On the Origin of Neutrino Masses

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CASE WESTERN RESERVE UNIVERSITY EST. 1826
think beyond the possible

Seminari generali at NFN - Laboratori Nazionali di Frascati, Italy, Nov 27, 2024

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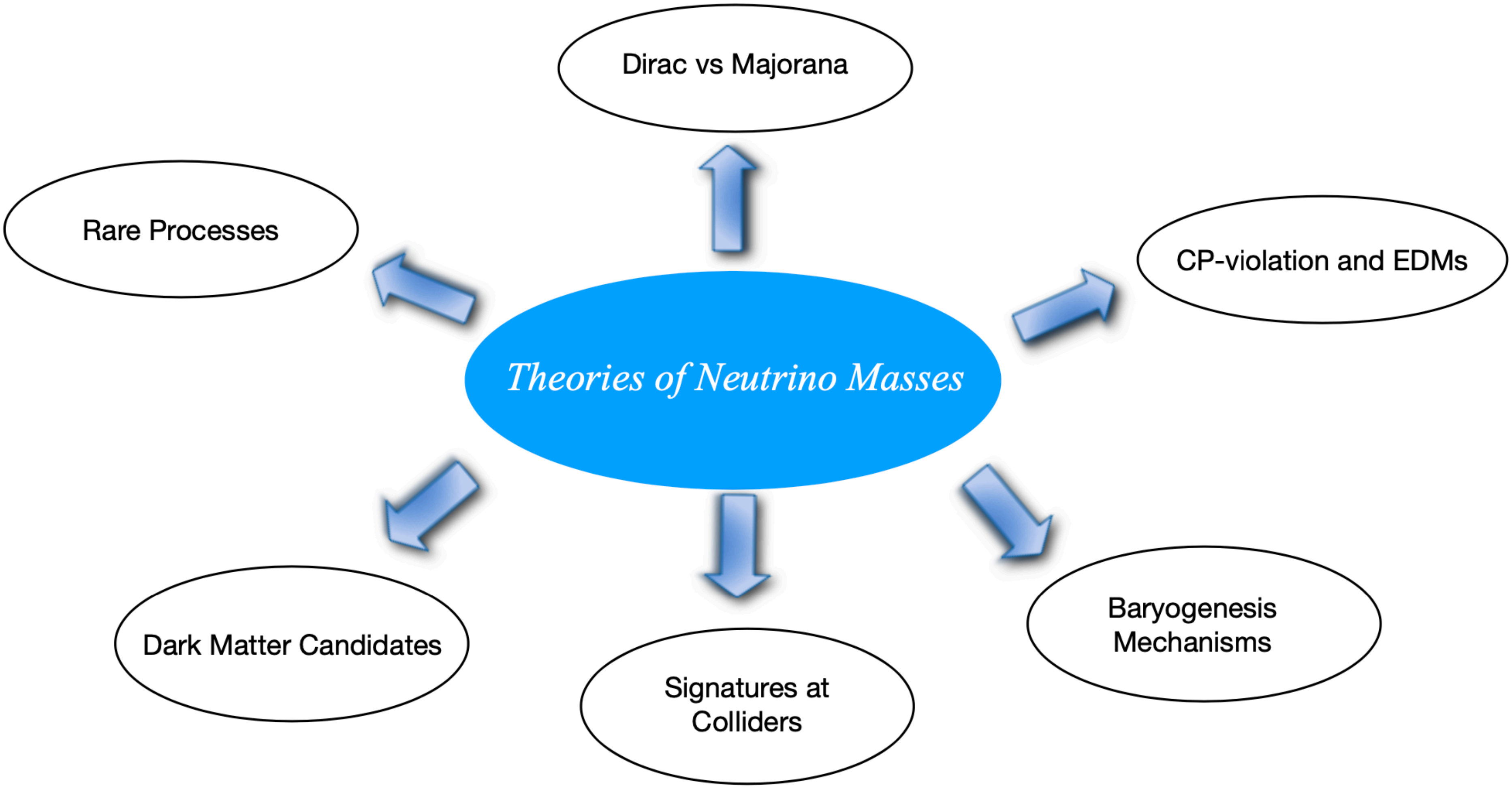
Massive Neutrinos

What is the origin of neutrino masses ?

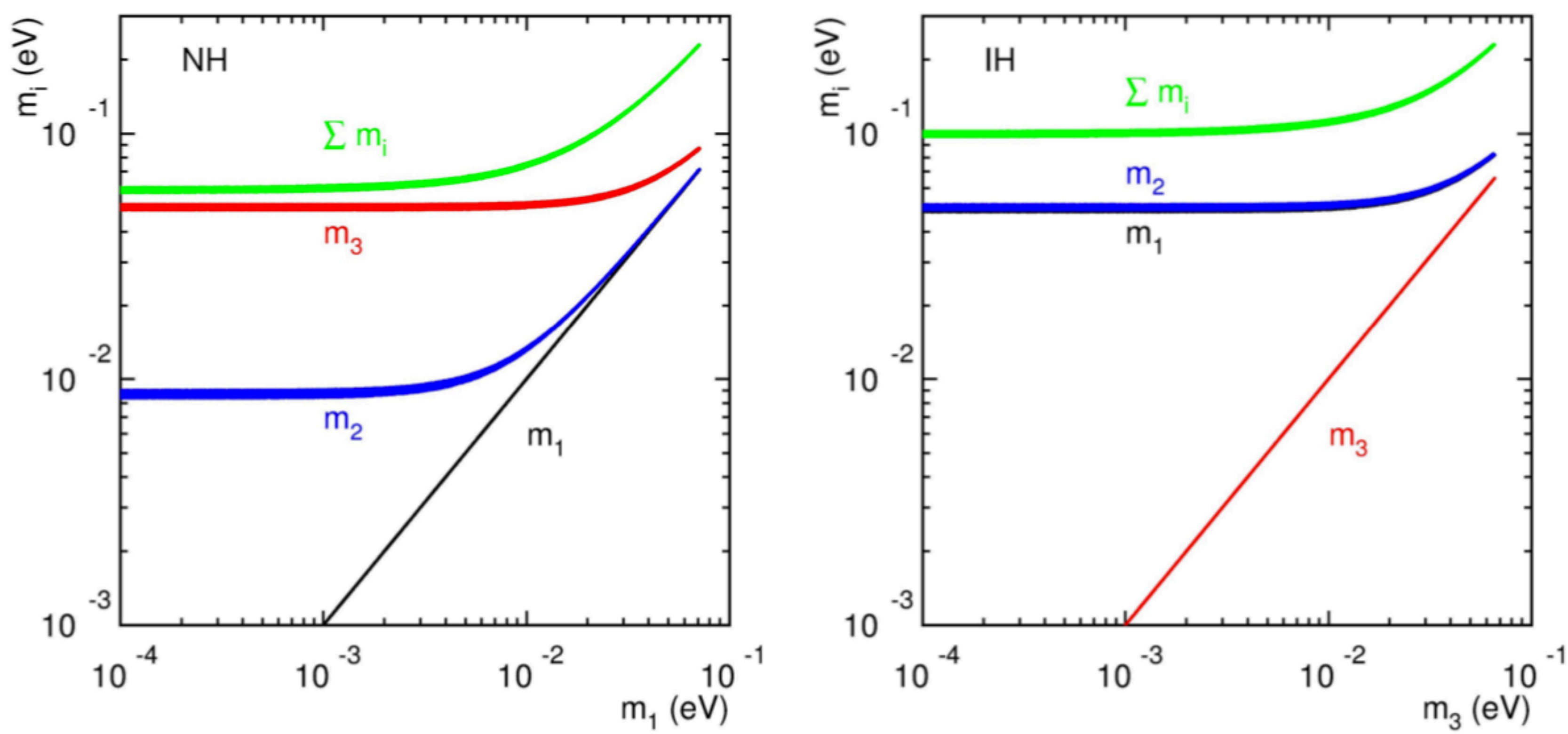
How do we test the theory of neutrino masses ?

Main Goal


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

Massive Neutrinos

Normal Hierarchy *Inverted Hierarchy*



(a) (b)

Leptons in the SM

VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons

and on a right-handed singlet

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e. \qquad (2)$$

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

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

S. Weinberg, 1967

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

S. Weinberg, 1967

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

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

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

$$\Delta L = 3$$

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

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

$\Rightarrow$ $v = 246$ GeV , μ ? M_Δ ?

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

Maybe $M_\Delta \sim 1$ TeV $Y_\nu \sim 1$ $\Rightarrow$ $\mu \lesssim 1$ 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, $H^\pm$, $H^{\pm\pm}$

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

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

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

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

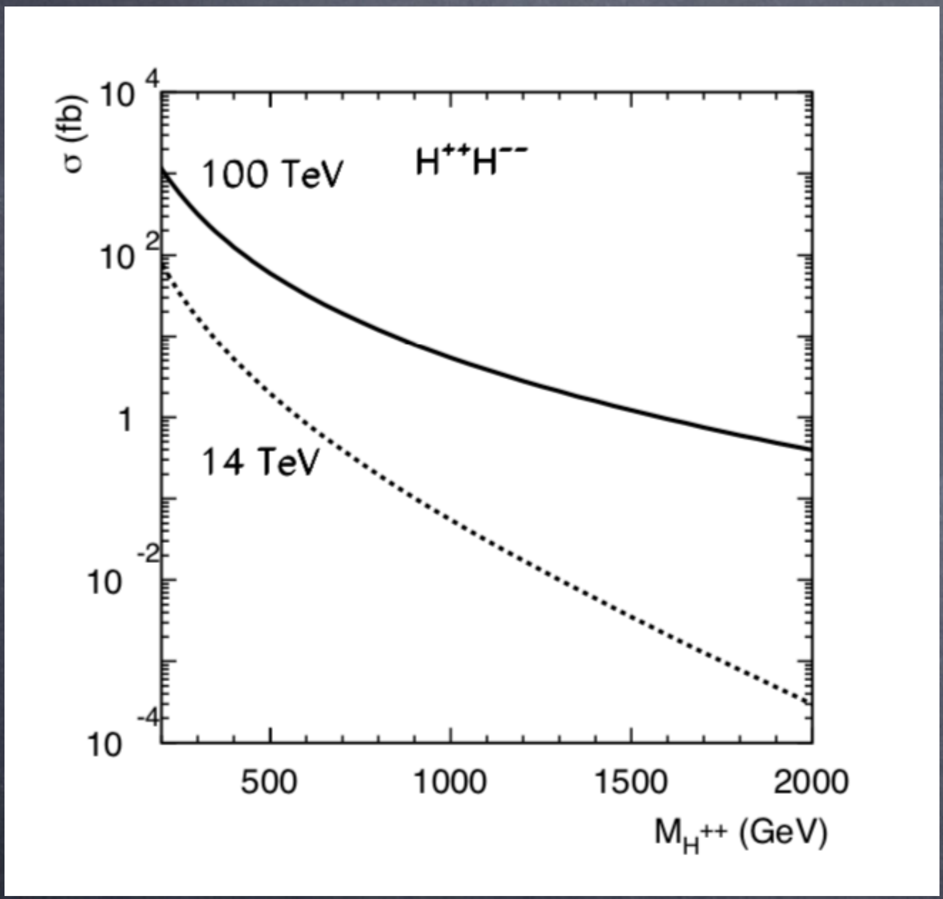
$$\frac{g_2}{\sqrt{2}} \bar{\nu}_L^i \, V_{PMNS}^{ij} \, \gamma^\mu e_L^j \, W_\mu^+ + h.c.$$

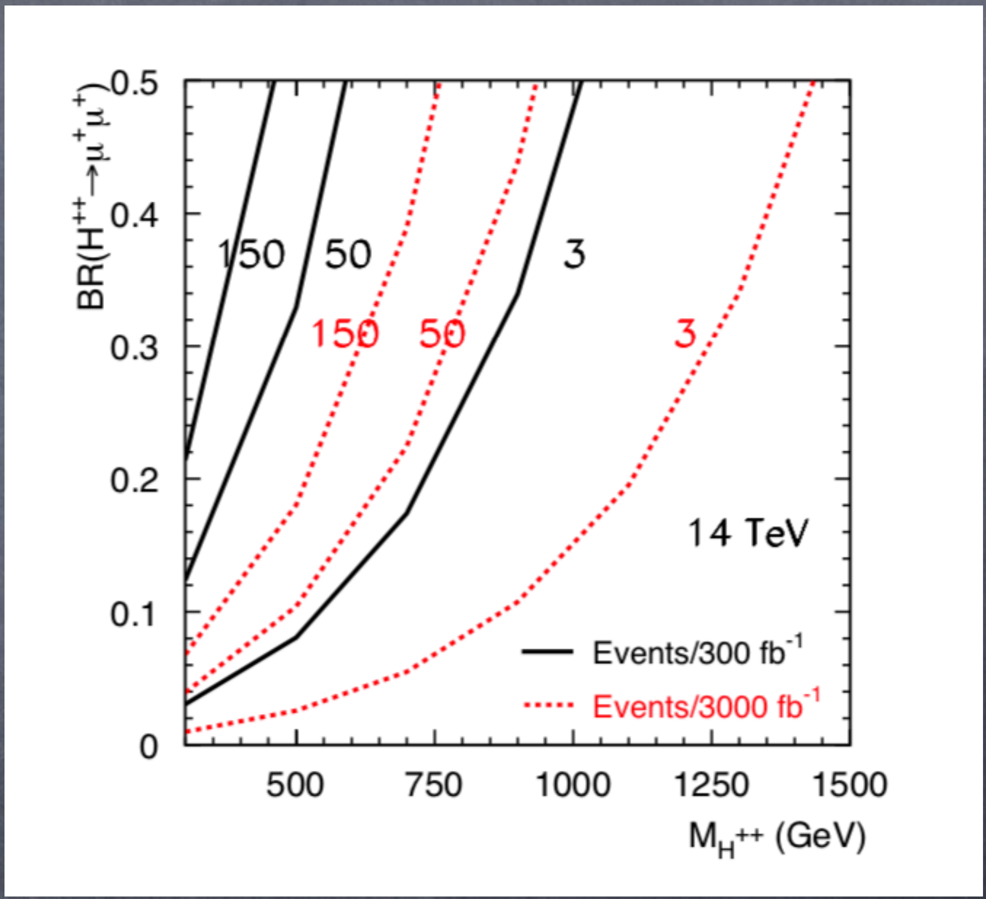
Bruno Pontecorvo nel 1955

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

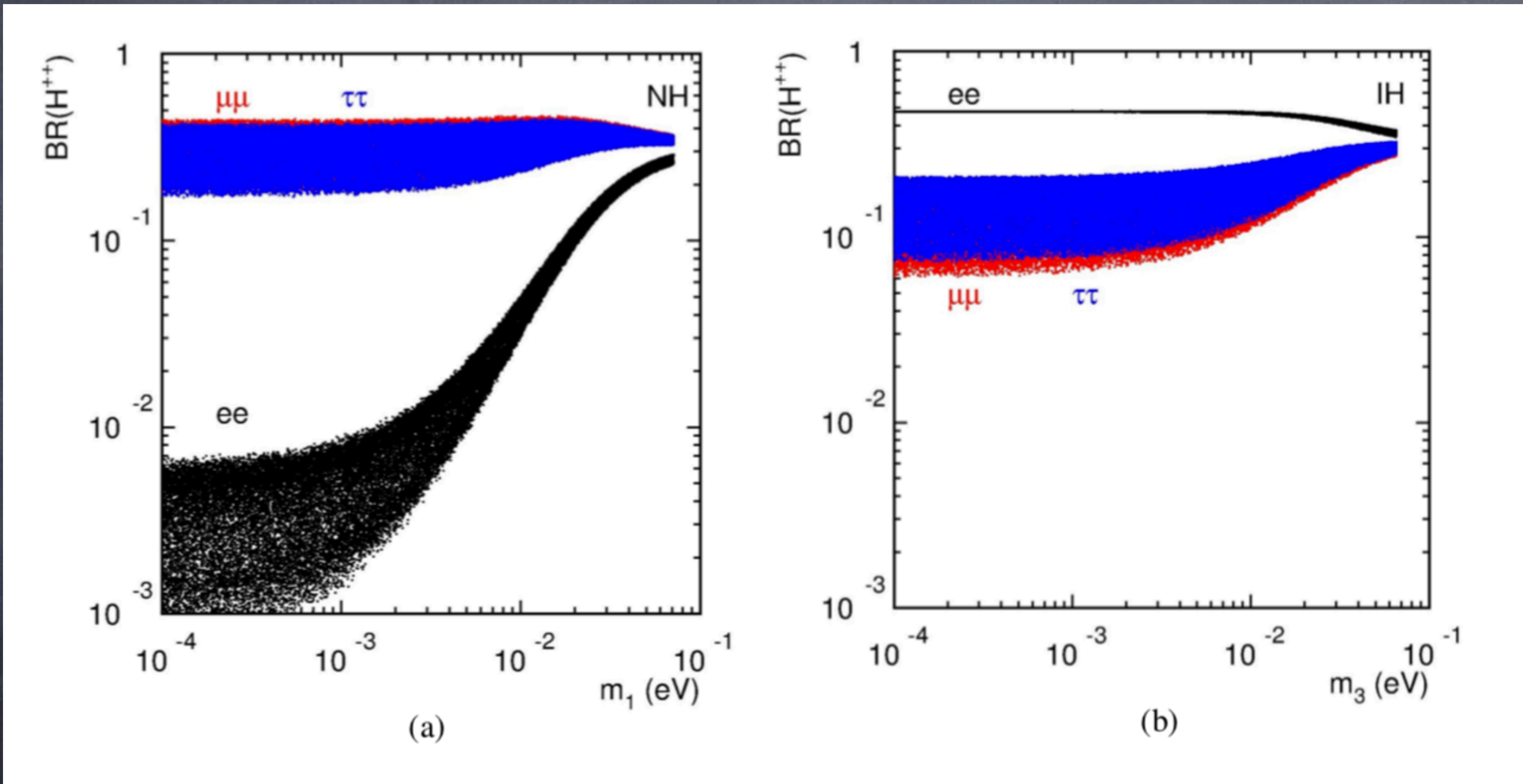
How do we test type II seesaw ?

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





Neutrino Spectra and Higgs Decays



Majorana Neutrinos
and
New Fermions

Type I Seesaw

$$(\nu^c_i)_L \sim (1,1,0) \qquad i=1,2,\ldots$$

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

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

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

$$M^D_\nu = Y^D_\nu \frac{v}{\sqrt{2}}$$

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

$$M_N \simeq M_R$$

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

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

Type II Seesaw

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

Type I Seesaw

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

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

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

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

Dirac

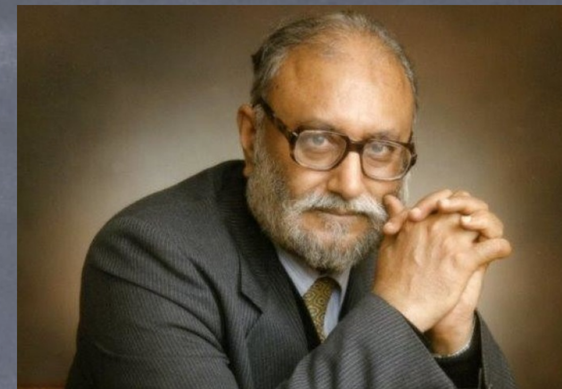
Dirac in 1933

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

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

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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Abdus Salam
International Centre for Theoretical Physics, Trieste, Italy
and Imperial College, London, England

(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

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

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

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

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

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

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

$$\chi = \begin{pmatrix} \chi_u & \chi_R^0 \end{pmatrix} \sim (4, 1, 1/2).$$

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

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

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

Inverse Seesaw

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

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

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

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

Low Scale Quark-Lepton Unification

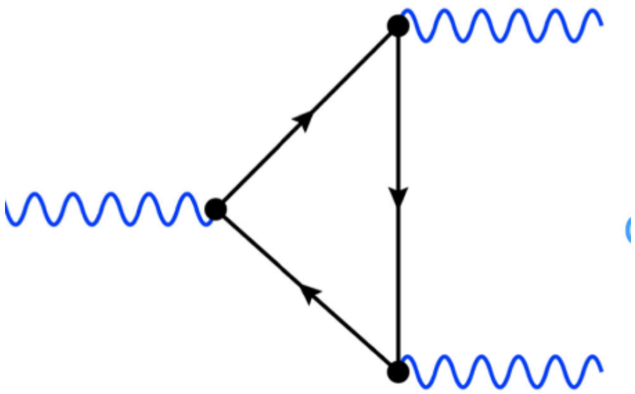
Theory for Neutrino Masses at the Low Scale

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

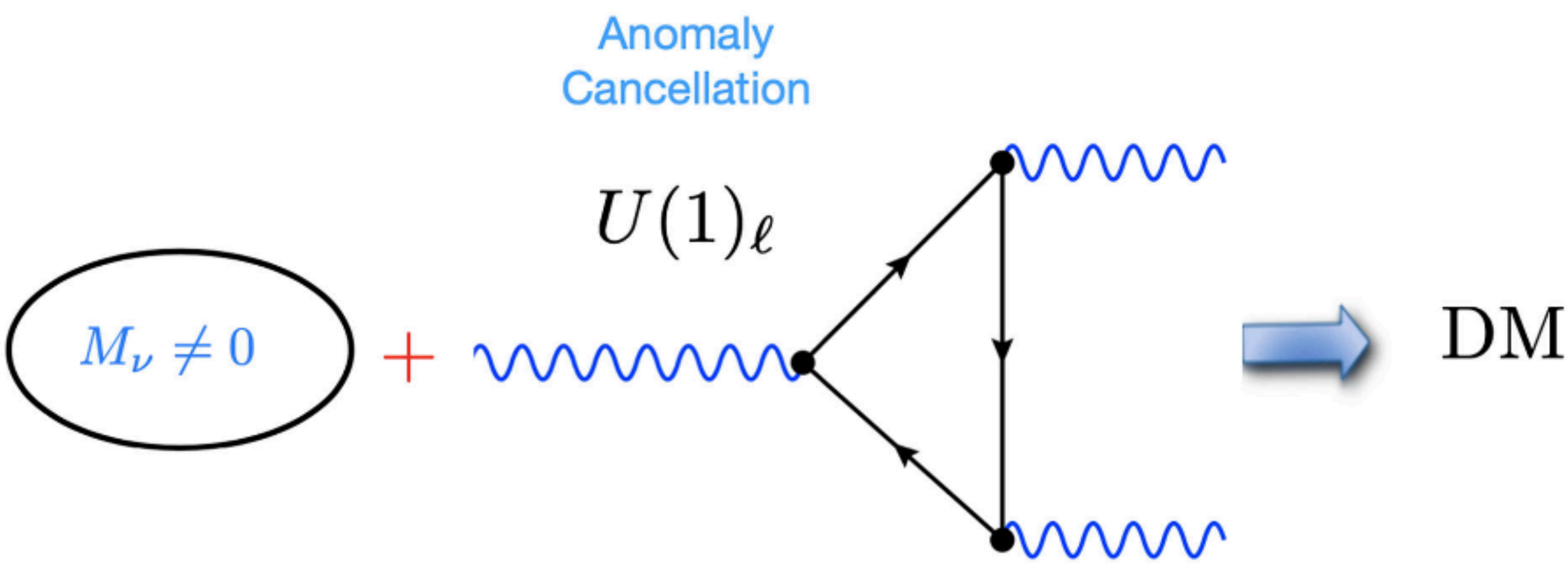
- Four representations

  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 !*

Vector-like Leptons

P. F. P., M. B. Wise

$$\ell_1 - \ell_2 = -3$$

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_\ell$
$\Psi_L = \begin{pmatrix} \Psi_L^0 \\ \Psi_L^- \end{pmatrix}$	**1**	**2**	$-\frac{1}{2}$	ℓ_1
$\Psi_R = \begin{pmatrix} \Psi_R^0 \\ \Psi_R^- \end{pmatrix}$	**1**	**2**	$-\frac{1}{2}$	ℓ_2
η_R	**1**	**1**	-1	ℓ_1
η_L	**1**	**1**	-1	ℓ_2
χ_R	**1**	**1**	0	ℓ_1
χ_L	**1**	**1**	0	ℓ_2

$\ell_1 = -\ell_2 = -3/2$ (Majorana DM)

P. F. P., M. B. Wise

Majorana DM and Dirac Neutrinos

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

$$\mathcal{L} \supset y_\Psi \bar{\Psi}_L \Psi_R S^* + y_\eta \bar{\eta}_R \eta_L S^*$$

$$+ y_\chi \bar{\chi}_R \chi_L S^* + \lambda_\chi \chi_L^T C \chi_L S^* + \lambda_\chi^{'} \chi_R^T C \chi_R S + h.c.$$

$$S \sim (\mathbf{1}, \mathbf{1}, 0, 3).$$

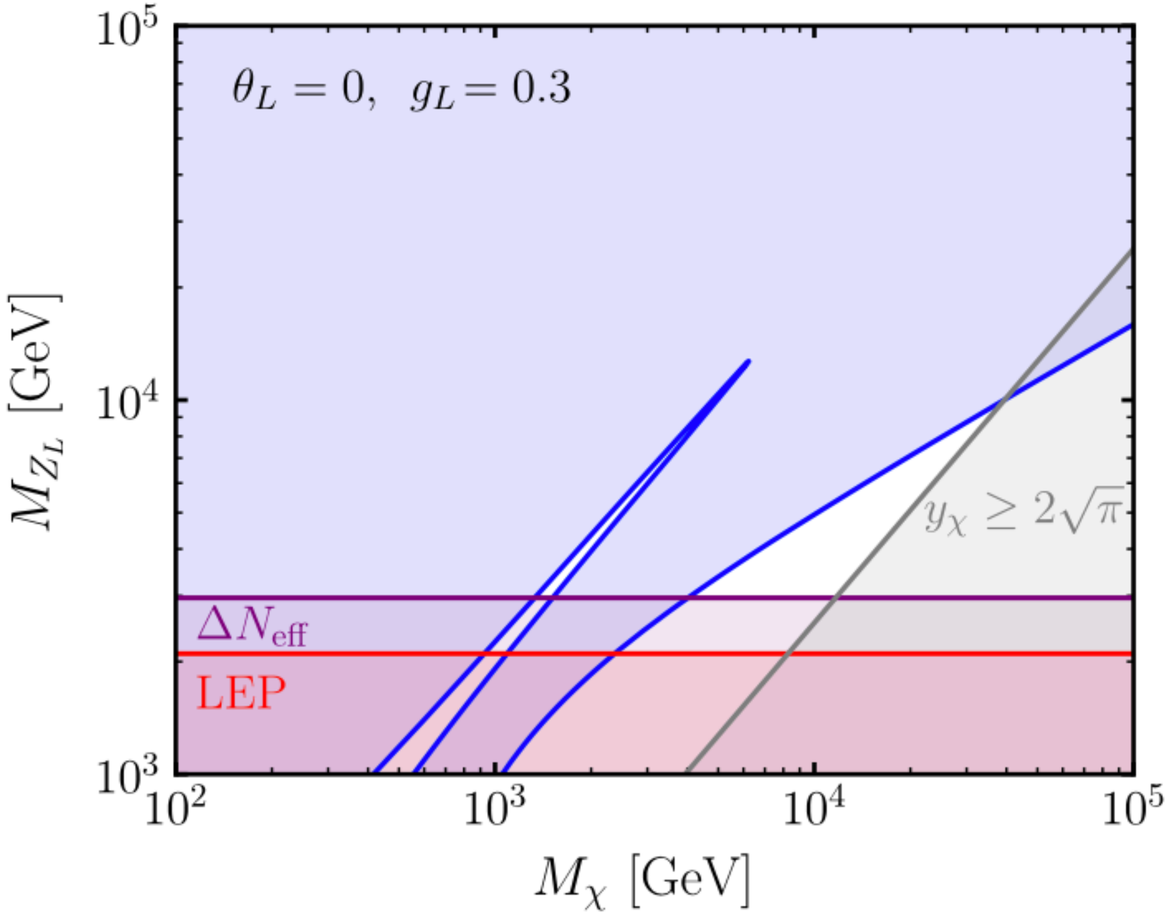
$$-\mathcal{L} \supset Y_\nu \bar{\ell}_L i \sigma_2 H^* \nu_R + \text{h.c.}$$ (Dirac Neutrinos)

$$\chi = \chi_L + (\chi_L)^C$$ → Dark Matter

Leptophilic Dark Matter

P. F. P., C. Murgui, A.D. Plascencia

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



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

Majorana DM and Neutrinos

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

$$\mathcal{L} \supset y_\Psi \bar{\Psi}_L \Psi_R S^* + y_\eta \bar{\eta}_R \eta_L S^*$$

$$+ y_\chi \bar{\chi}_R \chi_L S^* + \lambda_\chi \chi_L^T C \chi_L S^* + \lambda_\chi^{'} \chi_R^T C \chi_R S + h.c.$$

$$S \sim (\mathbf{1}, \mathbf{1}, 0, 3).$$

$$-\mathcal{L}_\nu \supset Y_\nu \bar{\ell}_L i\sigma_2 H^* \nu_R + \lambda_R \nu_R^T C \phi \nu_R + \text{h.c.}$$

$$\phi \sim (\mathbf{1}, \mathbf{1}, 0, -2)$$

Majorana Neutrinos !

Neutrino Masses

$$M_\nu = \frac{v_0^2}{2} Y_\nu M_N^{-1} Y_\nu^T,$$

$$M_N = \sqrt{2}\lambda_R v_\phi = \frac{\lambda_R}{\sqrt{2}} \frac{M_{Z_\ell}}{g_\ell} \cos\beta.$$

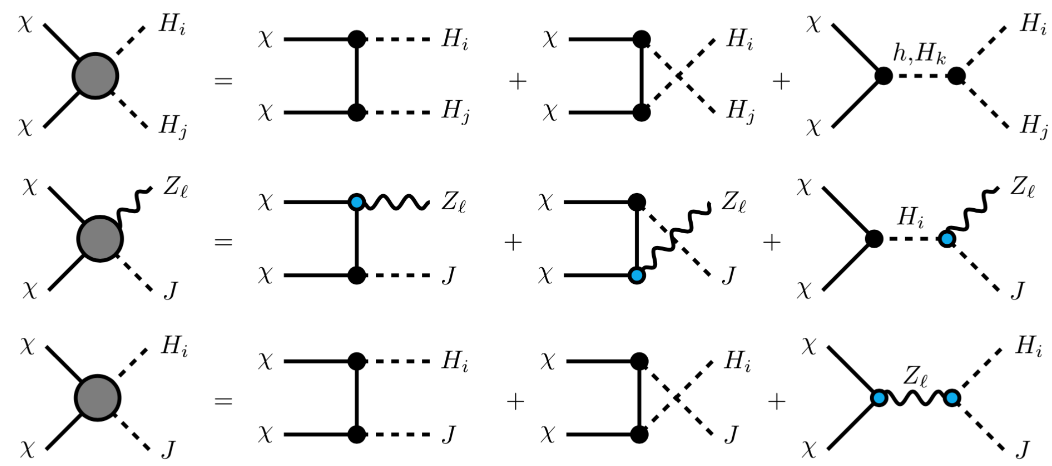
$$M_{Z_\ell}^2 = g_\ell^2 \left(9 v_s^2 \ + \ 4 v_\phi^2\right).$$

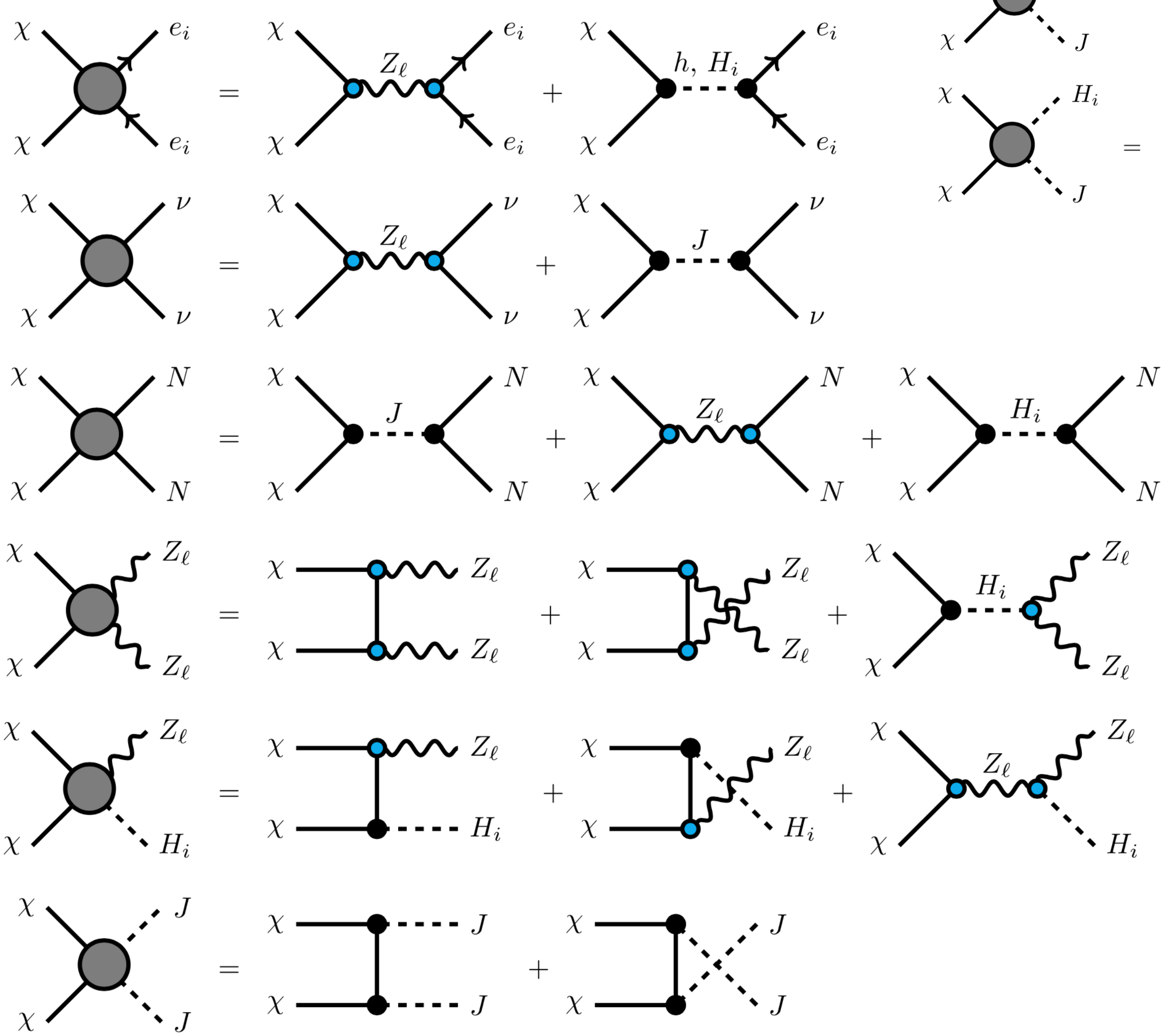
Since the scale for spontaneous L violation must be below the multi-TeV scale one has a **Low Scale Seesaw !**

H. Debnath, P.F.P., K. Gonzalez-Quesada, Physical Review D 109, 115030 (2024)

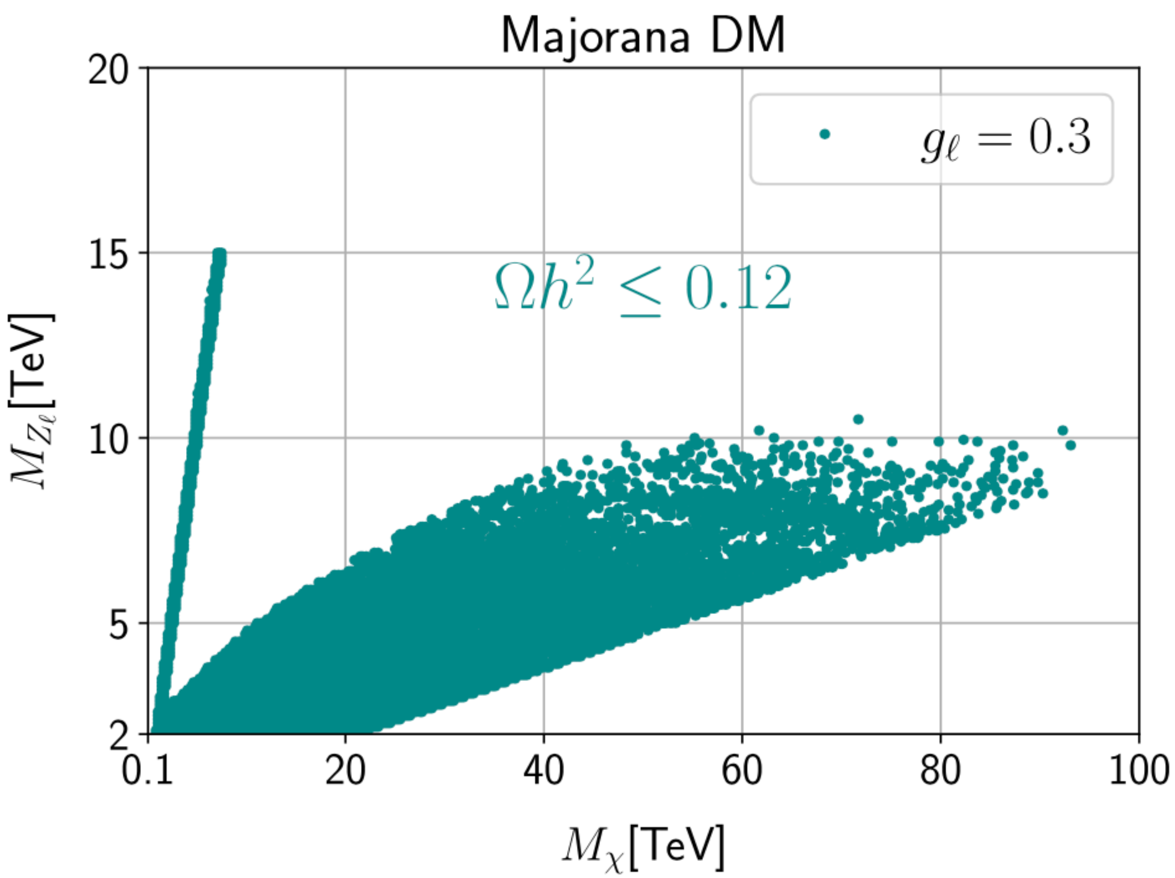
Dark Matter

$$\chi = \chi_L + (\chi_L)^C$$





Dark Matter

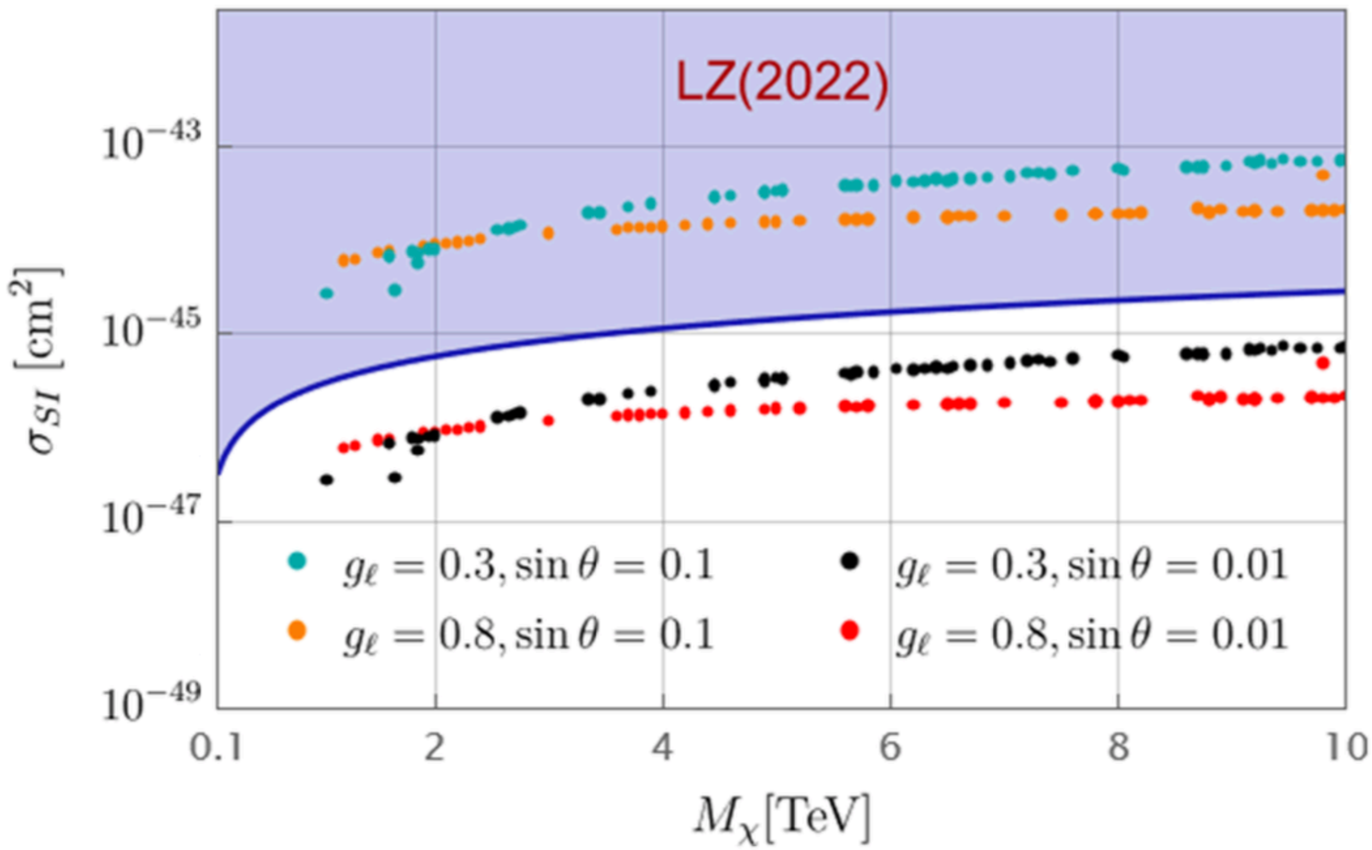


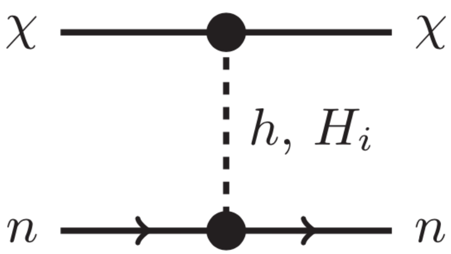
The scale for spontaneous L violation must be below the multi-TeV scale !

H. Debnath, P.F.P., K. Gonzalez-Quesada, Physical Review D 109, 115030 (2024)

Dark Matter

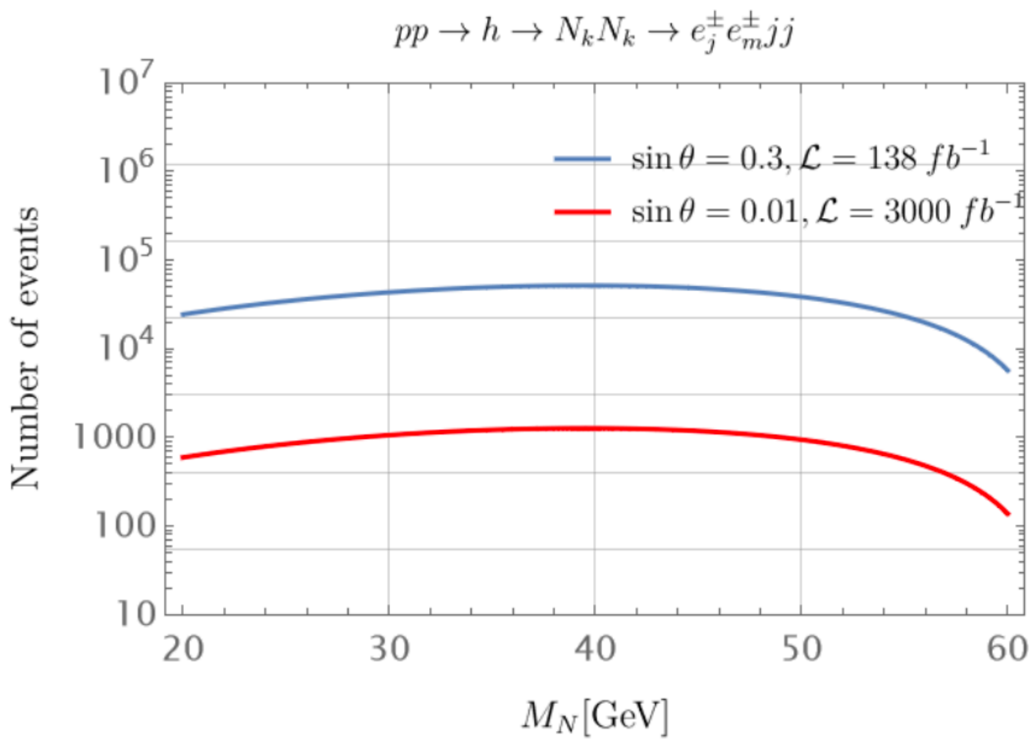
Direct detection:

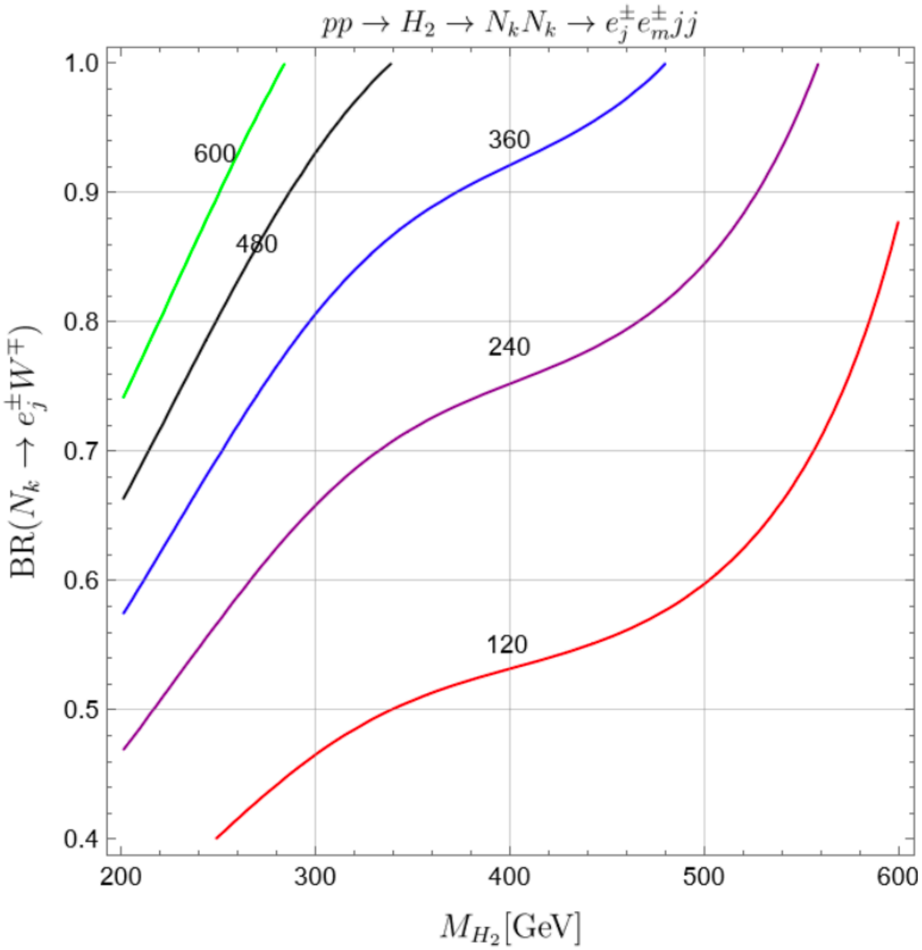




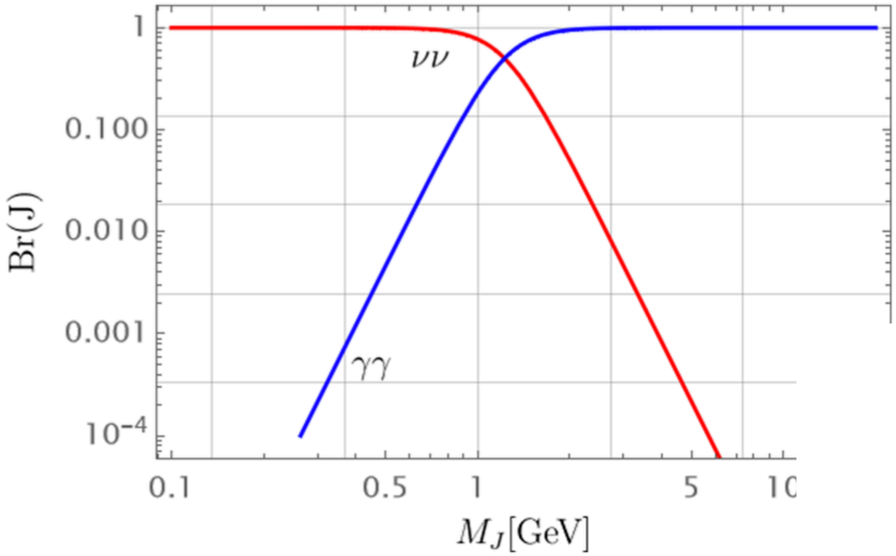
H. Debnath, P.F.P., Phys. Rev. D 108, 075009 (2023)

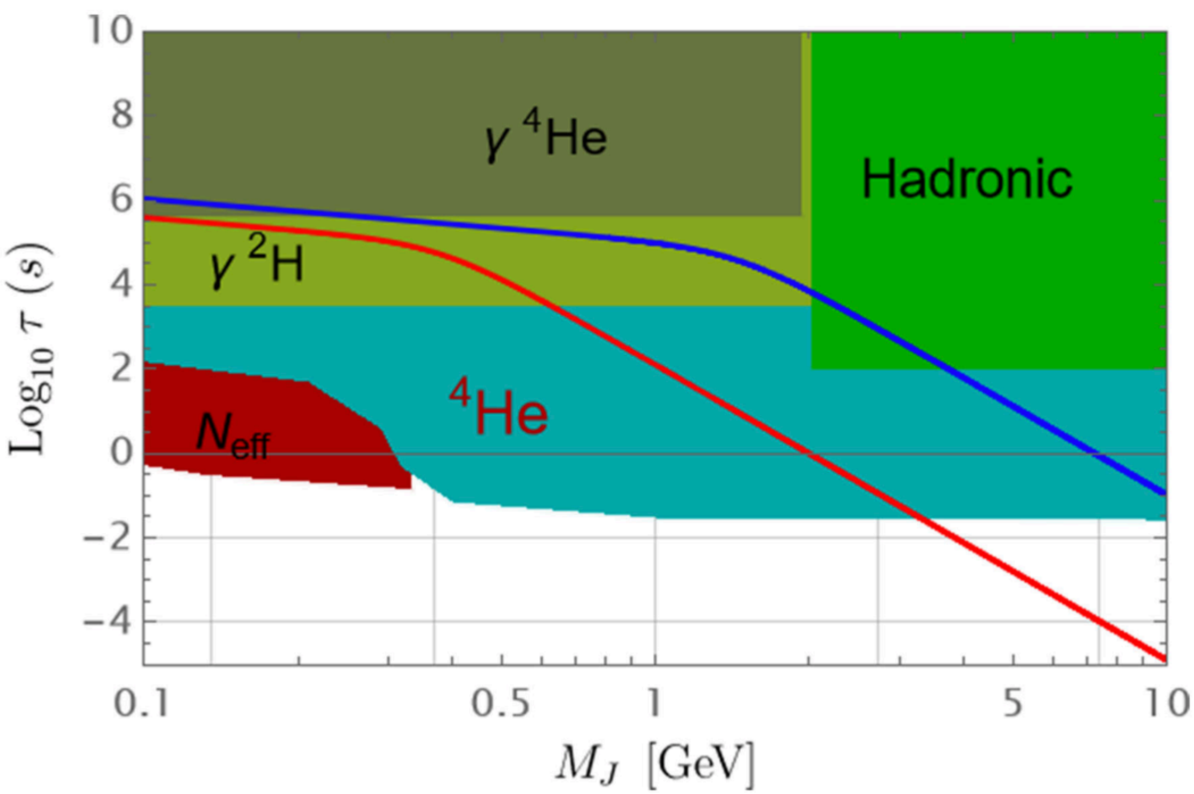
LNV at the LHC





H. Debnath, P.F.P., K. Gonzalez-Quesada, Physical Review D 109, 115030 (2024)





Minimal Theory for Lepton Number and Neutrino Masses

PHYSICAL REVIEW D **110,** 035018 (2024)

Lepton and baryon numbers as local gauge symmetries

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A simple theory where the total lepton number is a local gauge symmetry is proposed. In this context, the gauge anomalies are canceled with the minimal number of extra fermionic fields and one predicts that the neutrinos are Majorana fermions. The properties of the neutrino sector are discussed, showing that this theory predicts a $3 + 2$ light neutrino sector. We show that using the same fermionic fields one can gauge the baryon number and define a simple theory where the lepton and baryon numbers can be spontaneously broken at the low scale in agreement with experiments.

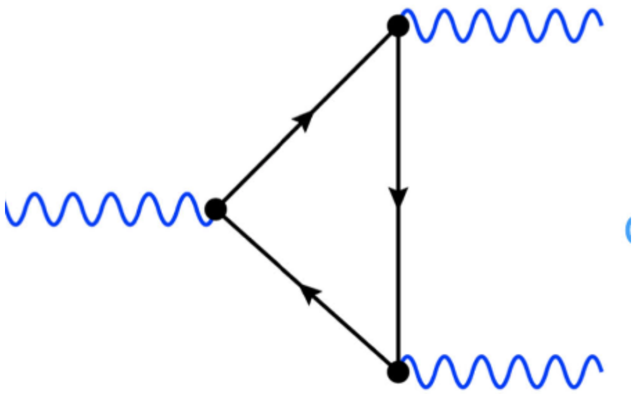
DOI: 10.1103/PhysRevD.110.035018

Lepton Number as Local Gauge Symmetry

Anomaly Cancellation:

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

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



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 (baryonic) gauge anomalies

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

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

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

$$-\mathcal{L} \supset \lambda_e \bar{\Psi}_L e_R \phi + \lambda_R \bar{\chi}_L \nu_R \phi + y_\nu \overline{\ell}_L i\sigma_2 H^* \nu_R + y_e \overline{\ell}_L H e_R + \frac{y}{\Lambda} \ell_L^T i\sigma_2 C \rho_L H \phi + \mathrm{H.c.}$$

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

Neutrino Masses

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$(v_\phi \neq 0)$

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

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

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

3+2 light neutrinos

Here, $\alpha = 4, 5$ and

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

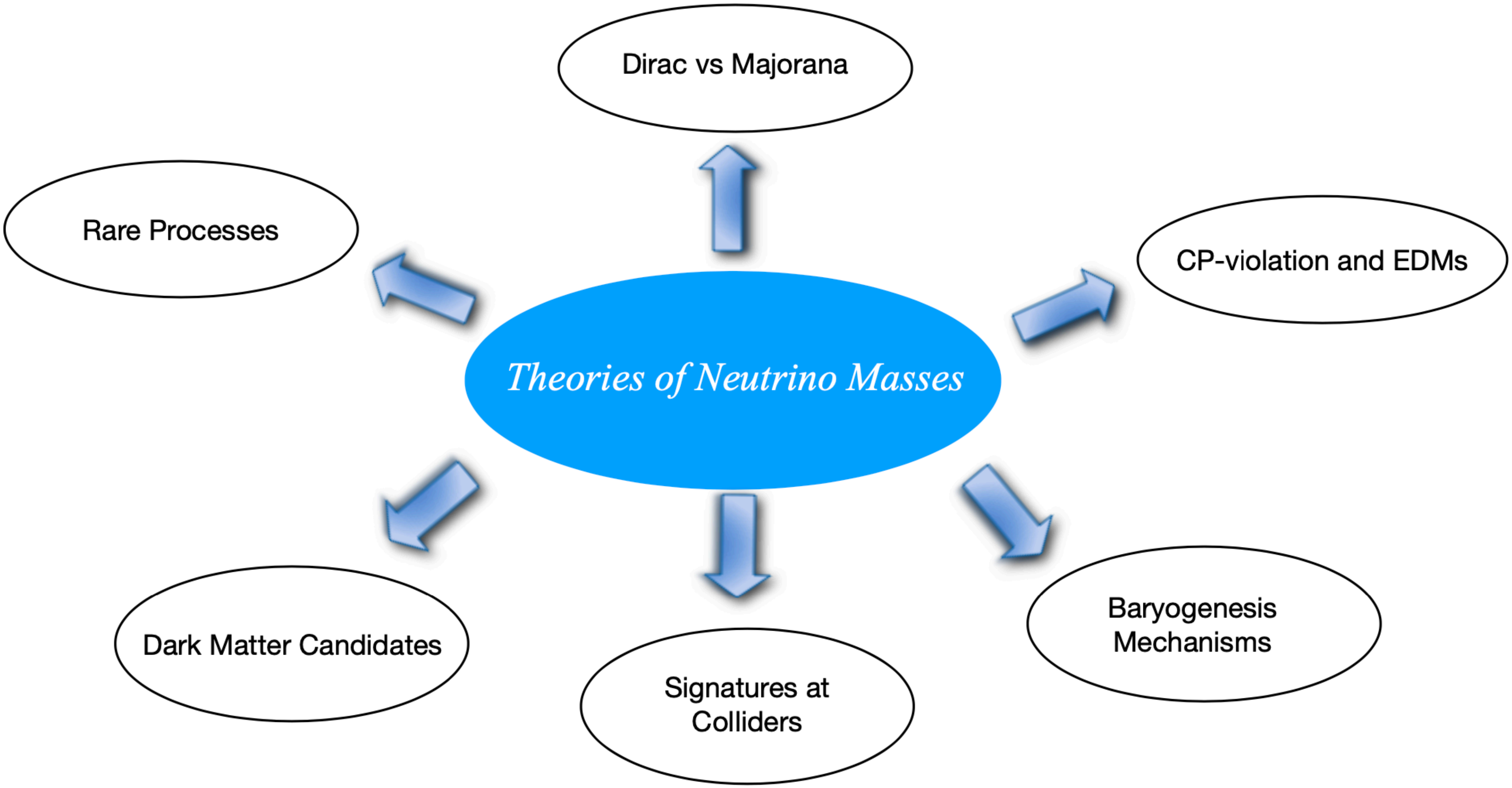
P. F. P., *Physical Review D 110, 035018 (2024)*

Neutrino Masses vs DM

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

→ $v_\phi = 0$ → Dirac Neutrinos → DM

Summary


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