Heavy Neutral Leptons and Slow LLPs at ATLAS

University of Warwick Seminar

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Intro

- I'm Gareth
- I work on software and firmware development for the ATLAS L1Calo Phase I upgrade
- I work on physics in my free (50%) time
- My time in Birmingham was spent on Heavy Neutral Leptons with RAL
- Today, I will:
  - Derive what a HNL is
  - How to probe TeV scale HNL models using one LHC [1] [2]
  - What else can we do with these models? Where could the future be hiding?

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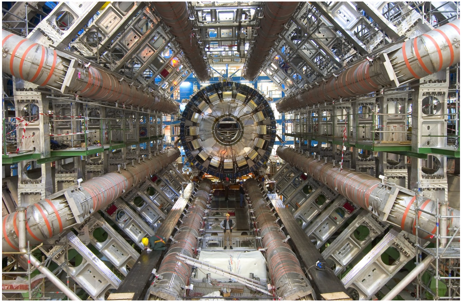
[1] ATLAS Collaboration. "Search for Majorana neutrinos in same-sign WW scattering events from pp collisions at $\sqrt{s} = 13$ TeV". In: *Eur. Phys. J. C* 83 (2023), p. 824. DOI: 10.1140/epjc/s10052-023-11915-y. arXiv: 2305.14931 [hep-ex]

[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]

What is ATLAS



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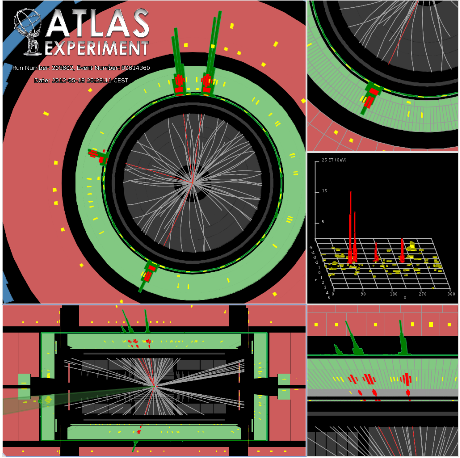

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General purpose pp detector on the LHC, tracking, calorimetry, muons, 2-stage trigger

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[3] Maximilien Brice. "Installing the ATLAS calorimeter". 2005. URL: https://cds.cern.ch/record/910381

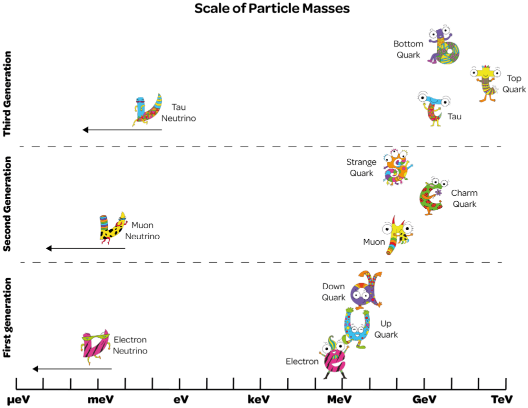
[4] Collaboration ATLAS. "Event display of a H 4e candidate event". General Photo. 2012. URL: https://cds.cern.ch/record/1459495

Part I

HNLs, a theoretical minimum

The canonical motivation

- Neutrino masses are tiny compared to everything else
- Why?
- We can use the Majorana particle hypothesis to suppress them: if the right-handed component is massive, we suppress mass scales
- Here we only talk about a minimal model: type I see-saw



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[5] ATLAS Collaboration. "ATLAS Colouring Books: a guide for Parents and Teachers". In: (2022). URL: https://cds.cern.ch/record/2801358

Majorana construction

Motivation: we want to construct a spinor from only the chiral part we can observe, which generates some additional properties. Take the chiral projections of Dirac equation (eq. (1)) and apply charge conjugate $\hat{C}$ operators deduced from minimal coupling as $i\gamma^2\gamma^0(\psi)^*$.

$$i\gamma^\mu\partial_\mu\psi_L = m\psi_R \tag{1a}$$

$$i\gamma^\mu\partial_\mu\psi_R = m\psi_L \tag{1b}$$

Fast-forwarding through a couple of pages of commutator trickery, we get eq. (2) from eq. (1b)

$$i\gamma^\mu\partial_\mu\left[\underbrace{C}_{i\gamma^2\gamma^0}\overline{\psi}_R^T\right] = m\left[C\overline{\psi}_L^T\right](\equiv m\psi_L^c) \tag{2}$$

From the solution of one half of Dirac equation, we can construct an opposite chirality object.
Manipulate this property to construct Majorana spinors and properties (intuitively charge violation).

$$\chi_L \overset{def}{=} \psi_L + \psi_L^c \text{ with } \chi_L^c = \chi_L \tag{3}$$

Type I see-saw

The most generic Majorana mass lagrangian we can write down with 2 fields ν_L, ν_R is as follows:

$$\underbrace{m_D \overline{\nu_R} \nu_L + m_D \overline{\nu_L^c} \nu_R^c}_{\text{Dirac mass terms}} + \underbrace{m_L \overline{\nu_L^c} \nu_L + m_R \overline{\nu_R^c} \nu_R}_{\text{Majorana mass terms}} + h.c. \tag{4}$$

Given $m_L = 0$ by constraints of EW gauge invariance ($T_3 = 1, Y = -2$)

$$(\overline{\nu_L^C}, \overline{\nu_R}) \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^C \end{pmatrix} + h.c. \tag{5}$$

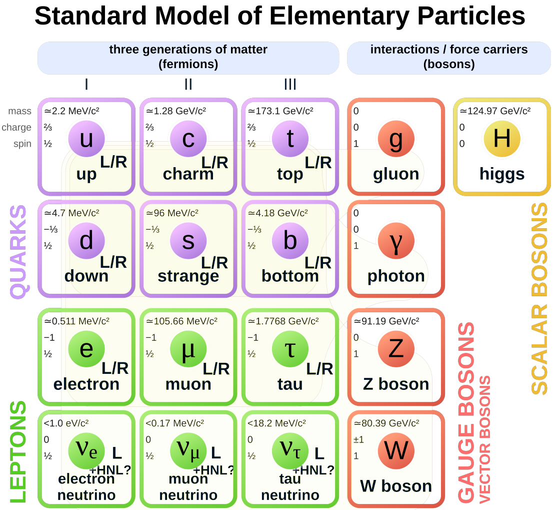
Then we trivially diagonalise (using $m_D \ll m_R$):

$$m_{N,\nu} = \frac{1}{2} \left[m_R \pm \sqrt{m_R^2 + 4m_D^2} \right] \approx m_R, \frac{m_D^2}{2m_R} \tag{6}$$

$$\nu \sim (\nu_L + \nu_L^c) - \frac{m_D}{m_R^2} (\nu_R + \nu_R^c) \, ; N \sim (\nu_R + \nu_R^c) + \frac{m_D}{m_R^2} (\nu_L + \nu_L^c) \tag{7}$$

Mass ratios become mixing angles; otherwise fits into the Standard Model.

Generalise to 3 masses



[6]

$$\nu_{L,\ell} = \sum_{\text{mass},i} U_{i,\ell}\nu_i + \sum_{\text{mass},j} V_{\ell,j}N_j \tag{8}$$

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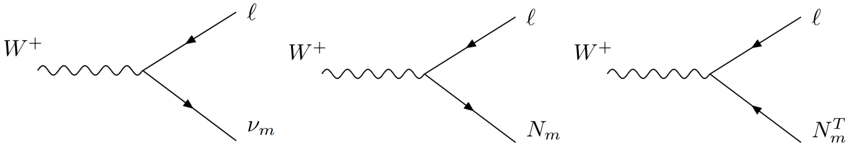
[6] Wikimedia Commons. *File:Standard Model of Elementary Particles.svg — Wikimedia Commons, the free media repository*. [Online; accessed 9-September-2020]. 2020. URL:

Non-cannonical justification



$-i\frac{g}{\sqrt{2}}U^*_{\ell m}\gamma^\mu P_L$ $\quad -i\frac{g}{\sqrt{2}}V^*_{\ell m}\gamma^\mu P_L$ $\quad -i\frac{g}{\sqrt{2}}V^*_{\ell m}C\gamma^\mu P_L$ [7]

- We've made a mechanism to explain the relative smallness of neutrinos
- This is great, but we can't make 10^5 GeV particles here on Earth that make the masses small enough
- The notion of these objects is still a powerful tool
- These are typically embedded in a larger model by theorists
- Arguments can be given to give Leptogenesis up to masses ∼TeV and Dark Matter $\sim keV \implies$ search complementarity [8]

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[7] Anupama Atre et al. "The search for heavy Majorana neutrinos". In: *Journal of High Energy Physics* 2009.05 (May 2009), pp. 030–030. ISSN: 1029-8479. DOI: 10.1088/1126-6708/2009/05/030. URL: http://dx.doi.org/10.1088/1126-6708/2009/05/030

[8] MARCO DREWES. "THE PHENOMENOLOGY OF RIGHT HANDED NEUTRINOS". In: *International Journal of Modern Physics E* 22.08 (Aug. 2013), p. 1330019. ISSN: 1793-6608. DOI: 10.1142/s0218301313300191. URL: http://dx.doi.org/10.1142/S0218301313300191

More terms: Weinberg

All of the theory is writing Lagrangians and considering all symmetrically allowed terms, so let's do this.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}\not{\partial}N - \bar{L}_\ell Y_\nu \Phi^c N - \frac{1}{2}\bar{N}^c M_N N + \sum_{n>4}\frac{\mathcal{O}^n}{\Lambda^{n-4}} + \text{ h.c. }^{9} \tag{9}$$

- This introduces a contact interaction term that doesn't conserve the lepton number
- This can be linked to an effective mass
- These terms can also be linked to DM models by higher-order electromagnetic terms

$$\mathcal{L}_{5,\text{ Weinberg}} = \sum_{\ell,\ell'}^{e,\mu,\tau}\frac{C_5^{\ell\ell'}}{\Lambda}\left[\Phi\cdot\bar{L}_\ell^c\right]\left[L_{\ell'}\cdot\Phi\right] + \text{ h.c.} \tag{10}$$

$$m_{\ell\ell'} = C_5^{\ell\ell'}v^2/\Lambda \tag{11}$$

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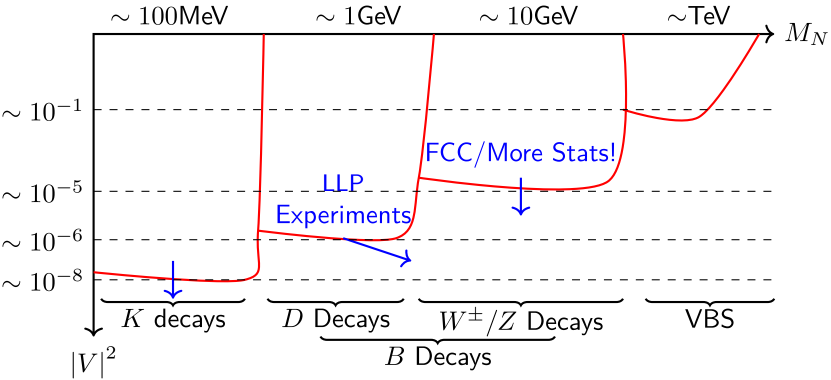
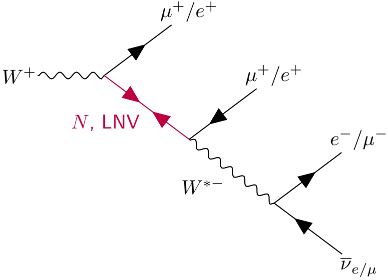
[9] Daniele Barducci et al. "Probing right-handed neutrinos dipole operators". In: *Journal of High Energy Physics* 2023.3 (Mar. 2023). ISSN: 1029-8479. DOI: `10.1007/jhep03(2023)239`. URL: `http://dx.doi.org/10.1007/JHEP03(2023)239`

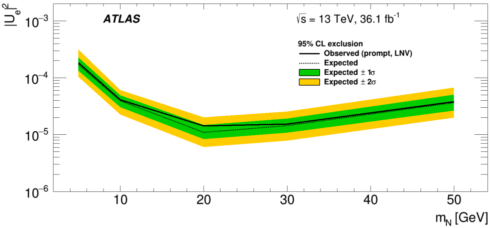
Oversimplified Collider Parameter Space



Previous ATLAS searches - Prompt



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



[10]

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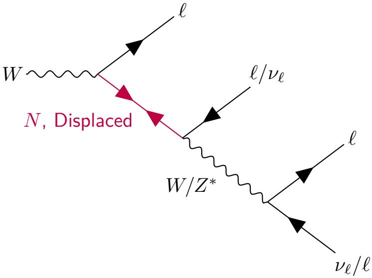
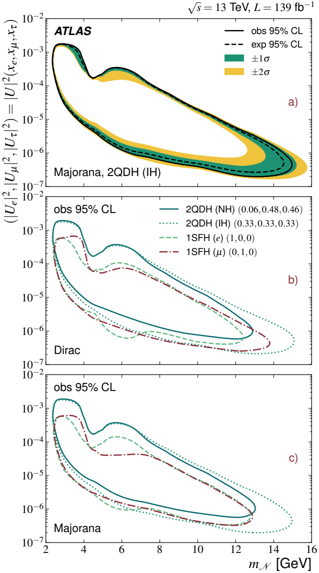
[10] ATLAS Collaboration. “Search for heavy neutral leptons in decays of W bosons produced in 13 TeV pp collisions using prompt and displaced signatures with the ATLAS detector”. In: *JHEP* 10 (2019), p. 265. DOI: `10.1007/JHEP10(2019)265`. arXiv: `1905.09787 [hep-ex]`

Previous ATLAS searches - Displaced



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



[11]

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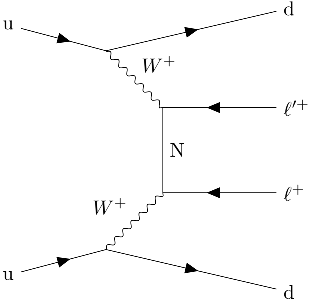
[11] ATLAS Collaboration. "Search for Heavy Neutral Leptons in Decays of W Bosons Using a Dilepton Displaced Vertex in $\sqrt{s} = 13$ TeV pp Collisions with the ATLAS Detector". In: *Phys. Rev. Lett.* 131 (2023), p. 061803. DOI: 10.1103/PhysRevLett.131.061803. arXiv: 2204.11988 [hep-ex]

Part II

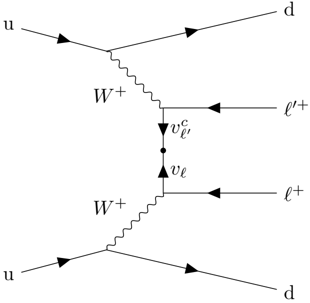
TeV Scale Physics: HNL VBS

Topology

HNLs



Weinberg

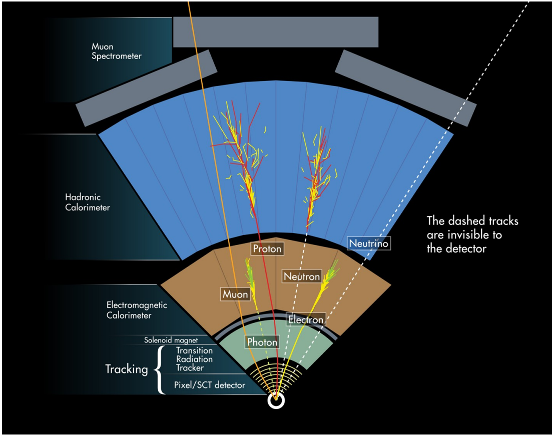


Targeting $\ell\ell \in (ee, \mu e, \mu\mu)$ channels NEW!

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

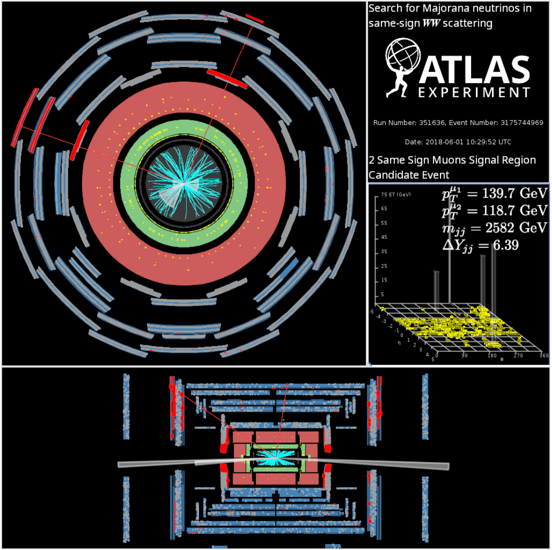
Complimentary to neutrinoless double beta decay searches, can the probe states not kinematically accessible ($e\mu$ and $\mu\mu$).

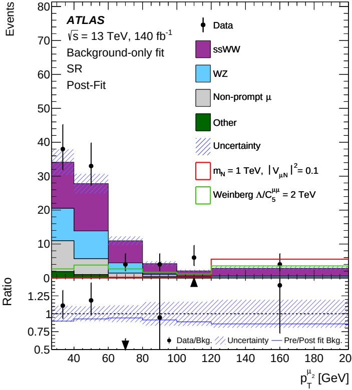
How ATLAS could see this



- Curved lepton tracks
- EM showers
- No missing $E_{\mathrm{T}}^{\mathrm{miss}}$
    - Resolution effects incorporated using $E_{\mathrm{T}}^{\mathrm{miss}}$ Significance ($\mathcal{S}$)
- 2 back-to-back hard forward jets

What this could look like

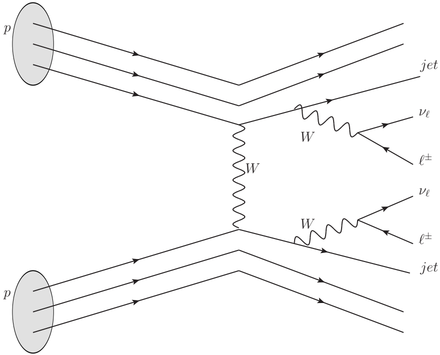




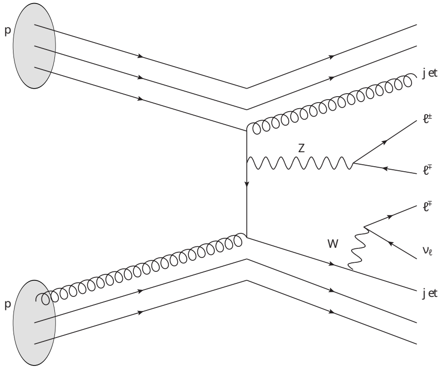
Bin in sub-leading lepton p_T

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 ssWW, 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 cuts (ID vs Anti-ID leptons)
- Calculate p_{T}, η dependant transfer factors using a di-jet enriched dataset, prompt contaminations in this region are corrected for with Monte Carlo
- Apply fake 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 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 $E_{\mathrm{T}}^{\mathrm{miss}}$, low central activity and back-to-backness.
- Invert the cuts to target prompt backgrounds CR
- Fit scale factors μ_{signal}, μ_{WW}, μ_{WZ}

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	–

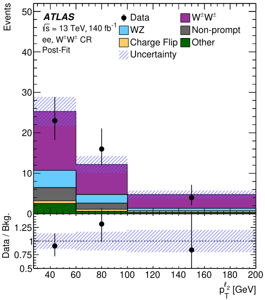
$ee/\mu e$

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	—

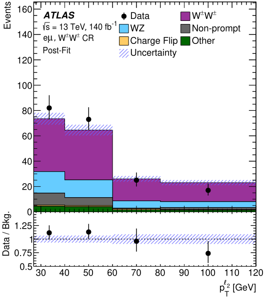
$\mu\mu$

Control Regions WW

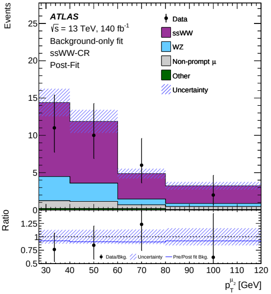
- Invert $\mathcal{S}/\Delta\phi_{e\mu}$ requirement
- All these CRs have good purity and scale factors consistent with 1



ee



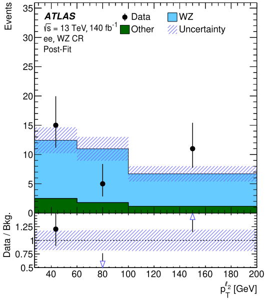
$e\mu$



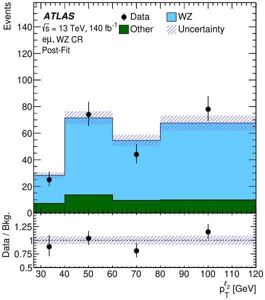
$\mu\mu$

Control Regions WZ

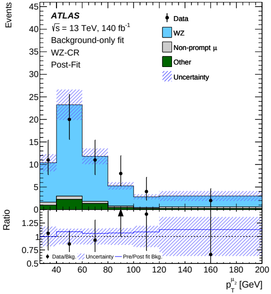
- ‘Invert’ number of leptons (3)



ee



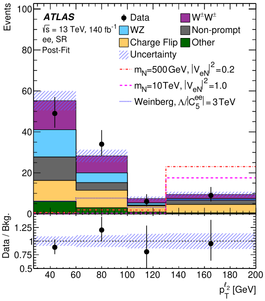
$e\mu$



$\mu\mu$

Signal Regions

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



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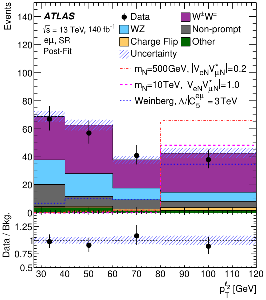
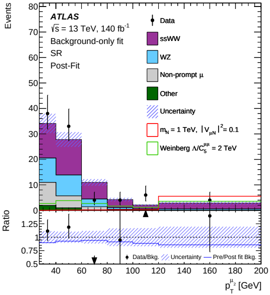
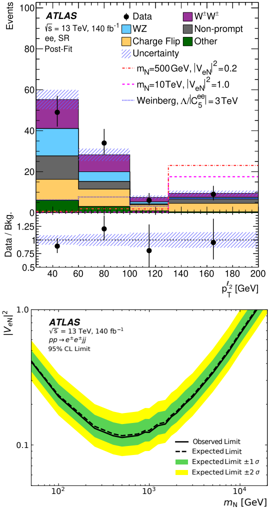


$e\mu$



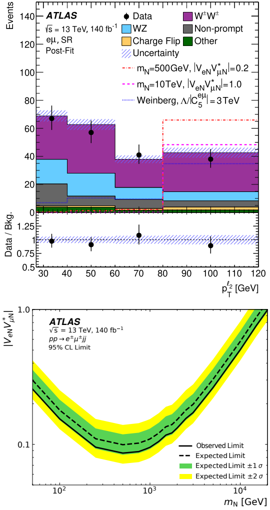
$\mu\mu$

Signal Regions + Exclusions



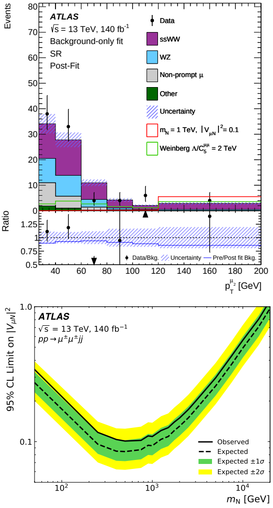
ee

$m_{ee} < 24(24)$ GeV



$e\mu$

$m_{e\mu} < 13(15)$ GeV

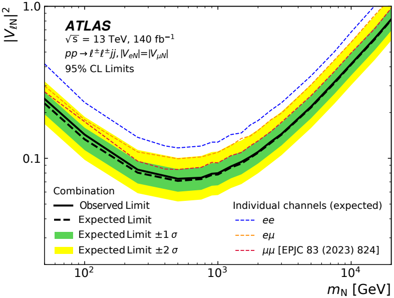


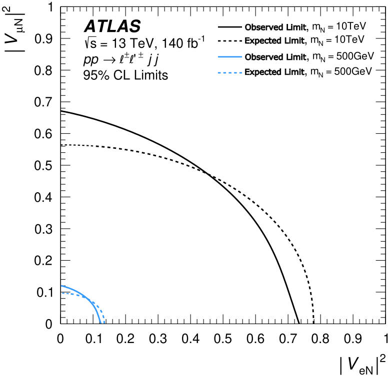
$\mu\mu$

$m_{\mu\mu} < 16.7(13.1)$ GeV

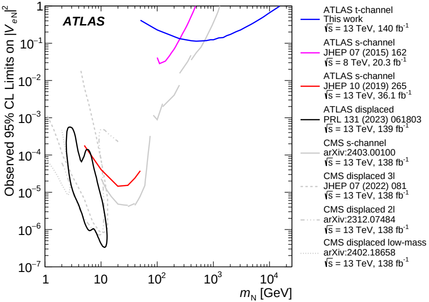
Combinations

- Combination is reasonably straightforward, 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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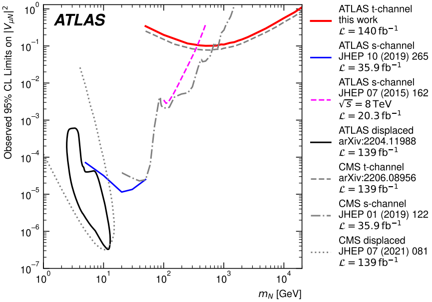
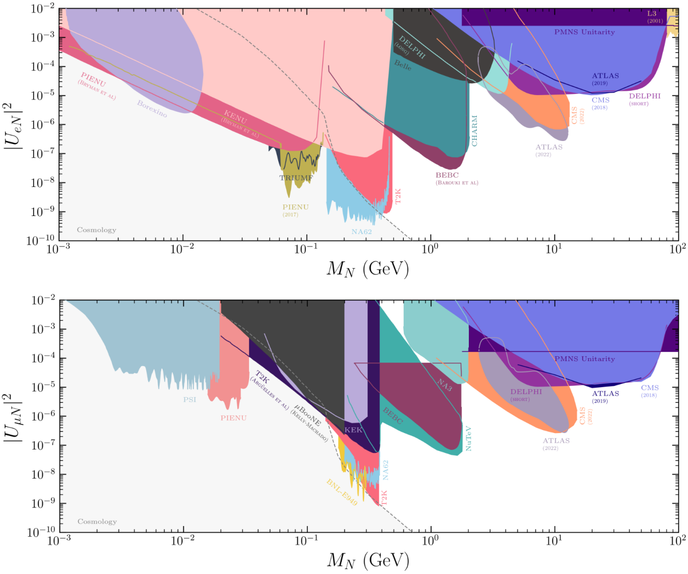


$\mu\mu$

First TeV scale $e - \mu$ mixing

The broader picture



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

Part III

HNLs at LHC: what else?

What are we excluding? I

Some critiques you can throw at these searches

- Large mixing angles wrt to unitarity
- Arguably fine tuning across all this parameter space (GeV+ scale HNLs need cancellation of divergences for loop corrected masses)
- LFV modes by some models can be suppressed by compression/oscillation style scenarios (contentious)

Similar games can inevitably be played when we probe many-parameter exotic models like supersymmetric ones.

What are we actually excluding? II

Some critiques you can throw at these searches

- Large mixing angles wrt to unitarity
- Arguably fine tuning across all this parameter space (GeV+ scale HNLs need cancellation of divergences for loop corrected masses)
- LFV HNL modes by some models can be suppressed by compression style scenarios (contentious)

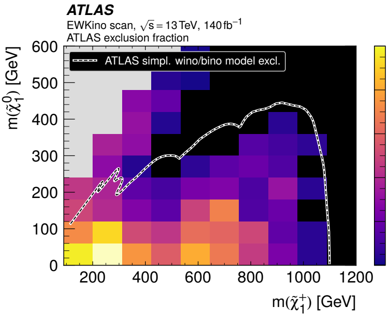
Similar games can inevitably be played when we probe many-parameter exotic models like supersymmetric ones.

Is This Hopeless?

What are we actually excluding? III

Is This Hopeless? No!

Motivate unique topologies, then reinterpret



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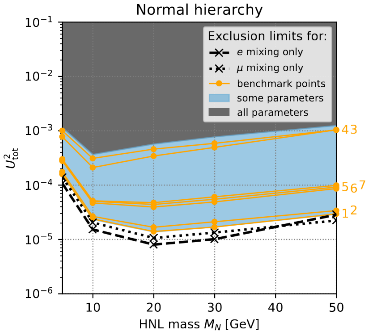

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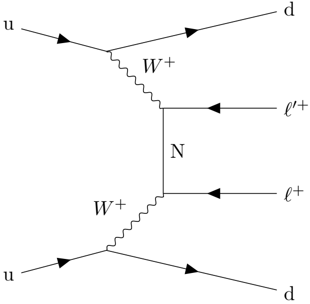
[13] *ATLAS Run 2 searches for electroweak production of supersymmetric particles interpreted within the pMSSM.* Tech. rep. Geneva: CERN, 2024. arXiv: 2402.01392. URL: `https://cds.cern.ch/record/2888303`

[14] J.-L. Tastet, O. Ruchayskiy, and I. Timiryasov. "Reinterpreting the ATLAS bounds on heavy neutral leptons in a realistic neutrino oscillation model". In: *Journal of High Energy Physics* 2021.12 (). ISSN: 1029-8479. DOI: `10.1007/jhep12(2021)182`. URL: `http://dx.doi.org/10.1007/JHEP12(2021)182`

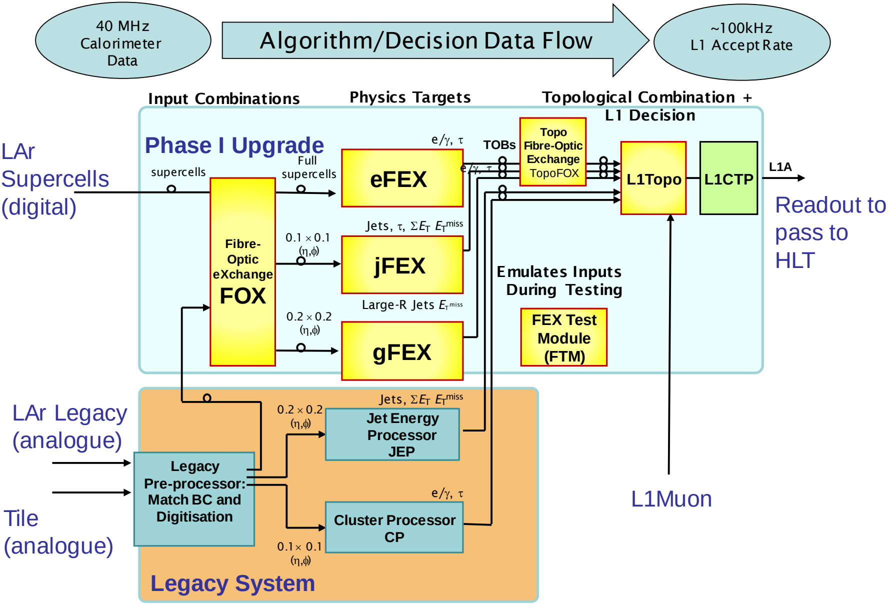
What are we actually excluding? IV

- Ultimately, we were benchmarking a same-sign di-lepton signal with a VBS-style marker indicating an anomalous Electroweak style high energy scale phenomena
- We do m sweeps for many resonant style searches
- We also do this with generic $c\tau$ exclusion plots for long-lived particle searches
- Where could we be overlooking sensitivity in our data acquisition design?

HNLs



A Seminar In A Slide



What Do You Need To Know

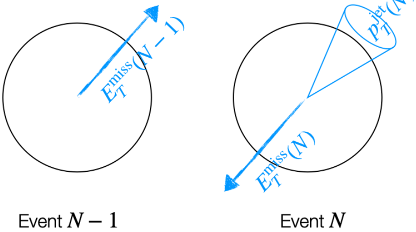
- All calorimeter energy deposits in a hardware trigger are assigned a bunch crossing (very accurately for most $\beta \sim 1$ signals).
- Algorithms at L1 have no knowledge of the previous 25ns or the one after... typically.
- QCD multi-jet very common, we must reject a lot of lower p_{T} objects before we can begin to consider wider time ranges on software-based High Level Trigger
- However, there is a limited scope to build a Topological combination of multiple L1Calo objects between bunch crossings: sensitivity to slow LLPs through correlations.

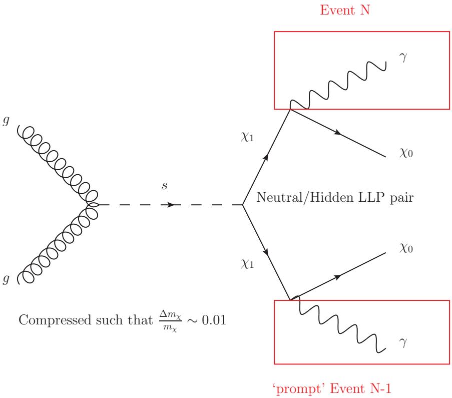
Slow LLPs with L1Calo

- We have a collider that has the kinematic capability to produce heavier objects than before
- We haven't found any big exotic excesses to date
- If we have a heavy object decaying to hierarchy of hidden compressed objects, the calorimeter energy deposits may be small and slow $\implies$ we don't fire the trigger
- Idea: use out of time information

All three quantities are about the same magnitude:

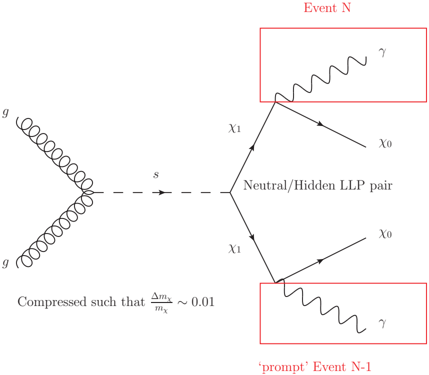
$$|E_T^{\text{miss}}(N-1)| \simeq |E_T^{\text{miss}}(N)| \simeq |p_T^{\text{jet}}(N)|$$





Hidden Sectors

- Ultimately, we are looking for a neutral, compressed, slow-moving signal.
- Take the inelastic dipole dark matter model from FASER paper[a]
- Instead of mesons, scalar mass hypothesis s ∼TeV, link to exotic higgs limits?
- near 100% BR to χ_1 pair, which then radiatively decay $\gamma, W/Z$
- Pair of soft out-of-time energy deposits, otherwise invisible
- Some overlap with ISR-style searches, but thresholds different/directness.



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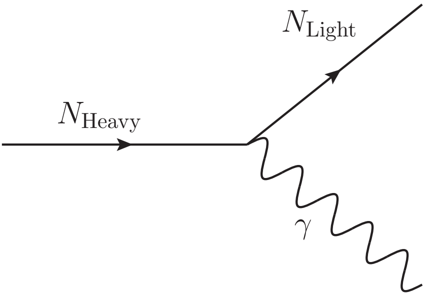
[a] Keith R. Dienes et al. "Extending the discovery potential for inelastic-dipole dark matter with FASER". In: *Physical Review D* 107.11 (June 2023). ISSN: 2470-0029. DOI: 10.1103/physrevd.107.115006. URL: http://dx.doi.org/10.1103/PhysRevD.107.115006

What is χ?

We have another dimension-5 term in our expansion![15]

$$\mathcal{O}^5_{NB} = \bar{N}^c \sigma^{\mu\nu} N B_{\mu\nu} \tag{12}$$

- This generates a higher-order hypercharge term to HNLs that comes with its own floating Wilson coefficient
- Scope to tune on-shell W/Z decay search with compressed HNLs?



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[15] Daniele Barducci et al. "Probing right-handed neutrinos dipole operators". In: *Journal of High Energy Physics* 2023.3 (Mar. 2023). ISSN: 1029-8479. DOI: 10.1007/jhep03(2023)239. URL: http://dx.doi.org/10.1007/JHEP03(2023)239

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
- With unusual triggers, we can probe more unusual LLP topologies.