Neutrino Physics at Future Colliders

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Corfu2024 Workshop on Future Accelerators

May 20, 2024

World's Largest Microscope

Figure from *CERN Courier*

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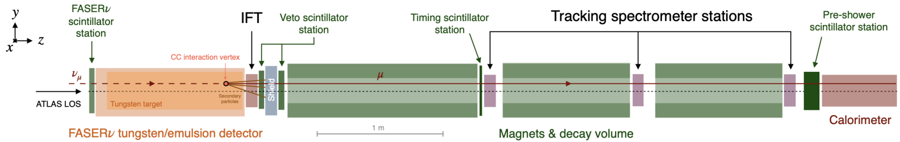
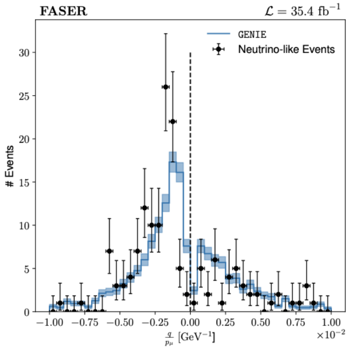
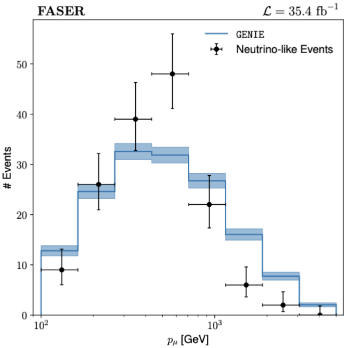
What could it tell about the 'invisible' neutrinos?

First Direct Observation of Collider Neutrinos



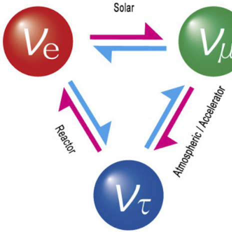




[FASER Collaboration, 2303.14185 (PRL)]

see Sebastian Trojanowski's talk on Wednesday

Neutrinos: Harbinger of New Physics



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

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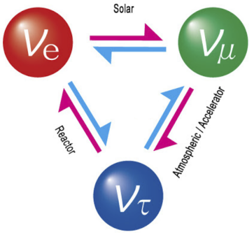

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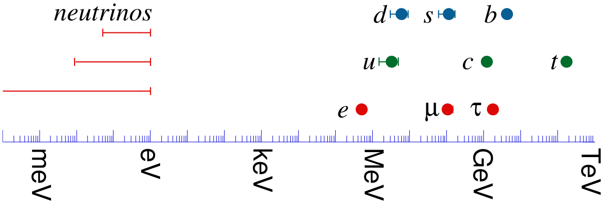

Perhaps something beyond the standard Higgs mechanism...

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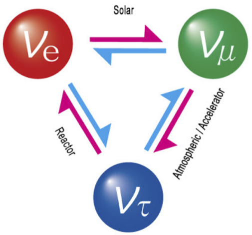

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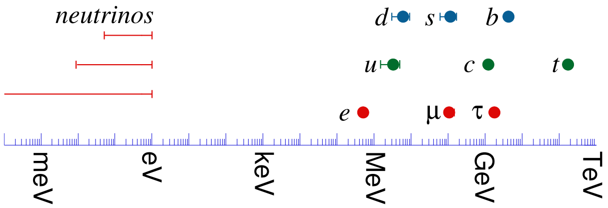

Perhaps something beyond the standard Higgs mechanism...

Can we probe the origin of neutrino mass at colliders?

Neutrino Mass Models

- From pheno point of view, can broadly categorize into
  - Tree-level ($d = 5$) vs. loop-level ($d \geq 7$)
  - Minimal (SM gauge group) vs. gauge-extended [e.g., $U(1)_{B-L}$, Left-Right, $SO(10)$]
  - Non-supersymmetric vs. Supersymmetric

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  - Non-supersymmetric vs. Supersymmetric
- New fermions, gauge bosons, and/or scalars – **messengers of neutrino mass**.
- Rich phenomenology, both at hadron and lepton colliders, for messenger scale $\lesssim \mathcal{O}(\text{few TeV})$. [Deppisch, BD, Pilaftsis, 1502.06541; Cai, Han, Li, Ruiz, 1711.02180]
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- Possible connections to other puzzles (e.g. baryogenesis, dark matter, anomalies, NSI).

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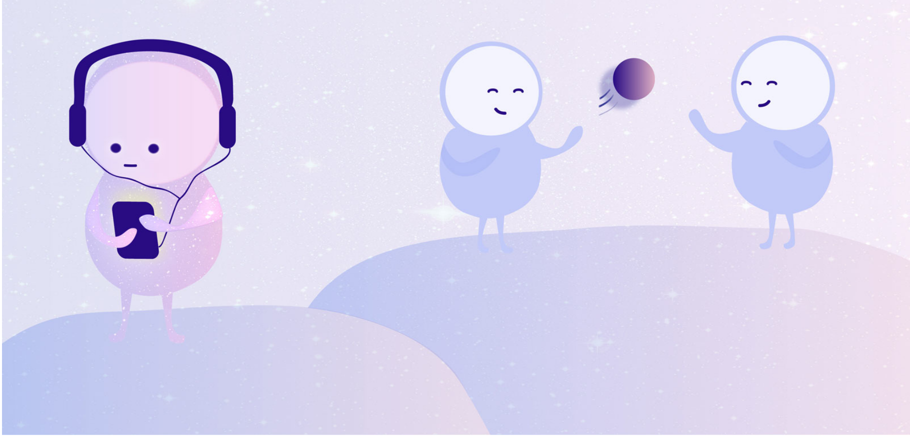
- **This talk: Testing neutrino mass models at colliders.**
- I'll mostly focus on (sub) TeV-scale mediators.
- For light mediators, see Vedran Brdar's talk on Thursday.

SM-singlet Fermions

(aka sterile neutrinos/heavy neutrinos/heavy neutral leptons/right-handed neutrinos)



Snowmass Whitepaper, 2203.08039

Figure from *Symmetry* Magazine

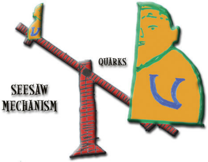
Motivated from Type-I Seesaw

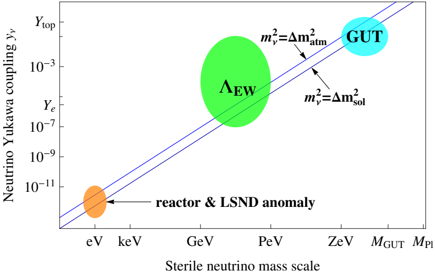
[Minkowski (PLB '77); Mohapatra, Senjanović (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79; Glashow '80]

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

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

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





[Figure from Antusch, Cazzato, Fischer, 1612.02728]

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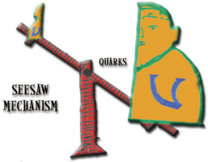
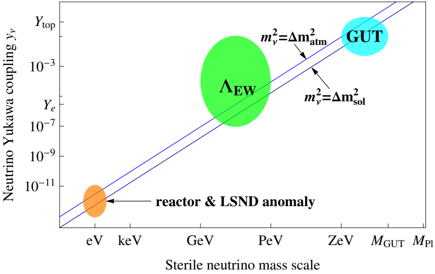




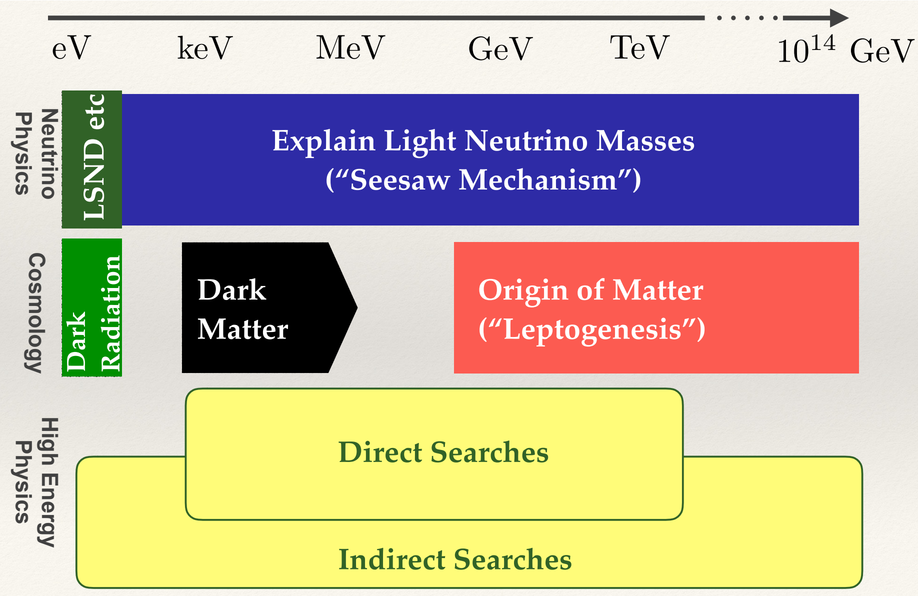
[Figure from Antusch, Cazzato, Fischer, 1612.02728]

- 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)]

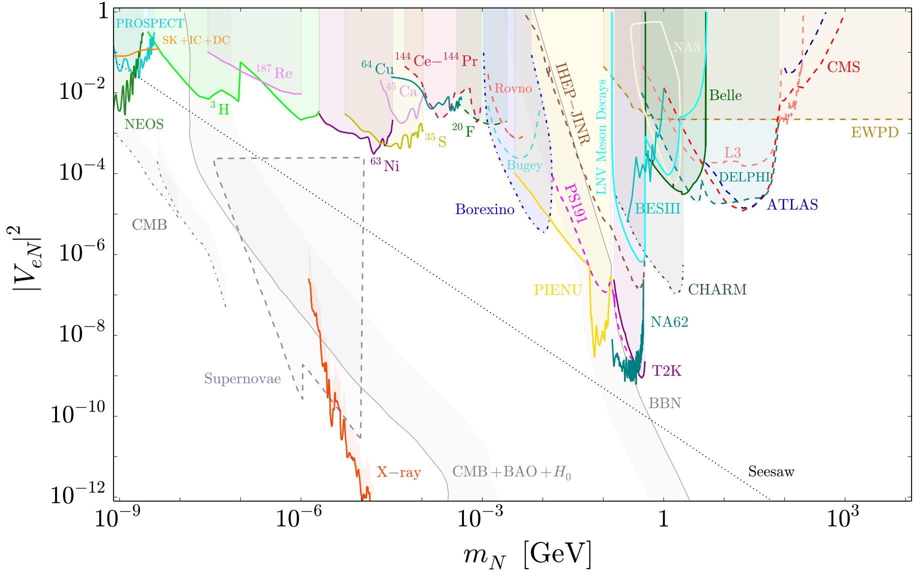
- Interesting collider signatures for GeV $\lesssim M_N \lesssim$ TeV.

Can do many things!



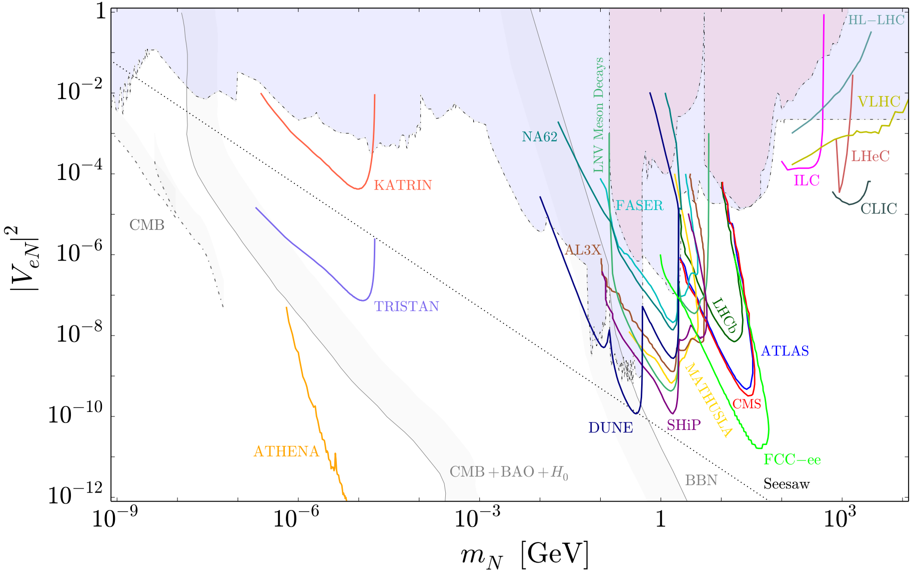
[Slide from Marco Drewes (PHENO '17)]

Summary of Current Constraints



Bolton, Deppisch, BD, 1912.03058 (JHEP '20); see http://sterile-neutrino.org for regular updates

Future Prospects



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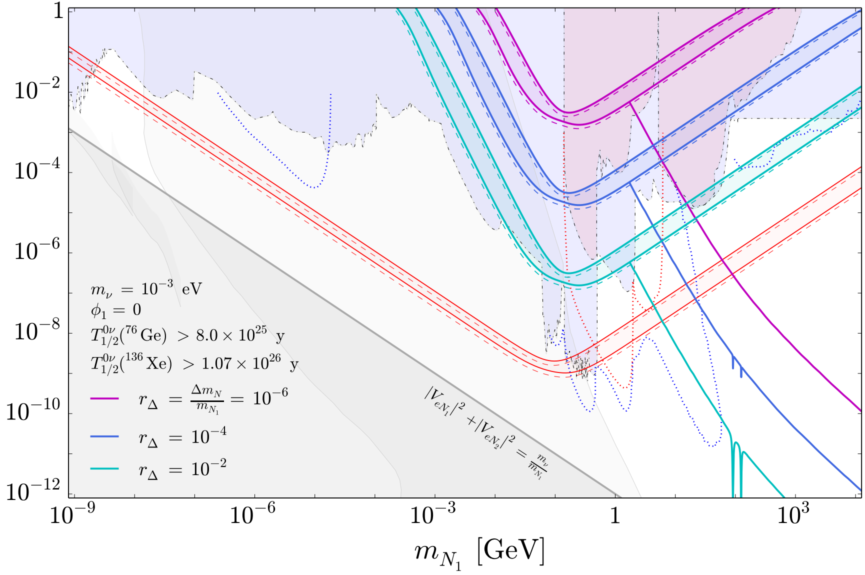
Comment on Neutrinoless Double Beta Decay Constraint

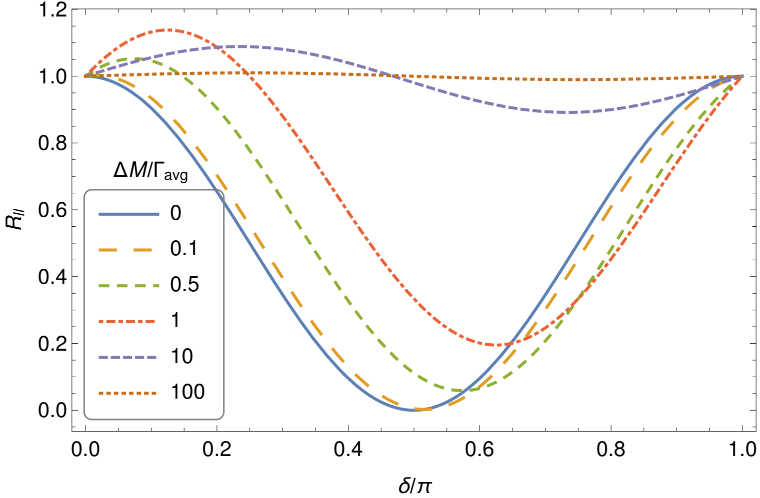


Bolton, Deppisch, BD, 1912.03058 (JHEP '20); see also Hernandez, Jones-Perez, Suarez-Navarro, 1810.07210 (EPJC '19)

(Pseudo-)Dirac vs. Majorana RHN

$$\begin{pmatrix} N_e \\ N_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta e^{-i\delta} \\ -\sin\theta e^{i\delta} & \cos\theta \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \end{pmatrix} . \quad \text{Define } R_{\ell\ell} = \frac{\int_0^\infty dt |A_{\mathrm{SS},\ell\ell}(t)|^2}{\int_0^\infty dt |A_{\mathrm{OS},\ell\ell}(t)|^2} \equiv \frac{N_{\mathrm{SS},\ell\ell}}{N_{\mathrm{OS},\ell\ell}}$$

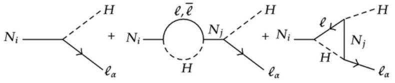
[BD, Mohapatra (PRL '15); Anamiati, Hirsch, Nardi (JHEP '16)]



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

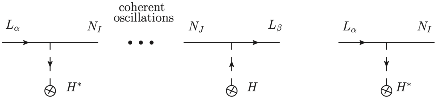
Leptogenesis

Freeze-out

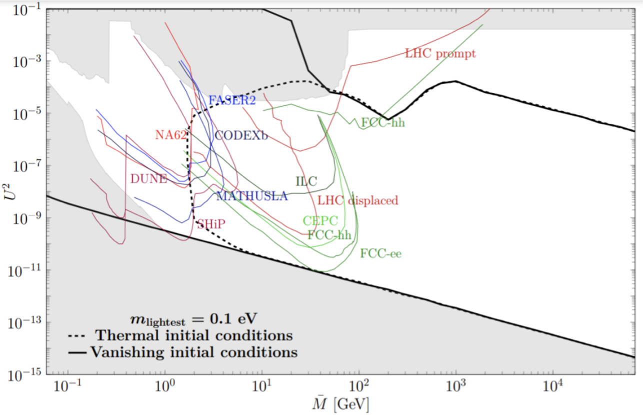


[Fukugita, Yanagida (PLB '86); Pilaftsis, Underwood (NPB '03); BD, Millington, Pilaftsis, Teresi (NPB '14); ...]

Freeze-in



[Akhmedov, Rubakov, Smirnov (PRL '98); Canetti, Drewes, Frossard, Shaposhnikov (PRD '13); Shuve, Yavin (PRD '14); ...]



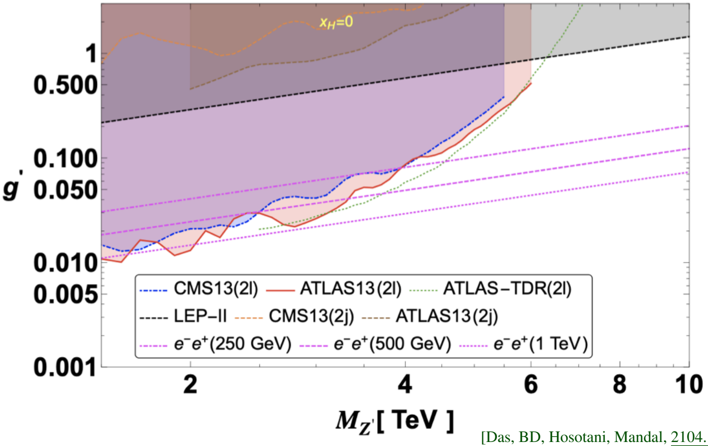
[Klaric, Shaposhnikov, Timiryasov, 2008.13771 (PRL '21); Drewes, Georis, Klaric, 2106.16226 (PRL '22)]

New Gauge Bosons

(W', Z')

$U(1)_X$ at Future Colliders

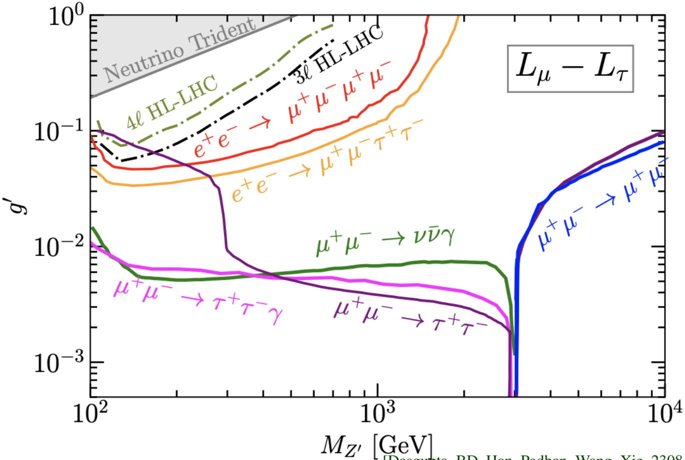
Gauge group	q_L^i	u_R^i	d_R^i	ℓ_L^i	e_R^i	N_R^i	H	Φ
$SU(3)_C$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**1**
$U(1)_Y$	$1/6$	$2/3$	$-1/3$	$-1/2$	-1	0	$1/2$	0
$U(1)_X$	$\frac{1}{6}x_H + \frac{1}{3}x_\Phi$	$\frac{2}{3}x_H + \frac{1}{3}x_\Phi$	$-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$	$-\frac{1}{2}x_H - x_\Phi$	$-x_H - x_\Phi$	$-x_\Phi$	$-\frac{x_H}{2}$	$2x_\Phi$



[Das, BD, Hosotani, Mandal, 2104.10902 (PRD '22)]

$U(1)_{L_\alpha - L_\beta}$ at Future Colliders

Gauge group	L_e	L_μ	L_τ	e_R	μ_R	τ_R	H	Φ
$SU(3)_c$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**2**	**2**	**1**	**1**	**1**	**2**	**1**
$U(1)_Y$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1	$\frac{1}{2}$	0
$U(1)_{L_\mu - L_\tau}$	0	1	-1	0	1	-1	0	2



[Dasgupta, BD, Han, Padhan, Wang, Xie, 2308.12804 (JHEP '23)]

Left-Right Symmetric Extension: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

- Parity restoration at high scale. [Mohapatra, Pati (PRD '75); Senjanovic, Mohapatra (PRD '75)]
- A natural UV-completion of seesaw. [Mohapatra, Senjanovic (PRD '81)]
- New contributions to collider signals. [Keung, Senjanovic (PRL '83); Chen, BD, Mohapatra (PRD '13);...]

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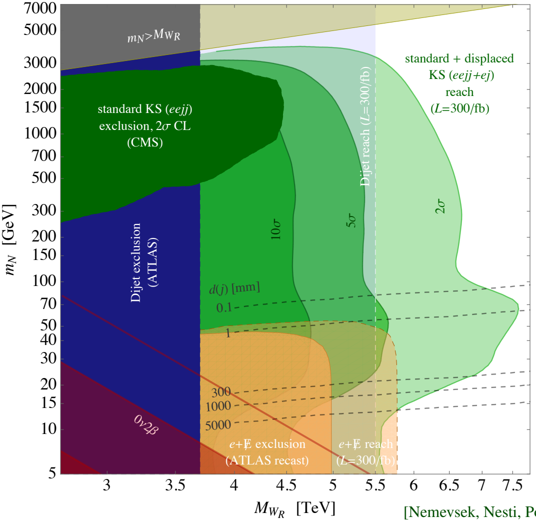
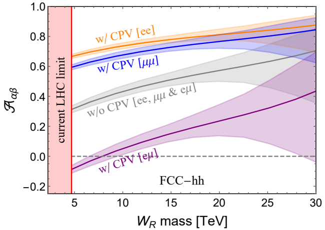


[Nemevsek, Nesti, Popara, 1801.05813 (PRD '18)]

CP Violation in the RHN Sector

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

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



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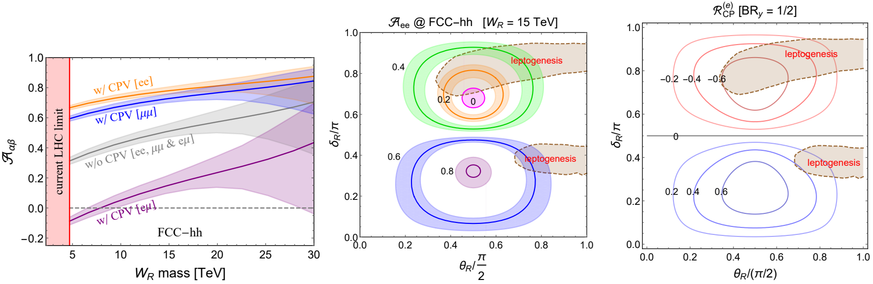

[BD, Mohapatra, Zhang, 1904.04787 (JHEP '19)]

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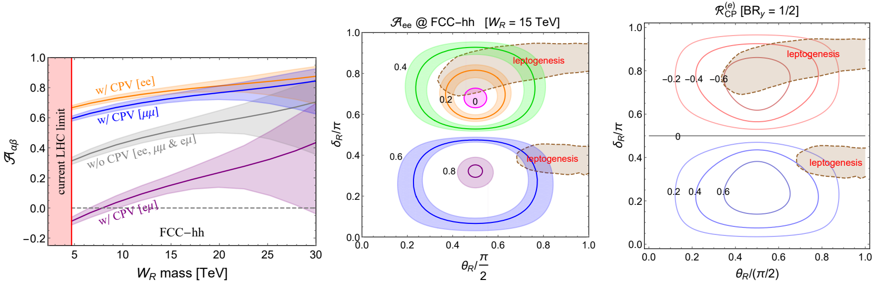

[BD, Mohapatra, Zhang, 1904.04787 (JHEP '19)]

- Lower bound on $M_{W_R} \gtrsim 15$ TeV from leptogenesis.
- Direct collider test of TeV-scale thermal leptogenesis.

[Frere, Hambye, Vertongen (JHEP '09); BD, Lee, Mohapatra (J. Phys '15)]

New Scalars

Minimal Left-Right Higgs Sector

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

- $\langle \delta_R^0 \rangle \equiv v_R$ gives rise to RH Majorana neutrino masses $\Longrightarrow$ type-I seesaw.
- 8 physical Higgs bosons: Rich phenomenology.

  [Gunion, Grifols, Mendez, Kayser, Olness (PRD '89); Bambhaniya, Chakrabortty, Gluza, Kordiaczyńska, Szafron (JHEP '14); BD, Mohapatra, Zhang (JHEP '16); Du, Dunbrack, Ramsey-Musolf, Yu (JHEP '19);...]

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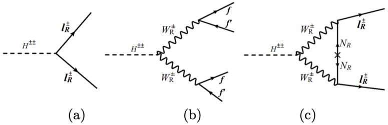
- But FCNC constraints require the bidoublet scalars (H_1^0, A_1^0, $H_1^\pm$) to be very heavy $\gtrsim 15$ TeV. [An, Ji, Mohapatra, Zhang (NPB '08); Bertolini, Maiezza, Nesti (PRD '14; PRD '20)] **Need FCC-hh**.
- Doubly-charged component ($H^{\pm\pm}$) constrained to be $\gtrsim$ 900 (700) GeV from prompt (displaced) multilepton searches. [ATLAS, 2211.07505]
- Neutral component (H_3^0) is hadrophobic and can be much lighter!
- Can even be a dark matter candidate (but highly fine-tuned). [Nemevsek, Senjanovic, Zhang, 1205.0844]

Doubly-charged Scalar



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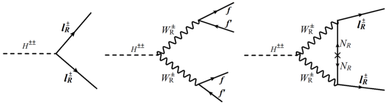
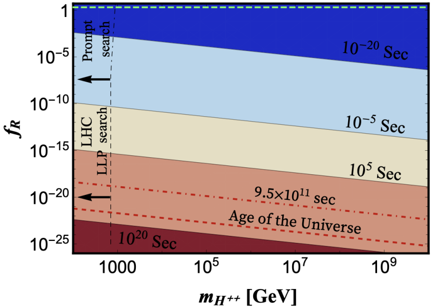


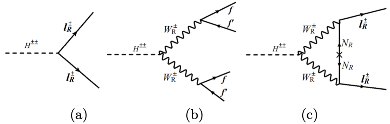
(a) (b) (c)

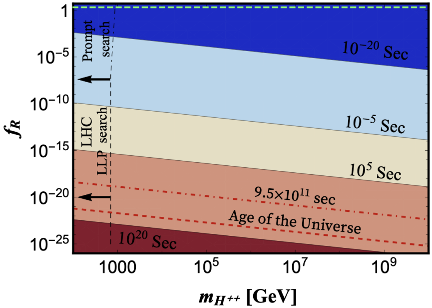


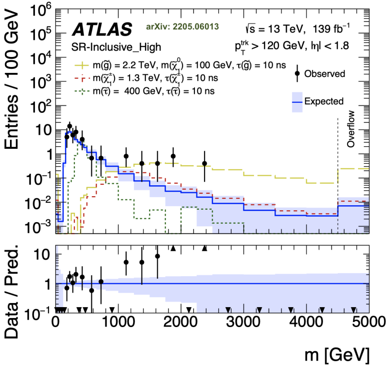
- Implications for HSCP searches at LHC.
- dE/dx excess!

  Akhmedov, BD, Jana, Mohapatra, 2401.15145 (PLB '24);

  see also Giudice, McCullough, Teresi, 2205.04473 (JHEP '22)





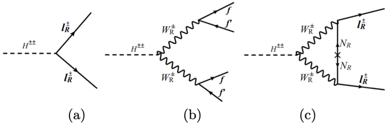


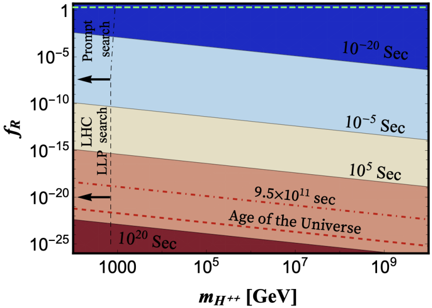
- Implications for HSCP searches at LHC.
- dE/dx excess!

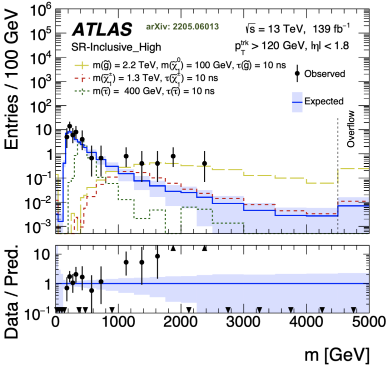
Akhmedov, BD, Jana, Mohapatra, 2401.15145 (PLB '24);

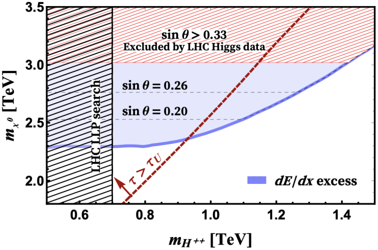
see also Giudice, McCullough, Teresi, 2205.04473 (JHEP '22)

Doubly-charged Scalar









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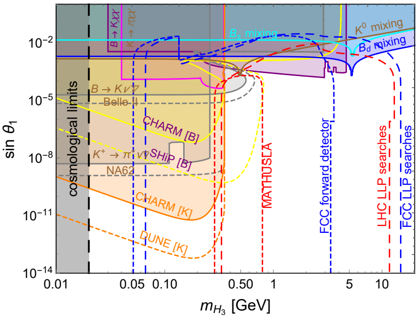
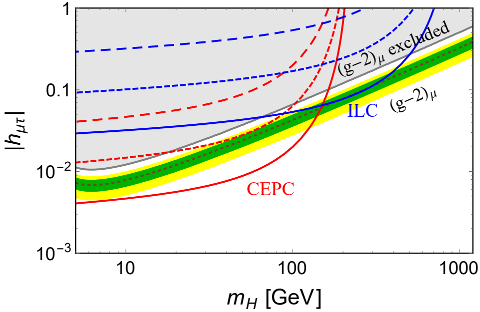
Neutral Scalar

- 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.

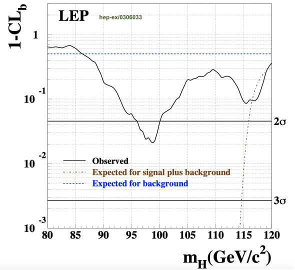


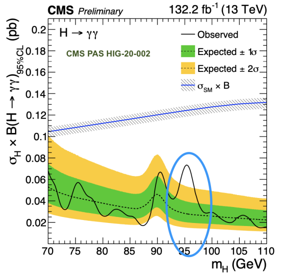
[BD, Mohapatra, Zhang (PRD '17; NPB '17)]

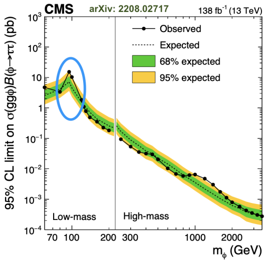


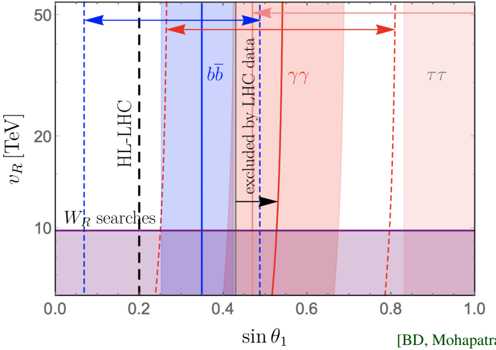
[BD, Mohapatra, Zhang (PRL '18; PRD '18)]

95 GeV Anomaly



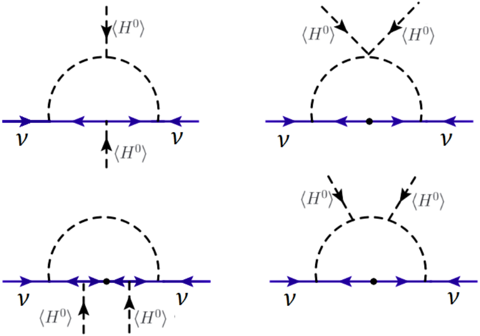






[BD, Mohapatra, Zhang, 2312.17733 (PLB '24)]

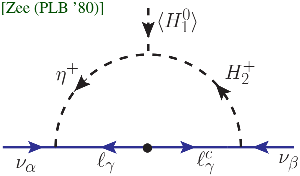
Radiative Models (One-loop)



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

Singlet Charged Scalar in Zee Model

[Zee (PLB '80)]



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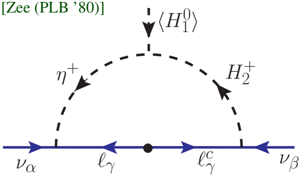

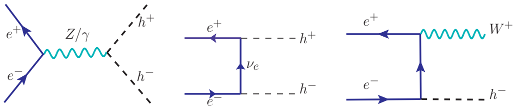

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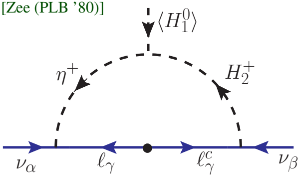
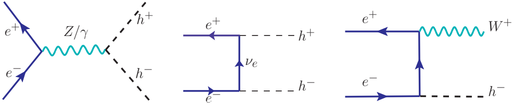
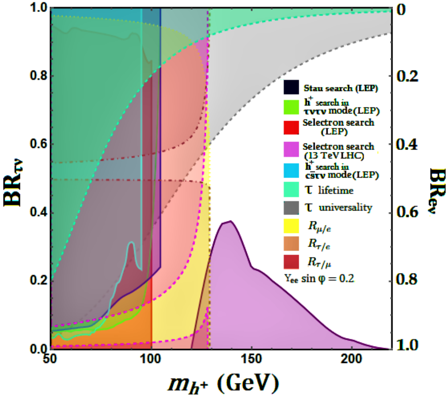
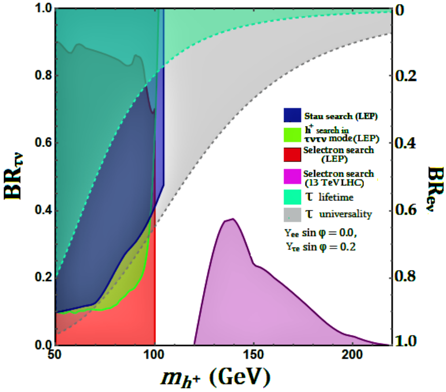


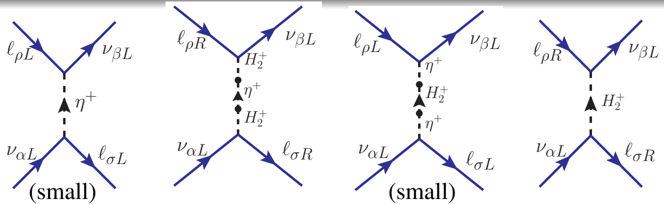




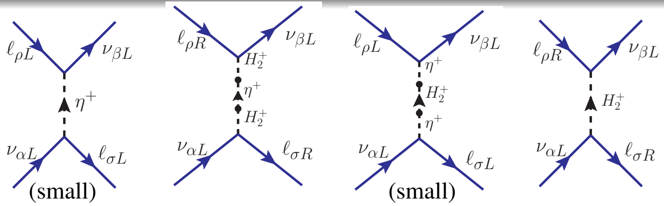


[Babu, BD, Jana, Thapa, 1907.09498 (JHEP '20)]

Nonstandard Neutrino Interactions



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



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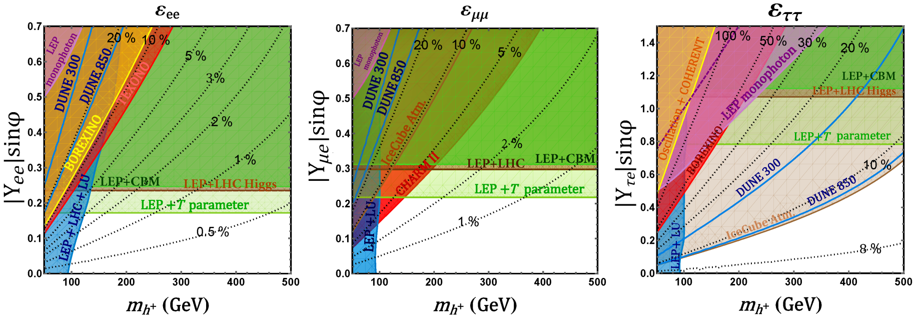
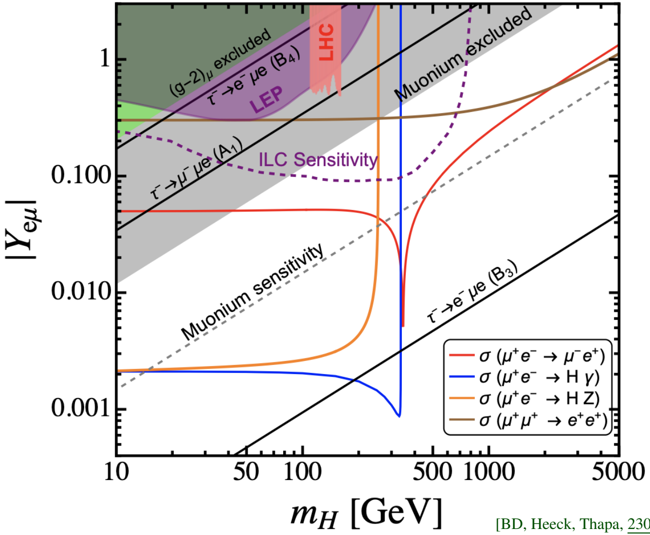


[Babu, BD, Jana, Thapa, 1907.09498 (JHEP '20)]

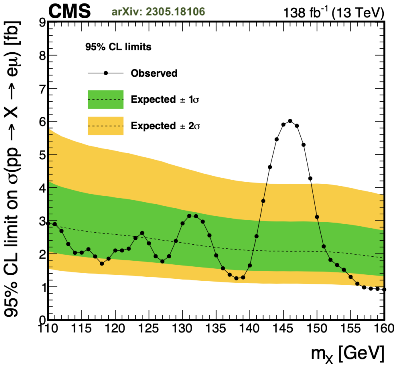
Extra Neutral Scalars in Zee Model

- Should have LFV couplings (to fit neutrino oscillation data).
- Stringent cLFV constraints. But depends on Yukawa texture.
- Lepton colliders provide an independent test.



[BD, Heeck, Thapa, 2309.06463 (EPJC '24)]

CMS $e\mu$ Excess



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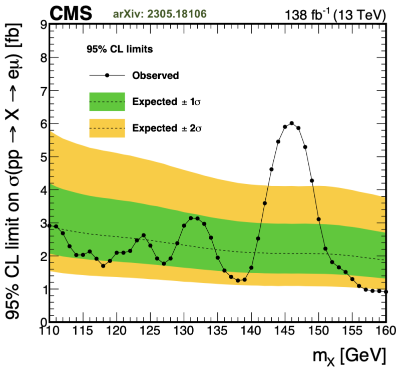

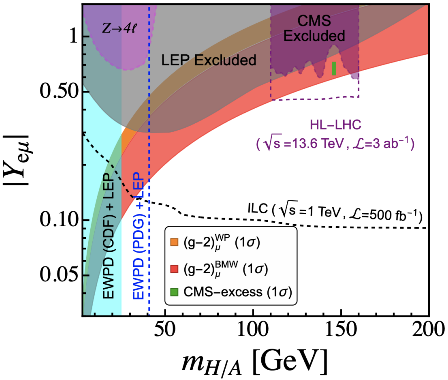

[Afik, BD, Thapa, 2305.19314 (PRD ’24)]

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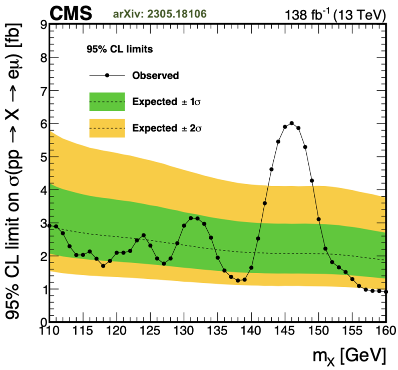

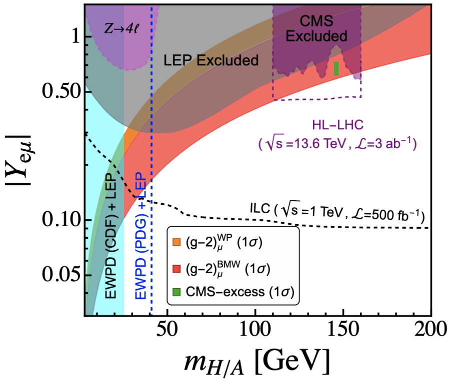

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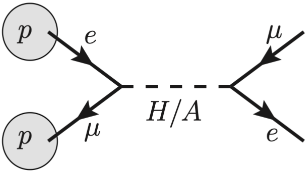
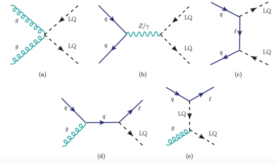
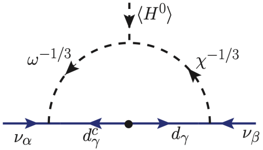
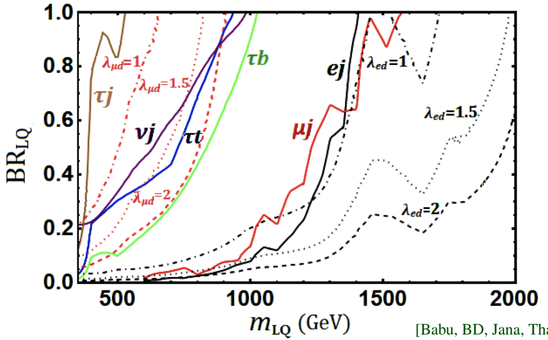


Using the lepton PDF of proton. [Buonocore, Nason, Tramontano, Zanderighi, 2005.06477 (JHEP '20)]

- Also generate radiative neutrino mass, e.g. RPV SUSY or colored Zee, Zee-Babu models [Hall, Suzuki (NPB '84); Cai, Clarke, Schmidt, Volkas, 1410.0689].
- Color triplets $\Longrightarrow$ Strong limits from LHC and flavor observables.
- Popularized by flavor anomalies and muon $g-2$.



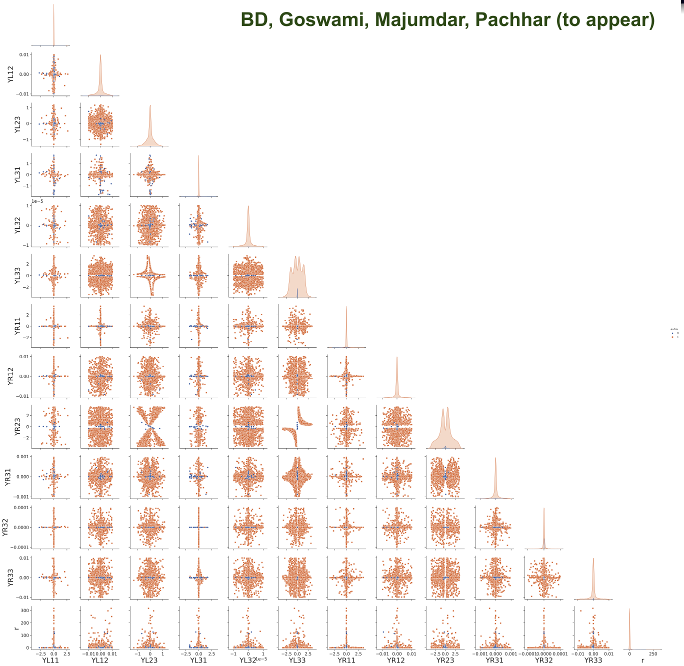




[Babu, BD, Jana, Thapa, 1907.09498 (JHEP '20)]

A Global Fit

BD, Goswami, Majumdar, Pachhar (to appear)



Conclusions

- Understanding the neutrino mass mechanism will provide key insights into the BSM world.
- Current and future colliders provide an ideal testing ground for (sub) TeV-scale neutrino mass models.
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Thank You!