Probing Majorana Neutrinos (in Rare Decays of Mesons)

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Outline

1. Prologue

2. Issues on neutrino masses

3. Probing Majorana neutrinos via
   (a) $0\nu\beta\beta$
   (b) $K, D, Ds, B, Bc$ meson RARE decays
   (c) at the LHC

4. Concluding remarks
1. Prologue

- Neutrinos are massless in the SM
  - No right-handed $\nu$’s $\Rightarrow$ Dirac mass term is not allowed.
  - Conserves the SU(2)$_L$ gauge symmetry, and only contains the Higgs doublet (the SM accidently possesses $(B - L)$ symmetry); $\Rightarrow$ Majorana mass term is forbidden.

- Historic Era in Neutrino Physics
  - Atmospheric $\nu_\mu$’s are lost. (SK) (1998)
  - converted most likely to $\nu_\tau$ (2000)
  - Solar $\nu_e$ is converted to either $\nu_\mu$ or $\nu_\tau$ (SNO) (2002)
  - Only the LMA solution left for solar neutrinos (Homestake+Gallium+SK+SNO) (2002)
  - Reactor anti-$\nu_e$ disappear (2002) and reappear (KamLAND) (2004)
What we have learned

- Lepton Flavor is not conserved
- Neutrinos have tiny mass, not very hierarchical
- Neutrinos mix a lot
- Very different from quark sectors

The first evidence for the incompleteness of Minimal Standard Model
What we don’t know

- absolute mass scale of neutrinos remains an open question.

- $m_1$ and $m_3$, which is bigger? ➔ normal or inverted hierarchy?

- What is the value of $\theta_{13}$? Is it zero or not? how small?
  ➔ Reactor & accelerator $\nu$-oscillation experiments can answer, but possibly estimated from a global fit

- Why $\theta_{23}$ and $\theta_{12}$ are large and close to special values?
  ➔ Very strong hints at a certain (underlying) flavor symmetry.

- Is CP violated in leptonic sector?

- Neutrinos are Dirac or Majorana?
2. Issues on neutrino masses

- Why are physicists interested in neutrino mass?
  - Window to high energy physics beyond the SM!

- How exactly do we extend it?
  - Without knowing if neutrinos are Dirac or Majorana, any attempts to extend the Standard Model are not successful.

- Effective Observability of Difference between Dirac and Majorana Nu is proportional to

$$\Delta(D - M) \propto m / E$$
2 possible types of neutrino masses

- Dirac: $\bar{\Psi}\Psi$, $\bar{\Psi}^c\Psi^c$
- Majorana: $\bar{\Psi}\Psi^c$, $\bar{\Psi}^c\Psi$

Chiral projection:

- Dirac: $\bar{\Psi}_L\Psi_R$, $\bar{\Psi}_R\Psi_L$
- Majorana: $\bar{\Psi}_L(\Psi_L)^c$, etc

- Dirac mass terms are invariant under a global symmetry $\Psi \rightarrow e^{i\theta}\Psi$, but Majorana mass terms are not so.

Thus Dirac mass can be associated with a conserved quantum number, but Majorana mass violates L number conservation.
If Neutrinos are Majorana

- The mass eigenstates are self-conjugate up to a phase. The relative phases between two $\nu$’s become observable

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = U
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
$$

$$
U = U_D X
$$

- The Majorana character is only observable for processes $\Delta L = 2$ through the mass term that connects interacting neutrinos with antineutrinos:

$$
^A Z \rightarrow ^A (Z+2) + 2e^-, \quad \mu^- + ^A Z \rightarrow e^+ + ^A (Z-2), \quad \text{etc.}
$$
- Neutrino masses, if neutrinos are of **Majorana** nature, must have a different origin compared to the masses of charged leptons and quarks.

- A natural **theoretical** way to understand why 3 $\nu$-masses are very small:

  - **Type-I**: Right-handed Majorana neutrinos.
  - **Type-II**: Higgs triplet.
  - **Type-III**: Triplet fermions.
Fundamental physics and seesaw scale

• For order of one, seesaw scale: $10^{13-14}$ GeV.  
  \[ \rightarrow \] no hope of direct observation

• For testability, low scale seesaw is desirable

• We may keep free and look for theoretical predictions
  \[ \rightarrow \] TeV scale seesaw
  it may harms naturalness problem
Alternative mechanisms for majorana $\nu$ mass

- **Loop Models:** Light neutrino masses are radiatively induced.

- **RPV:** Sneutrino gets small VeVs inducing a mixing between $\nu$ & $\chi$.

\[ M_\nu \approx \frac{\langle \tilde{\nu} \rangle^2}{M_\chi} \approx \frac{\text{MeV}^2}{\text{TeV}} \approx \text{eV} \]
3. Probing Majorana neutrinos

- Lepton number violation by 2 units $\Delta L = 2$ plays a crucial role to probe the Majorana nature of $\nu$'s,

(a) The observation of $0\nu\beta\beta$

- Provides a promising lab. method for determining the absolute neutrino mass scale that is complementary to other measurement techniques
**Opening Black Box $0\nu\beta\beta$**

- Exchange of a virtual **light neutrino**
- Helicity mismatch $\Rightarrow$ mass mechanism
- Neutrino $\Rightarrow$ Majorana particle

**L/R symmetric models**

- Exchange of a massive neutrino $m_{W_L} \ll m_{W_R}$
- Constraints on the model parameters:

$$m_{W_R} \geq 1.4 \left( \frac{m_N}{1 \text{TeV}} \right)^{-1/4} \text{TeV}$$
In the limit of small neutrino masses:

the half-life time, \( T_{0\nu}^{1/2} \), of the 0\(\nu\)\(\beta\beta\) decay can be factorized as:

\[
[T_{0\nu}^{1/2}]^{-1} = G^{0\nu}(E_0, Z) |M^{0\nu}|^2 |< m_{ee} >|^2
\]

- Nuclear matrix element
- Phase space factor
- Effective neutrino mass (model independent)

\[
< m_{ee} >= m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{i\alpha_{21}} + m_3 U_{e3}^2 e^{i\alpha_{31}}
\]

\(\Rightarrow\) depends on neutrino mass hierarchy
• Estimate by using the best fit values of parameters including uncertainties in Majorana phases.

**Uncertainties**  
(O. Cremonesi, 05)

- **Phase space factor**
  \[
  \tau^{-1} = G_{0\nu} \cdot |M^{0\nu}|^2 \cdot |\langle m_\nu \rangle|^2 = F_N \cdot \frac{|\langle m_\nu \rangle|^2}{m_e^2}
  \]

- **Effective Neutrino Mass**
- **Nuclear Matrix Element**
- **Nuclear Factor of Merit**

- Large uncertainties in NME
- About factor of 100 in NME → affect order 2-3 in \( |\langle m_\nu \rangle| \)
Best present bound:

\[ \langle m_{\nu} \rangle \leq 0.35 - 0.50 \text{ eV} \]

\[ ^{76}\text{Ge} \rightarrow ^{76}\text{Se} + e^- + e^- \]

Heidelberg-Moscow

\[ ^{76}\text{Ge} \quad \text{Half-life} \quad T_{1/2} > 1.2 \times 10^{25} \text{ ys} \]

consistent with cosmological bound

\[ \sum m_{\nu,i} \leq 2.0 \text{ eV} \]
(b) Probe of Majorana neutrinos via rare decays of mesons

\[ \Delta L = 2 \] Processes: \[ M^+ \rightarrow M^{-}\ell_1^+\ell_2^+ \]

- Taking mesons in the initial and final state to be pseudoscalar (M : K, D, Ds, B, Bc / M' = π, K, D,...)

- Not involve the uncertainties from nuclear matrix elements in $0\beta\nu\nu$
Effective Hamiltonian:

\[ H_{\text{eff}} = -\frac{G_F^2}{2} \left[ C_t O_{t}^{\mu\nu} + C_s O_{s}^{\mu\nu} \right] L_{\mu\nu} \times \left[ \frac{p_N + m_N}{p_N^2 - m_N^2 + im_N \Gamma_N} \right] \]

\[ O_{t}^{\mu\nu} = V_{q_2 q}^* V_{q_1 Q} J_{q_2 q}^{\mu} J_{q_1 Q}^{\nu} \]

\[ O_{s}^{\mu\nu} = V_{q_2 q_1}^* V_{q Q} J_{q_2 q_1}^{\mu} J_{q Q}^{\nu} \]

\[ J_{q Q}^{\mu} = \overline{Q} \gamma^{\mu} (1 - \gamma_5) q \]

\[ L_{\mu\nu} = U_{i\ell}^* U_{i\ell} \lambda_N [u_{\ell} \gamma_\mu \gamma_\nu (1 - \gamma_5) v_{\ell}] \]

Decay Amplitude:

\[ A(M^+ \rightarrow M^- \ell_1^+ \ell_2^+) = \langle M^- \ell_1^+ \ell_2^+ | H_{\text{eff}} | M^+ \rangle \]
transition rates are proportional to

\[
\langle m \rangle_{l_1 l_2}^2 = \left| \sum_{i=1}^{3} U_{l_1 i} U_{l_2 i} m_i \right|^2 \quad \text{for light } \nu
\]

\[
\sum_{i=4}^{3+n} \frac{U_{l_1 i} U_{l_2 i}}{m_i} \quad \text{for heavy } \nu
\]

\[
\frac{\Gamma(N \to i) \Gamma(N \to f)}{m_N \Gamma_N} \quad \text{for resonant } \nu \text{ production}
\]

\[
U_{l_i N} \times \left[ \frac{p + m_N}{p^2 - m_N^2 + i m_N \Gamma_N} \right] \times U_{l_j N}
\]
For example, leptonic current:

\[ L_{\mu\nu} = (U_{i\ell}U_{i\ell}) \times \bar{v}_i \gamma_\mu \frac{(1-\gamma_5)}{2} v_\ell \times (-\ldots--) \times \bar{v}_i \gamma_\nu \frac{(1-\gamma_5)}{2} v_\ell \]

\[ = (U_{i\ell}^* U_{i\ell}) \times \bar{u}_\ell \gamma_\mu \frac{(1+\gamma_5)}{2} v_i \times (-\ldots--) \times \bar{v}_i \gamma_\nu \frac{(1-\gamma_5)}{2} v_\ell \]

\[ = \sum_i (U_{i\ell}^* U_{i\ell}) \times \bar{u}_\ell \gamma_\mu \frac{(1+\gamma_5)}{2} \left( \frac{p_{v_i} + m_{v_i}}{p_{v_i}^2 - m_{v_i}^2} \right) \gamma_\nu \frac{(1-\gamma_5)}{2} v_\ell \]

\[ = \sum_i U_{i\ell}^* U_{i\ell} \frac{m_{v_i}}{p_{v_i}^2 - m_{v_i}^2} \times \bar{u}_\ell \gamma_\mu \gamma_\nu \frac{(1-\gamma_5)}{2} v_\ell \]
This could be any gauge boson, e.g. $W, W', W_R, \cdots$

\[
\begin{align*}
V_{\text{CKM}} & \rightarrow V' \\
U_{il} & \rightarrow U' \\
G_F & \rightarrow G_{NP}
\end{align*}
\]

This could be any Majorana particle, e.g. $\nu, \text{sterlie} - \nu$, neutralino, heavy N, \cdots

Propagator changed

\[
C_{s,t} \rightarrow C'
\]
FIG. 2: The main diagram in an effective meson theory for $M^+ \rightarrow M'^- \ell^+ \ell^+$ (plus diagram with leptons exchanged if they are identical), mediated by Majorana neutrinos, when the neutrino is much lighter than the final meson. The amplitude is estimated considering the intermediate state on its mass shell.
Neutrinoless decay, e.g. $B^+ \rightarrow D^- \ell_1^+ \ell_2^+$ with light neutrinos:

(In the limit of absorptive dominance, the amplitude can be expressed in a model independent way.)

$$\mathcal{M}_{\text{abs}}(B^+ \rightarrow D^- \ell_1^+ \ell_2^+) = \int dp_{DN} \ A_{B \rightarrow DN\ell} \ A_{DN \rightarrow D\ell}$$

$$dp_{DN} = \sum_s (1/16\pi^2)(|p_N|/m_{D\ell})d\Omega_N$$

$$A_{B^+ \rightarrow D^0 N\ell} = \frac{G_F}{\sqrt{2}} \ V_{cb} \ U_{Ne} \ \langle \bar{D}^0(p')|J_\mu(0)|B^+(p)\rangle \ \bar{u}_N(p_N)\gamma_\mu(1-\gamma_5)\nu_\ell(l_1)$$

$$A_{D^0 N \rightarrow D^- \ell} = \frac{G_F}{\sqrt{2}} \ V_{ud} \ U_{Ne} \ \langle D^-(p')|J_\mu(0)|\bar{D}^0(p)\rangle \ \bar{v}_N(p_N)\gamma_\mu(1-\gamma_5)\nu_\ell(l_2)$$

$$\langle \bar{D}^0(p')|J_\mu(0)|B^+(p)\rangle = F^+_{BD}(q^2)(p+p')^\mu + F^-_{BD}(q^2)(p-p')^\mu$$

$$Br(B^+ \rightarrow D^- \ell^+ \ell^+) \sim 1.2 \times 10^{-31} \left(\frac{U_{Ne\ell}^2 m_N}{1 \text{ eV}}\right)^2$$

$$Br(B^+ \rightarrow \pi^- \ell^+ \ell^+) \sim 2.3 \times 10^{-33} \left(\frac{U_{Ne\ell}^2 m_N}{1 \text{ eV}}\right)^2$$
(ii) Intermediate mass scale neutrino case $m_{M'^-} \leq m_{\nu_i} \leq m_{M'^+}$

- dominant contribution to the process is from the “$s$-type” diagram because the neutrino propagator is kinematically entirely on-shell

FIG. 3: The dominating diagram (plus diagram with leptons exchanged if they are identical) in an effective meson theory for $M^+ \rightarrow M'^- \ell^+ \ell^+$, mediated by Majorana neutrinos with mass in the range between $m_{M'}$ and $m_M$. 
Effective amplitude at meson level:

\[ \mathcal{M} = \frac{G_F^2}{2} U_{N\ell}^{\ast} V_{qQ}^{\ast} V_{q2q1}^{\ast} f_M f_{M'} \frac{\tilde{M} }{(p_N^2 - m_N^2) + i m_N \Gamma_N } \]

\[ \tilde{\mathcal{M}} = \lambda_N \, \bar{u}_\ell(l_1) p_M(1 + \gamma_5)(p'_N + m_N) p_{M'}(1 - \gamma_5)v(l_2) \]

\[ |\tilde{\mathcal{M}}|^2 = 32 \, m_N^2 \left\{ (m_N^2 - m_\ell^2)^2 (l_1 \cdot l_2) + m_\ell^2 \left( (m_N^2 - m_\ell^2)^2 - m_M^2 m_{M'}^2 \right) \right\} \]

\[ \frac{1}{(p_N^2 - m_N^2)^2 + m_N^2 \Gamma_N^2} \rightarrow \frac{\pi}{m_N \Gamma_N} \delta(p_N^2 - m_N^2). \quad \Gamma_N \approx 2 \sum_{\ell'} |U_{N\ell'}|^2 \left( \frac{m_N}{m_\tau} \right)^5 \times \Gamma_\tau \]

\[ \int d\psi_3 = \int \frac{d^2 p_N}{2\pi} \int d\psi_{(M \rightarrow l_1 N)} \int d\psi_{(N \rightarrow l_2 M')} \]

If we neglect charged lepton masses:

\[ \Gamma(M \rightarrow M' \ell^+ \ell^+) \approx \frac{1}{128 \pi^2} G_F^4 f_M^2 f_{M'}^2 \left| V_{qQ} V_{q2q1} \right|^2 \frac{|U_{N\ell}|^4 \ m_M m_\tau^5}{\sum_{\ell'} |U_{N\ell'}|^2 \ 2 \Gamma_\tau} \left( 1 - \frac{m_{M'}^2}{m_N^2} \right)^2 \left( 1 - \frac{m_M^2}{m_{M'}^2} \right)^2. \]
Br for $K^+ \rightarrow \pi^- \ell^+ \ell^+$ as function of $mN$, with lepton mixings divided out
FIG. 6: Branching ratios for $B^+ \to M^-\ell^+\ell^+$ as functions of the neutrino mass $m_N$, with the lepton mixing factor divided out as in Fig. 4. The produced pseudoscalars are $M' = \pi, K, D, D_s$. (a) The case of leptons with negligible mass ($\ell = e, \mu$); (b) the case $\ell = \tau$ (here $M' = D, D_s$ are kinematically forbidden).

FIG. 7: Branching ratios for $B_c \to M^-\ell^+\ell^+$ as functions of the neutrino mass $m_N$, with the lepton mixing factor divided out as in Fig. 4. The produced pseudoscalars are $M' = \pi, K, D, D_s$. (a) The case of leptons with negligible mass ($\ell = e, \mu$); (b) the case $\ell = \tau$. 
<table>
<thead>
<tr>
<th>decay</th>
<th>$\mathcal{C}$</th>
<th>$m_N$ at maximum</th>
<th>$Br &lt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \to \pi^- \ell^+ \ell^+$</td>
<td>2.8</td>
<td>0.26 GeV</td>
<td>$2.8 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$D^+ \to \pi^- \ell^+ \ell^+$</td>
<td>$4.5 \cdot 10^{-3}$</td>
<td>0.51 GeV</td>
<td>$4.5 \cdot 10^{-10}$</td>
</tr>
<tr>
<td>$D^+ \to K^- \ell^+ \ell^+$</td>
<td>$1.4 \cdot 10^{-4}$</td>
<td>0.96 GeV</td>
<td>$1.4 \cdot 10^{-11}$</td>
</tr>
<tr>
<td>$D_s^+ \to \pi^- \ell^+ \ell^+$</td>
<td>$6.9 \cdot 10^{-2}$</td>
<td>0.53 GeV</td>
<td>$6.9 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>$D_s^+ \to K^- \ell^+ \ell^+$</td>
<td>$2.2 \cdot 10^{-3}$</td>
<td>0.99 GeV</td>
<td>$2.2 \cdot 10^{-10}$</td>
</tr>
<tr>
<td>$D_s^+ \to D^- \ell^+ \ell^+$</td>
<td>$8.5 \cdot 10^{-8}$</td>
<td>1.92 GeV</td>
<td>$8.5 \cdot 10^{-15}$</td>
</tr>
<tr>
<td>$B^+ \to \pi^- \ell^+ \ell^+$</td>
<td>$6.3 \cdot 10^{-6}$</td>
<td>0.86 GeV</td>
<td>$6.3 \cdot 10^{-13}$</td>
</tr>
<tr>
<td>$B^+ \to K^- \ell^+ \ell^+$</td>
<td>$3.6 \cdot 10^{-7}$</td>
<td>1.61 GeV</td>
<td>$3.6 \cdot 10^{-14}$</td>
</tr>
<tr>
<td>$B^+ \to D^- \ell^+ \ell^+$</td>
<td>$1.7 \cdot 10^{-7}$</td>
<td>3.14 GeV</td>
<td>$1.7 \cdot 10^{-14}$</td>
</tr>
<tr>
<td>$B^+ \to D_s^- \ell^+ \ell^+$</td>
<td>$4.5 \cdot 10^{-6}$</td>
<td>3.23 GeV</td>
<td>$4.5 \cdot 10^{-13}$</td>
</tr>
<tr>
<td>$B_c^+ \to \pi^- \ell^+ \ell^+$</td>
<td>$6.4 \cdot 10^{-4}$</td>
<td>0.94 GeV</td>
<td>$6.4 \cdot 10^{-11}$</td>
</tr>
<tr>
<td>$B_c^+ \to K^- \ell^+ \ell^+$</td>
<td>$3.9 \cdot 10^{-5}$</td>
<td>1.76 GeV</td>
<td>$3.9 \cdot 10^{-12}$</td>
</tr>
<tr>
<td>$B_c^+ \to D^- \ell^+ \ell^+$</td>
<td>$2.4 \cdot 10^{-5}$</td>
<td>3.43 GeV</td>
<td>$2.4 \cdot 10^{-12}$</td>
</tr>
<tr>
<td>$B_c^+ \to D_s^- \ell^+ \ell^+$</td>
<td>$6.5 \cdot 10^{-4}$</td>
<td>3.52 GeV</td>
<td>$6.5 \cdot 10^{-11}$</td>
</tr>
<tr>
<td>$B_c^+ \to B^- \ell^+ \ell^+$</td>
<td>$1.6 \cdot 10^{-11}$</td>
<td>5.76 GeV</td>
<td>$1.6 \cdot 10^{-18}$</td>
</tr>
</tbody>
</table>

\[
Br_{\text{max}}(M^+ \to M^- \ell^+ \ell^+) = \mathcal{C} \times \frac{|U_{N\ell}|^2}{\sum_{\ell'} |U_{N\ell'}|^2} \quad \sum_N |U_{N\ell}|^2 \equiv (s_L^{\nu\ell})^2 \leq 0.005, \quad (s_L^{\nu\ell})^2 \leq 0.002, \quad (s_L^{\nu\ell})^2 \leq 0.010.
\]

In the last column, the expected upper bound on the branching ratios, provided $|U_{N\ell}|^2 \sim 10^{-6}$ or $10^{-7}$, for $m_N \sim 0.1$ GeV or $\sim 1$ GeV, respectively.
(iii) Heavy neutrino case \[ m_{\nu_i} \gg m_{M^+} \]

- In this case, both contributions of "s-type" and "t-type" diagrams are rather comparable.

- Neutrino propagators reduce to \(-1/(m_N)^2\)
\[ \mathcal{M}_{1a} = \frac{G_F^2}{2} U_{N \ell}^{*2} \lambda_* \left( V_{q_1 Q}^* V_{q_2}^* \right) \langle M' | J_{(\bar{q}_2 q)}^\mu \rangle \langle (\bar{q}_1 q_1) \mu | M \rangle \frac{4}{m_N} \left[ \bar{u}_\ell(l_2)(1 - \gamma_5)\nu_\ell(l_1) \right] \]

\[ \mathcal{M}_{1b} = \frac{G_F^2}{2} U_{N \ell}^{*2} \lambda_* \left( V_{q Q}^* V_{q_2}^* \right) \langle M' | J_{(\bar{q}_2 q_1) \mu} \rangle \langle (\bar{q}_1 q) \mu | M \rangle \frac{4}{m_N} \left[ \bar{u}_\ell(l_2)(1 - \gamma_5)\nu_\ell(l_1) \right] \]

\[ \mathcal{M}_h = \mathcal{M}_{1a} + \mathcal{M}_{1b} \]

\[ = \frac{G_F^2}{2} U_{N \ell}^{*2} \lambda_* \left[ V_{q Q}^* V_{q_2}^* + \frac{V_{q_1 Q}^* V_{q_2}^*}{N} \right] f_M f_{M'}(p_M \cdot p_M') \frac{4}{m_N} \left[ \bar{u}_\ell(l_2)(1 - \gamma_5)\nu_\ell(l_1) \right] \]

\[ |\mathcal{M}_h|^2 = |\mathcal{K}_h|^2 \left( p_M \cdot p_M' \right)^2 (l_1 \cdot l_2) \]

\[ |\mathcal{K}_h|^2 = G_F^4 \left| \frac{U_{N \ell}^{*2}}{m_N} \right|^2 \left| \frac{V_{q Q}^* V_{q_2}^*}{N} \right|^2 \frac{f_M f_{M'}^2}{f_M f_{M'}} \]

\[ \Gamma(M^+ \rightarrow M' - \ell^+ \ell^+) = \frac{1}{2!} \frac{1}{8\pi^2} \left| \frac{\mathcal{K}_h}{m_M} \right|^2 \int \frac{d m_{\ell \ell}^2}{2\pi} \frac{|P_{M'}| |l_2|}{m_M m_{\ell \ell}} (m_M^2 + m_{M'}^2 - m_{\ell \ell}^2)^2 (m_{\ell \ell}^2 - 2m_{\ell \ell}^2) \]

\[ \text{Br}(M^+ \rightarrow M' - \ell^+ \ell^+) \equiv \frac{\Gamma(M^+ \rightarrow M' - \ell^+ \ell^+)}{\Gamma_M} = B \times \left( \frac{100 \ \text{GeV}}{m_N} \right)^2 \left( \frac{|U_{N \ell}|^2}{10^{-2}} \right)^2 \]

Present bounds on PMNS for MN > 100 GeV [Nardi et al., PLB327,319]:

\[ \sum_N |U_{N e}|^2 \equiv (s_L^e)^2 \leq 0.005 , \quad (s_L^\mu)^2 \leq 0.002 , \quad (s_L^\tau)^2 \leq 0.010 \]
TABLE III: Branching ratio coefficients $\mathcal{B}$ appearing in Eq. (17), for various decays $M^+ \rightarrow M' - \ell^+ \ell^+$, if the process is dominated by heavy neutrinos ($m_N \gg m_M$). $\mathcal{B}$ values correspond to branching ratios if $m_N = 100$ GeV and $|U_{N\ell}|^2 = 10^{-2}$. All three lepton flavors are considered ($\ell = e, \mu, \tau$). Entries are empty for decays that are kinematically forbidden.

<table>
<thead>
<tr>
<th>decay</th>
<th>$\mathcal{B}(\ell = e)$</th>
<th>$\mathcal{B}(\ell = \mu)$</th>
<th>$\mathcal{B}(\ell = \tau)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+ \ell^+ \ell^+$</td>
<td>$8.47 \cdot 10^{-24}$</td>
<td>$2.44 \cdot 10^{-24}$</td>
<td>-</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^+ \ell^+ \ell^+$</td>
<td>$1.90 \cdot 10^{-23}$</td>
<td>$1.78 \cdot 10^{-23}$</td>
<td>-</td>
</tr>
<tr>
<td>$D^+ \rightarrow \bar{K}^0 \ell^+ \ell^+$</td>
<td>$1.58 \cdot 10^{-23}$</td>
<td>$1.47 \cdot 10^{-23}$</td>
<td>-</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \pi^+ \ell^+ \ell^+$</td>
<td>$2.14 \cdot 10^{-22}$</td>
<td>$2.02 \cdot 10^{-22}$</td>
<td>-</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \bar{K}^0 \ell^+ \ell^+$</td>
<td>$2.46 \cdot 10^{-23}$</td>
<td>$2.30 \cdot 10^{-23}$</td>
<td>-</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow D^- \ell^+ \ell^+$</td>
<td>$6.99 \cdot 10^{-28}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^+ \ell^+ \ell^+$</td>
<td>$1.13 \cdot 10^{-23}$</td>
<td>$1.12 \cdot 10^{-23}$</td>
<td>$7.42 \cdot 10^{-25}$</td>
</tr>
<tr>
<td>$B^+ \rightarrow \bar{K}^0 \ell^+ \ell^+$</td>
<td>$8.44 \cdot 10^{-25}$</td>
<td>$8.37 \cdot 10^{-25}$</td>
<td>$5.01 \cdot 10^{-26}$</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^- \ell^+ \ell^+$</td>
<td>$1.02 \cdot 10^{-22}$</td>
<td>$1.01 \cdot 10^{-22}$</td>
<td>-</td>
</tr>
<tr>
<td>$B^+ \rightarrow D_s^- \ell^+ \ell^+$</td>
<td>$5.02 \cdot 10^{-23}$</td>
<td>$4.96 \cdot 10^{-23}$</td>
<td>-</td>
</tr>
<tr>
<td>$B_c^+ \rightarrow \pi^+ \ell^+ \ell^+$</td>
<td>$1.76 \cdot 10^{-21}$</td>
<td>$1.75 \cdot 10^{-21}$</td>
<td>$3.04 \cdot 10^{-22}$</td>
</tr>
<tr>
<td>$B_c^+ \rightarrow \bar{K}^0 \ell^+ \ell^+$</td>
<td>$1.73 \cdot 10^{-22}$</td>
<td>$1.72 \cdot 10^{-22}$</td>
<td>$2.89 \cdot 10^{-23}$</td>
</tr>
<tr>
<td>$B_c^+ \rightarrow D^- \ell^+ \ell^+$</td>
<td>$3.20 \cdot 10^{-22}$</td>
<td>$3.17 \cdot 10^{-22}$</td>
<td>$2.14 \cdot 10^{-23}$</td>
</tr>
<tr>
<td>$B_c^+ \rightarrow D_s^- \ell^+ \ell^+$</td>
<td>$9.17 \cdot 10^{-21}$</td>
<td>$9.10 \cdot 10^{-21}$</td>
<td>$5.17 \cdot 10^{-22}$</td>
</tr>
<tr>
<td>$B_c^+ \rightarrow B^- \ell^+ \ell^+$</td>
<td>$3.31 \cdot 10^{-28}$</td>
<td>$2.96 \cdot 10^{-28}$</td>
<td>-</td>
</tr>
</tbody>
</table>
• In accelerator-based experiments, neutrinos in the final state are undetectable by the detectors, leading to the “missing energy”. So it is desirable to look for charged leptons in the final state.

• It is **hard to avoid** the TeV-scale physics to contribute to **flavor-changing effects** in general whatever it is,
  – SUSY, extra dimensions, TeV seesaw, technicolor, Higgsless, little Higgs
Basic process we consider

transition rates are proportional to

\[
\langle m \rangle_{l_1 l_2}^2 = \left| \sum_{i=1}^{3} U_{l_1 i} U_{l_2 i} m_i \right|^2 \quad \text{for light } \nu
\]

\[
\sum_{i=4}^{3+n} \frac{U_{l_1 i} U_{l_2 i}}{m_i} \left( \Gamma(N \rightarrow i) \Gamma(N \rightarrow f) \right) \quad \text{for resonant } N \text{ production}
\]

\[
U_{l_i N} \frac{p + m_N}{p^2 - m_N^2 + i\epsilon} U_{l_j N}
\]
Testability at the LHC

- Two necessary conditions to test at the LHC:
  -- Masses of heavy Majorana $\nu$’s must be less than TeV
  -- Light-heavy neutrino mixing (i.e., $M_D/M_R$) must be large enough.

$$\Delta(D - M) \propto m/E \Rightarrow m \approx O(100\,\text{GeV} - 1\,\text{TeV})$$

- LHC signatures of heavy Majorana $\nu$’s are essentially decoupled from masses and mixing parameters of light Majorana $\nu$’s.

- Non-unitarity of the light neutrino flavor mixing matrix might lead to observable effects.
Nontrivial limits on heavy Majorana neutrinos can be derived at the LHC, if the SM backgrounds are small for a specific final state.

\[ \Delta L = 2 \text{ like-sign dilepton events} \]

\[ pp \rightarrow W^\pm W^\pm \rightarrow \mu^\pm \mu^\pm jj \text{ and } pp \rightarrow W^\pm \rightarrow \mu^\pm N \rightarrow \mu^\pm \mu^\pm jj \]
Lepton number violation: like-sign dilepton events at hadron colliders, such as Tevatron ($\sim 2$ TeV) and LHC ($\sim 14$ TeV).

collider analogue to $0\nu\beta\beta$ decay

dominant channel

$N$ can be produced on resonance
Some Results

- Cross sections are generally smaller for larger masses of heavy Majorana neutrinos. [ Han, Zhang (hep-ph/0904064) ]

- Signal & background cross sections (in fb) as a function of the heavy Majorana neutrino mass (in GeV):
  [ Del Aguila et al (hep-ph/0906198) ]

*Background could be much larger by soft-filing up !!*

<table>
<thead>
<tr>
<th>$m_N$</th>
<th>$\mu^+\mu^-jj$ signal</th>
<th>$W^+W^-W\mp$ background</th>
<th>LHC $\mu^+\mu^-jj$ signal</th>
<th>LHC $W^+W^-W\mp$ background</th>
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</thead>
<tbody>
<tr>
<td>100</td>
<td>0.40</td>
<td>0.00001</td>
<td>2.0</td>
<td>0.0012</td>
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<td>0.071</td>
<td>0.00004</td>
<td>0.48</td>
<td>0.00044</td>
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<tr>
<td>300</td>
<td>0.014</td>
<td>0.00001</td>
<td>0.16</td>
<td>0.00023</td>
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<tr>
<td>400</td>
<td>0.0032</td>
<td>0.000005</td>
<td>0.068</td>
<td>0.00012</td>
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<tr>
<td>500</td>
<td>0.0008</td>
<td>0.000001</td>
<td>0.034</td>
<td>0.00007</td>
</tr>
</tbody>
</table>
4. Concluding Remarks

- Knowing that neutrinos are Dirac or Majorana is THE MOST important to go beyond the SM.

- We have discussed three possible ways to probe Majorana neutrinos in meson decays.

- Hoping that probing Majorana neutrinos via meson’s rare decays and collider signature would become more and more relevant.