Baryon and Lepton Number Violation at Colliders

Bhupal Dev
(bdev@wustl.edu)

Washington University in St. Louis

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University of Cincinnati
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Motivation

We want to understand the origin of $\mathcal{B}$ and $\mathcal{L}$ violation to explain :

- The origin of neutrino masses
- The origin of the matter-antimatter asymmetry in the Universe
- New Exotic $\mathcal{BLV}$ processes
- The origin of the SM-EFT

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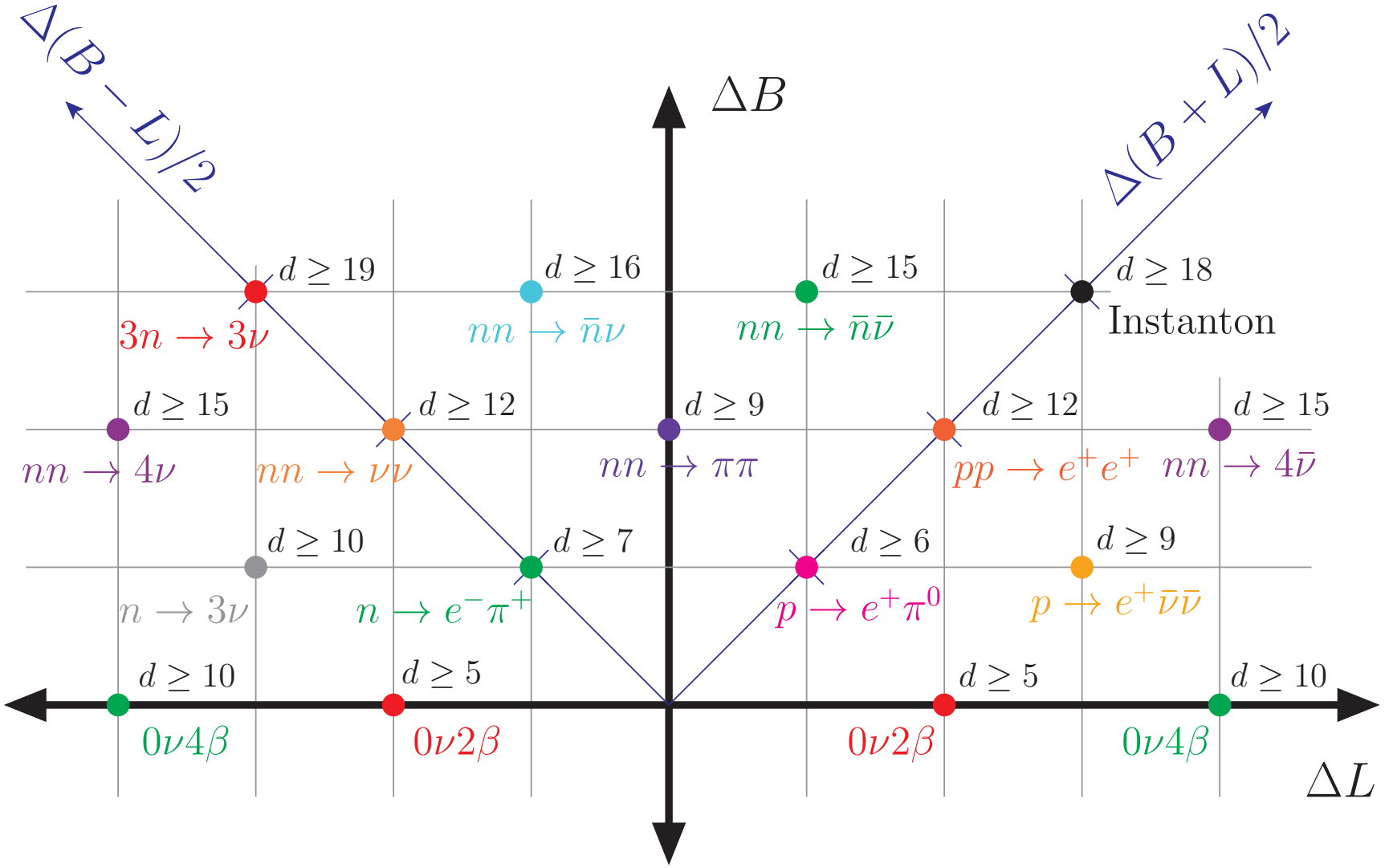
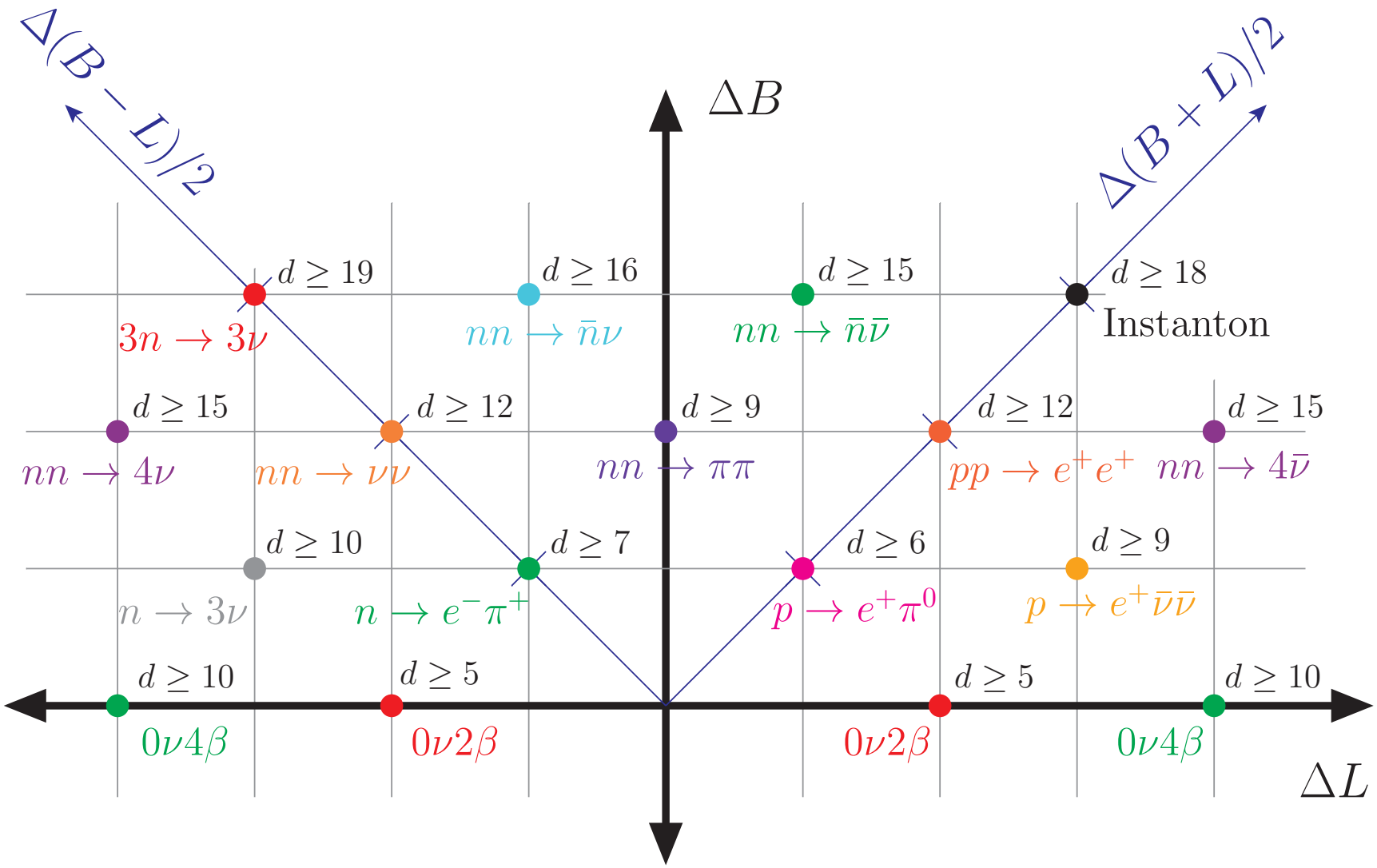
[see Plenary talks by P. Fileviez Perez and A. Pocar]

B and L Violating Processes



[Heeck & Takhistov, 1910.07647 (PRD '20)]

B and L Violating Processes

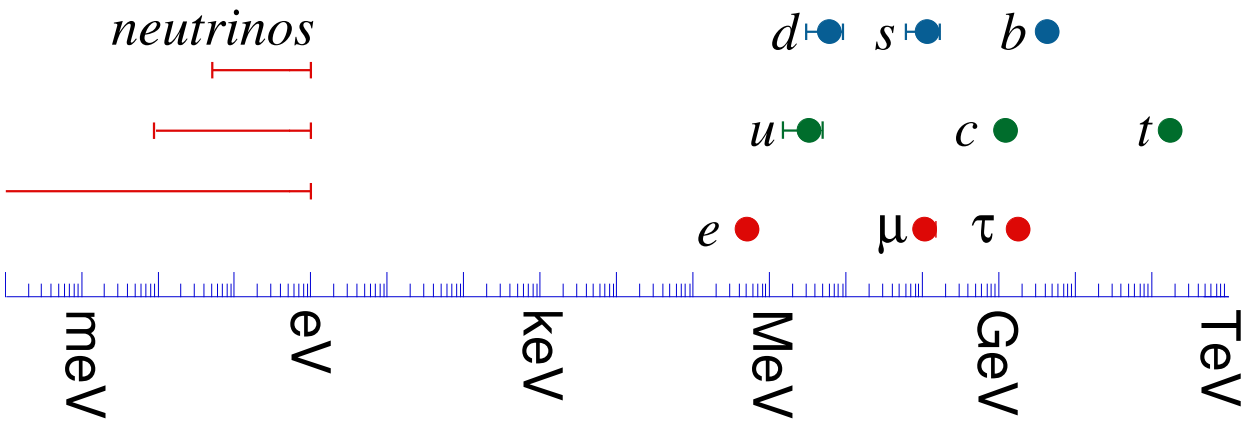


[Heeck & Takhistov, 1910.07647 (PRD '20)]

Collider signals – This talk will focus on L violation.

For B violation searches, see Wednesday talk by J. P. Ochoa-Ricoux and whitepaper 2203.08771.

Neutrino Mass



Perhaps something beyond the standard Higgs mechanism...

- 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 collider and/or low-energy experiments.
- Connection to other puzzles (e.g. baryogenesis, dark matter, anomalies, NSI).
- Relevant to multiple frontiers (EF, NF, RF, CF, TF).

SM-singlet Fermions

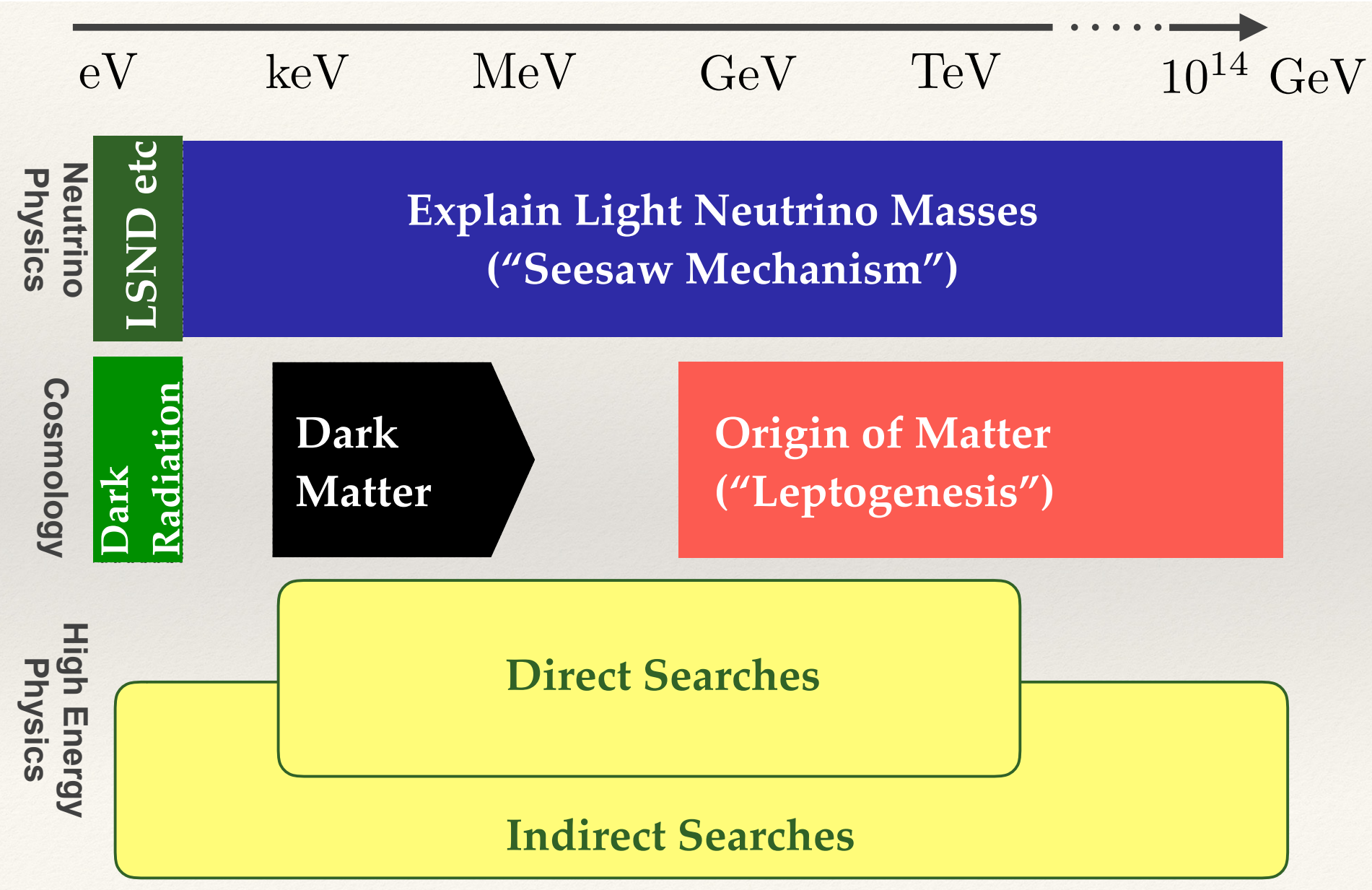
(aka sterile neutrinos/heavy neutrinos/RHNs/HNLs)

Originally motivated by **Type-I seesaw**

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

Snowmass Whitepaper 2203.08039

RHN Mass Scale

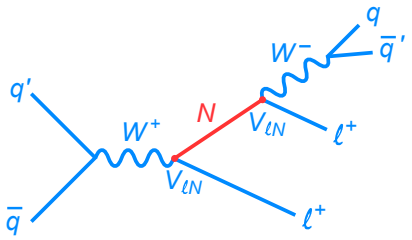


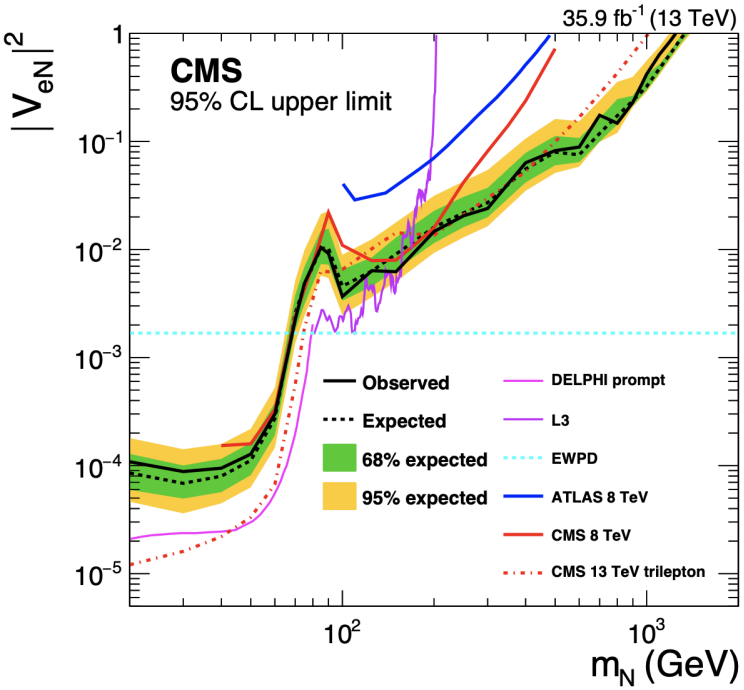
[Slide from M. Drewes (PHENO '17 plenary talk)]

Golden Channels at the LHC

Same-sign dilepton plus jets (without $\not{E}_T$)

[Keung, Senjanović (PRL '83); Datta, Guchait, Pilaftsis (PRD '94); Han, Zhang (PRL '06); del Aguila, Aguilar-Saavedra, Pittau (JHEP '07); BD, Pilaftsis, Yang (PRL '13); Alva, Han, Ruiz (JHEP '15); Das, Okada (PRD '16); ...]

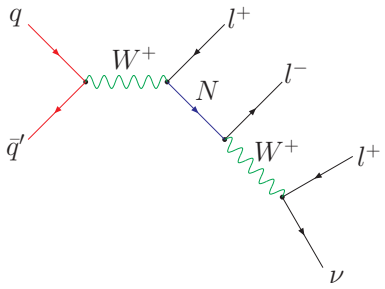


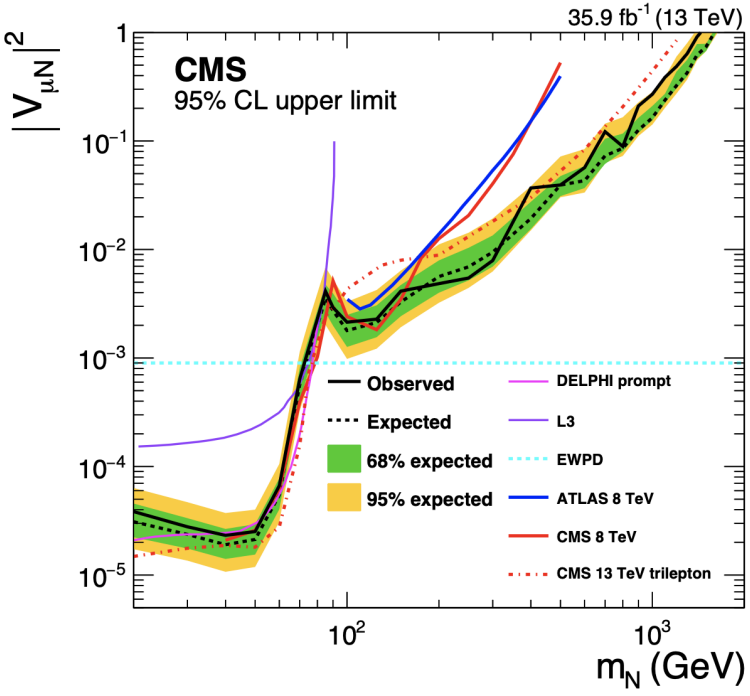


[CMS 1911.04968]

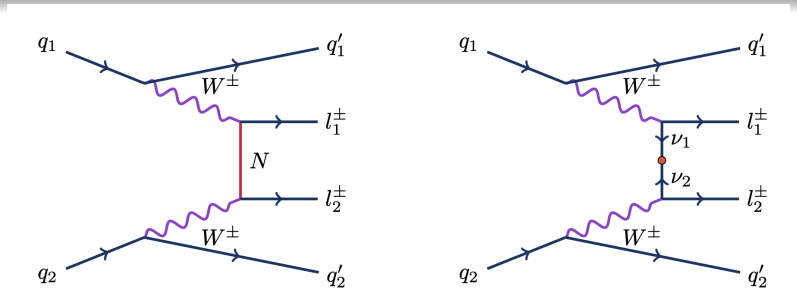
Trilepton plus $\not{E}_T$

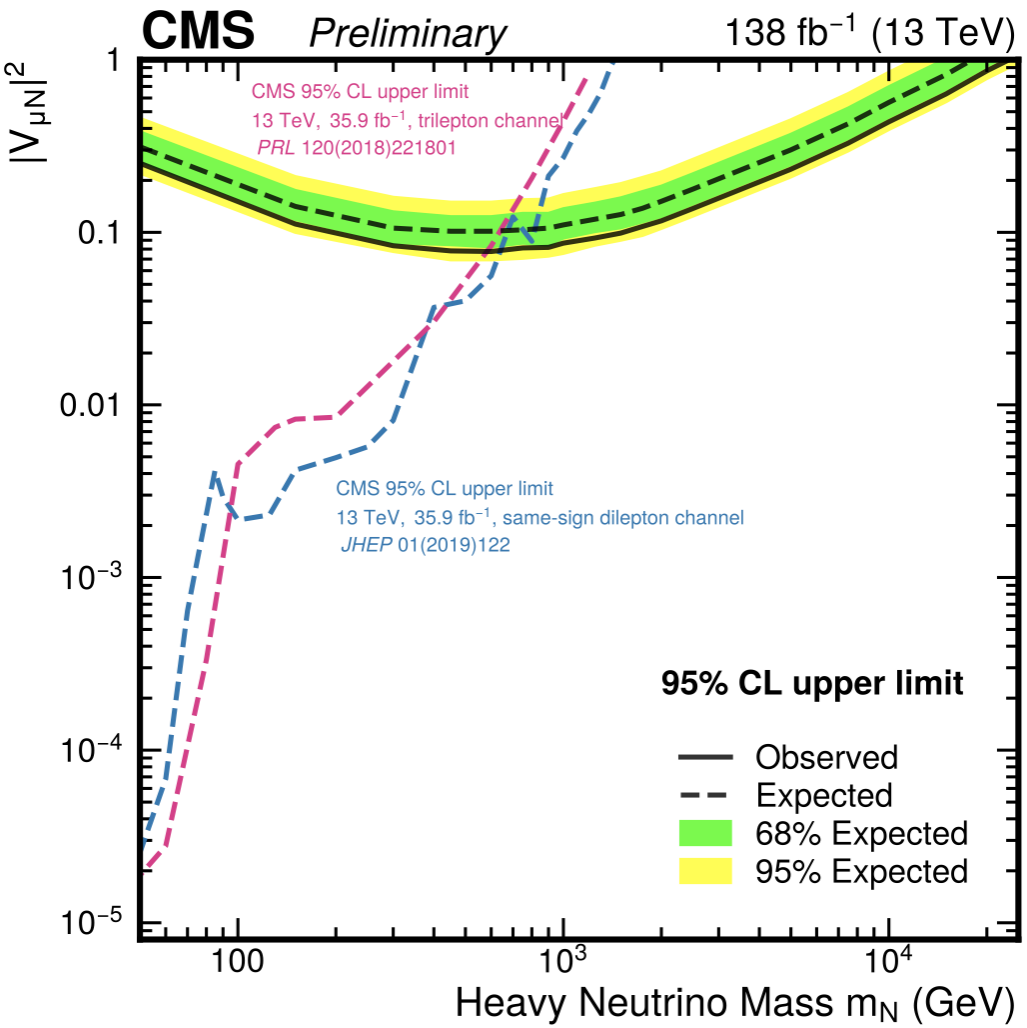
[del Aguila, Aguilar-Saavedra (PLB '09; NPB '09); Chen, BD (PRD '12); Das, BD, Okada (PLB '14); Izaguirre, Shuve (PRD '15); Dib, Kim (PRD '15); Dib, Kim, Wang (PRD '17; CPC '17); Dube, Gadkari, Thalapillil (PRD '17); ...]





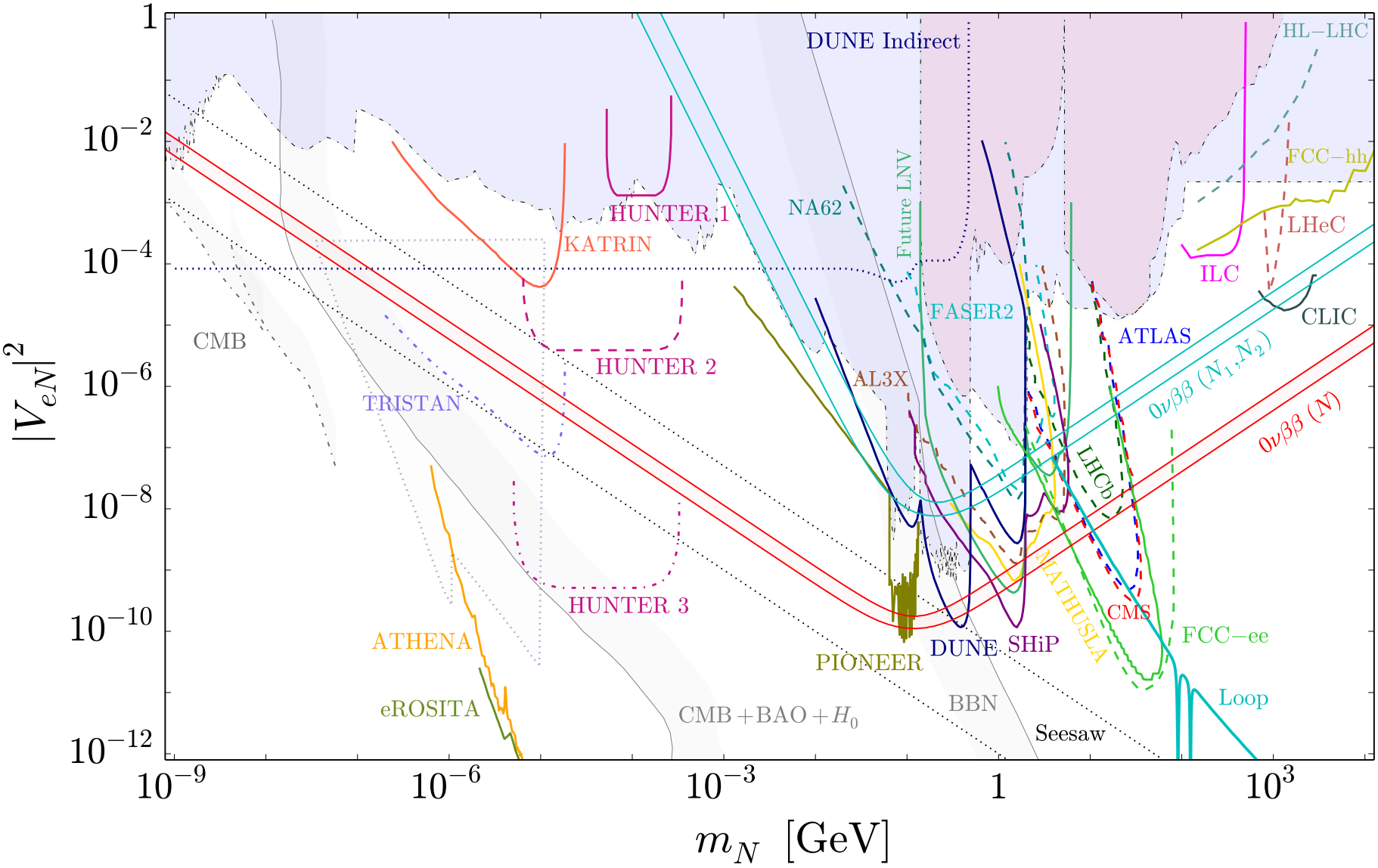
$0\nu\beta\beta$ Analog at the LHC





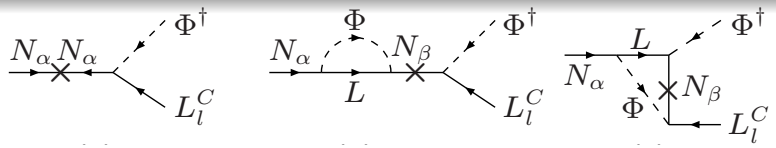
[EXO-21-003-pas]

Current Status and Future Prospects

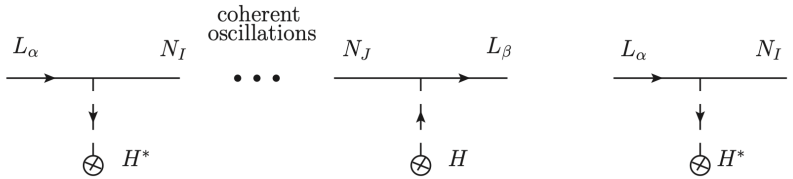


[Bolton, Deppisch, BD, 1912.03058 (JHEP '20); see http://sterile-neutrino.org for regular updates]

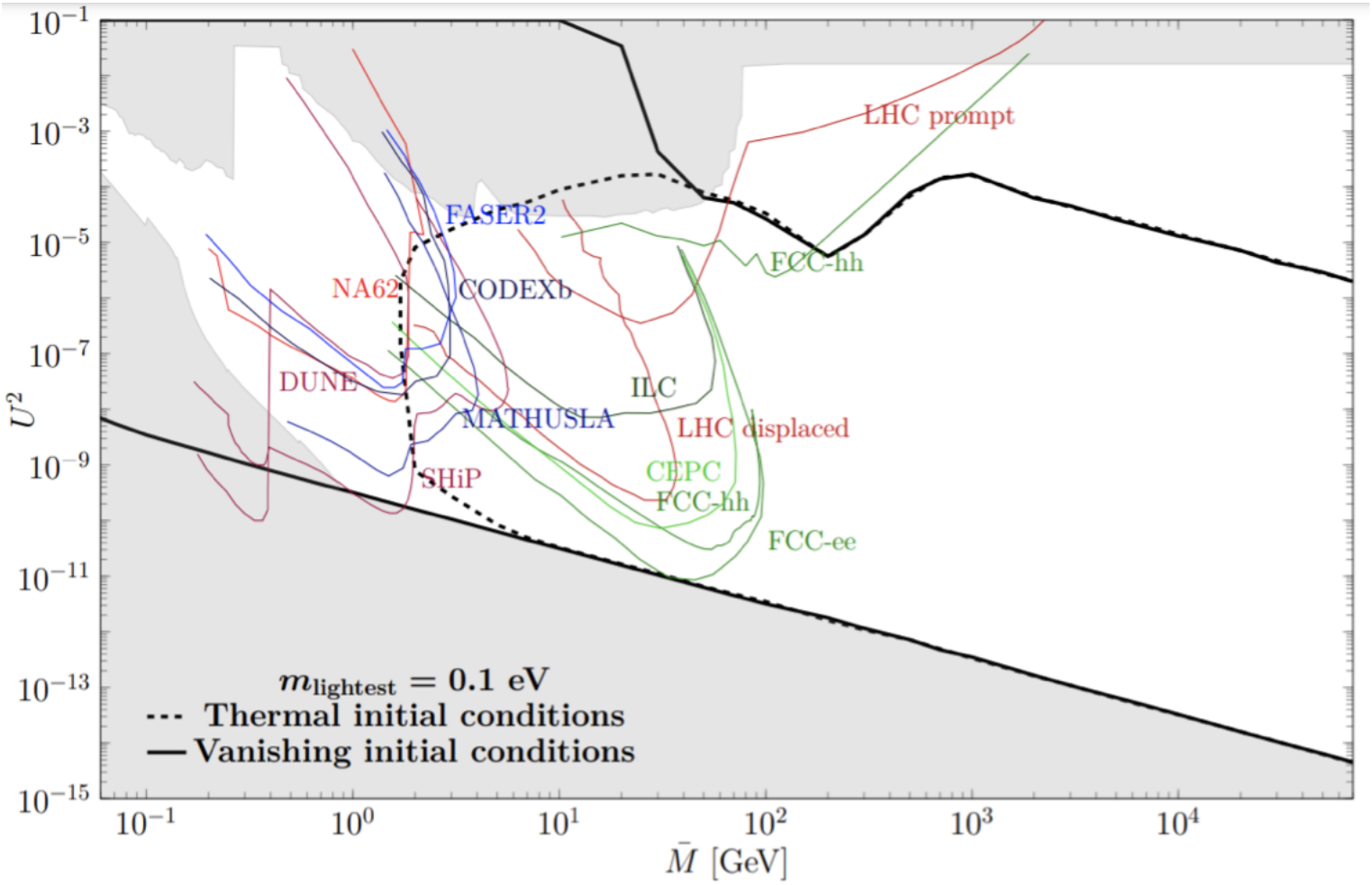
Leptogenesis



[Fukugita, Yanagida (PLB '86); Pilaftsis, Underwood (NPB '03); BD, Millington, Pilaftsis, Teresi (NPB '14); Fileviez Perez, Murgui, Plascencia (PRD '21); ...]



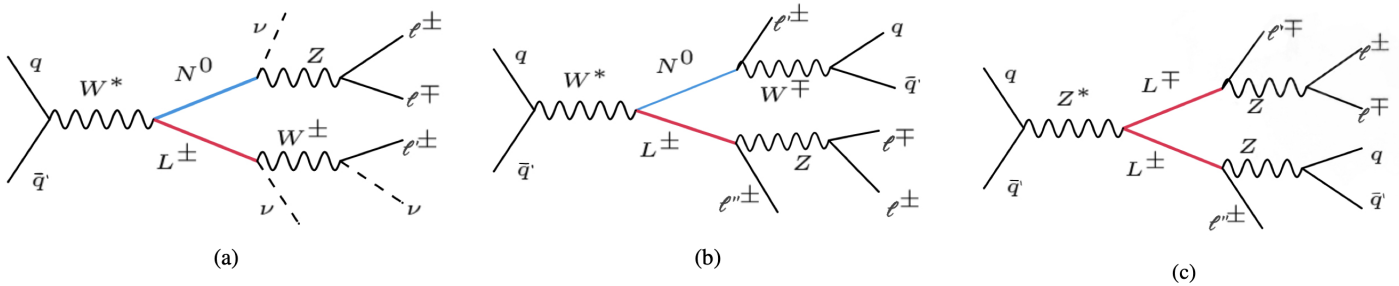
[Akhmedov, Rubakov, Smirnov (PRL '98); Canetti, Drewes, Frossard, Shaposhnikov (PRD '13); Shuve, Yavin (PRD '14); ...]

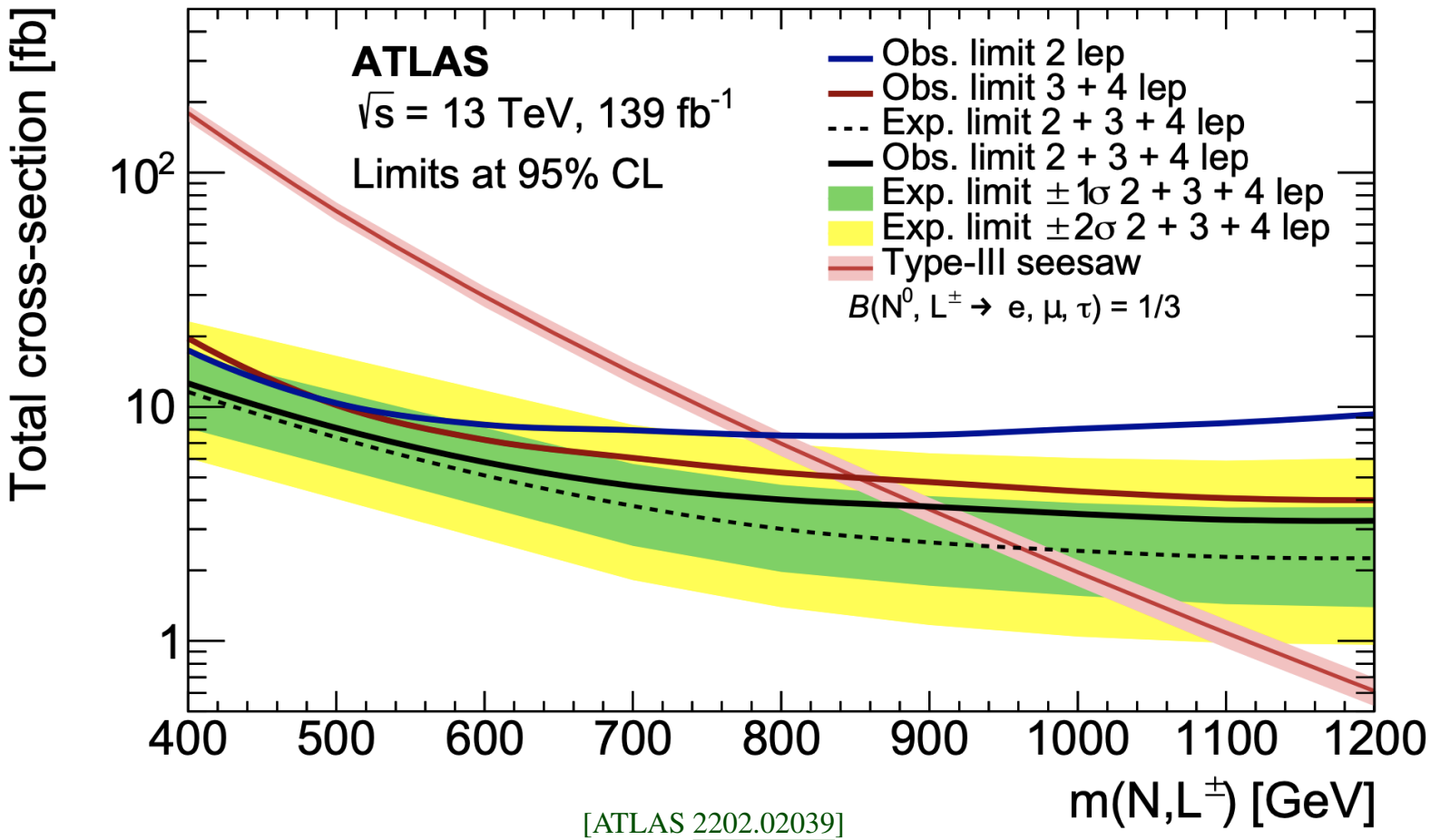


[Klarić, Shaposhnikov, Timiryasov (PRL '21); Drewes, Georis, Klarić, 2106.16226 (PRL '22)]

$SU(2)_L$-Triplet Fermions

Type-III seesaw [Foot, Lew, He, Joshi (ZPC '89); Franceschini, Hambye, Strumia (PRD '08); Fileviez Perez (JHEP '09); Biggio, Bonnet (EPJC '12); Ruiz (JHEP '15)]





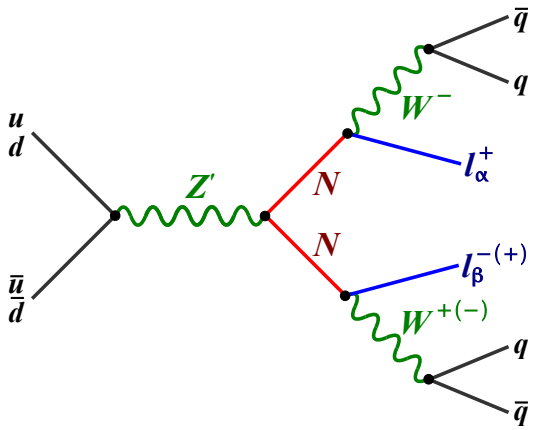
[ATLAS 2202.02039]

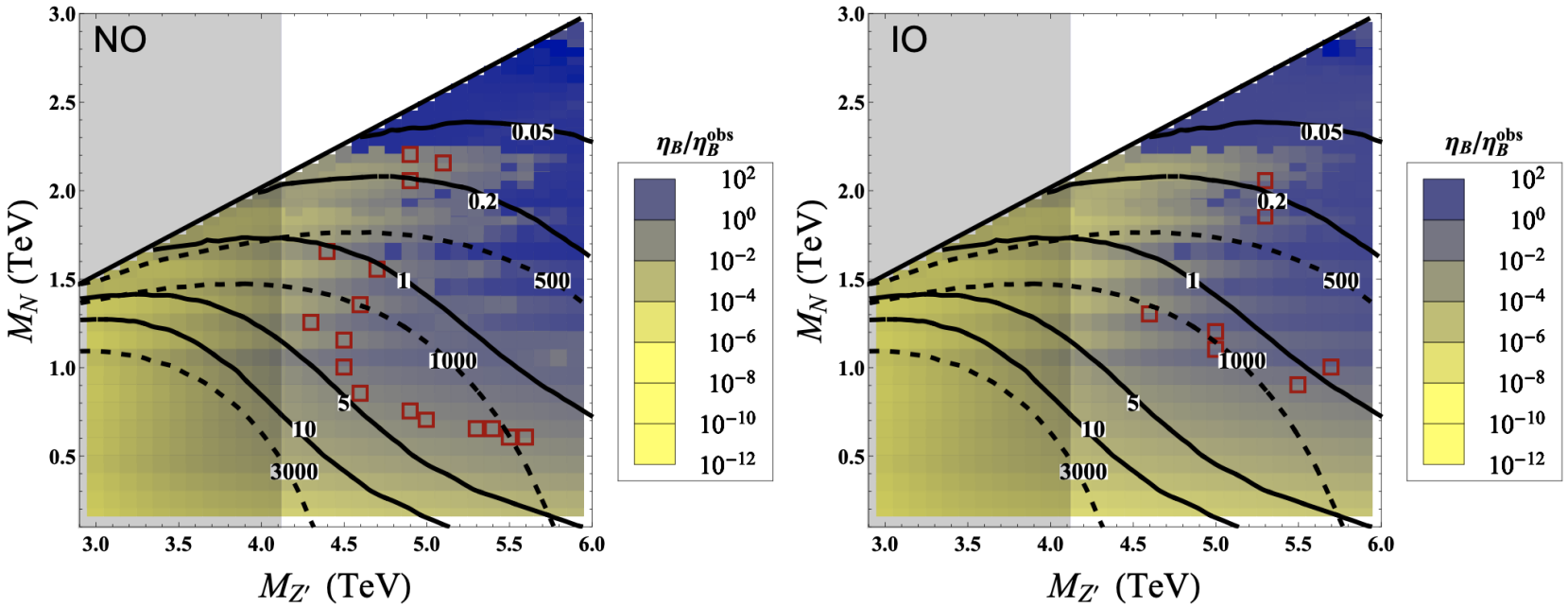
New Gauge Bosons

(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);...]

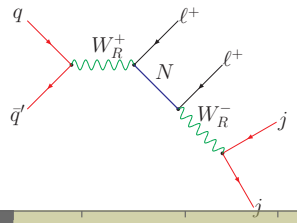


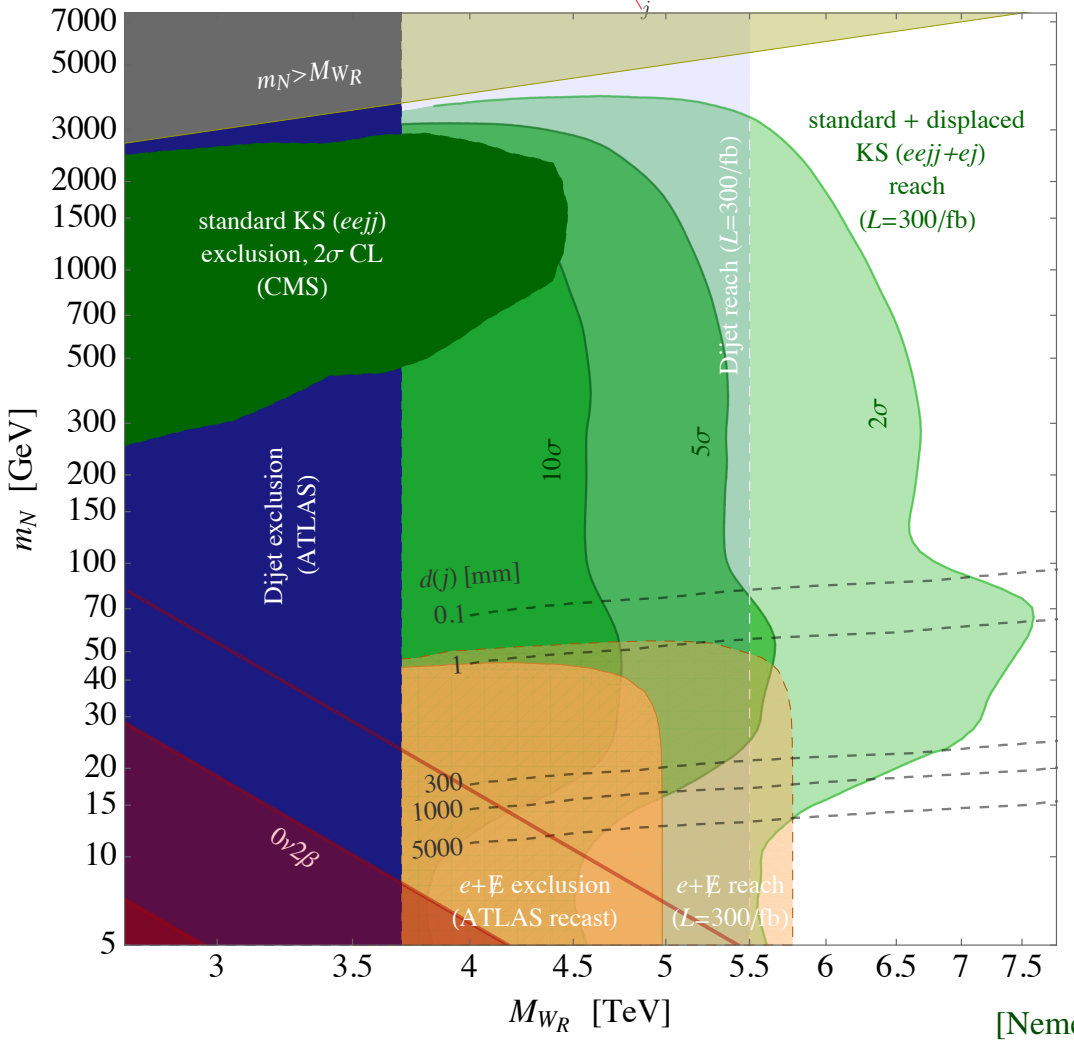


[Chauhan, BD, 2112.09710]

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);...]



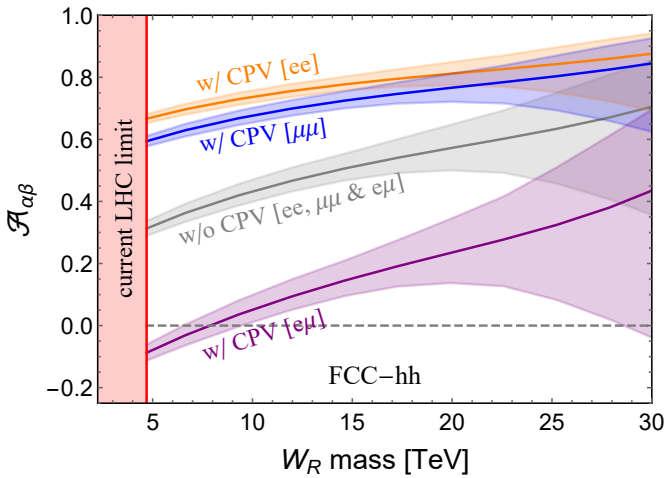


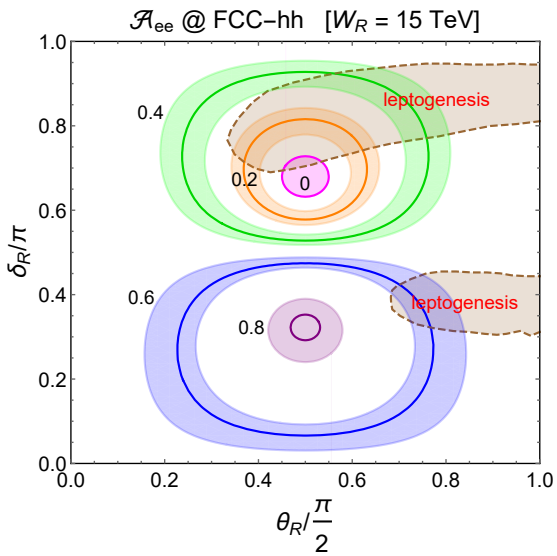
[Nemevsek, Nesti, Popara (PRD '18)]

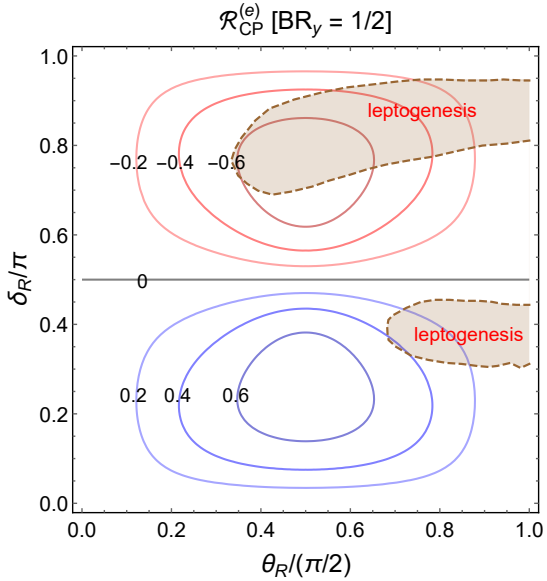
CP Violation in the RHN Sector

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

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







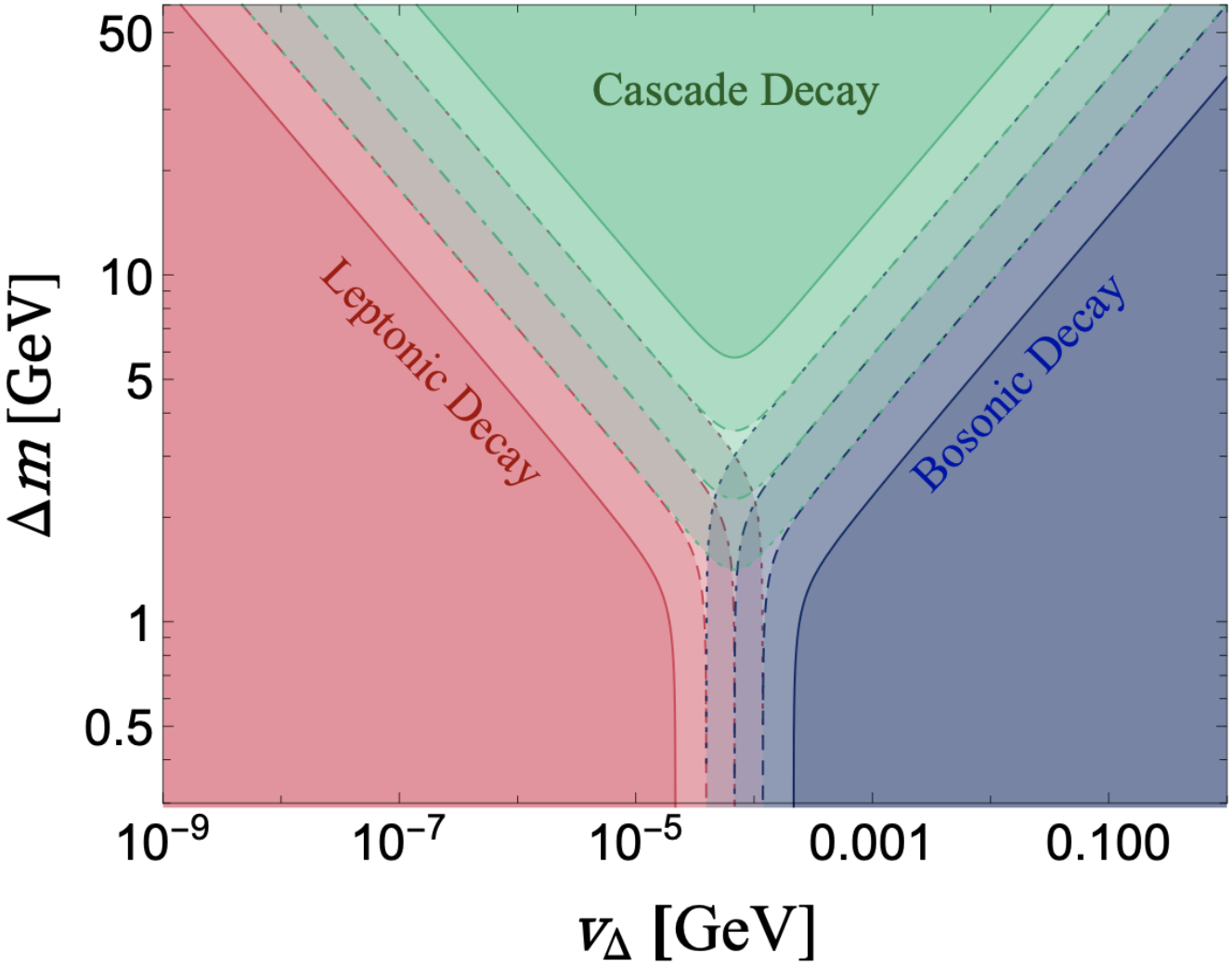
[BD, Mohapatra, Zhang, 1904.04787 (JHEP '19)]

A direct test of CP Violation in the RHN Sector

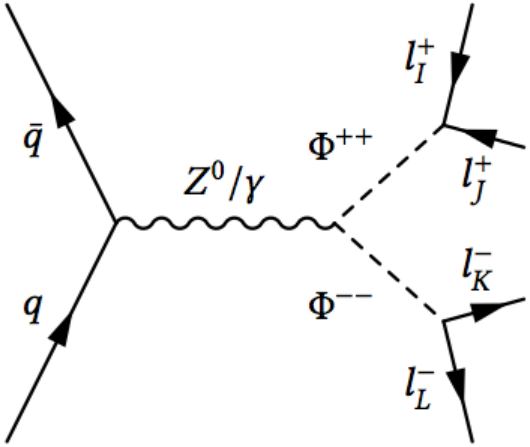
New Scalars

$SU(2)_L$-Triplet Scalar

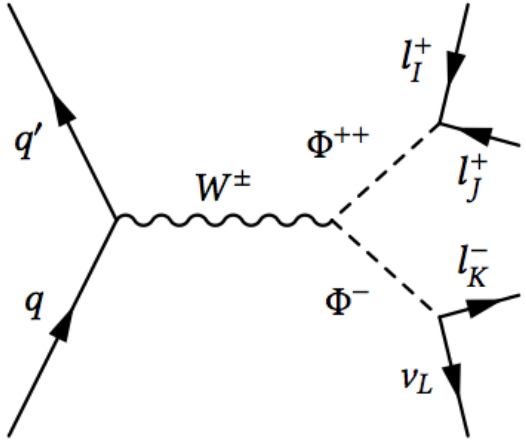
- **Type-II seesaw** [Magg, Wetterich (PLB '80); Schechter, Valle (PRD '80); Lazarides, Shafi, Wetterich (NPB '81); Mohapatra, Senjanovic (PRD '81)]
- Collider signatures depend on the triplet VEV. [Fileviez Perez, Han, Huang, Li, Wang (PRD '08); Melfo, Nemevsek, Nesti, Senjanovic, Zhang (PRD '12); BD, Zhang (JHEP '18); Du, Dunbrack, Ramsey-Musolf, Yu (JHEP '19); ...]



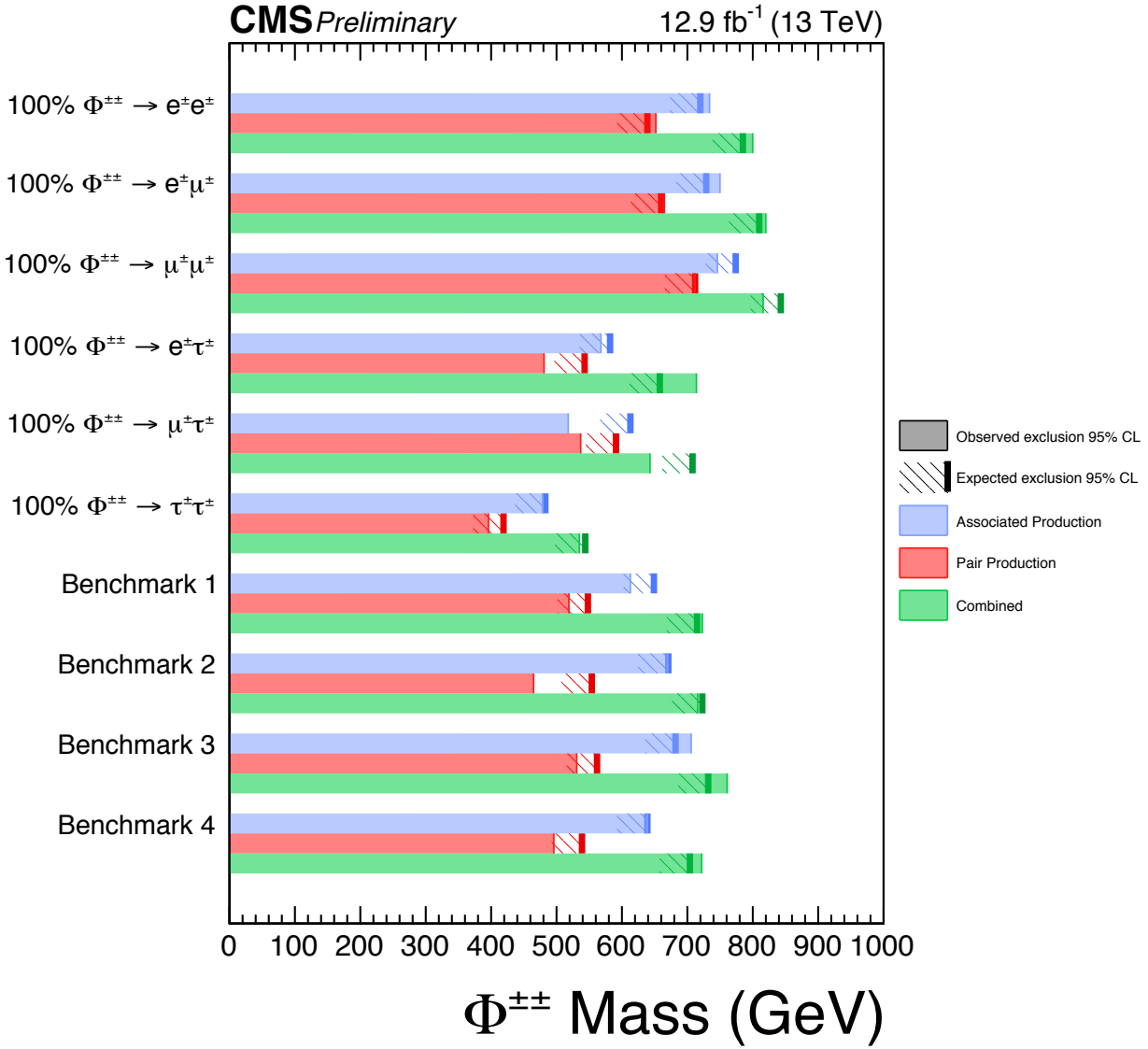
$SU(2)_L$-Triplet Scalar (Small v_Δ)



(a) 4ℓ

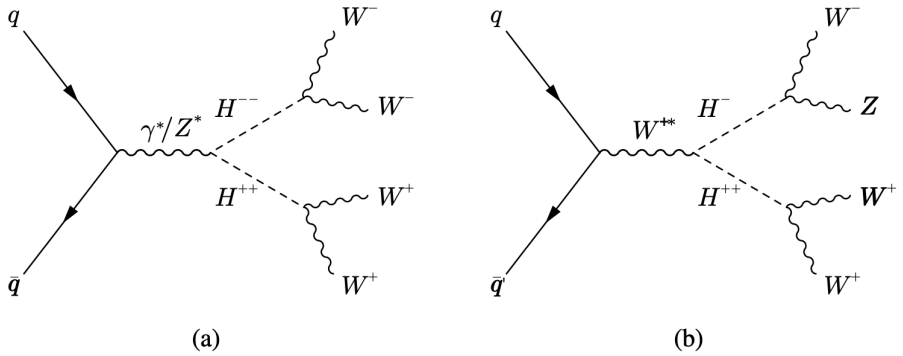


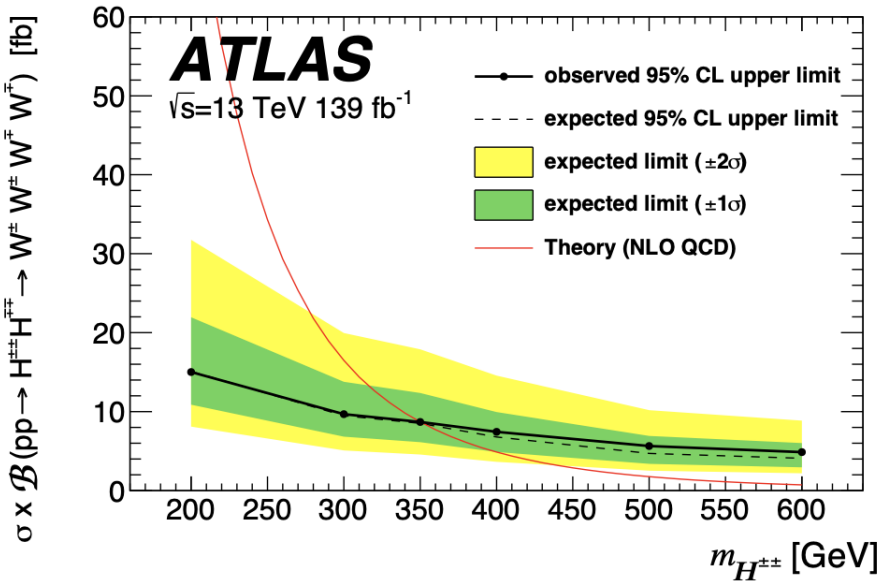
(b) 3ℓ



[CMS-PAS-HIG-16-036]

$SU(2)_L$-Triplet Scalar (Large v_Δ)

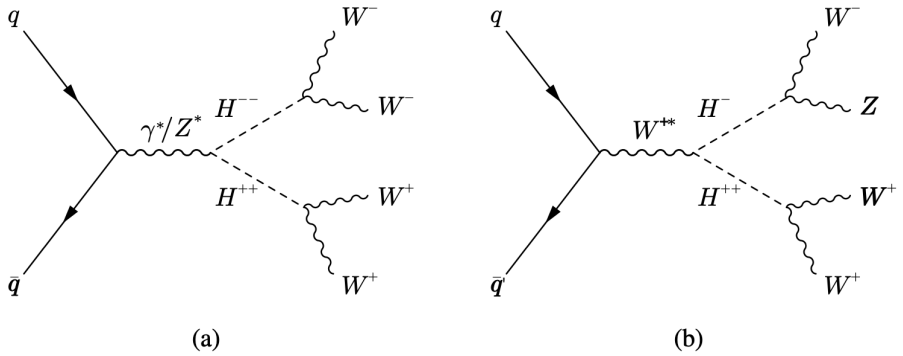


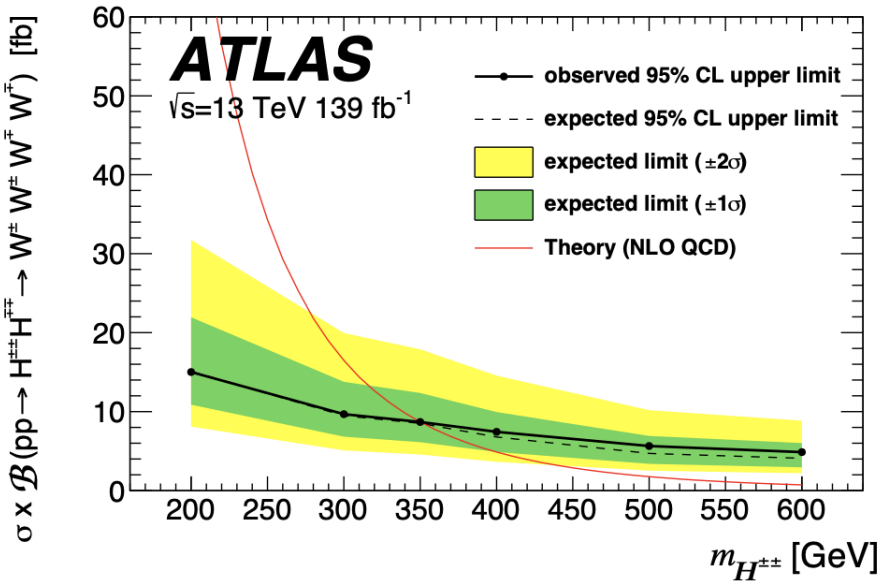


[ATLAS, 2101.11961 (JHEP '21)]

Small window remains unexplored below 200 GeV.

$SU(2)_L$-Triplet Scalar (Large v_Δ)





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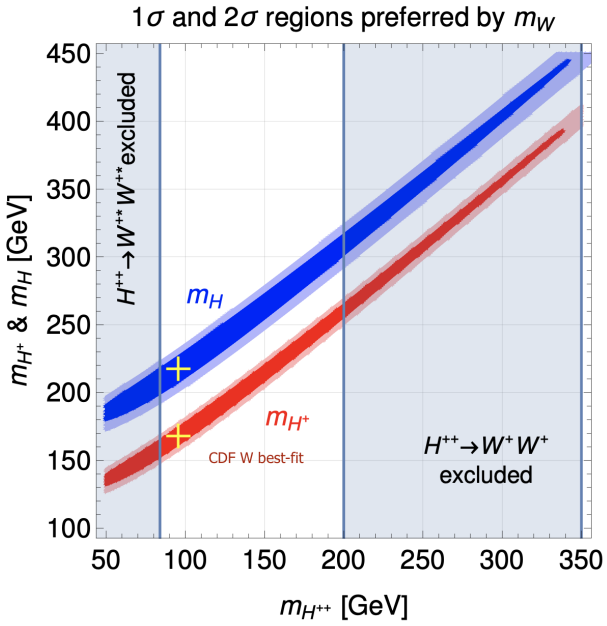
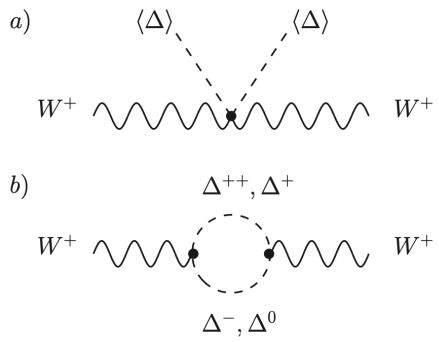


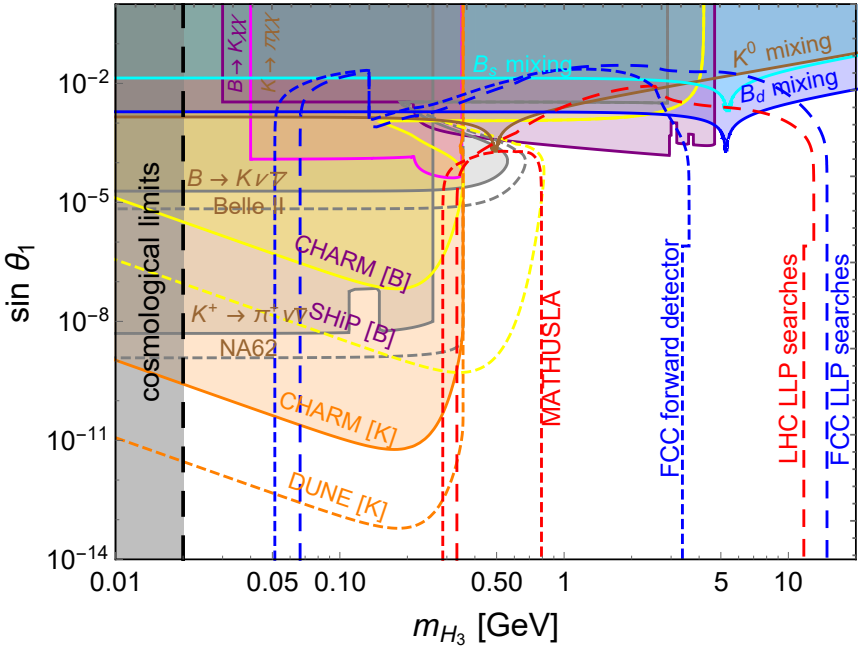


[Heeck, 2204.10274]

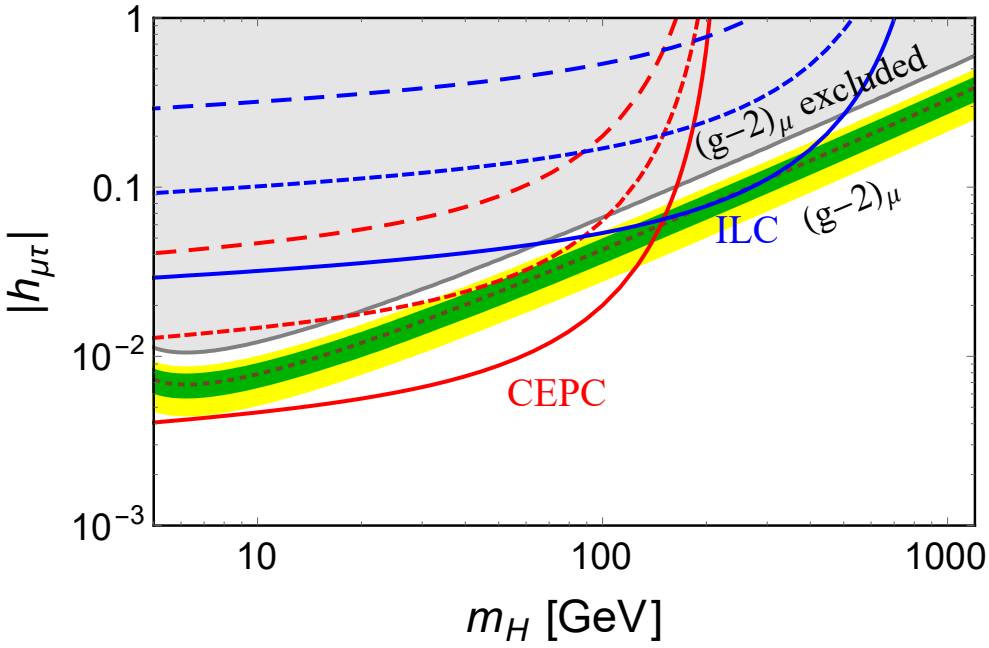
Small window remains unexplored below 200 GeV.

SM-singlet Neutral Scalar

- E.g., Neutral component of the $SU(2)_R$-triplet in LRSM.
- If hadrophobic, 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.



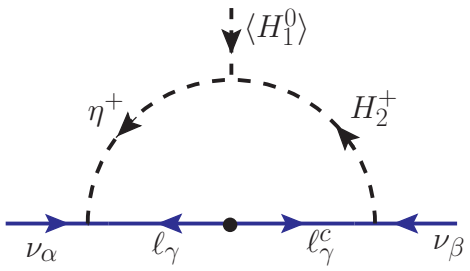
[BD, Mohapatra, Zhang (PRD '17; NPB '17)]



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

SM-singlet Charged Scalar

- Appears in radiative neutrino mass models, e.g., Zee model [Zee (PLB '80)].
- Can be as light as 100 GeV. [Babu, BD, Jana, Thapa, 1907.09498 (JHEP '20)]
- Potentially observable non-standard neutrino interactions. [Babu, BD, Jana, 2202.06975]



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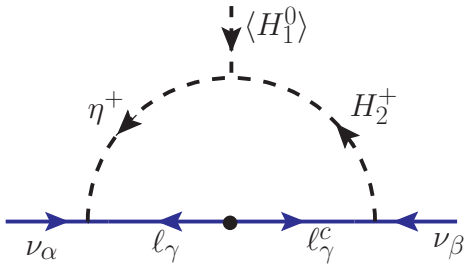

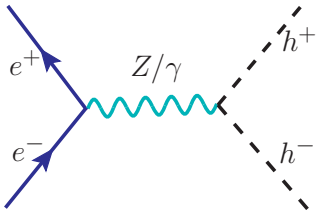

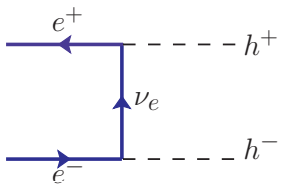

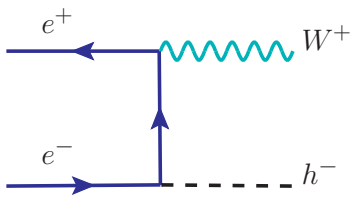

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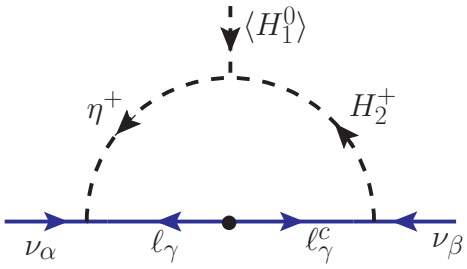
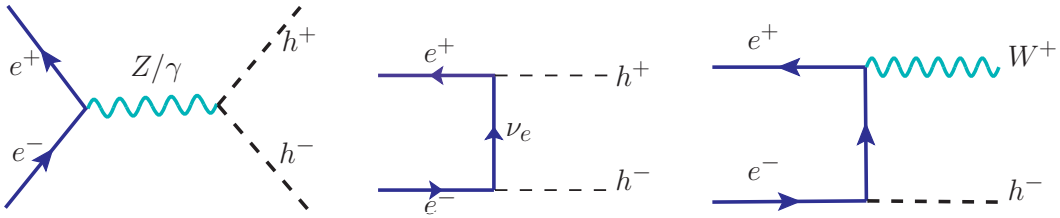
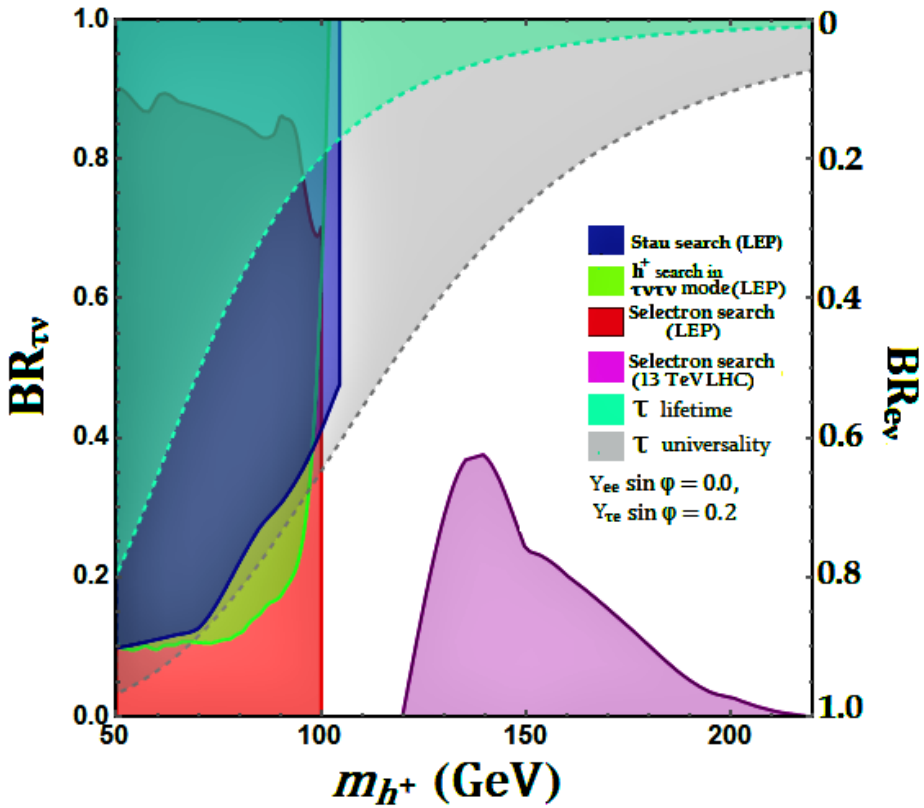
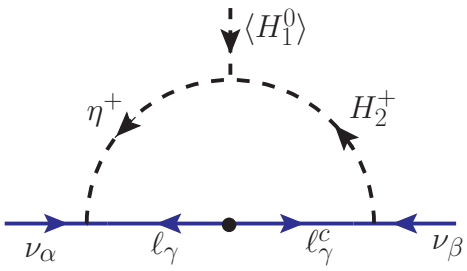


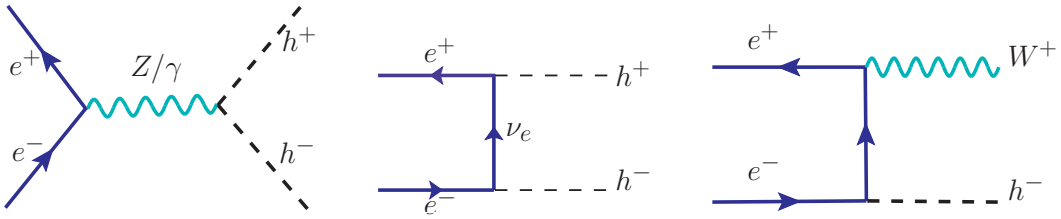


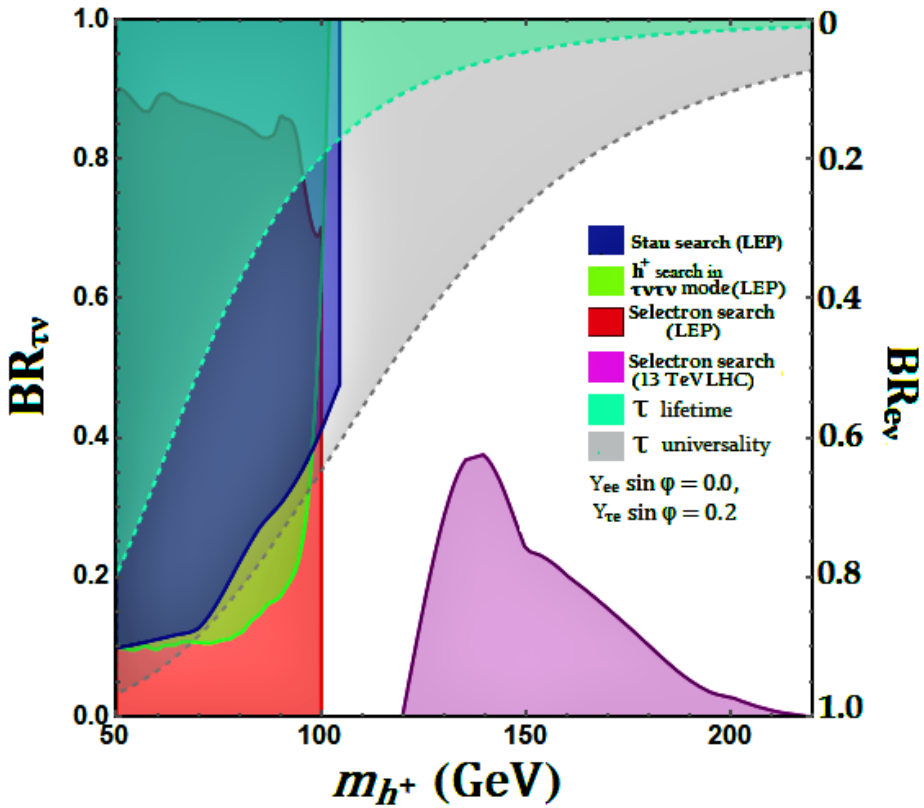


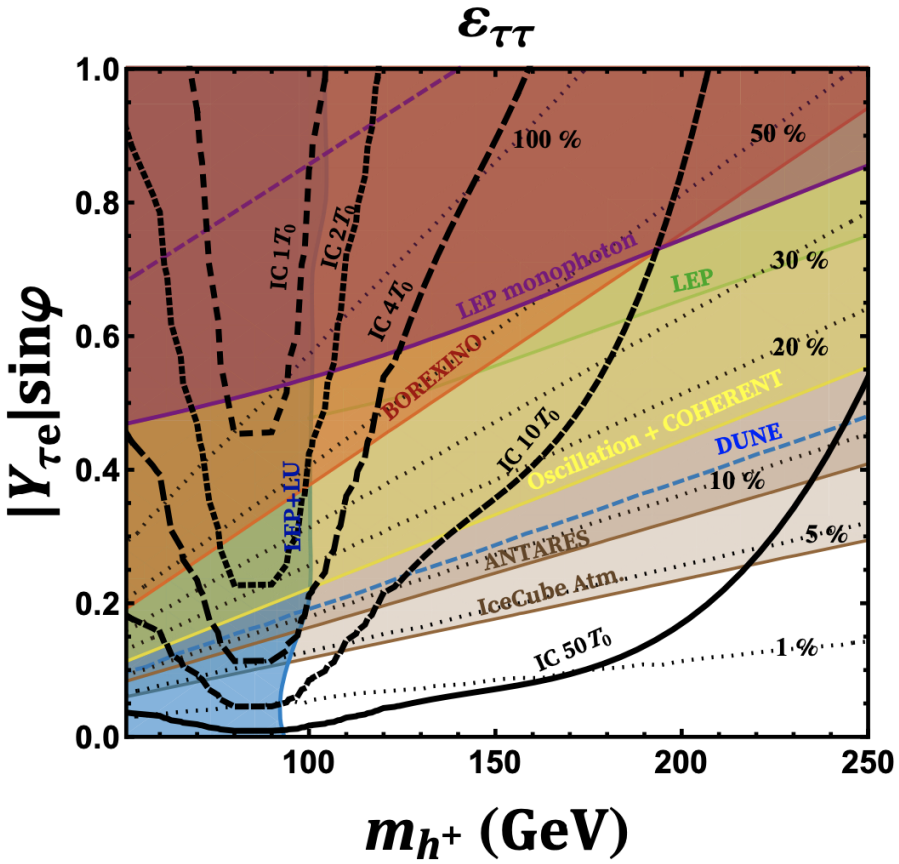
SM-singlet Charged Scalar

- Appears in radiative neutrino mass models, e.g., Zee model [Zee (PLB '80)].
- Can be as light as 100 GeV. [Babu, BD, Jana, Thapa, 1907.09498 (JHEP '20)]
- Potentially observable non-standard neutrino interactions. [Babu, BD, Jana, 2202.06975]



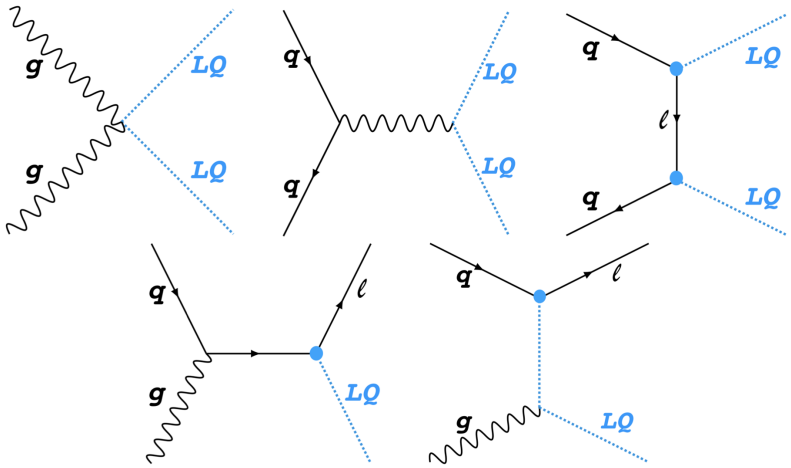


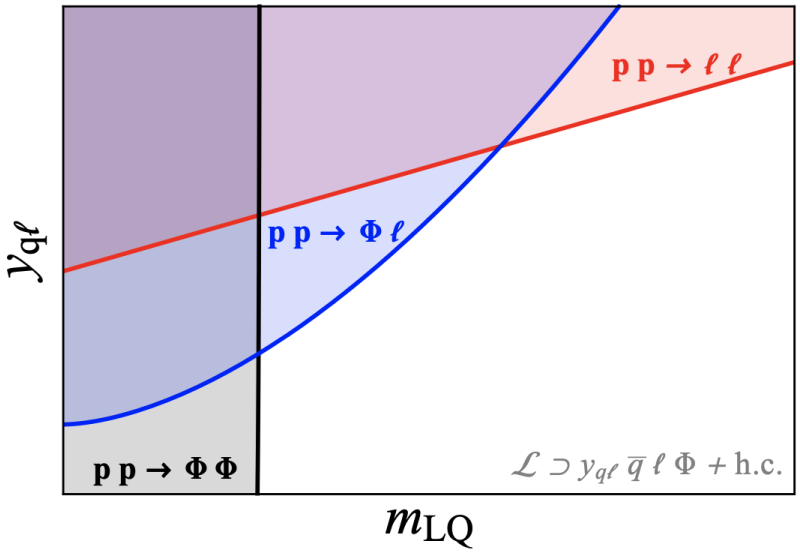




Leptoquarks

- Also appear in radiative neutrino mass models, e.g., colored Zee model and RPV SUSY.
- $SU(3)_c$ triplets $\Longrightarrow$ Strong limits from the LHC.
- Three types: pair-production, single-production and indirect dilepton limits.





[Doršner, Greljo, 1801.07641 (JHEP '18)]

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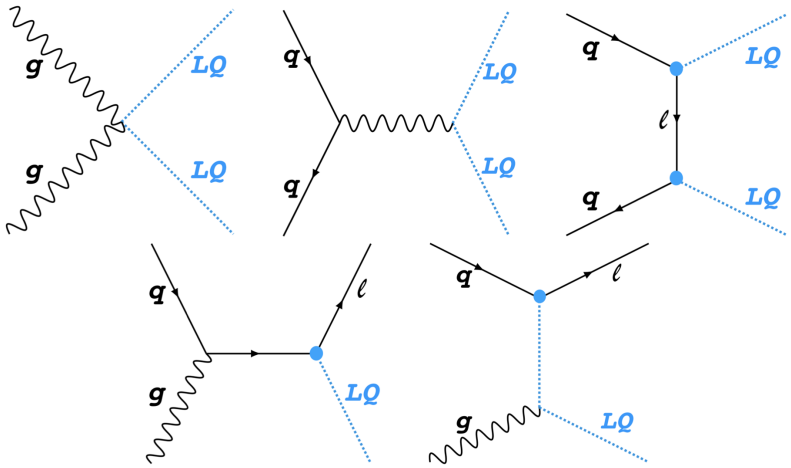
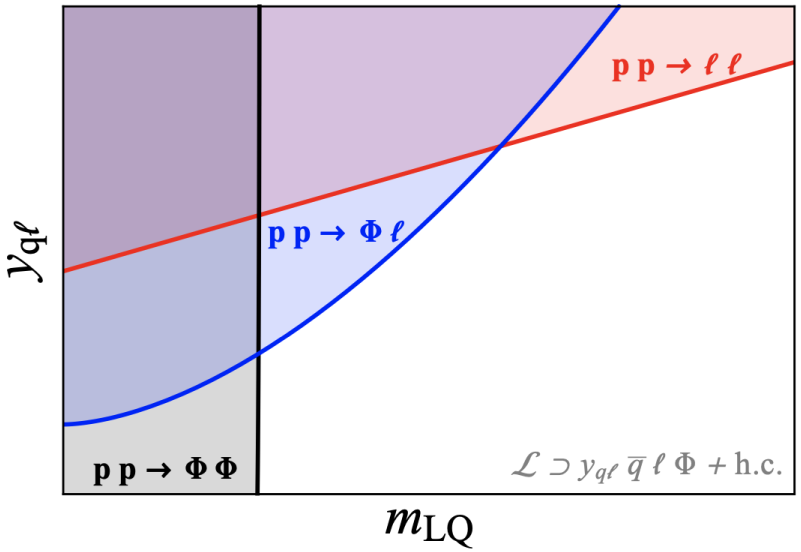




[Doršner, Greljo, 1801.07641 (JHEP '18)]

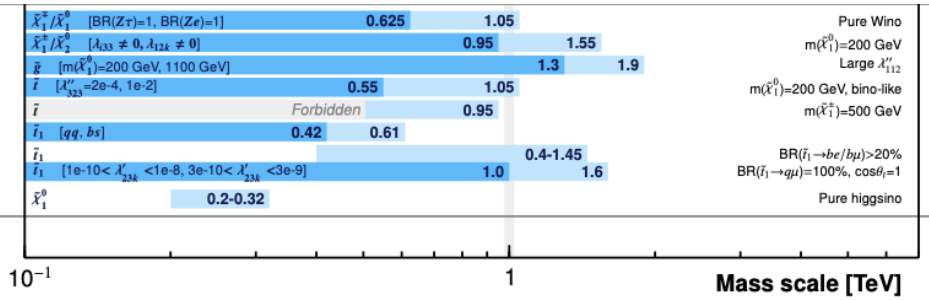
Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_3 $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
S_1 $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
R_2 $(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗
U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

[Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, 2103.12504 (PRD '21)]

RPV SUSY

$$W_{\mathrm{RPV}} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$$

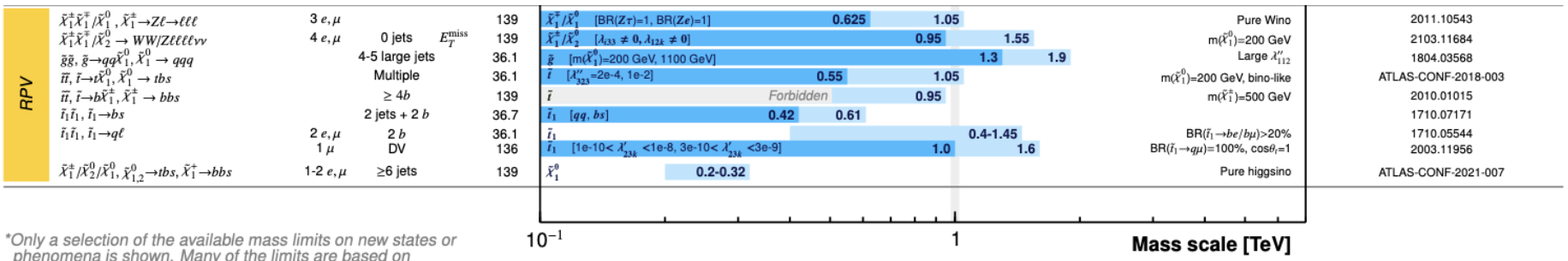
RPV	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm \to Z\ell \to \ell\ell\ell$	3 e,μ		139	Pure Wino	2011.10543
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets E_T^{miss}	139	m($\tilde{\chi}_1^0$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g} \to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to qqq$		4-5 large jets	36.1	Large λ''_{112}	1804.03568
	$\tilde{t}\tilde{t}$, $\tilde{t} \to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to tbs$		Multiple	36.1	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t} \to b\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \to bbs$		$\geq 4b$	139	m($\tilde{\chi}_1^\pm$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to bs$		2 jets + 2 b	36.7		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to q\ell$	2 e,μ	2 b	36.1	BR($\tilde{t}_1 \to be/b\mu$)>20%	1710.05544
		1 μ	DV	136	BR($\tilde{t}_1 \to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0$, $\tilde{\chi}_{1,2}^0 \to tbs$, $\tilde{\chi}_1^\pm \to bbs$	1-2 e,μ	$\geq$6 jets	139	Pure higgsino	ATLAS-CONF-2021-007

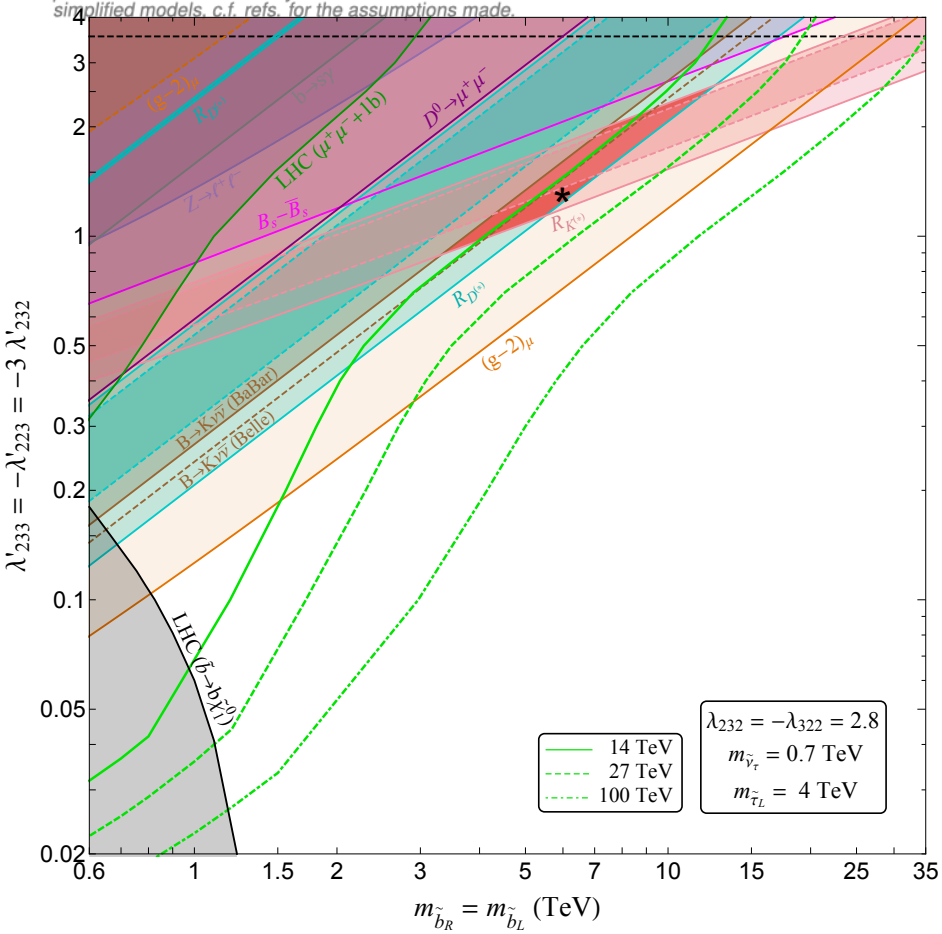


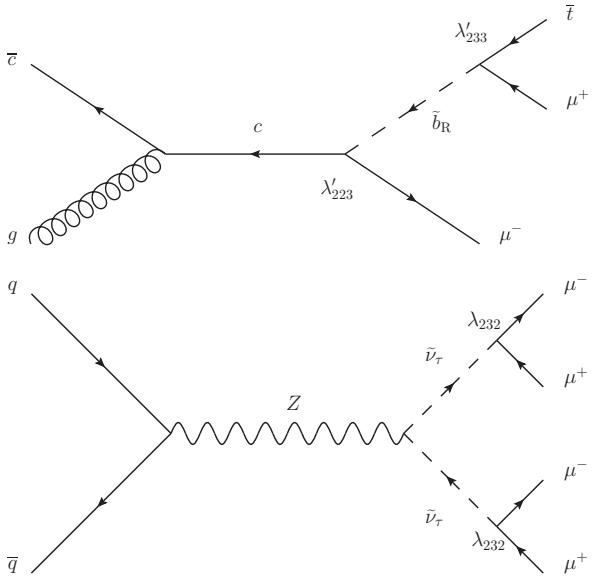
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

RPV SUSY

$$W_{\rm RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k$$







Distinct collider tests of the B-anomalies and the muon $g-2$.

[BD, Soni, Xu, 2106.15647]

Conclusion

- Discovery of $B - L$ Violation would be a clear BSM signal.
- Deep connection to neutrino mass physics and baryogenesis.
- Current and future colliders provide a ripe testing ground for low-scale $B - L$ breaking effects.
- Can probe the seesaw messengers (new fermions/gauge bosons/scalars) in a wide range of parameter space.
- Healthy complementarity at the intensity frontier.
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- Might explain some of the current experimental anomalies.

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Thank You!