INTURN 24-2 Elucidating the Nature of Neutrinos Using Collider Probes

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Background

- **Neutrinos** are among the most abundant elementary particles in the universe. They are charge-neutral, spin-1/2 particles that interact solely via weak and gravitational interactions.

- Due to its charge-neutrality, neutrino can be a **Majorana Particle**, meaning that it can be its own antiparticle.

- The key distinction between Majorana/Dirac particle is the number of degrees of freedom to describe a neutrino helicity state[1]:

$$\begin{array}{ccc} \nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R & & \nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R \\ \updownarrow \text{“Lorentz”} & & \updownarrow \text{“Lorentz”} \\ \nu_R \leftarrow \text{CPT} \rightarrow \bar{\nu}_L & & \bar{\nu}_R \leftarrow \text{CPT} \rightarrow \nu_L \\ \text{Dirac} & & \text{Majorana} \end{array}$$

- To construct an observable A to probe the right handed helicity state neutrino at an energy E, the observable will be proportional to the mass of the neutrino[1]:

$$A \propto \frac{m_\nu}{E}$$

- Neutrinos are very light, which means the probability of observing a neutrino in the right-handed helicity state ($\propto |A|^2$) will be very small.

- The seesaw mechanism postulates the existence of a **heavy sterile neutrino** (N) which is a great candidate and provides another potential solution in **collider** experiment to the question of Dirac vs Majorana by considering the following collision events[2]:

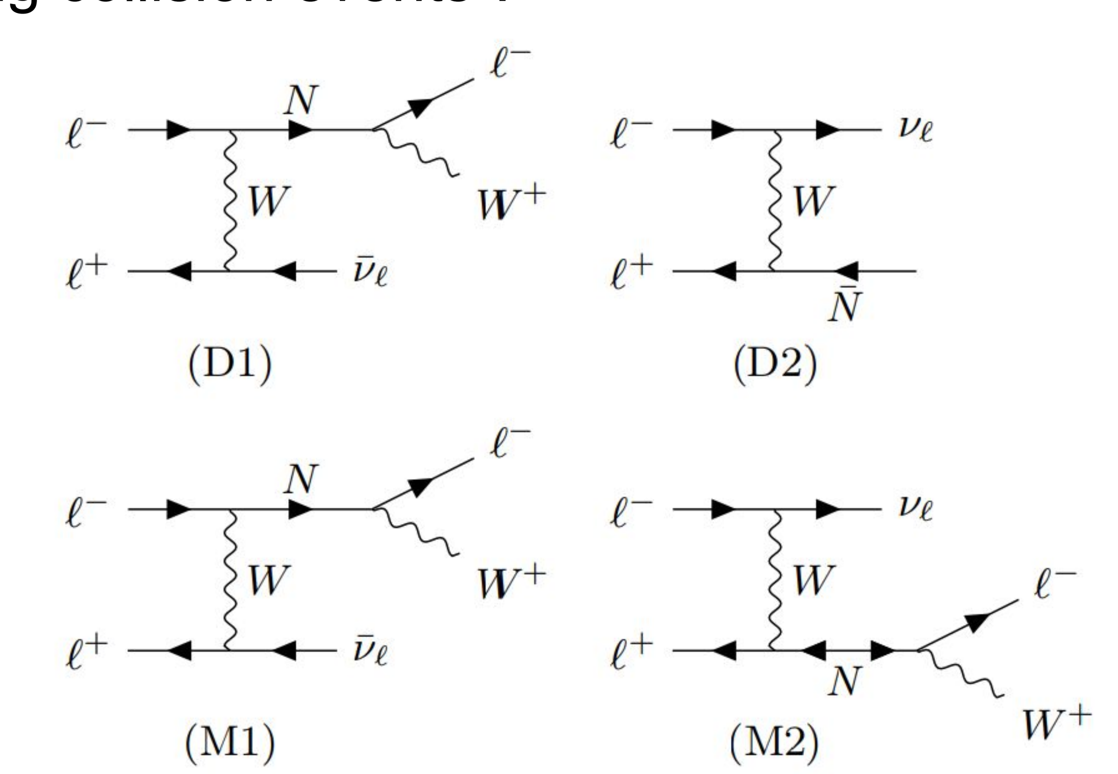

Fig. 1 Feynman diagrams of the SN production and decay[2]

Method

- We use **MadGraph**, A powerful computational tool widely used in high-energy physics to efficiently generate and simulate collision events.

- We generated the collision events in Fig. 1 by using models from Ref 3.

- We focus on the rapidity distribution of the heavy sterile neutrino y_N:

$$y_N = \frac{1}{2}\log\frac{E + p\cos\theta_N}{E - p\cos\theta_N}$$

Which θ_N is the scattering angle of N.

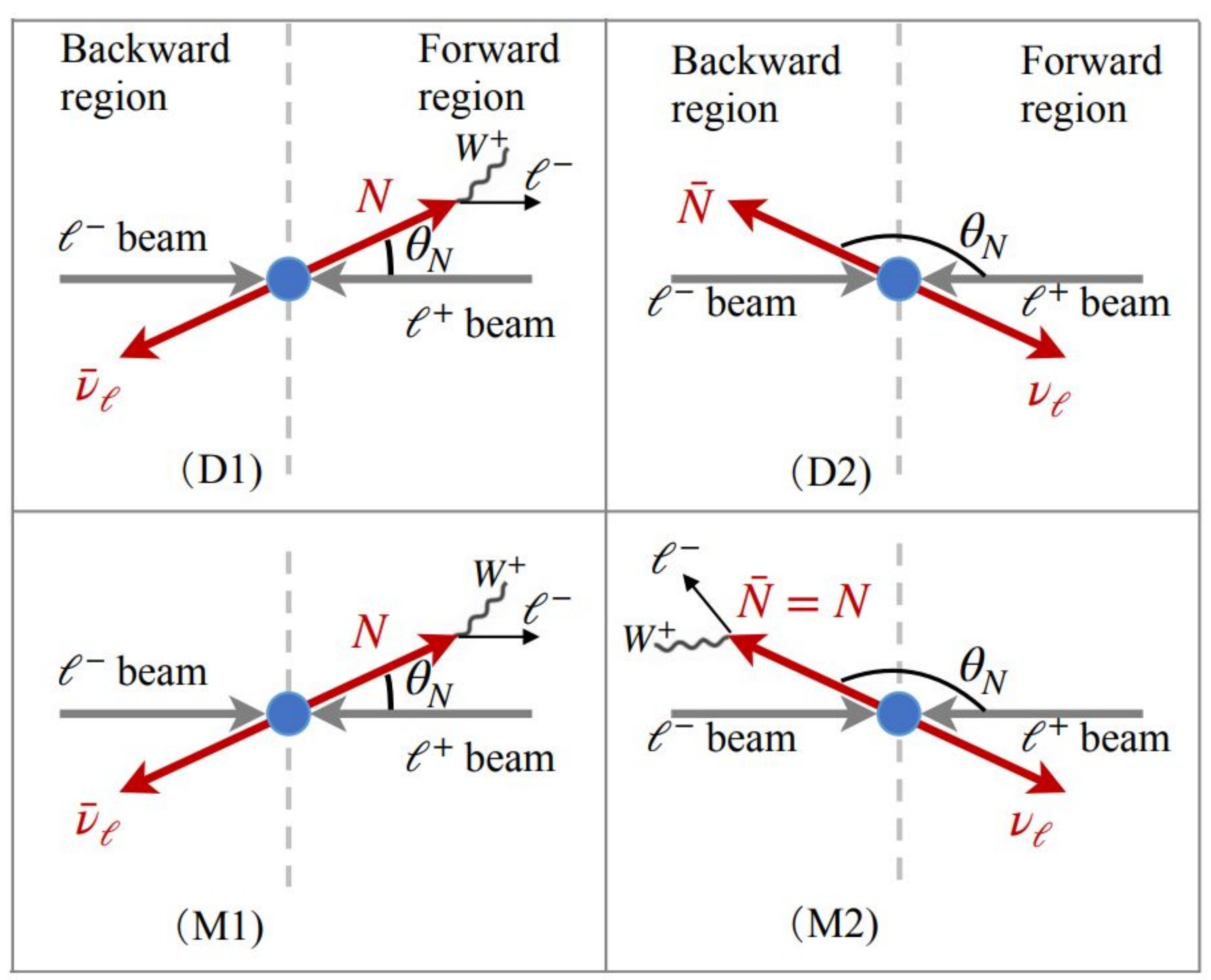

Fig. 2 illustration figure of the SN production[2]

- We simulated e+ e- collision by setting ebeam1 = ebeam2 = 1500 GeV, mass of N = 1000 GeV.

- Since the model consists of 3 generations of N's, we focus only on the first one. Then, we set the mass of the other two N's to be very heavy to avoid generating processes involving them.

- To reject the backgrounds, we apply some cuts. First, we require that the invariant mass of the electron and the missing momentum differs from the invariant mass of W more than 20 GeV². Secondly, we also require the **invariant mass of reconstructed e- W+ pair within the mass windows mN ± 5%mN²**.

Result

- The rapidity distribution after cuts shows a qualitatively distinction between Dirac type neutrinos and Majorana type neutrinos: Dirac type neutrinos have one peak and Majorana type neutrinos have two peaks.

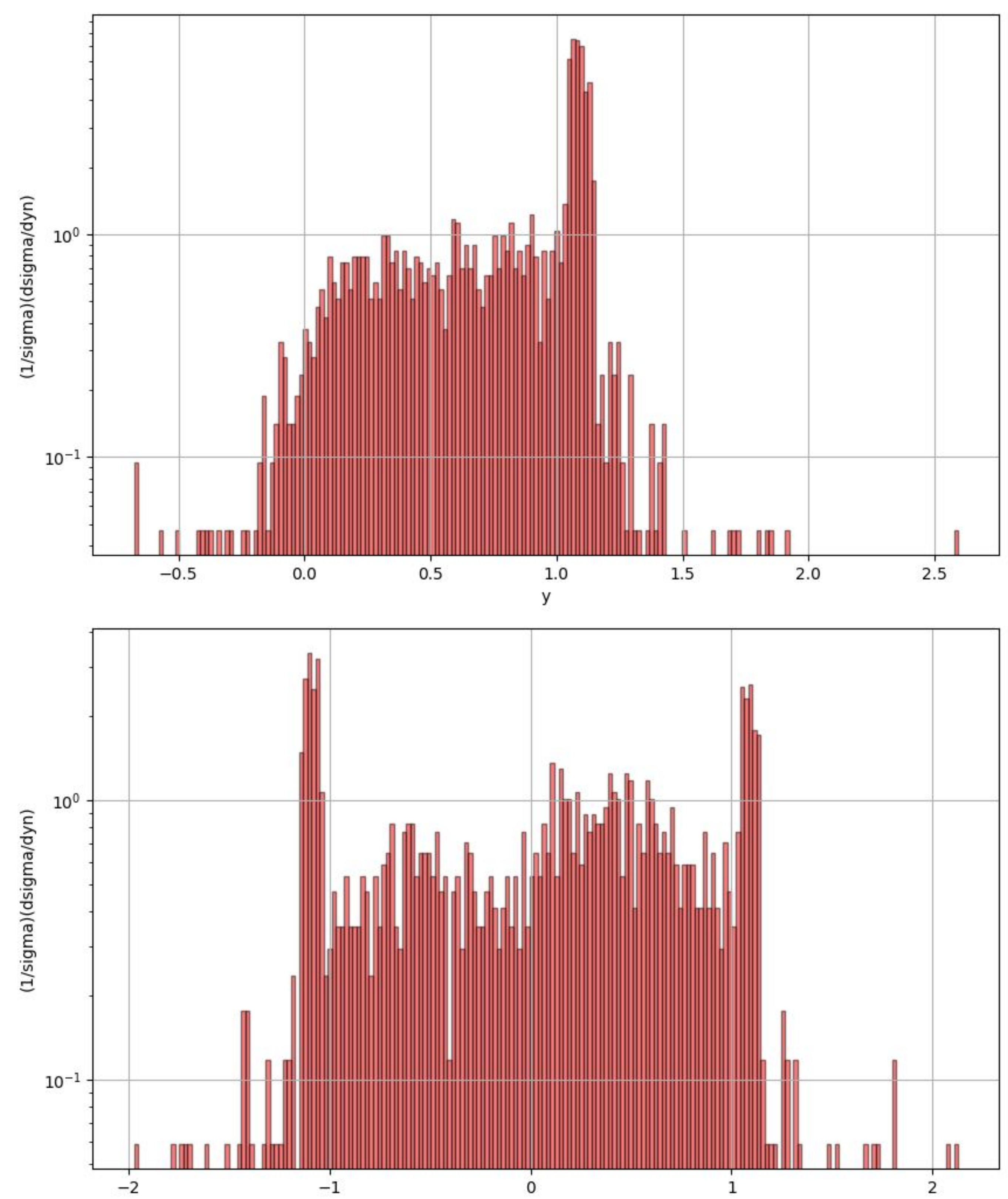

Fig. 3 Rapidity distribution

- The limitation of this method is that we need to know the mass of the heavy sterile neutrino, which is an expensive precondition at the first place.

Reference & Acknowledgement

1. Andre Luiz de Gouvea. Majorana or Dirac, That is the Question 6-3-21. Online; accessed 5-September-2024. YouTube, https://www.youtube.com/watch?v=vo05ctycro0. 2021
2. Qing-Hong Cao, Kun Cheng, and Yandong Liu. “Distinguishing Dirac/Majorana Heavy Neutrino at Future Lepton Colliders”. In: (Mar. 2024). arXiv: 2403.06561 [hep-ph]
3. Richard Ruiz, In collaboration with: Alva and T. Han [1]; C. Degrande, O. Mattelear, and J. Turner [2]; S. Pascoli and C. Weiland [3, 4]; and V. Cirigliano, W. Dekens, J. de Vries, K. Fuyuto, E. Mereghetti [5]. “The Standard Model + Heavy Neutrinos at NLO in QCD”. https://feynrules.irmp.ucl.ac.be/wiki/HeavyN

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