Sterile Neutrinos at the FCC

Searches for physics beyond the Standard Model

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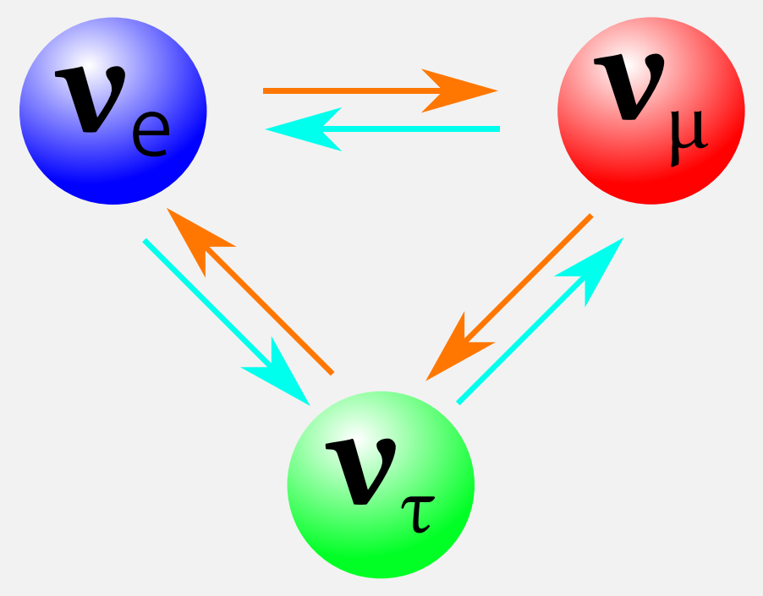
Abstract

Sterile neutrinos are among the most attractive extensions of the SM to generate the light neutrino masses observed in neutrino oscillation experiments. When the sterile neutrinos are subject to a protective symmetry, they can have masses around the electroweak scale and potentially large neutrino Yukawa couplings, which makes them testable at planned future particle colliders. We systematically discuss the production and decay channels at electron-positron, proton-proton and electron-proton colliders and provide a complete list of the leading order signatures for sterile neutrino searches. Among other things, we discuss several novel search channels, and present a first look at the possible sensitivities for the active-sterile mixings and the heavy neutrino masses. We compare the performance of the different collider types and discuss their complementarity.

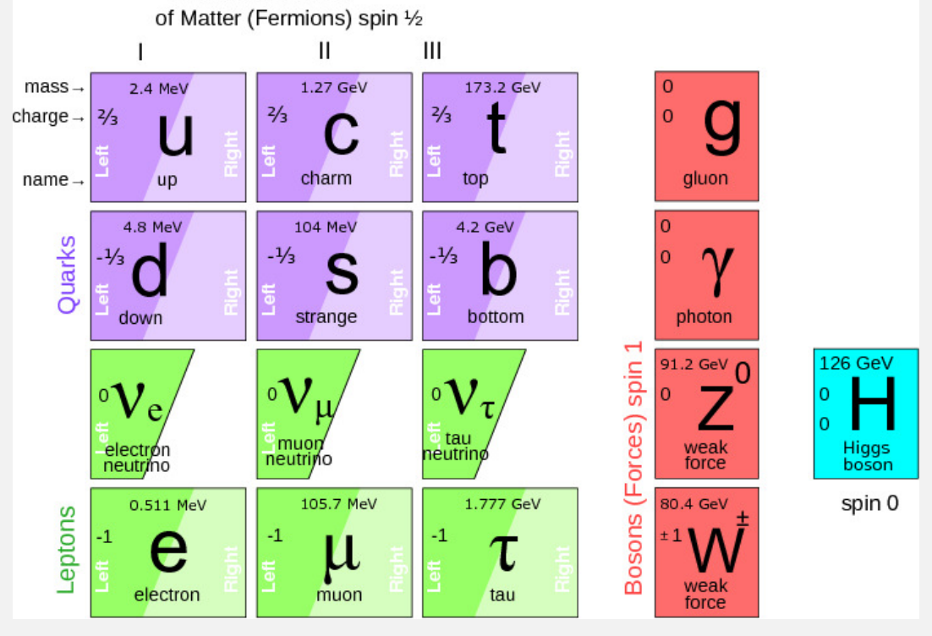
Introduction: The Origin Of Neutrino Masses

Observation of neutrino oscillations



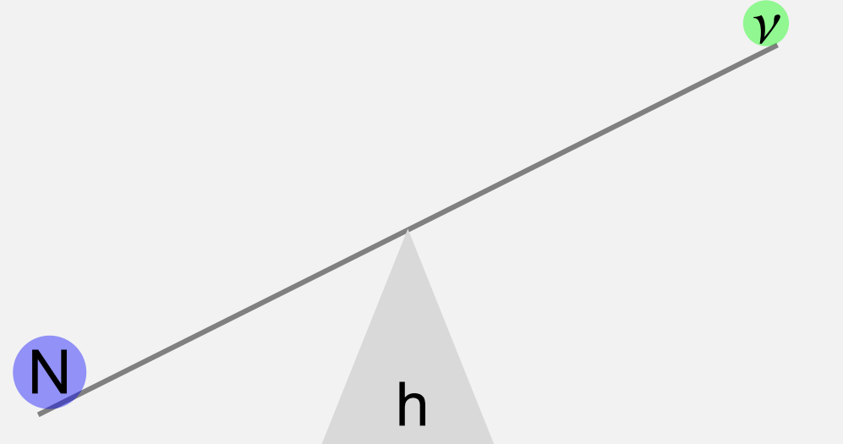
Nobelprize 2015 for T. Kajita and A. McDonald
Light neutrinos are flavor mixed mass eigenstates
Requires a neutrino mass matrix

Neutrino Masses in the SM



No $\nu_R \Rightarrow$ no mass matrix in the SM
Extension with ν_R is physics beyond the SM.

The (naïve) Seesaw Mechanism

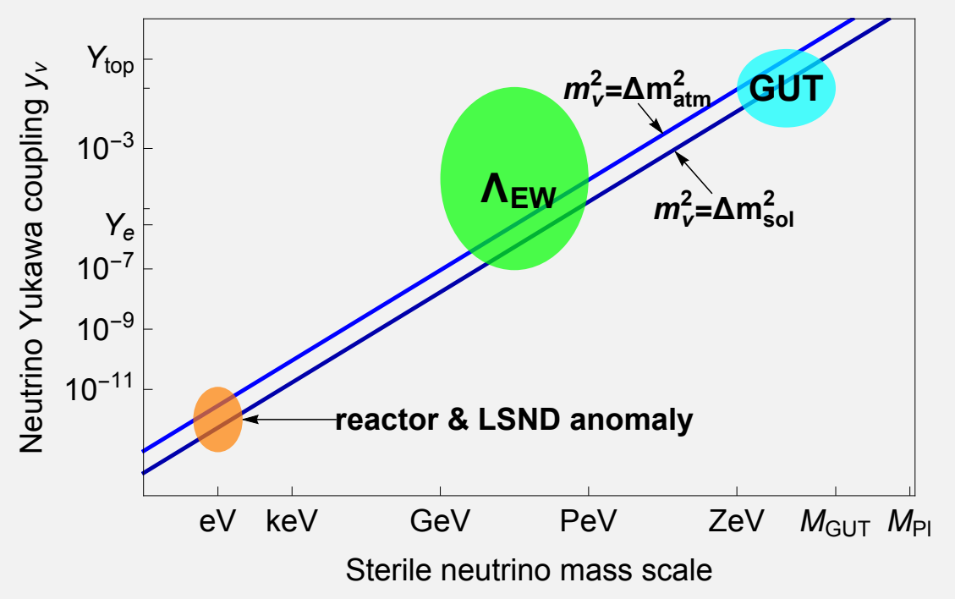


Simplified version with one ν_L and one ν_R.
Mass matrix with Dirac and Majorana masses:

$$\begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix} \Rightarrow m_\nu = \frac{m_D^2}{2\,M_M}$$

More realistic version with two ν_L and 2 ν_R:
m_D and $M_M \rightarrow$ matrices.

Lowscale Seesaw



Special structure of m_D and M_M:

$$m_D=\begin{pmatrix} m & 0 \\ m & 0 \end{pmatrix},\quad M_M=\begin{pmatrix} 0 & M \\ M & \varepsilon \end{pmatrix} \Rightarrow m_{\nu_i} = \varepsilon\frac{m^2}{M^2}$$

Large m_D compatible with neutrino oscillations

The Symmetry Protected Seesaw Scenario

The Model

Sterile neutrinos N_1 and N_2, opposite symmetry charge, additional sterile neutrinos decoupled:

$$\mathscr{L}_N = -\frac{1}{2}\overline{N_R^1} M (N_R^2)^c - y_{\nu_\alpha}\overline{N_R^1}\widetilde{\phi}^\dagger L^\alpha + \text{H.c.}$$

Mass matrix:

$$\mathcal{M}_\nu = -\frac{1}{2}\begin{pmatrix} 0 & \frac{y_{\nu_\alpha} v_{\rm EW}}{\sqrt{s}} & 0 \\ \frac{y_{\nu_\alpha} v_{\rm EW}}{\sqrt{s}} & 0 & M \\ 0 & M & 0 \end{pmatrix} + \text{ H.c.}$$

Neutrino mixing: $\theta_\alpha = \frac{m_D}{M}$, $\quad\theta^2 = \sum|\theta_\alpha|^2$

The leptonic mixing matrix $\mathcal{U}$

$$\begin{pmatrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} & -\frac{\rm i}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{\mu1} & \mathcal{N}_{\mu2} & \mathcal{N}_{\mu3} & -\frac{\rm i}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{\tau1} & \mathcal{N}_{\tau2} & \mathcal{N}_{\tau3} & -\frac{\rm i}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\rm i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & -\frac{\rm i}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) & \frac{1}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) \end{pmatrix}$$

$\mathcal{N} \sim$ PMNS as submatrix **not** unitary.

$$J^{\mu,\pm} = \ell_\alpha\gamma^\mu\nu_i\mathcal{N}_{\alpha i}\,,\quad J^{\mu,0} = \nu_i\gamma^\mu\nu_j\,(\mathcal{N}^\dagger\mathcal{N})_{ij}$$

Constraints from precision measurements

Analysis of non-unitarity of the PMNS matrix:
EWPO, lepton universality, cLFV, CKM unitarity
Results from [1] at 90% Bayesian C.L.:

$$\begin{array}{rcrcl} -0.0021 & \leq \varepsilon_{ee} \leq & -0.0002 & |\varepsilon_{e\mu}| & < 1.0\times10^{-5} \\ -0.0004 & \leq \varepsilon_{\mu\mu} \leq & 0 & |\varepsilon_{e\tau}| & < 2.1\times10^{-3} \\ -0.0053 & \leq \varepsilon_{\tau\tau} \leq & 0 & |\varepsilon_{\mu\tau}| & < 8.0\times10^{-4} \end{array}$$

- ⋆ Non-unitarity parameters: $\varepsilon_{\alpha\beta} = -\theta_\alpha^*\theta_\beta$.
- ⋆ Weak statistical preference for non-zero mixing for ε_{ee}.

Direct searches for heavy neutral leptons

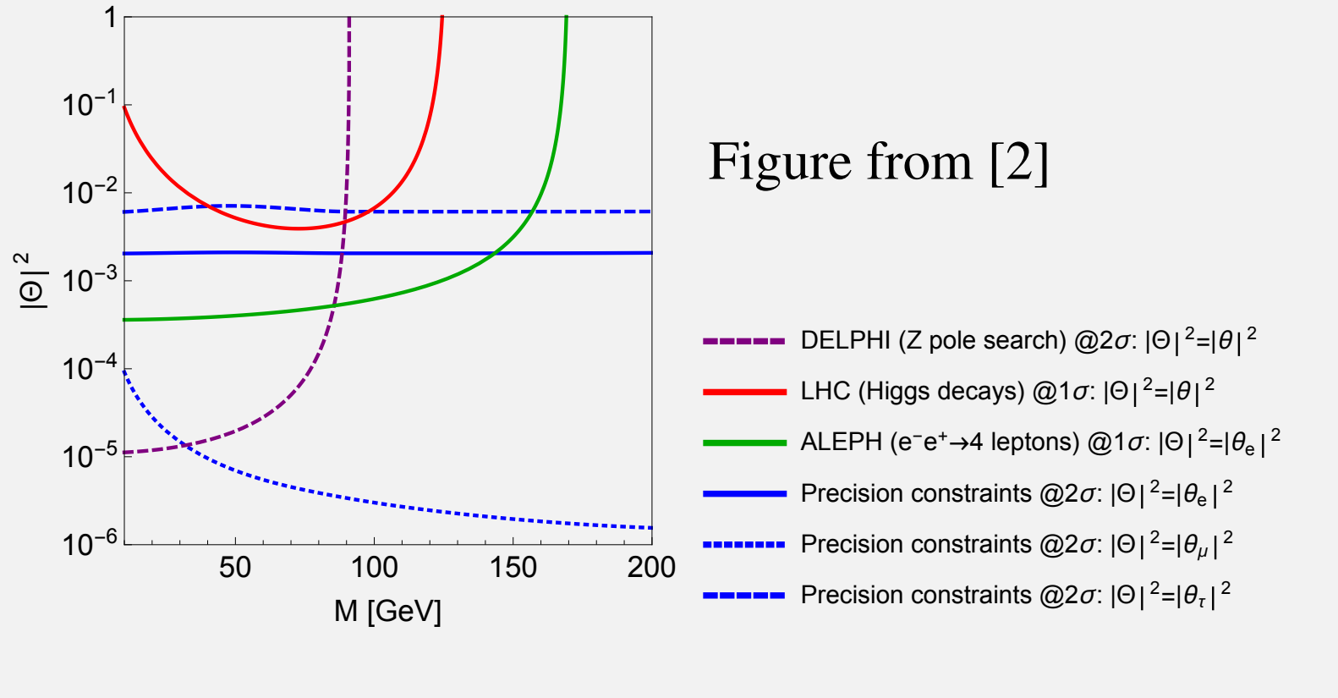
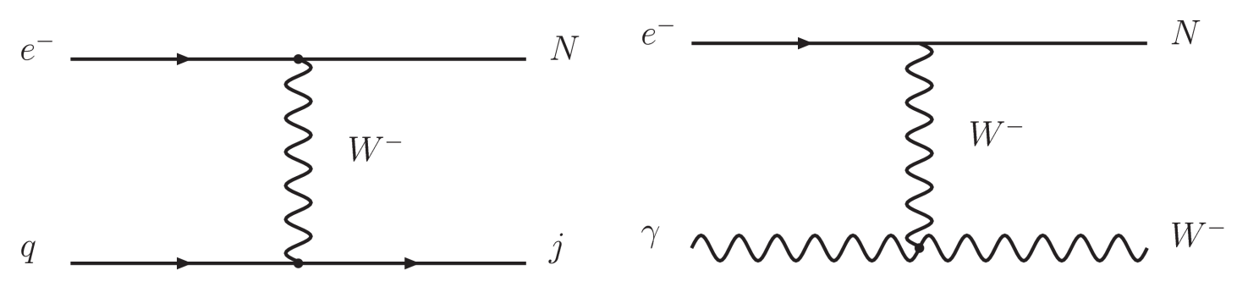


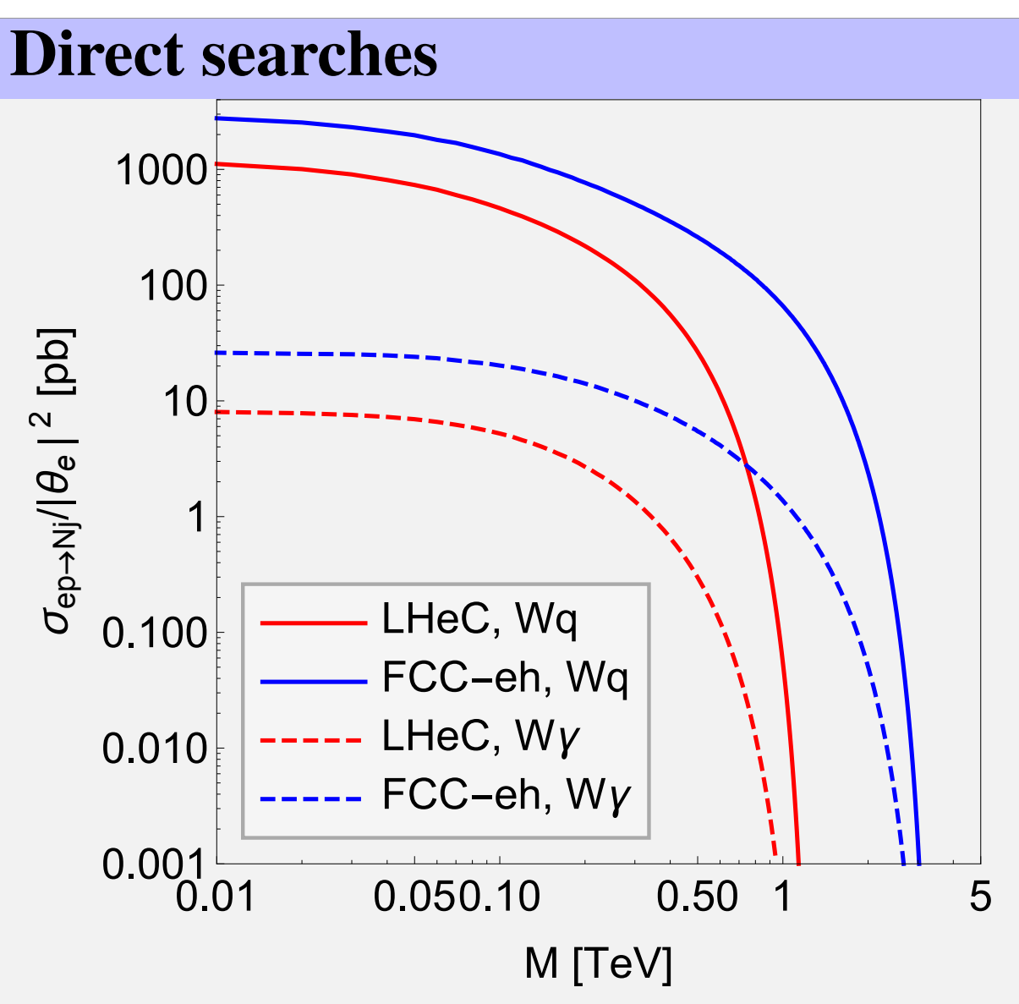
Figure from [2]

- Z pole search: limits from Z branching ratios.
- Higgs decays: Best constraints from $h \rightarrow \gamma\gamma$.
- Direct Searches from the LEP collaborations.

Searches at the FCC-eh



Direct searches



- Production from the electron beam via $|\theta_e|$
- Final states: $jjj\ell_\alpha^-$, $j\ell_\alpha^-\ell_\beta^+\nu$, $jjj\nu$, $j\nu\nu\nu$, + final states from Wγ fusion.
- LFV unambiguous: μ^- +jets, τ^- +jets, $\mu\tau$ + jets

Exotic signatures

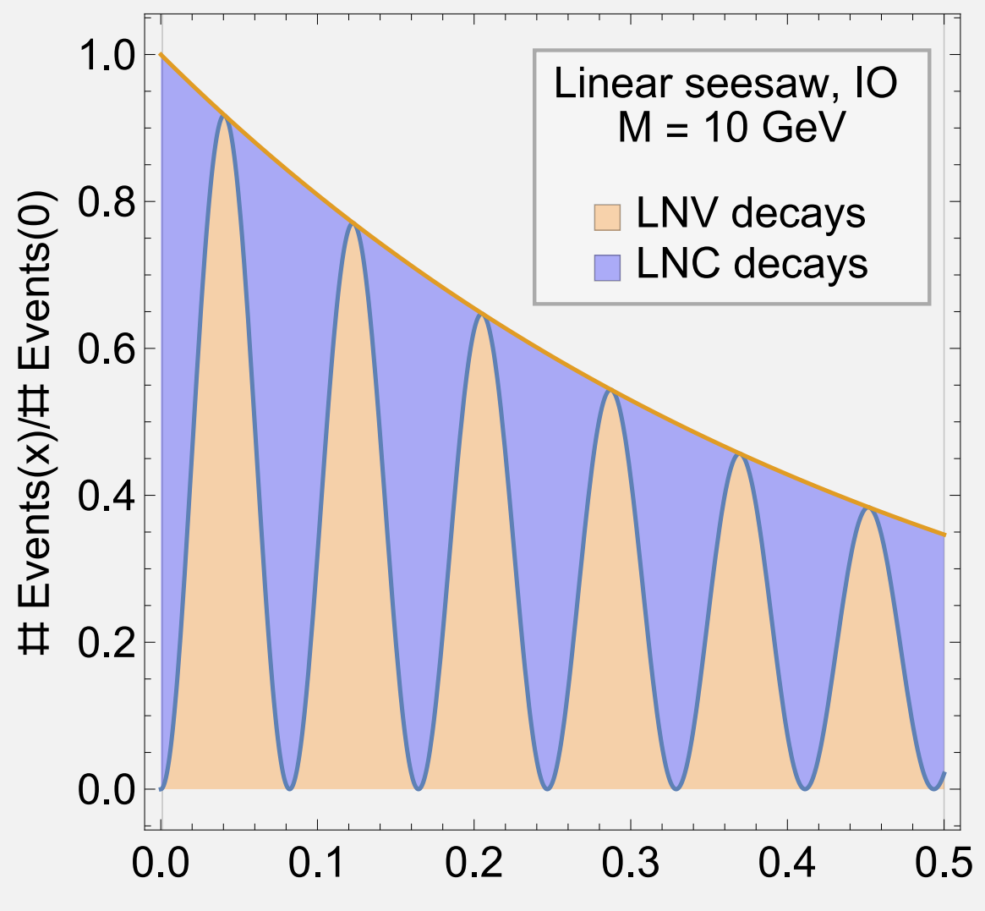
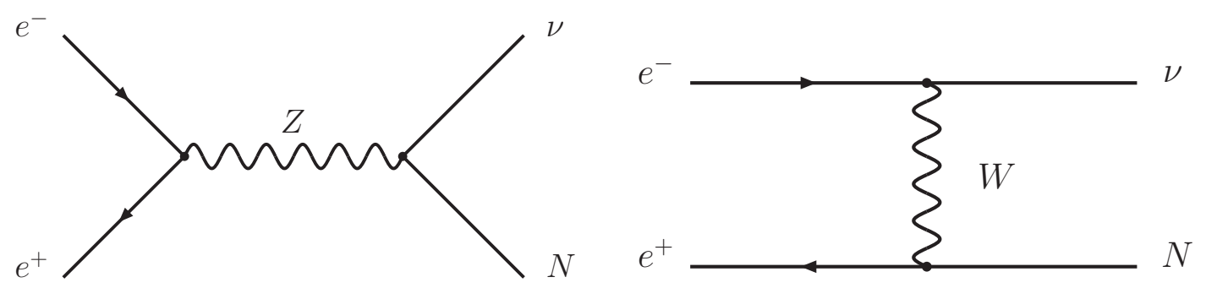


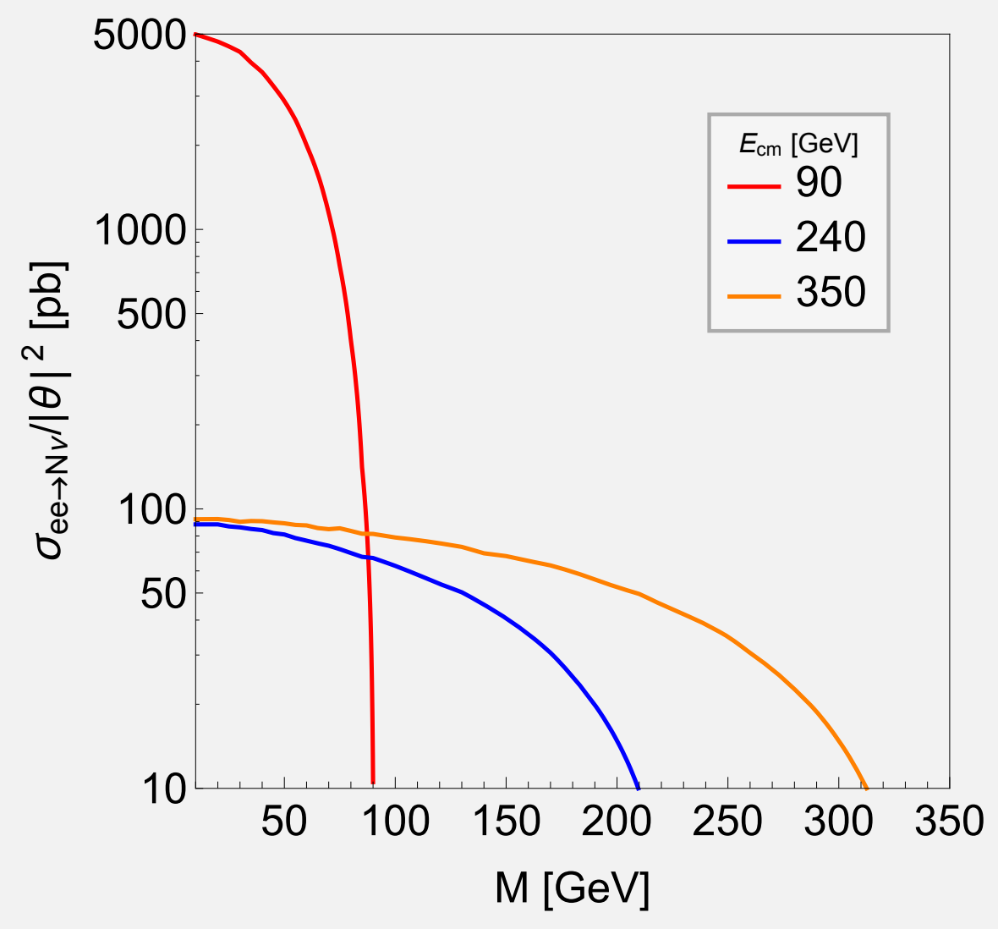
Figure from [5]

- Displaced vertex searches possible [6]
- LNV and heavy neutrino oscillations: $\ell^- \leftrightarrow \ell^+$ [5]
- Oscillation from Δm_ν^2, can be $\sim$ mm.

Searches at the FCC-ee



Direct searches



- Production: $|\theta|$ @ Z pole and $|\theta_e|$ for $\sqrt{s} > m_Z$
- Final states: $\ell_\alpha jj$, $\ell_\alpha\ell_\beta$, jj
- Mono-Higgs production cross section [3]
- LNV only via kinematic analysis
- Displaced vertices very powerful for $M < m_Z$ [4]

Electroweak precision measurements

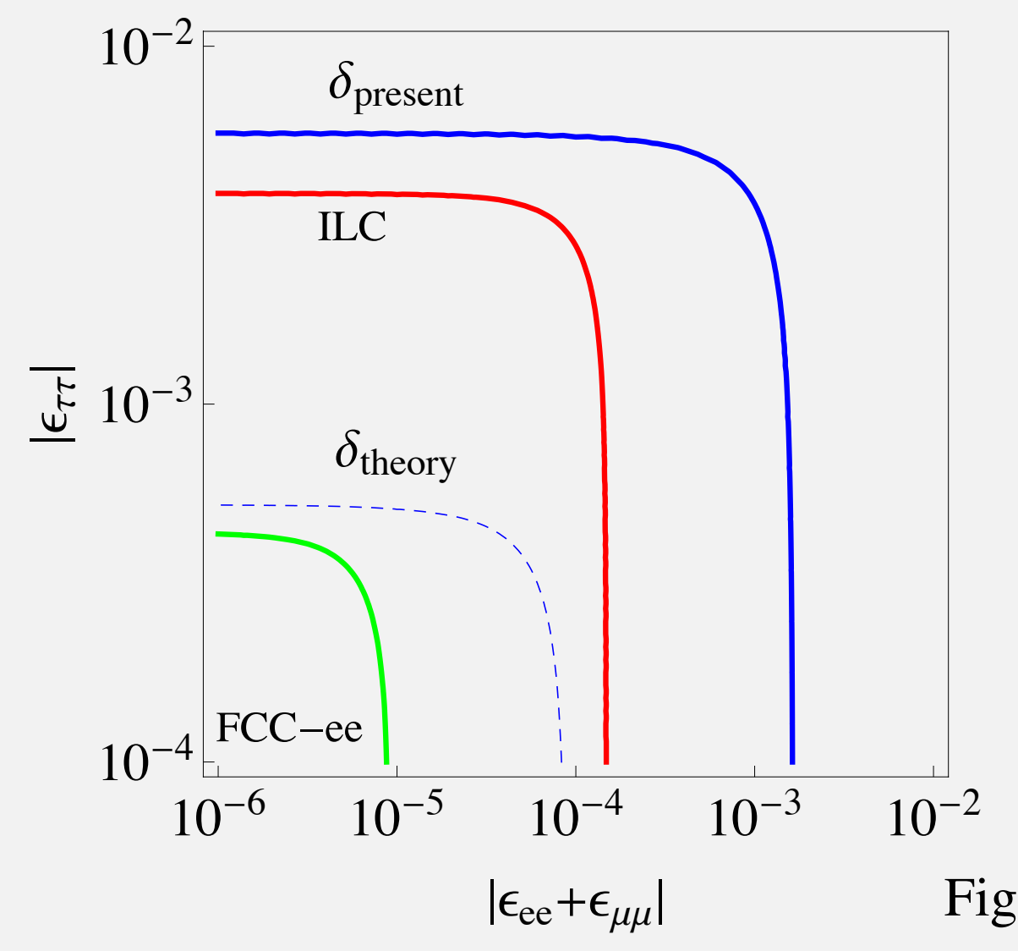
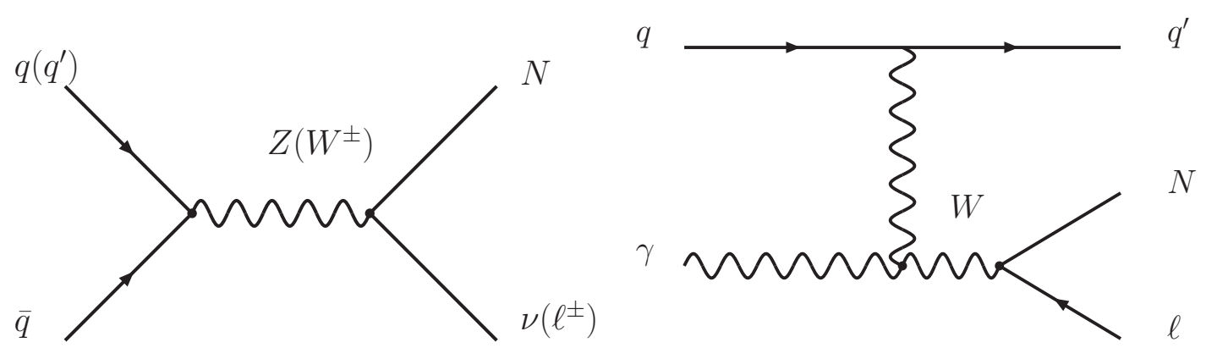


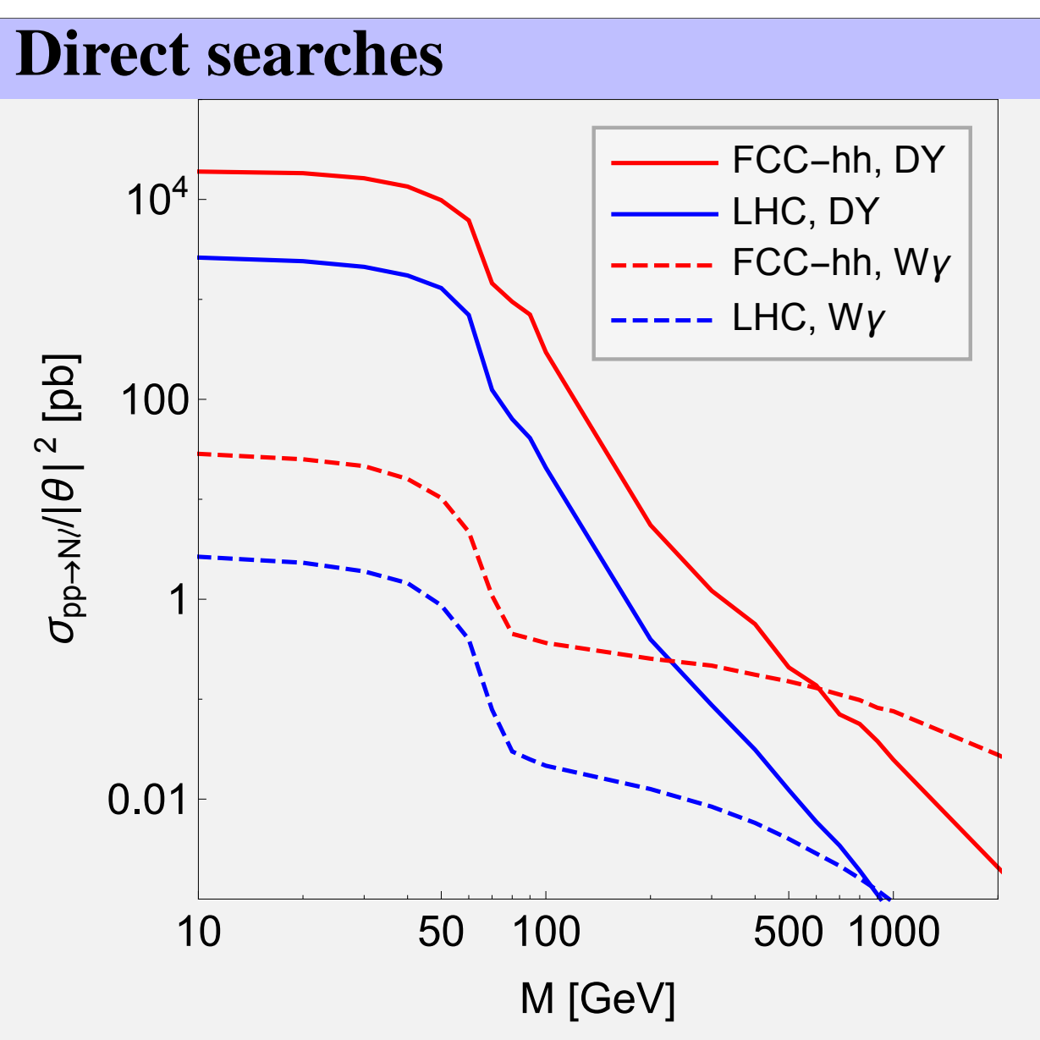
Figure from [1]

- Weak mixing angle from $\mathcal{A}_{\rm fb}(\mu)$
- Z decay rates: $R_\ell,\ R_b,\ R_c,\ R_{\rm inv}$
- Invisible Z and Higgs decays
- W boson mass
- Leptonic W branching ratios

Searches at the FCC-hh



Direct searches



- Production via Drell Yan or Wγ fusion
- Final states: $\ell_\alpha\ell_\beta jj$, $\ell_\alpha\ell_\beta\ell_\gamma\nu$, $\ell_\alpha\nu jj$, $\ell_\alpha\ell_\beta\nu\nu$, $\ell_\alpha\nu\nu\nu$ + final states from Wγ fusion
- LFV promising via $\ell_\alpha^\pm\ell_\beta^\mp jj$, $\alpha \neq \beta$

Exotic signatures

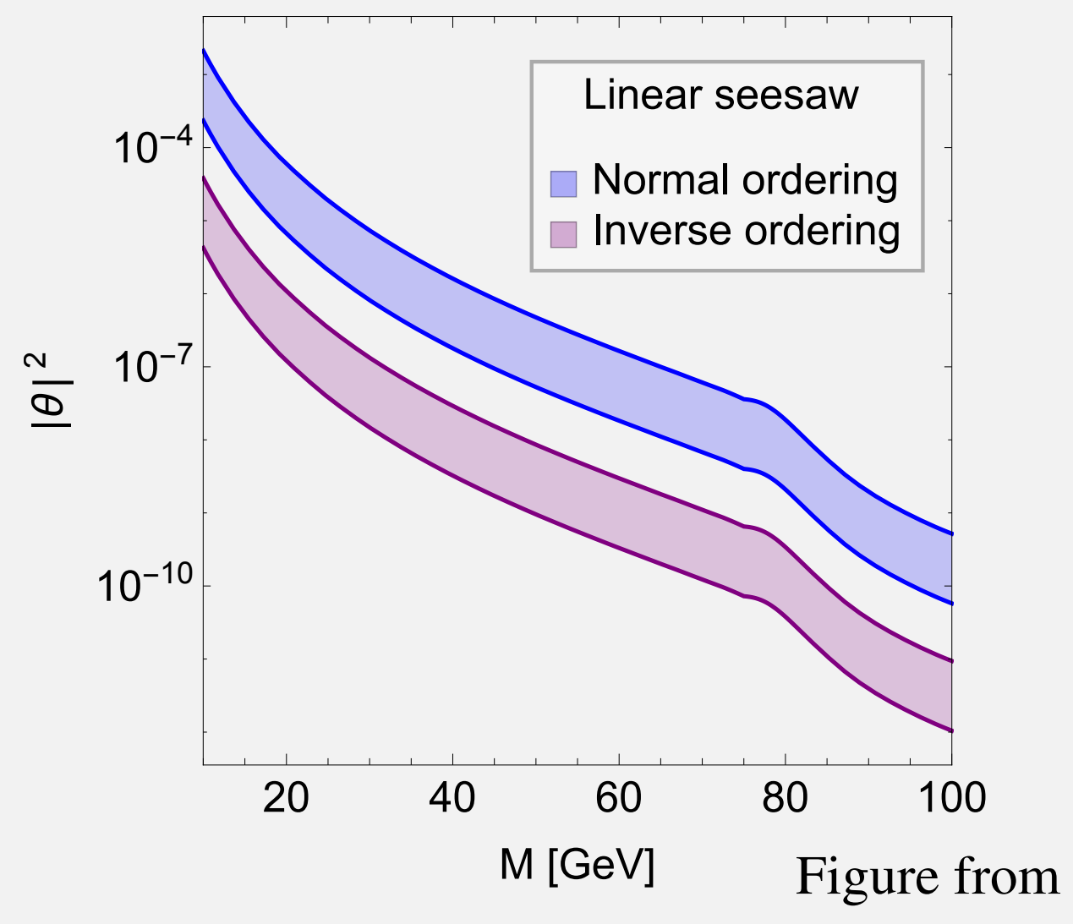


Figure from [5]

- Displaced vertex search difficult (pileup)
- LNV same-sign dileptons, e.g. $\mu^\pm\mu^\pm jj$
- Heavy neutrino-antineutrino oscillations for $M < m_W$

Complementarity, Synergy, and Prospects

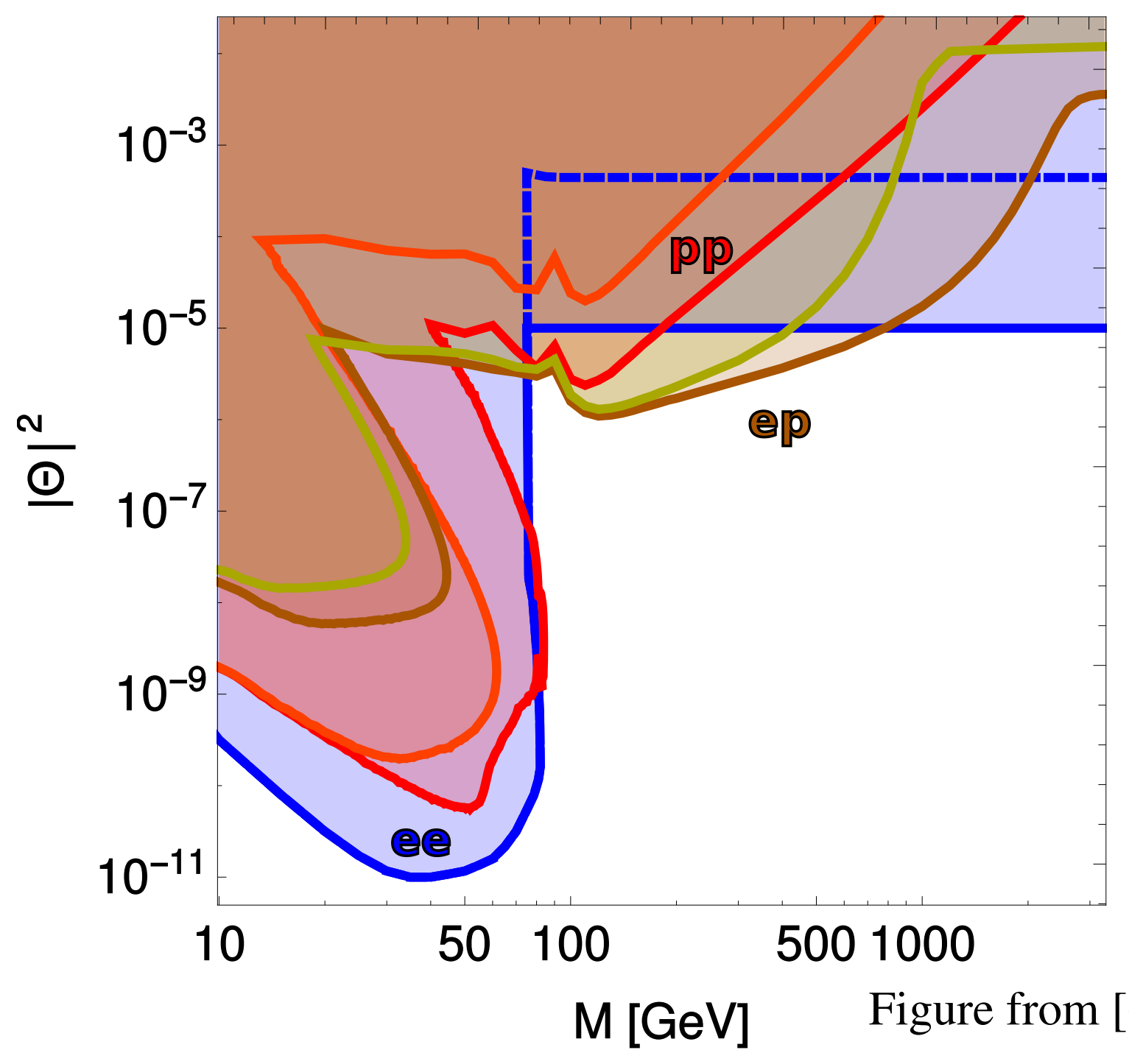
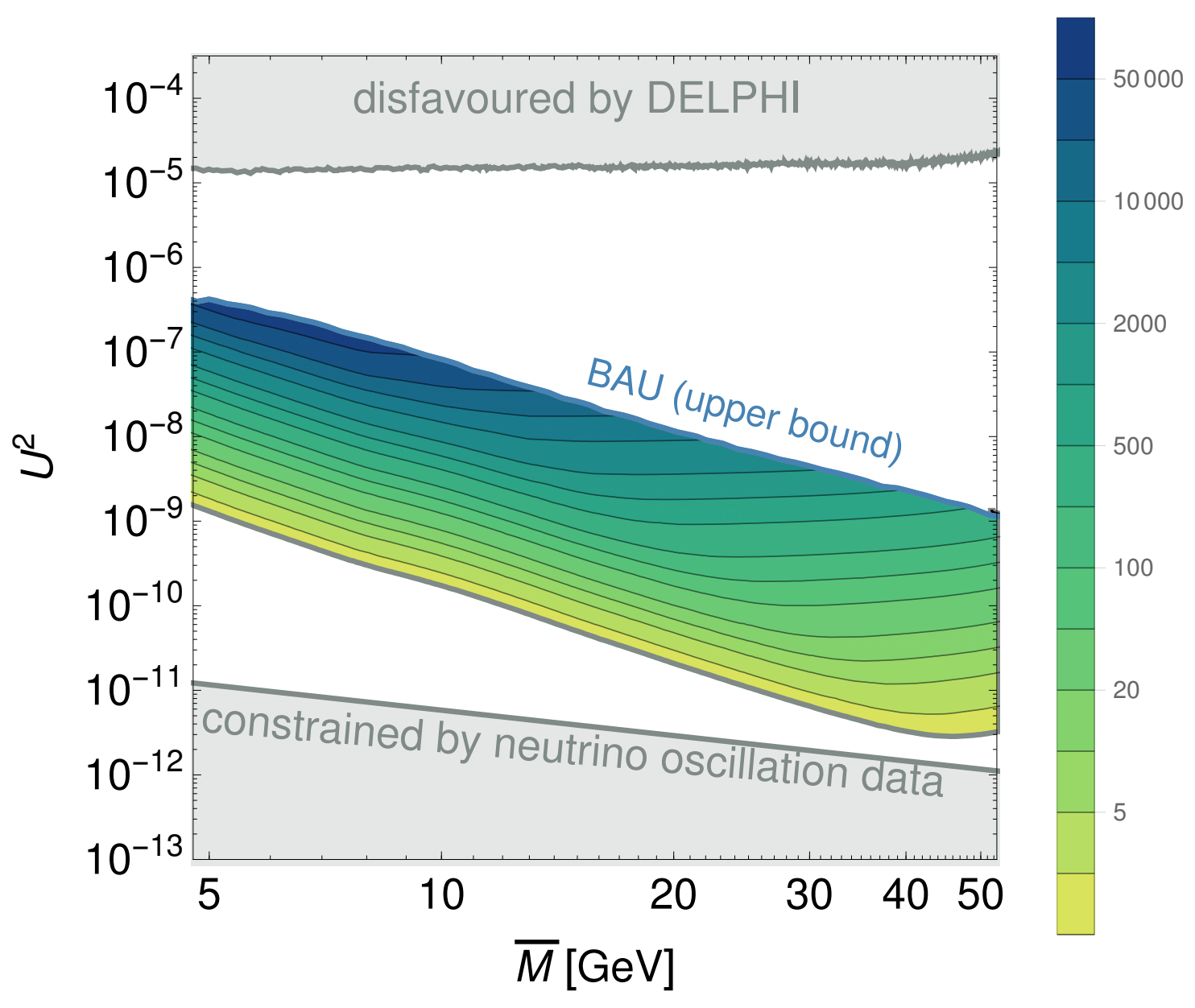


Figure from [6]

Parameter space for Leptogenesis from [7]



Combination of ee, pp, and ep provides complementary tests for symmetry protected sterile neutrinos:

- Direct searches: Great prospects at pp and ep via Lepton Flavor Violating signatures.
- Indirect searches: FCC-ee powerful via precision measurements at Z pole.
- Exotic signatures: Displaced vertices promising at all colliders, best sensitivity at FCC-ee
- Precision measurements allow tests of Leptogenesis in minimal models.

References

[1] S. Antusch and O. Fischer, JHEP **1410** (2014) 094 [arXiv:1407.6607 [hep-ph]].
[2] S. Antusch and O. Fischer, JHEP **1505** (2015) 053 [arXiv:1502.05915 [hep-ph]].
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[4] S. Antusch, E. Cazzato and O. Fischer, JHEP **1612** (2016) 007 doi:10.1007/JHEP12(2016)007 [arXiv:1604.02420 [hep-ph]].
[5] S. Antusch, E. Cazzato and O. Fischer, arXiv:1709.03797 [hep-ph].
[6] S. Antusch, E. Cazzato and O. Fischer, Int. J. Mod. Phys. A **32** (2017) no.14, 1750078 [arXiv:1612.02728 [hep-ph]].
[7] S. Antusch, E. Cazzato, M. Drewes, O. Fischer, B. Garbrecht, D. Gueter and J. Klaric, arXiv:1710.03744 [hep-ph].

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