Neutrino Portal to New Physics

BHUPAL DEV

Max-Planck-Institut für Kernphysik, Heidelberg

"Collider Physics" Symposium

University of Silesia, Katowice

May 15, 2016

ν

$m_\nu = m_L^T - m_D M_R^{-1} m_D$

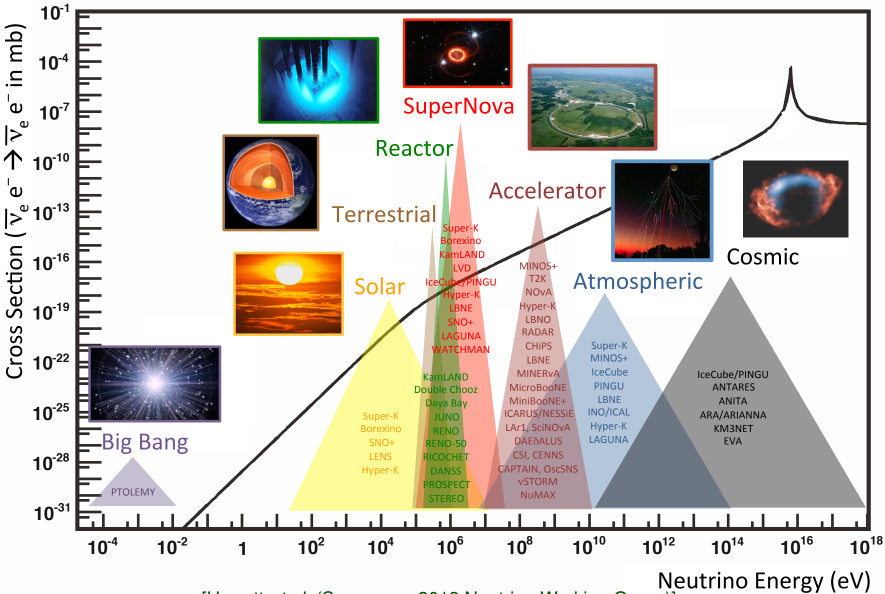
MANITOP

Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

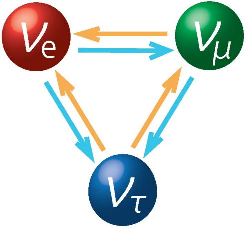
MAX-PLANCK-GESELLSCHAFT

Friends across 20 orders of magnitude



[Hewett *et al.* (Snowmass 2013 Neutrino Working Group)]

Neutrinos have a Mass



Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

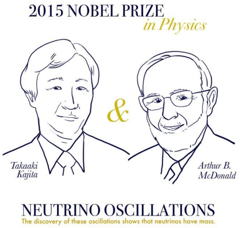
The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that a significant part of the mass of the universe might be in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and

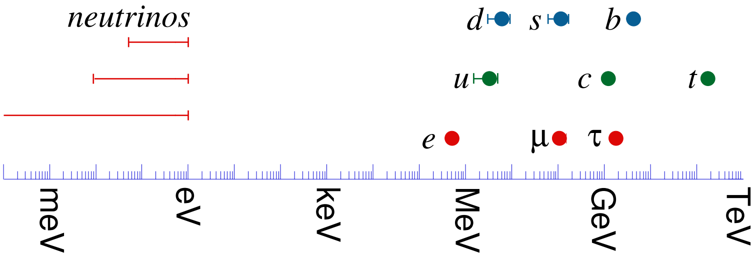
Detecting Neutrinos

And Detecting Their Mass

By analyzing the cones of light,

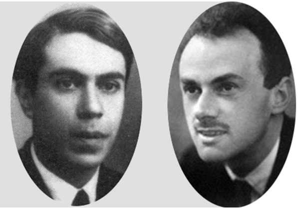


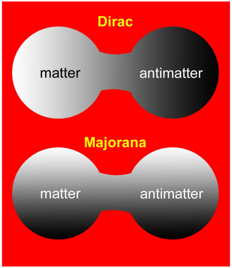
Harbinger of New Physics

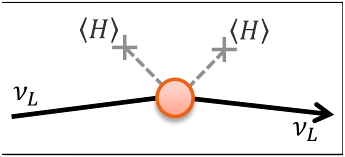


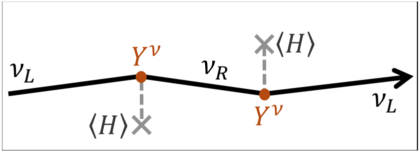
- Neutrinos are massless in the SM, because
  - No RH counterpart (i.e. no Dirac mass term).
  - ν_L part of $SU(2)_L$ doublet $\Rightarrow$ No Majorana mass term $\bar{\nu}_L^C \nu_L$.
  - Accidental global $(B-L)$-symmetry.
- Simply adding RH neutrinos to write a Dirac mass term $\mathcal{L}_{\nu,Y} = Y_N \bar{L} H N + \mathrm{H.c.}$ requires $Y_N \lesssim 10^{-12}$.
- A more *natural* way is to break $(B-L)$.

Majorana or Dirac?



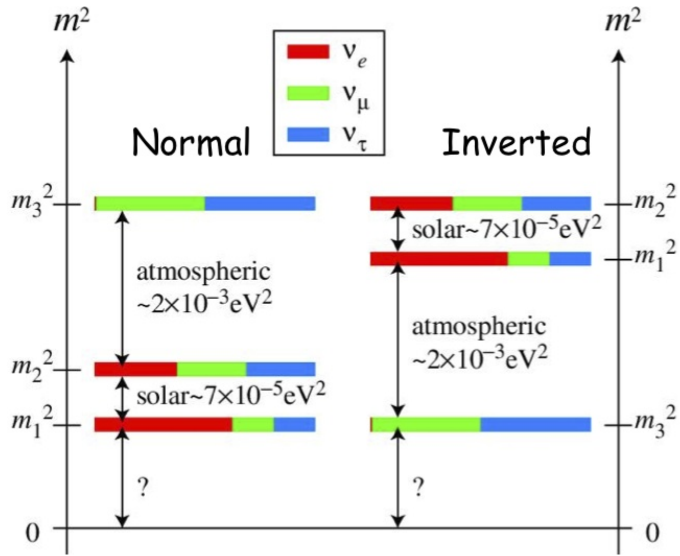






Can be tested in Neutrinoless Double Beta Decay and collider experiments.

Normal or Inverted?



Can be tested in oscillation experiments and precision cosmology.

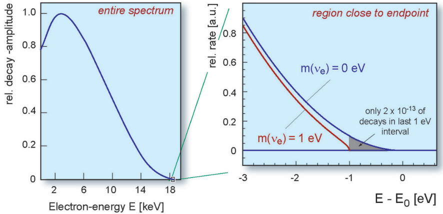
Absolute neutrino mass?

- Energy endpoint in β-decay spectrum:

$$m_\beta = \sqrt{\sum_i U_{ei}^2 m_i^2} \;\leq\; 2.2 \text{ eV}$$

[C. Kraus *et al.*, EPJC '05)]

KATRIN sensitivity: $m_\beta < 0.2$ eV.

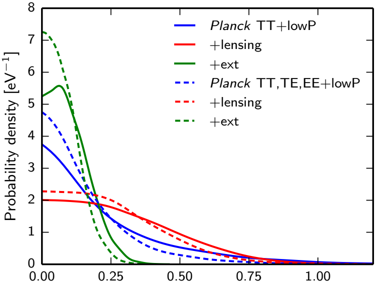


- Impact on large scale structure:

$$\sum_i m_i < 0.17 - 0.72 \text{ eV}$$

[Planck Collaboration '15]

EUCLID sensitivity: $\sum_i m_i < 0.03$ eV.



Other unresolved issues

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}.$$

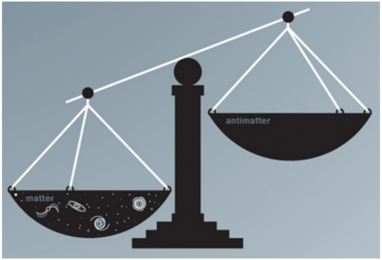
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

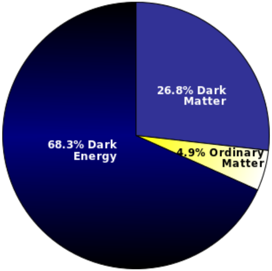
3σ allowed range: [Particle Data Group (2016)]

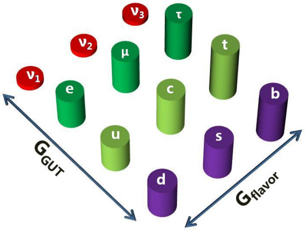
$$\theta_{12} = 31.3^\circ - 35.9^\circ; \quad \theta_{23} = 38.3^\circ - 53.3^\circ; \quad \theta_{13} = 7.9^\circ - 9.1^\circ.$$

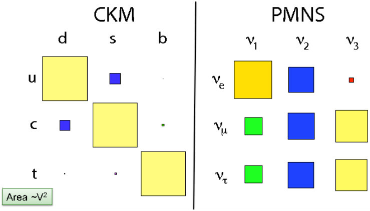
- Value of δ? (Hints for $\delta \simeq -\pi/2$ at T2K and NOvA)
- Octant of θ_{23}? (T2K+NOvA, PINGU, DUNE,....)
- Values of $\alpha_{1,2}$? (Some ambitious proposals)
- Number of *light* neutrino species? (Short-baseline experiments vs cosmological observations)

Connections to other Puzzles?

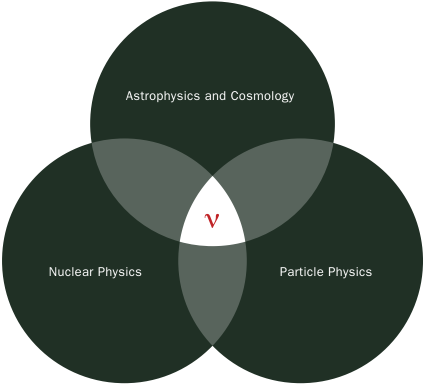


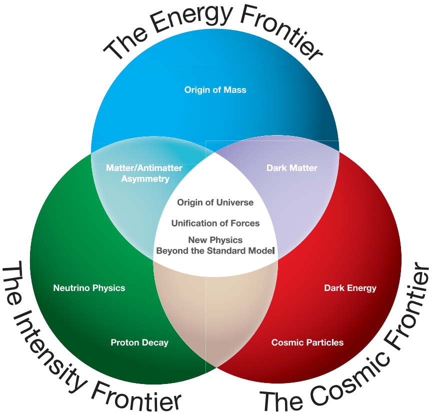






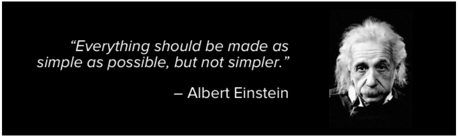
A Synergistic Approach





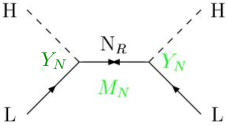
A symbiosis between theory, experiment and observations.

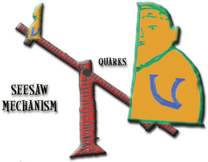
A Simple Paradigm



- $B - L$ violation through the dim-5 operator $\frac{1}{\Lambda}(LLHH)$. [Weinberg (PRL '79)]
- Simplest tree-level realization: Type I Seesaw mechanism.

  [Minkowski (PLB '77); Mohapatra, Senjanović (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79]





$\boxed{\text{Predicts lepton number and (charged) lepton flavor violation.}}$

Low-scale Seesaw

- Upper limit on seesaw scale $M_N \lesssim 10^7$ GeV from naturalness arguments.
  [Vissani (PRD '98); Casas, Espinosa, Hidalgo (JHEP '04); Clarke, Foot, Volkas (PRD '15)]
- In the 'traditional' seesaw,

$$V_{lN} \equiv M_D M_N^{-1} \simeq \sqrt{\frac{M_\nu}{M_N}} \lesssim 10^{-6} \sqrt{\frac{100 \text{ GeV}}{M_N}}$$

- 'Large' mixing effects allowed due to special structures of M_D and M_N.
  [Pilaftsis (ZPC '92); Gluza (APPB '02); Kersten, Smirnov (PRD '07); Gavela, Hambye, Hernandez^2 (JHEP '09); Ibarra, Molinaro, Petcov (JHEP '10); Mitra, Senjanović, Vissani (NPB '12)]
- In the minimal scenario, essentially two ways: (i) symmetry (ii) anarchy.

A Fine-tuned Example

[Pilaftsis (ZPC '92)]

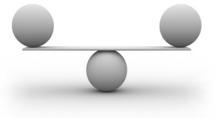
$$M_D = \begin{pmatrix} 0 & 0 \\ a & b \\ c & d \end{pmatrix} \text{ and } M_N = \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}.$$

- Assuming $a \neq 0$, $M_\nu \simeq -M_D M_N^{-1} M_D^\mathsf{T} = 0$ if

$$d = \frac{bc}{a}, \qquad B = -\frac{b^2}{a^2}A.$$

- For $b \neq a$, LNV in the μ and τ sectors can be potentially large.
- Mixing in the electron sector cannot be large due to $0\nu\beta\beta$ constraints.
  [Mitra, Senjanović, Vissani (NPB '12); Lopez-Pavon, Molinaro, Petcov (JHEP '15)]

A Symmetry-protected Example

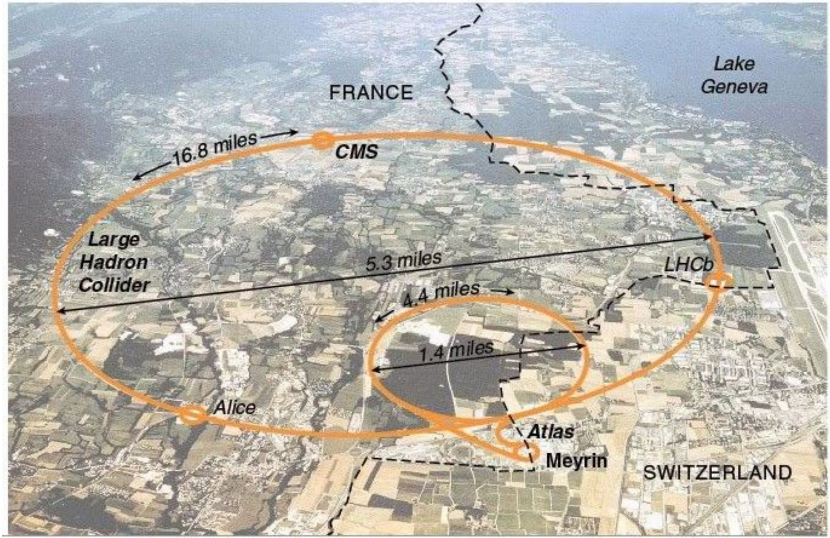


[Kersten, Smirnov (PRD '07)]

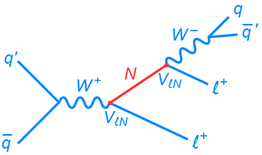
$$M_D = \begin{pmatrix} m_1 & \delta_1 \\ m_2 & \delta_2 \\ m_3 & \delta_3 \end{pmatrix} \quad \text{and} \quad M_N = \begin{pmatrix} 0 & M_1 \\ M_1 & 0 \end{pmatrix} \quad \text{with} \quad \delta_i \ll m_i.$$

- Can be embedded in higher gauge groups. [BD, Lee, Mohapatra (PRD '13)]
- In the minimal seesaw, LNV is suppressed due to quasi-degeneracy of the heavy neutrinos. [Ibarra, Molinaro, Petcov (JHEP '10)]
- Sizable LNV in extended gauge theories. [BD, Mohapatra (Snowmass '13)]

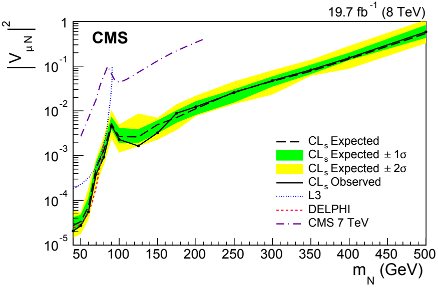
Energy Frontier

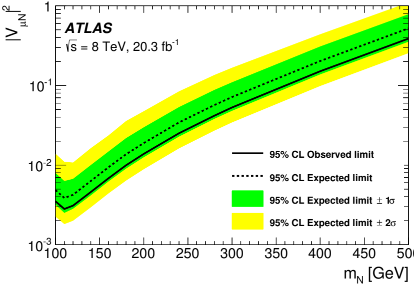


Seesaw Signal at the LHC



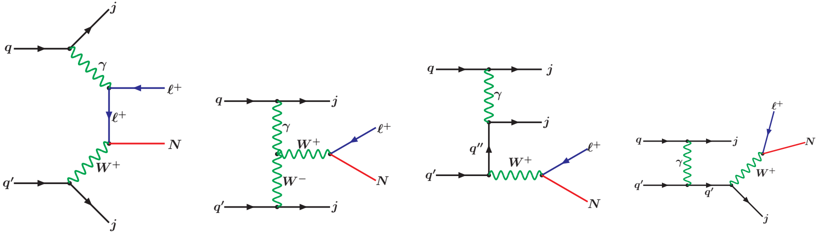
Same-sign dilepton plus jets without missing E_T [Keung, Senjanović (PRL '83); Datta, Guchait, Pilaftsis (PRD '94); Han, Zhang (PRL '06); Bray, Lee, Pilaftsis (NPB '07); del Aguila, Aguilar-Saavedra, Pittau (JHEP '07)]

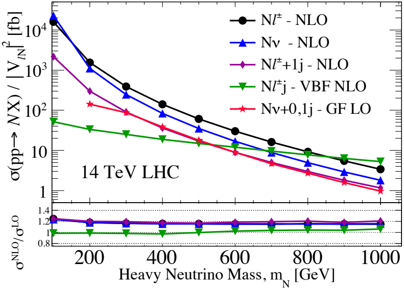


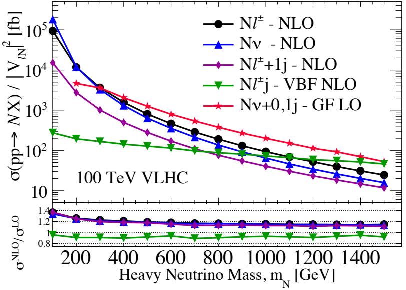


New Dominant Contribution

Collinear-enhancement mechanism [BD, Pilaftsis, Yang (PRL ’14); Alva, Han, Ruiz (JHEP ’15)]







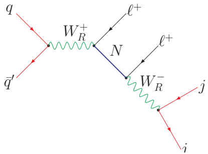
[Degrande, Mattelaer, Ruiz, Turner ’16]

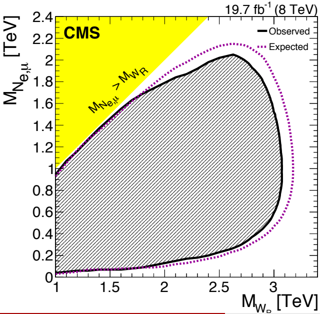
Left-Right Seesaw

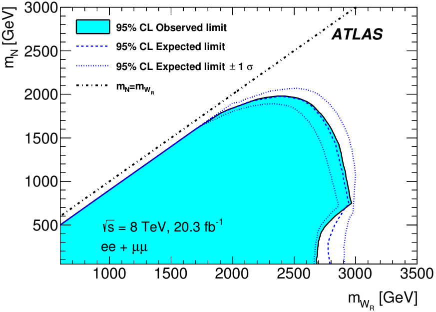
- Provides a natural framework for type-I seesaw (at TeV scale).

  [Pati, Salam (PRD '74); Mohapatra, Pati (PRD '75); Senjanović, Mohapatra (PRD '75)]
- New contribution to Drell-Yan process via W_R exchange.

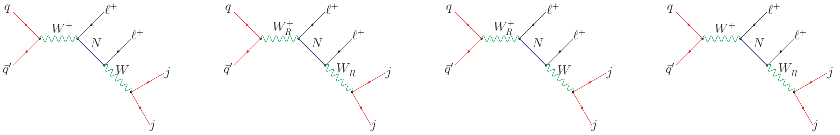
  [Keung, Senjanović (PRL '83)]



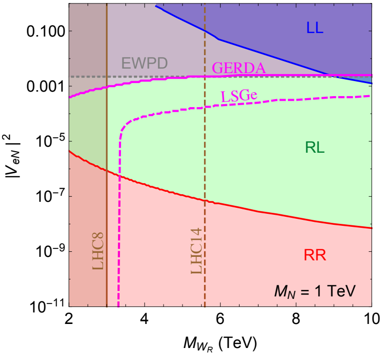




L-R Seesaw Phase Diagram

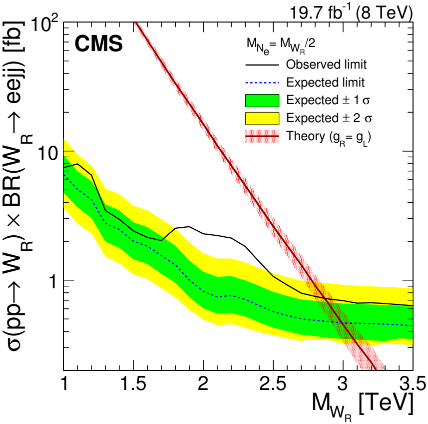


(a) LL (b) RR (c) RL (d) LR



[Chen, BD, Mohapatra (PRD '13); BD, Kim, Mohapatra (JHEP '16)]

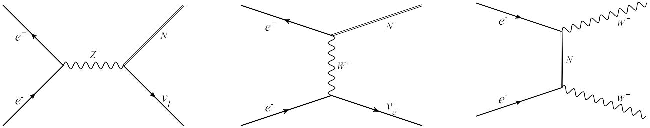
Same-sign vs. Opposite-sign

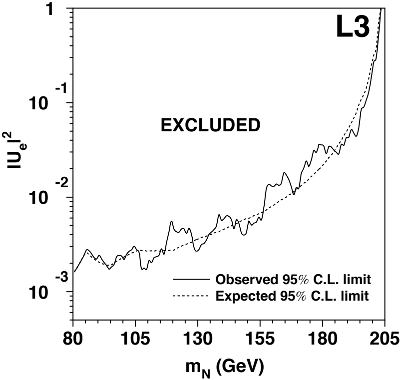


- Possible in the minimal LR model with special CP phases and quasi-degenerate heavy neutrinos. [Gluza, Jeliński (PLB '15); Gluza, Jeliński, Szafron '16]
- Other possibility: Inverse seesaw [BD, Mohapatra (PRL '15); Deppisch *et al* (PRD '16)]

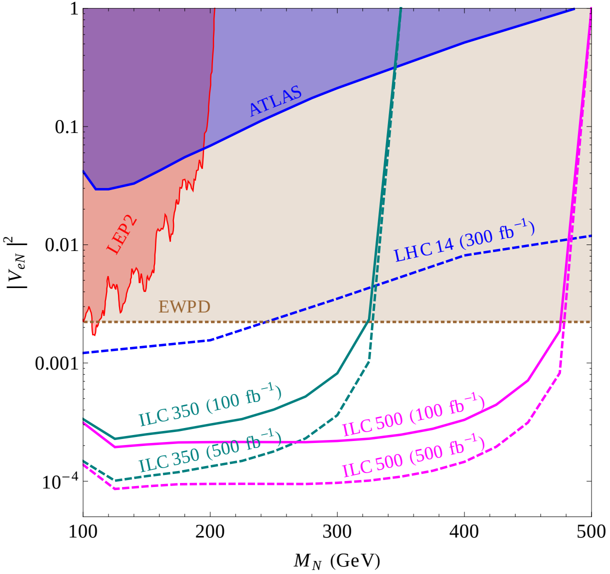
Lepton Collider Searches

[Buchmuller, Greub (NPB ’91); Azuelos, Djouadi (ZPC ’94); Ananthanarayan, Minkowski (PLB ’96); Gluza, Zralek (PLB ’96); Gluza, Maalampi, Raidal, Zralek (PLB ’97); Rodejohann (PRD ’10); Asaka, Tsuyuki (PRD ’15)]



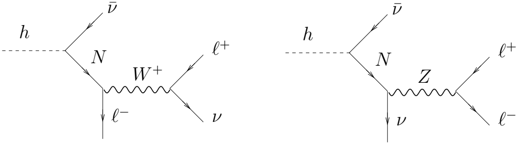


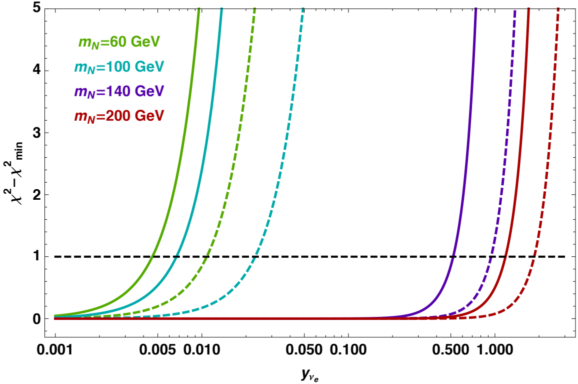
Future Prospects at ILC (or CEPC or FCC-ee)



[Banerjee, BD, Ibarra, Mandal, Mitra (PRD ’15); Antusch, Cazzato, Fischer (JHEP ’16)]

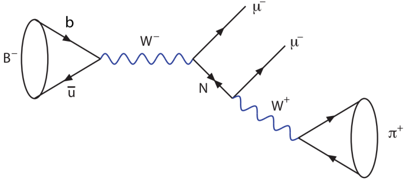
Constraints from LHC Higgs Data

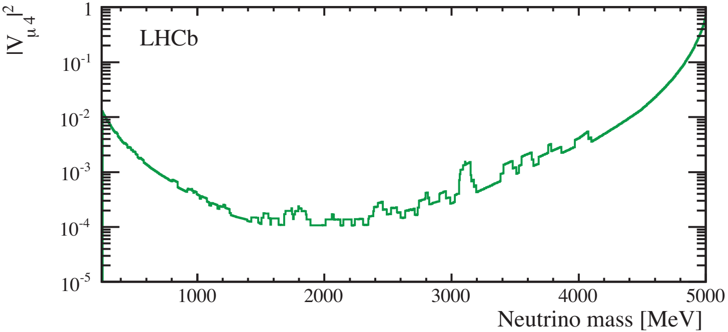




[BD, Franceschini, Mohapatra (PRD '12); Antusch, Fischer (JHEP '15)]

Constraints from LHCb

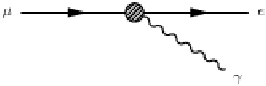


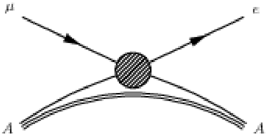


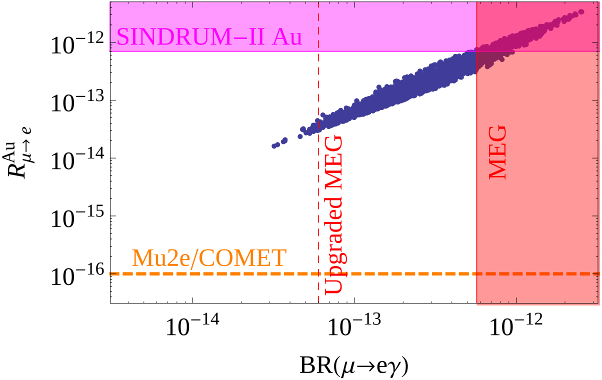
[R. Aaij *et al.* (PRL '14)]

Intensity Frontier

Lepton Flavor Violation

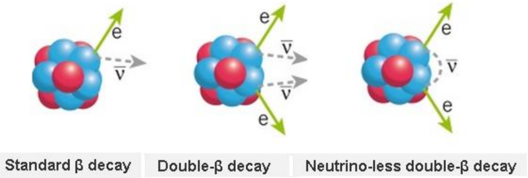


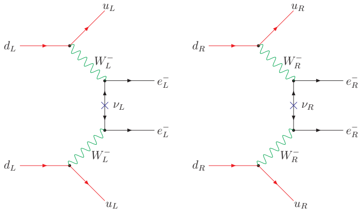


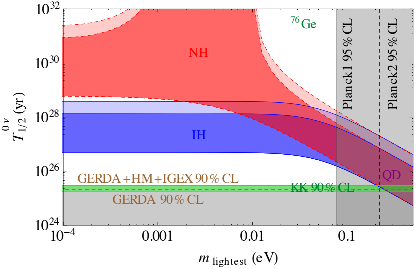


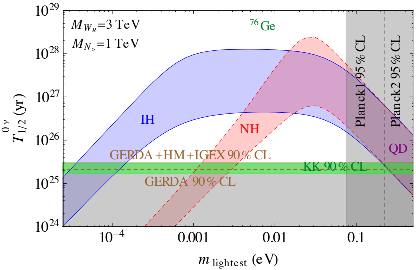
[BD, Lee, Mohapatra (PRD '13)]

Neutrinoless Double Beta Decay



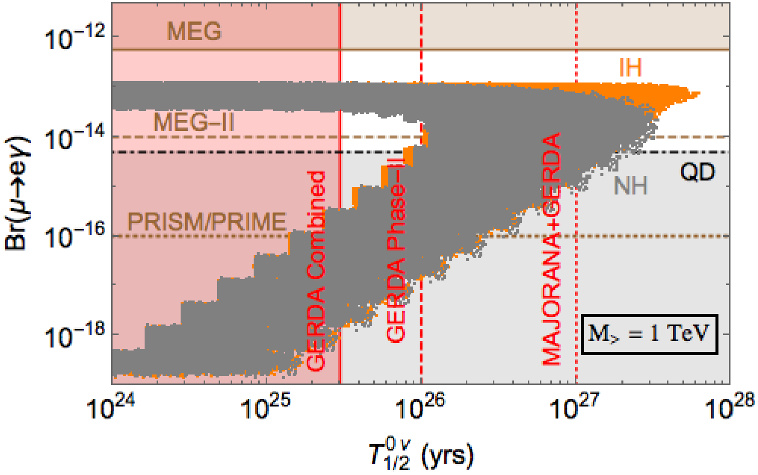




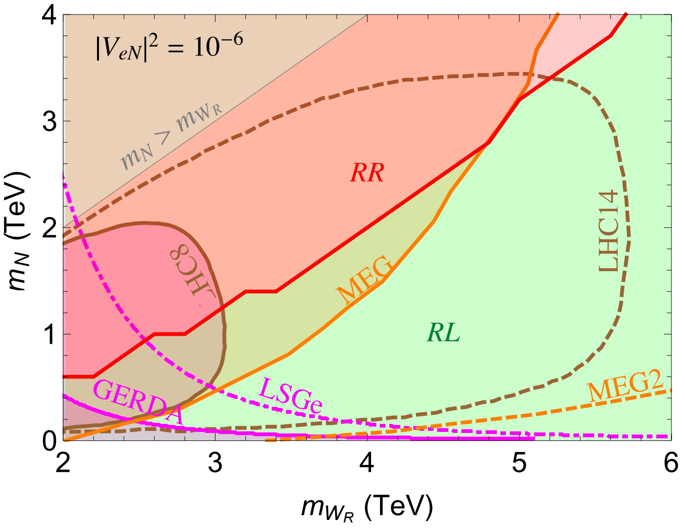


[BD, Goswami, Mitra, Rodejohann (PRD Rapid Commun. ’13)]

Complementarity

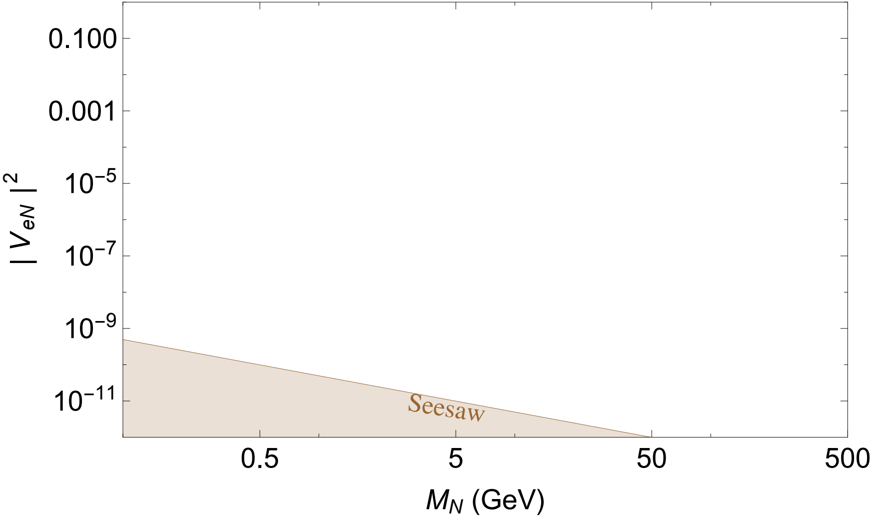


[Awasthi, BD, Mitra (PRD Rapid Commun. '16)]



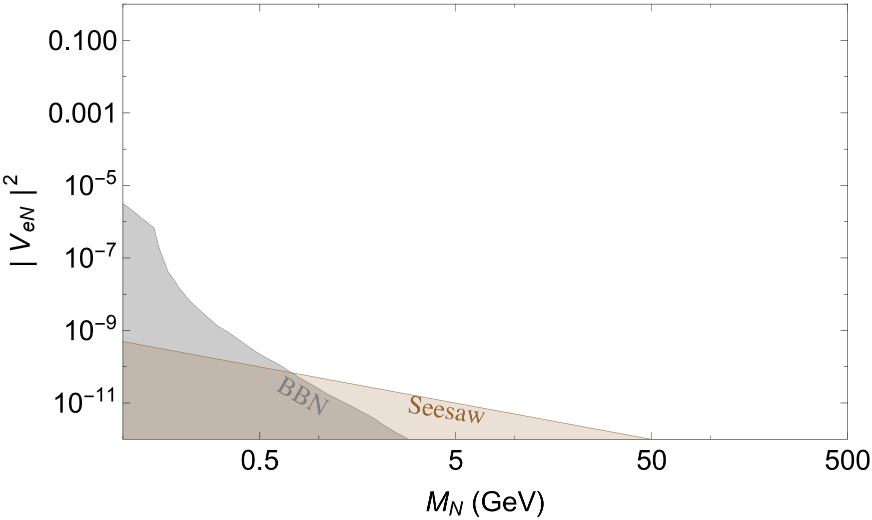
[BD, Kim, Mohapatra (JHEP '16)]

Theoretical Constraint



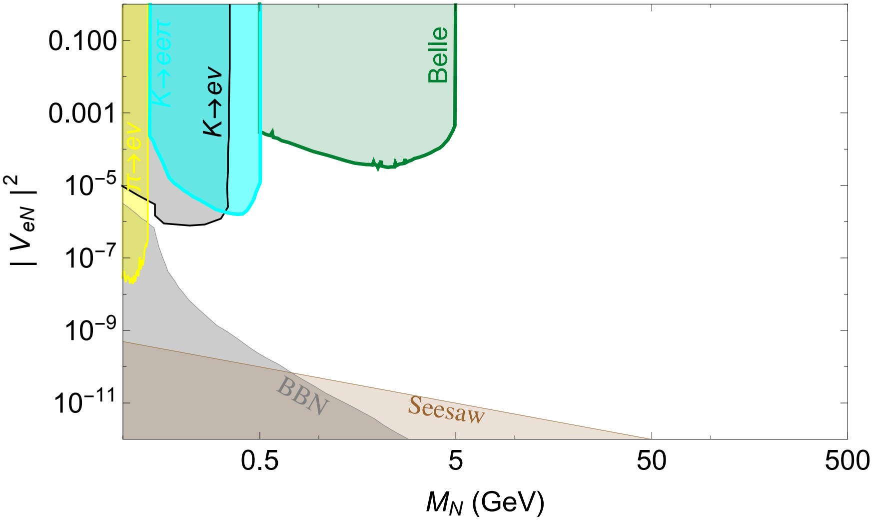
[Deppisch, BD, Pilaftsis (NJP '15)]

BBN Constraint



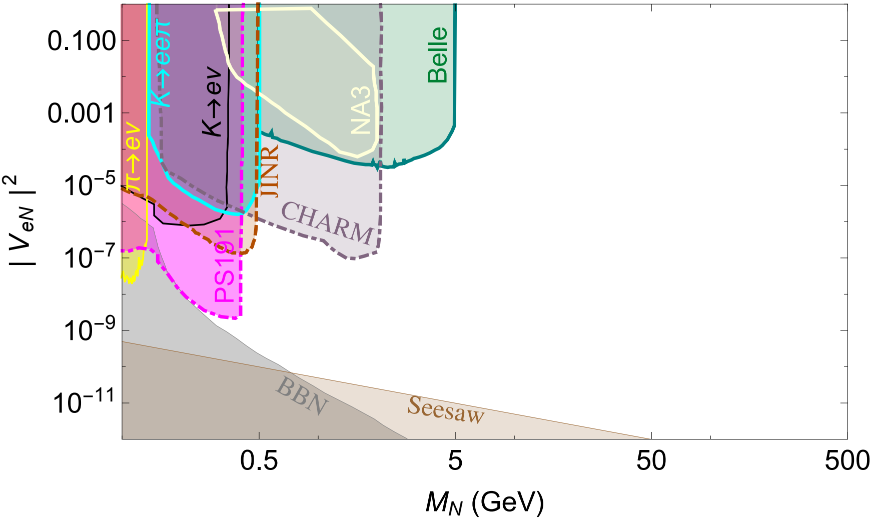
[Deppisch, BD, Pilaftsis (NJP '15)]

Peak Searches in Meson Decay



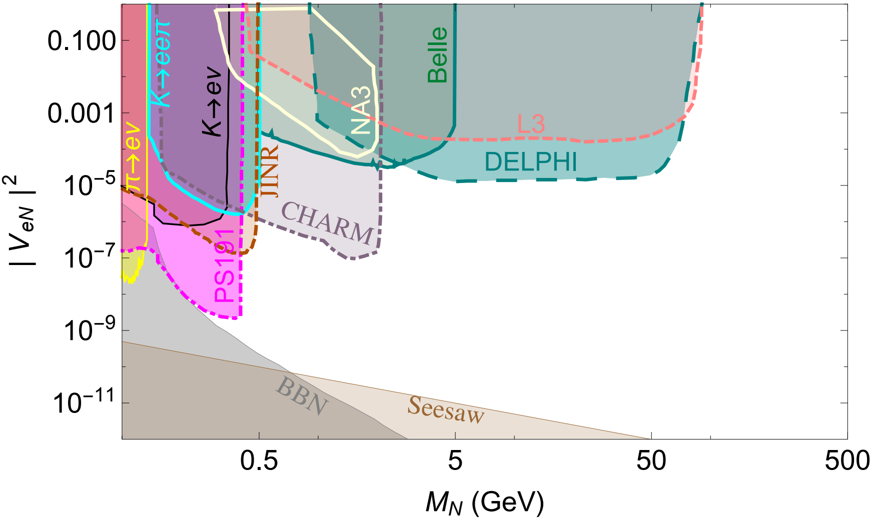
[Deppisch, BD, Pilaftsis (NJP '15)]

Beam Dump Searches



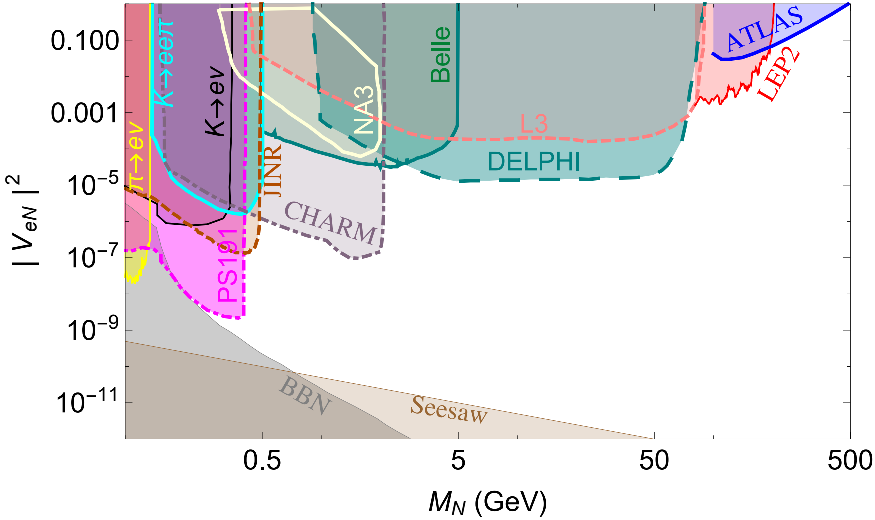
[Deppisch, BD, Pilaftsis (NJP '15)]

Searches in Z-decay



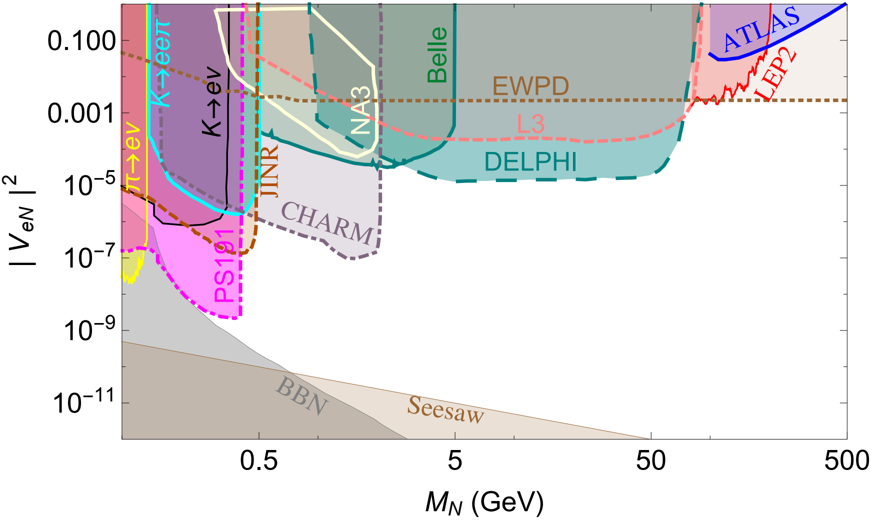
[Deppisch, BD, Pilaftsis (NJP ’15)]

Direct Collider Searches



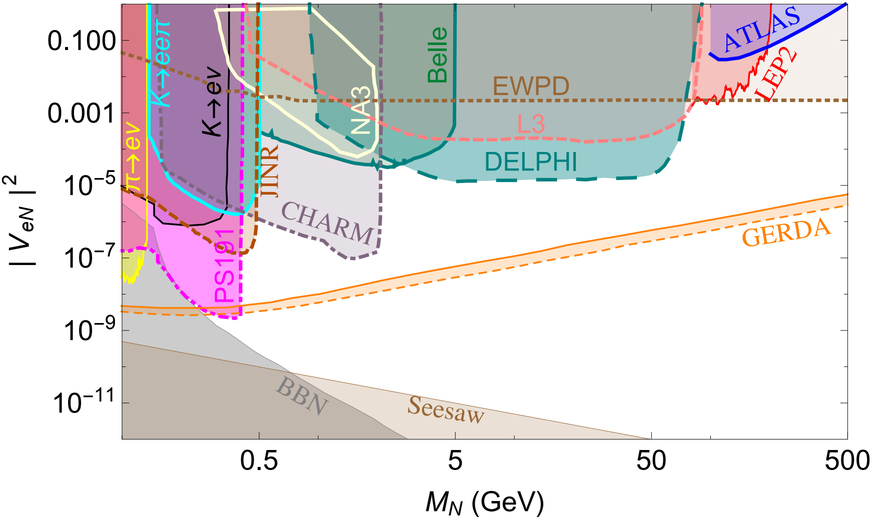
[Deppisch, BD, Pilaftsis (NJP ’15)]

EW Precision Constraint



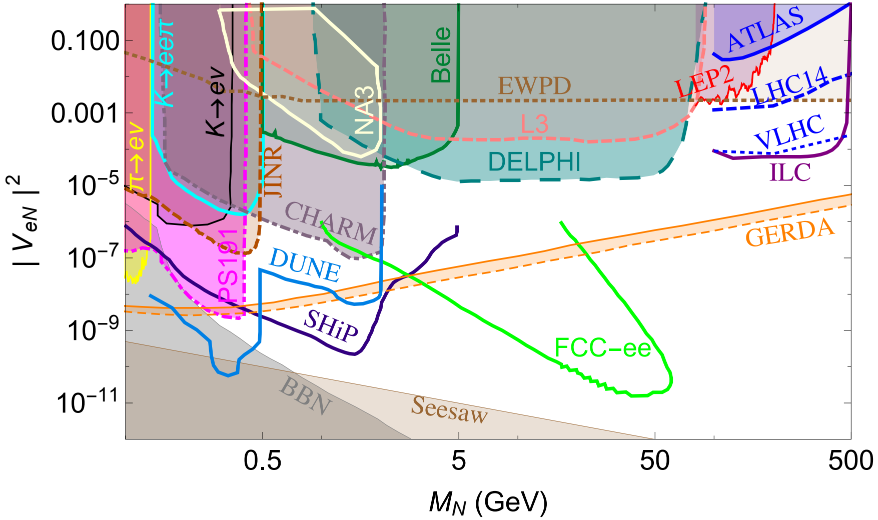
[Deppisch, BD, Pilaftsis (NJP '15)]

$0\nu\beta\beta$ Constraint



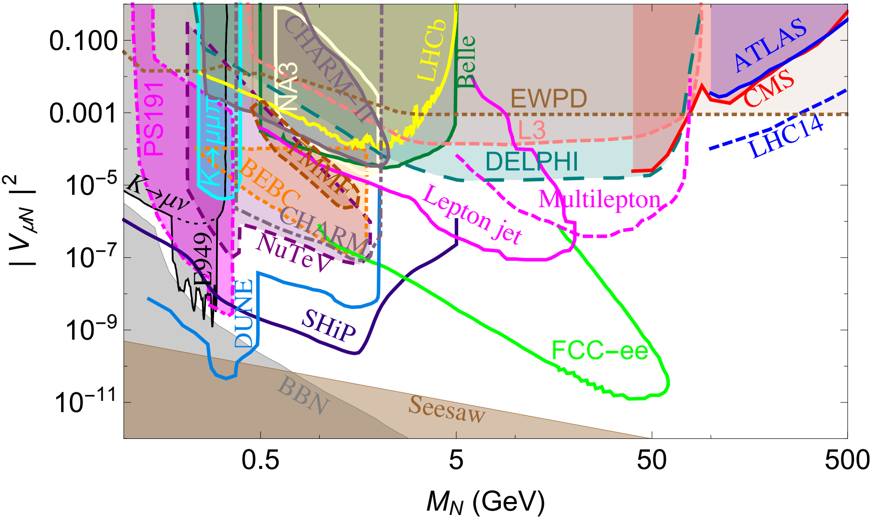
[Deppisch, BD, Pilaftsis (NJP '15)]

Future Prospects



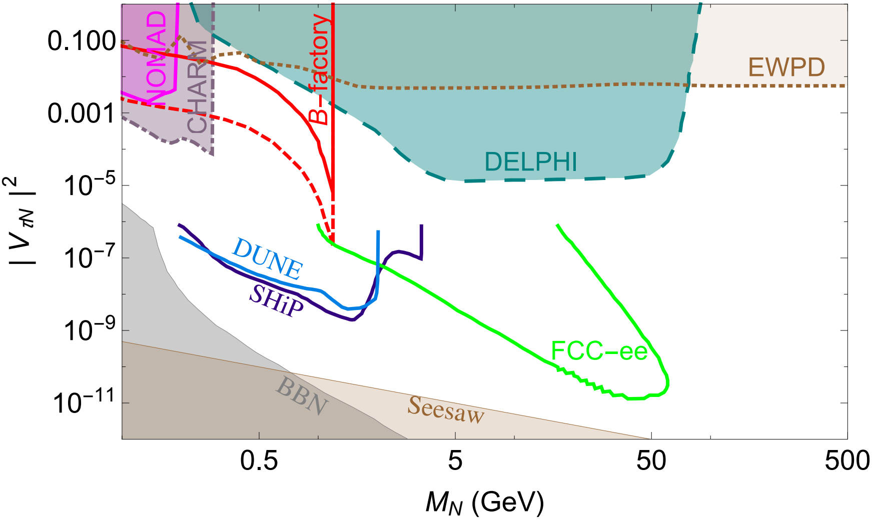
[Deppisch, BD, Pilaftsis (NJP '15)]

Muon Sector



[Deppisch, BD, Pilaftsis (NJP '15)]

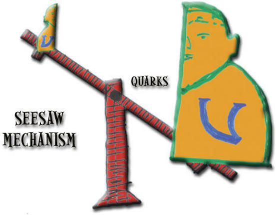
Tau Sector

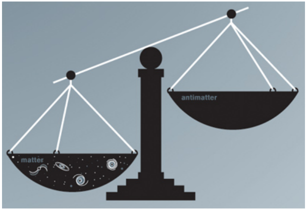


[Deppisch, BD, Pilaftsis (NJP '15)]

Cosmic Frontier

Matter-Antimatter Asymmetry



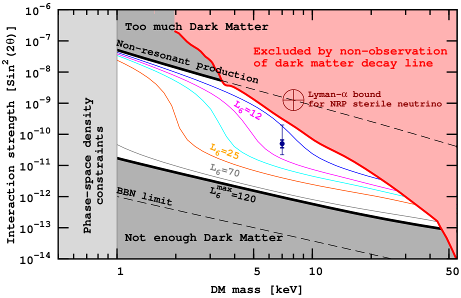


- Baryon Asymmetry via Leptogenesis [Fukugita, Yanagida (PLB '86)].
- Testable predictions for LFV and LNV in low-scale leptogenesis models.
- Can be falsified at the LHC [Frere, Hambye, Vertongen (JHEP '09); BD, Lee, Mohapatra (PRD '14, '16); Deppisch, Harz, Hirsch (PRL '14); Dhuria, Hati, Rangarajan, Sarkar (PRD '15)].

Dark Matter

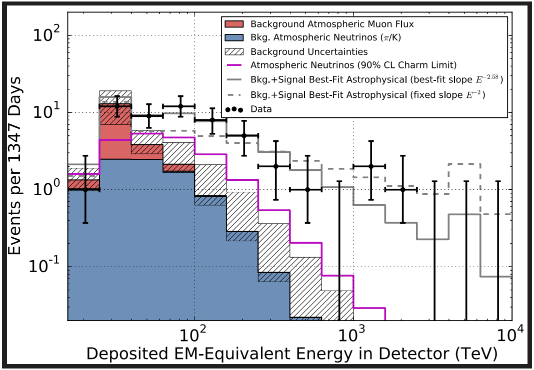
- Neutrino relic density: $\Omega_\nu h^2 = m_\nu/91.5$ eV. [Cowsik, McClelland (PRL '72)]
- A keV-scale sterile neutrino is still a good (warm) DM candidate.

  [Adhikary *et al.* (White paper '16)]



- In SUSY seesaw, lightest (RH) sneutrino is another natural DM candidate.
- Distinct signals in direct detection [An, BD, Cai, Mohapatra (PRL '12)] and collider experiments [Belanger, Kraml, Lessa (JHEP '11); BD, Mondal, Mukhopadhyaya, Roy (JHEP '12)].

Ultra-high Energy Neutrinos



[IceCube Collaboration (PRL '13; Science '14; PRL '15; ICRC '15)]

- Unique opportunity to probe New Physics at highest possible energies.
- E.g., PeV-scale decaying DM, NSI, leptoquarks, (RPV) SUSY.

Conclusion

- Neutrinos play an important role in our understanding of the Universe.
- Neutrino oscillations: first conclusive evidence of BSM physics.
- Understanding the neutrino mass mechanism is a key to the BSM world.

- Rich phenomenology at the energy frontier.
- Healthy complementarity at the intensity and cosmic frontiers.
- Upcoming experiments could be game-changers.