HNLs at CMS

Leonardo Lunerti[†]

on behalf of the CMS Collaboration

[†] INFN Bologna

LHCP2024

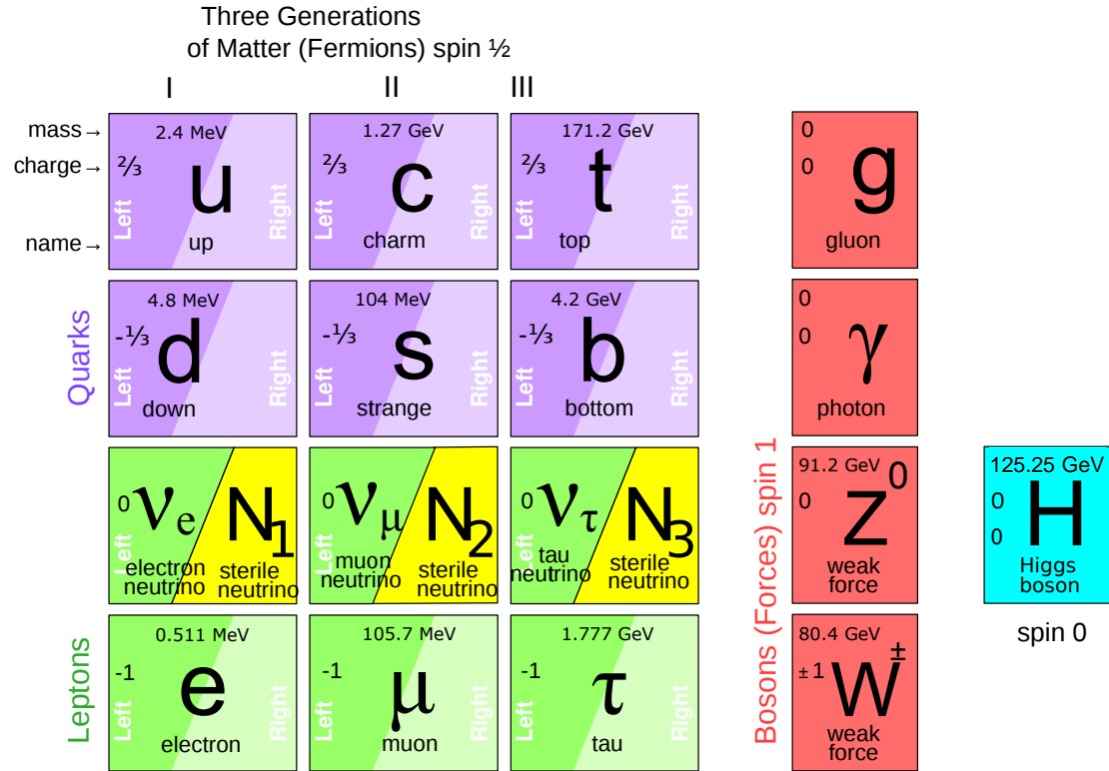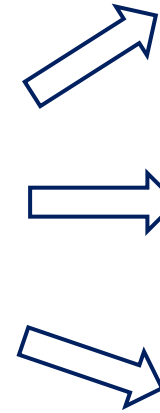Three Generations of Matter (Fermions) spin ½
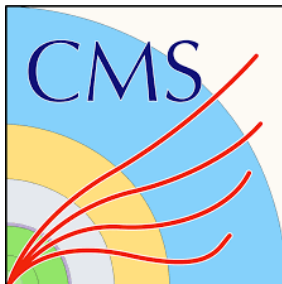
Figure from *Search for GeV-scale sterile neutrinos responsible for active neutrino oscillations and baryon asymmetry of the Universe* arXiv:1301.5516v1

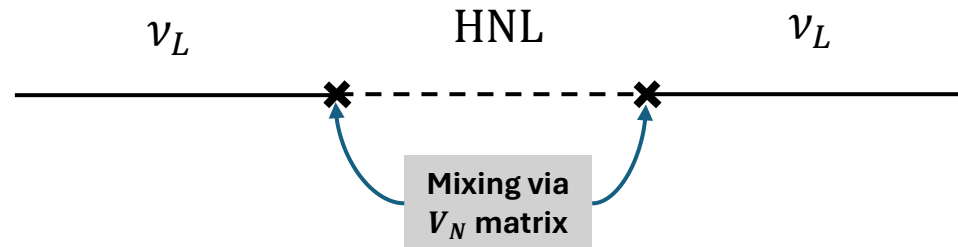A sterile right-handed neutrino or heavy neutral lepton (HNL) could

Provide a dark matter candidate

Be responsible for the baryon asymmetry

Explain the smallness of left-handed neutrino masses

HNLs are singlets under SM gauge group

ν_L HNL ν_L

Mixing via V_N matrix

HNLs can interact with SM via mixing with active left-handed neutrinos

- **HNL lifetime** depends on its mass and mixing matrix

$$\tau \sim \frac{1}{m_N^5 \, |V_{\ell N}|^2}$$

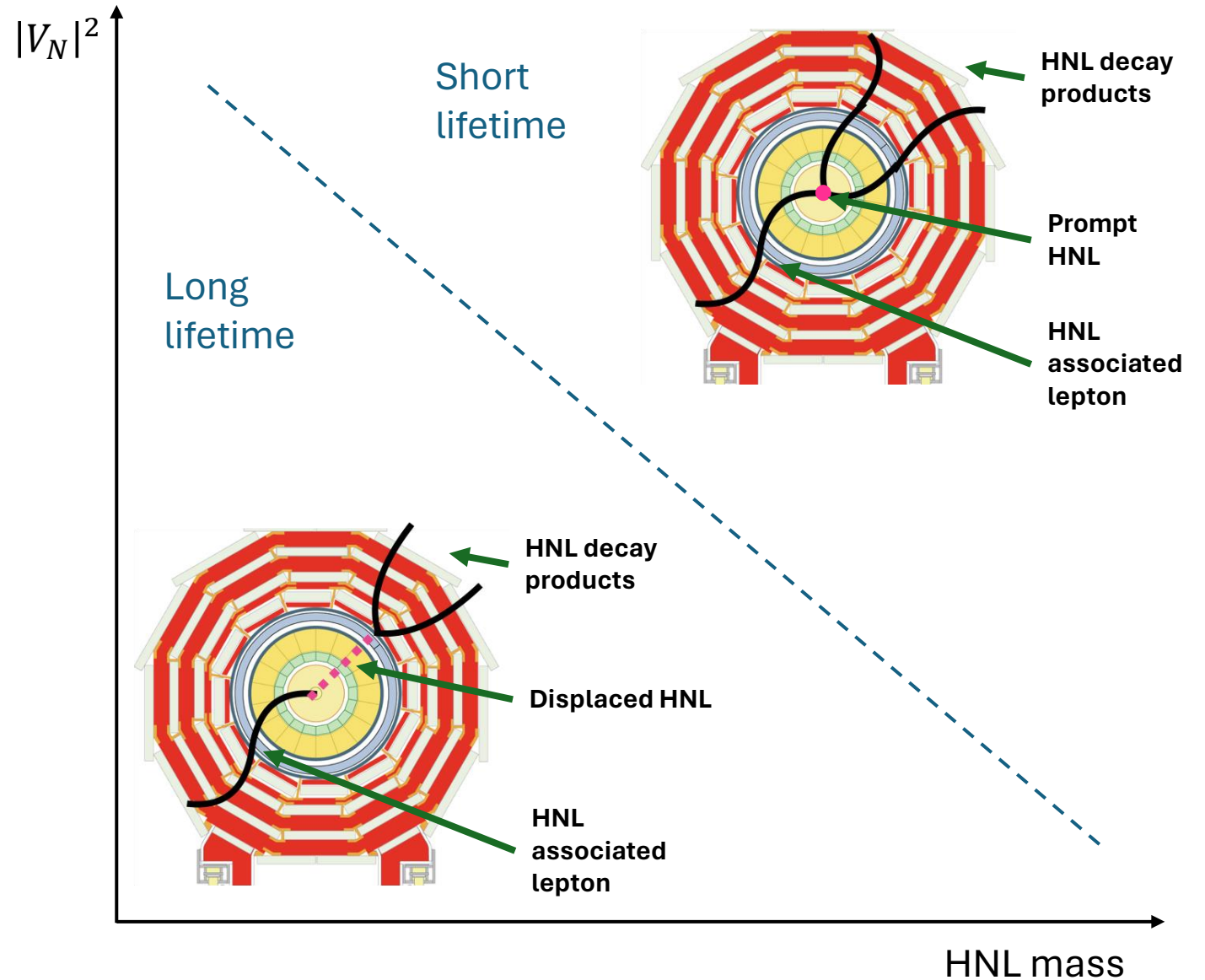- CMS can measure the active-sterile neutrino mixing for HNL masses from GeV to TeV scale

$$f_\ell = \frac{|V_{\ell N}|^2}{|V_{eN}|^2 + \left|V_{\mu N}\right|^2 + |V_{\tau N}|^2}$$

- **Exclusive** coupling scenario:

$$f_e : f_\mu : f_\tau = 1 : 0 : 0, \, 0 : 1 : 0, \, 0 : 0 : 1$$
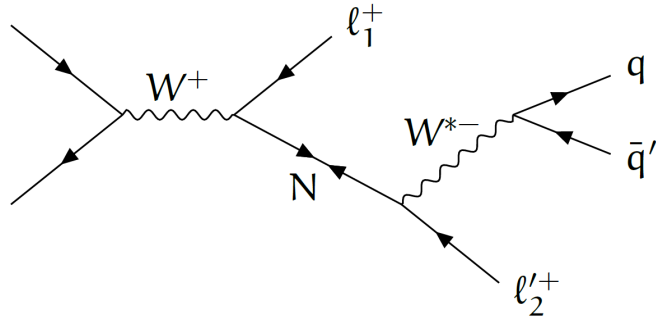
- **"Democratic"** mixing scenario:
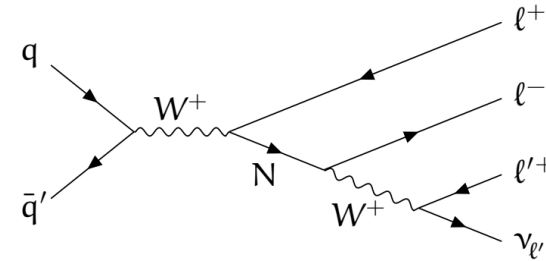
$$f_e : f_\mu : f_\tau = x_e : x_\mu : x_\tau$$

Prompt $1\ell + \geq 1$ displaced jet

- Prompt HNL production
- Displaced $N \to \ell qq'$ decay

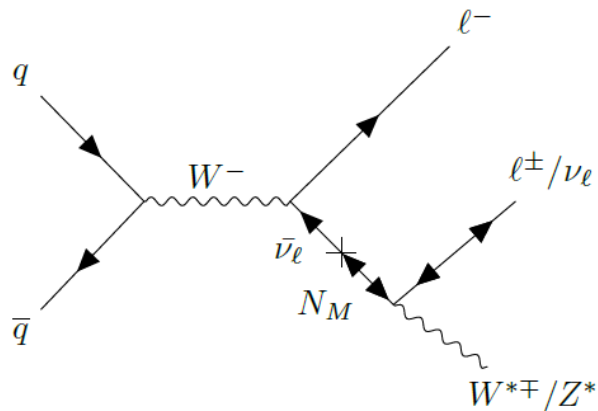**Prompt $3\ell = (e, \mu, \tau)$**

- Prompt HNL production
- Prompt $N \to \ell\ell\nu_\ell$ decay

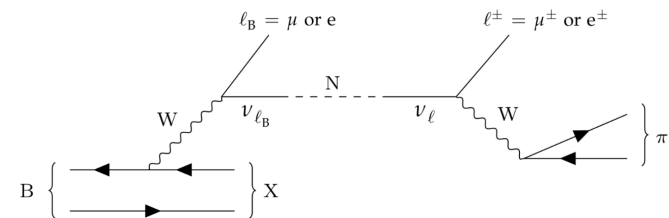**Prompt 1ℓ + MSD**
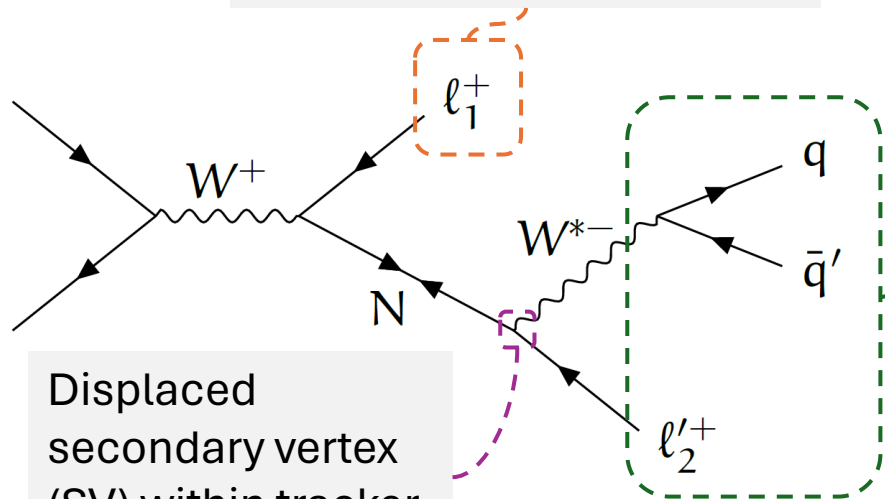
- Prompt HNL production
- HNL decay within muon system

Prompt $2\ell + \pi$

- HNL from B decays
- Displaced $N \to \ell\pi$ decay

4

Triggering prompt lepton

- Boosted HNL topology
- $q\bar{q}'$ merged into a single jet

Displaced secondary vertex (SV) within tracker volume (<1 m)

HNL+ ℓ_1 invariant mass

- Final state leptons: e, μ
- **Single HNL** scenario
- Probing **exclusive** $|V_e|^2$ and $|V_\mu|^2$ **couplings**
- Probing $|V_e V_\mu|^2 / (|V_e|^2 + |V_\mu|^2)$ **mixed coupling**

- Focused on **long HNL lifetimes** → sensitive to HNL masses down to few GeV
- **Multivariate classifier** dedicated to **displaced vertex identification** in low- and high-mass regions
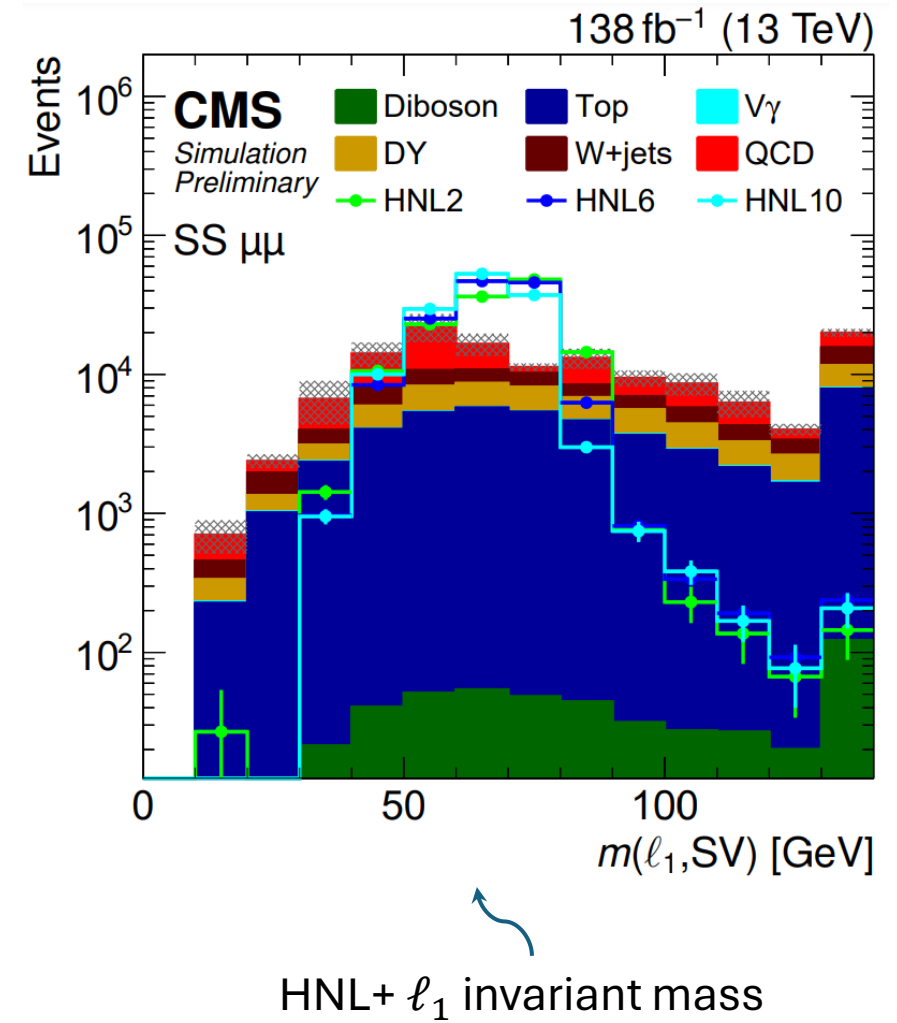
5

Low-mass HNL

High-mass HNL
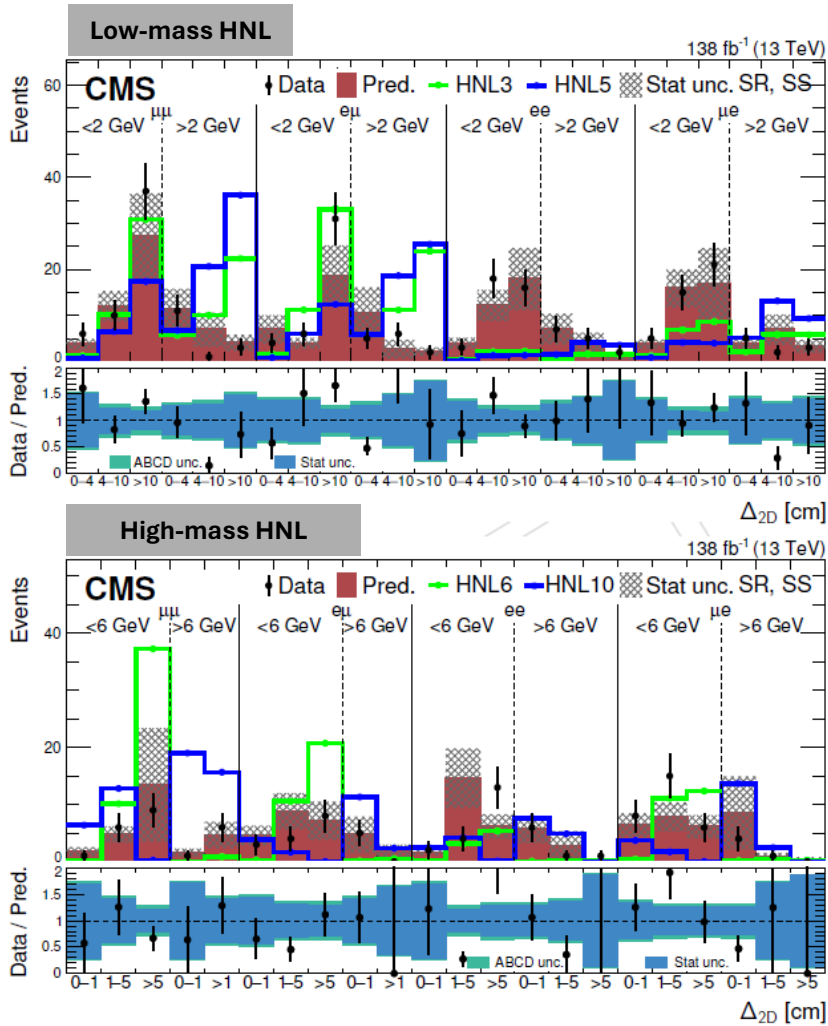
Event counting over each analysis category

- **Data-based background estimation**
- Events are categorized based on
  - $\ell_1\ell_2$ flavor
  - $\ell_1\ell_2$ relative sign
  - HNL decay vertex distance

- **Limits** on $|V_\mu|^2$ **extended** in 10-17 GeV region w.r.t. previous $N \to \ell qq'$ analysis (next slide)

- **Limits** on $|V_e|^2$ and $|V_\mu|^2$ in the 10-17 GeV **extended** by more than an order of magnitude w.r.t. previous CMS prompt lepton search (later in this talk)
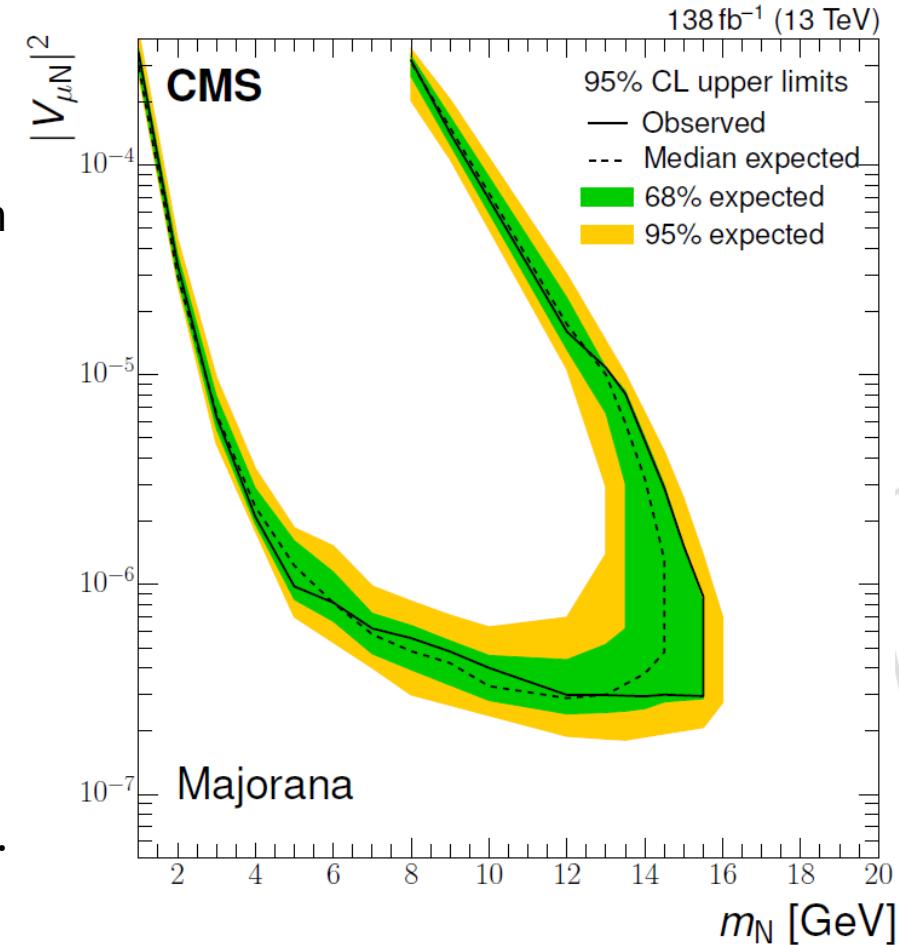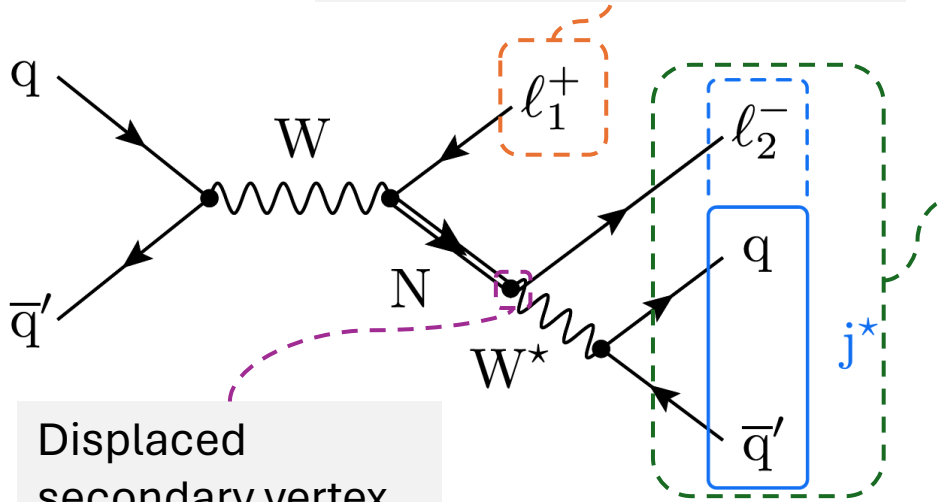
Triggering prompt lepton

- Boosted HNL topology
- $q\bar{q}'$ merged into a single jet

Displaced secondary vertex (SV) within tracker volume (<1 m)

ℓ_1 + HNL invariant mass distribution

- Final state leptons: e, μ, τ
- **Single HNL** scenario
- Probing **exclusive** and **democratic coupling** scenarios

- **Novel jet tagger technique**
  - identification of displaced jets using DNN that does not explicitly require the reconstruction of displaced vertices
  - **Good performances** for both **short-** and **long-lived HNL**

7

Results

- **Data-based background estimation**
- Events are categorized based on
  - $\ell_1 \ell_2$ flavor
  - $\ell_1 \ell_2$ relative sign
  - HNL decay vertex distance
  - "Boosted" or "resolved" DNN optimization region based on lepton-jet overlap

- **Best results** on $|V_\mu|^2$ limit thanks to excellent muon identification performances
- **Sensitivity comparable** with latest results from **CMS**, **ATLAS** and **LHCb** on orthogonal final states
- **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**
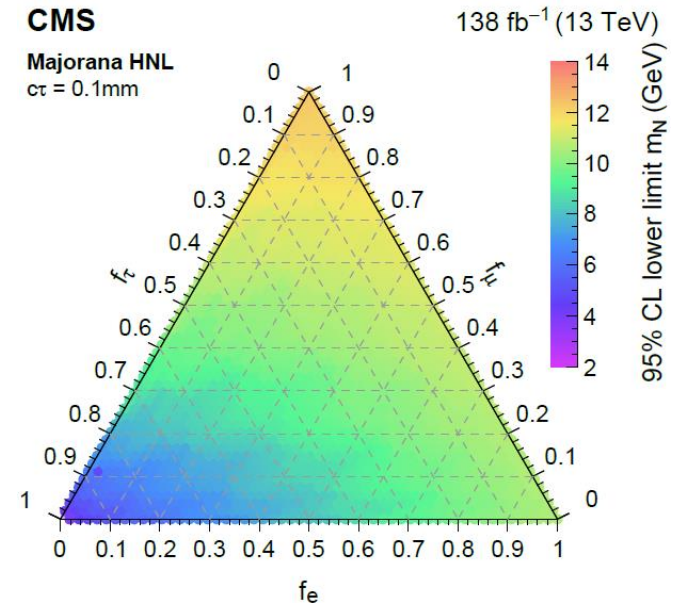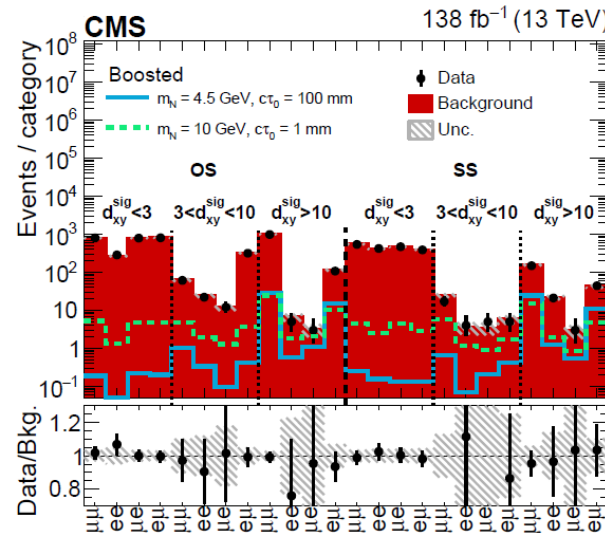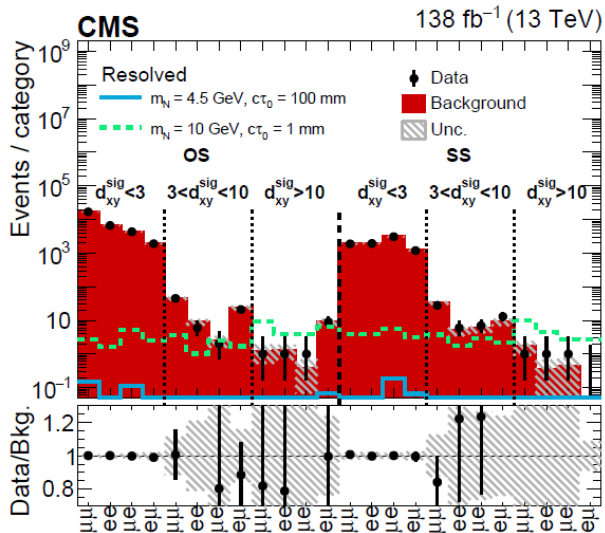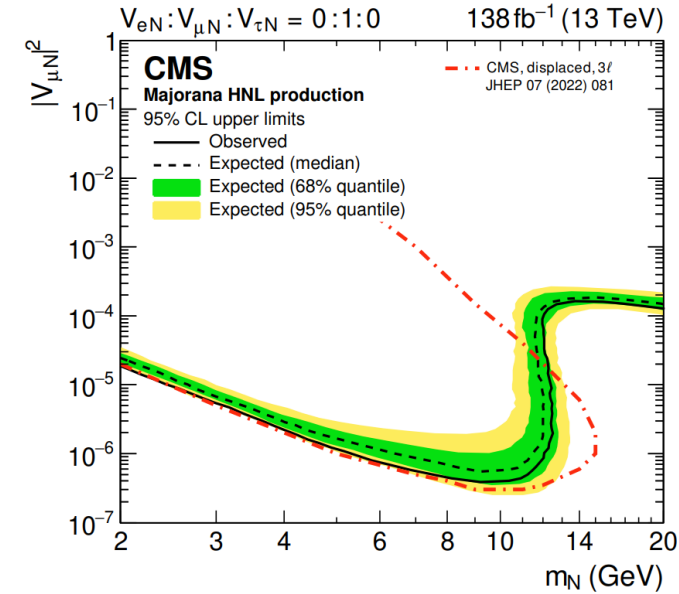
Event counting over each analysis category
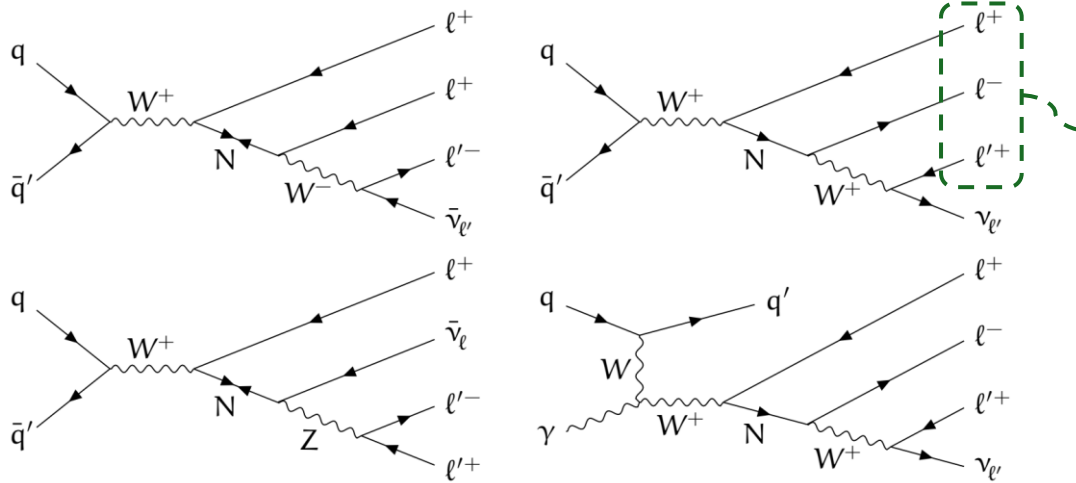
3 leptons **compatible** with **interaction vertex**

Counting exp.

- HNL presence would result in:
  - **Excess** of **event yield** in search region
  - **Excess** of events in **BDT score**
- **Combining** both to achieve **best sensitivity**

- Final state leptons: e, μ, τ
- **Single HNL** scenario
- Probing **exclusive coupling** scenarios

- Focused on **short HNL lifetimes → large HNL mass** (>10 GeV)
- **BDT** dedicated to **signal-background separation**

Accepted by JHEP

arXiv:2403.00100

9
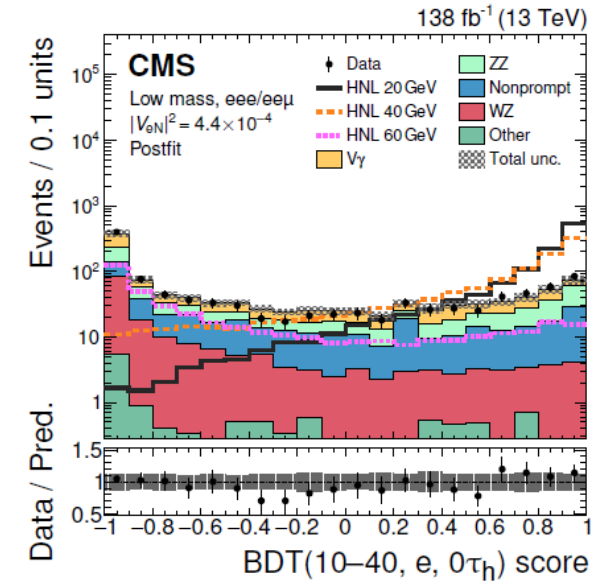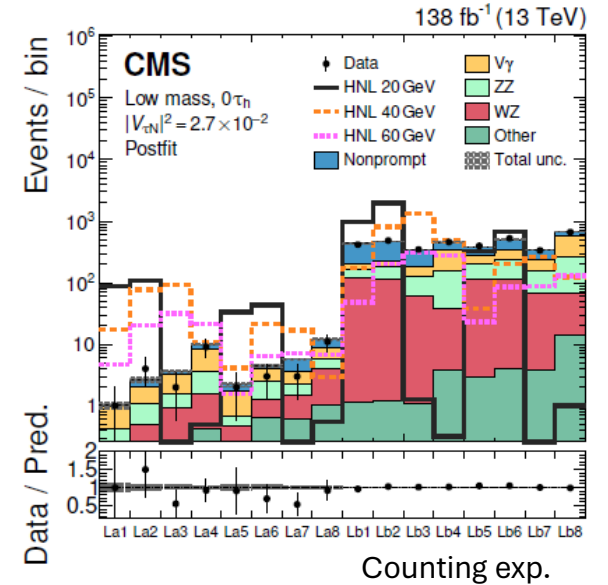
- **Improve x10** limits for **exclusive coupling** to ν_e and ν_μ w.r.t. previous CMS search from prompt HNL ([Phys. Rev. Lett. **120**, 221801](#))

- **Complementary** to current results on the **<20 GeV** mass range

- **Exclusive coupling** to ν_τ probed for the **first time above W mass**

138 fb^{-1} (13 TeV)

CMS

Majorana

$V_{eN} : V_{\mu N} : V_{\tau N} = 0:1:0$

Legend:
— Observed
···· Median expected
■ 68% expected
■ 95% expected
···· DELPHI
– – 3ℓ prompt (2016)
···· 3ℓ displaced
– – t-channel VBF
–·–· 2ℓ displaced

Axes: $|V_{\mu N}|^2$ vs m_N [GeV]

Triggering lepton

Shower in muon system

Displaced HNL vertex in μ system, >4 (7) m in barrel (endcap)
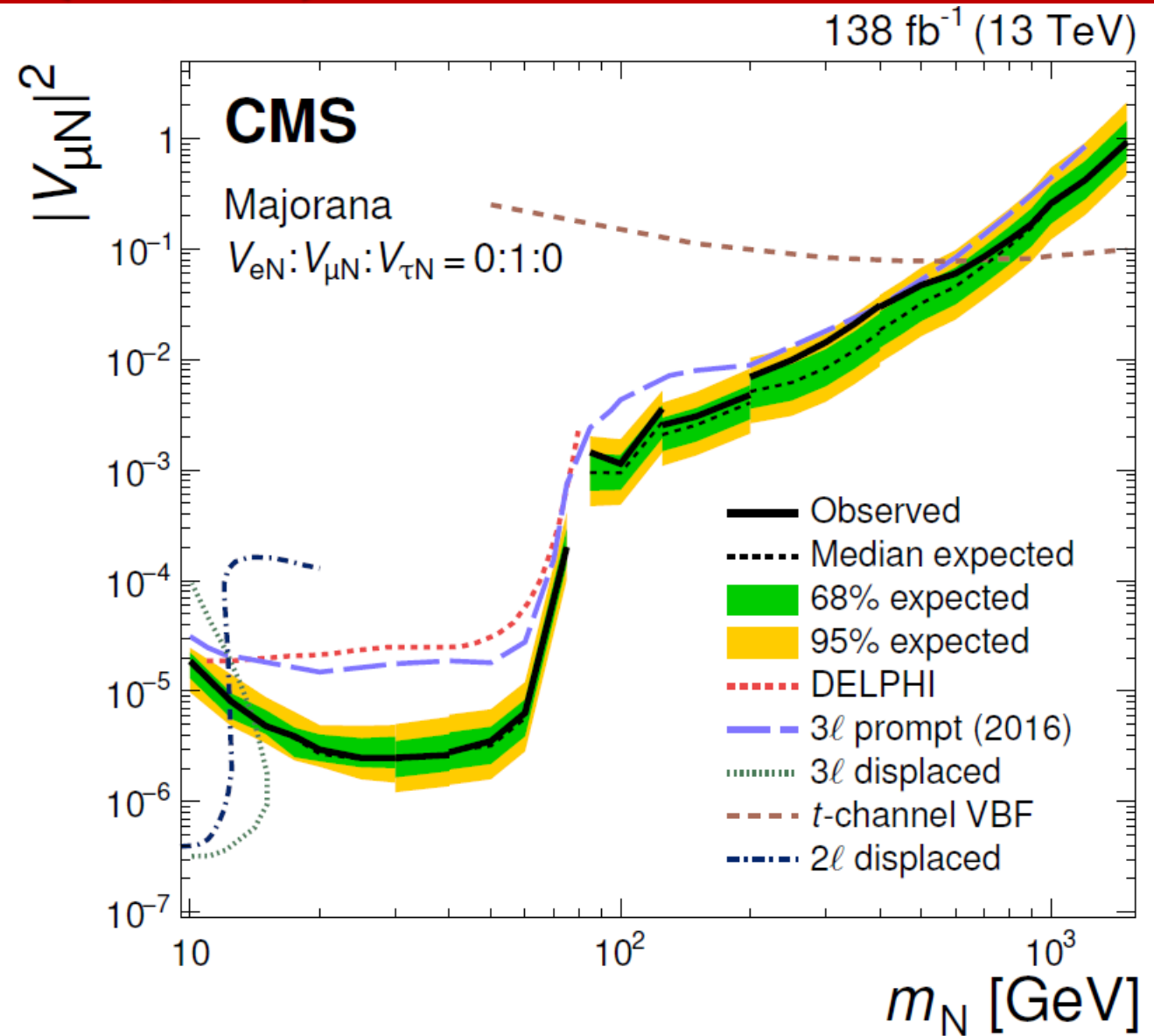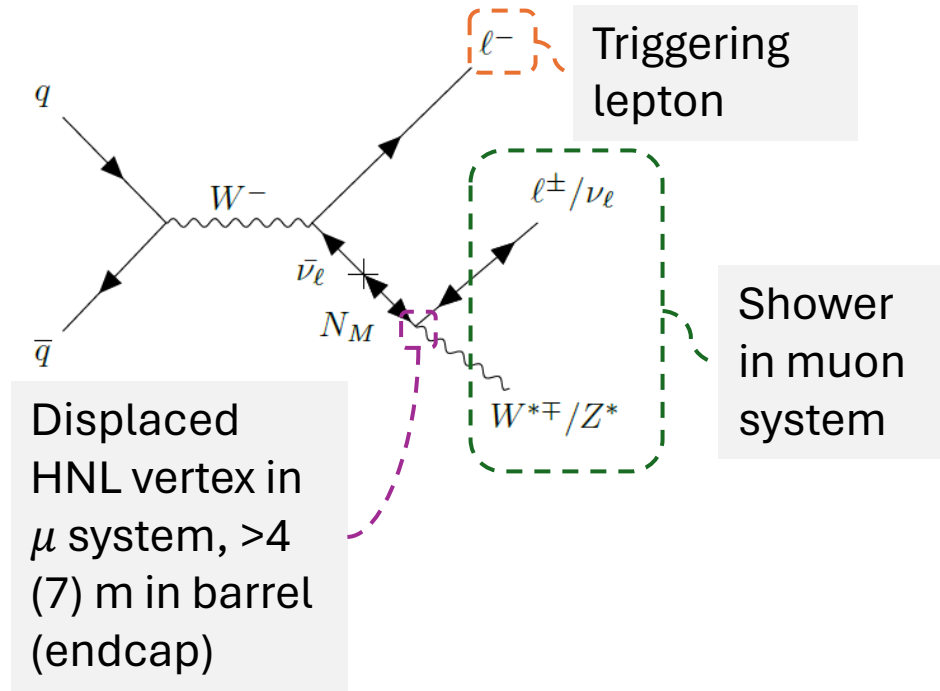
CMS *Simulation Preliminary*
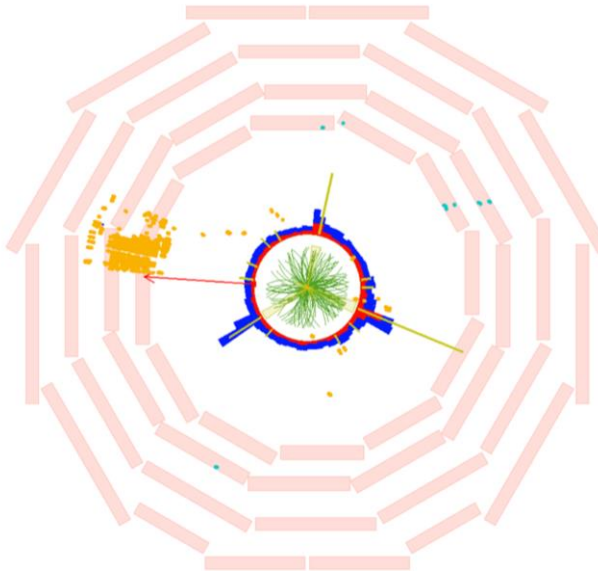
Accepted by PRD

arXiv:2402.18658

- Final state leptons: $\boldsymbol{e, \mu, \tau}$
- **Single HNL** scenario
- Probing **exclusive** and **democratic coupling scenarios**

- **Muon detector showers** (MDS) have a **huge discriminant power**
  - Background suppression of 10^7 and retaining 25-35% of signal
- **Background** contributions
  - **Non muon-induced** (e.g. prompt lepton from W + soft hadron from PU)
  - **Muon-induced** (e.g. $Z \to \mu\mu$ event + μ bremsstrahlung)

138 fb^{-1} (13 TeV)

CMS

- Data
- Background uncertainty
- $Z \to \mu\mu$
- Non-muon-induced
- $m_N = 2$ GeV, $c\tau_0 = 1$ m

Electron CSC · Electron DT · Muon CSC · Muon MB2 · Muon MB34
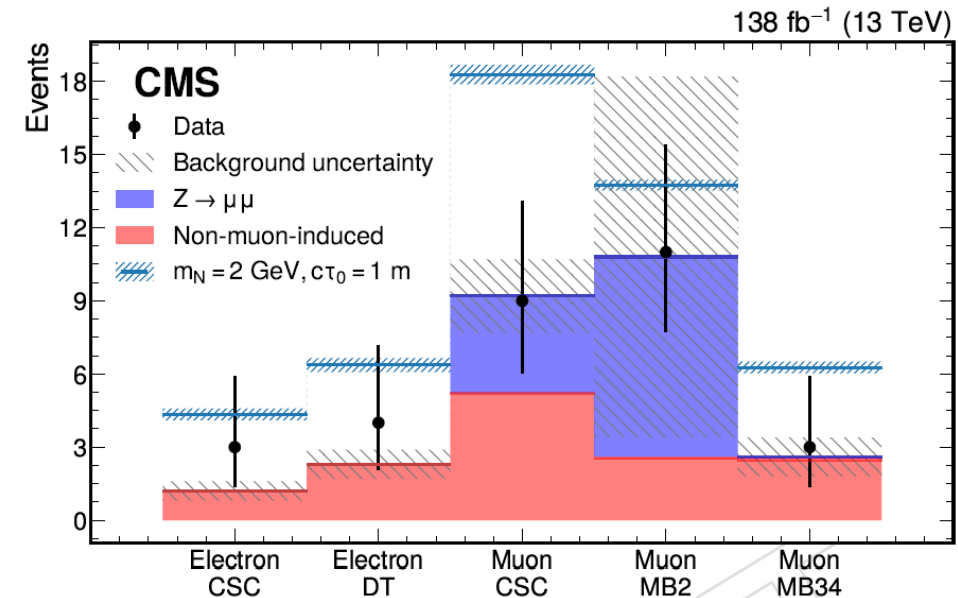
Event counting in each category

11

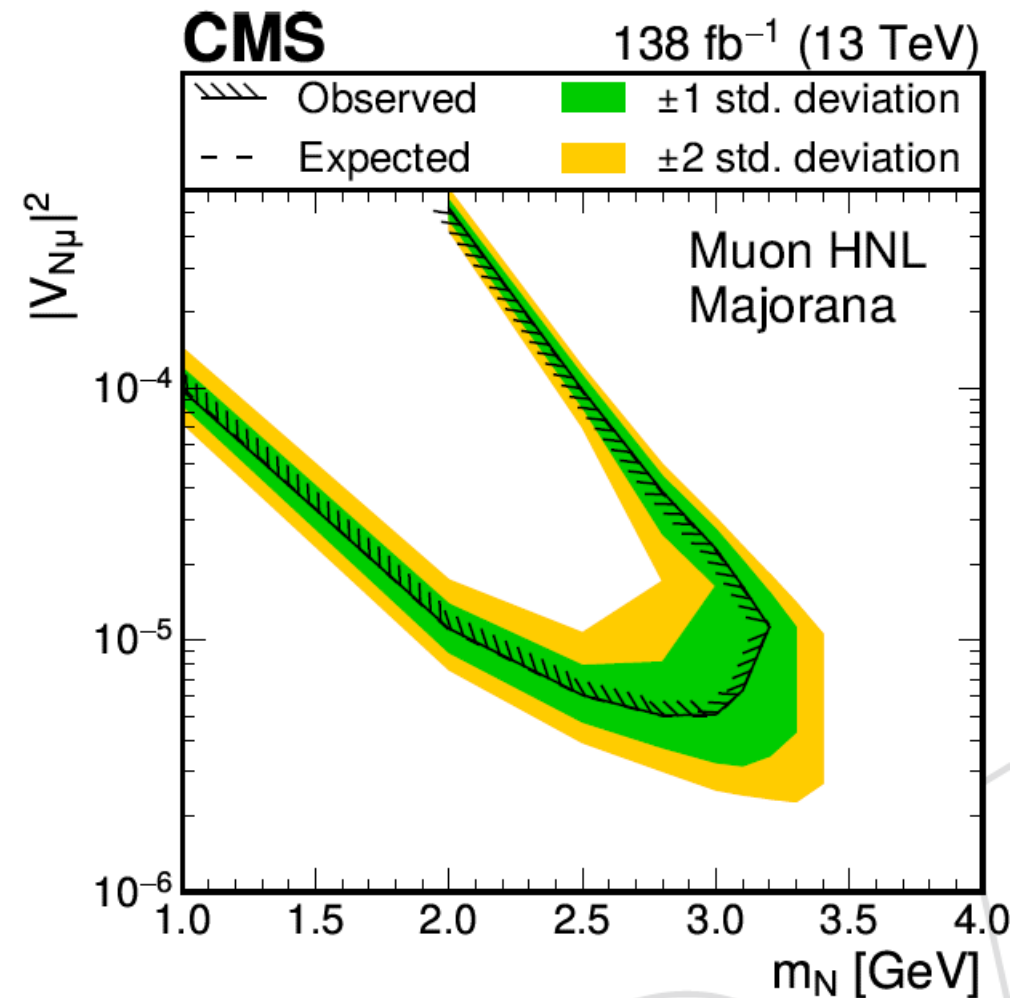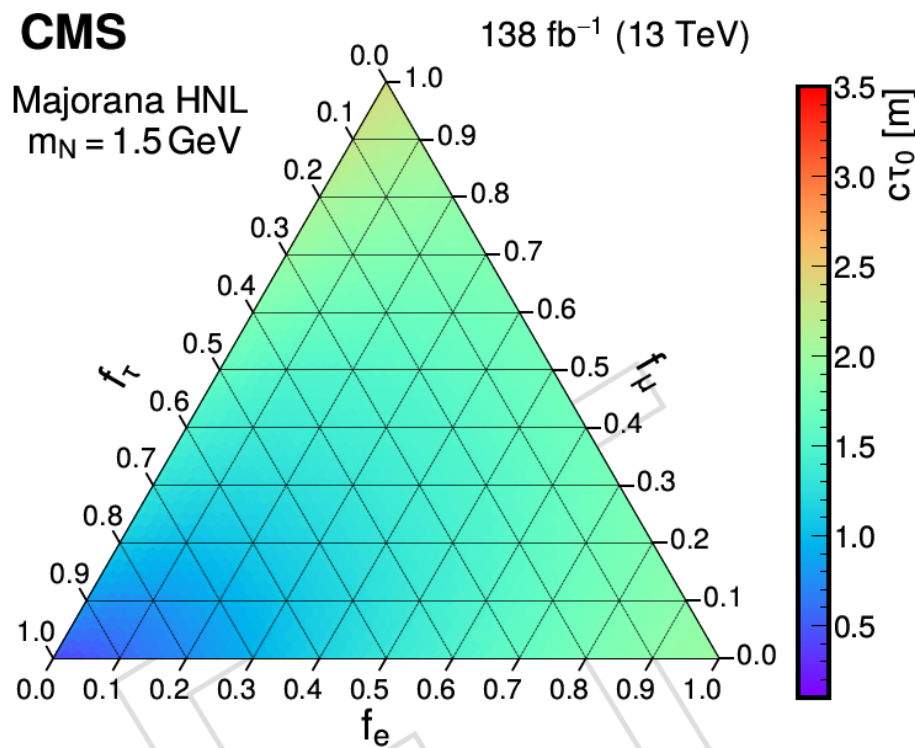**Muon detector shower**-based analysis allow to have **good sensitivity** on **long lived HNL** → **excellent results** on $|V_{\ell N}|^2$ limit for **light HNL**
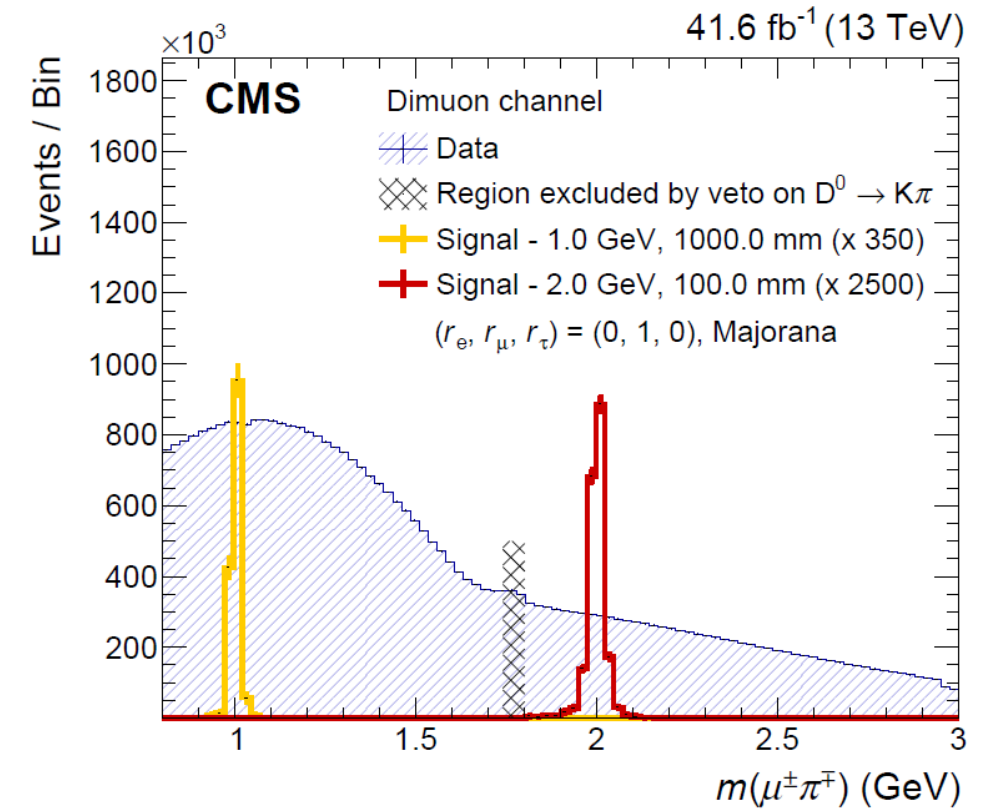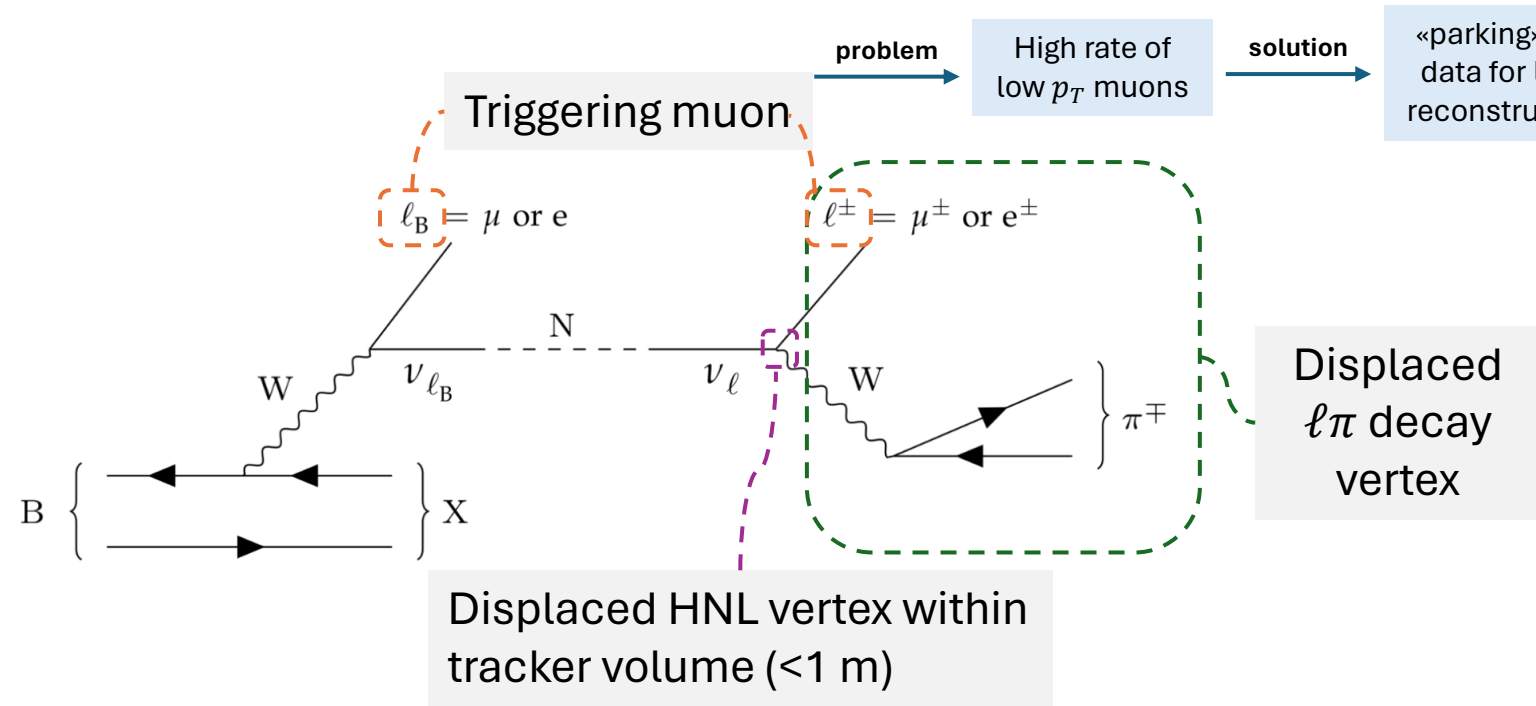
- **Most stringent limits** to date in $|V_e|^2$ in the **2.1-3.0 GeV** mass range

- **Most stringent limits** to date in $|V_\mu|^2$ in the **1.9-3.3 GeV** mass range

12

problem → High rate of low p_T muons → solution → «parking» raw data for later reconstruction → Large sample of $b\bar{b}$ events

Triggering muon

$\ell_B = \mu$ or e

$\ell^{\pm} = \mu^{\pm}$ or $e^{\pm}$

Displaced $\ell\pi$ decay vertex

Displaced HNL vertex within tracker volume (<1 m)

- Exploiting the **large statistics** available in **2018 B-Parking dataset**
  - ~ **10 billion** events containing **unbiased B hadron decays**
- Final state leptons: e, μ
- **Single HNL** scenario
- Probing exclusive and democratic coupling scenarios

- Sensitive to **low HNL mass** spectrum
- Clear **HNL displaced signature** over combinatorial background

HNL would show up as a peak in the $\ell\pi$ invariant mass

13

- **Most stringent limits** on $|V_N|^2$ in the **1-1.7 GeV** mass range at **collider experiments**

- **Best sensitivity** reached for $\left|V_\mu\right|^2$ thanks to excellent muon identification efficiency

- **Extended previous CMS limits** up to a **factor 2** in the **1-2 GeV** mass region
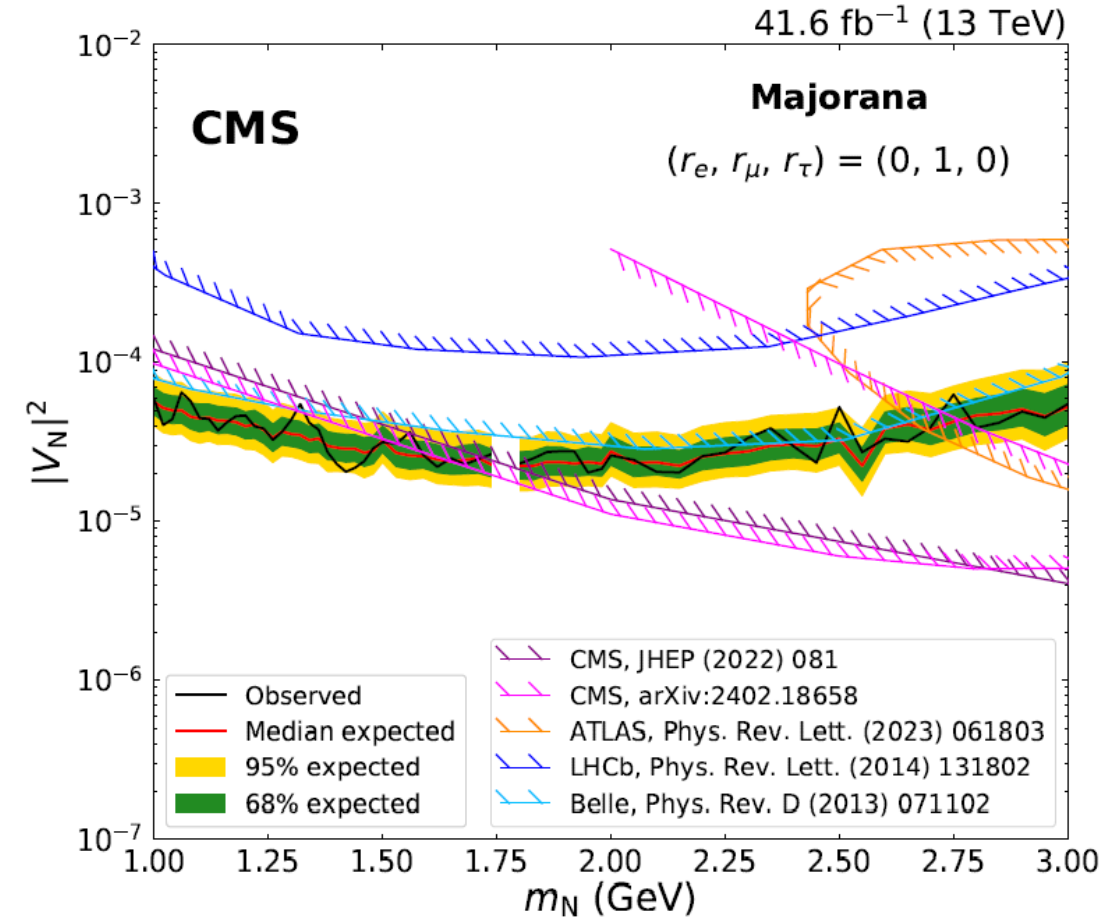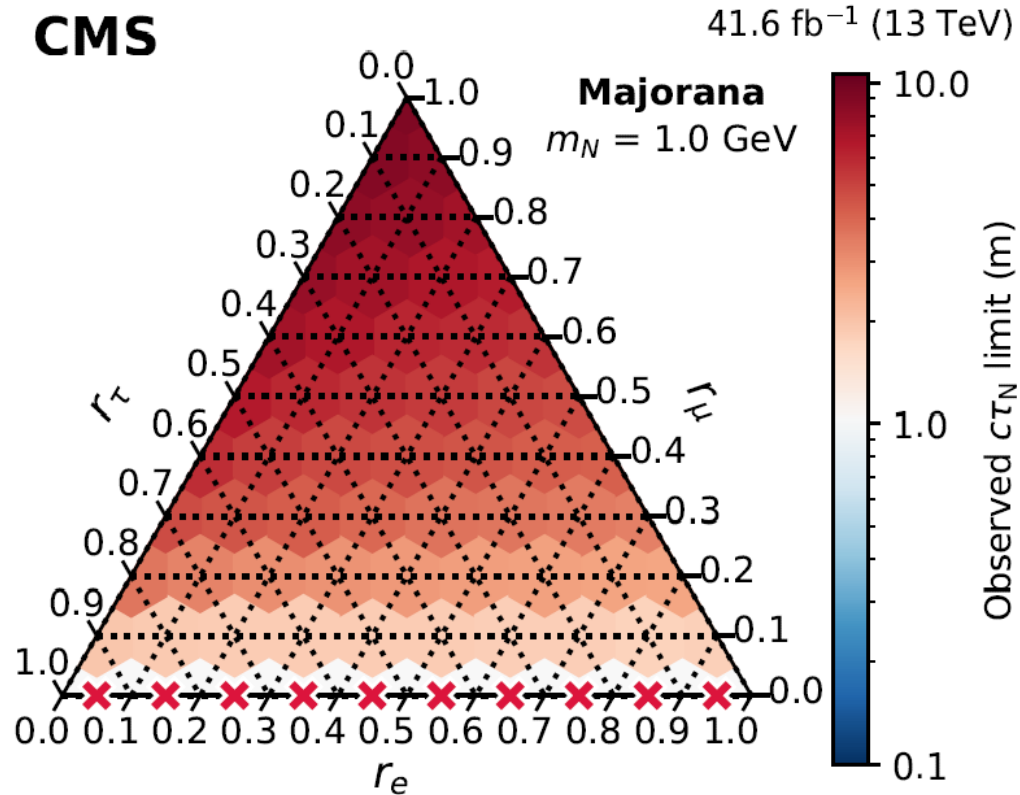
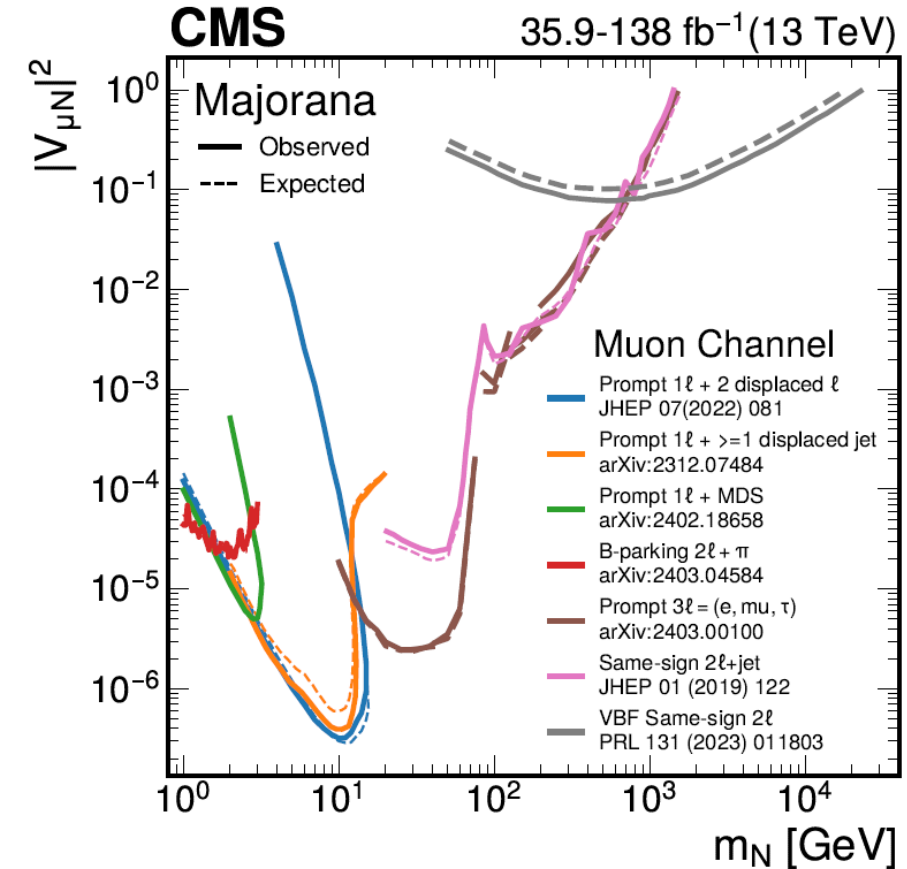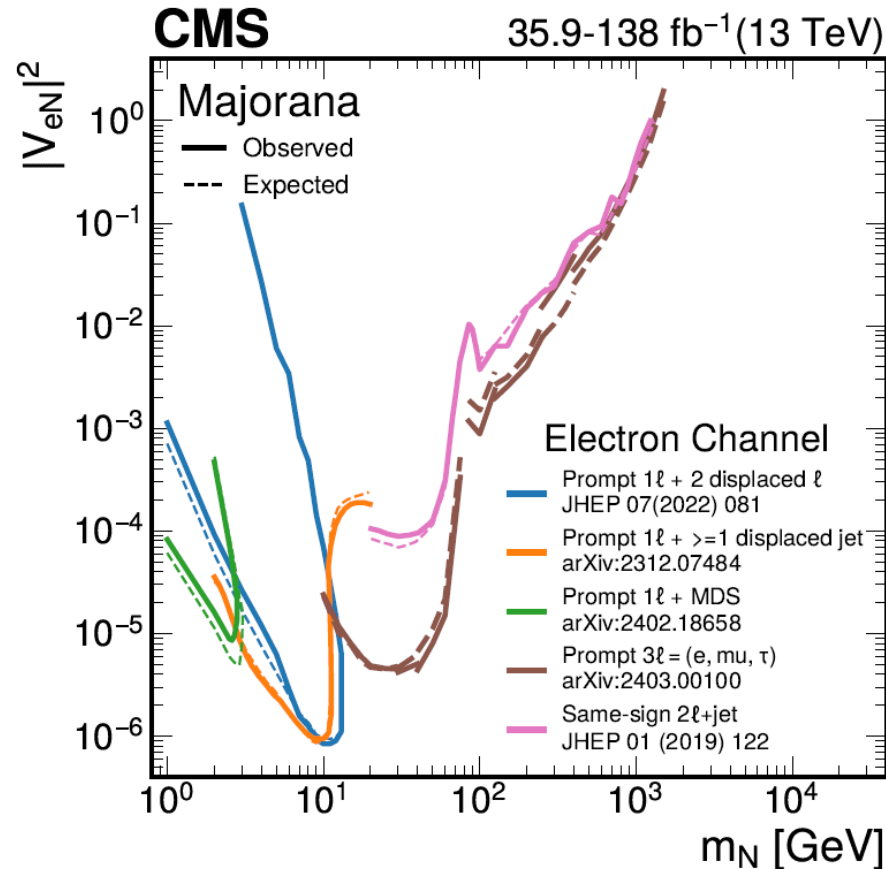arXiv:2405.17605

Submitted to Phys. Rept.

Soon to be published paper will contain a **review of HNL searches @ CMS**:

- All results on **type-I seesaw** HNL searches
- All searches involving:
  - **Type-III seesaw** HNL
  - **Left-right symmetric model** HNL
  - Majorana neutrinos in **composite model scenario**

CMS searches for type-I seesaw HNL

Conclusion

Review of most recent results on HNL searches has been presented:
- **CMS shows good performances** over a large part of the HNL mass-lifetime phase space
- Thanks to **novel analysis techniques** and to **new data-taking conditions** CMS was able to obtain **competitive results down to 1 GeV HNL masses**

Prospects for HNL searches @ CMS:
- Exploit **new displaced lepton trigger** in **Run3** data-taking
- **Run2+Run3 combination**
- **Exploit Z boson** production channel
  - Prompt topology only explored for the LRSM for masses above 400 GeV
  - Cleaner signature than W-channel in the displaced topology
- Profiting from large B-Parking dataset also to **search for HNL from charmed meson decays**
- Probe the **inverse seesaw mechanism model** (predicting $O(1)$ Yukawa coupling)

Summary

Most recent results from CMS on type-I seesaw HNL searches

- *Search for long-lived heavy neutral leptons in proton-proton collision events with a lepton and a jet from a secondary vertex at $\sqrt{s} = 13\ TeV$*
- *Search for long-lived heavy neutral leptons with lepton flavour conserving or violating decays to a jet and a charged lepton -* JHEP03(2024)105 arXiv:2312.07484
- *Search for heavy neutral leptons in final states with electrons, muons, and hadronically decaying tau leptons in proton-proton collisions at $\sqrt{s} = 13\ TeV$ -* Submitted to JHEP arXiv:2403.00100v1
- *Search for long-lived heavy neutral leptons decaying in the CMS muon detectors in proton-proton collisions at $\sqrt{s} = 13\ TeV$ -* Submitted to PRD arXiv:2402.18658v1
- *Search for long-lived heavy neutrinos in the decays of B mesons produced in proton-proton collisions at $\sqrt{s} = 13\ TeV$ -* Submitted to JHEP arXiv:2403.04584v1

Soon to be published HNL-dedicated review paper w/ comprehensive CMS results

- *Review of searches for vector-like quarks, vector-like leptons, and heavy neutral leptons in proton-proton collisions at $\sqrt{s} = 13\ TeV$ at the CMS experiment – Submitted to Phys. Rept. -* arXiv:2405.17605

Stay tuned for new results!