SEARCHES FOR MAJORANA NEUTRINOS

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DIRAC vs MAJORANA ?

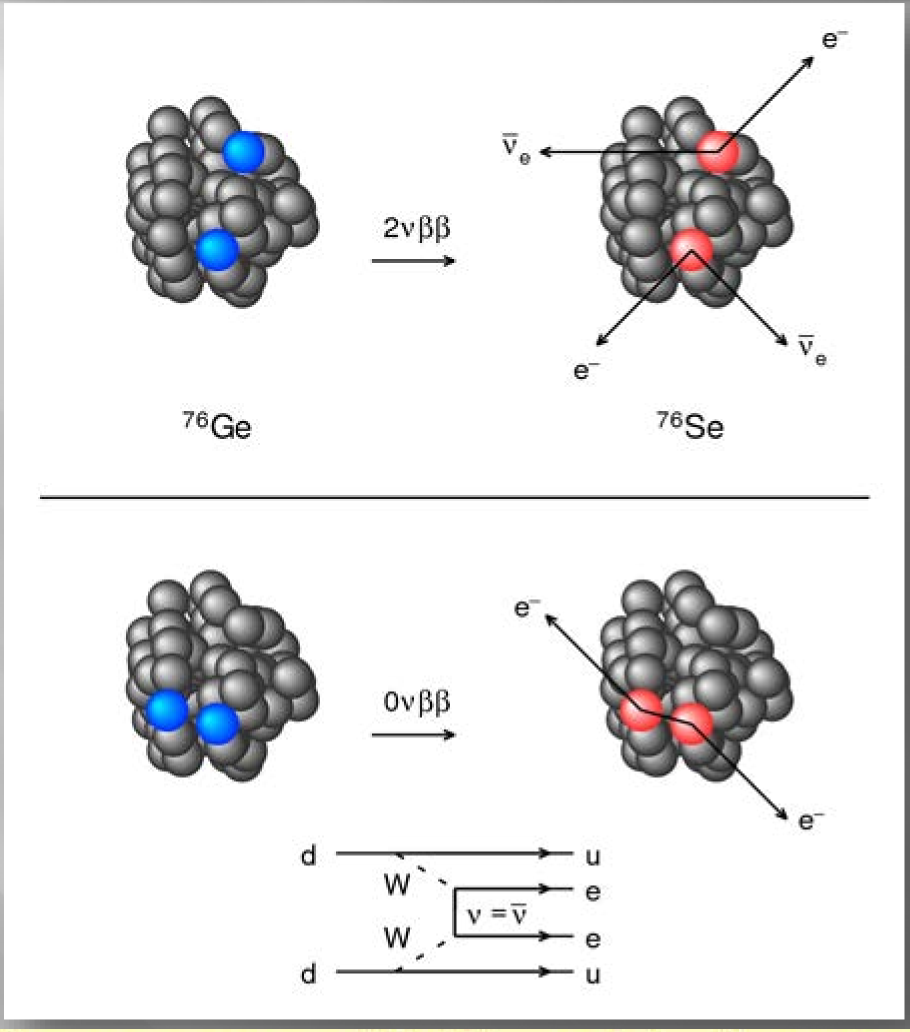
Neutrinos are the only electrically neutral fermions

- *If a fermion is charged, $f \neq \bar{f}$ (quarks, charged leptons)*

- *Majorana Neutrino: $f = \bar{f}$, cannot carry lepton number.*

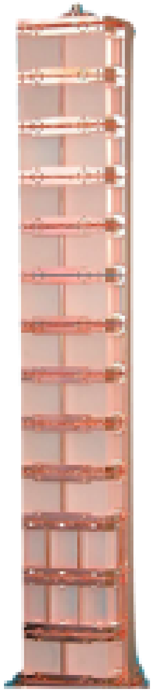
- *The charge properties closely related to mass.*

NEUTRINOLESS DOUBLE BETA DECAY



The process is $(A, Z) \rightarrow (A, Z+2) + 2e^-$

HUGE WORLD WIDE EXPERIMENTAL EFFORT



^{130}Te

- Bolometer-based searches
- $T_{1/2} > 2.8 \times 10^{24}$ y
- Cuoricino / CUORE-0 / CUORE

^{76}Ge

- High-purity germanium detectors
- $T_{1/2} > 2.1 \times 10^{25}$ y
- GERDA / MAJORANA

^{136}Xe

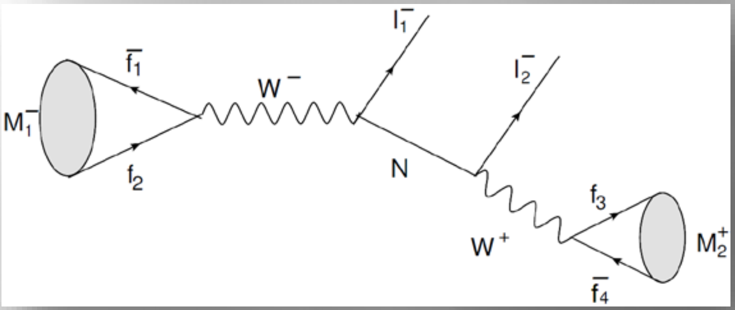
- Liquid Xe scintillation / TPC
- $T_{1/2} > 2.6 \times 10^{25}$ y
- Kamland-Zen, EXO-200, nEXO

NEMO-3 / SuperNEMO

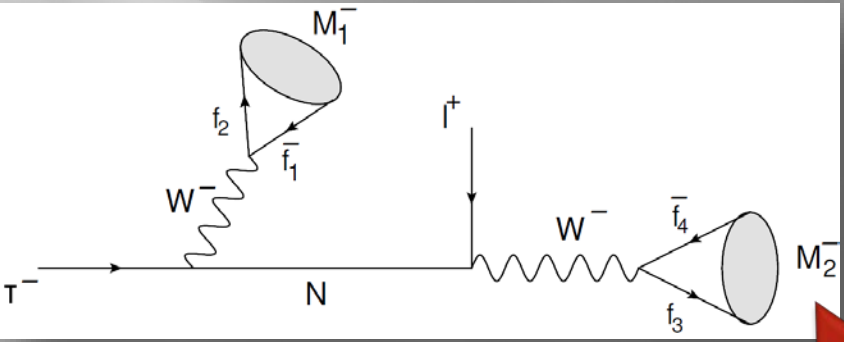
- Source foils with tracking and calorimetry
- Half-lives on ^{48}Ca, ^{82}Se, ^{96}Zr, …

- ***While these efforts will continue, one needs alternate methods for probing if neutrinos are Majorana particles***
- ***Nu-less double beta decay could vanish due to some cancellations, even if Neutrinos are Majorana***
- ***Uncertainties in Nuclear Matrix elements are a concern in Nu-less double beta decay***
- ***Alternate Searches important***

Search for LNV through MESON AND TAU DECAYS



$M_1^- \to \ell_1^- \ell_2^- M_2^+$



$\tau^- \to M_1^- \ell^+ M_2^-$

If the mass of N is lies in the range $\sim (100\ MeV - 5\ GeV)$,
N on shell.

Resonant enhancement of the rates

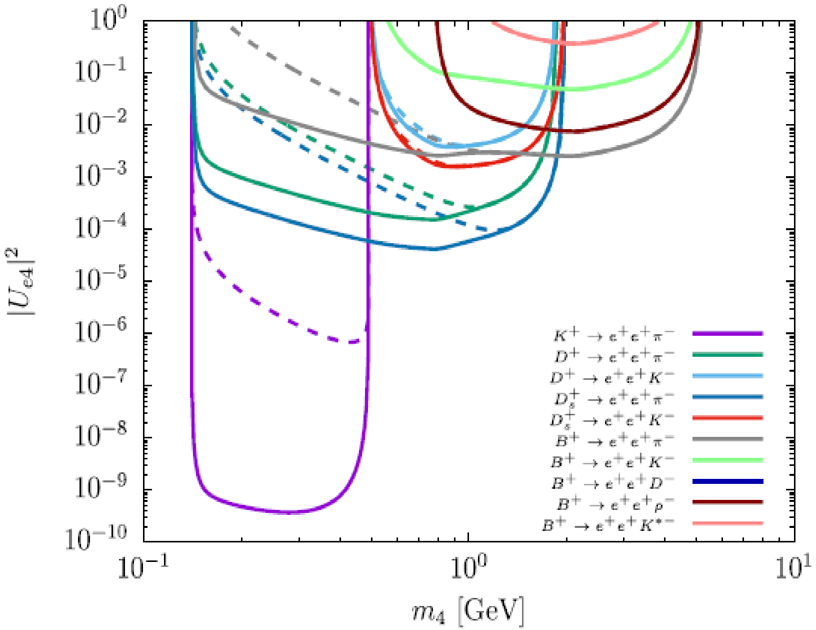
Mixing element	Range of m_4 (MeV)	Decay mode	B_{exp}
$\|V_{e4}\|^2$	140 - 493	$K^+ \to e^+e^+\pi^-$	6.4×10^{-10}
	140 - 1868	$D^+ \to e + e^+\pi^-$	3.6×10^{-6}
	494 - 1868	$D^+ \to e^+e^+K^-$	4.5×10^{-6}
	140 - 1967	$D_s^+ \to e^+e^+\pi^-$	6.9×10^{-4}
	494 - 1967	$D_s^+ \to e^+e^+K^-$	6.3×10^{-4}
	140 - 5278	$B^+ \to e^+e^+\pi^-$	1.6×10^{-6}
	494 - 5278	$B^+ \to e^+e^+K^-$	1.0×10^{-6}
	776 - 5278	$B^+ \to e^+e^+\rho^-$	2.6×10^{-6}
	892 - 5278	$B^+ \to e^+e^+K^{*-}$	2.8×10^{-6}
$\|V_{\mu 4}\|^2$	245 - 388	$K^+ \to \mu^+\mu^+\pi^-$	3.0×10^{-9}
	245 - 1763	$D^+ \to \mu^+\mu^+\pi^-$	4.8×10^{-6}
	599 - 1763	$D^+ \to \mu^+\mu^+K^-$	1.3×10^{-5}
	881 - 1763	$D^+ \to \mu^+\mu^+\rho^-$	5.6×10^{-4}
	997 - 1763	$D^+ \to \mu^+\mu^+K^{*-}$	8.5×10^{-4}
	245 - 1862	$D_s^+ \to \mu^+\mu^+\pi^-$	2.9×10^{-5}
	599 - 1862	$D_s^+ \to \mu^+\mu^+K^-$	1.3×10^{-5}
	997 - 1862	$D_s^+ \to \mu^+\mu^+K^{*-}$	1.4×10^{-3}
	245 - 5173	$B^+ \to \mu^+\mu^+\pi^-$	1.4×10^{-6}
	599 - 5173	$B^+ \to \mu^+\mu^+K^-$	1.8×10^{-6}
	881 - 5173	$B^+ \to \mu^+\mu^+\rho^-$	5.0×10^{-6}
	997 - 5173	$B^+ \to \mu^+\mu^+K^{*-}$	8.3×10^{-6}
$\|V_{e4}V_{\mu 4}\|$	140 - 493	$K^+ \to e^+\mu^+\pi^-$	5.5×10^{-10}
	140 - 1868	$D^+ \to e^+\mu^+\pi^-$	5.0×10^{-5}
	494 - 1868	$D^+ \to e^+\mu^+K^-$	1.3×10^{-4}
	140 - 1862	$D_s^+ \to e^+\mu^+\pi^-$	7.3×10^{-4}
	494 - 1967	$D_s^+ \to e^+\mu^+K^-$	6.8×10^{-4}
	140 - 5278	$B^+ \to e^+\mu^+\pi^-$	1.3×10^{-6}
	494 - 5278	$B^+ \to e^+\mu^+K^-$	2.0×10^{-6}
	776 - 5278	$B^+ \to e^+\mu^+\rho^-$	3.3×10^{-6}
	892 - 5278	$B^+ \to e^+\mu^+K^{*-}$	4.4×10^{-6}

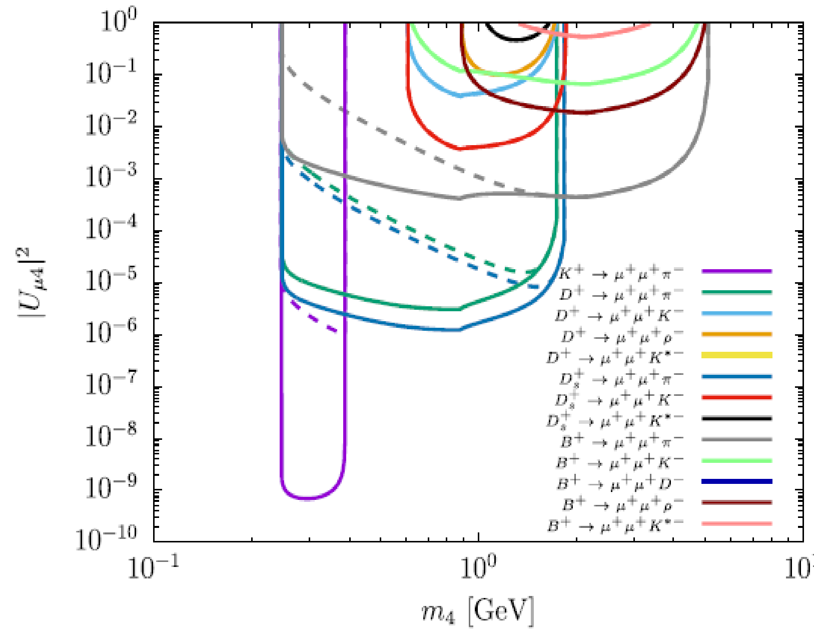
Below Tau Mass!

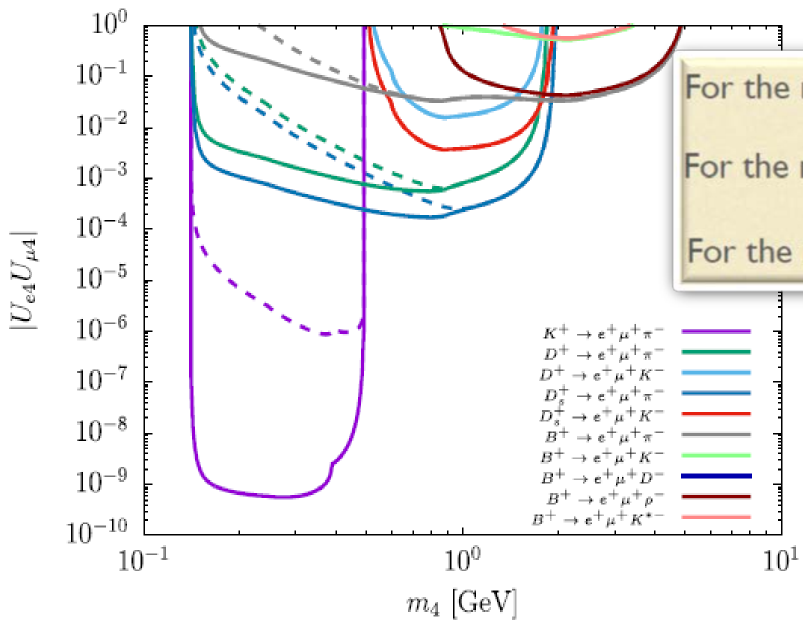
Mixing element	Range of m_4 (MeV)	Decay mode	B_{exp}
$\|V_{e4}V_{\tau 4}\|$	140 - 1637	$\tau^- \to e^+\pi^-\pi^-$	2.7×10^{-7}
	140 - 1637	$\tau^- \to e^+\pi^-K^-$	1.8×10^{-7}
	494 - 1283	$\tau^- \to e^+K^-K^-$	1.5×10^{-7}
$\|V_{\mu 4}V_{\tau 4}\|$	245 - 1637	$\tau^- \to \mu^+\pi^-\pi^-$	0.7×10^{-7}
	245 - 1637	$\tau^- \to \mu^+\pi^-K^-$	2.2×10^{-7}
	599 - 1283	$\tau^- \to \mu^+K^-K^-$	4.8×10^{-7}

Huge Experimental effort to search for these modes has been going on!

Limits on Branching ratios, constrain the Mixing angles







For the mass range 0.1-0.4 GeV, tightest bound comes from $K^+ \to e^+e^+\pi^-$

For the mass range 0.4-2 GeV, tightest bound comes from $D_s^+ \to e^+e^+\pi^-$

For the mass range 2-5 GeV, tightest bound comes from $B^+ \to e^+e^+\pi^-$

Proposal to look at B_c DECAYS

S. Mandal, N.Sinha, **Phys.Rev. D94 (2016)**

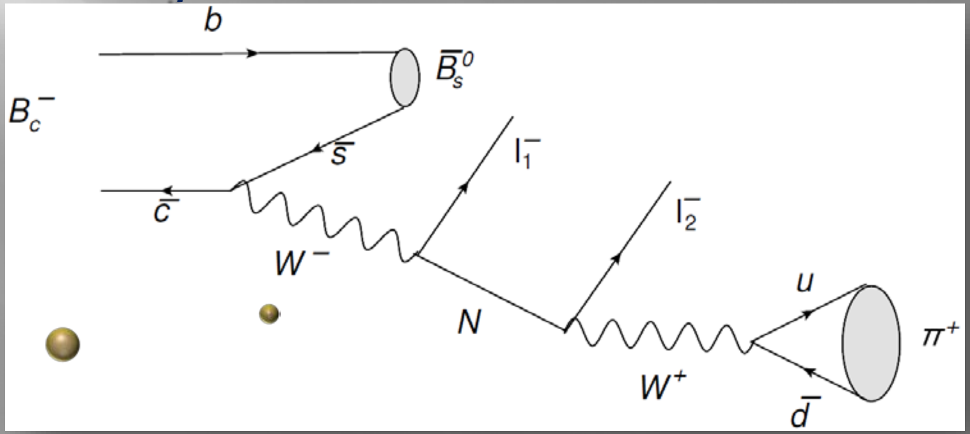
B_c mesons are unique-only states consisting of two heavy quarks of different flavors.

Weak Decays of b quark will be Cabibbo suppressed:

$b \to c$, λ^2 supp., $b \to u$, λ^3 supp.

However, the $c \to s$ transition is Cabibbo favoured.

Expect $B_c \to \overline{B_s^0} \ell_1^- \ell_2^- \pi^+$ to have a larger B.R. than other LNV B meson decays.



If on-shell, Resonant Enhancement

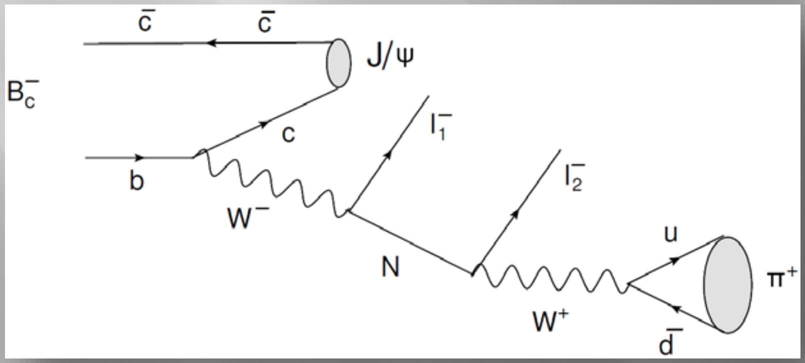
$B_c^- \to \overline{B_s^0}\, \pi^-$ has already been observed by LHCb with the largest exclusive B.R. amongst known decay modes of all B mesons.

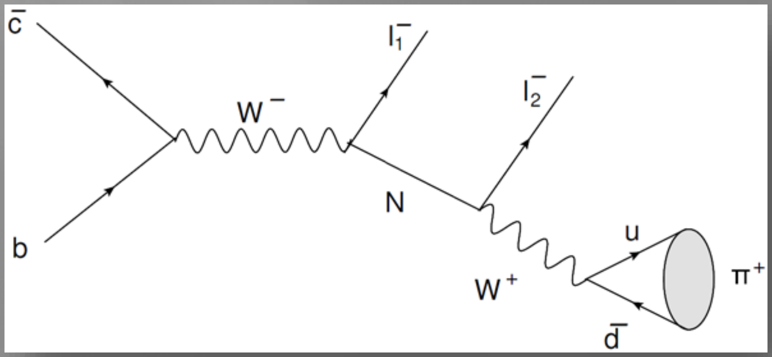
OTHER B_c MODES

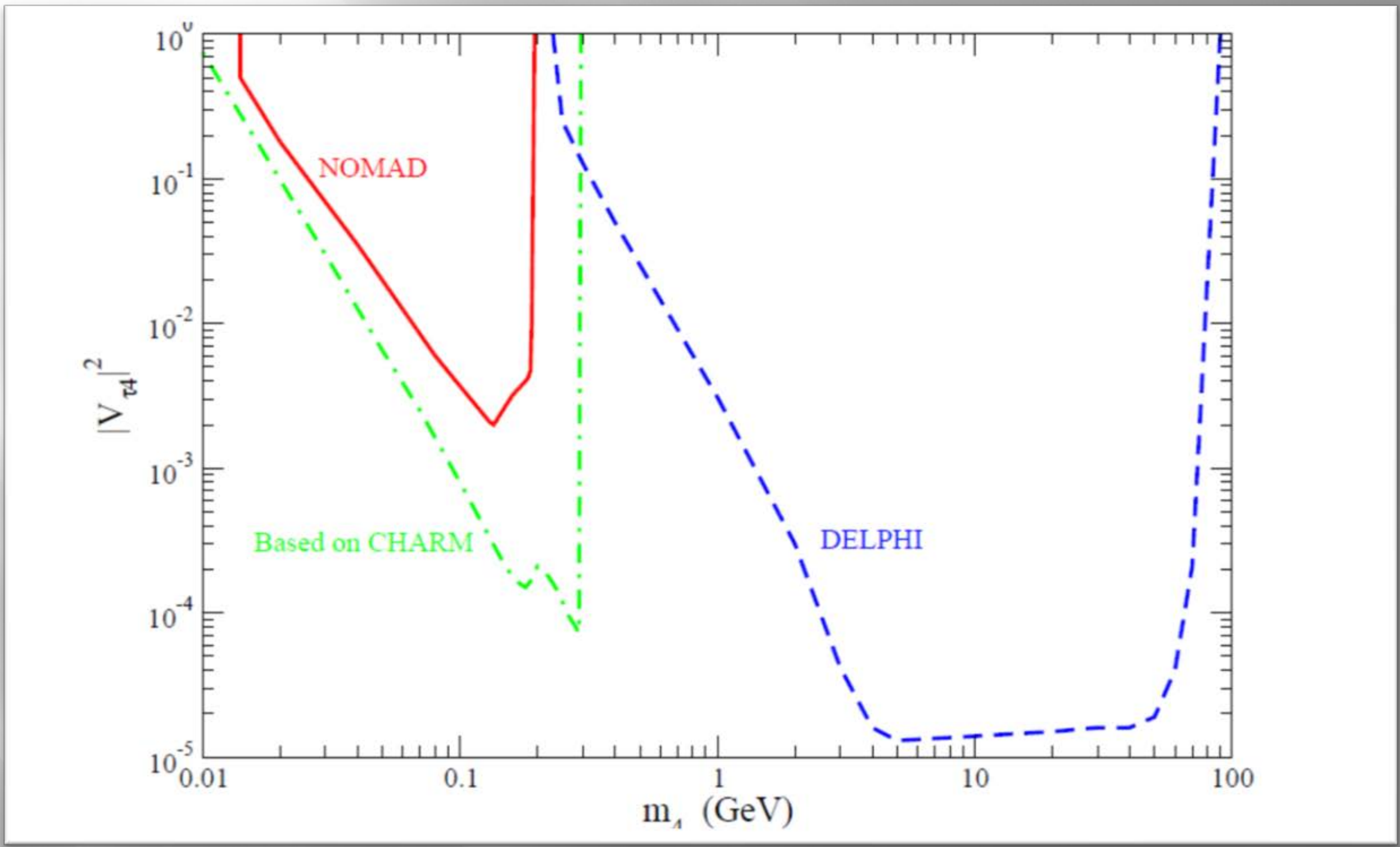
- *Although the $B_c \to \overline{B_s^0}\ell_1^-\ell_2^-\pi^+$ is expected to have a large B.R., reconstruction of the $\overline{B_s^0}$, results in a penalty of ~10^{-4} Hence upper limits of 10^{-5}, may only be possible. This still results in constraints tighter than those obtained earlier.*
- *Interestingly, the $B_c \to \psi\ell_1^-\ell_2^-\pi^+$ and $B_c \to \ell_1^-\ell_2^-\pi^+$, while suppressed but due to ease of reconstruction and phase space enhancement results in even tighter constriants.*
- *A crude estimate using the measured ratio of production cross section times branching fractions between the $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ at 8TeV, indicates ~ O(10^{10}) Bc events with $10\ fb^{-1}$luminosity at 13TeV.*

- ✓ For $B_c \to \psi \ell_1^- \ell_2^- \pi^+$, one of the leptons can be a tau, while for $B_c \to \ell_1^- \ell_2^- \pi^+$, both leptons being taus is also permitted.
- ✓ This results in exclusion curves for $|V_{eN} V_{\tau N}|$ and $|V_{\mu N}\, V_{\tau N}|$ on which bounds exist only from tau decays, exclusion curves for masses upto 6 GeV can be provided.

- ✓ Also for $|V_{\tau N}|^2$ which is very loosely constrained, exclusion curves in the mass range (0.3-5.0) GeV can be provided







NOMAD
Based on CHARM
DELPHI
$|V_{\tau 4}|^2$
m_4 (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.01
0.1
1
10
100

LNV Decays to set limits on the mass of the RH Gauge Boson

- *These can of course be used to get constriants on the active-sterile mixing angles.*

- *Alternately, approximating this angle in accordance with the seesaw condition, the rates or upper limits on the branching ratios of the LNV decays of mesons can be used to get limits on the right handed gauge boson mass.*

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Majorana Neutrinos and the Production of the Right-Handed Charged Gauge Boson

Wai-Yee Keung and Goran Senjanović

Physics Department, Brookhaven National Laboratory, Upton, New York 11973

(Received 14 February 1983)

A possibility of a very clean signature for the production of $W_R^\pm$ is pointed out. If the right-handed neutrino is lighter than $W_R^\pm$, left-right symmetric gauge theory predicts the decay $W_R^+ \to \mu^+\mu^+ + 2$ hadronic jets, with the branching ratio $\simeq 3\%$. The lack of neutrinos in the final state and the absence of a sizable background make $W_R^\pm$ rather easy to detect (if it exists). Detailed predictions regarding the production and decay rates of $W_R^\pm$ are presented.

LEFT RIGHT SYMMETRY

On the theoretical side

Based on the gauge group, $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

An attractive framework to explain the light neutrino masses

Appearance of right-handed neutrino components is not accidental but ***required*** *in order to complete the right-handed lepton doublets*

FERMIONS:

$$Q_{L,i} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i : \left(\mathbf{3}, \mathbf{2}, \mathbf{1}, \tfrac{1}{3}\right), \qquad Q_{R,i} = \begin{pmatrix} u_R \\ d_R \end{pmatrix}_i : \left(\mathbf{3}, \mathbf{1}, \mathbf{2}, \tfrac{1}{3}\right),$$
$$\psi_{L,i} = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_i : (\mathbf{1}, \mathbf{2}, \mathbf{1}, -1), \qquad \psi_{R,i} = \begin{pmatrix} N_R \\ e_R \end{pmatrix}_i : (\mathbf{1}, \mathbf{1}, \mathbf{2}, -1),$$

Includes High scale parity symmetry

Existence of right-handed currents

LEFT RIGHT SYMMETRY-SCALAR SECTOR

Higgs multiplets must be LR symmetric

(i) Bi-doublet under $SU(2)_L \times SU(2)_R$
Couples to fermion bilinears and gives masses to quarks and leptons after SSB by its VEV

$$\langle \Phi \rangle = \mathrm{diag}(\kappa_1, \kappa_2)/\sqrt{2}.$$

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} : (\mathbf{1}, \mathbf{2}, \mathbf{2}, 0),$$

(ii) SU(2) triplets that break the L-R symmetry and also give the Majorana mass terms for heavy neutrinos

$$\Delta_L \equiv \begin{pmatrix} \Delta_L^+/\sqrt{2} & \Delta_L^{++} \\ \Delta_L^0 & -\Delta_L^+/\sqrt{2} \end{pmatrix} : (\mathbf{1}, \mathbf{3}, \mathbf{1}, 2), \qquad \Delta_R \equiv \begin{pmatrix} \Delta_R^+/\sqrt{2} & \Delta_R^{++} \\ \Delta_R^0 & -\Delta_R^+/\sqrt{2} \end{pmatrix} : (\mathbf{1}, \mathbf{1}, \mathbf{3}, 2)$$

$\langle \Delta_R \rangle$ breaks the $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$

Finally, VEV of bidoublet breaks $SU(2)_L \times U(1)_Y \to U(1)_Q$

Mixing Matrix

The Yukawa Lagrangian in the lepton sector is given by :

$$-\mathcal{L}_Y = h_{ij}\bar{\psi}_{L,i}\Phi\psi_{R,j} + \tilde{h}_{ij}\bar{\psi}_{L,i}\tilde{\Phi}\psi_{R,j} + f_{L,ij}\psi^{\mathsf{T}}_{L,i}Ci\tau_2\Delta_L\psi_{L,j} + f_{R,ij}\psi^{\mathsf{T}}_{R,i}Ci\tau_2\Delta_R\psi_{R,j} + \mathrm{H.c.},$$

Upon symmetry breaking the light –heavy neutrino mass matrix has the form,

$$\mathcal{M}_\nu = \begin{pmatrix} M_L & M_D \\ M_D^{\mathsf{T}} & M_R \end{pmatrix}$$

where the 3×3 Dirac and Majorana mass matrices are given by

$$M_D = \frac{1}{\sqrt{2}}\left(\kappa_1 h + \kappa_2 \tilde{h}\right), \quad M_L = \sqrt{2}v_L f_L, \quad M_R = \sqrt{2}v_R f_R .$$

which can be diagonalized by a 6 × 6 unitary matrix.

$$\mathcal{V} = \begin{pmatrix} U & S \\ T & V \end{pmatrix}$$

The mixing matrix to be used in our analysis is denoted by

$$U \approx 1 \qquad V \approx 1$$

$$S \approx \sqrt{\frac{m_\nu}{M_N}} \qquad T \approx \sqrt{\frac{m_\nu}{M_N}}$$

Gauge sector and charged current Lagrangian

In addition to the SM gauge bosons, this model consists of a RH charged gauge boson, W_R and an additional neutral gauge boson, Z'. $M_{Z'} \sim 1.7 M_{W_R}$

Charged current Lagrangian for the quarks and lepton-neutrino have the form:

Will contribute in some of the decay channels of the RH neutrino

$$\mathcal{L}^q_{CC} = \frac{g}{\sqrt{2}} \sum_{i,j} \bar{u}_i V^{\text{CKM}}_{ij} W^+_{L\mu} \gamma^\mu P_L d_j + \frac{g}{\sqrt{2}} \sum_{i,j} \bar{u}_i V^{\text{R-CKM}'}_{ij} W^+_{R\mu} \gamma^\mu P_R d_j + \text{H.c.},$$

$$\mathcal{L}^\ell_{CC} = \frac{g}{\sqrt{2}} \sum_{i,j} \bar{\ell}_{L_i} W^-_{L\mu} \gamma^\mu P_L (U_{ij} \nu_{L_j} + S_{ij} N^c_j) + \frac{g}{\sqrt{2}} \sum_{i,j} \bar{\ell}_{R_i} W^-_{R\mu} \gamma^\mu P_R (V^*_{ij} N_j + T^*_{ij} \nu^c_L) + \text{H.c.}$$

$$\mathcal{L}_{\text{NC}} = \frac{g_L}{\cos\theta_w} \left(Z_\mu J^\mu_Z + \frac{cos^2\theta_w}{\sqrt{\cos 2\theta_w}} Z'_\mu J^\mu_{Z'} \right)$$

$$J^\mu_Z = \sum_i \bar{f} \gamma^\mu (T^3_L P_L - Q sin^2\theta_w) f,$$

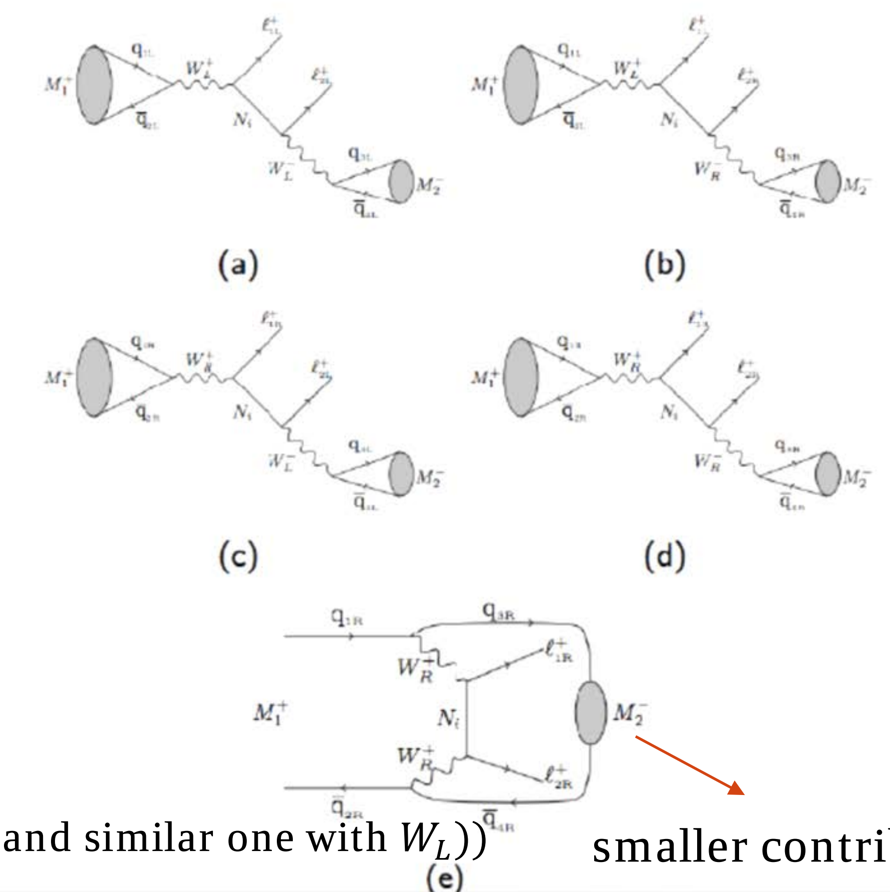
$$J^\mu_{Z'} = \sum_i \bar{f} \gamma^\mu (T^3_R P_R - tan^2\theta_w (Q - T^3_{3L}) f.$$

IMPRINT OF MAJORANA SIGNATURE IN MESON DECAYS

In LRSM, Heavy Neutrinos are Majorana and hence can mediate the lepton number violating decays

$$M_1^+(p) \to \ell_1^+(k_1)\ell_2^+(k_2)M_2^-(k_3)$$

Assume 3 RH neutrinos in the mass range $100\ MeV - 5\ GeV$, that contribute to these Meson Decays. The different contributions are mediated through



(and similar one with W_L))

smaller contribution

Neglect contributions from light neutrino exchange

The Amplitudes

$$\mathcal{M}^P_{1LL} = \sum_i G_F^2 V^{\mathrm{CKM}}_{M_1} V^{\mathrm{CKM}}_{M_2} f_{M_1} f_{M_2} M_{N_i} (S^*_{\ell_1 N_i} S^*_{\ell_2 N_i}) \frac{\bar{u}(k_2) \not{k}_3 \not{p} (1-\gamma_5) v(k_1)}{(p-k_1)^2 - M^2_{N_i} + i M_{N_i} \Gamma_{N_i}},$$

$$\mathcal{M}^P_{1RR} = \sum_i G_F^2 V^{\mathrm{CKM}}_{M_1} V^{\mathrm{CKM}}_{M_2} f_{M_1} f_{M_2} M_{N_i} \left(\frac{M^4_{W_L}}{M^4_{W_R}}\right) (V_{\ell_1 N_i} V_{\ell_2 N_i}) \frac{\bar{u}(k_2) \not{k}_3 \not{p} (1+\gamma_5) v(k_1)}{(p-k_1)^2 - M^2_{N_i} + i M_{N_i} \Gamma_{N_i}}.$$

where k_3 and p are the four momentums of M_2^+ and M_1^- mesons. The LR and RL contributions are

$$\mathcal{M}^P_{1LR} = \sum_i G_F^2 V^{\mathrm{CKM}}_{M_1} V^{\mathrm{CKM}}_{M_2} f_{M_1} f_{M_2} \left(\frac{M^2_{W_L}}{M^2_{W_R}}\right) (S^*_{\ell_1 N_i} V_{\ell_2 N_i}) \frac{\bar{u}(k_2) \not{k}_3 (\not{p} - \not{k}_1) \not{p} (1-\gamma_5) v(k_1)}{(p-k_1)^2 - M^2_{N_i} + i M_{N_i} \Gamma_{N_i}},$$

$$\mathcal{M}^P_{1RL} = \sum_i G_F^2 V^{\mathrm{CKM}}_{M_1} V^{\mathrm{CKM}}_{M_2} f_{M_1} f_{M_2} \left(\frac{M^2_{W_L}}{M^2_{W_R}}\right) (V_{\ell_1 N_i} S^*_{\ell_2 N_i}) \frac{\bar{u}(k_2) \not{k}_3 (\not{p} - \not{k}_1) \not{p} (1+\gamma_5) v(k_1)}{(p-k_1)^2 - M^2_{N_i} + i M_{N_i} \Gamma_{N_i}}.$$

In the above, the decay rate Γ^P is

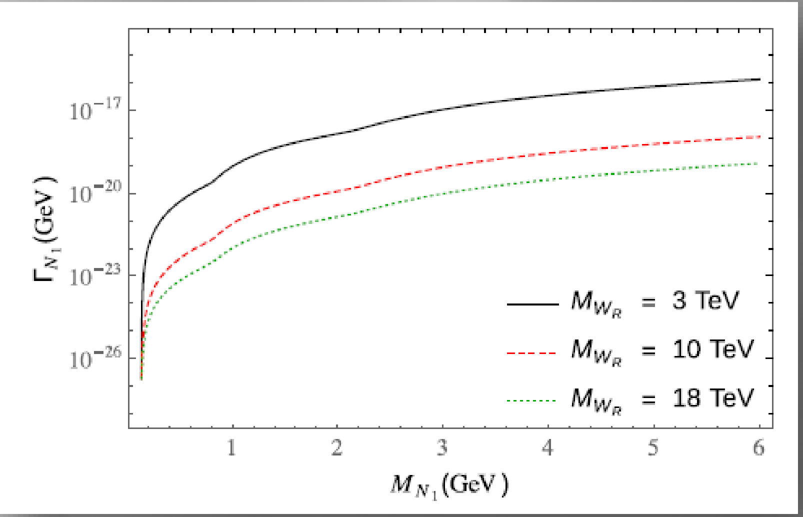
$$\Gamma^P(M_1 \to \ell_1 \ell_2 M_2) = \frac{1}{n!} (|\mathcal{M}^P_{LL} + \mathcal{M}^P_{RR} + \mathcal{M}^P_{LR} + \mathcal{M}^P_{RL}|^2) d_3(PS).$$

For the final meson M_2, being a pseudoscalar; for the vector case, will also involve the polarization of the vector meson

TOTAL DECAY WIDTH OF THE HEAVY MAJORANA NEUTRINO, N

$$\Gamma_{N_i} = \sum_{\ell,P} 2\Gamma^{\ell P} + \sum_{\ell,P} \Gamma^{\nu_\ell P} + \sum_{\ell,V} 2\Gamma^{\ell V} + \sum_{\ell,V} \Gamma^{\nu_\ell V},$$

$$+ \sum_{\ell_1,\ell_2(\ell_1\neq\ell_2)} 2\Gamma^{\ell_1\ell_2\nu_{\ell_2}} + \sum_{\ell_1,\ell_2} \Gamma^{\nu_{\ell_1}\ell_2\ell_2} + \sum_{\nu_{\ell_1}} \Gamma^{\nu_{\ell_1}\nu\bar{\nu}}.$$



Narrow Width

SIGNAL EVENTS

The expected number of events for the LNV decay modes in a particular experiment depend on:

Number of parent meson M_1's produced (N_{M_1}), Their momentum ($\vec{p}_{M_1}$)

Branching Ratio for these mesons to decay to the LNV modes

Probability of the RH neutrino to decay within a detector of length L_D, given by

$$\begin{aligned} N_{\text{event}} &= 2N_{M_1^+}\mathrm{Br}(M_1^+ \to \ell^+\ell^+M_2^-)\mathcal{P}_N, \\ &\approx 2N_{M_1^+}\mathrm{Br}(M_1^+ \to \ell^+N_i)\frac{\Gamma(N_i \to \ell^+M_2^-)}{\Gamma_{N_i}}\mathcal{P}_N \end{aligned}$$

$$\mathcal{P}_N = \left[1 - \exp\left(-\frac{M_{N_i}\Gamma_{N_i}L_D}{p^*_{N_i}}\right)\right]$$

Momentum of N_i in M_1 rest frame

For mesons decaying in flight, the appropriate boost factor has to be used

Since the LNV decays will be rare, the expected number of events for these can be assumed to follow a Poisson distribution. Using the method of Feldman and Cousins, we get the average upper limit on the number of events at 95% C.L.

Inputs for the different Experiments

$$N_K = 1.35 \times 10^{13}\,,\; L_D = 100\,\mathrm{m}\,, \quad \beta_K = 75\,\mathrm{GeV}$$

$$N_D = 3.4 \times 10^{10}, N_{D_s} = 10^{10}, N_B = 5.5 \times 10^{10}$$

$$L_D = 1.5\,\mathrm{m}, \quad \beta_{D,D_s,B} \approx 0$$

$$N_D = 5 \times 10^{12}, N_{D_s} = 2.3 \times 10^{12}, N_B = 7.7 \times 10^{11}$$

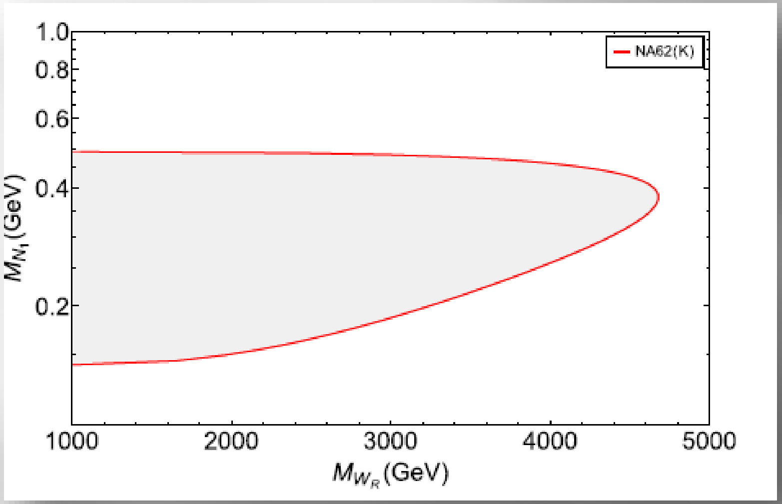
$$L_D = 20\,\mathrm{m}\,, \quad \beta_{B,D} = 100\,\mathrm{GeV}$$

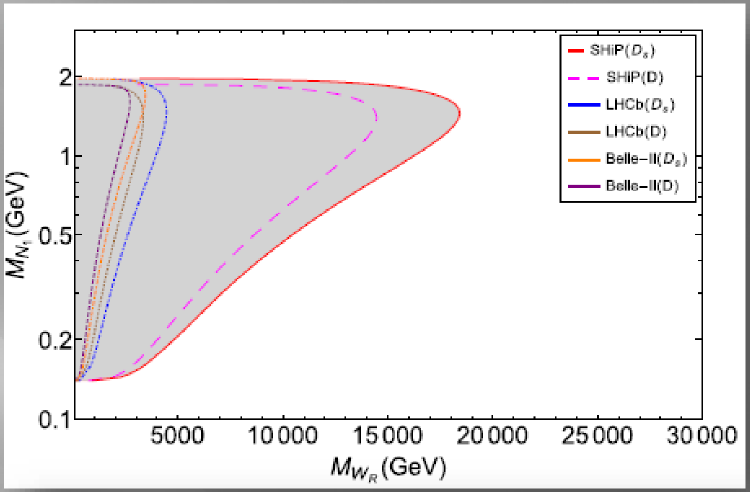
$$N_B = 6 \times 10^{11}\,,\; L_D = 2\,\mathrm{m}\,, \quad \beta_B = \frac{M_Z}{2}$$

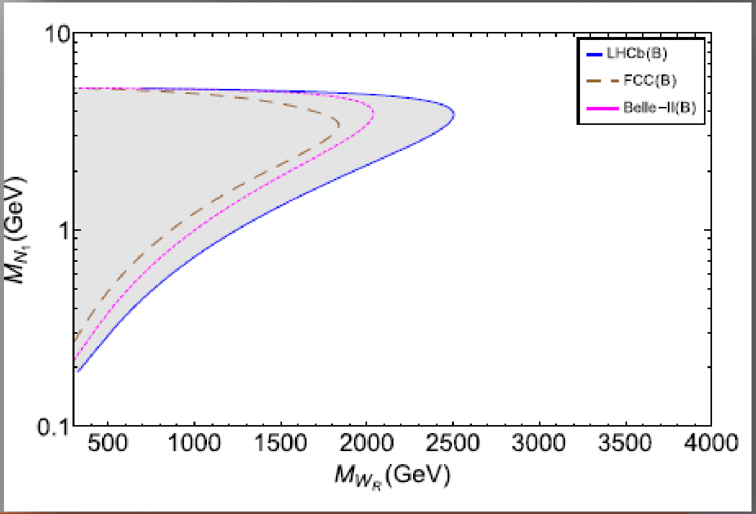
$$N_D = 1.02 \times 10^{17}\,,\; N_{D_s} = 2.72 \times 10^{16}\,,\; L_D = 60\,\mathrm{m}$$

$$\beta_{D,D_s} = 58\,\mathrm{GeV}$$

Constraints on M_{W_R} for LNV decays with Like Sign Dielectrons







$M_{W_R} > 4.6\, TeV, M_N \sim 0.38\, GeV$,

S. Mandal, M. Mitra and N. Sinha
Phys.Rev. D96 (2017)

Comparison with constraints from other Experiments

Calculation of K meson mass difference in MLRSM gives constraint,
$M_{W_R} > 2.5\,\mathrm{TeV}$ *Phys. Rev. D 82, 055022 (2010)*

From $0\nu\nu\beta$ tightest bound is $M_{W_R} > 9 - 10\,\mathrm{TeV}$ for $M_N \approx 0.1\,\mathrm{GeV}$
Phys. Rev. D 92, 073017 (2015)

13 TeV ATLAS dijet search ruled out the W_R mass upto 3 TeV
ATLAS Collaboration, Report No. ATLAS-CONF-2016-069

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Thank You