Workshop

Summary

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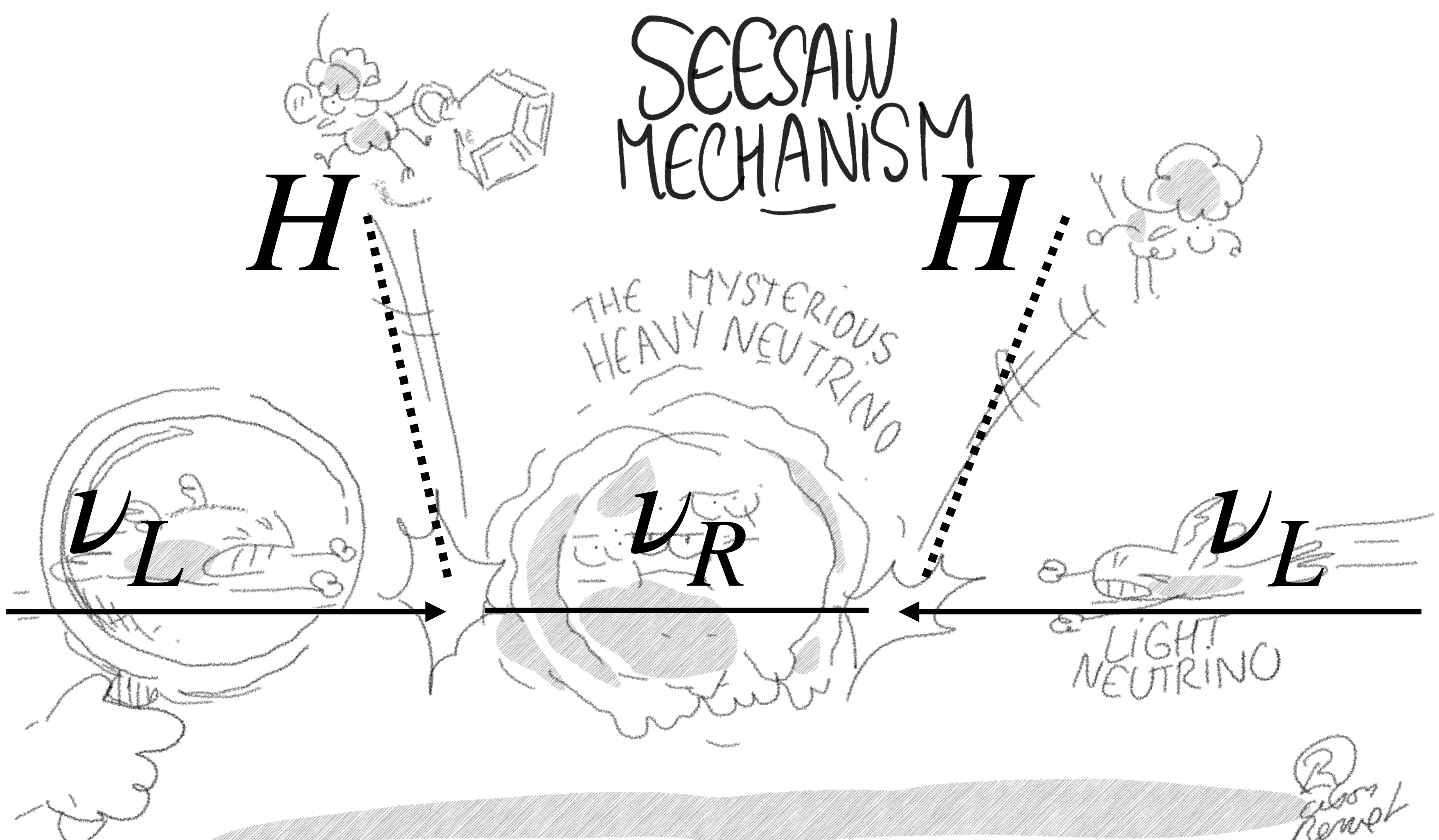
Summary

Why new νs?

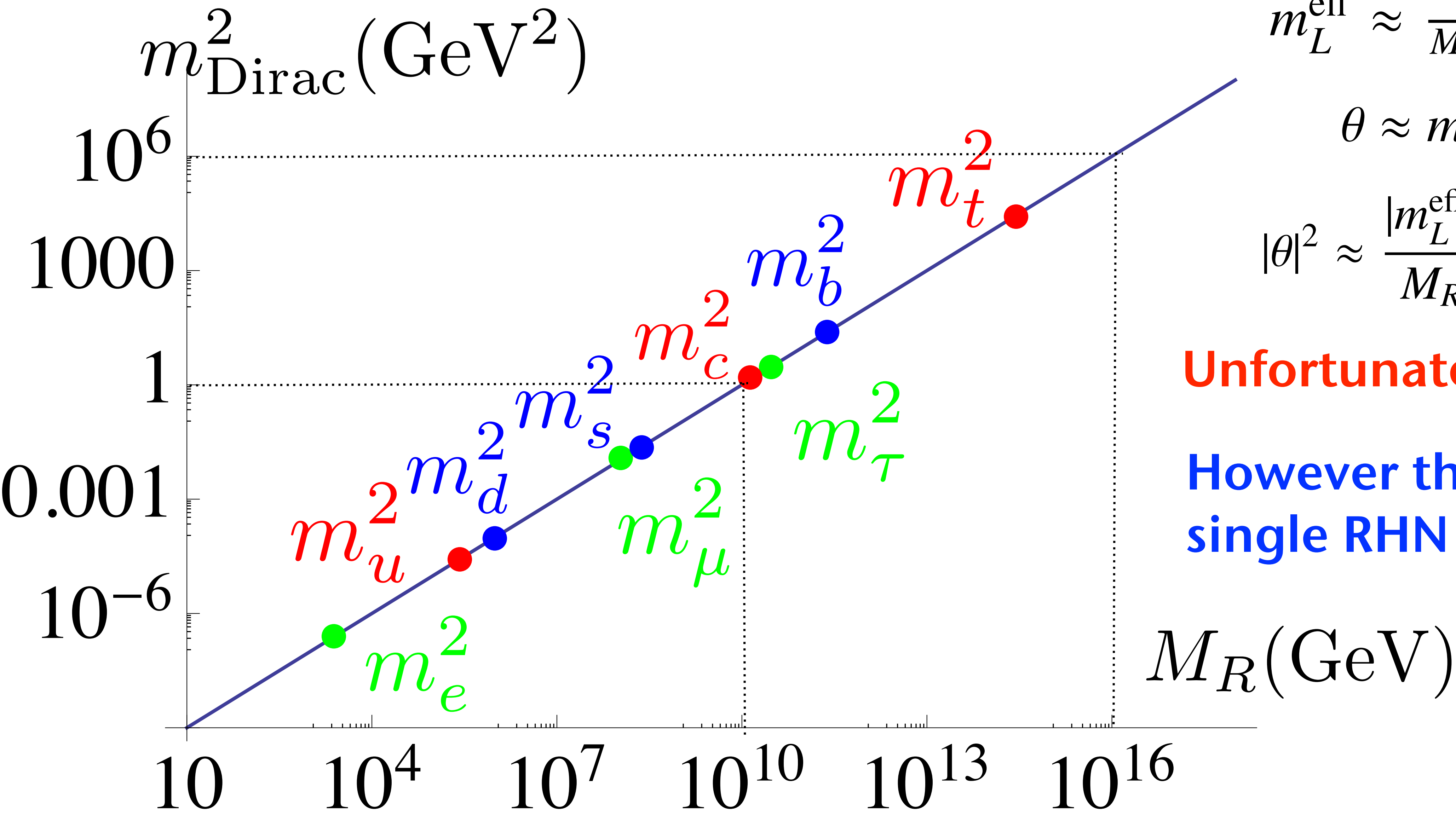
Yukawas **Weinberg**

$$\mathcal{L}^{\rm lepton}_{\rm mass} = -\bar{e}_{Li} m^{e}_{ij} e_{Rj} - \frac{1}{2}\overline{\nu_{Li}} m^{\nu}_{ij} \nu^{c}_{Lj} + H.c.$$



Steve King

Why new νs?



$$m_L^{\mathrm{eff}} \approx \frac{m_D^2}{M_R} \approx 0.1 \text{ eV},$$

$$\theta \approx m_D/M_R$$

$$|\theta|^2 \approx \frac{|m_L^{\mathrm{eff}}|}{M_R} \approx 10^{-10}\left(\frac{1\mathrm{GeV}}{M_R}\right)$$

Unfortunately this is very small

However this is for unrealistic single RHN case…

Steve King

Why new νs?

E.g. Littlest Seesaw gives good fit to data

$$d = 0 \qquad b = 3a$$
$$e = f \qquad c = a$$
$$\arg(a^2/e^2) = \exp(2\pi i/3)$$

$$\Rightarrow$$

$$\theta_{23} \approx 45^o$$
$$\theta_{12} \approx 34^o$$
$$\theta_{13} \approx 8.5^o$$
$$\delta \approx 270^o$$

Predicts

U_e^2

U_μ^2

$$|\theta_{lN}|^2 \approx \begin{pmatrix} 0 & \frac{m_2}{3M_{\rm sol}} \\ \frac{m_3}{2M_{\rm atm}} & \frac{3m_2}{M_{\rm sol}} \\ \frac{m_3}{2M_{\rm atm}} & \frac{m_2}{3M_{\rm sol}} \end{pmatrix} \approx \begin{pmatrix} 0 & 0.03 \\ 0.25 & 0.26 \\ 0.25 & 0.03 \end{pmatrix} \times 10^{-10} \left(\frac{1\text{GeV}}{M}\right)$$

Both smaller than SRHN estimate

E.g. Minimal Inverse Seesaw model

$$m_D = \begin{pmatrix} d & a \\ e & b \\ f & c \end{pmatrix}, \qquad M = \begin{pmatrix} M_{\rm atm} & 0 \\ 0 & M_{\rm sol} \end{pmatrix}, \qquad \mu = \begin{pmatrix} \mu_{\rm atm} & 0 \\ 0 & \mu_{\rm sol} \end{pmatrix}$$

Inverse seesaw formula $m_\nu = m_D (M^T)^{-1} \mu M^{-1} m_D^T$

$$m^\nu = \frac{\mu_{\rm atm}}{M_{\rm atm}^2} \begin{pmatrix} d^2 & de & df \\ de & e^2 & ef \\ df & ef & f^2 \end{pmatrix} + \frac{\mu_{\rm sol}}{M_{\rm sol}^2} \begin{pmatrix} a^2 & ab & ac \\ ab & b^2 & bc \\ ac & bc & c^2 \end{pmatrix}$$

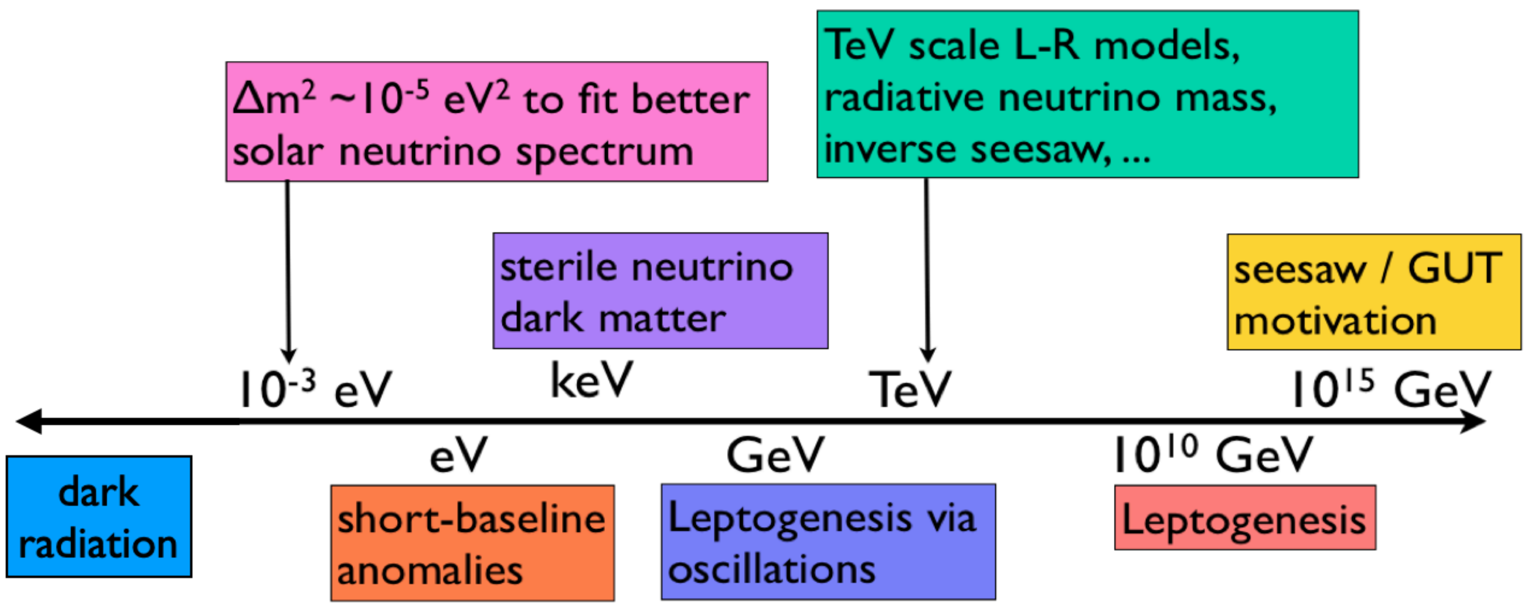
Littlest Inverse Seesaw predicts

$$|\theta_{lN}|^2 \approx \begin{pmatrix} 0 & \frac{m_2}{3\mu_{\rm sol}} \\ \frac{m_3}{2\mu_{\rm atm}} & \frac{3m_2}{\mu_{\rm sol}} \\ \frac{m_3}{2\mu_{\rm atm}} & \frac{m_2}{3\mu_{\rm sol}} \end{pmatrix}$$

HNL mixing enhanced by small μ

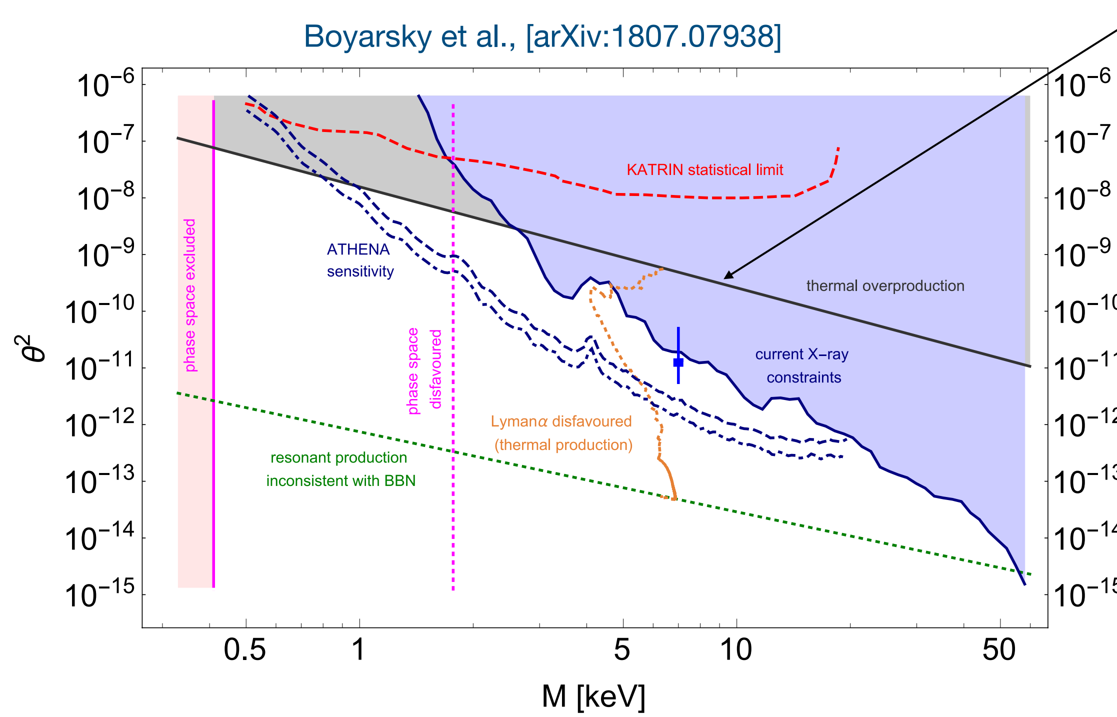
Steve King

Why new νs?



new-ν dark matter: 1 keV – 100 keV

minimal scenario ruled out



Thomas Schwetz

Why new νs?

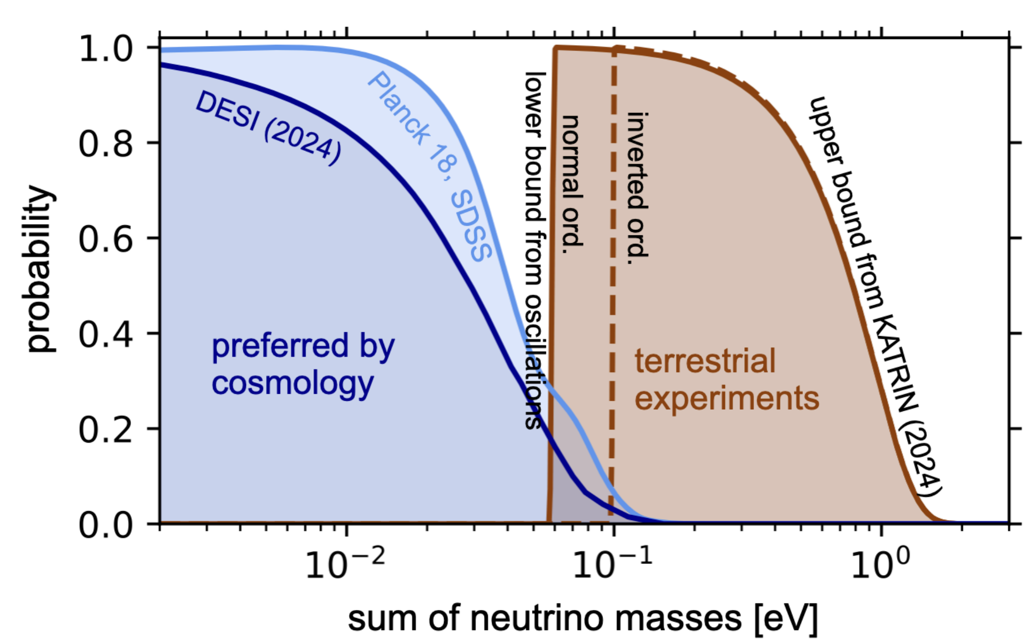
Short-baseline anomalies — summary

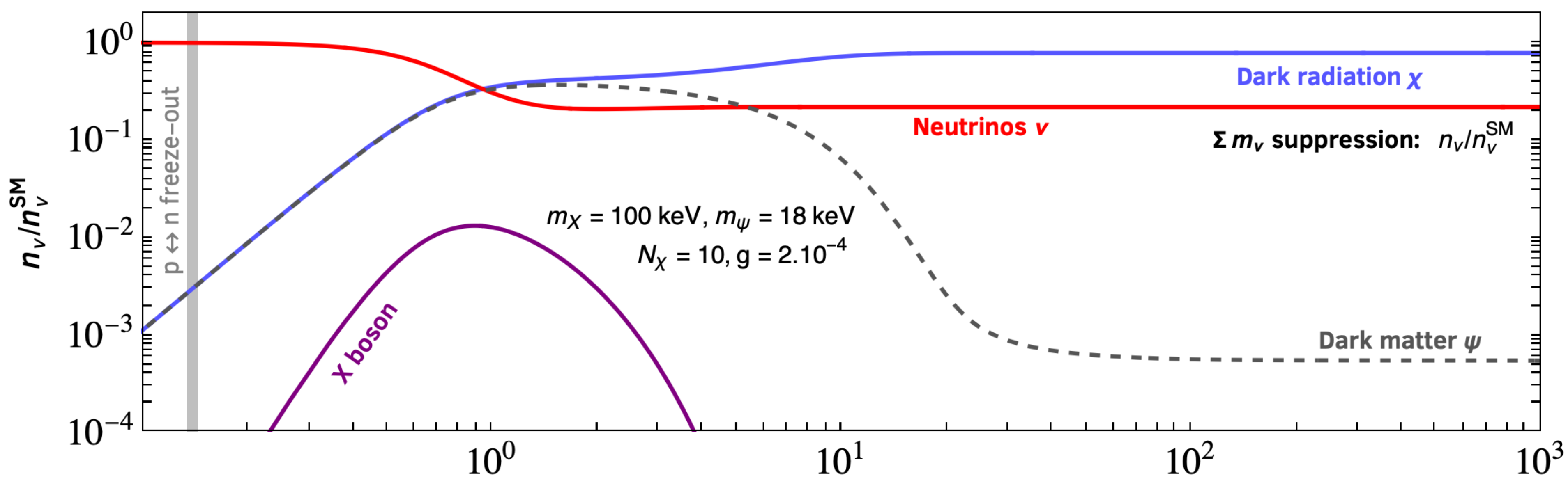
Anomaly	Channel	Status	Explanation?
Reactor rate and shape	$\nu_e \to \nu_e$	fading away ($< 2\sigma$) systematics dominated	systematics/nuclear physics
Gallium / BEST	$\nu_e \to \nu_e$	very significant ($\sim 5\sigma$)	sterile oscillations in strong tension w reactor, solar, cosmology difficult to explain exotic decoherence (?)
LSND	$\nu_\mu \to \nu_e$	significant (3.8σ) ~25 yr anomaly	sterile oscillations in strong tension w disappearance data, cosmology difficult to explain HNL decay
MiniBooNE	$\nu_\mu \to \nu_e$	very significant (4.8σ) relies on background estimate	

Thomas Schwetz

Why new νs?

Tension between cosmology and oscillation results?

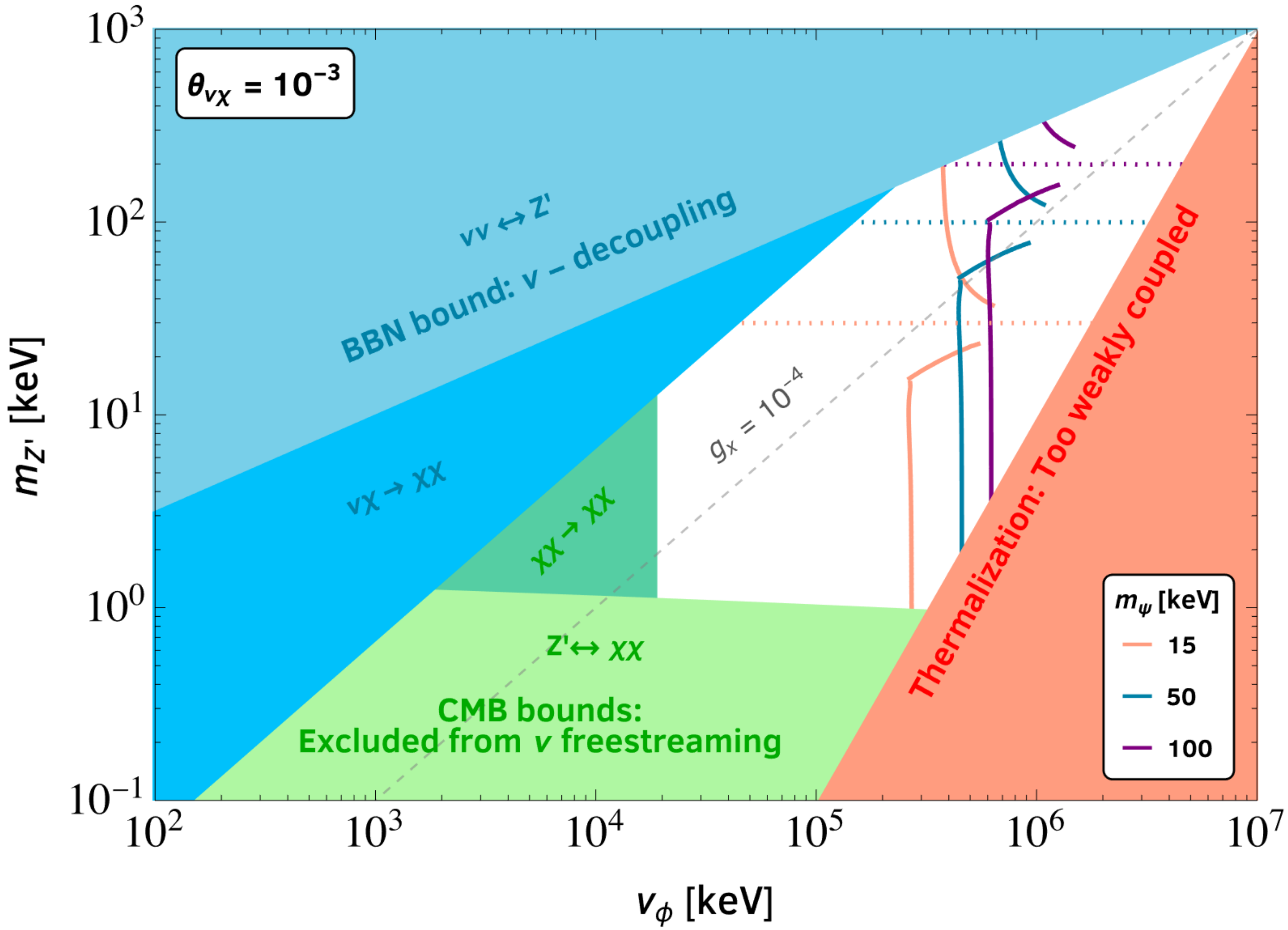


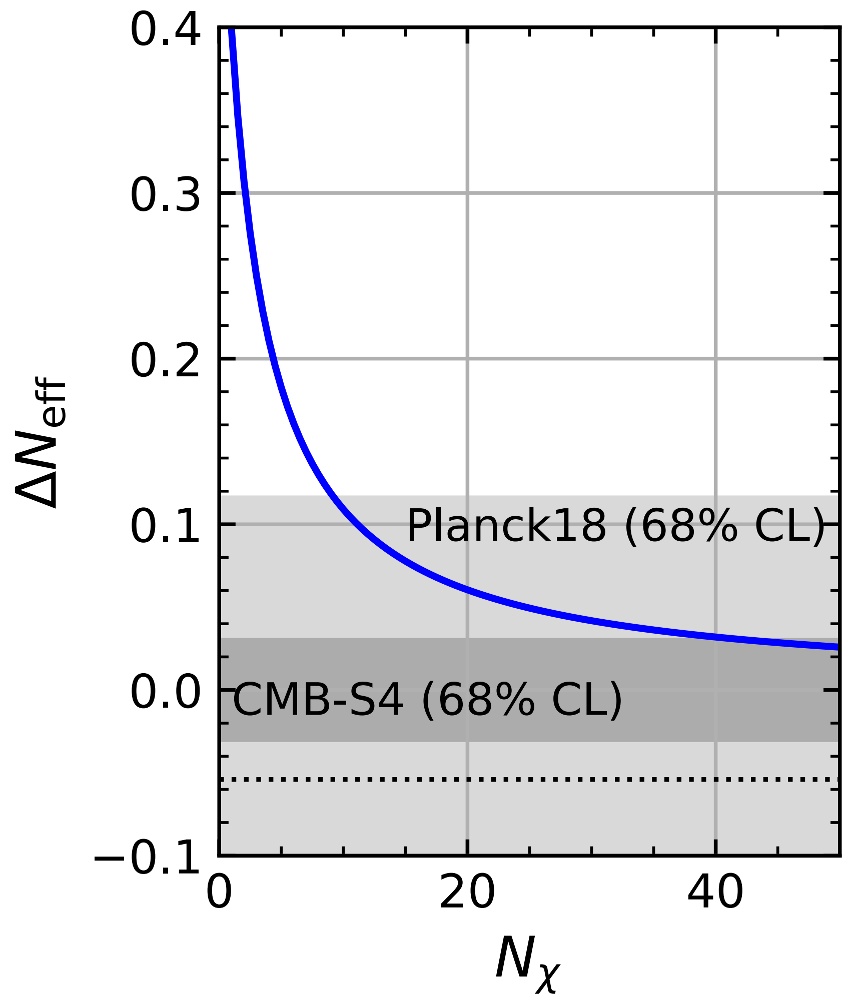


Thomas Schwetz

couplings to neutrinos induced by mixing: $Z' \leftrightarrow \nu\nu/\nu\chi/\chi\chi$

Why new νs?



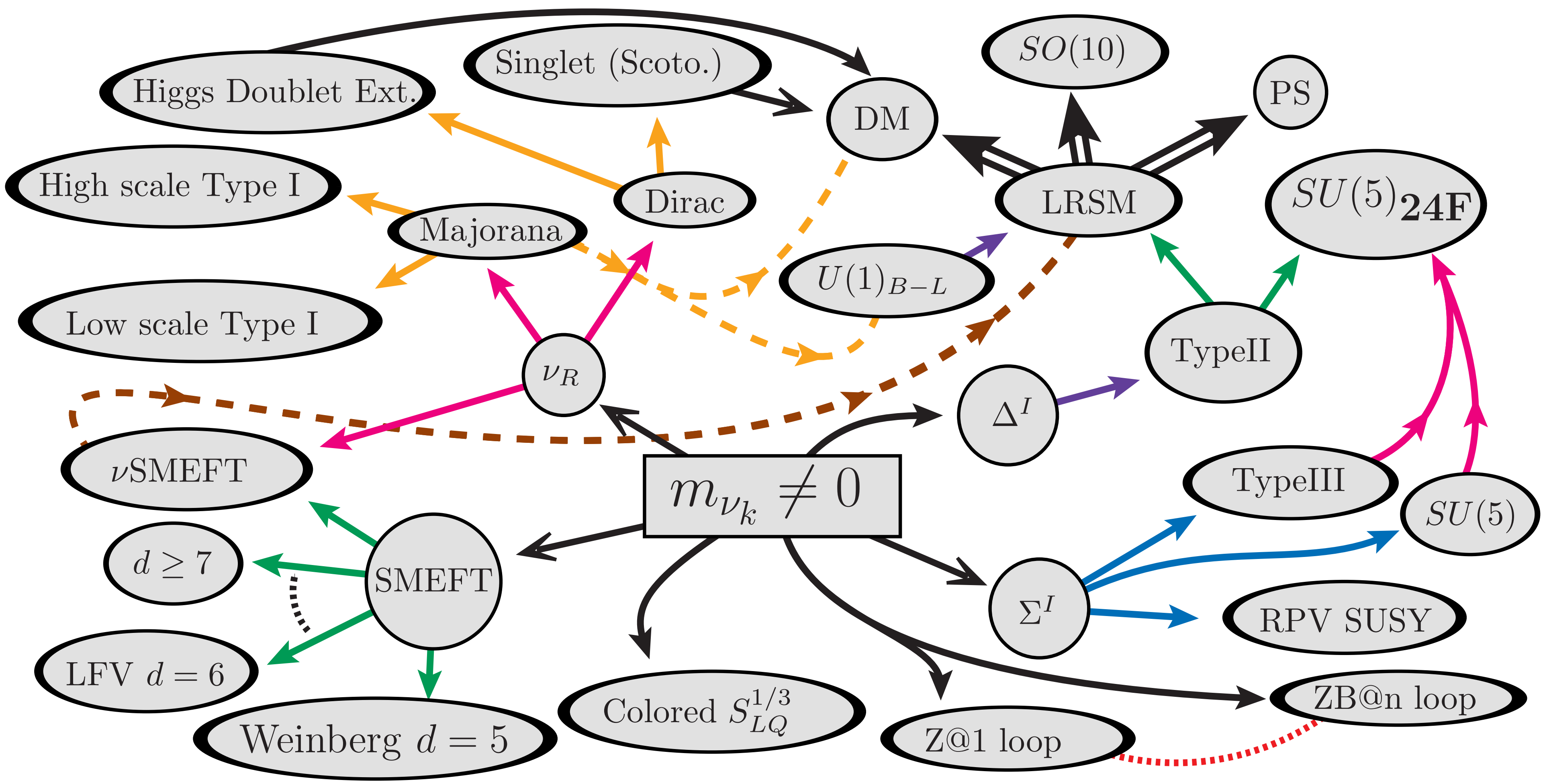


Thomas Schwetz

Lepton number/flavor violation

Theory solution to $m_\nu \neq 0$ can be realized in ***many*** ways!

Minkowski ('77); Yanagida ('79); Glashow & Levy ('80); Gell-Mann et al., ('80); Mohapatra & Senjanović ('82); + *many* others



Richard Ruiz

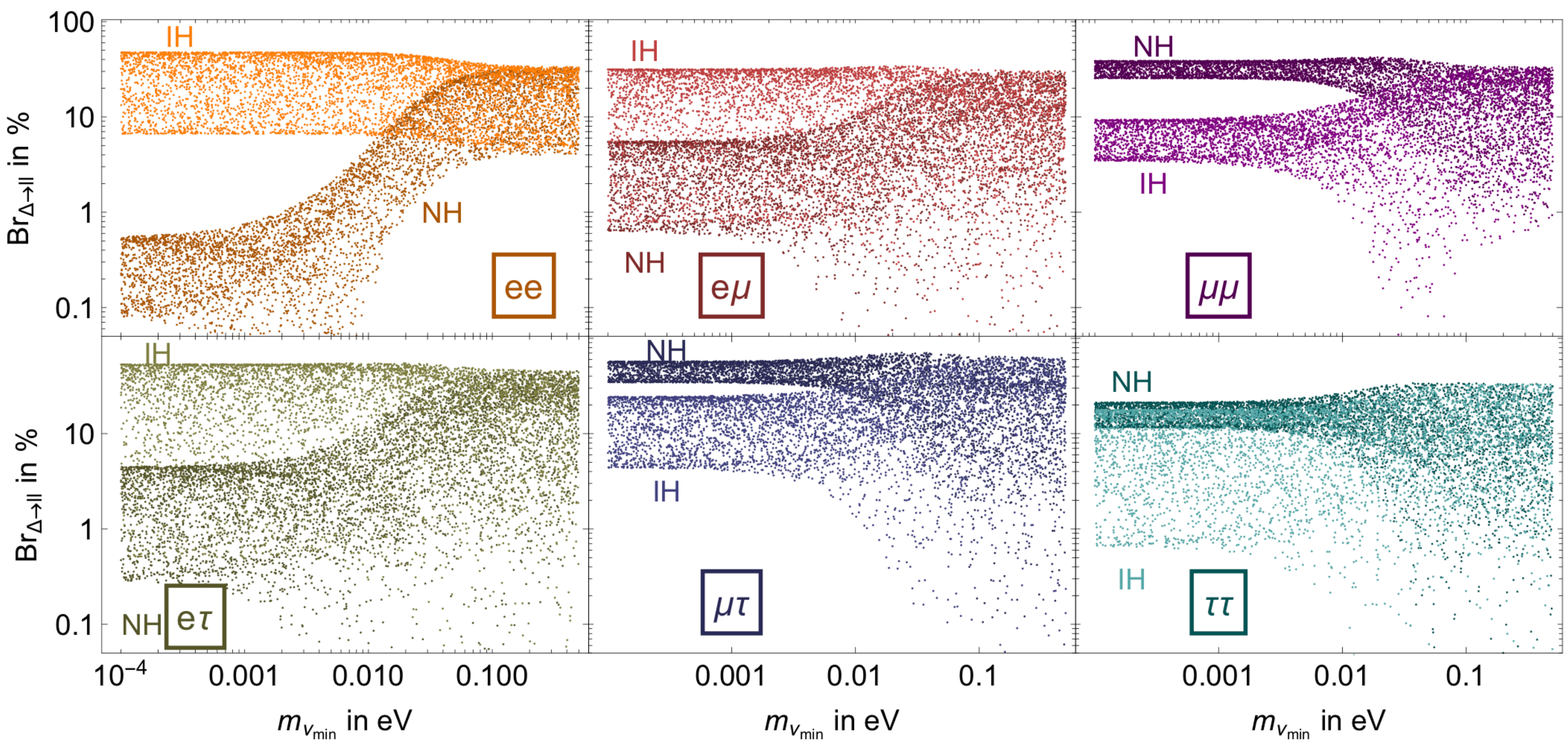
Lepton number/flavor violation

The Type II Seesaw is special: generates m_ν ***without*** hypothesizing ν_R

Hypothesize a **scalar** $\mathrm{SU}(2)_L$ triplet with **lepton number** $L = -2$

- **Example:** $\triangle$ decay rates encode inverse (IH) vs normal (NH) ordering of light neutrino masses

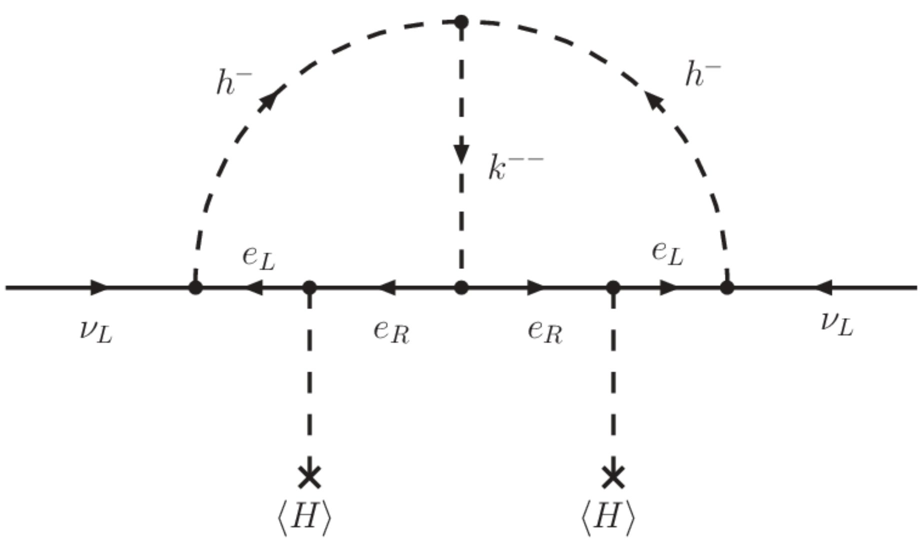
$$\Gamma(\Delta^{\pm\pm} \to \ell_i^\pm \ell_j^\pm) \sim y_\Delta^{ij} \sim (U^*_{\rm PMNS}\,\tilde{m}_\nu^{\rm diag}\,U^\dagger_{\rm PMNS})_{ij}$$



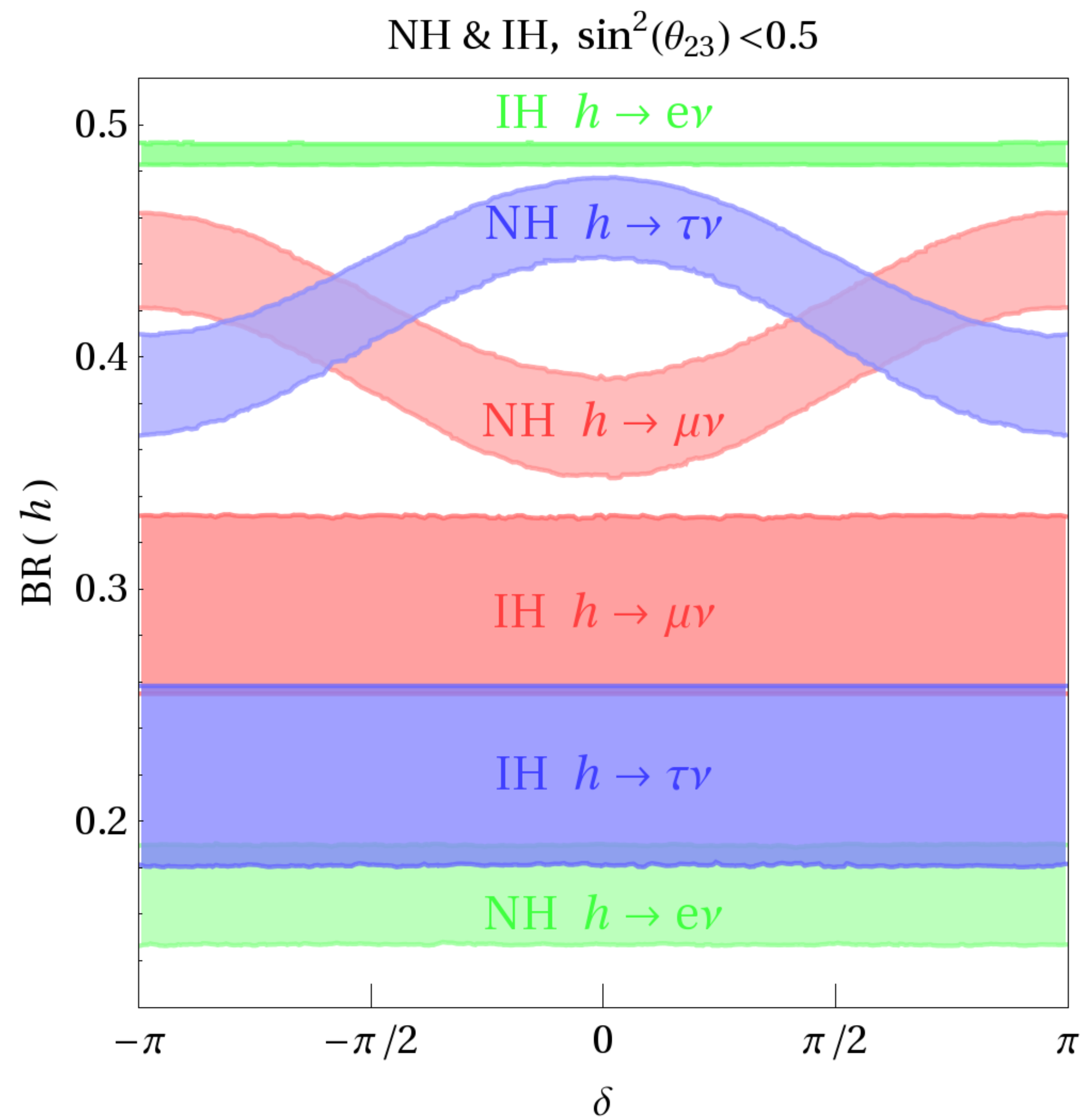
Richard Ruiz

Lepton number/flavor violation

Zee-Babu model generates m_ν radiatively ***without*** hypothesizing ν_R



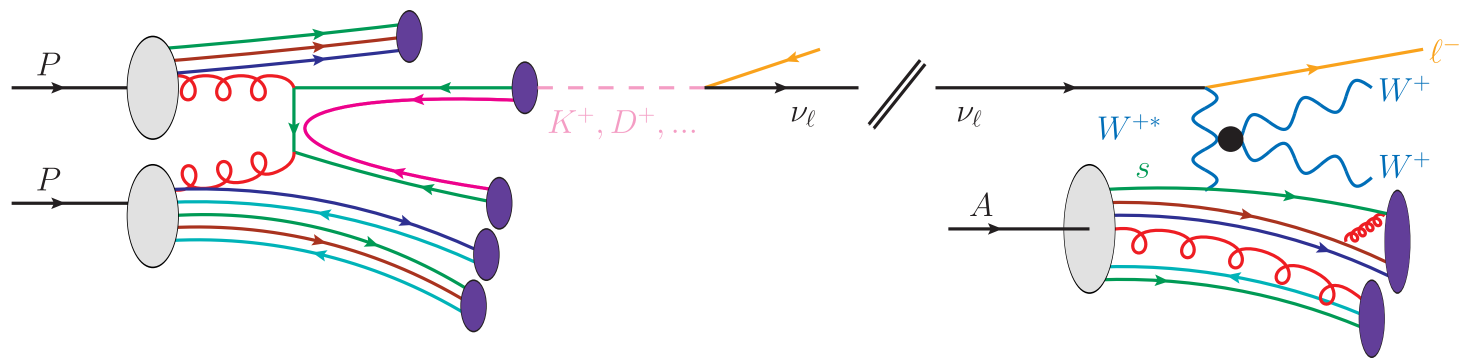
Few free parameters $\implies$ rich experimental predictions



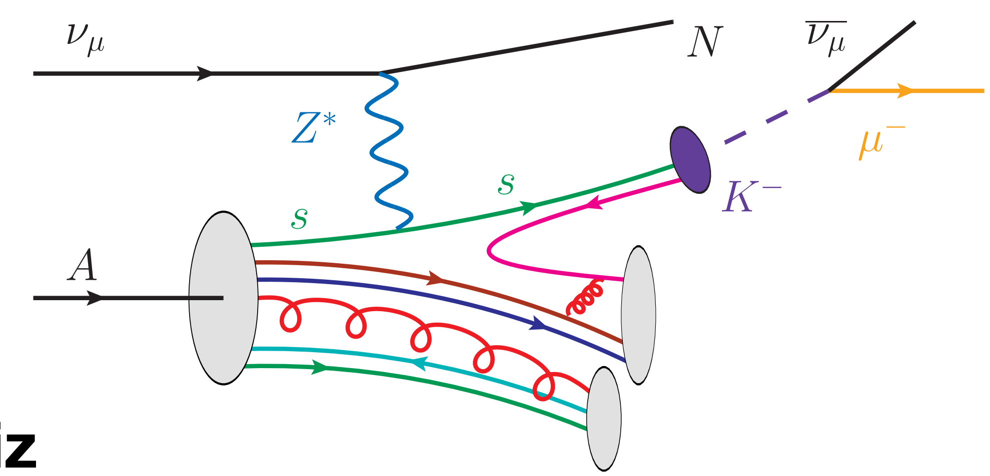
Richard Ruiz

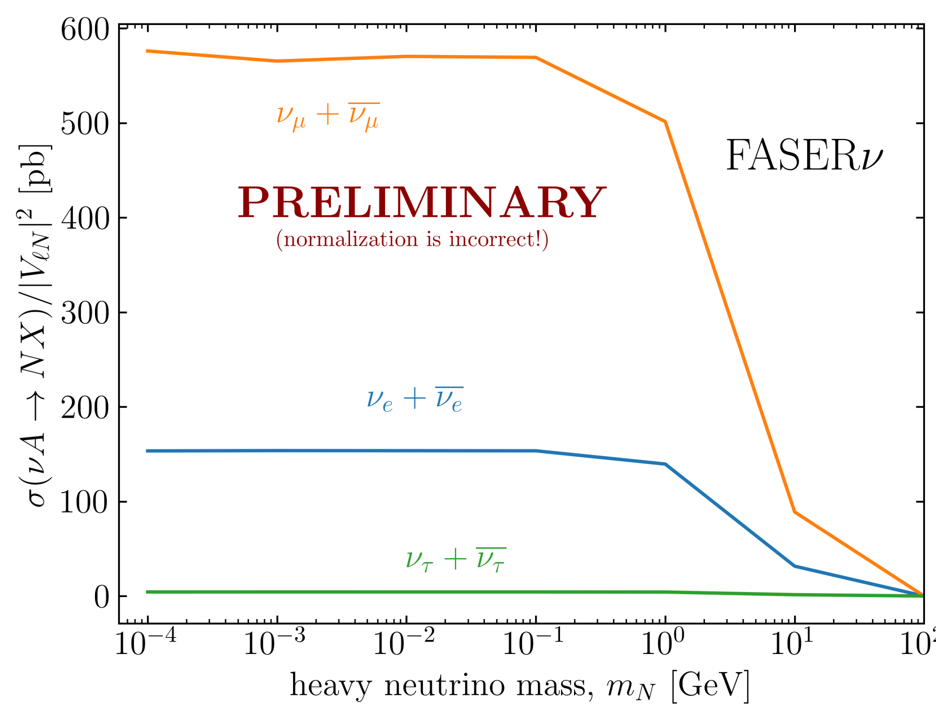
Lepton number/flavor violation

New programs (FASER, SND@LHC) **now collecting ν-nucleus scattering data**



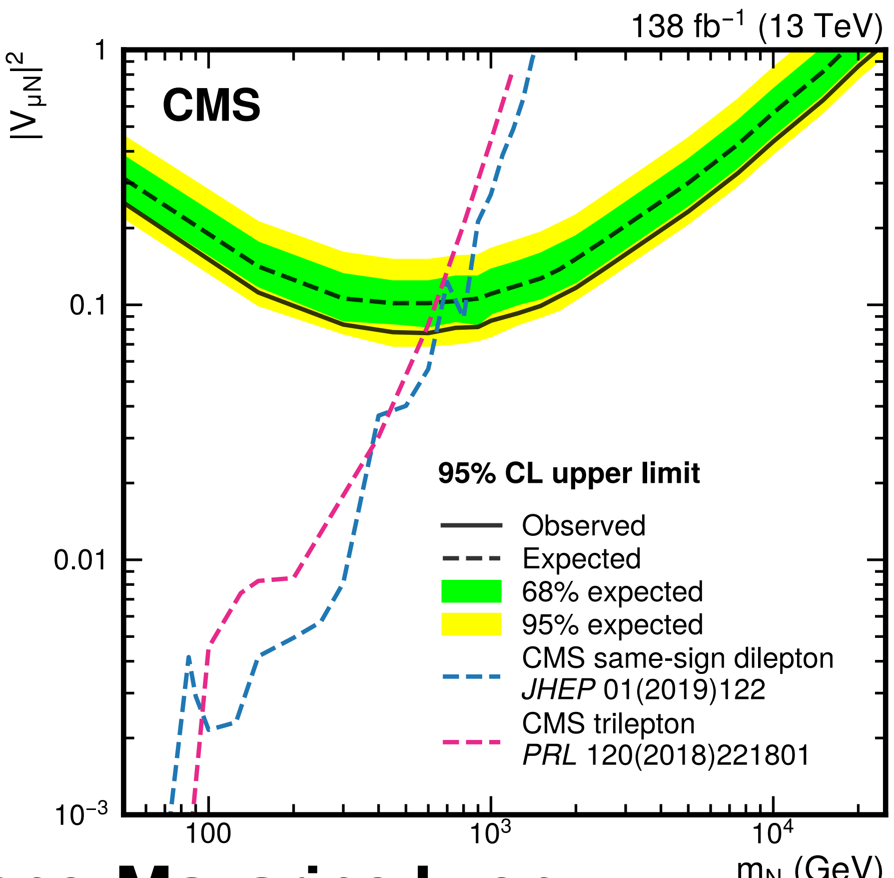
$$d\sigma(\nu\mathcal{A}\to \ell X) = \underbrace{\sum_{f,k,X_n}}_{\textit{inclusive}} \underbrace{\Delta_{kk'}}_{\text{shower/RGE}} \otimes \underbrace{f_{\nu_f}\otimes f_{k'}}_{\text{PDF}} \otimes \underbrace{d\hat{\sigma}_{\nu_f k'\to X_n}}_{\text{hard scattering}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{\mathrm{NP}}^{2+k}}{Q^{2+k}}\right)}_{\text{HT}}$$





Indirect searches at CMS

a. Majorana HNL process
- Results are interpreted in terms of upper limits at 95% CL on the total mixing amplitude $|V_{\mu \mathrm{N}}|^2$



b. Weinberg operator process
- Observed 95% CL upper limit on $m_{\mu\mu}$ is equal to 10.8 GeV

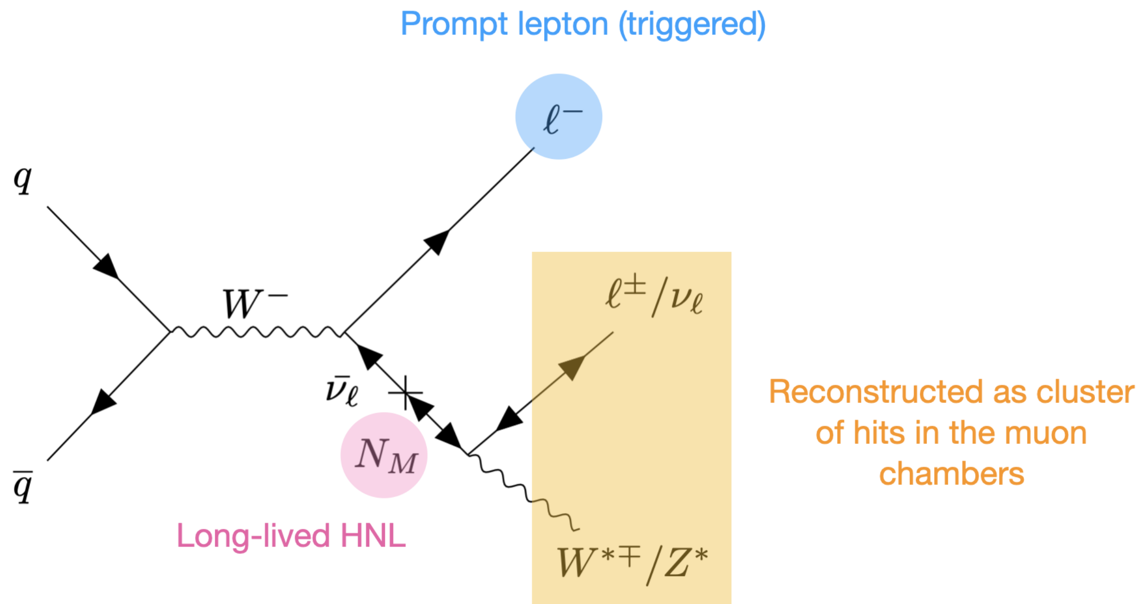
Not competitive

Sensitive to dimension-7 operators

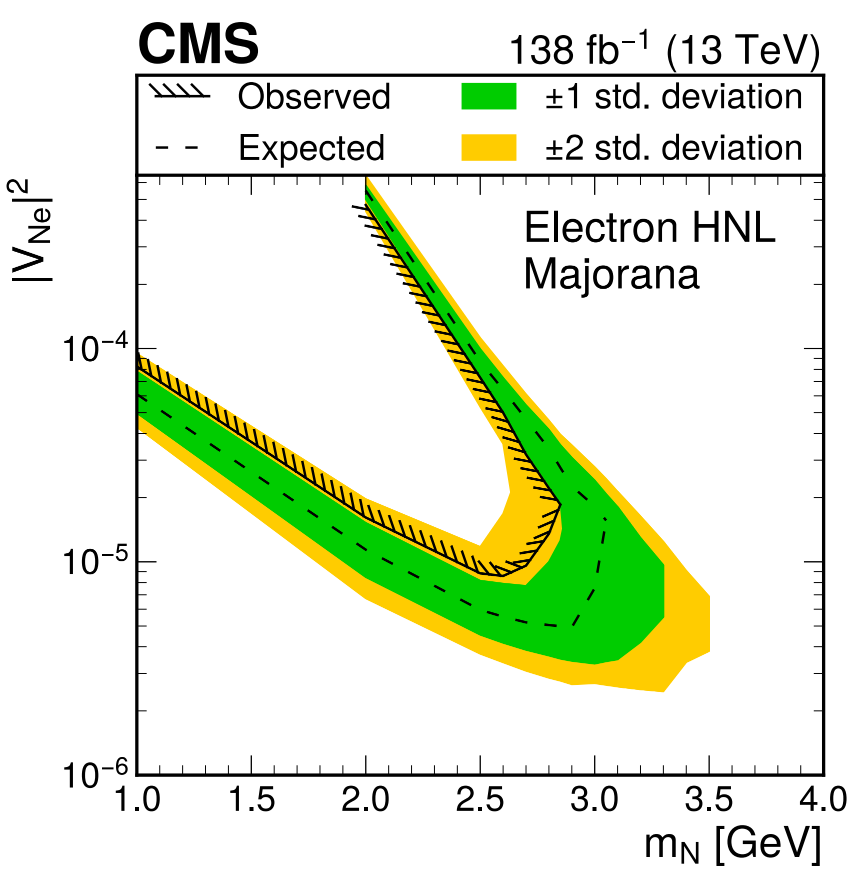
Paper?

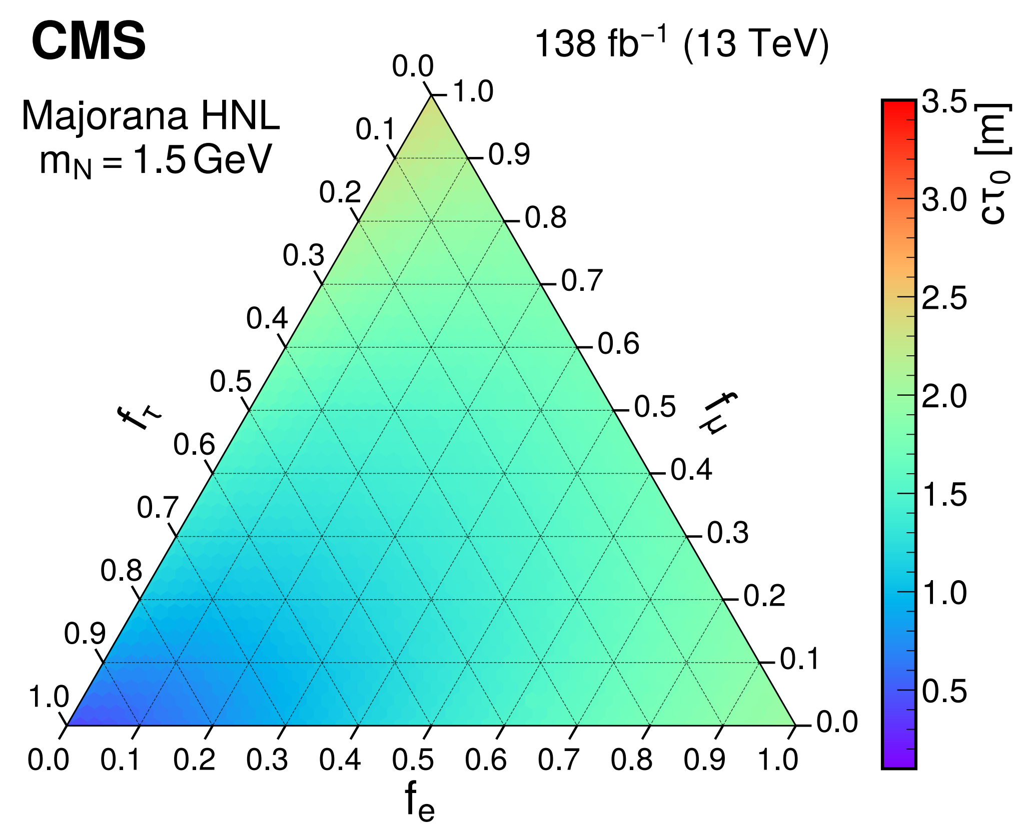
Anne-Mazarine Lyon

Indirect searches at CMS



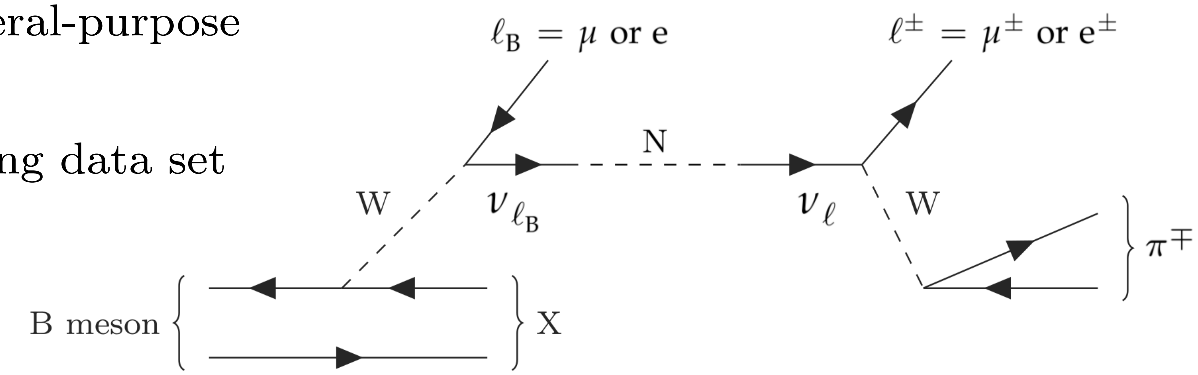
- Results are interpreted as 95% CL upper exclusion limits on $|V_{\ell N}|^2$
  - For both the Majorana and Dirac scenarios
- Scenario in which the HNL mixes exclusively with one lepton family

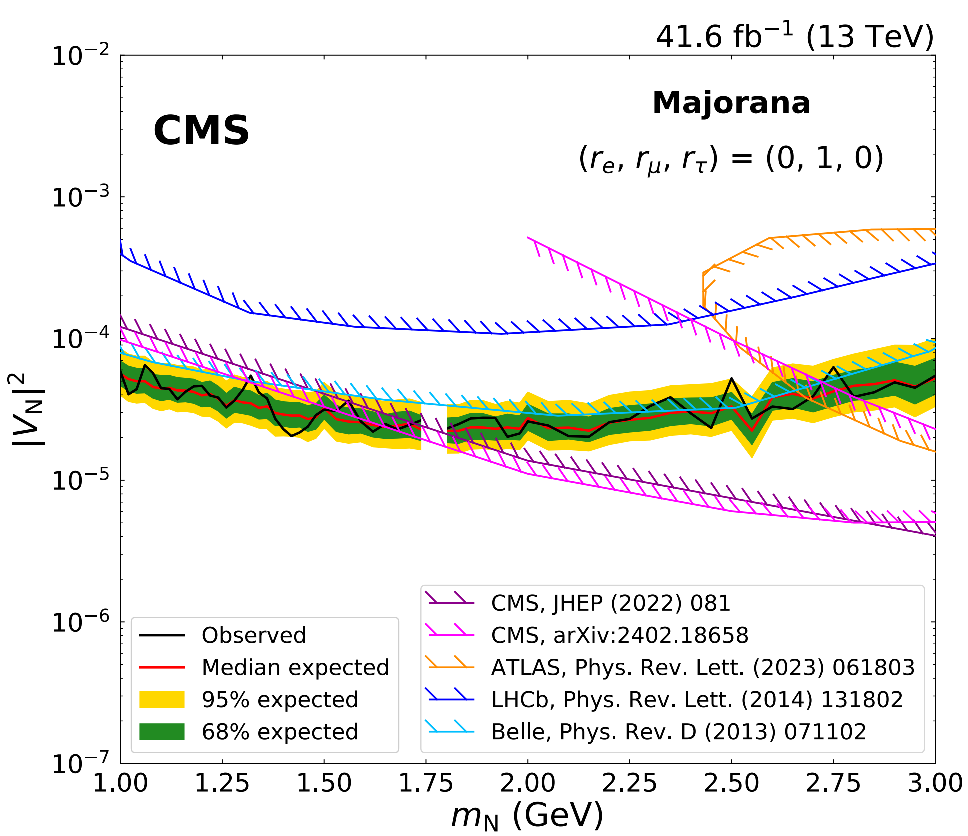


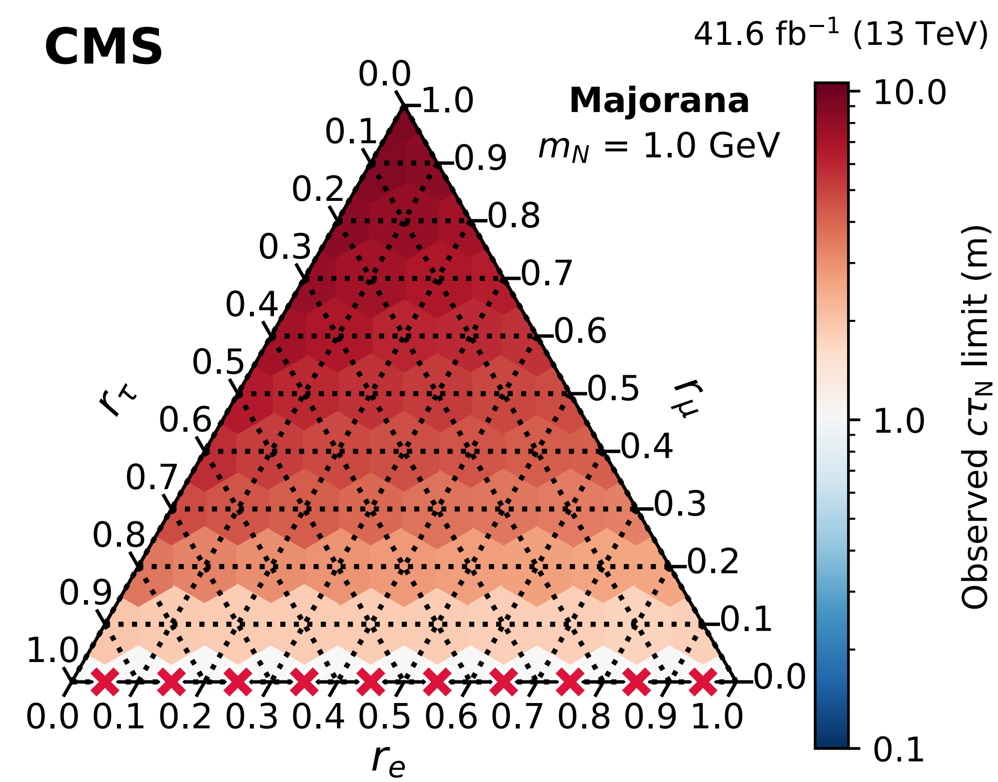


Indirect searches at CMS

- First search for HNLs in B meson decays performed at a general-purpose experiment at the LHC
- Made possible thanks to the collection in 2018 of the B-parking data set
  - 41.6 fb^{-1}, $\mathcal{O}(10^{10})$ $\text{b}\overline{\text{b}}$ events



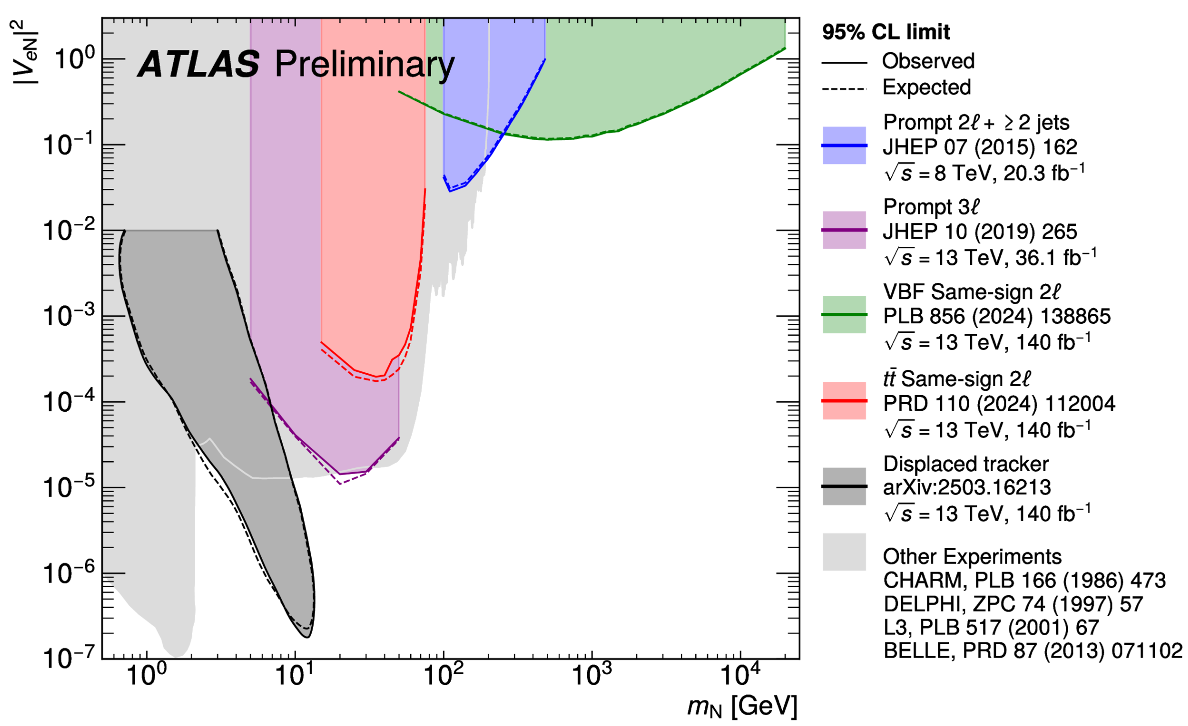


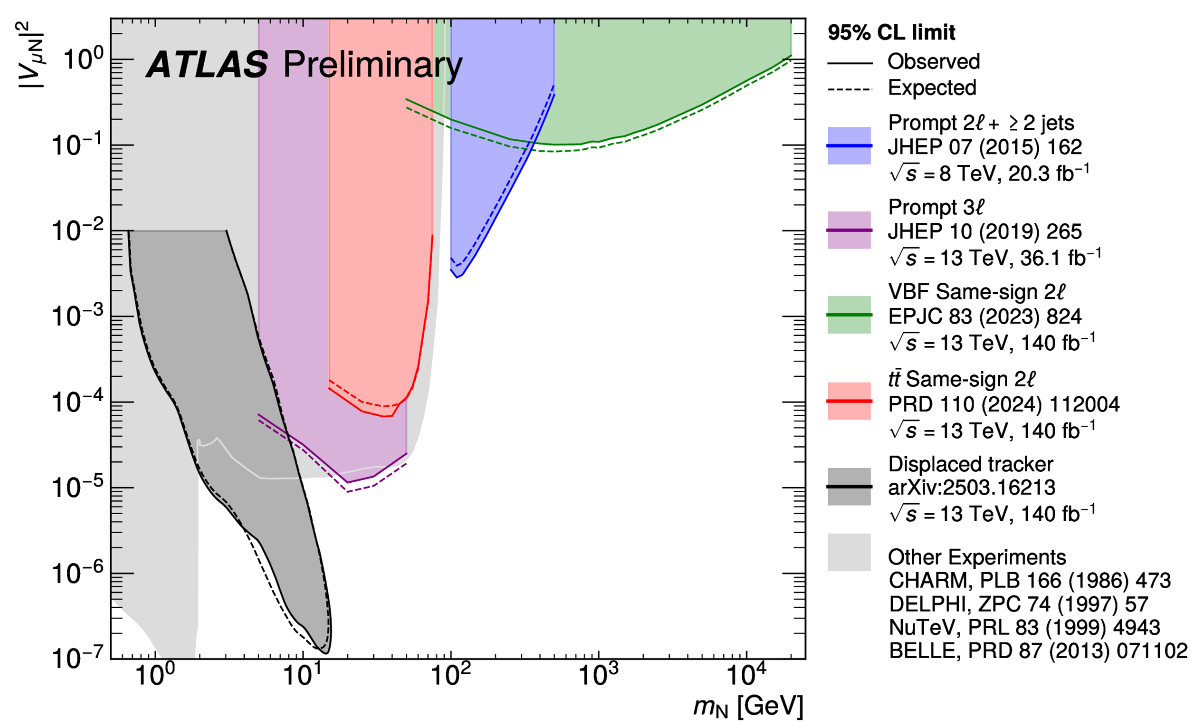


Indirect searches at ATLAS

ATLAS summary plots (electrons & muons)

ATL-PHYS-PUB-2025-008   electron mixing   muon mixing





- **Colliders** currently provide strongest direct constraints for $\boldsymbol{m_N > m_K}$

Matthias Siampert

The νSMEFT

In what follows, we will assume

- lepton number conservation (LNC)

or

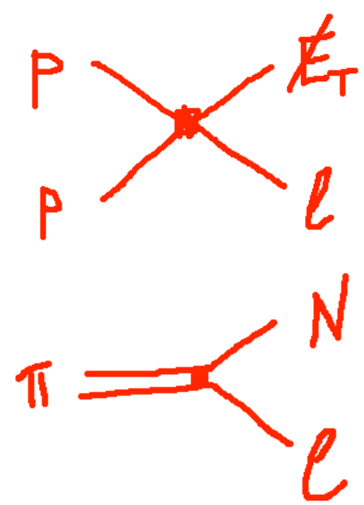
- lepton number violation (LNV) by $M \lesssim \mathrm{v}$
- new heavy physics exists at scale $\Lambda \gg \mathrm{v}$

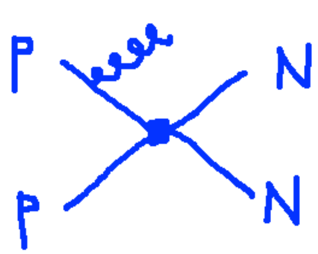
Arsenii Titov

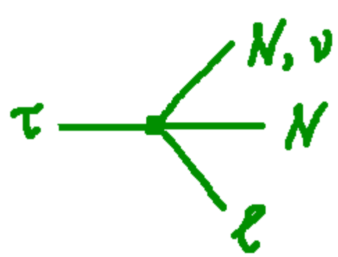
Under these assumptions, N_R should be present in the EFT

Alcaide, Banerjee, Chala, **AT**, 1905.11375

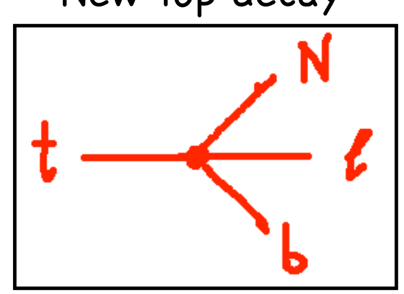
RRRR	$\mathcal{O}_{NN} = (\overline{N_R}\gamma_\mu N_R)(\overline{N_R}\gamma^\mu N_R)$	
	$\mathcal{O}_{eN} = (\overline{e_R}\gamma_\mu e_R)(\overline{N_R}\gamma^\mu N_R)$	$\mathcal{O}_{uN} = (\overline{u_R}\gamma_\mu u_R)(\overline{N_R}\gamma^\mu N_R)$
	$\mathcal{O}_{dN} = (\overline{d_R}\gamma_\mu d_R)(\overline{N_R}\gamma^\mu N_R)$	$\mathcal{O}_{duNe} = (\overline{d_R}\gamma_\mu u_R)(\overline{N_R}\gamma^\mu e_R)$
LLRR	$\mathcal{O}_{LN} = (\overline{L}\gamma_\mu L)(\overline{N_R}\gamma^\mu N_R)$	$\mathcal{O}_{QN} = (\overline{Q}\gamma_\mu Q)(\overline{N_R}\gamma^\mu N_R)$
LRLR	$\mathcal{O}_{LNLe} = (\overline{L}N_R)\epsilon(\overline{L}e_R)$	$\mathcal{O}_{LNQd} = (\overline{L}N_R)\epsilon(\overline{Q}d_R)$
	$\mathcal{O}_{LdQN} = (\overline{L}d_R)\epsilon(\overline{Q}N_R)$	
LRRL	$\mathcal{O}_{QuNL} = (\overline{Q}u_R)(\overline{N_R}L)$	

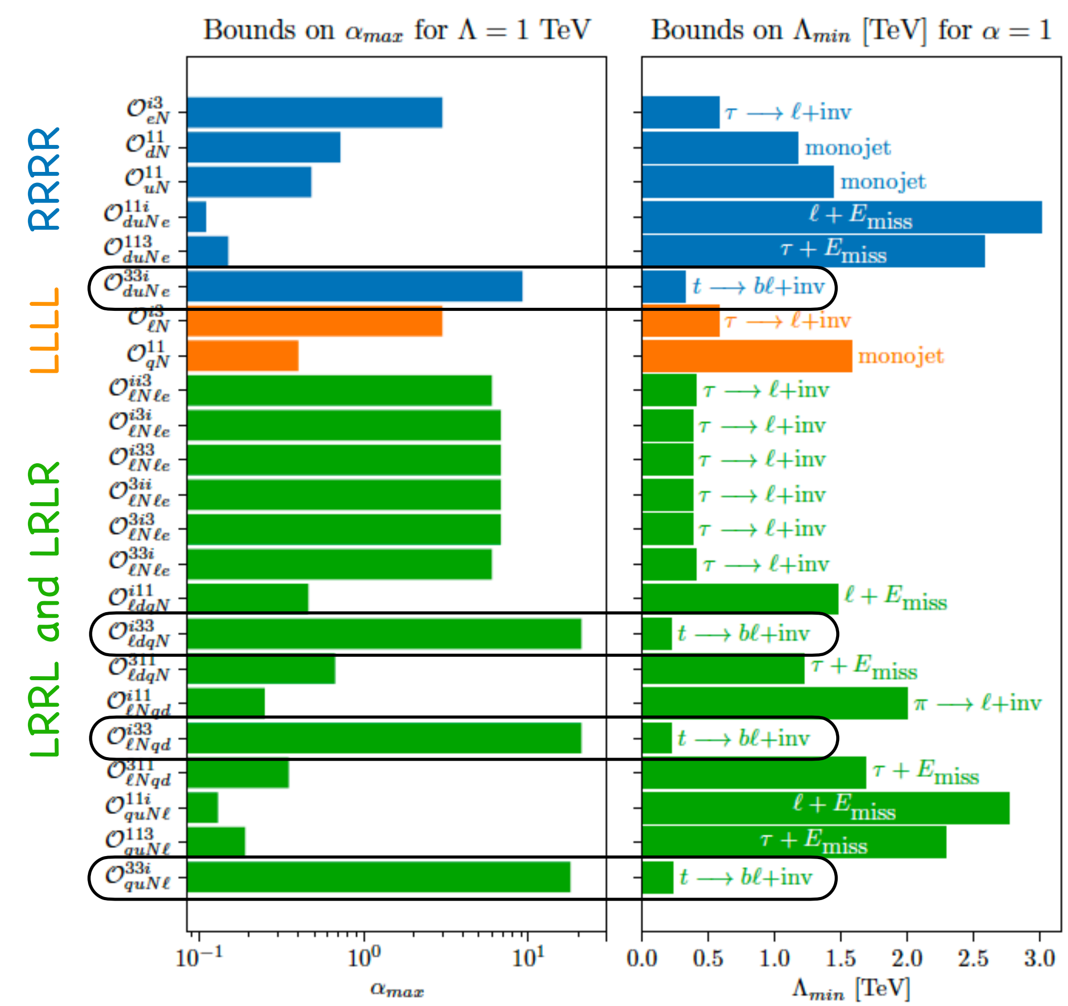






New top decay



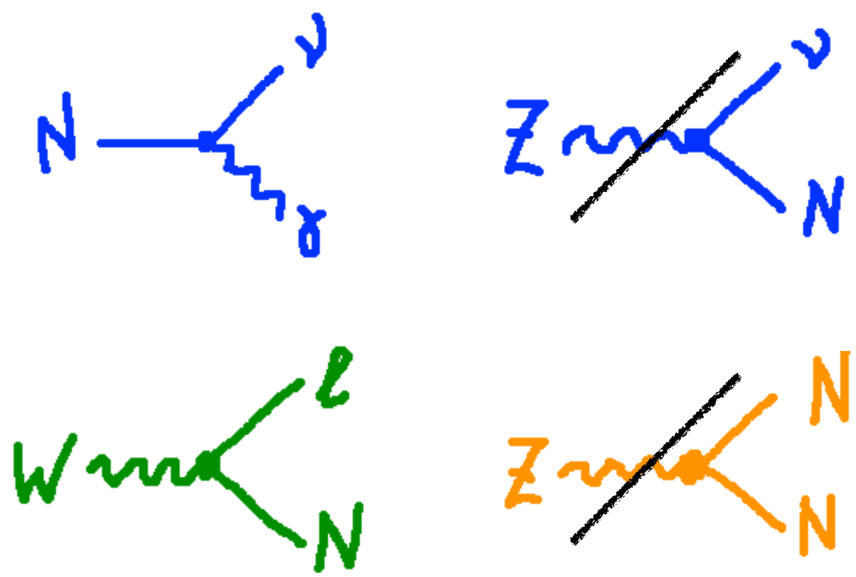


The νSMEFT

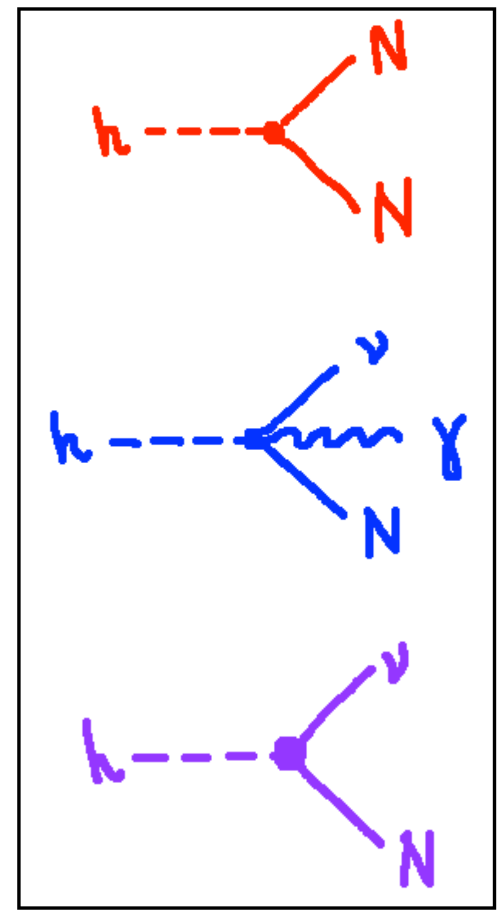
Higgs-N operators

$$\mathcal{O}_{NNH} = \left(\overline{N^c} N\right)\left(H^\dagger H\right)$$

$1H$	$\mathcal{O}_{NB} = \overline{L}\sigma^{\mu\nu} N \tilde{H} B_{\mu\nu}$	$\mathcal{O}_{NW} = \overline{L}\sigma^{\mu\nu} N \sigma_I \tilde{H} W^I_{\mu\nu}$
$2H$	$\mathcal{O}_{HN} = \overline{N}\gamma^\mu N (H^\dagger i \overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{HNe} = \overline{N}\gamma^\mu e (\tilde{H}^\dagger i D_\mu H)$
$3H$	$\mathcal{O}_{LNH} = \overline{L}\tilde{H} N (H^\dagger H)$	



New Higgs decays



Arsenii Titov

$$\mathscr{B}(h \to \gamma + p_T^{\text{miss}}) \sim 1.2 \times 10^{-4}$$

$$\mathscr{B}(h \to \gamma\gamma + p_T^{\text{miss}}) \sim 4.2 \times 10^{-5}$$

@ HL-LHC with $\mathscr{L} = 3\ \text{ab}^{-1}$

Operator	$\alpha_{\max}$ for $\Lambda = 1$ TeV	$\Lambda_{\min}$ [TeV] for $\alpha = 1$	Channel
$\mathcal{O}_{LNH}$	4.2×10^{-3}	15	$h \to \gamma + p_T^{\text{miss}}$
$\mathcal{O}_{NNH}$	5.3×10^{-4}	1900	$h \to \gamma\gamma + p_T^{\text{miss}}$
$\mathcal{O}_{NA}$	0.21	2.2	$h \to \gamma\gamma + p_T^{\text{miss}}$

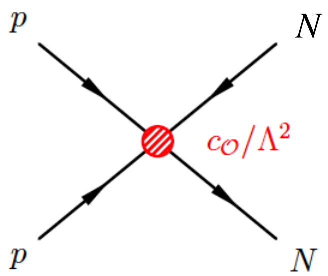
The νSMEFT

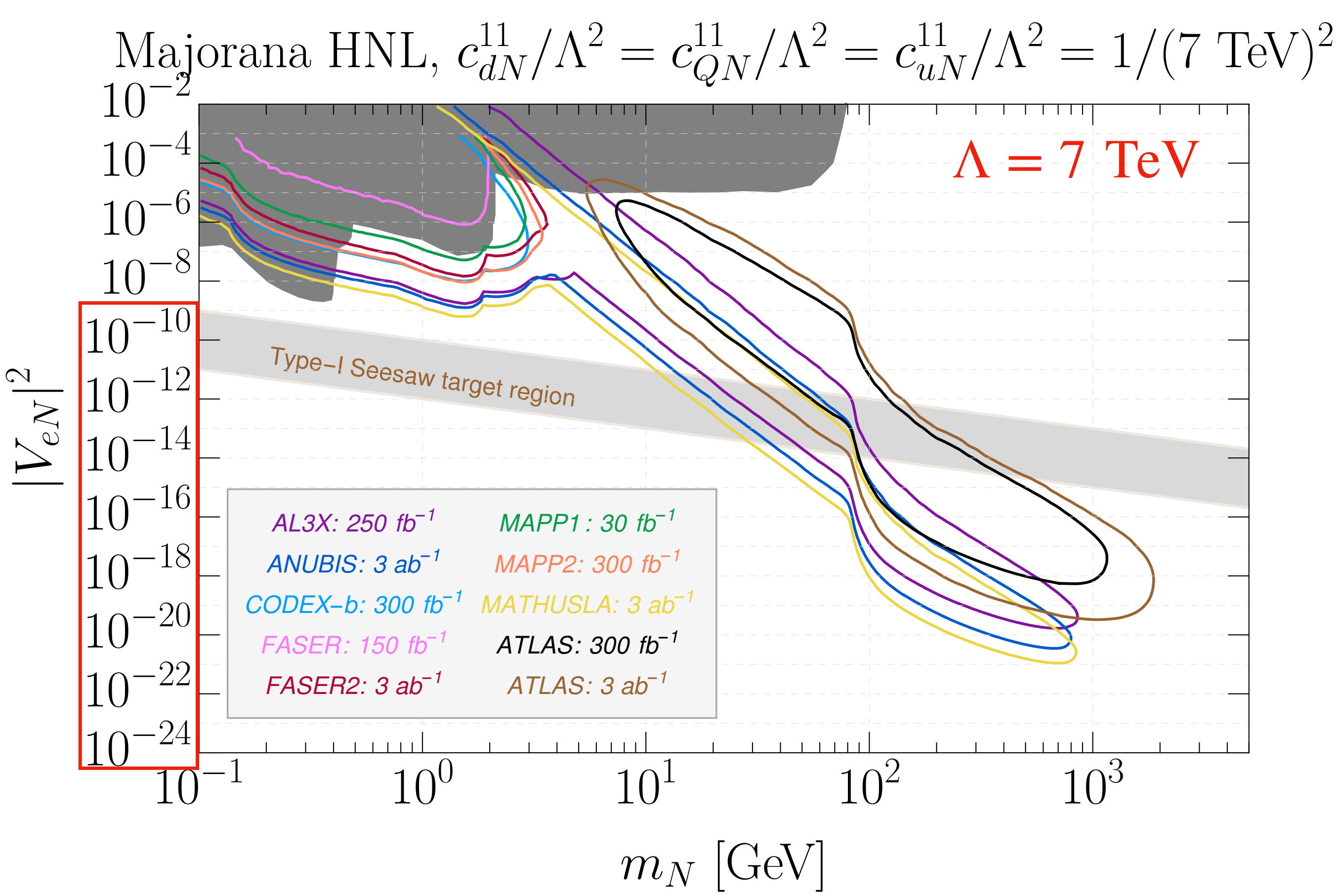
Arsenii Titov

4-fermion pair-N operators

Name	Structure	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma^\mu d_R)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{uN}$	$(\overline{u_R}\gamma^\mu u_R)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{QN}$	$(\overline{Q}\gamma^\mu Q)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{eN}$	$(\overline{e_R}\gamma^\mu e_R)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{NN}$	$(\overline{N_R}\gamma_\mu N_R)\,(\overline{N_R}\gamma_\mu N_R)$	1	36
$\mathcal{O}_{LN}$	$(\overline{L}\gamma^\mu L)\,(\overline{N_R}\gamma_\mu N_R)$	9	81

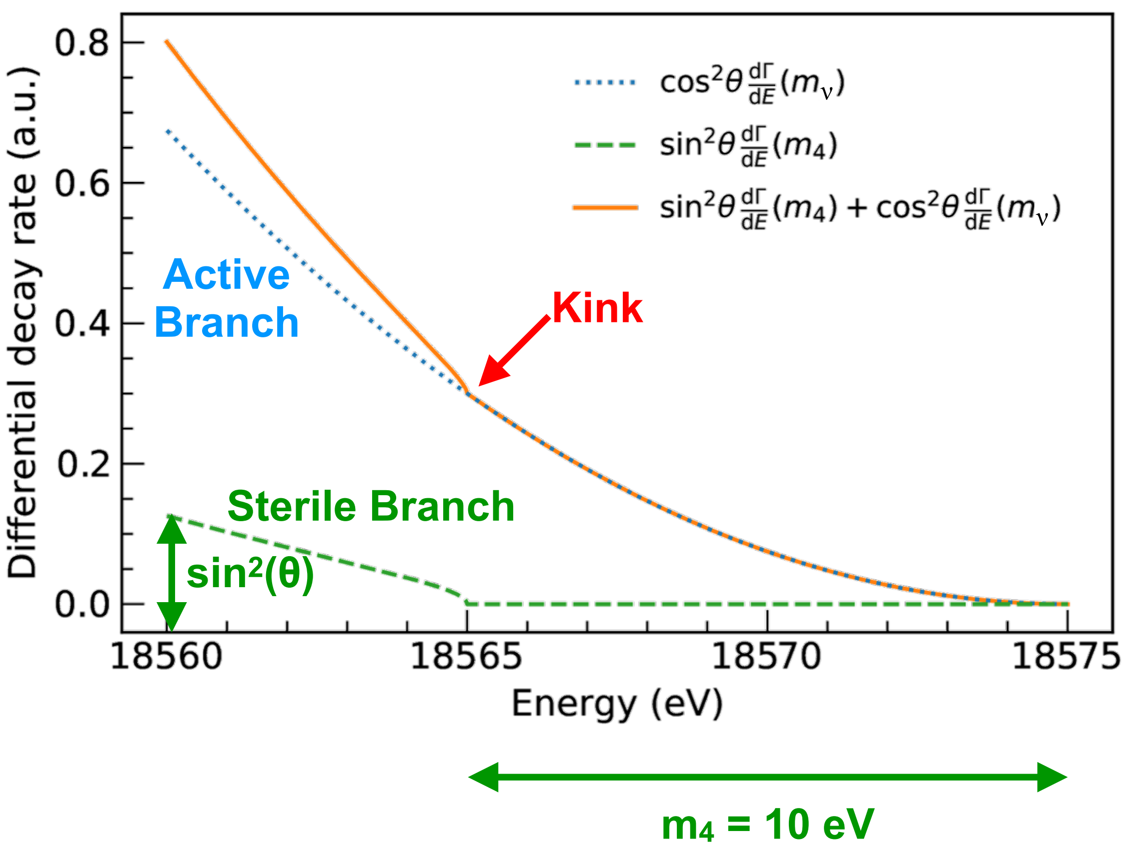
- HNLs are pair produced via pair-N_R operators

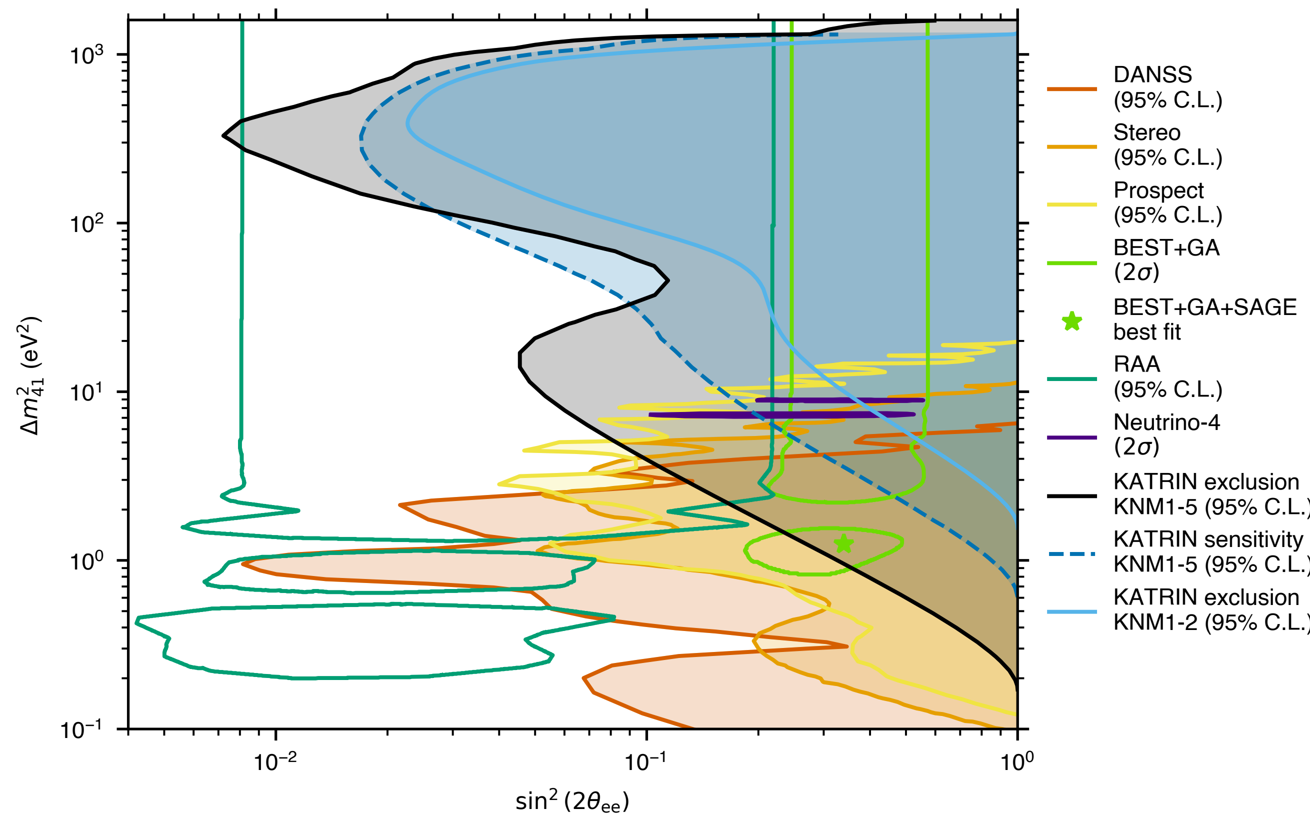


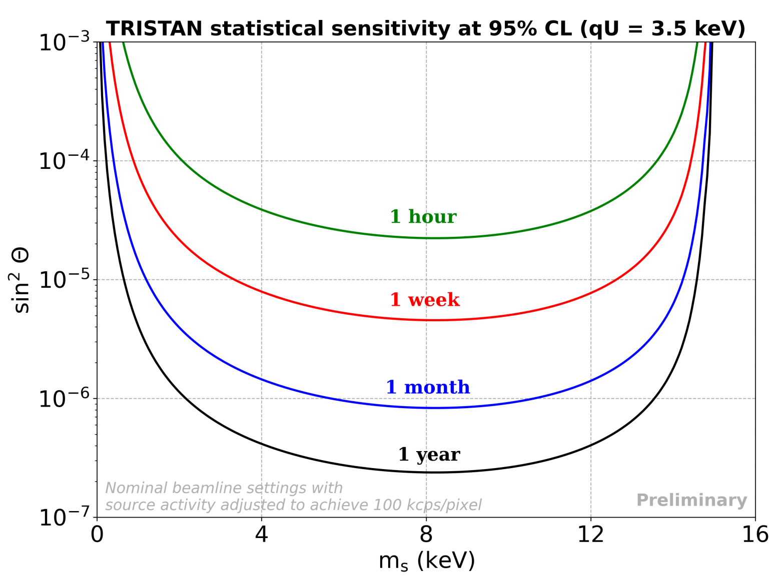


Constraints from KATRIN

Expected signature in KATRIN







- Almost excluded the allowed region with the Gallium anomaly except a small region.

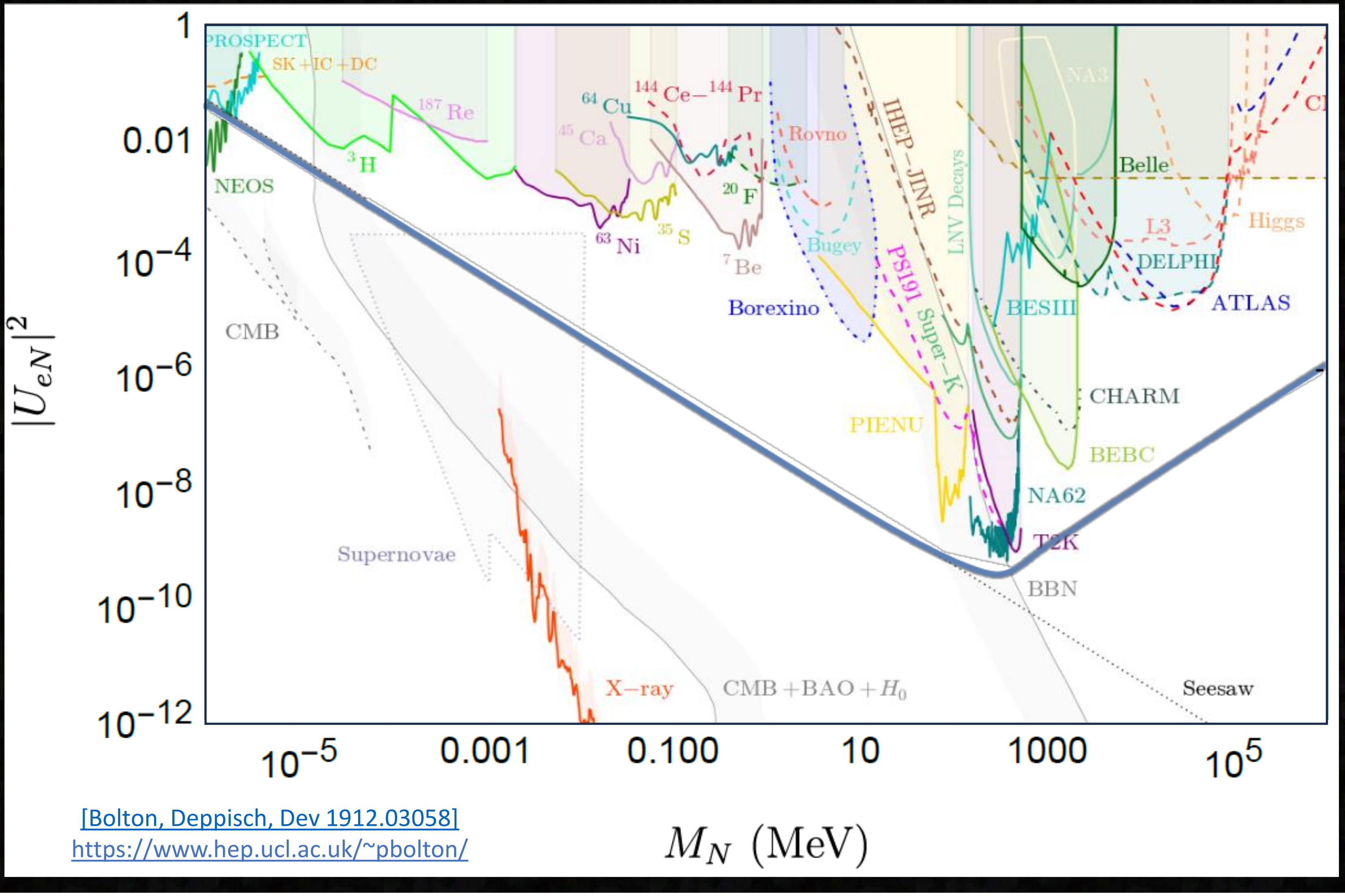
- A large section of the Reactor Antineutrino Anomaly was also excluded as exemplified.

Claudio Silva

Constraints from $0\nu\beta\beta$

Limits on heavy neutrinos

$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4\, V_{ud}^2\, G_{01} \left| \mathcal{U}_{eN}^2 \frac{M_N}{m_e} A_\nu(M_N) \right|^2$$



[Bolton, Deppisch, Dev 1912.03058]
https://www.hep.ucl.ac.uk/~pbolton/

Vaisakh Plakkot

Constraints from $0\nu\beta\beta$

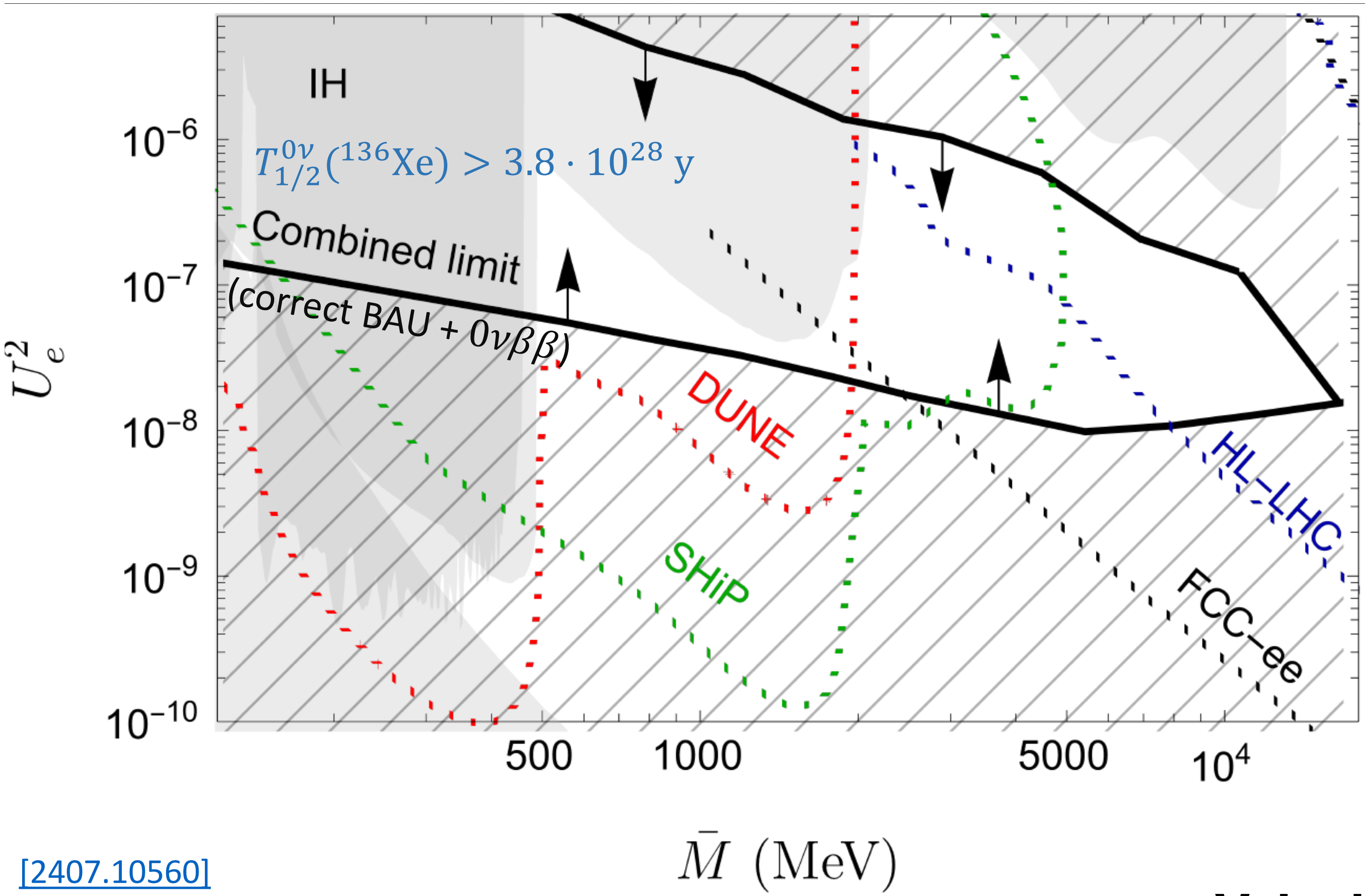
The "minimal" 3+2 type-I seesaw model

- Sterile mass matrix: $M_M = \begin{pmatrix} \bar{M}\left(1-\frac{\mu}{2}\right) & 0 \\ 0 & \bar{M}\left(1+\frac{\mu}{2}\right) \end{pmatrix}$

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix}$$

- Five Majorana neutrinos; lightest neutrino massless

$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto \left| A_\nu(0) \sum_{i=1,2,3} \mathcal{U}_{ei}^2 m_i + \sum_{I=4,5} \mathcal{U}_{eI}^2 M_I A_\nu(M_I) \right|^2$$



[2407.10560]

Vaisakh Plakkot

Long-lived new νs

Minimal Left-Right Symmetric Model

Simplest case is the **Type-II seesaw scenario:**

$M_D \to 0$. No mixing between SM neutrinos and sterile neutrinos.

Free parameters: RH gauge boson mass M_{W_R} and **mixing parameter** ξ

Mixing matrix: $\begin{pmatrix} W_L^\pm \\ W_R^\pm \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} W_1^\pm \\ W_2^\pm \end{pmatrix}$

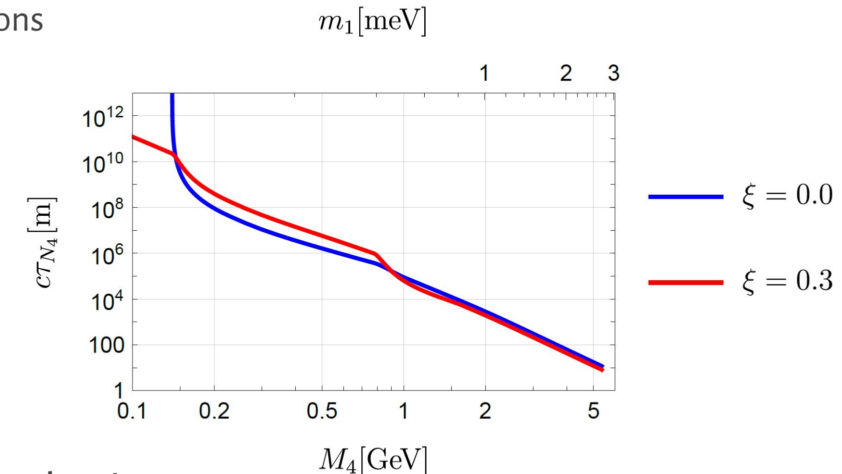
Sterile neutrino decay rates:

Possible final-state particle contents:

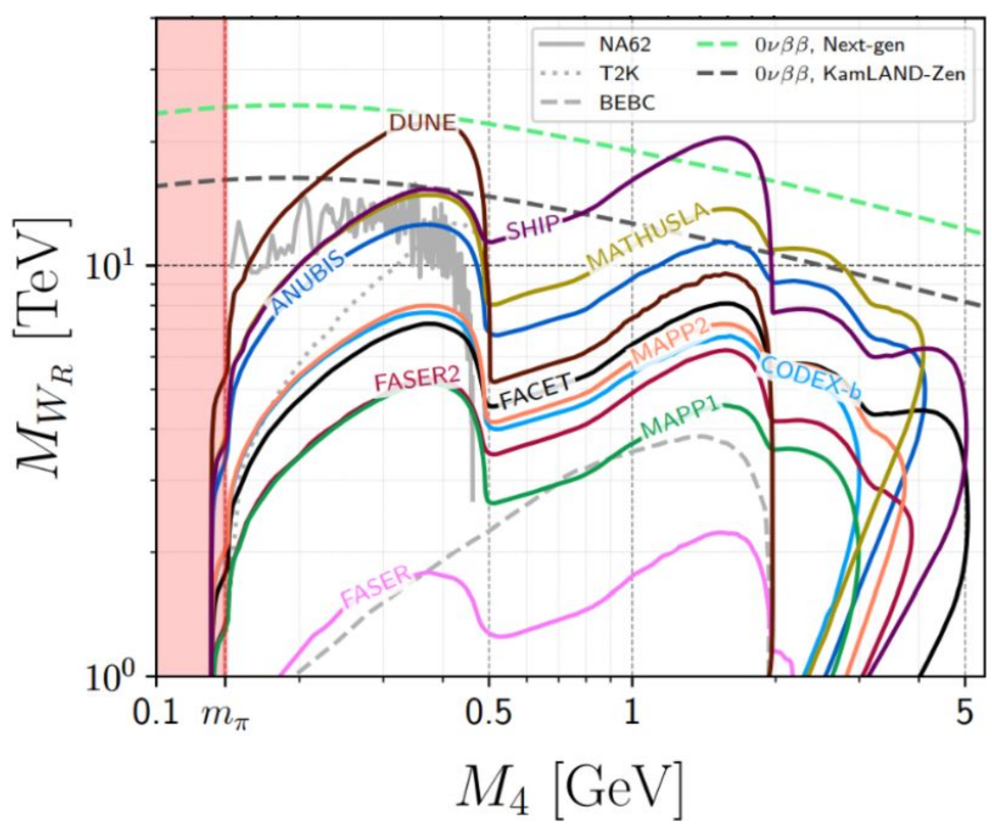
- Quarks: final-state mesons
- SM leptons
- SM neutrinos (invisible)

Sterile neutrino decay lengths:

Are DV searches viable?



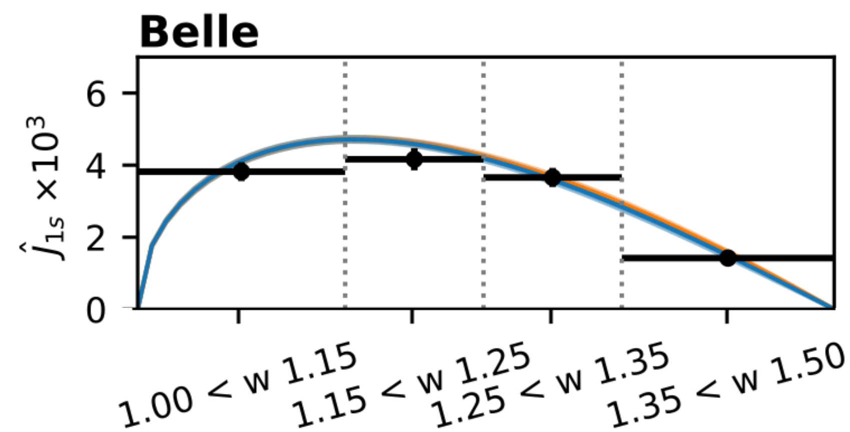
Future $0\nu\beta\beta$ and DV experiments have competitive sensitivity reaches!



$\xi = 0.3$

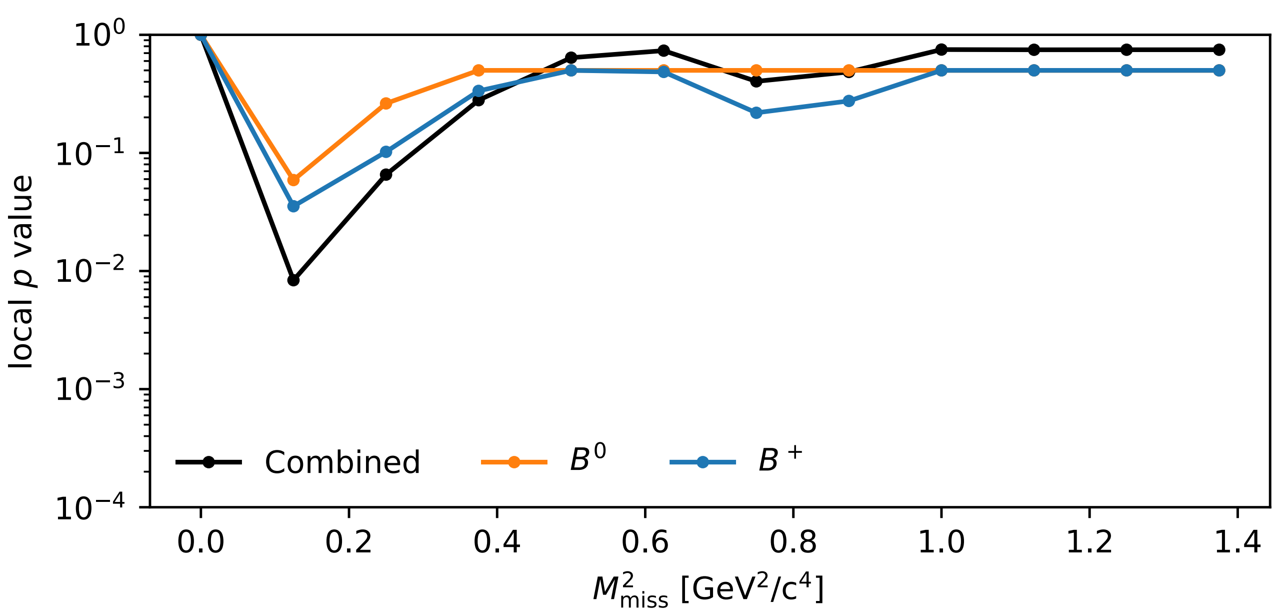
Constraints from hadron decays

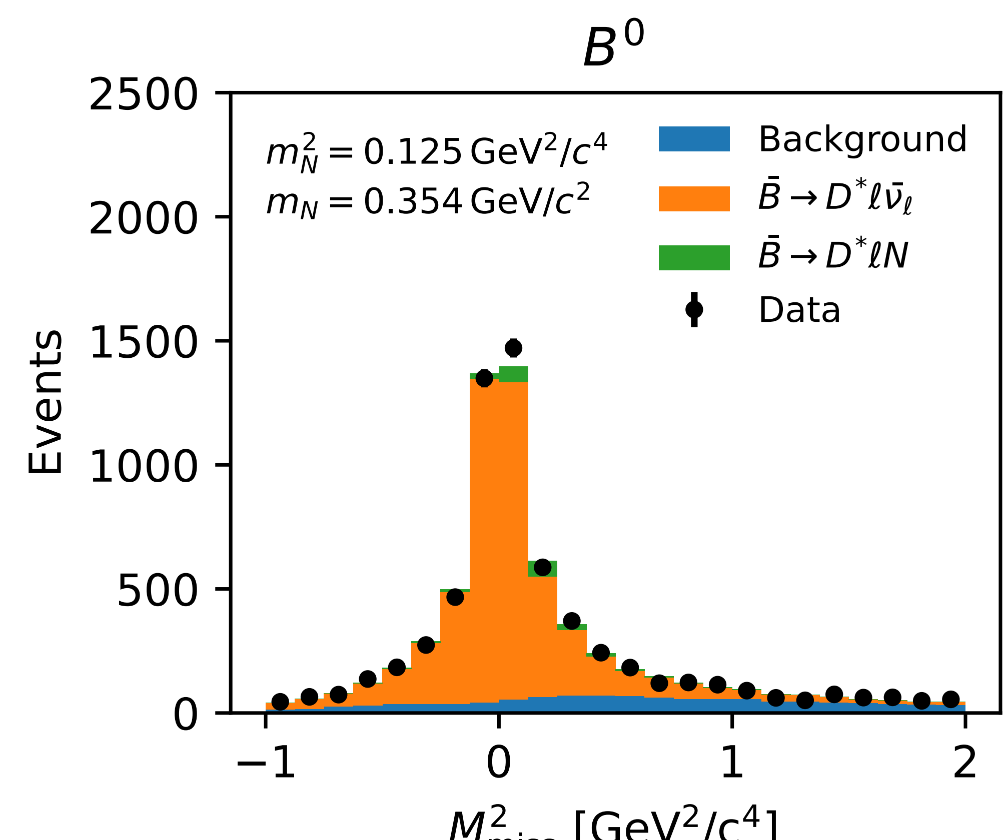
- Sterile neutrinos described by four energy dimension-6 operators



$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb}\Big[(\bar{c}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma^\mu \nu_{\ell,L}) + g^N_{V_R}(\bar{c}_R\gamma_\mu b_R)(\bar{\ell}_R\gamma^\mu N_R) + g^N_{S_L}(\bar{c}_R b_L)(\bar{\ell}_L N_R)$$
$$+ g^N_{S_R}(\bar{c}_L b_R)(\bar{\ell}_L N_R) + g^N_T(\bar{c}_L\sigma_{\mu\nu} b_R)(\bar{\ell}_L\sigma^{\mu\nu}N_R) + \text{h.c.}\Big]$$

- Hint at sterile neutrino with a mass of $m_N = 354\,\text{MeV}$



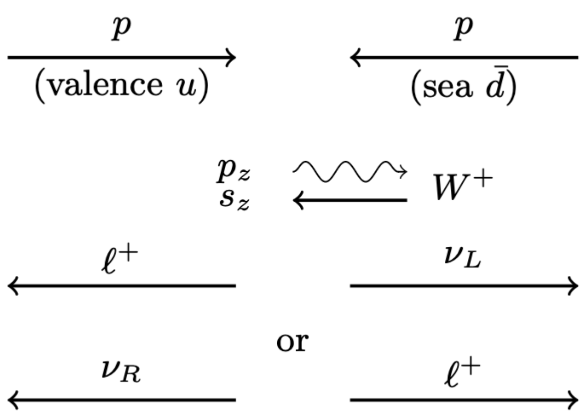


Tim Kretz

Constraints from W measurements

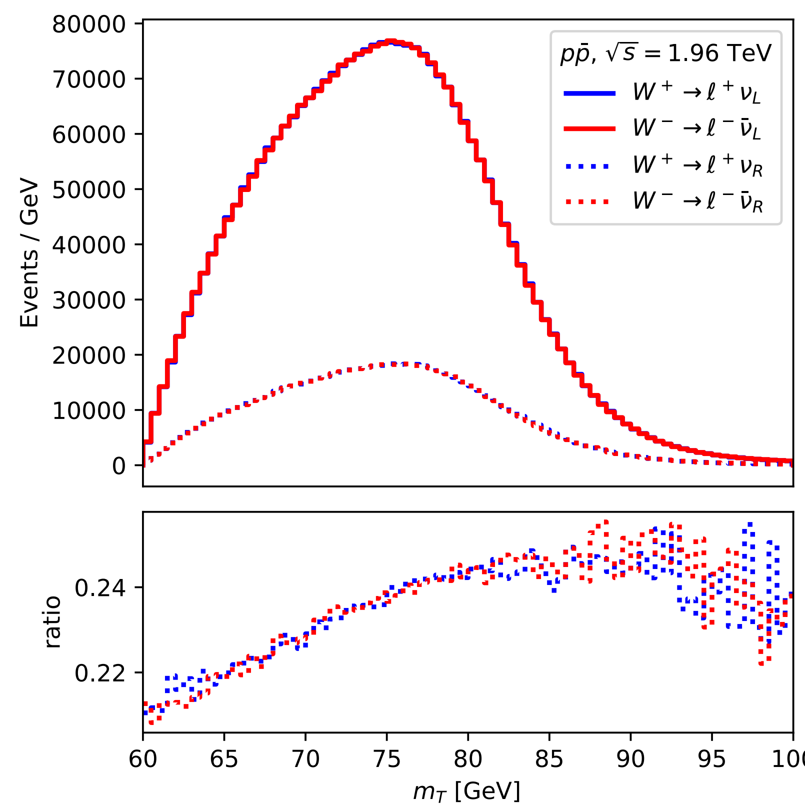
Operators contributing to $W \to Ne$:

$$\Delta\mathcal{L} = \frac{c^i_{LNH}}{\Lambda^2}\bar{L}_i \nu_R \tilde{H} H^\dagger H + \frac{c^i_{HNe}}{\Lambda^2}\bar{\nu}_R \gamma^\mu e_{iR} H^\dagger i D_\mu H + \frac{c^i_{NW}}{\Lambda^2}\bar{L}_i \sigma^{\mu\nu}\nu_R \sigma_I \tilde{W}^I_{\mu\nu}$$

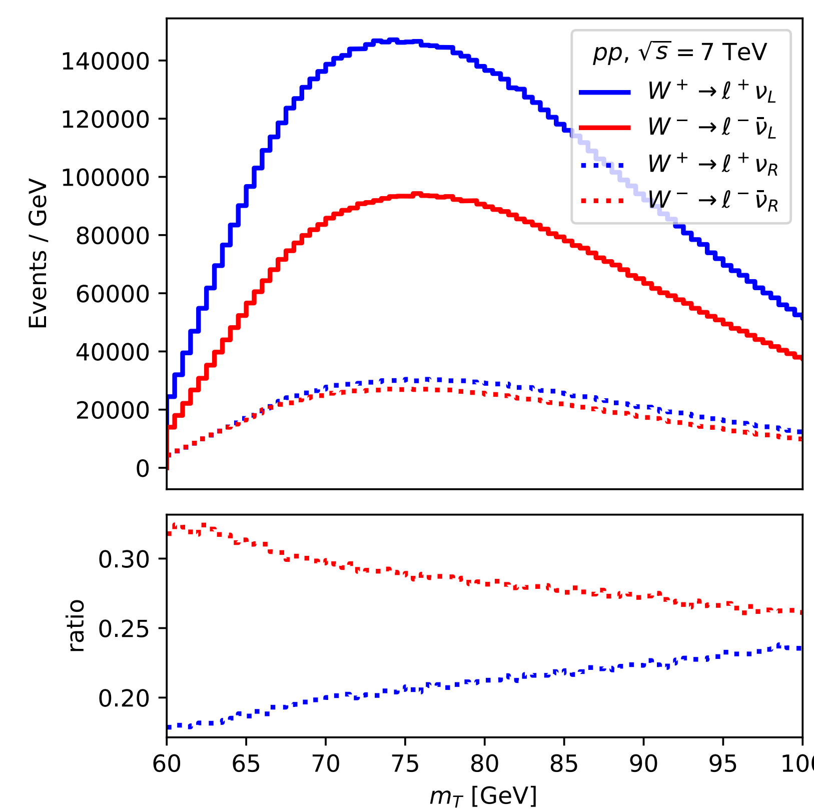


(a) W^+ production and decay at the LHC.

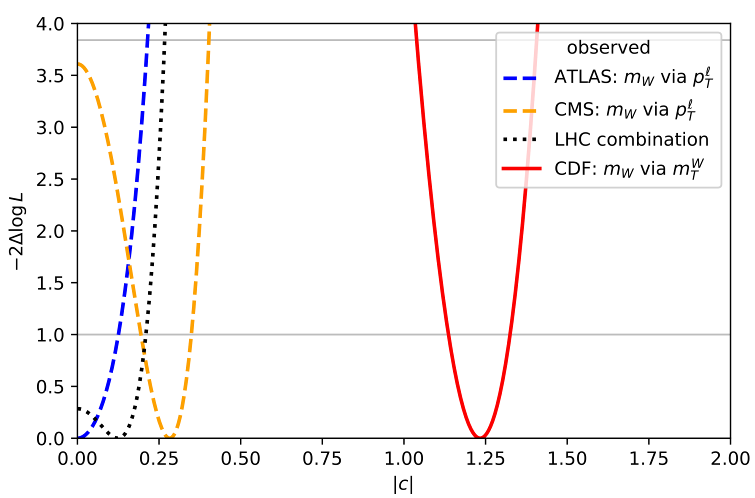
c^i_{LNH} and c^i_{NW} give rise to parity conserving interactions, while c^i_{HNe} gives rise to a parity-violating V+A interaction - only this operator changes the kinematics of the W decays



m_T distribution at CDF



m_T distribution at ATLAS



Sam Bates

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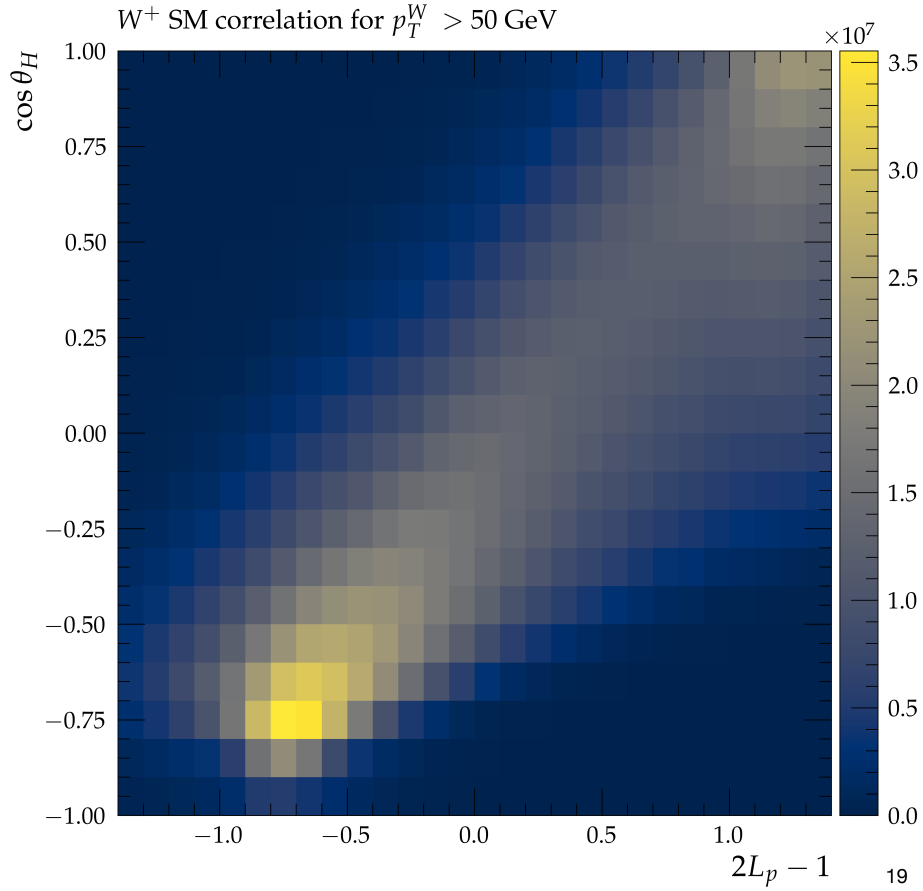
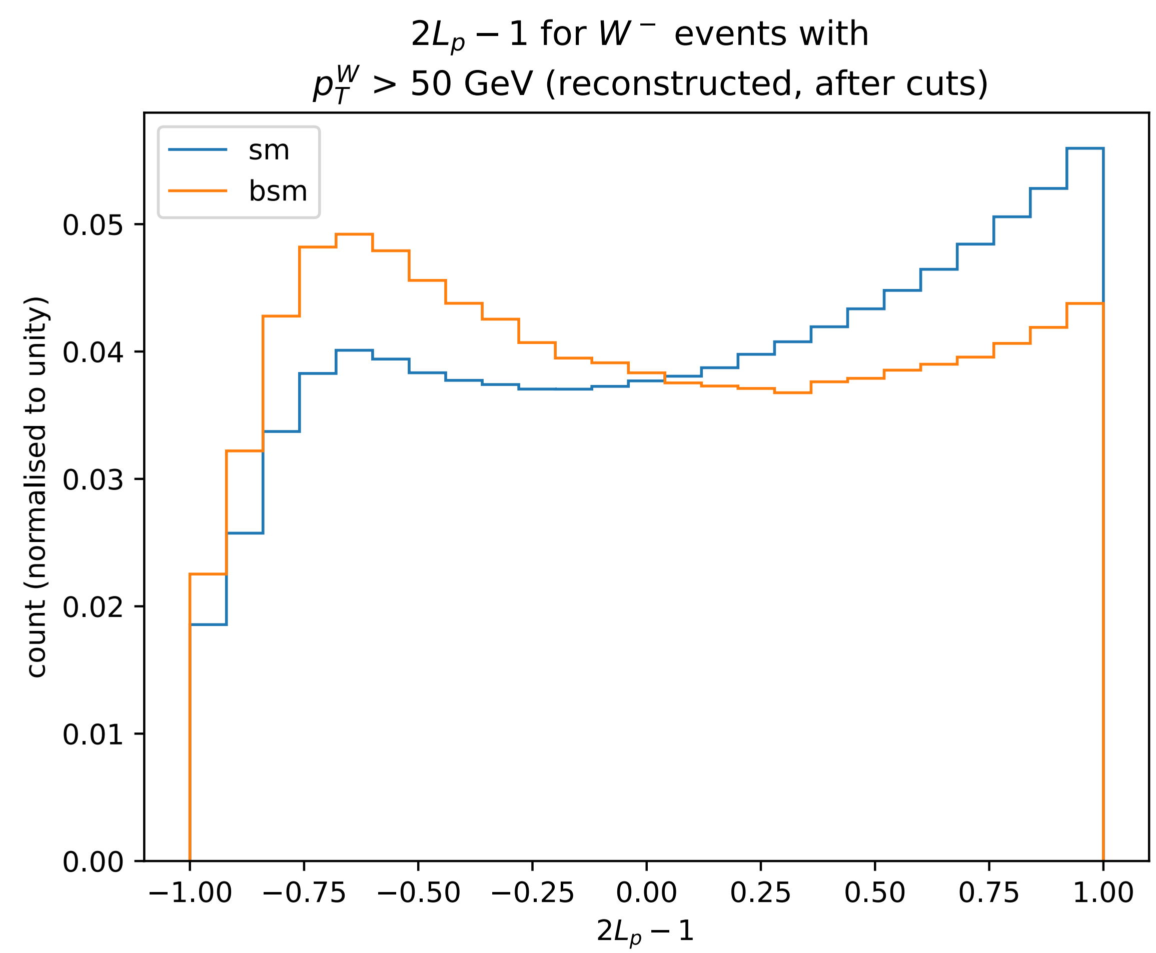
Constraints from W measurements

An ideal observable for detecting the difference between the SM and BSM decays would be $\cos\theta_{CS}$

- There is a well documented variable, L_p, such that $2L_p - 1$ is highly correlated to $\cos\theta_H$ at high p_T^W.





$c_{HNe} = 0.090\,(0.072)$ for $W^-\,(W^+)$
at 95% CL

Sam Bates

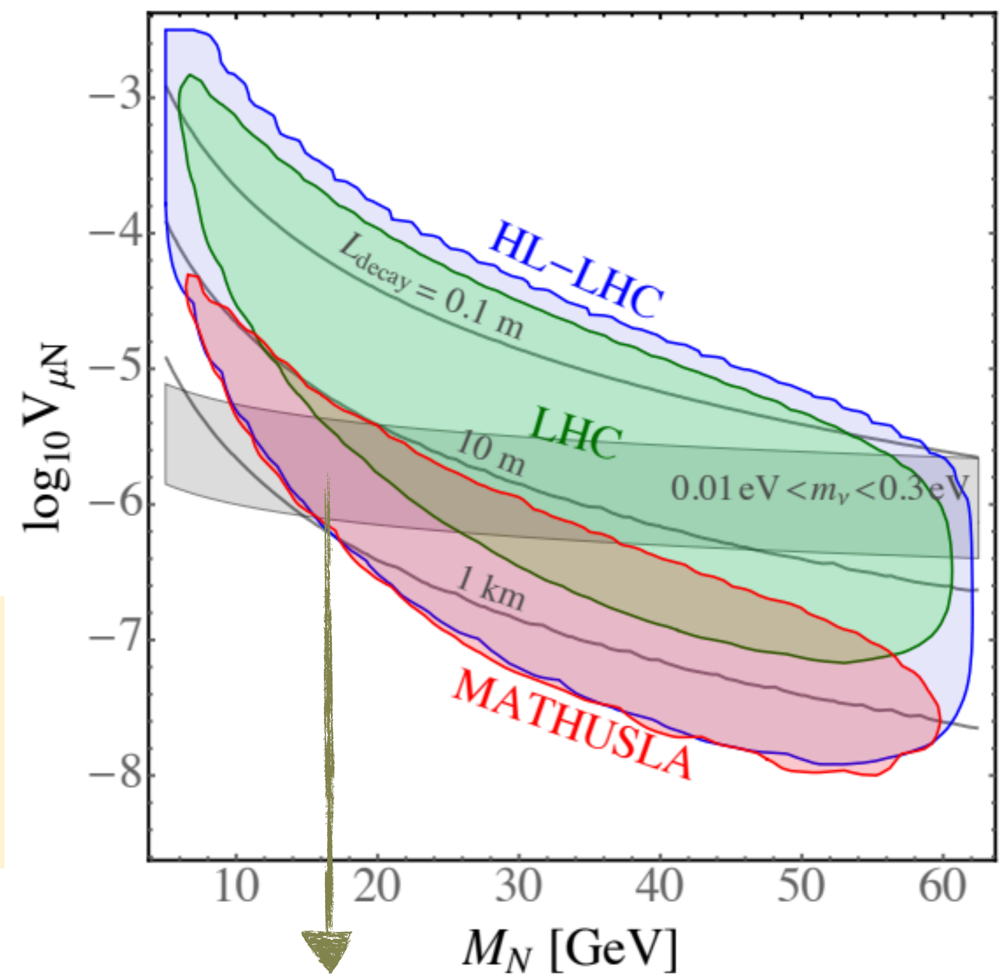
Need to compare to decay constraints

Discovering new νs at the LHC

RHN decay can give rise to displaced decay signatures

Production vertex and decay vertex are separated

One of the most important probe of BSM physics



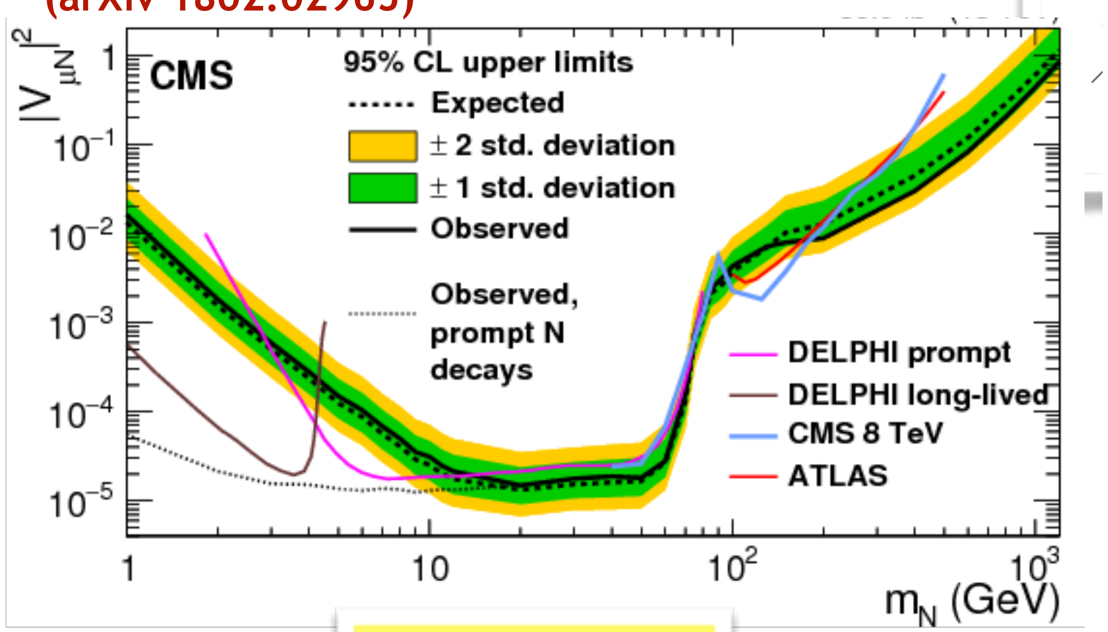
Seesaw favoured region can be accessed at the LHC/HL-LHC

Manimala Mitra

Discovering new νs at the LHC

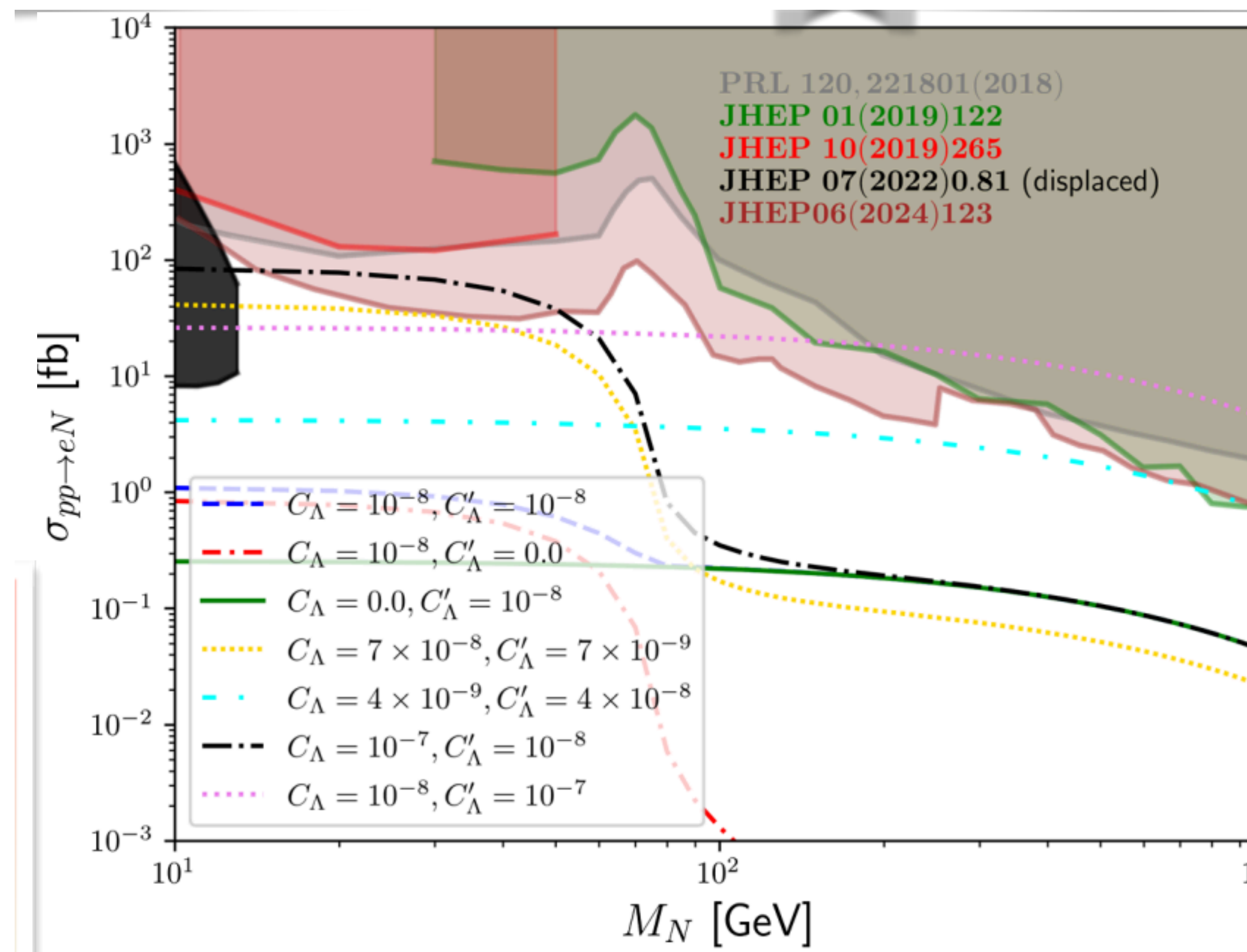
Reinterpretation of LHC constraint for HNL search

CMS collaboration, *PRL*120 (2018) 22, 221801
(arXiv 1802.02965)



Road Block??

- HEP data files, distributions, cut-efficiencies are not available for the above CMS search and the previous tri-lepton+MET HNL searches
- JHEP 06 (2024) 123 involves information about cut-efficiencies for few mass points. For high mass, more informations required. Informations about distributions Fig 2,3,4 not available and validation is difficult.



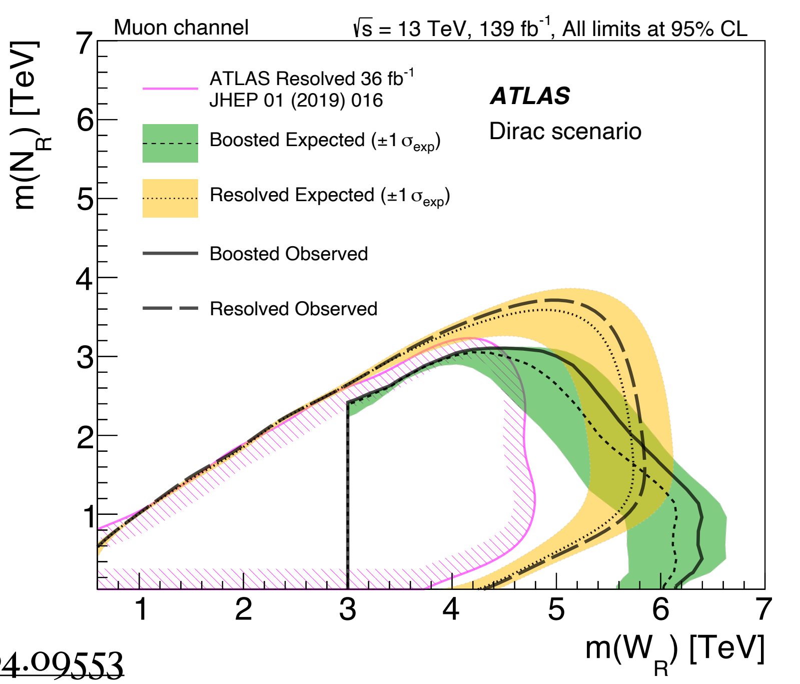
To follow up?

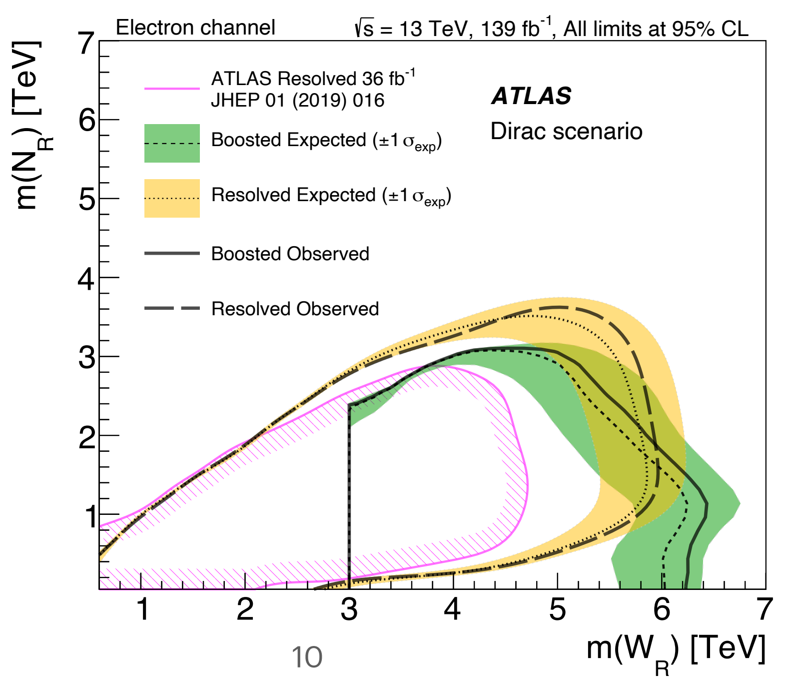
Manimala Mitra

Direct searches at ATLAS

Heavy right handed W_R and N_R

- No significant excess seen, set limits at 95% CL
- Resolved and boosted channels not orthogonal and are not combined
- Significant increase in sensitivity in Dirac and Majorana scenarios for *e* and *μ* coupling
- Does not see the same ~3σ local excess observed by previous CMS search



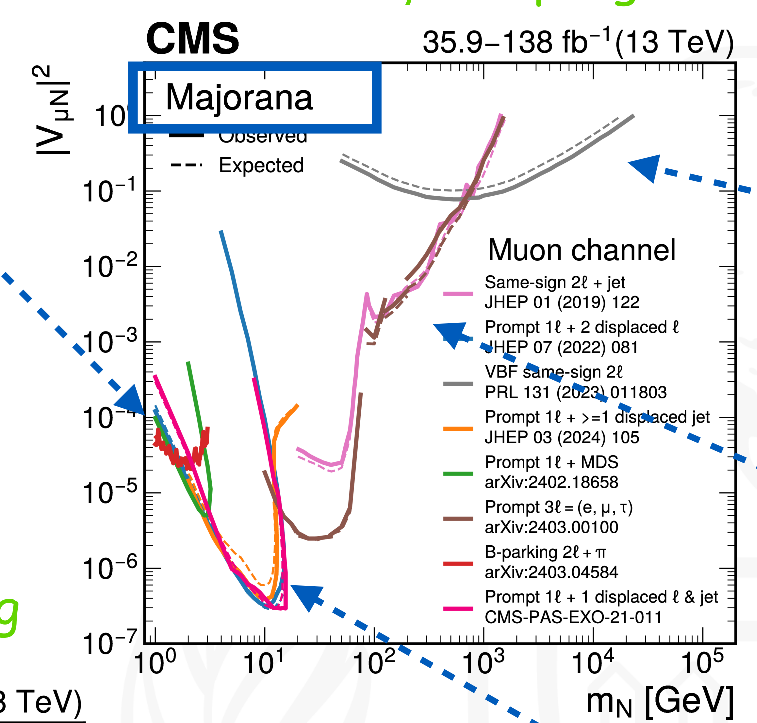


arXiv:2304.09553

Need to revisit Dirac scenario?

Direct searches at CMS

Exclusive μ coupling

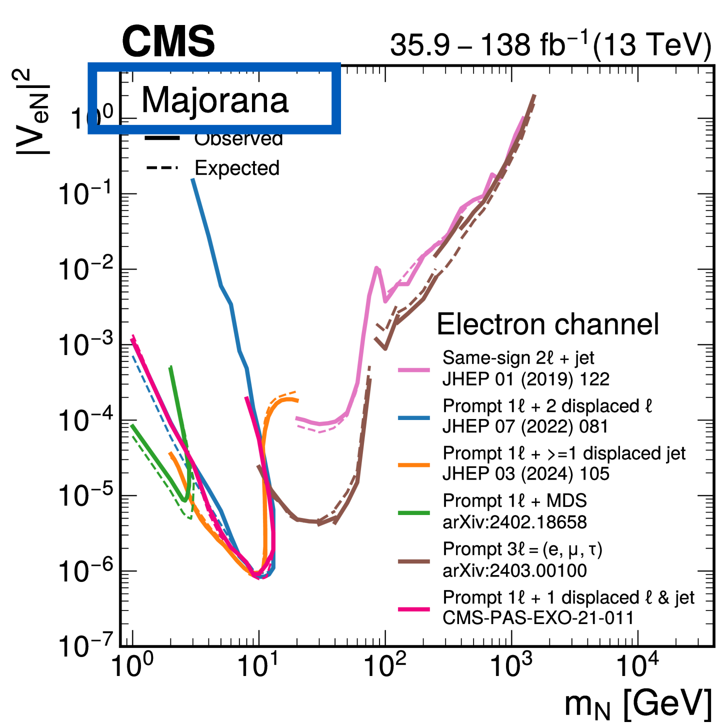


Very Low mass sophisticated Techniques

HNLs in VBF Indirect search

prompt 3ℓ

Exclusive e coupling



Intermediate mass s-channel
Displaced decay in Tracker volume

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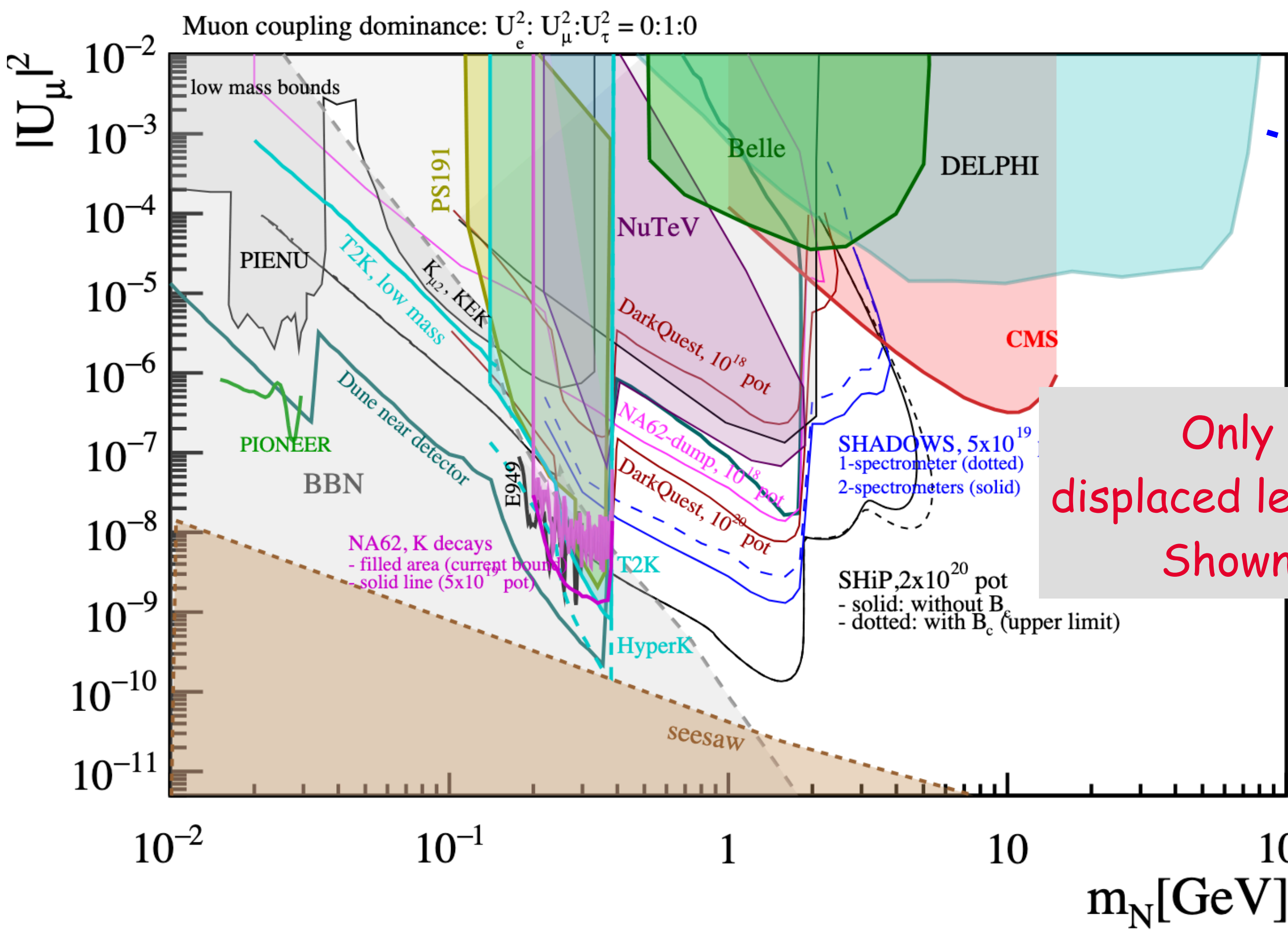
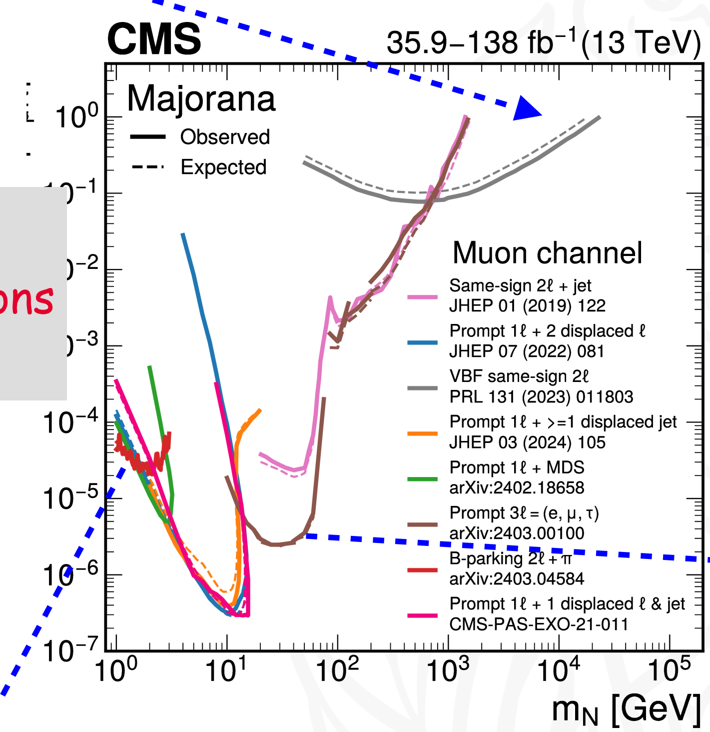
Direct searches at CMS

arxiv.2203.08039



Only displaced leptons Shown

First search at very high mass in type-I seesaw



Would be nice to provide common Summary plot + ATLAS

Improve DELPHI results

Very low mass searches, exclude new extra parameters space At 1-2 GeV!

Overall improvement of DELPHI's + Belle's boundaries!

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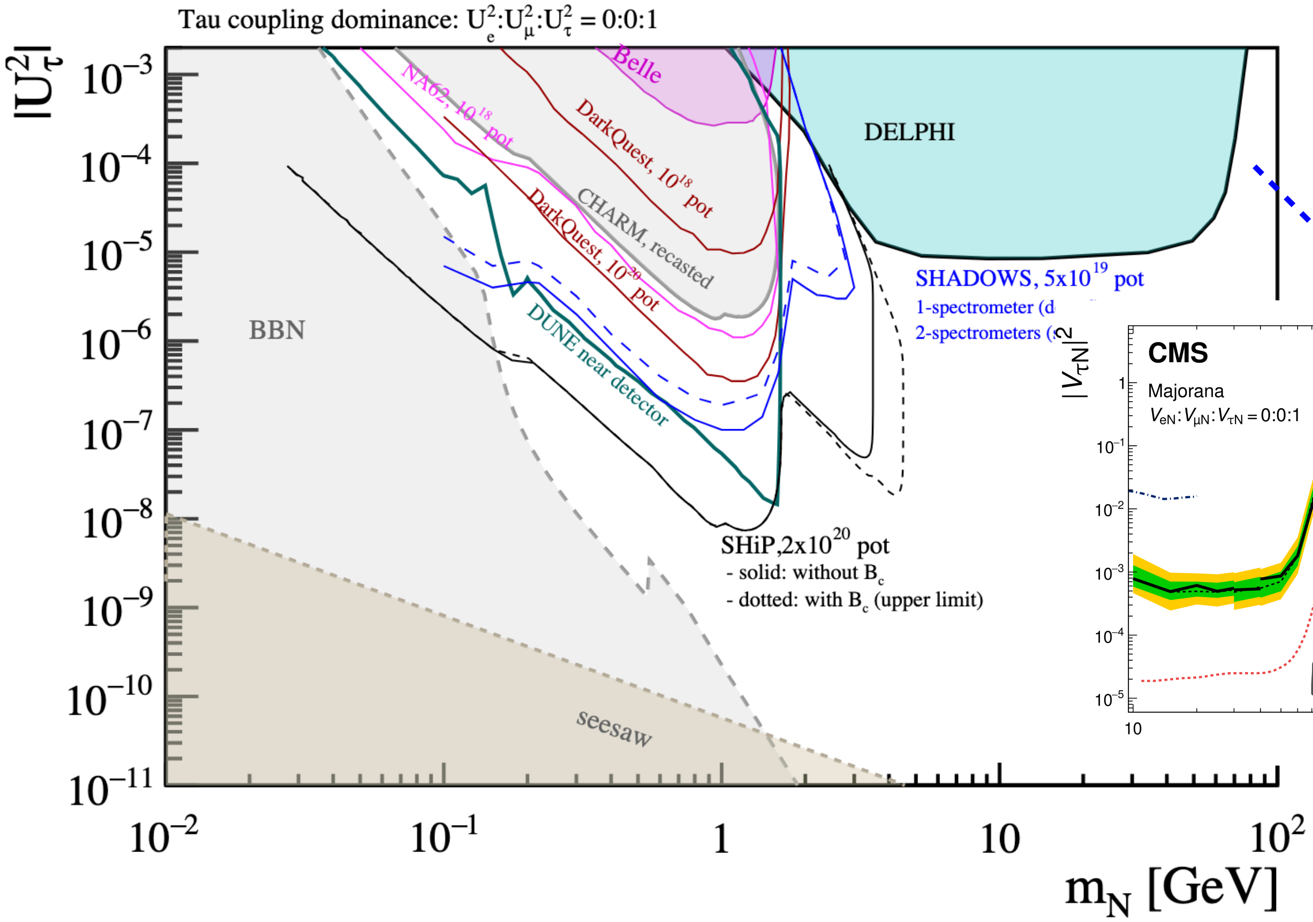
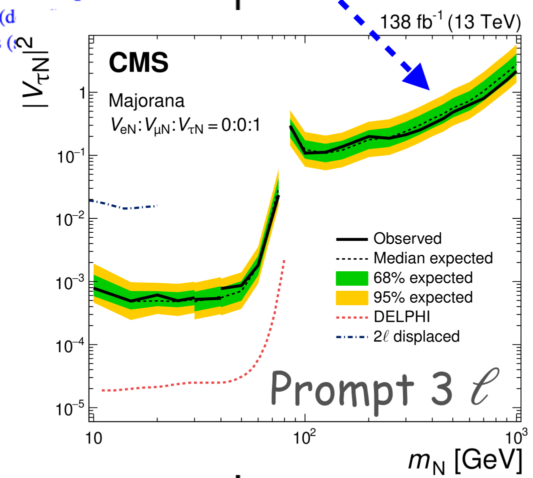
Haifa Sfar

Direct searches at CMS

arxiv.2203.08039

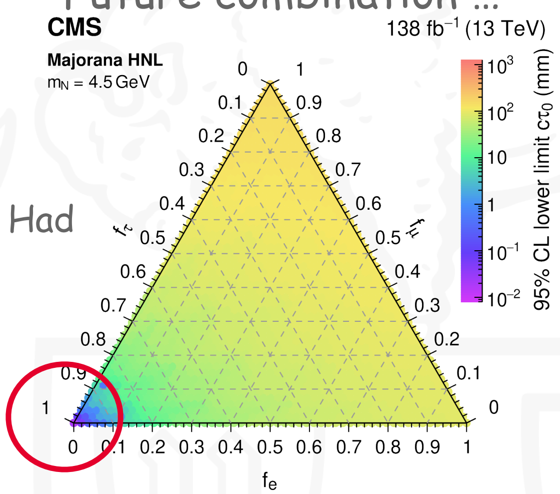


New to the big picture

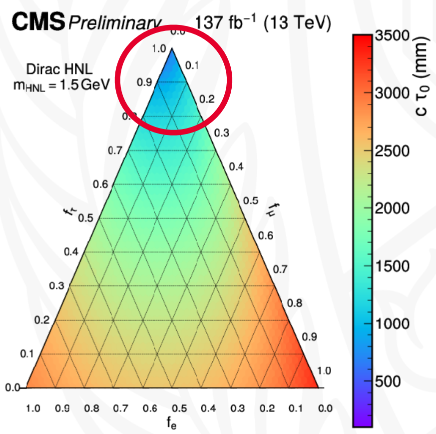


Prompt 3 ℓ

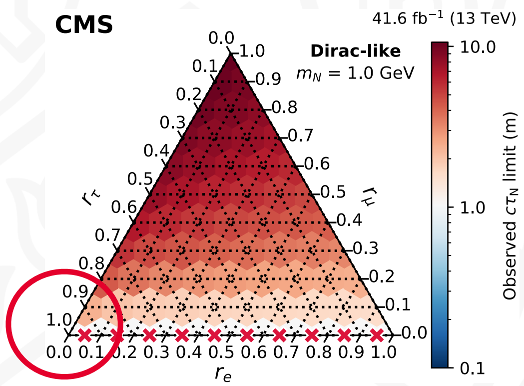
Not only… New interpretation(incl. lifetime) and possible Future combination …



LL- Had



Decay in muon syst.

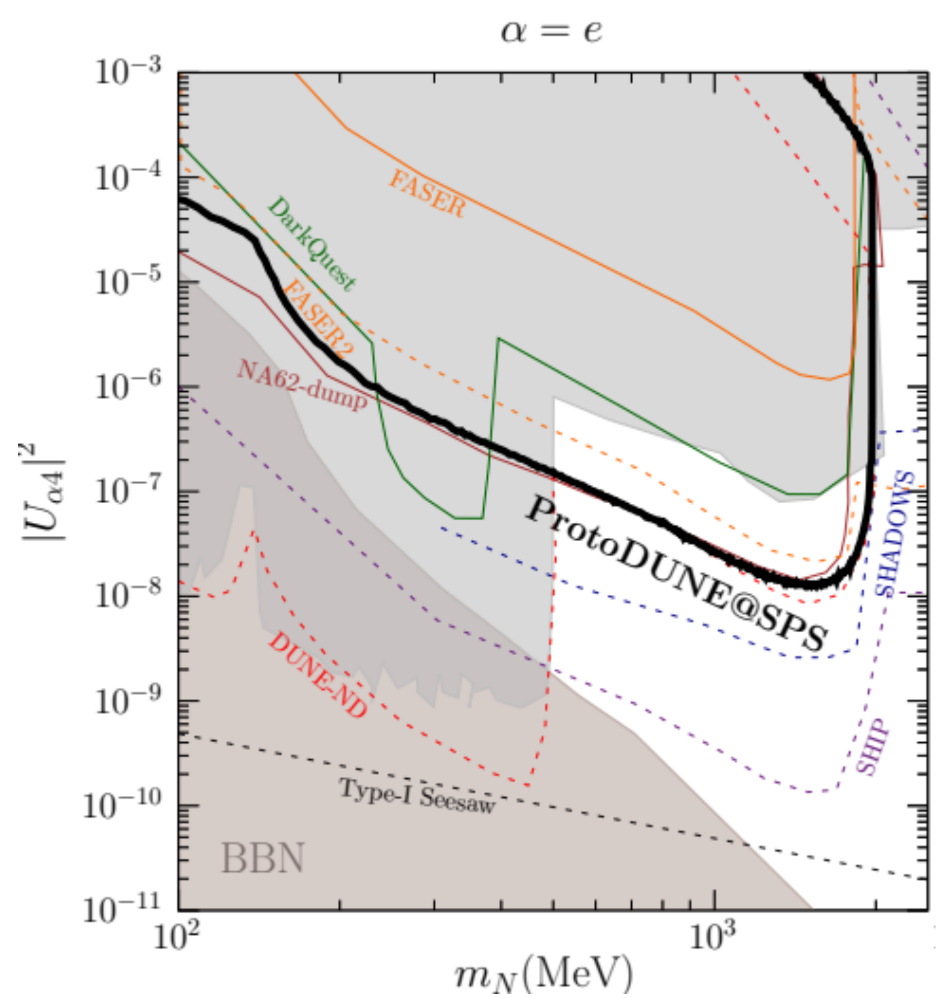


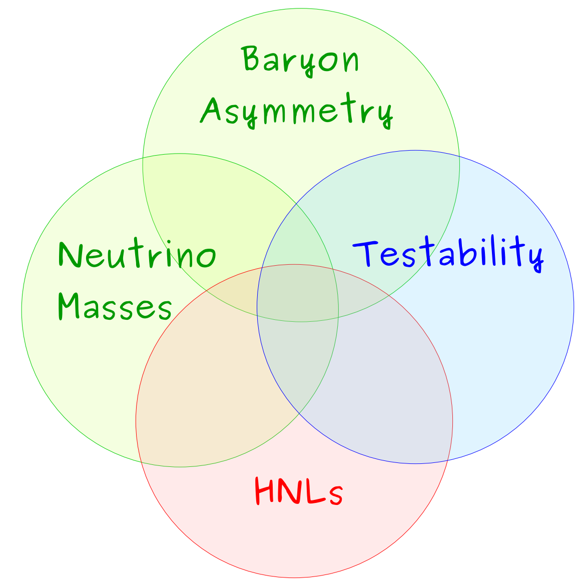
B-HNL

Haifa Sfar

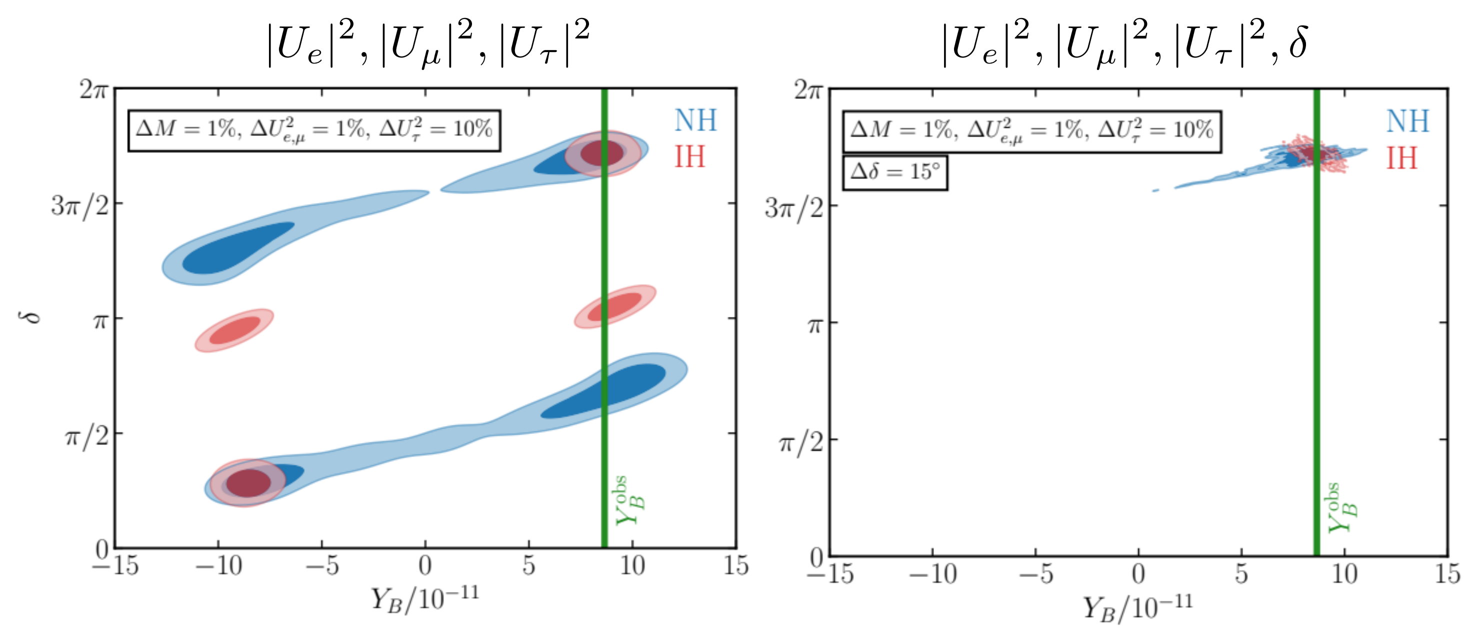
Testing the origin of ν masses

ProtoDUNE in beam dump configuration?





- Measurement of CP violation in neutrino oscillations, HNL mass and mixing with electron, muon and tau flavours can suffice to pin down matter-antimatter asymmetry.



	$M^{\rm true}$/GeV	$(U_e^2)_{\rm true}$	$(U_\mu^2)_{\rm true}$	$(U_\tau^2)_{\rm true}$	$\delta^{\rm true}$/rad
NH	31.60	2.843×10^{-12}	1.087×10^{-11}	1.234×10^{-11}	5.396
IH	20.731	3.291×10^{-11}	4.823×10^{-12}	3.465×10^{-12}	5.402

Hernandez, JLP, Rius, Sandner 2305.14427

$\boxed{\text{FCC-ee + DUNE/T2HK}}$

Cosmological constraints on νs

Early Universe Constraints

The total neutrino mass $\sum m_\nu$ impacts the CMB in various ways:

1) it **boosts the late-time non-relativistic density**, affecting the scale-angle relations on the last scattering surface and the **late ISW effects**.

2) affects the non-relativistic transition of neutrinos by changing the pressure-to-density ratio and causing metric fluctuations observable in the **early ISW effect**.

3) it **reduces weak lensing effects** on the CMB by **suppressing the matter power spectrum and CMB spectra at small scales**.

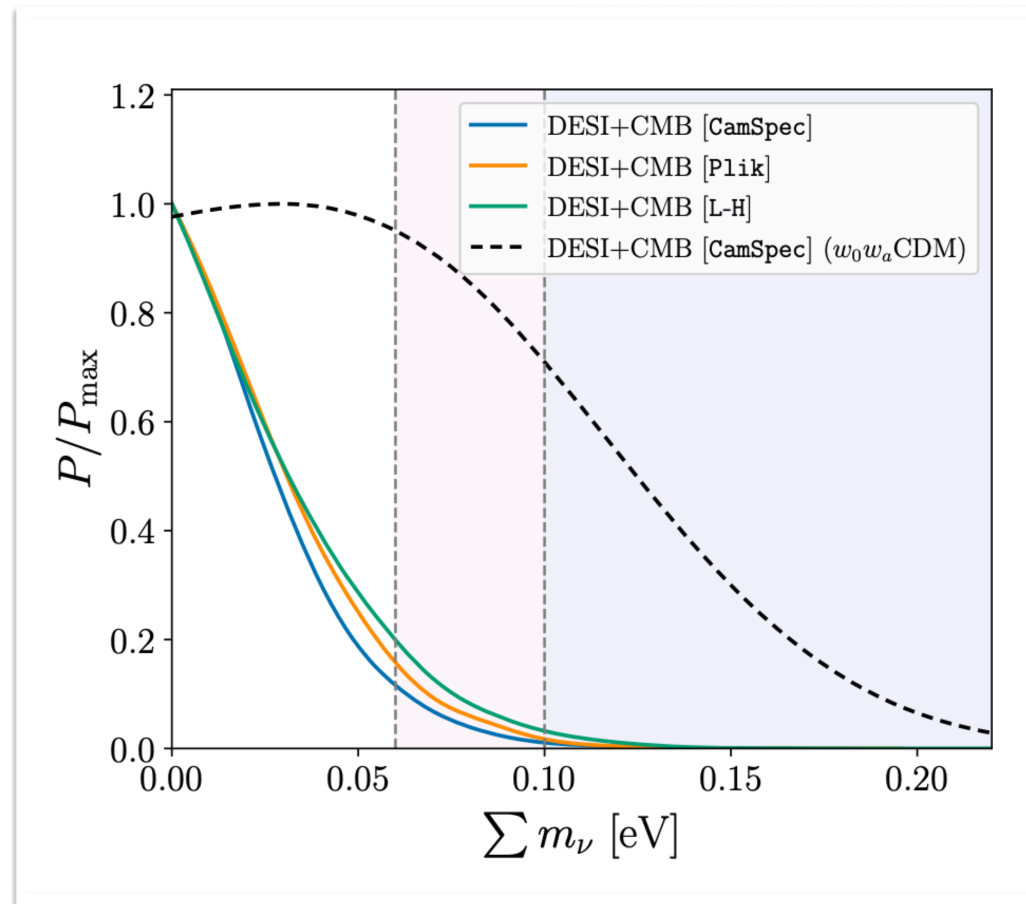
Late Universe Constraints

How can we improve the CMB limit on Neutrinos?

1) Neutrinos will become non-relativistic particles, contributing to the matter energy density at late times. Depending on their mass, they will alter **cosmic distances**, measured by BAO and, in part, Supernovae.

2) Neutrinos will suppress structure formation, affecting other local observables such as the matter power spectrum and weak lensing. We can examine the **large-scale structure** of the Universe.

DESI 2025 — [arXiv:2503.14738]



- **CMB+DESI-DR2:** $\sum m_\nu < 0.064$ **eV**

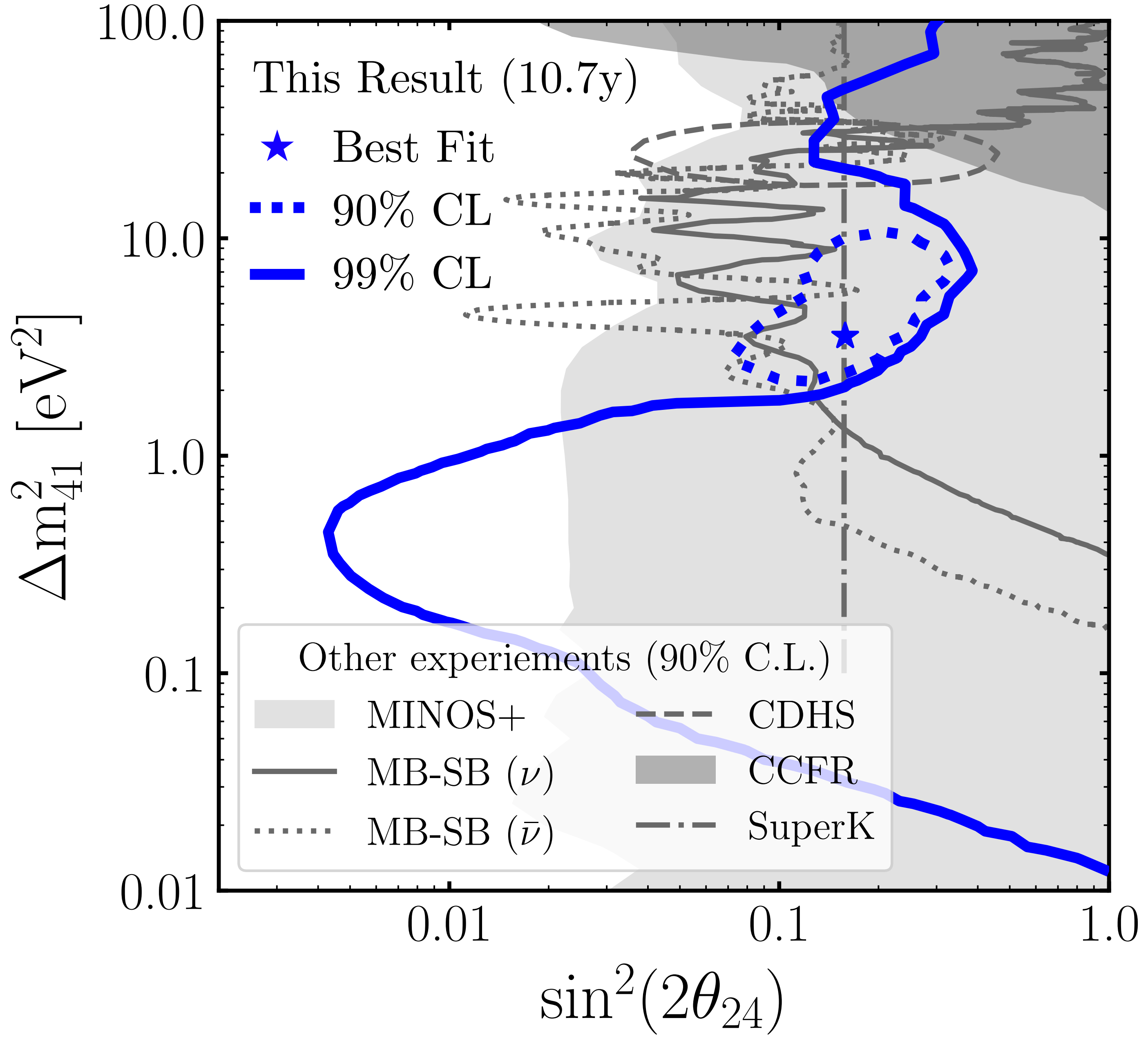
Oscillation Experiments NO: $\sum m_\nu > 0.06$ **eV**

Oscillation Experiments IO: $\sum m_\nu > 0.1$ **eV**

William Giare

New-ν searches with Ice Cube

There is a slight preference for sterile neutrinos, which is in tension with other measurements



New-ν summary

Many new results, a wide survey of new-ν physics

Plenty of issues to follow up

Thanks to all the speakers for the insightful talks!


New
Neutrinos
New Physics
New Searches