Neutrino Physics at Future Colliders

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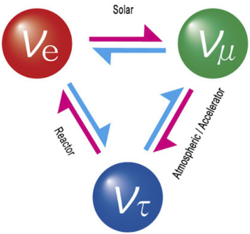
Neutrino Oscillations Primer



$$|\nu_i\rangle = U_{\alpha i}|\nu_\alpha\rangle$$

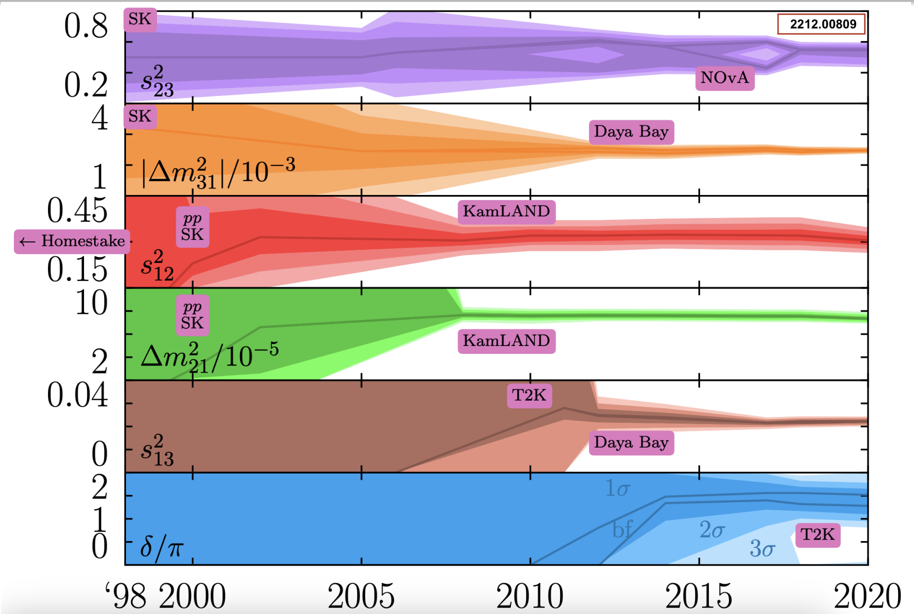
$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) \pm 8J\prod_{i>j}\sin\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

Requires nonzero neutrino masses and mixing $\Longrightarrow$ Physics beyond the Standard Model

Oscillation Parameters: Current Status



[Snowmass NF01 Topical Group Report, 2212.00809]

Future Prospects and Wish-List

		Atmospheric Mass Ordering	θ_{23} Octant	$\sin\delta \neq 0$ for 50% of δ
JUNO	Optimistic	2030: 3σ	-	-
	Conservative	2030: 2.5σ	-	-
DUNE	Optimistic	2030: 5σ	2036: 3σ, 2040: 5σ	2035: 3σ, 2039: 5σ
	Conservative	2032: 5σ	2040: 2σ	2037: 3σ
HK	Optimistic	2033: 5σ	2033: 5σ	2029: 3σ, 2032: 5σ
	Conservative	2032: 3σ	2034: 3σ	2029: 3σ, 2037: 5σ
IceCube	Optimistic	2030: 3σ, 2033: 4σ	-	-
	Conservative	2033: 2σ	-	-
KM3NeT	Optimistic	2026: 3σ, 2029 5σ	-	-
	Conservative	2030: 3σ, 2032: 4σ	-	-

[Snowmass NF01 Topical Group Report, 2212.00809]

What else do we want to learn about neutrinos?

Future Prospects and Wish-List

		Atmospheric Mass Ordering	θ_{23} Octant	$\sin\delta \neq 0$ for 50% of δ
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DUNE	Optimistic	2030: 5σ	2036: 3σ, 2040: 5σ	2035: 3σ, 2039: 5σ
	Conservative	2032: 5σ	2040: 2σ	2037: 3σ
HK	Optimistic	2033: 5σ	2033: 5σ	2029: 3σ, 2032: 5σ
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KM3NeT	Optimistic	2026: 3σ, 2029 5σ	-	-
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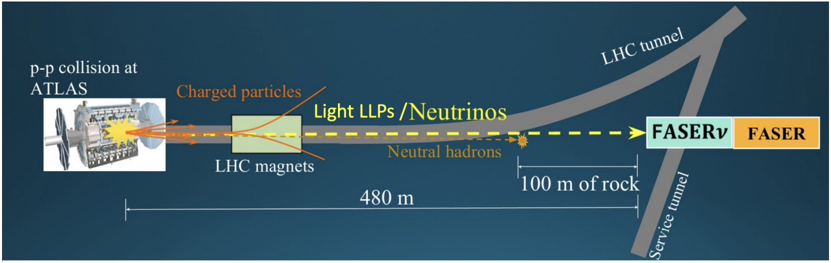
[Snowmass NF01 Topical Group Report, 2212.00809]

What else do we want to learn about neutrinos?

- How do they get mass? Dirac or Majorana (or something else)?
- Do they have more than 3 species? Must be 'sterile'! [LEP, hep-ex/0509008 (Phys. Rep.)]
- Do they have nonstandard interactions with matter or with themselves?
- Is the low-energy $\delta_{\rm CP}$ related to baryogenesis?
- Any connection to dark matter?

High-energy colliders can help us address some of these questions.

Seeing the 'Invisible' at LHC



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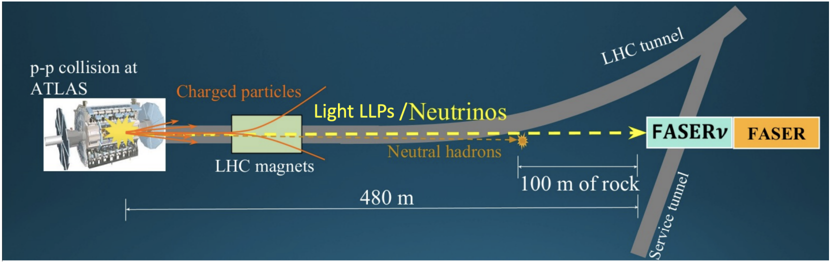
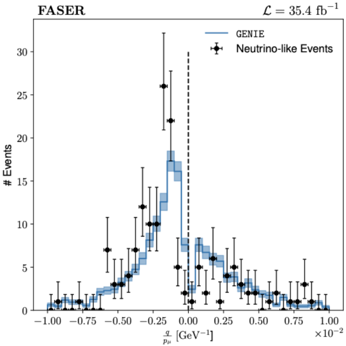
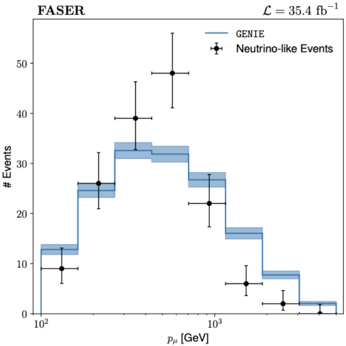
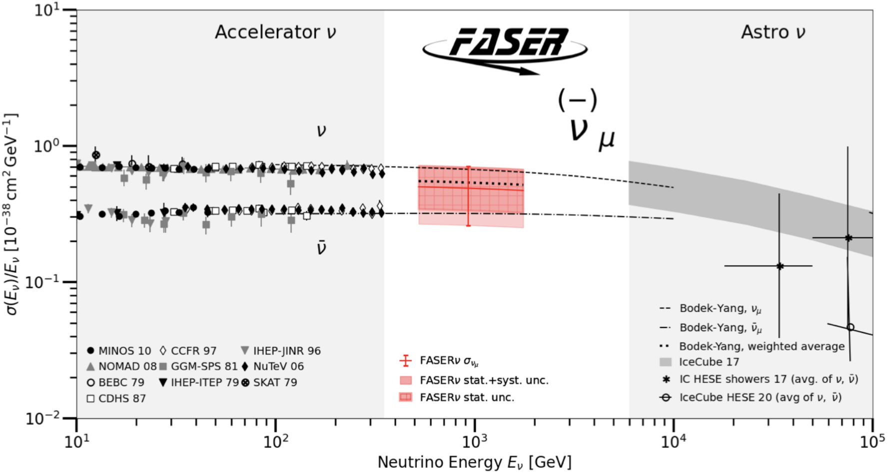






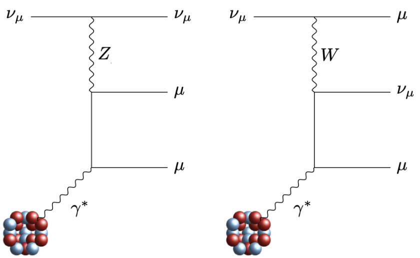
[FASER Collaboration, 2303.14185 (PRL '23)]



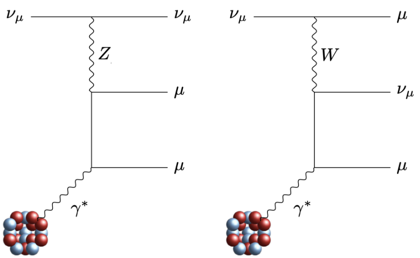
[FASER Collaboration, 2403.12520 (PRL '24)]

VERY important for validating neutrino-nucleus cross section models at different energies.

Rare SM Processes



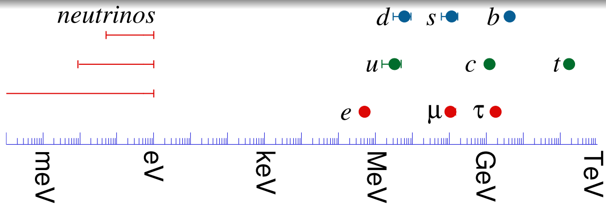
Rare SM Processes



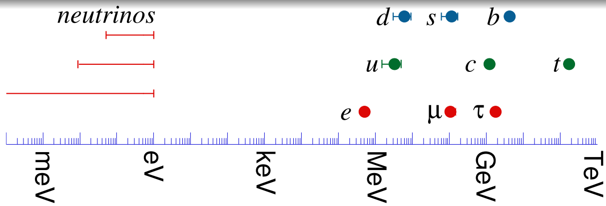
Name	Mass [tons]	Target nucleus	On(Off)- -Axis	$L^{-1}_{\mathrm{int,TeV}\nu \to \mu\mu}$ $\times 10^{17}$ [cm^{-1}]	Neutrino Tridents, $\nu N \to \nu N' \ell^+ \ell^-$						
					$\mu^+\mu^-$	$\mu^+\mu^-_{f_s=0.5}$	e^+e^-	$\tau^+\tau^-$	$e^\pm\mu^\mp$	$e^\pm\tau^\mp$	$\mu^\pm\tau^\mp$
Run 3 (150 fb^{-1})											
FASERν	1.1	W	On	252	0.22	0.54	0.24	0.0029	0.83	0.035	0.060
SND@LHC	0.83	W	Off	252	0.024	0.06	0.03	0.0002	0.10	0.004	0.004
HL-LHC (3 ab^{-1})											
FASERν2	20	W	On	252	40	97	44	0.51	150	6.3	10
AdvSND@LHC (Far)	5	W	Off	252	2.2	5.3	2.7	0.02	9.0	0.3	0.4
FLArE	10	LAr	On	8.56	4.5	11	4.5	0.07	16	0.7	1.2
FLArE-100	100	LAr	On	8.56	26	63	27	0.37	91	4.1	6.8
NuTeV-like (Fe)	95	Fe	On	65.4	21	52	22	0.29	76	3.4	5.5
NuTeV-like (Pb)	135	Pb	On	154	48	116	57	0.45	190	7.0	10

[Altmannshofer, Makela, Sarkar, Trojanowski, Xie, Zhou, 2406.16803;
see also Bigaran, BD, Lopez Gutierrez, Machado, 2406.20067]

Probing Neutrino Mass Mechanism



Perhaps something beyond the standard Higgs mechanism...



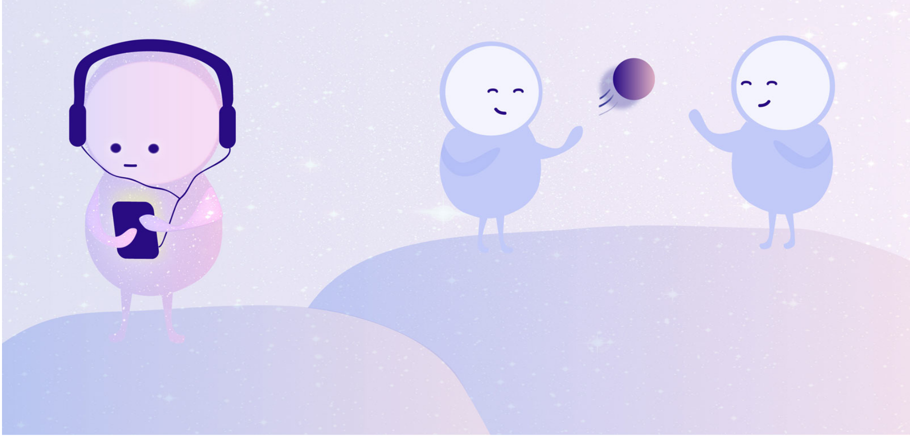
Perhaps something beyond the standard Higgs mechanism...

Can we probe the origin of neutrino mass at colliders?

- 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]
- Complementarity with low-energy lepton number/flavor violation searches.
- Possible connections to other sectors (e.g. NSI and oscillation physics, anomalies, baryogenesis, dark matter).

SM-singlet Fermions

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



Snowmass Whitepaper, 2203.08039

Figure from *Symmetry* Magazine

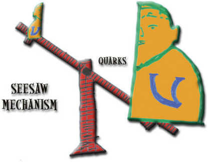
Motivated from Type-I Seesaw

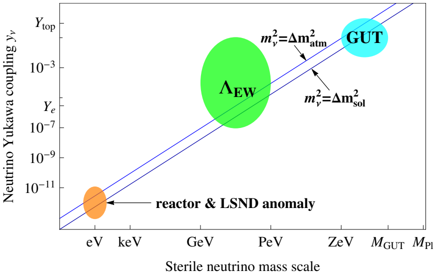
[Minkowski (PLB ’77); Mohapatra, Senjanović (PRL ’80); Yanagida ’79; Gell-Mann, Ramond, Slansky ’79; Glashow ’80]

- 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 $M_D = vY_\nu$.





[Antusch, Cazzato, Fischer, 1612.02728]

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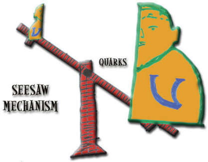
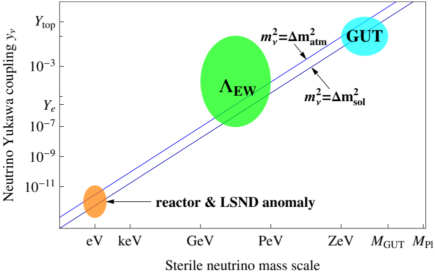
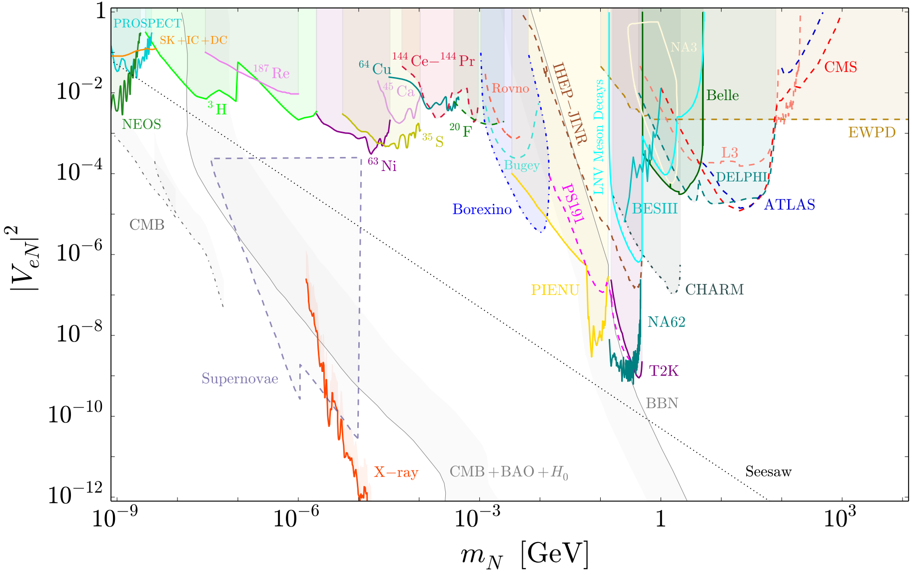




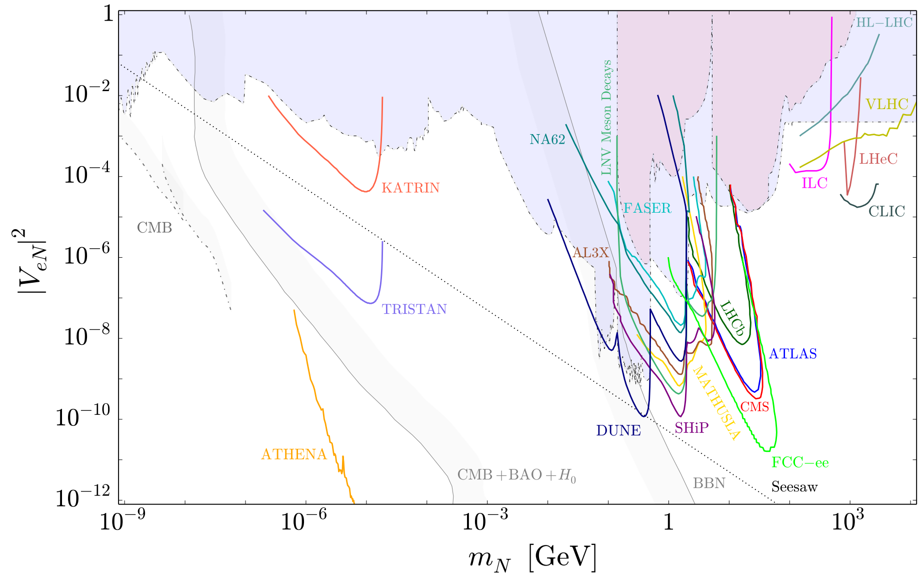
[Antusch, Cazzato, Fischer, 1612.02728]

- Each N_i corresponds to $m_{\nu_i} \neq 0$. Need at least 2 (3 is better).
- Naturalness of Higgs mass suggests $M_N \lesssim 10^7$ GeV. [Vissani (hep-ph/9709409); Farina, Pappadopulo, Strumia (1303.7244); Clarke, Foot, Volkas (1502.01352); Bambhaniya, BD, Goswami, Khan, Rodejohann (1611.03827)]

Summary of Current Constraints on Sterile Neutrinos



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



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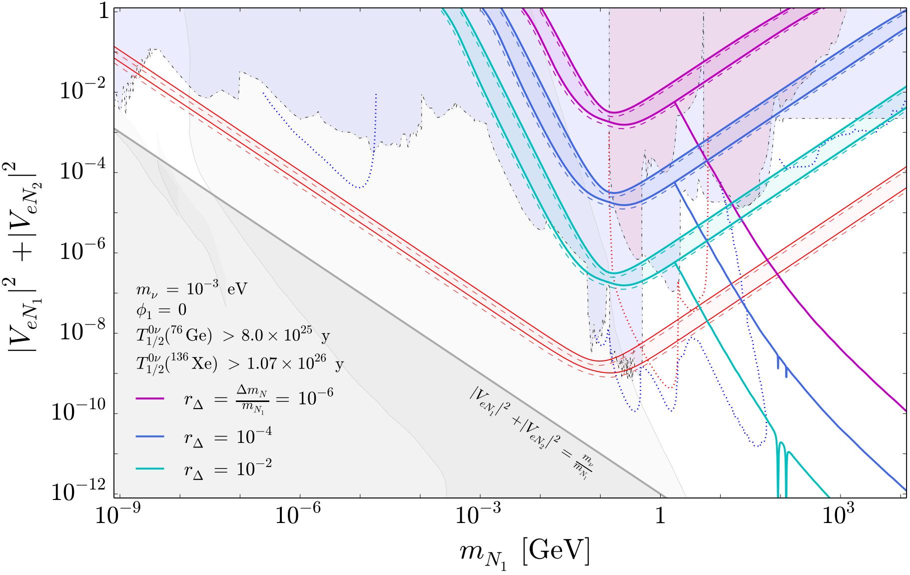
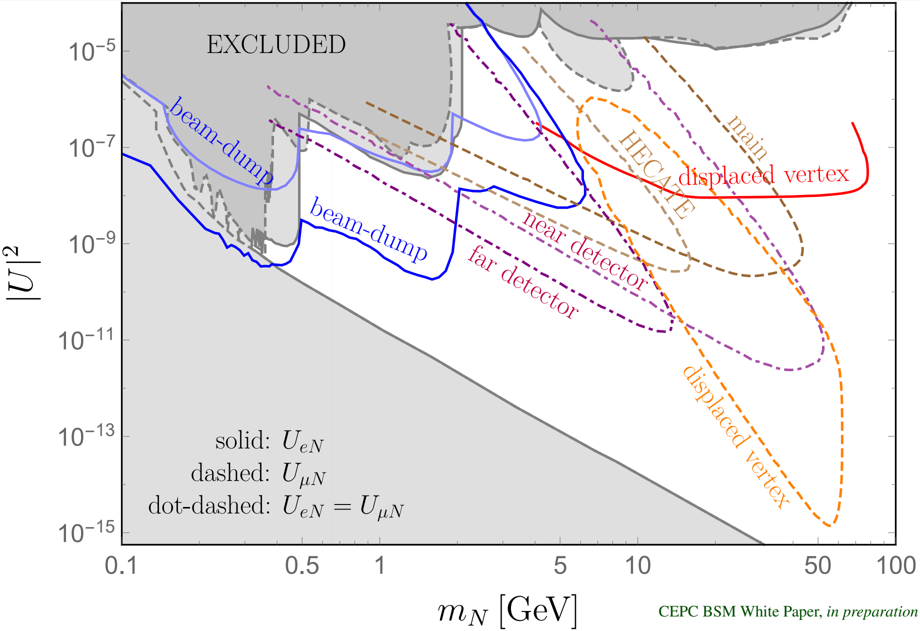
Neutrinoless Double Beta Decay



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

Future Prospects at CEPC



CEPC BSM White Paper, *in preparation*

see previous talk by M. Drewes

New Gauge Bosons

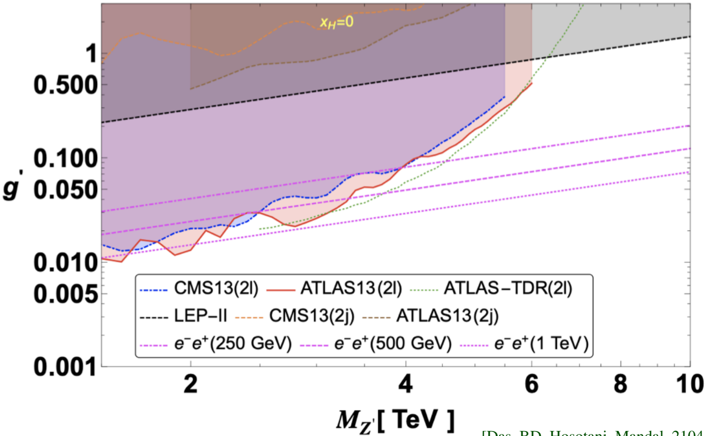
(W', Z')

$U(1)_X$ 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
$SU(3)_C$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	$1/6$	$2/3$	$-1/3$	$-1/2$	-1	0	$1/2$	0
$U(1)_X$	$\frac{1}{6}x_H + \frac{1}{3}x_\Phi$	$\frac{2}{3}x_H + \frac{1}{3}x_\Phi$	$-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$	$-\frac{1}{2}x_H - x_\Phi$	$-x_H - x_\Phi$	$-x_\Phi$	$-\frac{x_H}{2}$	$2x_\Phi$

$U(1)_X$ at Future Colliders

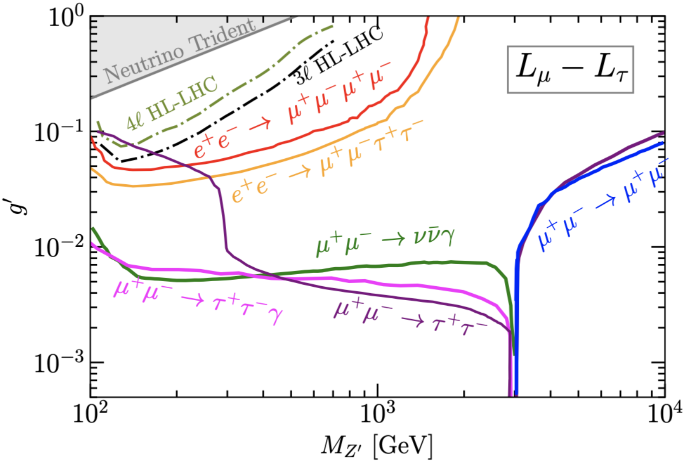
Gauge group	q_L^i	u_R^i	d_R^i	ℓ_L^i	e_R^i	N_R^i	H	Φ
$SU(3)_C$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**1**
$U(1)_Y$	$1/6$	$2/3$	$-1/3$	$-1/2$	-1	0	$1/2$	0
$U(1)_X$	$\frac{1}{6}x_H + \frac{1}{3}x_\Phi$	$\frac{2}{3}x_H + \frac{1}{3}x_\Phi$	$-\frac{1}{3}x_H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



[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)]

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

- 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, 1306.2342 (PRD '13)]

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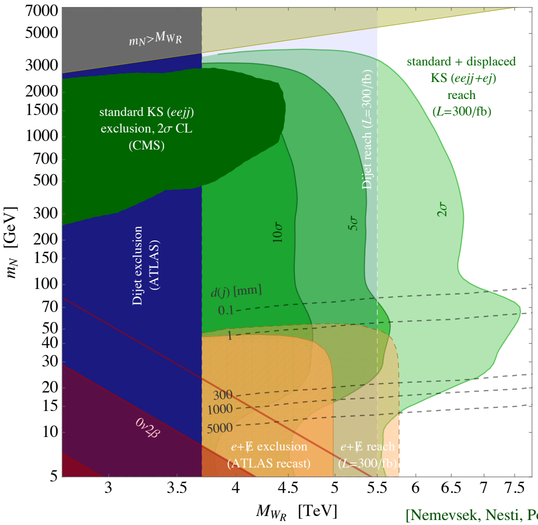
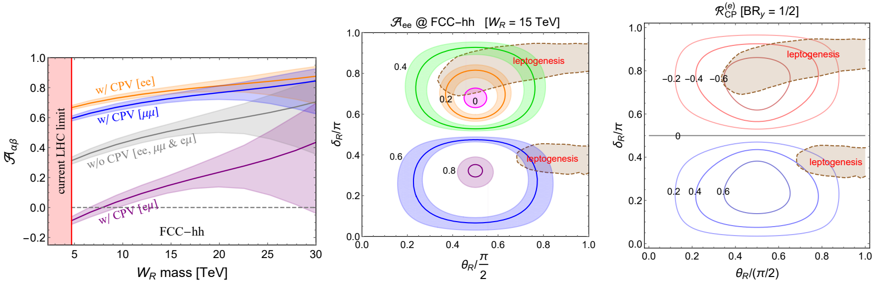


[Nemevsek, Nesti, Popara, 1801.05813 (PRD '18)]

CP Violation in the RHN Sector

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

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



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

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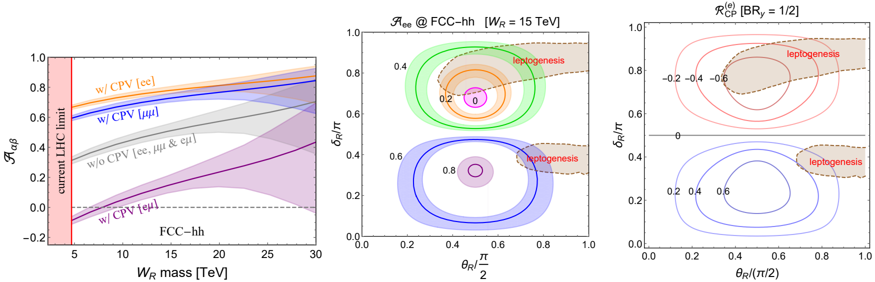
$$\mathcal{A}_{\alpha\beta} \equiv \frac{\mathcal{N}(\ell_\alpha^+ \ell_\beta^+) - \mathcal{N}(\ell_\alpha^- \ell_\beta^-)}{\mathcal{N}(\ell_\alpha^+ \ell_\beta^+) + \mathcal{N}(\ell_\alpha^- \ell_\beta^-)} \; ; \; \mathcal{R}_{\rm CP}^{(\ell)} \equiv \frac{\frac{\sigma(pp\to W_R^+ \to \ell^+\ell^+ jj)}{\sigma(pp\to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



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

- Lower bound on $M_{W_R} \gtrsim 15$ TeV from leptogenesis.

  [Frere, Hambye, Vertongen (0806.0841); BD, Lee, Mohapatra (1503.04970)]

- FCC-hh will provide a direct collider test of thermal leptogenesis in LRSM.

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 (14 if δ_L included) physical Higgs bosons: Rich phenomenology.

[Gunion, Grifols, Mendez, Kayser, Olness (PRD '89); Chao, Luo, Xing, Zhou (PRD '08); Fileviez Perez, Han, Huang, Li, Wang (PRD '08); Kanemura, Yagyu, Yokoya (PLB '13); Bambhaniya, Chakrabortty, Gluza, Kordiaczyńska, Szafron (JHEP '14); BD, Mohapatra, Zhang (JHEP '16); Babu, Jana (PRD '17); BD, Ramsey-Musolf, Zhang (PRD '18); BD, Zhang (JHEP '18); ...]

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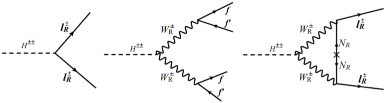
- 8 (14 if δ_L included) physical Higgs bosons: Rich phenomenology.

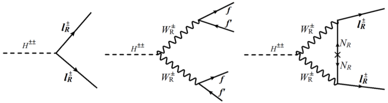
  [Gunion, Grifols, Mendez, Kayser, Olness (PRD '89); Chao, Luo, Xing, Zhou (PRD '08); Fileviez Perez, Han, Huang, Li, Wang (PRD '08); Kanemura, Yagyu, Yokoya (PLB '13); Bambhaniya, Chakrabortty, Gluza, Kordiaczyńska, Szafron (JHEP '14); BD, Mohapatra, Zhang (JHEP '16); Babu, Jana (PRD '17); BD, Ramsey-Musolf, Zhang (PRD '18); BD, Zhang (JHEP '18); ...]
- 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 scalars ($H^{\pm\pm}$) constrained to be $\gtrsim 900$ (700) GeV from prompt (displaced) multilepton searches. [ATLAS, 2211.07505 (EPJC '23)]
- Neutral component (H_3^0) is hadrophobic and can be much lighter!
- Can even be a dark matter candidate (albeit highly fine-tuned).

  [Nemevsek, Senjanovic, Zhang, 1205.0844 (JCAP '12)]



(a) (b) (c)

Doubly-charged Scalar from $SU(2)_R$ Triplet



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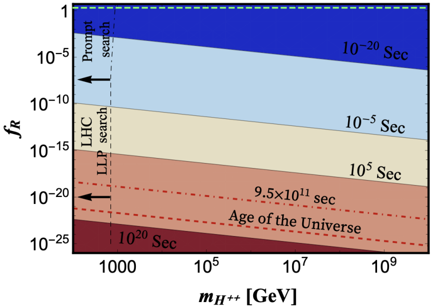

- Implications for HSCP searches at LHC.

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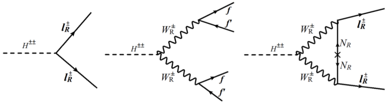

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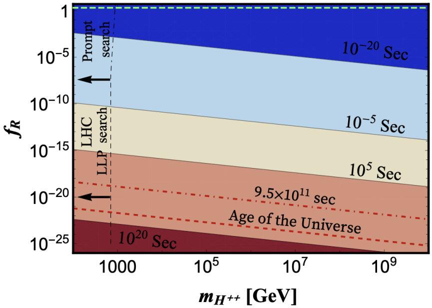

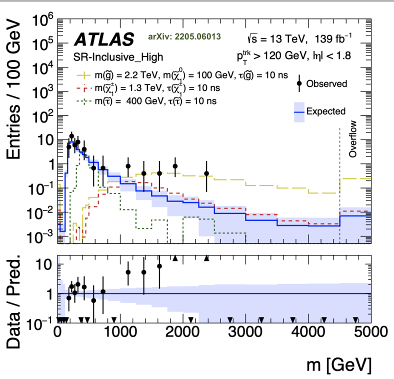

- Implications for HSCP searches at LHC.
- Can explain the ATLAS dE/dx excess!

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

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

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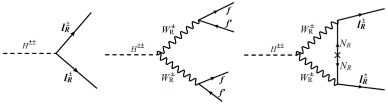

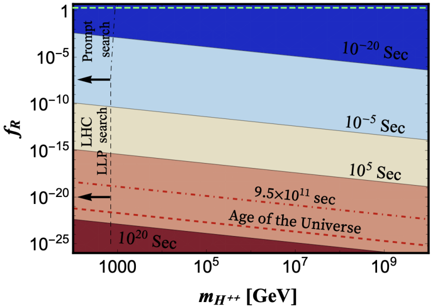

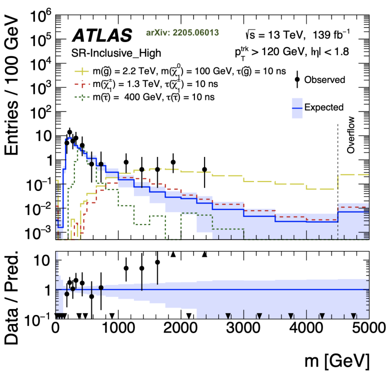

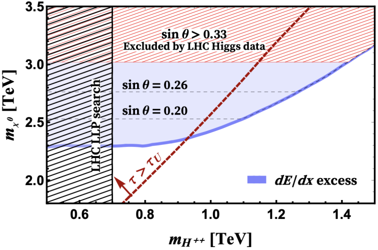

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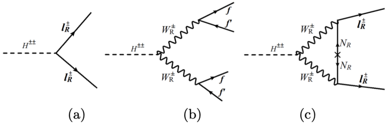

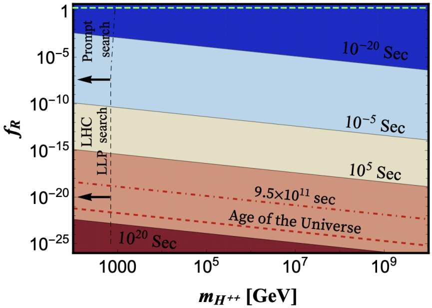

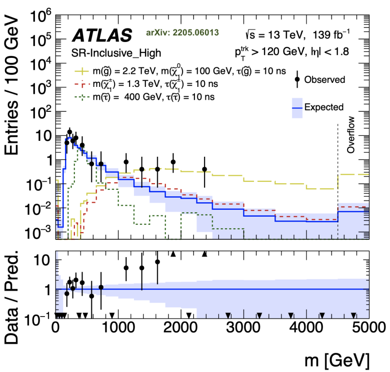

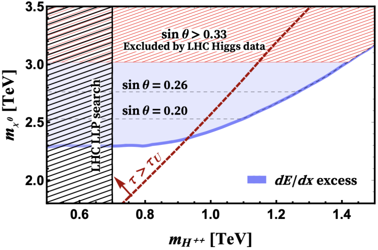

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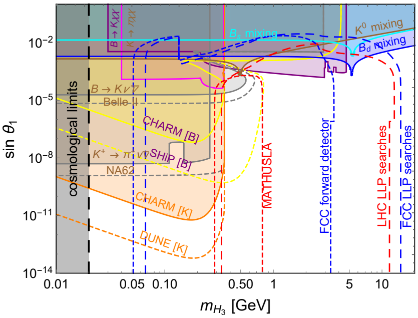
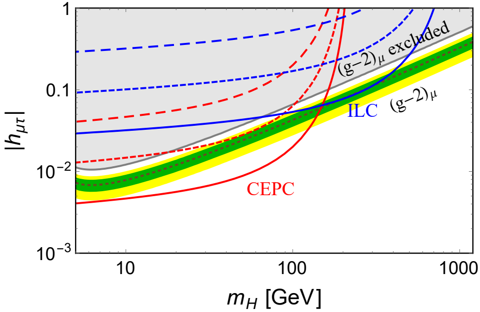
Catalyzed nuclear fusion to solve energy problem. [Akhmedov, 2109.13960 (PRD '21)]

Neutral Scalar from $SU(2)_R$ Triplet

- Hadrophobic and allowed to be light (down to sub-GeV scale) by current constraints.
- Suppressed couplings 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.

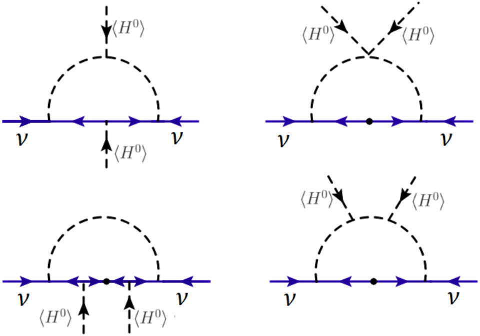


[BD, Mohapatra, Zhang (PRD '17; NPB '17)]



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

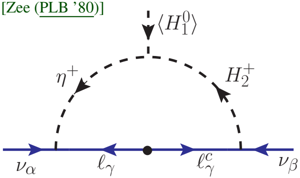
Radiative Models (One-loop Only)



[Zee (PLB '80); Ma (PRL '98); Babu, Leung (NPB '01); de Gouvêa, Jenkins (PRD '08); Bonnet, Hirsch, Ota, Winter (JHEP '12); Cai, Clarke, Schmidt, Volkas (JHEP '14); Babu, BD, Jana, Thapa, (JHEP '20); Wang, Zhang, Zhou (JHEP '23); ...]

Singlet Charged Scalar in Zee Model

[Zee (PLB '80)]



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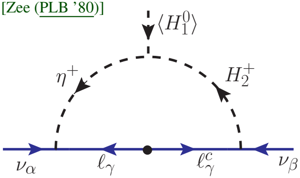

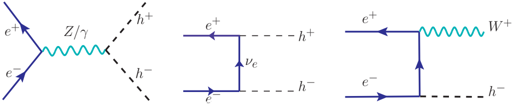

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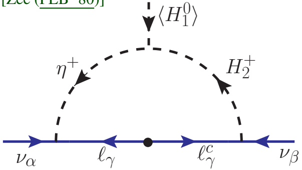
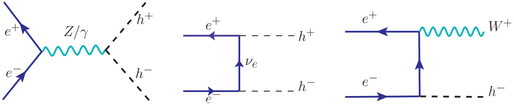
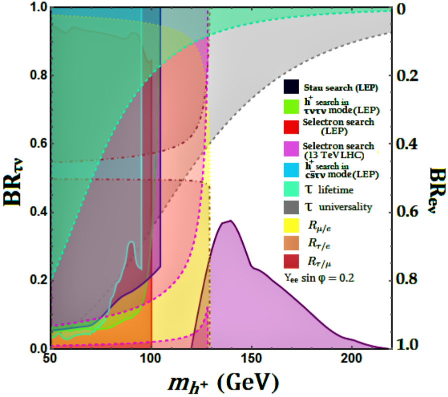
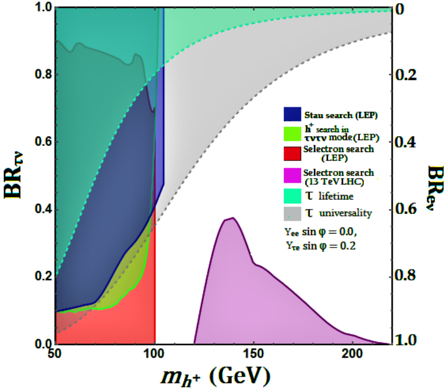


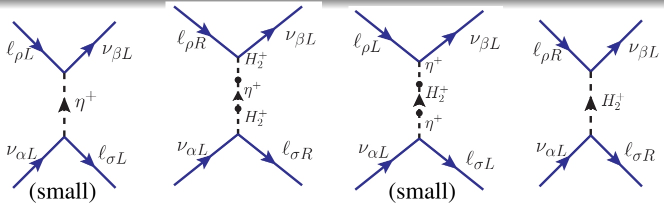




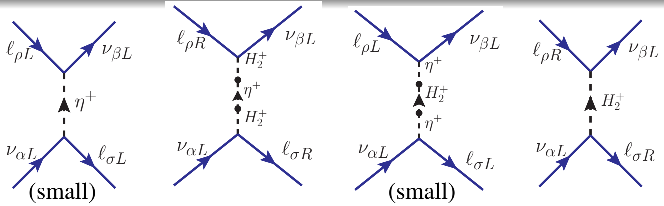


[Babu, BD, Jana, Thapa, 1907.09498 (JHEP '20)]

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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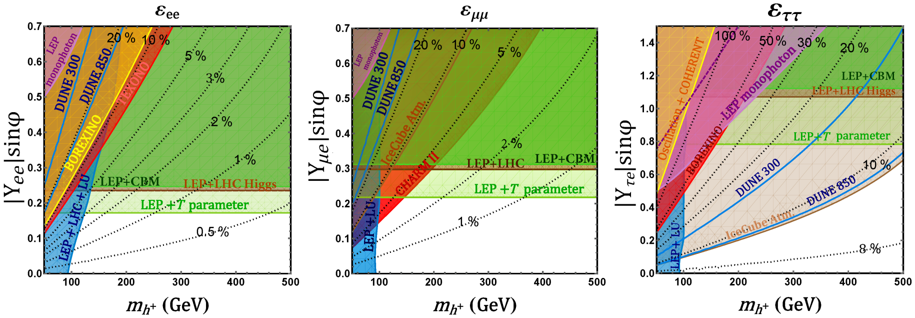
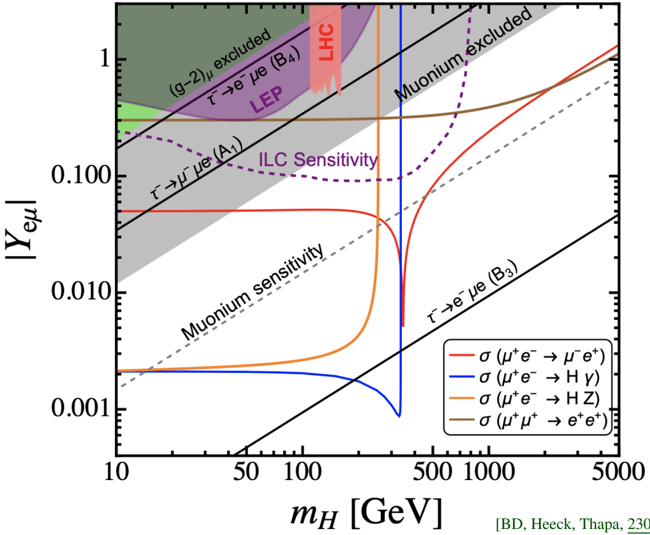


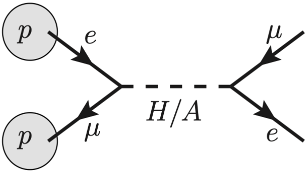
[Babu, BD, Jana, Thapa, 1907.09498 (JHEP '20)]

Extra Neutral Scalars in Zee Model

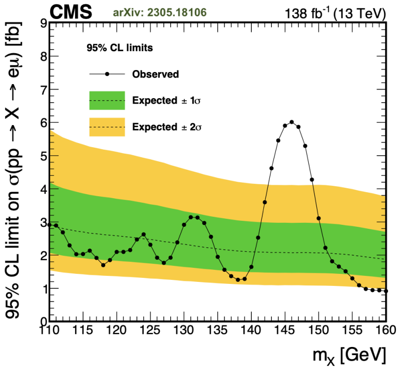
- Must have LFV couplings (to fit neutrino oscillation data).
- Stringent cLFV constraints. But depend on Yukawa texture.
- Future lepton colliders could provide an independent test.

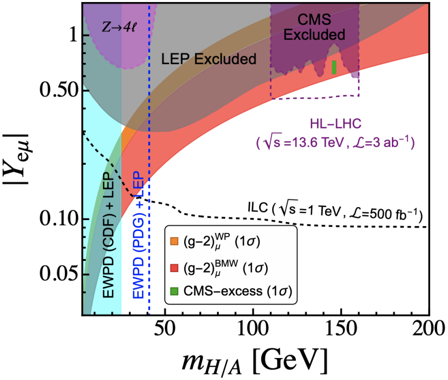


[BD, Heeck, Thapa, 2309.06463 (EPJC '24)]



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





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

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.
- Can probe the messenger particles (new fermions/gauge bosons/scalars) in a wide range of open parameter space.
- Complementary to the low-energy precision measurements.
- Important implications for current experimental anomalies.