CERN

ATLAS EXPERIMENT

# Searches for new physics using leptons with the ATLAS detector

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LeptonPhoton 2025 – Madison, Wisconsin

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IFAE Institut de Física d'Altes Energies

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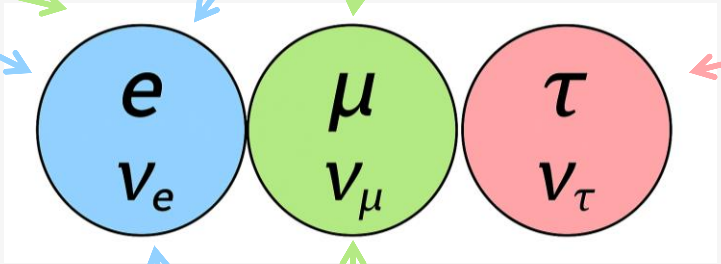
# Overview of this talk:

- **Small selection** of recent searches in leptonic final states by the ATLAS Collaboration, using 140 $\mathrm{fb}^{-1}$ of Run-2 data.

Prompt Heavy Neutral Leptons (HNLs) NEW!
CERN-EP-2025-164

Vector-like Leptons (VLLs)
JHEP05(2025)075

Vector-like Leptons in ‘4321’
2503.22581




Model-independent multilepton using anomaly detection NEW!
2508.19778

Plenty more results to be found on the ATLAS public pages.

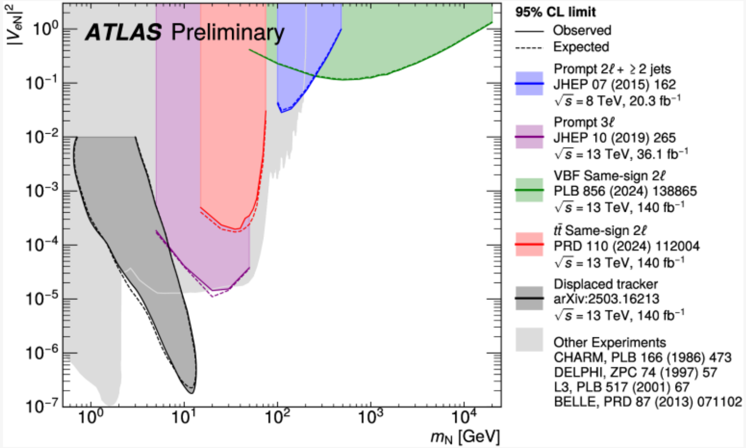
**This talk will not cover**: Long-lived particles, High mass di-tau, Z’ searches.

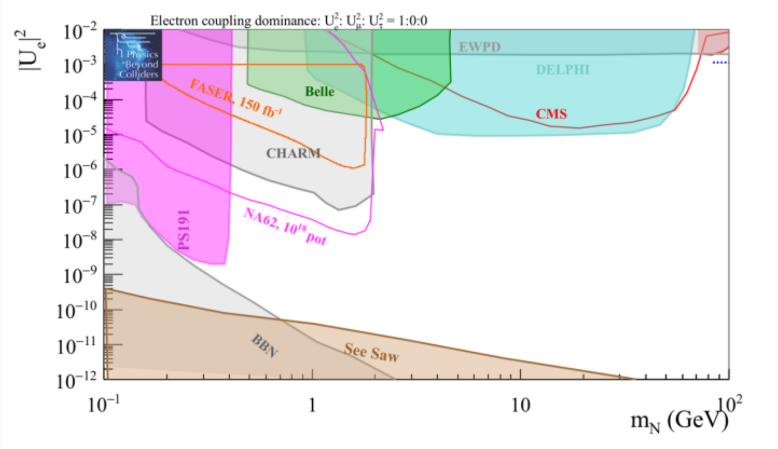
# Heavy Neutral Leptons (HNLs)

- Neutrino masses can be introduced to the SM through the inclusion of Dirac and Majorana mass terms to the SM Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial_\mu \gamma^\mu \nu_R \; - (\Sigma F_{\alpha I}(\bar{L}_\alpha H) N_I + \frac{M_M}{2} \bar{N}_R^c N_R)$$

- produces massive neutral leptons (HNLs), with mixing $U$ between $\nu$ and $N_R$ [2203.08039].
- All the kinematics of production and decay can be determined by $U$ and the mass of the HNL, $m_N$.
- These models implement a seesaw mechanism, $m_\nu \sim \frac{F^2 v^2}{m_N}$, motivating searches for HNLs at electroweak scales.



# Search for Heavy Neural Leptons in W decays

CERN-EP-2025-164

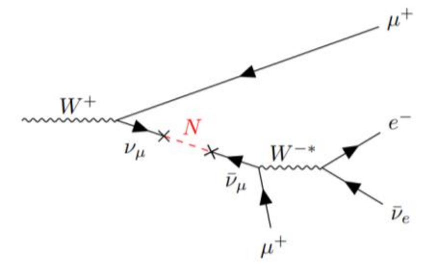
- Target prompt HNLs, focusing on dominant $U_e$ and $U_\mu$ couplings.

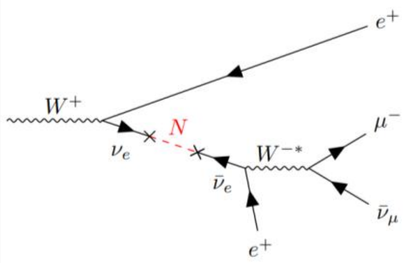
- Target $3\ell$ events ($ee\mu$ and $\mu\mu e$):
  - Define several (overlapping) SRs with $2$ and $3$ ‘signal’ leptons.
  - Use cut-and-count, taking the most sensitive SR for each mass point.

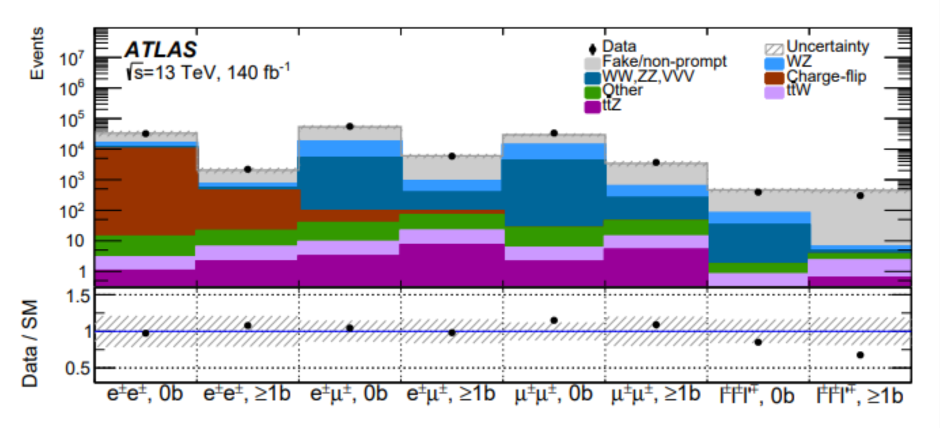
- Focus on the low-$p_T$ region within the mass range 8 – 65 GeV ($m_N < m_W$)

- Ensure no $e^+e^-$/ $\mu^+\mu^-$ pairs to avoid large diboson background.

- Dominant backgrounds are WZ to leptonic tau decays, fake leptons and charge mis-assigned leptons.
  - Use $b$-veto for top related processes
  - Use Matrix Method to estimate fake rates



# Search for Heavy Neural Leptons in W decays (2)

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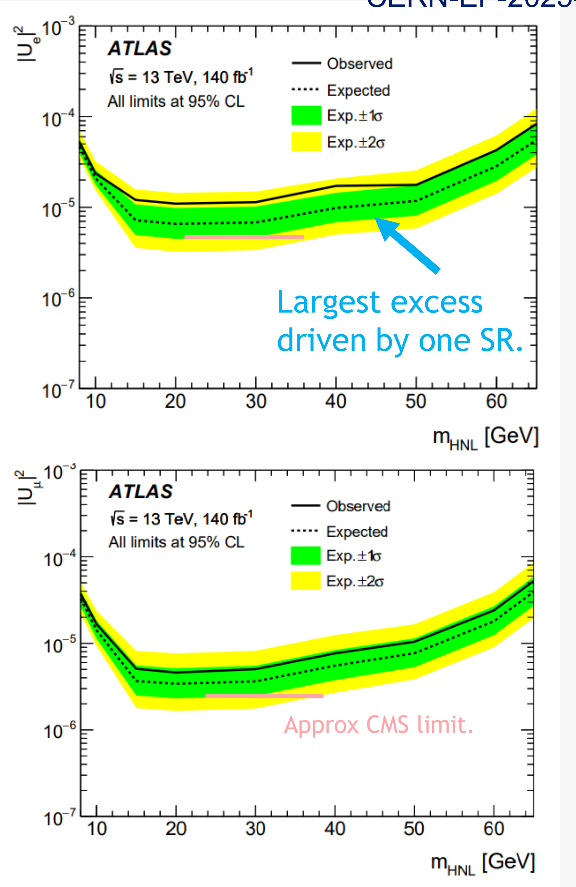
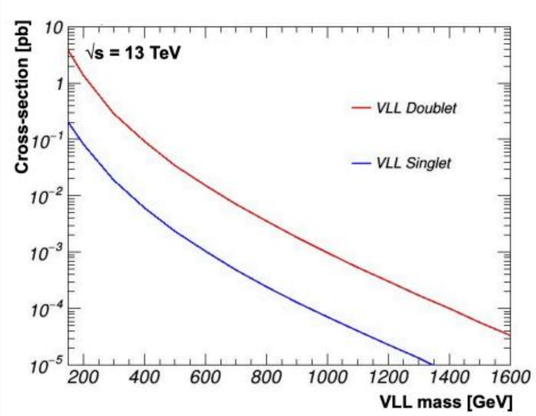
- Very low statistics levels - largest excess seen of $1.7\sigma$, 15 events observed.
- Improve on previous partial Run-2 search by approx. a factor of 2, with a widened mass range [JHEP10(2019)265].
- No significant excess observed within the 8 – 65 GeV range.
- Lifetime of the HNL $\propto m_N^{-5}U^{-2}$, increasing rapidly as the mass decreases.
  - Low-mass limits weaken due to impact-parameter selections causing a loss in signal efficiency.
- Inclusion of $2\ell$ signal lepton regions improves limits by 10-15%.
- Full Run-2 searches started becoming competitive with DELPHI results looking ahead to Run-3 statistics will improve the sensitivity significantly
  - Improved fake rejection
  - Doubled statistics

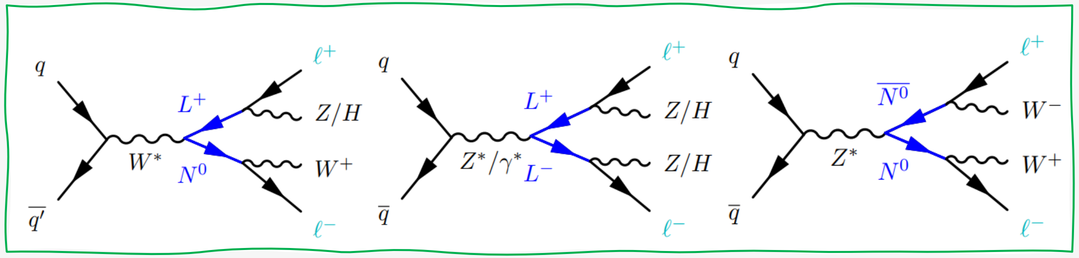


# Vector-like leptons (VLLs)

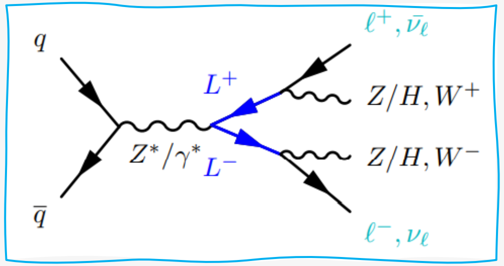
- Colour-singlet counterparts of vector-like quarks (VLQs), see talk from Elin on Monday.
  - Searches at the LHC are relatively new!
- Arise in a range of different scenarios, including GUTs, supersymmetry, dark matter explanations and mass hierarchy explanations [2405.17605].
- Come in the form of SU(2) doublet ($L^{\pm}$, $N^0$) or singlet ($L^{\pm}$)
- Production cross section for doublet model is significantly larger
  - Pair production cross section also larger than single production.
- Decays to $Z/H+\ell$ or $W+\ell$ to give final states with high lepton multiplicity along with jets and missing transverse momentum.




Production cross section adapted from [1510.03456]




VLL Doublet
[JHEP05(2025)075]




VLL Singlet
[JHEP05(2025)075]

# Search for VLLs in first and second generations

JHEP05(2025)075

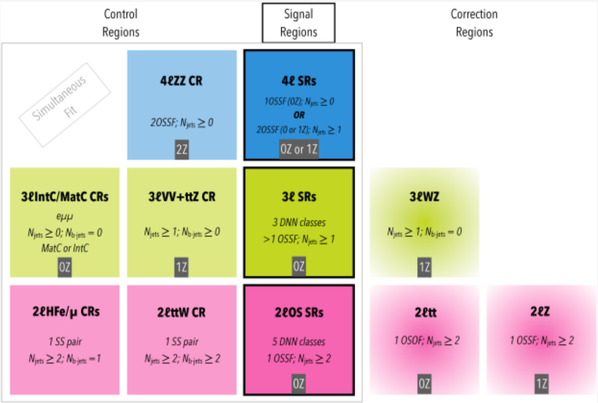
- Search for VLL$e/\mu$ covering the $2\ell$, $3\ell$ and $4\ell$ phase space focusing on masses in the range 150 – 1400 GeV.

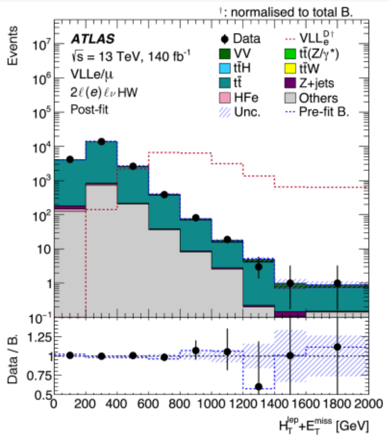
- Divide the phase space into orthogonal control regions for the dominant background sources across each lepton multiplicity;
  - $VV$, $t\bar{t}Z$, $Z$+jets, $t\bar{t}$

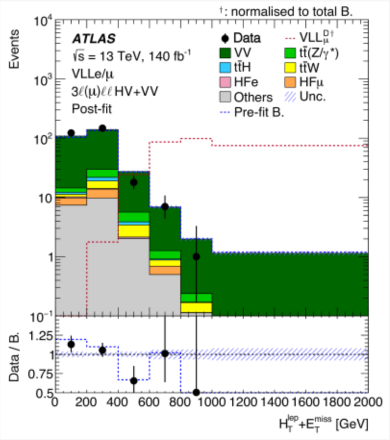
- Use a multi-class DNN in $2\ell$, $3\ell$ - variables like $N_{jets}$, $\mathrm{N_{Whad}}$, $\mathrm{E_T^{miss}}$
  - In $4\ell$ use cut-and-count.

- Derive specific corrections such as $WZ$ $N_{jet}$-dependent reweighting, along with $t\bar{t}$ reweighted to NNLO.

- Build it all into a simultaneous profile likelihood fit across all regions, using $^*\mathrm{H_T^{lep}} + E_T^{miss}$ as final observable.



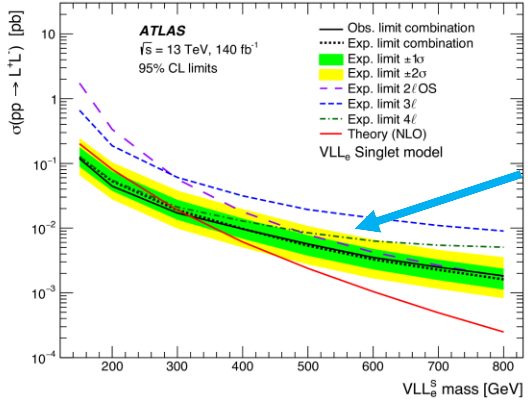




$^*\mathrm{H_T^{lep}} = \Sigma_\ell\, p_T\,,\quad E_T^{miss} = -\Sigma_\ell \vec{p}_T$

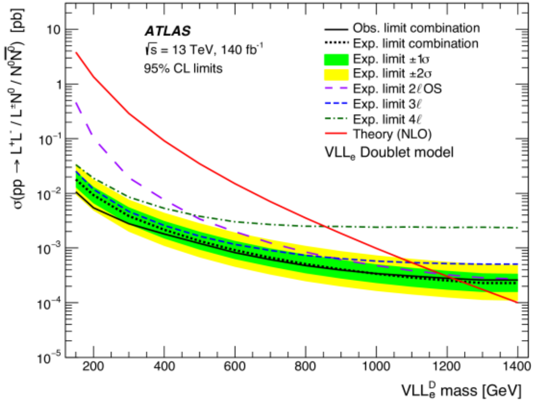
# Search for VLLs in first and second generations (2)

JHEP05(2025)075

- First ever direct LHC search for Doublet model.
- No excess found for singlets or doublets.
- Combined limits exclude up to:
  - **Doublet**: 1270 GeV for VLLmu and 1220 GeV for VLLe
  - **Singlet**: 400 GeV for VLLmu and 320 GeV for VLLe
- Singlet production cross section is significantly smaller, hence weaker limits
  - Motivates future searches with increased luminosity!
- Analysis is also statistically limited when pushing to higher mass, future Run-3 search underway.




Singlet sensitivity dominated by $4\ell$.

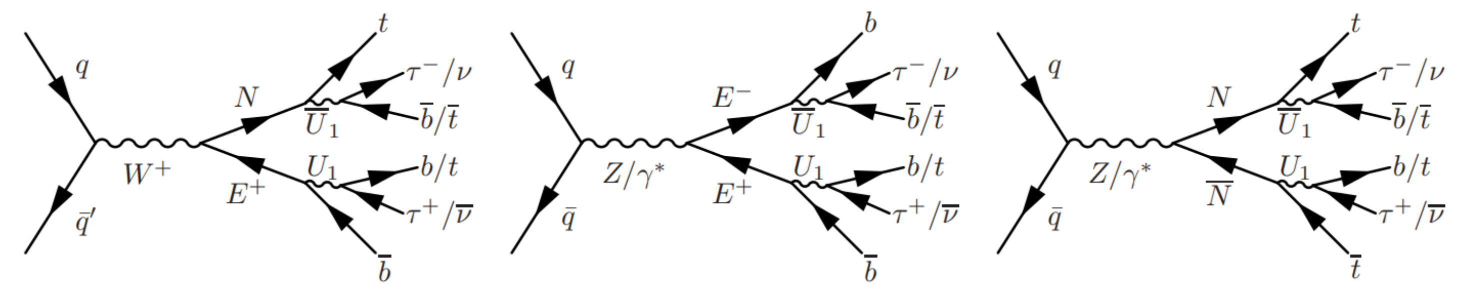


# Third-generation VLLs

- More commonly VLLs are searched for when coupling to third generation, for example as part of the '4321' model.
- UV complete extension of the SM including a new symmetry group:

$$SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$$

- giving rise to extended phenomenology including vector leptoquarks, Z' and VLL doublets.
- VLLs decay primarily through an off-shell leptoquark to third-generation leptons and quarks giving final states with multiple $\tau$'s and $b$-jets.




VLL production and decay in the '4321' model [2503.22581]

# Search for third-generation VLLs in '4321'

2503.22581

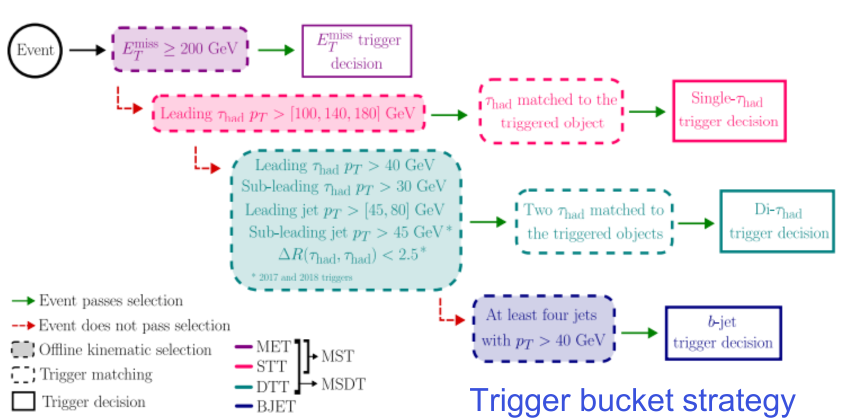
- Search targeting third-generation VLLs, also aiming to address a previous broad 2.8$\sigma$ excess reported by CMS.

- Search focuses on hadronic tau decays, selecting 1 or 2$\tau$ final states and 0$\ell$, and signal regions requiring $\geq 3$ $b$-jets.

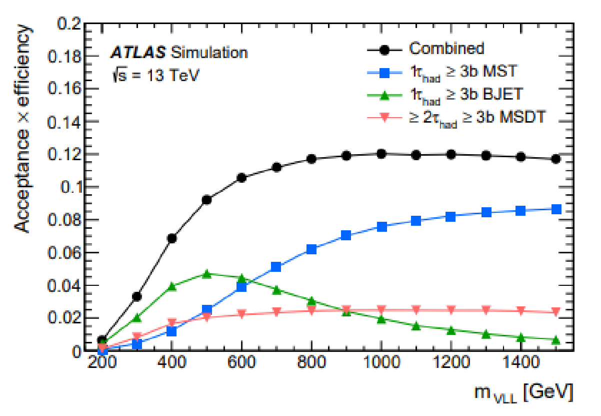
- Divide the phase space in a complex 'trigger-bucket' strategy:
  - Separate by $E_T^{miss}$, $b$-jet and $\tau_{had}$ triggers.
  - Maximises acceptance across several orthogonal channels

- Dominant backgrounds are $t\bar{t}$ + jets with real or fake taus in STT buckets, and multijet backgrounds for the BJET trigger buckets.

- Analysis derives a series of corrections:
  - $t\bar{t}$ corrections for high jet multiplicities using the semileptonic channel.
  - Fake factor method for fake-$\tau$ backgrounds from QCD multijet
  - All corrections validated in $< 3$ $b$-jets regions.



Trigger bucket strategy



# Search for third-generation VLLs in ‘4321’ (2)

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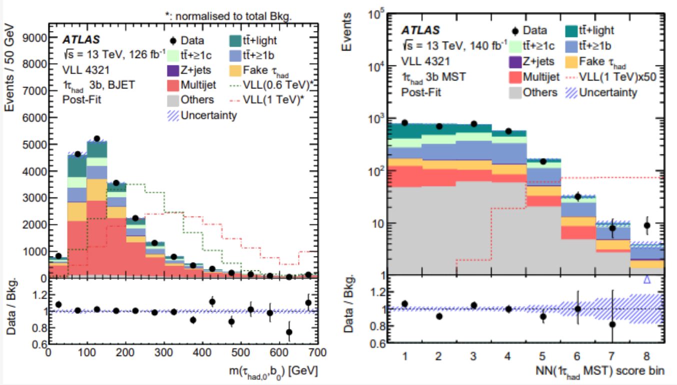
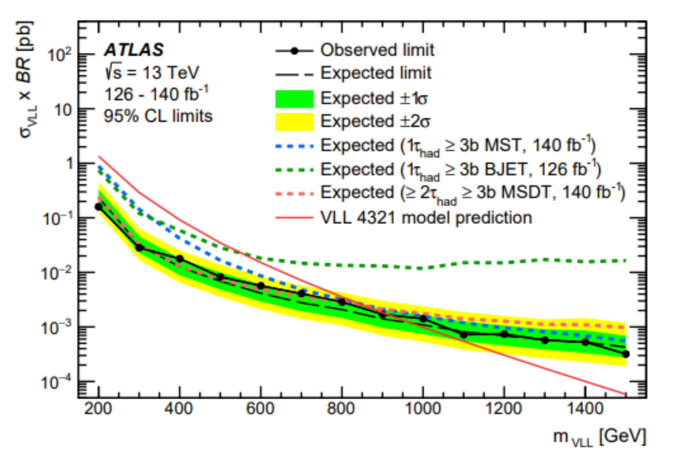
- Use a mass-parameterised NN to give optimal sensitivities:
  - 19 inputs including $\Delta\phi$’s, $p_T$’s, charge…
  - NN score used as final observable.
- Largest uncertainties are due to:
  - $t\bar{t}$ modelling
  - Uncertainties due to data-driven backgrounds
  - QCD multijet modelling
  - Statistical uncertainty
- Exclude vector-like leptons of $m_{VLL}$ < 910 GeV, including the previous broad excess from CMS that was most significant at $m_{VLL}$= 600 GeV.
- Sensitivity is dominated by the 2$\tau$ channel at low mass, and 1$\tau$ channel at high mass.



# Model-independent multilepton search

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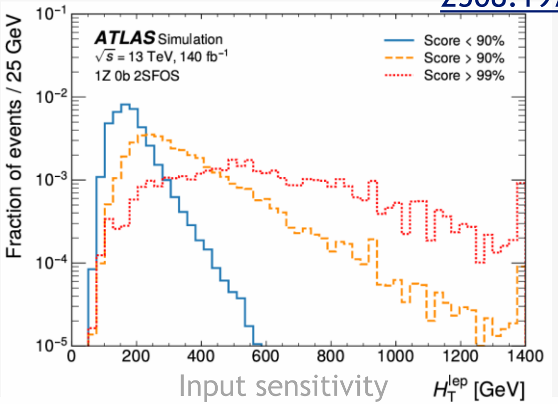
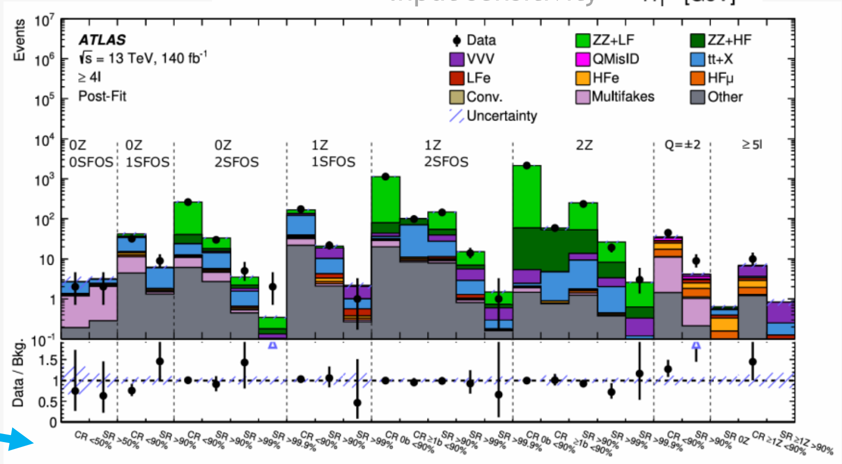
2508.19778

- Recent general search targeting high lepton multiplicity final states ($\geq 4\ell$).
- Exploit anomaly detection to boost sensitivity, specifically targeting outlier detection.
- Divide the phase space into $4\ell$ charge=0, $4\ell$ charge=$\pm 2$, $\geq 5\ell$
  - Further categorise to produce interesting final states (e.g. $Z + e^+\mu^-$, $e^+e^+\mu^-\mu^-$)
- Search in kinematic variables ($m(4\ell)$, $H_T^{lep}$, $p_T(Z)$, $N_{jets}$, etc…) using normalising flows to learn the SM background probability, which is built into a per-event anomaly score.
- Dual analysis strategy, optimising for discovery through a smaller number of broad regions, and model sensitivity with a finer granularity of signal regions.




Input sensitivity




Anomaly score bins

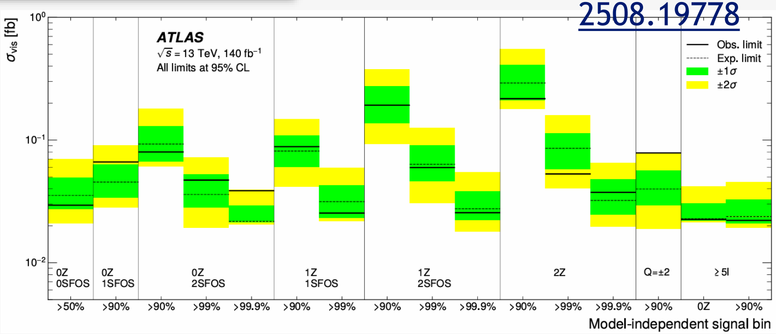
'Discovery' search regions

# Model-independent multilepton search

2508.19778

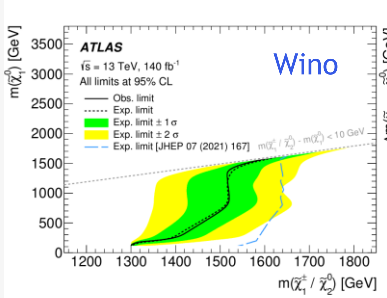
## Discovery limits

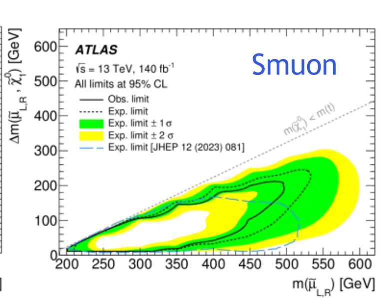
- No significant excess is seen: $2\sigma$ local, $0.9\sigma$ global
  - Largest in Q=2 Score >90% and 0Z 2SFOS Score >99.9% regions.
- Sets model-independent limits in a range of interesting regions
  - Useful for reinterpretation of future models with multilepton signatures!

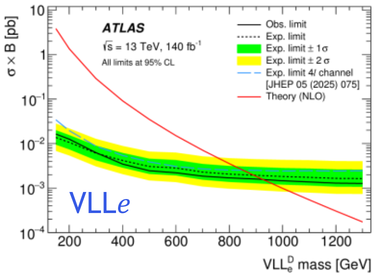


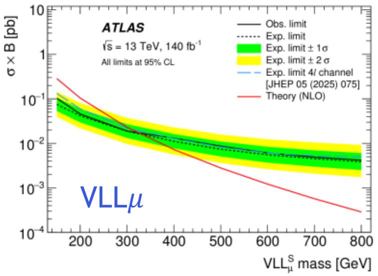

## Benchmark sensitivity

- Set exclusion limits on three already published analyses;
  - RPV Winos, Smuons, and VLL$e/\mu$.
- Demonstrates competitive sensitivity across all three model scenarios simultaneously.



# Model-independent multilepton search

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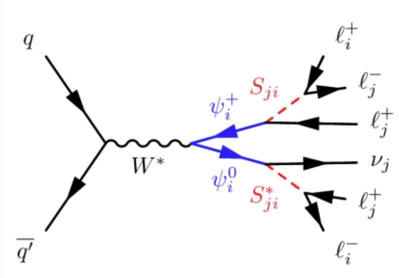
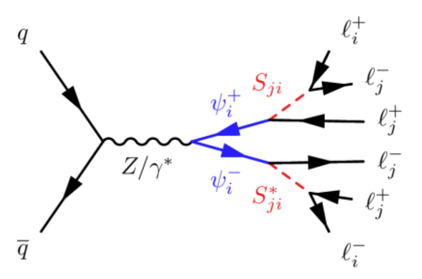
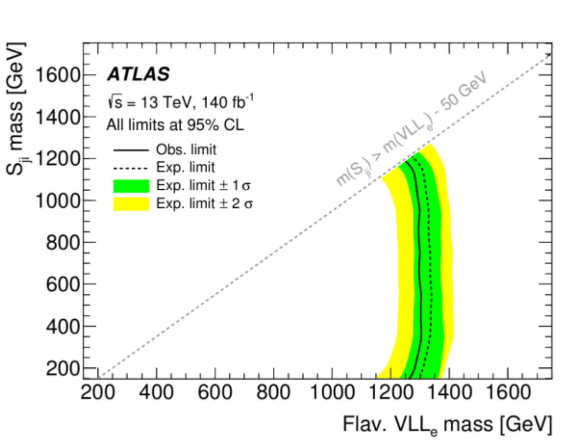
- Search also produces an LHC first exclusion of VLLs decaying through a flavourful scalar $S$ [2011.12964].

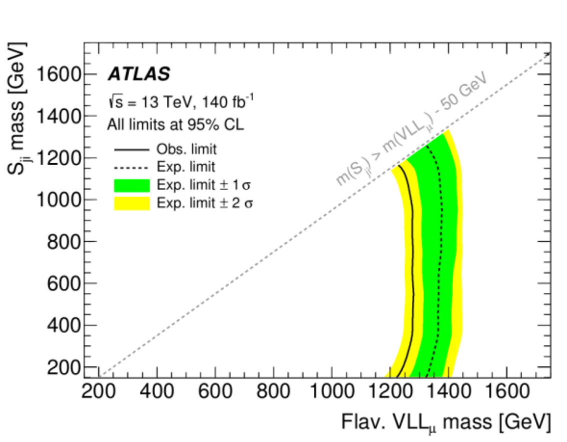



Can give flavour violating decays and high lepton multiplicity ($\geq 5\ell$)

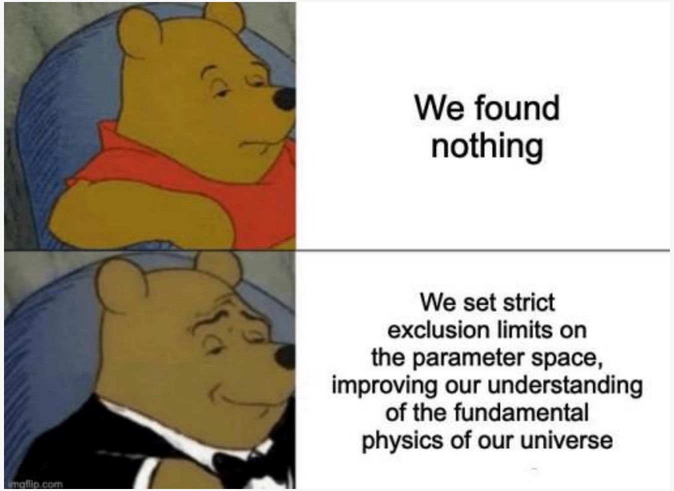
- Analysis excludes up to 1.3 (1.25) TeV for the Fl. VLL$e$($\mu$):



# Summary

- A range of interesting phenomenology being explored in prompt lepton final states.
- Currently no clear signal of BSM phenomena.
- Starting to properly exploit the collected data with ML techniques and anomaly detection.
- Run-3 poses a real opportunity with already double the amount of statistics!



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# Backup

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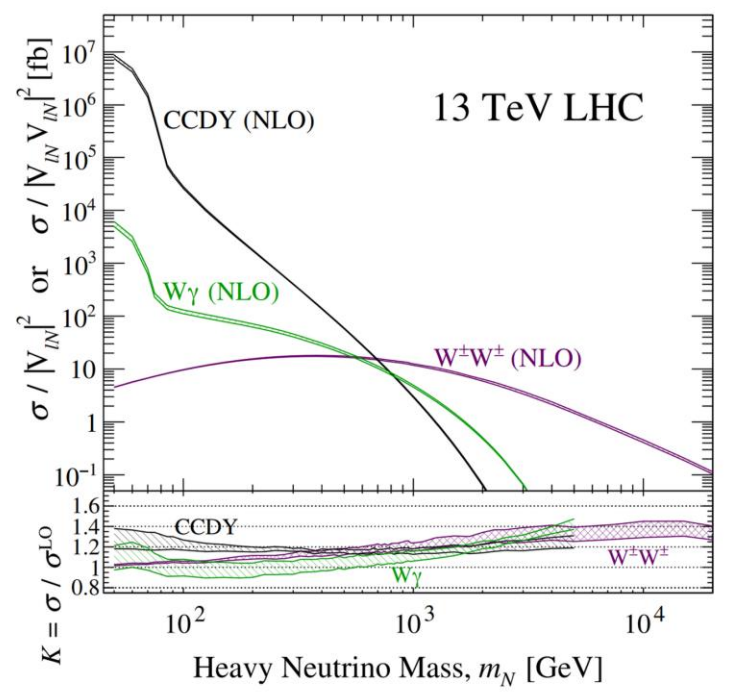
# HNL production cross section

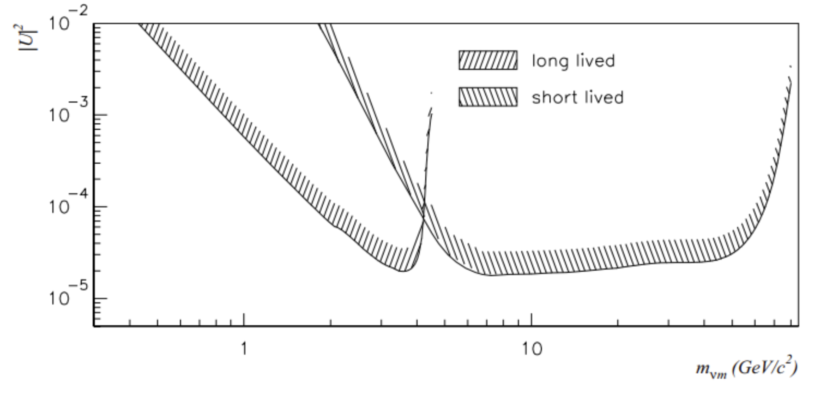



PhysRevD.103.055005

# Search for Heavy Neural Leptons in W decays

CERN-EP-2025-164

- Comparison limits from other experiments:

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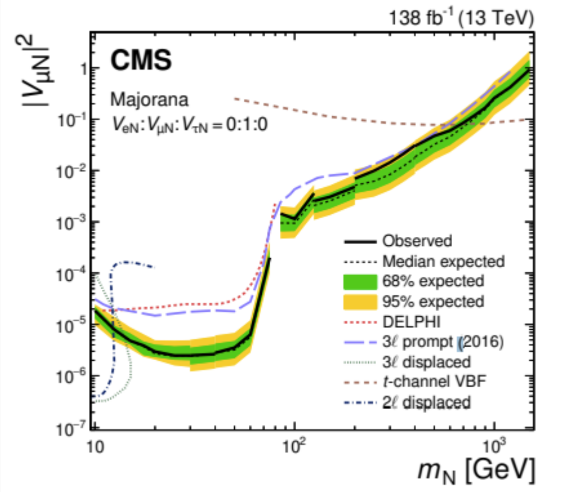



JHEP06(2024)123

# Search for Heavy Neural Leptons in W decays

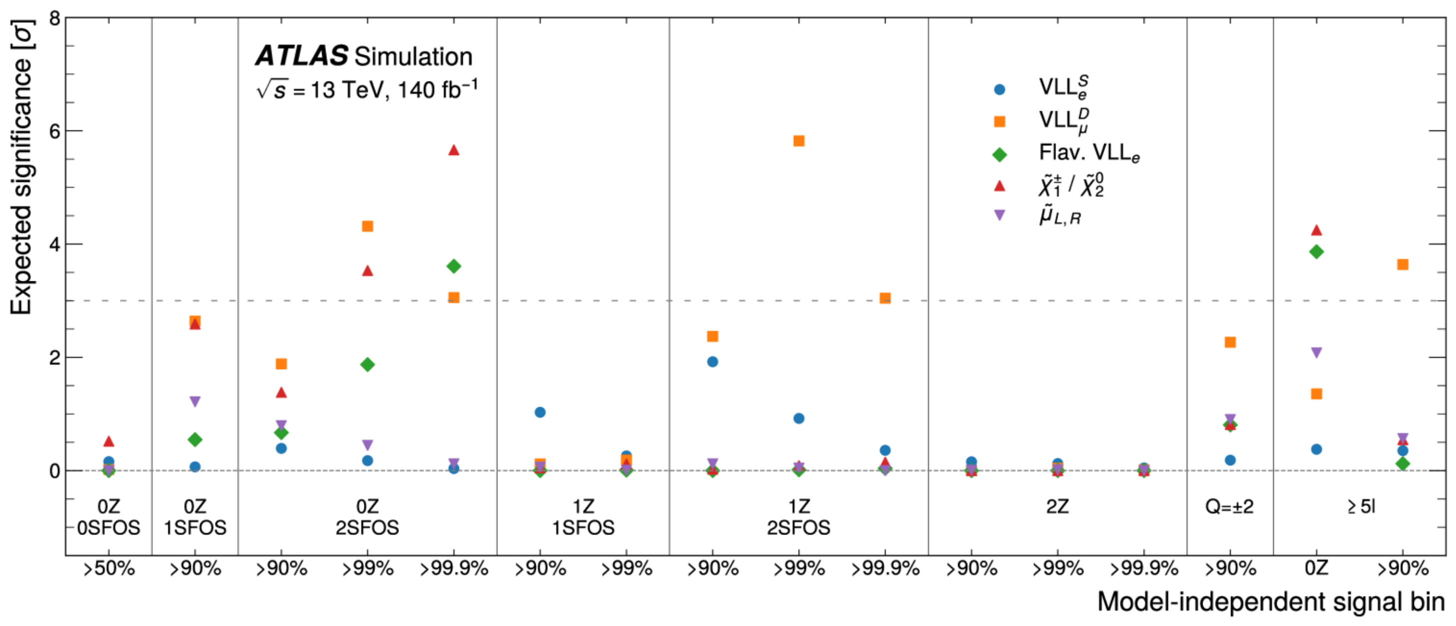
CERN-EP-2025-164

- Signal region definition:

| SR name | $N_{\text{lept}}^{\text{signal}}$ | $m_{\text{T}}$ [GeV] | $m_{\text{eff}}$ [GeV] | $\Delta R(\ell 1^{\pm}, \ell 2^{\pm})$ | $m_{\text{DFOC}}^{\text{min}}$ [GeV] | $m_{\text{SC}}^{\ell\ell}$ [GeV] | $\text{m}_W^{\text{max}} - \text{m}_W^{\text{min}}$ [GeV] | $N_{b\text{-jets}}$ | Additional requirements |
|---|---|---|---|---|---|---|---|---|---|
| $3\ell$ SRs | | | | | | | | | |
| SRE1 | =3 | $< 70$ | $< 250$ | $> 2.0$ | $< 20$ | $< 75$ | $< 60$ | =0 | - |
| SRE2 | =3 | $< 65$ | $< 200$ | – | $< 25$ | $< 65$ | $< 60$ | =0 | - |
| SRE3 | =3 | $< 50$ | $< 150$ | $> 1.5$ | $< 35$ | $< 60$ | $< 70$ | =0 | - |
| SRE4 | =3 | - | $< 250$ | – | $< 50$ | - | $< 70$ | =0 | $m_{\ell\ell\ell} < 80$ GeV, $p_{\text{T}}^{\ell 1} < 30$ GeV |
| SRM1 | =3 | $< 70$ | $< 120$ | $> 2.0$ | $< 25$ | $< 70$ | $< 70$ | =0 | - |
| SRM2 | =3 | $< 45$ | $< 120$ | – | $< 40$ | $< 65$ | $< 70$ | =0 | $\Delta\phi((\mathbf{p}_{\text{T}}^{\ell 1} + \mathbf{p}_{\text{T}}^{\ell 2}), \mathbf{p}_{\text{T}}^{\text{miss}}) > 1.0$ |
| $2\ell$ SRs | | | | | | | | | |
| SRM3 | =2 (SC) | $< 60$ | $< 120$ | $> 2.5$ | – | $< 75$ | - | - | - |
| SRM4 | =2 (SC) | $< 55$ | $< 150$ | $> 2.0$ | – | $< 70$ | - | =0 | - |
| SRM5 | =2 (SC) | $< 70$ | $< 120$ | $> 2.0$ | – | $< 75$ | - | - | - |

# Model-independent multilepton

- The sensitivity of the discovery regions is demonstrated by testing benchmark models:



# Model-independent multilepton

- Examples of granular splitting ‘benchmark’ regions for producing model-dependent limits: