# Searches for Heavy Neutral Leptons (HNL) in CMS

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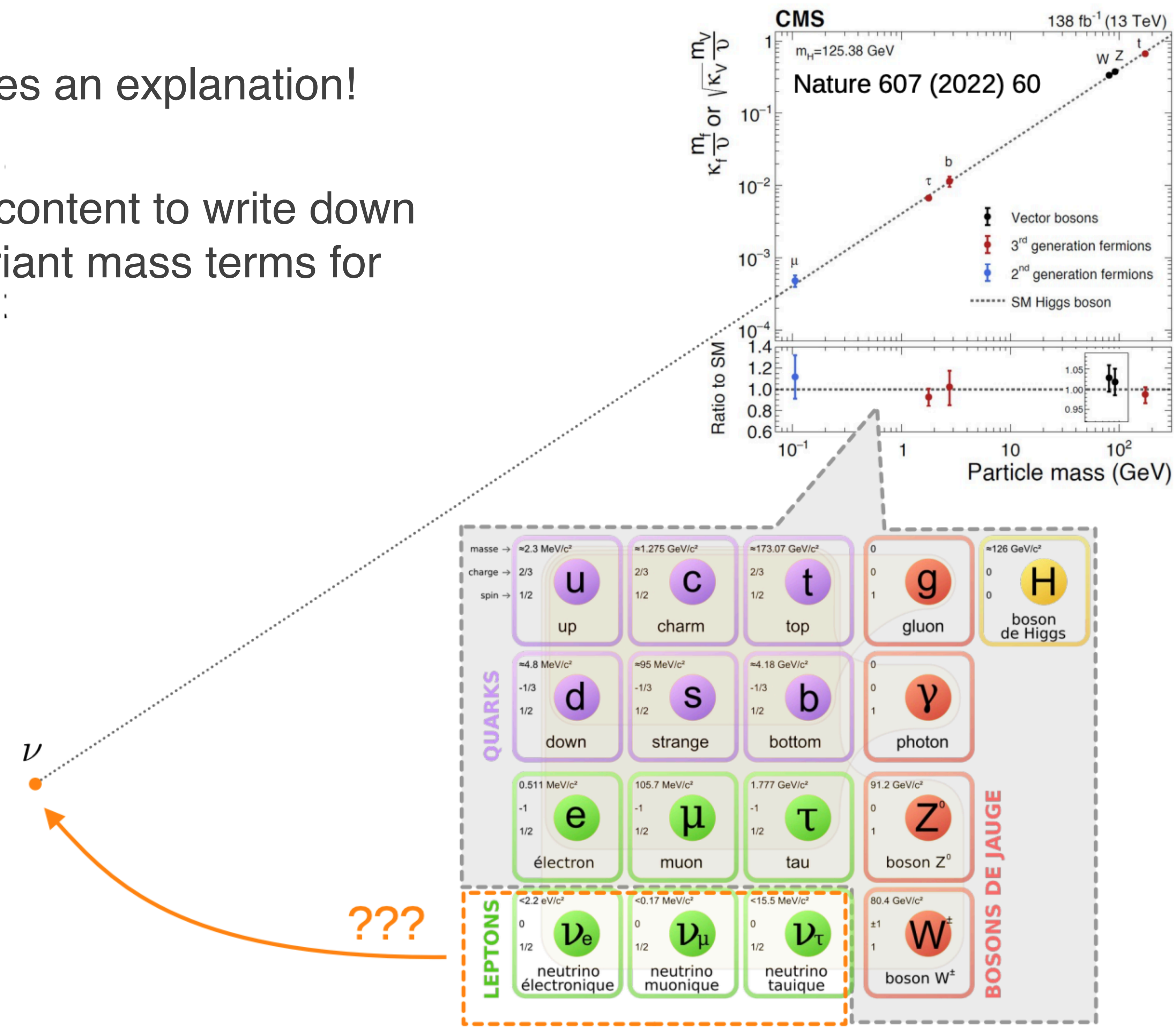
On behalf of the CMS collaboration

NuFact 2024 - Argonne National Laboratory
18 Sep, 2024

CMS

# Why search for Heavy Neutron Lepton?

- Non-zero neutrino mass requires an explanation!
- SM does not have the particle content to write down renomalizable and gauge invariant mass terms for neutrino
  - Must add new particles[1]!




[1] arxiv.org:9805219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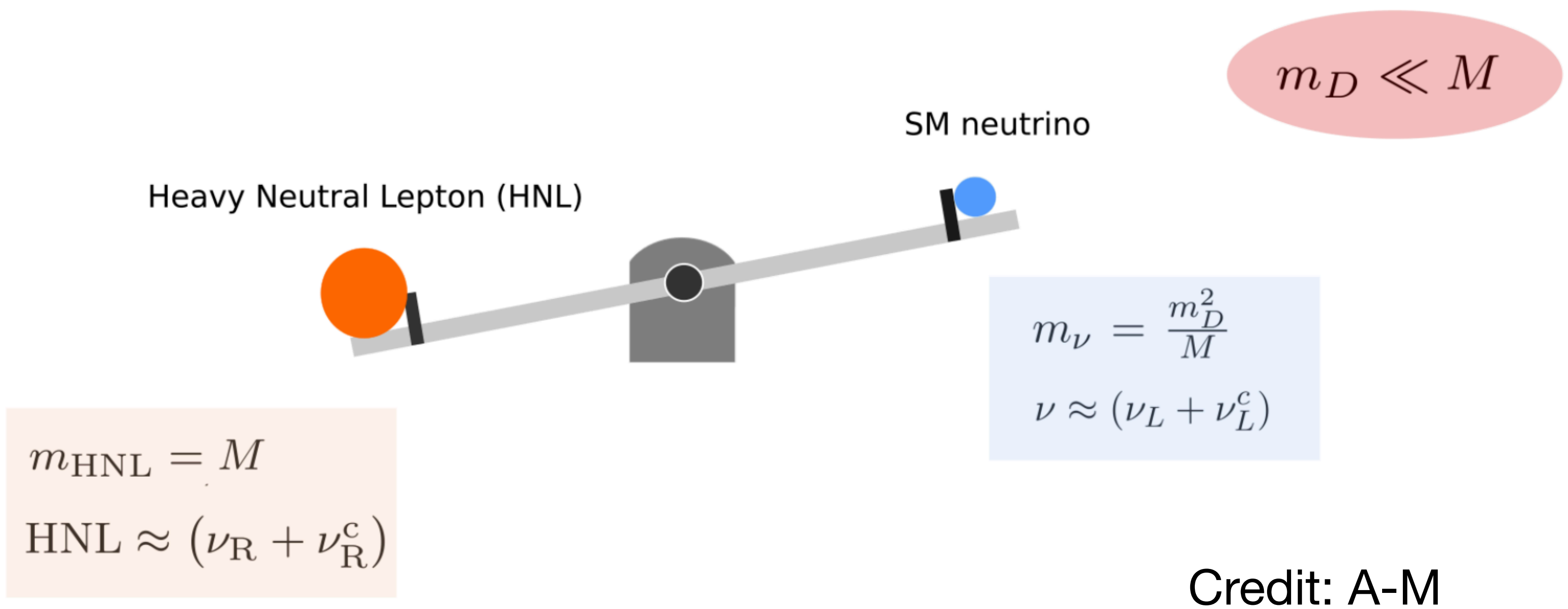
# Type-I see-saw model

Simplest extension to SM neutrino sector:
Right-handed SM singlet called HNL
(Type-I see-saw model)

- ☑ Interact with SM neutrino through mixing


- ☑ Suppresses SM neutrino mass if heavier than SM
- ☑ “Sterile” since it’s an electroweak singlet

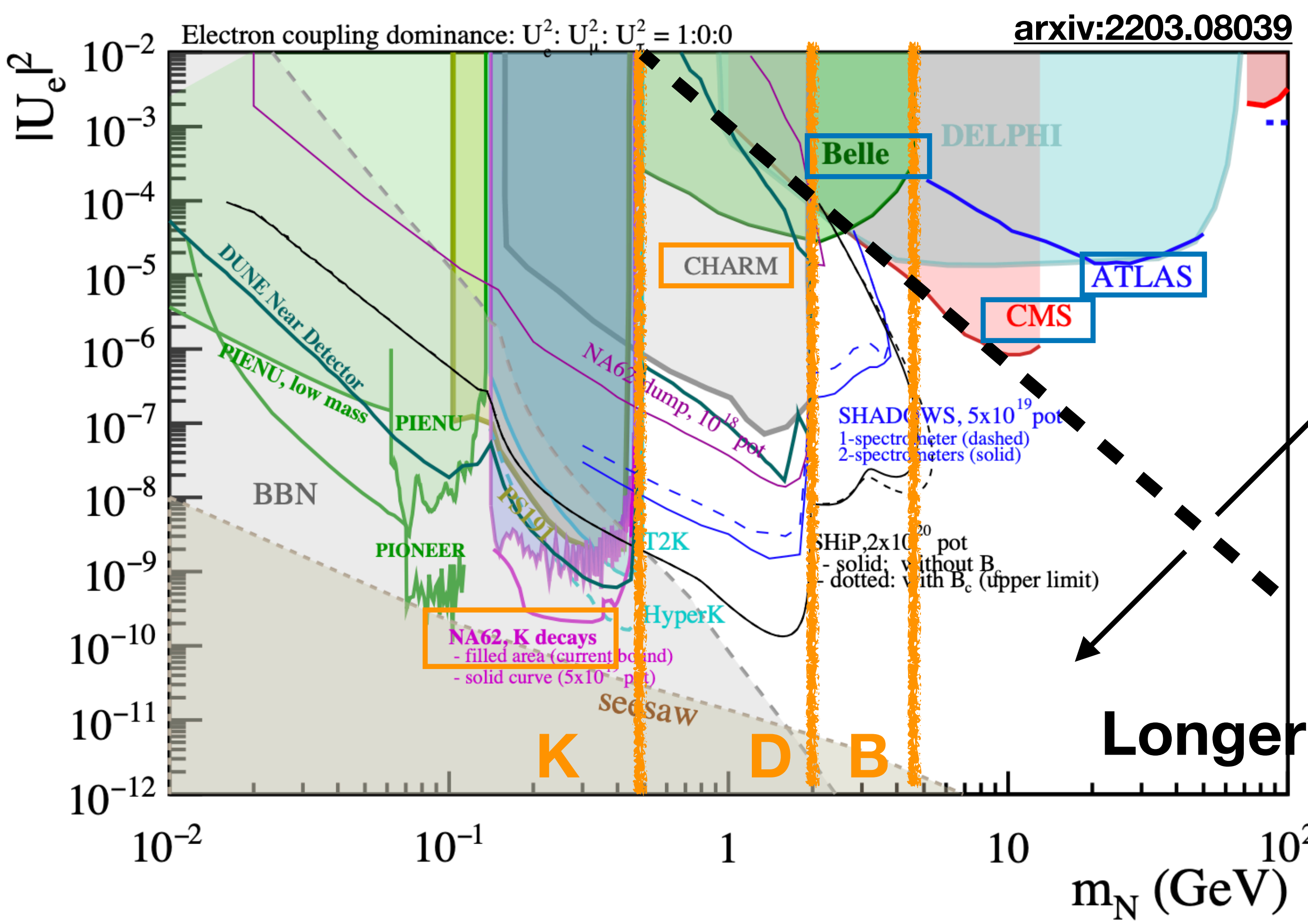



Credit: A-M

# Experimental landscape

- Huge parameter space
- Rich phenomenology: prompt/displaced, many production x decay modes
- Probed by many different experiments: collider & beam dump
- CMS is **actively** exploring new parameter space with novel techniques!
  - low-mass, long-lived, final states involving a $\tau$-lepton

**~10 orders magnitude of $|V_{lN}|^2$**




**Shorter lifetime**

$$c\tau \sim |V|^{-2} m_N^{-5} = \text{const}\,.$$

**Longer lifetime**

**4 orders magnitude of $m_N$**



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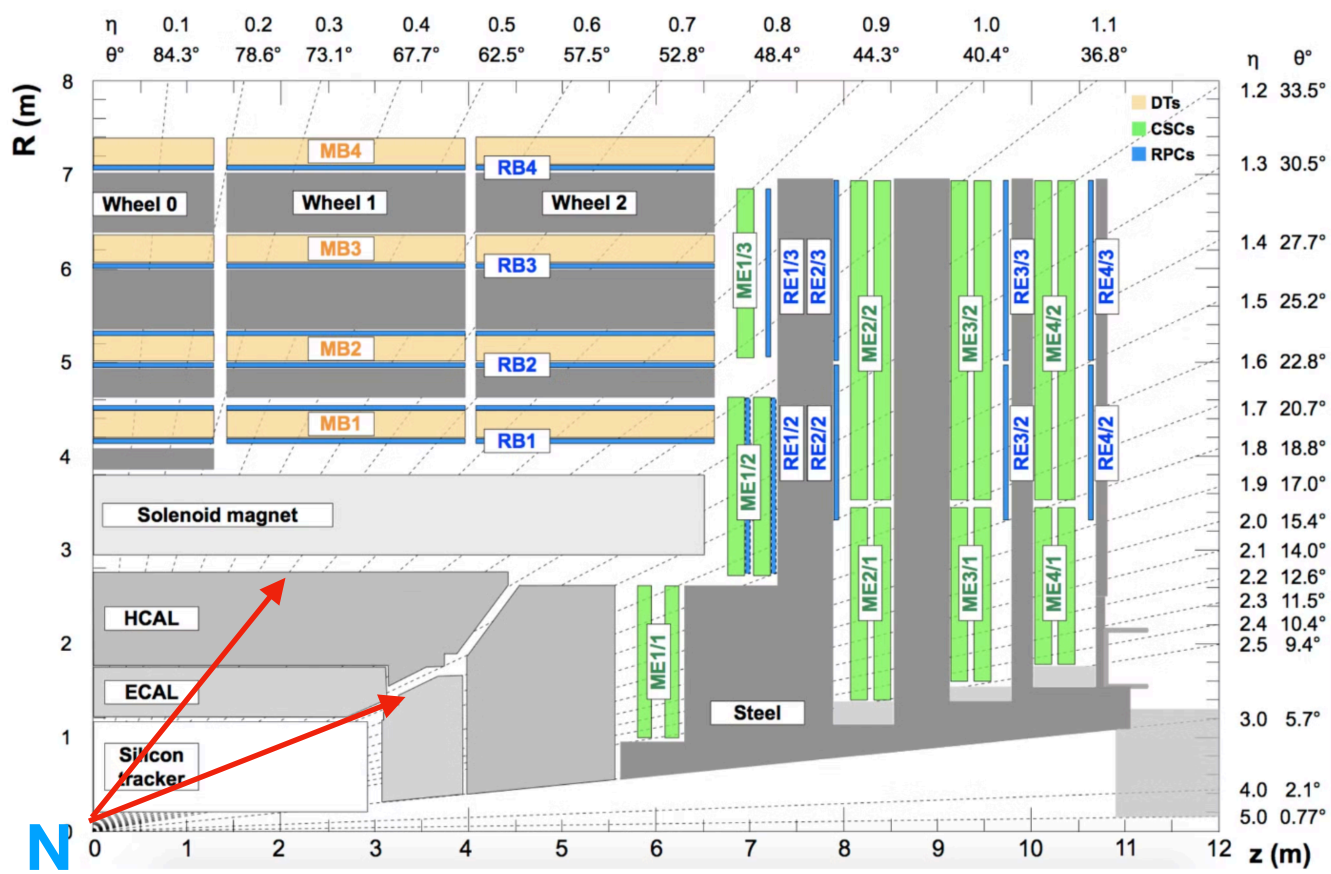
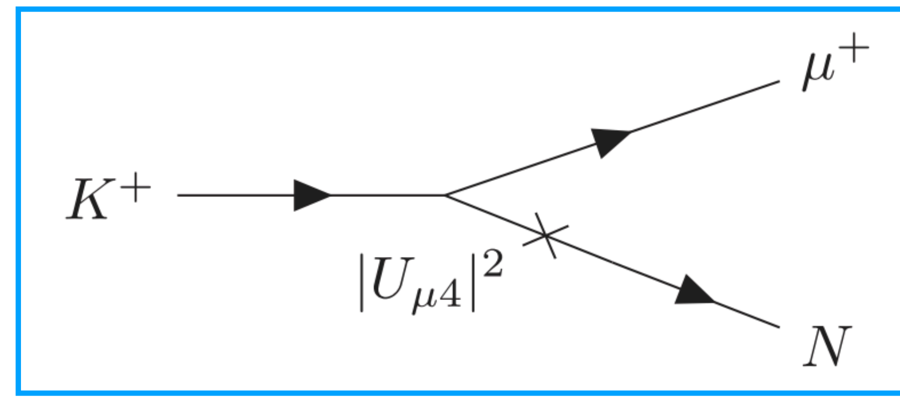
# How to search for HNLs?

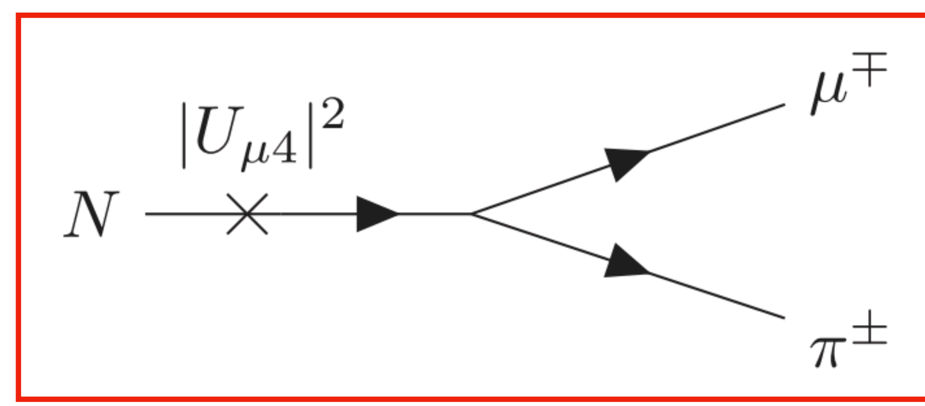
**CMS is a hermetic, multi-system detector**
**Excellent tracking and muon system**




**Example production at neutrino exp. searches**




**Example decay at neutrino exp. searches**




**PhysRevD.101.052001**

**CMS has access to different production and decay modes than neutrino experiments**

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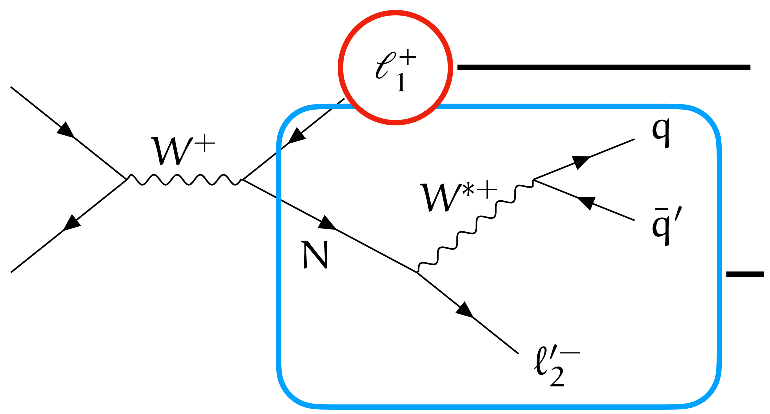
# In this talk

- 5 new results in the past ~1 year!

**Displaced object reconstructions with ML**

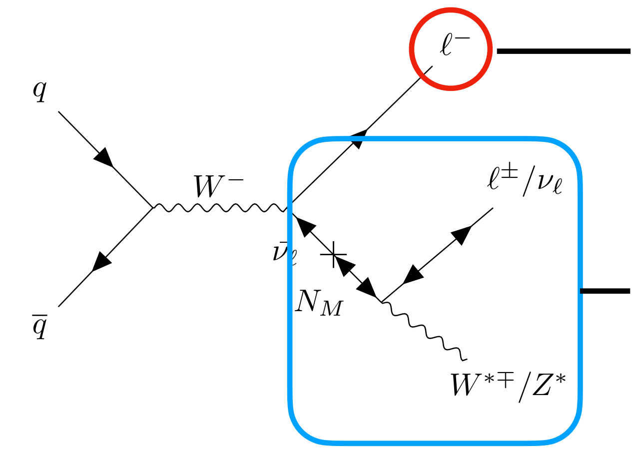



Prompt lepton

Displaced $N \to \ell qq$

**EXO-21-011, EXO-21-013**

**Novel displaced signature - Muon Detector Shower**

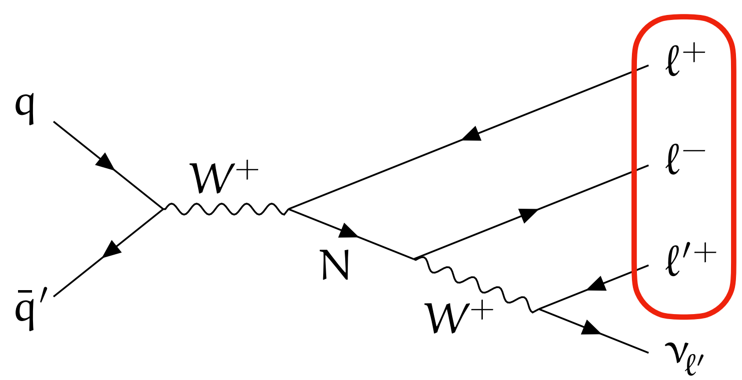



Prompt lepton

Displaced $N$ inclusive decay

**EXO-22-017**

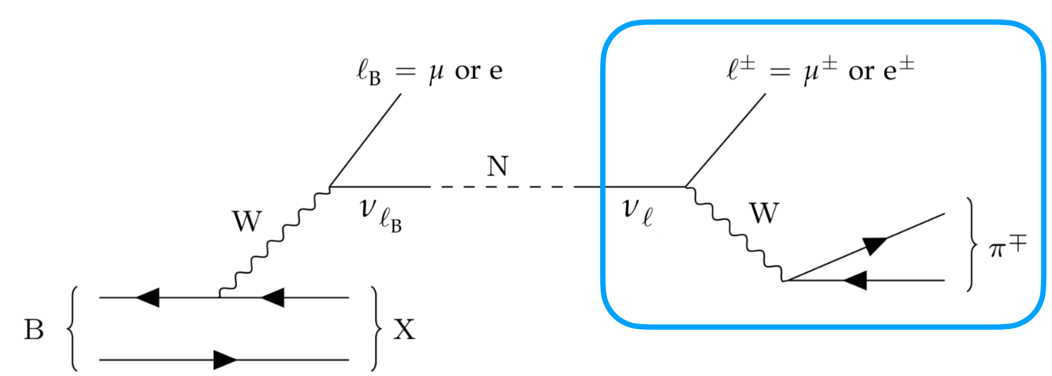
**Prompt 3$\ell = (e, \mu, \tau)$**




Prompt leptons from PV

**EXO-22-011**

**Novel data stream - HNL with B-parking dataset**



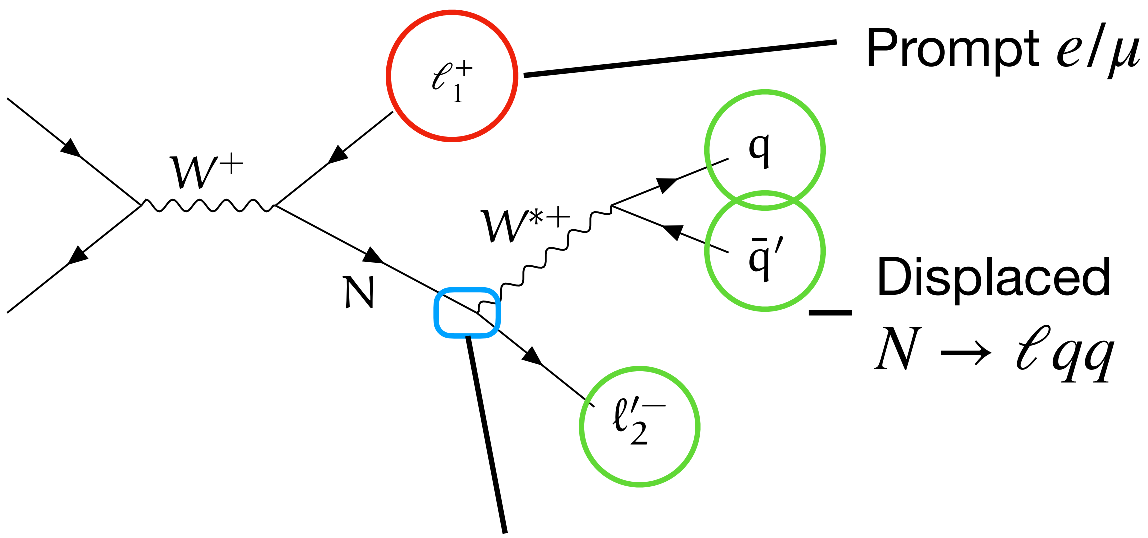

$N \to l\pi$

**EXO-22-019**

# Displaced object with ML technique

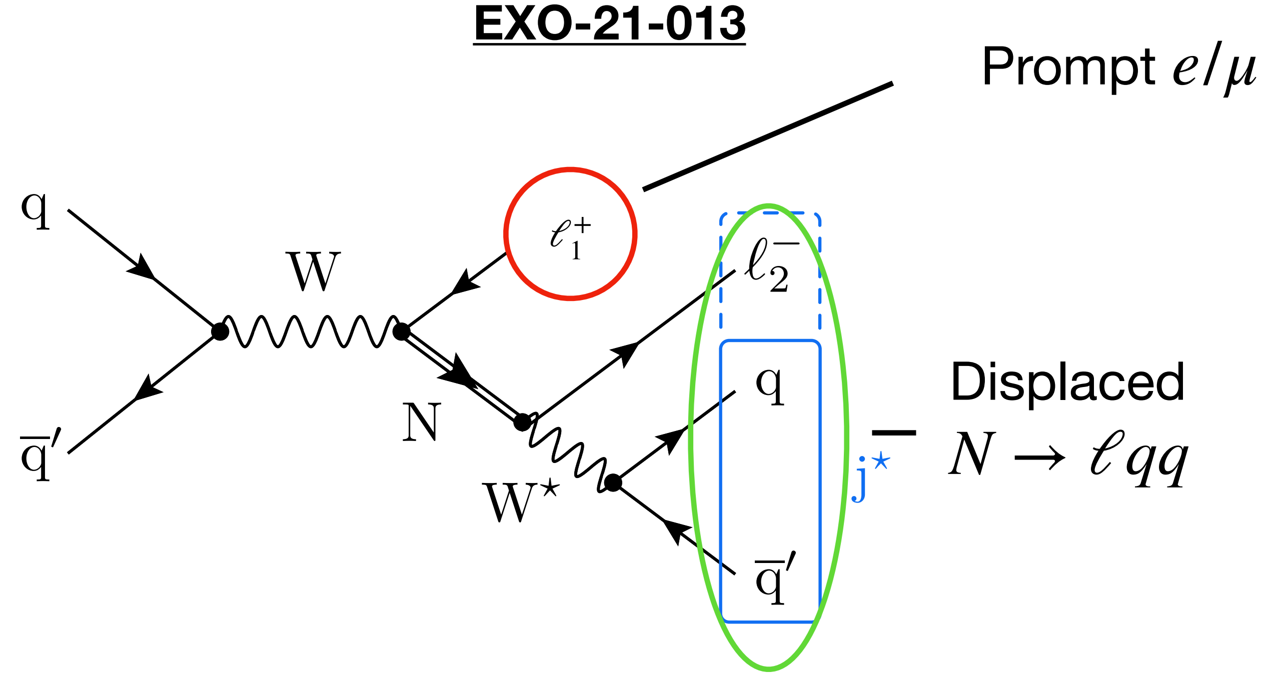
- Two different ML approaches to reconstruct displaced, semi-leptonic HNL decays

EXO-21-011




Explicitly reconstruct a Secondary Vertex(SV)

EXO-21-013




Boosted (lepton)-jet

**Particle Flow Net (PFN):**

- A **deep set NN** built around the *displaced objects* associated with the SV
- Separate trainings for high/low $m_N$ and $l_2 = e$ or $\mu$

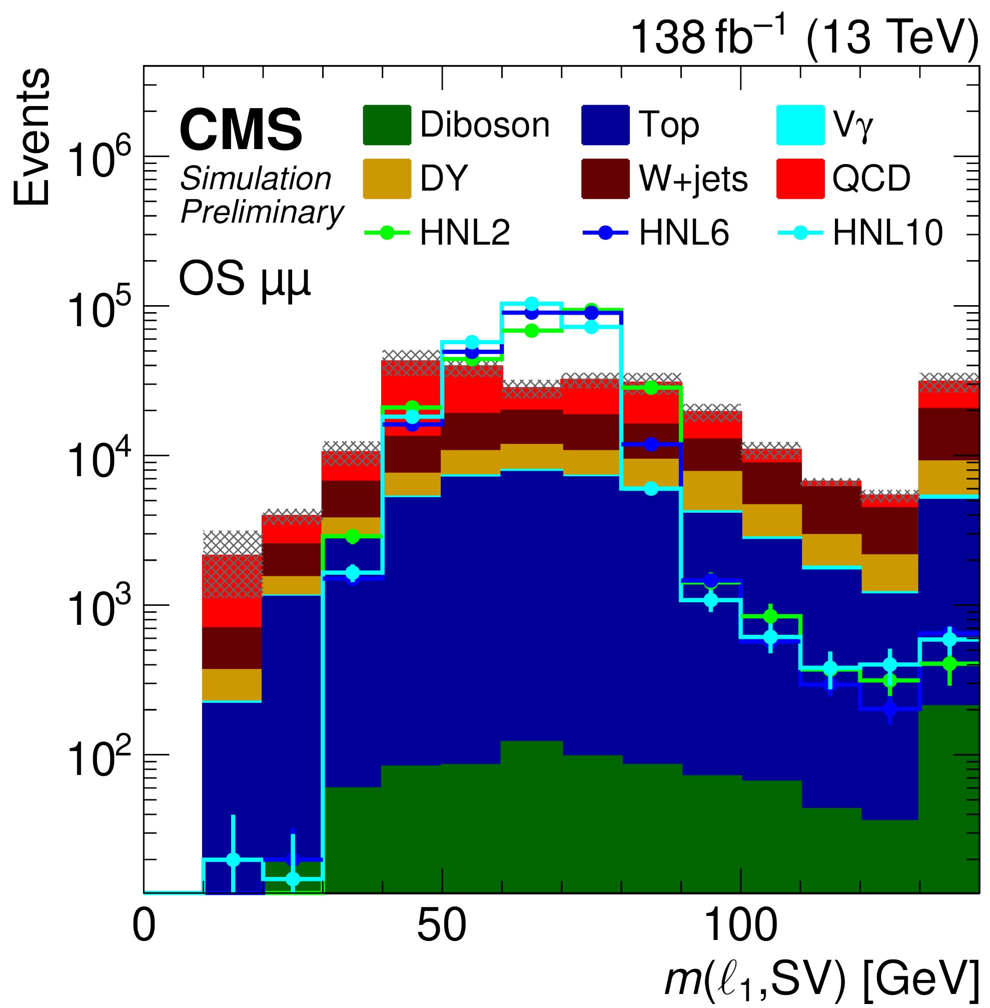
**Displaced (lepton) Jet tagger:**

- A DNN trained with displaced jet constituents features
- Parametrized for with HNL displacement
- Cover broad range of similar signatures (e.g. resolved & boosted)
- No explicit SV requirements

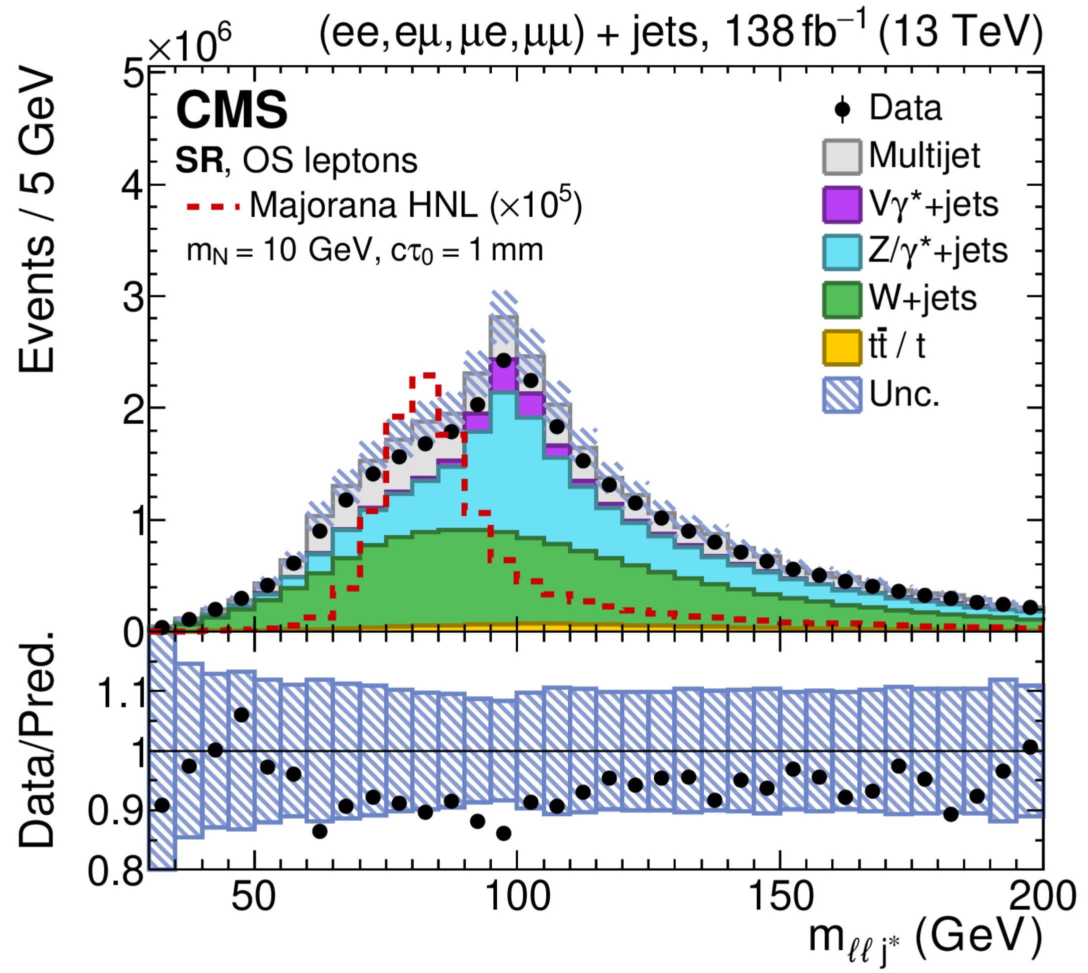
# Displaced object with ML technique

- Able to reconstruct a broad W-mass peak after network cuts

**Particle Flow Net**




**Displaced (lepton) Jet tagger**

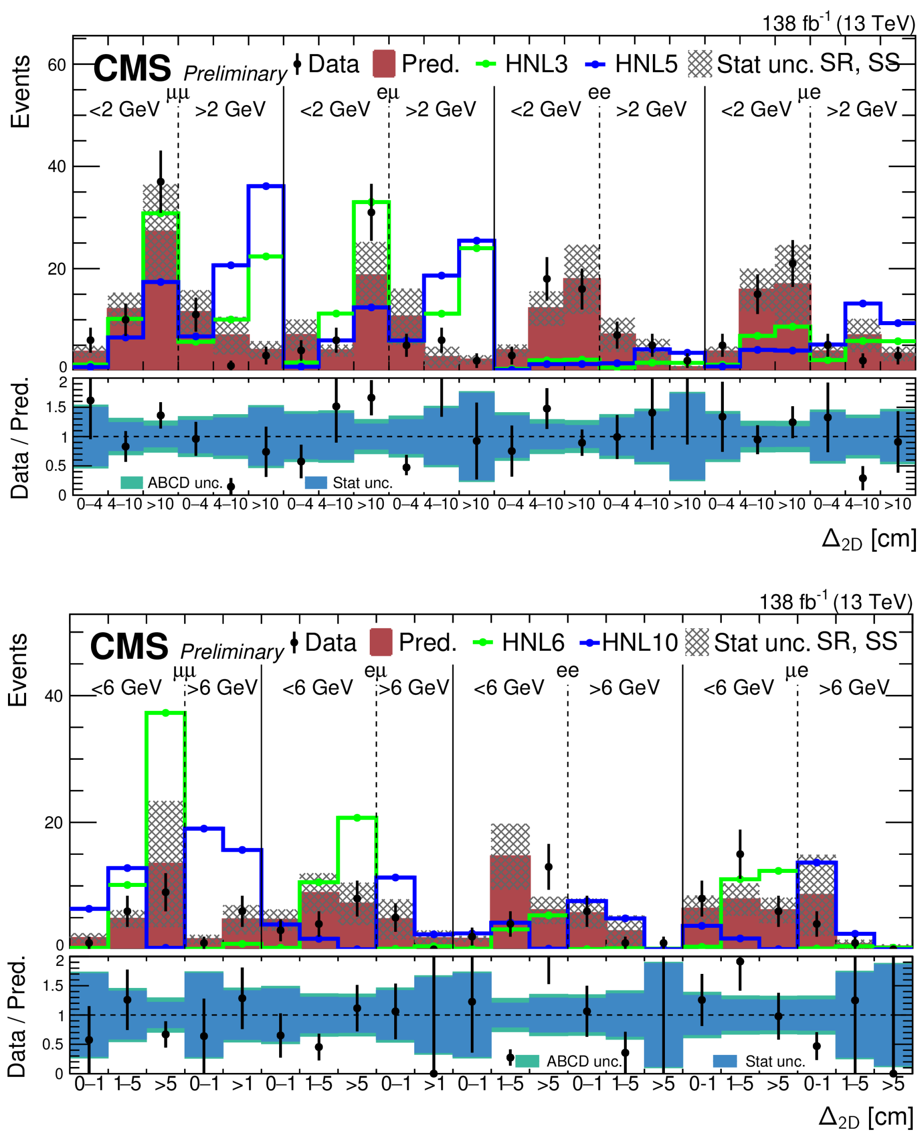


# Displaced object with ML technique

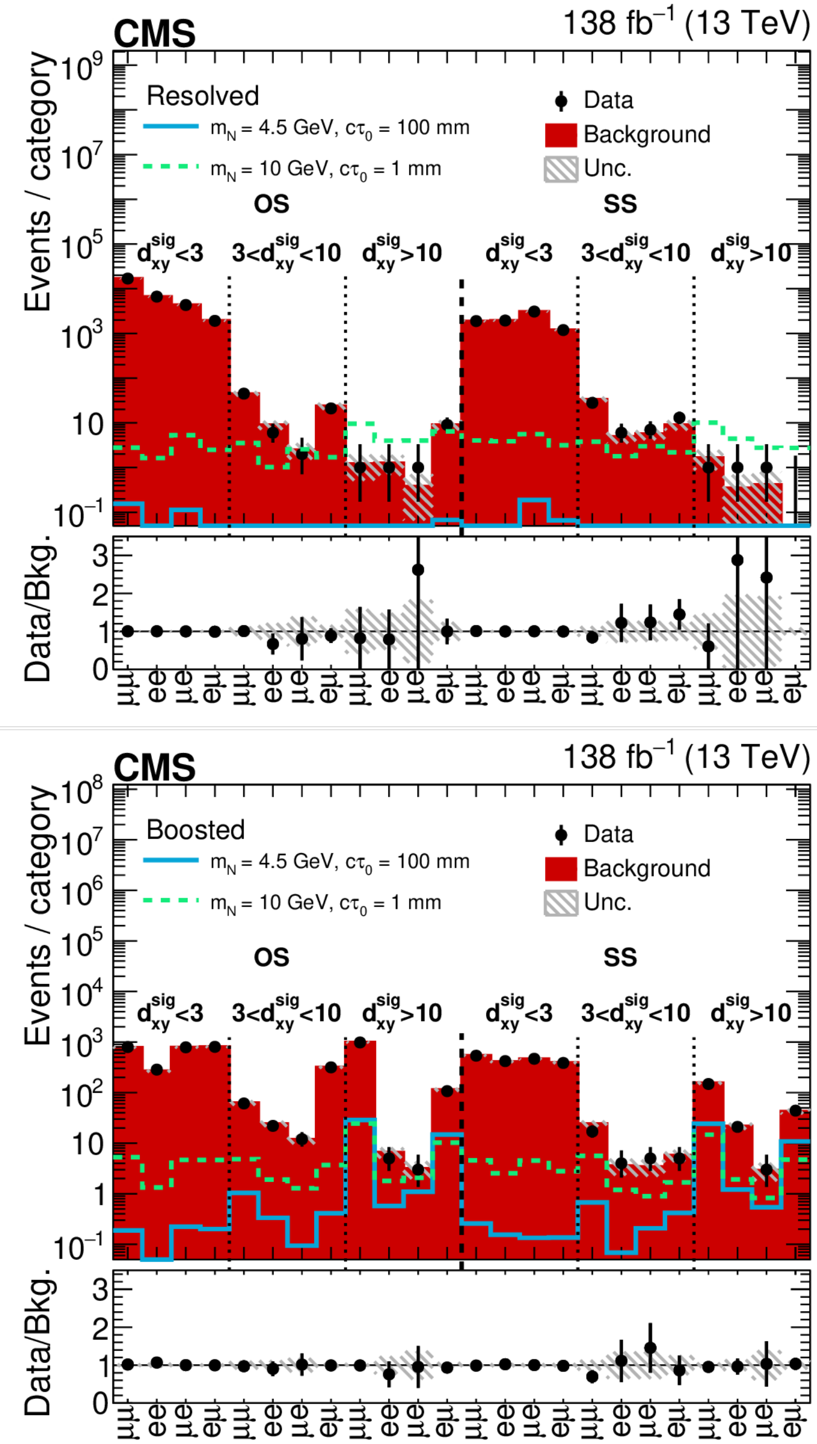
**EXO-21-011, EXO-21-013**

- Events categorized based on
  - $\ell_1, \ell_2$ flavors / $\ell_1, \ell_2$ charges / HNL candidate displacement
  - High/Low mass training (PFN) / Boosted/resolve (DNN)
- Event counting over each categories

## Particle Flow Net




## Displaced (lepton) Jet tagger



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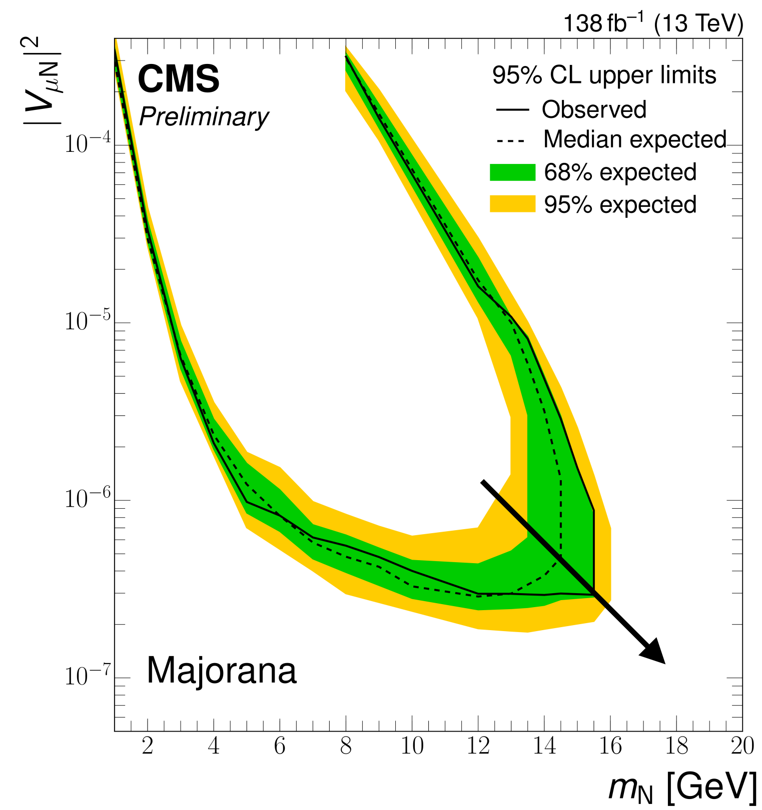
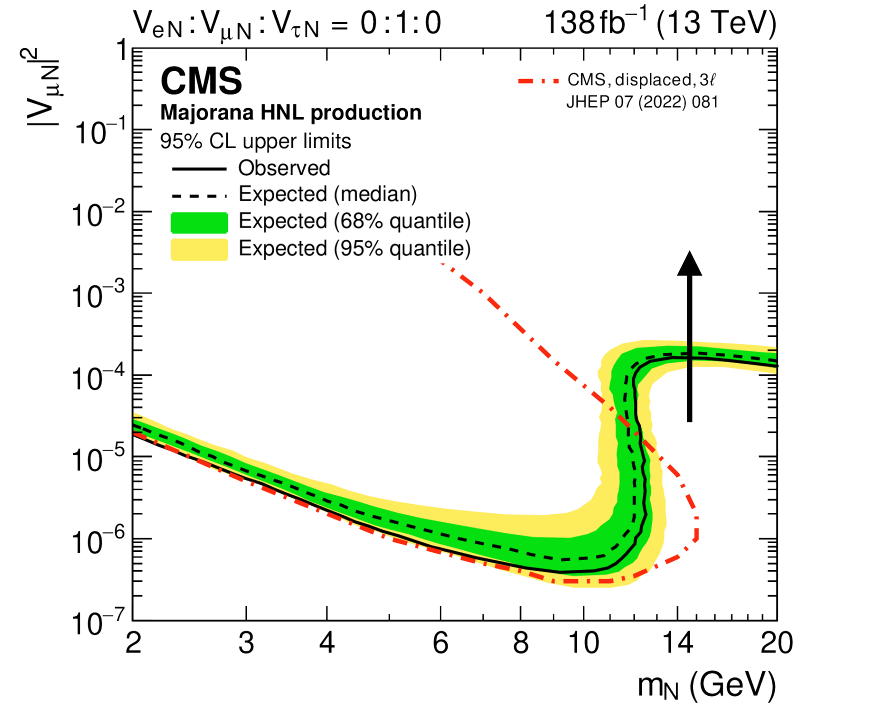
EXO-21-011, EXO-21-013

# Displaced object with ML technique

## Particle Flow Net




## Displaced (lepton) Jet tagger

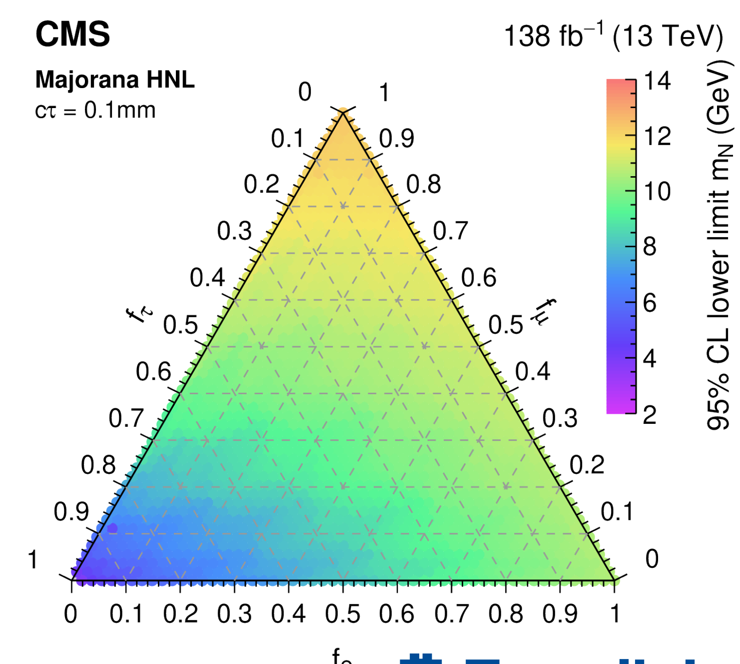



### Complementary coverage

- PFN analysis has better sensitivity at >10 GeV for HNL with longer lifetime
- DNN analysis able to cover shorter lifetimes even at higher mass (No SV cut)

### Sensitivity to $\tau$-HNL

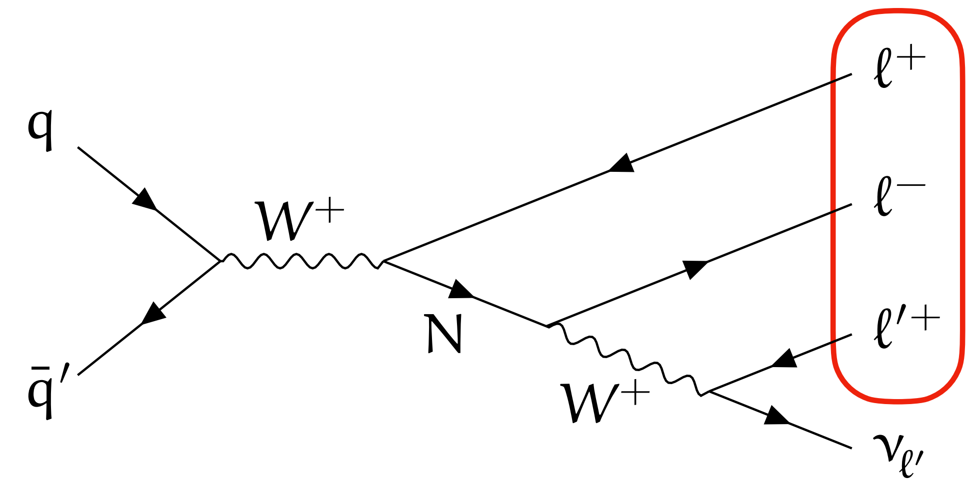
- For DNN, $\ell_2$ can be from leptonic decay of $\tau \to \mu/e + \nu$
- First HNL search at LHC targeting long-lived and hadronically decaying HNLs in the 2–20 GeV mass, with inclusive coupling to all three lepton generations



# Prompt $3\ell = (e, \mu, \tau)$

EXO-22-011

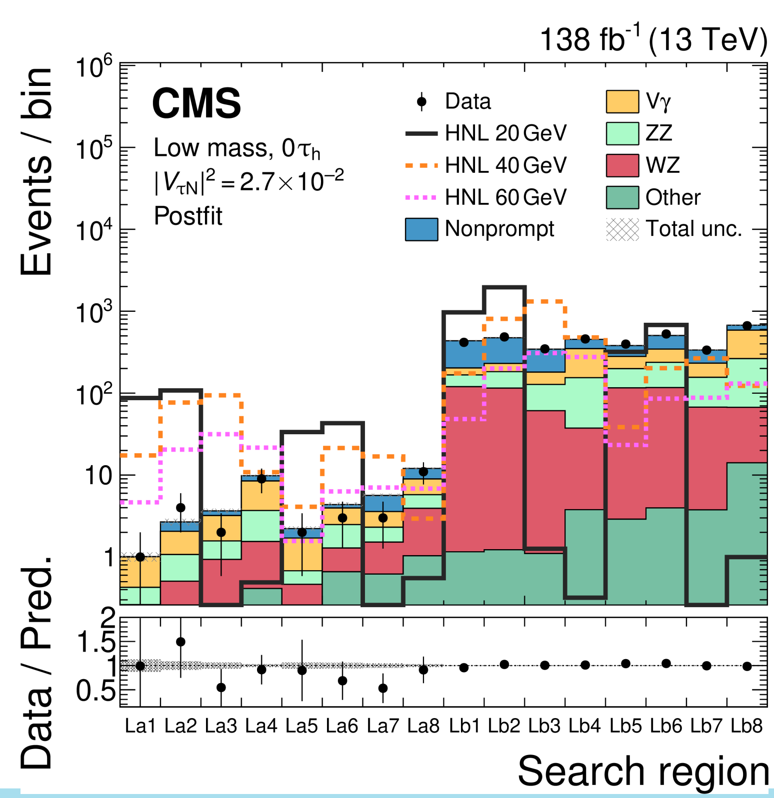
- Around 10-20 GeV, HNL decay signature are reconstructed as prompt objects
- Extending the previous CMS result with
  - **Full Run 2 luminosity**
  - **Hadronic $\tau$-lepton**
    (Reconstructed using DeepTau)
- Construct kinematic variables from the well-measured leptons
  - Carefully optimized for 25+ categories!



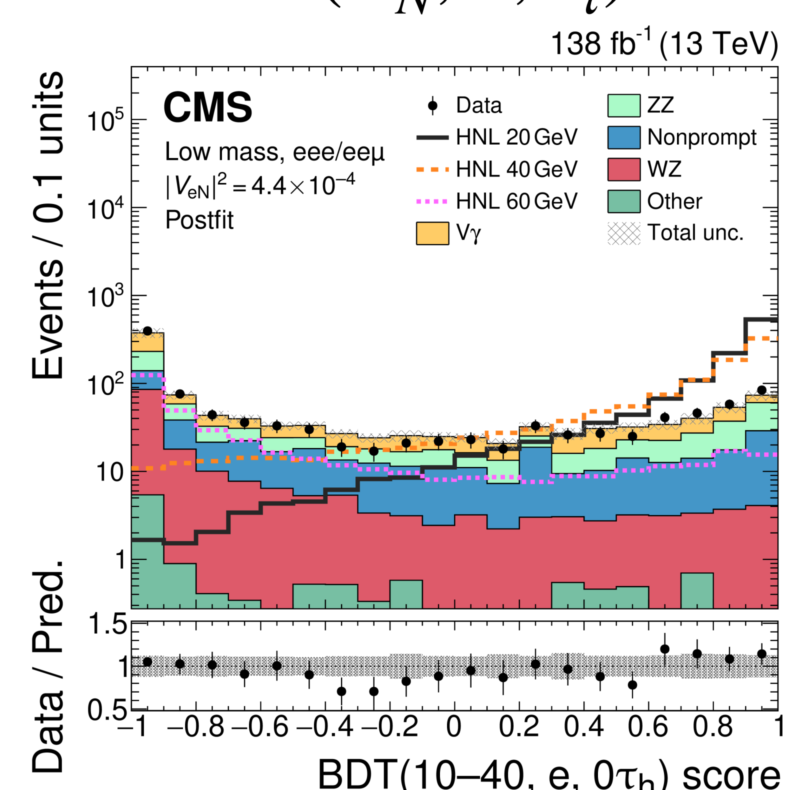

**Input**

**OSSF pair,**
$p_T(\ell_1)$**,**
$m(3\ell)$**,**
$\min\ m(\ell^+\ell^-)$
$m_T$

**Cut-based**



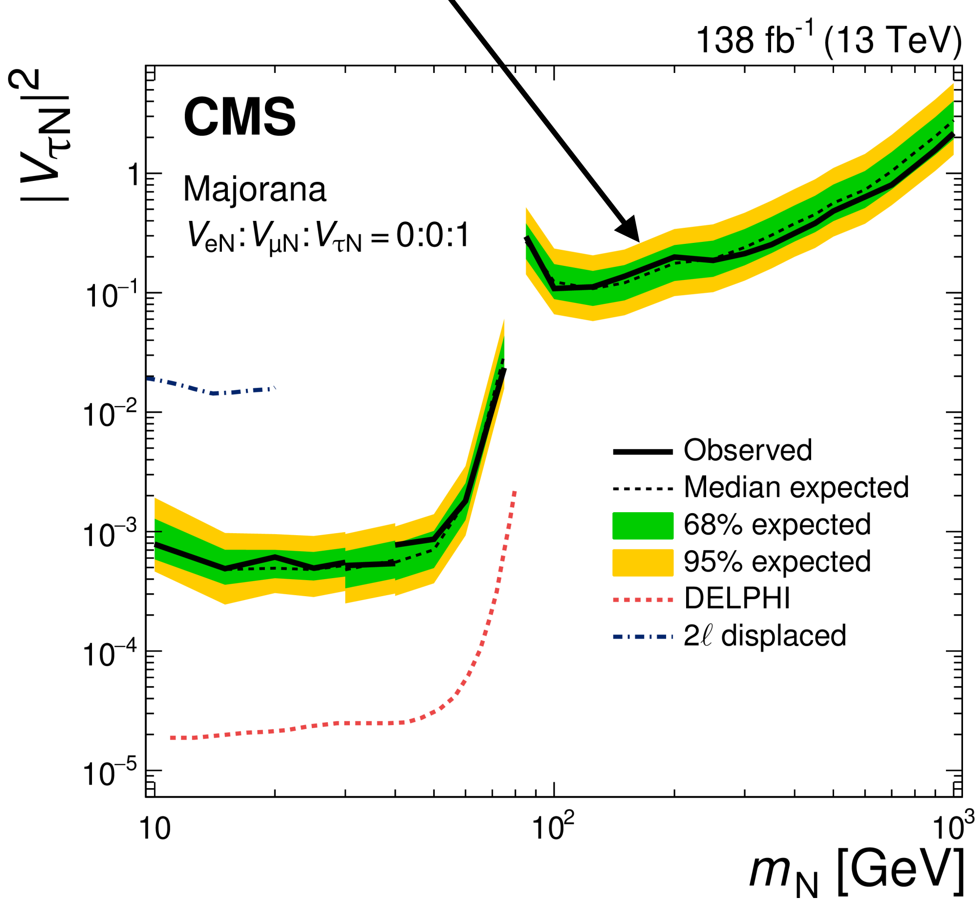

**BDT**$(m_N, \ell, n_\tau)$

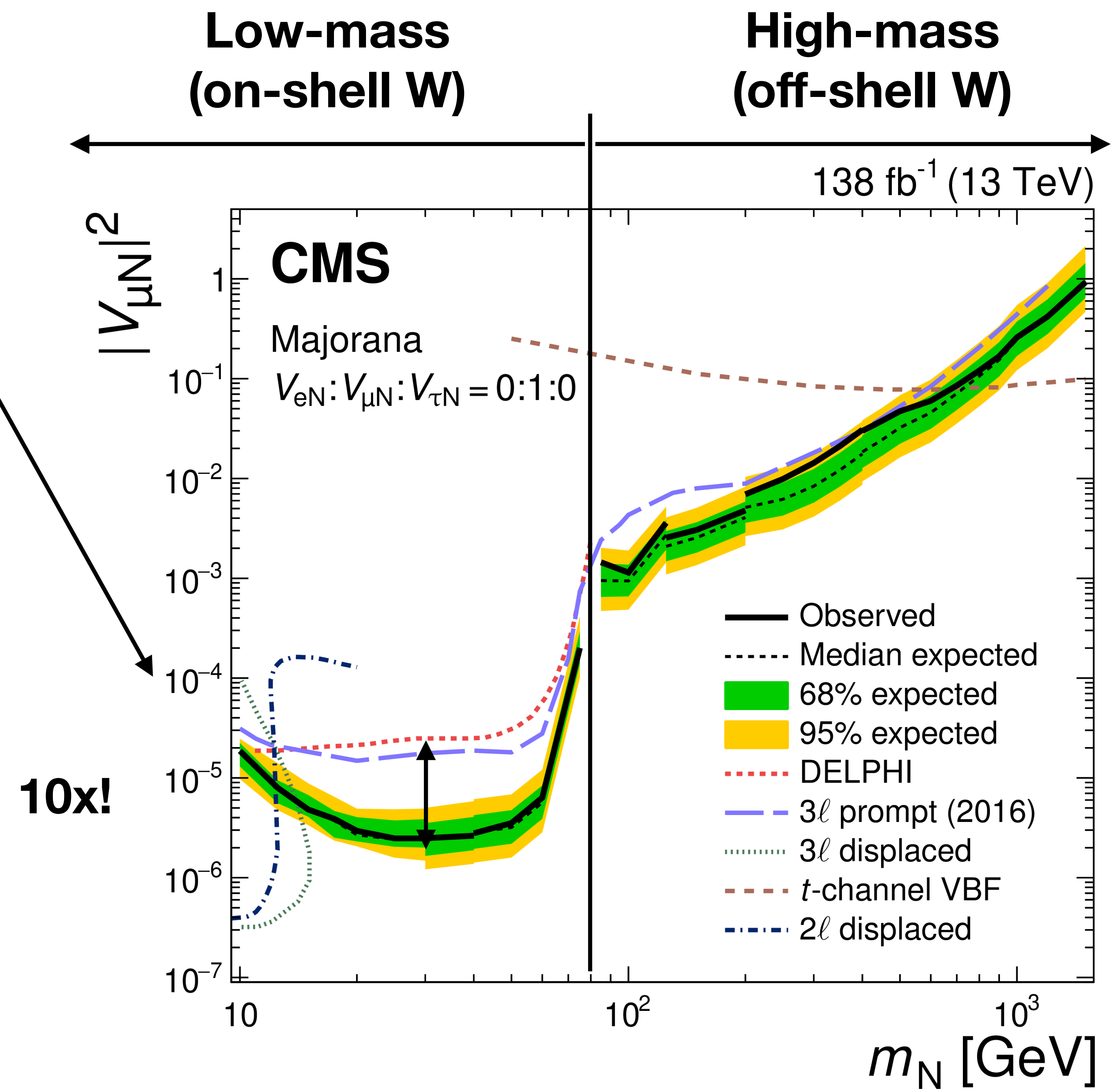


# Prompt $3\ell = (e, \mu, \tau)$

**EXO-22-011**

- Kinematics varies across 3 orders of magnitude of $m_N$ mass
- ~10x improvement for $|V_{\mu N}|^2$!
- **First $|V_{\tau N}|^2$ limit above $m_W$!**

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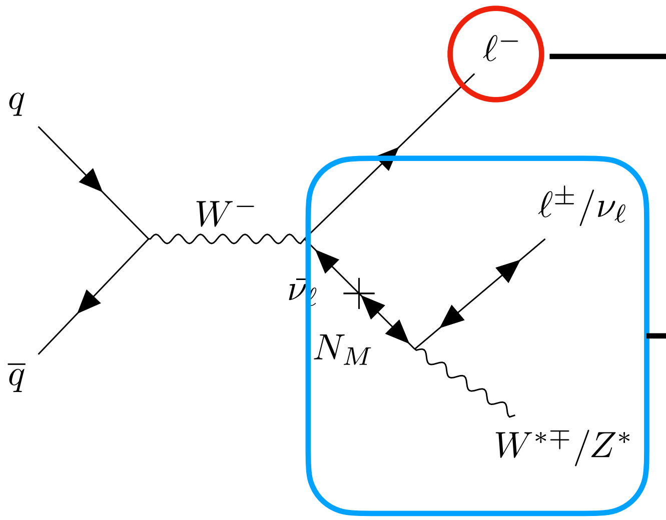
# Muon Detector Shower (MDS)

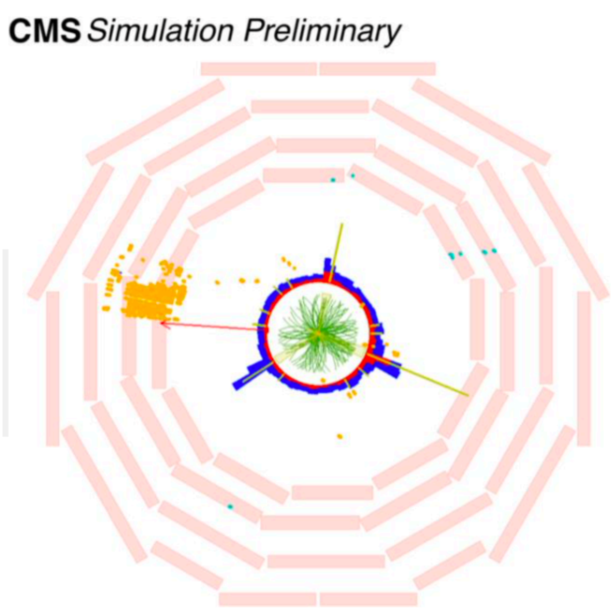
- Steel between muon stations in CMS can act as absorbers in a sampling calorimeter
  - Shielding of 12-27 interaction length → $\sim 10^7$ background rejection
- Sensitive to (quarks, electrons, photons, taus) except muons!
  - Inclusive decay modes of the HNL → 25-30% signal efficiency
- Powerful generic LLP signature

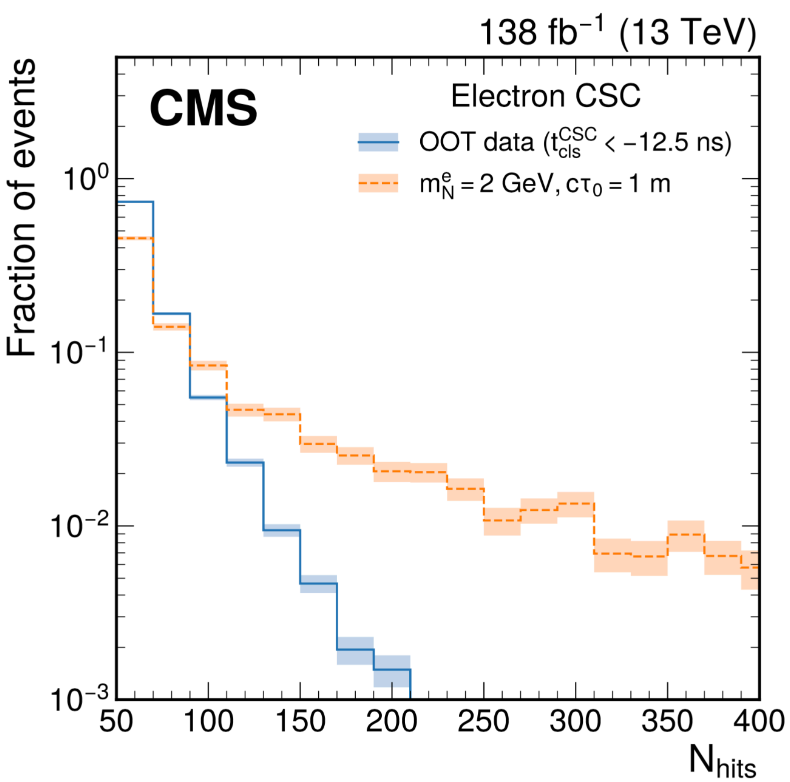
- Categorize events based on the triggering lepton flavor ($e/\mu$) and shower location (CSC or DT)


Prompt lepton

Displaced $N$ inclusive decay, reconstructed as clusters of hits in Muon system

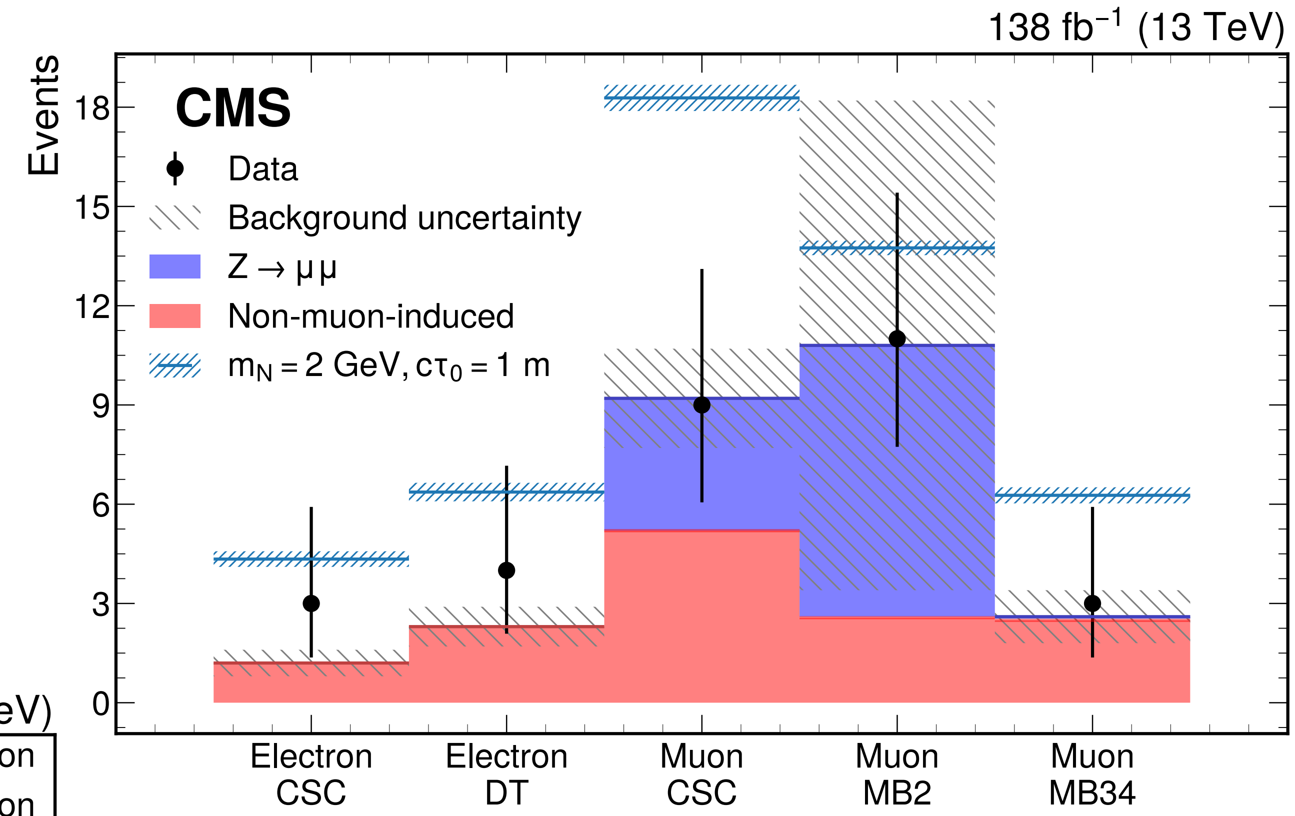


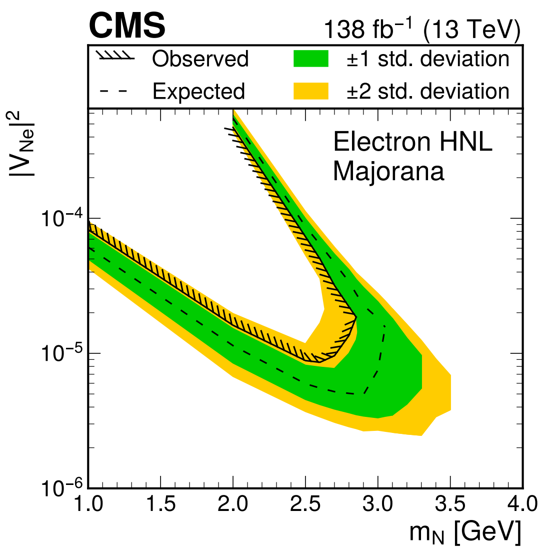



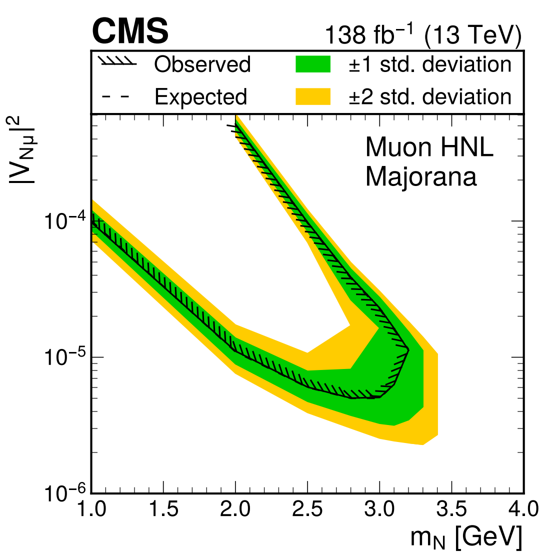
# Muon Detector Shower (MDS)

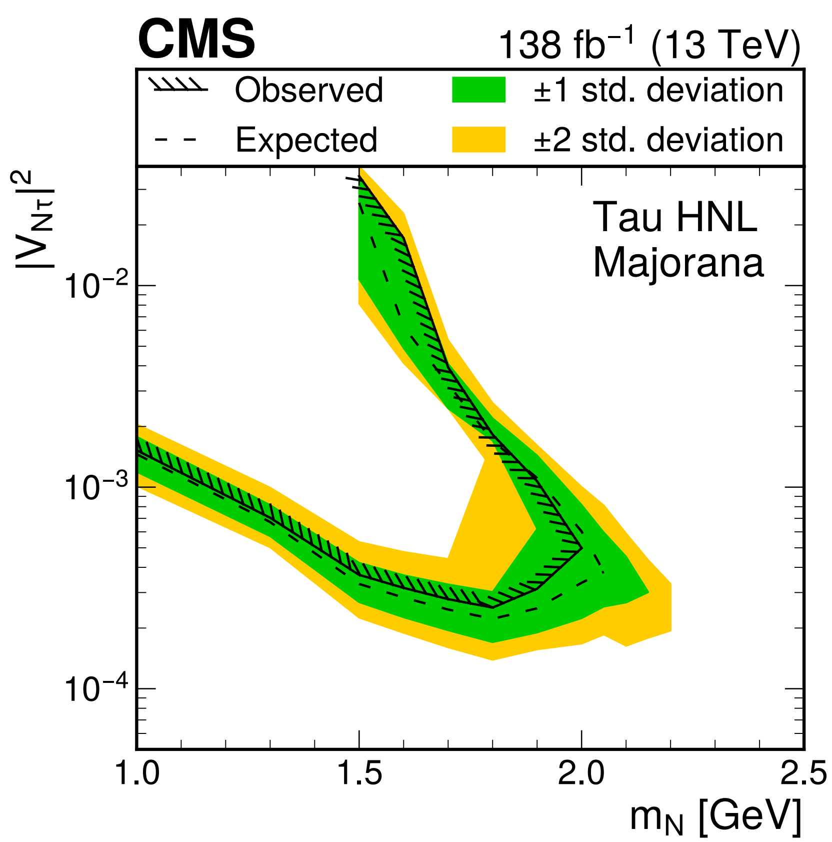
**EXO-22-017**

- Backgrounds events can come from…
  - W + soft hadrons (ABCD method)
  - $Z \rightarrow \mu\mu$ (Z-enriched CR + transfer factor)



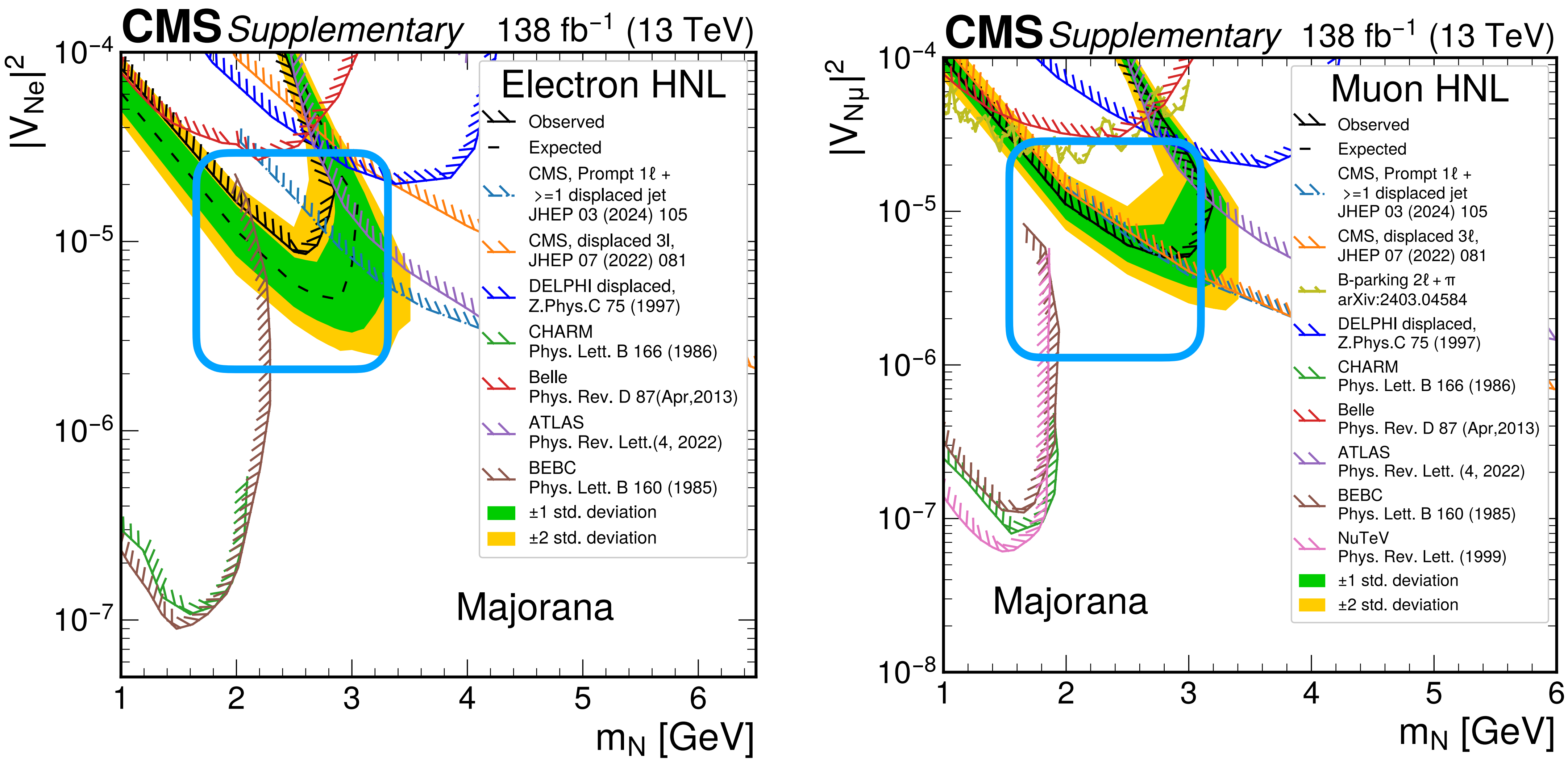




- MDS has good signal efficiency for all 3 flavors for different mass/lifetime
- Similar shape of limits in $|V_{eN}|^2, |V_{\mu N}|^2, |V_{\tau N}|^2$

# Muon Detector Shower (MDS)

**EXO-22-017**

- MDS being 4 -12 m from PV favors probing low mass/long lifetime HNL
- Most stringent limits in $|V_{eN}|^2$ in 2.1 - 3.0 GeV
- Most stringent limits in $|V_{\mu N}|^2$ in 1.9 - 3.3 GeV



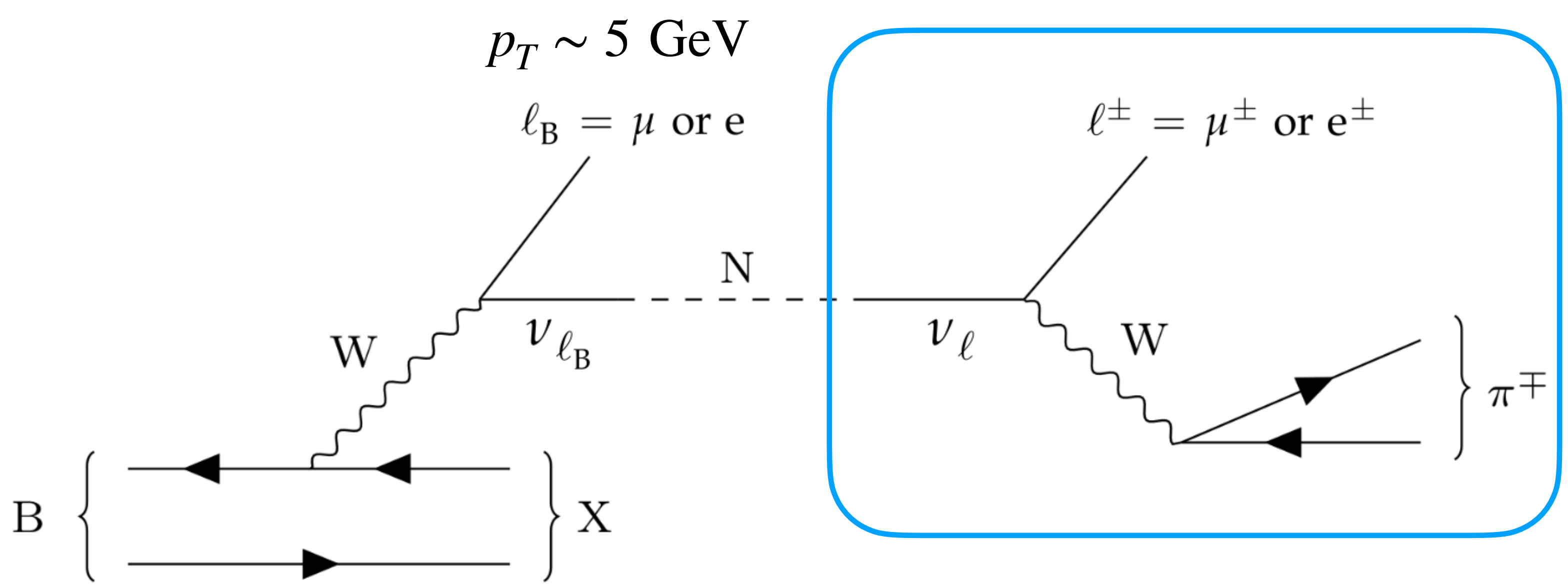
# HNL in B-parking dataset

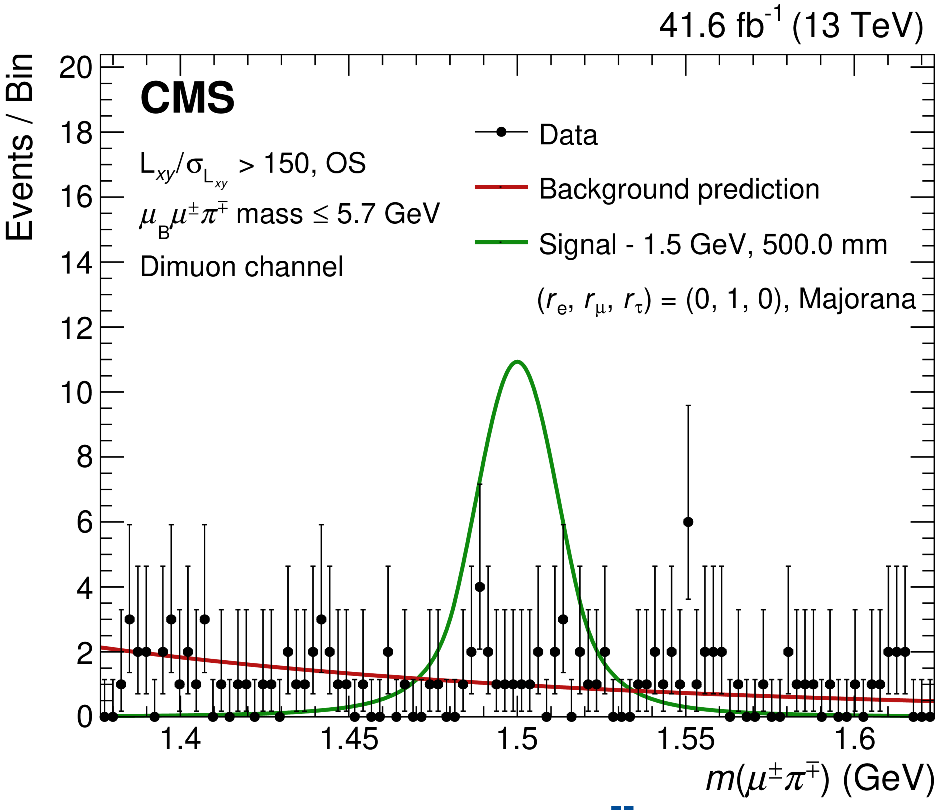
**EXO-22-019**

- B-meson cross section is ~O(10,000) than $W$ cross section at LHC
  - Search for HNL in the semi-leptonic B-decays!
- The soft pT spectrum (~ 5GeV) makes it difficult to trigger for normal CMS data stream
- 2018 B-parking dataset solved the trigger problem
  - O($10^{10}$) $b\bar{b}$ decay recorded!

- 1) Trigger with either muon from $B$-meson or N ,
  2) Parametric Neural Network(PNN) to reconstruct displaced N with different $m_N$
  3) Bump hunt with $m(\ell, \pi)$

Displaced $N \to l + \pi$

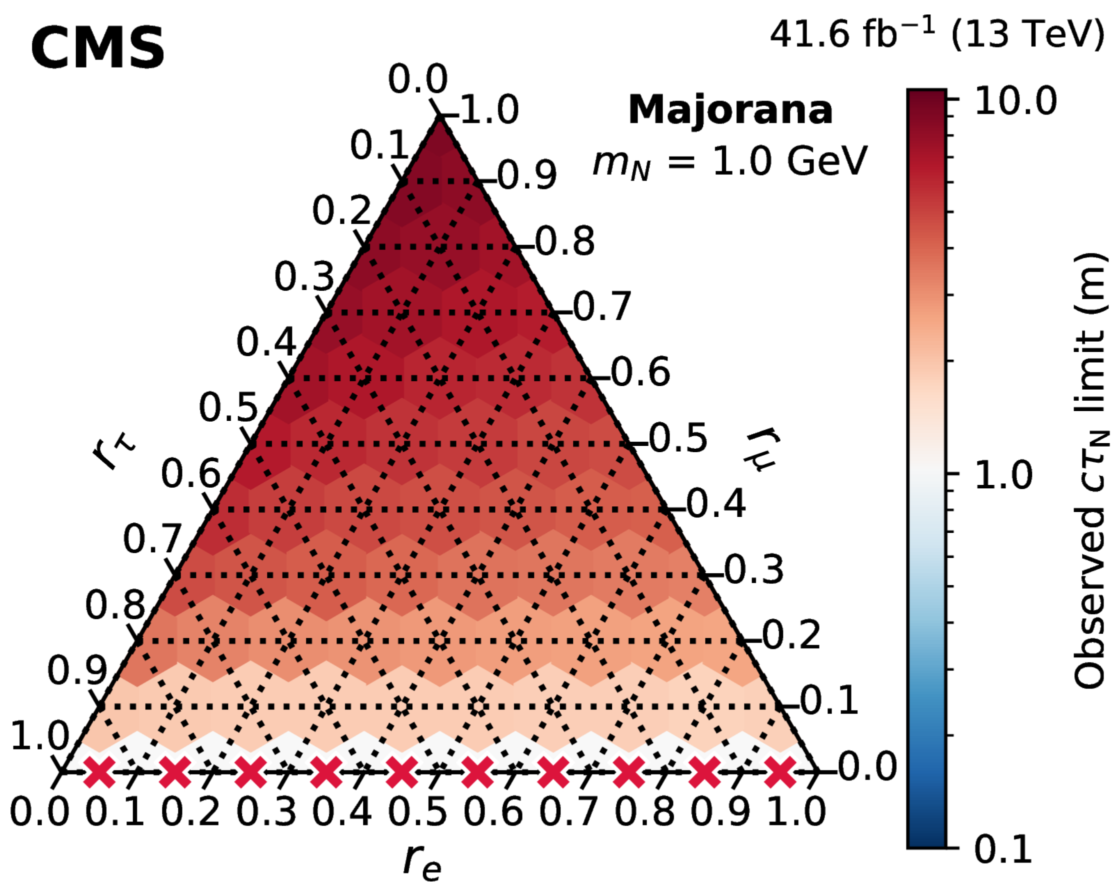


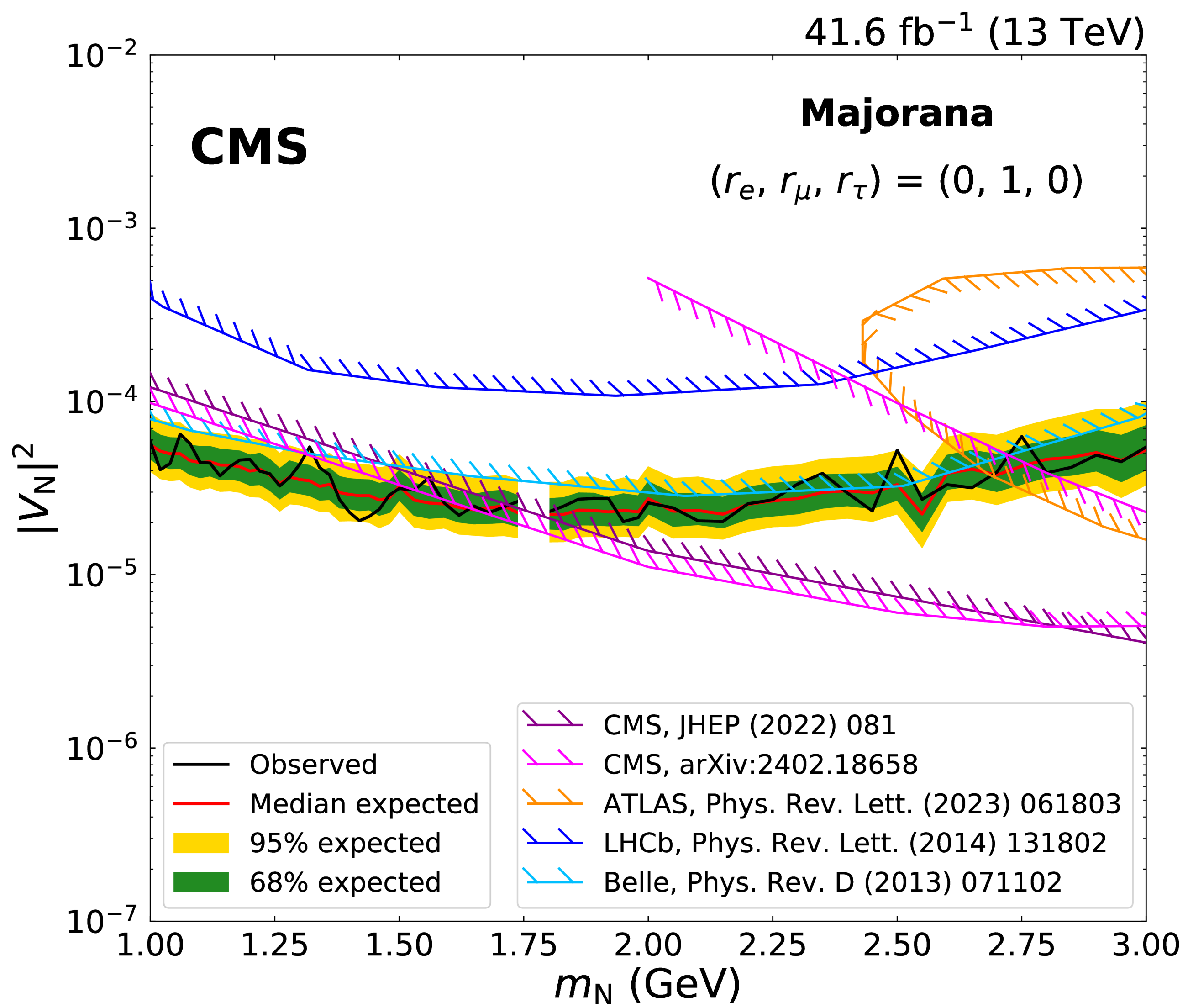



# HNL in B-parking dataset

**EXO-22-019**

- Set 2x better limit than Belle, 10x better limit than LHCb
  2x better than previous CMS limit
- Most stringent limits in 1-1.7 GeV at a collider experiment
- Interpreted for different relative mixing $\tau_\ell$ scenarios





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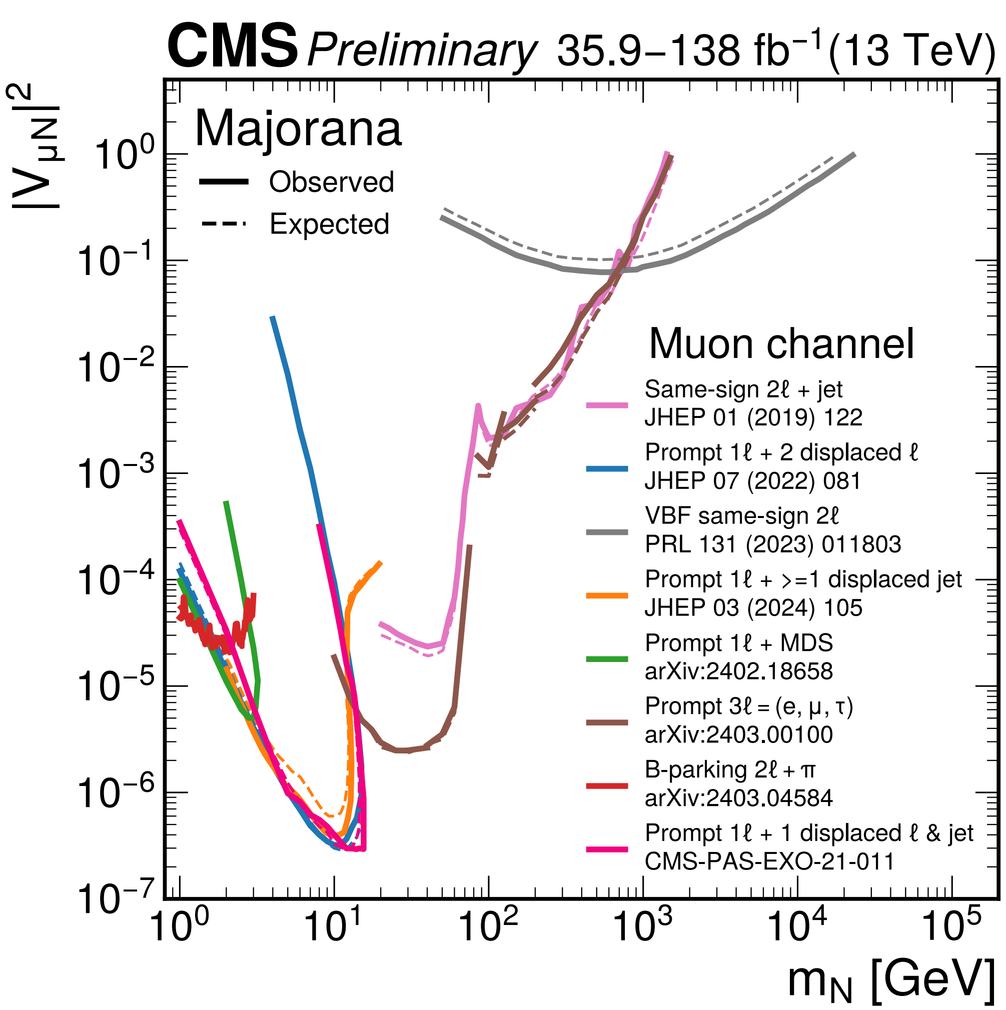
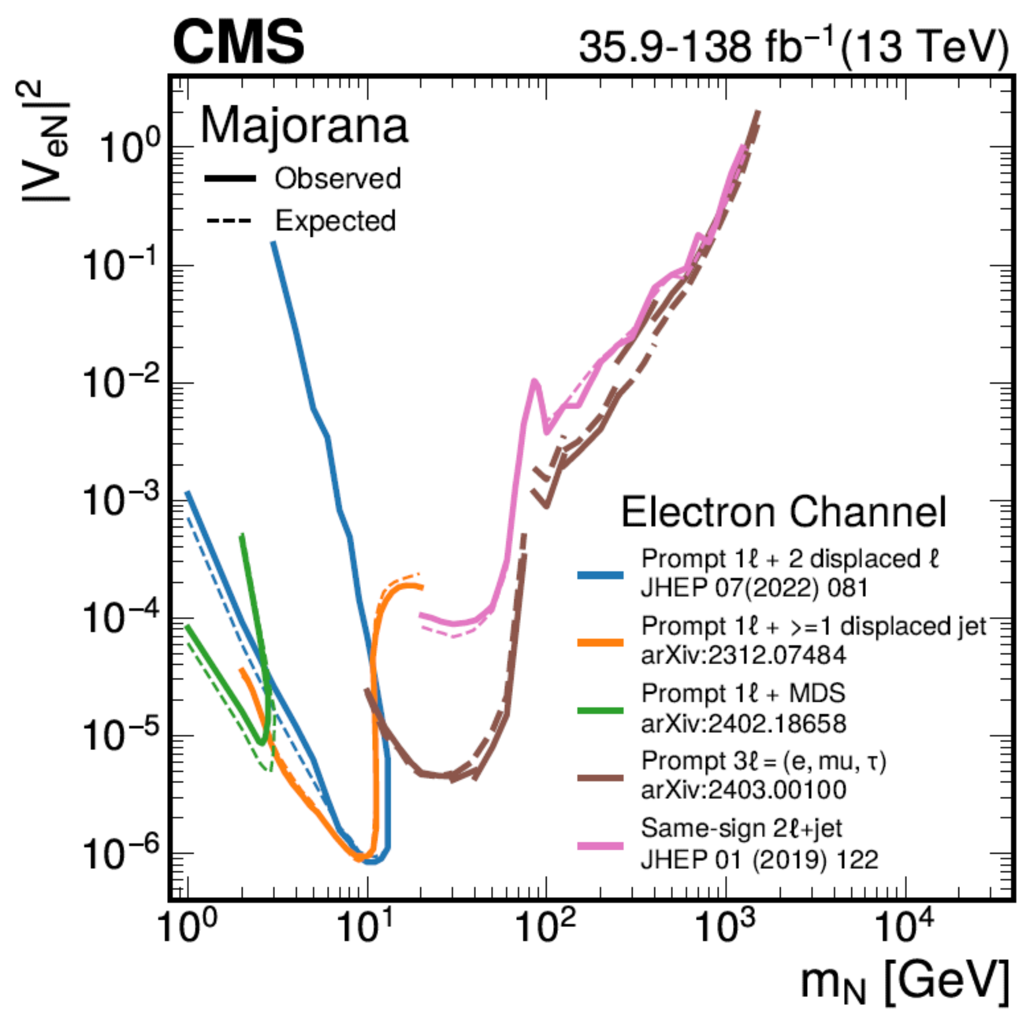
# Summary

- CMS is **actively** exploring new parameter space with novel techniques!
  - low-mass, long-lived, final states involving a $\tau$-lepton
- New ideas can bring substantial improvements

- Too much information?
  Summarized in the review of CMS HNL searches

**EXO-23-006**



# Thank you!