Search for long-lived HNLs using a displaced jet tagger

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LLP13 workshop

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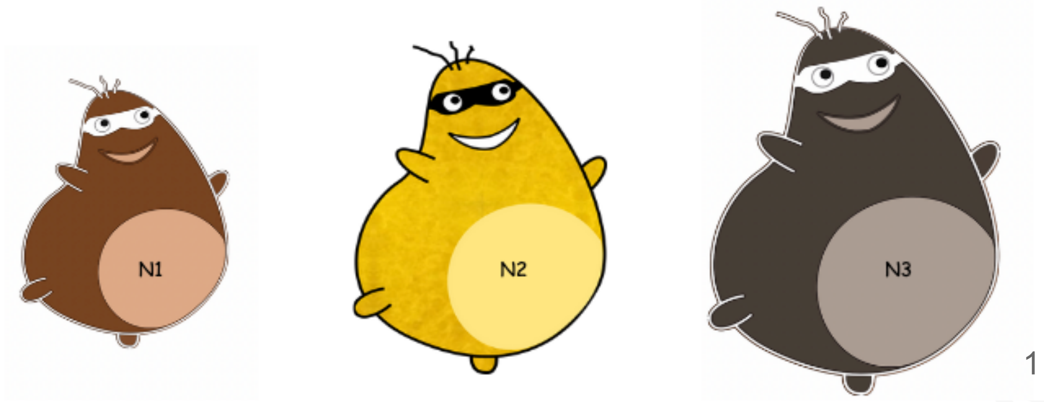
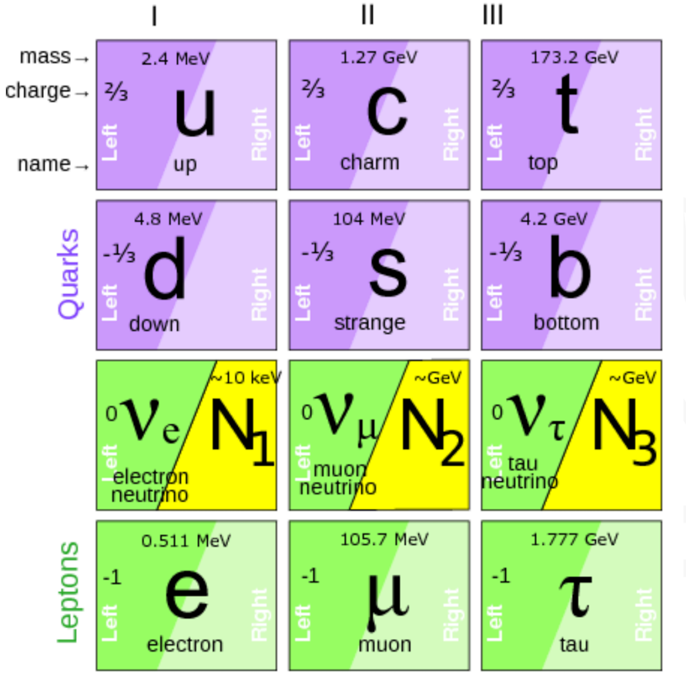


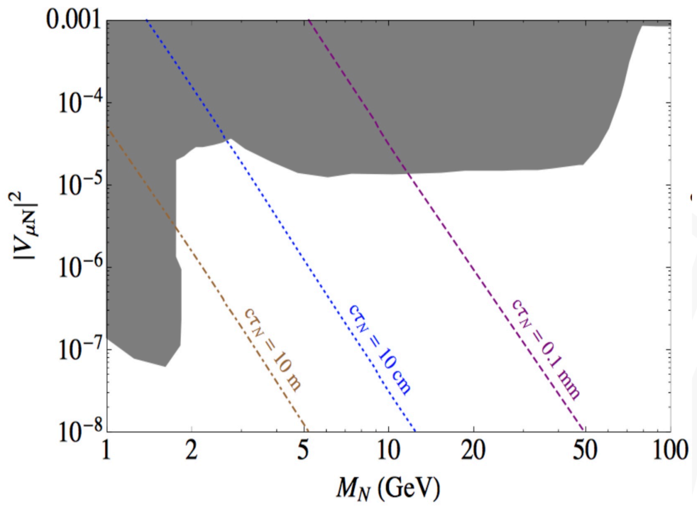
Introduction - Heavy neutral leptons (HNLs)

- ✦ New CMS results, Moriond EWK 2023 - http://cds.cern.ch/record/2852843.
- ✦ Search for three right-handed neutrinos as a minimal extension to the SM.
- ✦ Mass and coupling to the SM neutrinos (m_N, $V_{\ell N}$ i.e. $\ell = e, \mu, \tau$) are free parameters
- ✦ Can have Dirac(Majorana) nature process with LNC(LNC +LNV) respectively.
- ✦ Inclusive coupling to the three lepton generation i.e. LFC and LFV.
- ✦ Can be short or longlived:

$$\Gamma_N \propto G_F^2 m_N^5 \sum_{e,\mu,\tau} |V_{\ell N}|^2 \text{ and the proper lifetime } \tau \propto \frac{1}{\Gamma_N}$$

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

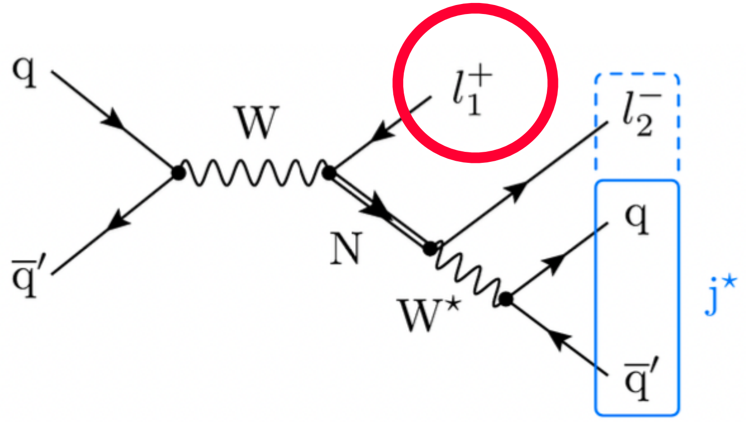




The big picture: Analysis strategy

2 leptons + jet final state

Lepton used for the trigger



Resolved

Boosted

Low mass. → ℓ_2 inside the jet cone (boosted)
High mass → ℓ_2 outside the jet cone (resolved)

- ✦ HNL events with $\ell\ell + j^{\star}$ final state, highest branching ratio $B(N \rightarrow \ell^{\pm} q \bar{q}') \approx 52\,\%$.
- ✦ A broad categorization to probe different HNL scenarios.
- ✦ Displaced jet tagger based on deep neural network techniques developed primarily in EXO-19-011.
- ✦ Background estimation using the ABCD method: Two discriminant variables: $m_{\ell_1 \ell_2 j^*}$ and tagger score.
- ✦ Determine limits in $m_N, |V_{\ell N}|^2$ plane

Event selections

✦Leading lepton (e or μ): Tight lepton: $p_T > 26 - 34$ GeV, $|\eta| < 2.4$ → Tight isolation

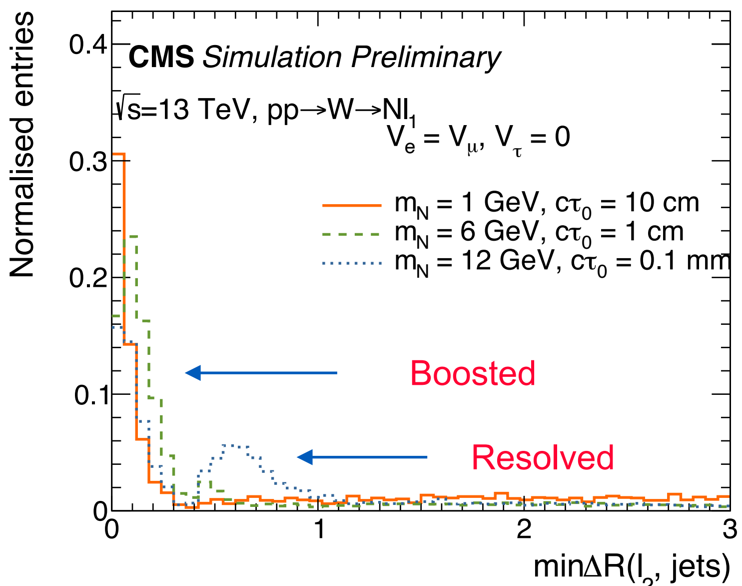
✦Subleading lepton (e or μ): Loose lepton: $p_T > 3 - 5$ GeV, $|\eta| < 2.4$ → No isolation

✦HNL jet candidate $j^\star$: Ak4CHS jet - the closest to ℓ_2 in ΔR.

- Boosted ($\Delta R(\ell_2, j^\star) < 0.4$): $p_T > 30$ GeV, $|\eta| < 2.4$
- Resolved ($0.4 < \Delta R(\ell_2, j^\star) < 1.3$): $p_T > 20$ GeV, $|\eta| < 2.4$

✦dilepton mass: $m_{\ell_1,\ell_2} \in [20,80]$ GeV and missing momentum $p_T^{miss} < 60$ GeV

Private work



Analysis categorization

4 categories × 2

The di-lepton flavor and charge

LFC and LFV, i.e. SF and OF : $\mu\mu, ee, \mu e, e\mu$

LNC and LNV, i.e., OS and SS

2 categories

The topology of the HNL decay product

Boosted : $\Delta R(\ell_2, j^*) < 0.4$

Resolved: $0.4 < \Delta R(\ell_2, j^*) < 1.3$

3 categories

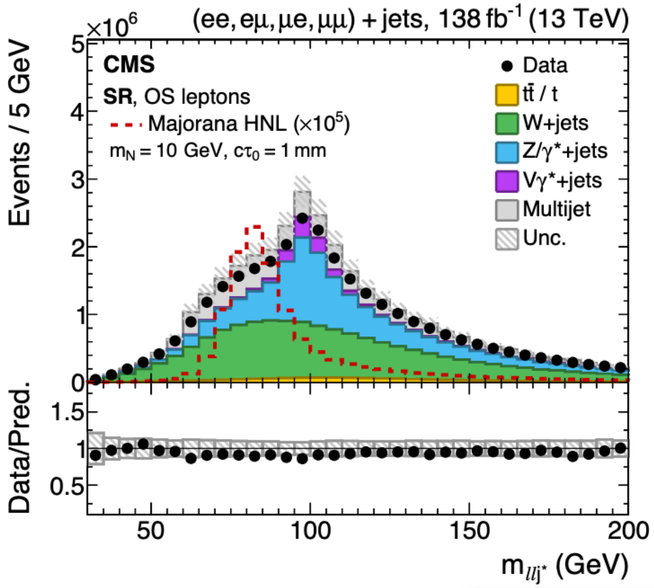
The 2D displacement: $d_{xy}^{sig}(\ell_2) = d_{xy}(\ell_2)/d_{xy}^{err}(\ell_2)$

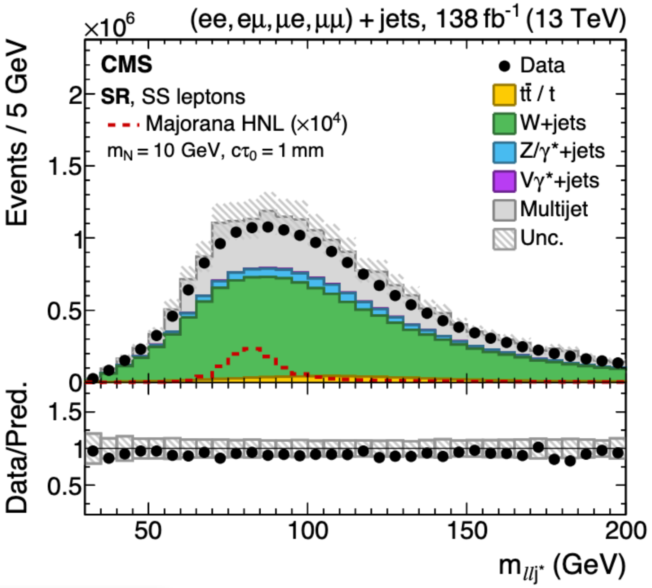
Prompt $d_{xy}^{sig} < 3$

Medium $3 < d_{xy}^{sig} < 10$

Displaced $d_{xy}^{sig} > 10$

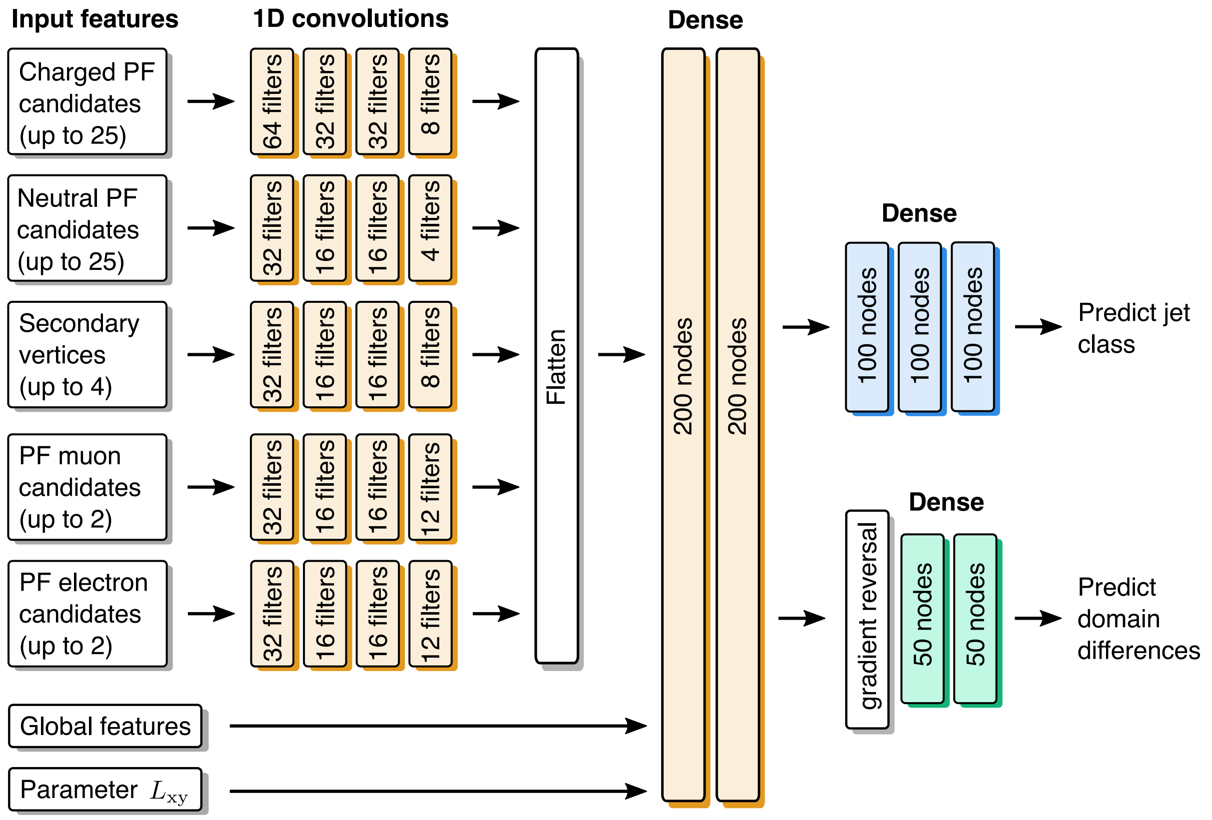
Combined Flavor categories





48 categories in total

Displaced jet tagger

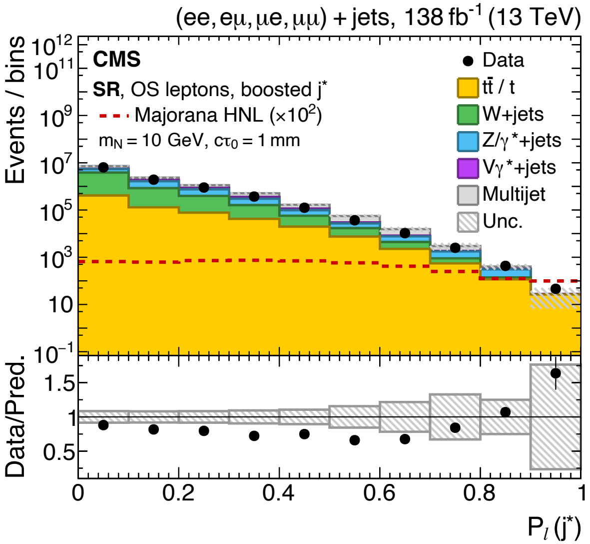


- ✦ Extension of [this work]
- ✦ Outputs to cover jets with leptons inside.
  - ✓ **Prompt leptons & photon, uds, g, c, b, pileup,**
  - ✓ **Displaced HNL jets(w/ and w/o leptons).**
- ✦ Parametrization of the tagger using the generator level displacement L_{xy}
- ✦ Domain adaptation: Train tagger on data in the control region.
  - →to improve data/MC agreement

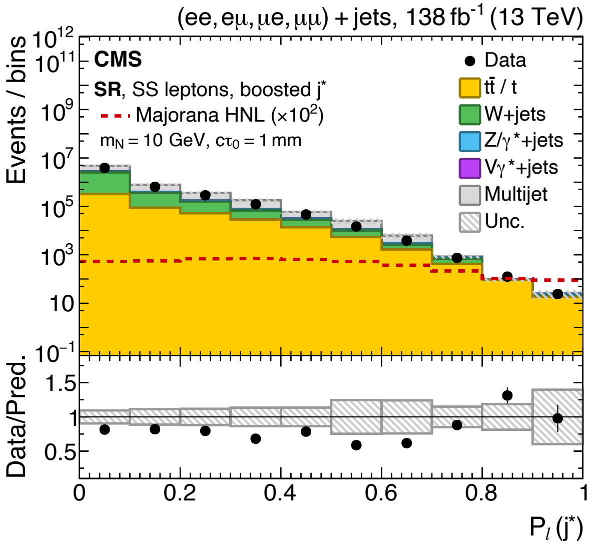
Displaced jet tagger : Signal Region

- ✦ Tagger output distribution: simulation scaled to Xsec × Lumi
- ✦ Pre-fit distributions - Good agreement in general
- ✦ All signal region cuts applied except the $m_{\ell_1,\ell_2,j^\star}$

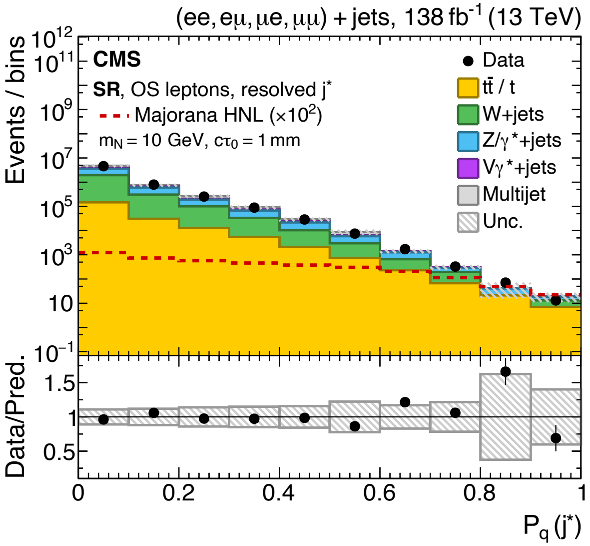
Boosted OS



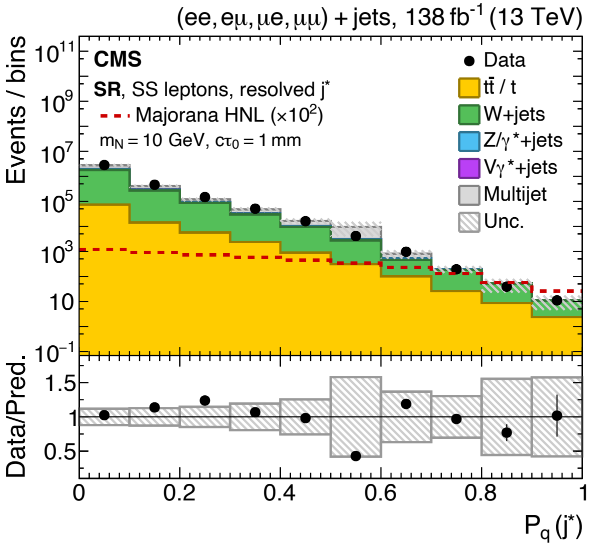
Boosted SS



Resolved OS



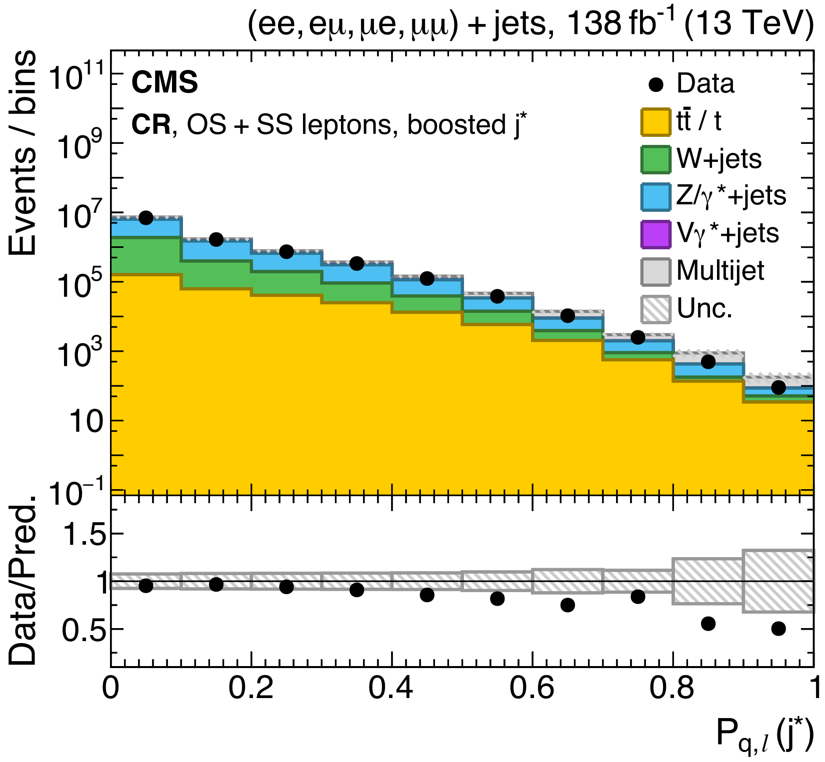
Resolved SS

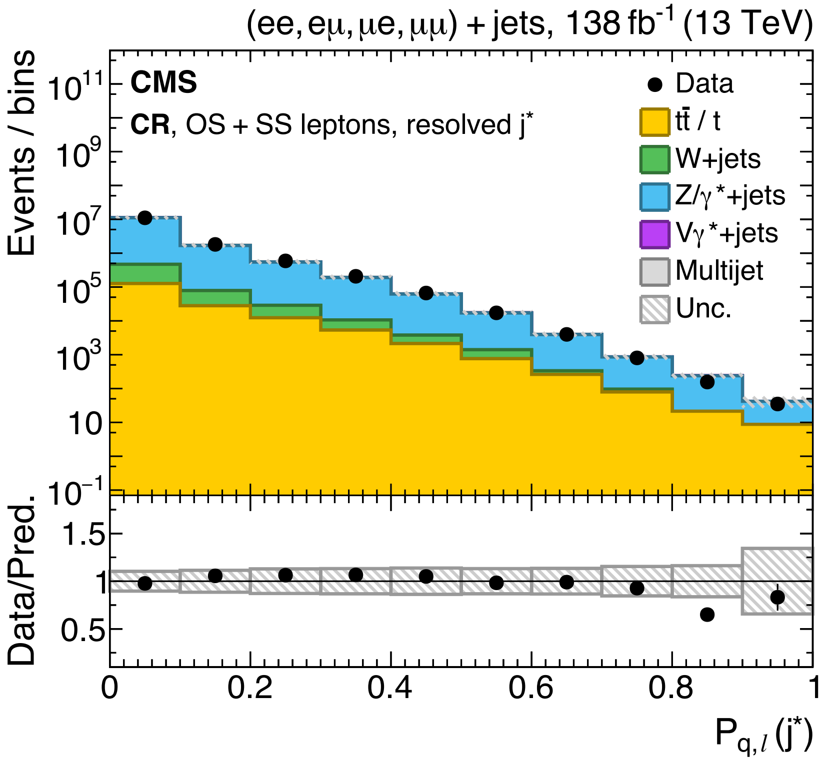


Displaced jet tagger control region

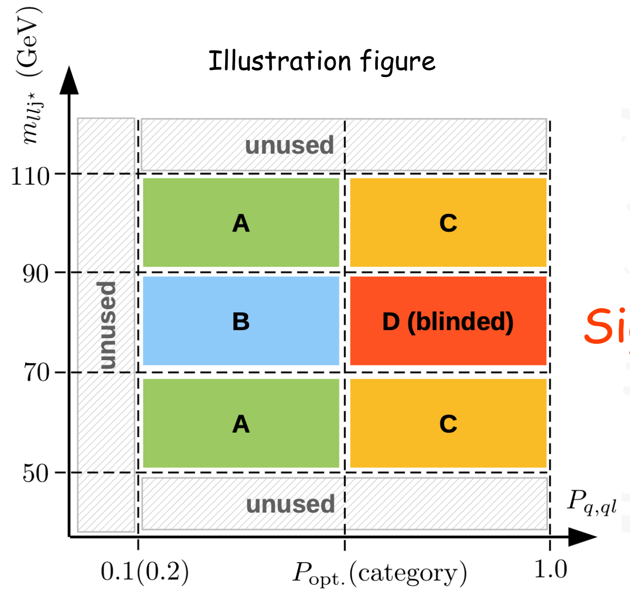
✦DY+jets control region: high dilepton mass for inclusive leptons categories and combined OS + SS

✦Pre-fit distribution: good modeling in general (simulation scaled to Xsec × Lumi)



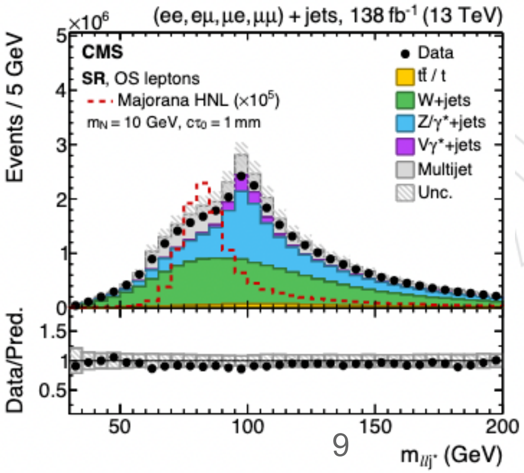


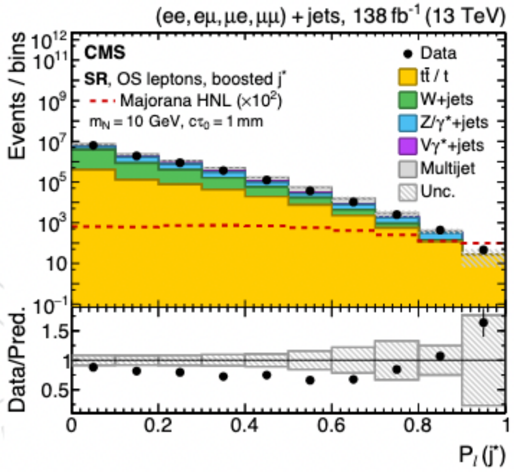
Background estimation strategy



Signal Region

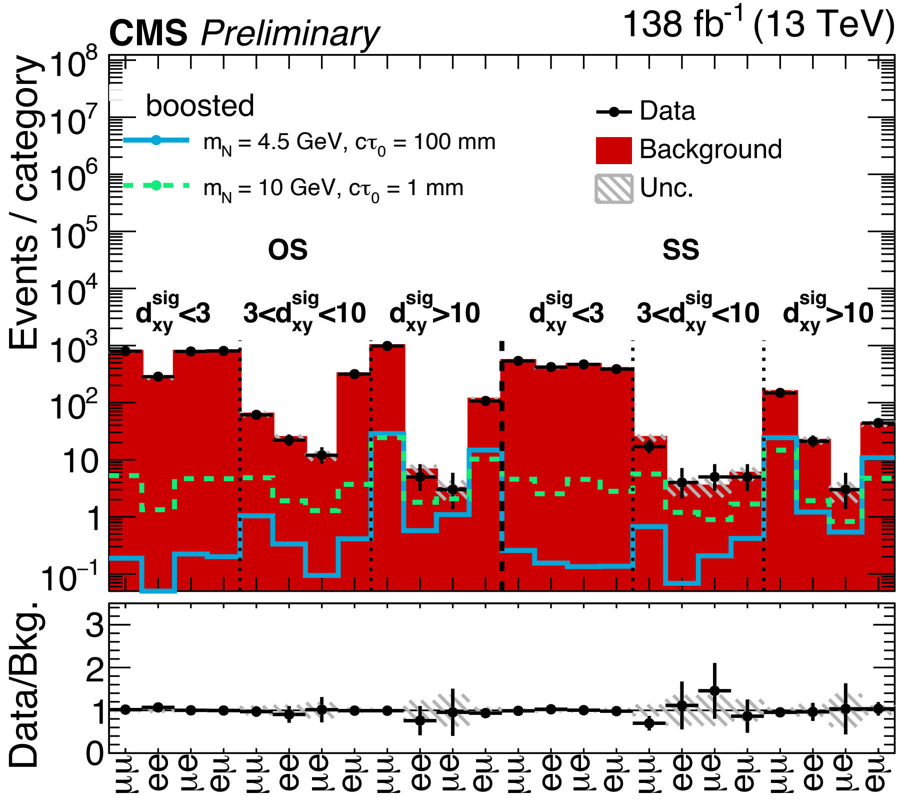
- ✦Multiple sources of background: SM processes, i.e., DY+jets, Multijet, W+jets
  - ✓Prompt, displaced from Heavy Flavour decays, mis-reconstructed objects.
- ✦Estimate all backgrounds inclusively.
- ✦Rejecting residual prompt background at a high tagger score
  - ✓The **HNL jet hadronic fraction** → backgrounds with low p_T non-isolated 2nd lepton: $p_T(j^\star)/p_T(\ell_2) < 2-4$
  - ✓ $m_{\ell\ell} < 70$ GeV → Specific to DY+jets background in $\mu\mu$ OS categories.
- ✦Estimate irreducible background (high tagger score) per category.

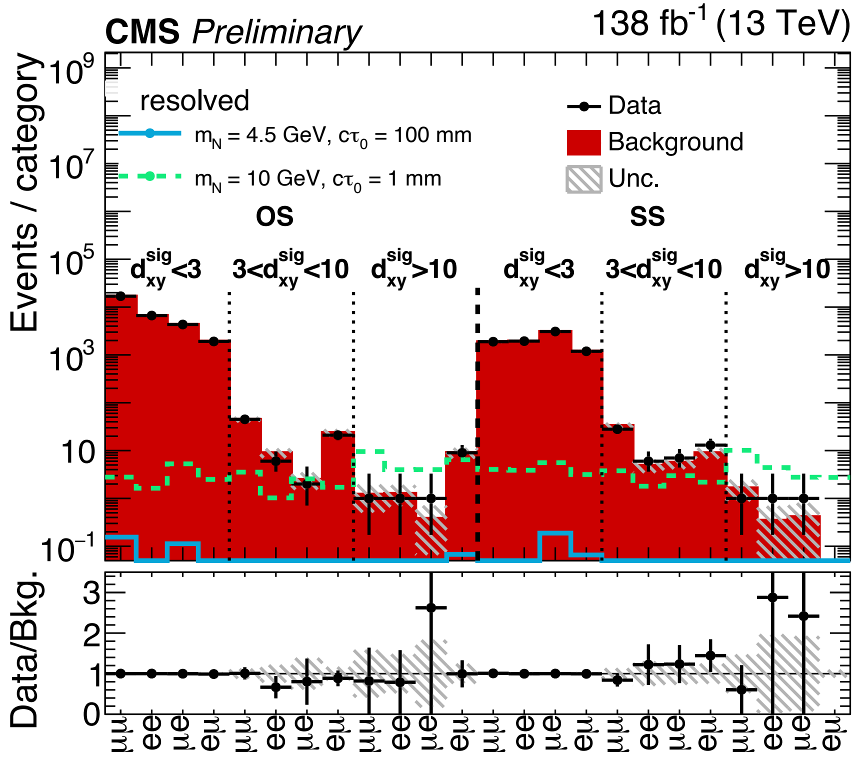




Results: Expected vs observed yields

- ✦Expected (Post-fit) and observed (unblinded) yields in 48 categories overlaid with two signal scenarios.
- ✦The thresholds of the tagger are optimized per category.
- ✦No significant deviation from the expected background is observed.



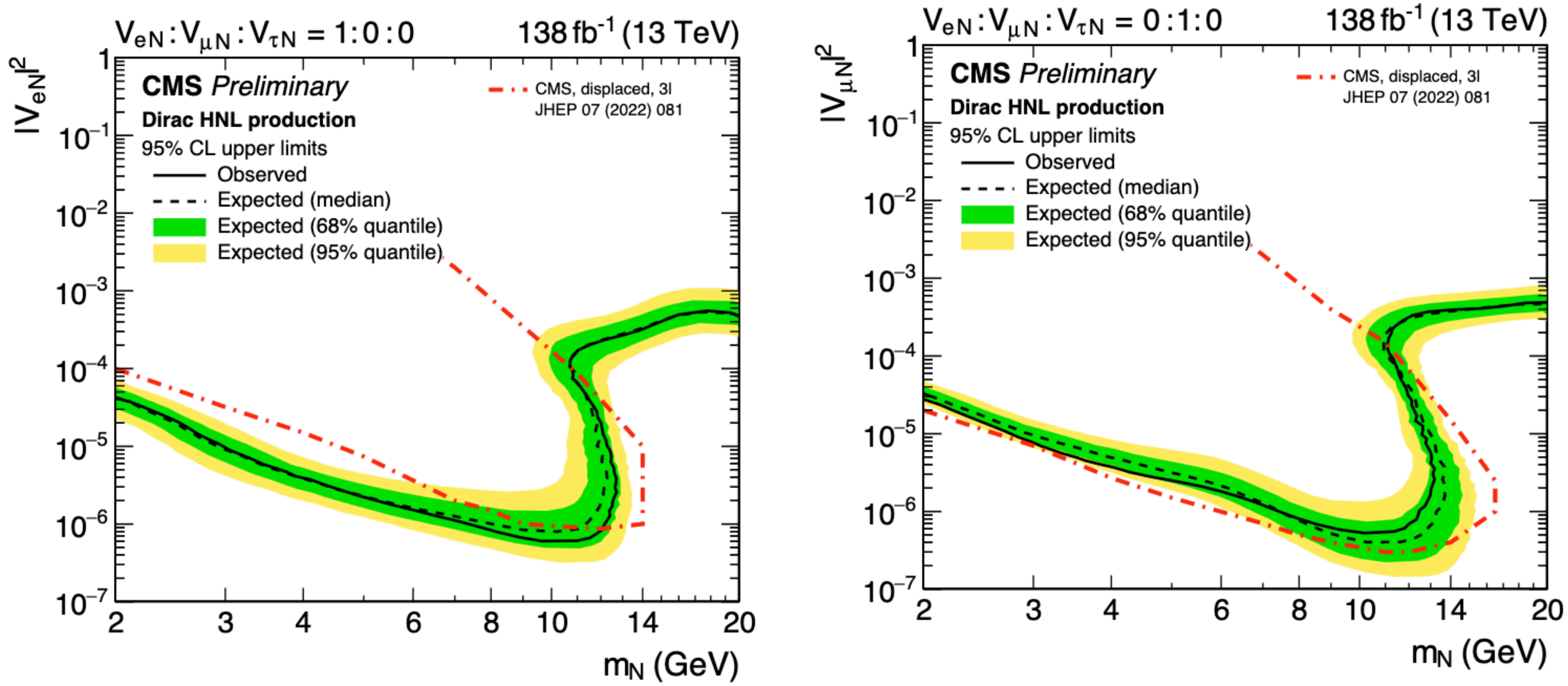


Exclusion limits: 2D plane $(|V_{\ell N}|^2, m_N)$

✦Results using full Run 2 data for different couplings scenarios to the three leptons generation

✦Best observed limits for pure muon coupling scenario $\rightarrow |V_{\mu N}|^2 > 5(4) \times 10^{-7}$ for Dirac(Majorana)

DIRAC HNL scenario



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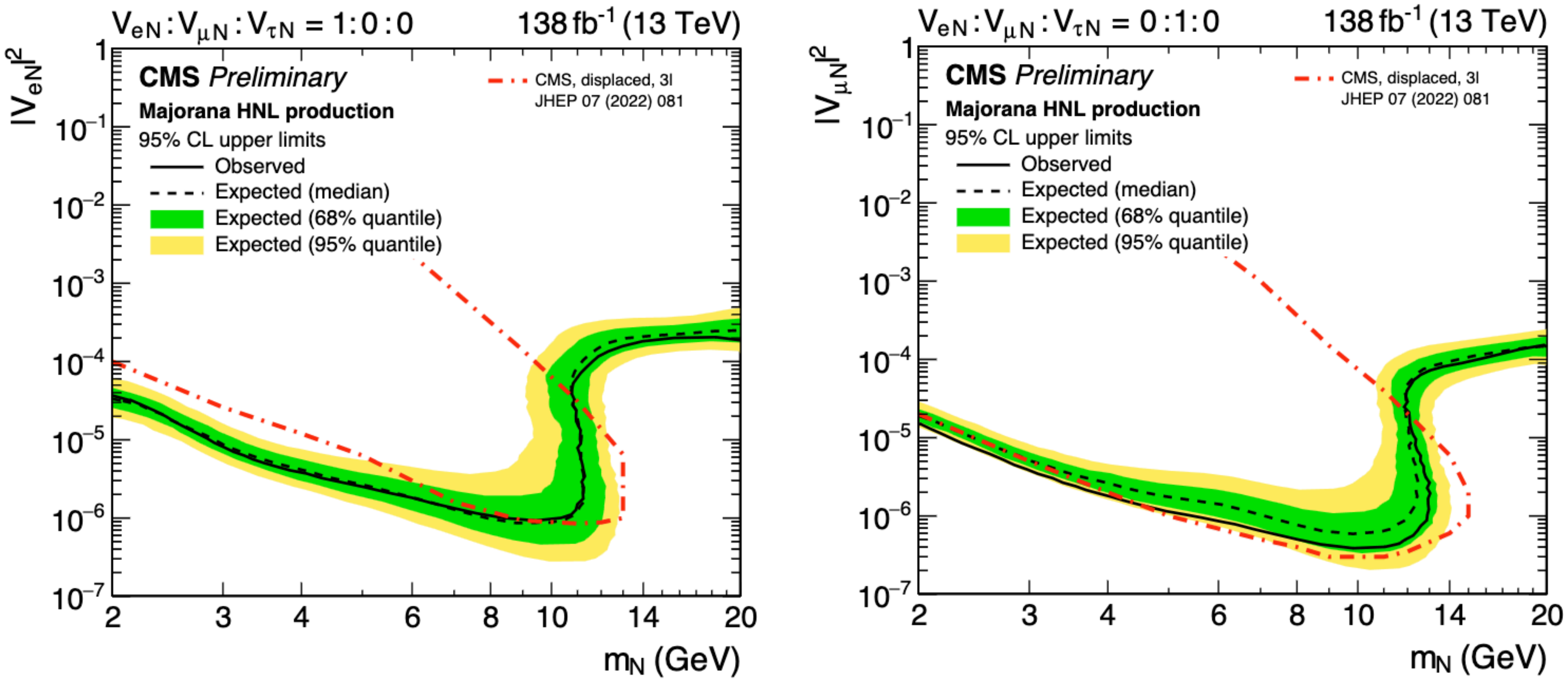
Majorana HNL scenario



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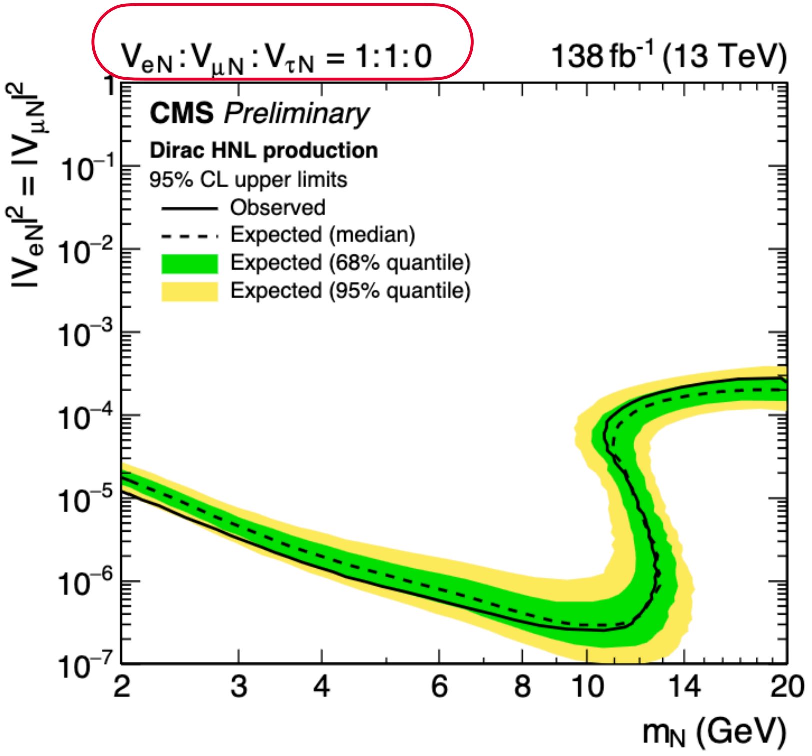

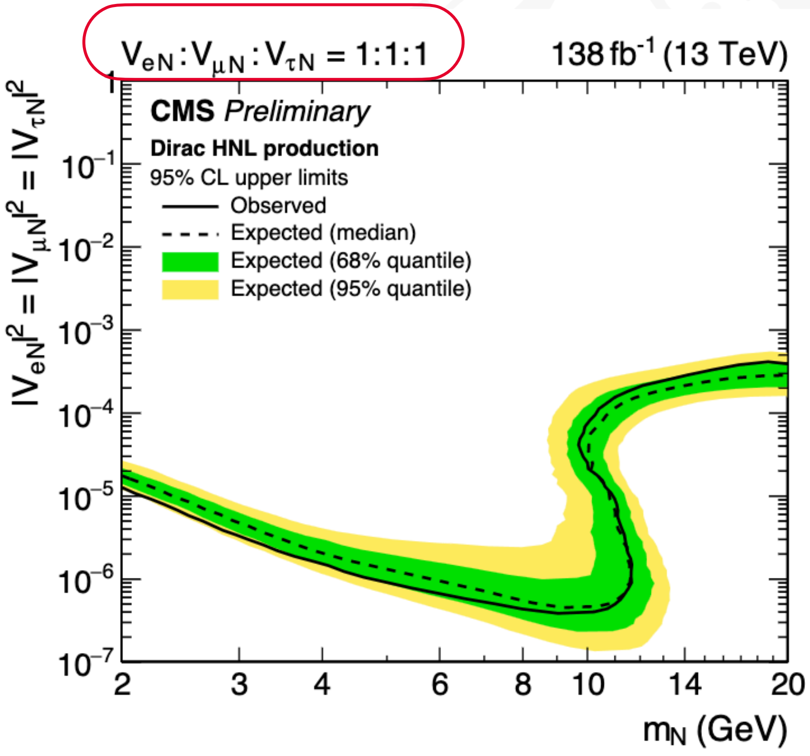

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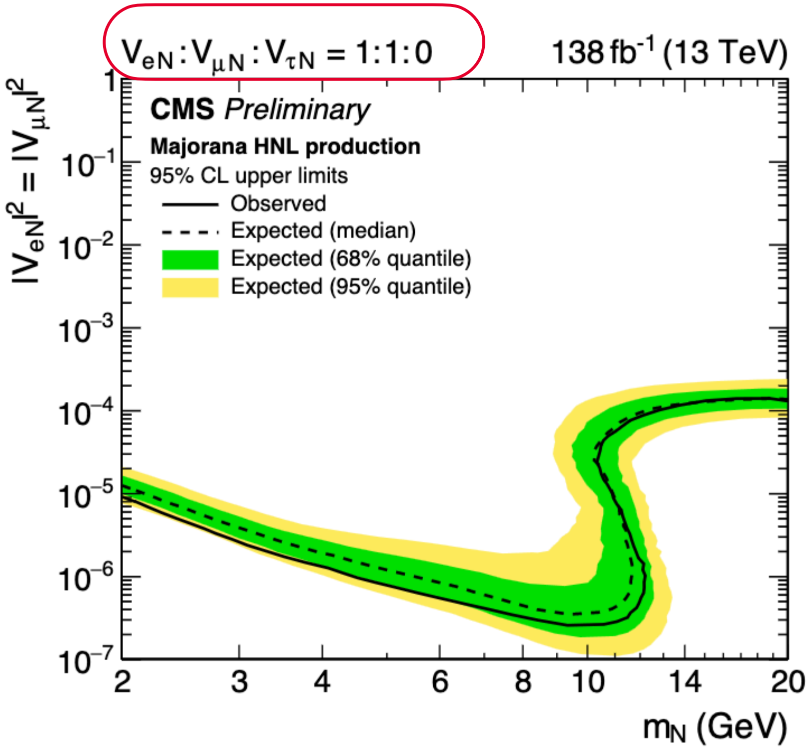
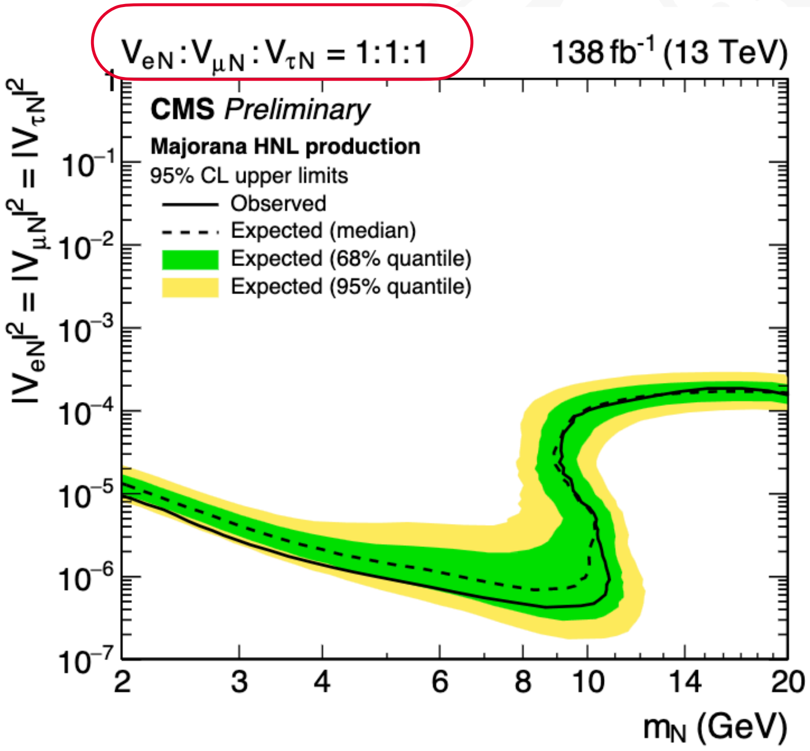
Majorana HNL scenario



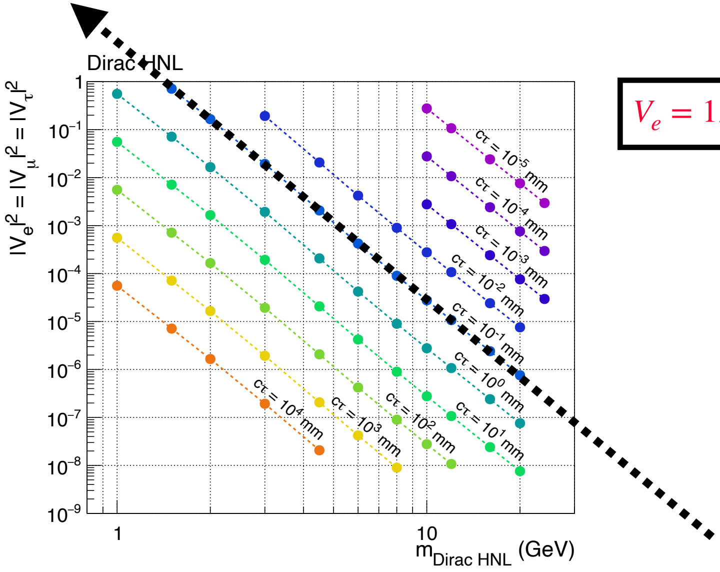


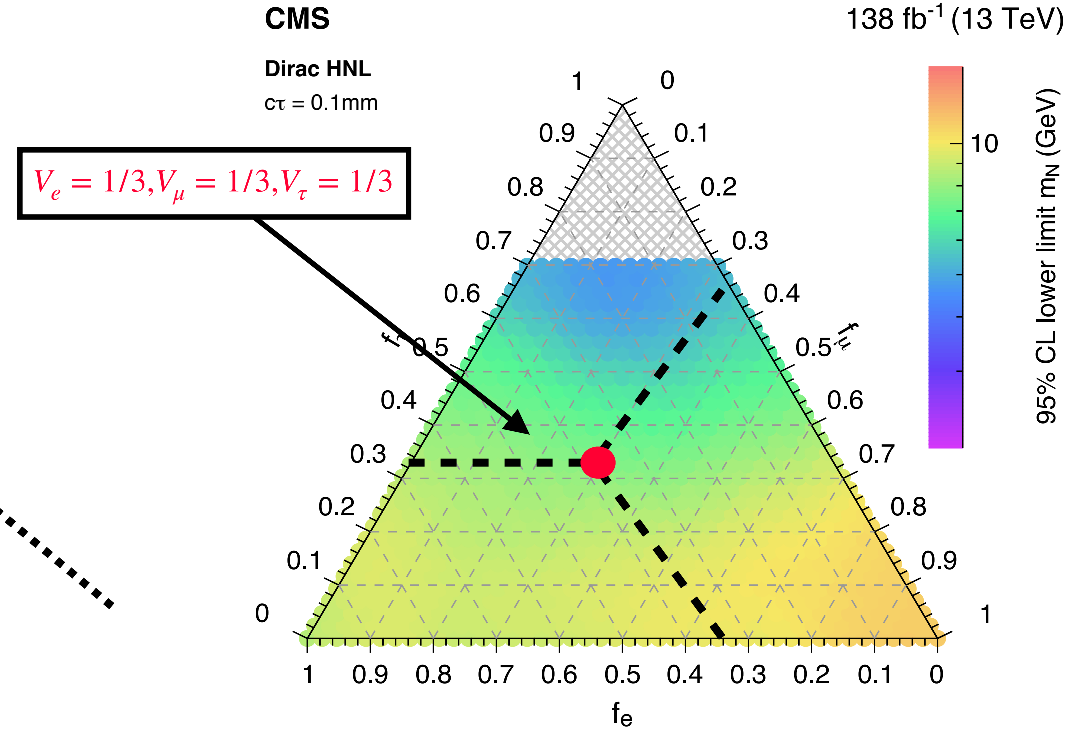
Exclusion limits: Fixed HNL lifetime

✦Exclusion limits as a function of the relative coupling to the three lepton generation

✦For fixed $c\tau_0$, scan over possible couplings → Find the maximum excluded m_N.

Illustration figure





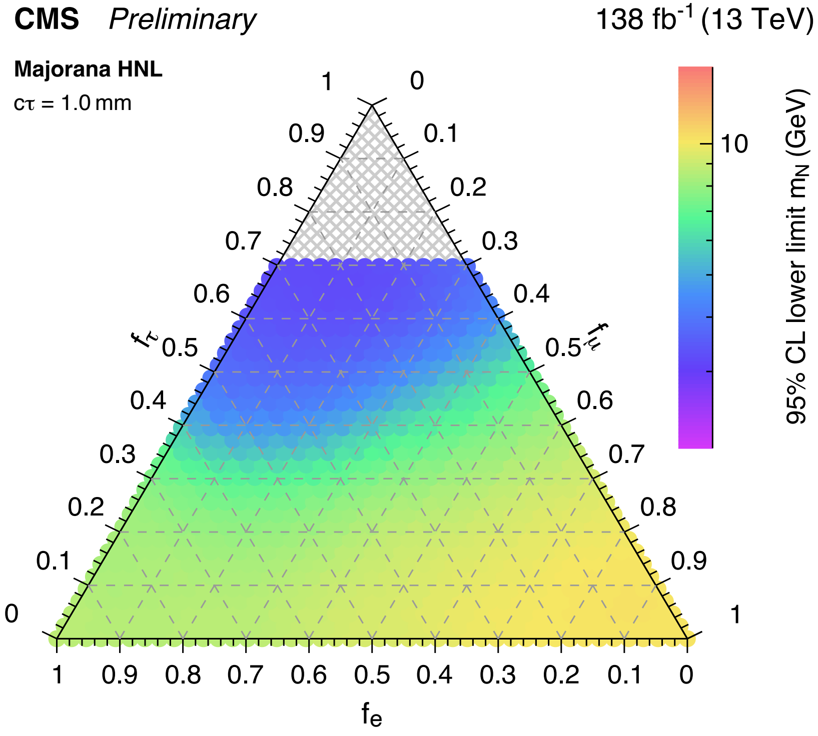


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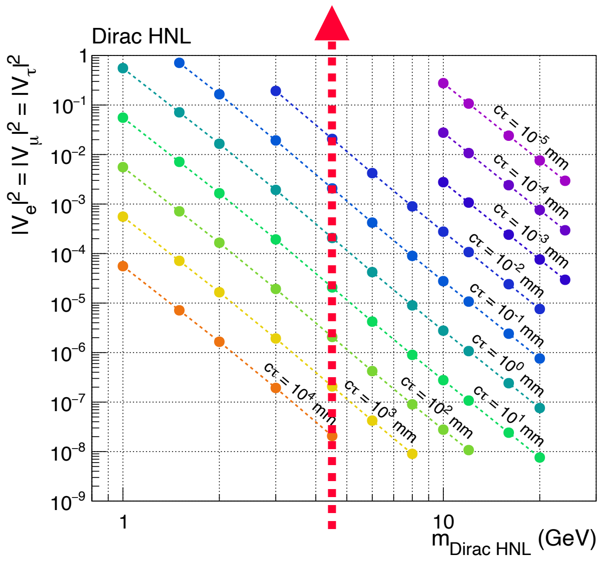
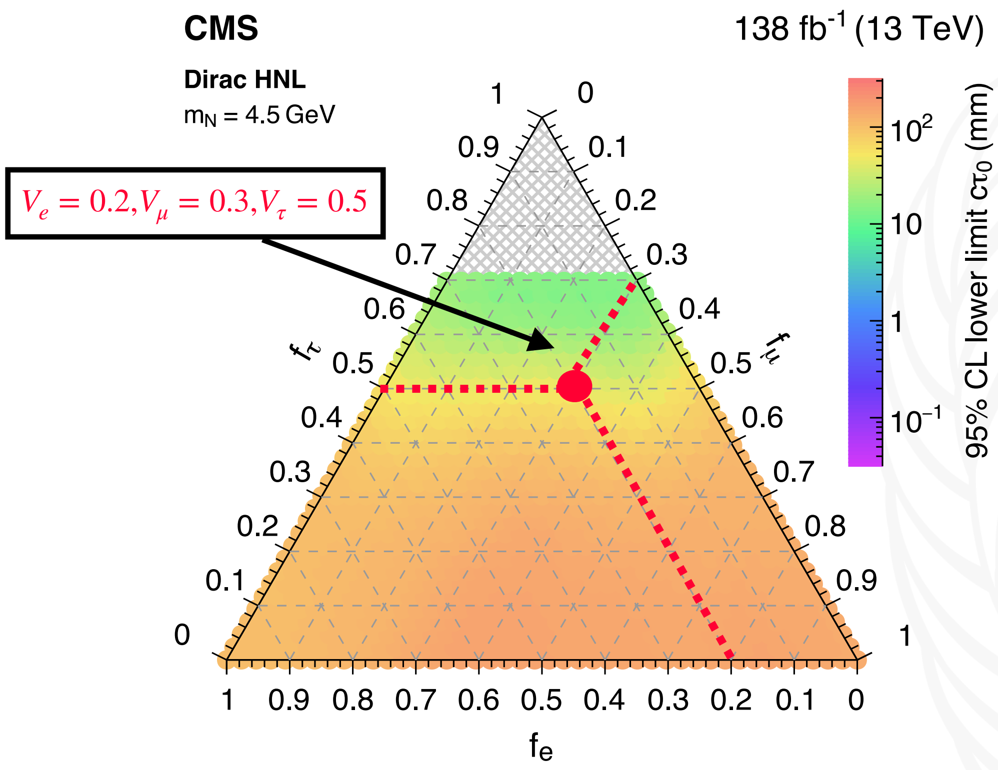
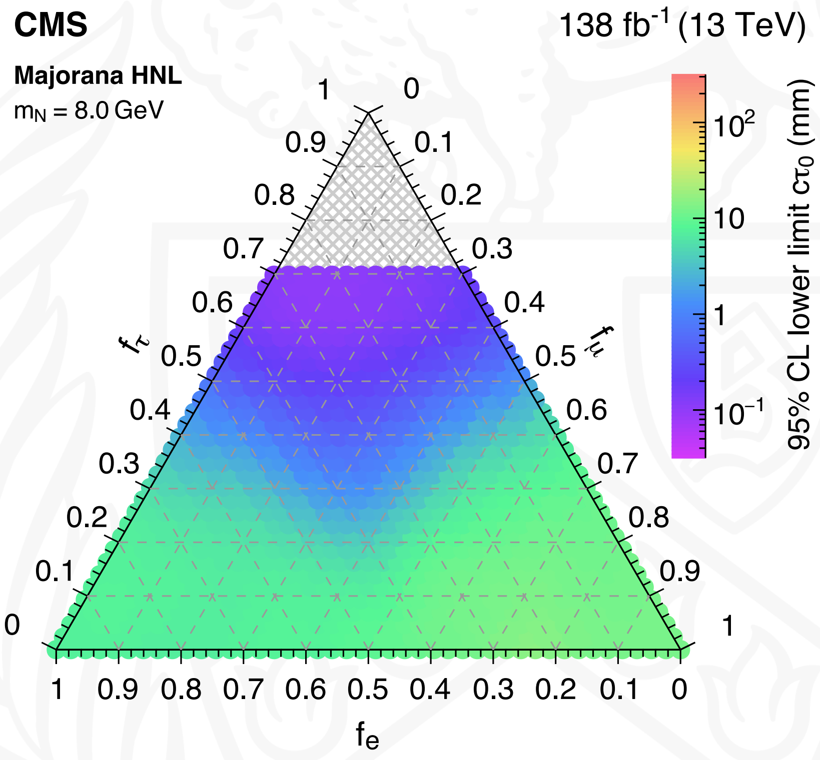
Illustration figure





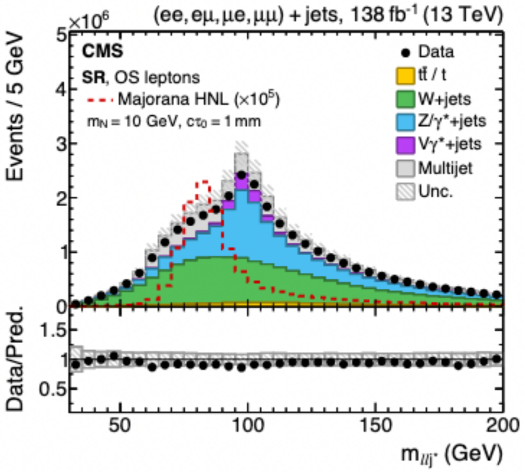


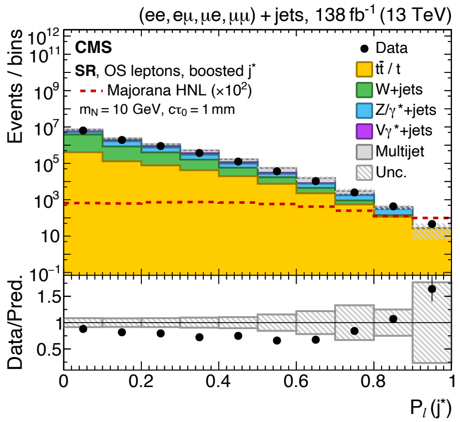
Impact

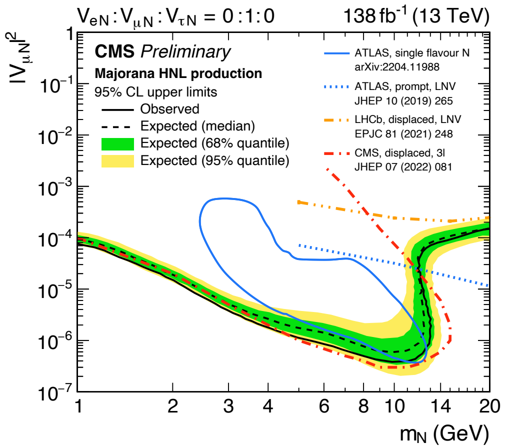
✦ Most significant Impacts on the results

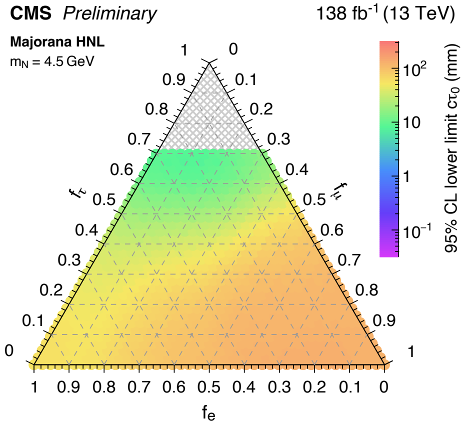
Uncertainty source	Process	Uncertainty Size %
Stat. unc. From the sideband region	Background	10
Loose muon reco	Signal	7
Displaced jet tagger	Signal	6
Jet energy scale and resolution	Signal	2

Summary









✦First Analysis in CMS to probe HNL coupling to the three lepton generation simultaneously.

✦Broad categorization to probe both Dirac and Majorana.

✦Displaced jet tagger to be sensitive over a broad range of lifetimes.

✦Background estimated from data.

✦No excess was observed

✦Setting limits on the mass and coupling plane

→ Best limits observed for muon and electron pure couplings.

✦Limits determined in relative coupling space (triangle plots.)