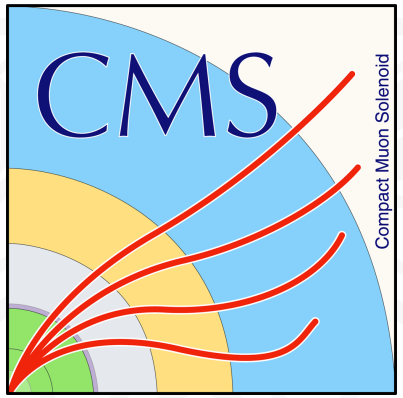
New ν Physics: From Colliders to Cosmology

Direct Searches for Heavy Neutral Leptons at CMS

Haifa Sfar

On behalf of the CMS Collaborations

10 - 04 - 2025



To put things in context… Heavy Neutral Leptons (HNLs)

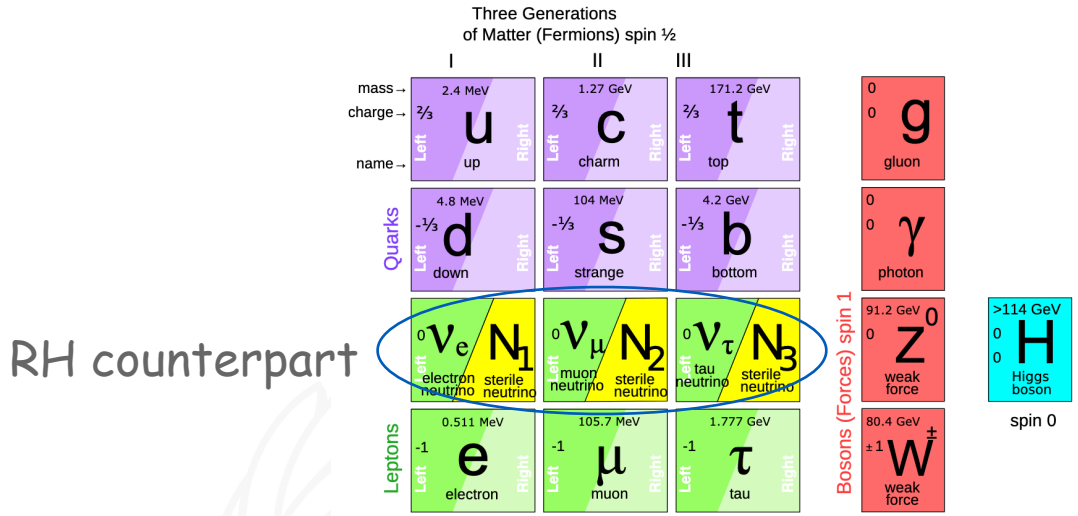
- Only left-handed neutrinos observed in weak interactions
- The Higgs gives mass by coupling left- and right-chiral fields

  → Neutrinos remain massless in SM.
- Oscillations prove neutrinos have non-zero mass

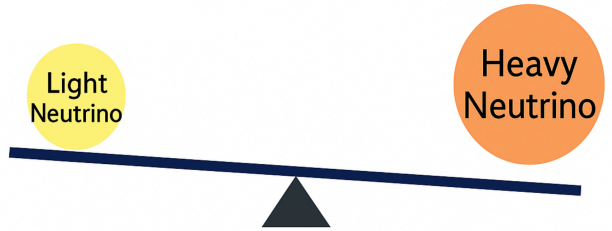
  → SM is incomplete
- HNLs explain neutrino mass beyond the SM Higgs.

CMS searches for HNLs in:

- Type-I seesaw
- Left-Right Symmetric Model (LRSM)



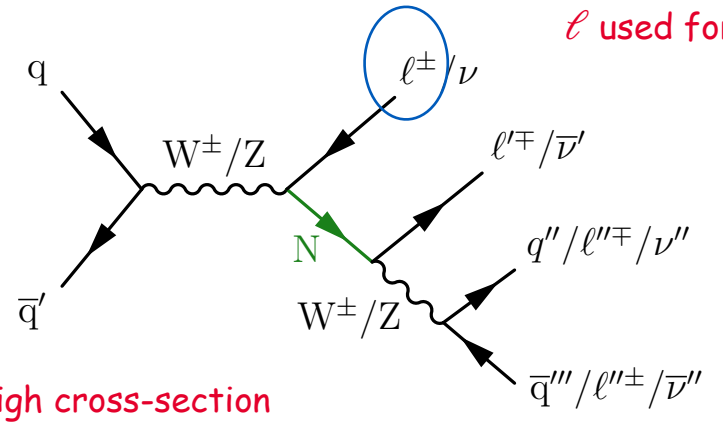
Seesaw Mechanism



Not only a solution to the neutrino mass, but why it is also so small…

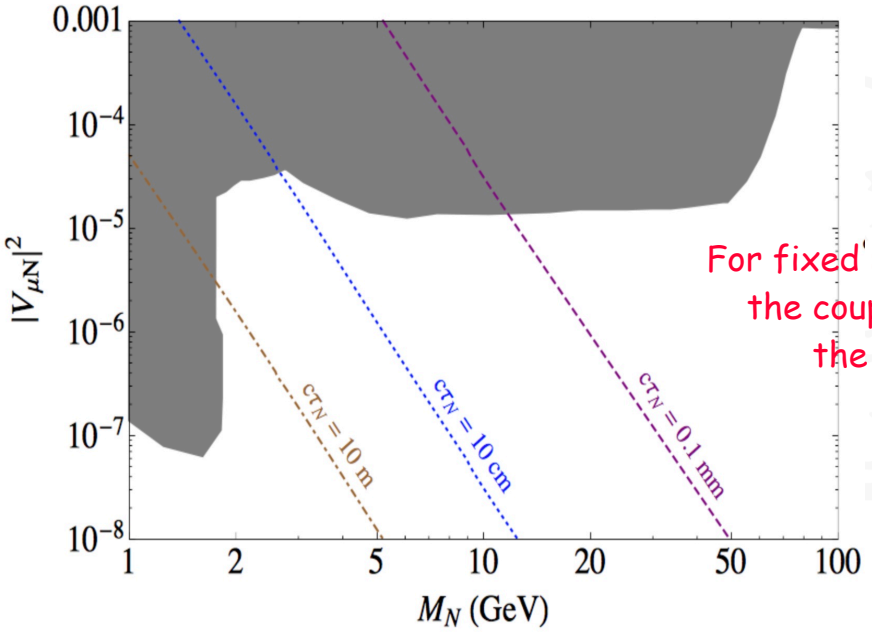
Banchmark models for HNL in CMS

Type- I seesaw model:



ℓ used for the trigger

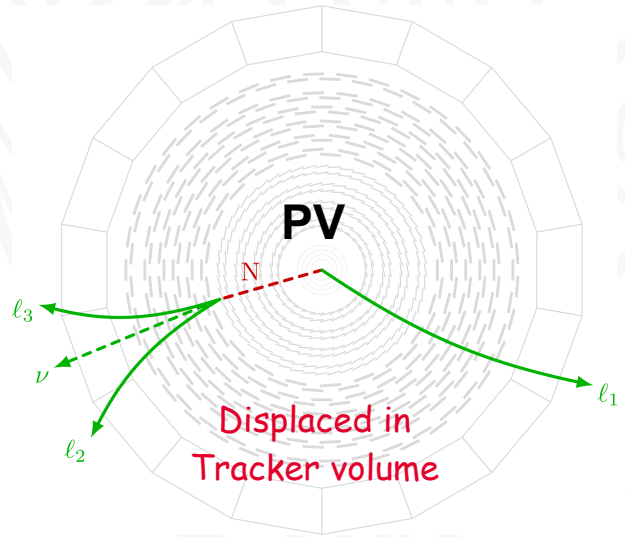
High cross-section



For fixed mass: The weaker the coupling the longer the lifetime is.

- Dirac and Majorana HNLs (N) → LNC and LNV signatures.
- Excl./Incl. coupling to lepton generations

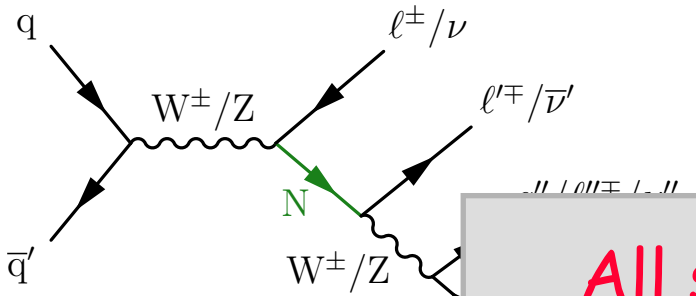
  → Lepton flavor conservation and violation
- Mass and coupling as free parameters.
- Prompt vs long-lived decays: $\tau = \frac{1}{\Gamma_N} \propto \frac{1}{m_N^5 |V_{\ell N}|^2}$

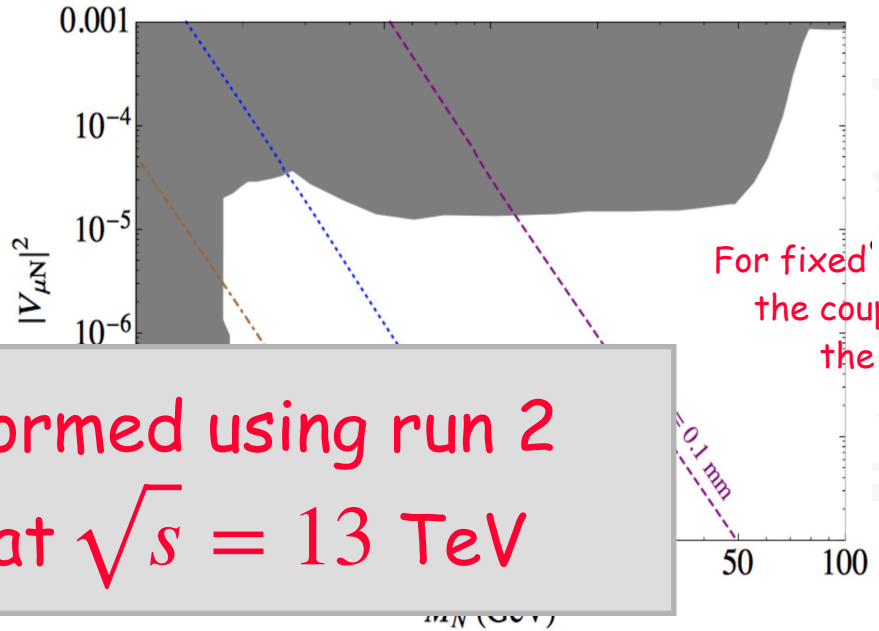


Specific Reconstruction Techniques

Banchmark models for HNL in CMS

Type- I seesaw model:



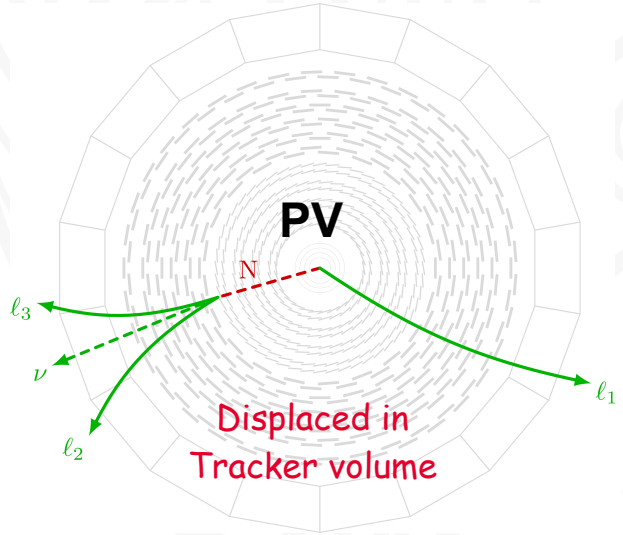


For fixed mass: The weaker the coupling the longer the lifetime is.

All searches are performed using run 2 dataset → 138 fb-1 at $\sqrt{s} = 13$ TeV

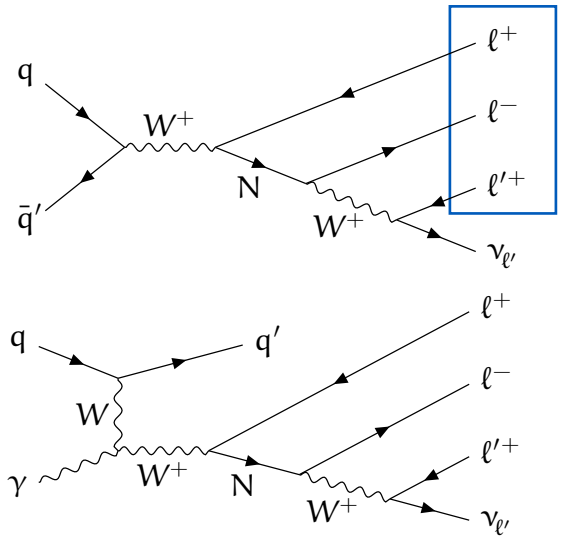
- Dirac and Majorana HNLs (N) → LNC and LNV signatures.
- Excl./Incl. coupling to lepton generations

  → Lepton flavor conservation and violation
- Mass and coupling as free parameters.
- Prompt vs long-lived decays: $\tau = \frac{1}{\Gamma_N} \propto \frac{1}{m_N^5 |V_{\ell N}|^2}$



Specific Reconstruction Techniques

Prompt 3ℓ (e, μ, τ)



$\ell = e, \mu$ or τ

VBF process relevant in the high mass region

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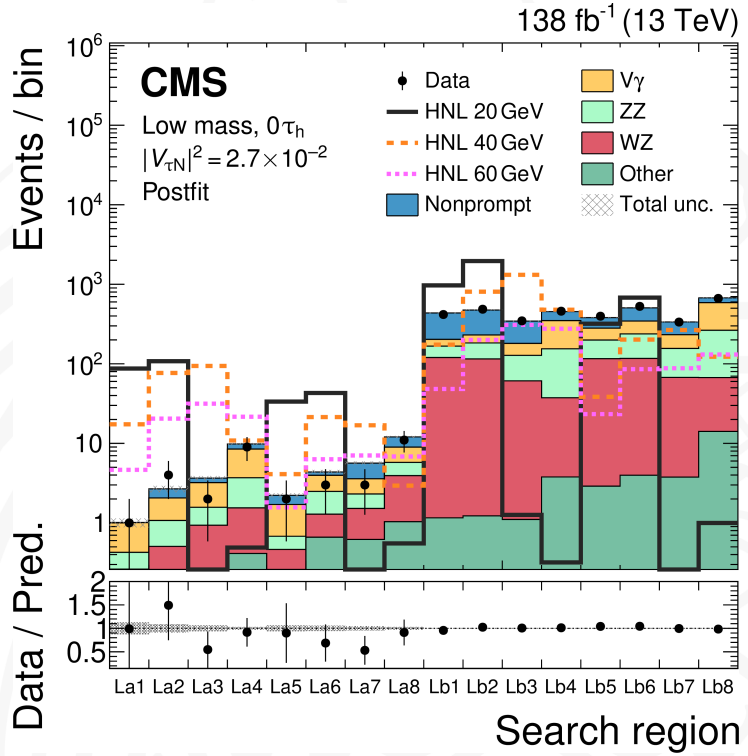
yields per category



- Mass range: 10 GeV to 1.5 TeV → Prompt HNL decays.
- Dirac and Majorana HNLs
- Excl. HNL coupling to $\ell = e, \mu$ or τ
- Broad categorization:
  - $p_T(\ell_1)$, $m(3\ell)$, $min(m(\ell^+, \ell^-))$, m_T and BDT accross categories

Prompt 3ℓ (e, μ, τ)

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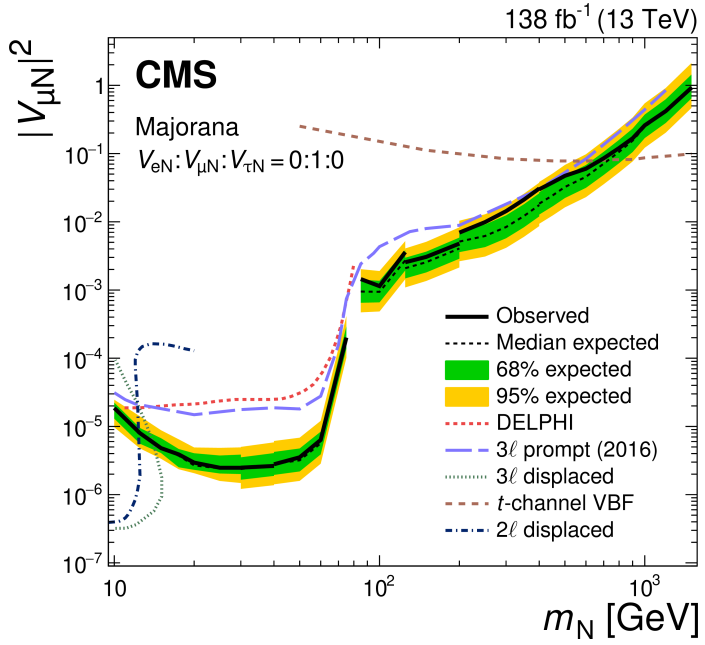
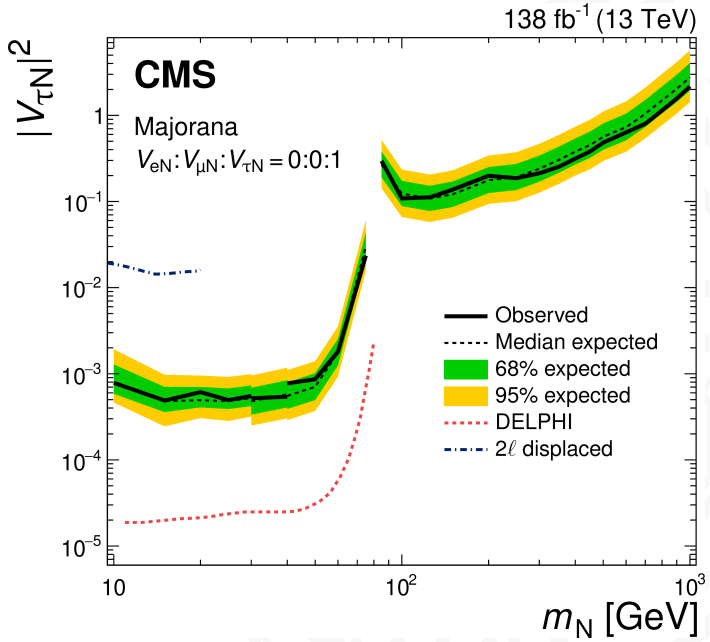
Exclusive μ Couling



Exclusive τ Couling



Prompt 3ℓ (e, μ, τ)

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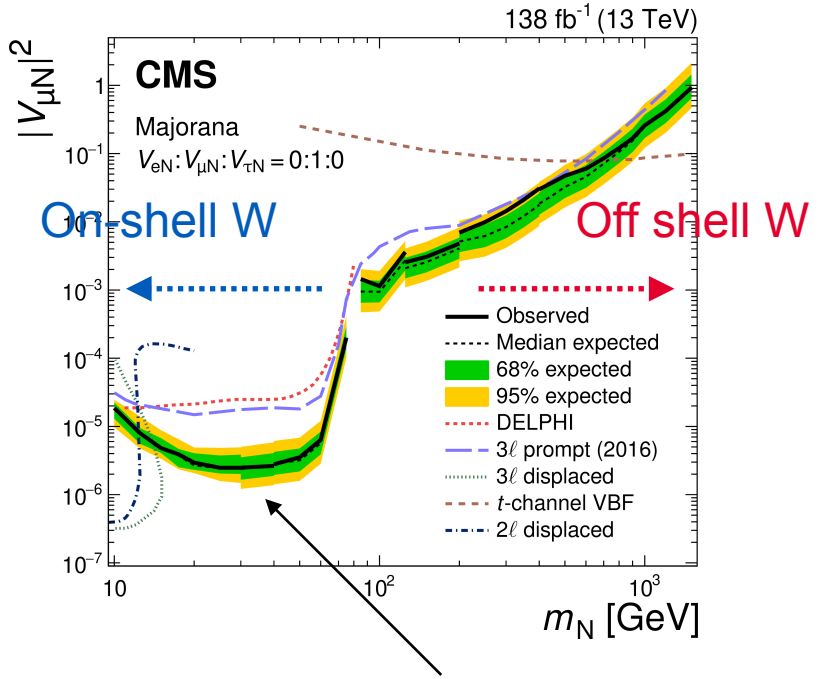
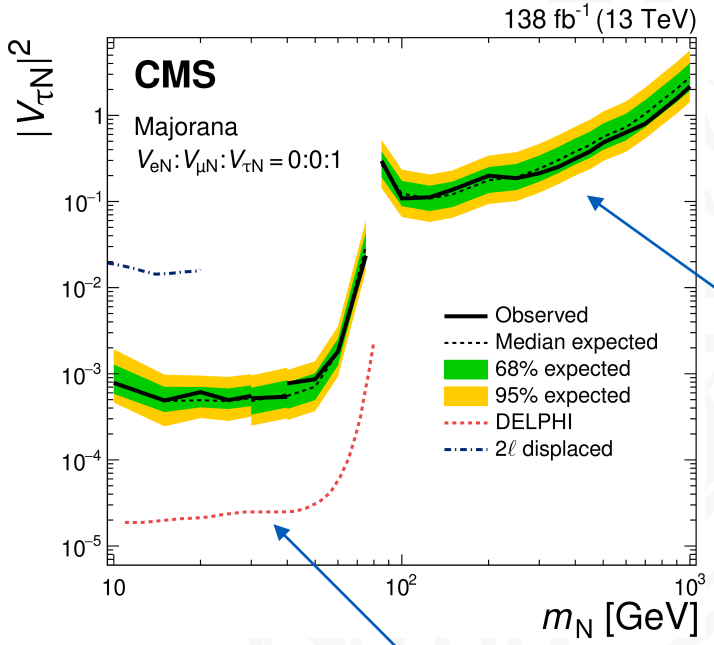
Exclusive μ Couling



X 10 improvement at low mass

Exclusive τ Couling



Probing coupling to tau above W mass for the first time.

DELPHI below W mass

Displaced 3ℓ (e, μ)

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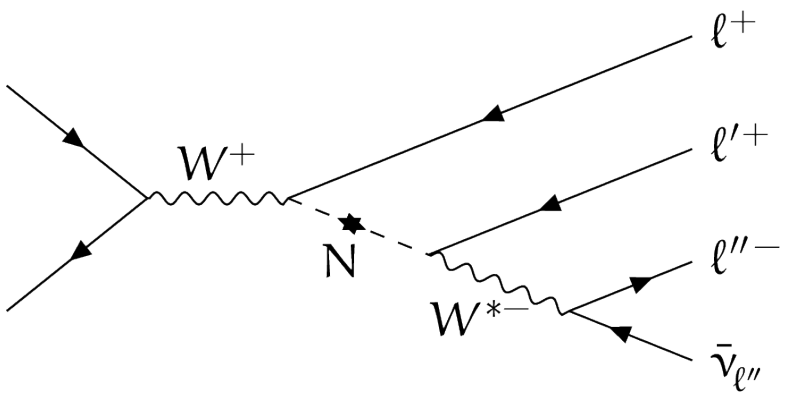
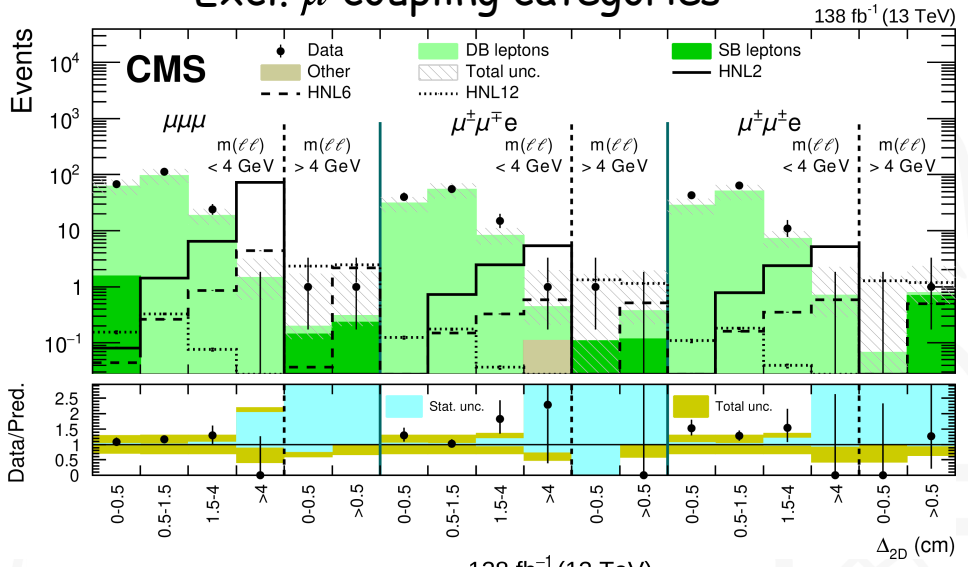
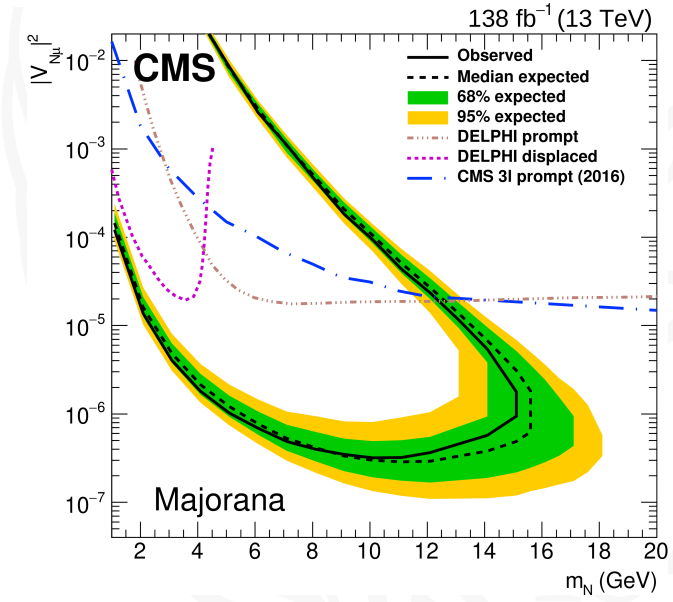


$\ell = (e, \mu)$

- HNL mass range 1 → 20 GeV → Longlived search
- Dirac and Majorana HNLs
- Excl. HNL coupling to e, μ.
- Longlived HNL →Displaced vertex reconstruction.
- Broad categorization:
  - leptons flavor, (OS - SS), $m_{\ell\ell}$ and Δ_{2D}.

Excl. μ coupling categories





Displaced $2\ell(e, \mu, \tau)$ + jets

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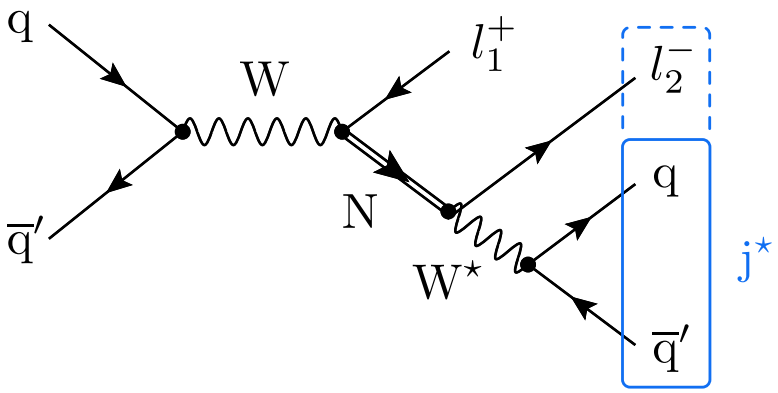
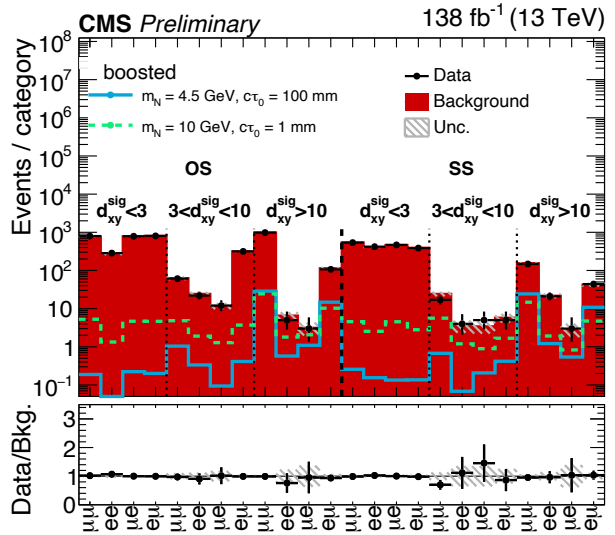


2ℓ + jets final state

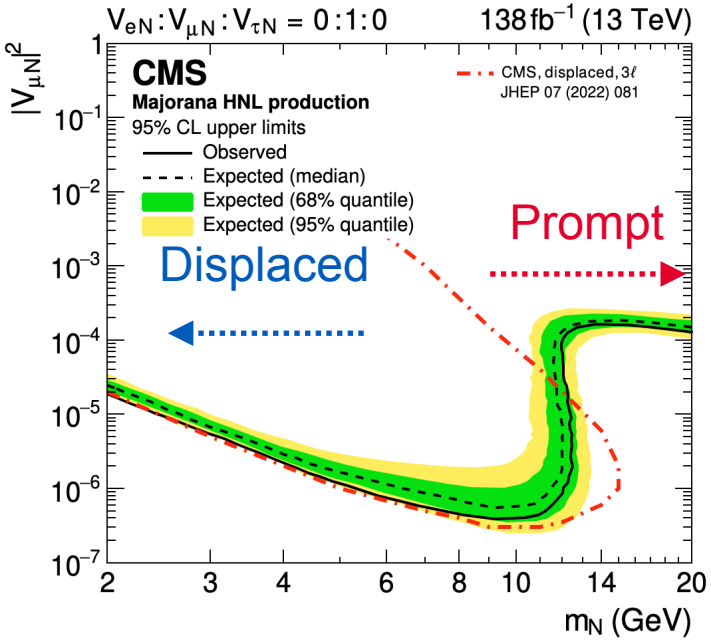
e, μ or τ

- HNL mass range 2 → 20 GeV → Longlived search
- Dirac and Majorana HNLs
- Excl./Incl. HNL coupling to e, μ, τ
- Longlived HNL A displaced jet tagger, no explicit requirement of SV.
- Broad categorization:
  - $\ell_2, j^\star$ topology, $\ell_1\ell_2$ SF/OF, OS/SS, $d_{xy}^{sig}(\ell_2)$

#yields SR:boosted



Exclusive μ Couling



No SV Requirement

Displaced $2\ell(e, \mu, \tau)$ + jets

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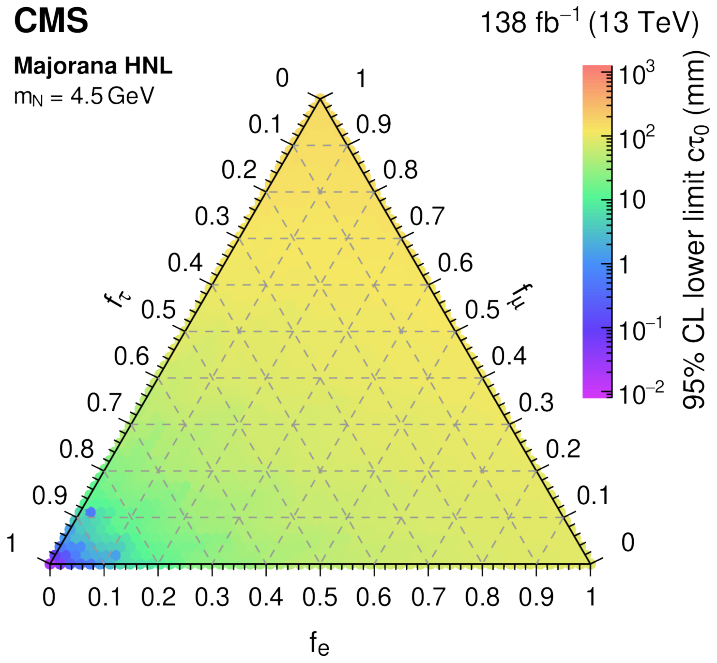
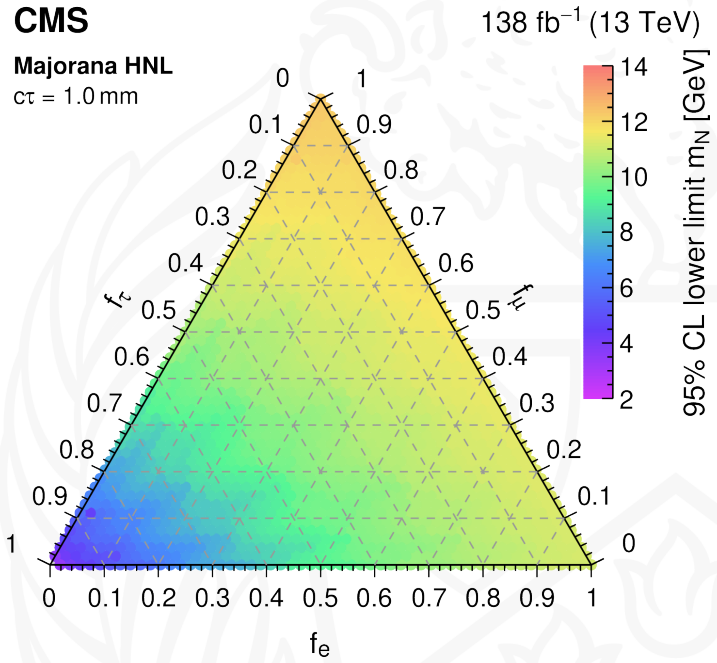
New interpretation: relative coupling to e, μ and τ



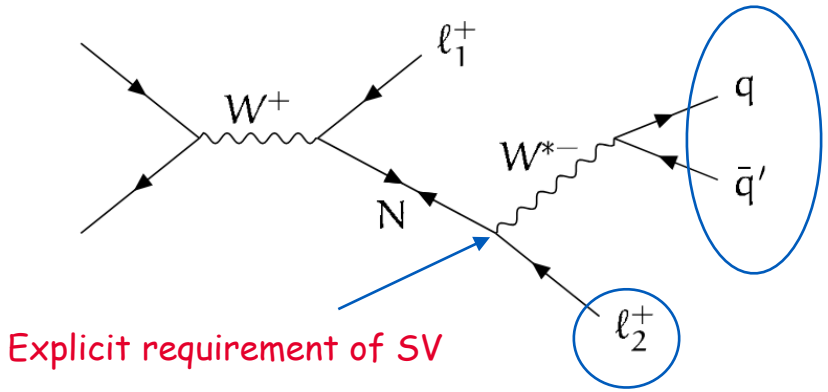
Max excl. $c\tau_0$ for fixed m_N



Max excl. m_N for fixed $c\tau_0$

New Interpretation! First at the LHC!

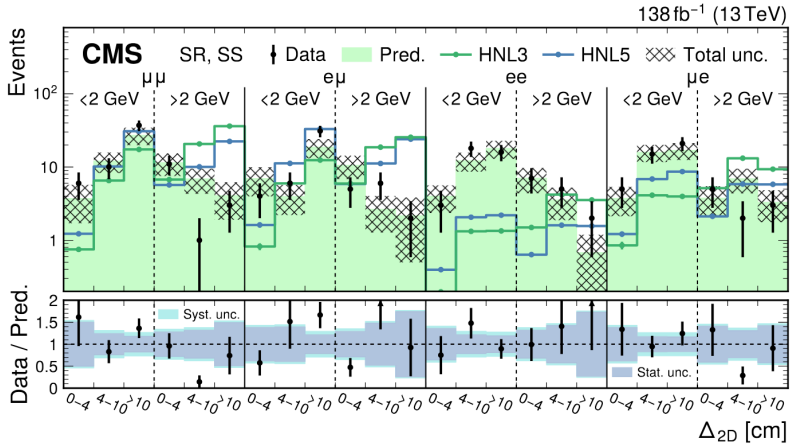
Displaced $2\ell(e,\mu)$ + jets (2)



Explicit requirement of SV

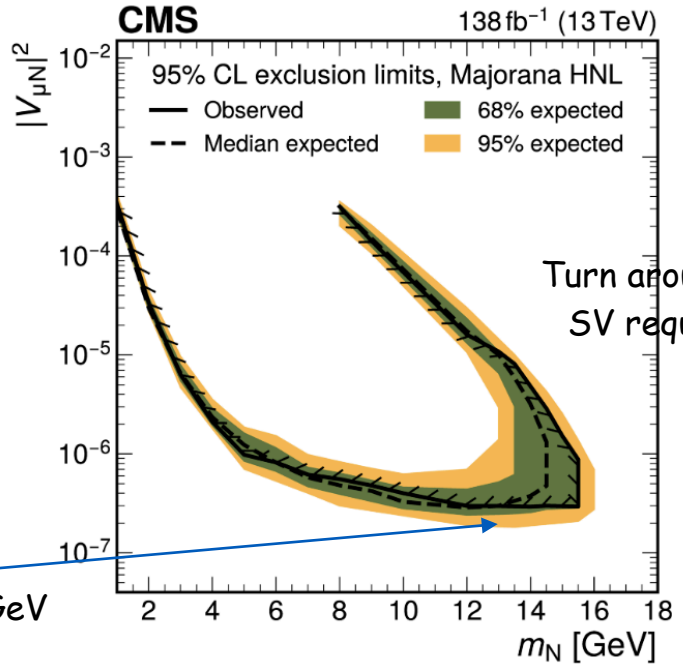
JHEP02(2025)036

2ℓ + jets final state



- HNL mass range 1 → 20 GeV → Longlived search
- Dirac and Majorana.
- Excl. HNL coupling to e, μ.
- Displaced vertex reconstruction
- Broad categorization:
  - leptons flavor, (OS - SS), m_{sv}, and Δ_{2D}.

Exclusive coupling to μ



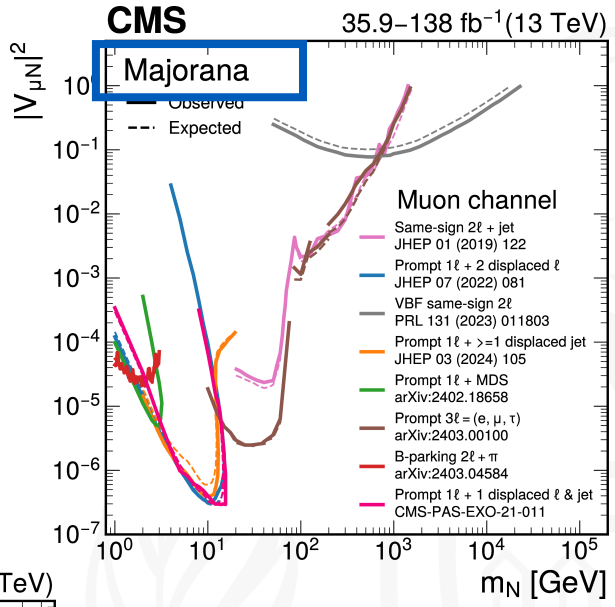
Turn around due to SV requirement

Improve limits ~10-16 GeV

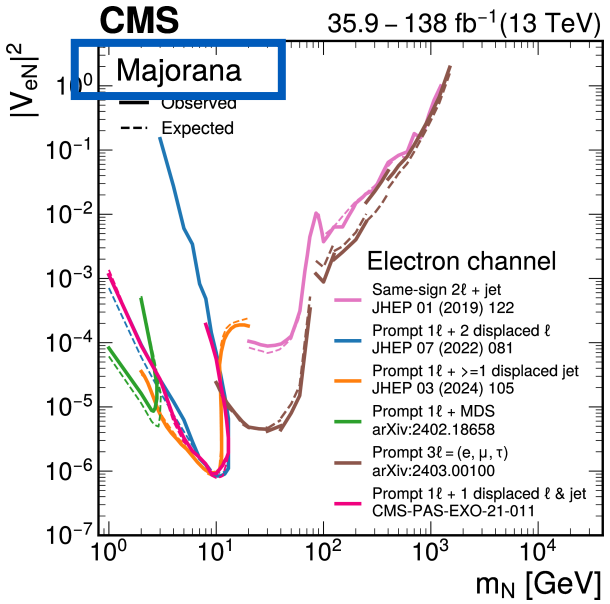
HNL Review Paper

- CMS HNL review paper
- Published last week! j.physrep
- Including all CMS HNL results so far.
  - Not only TypeI!

Exclusive μ coupling



Exclusive e coupling



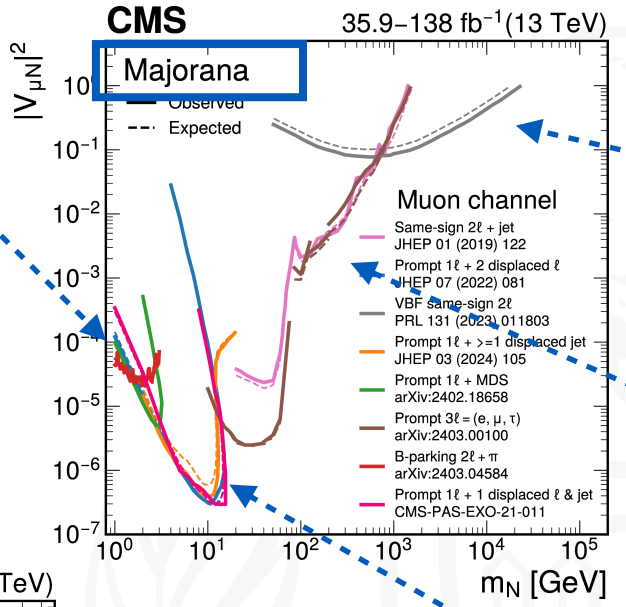
HNL Review Paper

- CMS HNL review paper
- Published last week! j.physrep
- Including all CMS HNL results so far.
  - Not only TypeI!
- Complementary searches.

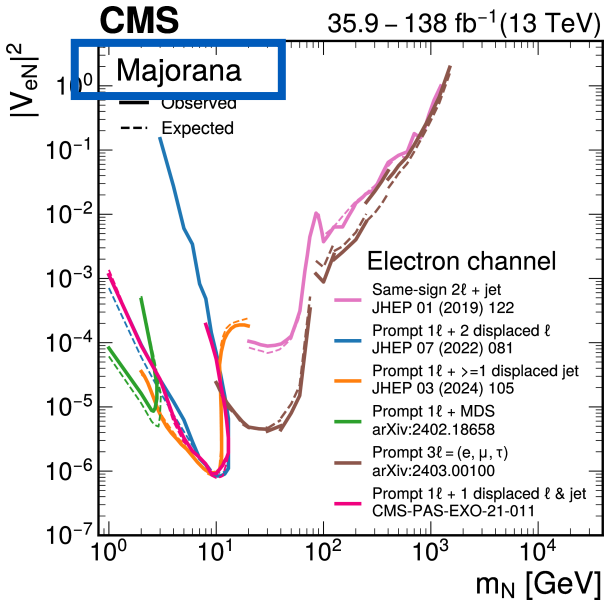
→ No significant gain from stat. Combination.

- Could extract best CMS contour.

Exclusive μ coupling



Exclusive e coupling



Very Low mass sophisticated Techniques

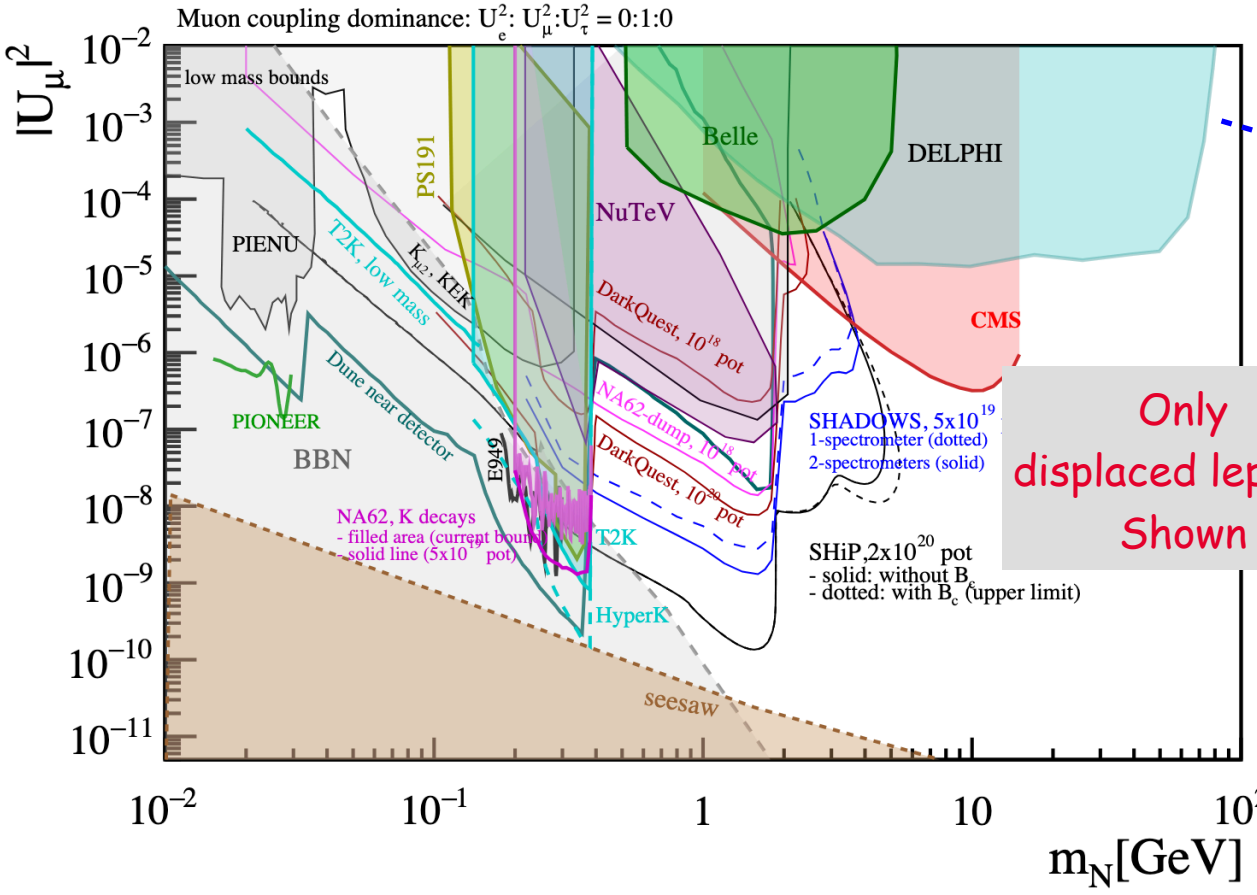
HNLs in VBF Indirect search

prompt 3ℓ

Intermediate mass s-channel
Displaced decay in Tracker volume

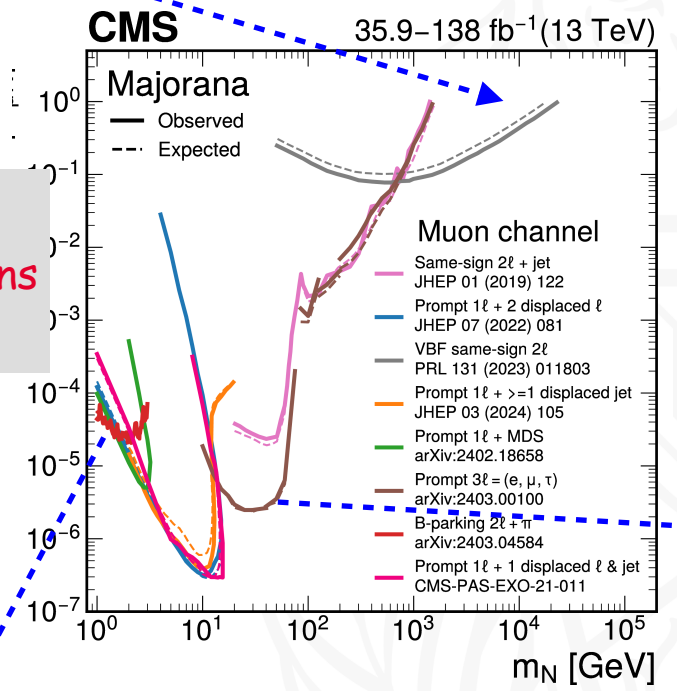
Filling the gaps…

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

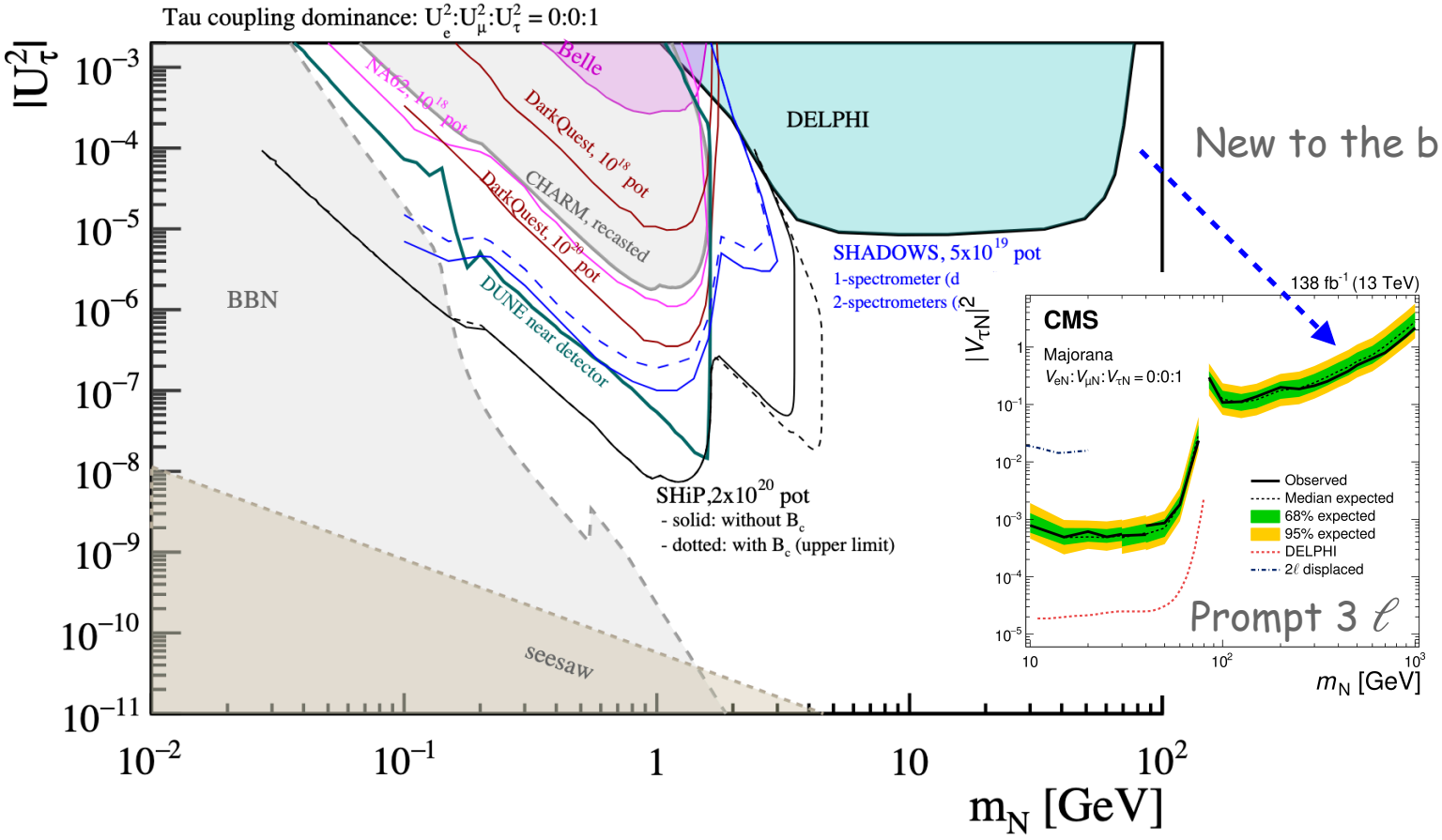
Improve DELPHI results

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

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

Filling the gaps…

arxiv.2203.08039

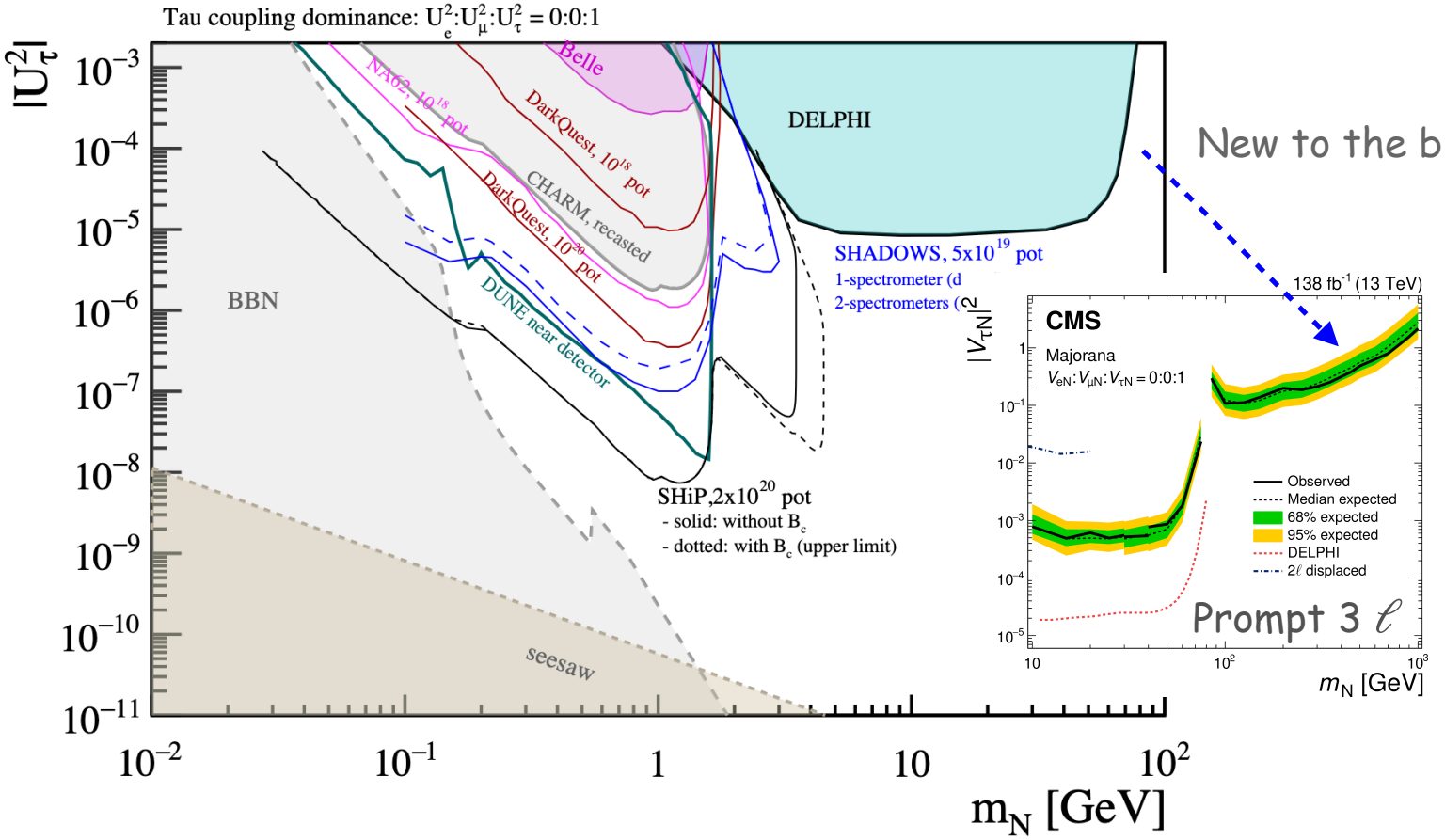


New to the big picture

Filling the gaps…

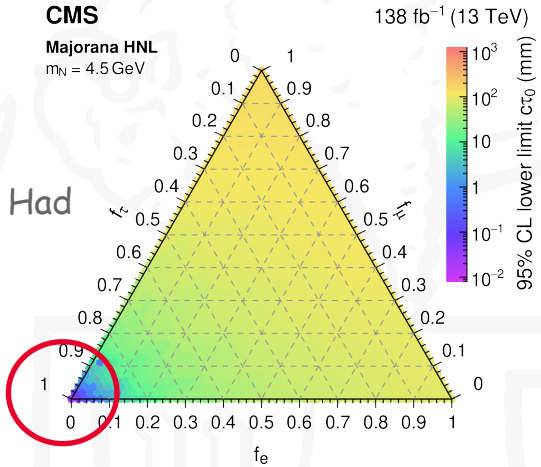
arxiv.2203.08039

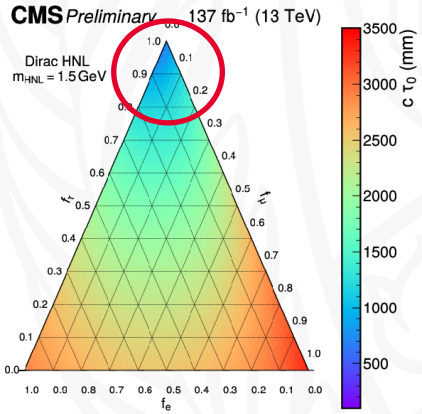
Not only… New interpretation(incl. lifetime) and possible Future combination …



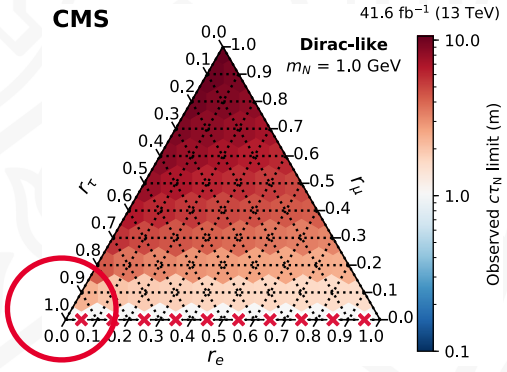
New to the big picture

LL- Had





Decay in muon syst.



B-HNL

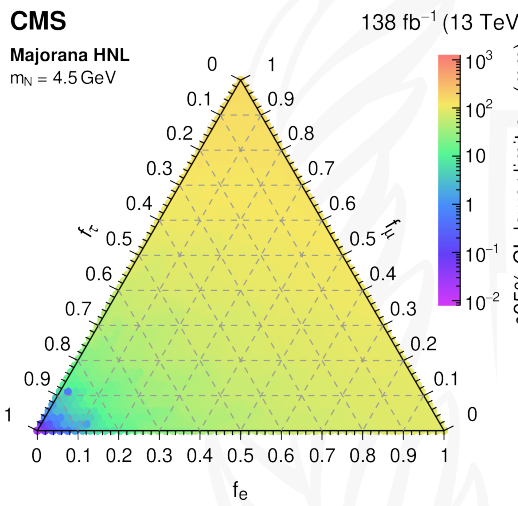
Summary and future Prospect

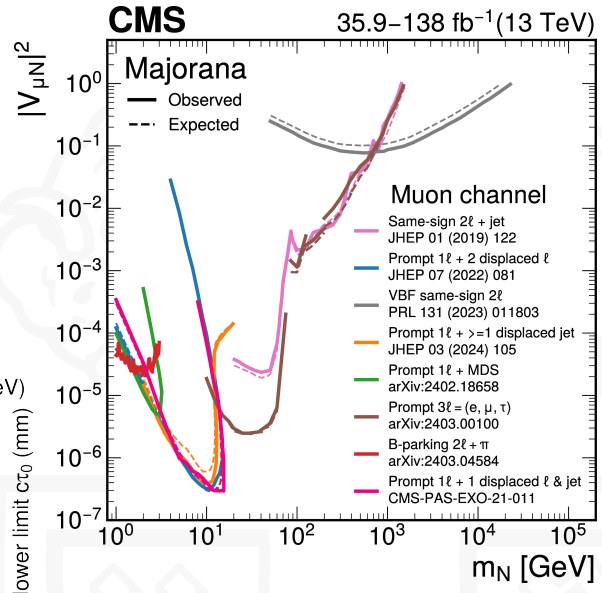
- Dived through most of the CMS run2 direct HNL results.
- Explored wide range of new parameter space
  - complementary searches.
- New Interpretation using the lifetime information and fine grid of coupling to 3 leptons generation → Triangle plots.
- Still windows for improvements:

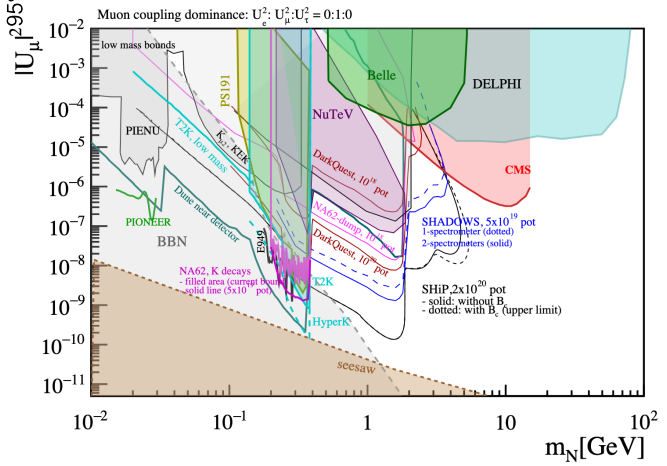
  → New search ideas

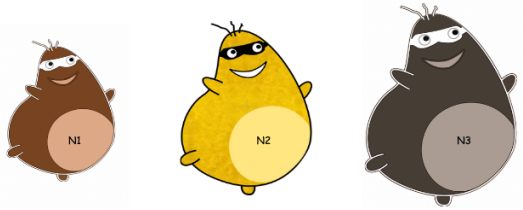
  → New Trigger and reconstruction techniques + More data

  → further pushing boundaries.



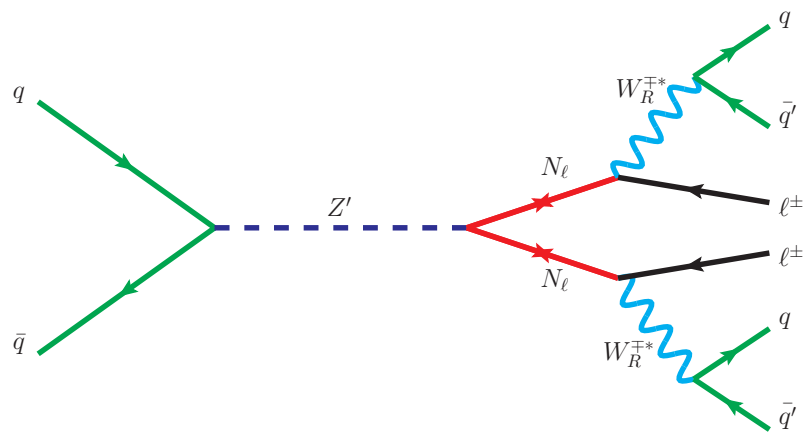




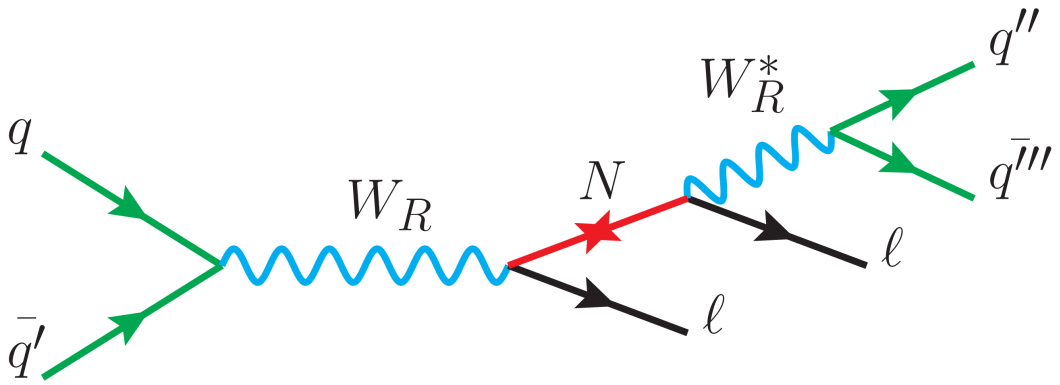


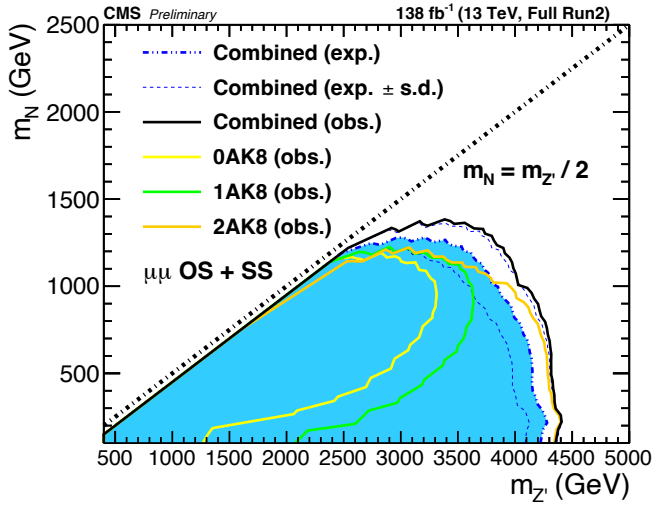
HNL in the left-right symmetric model

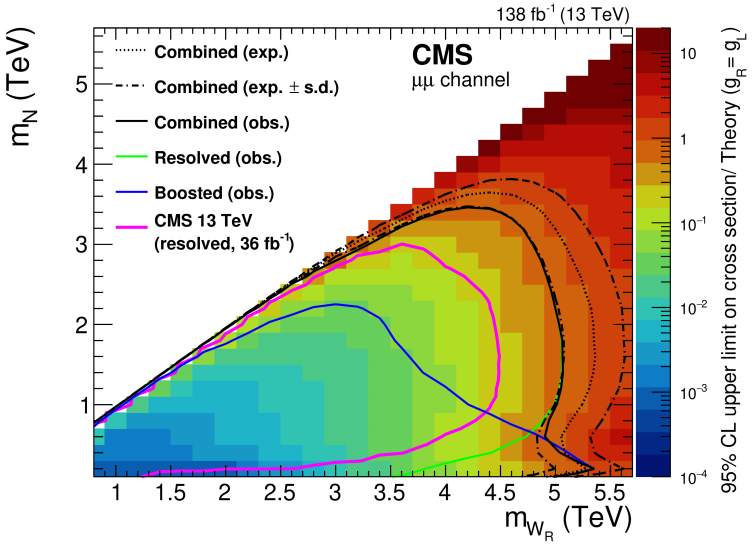
- LRSM: New interaction Z' and new N_ℓ , $(\ell = e, \mu)$



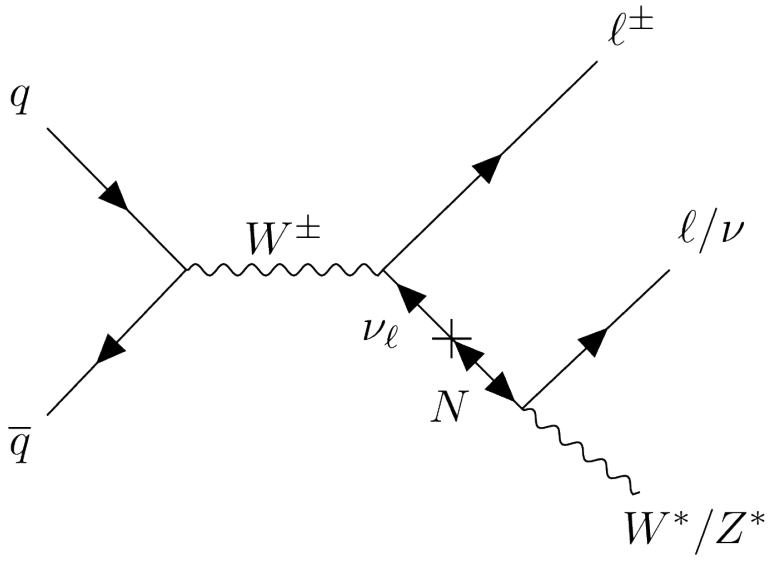
- LRSM: new interactions W_R and new N_ℓ, $(\ell = e, \mu)$

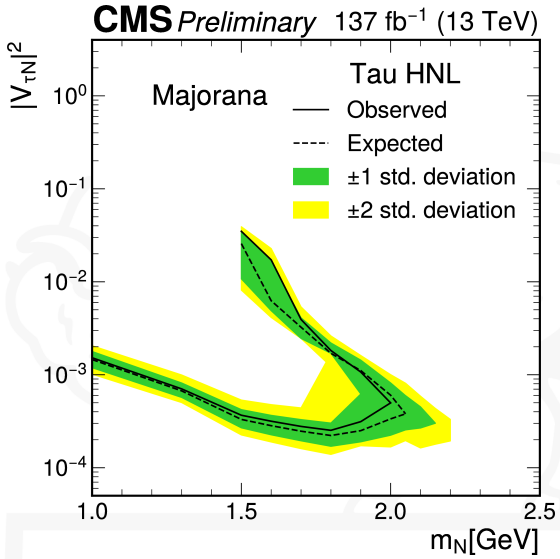




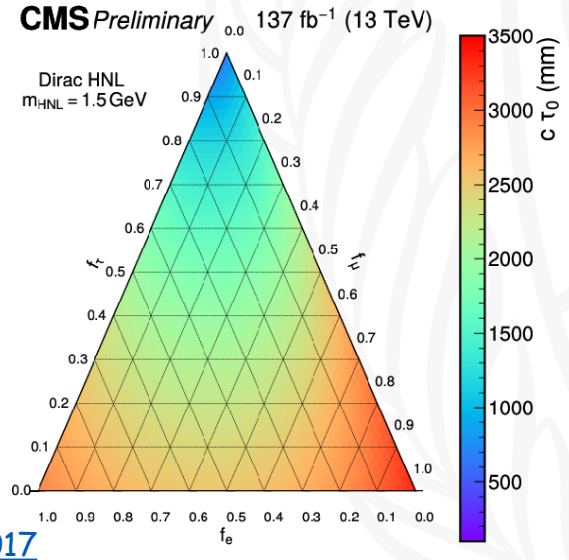


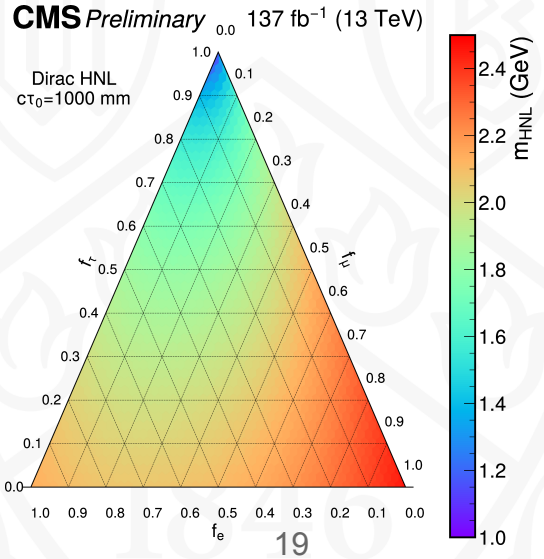
Long-lived HNLs in the muon system





Relative coupling to the 3 lepton generation

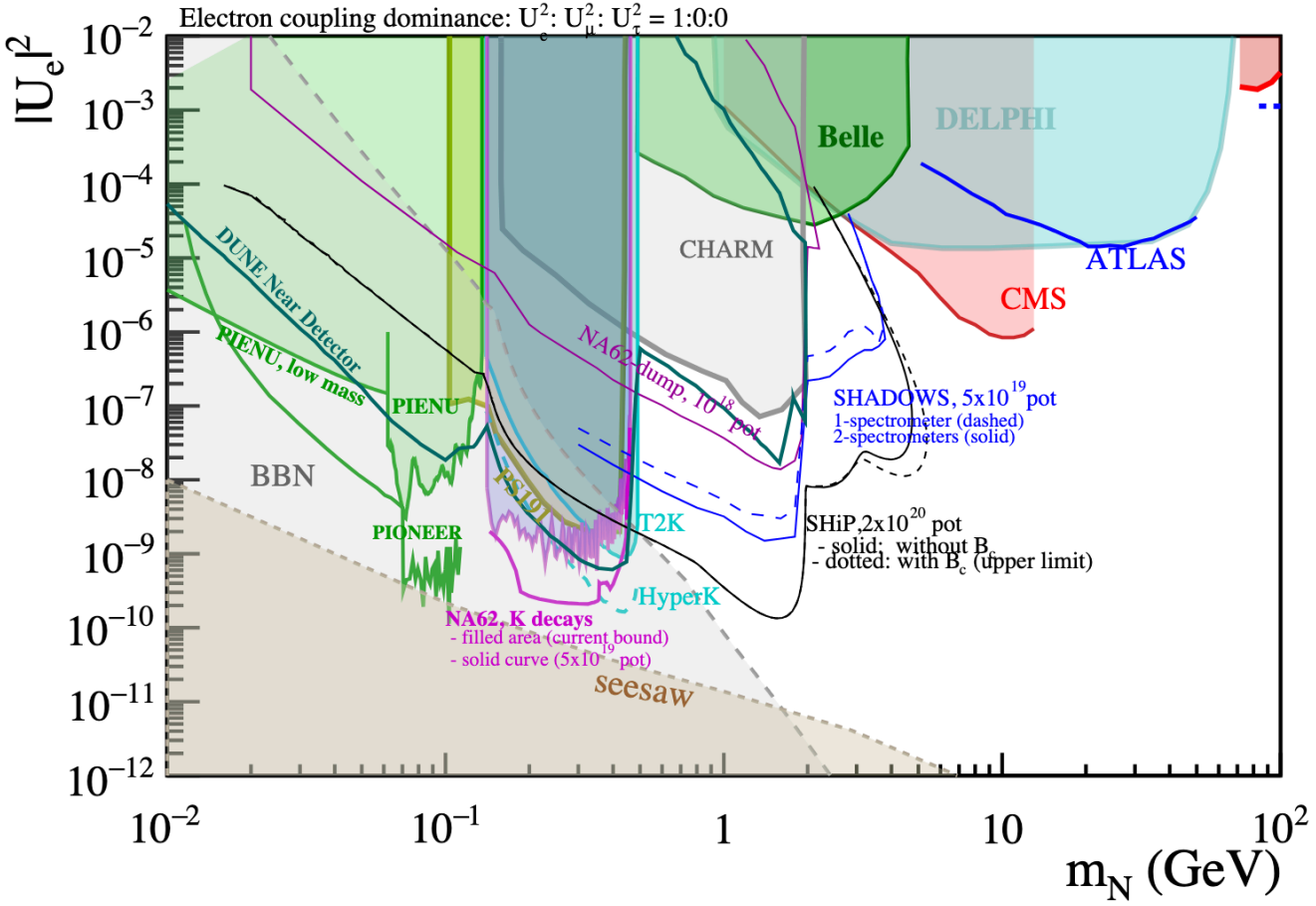


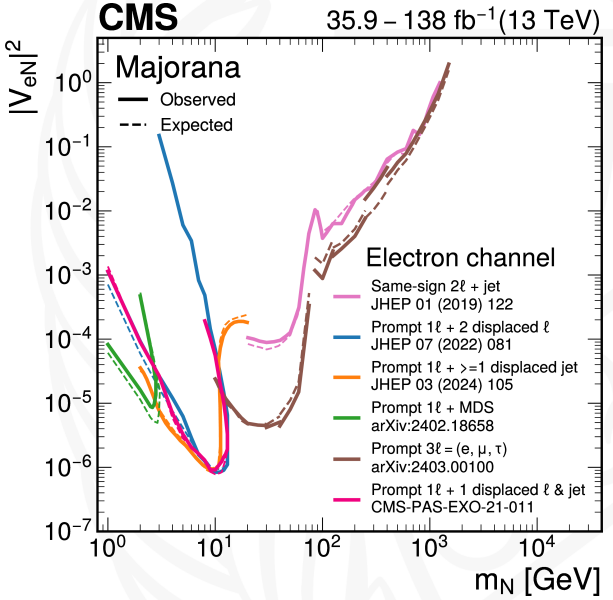


- Dirac and Majorana HNLs
- Inclusive coupling to the 3-lepton generations.
- Inclusive HNL decay search.
- 1 - 3 Low mass region → displaced decays
- HNL decay in the muon system (MS)
- 1 prompt lepton + hit clusters in the MS
- Event categorised based on lepton flavor and the muon subsystem

CMS-PAS-EXO-22-017

Filling the gap…

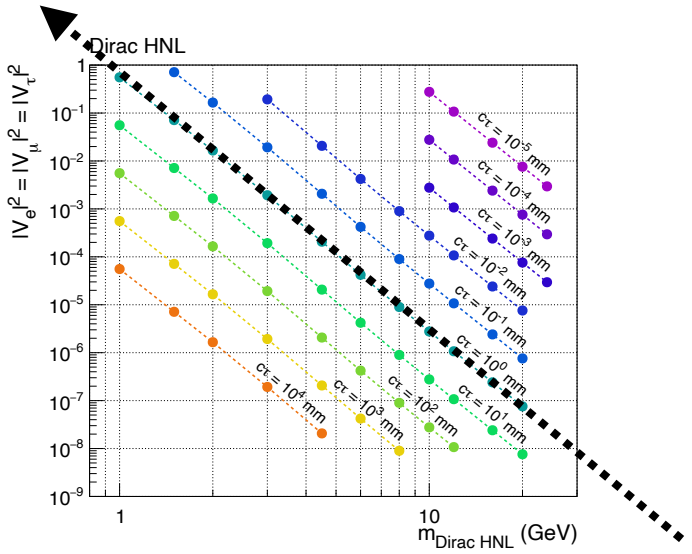


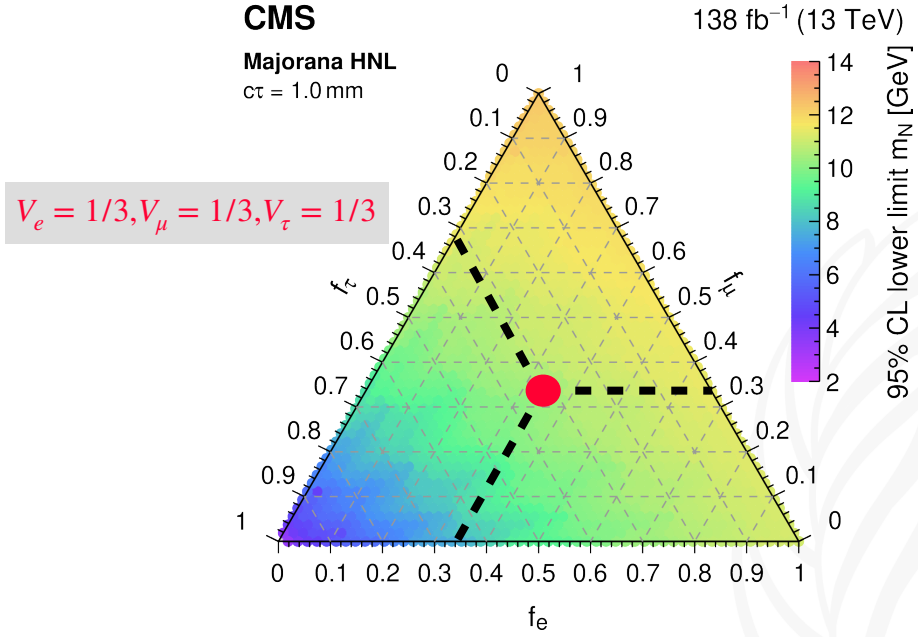


Limits : Fixed HNL lifetime

- For fixed $c\tau_0$, scan over possible couplings

  - Find the maximum excluded m_N.

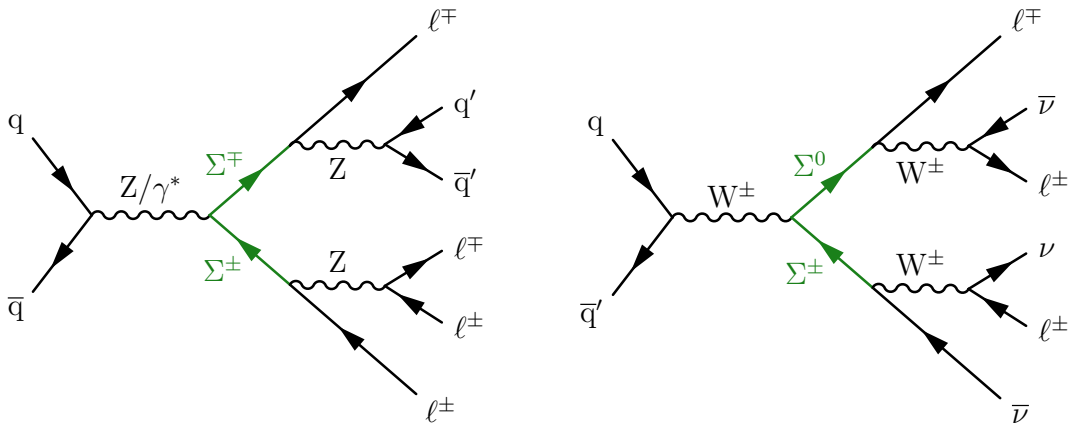




Max excluded mass

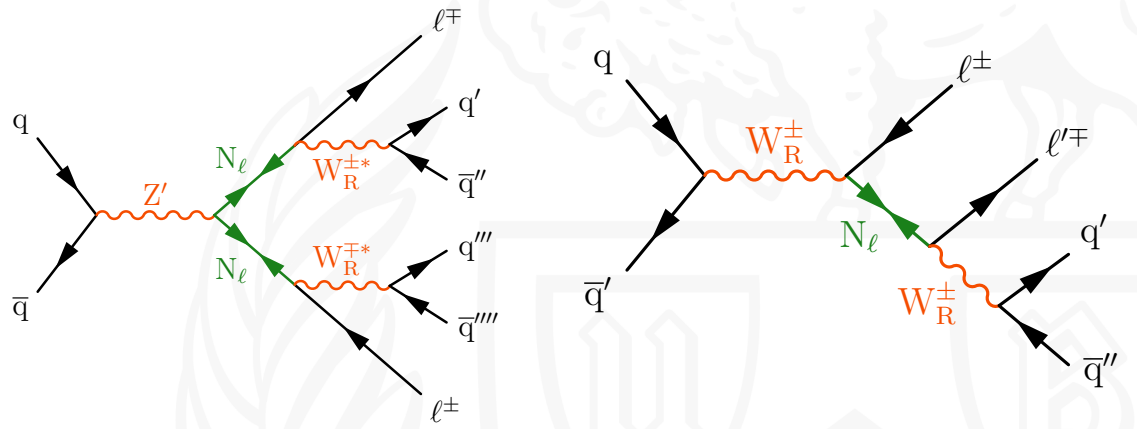
Banchmark models for HNL in CMS

Type III seesaw (Fermion Triplets)



- Fermionic $SU(2)_L$ triplets $\Sigma^0, \Sigma^{\pm}$
- Produced via Drell-Yan → decay to leptons + gauge bosons
- → Final states: multileptons, lepton + MET + jets, etc.

LRSM model (New gauge bosons $W_R^{\pm}$, Z')



- New particles: $W_R^{\pm}$, Z' and 3 ν_R denoted N_ℓ , $(\ell = e, \mu, \tau)$
- HNLs produced via $(W_R^{\pm} \to \ell N)$ or $(Z' \to NN)$
- Majorana neutrinos → LNV

Review paper: Dirac summary plots.