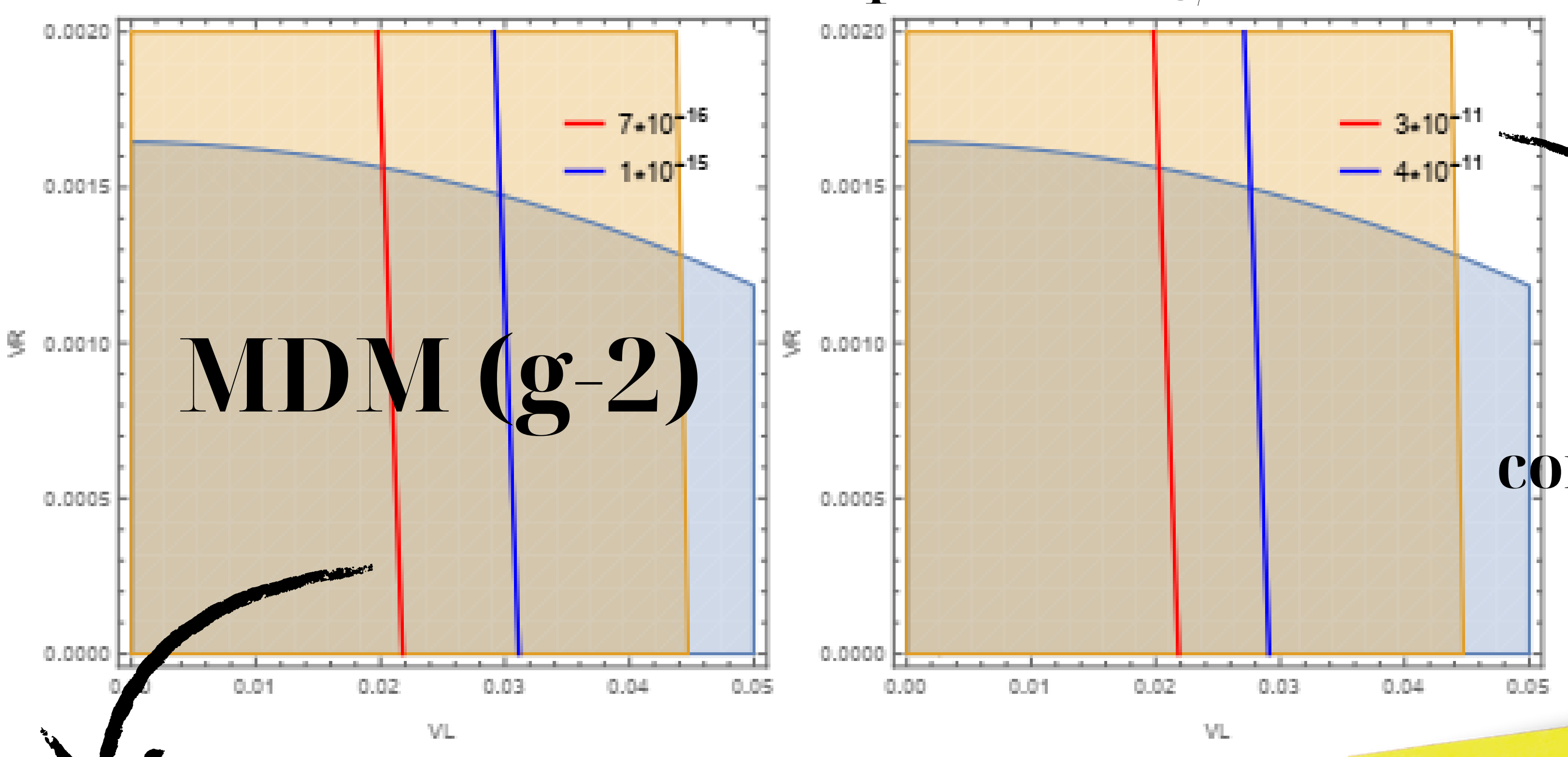

(a) Electron MDM

(b) Muon MDM

Positive contribution

Charged Vector

$|\xi|$

G_F

Tthe mass scale for the SM-like W' with only left-handed and only right-handed are <u>3.3 TeV and 637 GeV</u>, respectively. These limits are compared to <u>the 2016 PDG values of 3.7 TeV for left-handed and 715 GeV for right-handed</u>

- $\rho = 0.74979(26)$
- $\delta = 0.75047(34)$
- $|\xi| = 1.0009^{+0.0016}_{-0.0007}$

$\Delta a_\mu = (2.74 \pm 0.73)\times 10^{-9}$ [5]

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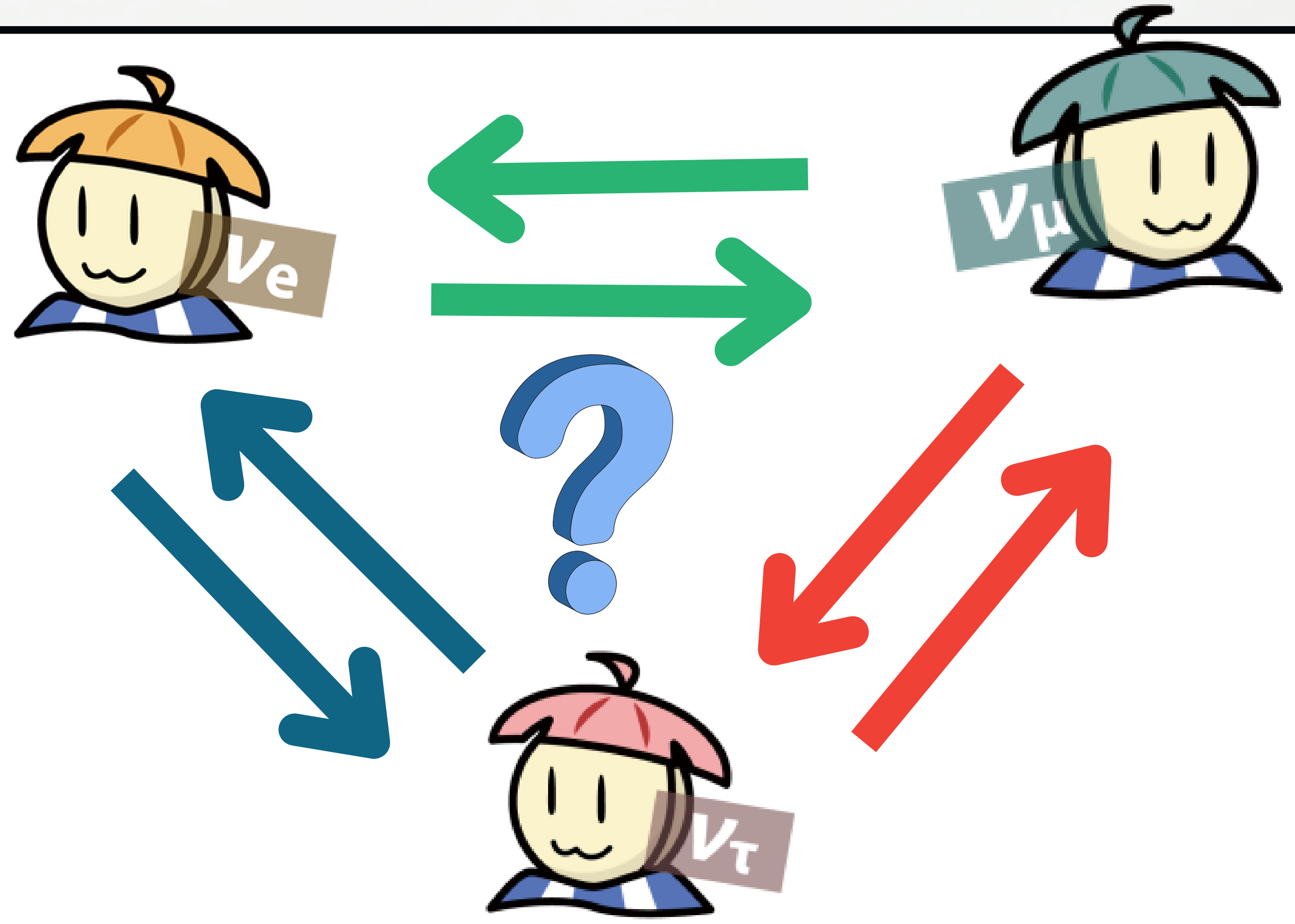
Overview

- Neutrino Oscillation
- Zee model
- LFV decays
- Muon decays
- Conclusions

Phenomenological Constraints on the Leptophilic Zee Model



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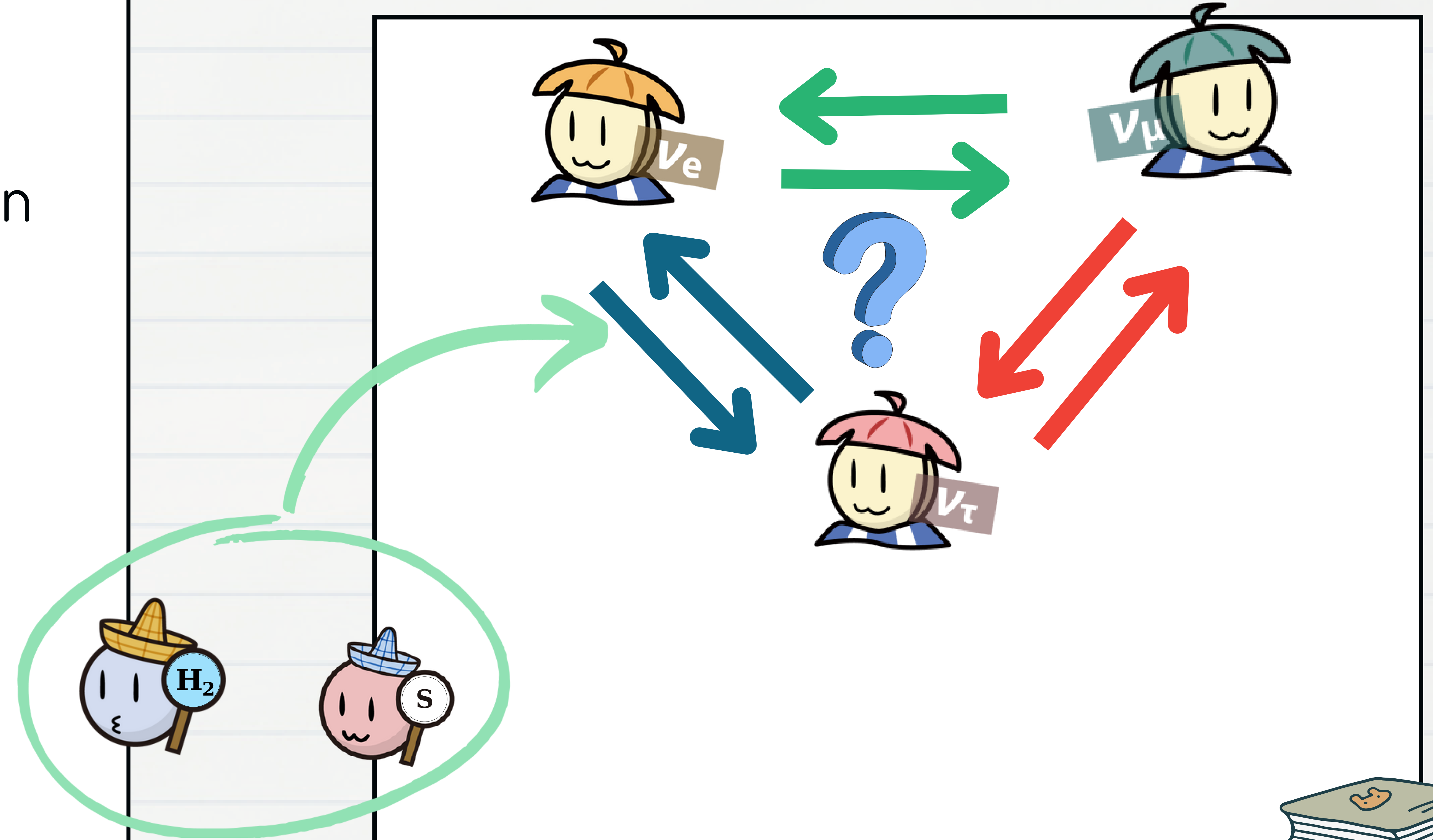

Phenomenological Constraints on the Leptophilic Zee Model

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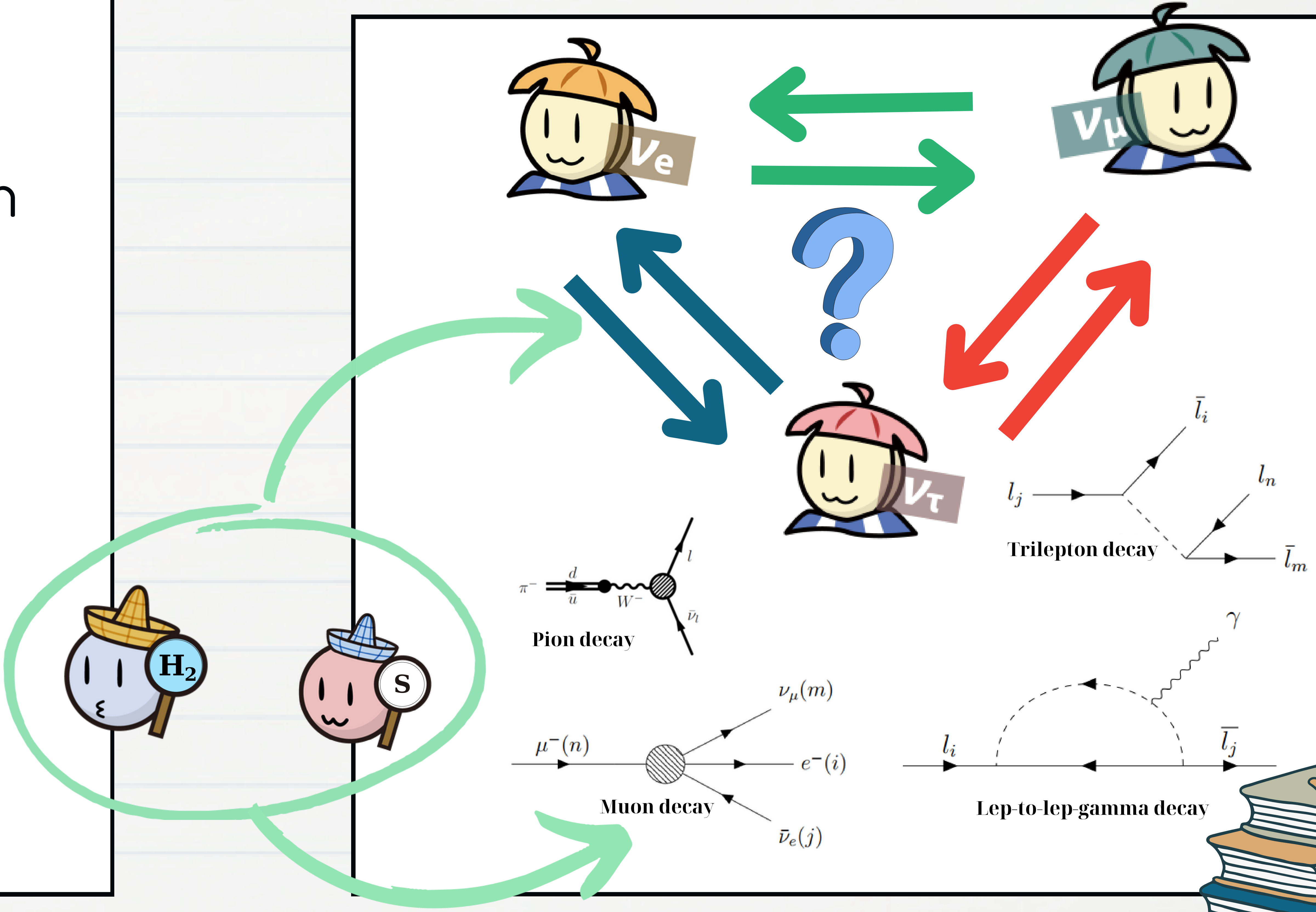
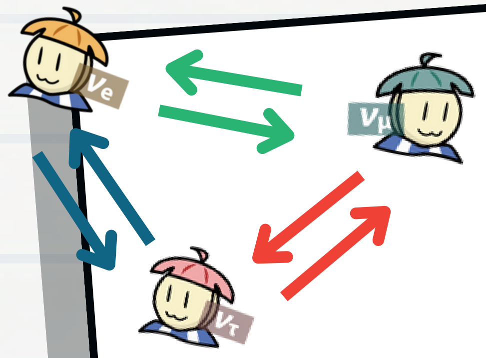
- Conclusions





Neutrino Oscillation

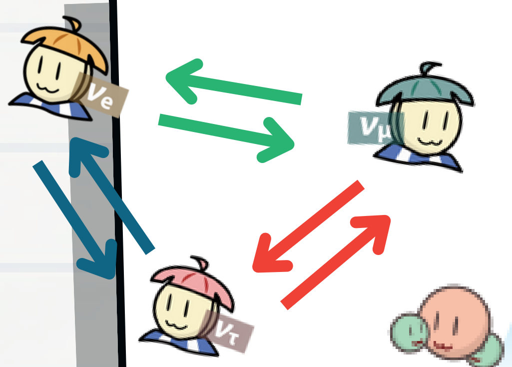
"Neutral" and "ino" → "neutrino"!

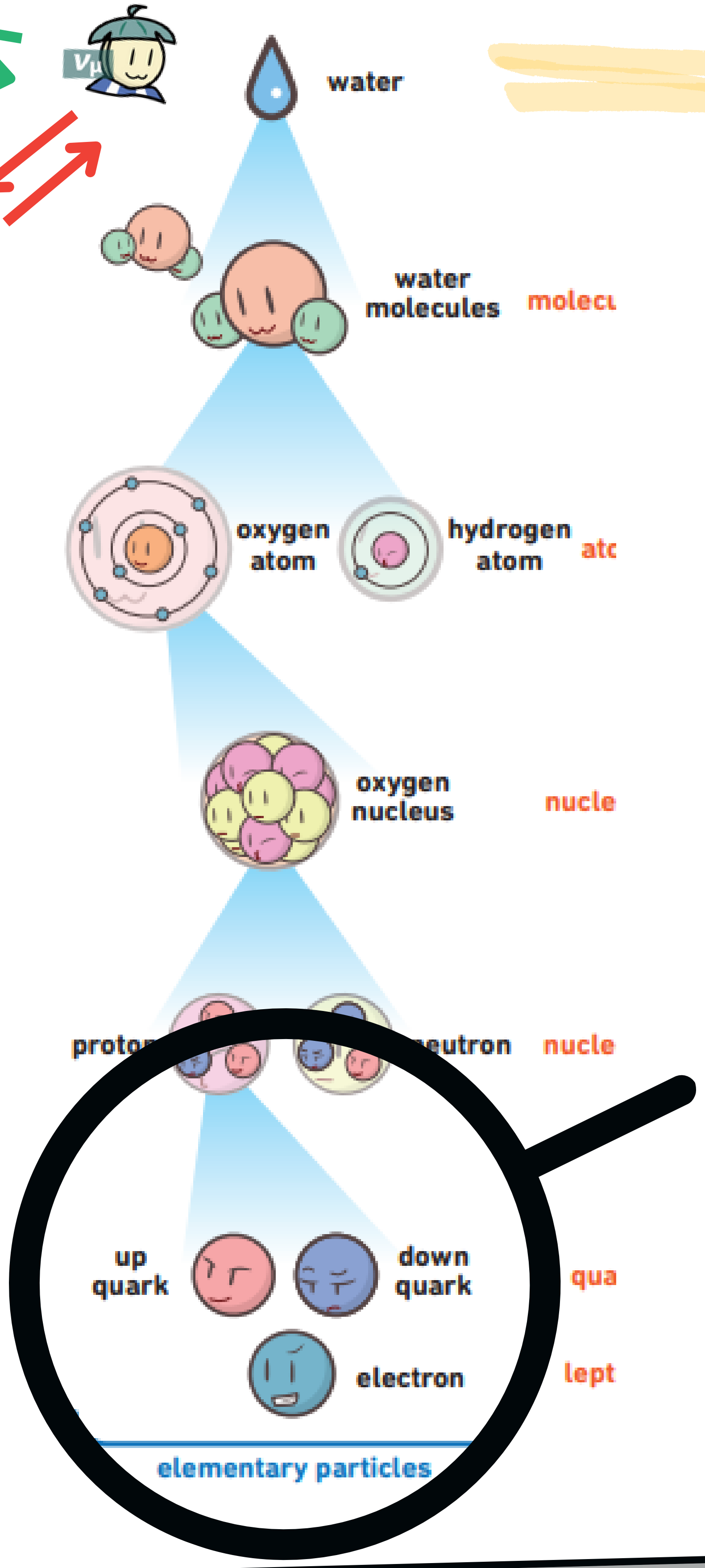
Neutrino means "**Neutral** = **no electric charge**" and "**-ino** = **small** (in Italian)"

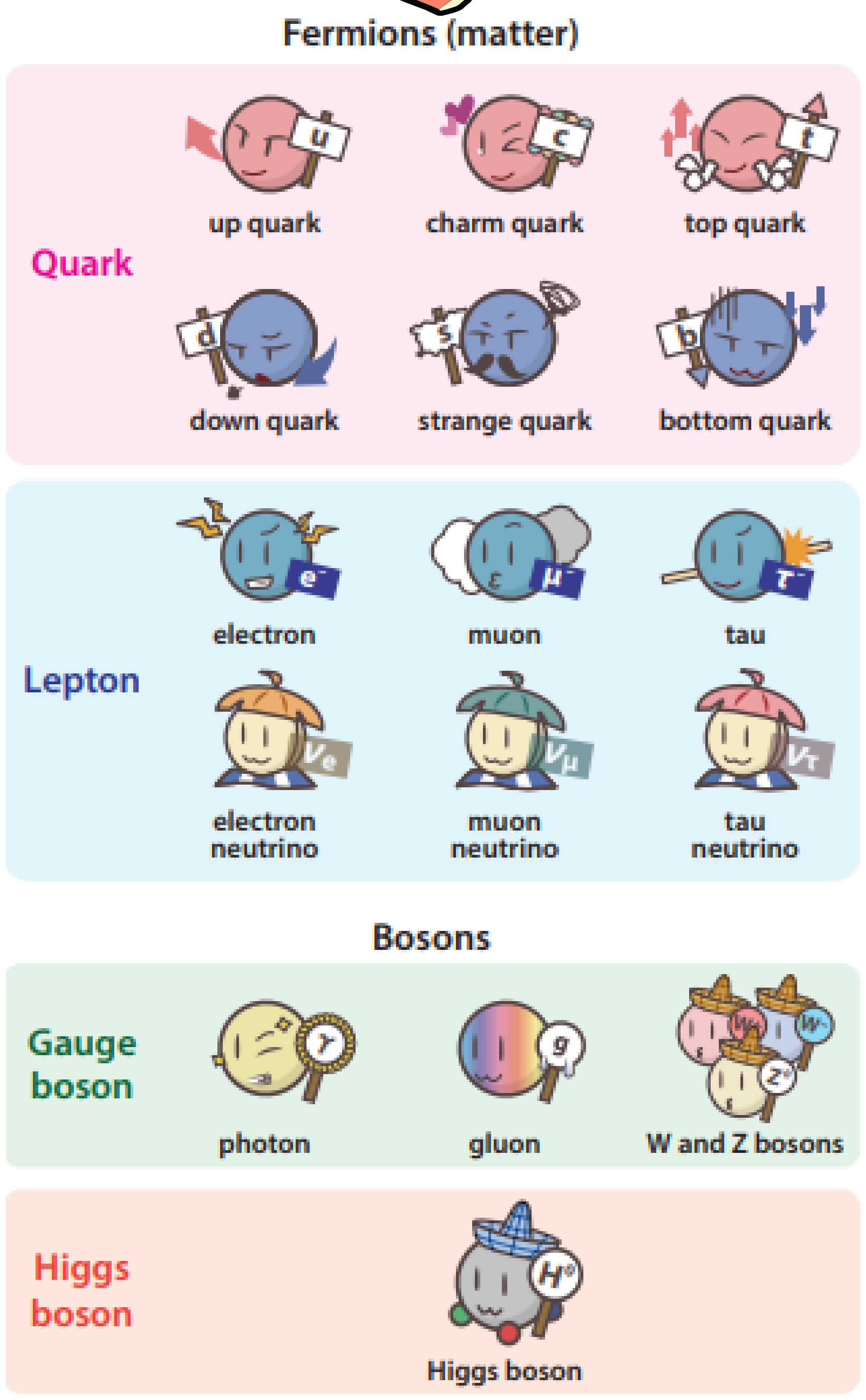
Oscillation: Neutrinos **change flavor state** as they **travel**

- Discovered in 1998 by the SuperKamiokande group through their analysis of atmospheric neutrinos
- Challenging our traditional understanding embedded within the Standard Model framework
- Sources of neutrinos: Solar, Atmospheric, Reactor, Accelerator

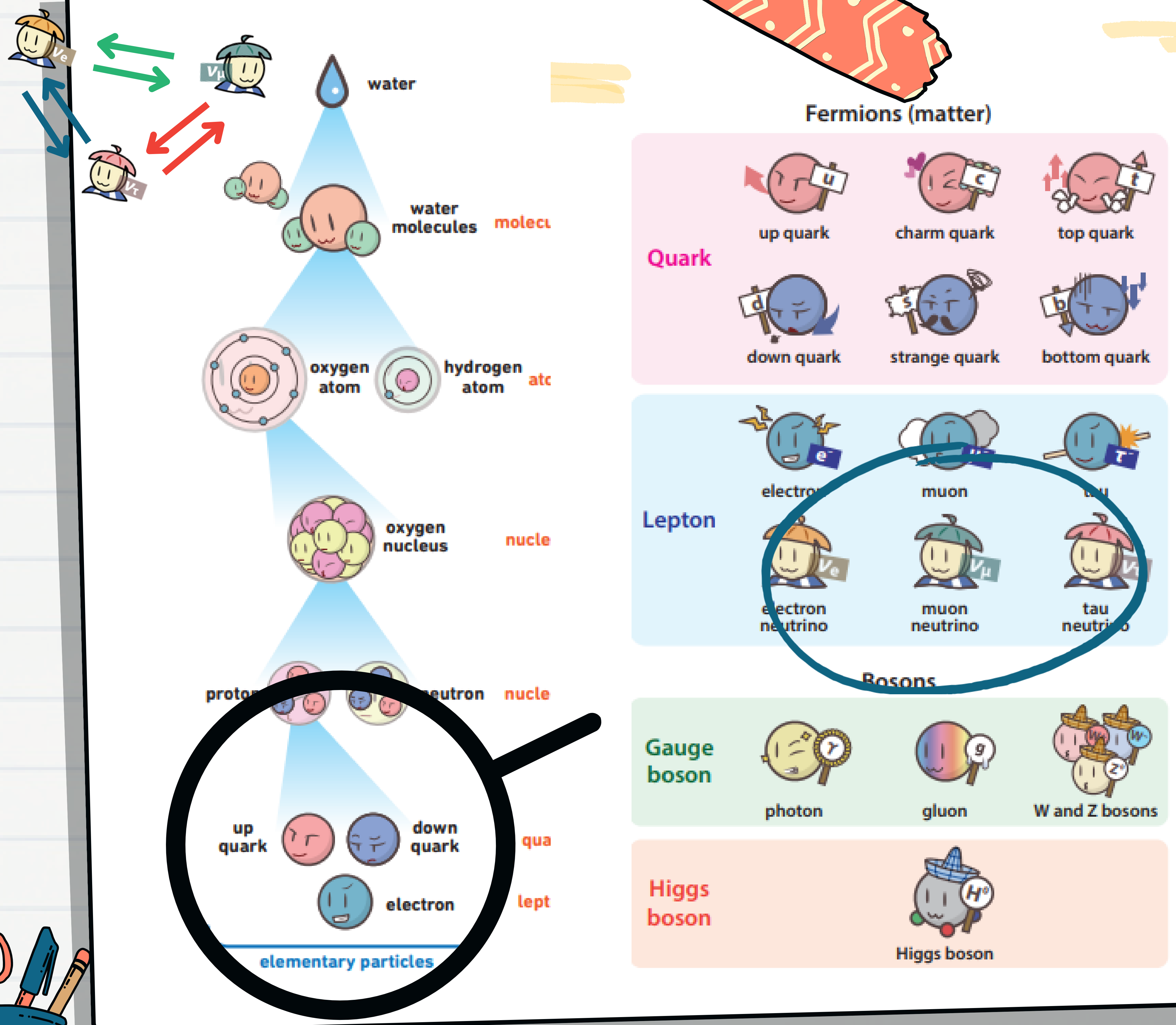
Why is it a fundamental puzzle in our current understanding?




water
water molecules
oxygen atom
hydrogen atom
oxygen nucleus
up quark
down quark
electron
elementary particles


Fermions (matter)
Quark
up quark
charm quark
top quark
down quark
strange quark
bottom quark
Lepton
electron
muon
tau
electron neutrino
muon neutrino
tau neutrino
Bosons
Gauge boson
photon
gluon
W and Z bosons
Higgs boson
Higgs boson

Neutrinos in Standard Model



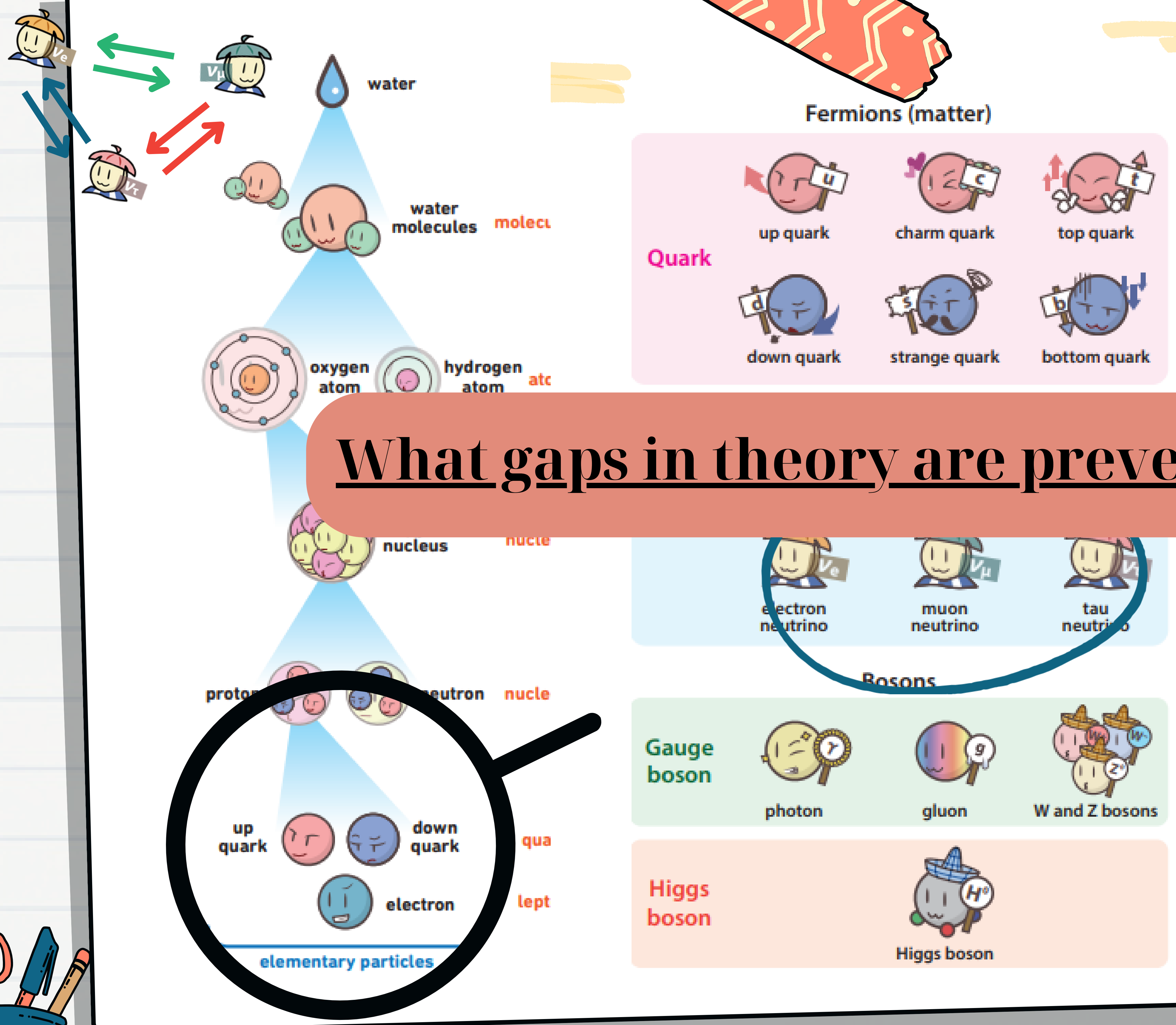
- A fundamental neutral particle interact weakly with anything (through weak and gravity force)
- “Catch it” indirectly via Cherenkov effects when neutrinos interact with the substance
- Beta decay (first evidence for the existence of neutrinos)

$\Rightarrow$ Only left-handed netrinos involved

- Therefore **no mass term** generated through Higgs mechanism

$\Rightarrow$ **No neutrino oscillation**

Neutrinos in Standard Model



- A fundamental neutral particle interact weakly with anything (through weak and gravity force)
- "Catch it" indirectly via Cherenkov effects when neutrinos interact with the substance

<u>What gaps in theory are preventing a resolution?</u>

existence

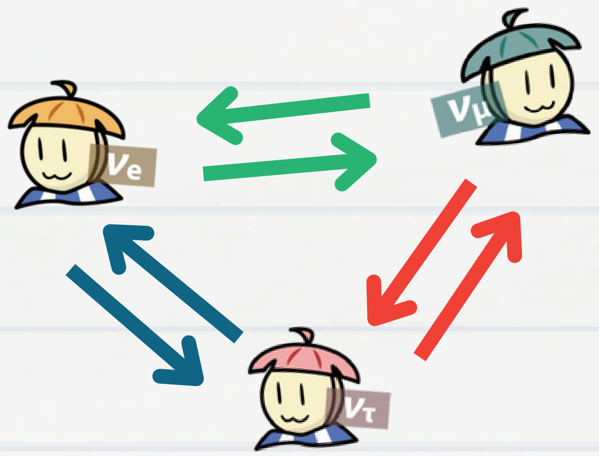
$\Rightarrow$ Only left-handed netrinos involved

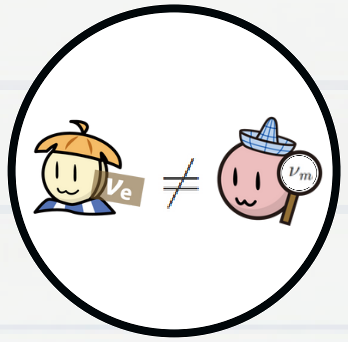
- Therefore **no mass term** generated through Higgs mechanism

$\Rightarrow$ <u>**No neutrino oscillation**</u>

Oscillation

$$P\left(\nu_\alpha \rightarrow \nu_\alpha\right) = 1 - 4 \sum_{i>j} |U_{\alpha i}|^2 |U_{\alpha j}|^2 \sin\left(X_{ij}\right)^2$$





Difference between interacting
state and mass state

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta^D_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta^D_{CP}} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \mathrm{Diag}\left(1, e^{i\frac{\mu_1}{2}}, e^{i\frac{\mu_2}{2}}\right)$$

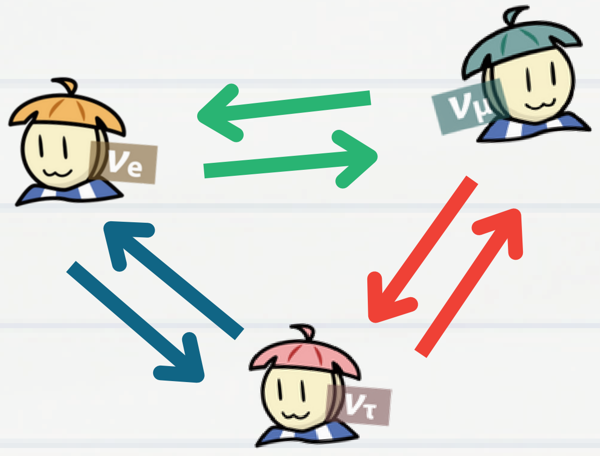
PMNS matrix

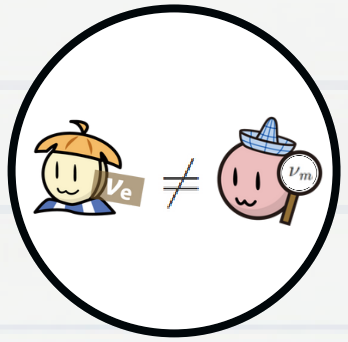
Oscillation

$$P\left(\nu_\alpha \rightarrow \nu_\alpha\right) = 1 - 4\sum_{i>j} |U_{\alpha i}|^2 |U_{\alpha j}|^2 \sin\left(X_{ij}\right)^2$$

Mass

Mass difference





Difference between interacting state and mass state

$$X_{ij} \equiv \frac{m_i^2 - m_j^2}{4E} L$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}^D} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}^D} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \mathrm{Diag}\left(1, e^{i\frac{\mu_1}{2}}, e^{i\frac{\mu_2}{2}}\right)$$

Atmosphere | **Reactor** | **Solar** | **Neutrinoless Double beta decay**

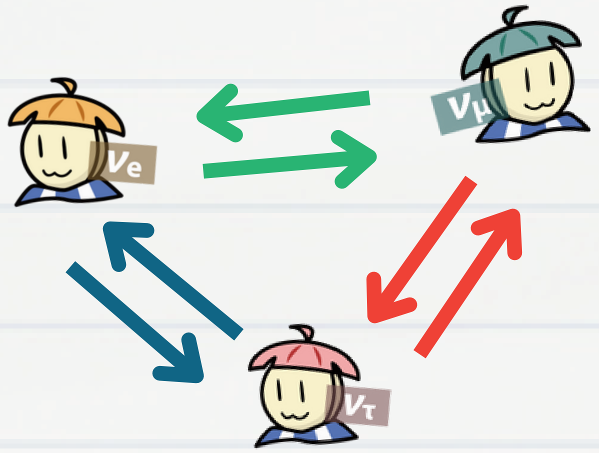
PMNS matrix

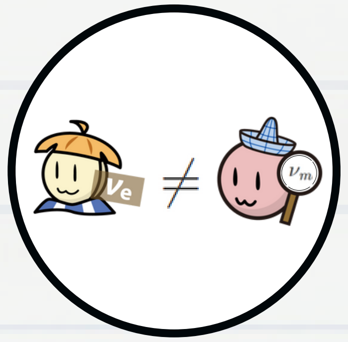
Oscillation

$$P\left(\nu_\alpha \to \nu_\alpha\right) = 1 - 4\sum_{i>j} |U_{\alpha i}|^2 |U_{\alpha j}|^2 \sin\left(X_{ij}\right)^2$$

Mass

Mass difference





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Atmosphere | Reactor | Solar | Neutrinoless Double beta decay

PMNS matrix

Mass term for neutrino in new model !!

Neutrino mass generation

$$\mathcal{L}_{M_\nu} = -M_D^{ij}\overline{\nu_i^R}\nu_j^L - \frac{1}{2}M_M^{ij}\overline{\left(\nu_i^L\right)^c}\nu_j^L + h.c.$$

$\boxed{m_\nu \sim 1\text{eV}}$

$\boxed{Y^\nu \sim 10^{-11} \ll Y^{l,u,d}}$

Naturalness problem!!

Neutrino mass generation

$$\mathcal{L}_{M_\nu} = \underbrace{-M_D^{ij}\,\overline{\nu_i^R}\,\nu_j^L}_{\text{Dirac mass term}} - \underbrace{\frac{1}{2}M_M^{ij}\,\overline{(\nu_i^L)^c}\,\nu_j^L}_{\text{Majorana mass term}} + h.c.$$

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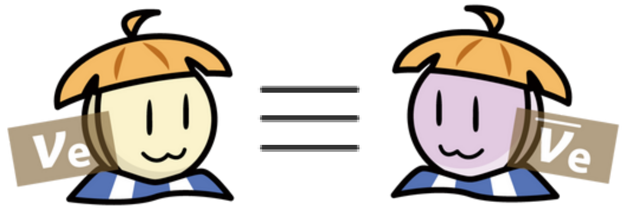
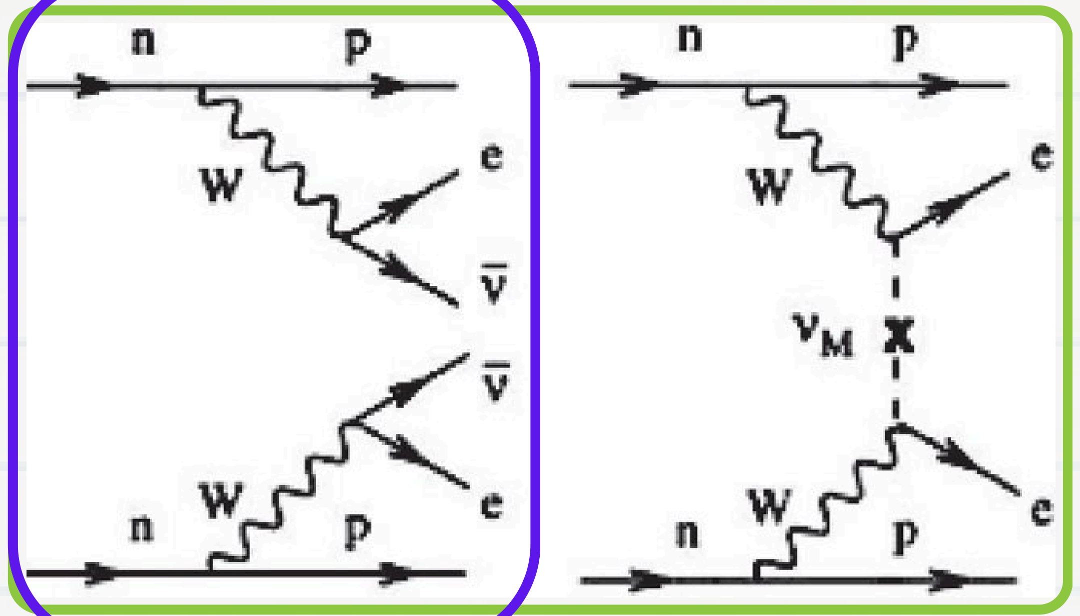
Majorana particle



Dirac particle



Neutrinoless double beta decay

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Naturalness problem!!

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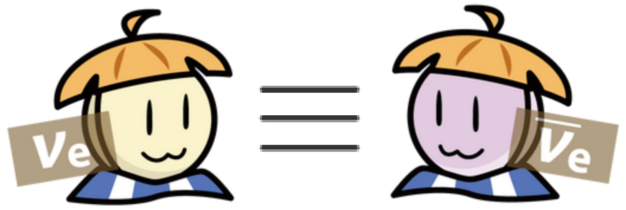
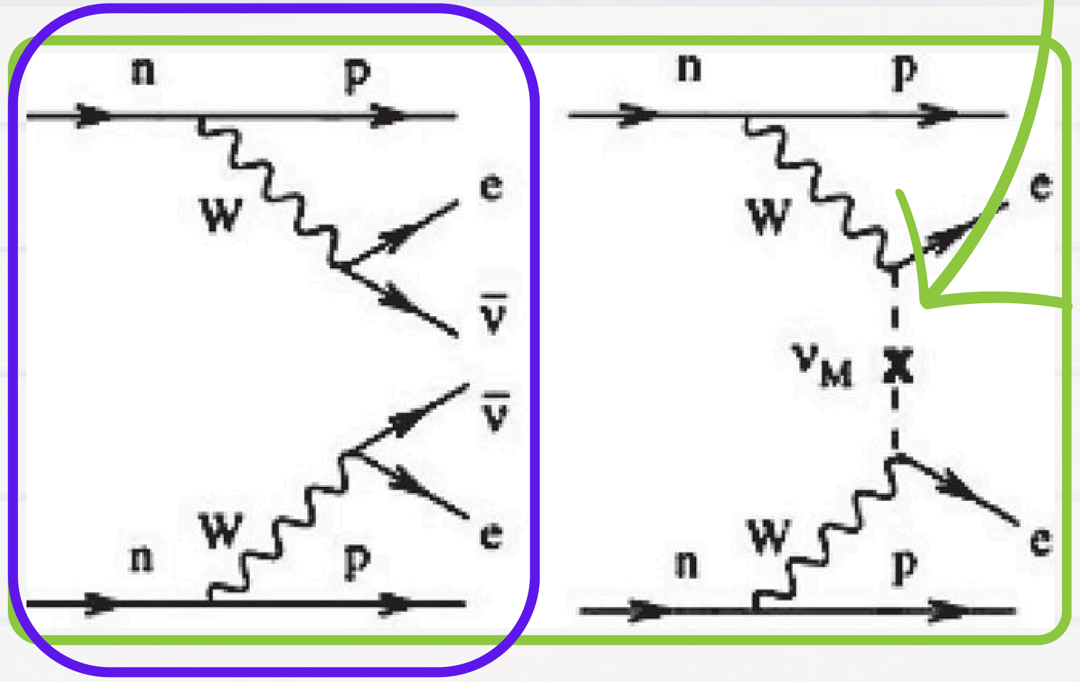
Dirac mass term

Majorana mass term

Majorana particle



Dirac particle



Neutrinoless double beta decay

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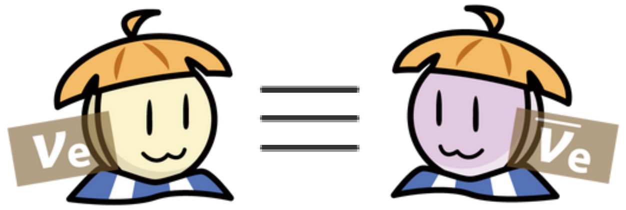
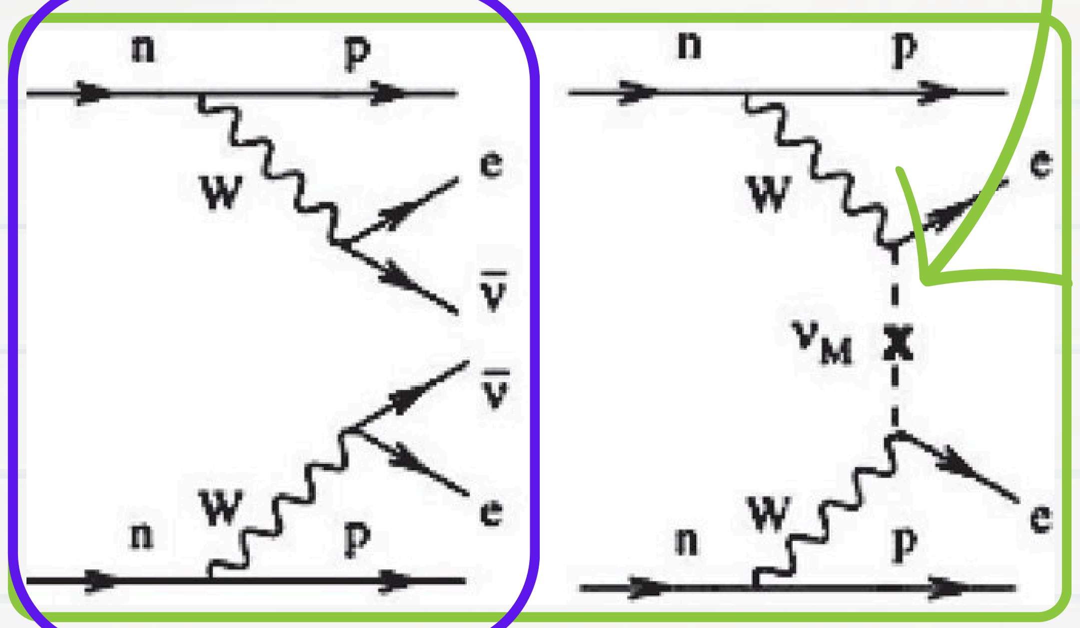
Dirac mass term

Majorana mass term

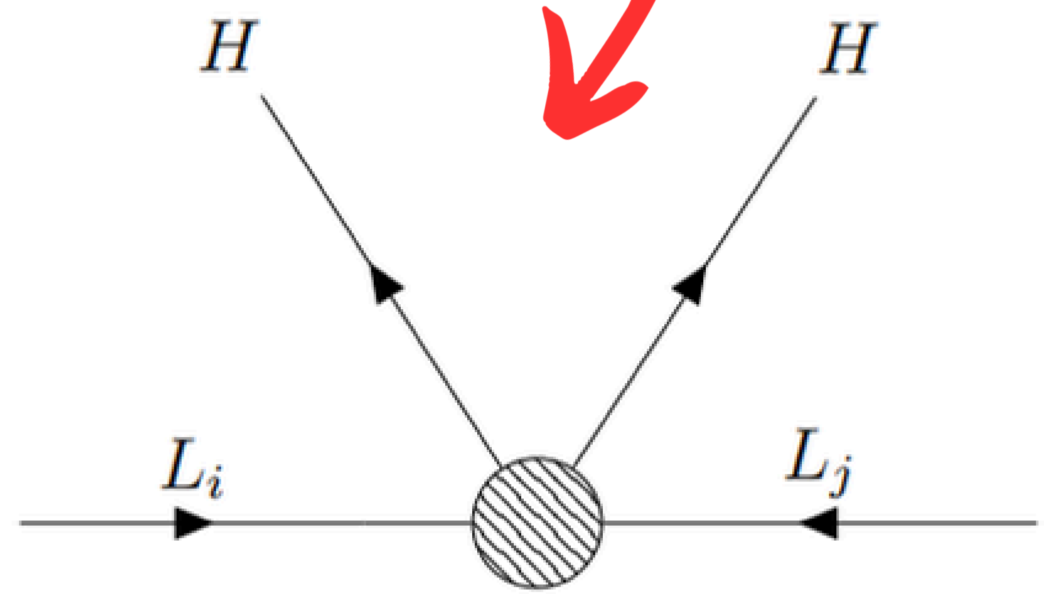
Majorana particle



Dirac particle



Neutrinoless double beta decay



$$\mathcal{L}_5 = \frac{c_{ij}}{\Lambda}\left(\overline{\tilde{L}_i}H\right)\left(\tilde{H}^\dagger L_j\right) \xrightarrow[\langle H\rangle = \frac{v}{\sqrt{2}}]{\text{After SSB}} \mathcal{L}_5 \supset \frac{c_{ij}}{\Lambda}\frac{v^2}{2}\overline{(\nu_i^L)^c}\nu_j^L,$$

Effective dim-5 Weinberg operator

Neutrino mass generation

$m_\nu \sim 1\text{eV}$

$Y^\nu \sim 10^{-11} \ll Y^{l,u,d}$

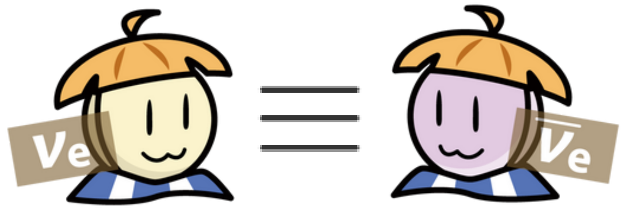
Naturalness problem!!

$$\mathcal{L}_{M_\nu} = -M_D^{ij}\overline{\nu_i^R}\nu_j^L + \frac{1}{2}M_M^{ij}\overline{(\nu_i^L)^c}\nu_j^L + h.c.$$

Dirac mass term

Majorana mass term

Majorana particle



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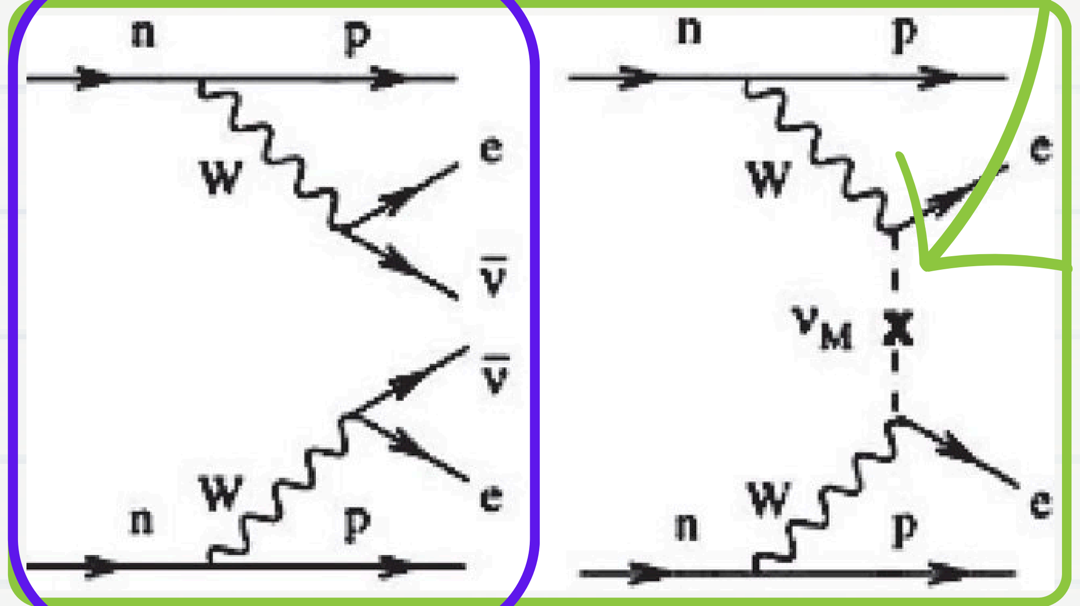
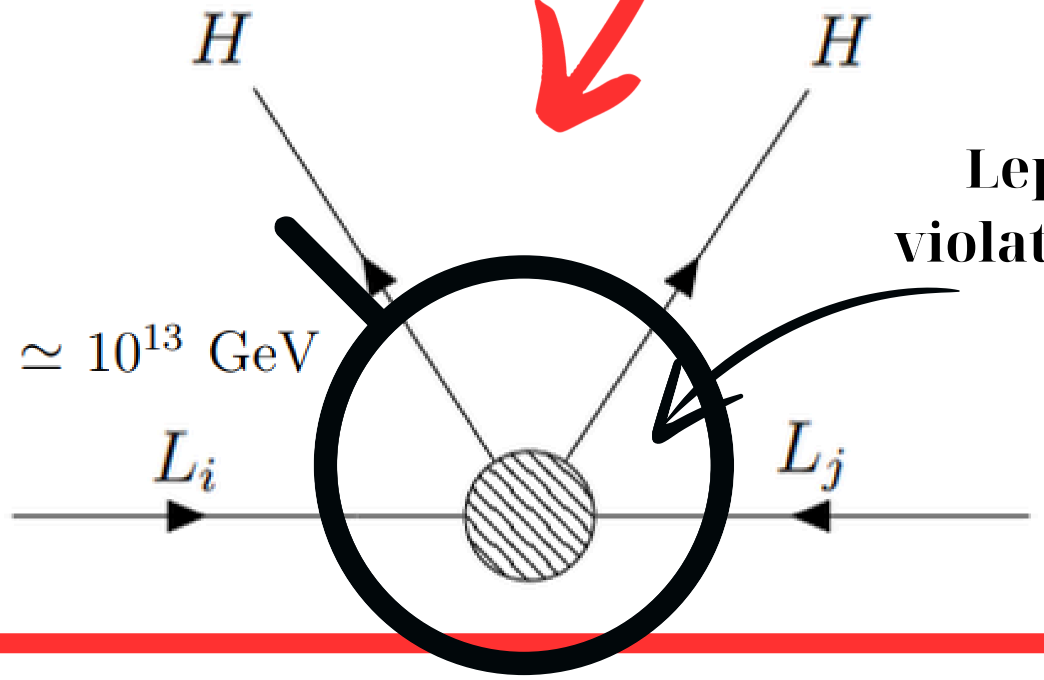


Neutrinoless double beta decay

NP scale $\Lambda \simeq \frac{\langle H\rangle^2}{m_\nu} \simeq 10^{13}$ GeV



Lepton number violation beyond SM

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$$\mathcal{L}_{M_\nu} = \boxed{-M_D^{ij}\overline{\nu_i^R}\nu_j^L} + \boxed{\frac{1}{2}M_M^{ij}\overline{(\nu_i^L)^c}\nu_j^L} + h.c.$$

Dirac mass term

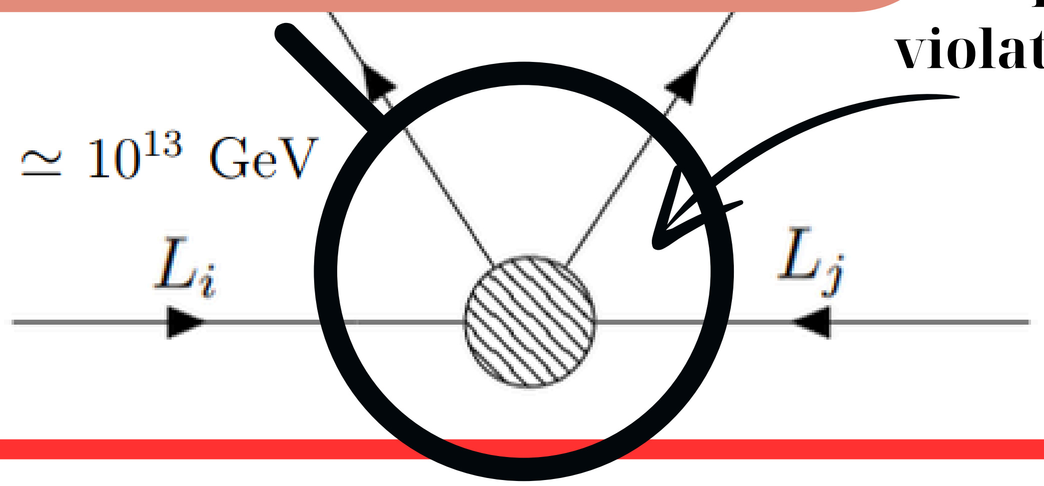
Majorana mass term

Majorana particle

New fields shoul be showed up

Lepton number violation beyond SM

NP scale $\Lambda \simeq \frac{\langle H\rangle^2}{m_\nu} \simeq 10^{13}$ GeV



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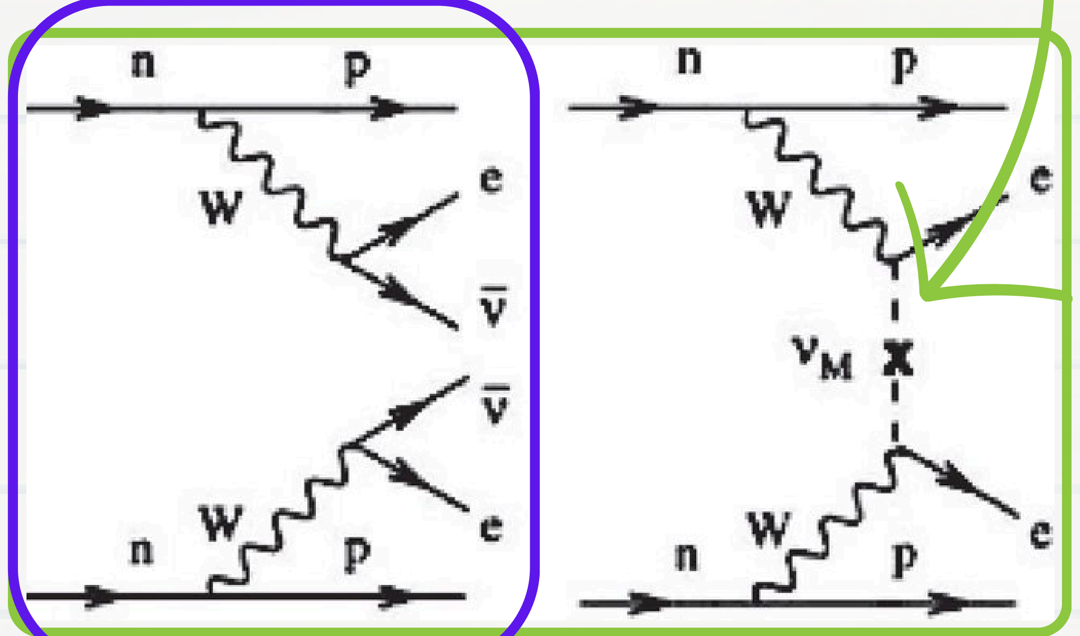
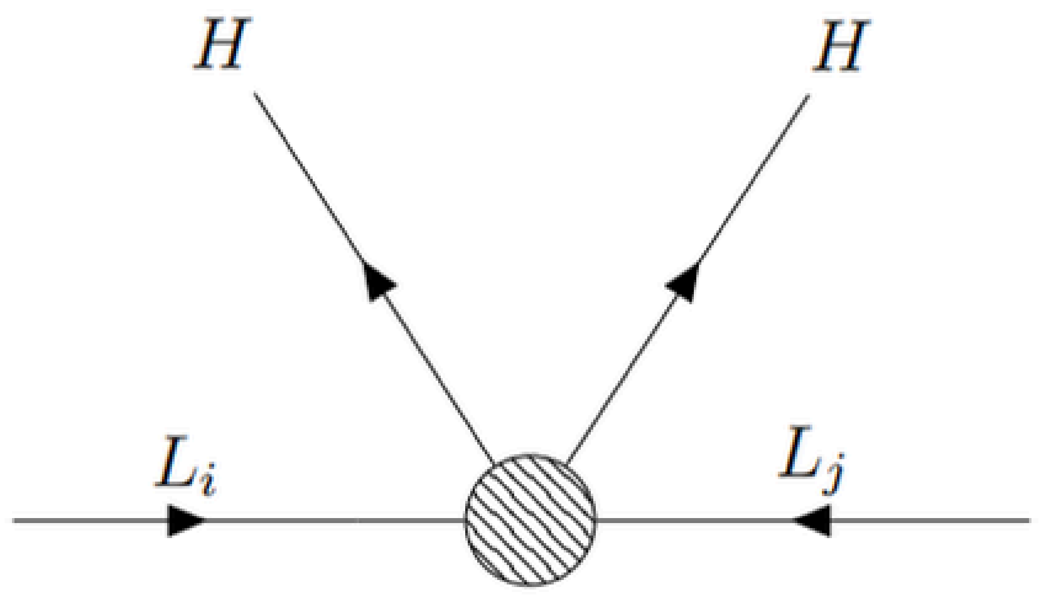
Dirac particle



Neutrinoless double beta decay

Effective dim-5 Weinberg operator

Effective dim-5 Weinberg operator



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<u>Effective dim-5 Weinberg operator</u>

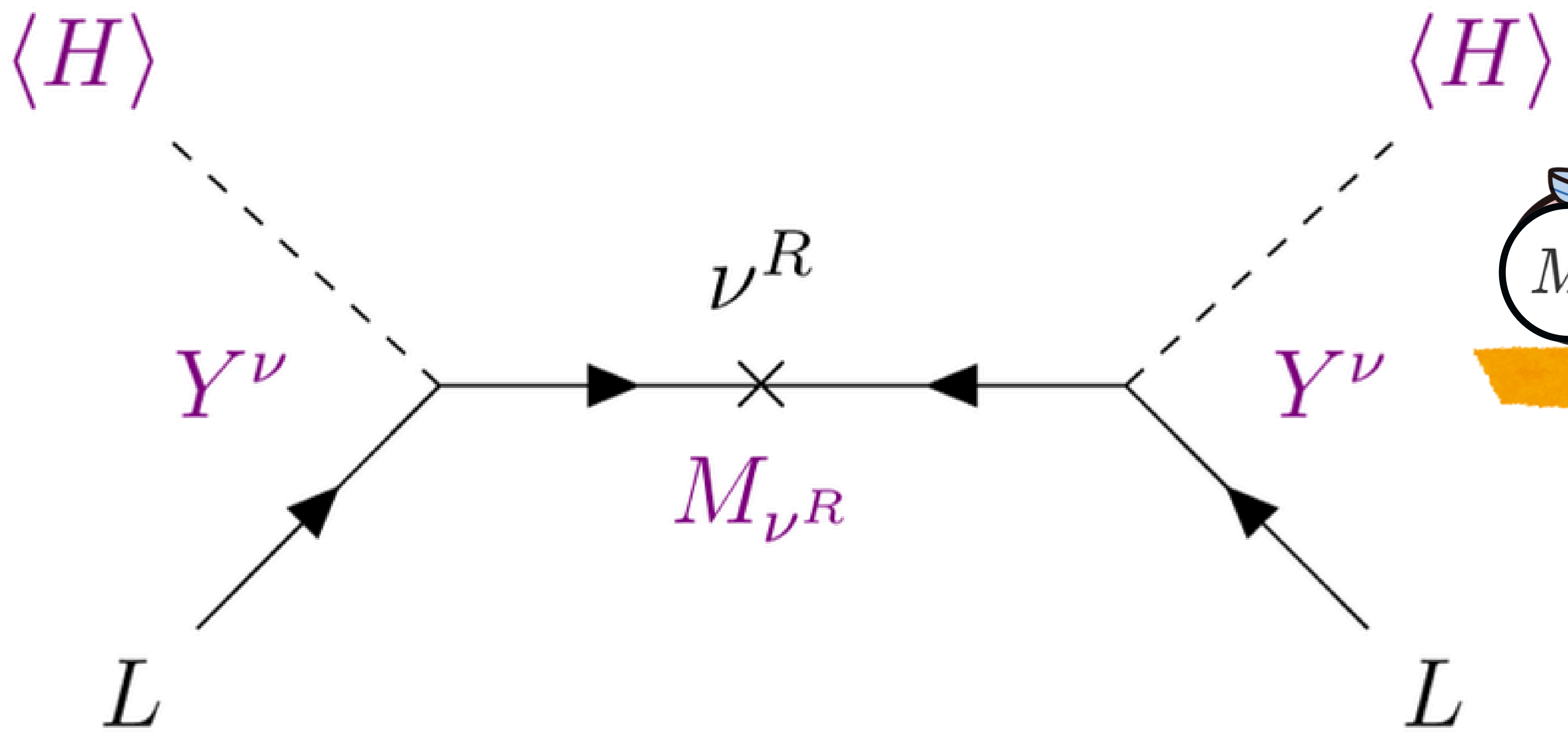
SM gauge invariance SU(2) x U(1)

At minimal extension, to form a singlet SU(2) creating the neutrino's mass from SM materials, e.g. doublet lepton **L** and scalar **H**, we get

$$\boxed{2 \otimes 2 = 1 \oplus 3}$$

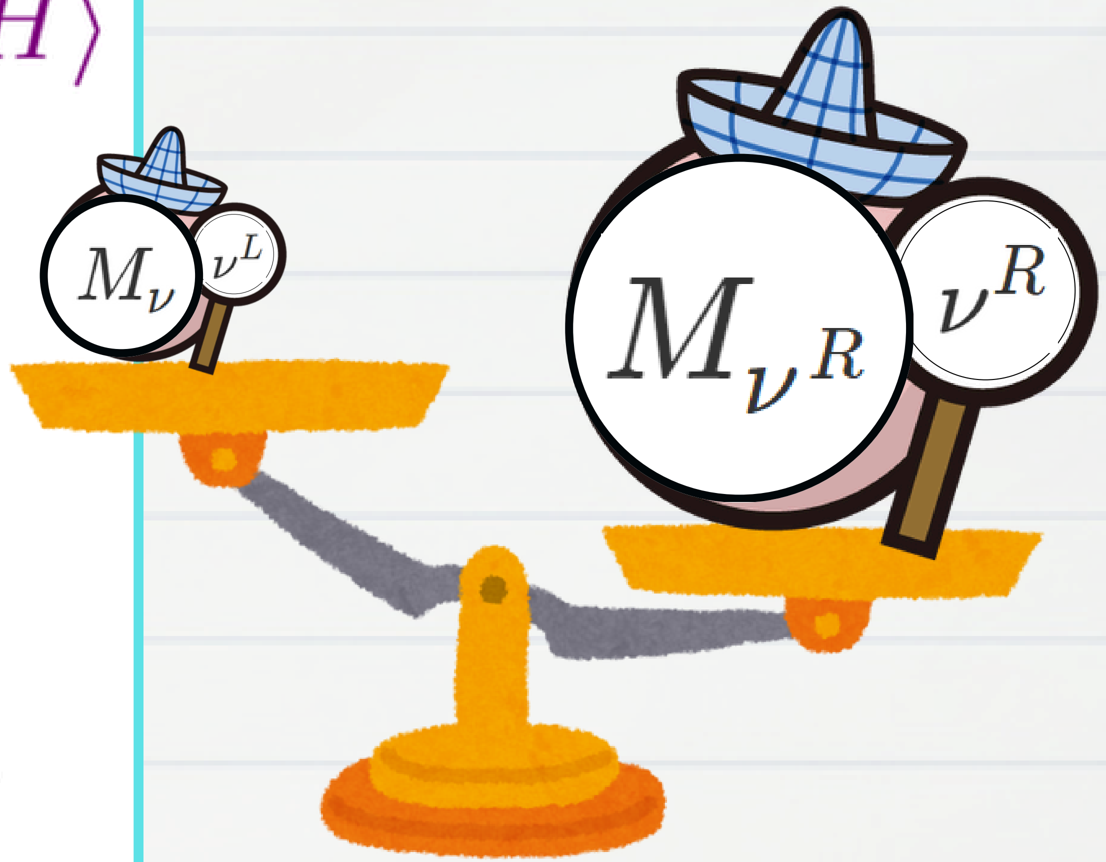
New fermion field with Hypercharge Y = 0

Singlet ferimon ν^R: $Y^{\nu}_{ij}\overline{\nu^R_i}\tilde{H}^{\dagger}L_j$ (e.g. Type-I Seesaw sterile neutrino)



$$M_{\nu} = Y^{\nu}\frac{1}{M_{\nu^R}}(Y^{\nu})^T \langle H \rangle^2.$$

Seesaw effect



O. Sawada and A. Sugamoto, eds., *Proceedings: Workshop on the Unified Theories and the Baryon Number in the Universe: Tsukuba, Japan, February 13-14, 1979*, (Tsukuba, Japan), Natl.Lab.High Energy Phys., 1979

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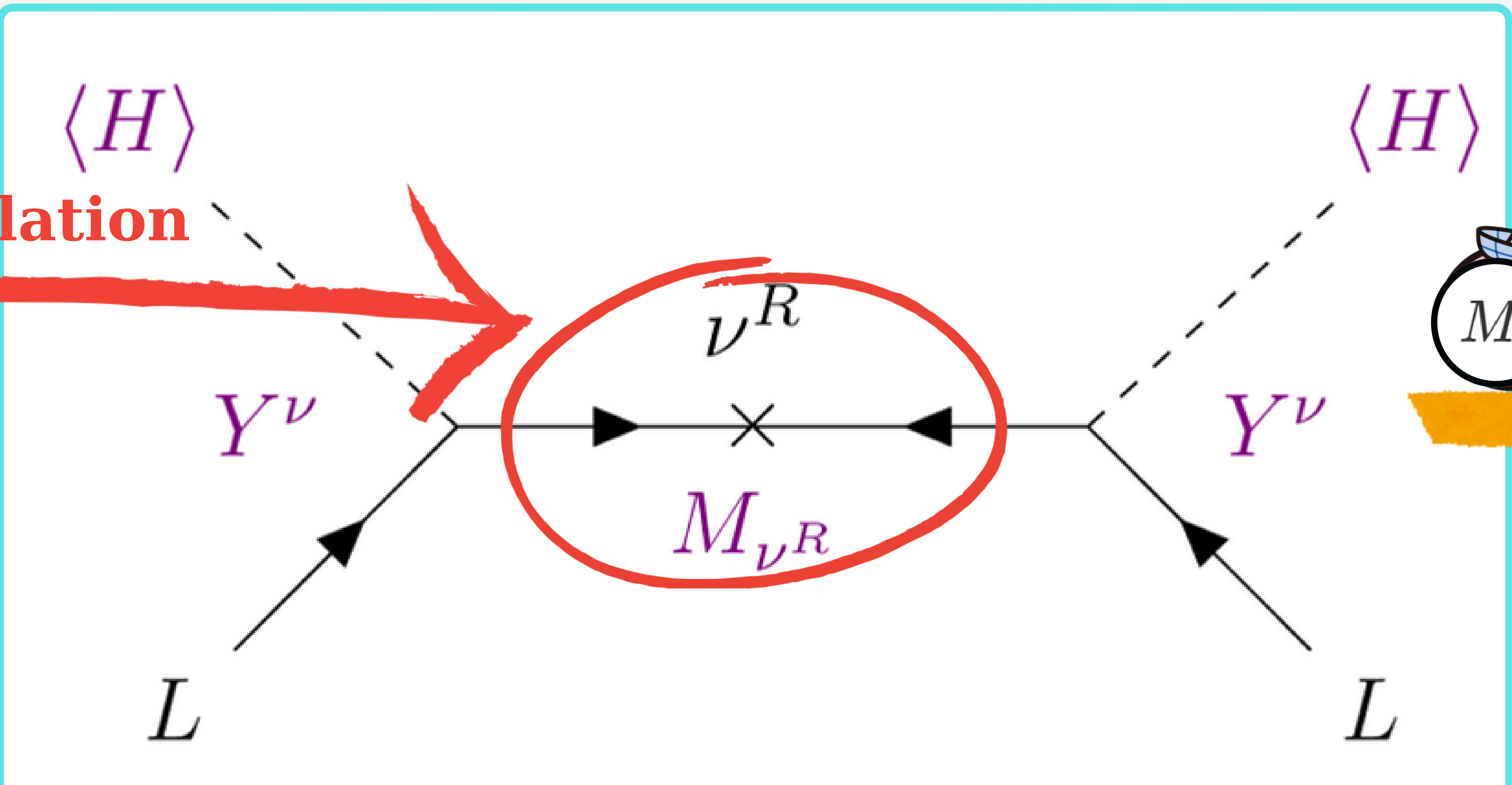
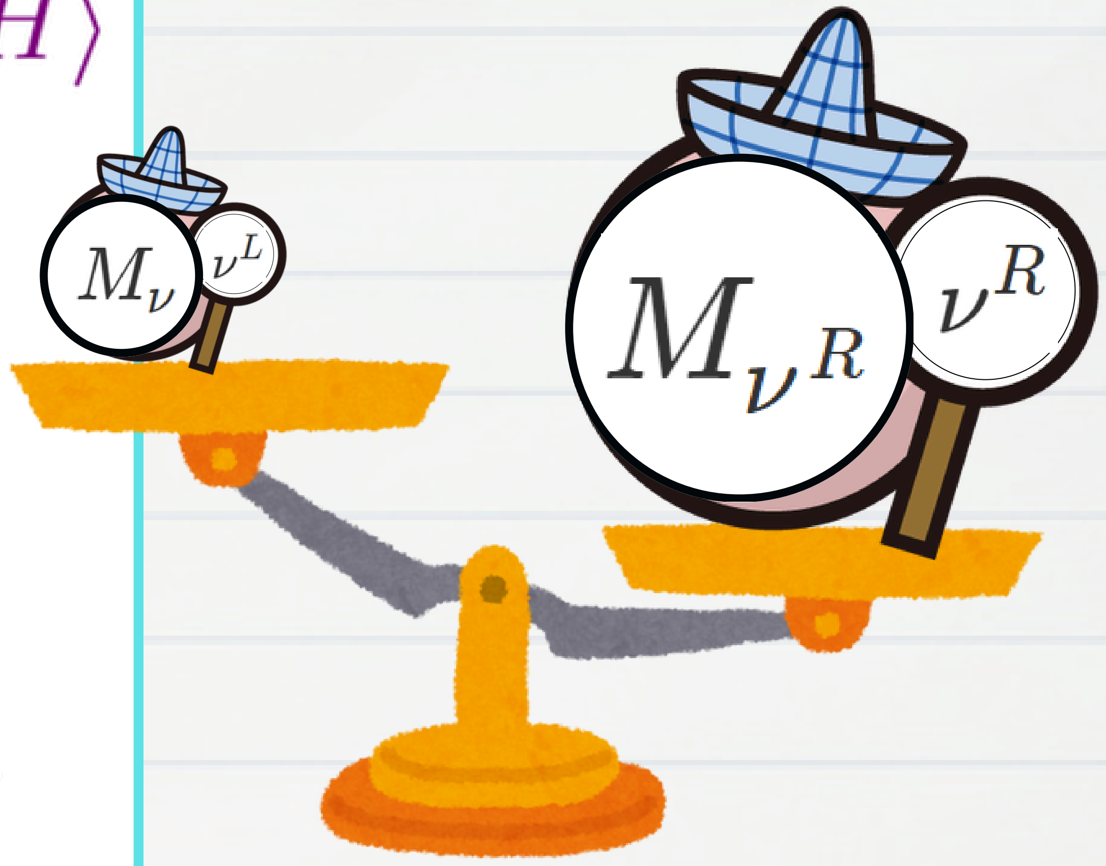
Lepton number violation





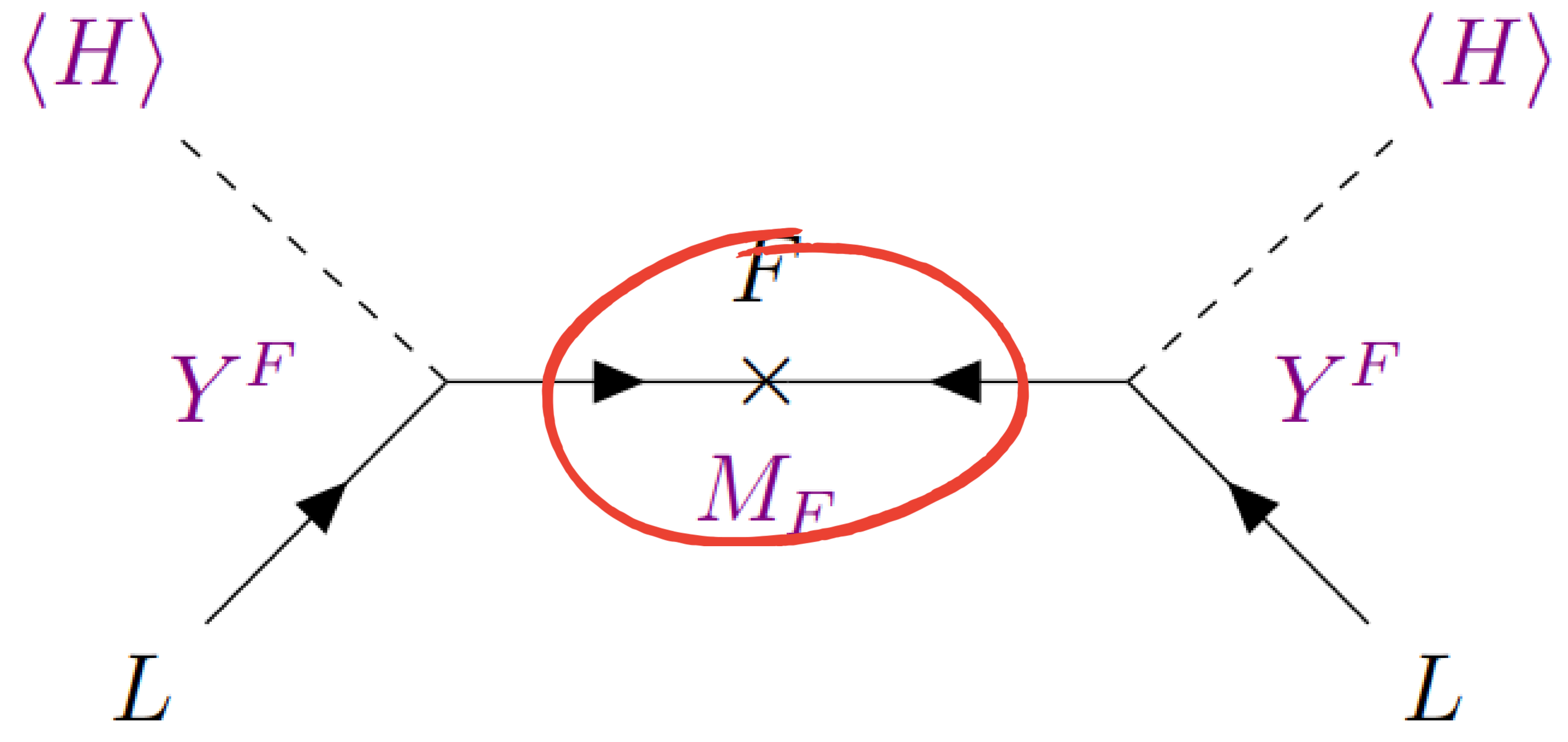
$$M_\nu = Y^\nu \frac{1}{M_{\nu^R}} (Y^\nu)^T \langle H\rangle^2.$$

Seesaw effect

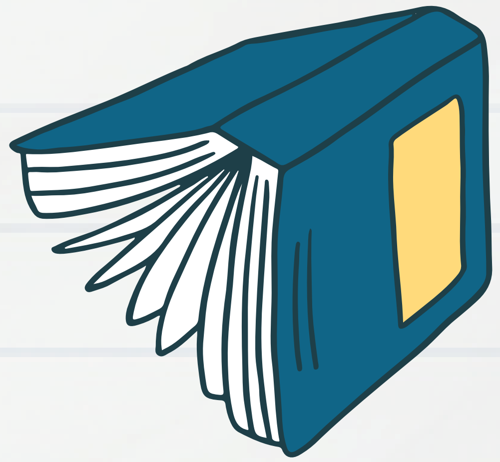
O. Sawada and A. Sugamoto, eds., *Proceedings: Workshop on the Unified Theories and the Baryon Number in the Universe: Tsukuba, Japan, February 13-14, 1979*, (Tsukuba, Japan), Natl.Lab.High Energy Phys., 1979

New fermion field with Hypercharge Y = 0

Triplet fermion F: $Y_{ij}^F \tilde{H}^\dagger \overline{F_i} L_j$ (e.g. Type-III Seesaw)



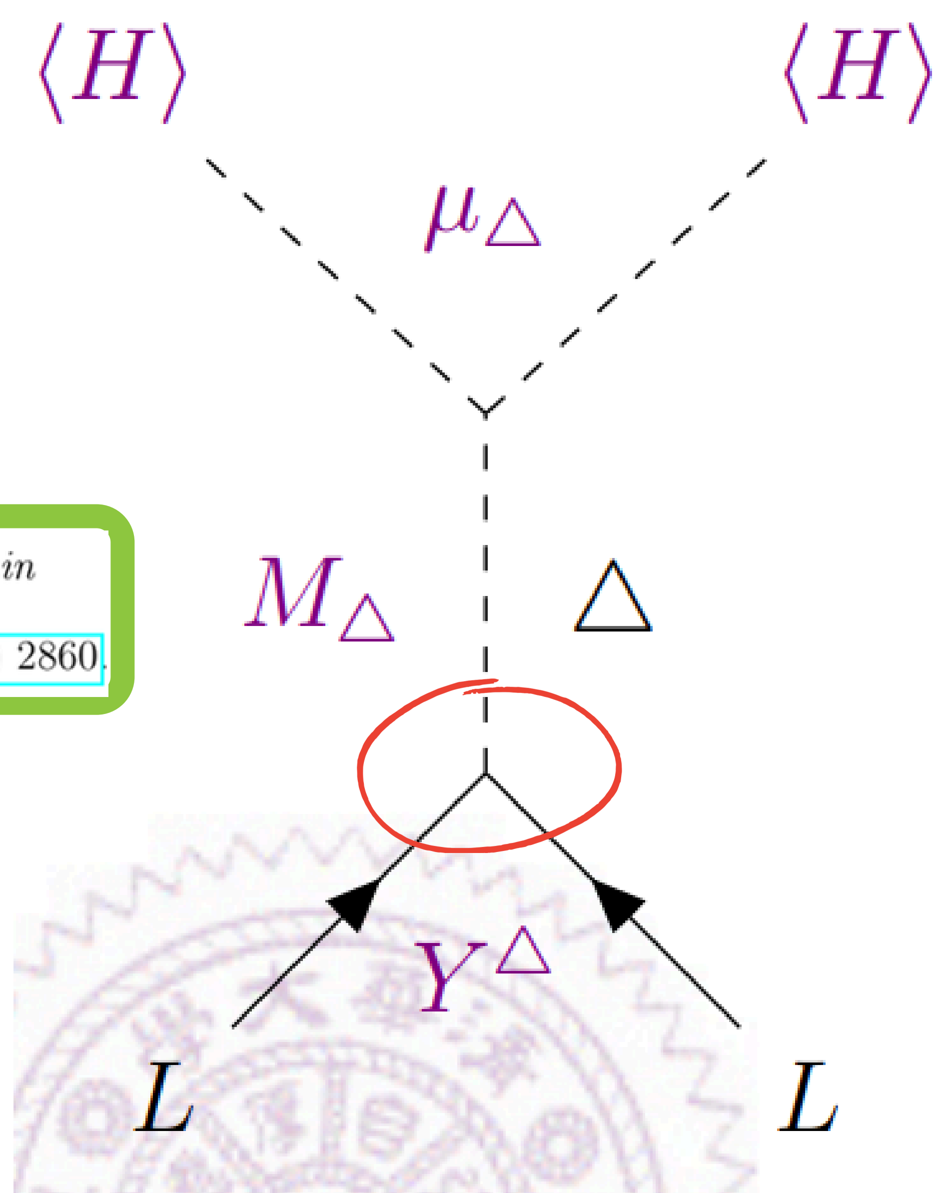
$$M_\nu = Y^F \frac{1}{M_F} (Y^F)^T \langle H \rangle^2$$



R. Foot, H. Lew, X. G. He and G. C. Joshi, *Seesaw Neutrino Masses Induced by a Triplet of Leptons*, *Z. Phys. C* **44** (1989) 441.

New scalar field with Hypercharge Y = 2

Scalar triplet Δ: $Y^{\Delta}_{ij}\overline{L^c_i}i\sigma_2\Delta L_j$ (e.g. Type-II Seesaw)



$$M_\nu = Y^\Delta \frac{\mu_\Delta}{M_\Delta^2}\langle H \rangle^2$$

T. P. Cheng and L.-F. Li, *Neutrino masses, mixings, and oscillations in su(2)xu(1) models of electroweak interactions*, *Phys. Rev. D* **22** (1980) 2860.

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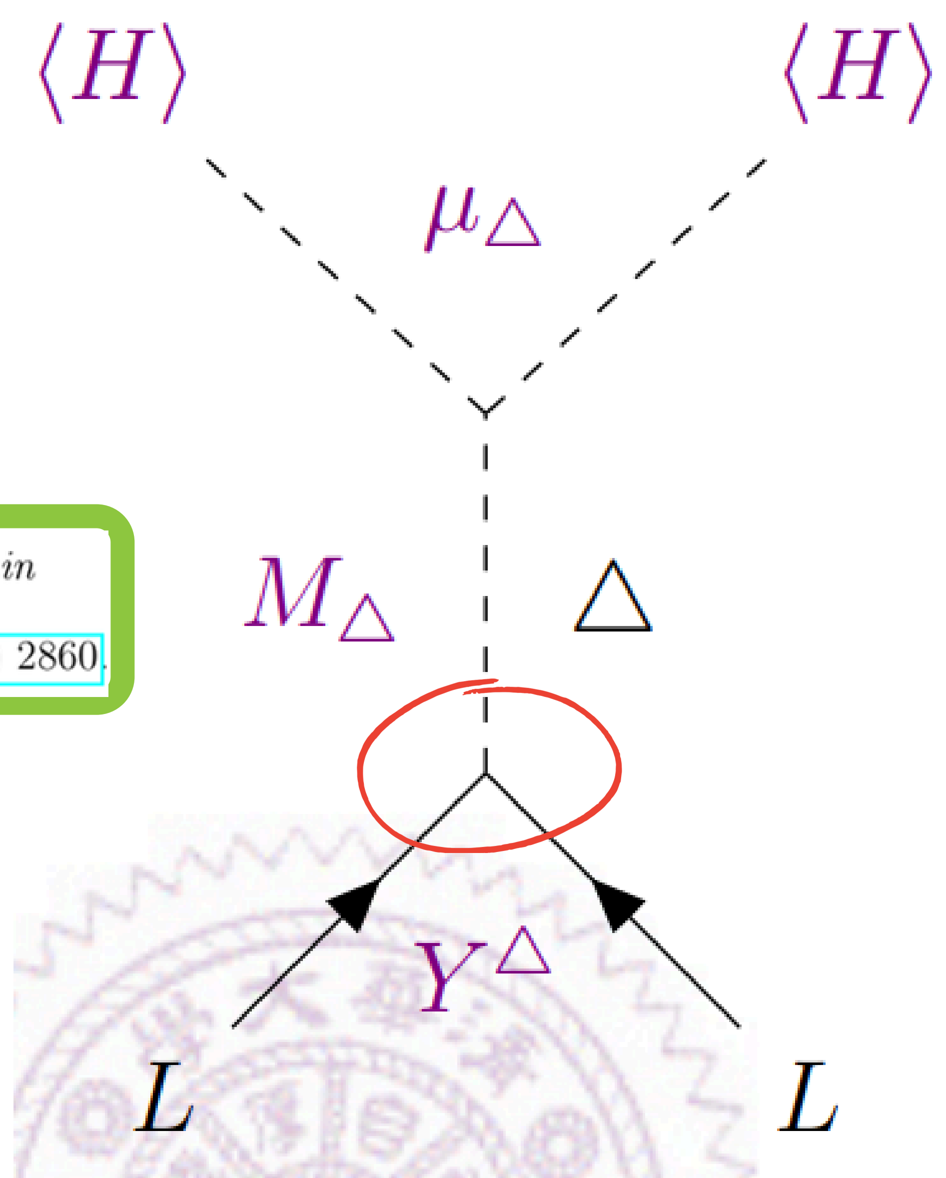
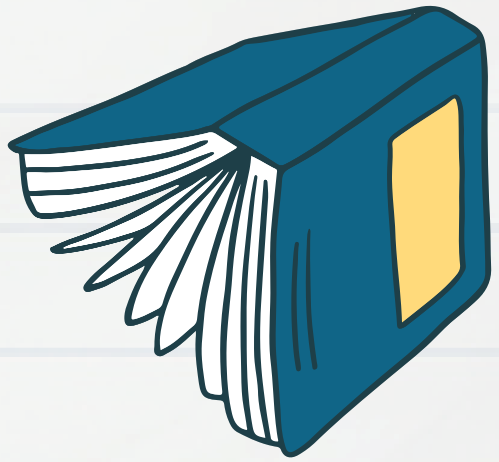


$$M_\nu = Y^\Delta \frac{\mu_\Delta}{M^2_\Delta}\langle H\rangle^2$$

T. P. Cheng and L.-F. Li, *Neutrino masses, mixings, and oscillations in su(2)xu(1) models of electroweak interactions*, Phys. Rev. D **22** (1980) 2860.



~~**Custodial symmetry**~~

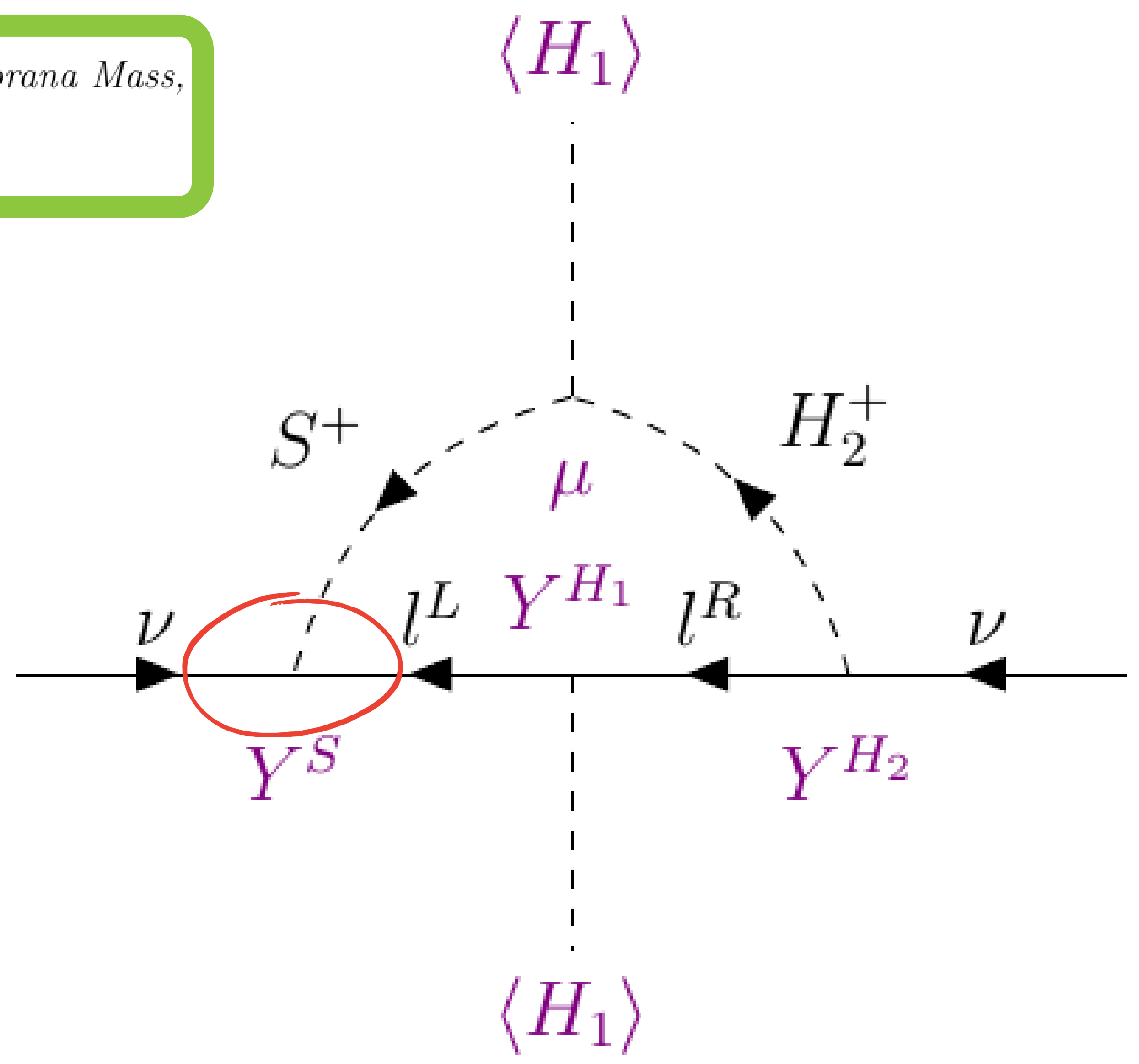
$$\cancel{\rho = \frac{M_W^2}{M_Z^2 c_W^2} \approx 1}$$

$$\cancel{4I_3(I_3+1) = 3Y^2}$$

New scalar field with Hypercharge Y = 2

Scalar singlet S^+: $Y^S_{ij}\overline{L^c_i}i\sigma_2 L_j S^+$ (e.g. Zee-singlet scalar)

A. Zee, *A Theory of Lepton Number Violation, Neutrino Majorana Mass, and Oscillation*, *Phys. Lett. B* **93** (1980) 389.

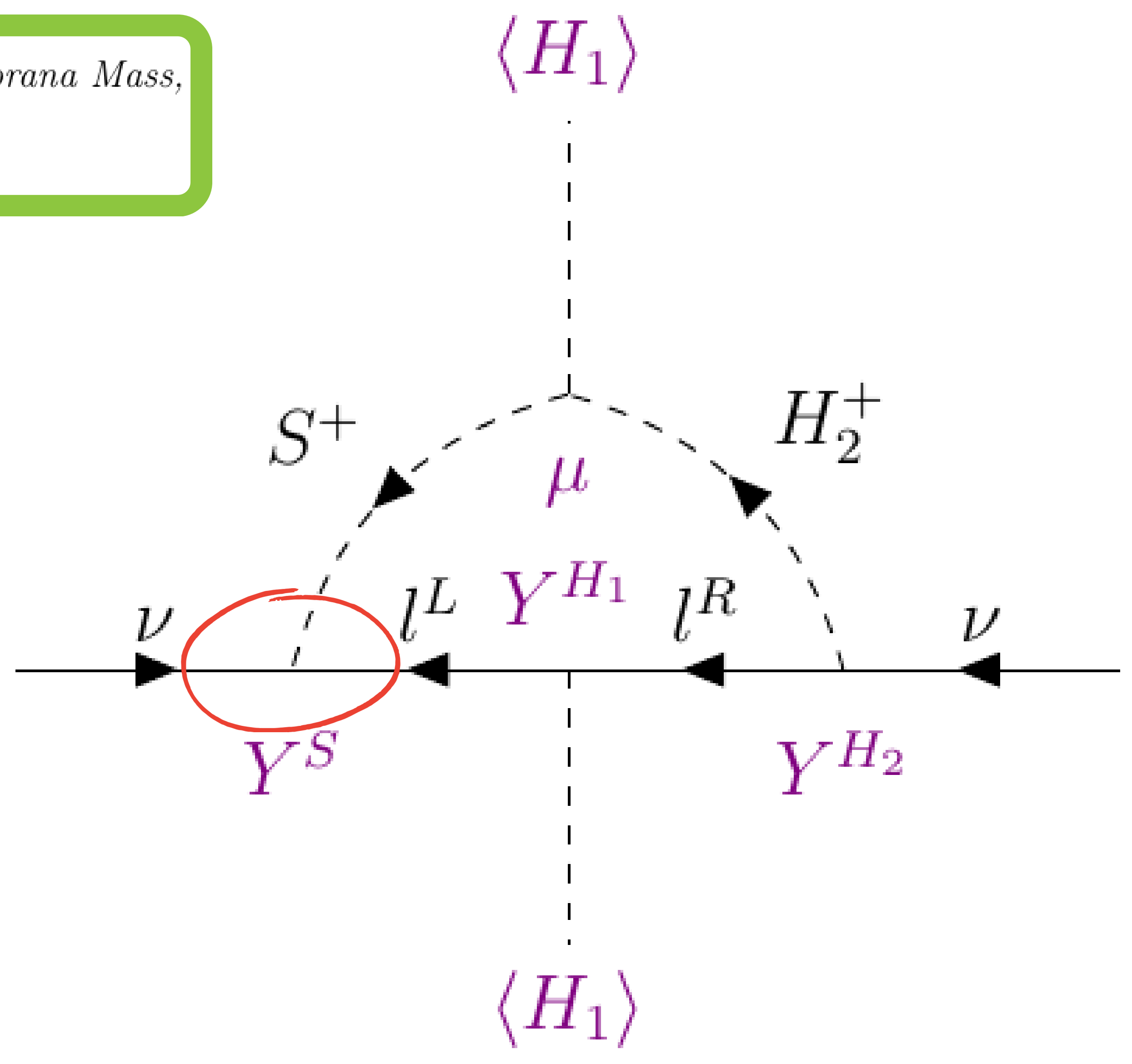


$$M_\nu = \frac{1}{8\pi^2}\frac{\mu\langle H_1\rangle}{m^2_{\eta^+} - m^2_{H^+}}\log\left(\frac{m^2_{\eta^+}}{m^2_{H^+}}\right)\left[Y^S\left(\langle H_1\rangle Y^{H_1}\right)\left(Y^{H_2}\right)^{\mathrm{T}} + Y^{H_2}\left(\langle H_1\rangle Y^{H_1}\right)\left(Y^S\right)^{\mathrm{T}}\right]$$

New scalar field with Hypercharge Y = 2

Scalar singlet S^+: $Y^S_{ij}\overline{L^c_i} i\sigma_2 L_j S^+$ (e.g. Zee-singlet scalar)

A. Zee, *A Theory of Lepton Number Violation, Neutrino Majorana Mass, and Oscillation*, Phys. Lett. B **93** (1980) 389.



No need new high massive particles

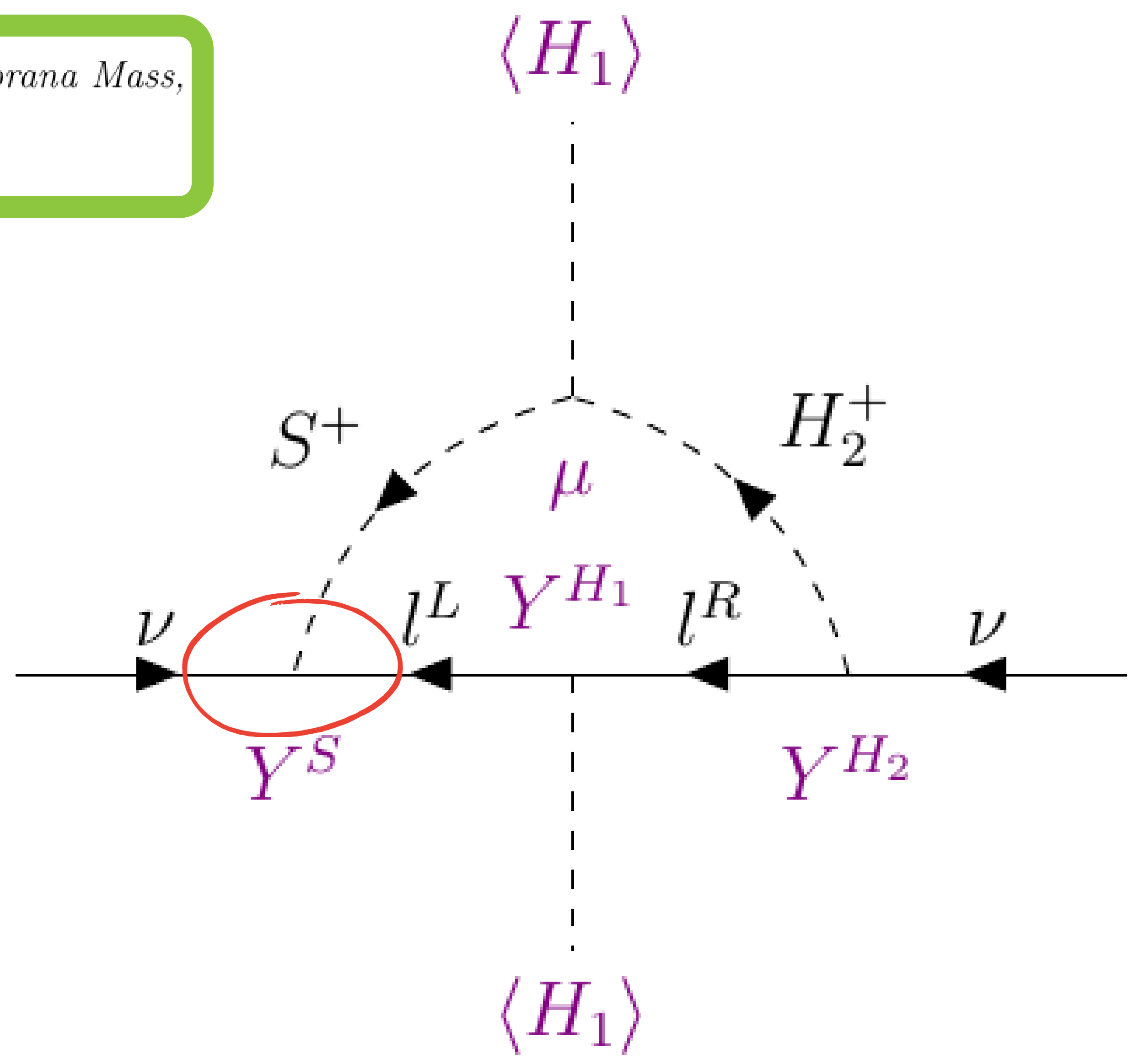
$$M_\nu = \frac{1}{8\pi^2}\frac{\mu\langle H_1\rangle}{m^2_{\eta^+} - m^2_{H^+}} \log\left(\frac{m^2_{\eta^+}}{m^2_{H^+}}\right)\left[Y^S\left(\langle H_1\rangle Y^{H_1}\right)\left(Y^{H_2}\right)^{\mathrm{T}} + Y^{H_2}\left(\langle H_1\rangle Y^{H_1}\right)\left(Y^S\right)^{\mathrm{T}}\right]$$

New scalar field with Hypercharge Y = 2

Scalar singlet S^+: $Y^S_{ij}\overline{L^c_i}i\sigma_2 L_j S^+$ (e.g. Zee-singlet scalar)

An acceptable solution of the neutrino mass hierarchy

no Majorana Mass,



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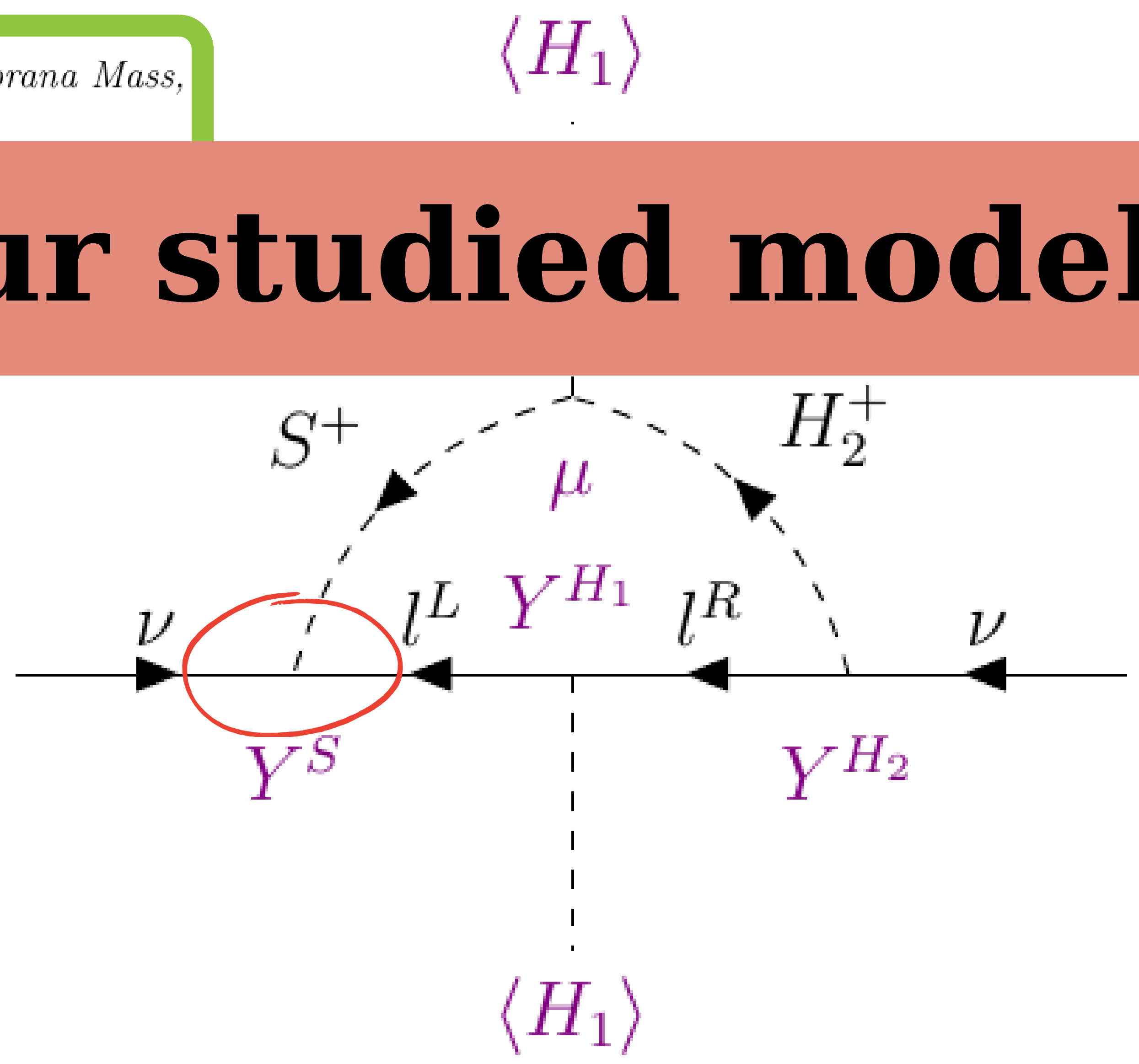
An acceptable solution of the neutrino mass hierarchy

no Majorana Mass,

Our studied model !!

No need new high massive particles



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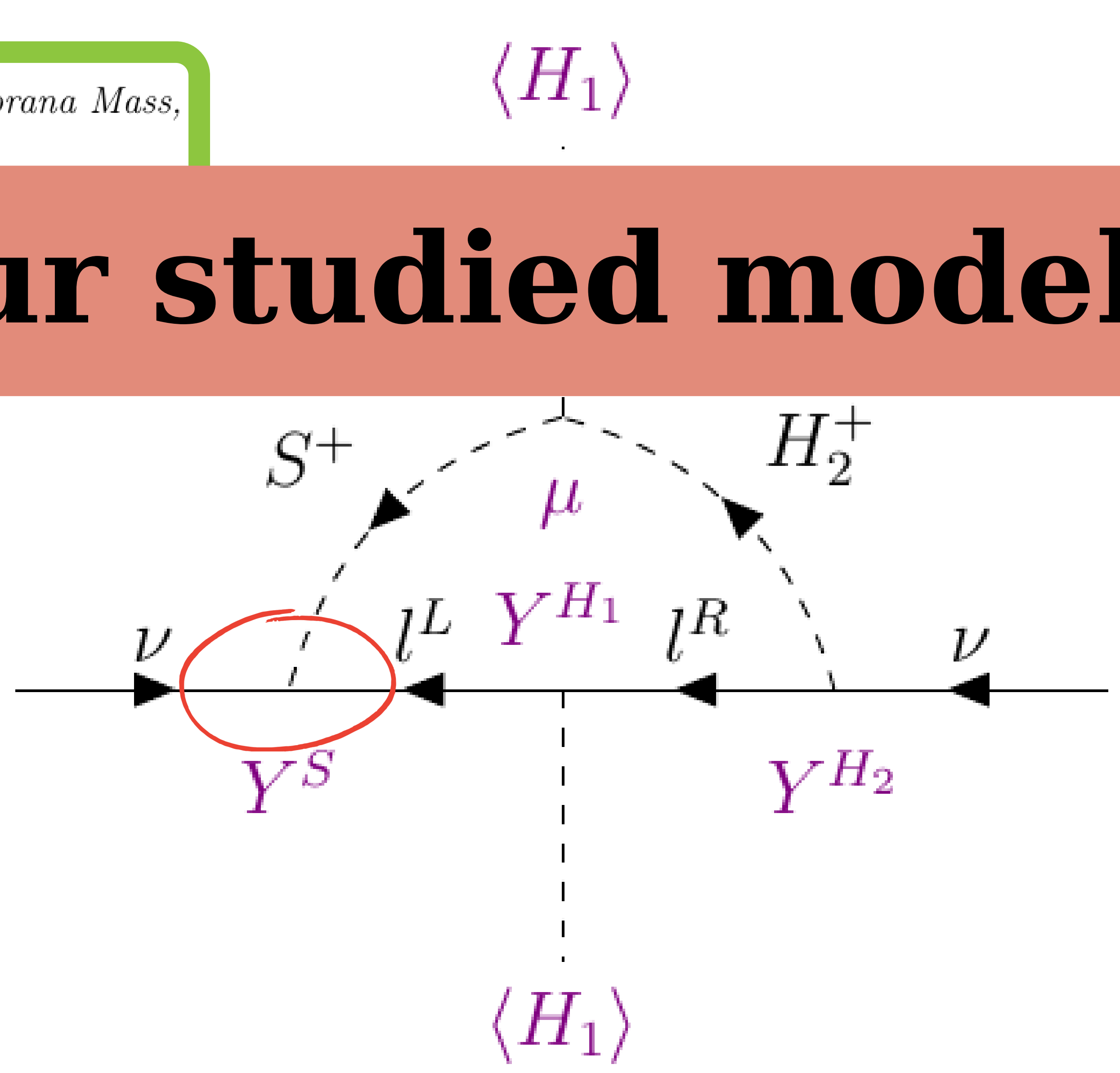

No need new high massive particles

Based on alignment/decoupling limit

$H_1^0 \quad H_2^0$

$$M_\nu = \frac{1}{8\pi^2}\frac{\mu\langle H_1\rangle}{m^2_{\eta^+} - m^2_{H^+}}\log\left(\frac{m^2_{\eta^+}}{m^2_{H^+}}\right)\left[Y^S(\langle H_1\rangle Y^{H_1})(Y^{H_2})^{\mathrm{T}} + Y^{H_2}(\langle H_1\rangle Y^{H_1})(Y^S)^{\mathrm{T}}\right]$$

New scalar field with Hypercharge Y = 2

Scalar singlet S^+: $Y^S_{ij}\overline{L^c_i}i\sigma_2 L_j S^+$ (e.g. Zee-singlet scalar)

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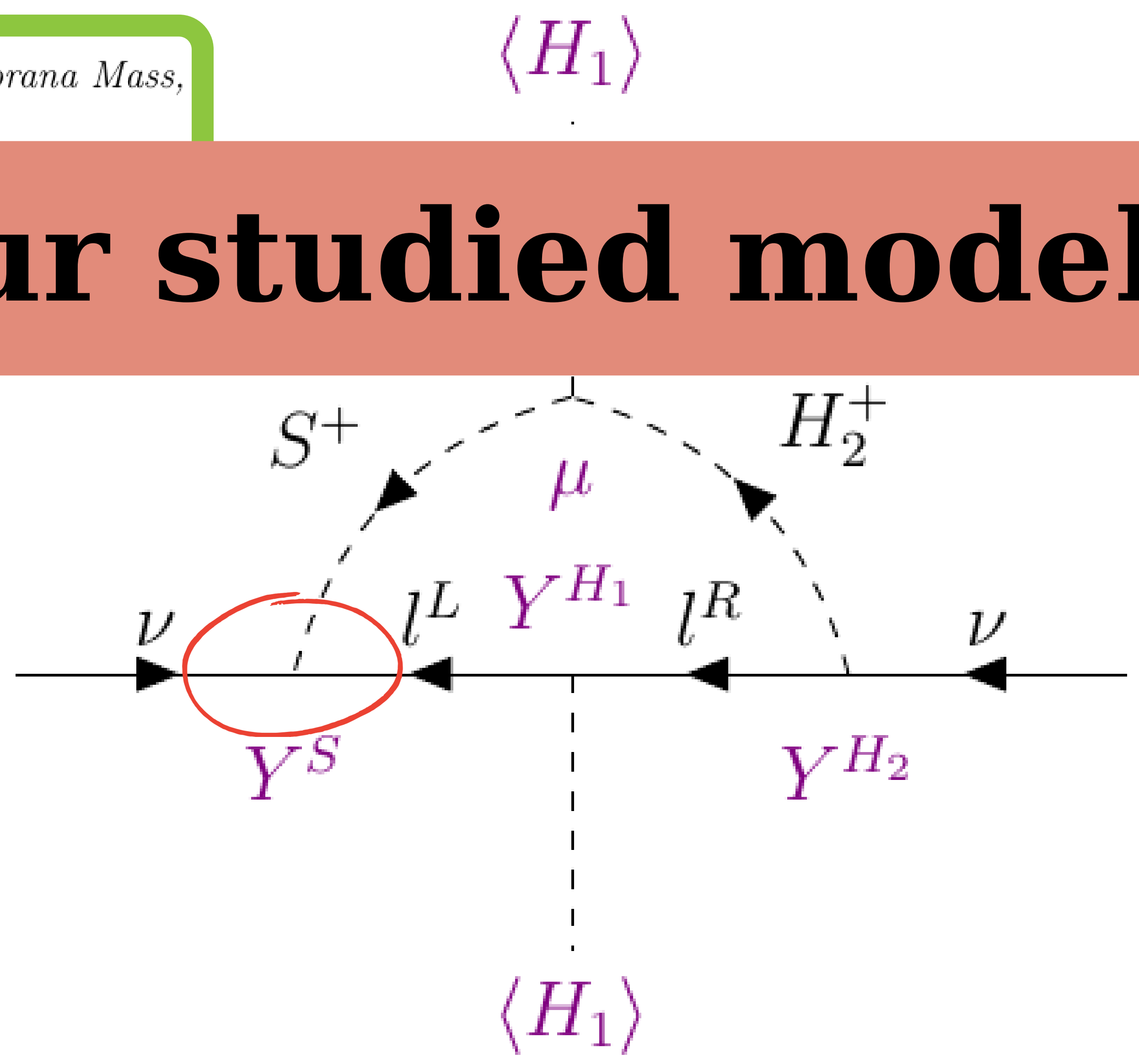


Based on alignment/decoupling limit

For simplicity, forcusing on the Leptophilic Zee model's

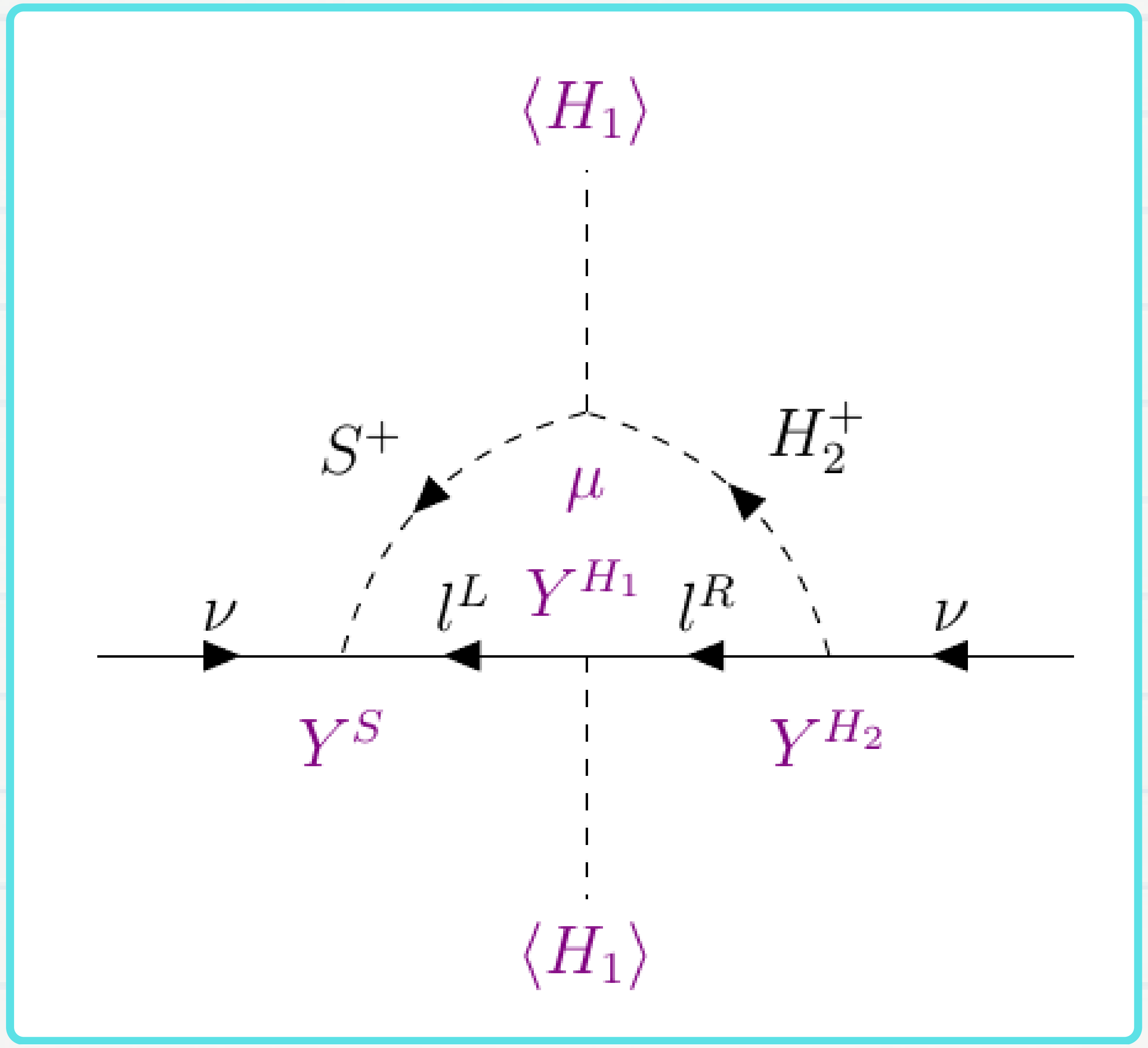
H_1^0 ✗ H_2^0

$$M_\nu = \frac{1}{8\pi^2}\frac{\mu\langle H_1\rangle}{m^2_{\eta^+}-m^2_{H^+}}\log\left(\frac{m^2_{\eta^+}}{m^2_{H^+}}\right)\left[Y^S(\langle H_1\rangle Y^{H_1})(Y^{H_2})^{\mathrm{T}}+Y^{H_2}(\langle H_1\rangle Y^{H_1})(Y^S)^{\mathrm{T}}\right]$$

$H_2 l\bar{l}$ $\cancel{H_2 q\bar{q}}$

Leptophiclic Zee model

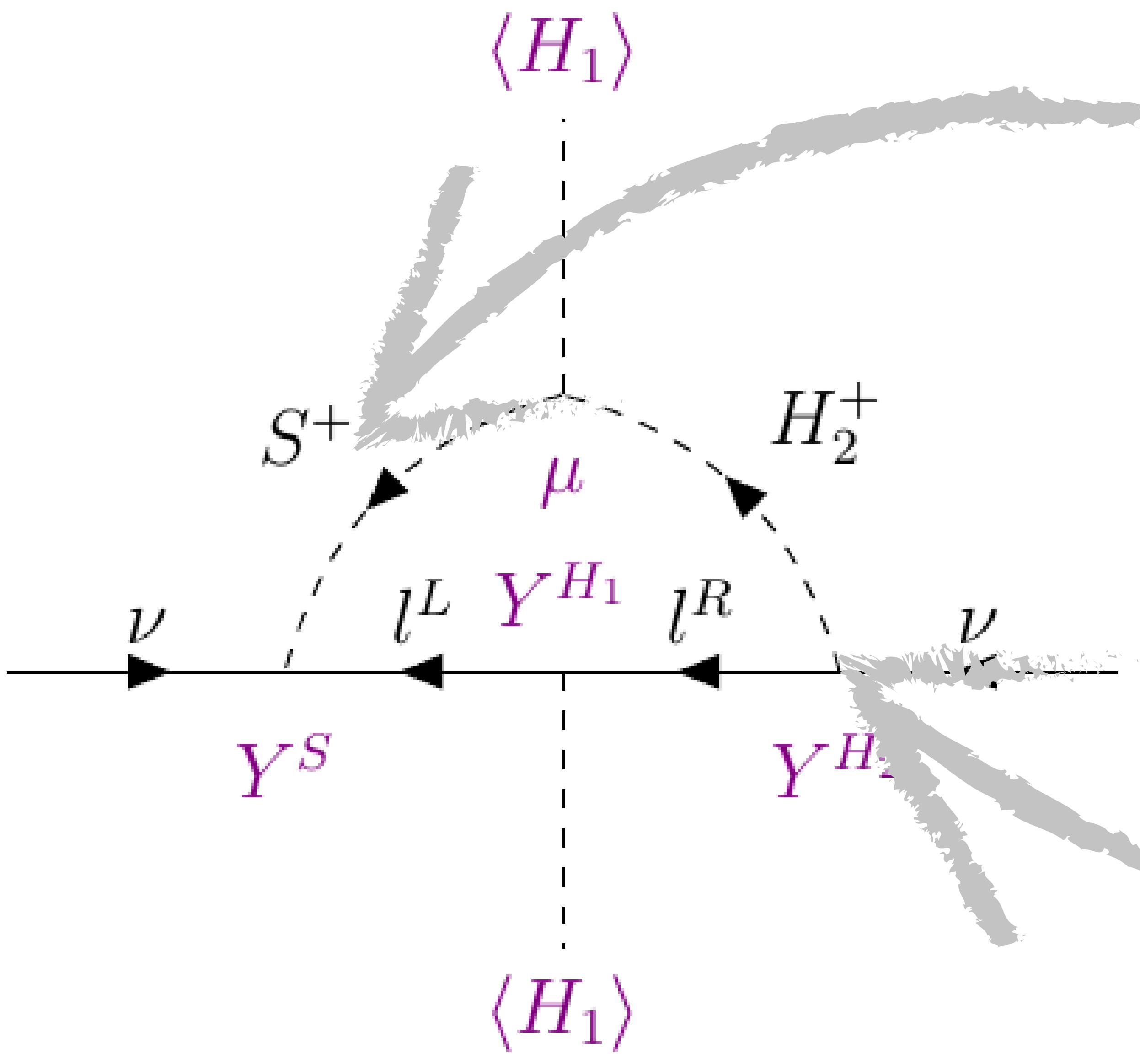
Zee model



$$\mathcal{L}_{Yuk} \supset -Y^S_{\alpha\beta}\overline{L^c}_\alpha i\sigma_2 L_\beta S^+ - Y^{H_2}_{\alpha\beta}\overline{L}_\alpha H_2 l^R_\beta - Y^{H_1}_{\alpha\beta}\overline{L}_\alpha H_1 l^R_\beta + \text{h.c.}$$

$$M_\nu = \frac{s_\beta c_\beta}{8\pi^2}\log\left(\frac{m^2_{\eta^+}}{m^2_{H^+}}\right)\left[Y^S M_l \left(Y^{H_2}\right)^{\mathrm{T}} + Y^{H_2} M_l \left(Y^S\right)^{\mathrm{T}}\right]$$

Zee model



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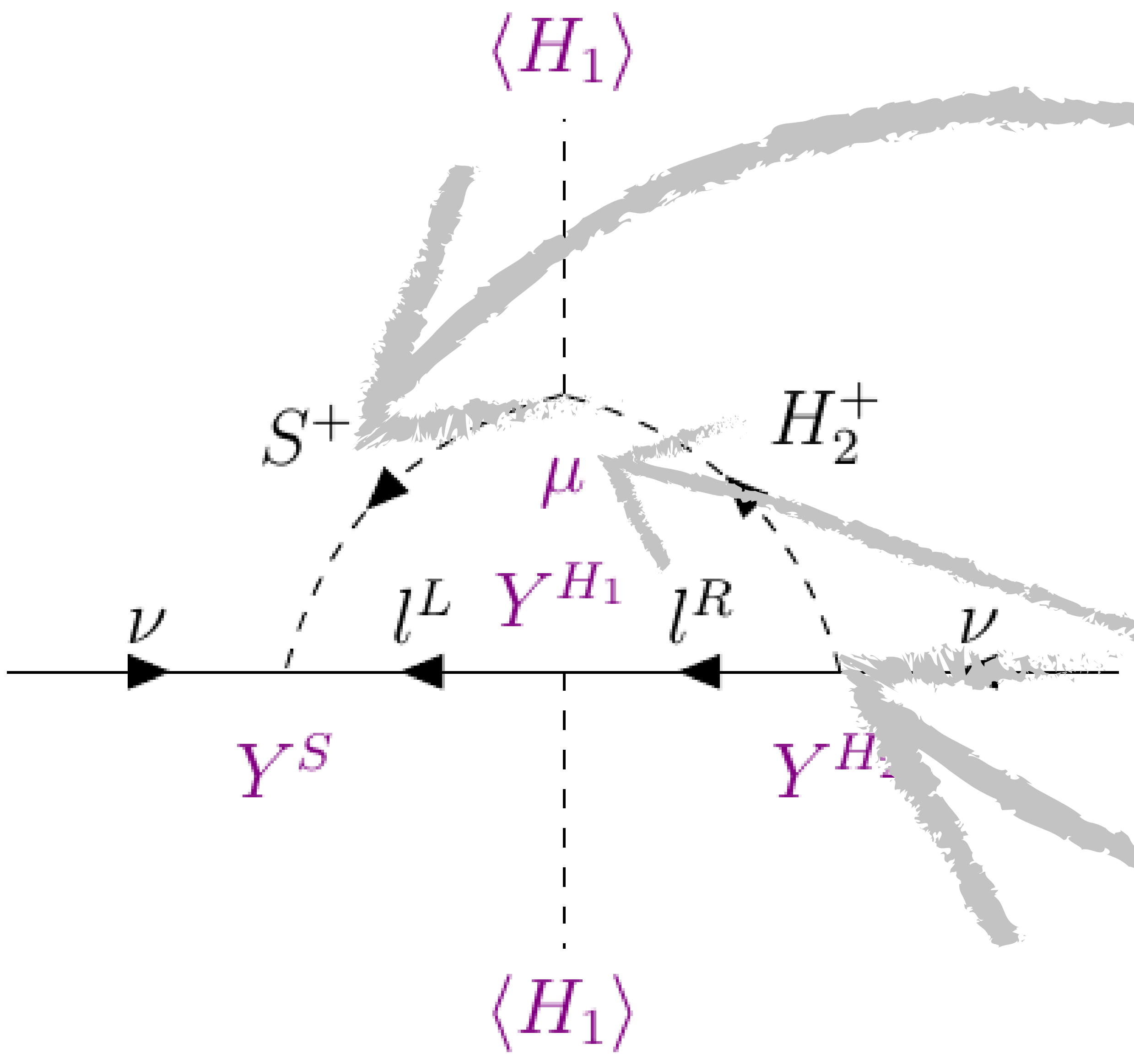
Zee model



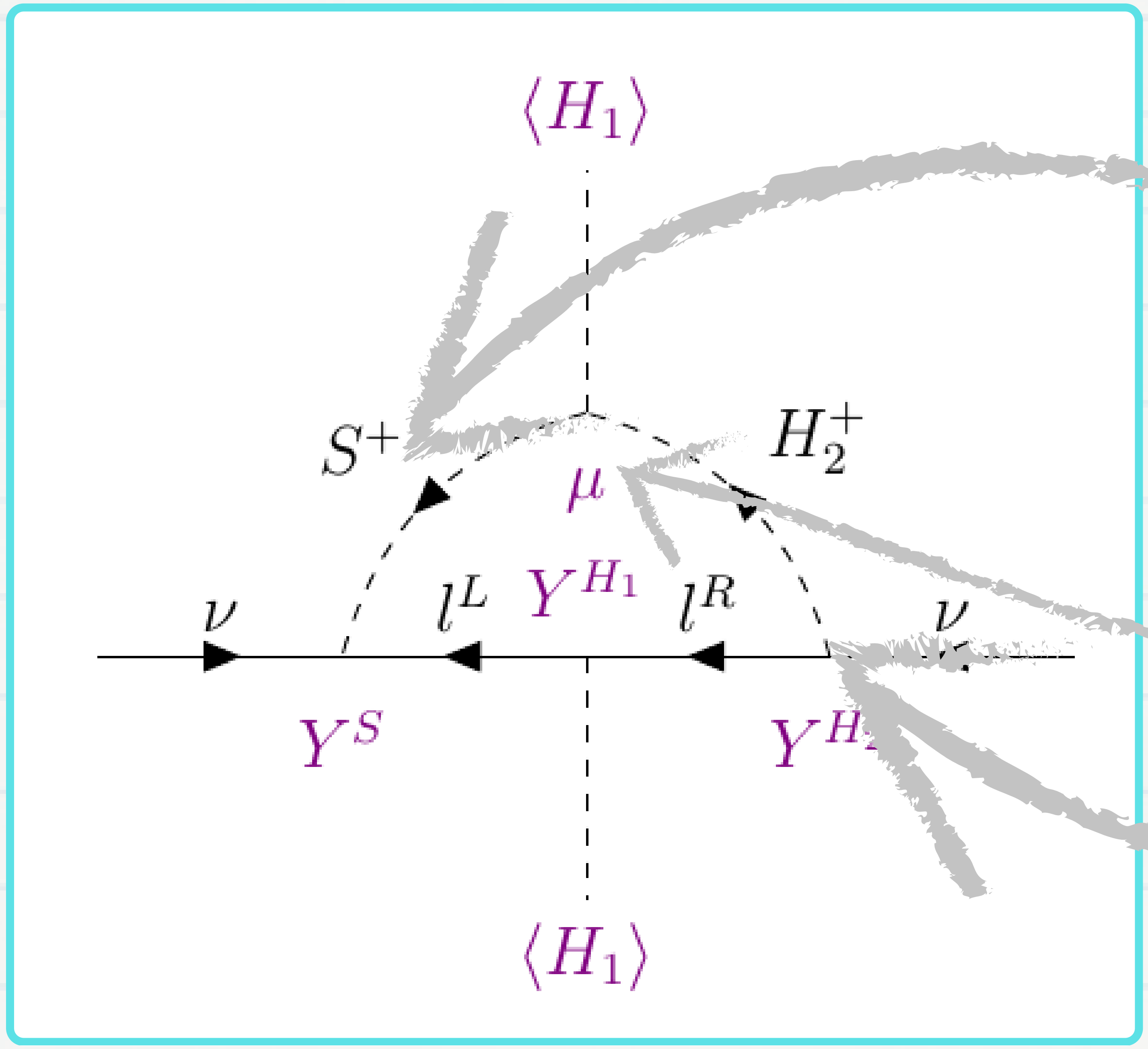
$$\mathcal{L}_{Yuk} \supset -Y^S_{\alpha\beta}\overline{L^c}_\alpha i\sigma_2 L_\beta S^+ - Y^{H_2}_{\alpha\beta}\overline{L}_\alpha H_2 l^R_\beta - Y^{H_1}_{\alpha\beta}\overline{L}_\alpha H_1 l^R_\beta + \text{h.c.}$$

$$V\left(H_1, H_2, S^+\right) \supset \mu H_1^{\mathrm{T}} i\sigma_2 H_2 S^-$$

The mixing angle $c_\beta s_\beta = \frac{\mu\langle H_1\rangle}{m^2_{\eta^+}-m^2_{H^+}}$

$$\begin{pmatrix} \eta^+ \\ H^+ \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} S^+ \\ H_2^+ \end{pmatrix}$$

$$M_\nu = \frac{s_\beta c_\beta}{8\pi^2}\log\left(\frac{m^2_{\eta^+}}{m^2_{H^+}}\right)\left[Y^S M_l \left(Y^{H_2}\right)^{\mathrm{T}} + Y^{H_2} M_l \left(Y^S\right)^{\mathrm{T}}\right]$$



Zee model

$$\mathcal{L}_{Yuk} \supset -Y^S_{\alpha\beta}\overline{L^c}_\alpha i\sigma_2 L_\beta S^+ - Y^{H_2}_{\alpha\beta}\overline{L}_\alpha H_2 l^R_\beta - Y^{H_1}_{\alpha\beta}\overline{L}_\alpha H_1 l^R_\beta + \text{h.c.}$$

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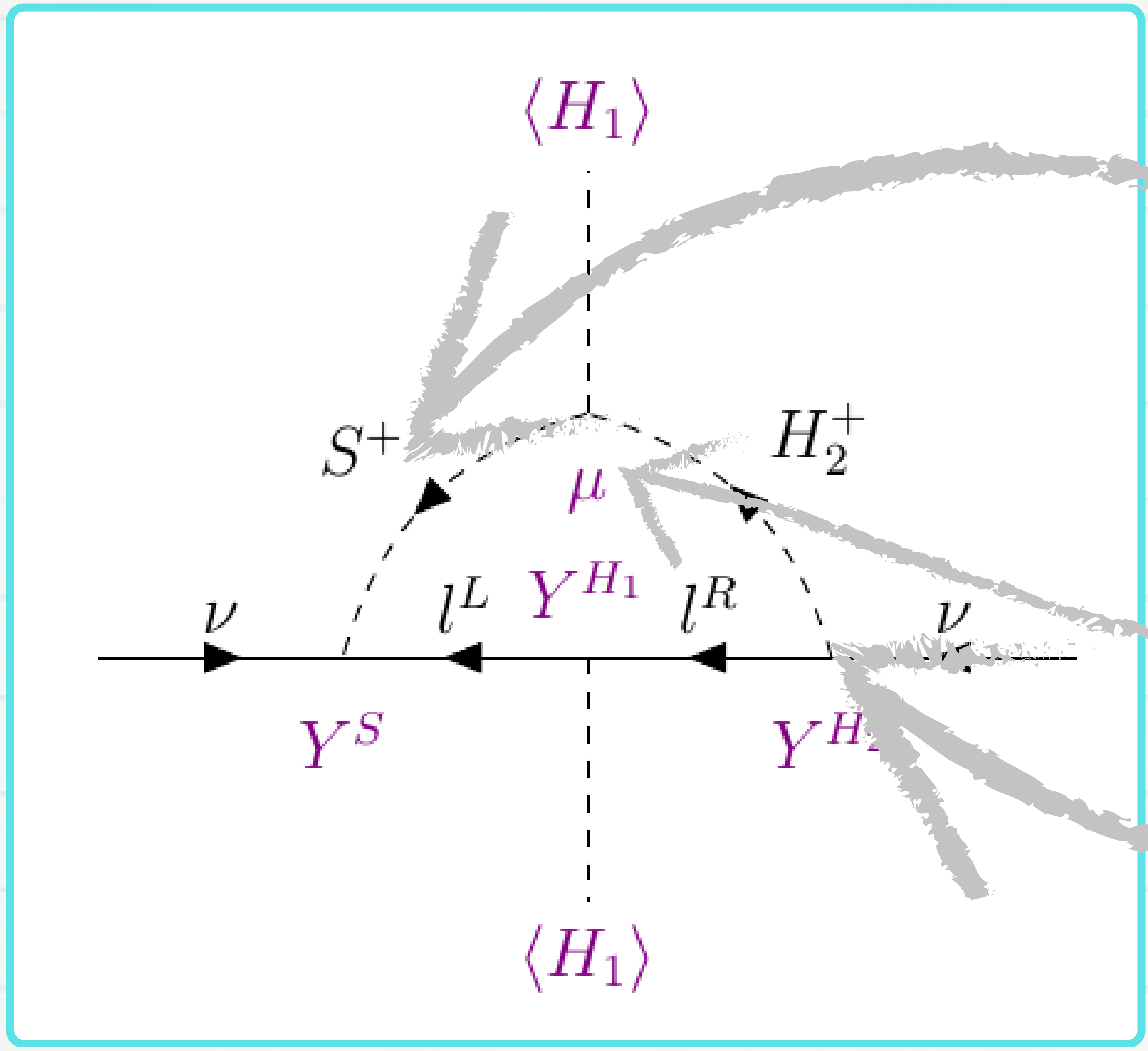
$$M_\nu = \frac{s_\beta c_\beta}{8\pi^2} \log\left(\frac{m^2_{\eta^+}}{m^2_{H^+}}\right)\left[Y^S M_l \left(Y^{H_2}\right)^{\mathrm{T}} + Y^{H_2} M_l \left(Y^S\right)^{\mathrm{T}}\right]$$

$$H_2 = \begin{pmatrix} H_2^+ \\ H_0 \end{pmatrix}, \quad H_1 \begin{pmatrix} 0 \\ \frac{H_1^0 (\equiv H_{SM})}{\sqrt{2}} \end{pmatrix}$$

Higgs basis

Alignment/decoupling limit

Zee model



$$\mathcal{L}_{Yuk} \supset -Y^S_{\alpha\beta}\overline{L^c}_\alpha i\sigma_2 L_\beta S^+ - Y^{H_2}_{\alpha\beta}\overline{L}_\alpha H_2 l^R_\beta - Y^{H_1}_{\alpha\beta}\overline{L}_\alpha H_1 l^R_\beta + \text{h.c.}$$

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The mixing angle $c_\beta s_\beta = \frac{\mu\langle H_1\rangle}{m^2_{\eta^+} - m^2_{H^+}}$

$$\begin{pmatrix} \eta^+ \\ H^+ \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} S^+ \\ H_2^+ \end{pmatrix}$$

$$M_\nu = \frac{s_\beta c_\beta}{8\pi^2}\log\left(\frac{m^2_{\eta^+}}{m^2_{H^+}}\right)\left[Y^S M_l \left(Y^{H_2}\right)^{\mathrm{T}} + Y^{H_2} M_l \left(Y^S\right)^{\mathrm{T}}\right]$$

$\sim$**1 eV**

$$\left|Y^{S,H_2}\right| \sim \frac{\mathcal{O}\left(10^{-2}–10^{-3}\right)}{\sqrt{\left|c_\beta s_\beta\right|}}$$

$$H_2 = \begin{pmatrix} H_2^+ \\ H_0 \end{pmatrix}, \quad H_1 \begin{pmatrix} 0 \\ \frac{H_1(\equiv H_{SM})}{\sqrt{2}} \end{pmatrix}$$

Higgs basis

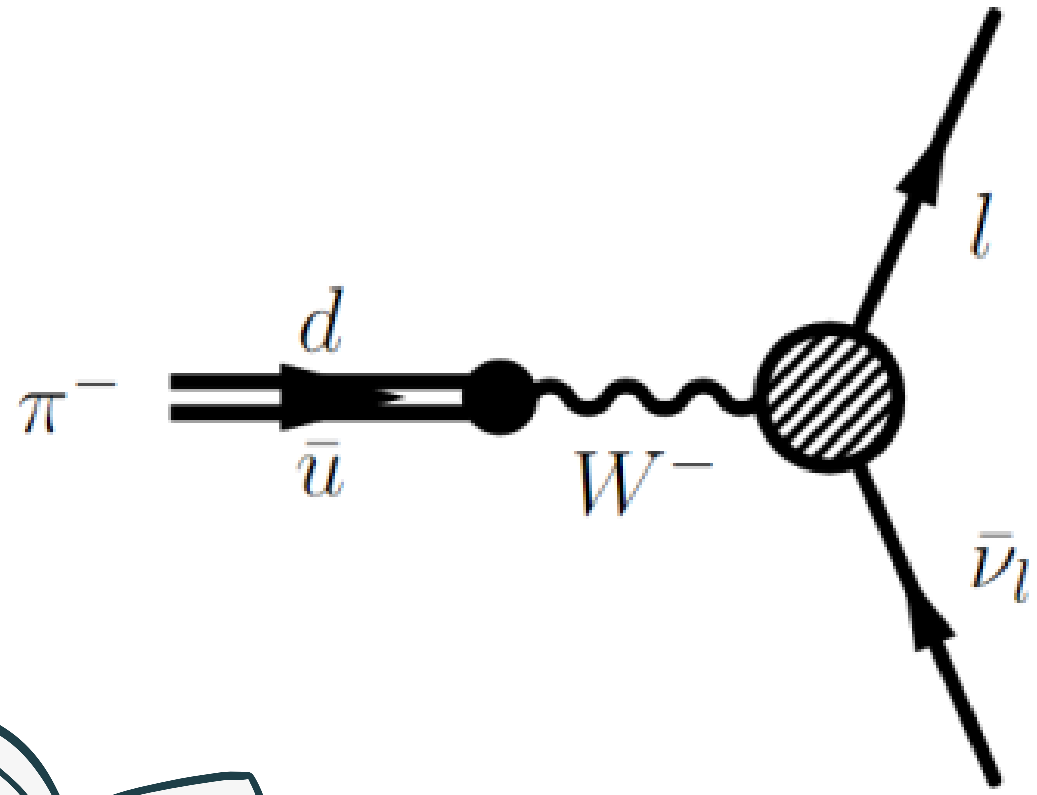
Alignment/decoupling limit

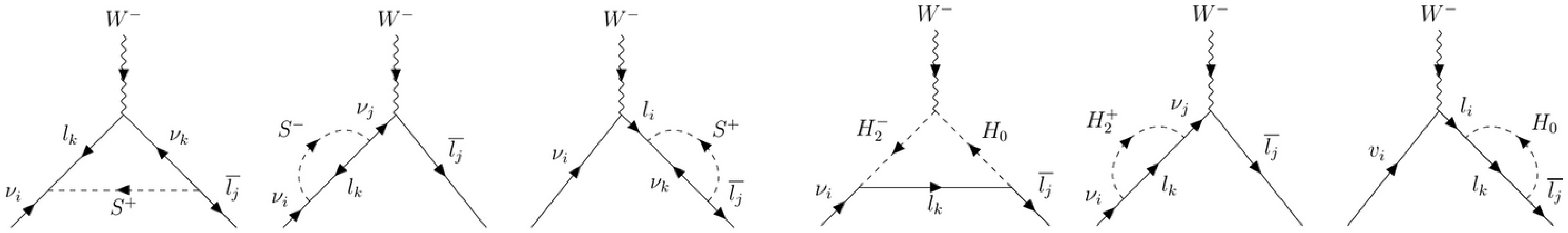
Phenomenological constraints

*All data taken from PDG

Universality test in Pion decay

Pion decay

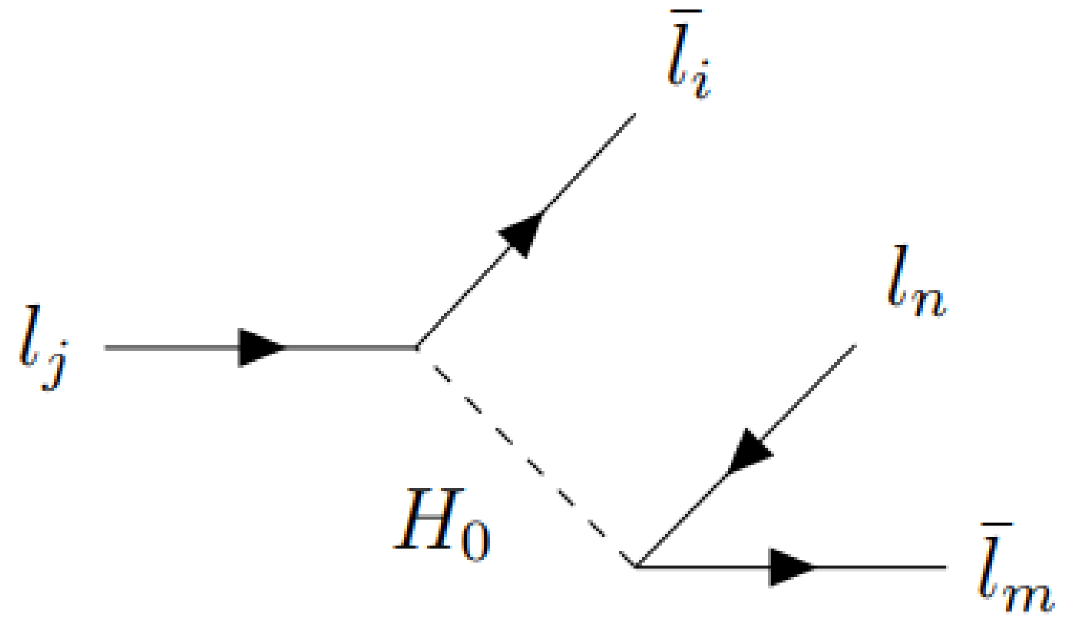




$$\begin{cases} \left| |Y^S_{e\tau}|^2 - |Y^S_{\mu\tau}|^2 \right| < \mathcal{O}\left(10^2 - 10^5\right) & m_S \in (100 - 1000) \text{ and } m_{H_2^+} \approx m_{H_0} \\ \left| |Y^{H_2}_{ek}|^2 - |Y^{H_2}_{\mu k}|^2 \right| < \mathcal{O}\left(10^{-3}\right) & m_{H_2^+} \neq m_{H_0} \end{cases}$$

Weak contraint !

Trilepton decays L->3l

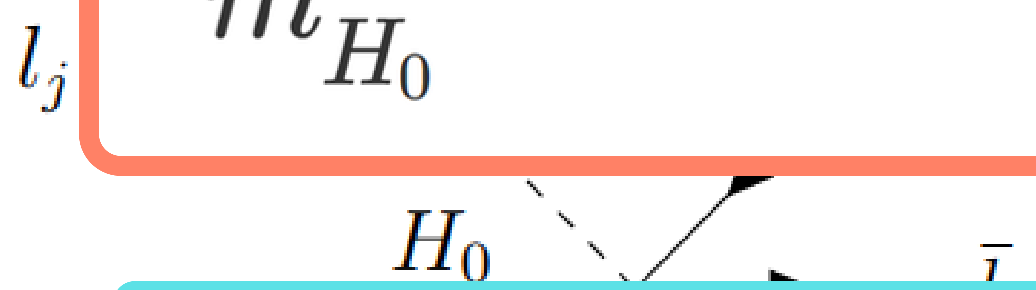


$$Br\left(l_i \to l_j \bar{l}_m l_n\right) = \frac{\mathbf{Y}}{n!128G_F^{i2}} Br\left(l_i \to l_j \bar{\nu}_m \nu_n\right)$$

$$\mathbf{Y} = \frac{1}{16m_{H_0}^4}\left(\left|2Y_{ji}^{H_2}Y_{nm}^{H_2*} - Y_{mi}^{H_2}Y_{nj}^{H_2*}\right|^2 + \left|2Y_{ij}^{H_2}Y_{mn}^{H_2*} - Y_{im}^{H_2}Y_{jn}^{H_2*}\right|^2 + 4\left|Y_{ji}^{H_2}Y_{mn}^{H_2}\right|^2 \right.$$
$$\left. +4\left|Y_{ij}^{H_2}Y_{nm}^{H_2}\right|^2 + 3\left|Y_{mi}^{H_2}Y_{nj}^{H_2}\right|^2 + 3\left|Y_{im}^{H_2}Y_{jn}^{H_2}\right|^2 + 4\left|Y_{mi}^{H_2}Y_{jn}^{H_2}\right|^2 + 4\left|Y_{im}^{H_2}Y_{nj}^{H_2}\right|^2\right)$$

Trilepton decays L->3l

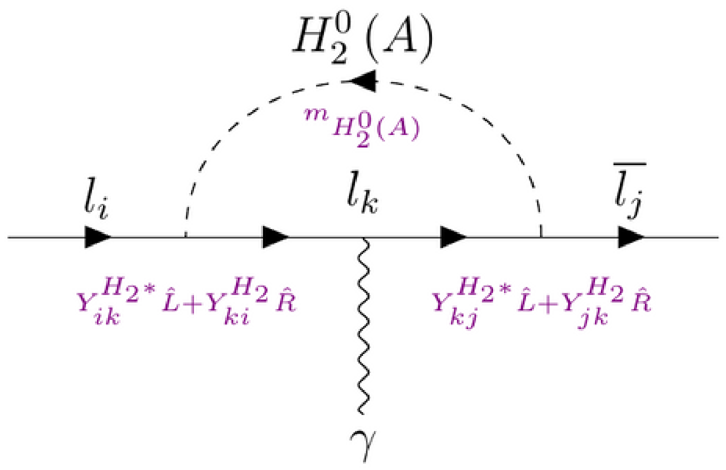
$$\frac{\left|Y^{H_2}\right|^2}{m_{H_0}^2} < \mathcal{O}\left(10^{-9} - 10^{-8}\right)\mathrm{GeV}^{-2}$$

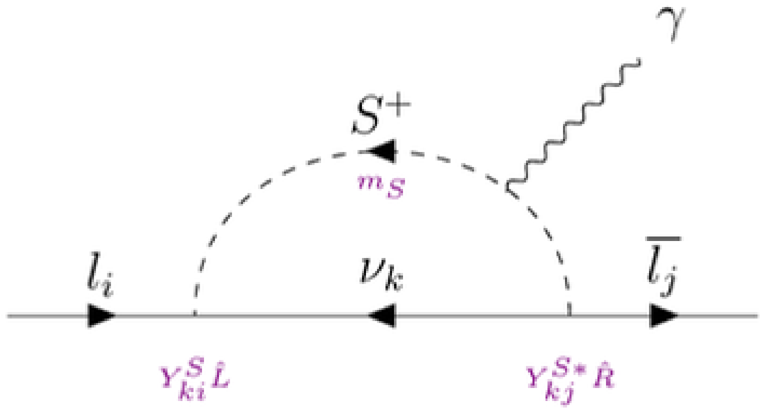


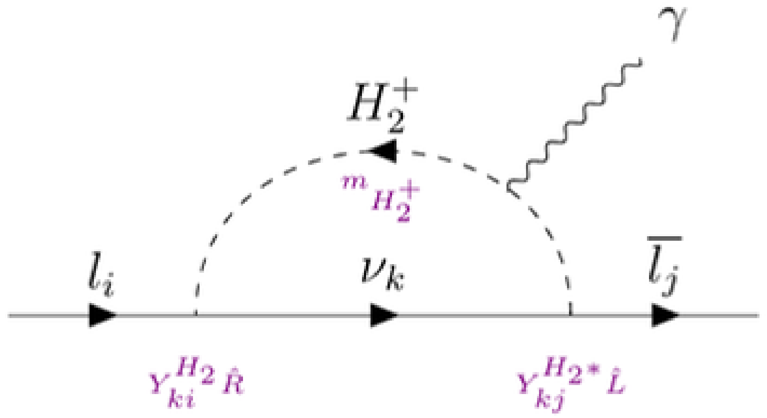
Process	Exp. data	Coupling	Constraint $\left(\frac{m_{H_0}}{GeV}\right)^4$
$\mu^- \to e^- e^+ e^-$	$< 10^{-12}$	$\left\|Y_{ee}^{H_2}\right\|^2 \left\|Y_{e\mu}^{H_2}\right\| \left\|Y_{\mu e}^{H_2}\right\|$	$< 1.45 \times 10^{-21}$
$\tau^- \to e^- e^+ e^-$	$< 2.7 \times 10^{-8}$	$\left\|Y_{ee}^{H_2}\right\|^2 \left\|Y_{e\tau}^{H_2}\right\| \left\|Y_{\tau e}^{H_2}\right\|$	$< 2.24 \times 10^{-16}$
$\tau^- \to \mu^- \mu^+ \mu^-$	$< 2.1 \times 10^{-8}$	$\left\|Y_{\mu\mu}^{H_2}\right\|^2 \left\|Y_{\tau\mu}^{H_2}\right\| \left\|Y_{\mu\tau}^{H_2}\right\|$	$< 1.74 \times 10^{-16}$
$\tau^- \to e^- \mu^+ e^-$	$< 1.5 \times 10^{-8}$	$\left\|Y_{\mu e}^{H_2}\right\| \left\|Y_{e\tau}^{H_2}\right\| \left\|Y_{e\mu}^{H_2}\right\| \left\|Y_{e\tau}^{H_2}\right\|$	$< 1.32 \times 10^{-16}$
$\tau^- \to \mu^- e^+ \mu^-$	$< 1.7 \times 10^{-8}$	$\left\|Y_{e\mu}^{H_2}\right\| \left\|Y_{\mu\tau}^{H_2}\right\| \left\|Y_{e\mu}^{H_2}\right\| \left\|Y_{\tau\mu}^{H_2}\right\|$	$< 1.49 \times 10^{-16}$
$\tau^- \to \mu^- \mu^+ e^-$	$< 2.7 \times 10^{-8}$	$\left\|Y_{\mu e}^{H_2}\right\| \left\|Y_{e\mu}^{H_2}\right\| \left\|Y_{\tau e}^{H_2}\right\| \left\|Y_{e\tau}^{H_2}\right\| + \left\|Y_{\mu\mu}^{H_2}\right\|^2 \left\|Y_{\tau e}^{H_2}\right\| \left\|Y_{e\tau}^{H_2}\right\|$ $-\frac{1}{8}\left\|Y_{\mu\mu}^{H_2}\right\| \left(\left\|Y_{\mu\tau}^{H_2}\right\| \left\|Y_{\mu e}^{H_2}\right\| \left\|Y_{e\tau}^{H_2}\right\| + \left\|Y_{\tau\mu}^{H_2}\right\| \left\|Y_{e\mu}^{H_2}\right\| \left\|Y_{\tau e}^{H_2}\right\|\right)$	$< 1.68 \times 10^{-16}$
$\tau^- \to e^+ \mu^- e^-$	$< 1.8 \times 10^{-8}$	$\left\|Y_{\mu e}^{H_2}\right\| \left\|Y_{e\mu}^{H_2}\right\| \left\|Y_{\tau e}^{H_2}\right\| \left\|Y_{e\tau}^{H_2}\right\| + \left\|Y_{ee}^{H_2}\right\|^2 \left\|Y_{\tau\mu}^{H_2}\right\| \left\|Y_{\mu\tau}^{H_2}\right\|$ $-\frac{1}{8}\left\|Y_{ee}^{H_2}\right\| \left(\left\|Y_{\mu\tau}^{H_2}\right\| \left\|Y_{e\mu}^{H_2}\right\| \left\|Y_{e\tau}^{H_2}\right\| + \left\|Y_{\tau\mu}^{H_2}\right\| \left\|Y_{\mu e}^{H_2}\right\| \left\|Y_{\tau e}^{H_2}\right\|\right)$	$< 1.11 \times 10^{-16}$

Lep-to-lep-gamma decay L-lγ

$$Br\left(l_i \to l_j \gamma\right) = \frac{24\pi^2}{m_i^2 G_F^2}\left(\left|F_2\right|^2 + \left|G_2\right|^2\right) Br\left(l_i \to l_j \nu\overline{\nu}\right)$$







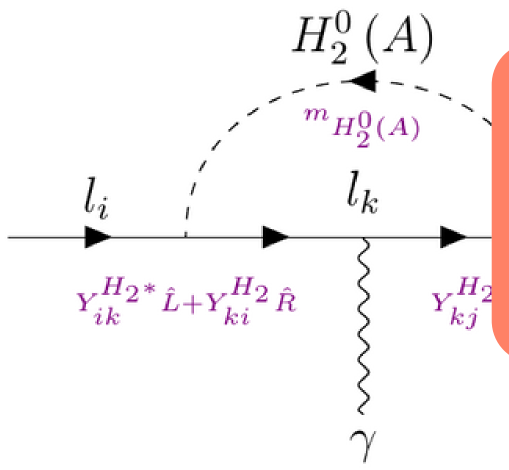
$$\frac{\left|Y_{ij}^{F_2}\right|^2}{m_{S,H_2}^2} = \left[2\frac{\left(Y_{ki}^{H_2}Y_{kj}^{H_2*} + Y_{jk}^{H_2}Y_{ik}^{H_2*}\right)}{m_{H_0}^2} - \sum_{\alpha=S,H_2^+}\frac{Y_{ki}^{\alpha}Y_{kj}^{\alpha*}}{m_\alpha^2}\right],$$

$$\frac{\left|Y_{ij}^{G_2}\right|^2}{m_{S,H_2}^2} = \left[2\frac{\left(Y_{ki}^{H_2}Y_{kj}^{H_2*} - Y_{jk}^{H_2}Y_{ik}^{H_2*}\right)}{m_{H_0}^2} + \sum_{\alpha=S,H_2^+}\frac{Y_{ki}^{\alpha}Y_{kj}^{\alpha*}}{m_\alpha^2}\right].$$

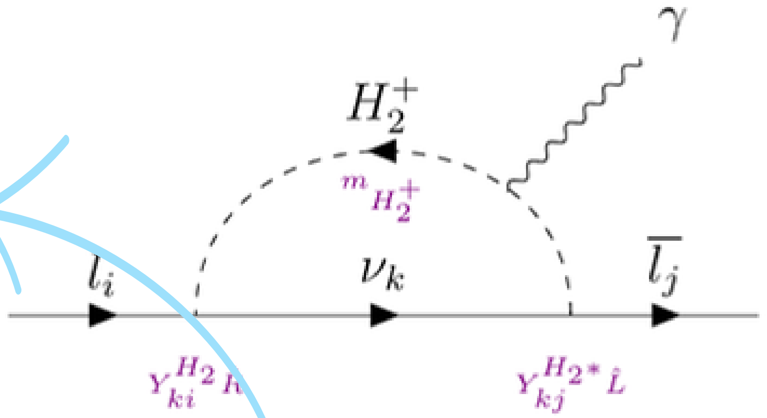
Process	Exp. data	Coupling	Constraint
$\mu^- \to e^-\gamma$	$< 5.7\times10^{-13}$	$\frac{\left\lvert Y_{\mu e}^{G_2}\right\rvert^4}{m_{S,H_2}^4} + \frac{\left\lvert Y_{\mu e}^{F_2}\right\rvert^4}{m_{S,H_2}^4}$	$< 2.93\times10^{-16}$
$\tau^- \to e^-\gamma$	$< 3.3\times10^{-8}$	$\frac{\left\lvert Y_{\tau e}^{G_2}\right\rvert^4}{m_{S,H_2}^4} + \frac{\left\lvert Y_{\tau e}^{F_2}\right\rvert^4}{m_{S,H_2}^4}$	$< 1.70\times10^{-11}$
$\tau^- \to \mu^-\gamma$	$< 4.4\times10^{-8}$	$\frac{\left\lvert Y_{\tau\mu}^{G_2}\right\rvert^4}{m_{S,H_2}^4} + \frac{\left\lvert Y_{\tau\mu}^{F_2}\right\rvert^4}{m_{S,H_2}^4}$	$< 2.26\times10^{-11}$

Lep-to-lep-gamma decay L-lγ

$$Br\left(l_i \to l_j \gamma\right) = \frac{24\pi^2}{m_i^2 G_F^2}\left(|F_2|^2 + |G_2|^2\right) Br\left(l_i \to l_j \nu \overline{\nu}\right)$$



$$\frac{\left|Y^{S,H_2}\right|^2}{m_{S,H_2}^2} < \mathcal{O}\left(10^{-6} - 10^{-7}\right)\,\mathrm{GeV}^{-2}$$



$$\frac{\left|Y_{ij}^{F_2}\right|^2}{m_{S,H_2}^2} = \left[2\frac{\left(Y_{ki}^{H_2}Y_{kj}^{H_2*} + Y_{jk}^{H_2}Y_{ik}^{H_2*}\right)}{m_{H_0}^2} - \sum_{\alpha=S,H_2^+}\frac{Y_{ki}^{\alpha}Y_{kj}^{\alpha*}}{m_\alpha^2}\right],$$

$$\frac{\left|Y_{ij}^{G_2}\right|^2}{m_{S,H_2}^2} = \left[2\frac{\left(Y_{ki}^{H_2}Y_{kj}^{H_2*} - Y_{jk}^{H_2}Y_{ik}^{H_2*}\right)}{m_{H_0}^2} + \sum_{\alpha=S,H_2^+}\frac{Y_{ki}^{\alpha}Y_{kj}^{\alpha*}}{m_\alpha^2}\right].$$

Process	Exp. data	Coupling	Constraint
$\mu^- \to e^-\gamma$	$< 5.7 \times 10^{-13}$	$\frac{\left\|Y_{\mu e}^{G_2}\right\|^4}{m_{S,H_2}^4} + \frac{\left\|Y_{\mu e}^{F_2}\right\|^4}{m_{S,H_2}^4}$	$< 2.93 \times 10^{-16}$
$\tau^- \to e^-\gamma$	$< 3.3 \times 10^{-8}$	$\frac{\left\|Y_{\tau e}^{G_2}\right\|^4}{m_{S,H_2}^4} + \frac{\left\|Y_{\tau e}^{F_2}\right\|^4}{m_{S,H_2}^4}$	$< 1.70 \times 10^{-11}$
$\tau^- \to \mu^-\gamma$	$< 4.4 \times 10^{-8}$	$\frac{\left\|Y_{\tau\mu}^{G_2}\right\|^4}{m_{S,H_2}^4} + \frac{\left\|Y_{\tau\mu}^{F_2}\right\|^4}{m_{S,H_2}^4}$	$< 2.26 \times 10^{-11}$

Lep-to-lep-gamma decay L-lγ

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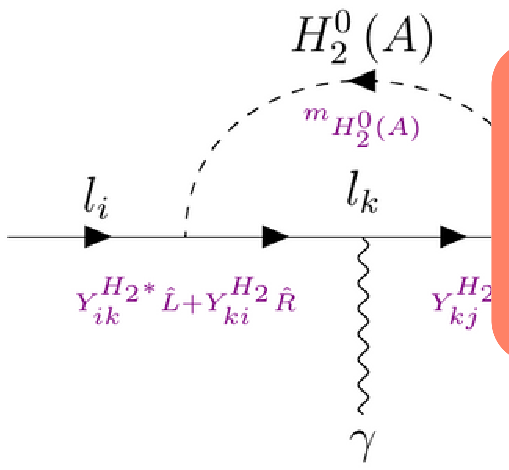
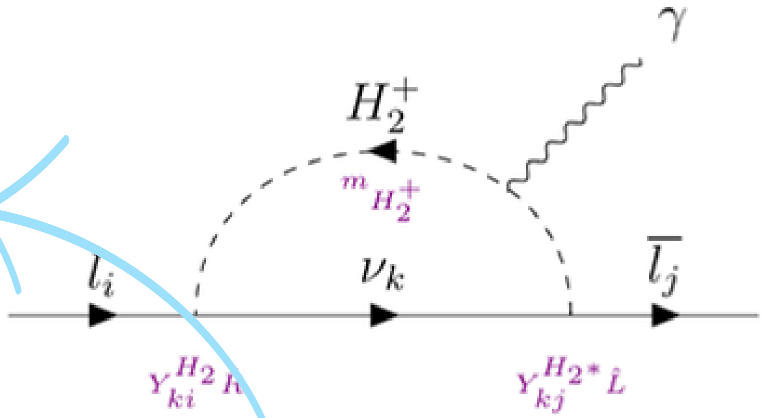


$$\frac{\left|Y^{S,H_2}\right|^2}{m_{S,H_2}^2} < \mathcal{O}\left(10^{-6} - 10^{-7}\right)\,\mathrm{GeV}^{-2}$$



$$\frac{\left|Y_{ij}^{F_2}\right|^2}{m_{S,H_2}^2} = \left[2\frac{\left(Y_{ki}^{H_2}Y_{kj}^{H_2*} + Y_{jk}^{H_2}Y_{ik}^{H_2*}\right)}{m_{H_0}^2} + \sum_{\alpha=S,H_2^+}\frac{Y_{ki}^{\alpha}Y_{kj}^{\alpha*}}{m_\alpha^2}\right],$$

$$\frac{\left|Y_{ij}^{G_2}\right|^2}{m_{S,H_2}^2} = \left[2\frac{\left(Y_{ki}^{H_2}Y_{kj}^{H_2*} - Y_{jk}^{H_2}Y_{ik}^{H_2*}\right)}{m_{H_0}^2} + \sum_{\alpha=S,H_2^+}\frac{Y_{ki}^{\alpha}Y_{kj}^{\alpha*}}{m_\alpha^2}\right].$$

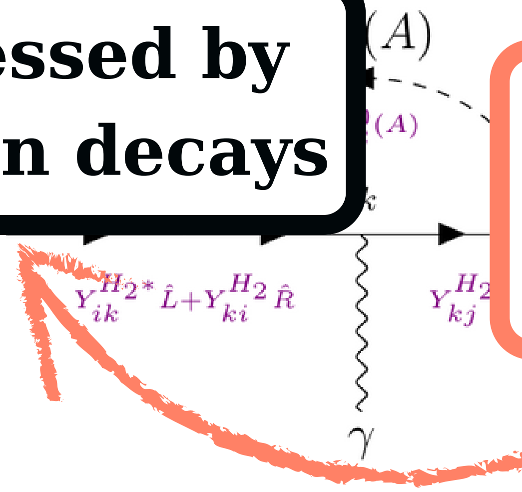
Heavy charged scalar mass

Process	Exp. data	Coupling	Constraint
$\mu^- \to e^-\gamma$	$< 5.7\times10^{-13}$	$\frac{\left\|Y_{\mu e}^{G_2}\right\|^4}{m_{S,H_2}^4} + \frac{\left\|Y_{\mu e}^{F_2}\right\|^4}{m_{S,H_2}^4}$	$< 2.93\times10^{-16}$
$\tau^- \to e^-\gamma$	$< 3.3\times10^{-8}$	$\frac{\left\|Y_{\tau e}^{G_2}\right\|^4}{m_{S,H_2}^4} + \frac{\left\|Y_{\tau e}^{F_2}\right\|^4}{m_{S,H_2}^4}$	$< 1.70\times10^{-11}$
$\tau^- \to \mu^-\gamma$	$< 4.4\times10^{-8}$	$\frac{\left\|Y_{\tau\mu}^{G_2}\right\|^4}{m_{S,H_2}^4} + \frac{\left\|Y_{\tau\mu}^{F_2}\right\|^4}{m_{S,H_2}^4}$	$< 2.26\times10^{-11}$

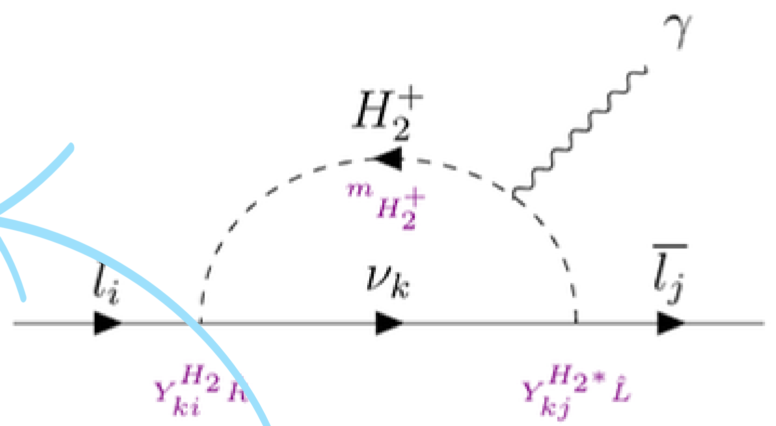
Lep-to-lep-gamma decay L-lγ

$$Br\left(l_i \to l_j\gamma\right) = \frac{24\pi^2}{m_i^2 G_F^2}\left(|F_2|^2 + |G_2|^2\right) Br\left(l_i \to l_j \nu\overline{\nu}\right)$$

Suppressed by Trilepton decays



$$\frac{\left|Y^{S,H_2}\right|^2}{m^2_{S,H_2}} < \mathcal{O}\left(10^{-6} - 10^{-7}\right)\mathrm{GeV}^{-2}$$



$$\frac{\left|Y^{F_2}_{ij}\right|^2}{m^2_{S,H_2}} = \left[2\frac{\left(Y^{H_2}_{ki}Y^{H_2*}_{kj} + Y^{H_2}_{jk}Y^{H_2*}_{ik}\right)}{m^2_{H_0}} + \sum_{\alpha=S,H_2^+}\frac{Y^{\alpha}_{ki}Y^{\alpha*}_{kj}}{m^2_{\alpha}}\right],$$

$$\frac{\left|Y^{G_2}_{ij}\right|^2}{m^2_{S,H_2}} = \left[2\frac{\left(Y^{H_2}_{ki}Y^{H_2*}_{kj} - Y^{H_2}_{jk}Y^{H_2*}_{ik}\right)}{m^2_{H_0}} + \sum_{\alpha=S,H_2^+}\frac{Y^{\alpha}_{ki}Y^{\alpha*}_{kj}}{m^2_{\alpha}}\right].$$

Heavy charged scalar mass

Process	Exp. data	Coupling	Constraint
$\mu^- \to e^-\gamma$	$< 5.7 \times 10^{-13}$	$\frac{\left\lvert Y^{G_2}_{\mu e}\right\rvert^4}{m^4_{S,H_2}} + \frac{\left\lvert Y^{F_2}_{\mu e}\right\rvert^4}{m^4_{S,H_2}}$	$< 2.93 \times 10^{-16}$
$\tau^- \to e^-\gamma$	$< 3.3 \times 10^{-8}$	$\frac{\left\lvert Y^{G_2}_{\tau e}\right\rvert^4}{m^4_{S,H_2}} + \frac{\left\lvert Y^{F_2}_{\tau e}\right\rvert^4}{m^4_{S,H_2}}$	$< 1.70 \times 10^{-11}$
$\tau^- \to \mu^-\gamma$	$< 4.4 \times 10^{-8}$	$\frac{\left\lvert Y^{G_2}_{\tau \mu}\right\rvert^4}{m^4_{S,H_2}} + \frac{\left\lvert Y^{F_2}_{\tau \mu}\right\rvert^4}{m^4_{S,H_2}}$	$< 2.26 \times 10^{-11}$

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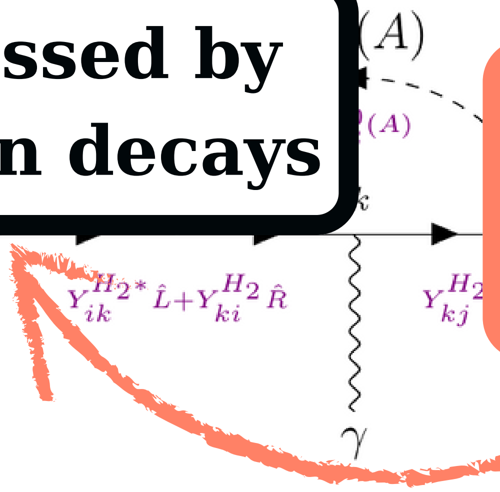

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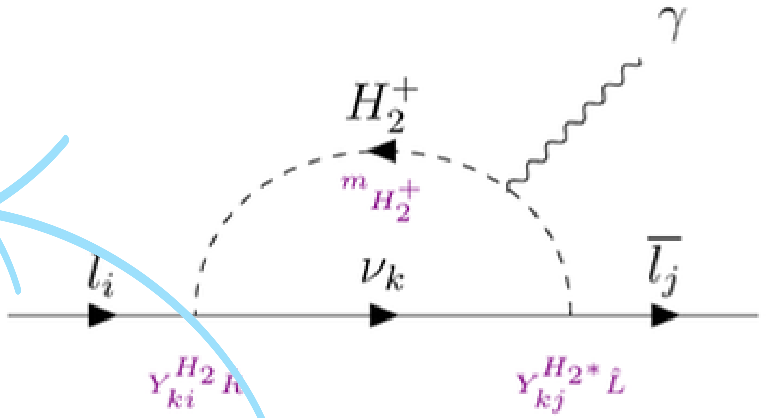

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$$\frac{\left|Y^{G_2}_{ij}\right|^2}{m^2_{S,H_2}} = \left[2\frac{\left(Y^{H_2}_{ki}Y^{H_2*}_{kj} - Y^{H_2}_{jk}Y^{H_2*}_{ik}\right)}{m^2_{H_0}} + \sum_{\alpha=S,H_2^+} \right]$$

SEE IN MUON DECAY

Heavy charged scalar mass

Process	Exp. data	Coupling	Constraint
$\mu^- \to e^-\gamma$	$< 5.7 \times 10^{-13}$	$\frac{\left\lvert Y^{G_2}_{\mu e}\right\rvert^4}{m^4_{S,H_2}} + \frac{\left\lvert Y^{F_2}_{\mu e}\right\rvert^4}{m^4_{S,H_2}}$	$< 2.93 \times 10^{-16}$
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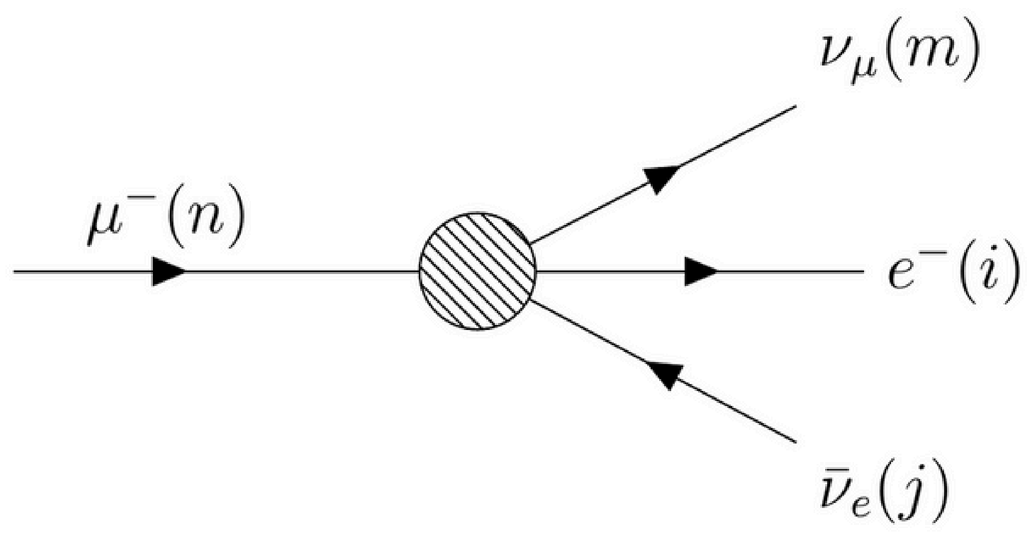
Muon decay



Fermi constant

$$G_F^\mu \qquad \boxed{G_F^Z \equiv G_F^{SM}}$$

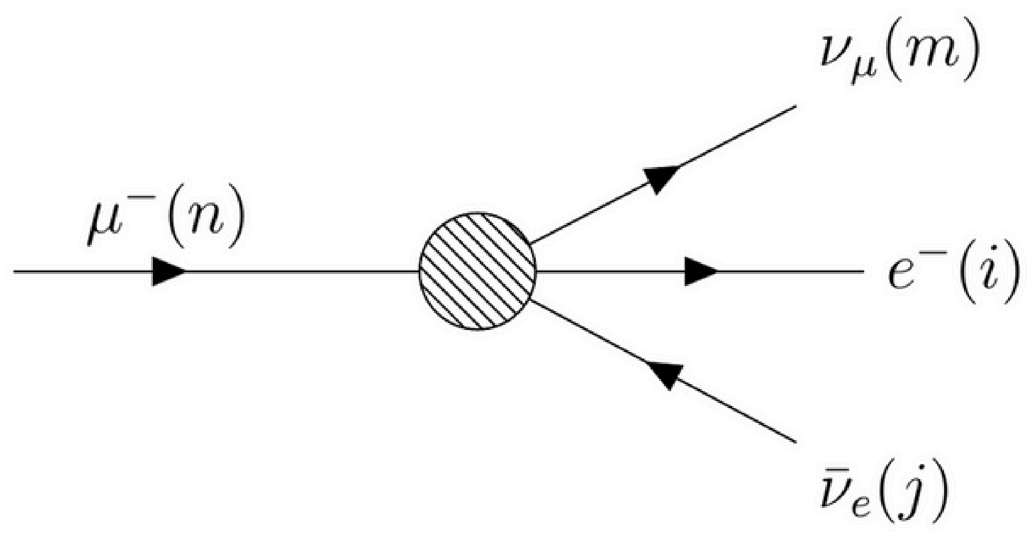
Michel parameters

$$\rho, \delta, \xi$$

$$d\Gamma = \frac{m_\mu^5}{3 * 2^9 * \pi^4} * (a + 4b + 6c) \left\{ 3(1-x) + 2\rho \left(\frac{4}{3}x - 1 \right) - \xi \cos\theta \left[(1-x) + 2\delta \left(\frac{4}{3}x - 1 \right) \right] \right\} x^2 dx$$

3/4 **1** **3/4**

Muon decay



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3/4 **1** **3/4**

$\xi > 1$

Only one chirality in the model

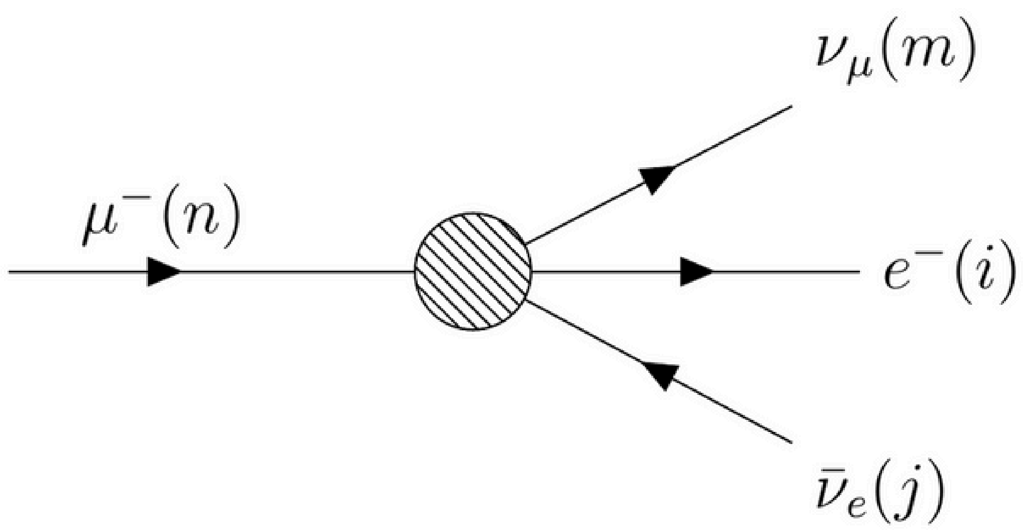
Involving both chirality effect

$\xi \leq 1$

L. Michel, *Interaction between four half spin particles and the decay of the μ meson*, Proc. Phys. Soc. A **63** (1950) 514

Muon decay

- $\rho = 0.74979(26)$
- $\delta = 0.75047(34)$
- $|\xi| = 1.0009^{+0.0016}_{-0.0007}$



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3/4   **1**   **3/4**

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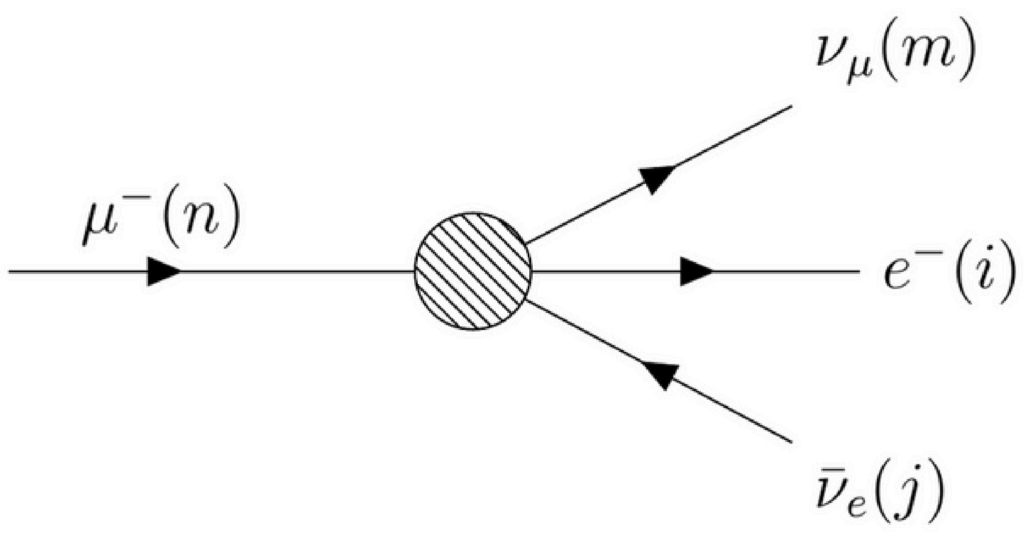

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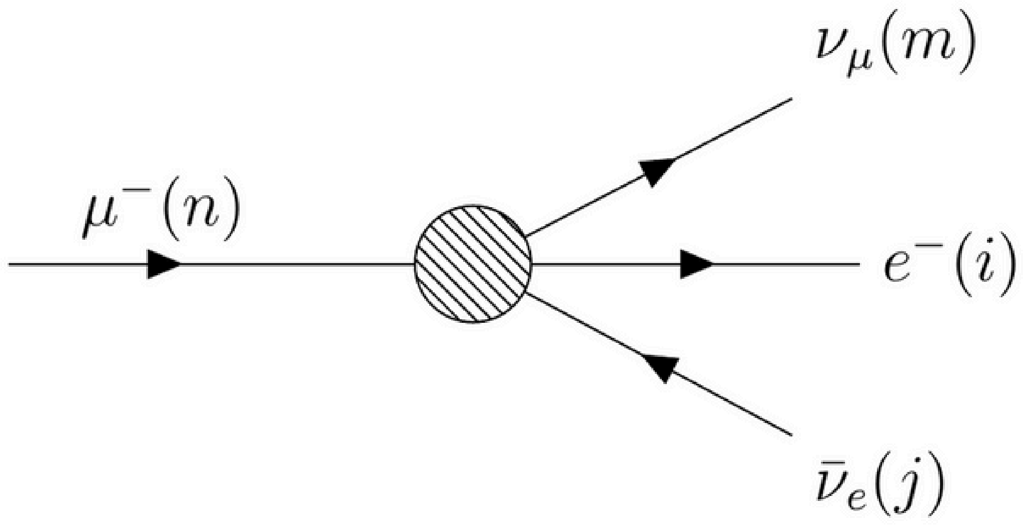

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3/4 **1** **3/4**

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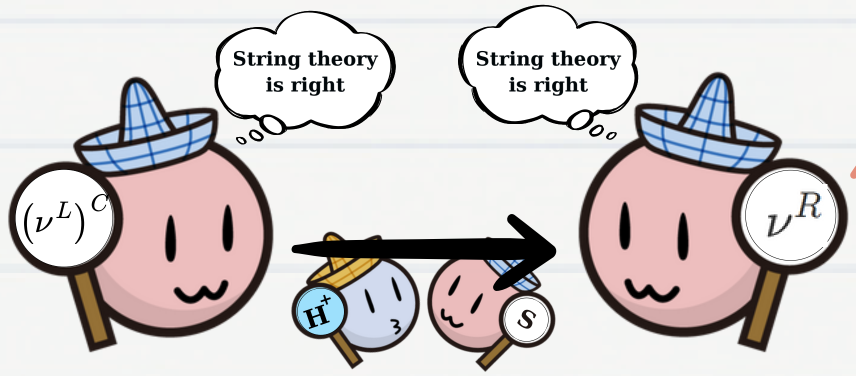

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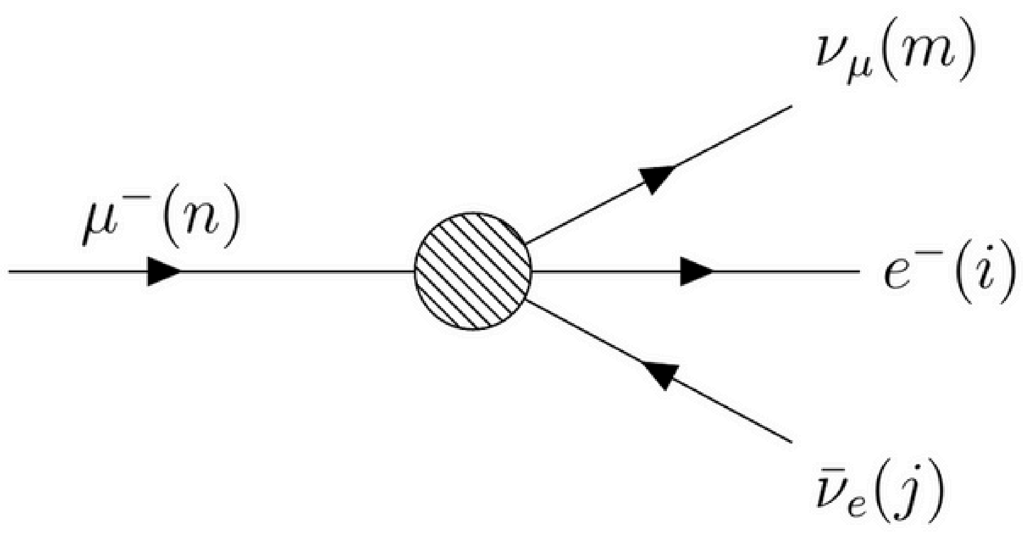

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Michel parameters

$$\rho, \delta, \xi$$

$$-1) -\xi \cos\theta \left[(1-x) + 2\delta\left(\frac{4}{3}x - 1\right)\right]\Bigg\} x^2 dx$$

A favorable reason for the Zee model !

3/4 **1** **3/4**

$\xi > 1$

Involving both chirality effect

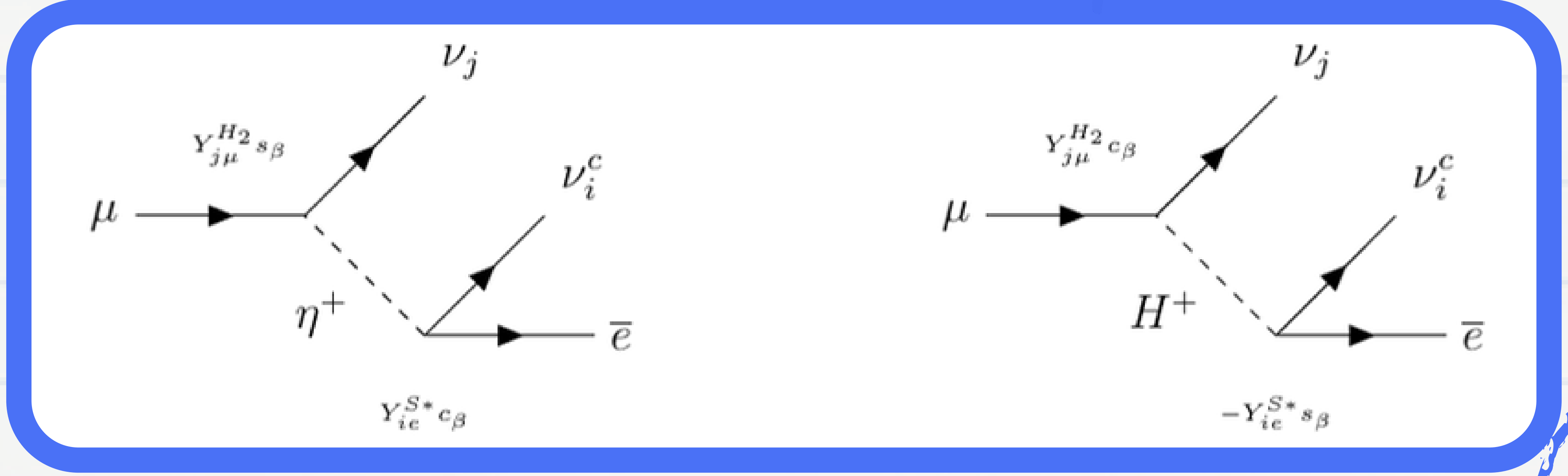
Only one chirality in the model

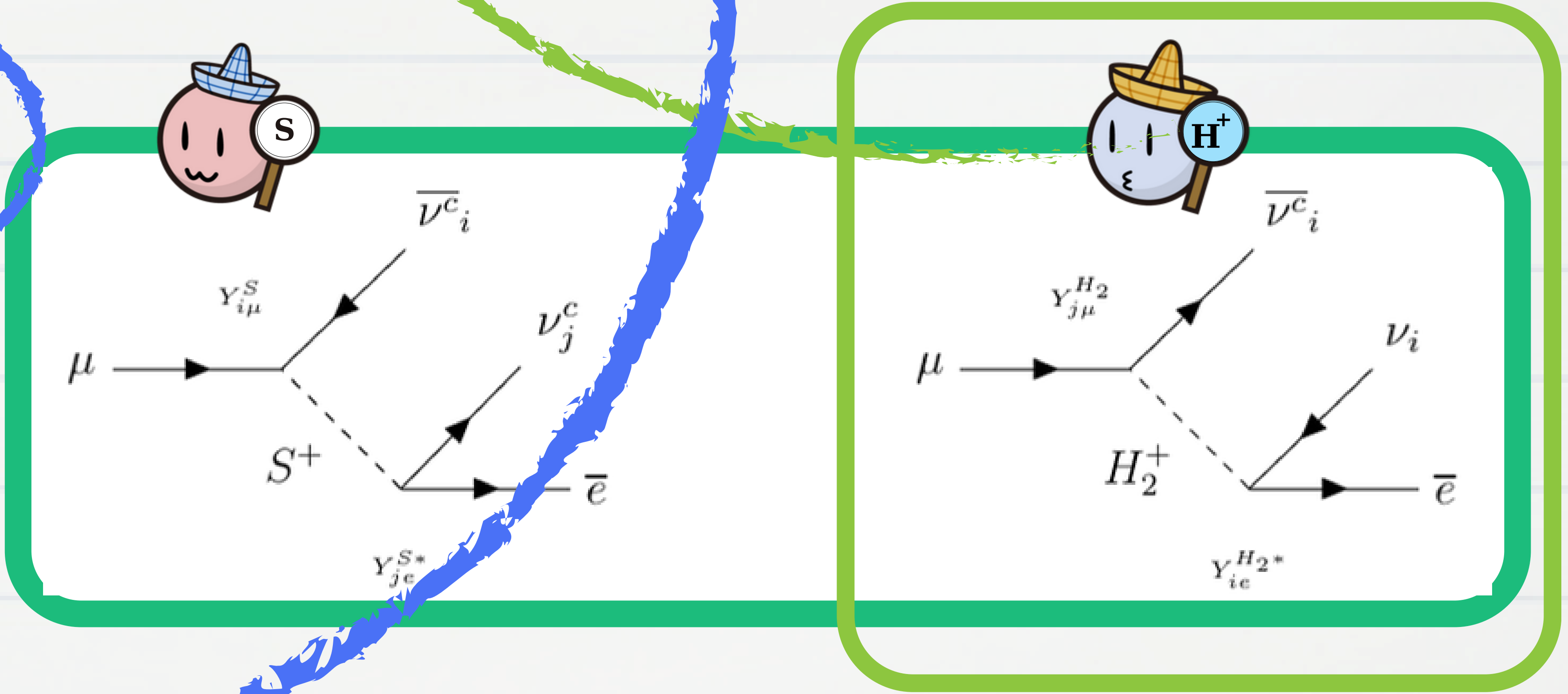
$\xi \leq 1$

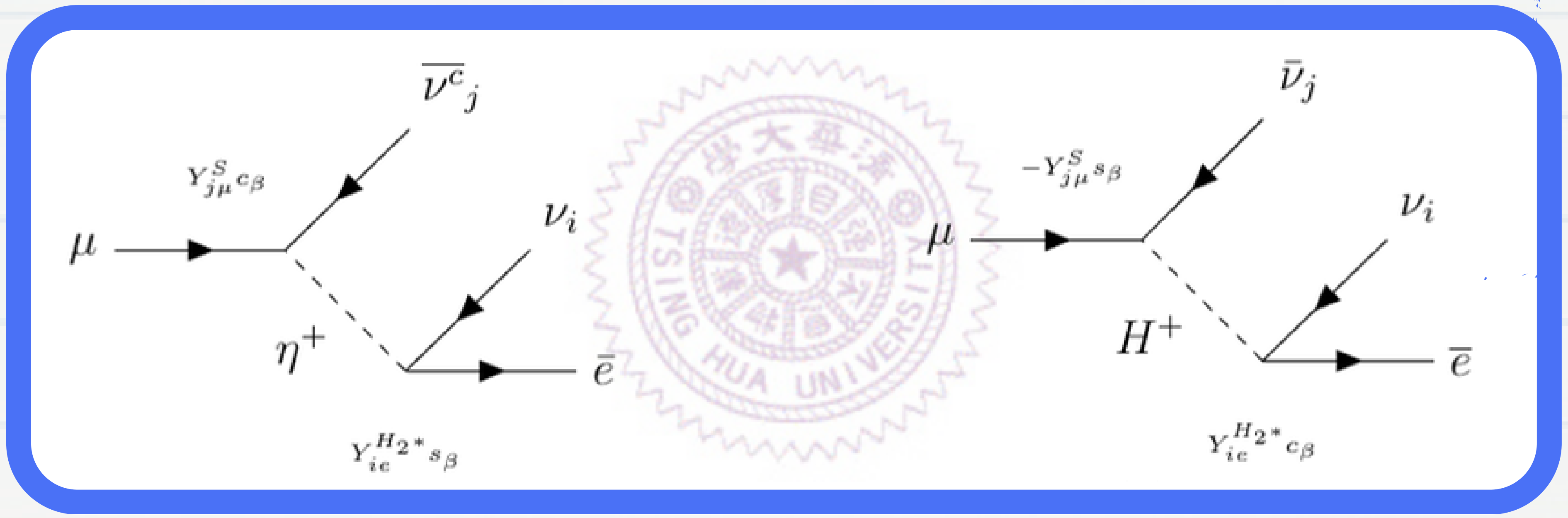
S H^+ $(\nu^L)^C$ ν^R

Zee model in Muon decay

$$d\Gamma = \frac{m_\mu^5}{3 * 2^9 * \pi^4} * (a + 4b + 6c) \left\{ 3(1-x) + 2\rho\left(\frac{4}{3}x - 1\right) - \xi \cos\theta \left[(1-x) + 2\delta\left(\frac{4}{3}x - 1\right)\right]\right\} x^2 dx$$







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$$\triangle\rho = \frac{3}{16} \left(\frac{1}{m_{\eta^+}^2} - \frac{1}{m_{H^+}^2} \right)^2 \frac{c_\beta^2 s_\beta^2}{a + 4b + 6c} \mathrm{Re} \left(Y_{j\mu}^{H_2} Y_{ie}^{S*} Y_{i\mu}^{H_2*} Y_{je}^{S} + Y_{j\mu}^{S} Y_{ie}^{H_2*} Y_{i\mu}^{S*} Y_{je}^{H_2} \right)$$
$$= (-47 - 5) \times 10^{-5},$$

$$\triangle G_F^2 = \frac{G_F^{SM}}{2\sqrt{2} m_S^2} \left| Y_{e\mu}^S \right|^2 + \frac{1}{32 m_S^4} \sum_{i,j} \left| Y_{i\mu}^S \right|^2 \left| Y_{je}^S \right|^2 + \frac{1}{32 m_{H_2^+}^4} \sum_{i,j} \left| Y_{i\mu}^{H_2} \right|^2 \left| Y_{je}^{H_2} \right|^2 + \frac{a + 6c}{8}$$
$$= (-1.6 - 3.6) \times 10^{-13}.$$

$$\Delta\delta = \frac{21}{16} \left(\frac{1}{m_{\eta^+}^2} - \frac{1}{m_{H^+}^2} \right)^2 \frac{c_\beta^2 s_\beta^2}{-3a' + 4b' - 14c'} \mathrm{Re} \left(Y_{j\mu}^{H_2} Y_{ie}^{S*} Y_{i\mu}^{H_2*} Y_{je}^{S} - Y_{j\mu}^{S} Y_{ie}^{H_2*} Y_{i\mu}^{S*} Y_{je}^{H_2} \right)$$
$$= (1.3 - 8.1) \times 10^{-4}.$$

$$\Delta\xi = \frac{1}{2} \left(\frac{1}{m_{\eta^+}^2} - \frac{1}{m_{H^+}^2} \right)^2 \frac{c_\beta^2 s_\beta^2}{a + 4b + 6c} \mathrm{Re} \left(Y_{j\mu}^{S} Y_{ie}^{H_2*} Y_{i\mu}^{S*} Y_{je}^{H_2} - \frac{3}{2} Y_{j\mu}^{H_2} Y_{ie}^{S*} Y_{i\mu}^{H_2*} Y_{je}^{S} \right)$$
$$- \frac{1}{2} \left(\frac{1}{m_{\eta^+}^2} - \frac{1}{m_{H^+}^2} \right)^2 \frac{c_\beta^2 s_\beta^2}{a + 4b + 6c} \left(\left| Y_{j\mu}^{H_2} \right|^2 \left| Y_{ie}^{S} \right|^2 + \left| Y_{i\mu}^{H_2} \right|^2 \left| Y_{je}^{S} \right|^2 \right) - \frac{1}{8 m_{H_2^+}^4} \sum_{i,j} \frac{\left| Y_{i\mu}^{H_2} \right|^2 \left| Y_{je}^{H_2} \right|^2}{a + 4b + 6c}$$
$$= (2 - 25) \times 10^{-4},$$

Zee model in Muon decay

$$d\Gamma = \frac{m_\mu^5}{3 * 2^9 * \pi^4} * (a+4b+6c)\left\{3(1-x) + 2\rho\left(\frac{4}{3}x - 1\right) - \xi\cos\theta\left[(1-x) + 2\delta\left(\frac{4}{3}x-1\right)\right]\right\} x^2 dx$$

$$\triangle\rho = \frac{3}{16}\left(\frac{1}{m_{\eta^+}^2} - \frac{1}{m_{H^+}^2}\right)^2 \frac{c_\beta^2 s_\beta^2}{a+4b+6c}\mathrm{Re}\left(Y_{j\mu}^{H_2} Y_{ie}^{S*} Y_{i\mu}^{H_2*} Y_{je}^{S} + Y_{j\mu}^{S} Y_{ie}^{H_2*} Y_{i\mu}^{S*} Y_{je}^{H_2}\right)$$
$$= (-47-5)\times 10^{-5},$$

$$\triangle G_F^2 = \frac{G_F^{SM}}{2\sqrt{2}m_S^2}\left|Y_{e\mu}^S\right|^2 + \frac{1}{32 m_S^4}\sum_{i,j}\left|Y_{i\mu}^S\right|^2\left|Y_{je}^S\right|^2 + \frac{1}{32 m_{H_2^+}^4}\sum_{i,j}\left|Y_{i\mu}^{H_2}\right|^2\left|Y_{je}^{H_2}\right|^2 + \frac{a+6c}{8}$$
$$= (-1.6-3.6)\times 10^{-13}.$$

$$\Delta\delta = \frac{21}{16}\left(\frac{1}{m_{\eta^+}^2} - \frac{1}{m_{H^+}^2}\right)^2 \frac{c_\beta^2 s_\beta^2}{-3a' + 4b' - 14c'}\mathrm{Re}\left(Y_{i\mu}^{H_2} Y_{ie}^{S*} Y_{i\mu}^{H_2*} Y_{je}^{S} - Y_{j\mu}^{S} Y_{ie}^{H_2*} Y_{i\mu}^{S*} Y_{je}^{H_2}\right)$$
$$= (1.3-8.1)\times 10^{-4}.$$

$$\Delta\xi = \frac{1}{2}\left(\frac{1}{m_{\eta^+}^2} - \frac{1}{m_{H^+}^2}\right)^2 \frac{c_\beta^2 s_\beta^2}{a+4b+6c}\mathrm{Re}\left(Y_{j\mu}^{S} Y_{ie}^{H_2*} Y_{i\mu}^{S*} Y_{je}^{H_2} - \frac{3}{2} Y_{j\mu}^{H_2} Y_{ie}^{S*} Y_{i\mu}^{H_2*} Y_{je}^{S}\right)$$
$$- \frac{1}{2}\left(\frac{1}{m_{\eta^+}^2} - \frac{1}{m_{H^+}^2}\right)^2 \frac{c_\beta^2 s_\beta^2}{a+4b+6c}\left(\left|Y_{j\mu}^{H_2}\right|^2\left|Y_{ie}^{S}\right|^2 + \left|Y_{i\mu}^{H_2}\right|^2\left|Y_{je}^{S}\right|^2\right) - \frac{1}{8 m_{H_2^+}^4}\sum_{i,j}\frac{\left|Y_{i\mu}^{H_2}\right|^2\left|Y_{je}^{H_2}\right|^2}{a+4b+6c}$$
$$= (2-25)\times 10^{-4},$$

$$c_\beta s_\beta \equiv s_{2\beta} \approx \beta > \mathcal{O}\left(10^{-2}\right)$$

Zee model in Muon decay

$$d\Gamma = \frac{m_\mu^5}{3 * 2^9 * \pi^4} * (a+4b+6c)\left\{3(1-x) + 2\rho\left(\frac{4}{3}x - 1\right) - \xi\cos\theta\left[(1-x) + 2\delta\left(\frac{4}{3}x - 1\right)\right]\right\} x^2 dx$$

$$\Delta\rho = \frac{3}{16}\left(\frac{1}{m_{\eta^+}^2} - \frac{1}{m_{H^+}^2}\right)^2 \frac{c_\beta^2 s_\beta^2}{a+4b+6c}\mathrm{Re}\left(Y_{j\mu}^{H_2} Y_{ie}^{S*} Y_{i\mu}^{H_2*} Y_{je}^{S} + Y_{j\mu}^{S} Y_{ie}^{H_2*} Y_{i\mu}^{S*} Y_{je}^{H_2}\right)$$
$$= (-47 - 5) \times 10^{-5},$$

$$\triangle G_F^2 = \frac{G_F^{SM}}{2\sqrt{2}m_S^2}\left|Y_{e\mu}^S\right|^2 + \frac{1}{32 m_S^4}\sum_{i,j}\left|Y_{i\mu}^S\right|^2\left|Y_{je}^S\right|^2 + \frac{1}{32 m_{H_2^+}^4}\sum_{i,j}\left|Y_{i\mu}^{H_2}\right|^2\left|Y_{je}^{H_2}\right|^2 + \frac{a+6c}{8}$$
$$= (-1.6 - 3.6) \times 10^{-13}.$$

$$\Delta\delta = \frac{21}{16}\left(\frac{1}{m_{\eta^+}^2} - \frac{1}{m_{H^+}^2}\right)^2 \frac{c_\beta^2 s_\beta^2}{-3a' + 4b' - 14c'}\mathrm{Re}\left(Y_{j\mu}^{H_2} Y_{ie}^{S*} Y_{i\mu}^{H_2*} Y_{je}^{S} - Y_{j\mu}^{S} Y_{ie}^{H_2*} Y_{i\mu}^{S*} Y_{je}^{H_2}\right)$$
$$= (1.3 - 8.1) \times 10^{-4}.$$

$$\Delta\xi = \frac{1}{2}\left(\frac{1}{m_{\eta^+}^2} - \frac{1}{m_{H^+}^2}\right)^2 \frac{c_\beta^2 s_\beta^2}{a+4b+6c}\mathrm{Re}\left(Y_{j\mu}^{S} Y_{ie}^{H_2*} Y_{i\mu}^{S*} Y_{je}^{H_2} - \frac{3}{2} Y_{j\mu}^{H_2} Y_{ie}^{S*} Y_{i\mu}^{H_2*} Y_{je}^{S}\right)$$
$$- \frac{1}{2}\left(\frac{1}{m_{\eta^+}^2} - \frac{1}{m_{H^+}^2}\right)^2 \frac{c_\beta^2 s_\beta^2}{a+4b+6c}\left(\left|Y_{j\mu}^{H_2}\right|^2\left|Y_{ie}^{S}\right|^2 + \left|Y_{i\mu}^{H_2}\right|^2\left|Y_{je}^{S}\right|^2\right) - \frac{1}{8 m_{H_2^+}^4}\sum_{i,j}\frac{\left|Y_{i\mu}^{H_2}\right|^2\left|Y_{je}^{H_2}\right|^2}{a+4b+6c}$$
$$= (2 - 25) \times 10^{-4},$$

$$c_\beta s_\beta \equiv s_{2\beta} \approx \beta > \mathcal{O}\left(10^{-2}\right)$$

$$\frac{\left|Y^{S,H_2}\right|^2}{m_{S,H_2^+}^2} < \left(10^{-6} - 10^{-5}\right)\ \mathrm{GeV}^{-2}$$

Conclusion

Exp.	Coupling form	Order of magnitude
Michel Parameters at 1σ	$\frac{\lvert Y^{S,H_2}\rvert^2}{m^2_{S,H_2^+}}$	$\sim (10^{-6} - 10^{-5})\ \mathrm{GeV}^{-2}$
Michel Parameters at 2σ	$\frac{\lvert Y^{S,H_2}\rvert^2}{m^2_{S,H_2^+}}$	$< (10^{-6} - 10^{-5})\ \mathrm{GeV}^{-2}$
G_F	$\frac{\lvert Y^{S,H_2}\rvert^2}{m^2_{S,H_2^+}}$	$< (10^{-6} - 10^{-5})\ \mathrm{GeV}^{-2}$
Neutrino mass	$\lvert Y^{S,H_2}\rvert^2$	$\sim (10^{-6} - 10^{-4})$
$l_i \to l_j \bar{l}_m l_n$	$\frac{\lvert Y^{H_2}\rvert^2}{m^2_{H_0}}$	$< (10^{-9} - 10^{-8})\ \mathrm{GeV}^{-2}$
$L \to l\gamma$	$\frac{\lvert Y^{S,H_2}\rvert^2}{m^2_{S,H_2}}$	$< (10^{-7} - 10^{-6})\ \mathrm{GeV}^{-2}$

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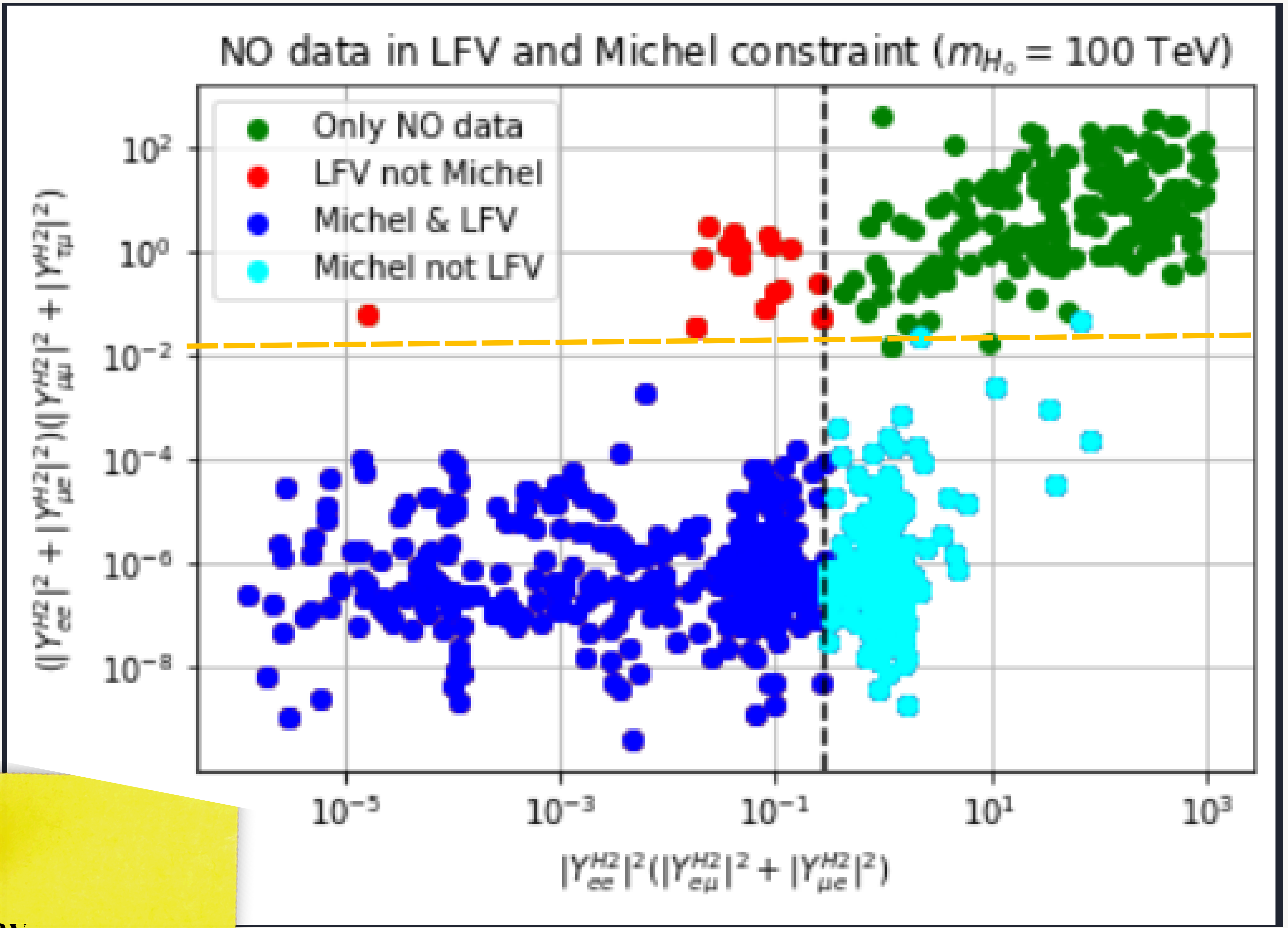
Outlook



Reach current experimental limit of scalar mass at $\mathcal{O}(1)$ TeV to explore the usefulness of the Michel parameter constraint on the Zee model.

Just for illustration, $c_\beta = 0.9$, $m_{H_0} = 100$ TeV, $m_{H^+} = 210$ and $m_{\eta^+} = 200$ GeV

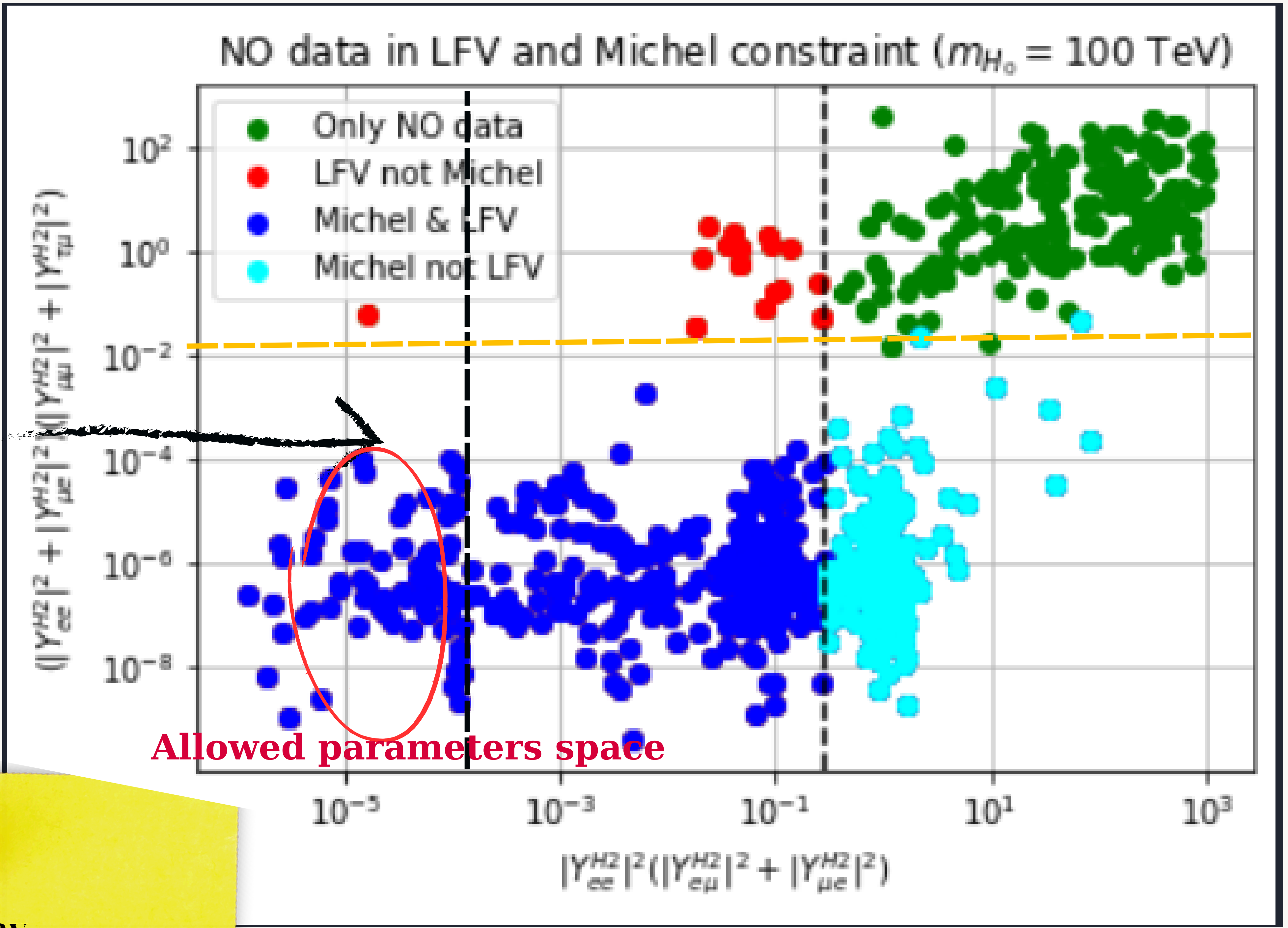
LFV = Trilepton decay

NO = Neutrino oscillation

Michel = Michel paramter \xi from muon decay

Outlook

$m_{H_0} = 10$ TeV



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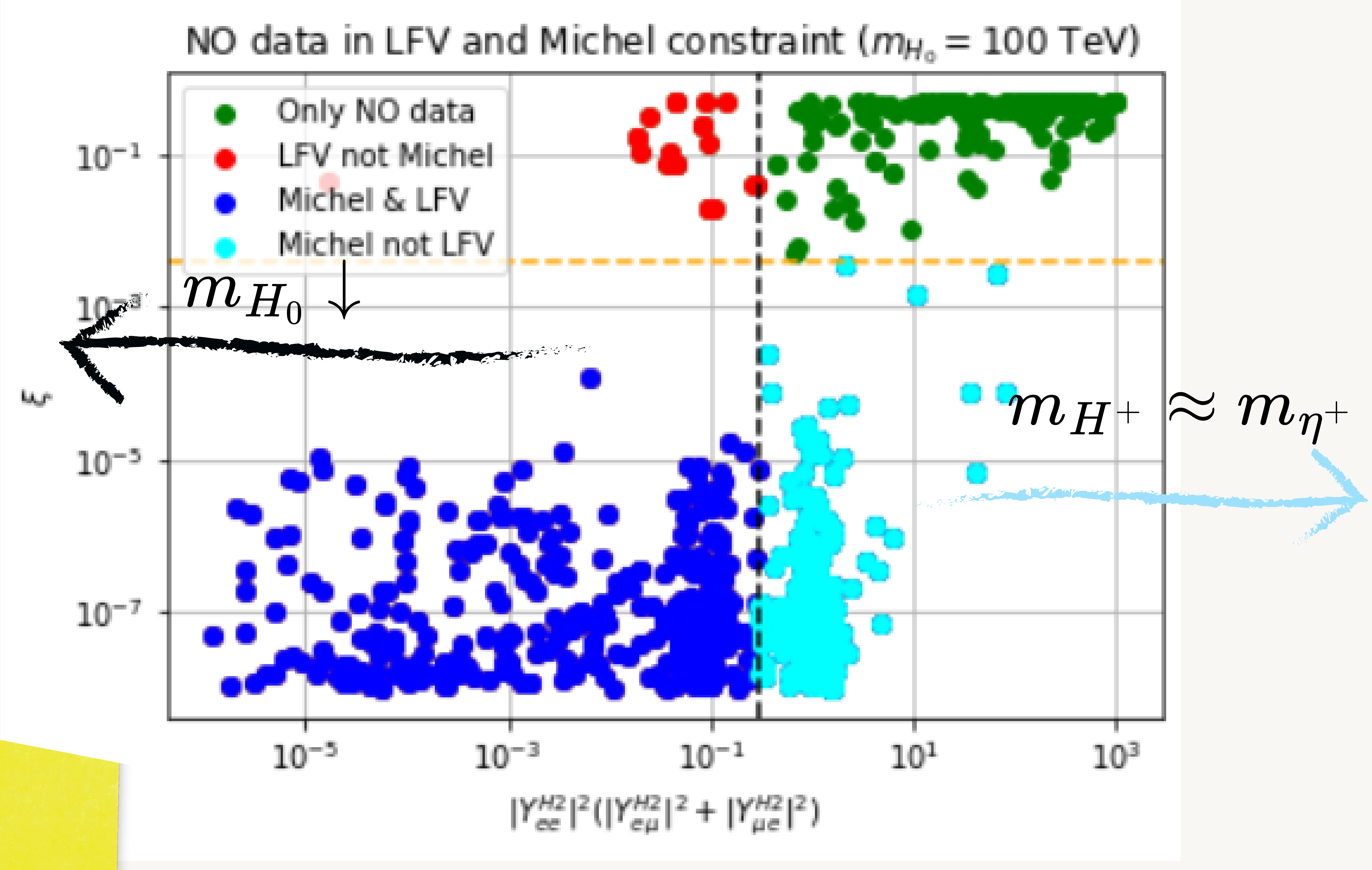
Thank's For Listening



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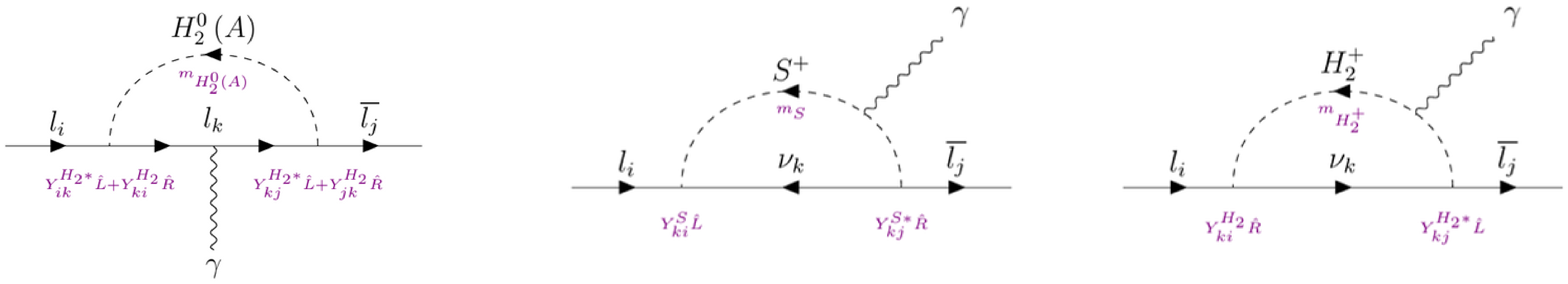
Lep-to-lep-gamma decay L-lγ

$$Br\left(l_i \to l_j \gamma\right) = \frac{24\pi^2}{m_i^2 G_F^2}\left(|F_2|^2 + |G_2|^2\right) Br\left(l_i \to l_j \nu \overline{\nu}\right)$$



$$F_2^{H_2^0(A)} = \frac{e}{3.2^7\pi^2}\frac{m_i+m_j}{m^2_{H_2^0(A)}}\left[\left(Y_{ki}^{H_2}Y_{kj}^{H_2*} + Y_{jk}^{H_2}Y_{ik}^{H_2*}\right)\right.$$
$$\left.\mp\frac{3m_k}{m_i+m_j}\left(3+4\log\frac{m_k}{m_{H_2^0(A)}}\right)\left(Y_{ki}^{H_2}Y_{jk}^{H_2} + Y_{ik}^{H_2*}Y_{kj}^{H_2*}\right)\right],$$

$$G_2^{H_2^0(A)} = \frac{e}{3.2^7\pi^2}\frac{m_i-m_j}{m^2_{H_2^0(A)}}\left[\left(Y_{ki}^{H_2}Y_{kj}^{H_2*} - Y_{jk}^{H_2}Y_{ik}^{H_2*}\right)\right.$$
$$\left.\pm\frac{3m_k}{m_i-m_j}\left(3+4\log\frac{m_k}{m_{H_2^0(A)}}\right)\left(Y_{ki}^{H_2}Y_{jk}^{H_2} - Y_{ik}^{H_2*}Y_{kj}^{H_2*}\right)\right].$$

$$F_2^{H_2^+(S^+)} = \frac{-e}{3.2^7\pi^2}\frac{m_i+m_j}{m^2_{H_2^+(S)}}Y_{ki}^{H_2(S)}Y_{kj}^{H_2(S)*},$$

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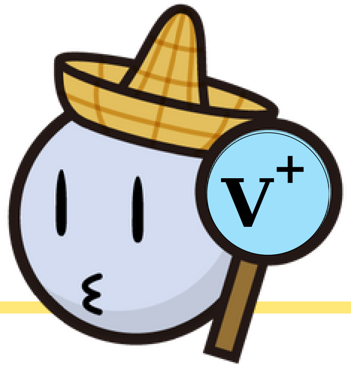
Anomalous magnetic moment (g-2)

$$i\mathcal{M}^{\nu} = \bar{l}\,\sigma^{\mu\nu}\,\left(F_2 + G_2\gamma_5\right) l\, q_{\mu}$$

$$a_l = \frac{(g-2)}{2} = \frac{2m_l F_2}{-eQ_l}$$



$$F_2^V = \frac{e}{3.2^7 m_V^2 \pi^2}\Big[(m_i + m_j)\left(Q_V - 8Q_k + 9aQ_V\right)\left(V_L^{*ki}V_L^{kj} + V_R^{*ki}V_R^{kj}\right) - 6m_k\left(5a-1\right)Q_V\left(V_L^{*ki}V_R^{kj} + V_R^{*ki}V_L^{kj}\right)\Big]$$

$$F_2^{\phi} = \frac{-e}{3.2^7 m_{\phi}^2 \pi^2}\Big[(m_i + m_j)\left(Q_{\phi} - 2Q_k\right)\left(Y_L^{*ki}Y_L^{kj} + Y_R^{*ki}Y_R^{kj}\right) + 6m_k\left(Q_{\phi} + 3Q_k + 2Q_k \log\left[\frac{m_k^2}{m_{\phi}^2}\right]\right)\left(Y_L^{*ki}Y_R^{kj} + Y_R^{*ki}Y_L^{kj}\right)\Big]$$

Michel parameters

$$\frac{d\Gamma}{d\Omega} = \frac{m_\mu^5}{3\cdot 2^9\cdot \pi^4}(a+4b+6c)\left\{3(1-x)+2\rho\left(\frac{4}{3}x-1\right)-\xi\cos\theta\left[(1-x)+2\delta\left(\frac{4}{3}x-1\right)\right]\right\}x^2\,dx$$

$$a = \frac{\left|Y_{ij}^L Y_{nm}^{R*}\right|^2+\left|Y_{ij}^R Y_{nm}^{L*}\right|^2}{16m_\phi^4}$$

$$a' = \frac{\left|Y_{ij}^L Y_{nm}^{R*}\right|^2-\left|Y_{ij}^R Y_{nm}^{L*}\right|^2}{16m_\phi^4}$$

$$b = \frac{\left|Y_{ij}^L Y_{nm}^{L*}\right|^2+\left|Y_{ij}^R Y_{nm}^{R*}\right|^2}{16m_\phi^4}+\frac{g^4}{16m_W^4}$$

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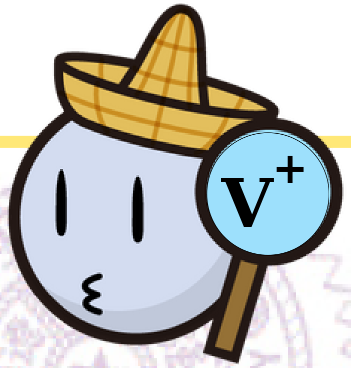
$$c = \frac{\left|Y_{ij}^L Y_{nm}^{R*}\right|^2+\left|Y_{ij}^R Y_{nm}^{L*}\right|^2}{32m_\phi^4}$$

$$c' = \frac{\left|Y_{ij}^R Y_{nm}^{L*}\right|^2-\left|Y_{ij}^L Y_{nm}^{R*}\right|^2}{32m_\phi^4},$$



$$a = \frac{\left|V_{ij}^L V_{nm}^{R*}\right|^2+\left|V_{ij}^R V_{nm}^{L*}\right|^2}{m_V^4}$$

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$$\rho = \frac{3b+6c}{a+4b+6c}$$

$$\delta = \frac{3b'-6c'}{-3a'+4b'-14c'}$$

$$\xi = \frac{3a'-4b'+14c'}{a+4b+6c}.$$