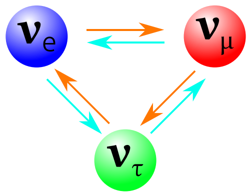
Testing the origin of neutrino masses at lepton colliders

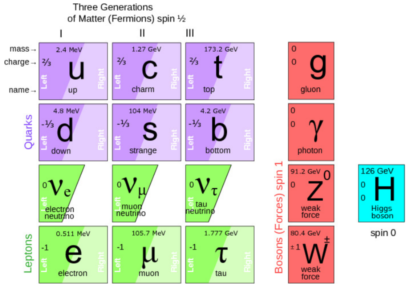
Oliver Fischer

Karlsruher Institut für Technologie

IAS Program on High Energy Physics
January 11, 2019, Hong Kong

New Physics in the neutrino sector





Shaposhnikov *et al.*

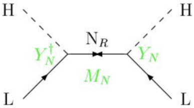
- Neutrino oscillations: *at least* two massive light neutrinos.
- No renormalisable way in the SM ⇒ evidence for new physics.
- Successful models: type I, II, III seesaw mechanism.
- The seesaws can be combined and/or embedded in a more general theory.

New Physics could be a Dirac mass with tiny Yukawa coupling.

The 3 basic seesaw models

i.e. tree level ways to generate the dim 5 operator

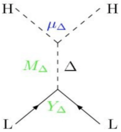
Right-handed singlet:
(type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Minkowski; Gellman, Ramon, Slansky; Yanagida;Glashow; Mohapatra, Senjanovic

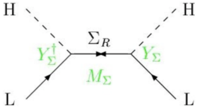
Scalar triplet:
(type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Magg, Wetterich; Lazarides, Shafi; Mohapatra, Senjanovic; Schechter, Valle

Fermion triplet:
(type-III seesaw)

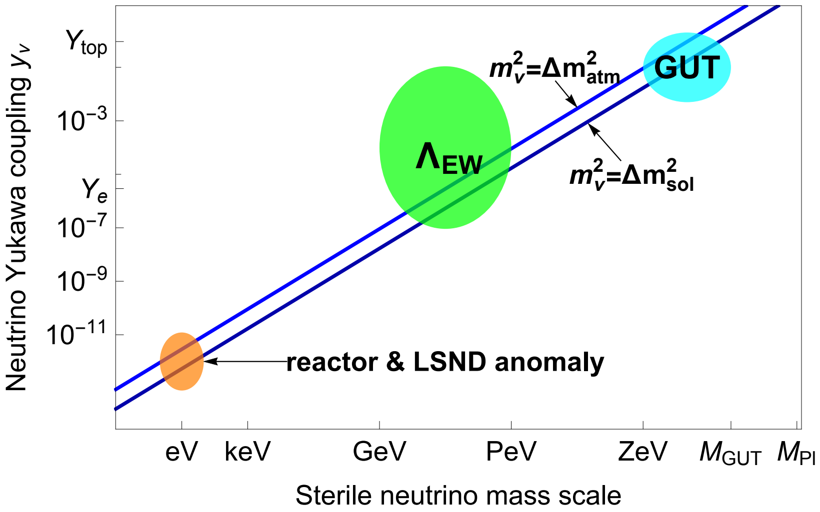


$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Foot, Lew, He, Joshi; Ma; Ma, Roy;T.H., Lin, Notari, Papucci, Strumia; Bajc, Nemevsek, Senjanovic; Dorsner, Fileviez-Perez;....

Slide from T. Hambye.

The Big Picture - and the problem

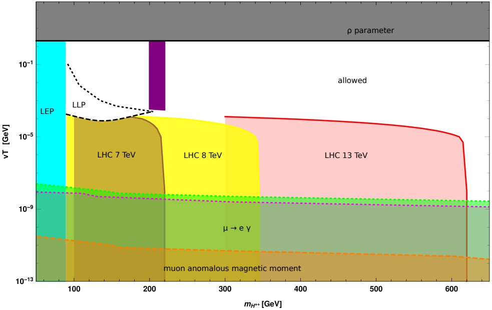


Lepton number violation - type I

- If neutrinos are Majorana particles, the mechanism that generates their mass can generate LNV.
- Observation of LNV is not unambiguous when light neutrinos are in the final state.
- Dominant production mode $e^- e^+ \to \nu N$.
- Best observable is the invariant mass from the decay $N \to \ell W$.
- LNV can in principle be observed in kinematic distributions.

  del Aguila *et al.*, Phys. Lett. B **613** (2005) 170
- Unambiguous signature $e^- e^+ \to \ell^\pm \ell^\pm + 4j$; subdominant rates. Y. Zhang and B. Zhang, arXiv:1805.09520 [hep-ph]
- LNV is absent in lowscale seesaw models with sizable mixings and production rates e.g. Kersten&Smirnov, Phys. Rev. D **76** (2007) 073005

Lepton number violation - type II



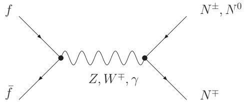
Antusch *et al.*, arXiv:1811.03476

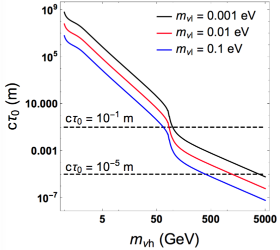
- Rich pheno, but many parameters to "evade constraints".
- Interesting "hole" in LHC analyses: $\mathcal{O}(100)$ GeV doubly charged LNV scalar with lifetime > 1 mm.
- Triplet vev $> 10^{-4}$ GeV difficult to test at LHC.

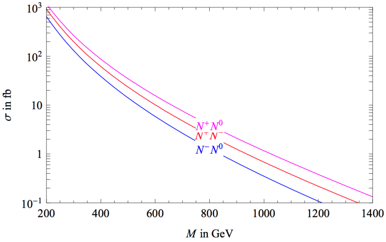
Dilip Kumar Ghosh *et al.*, Phys. Rev. D **97** (2018) no.11, 115022

- Masses $\gtrsim 1$ TeV $\Rightarrow$ Manimala's talk.

Type III seesaw





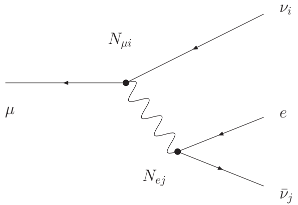


Franceschini *et al.*, Phys. Rev. D **78** (2008) 033002

- LHC Analyses: prompt Decays or missing energy.
- Limit ($\sqrt{s} = 13$ TeV, 79.8/fb) is 560 GeV ATLAS-CONF-2018-020 and 35.9/fb 840 GeV from CMS (both prompt decays) 1708.07962.
- Larger masses $\Rightarrow$ lepton colliders at high energy.
- Can be long lived: multiple displaced vertices.
- Might just escape current searches...

Precision for discovery

Input parameters: M_Z, $\alpha(M_Z)$, G_F.



The Fermi constant:

- Muon decay $\propto \left(NN^\dagger\right)_{ee} \left(NN^\dagger\right)_{\mu\mu}$
- Fermi constant $G_F \neq$ muon decay constant G_μ.
- Tree-level relation: $G_F = \frac{G_\mu}{\sqrt{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}} = \frac{\alpha\pi}{\sqrt{2}s_W^2 c_W^2 m_Z^2}$
- Analogous: Observables involving weak decays.

$\Rightarrow$ Theory prediction for electroweak observables.

del Aguila *et al.*, Phys. Rev. D **78** (2008) 013010

Antusch *et al.*, JHEP **0610** (2006) 084

Fernandez-Martinez *et al.*, JHEP **1608** (2016) 033

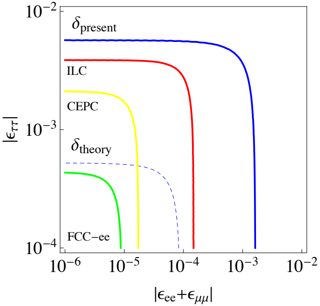
...

Indirect Signatures: Electroweak precision tests

Observable	LEP precision	from CEPC preCDR
M_W [MeV]	33	3
$\sin^2 \theta_W^{\mathrm{eff}}$	0.07%	0.01%
R_b	0.3%	0.08%
R_c	0.3%	0.07%
R_{inv}	0.27%	8.9×10^{-4}
R_ℓ	0.1%	0.1%
Γ_ℓ	0.1%	0.1%
σ_h^0 [nb]	8.9×10^{-4}	1×10^{-4}

FCC-ee: much more ambitious;

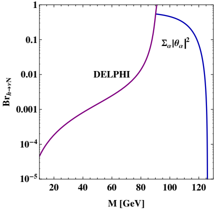
ILC: no strong Z pole program.

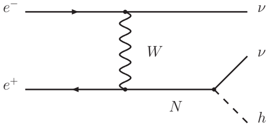


S. Antusch and OF, JHEP **1410** (2014) 094

- Measuring the non-unitarity of the PMNS matrix.
- Improvement required: δ_{theory} and δ_{syst}.
- Not included: lepton universality tests, low energy data

Indirect signatures: Higgs boson properties





- New Higgs decay channels, w/ large branching e.g. $h \to \nu N$.
- Additional mono-Higgs production at high energies.

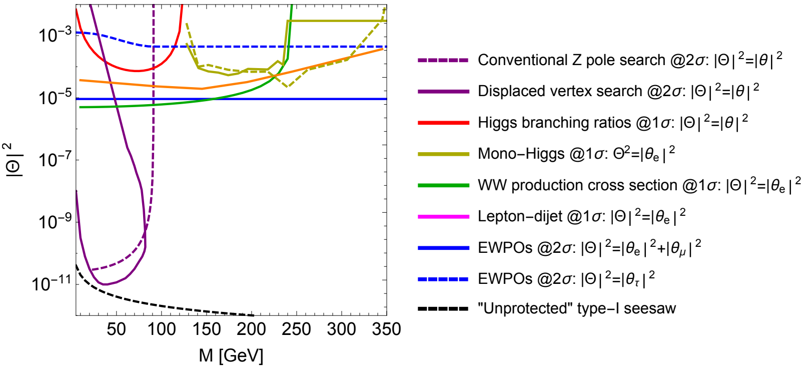
S. Antusch, OF; JHEP **1604** (2016) 189

- Decays of Higgs into two LLP with displaced vertices

Accomando *et al.*, JHEP **1704** (2017) 081 Maiezza *et al.*, Phys. Rev. Lett. **115** (2015) 081802

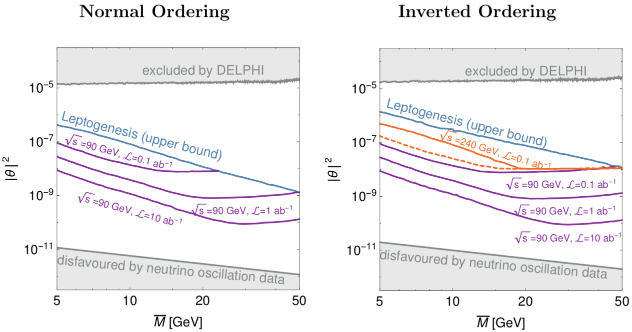
- Anomalous diphoton decays Melfo *et al.*, Phys. Rev. D **85** (2012) 055018
- Modified Higgs self couplings Baglio *et al.*, JHEP **1704** (2017) 038
- ...

FCC-ee sensitivities for type I seesaw



- For “symmetry protected” models (pseudo Dirac)
- Similar studies for CEPC and ILC exist (cf. e.g. Antusch *et al.*, Int. J. Mod. Phys. A **32**, no. 14, 1750078 (2017).

Leptogenesis



Drewes *et al.*, JHEP **1809** (2018) 124

- Matter-antimatter asymmetry (BAU).
- Naturally adressed in lowscale type I seesaw.
- Displaced vertex search
  $\Rightarrow$ origin of neutrino mass & BAU can be tested
- Mass splitting of pseudo-Dirac pair via heavy neutrino-antineutrino oscillations

Antusch *et al.*, 1709.03797

Conclusion

- Neutrino mass physics has extremely rich phenomenology.
- Toy models for experimentalists, strong constraints.
- Embedding in theory frameworks opens up a lot of room.
- pp, ee, and ep colliders are very complementary.
- Especially EW (+Higgs) precision measurements important.
- CEPC CDR neutrino section* contains more information.

*Authors: M. Drewes, OF, M. Nemevšek

Note on electron-proton colliders

Please have a look at my short overview talk at the LLP workshop:
https://indico.cern.ch/event/714087/contributions

MC simulation at reco level $\Rightarrow$ Pythia6 has to be patched!

Delphes card available here:
https://indico.cern.ch/event/774889/contributions/3220312/

(Hyperlinks in the online version)