Universität Basel
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Displaced vertex searches for sterile neutrinos at future e^+e^--colliders

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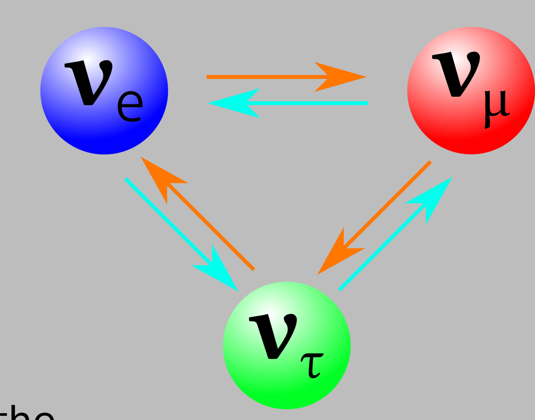
Baseline

The discovery of the Higgs boson at the Large Hadron Collider (LHC) plays an important role for the search strategies for new physics at future colliders. Although the discovered Higgs boson is compatible with the one of the Standard Model (SM) of elementary particle physics, its properties are not really well tested to date and important questions are partly unanswered.

The **main physics goal of future e^+e^--colliders** (accelerator facilities that collide electron and positron beams) is to investigate the discovered Higgs boson and to search for physics byond the SM, i.e. new particles and new interactions not present in the SM.

The existence of such new physics is guaranteed by various observations from particle physics as well as from cosmology, which can not be explained within the SM, such as neutrino oscillations, etc.



Neutrino oscillations are quantum mechanical phenomena that describe the conversion from one neutrino flavour to another. The oscillations imply small non-zero masses for the neutrinos which requires an extension of the SM to incorporate a mass mechanism for the neutrinos.

The following important questions rise:
Is the Higgs boson also responsible for giving mass to the neutrinos as it is the case for the other elementary particles?
What new particles are needed for the mass mechanism?

If the answer to the first question is "yes", then the new particles needed for the neutrino mass generation can be produced in electroweak processes. This allows to study them at future accelerators.

Theory

Neutrino mass mechanism

In the SM, neutrinos are the only fermions without a right-chiral counterpart and thus they are massless. The observed neutrino masses can easily be explained by extending the SM with additional **right-handed (i.e. sterile) neutrinos**.

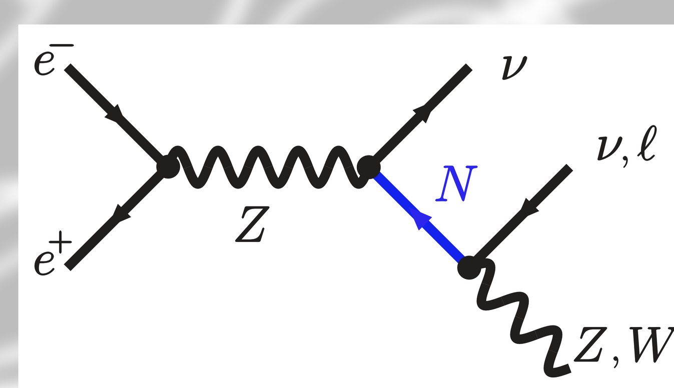
These sterile neutrinos are singlets under the gauge symmetries of the SM. They can have a so-called Majorana mass term, that involves exclusively the sterile neutrinos, as well as Yukawa couplings to the three SM neutrinos and the Higgs boson.

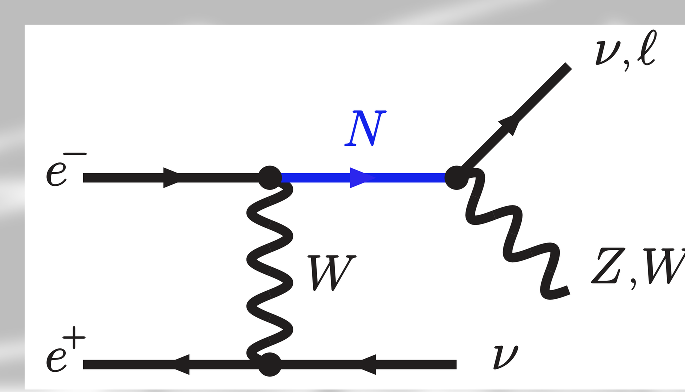
This neutrino mass mechanism is referred to as the seesaw mechanism. Usually, it is assumed that the mass of the sterile neutrinos is comparatively large to the accessible energies. Then the smallness of the light neutrino masses is explained by the large Majorana mass scale.

Alternatively, one may add **discrete symmetries**, for instance a "lepton-number-like" symmetry, in order to explain the smallness of the light neutrino masses with Majorana masses around the electroweak scale, which avoids an explicit hierarchy problem.

Neutrino interactions and production

The SM neutrinos interact via the mediators of the weak force, the weak gauge bosons (W and Z), thus they are referred to as active neutrinos while the steriles do not interact. However, **the active neutrinos mix with the sterile ones**. Due to the mixing, the light and the heavy neutrino mass eigenstates both interact with the weak gauge bosons. This allows for the heavy neutrino states (mostly sterile) to be produced in electron-positron collisions, which ultimately decay into SM particles.





Displaced vertex

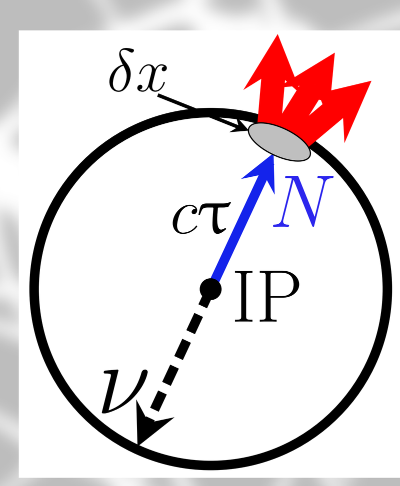
A very interesting effect arises from heavy neutrinos with masses below the W boson mass and with small mixings. Such heavy neutrinos have suppressed couplings to the W and Z as well as to the Higgs boson, which leads to a **long enough lifetime for a potentially visible displacement** from the interaction point. Via virtual W, Z and Higgs bosons they decay into detectable SM particles.

The **lifetime is dependent on the neutrino parameters**, i.e. the mixing of the active and sterile neutrinos as well as the Majorana mass of the sterile neutrinos. Overall, one can say that the smaller the Majorana mass the longer the lifetime of the heavy neutrinos.

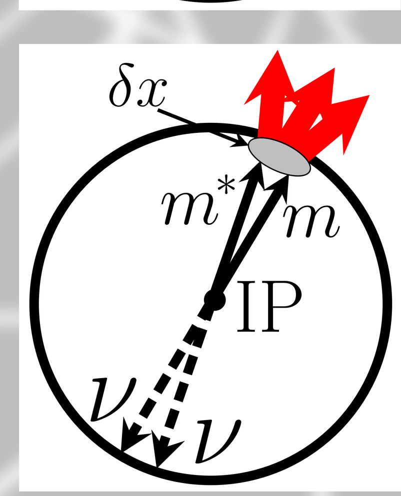
Displaced Vertex Search

Experimental signature

The experimental signature of a long-lived heavy neutrino (with mean lifetime τ) is given by a displacement of the secondary vertex from the interaction point (IP), i.e. where the electron-positron beams collided. Striking about this signature is that there is **exactly one secondary vertex from which all visible particles originate**.



In the SM, the heavy neutrino signature can be **faked** when SM particles with finite lifetime are produced in pairs and decay sufficiently close to each other, such that their individual secondary vertices cannot be resolved from the detector (with a resolution δx). This implies that the particles have to be emitted in a very narrow solid angle, which necessitates the production of additional invisible particles, (i.e. light neutrinos) in order to balance the overall momentum.

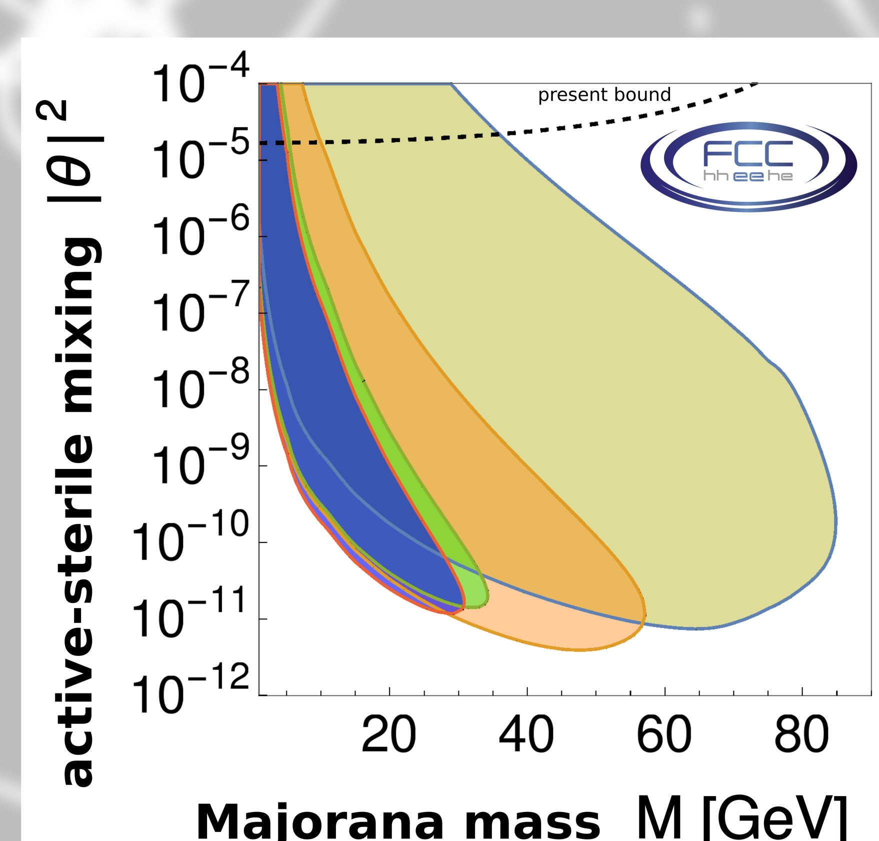


Overall, there are only few SM processes which can fake the displaced vertex signature of the heavy neutrinos because there are only few particles with a long lifetime that allow for displacement and in our paper we discussed how these backgrounds can be distinguished from the signal.

Detector and sensitivity to the neutrino parameters

Depending on the displacement of the long-lived heavy neutrino, its decay can take place in any of the detector components. Therefore every component can be considered as an independent probe for displaced vertices. From the inferred lifetime of the heavy neutrinos, which is dependent on the mixing of the active and sterile neutrinos, and the Majorana mass of the sterile neutrinos, one is able to probe these relevant neutrino parameters.

Estimations on the **sensitivity of the different detector components to the displaced vertex signature** (the neutrino parameteres equivalently) is shown below for the envisaged Future Circular electron positron Collider (FCC-ee) with an integrated luminosity of 110ab^{-1} at the Z pole (i.e. center-of-mass energy ~91GeV) for a confidence level of 2σ.



Punchline

The origin of neutrino masses is one of the big open question of particle phycis. If neutrino mass generation happens around the electroweak scale, this question could be answered at future colliders.

In our paper, the sensitivity to displaced vertex searches have been estimated for future colliders such as the Future Circular electron positron Collider (FCC-ee), Circular Electron Positron Collider (CEPC), and the International Linear Collider (ILC) with their respective phyics program, i.e. the Z pole run, the Higgs run, the top threshold scan and, for the ILC, also a high energy run.

The displaced vertex searches from the decays of long-lived heavy neutrinos look very promising, reaching sensitivities far beyond the present bounds.

Reference:
arXiv: 1604.02420
by Stefan Antusch, Eros Cazzato, Oliver Fischer