HNLs at ATLAS, a 2024 Summary

LHCP 2024

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On behalf of the ATLAS collaboration

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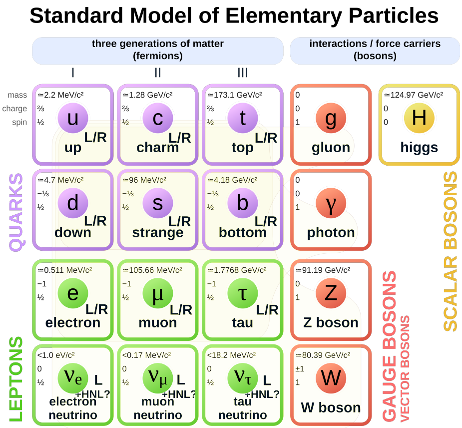
Intro

- I'm Gareth
- Today, I'm going to:
  - Give a one-slide summary of our HNL models
  - Give the context of previous HNL searches at ATLAS
  - Present the TeV scale HNL t-channel searches in more detail [1] [2]

[1] ATLAS Collaboration. "Search for Majorana neutrinos in same-sign WW scattering events from pp collisions at $\sqrt{s} = 13$ TeV". In: *Eur. Phys. J. C* 83 (2023), p. 824. DOI: 10.1140/epjc/s10052-023-11915-y. arXiv: 2305.14931 [hep-ex]

[2] ATLAS Collaboration. *Search for heavy Majorana neutrinos in $e^{\pm}e^{\pm}$ and $e^{\pm}\mu^{\pm}$ final states via WW scattering in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*. 2024. arXiv: 2403.15016 [hep-ex]

Targeted Models



[3]

- Standard νMSM except for
  - 2QDH: 2 Quasi-Dirac HNLs. The model can cause LNV suppression and give extended phenomenology.
  - Weinberg operator, higher order term with wilson coefficent and effective mass related to that probed at $0\nu\beta\beta$ experiments.

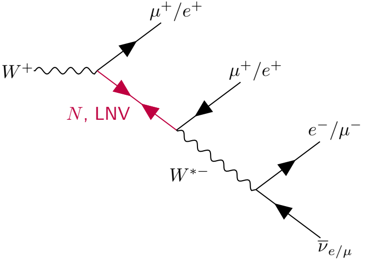
$$\mathcal{L}_{5,\text{ Weinberg}} = \sum_{\ell,\ell'}^{e,\mu,\tau} \frac{C_5^{\ell\ell'}}{\Lambda} \left[\Phi \cdot \bar{L}_\ell^c\right] \left[L_{\ell'} \cdot \Phi\right] \quad (1)$$

$$m_{\ell\ell'} = C_5^{\ell\ell'} v^2/\Lambda \quad (2)$$

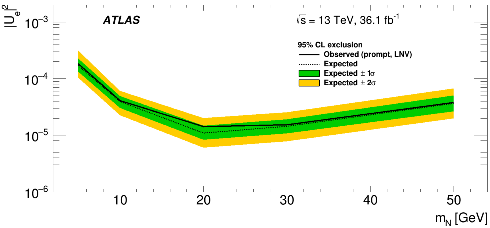
$$\nu_{L,\ell} = \sum_{\text{mass},i} U_{i,\ell}\nu_i + \sum_{\text{mass},j} V_{\ell,j} N_j \quad (3)$$

[3] Wikimedia Commons. *File:Standard Model of Elementary Particles.svg — Wikimedia Commons, the free media repository.* [Online; accessed 9-September-2020]. 2020. URL: https://commons.wikimedia.org/w/index.php?title=File:Standard_Model_of_Elementary_Particles.svg&oldid=430960007

Previous ATLAS searches - Prompt



- Partial run 2
- Probes short lifetime regime relying on Lepton Flavour Violation
- Competitive limits for ∼20-50 GeV[4]

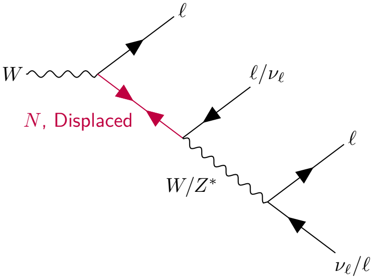


[5]

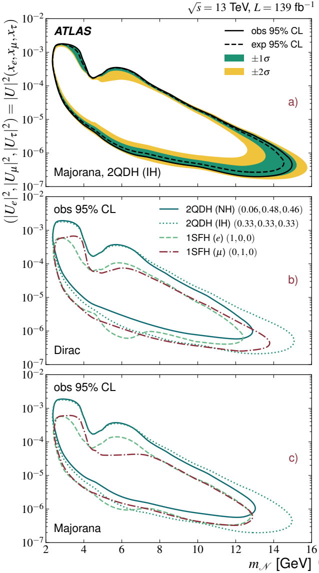
[4] CMS Collaboration. *Search for heavy neutral leptons in final states with electrons, muons, and hadronically decaying tau leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV*. Tech. rep. Submitted to the Journal of High Energy Physics. All figures and tables can be found at http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-22-011 (CMS Public Pages). Geneva: CERN, 2024. arXiv: 2403.00100. URL: https://cds.cern.ch/record/2890510

[5] ATLAS Collaboration. "Search for heavy neutral leptons in decays of W bosons produced in 13 TeV pp collisions using prompt and displaced signatures with the ATLAS detector". In: *JHEP* 10 (2019), p. 265. DOI: 10.1007/JHEP10(2019)265. arXiv: 1905.09787 [hep-ex]

Previous ATLAS searches - Displaced



- Full run 2
- Displaced lepton pair in the tracker+ prompt triggered-on lepton
- Lifetime ∼mm exclusion
- 2QDH re-interpretation alongside simple scenario

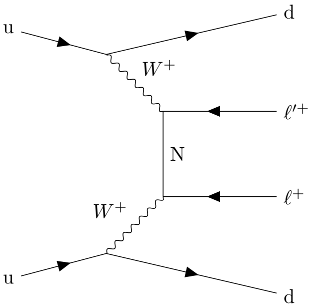


[6]

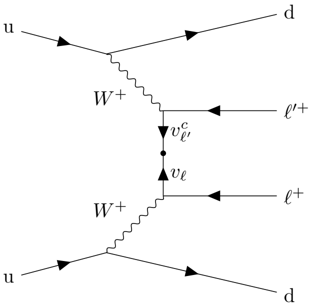
[6] ATLAS Collaboration. "Search for Heavy Neutral Leptons in Decays of W Bosons Using a Dilepton Displaced Vertex in $\sqrt{s} = 13$ TeV pp Collisions with the ATLAS Detector". In: *Phys. Rev. Lett.* 131 (2023), p. 061803. DOI: 10.1103/PhysRevLett.131.061803. arXiv: 2204.11988 [hep-ex]

WW scattering Topology

HNLs



Weinberg



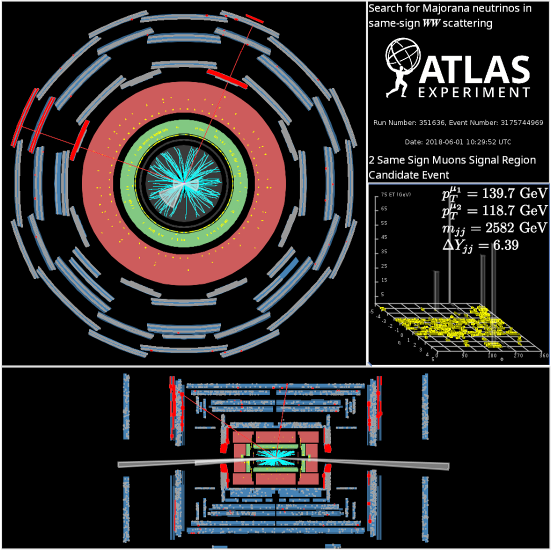
Targeting $\ell\ell' \in (ee, \mu e, \mu\mu)$ channels with combinations (Recent![7])

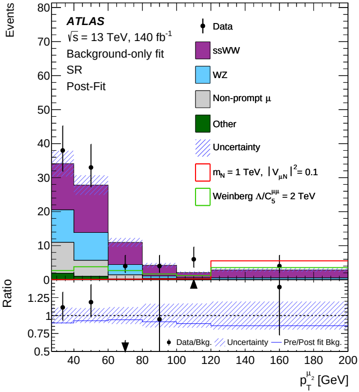
- Lepton Flavour Violation
- Excess of high p_{T} leptons (for HNLs)
- Back-to-back jets: colour connectedness (high-m_{jj} and rapidity separation)

Complimentary to neutrinoless double beta decay searches, can probe states not kinematically accessible ($e\mu$ and $\mu\mu$).

[7] ATLAS Collaboration. *Search for heavy Majorana neutrinos in $e^{\pm}e^{\pm}$ and $e^{\pm}\mu^{\pm}$ final states via WW scattering in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.* 2024. arXiv: 2403.15016 [hep-ex]

What this could look like

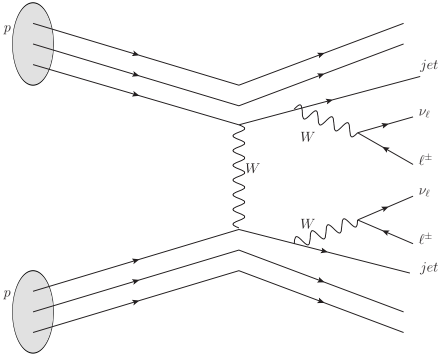




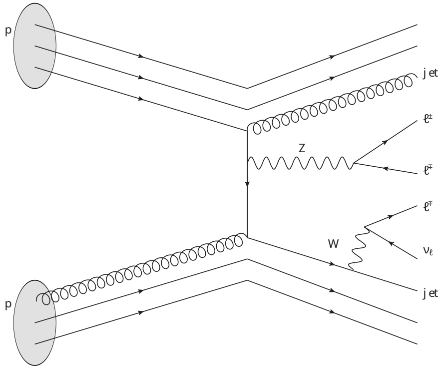
Bin in sub-leading lepton p_{T}

Backgrounds: Prompt

Sample	Origin
Same Sign WW	Similar signature, but with outgoing neutrinos
WZ scattering	Co-incidental lost lepton gives similar signature
$t\bar{t}$ + EWK, Triboson	Sub-leading prompt contribution



EWK production dominates as it also creates back-to-back jets



One lepton lost in reconstruction

Backgrounds: Non-Prompt

Using the power of a pre-existing analysis targeting same-sign WW, two styles of background are poorly modelled in Monte Carlo.

Non prompt Leptons: Mostly B decays

- Non-prompt object rejection power comes from tracking/isolation, keep set that fails some of these cuts (ID vs Anti-ID leptons)
- Calculate p_{T}, η dependant transfer factors using a di-jet enriched dataset e/μ, prompt contaminations corrected for with Monte Carlo
- Apply transfer factors to regions adjacent to our SRs and CRs

'Charge-Flip' leptons: Mostly e brehms

- Design region with $Z \to ee$ enrichment
- Derive a mis-ID probability
- Apply to a SR with opposite sign leptons

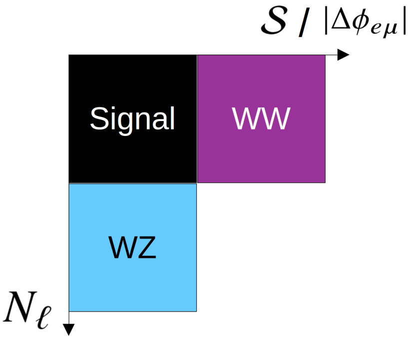
Also considered and determined to be negligible:

- Double-parton scattering
- Co-incidental W productions
- Charge flip μ

Region Designs

Low background search with limited statistics.
Three channels with similar designs/strategies for combination purposes.

- Benefit from high energy leptons, easy-to-fire triggers on
- Design Signal Region cuts with low $E_{\mathrm{T}}^{\mathrm{miss}}$ significance ($\mathcal{S}$), low central activity and back-to-backness
- Invert the cuts to target prompt backgrounds for Control Regions
- Fit scale factors μ_{signal}, μ_{WW}, μ_{WZ}



Region Definitions in Detail

Control Regions WW

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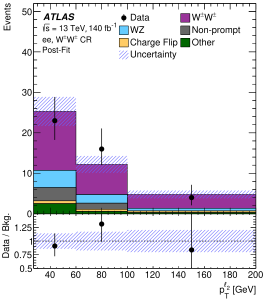
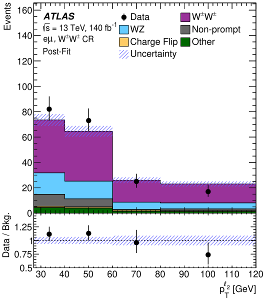
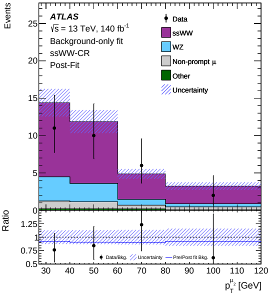
- Invert $\mathcal{S}/\Delta\phi_{e\mu}$ requirement
- All these CRs have good purity and scale factors consistent with 1



ee



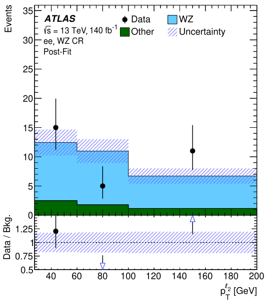
$e\mu$



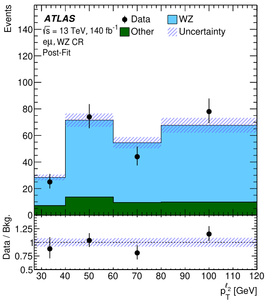
$\mu\mu$

Control Regions WZ

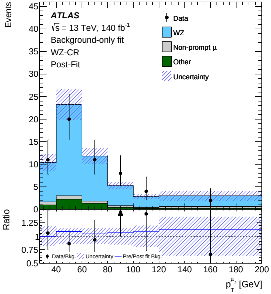
- 'Invert' number of leptons (3)



ee



$e\mu$



$\mu\mu$

Signal Regions

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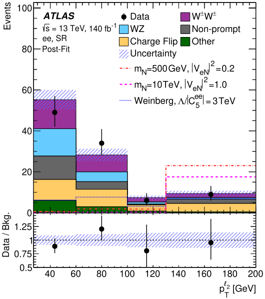
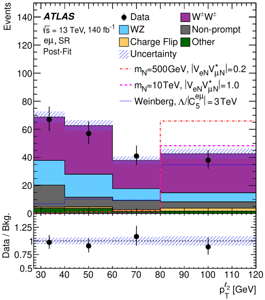
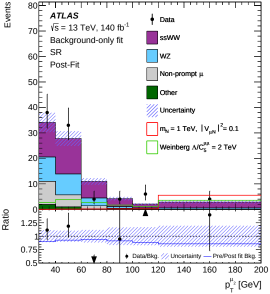
- Unblinded: No new physics!
- Once you consider binning + competitive sensitivity, ultimately, a cut and count in final bin.
- Very statistically limited.



ee

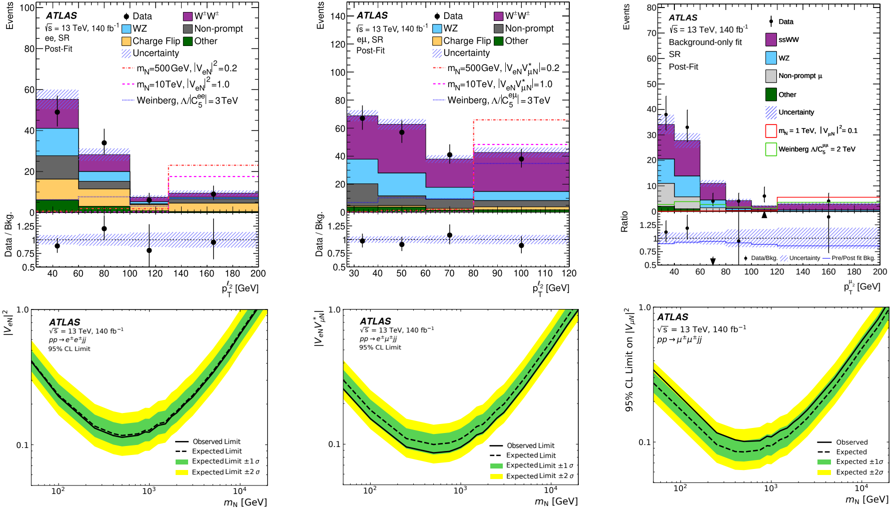


$e\mu$



$\mu\mu$

Signal Regions + Exclusions



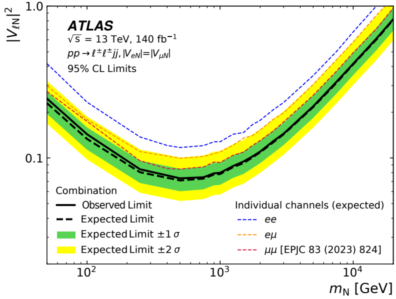
ee | $e\mu$ | $\mu\mu$

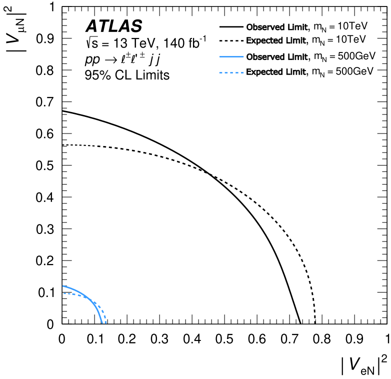
$m_{ee} > 24(24)$ GeV | $m_{e\mu} > 13(15)$ GeV | $m_{\mu\mu} > 16.7(13.1)$ GeV

Effective Weinberg majornana mass Limits: Expected (observed) 95% confidence

Combinations

- Combination is reasonably intuitive, float correlated signal strengths and combine nuisance parameters between channels (almost entirely negligible)
- Normalisations for each prompt background are floated separately for each channel (not the same phase space)





The broader LHC picture

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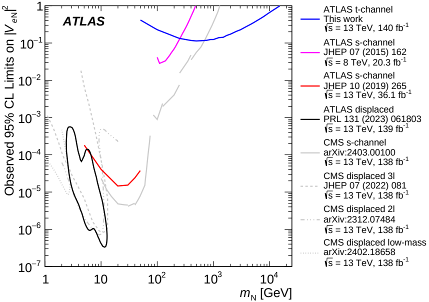
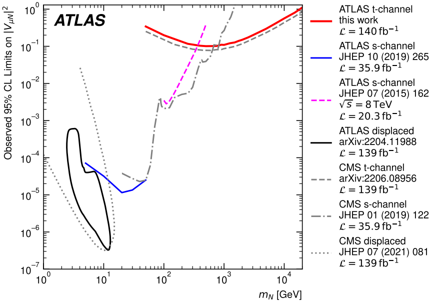


ee



$\mu\mu$

ALSO: First TeV scale $e - \mu$ mixing

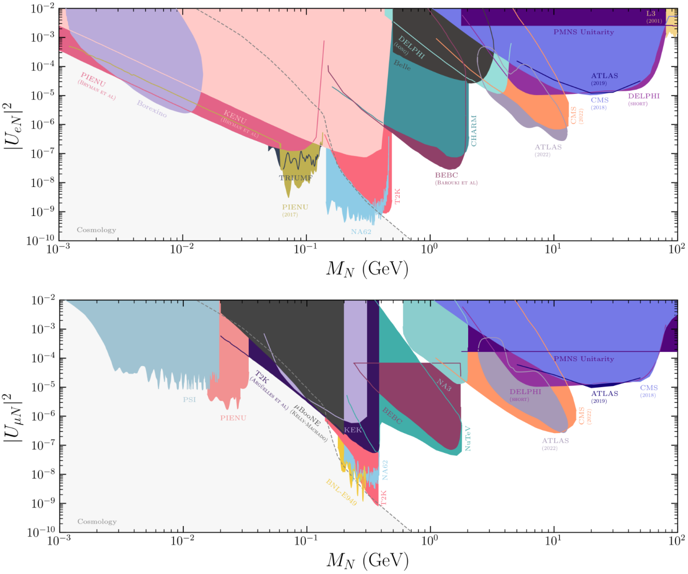
Conclusions

- HNLs are a historically powerful tool for explaining neutrino masses and cosmological phenomena
- We can use ATLAS to search for VBS-style excesses in the TeV regime with this framework
- ATLAS has created competitive limits of minimal and extended HNL models between $m_N \sim 10 - 10^4$ GeV alongside new Weinberg limits on $C_5^{\mu e}/\Lambda$ and $C_5^{\mu\mu}/\Lambda$

Part I

Back-up

The broader picture



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[8] Enrique Fernández-Martínez et al. "Effective portals to heavy neutral leptons". In: *Journal of High Energy Physics* 2023.9 (Sept. 2023). ISSN:

Precise Region Defintions

Channel	Variable	SR	$W^{\pm}W^{\pm}$ CR	WZ CR
$ee/e\mu$	N_{ℓ}	=2		=3
	$\lvert\Delta y_{jj}\rvert$	> 2		
	m_{jj}	> 500 GeV		
	$m_{\ell\ell\ell}$	–	–	> 106 GeV
ee	$\lvert m_{\ell\ell} - m_Z\rvert$	> 15 GeV		–
	$\lvert\eta_{\ell}\rvert$	<2		
	$m_{\ell\ell}$	> 20 GeV		
	$p_{\mathrm{T}}^{\ell_1}$	–	< 250	–
	$p_{\mathrm{T}}^{j_1}$	> 30 GeV	> 45 GeV	> 30 GeV
	$p_{\mathrm{T}}^{j_2}$	> 25 GeV	> 30 GeV	> 25 GeV
	$\mathcal{S}$	< 4.5	> 4.5	–
$e\mu$	$p_{\mathrm{T}}^{j_1}$	> 30 GeV	> 45 GeV	> 45 GeV
	$p_{\mathrm{T}}^{j_2}$	> 25 GeV	> 30 GeV	> 30 GeV
	$\lvert\Delta\phi_{e\mu}\rvert$	> 2.0	< 2.0	–

$ee/\mu e$

Observable	SR	ssWW-CR	WZ-CR
Same-sign muons	= 2 (signal μ)		
Number of b-jets	= 0		
m_{jj}	> 300 GeV		
$\lvert\Delta y_{jj}\rvert$	> 4		
Third lepton (OS)	= 0 (baseline)	= 0 (baseline)	= 1 (signal μ)
$E_{\mathrm{T}}^{\mathrm{miss}}$ signif. $\mathcal{S}$	< 4.5	> 5.8	< 4.5
$m_{\ell\ell\ell}$	—	—	> 100 GeV
$p_{\mathrm{T}}^{\mu_2}$	—	< 120 GeV	—

$\mu\mu$