Status of heavy neutrino searches at ep colliders

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Contribution to the FCC week 2021
1- The measured neutrinos oscillation can only be explained when neutrinos have masses

2- The SM successfully describes an impressive amount of data, but neutrinos are massless in the SM framework
Introduction

1- The measured neutrinos oscillation can only be explained when neutrinos have masses

2- The SM successfully describes an impressive amount of data, but neutrinos are massless in the SM framework

3- The simplest extension is to add right handed neutrinos, $N$

$$\mathcal{L}_y \supset \mathcal{L}_y^{\text{SM}} - y^\nu \bar{L}_L \phi N_R - M_N \bar{N}_R^c N_R + \text{H.C.}$$

- fix the observed neutrino masses
- Mass of $N$ is unconstrained !!
Introduction

One can look for sterile neutrinos (for fixed mixing parameters) in different mass ranges as:

- $M_N \sim \text{KeV}$
  - sterile neutrino is very long-lived and it skip the detector before it decays.
  - In this mass range N can be probed as dark matter

- $M_N \sim \text{GeV}$
  - sterile neutrino is long-lived but it decay inside the detector.
  - In this mass range N can be probed via its displaced distance

- $M_N \sim \text{EW}$
  - sterile neutrino is no longer long-lived and it decays promptly.
  - In this mass range N can be probed via its LNV or LFV decays

- $M_N > \mathcal{O}(\text{TeV})$
  - This mass range is out of reach of the current colliders energy.
  - N can be probed indirectly from loop processes, $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, etc
Collider search

- Direct
- Indirect

Optimized cut based analysis or ML Algorithms
Direct search

1- The heavy neutrino has to be produced on mass shell (mass range is limited to $\sqrt{s}$)

2- Possible reconstruction of $N$ from its final state products

Indirect search

1- $N$ in the loop and not required to be on mass shell (mass range not limited)

2- The enhanced measurement for LFV is an indication for heavy neutrino contribution

3- We cannot reconstruct the properties of the $N$!!
At EW scale the LHC is sensitive to LNV but not LFV processes!!
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Where to look for LFV heavy neutrino decays??

arXiv:1806.10905
The Large Hadron electron Collider (LHeC)
In this talk we discuss two examples

1- Lepton flavor violating heavy neutrino decays at the LHeC and FCChe (prompt & displaced)

2- Induced Lepton flavor violation by heavy neutrino at the LHeC

So let us first introduce the proposed LHeC
Detector geometry

(60 GeV)  (7 TeV)
The LHeC is expected to provide a collision of proton beam with energy 7000 GeV and electron beam with energy 60 GeV.
LHeC Kinematics

Couple of equations that control the whole kinematics

\[ x = \frac{q^2}{s y_e}, \quad \text{with} \quad y_e = 1 - \frac{E_l}{2E_e} (1 - \cos \theta_e) \]
At the LHeC, Bjorken variable controls the incoming quark energy. For most of the parameter space the energy of the incoming electron and quark are similar.

For small energy transfer, the final state lepton scatter in the backward direction of the detector: "Lepton back scattering at ep colliders"
Delphes event display
Part 1

Direct search:

Lepton-Trijet Searches for Heavy Neutrinos

prompt decays
The model

Low scale seesaw model with two right handed neutrinos

$$\mathcal{L} = \mathcal{L}_{SM} - y_{\nu\alpha} \bar{N}_R^1 \phi^+ L^\alpha - \bar{N}_R^1 M_N N_R^{2c} + H.C.$$  

$$u = \begin{pmatrix}  
N_{e1} & N_{e2} & N_{e3} \\
N_{\mu1} & N_{\mu2} & N_{\mu3} \\
N_{\tau1} & N_{\tau2} & N_{\tau3} \\
0 & 0 & 0 \\
\theta^*_e & \theta^*_\mu & \theta^*_\tau \\
\theta^*_e & \theta^*_\mu & \theta^*_\tau \\
-i\sqrt{2} & \frac{i}{\sqrt{2}} & \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}}(1 - \frac{1}{2}\theta^2) & \frac{1}{\sqrt{2}}(1 - \frac{1}{2}\theta^2) \\
\end{pmatrix}$$

with active-sterile mixing angels

$$\theta_\alpha = \frac{y_{\nu\alpha} v_{EW}}{\sqrt{2} M_N}$$
Kinematic variables

$e \rightarrow j e^+ VV,$ where $VV \rightarrow j j \mu^- \mu^+$

$e \rightarrow j e^+ VV,$ where $VV \rightarrow j j \mu^- \bar{\nu}_\mu$

$e \rightarrow j \nu e VV,$ where $VV \rightarrow j j \mu^- \mu^+$

$e \rightarrow j \nu e VV,$ where $VV \rightarrow j j \mu^- \bar{\nu}_\mu$
Kinematic variables

Optimized cut
MN = 500GeV

arXiv:1908.02852
Part 2

Direct search:

Lepton-Trijet Searches for Heavy Neutrinos

displaced decays

\[ \text{Diagram: } e \rightarrow N \rightarrow \mu \rightarrow j \rightarrow j \]
Heavy neutrino can be long-lived by $M_N < M_W$ and/or small $\theta_\alpha$.
\[ N_{dv}(\sqrt{s}, \mathcal{L}, m_N, |\theta|) = \sigma_{\text{tot}}(\sqrt{s}, m_N, |\theta|) \mathcal{L} \]
\[
\times \int D_N(\Theta, \gamma) P_{dv}(x_{\text{min}}(\Theta), x_{\text{max}}(\Theta), \Delta x_{\text{lab}}(\tau, \gamma)) d\Theta d\gamma
\]
Summary of heavy neutrino direct search

limited sensitivity to heavy neutrino mass around 1 TeV!!
Part 3

Indirect search
The model

Effective theory is a generic framework that can be fitted to any specific model

Tree level renormalized SM Lagrangian has no source for LFV
The model

Matrix element for the process

\[ \mathcal{M}_{\gamma^*} = \bar{u}_l \left[ B_{L,R}^\gamma \gamma P_{L,R} q^2 \gamma - i\sigma^{\mu\nu} q_{\mu} D_{L,R}^\gamma \right] u_e \left( -\frac{i e g_{\mu\nu}}{q^2} \right) \bar{u}_q (-i e Q_q \gamma^\mu) v_q, \]

\[ \mathcal{M}_Z = \bar{u}_l \left[ A_{L,R}^Z P_{L,R} \gamma \gamma + B_{L,R}^Z P_{L,R} q^2 \gamma - i\sigma^{\mu\nu} q_{\mu} D_{L,R}^Z \right] u_e \left( -\frac{ig_{\mu\nu}}{q^2 - M_Z^2} \right) \bar{u}_q (\gamma^\mu g_{L,R} P_{L,R}) v_q. \]
Example model: low scale seesaw

Tree level not exist

Processes are UV finite
Example model: low scale seesaw

UV finite

UV finite =

Sum Up + unitarity of the mixing matrix

UV finite =

Sum Up + unitarity of the mixing matrix
Example model: low scale seesaw

LHeC can provide better sensitivity for LFV search than all the existing searches

Current limit from different experiments

\[ Br(\mu \rightarrow e\gamma) \leq 4.2 \times 10^{-13} \]
\[ Br(\tau \rightarrow e\gamma) \leq 3.3 \times 10^{-8} \]
\[ Br(\mu \rightarrow e^- e^+ e^-) \leq 1. \times 10^{-12} \]
\[ Br(\tau \rightarrow e^- e^+ e^-) \leq 2.7 \times 10^{-8} \]
\[ Cr(\mu - e, \frac{197}{79} \text{Au}) \leq 7 \times 10^{-13} \]
Remark

Dominant contribution comes from the Z mediator

\[ M_Z = \bar{u}_\alpha \left[ A_{L,R}^Z P_{L,R} \gamma^\nu + B_{L,R}^Z P_{L,R} q^2 \gamma^\nu - i \sigma^{\mu\nu} q_\mu D_{L,R}^Z P_{L,R} \right] u_e \left( \frac{-i g_{\mu\nu}}{q^2 - M_Z^2} \right) \bar{u}_q (\gamma^\mu g_{L,R} P_{L,R}) v_q. \]

For the processes \( \mu \to e \gamma, \mu \to 3e \) and \( CR(\mu \to e) \) the energy (\( q^2 \sim M_{\mu}^2 \))

\[ M_Z \propto \frac{-i g_{\mu\nu}}{M_{\mu}^2 - M_Z^2} \]

The LHeC can provide energy about 1.3 TeV that can always produce on shell Z mediator
The LHeC provides the best sensitivity for heavy neutrino searches in all mass ranges.
THANK YOU FOR YOUR ATTENTION
Backup
Statistical analysis (Maximum likelihood) to provide the significance level/limit

Optimize ML output by maximizing signal to bkg yield

Highest ranked variables are fed to Machine Learning model

Constructing all kinematic variables

Detector simulation (Fast/full)

Jet clustering

Initial/Final state radiation, etc

Electroweak and QCD radiation

Start with hand written Lagrangian

Calculate all tree level vertices

Calculate total cross section for the process under consideration

Generate the events at parton level weighted by the cross section

Hadronization is required due to the color confinement

Ahmed Hammad 30/6/21
At the LHeC, Bjorken variable controls the incoming quark energy. For most of the parameter space the energy of the incoming electron and quark are similar.

For small energy transfer, the final state lepton scatter in the backward direction of the detector: “Lepton back scattering at ep colliders”
Kinematics of the scattered muon

![Graphs showing kinematics of scattered muons with various distributions and plots for different variables such as $\theta (\mu^{-}) [\text{rad}]$, $E_T [\text{GeV}]$, $P_T (\mu^{+}) [\text{GeV}]$, and $P_T (e) [\text{GeV}].