Searches for right-handed neutrinos at accelerators

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### Low scale seesaw (type I)

#### Three right handed neutrinos

\[
\mathcal{L}_{\nu_R} = -y_{ai} \bar{\nu}_a \epsilon \phi \nu_{Ri} - \frac{1}{2} \nu^c_{Ri} M_{ij} \nu_{Rj} + \text{h.c.}
\]

- \(y_{ai}\): Yukawa coupling
- \(M_{ij}\): Majorana mass

#### EWSB

SM is \(B - L\) symmetric

- Dirac mass \(m_{ai} = v y_{ai}\)
- Small \(M_{ij}\) minimizes breaking

#### Seesaw mechanism

\[
m_\nu = -m_{ai} M_{ij}^{-1} m_{bj} = -\theta_{ai} M_{ij} \theta_{bj}^T, \quad \theta_{ai} = m_{aj} M_{ij}^{-1}
\]

produces tiny masses for the left handed neutrinos

#### Small mixing into mass eigenstates

\[
\nu \simeq U_\nu^\dagger (\nu_L - \theta \nu_R^c), \quad N \simeq \nu_R + \theta^T \nu_L^c
\]

#### Coupling of \(N_i\) to the SM

\[
\mathcal{L} \supset -\frac{m_W}{\sqrt{2}} \bar{N} \theta^* \gamma^\mu e_L W_{\mu}^+ - \frac{M Z}{\sqrt{2} v} \bar{N} \theta^* \gamma^\mu \nu_L Z_{\mu} - \frac{M}{v} \theta a h \bar{\nu}_L \alpha \gamma^0 N + \text{h.c.}
\]

#### Abbreviation

\[
U^2_{ai} = \sum_i U^2_{ai}, \quad U^2_{ai} = |\theta_{ai}|^2
\]
Properties

Lifetime

<table>
<thead>
<tr>
<th>Lifetime</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 fs</td>
<td></td>
</tr>
<tr>
<td>1 ps</td>
<td></td>
</tr>
<tr>
<td>1 ns</td>
<td></td>
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<tr>
<td>1 μs</td>
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<tr>
<td>10 ps</td>
<td></td>
</tr>
<tr>
<td>100 ps</td>
<td></td>
</tr>
<tr>
<td>10 ns</td>
<td></td>
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<tr>
<td>100 ns</td>
<td></td>
</tr>
</tbody>
</table>

SM particles vs. coupling strength $U^2$

<table>
<thead>
<tr>
<th>SM Particle</th>
<th>$\tau$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^\pm$</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>$K_L$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>$K_S$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>$K^0$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>$K_L^0$</td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td>$K_S^0$</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>$\Xi^+$</td>
<td>$10^{-14}$</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>$\tau^+$</td>
<td>$10^{-16}$</td>
</tr>
</tbody>
</table>

Decay width for $M \gg 5$ GeV

$$\Gamma_N \simeq 11.9 \times \frac{G_F^2}{96\pi^3} U_a^2 M^5,$$
Probability contours for $U_{ai}^2$ (2 active flavours)

The ratio $U_a^2/U_2$ is independent of other heavy neutrino parameter

Normal Ordering

Inverted Ordering

Coloured areas consistent with neutrino oscillation data at $1\sigma$, $2\sigma$, $3\sigma$

Unknown Majorana phase correspond to the circular structure
NA62
Fixed target experiment in the North Area using the CERN SPS with the goal to

- measure the very rare kaon decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$
- $10\%$ measurement of the CKM parameter $|V_{td}|$
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Hidden sectors at NA62

- it can also be used to search for hidden new physics $\chi$ such as a heavy neutrino
- Target mode
- only $K^+$ induced processes
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Hidden sectors at NA62

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- Target mode
- only $K^+$ induced processes
- Dump mode
- $D$- and $B$-meson induced processes dominate
# Heavy Neutrinos in the Dump mode

**Simulation**
- Toy Monte Carlo of the dump mode
- Zero background assumption

**Run 3 (2021–2023)**
- $10^{18}$ proton on target (POT)
- About 80 days of data taking

## Production of heavy neutrinos via $2 \times 10^{15}$ $D$- and $10^{11}$ $B$-mesons

$n_N \simeq 2N_{\text{POT}} \left( \chi_c f_D \text{BR} (D \to XN) + \chi_b f_B \text{BR} (B \to XN) \right)$,

- $\chi$ production cross section
- $f$ production fractions of mesons

## Number of reconstructed events

$N_{\text{obs}} = n_N \sum_{f, f'=e, \mu, \tau, \pi, K} \text{BR} (N_i \to f^+ f'^- X) A_i \left( f^+ f'^- X, M_i, U^2_{e, \mu, \tau} \right) \epsilon \left( f^+ f'^- X, M_i \right)$,

- $A_i$ geometrical acceptance
- $\epsilon$ efficiency assumed to be 100%!
  (trigger, reconstruction, selection)
Branching Fractions

For $U_{ie}^2 : U_{i\mu}^2 : U_{i\tau}^2 = 1 : 160 : 27.8$

The dominant modes are

$$N_i \rightarrow 3\nu, \pi^0 \nu, \pi^\pm \ell^\mp, \rho^0 \nu, \rho^\pm \ell, \ell^+ \ell^- \nu$$

The detector is able to reconstruct all final states having two charged tracks.
10

pure $U^2_{\mu}$

$U^2_{e} : U^2_{\mu} : U^2_{\tau}$

$0 : 1 : 0$

$M_i$ [GeV]
pure $U_T^2$

<table>
<thead>
<tr>
<th>$U_2$</th>
<th>$\tau$</th>
<th>$U_2$</th>
<th>$e$</th>
<th>$U_2$</th>
<th>$\mu$</th>
<th>$U_2$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0$</td>
<td>$0$</td>
<td>$1$</td>
<td>$0$</td>
<td>$0$</td>
<td>$1$</td>
<td>$0$</td>
<td>$1$</td>
</tr>
</tbody>
</table>

$U_T^2$ vs $M_i$ [GeV]
LHC
**Signature**

**Z-decay**

\[ p \rightarrow W^+ N Z^* \]

\[ W^+ \rightarrow \nu_l \bar{f} \]

**W-decay**

\[ p \rightarrow W^+ N W^{**} \]

\[ W^+ \rightarrow l^- \bar{f} \]

**Search strategy**

- Trigger on first lepton
- Search for secondary vertex

**Displaced vertex reconstruction**

- At least 2 tracks
- Invariant mass of 5 GeV (in order to suppress nuclear interactions backgrounds)
- Particles must transverse at least half of the tracker
- Or the complete muon chamber

**Muon chamber**

- Muon chamber reaches farther than tracker
- Long lived particles can be search for using only muon chambers

[Bobrovskyi et al. 2011; CMS 2015]
Expectations

Simplified model

\[ N_d \sim L_{int} \sigma_\nu U^2 \left( e^{-\frac{l_0}{\lambda_N}} - e^{-\frac{l_1}{\lambda_N}} \right) f_{cut}, \]

- \( l_0 \): minimal displacement
- \( l_1 \): detector length
- \( \lambda_N = \frac{\beta \gamma}{\Gamma_N} \): decay length

Significances and major obstacles

Deviation of simplified model from full simulation

\[ U^2_{\text{a}} \]

\[ U^2_{\mu} \]

\[ M_i \text{ [GeV]} \]

\[ M_i \text{ [GeV]} \]

\[ U^2_{\text{a}} \text{ [10^{-8}]} \]

\[ U^2_{\mu} \text{ [10^{-8}]} \]

\[ 1, 2, 3, 5, 10 \]

\[ 10^{-8}, 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2} \]

\[ 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7}, 10^{-8} \]

\[ 0.1, 0.2, 1, 2, 5, 10 \]

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\[ 0.1, 0.2, 1, 2, 5, 10 \]
Maximal exclusion reach

pure $U^2_e$

pure $U^2_{\mu}$

pure $U^2_{\tau}$
Heavy Ion Collisions
## Properties of the heavy ions runs

### Advantage

- No pile-up; single primary vertex
- Large nucleon multiplicity
  - e.g. $A(Pb) = 208$, $Z(Pb) = 82$
- Number of parton level interactions per collision scales with $A$
  - e.g. $\frac{\sigma_{PbPb}}{\sigma_{pp}} \propto A^2 = 43 \times 10^3$

### Drawbacks

- There are a huge number of tracks near the interaction point which makes the search for prompt new physics extremely challenging
- The collision energy per nucleon is smaller. e.g. $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ for Pb which is problematic for heavy new physics
- The instantaneous luminosity is lower for heavier ions
- The LHC has allocated much less time to heavy ions runs than to protons runs

### Possible ways out

- Low luminosity allows for lower triggers
- Lighter ions allow for higher luminosity

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**Diagram:**

- Single primary vertex
  - invisible particle
  - incorrectly identified primary vertex
  - neutral LLP
  - charged particles

**Text:** Better event reconstruction possible.
The reason for the low luminosities are secondary beams [Jowett 2018]

For heavy ions there are additional contributions to the crosssection

**Bound-Free Pair Production (BFPP):**

\[ ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \rightarrow ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{81+} + e^+ \]  

[Meier et al. 2001]

**Electromagnetic Dissociation (EMD):**

\[ ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \rightarrow ^{208}\text{Pb}^{82+} + ^{207}\text{Pb}^{82+} + n \]  

[Pshenichnov et al. 2001]

Leads to

- Larger cross section results in faster beam decay
- Secondary beams consisting of ions with different charge/mass ratio

Can accidentally quench the magnets [Bruce et al. 2018]
The luminosity at one interaction point (IP) is

\[ L \propto N_b^2 \]  where \( N_b \) are number of ions per bunch

The initial bunch intensity

[Jowett 2018]

for arbitrary ions is fitted to the information of the lead run

\[ N_b \left( \frac{A}{Z} N \right) = N_b \left( ^{208}_{82} \text{Pb} \right) \left( \frac{Z}{82} \right)^{-p} \]

where \( p = 1 \) is a conservative assumption while \( p = 1.9 \) is an optimistic assumption.

The loss of number of ions per bunch \( N_b \) over time is given by

\[ \frac{dN_b}{dt} = - \frac{N_b^2}{N_0 \tau_b} , \]

\[ \tau_b = \frac{n_b N_0}{\sigma_{\text{tot}} n_{\text{IP}} L_0} , \]

where \( n_{\text{IP}} \) is the number of interaction points.

For a given turnaround time \( t_{\text{ta}} \) between the physics runs

the integrated luminosity is maximised by

\[ t_{\text{opt}} = \tau_b \sqrt{\theta_{\text{ta}}} , \]

with

\[ \theta_{\text{ta}} = \frac{t_{\text{ta}}}{\tau_b} . \]

The average luminosity using the optimal run time is

\[ L_{\text{ave}}(t_{\text{opt}}) = \frac{L_0}{(1 + \sqrt{\theta_{\text{ta}}})^2} . \]
Heavy ion collisions

Full simulation of $W$ production

Simplified simulation of $B$ production

Considerable lower trigger of $p_T > 3$ GeV for heavy ion collisions
Conclusion

- Heavy neutrinos constitute a minimal extension to the SM featuring long lived particles.
- At the moment NA62 is the leading experiment able to search for right-handed neutrinos with masses between the $K$- and $D$-meson mass.
- Displaced vertices are a promising signature to detect right-handed neutrinos at the LHC.
- Heavy ion collisions provide a new environment to search for right-handed neutrinos.


**CMS**. “Search for long-lived particles that decay into final states containing two muons, reconstructed using only the CMS muon chambers”. №: CMS-PAS-EXO-14-012.


