Testing Neutrino Mass Models

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TF11 Mini-Workshop on Neutrino Theory

SnowMass2021

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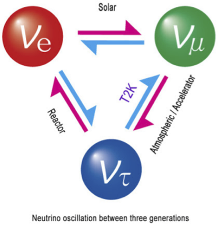
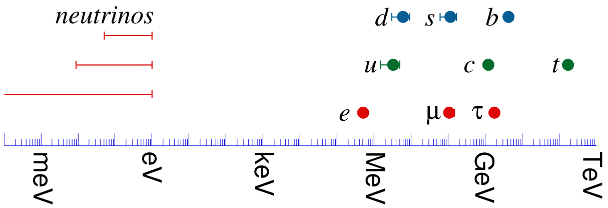
Harbinger of New Physics



[talks by M. C. Gonzalez-Garcia and I. Esteban]

Non-zero neutrino mass $\Longrightarrow$ physics beyond the Standard Model



Perhaps something beyond the standard Higgs mechanism...

Can we probe the origin of neutrino mass in laboratory experiments?

Neutrino Mass Models

[talk by M-C. Chen]

- From pheno point of view, can broadly categorize into
  - Tree-level (seesaw) vs. loop-level (radiative)
  - Minimal (SM gauge group) vs. gauge-extended [e.g. $U(1)_{B-L}$, Left-Right]
  - Non-supersymmetric vs. Supersymmetric

Neutrino Mass Models

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  - Minimal (SM gauge group) vs. gauge-extended [e.g. $U(1)_{B-L}$, Left-Right]
  - Non-supersymmetric vs. Supersymmetric
- New fermions, gauge bosons, and/or scalars – **messengers of neutrino mass**.
- Rich phenomenology. [Drewes (IJMPE'13); Deppisch, BD, Pilaftsis (NJP'15); Cai, Han, Li, Ruiz (Front. Phys.'18)]
- For messenger scale $\lesssim \mathcal{O}(\text{few TeV})$, accessible at either collider or low-energy experiments.
- Connection to other puzzles (e.g. baryogenesis, dark matter, anomalies, NSI).

Outline

- New fermions (right-handed neutrinos)
- New gauge bosons (W', Z')
- New scalars ($SU(2)_L$ singlet, (bi)doublet, triplet, quadruplet)

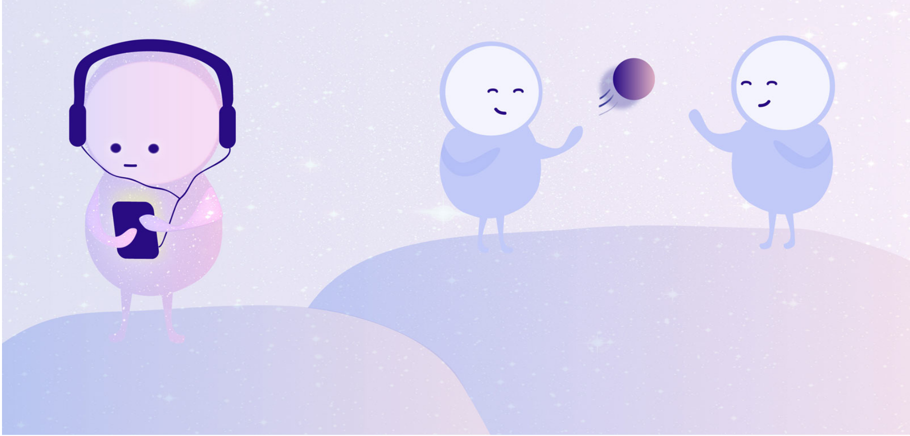
NF/SNOWMASS21-NF8_NF3-TF11_TF8_Julia_Gehrlein-114.pdf

Snowmass Letter of Interest:
Testable neutrino mass models

Asmaa Abada,[1] Kaustubh Agashe,[2] Stefan Antusch,[3] K.S. Babu,[4] Brian Batell,[5] Alain Blondel,[6] Vedran Brdar,[7] Joydeep Chakrabortty,[8] Sabya Sachi Chatterjee,[9] Garv Chauhan,[10] Mu-Chun Chen,[11] James M. Cline,[12] Hooman Davoudiasl,[13] Bhaskar Dutta,[14] André de Gouvêa,[15] Frank F. Deppisch,[16] Valentina De Romeri,[17] P.S. Bhupal Dev,[10] Marco Drewes,[18] Yasaman Farzan,[19] Enrique Fernandez-Martinez,[20,21] Julia Gehrlein*,[13] Janusz Gluza,[22] Dorival Gonçalves,[4] Rebeca Gonzalez Suarez,[23] Srubabati Goswami,[24] Elena Graverini,[25] Tao Han,[5] Julian Heeck,[26] Matheus Hostert,[27,28,29] Alejandro Ibarra,[30] Sudip Jana,[7] Kevin J. Kelly,[31] Manfred Lindner,[7] Jacobo Lopez-Pavon,[17] Michele Lucente,[32] Pedro A. N. Machado,[31] Manimala Mitra,[33] Irina Mocioiu,[34] Rabindra N. Mohapatra,[2] Gopolang Mohlabeng,[13] Viviana Niro,[35] Nobuchika Okada,[36] Rojalin Padhan,[33] Yuber F. Perez-Gonzalez,[37,15,38] Mathias Pierre,[20,21] Apostolos Pilaftsis,[39] Nuria Rius,[40] Werner Rodejohann,[7] Richard Ruiz,[32] Farinaldo S. Queiroz,[41] Michael A. Schmidt,[42] Zahra Tabrizi,[43] Anil Thapa,[4] Jessica Turner,[37] Jose Valle,[17] Raymond R. Volkas,[44] Cédric Weiland,[45] Xun-Jie Xu,[7] and Yongchao Zhang[10]

SM-singlet Fermions

(aka sterile neutrinos/heavy neutrinos/heavy neutral leptons)



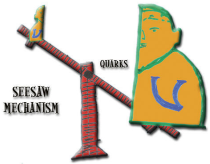
Type-I Seesaw

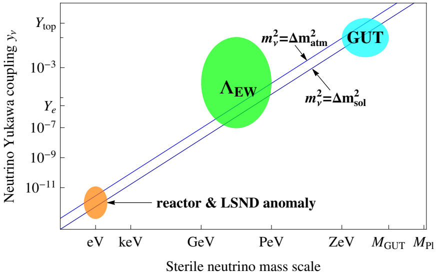
[Minkowski (PLB '77); Mohapatra, Senjanović (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79; Glashow '80]

- SM-singlet **Majorana** fermions (N):

$$-\mathcal{L} \supset Y_\nu \overline{L}\phi^c N + \frac{1}{2} M_N \overline{N}^c N + \mathrm{H.c.}$$

- After EWSB, $m_\nu \simeq -M_D M_N^{-1} M_D^T$, where $M_D = vY_\nu$.

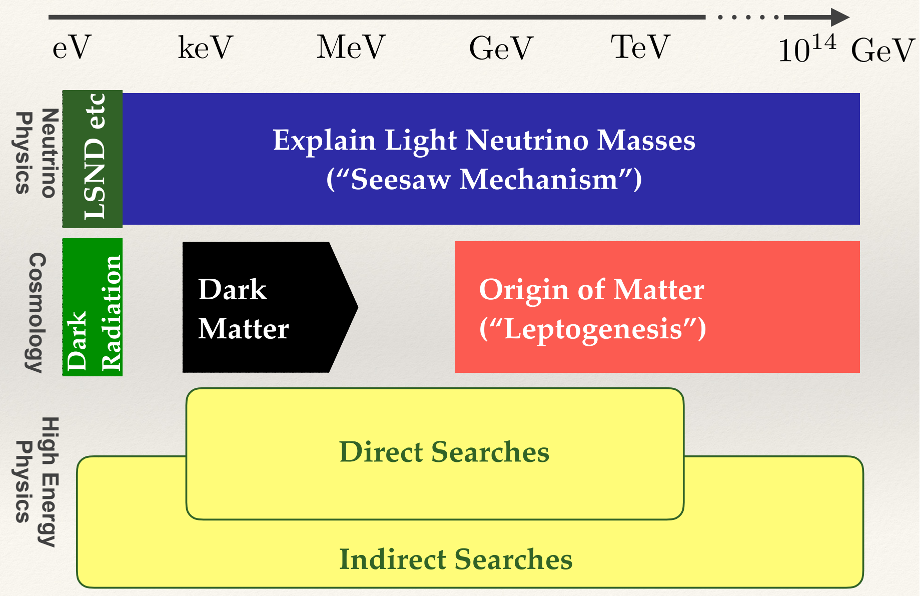




[Figure from Antusch, Cazzato, Fischer, 1612.02728 (IJMPA '17)]

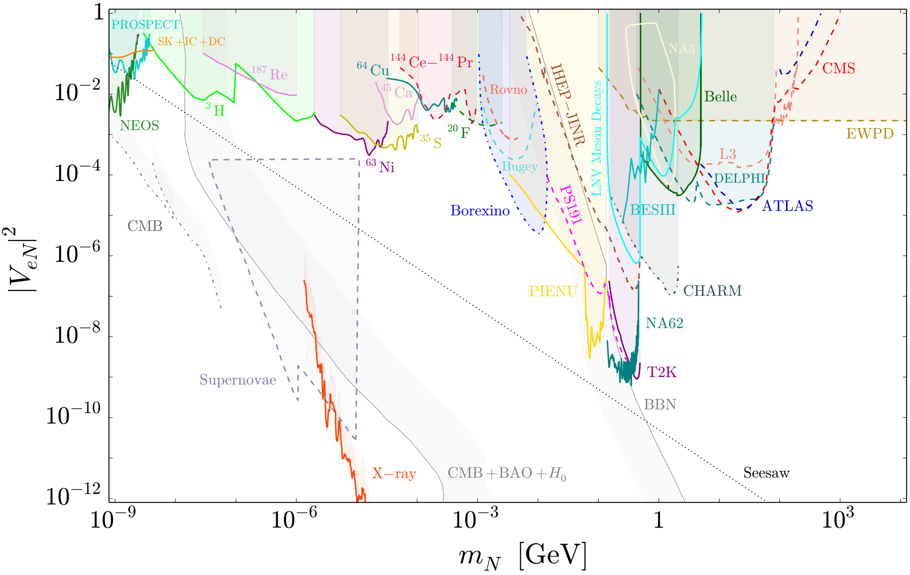
- Each N_i corresponds to $m_{\nu_i} \neq 0$. Need at least two.
- Naturalness of Higgs mass suggests $M_N \lesssim 10^7$ GeV.

  [Vissani (PRD '98); Clarke, Foot, Volkas (PRD '15); Bambhaniya, BD, Goswami, Khan, Rodejohann (PRD '17)]
- Interesting collider signatures for $\mathrm{GeV} \lesssim M_N \lesssim \mathrm{TeV}$. [talk by R. Ruiz]



[Slide from M. Drewes (PHENO '17 plenary talk)]

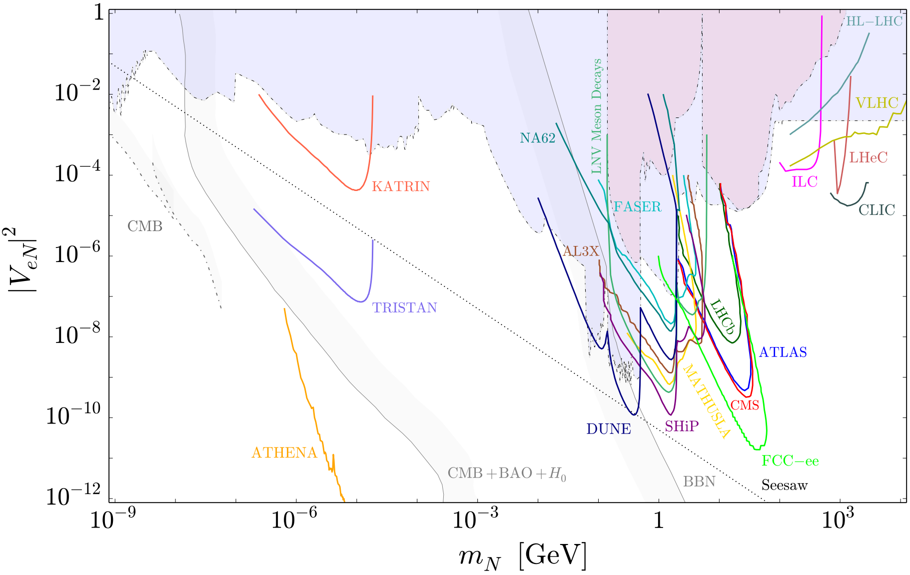
Summary of Current Constraints



[Bolton, Deppisch, BD, 1912.03058 (JHEP '20)]

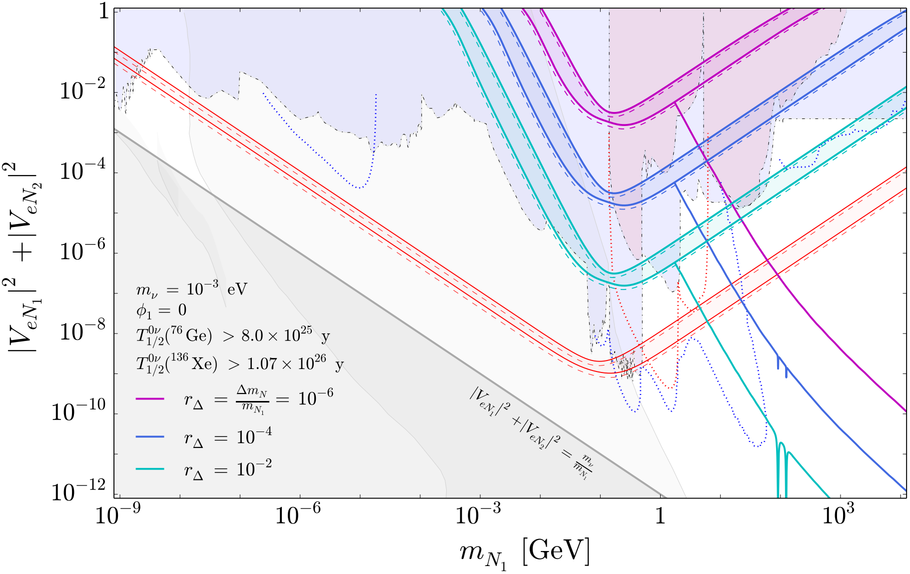
[Atre, Han, Pascoli, Zhang (JHEP '09); Deppisch, BD, Pilaftsis (NJP '15); de Gouvêa, Kobach (PRD '16); Drewes, Garbrecht (NPB '17)]

Future Prospects



[Bolton, Deppisch, BD, 1912.03058 (JHEP '20)]

Comment on $0\nu\beta\beta$ Constraint



[Bolton, Deppisch, BD, 1912.03058 (JHEP '20)]

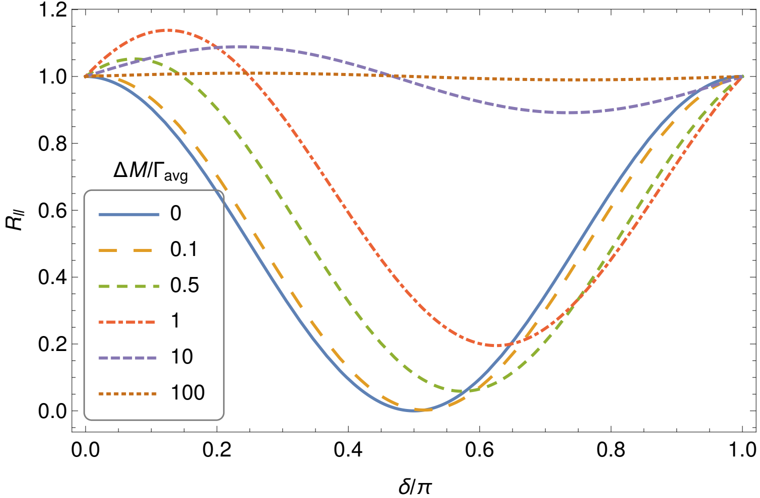
[Hernandez, Jones-Perez, Suarez-Navarro (EPJC '19)]

(Pseudo-)Dirac vs. Majorana

$$\begin{pmatrix} N_e \\ N_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta e^{-i\delta} \\ -\sin\theta e^{i\delta} & \cos\theta \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \end{pmatrix} .$$

Define $$R_{\ell\ell} = \frac{\int_0^\infty dt |A_{\mathrm{SS},\ell\ell}(t)|^2}{\int_0^\infty dt |A_{\mathrm{OS},\ell\ell}(t)|^2} \equiv \frac{N_{\mathrm{SS},\ell\ell}}{N_{\mathrm{OS},\ell\ell}} .$$

[BD, Mohapatra (PRL '15); Anamiati, Hirsch, Nardi (JHEP '16)]



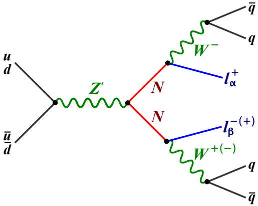
Can be used as a model discriminator [Das, BD, Mohapatra, 1709.06553 (PRD '17)]

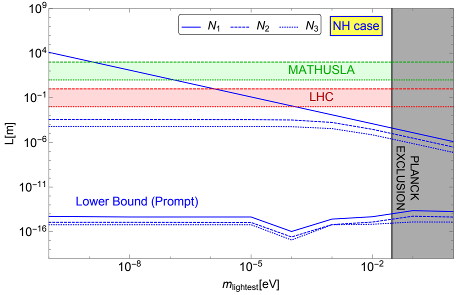
New Gauge Bosons

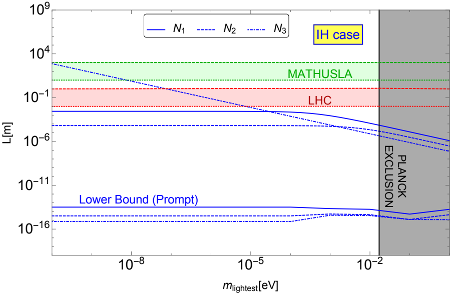
(W', Z')

$U(1)_X$ Extension

[Buchmüller, Greub (NPB ’91); Huitu, Khalil, Okada, Rai (PRL ’08); Basso, Belyaev, Moretti, Shepherd-Themistocleous (PRD ’09); Fileviez Perez, Han, Li (PRD ’09); Deppisch, Desai, Valle (PRD ’14); Kang, Ko, Li (PRD ’15); BD, Mohapatra, Zhang (JHEP ’17); Das, Okada, Raut (EPJC ’18); Cox, Han, Yanagida (JHEP ’18); Fileviez Perez, Plascencia (PRD ’20);...]



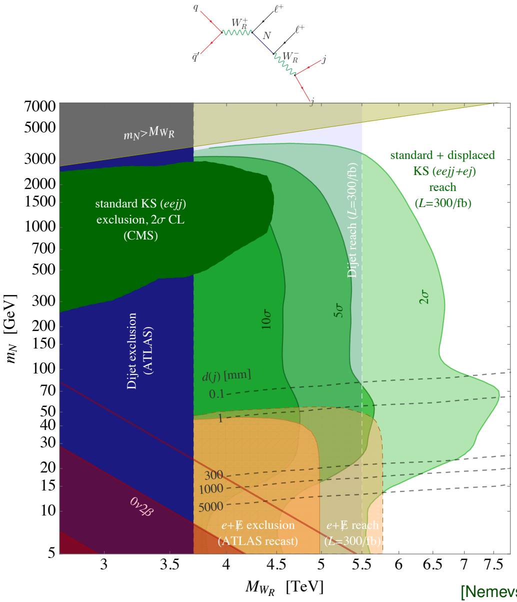




[Das, BD, Okada, 1906.04132 (PLB ’19)]

Left-Right Symmetric Extension

[Keung, Senjanović (PRL ’83); Ferrari *et al* (PRD ’00); Nemevsek, Nesti, Senjanović, Zhang (PRD ’11); Das, Deppisch, Kittel, Valle (PRD ’12); Chen, BD, Mohapatra (PRD ’13); BD, Kim, Mohapatra (JHEP ’16); Mitra, Ruiz, Scott, Spannowsky (PRD ’16);...]

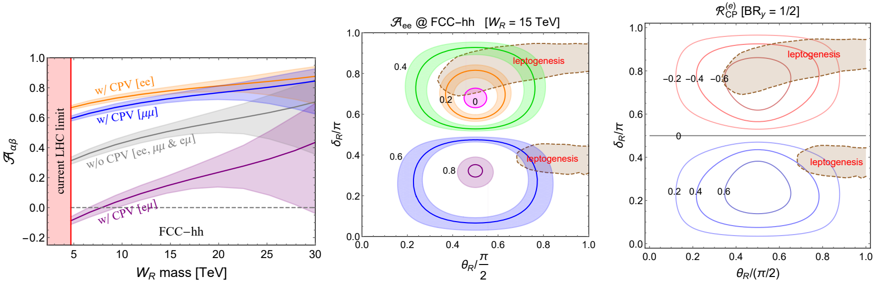


[Nemevsek, Nesti, Popara (PRD ’18)]

CP Violation in the RHN Sector

$$\begin{pmatrix} N_e \\ N_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_R & \sin\theta_R e^{-i\delta_R} \\ -\sin\theta_R e^{i\delta_R} & \cos\theta_R \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \end{pmatrix} .$$

$$\mathcal{A}_{\alpha\beta} \equiv \frac{\mathcal{N}(\ell_\alpha^+\ell_\beta^+) - \mathcal{N}(\ell_\alpha^-\ell_\beta^-)}{\mathcal{N}(\ell_\alpha^+\ell_\beta^+) + \mathcal{N}(\ell_\alpha^-\ell_\beta^-)} ; \quad \mathcal{R}_{\rm CP}^{(\ell)} \equiv \frac{\frac{\sigma(pp\to W_R^+\to\ell^+\ell^+jj)}{\sigma(pp\to W_R^+\to e^+\mu^+jj)} - \frac{\sigma(pp\to W_R^-\to\ell^-\ell^-jj)}{\sigma(pp\to W_R^-\to e^-\mu^-jj)}}{\frac{\sigma(pp\to W_R^+\to\ell^+\ell^+jj)}{\sigma(pp\to W_R^+\to e^+\mu^+jj)} + \frac{\sigma(pp\to W_R^-\to\ell^-\ell^-jj)}{\sigma(pp\to W_R^-\to e^-\mu^-jj)}} .$$



[BD, Mohapatra, Zhang, 1904.04787 (JHEP '19)]

A direct test of TeV-scale thermal leptogenesis at colliders.

New Scalars

L-R Seesaw Higgs Sector

$$\phi(\mathbf{2},\mathbf{2},0) = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}, \quad \delta_R(\mathbf{1},\mathbf{3},2) = \begin{pmatrix} \frac{\delta_R^+}{\sqrt{2}} & \delta_R^{++} \\ \delta_R^0 & -\frac{\delta_R^+}{\sqrt{2}} \end{pmatrix}, \quad \delta_L(\mathbf{3},\mathbf{1},2) = \begin{pmatrix} \frac{\delta_L^+}{\sqrt{2}} & \delta_L^{++} \\ \delta_L^0 & -\frac{\delta_L^+}{\sqrt{2}} \end{pmatrix}$$

- $\langle \delta_R^0 \rangle \equiv v_R$ gives rise to RH Majorana neutrino masses, and hence, type-I seesaw.
- $\langle \delta_L^0 \rangle \equiv v_L$ gives rise to a type-II seesaw contribution.
- 14 physical Higgs bosons (compared to just 1 in the SM) – Rich phenomenology.

  [Gunion, Grifols, Mendez, Kayser, Olness (PRD '89); Akeroyd, Aoki (PRD '05); Fileviez Perez, Han, Huang, Li, Wang (PRD '08); Bambhaniya, Chakrabortty, Gluza, Kordiaczyńska, Szafron (JHEP '14); Dutta, Eusebi, Gao, Ghosh, Kamon (PRD '14); Maiezza, Nemevsek, Nesti (PRL '15); BD, Mohapatra, Zhang (JHEP '16); Mitra, Niyogi, Spannowsky (PRD '17); Babu, Jana (PRD '17); Gehrlein, Goncalves, Machado, Perez-Gonzalez (PRD '18); BD, Ramsey-Musolf, Zhang (PRD '18); BD, Zhang (JHEP '18); Du, Dunbrack, Ramsey-Musolf, Yu (JHEP '19);...]

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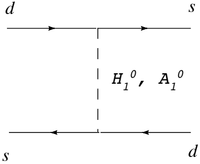
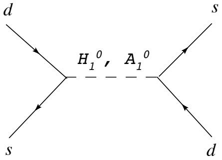
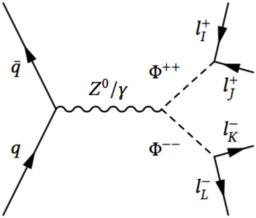
- FCNC constraints require the bidoublet scalars (H_1^0, A_1^0, $H_1^\pm$) to be very heavy $\gtrsim$ 15 TeV. No hope at the LHC. [An, Ji, Mohapatra, Zhang (NPB '08); Bertolini, Maiezza, Nesti (PRD '14; PRD '20)]

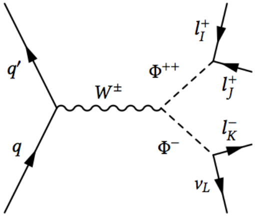




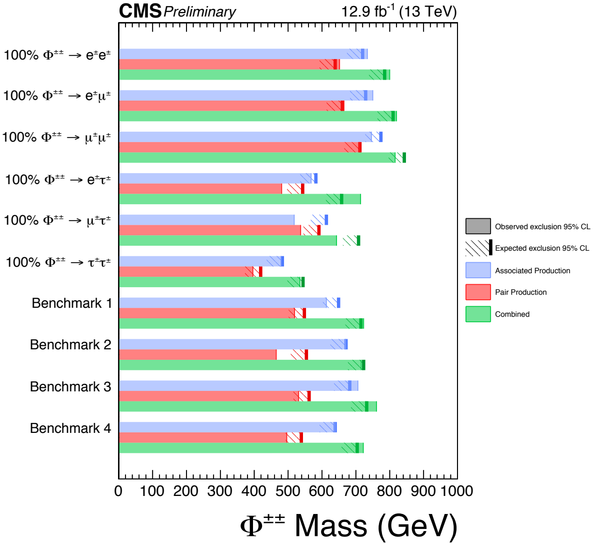
Charged Triplet Sector



(a) 4ℓ



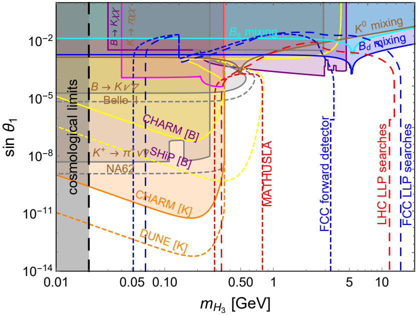
(b) 3ℓ



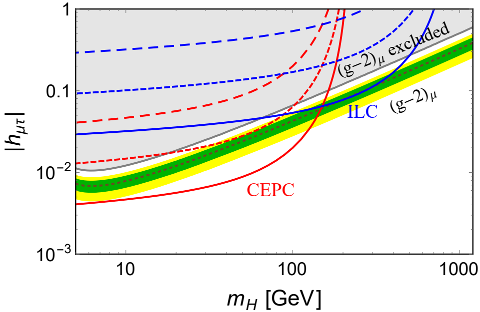
[CMS-PAS-HIG-16-036]

Neutral Triplet Sector

- Hadrophobic and allowed to be light (down to sub-GeV scale) by current constraints.
- Suppressed coupling to SM particles (either loop-level or small mixing).
- Necessarily long-lived at the LHC, with displaced vertex signals.
- Clean LFV signals at future lepton colliders.

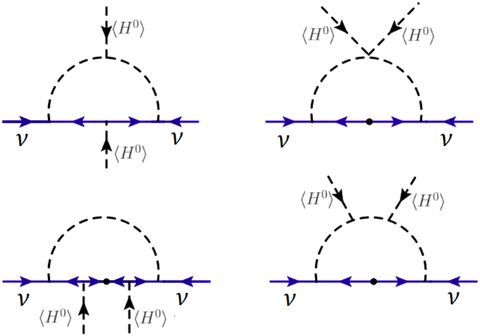


[BD, Mohapatra, Zhang (PRD '17; NPB '17)]



[BD, Mohapatra, Zhang (PRL '18; PRD '18)]

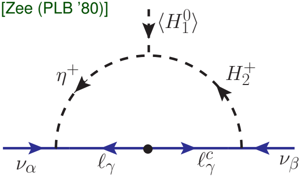
Radiative Models (One-loop)



[Ma (PRL '98); Babu, Leung (NPB '01); de Gouvêa, Jenkins (PRD '08); Bonnet, Hirsch, Ota, Winter (JHEP '12)]

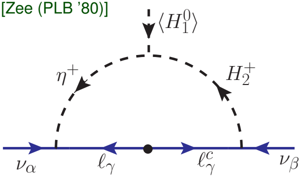
Zee Model

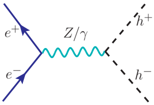
[Zee (PLB '80)]

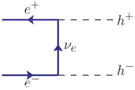


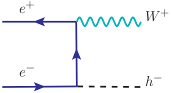
Zee Model

[Zee (PLB '80)]



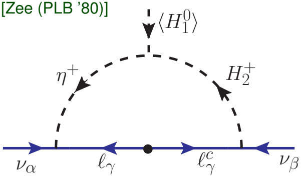


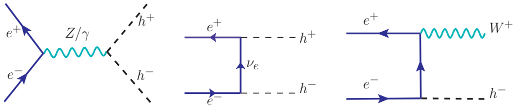


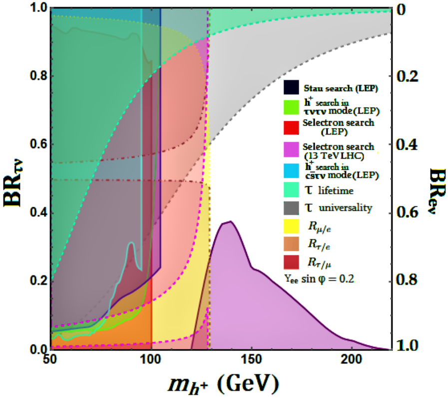


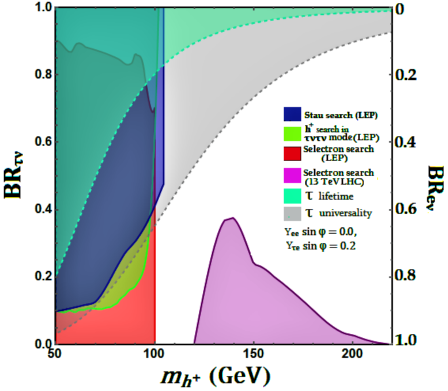
Zee Model

[Zee (PLB '80)]



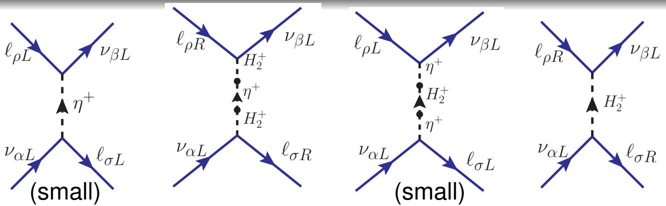




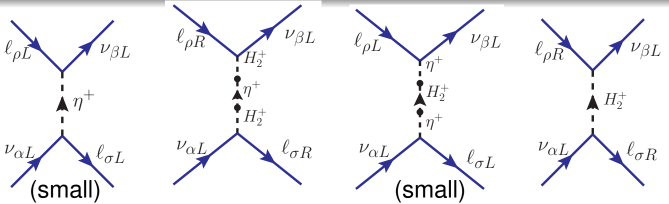


[Babu, BD, Jana, Thapa, 1907.09498 (JHEP '20)]

NSI in Zee Model



$$\boxed{\varepsilon_{\alpha\beta} \equiv \varepsilon_{\alpha\beta}^{(h^+)} + \varepsilon_{\alpha\beta}^{(H^+)} = \frac{1}{4\sqrt{2}G_F} Y_{\alpha e} Y^{\star}_{\beta e} \left(\frac{\sin^2\varphi}{m^2_{h^+}} + \frac{\cos^2\varphi}{m^2_{H^+}} \right) .}$$



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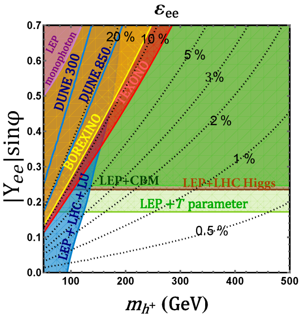
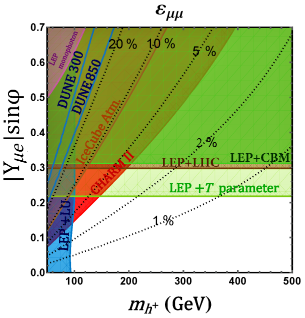
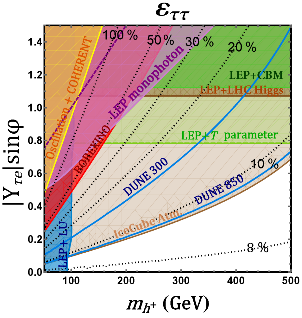
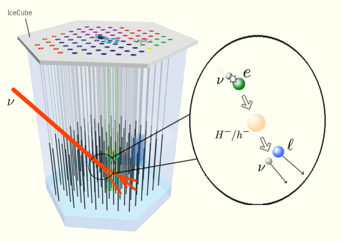


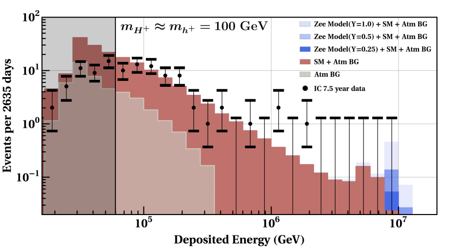




[Babu, BD, Jana, Thapa, 1907.09498 (JHEP '20)]

Zee Burst at IceCube





[Babu, BD, Jana, Sui, 1908.02779 (PRL ’20)]

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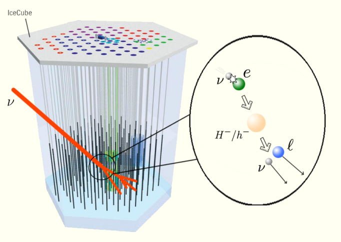

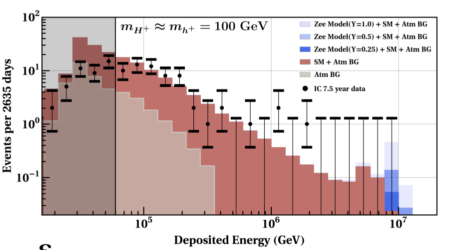

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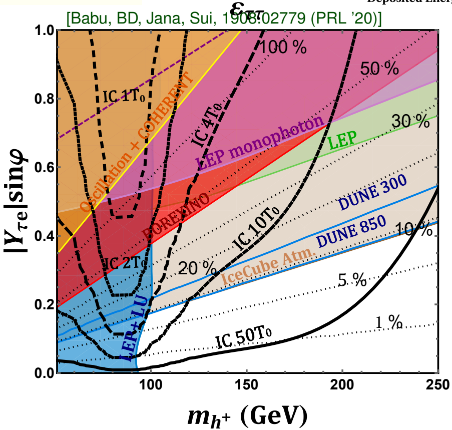

Neutrino Mass Model for B-anomalies and $(g-2)_\mu$

[Babu, BD, Jana, Thapa, 2009.01771]

$$R_2\ (\mathbf{3},\mathbf{2},7/6) = \left(\omega^{5/3}\ \omega^{2/3}\right)^T, \qquad S_3\ (\bar{\mathbf{3}},\mathbf{3},1/3) = \left(\rho^{4/3}\ \rho^{1/3}\ \rho^{-2/3}\right)^T,$$
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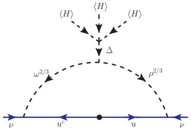

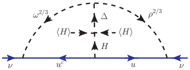

Neutrino Mass

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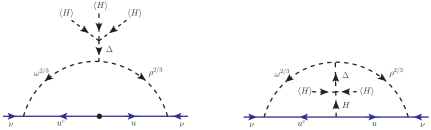

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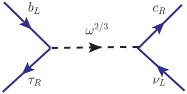
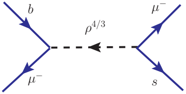


$R_{D^{(*)}}$



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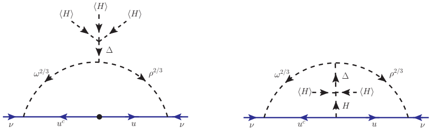

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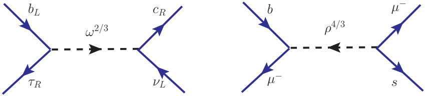

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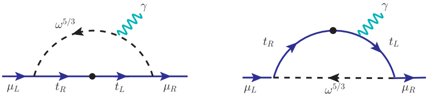

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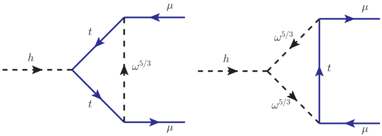
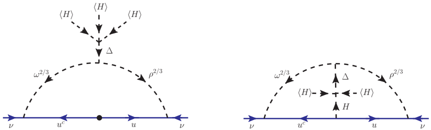
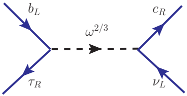


$h \to \mu^+\mu^-$



Neutrino Mass



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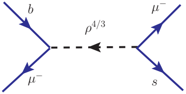
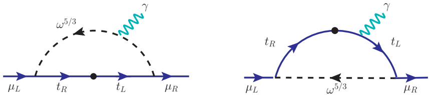


$R_{K^{(*)}}$



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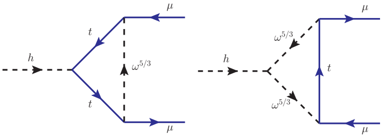

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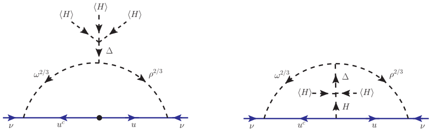

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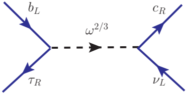

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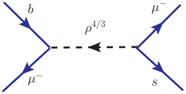

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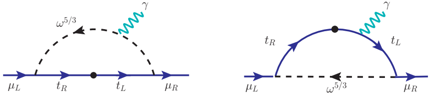

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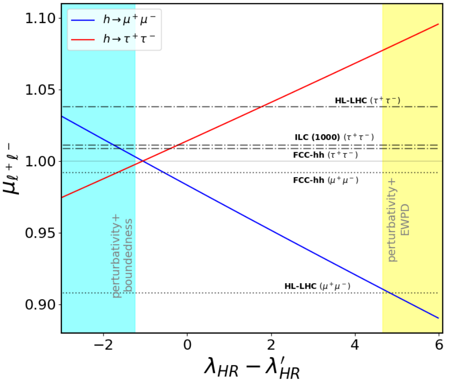

Conclusion

- Understanding the neutrino mass mechanism will provide important insights into the BSM world.
- Current and future colliders provide a ripe testing ground for low-scale neutrino mass models.
- Can probe the messenger particles (new fermions/gauge bosons/scalars) in a wide range of parameter space.
- Healthy complementarity at the intensity frontier.
- Potentially observable non-standard neutrino interactions.
- Could shed light on other outstanding puzzles, such as the matter-antimatter asymmetry and dark matter.

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Thank You!