On the Origin of Neutrino Masses

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CASE WESTERN RESERVE UNIVERSITY EST. 1826
think beyond the possible

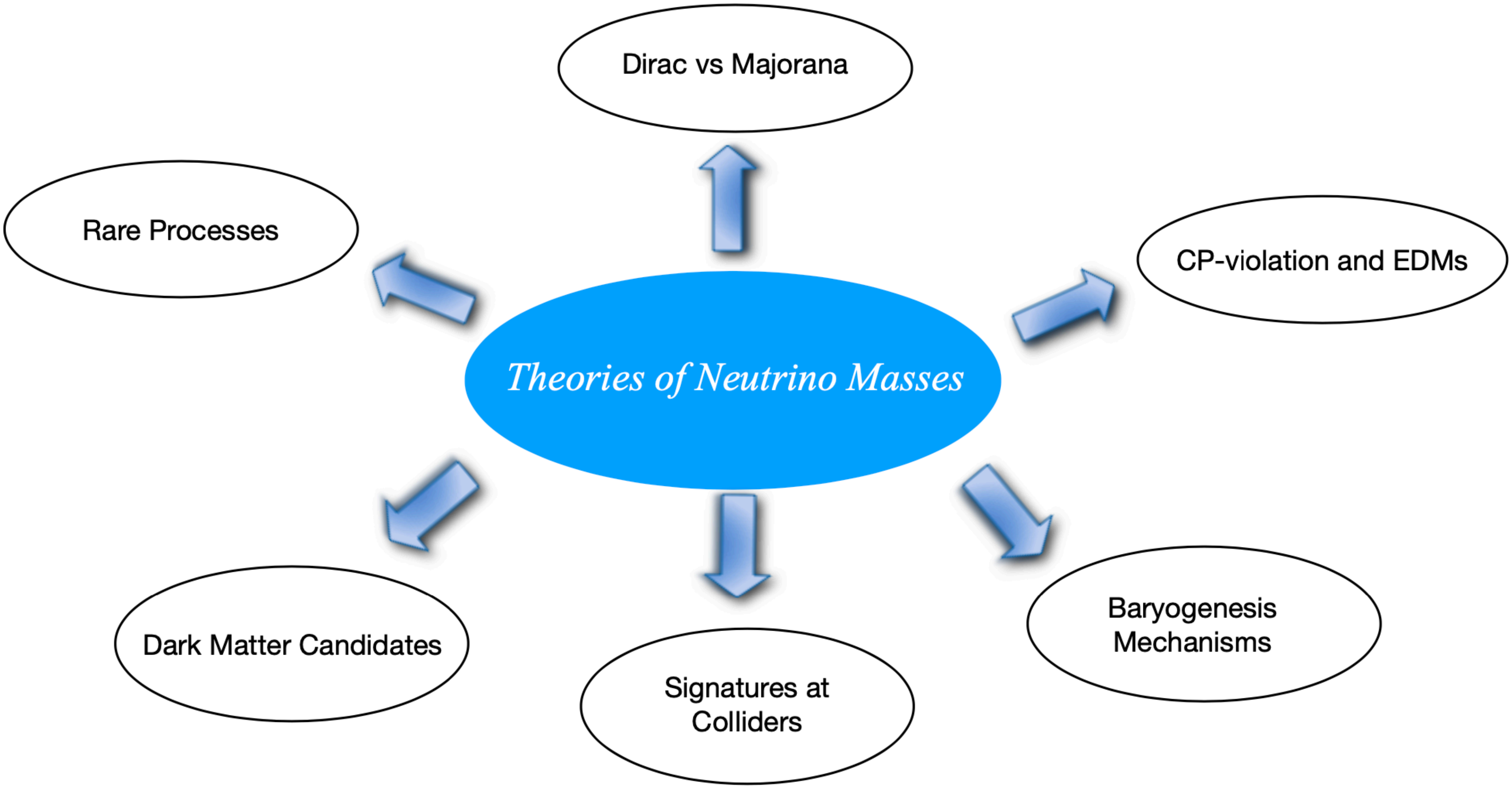
Theory Meets Experiments
"Neutrinoless double beta decay: the experimental programme and its fundamental and nuclear theory connections"
Galileo Galilei Institute for Theoretical Physics, Florence, Italy, Nov 2024

Massive Neutrinos

What is the origin of neutrino masses ?

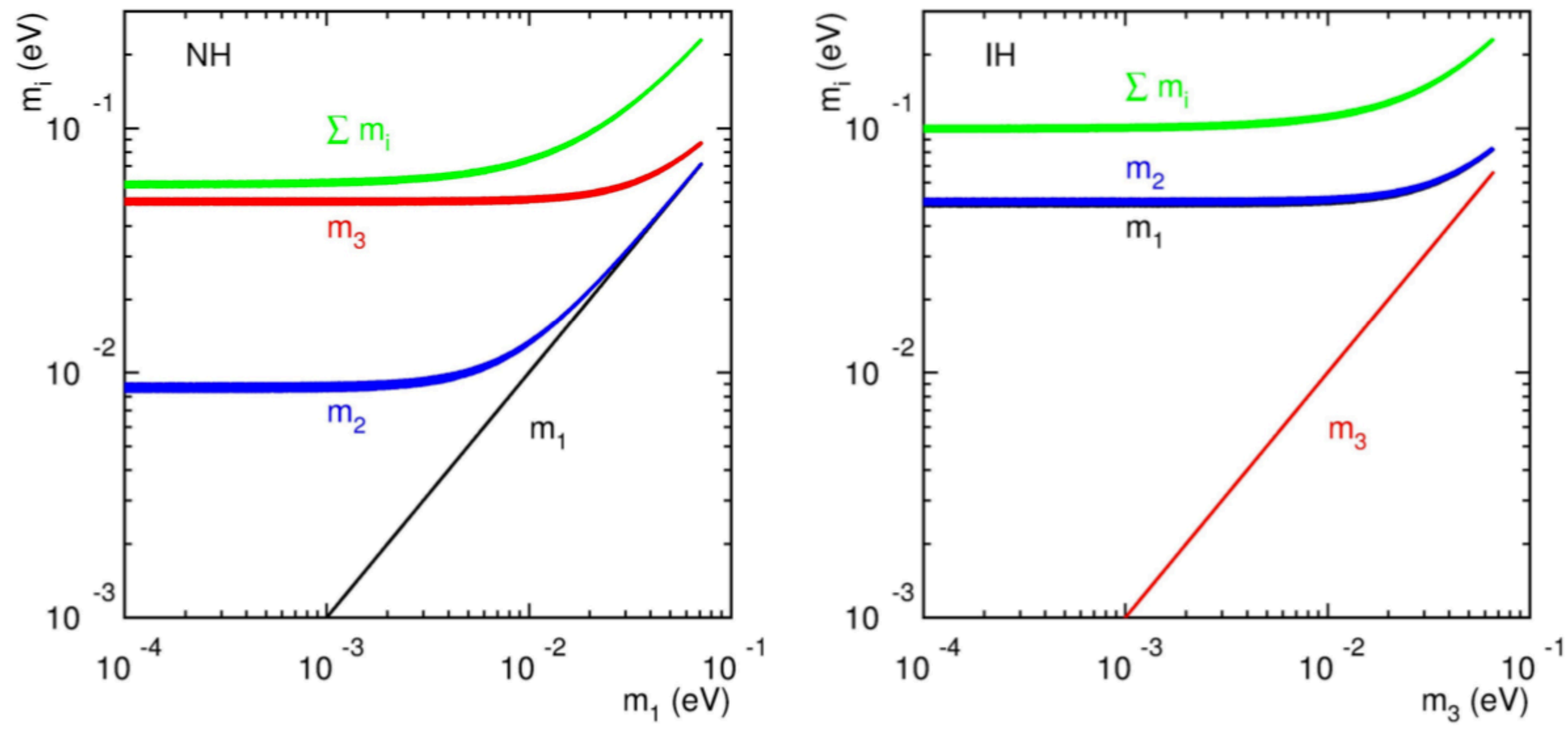
How do we test the theory of neutrino masses ?

Main Goal


Dirac vs Majorana
Rare Processes
CP-violation and EDMs
Theories of Neutrino Masses
Dark Matter Candidates
Signatures at Colliders
Baryogenesis Mechanisms

Massive Neutrinos

Normal Hierarchy *Inverted Hierarchy*



(a) (b)

Leptons in the SM

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

$$\ell^i_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \sim (1, 2, -1/2)$$

$$e^i_R = e_R, \mu_R, \tau_R \sim (1, 1, -1)$$

Leptonic Masses in the SM

$$\mathcal{L}_{SM} \ni y_e^{ij}\, \bar{l}_L^i H e_R^j + h.c.$$

where $$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \sim (1, 2, 1/2)$$

After SSB: $$\phi^0 \to \frac{v + h^0 + i A^0}{\sqrt{2}}$$

Leptonic Masses in the SM

$$\mathcal{L}_{SM} \xrightarrow{SSB} Y_e^{ij}\frac{v}{\sqrt{2}}\,\bar{e}_L^i e_R^j + Y_e^{ij}\frac{h^0}{\sqrt{2}}\,\bar{e}_L^i e_R^j + h.c.$$

$$e_L \to E_L\, e_L \quad ; \quad e_R \to E_R\, e_R$$

$$\Rightarrow \quad M_e^i\, \bar{e}_L^i e_R^i + \frac{M_e^i}{v}\,\bar{e}_L^i e_R^i h^0 + h.c$$

$$\Rightarrow \quad M_e^i = Y_e^i \frac{v}{\sqrt{2}} \qquad M_{\nu_i} \equiv 0$$

Massless Neutrinos

$$U(1)_\ell \text{ with } \ell = \ell_\mathrm{e} + \ell_\mu + \ell_\tau$$

Lepton Number is an accidental global symmetry in the SM broken by SU(2) Instantons

't Hooft, PRL1976

$$\partial_\mu J^\mu_\ell = \frac{n_f g_2^2}{32\pi^2} \epsilon^{\alpha\beta\gamma\delta} W_{\alpha\beta} W_{\gamma\delta}$$

$$J^\mu_\ell = \bar{\ell}_L \gamma^\mu \ell_L + \bar{e}_R \gamma^\mu e_R$$

$$W_\mu \to W_\mu^{inst}$$

What is the origin of Neutrino Masses ?

Massive Neutrinos

- Majorana Fermions

Lepton Number is broken !

$$\mathcal{L} \supset \frac{1}{2} \nu_L^T C M_M \nu_L$$

- Dirac Fermions

Lepton Number is conserved !

$$\mathcal{L} \supset M_D \bar{\nu}_L \nu_R$$

Majorana

Ettore Majorana nel 1930 circa

Mechanisms for Majorana Neutrino Masses

$$\mathcal{L} \supset \frac{1}{2} \nu_L^T C M_\nu \nu_L$$

- Type I Seesaw
- Type II Seesaw
- Type III Seesaw
- Zee's Model
- Colored Seesaw
- Witten's Model

…

…

Theories: B-L, Left-Right Symmetry, Pati-Salam, GUTs, ….

Majorana Neutrinos
and
New Scalar Bosons

Type II Seesaw

$$M_M \neq 0$$

$$\mathcal{L} \ni Y_\nu \, l_L^T C \, i\sigma_2 \, \Delta \, l_L + h.c.$$

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix} \sim (1,3,1)$$

Type II Seesaw

$$M_\nu \neq 0$$

$$V(H, \Delta) \ni \mu H^T i\sigma_2 \Delta^\dagger H$$

After SSB:

$$M_\nu = \sqrt{2}\, Y_\nu v_\Delta = Y_\nu \mu \frac{v^2}{M_\Delta^2}$$

$v = 246$ GeV, μ ? M_Δ ?

Type II Seesaw

$$M_\nu = \sqrt{2}\, Y_\nu v_\Delta = Y_\nu \mu \frac{v^2}{M_\Delta^2}$$

$$v = 246 \text{ GeV}, \quad \mu\,? \quad M_\Delta\,?$$

if $Y_\nu \sim 1$ $\mu \sim M_\Delta$ $M_\Delta \lesssim 10^{14}$ GeV

Maybe $M_\Delta \sim 1$ TeV $Y_\nu \sim 1$ $\mu \lesssim 1$ eV

μ is protected by $\mathrm{U(1)_{B-L}}$

Type II Seesaw

Physical Higgses

$H_1^0 \to$ SM-like Higgs

H_2^0, A^0, $H^{\pm}$, $H^{\pm\pm}$

$$\nu_L^T\, C\, \Gamma_+\, H^+\, e_L,$$

$$e_L^T\, C\, \Gamma_{++}\, H^{++}\, e_L,$$

$$\Gamma_+ = \cos\theta_+\, \frac{m_\nu^{diag}}{v_\Delta}\, V_{PMNS}^\dagger,$$

$$\Gamma_{++} = V_{PMNS}^*\, \frac{m_\nu^{diag}}{\sqrt{2}\, v_\Delta}\, V_{PMNS}^\dagger = Y_\nu.$$

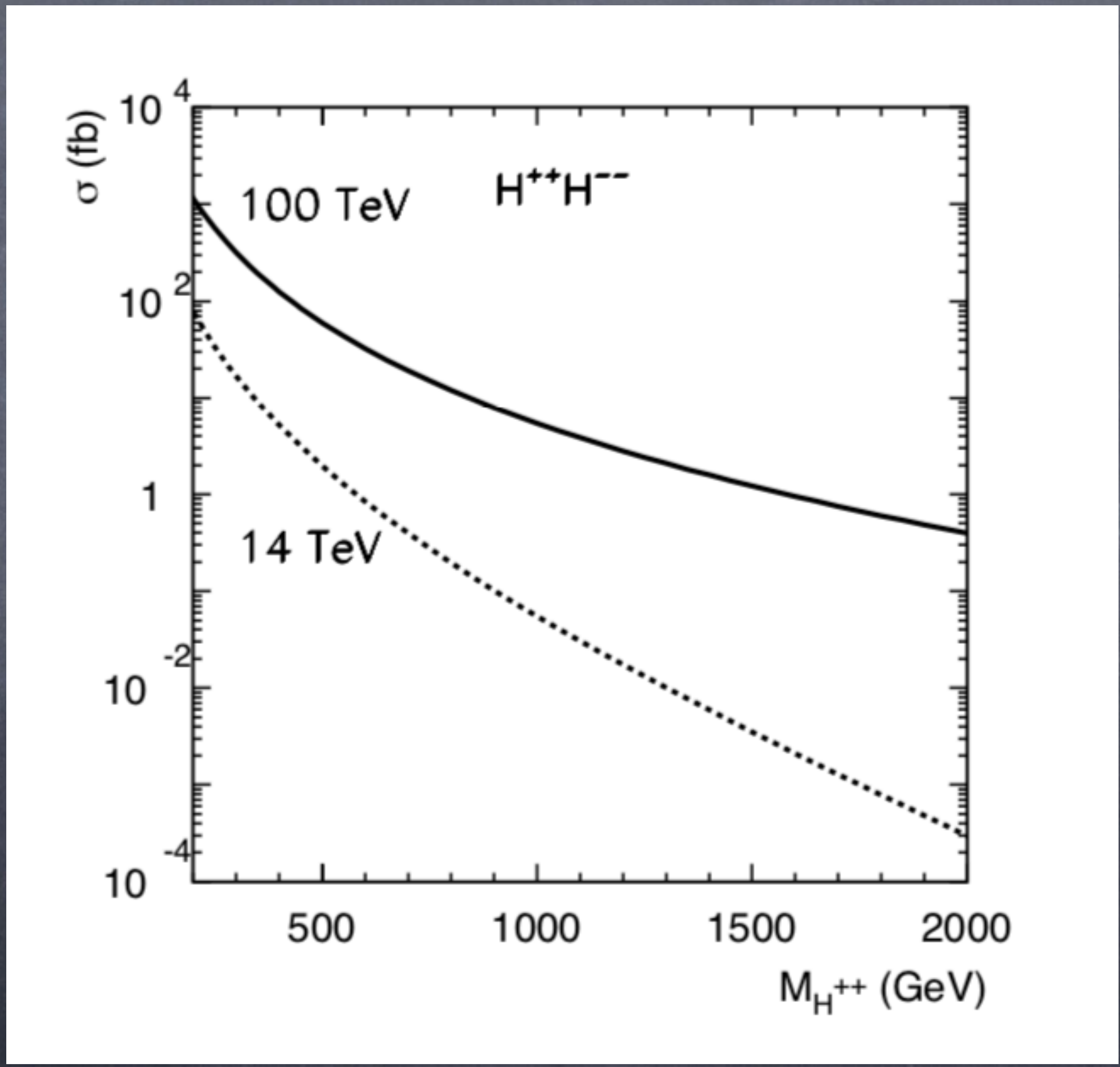
$$\frac{g_2}{\sqrt{2}}\, \bar{\nu}_L^i\, V_{PMNS}^{ij}\, \gamma^\mu\, e_L^j\, W_\mu^+ + h.c.$$

Bruno Pontecorvo nel 1955

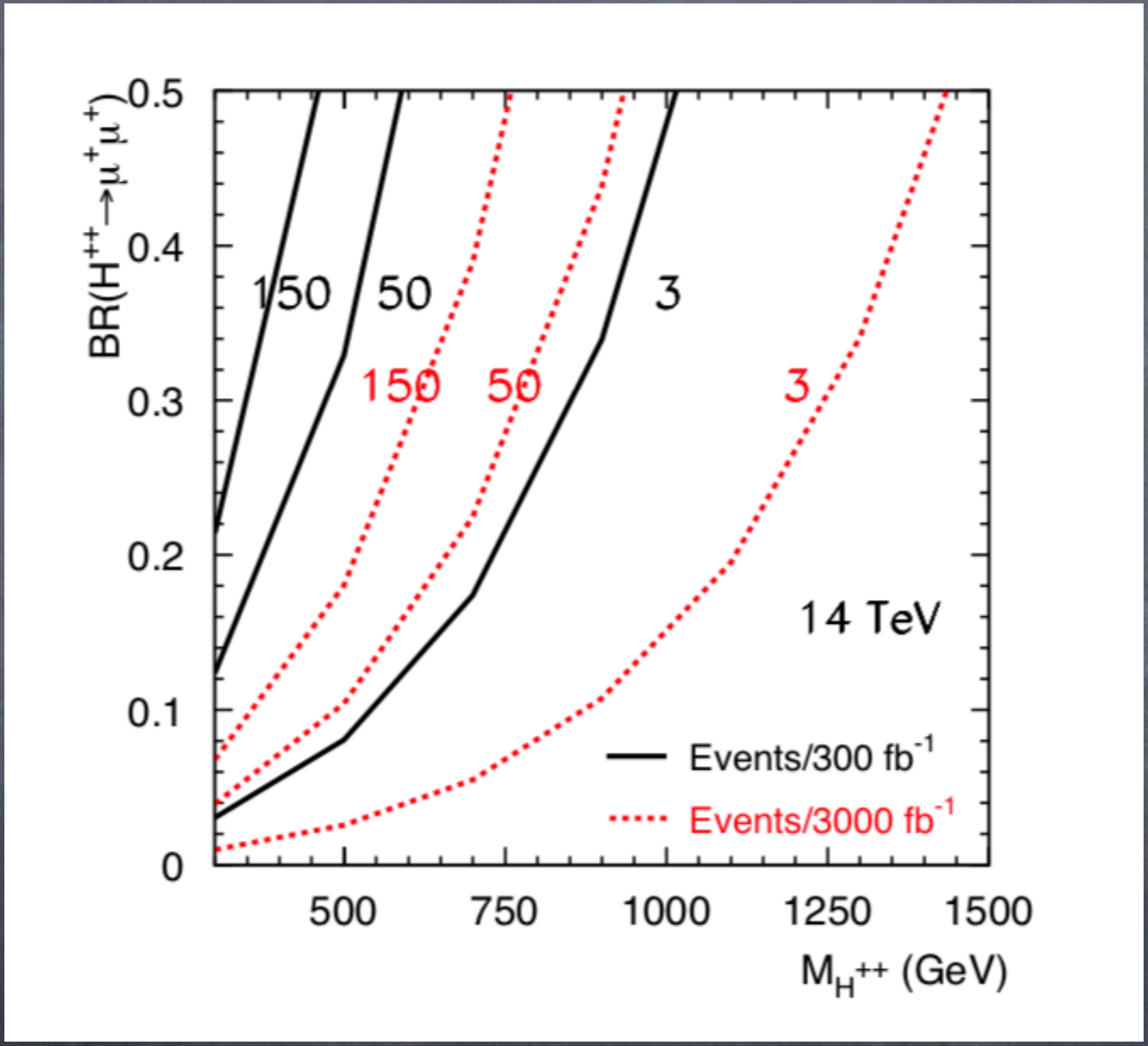
$$V_{PMNS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{12}s_{13}s_{23}e^{i\delta} - c_{23}s_{12} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta}c_{12}c_{23}s_{13} & -c_{23}s_{12}s_{13}e^{i\delta} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \times \mathrm{diag}(e^{i\Phi_1/2}, 1, e^{i\Phi_2/2})$$

How do we test type II seesaw ?

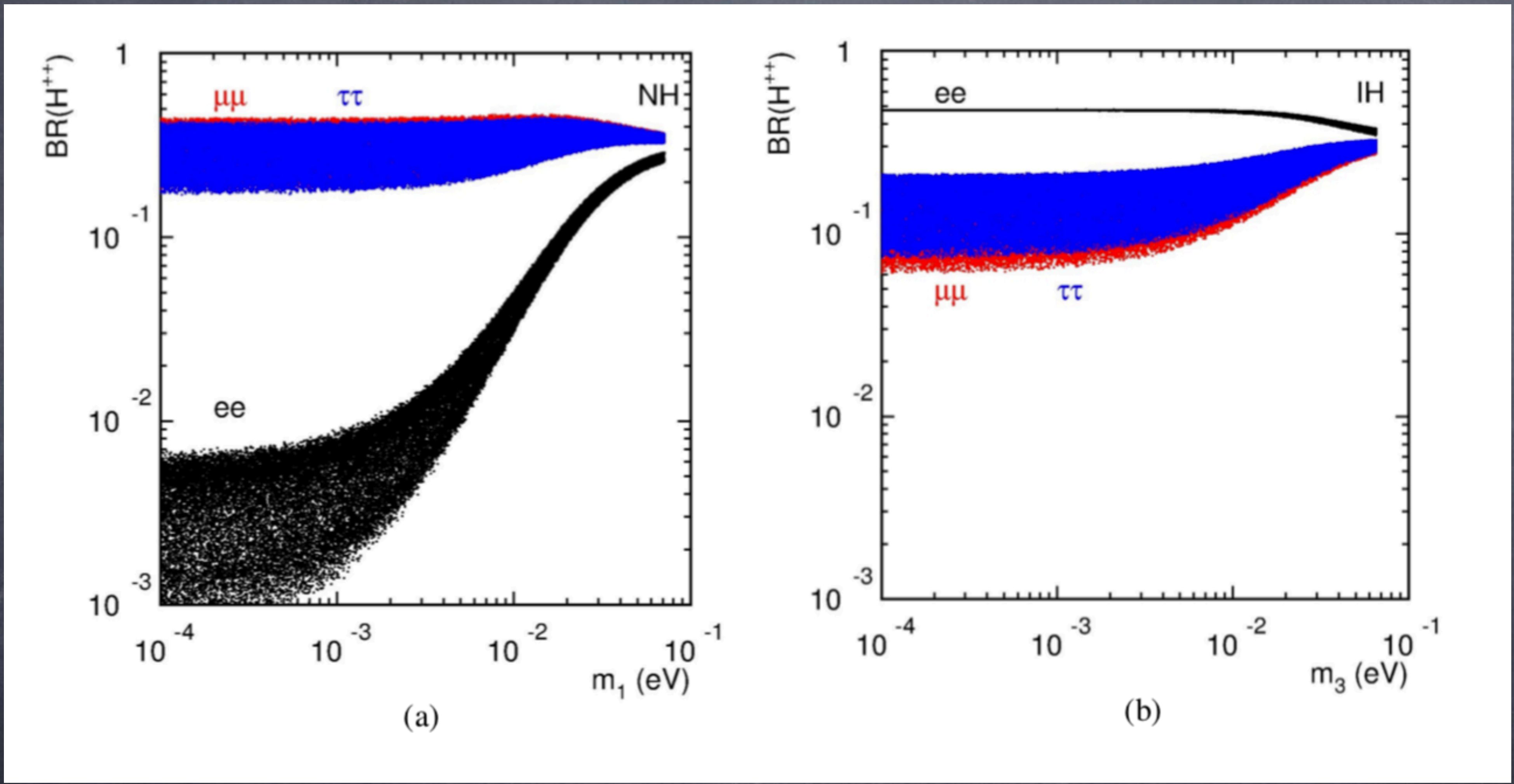
$$pp \rightarrow H^{++}H^{--} \ @ \ LHC$$



$$pp \rightarrow H^{++}H^{--} \rightarrow \mu^+\mu^+\mu^-\mu^- \;@\; LHC$$

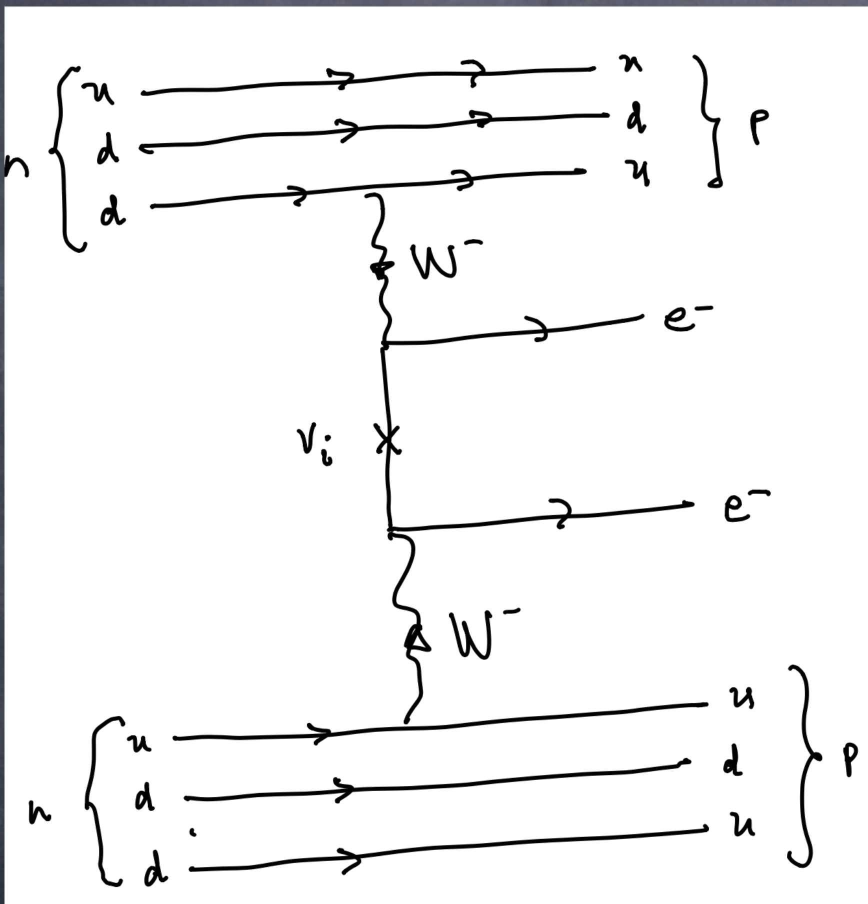


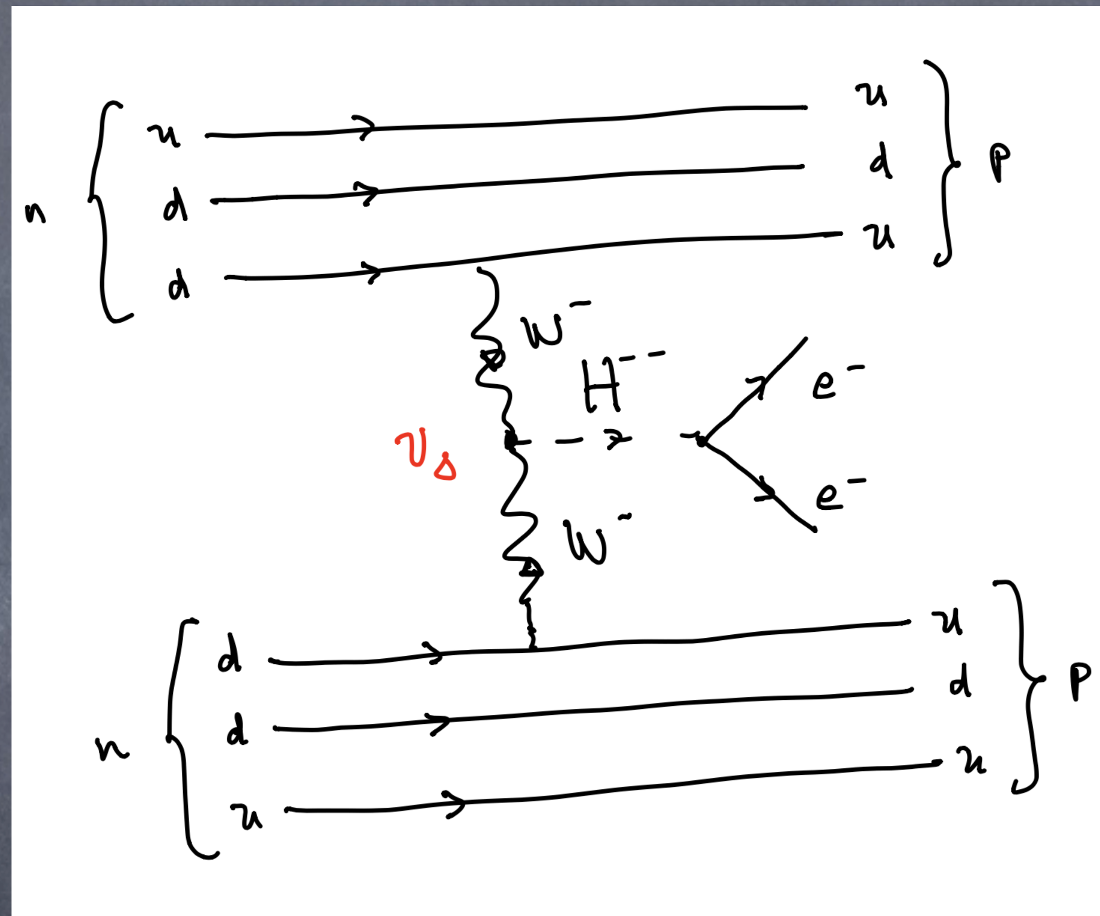
Neutrino Spectra and Higgs Decays



P. F. P., T. Han et al,

$0\nu\beta\beta$





Majorana Neutrinos
and
New Fermions

Type I Seesaw

$$(\nu_i^c)_L \sim (1,1,0) \qquad i = 1, 2, \ldots$$

$$(\nu^c)_L = (\nu_R)^C = C\,\overline{\nu}_R^T$$

$$-\mathcal{L} \supset y_\nu^D\, l_L^T C\, i\sigma_2 H\, (\nu^c)_L + \frac{1}{2} (\nu^c)_L^T C M_R (\nu^c)_L + h.c.$$

$$-\mathcal{L}_\nu^{mass} = \frac{1}{2} \begin{pmatrix} \nu_L & (\nu^c)_L \end{pmatrix} \begin{pmatrix} 0 & M_\nu^D \\ (M_\nu^D)^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ (\nu^c)_L \end{pmatrix} + h.c.$$

$$M_\nu^D = y_\nu^D \frac{v}{\sqrt{2}}$$

$$m_\nu \simeq M_\nu^D M_R^{-1} (M_\nu^D)^T \qquad (M_R \gg M_\nu^D)$$

$$M_N \simeq M_R$$

$$\begin{pmatrix} \nu \\ \nu^c \end{pmatrix}_L = N \begin{pmatrix} \nu_m \\ N_{m'} \end{pmatrix}_L$$

if $M_\nu^D \sim 10^2\ \text{GeV} \Rightarrow M_R \lesssim 10^{14-15}\ \text{GeV}$

Type II Seesaw

$$M_\nu^{II} = \sqrt{2}\, Y_\nu v_\Delta = Y_\nu \frac{\mu}{M_\Delta^2} v^2$$

Type I Seesaw

$$M_\nu^{I} = M_\nu^D M_R^{-1} (M_\nu^D)^T = Y_\nu^D M_R^{-1} (Y_\nu^D)^T \frac{v^2}{2}$$

$\Rightarrow$

$$M_\nu^{ij} = C_\nu^{ij} \frac{v^2}{\Lambda}$$

$$\Lambda^{II} = M_\Delta^2/\mu$$

$$\Lambda^{I} = M_R$$

Dirac

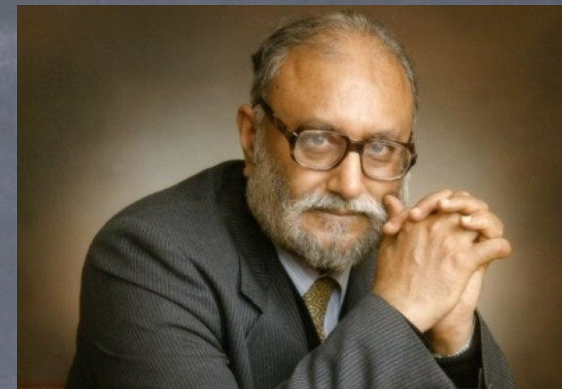
Dirac in 1933

$$-\mathcal{L} \supset y_\nu^D \, \bar{l}_L \, i\sigma_2 H^* \nu_R + h.c.$$

$$m_\nu = y_\nu^D \frac{v}{\sqrt{2}} \qquad y_\nu^D \lesssim 10^{-12}$$

Neutrino Masses:
"Standard Paradigm"

Quark-Lepton Unification



PHYSICAL REVIEW D VOLUME 10, NUMBER 1 1 JULY 1974

Lepton number as the fourth "color"

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(Received 25 February 1974)

Universal strong, weak, and electromagnetic interactions of leptons and hadrons are generated by gauging a non-Abelian renormalizable anomaly-free subgroup of the fundamental symmetry structure $SU(4)_L \times SU(4)_R \times SU(4')$, which unites three quartets of "colored" baryonic quarks and the quartet of known leptons into 16-folds of chiral fermionic multiplets, with lepton number treated as the fourth "color" quantum number. Experimental consequences of this scheme are discussed. These include (1) the emergence and effects of exotic gauge mesons carrying both baryonic as well as leptonic quantum numbers, particularly in semileptonic processes, (2) the manifestation of anomalous strong interactions among leptonic and semileptonic processes at high energies, (3) the independent possibility of baryon-lepton number violation in quark and proton decays, and (4) the occurrence of $(V+A)$ weak-current effects.

Pati, Salam, 1974

Quark-Lepton Unification

$$SU(4)_C \otimes SU(2)_L \otimes SU(2)_R \supset SO(10)$$

$$\begin{pmatrix} u_r & u_g & u_b & \nu \\ d_r & d_g & d_b & e \end{pmatrix}_L \qquad \begin{pmatrix} u_r & u_g & u_b & N \\ d_r & d_g & d_b & e \end{pmatrix}_R$$

$$M_\nu = m_D^\nu M_R^{-1} (m_D^\nu)^T \qquad m_D^\nu = m_U$$

$$M_R \approx 10^{14-15} \text{GeV}$$

Majorana Neutrinos and High Scale Seesaw !

Low Scale Quark-Lepton Unification

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

$$F_{QL} = \begin{pmatrix} u_r & u_g & u_b & \nu \\ d_r & d_g & d_b & e \end{pmatrix} \sim (\mathbf{4}, \mathbf{2}, 0),$$

$$F_u = \left(u_r^c \;\; u_g^c \;\; u_b^c \;\; \underline{\nu^c} \right) \sim (\bar{\mathbf{4}}, \mathbf{1}, -1/2),$$

$$F_d = \left(d_r^c \;\; d_g^c \;\; d_b^c \;\; e^c \right) \sim (\bar{\mathbf{4}}, \mathbf{1}, 1/2).$$

Low Scale Quark-Lepton Unification

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

$$\chi = (\chi_u \quad \chi_R^0) \sim (4, 1, 1/2).$$

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

$$A_\mu = \begin{pmatrix} G_\mu & X_\mu/\sqrt{2} \\ X_\mu^*/\sqrt{2} & 0 \end{pmatrix} + T_4 \, B_\mu^{'}.$$

P. F. P., M. B. Wise, Phys.Rev.D88, 057703

Inverse Seesaw

$$-\mathcal{L} \supset Y_5 F_u \chi S + \frac{1}{2}\mu S S + \text{h.c.}\,, \qquad S \sim (1,1,0)$$

$$\begin{pmatrix} \nu & \nu^c & S \end{pmatrix} \begin{pmatrix} 0 & M_\nu^D & 0 \\ (M_\nu^D)^T & 0 & M_\chi^D \\ 0 & (M_\chi^D)^T & \mu \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix},$$

$\Rightarrow$ $$m_\nu \approx \mu \left(\frac{M_\nu^D}{M_\chi^D}\right)^2, \qquad M_\chi^D \gg M_\nu^D \gg \mu,$$

$K_L^0 \to e^\pm \mu^\mp$ $\Rightarrow$ $M_{QL} \geq 10^3$ TeV

Low Scale Quark-Lepton Unification

Theory for Neutrino Masses at the Low Scale

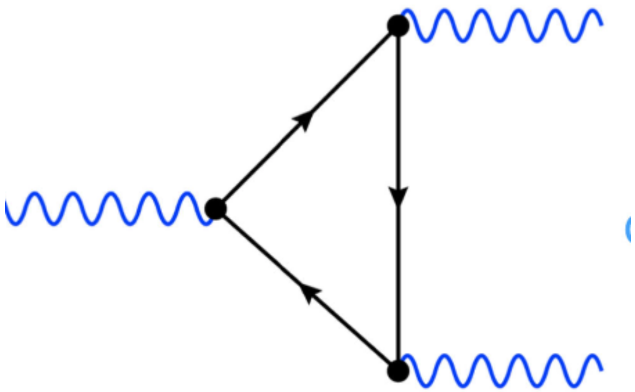
P. F. P., Wise

Lepton Number as Local Gauge Symmetry

Anomaly Cancellation:

$$\ell_L \sim (\mathbf{2}, -1/2, 1) \quad \text{and} \quad e_R \sim (\mathbf{1}, -1, 1),$$

$$\mathcal{A}_1\left(SU(3)_C^2 U(1)_\ell\right) = 0,$$
$$\mathcal{A}_2\left(SU(2)_L^2 U(1)_\ell\right) = 3/2,$$
$$\mathcal{A}_3\left(U(1)_Y^2 U(1)_\ell\right) = -3/2,$$
$$\mathcal{A}_4\left(U(1)_Y U(1)_\ell^2\right) = 0,$$
$$\mathcal{A}_5\left(U(1)_\ell^3\right) = 3, \quad \text{and} \quad \mathcal{A}_6\left(U(1)_\ell\right) = 3.$$



Solutions:

- Vector-like leptons

P. F. P., M. B. Wise, JHEP1108, 068

M. Duerr, P. F. P., M. B. Wise, Phys. Rev. Lett. 110, 231801

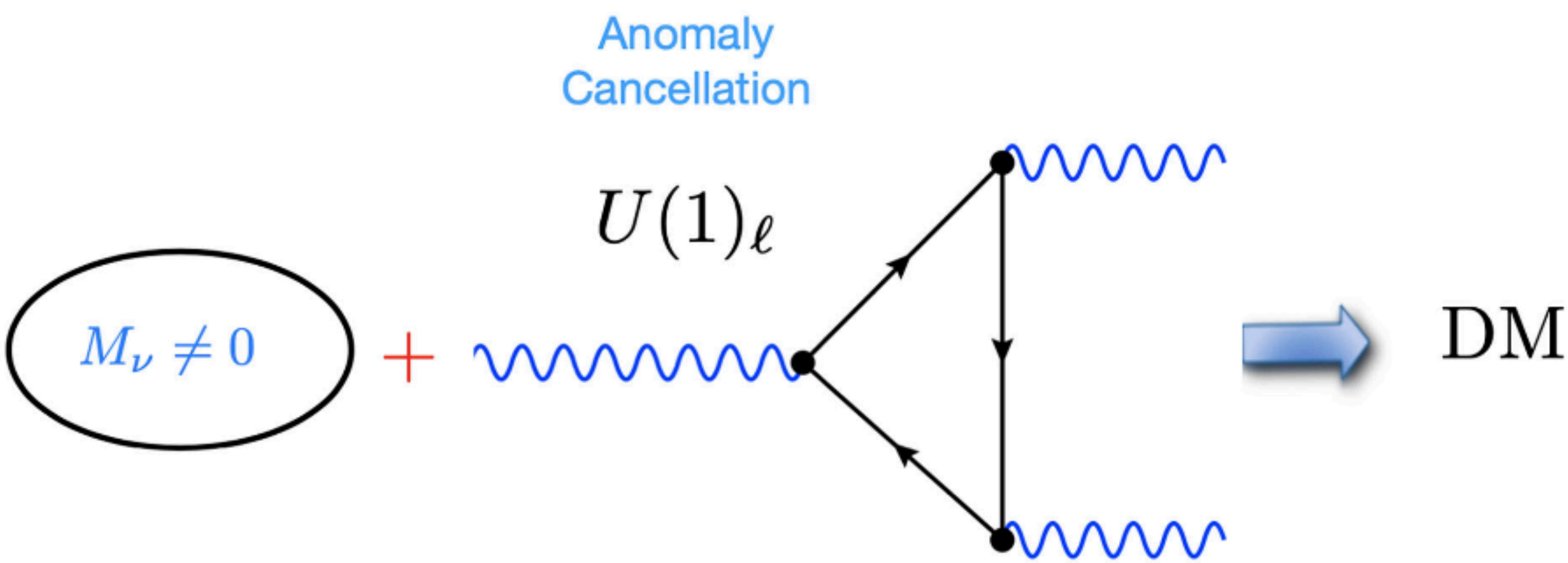
- Four representations

P. F. P., S. Ohmer, H. H. Patel, Phys. Lett. B735, 283

- Minimal Model

P. F. P., Physical Review D 110, 035018 (2024)

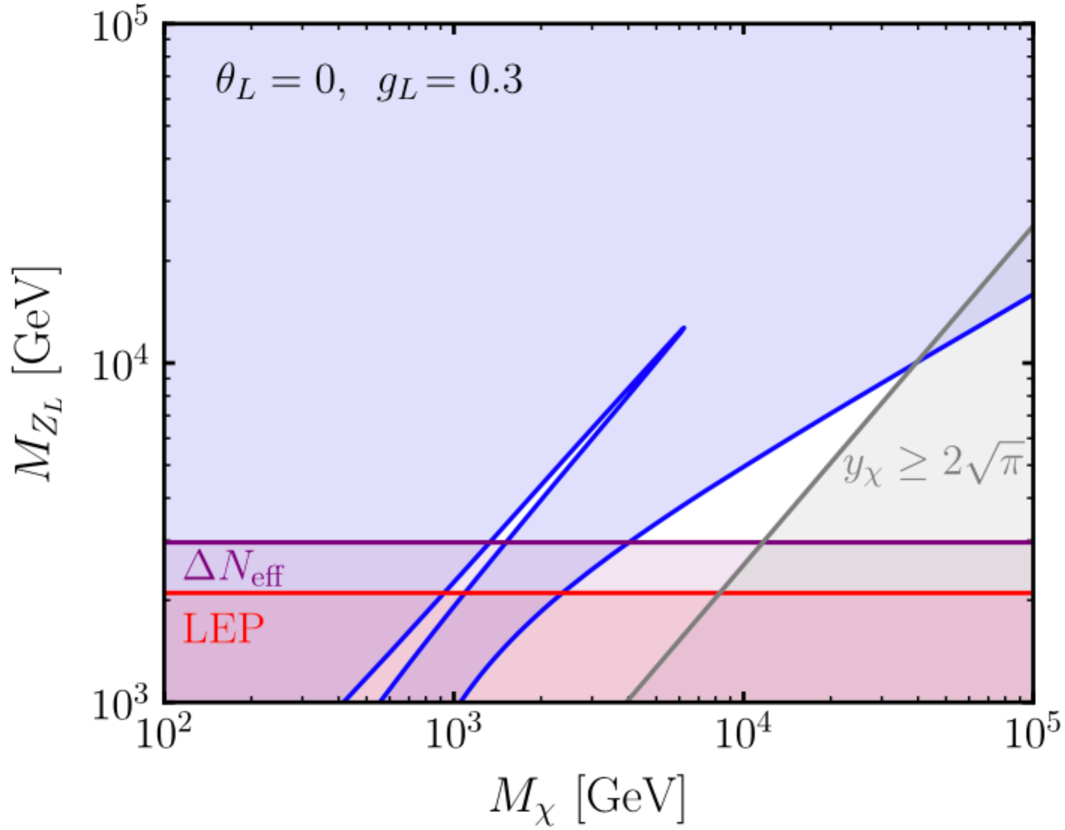
Lepton Number as Local Gauge Symmetry



$$\Omega_{DM} h^2 \leq 0.12$$ → *Low Scale Seesaw*

Leptophilic Dark Matter

$$\chi\chi \to e_i^+ e_i^-, \bar{\nu}_i \nu_i, Z_L Z_L, Z_L h_i, h_i h_j, WW, ZZ,$$



The scale for spontaneous Lepton number violation must be below the multi-TeV scale !

Physical Review D 110, 035018 (2024)

Lepton Number as Local Gauge Symmetry

$$\nu_R^i \sim (\mathbf{1}, 0, 1)$$

$$\Psi_L \sim (\mathbf{1}, -1, 3/4), \qquad \Psi_R \sim (\mathbf{1}, -1, -3/4),$$
$$\chi_L \sim (\mathbf{1}, 0, 3/4), \quad \text{and} \quad \rho_L \sim (\mathbf{3}, 0, -3/4).$$

Minimal number of fields to cancel all leptonic gauge anomalies

New Fermion Masses

$$-\mathcal{L} \supset \lambda_\rho \text{Tr}(\rho_L^T C \rho_L) S + \lambda_\Psi \bar{\Psi}_L \Psi_R S + \lambda_\chi \chi_L^T C \chi_L S^* + \text{H.c.}$$

$$S \sim (1, 1, 0, 3/2)$$

$$-\mathcal{L} \supset \lambda_e \bar{\Psi}_L e_R \phi + \lambda_R \bar{\chi}_L \nu_R \phi + \text{H.c.}$$

$$\phi \sim (1, 1, 0, -1/4)$$

Neutrino Masses

Physical Review D 110, 035018 (2024)

$v_\phi \neq 0$

$$-\mathcal{L}_\nu \supset \lambda_R^i \frac{v_\phi}{\sqrt{2}} \bar{\chi}_L \nu_R^i + \lambda_\chi \frac{v_S}{\sqrt{2}} \chi_L^T C \chi_L + \text{H.c.}$$

$$M_{\nu_R}^{ij} = \frac{\lambda_R^i \lambda_R^j v_\phi^2}{2\sqrt{2}\lambda_\chi v_S}.$$

$$-\mathcal{L}_\nu^m \supset \bar{\nu}_L^i (\tilde{M}_D^\nu)^{i\alpha} \nu_R^\alpha - \frac{1}{2} m_\nu^{ij} \nu_L^{iT} C \nu_L^j + \text{H.c.}$$

3+2 light neutrinos

Here, $\alpha = 4,\ 5$ and

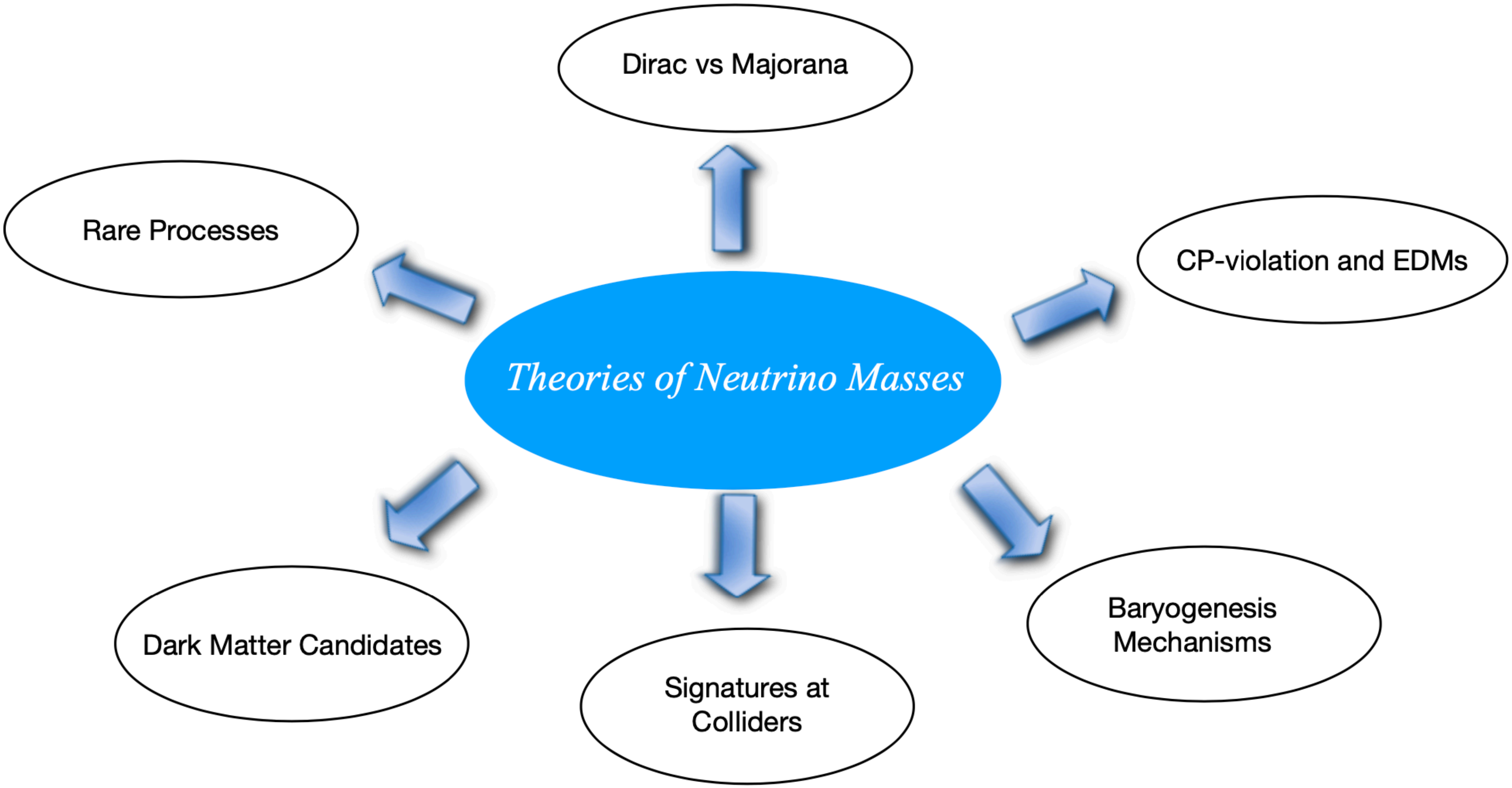
$$m_\nu^{ij} = \frac{(\tilde{M}_D^\nu)^{i3} (\tilde{M}_D^\nu)^{j3}}{M_R} + \frac{m_D^i m_D^j}{M_\rho}.$$

Neutrino Masses vs DM

⇒ $v_\phi \neq 0$ ⇒ Majorana Neutrinos

⇒ $v_\phi = 0$ ⇒ Dirac Neutrinos ⇒ DM

Summary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