

2nd Workshop on Feebly-Interacting Particles (FIPs2022)
October 17–21, 2022

Searches for heavy neutral leptons at the LHC

Recent results from the ATLAS and CMS experiments

Joscha Knolle

on behalf of the ATLAS & CMS Collaborations



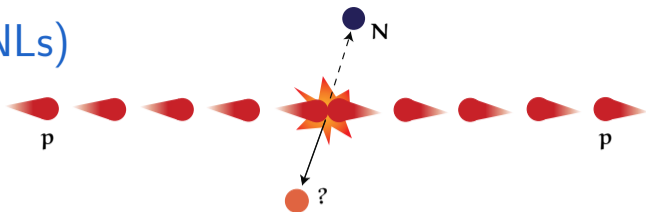
Heavy Neutral Leptons (HNLs)

Motivation

- nonzero SM neutrino mass
⇒ seesaw mechanism
- dark matter
- matter-antimatter asymmetry
⇒ baryogenesis ⇒ leptogenesis

Phenomenology

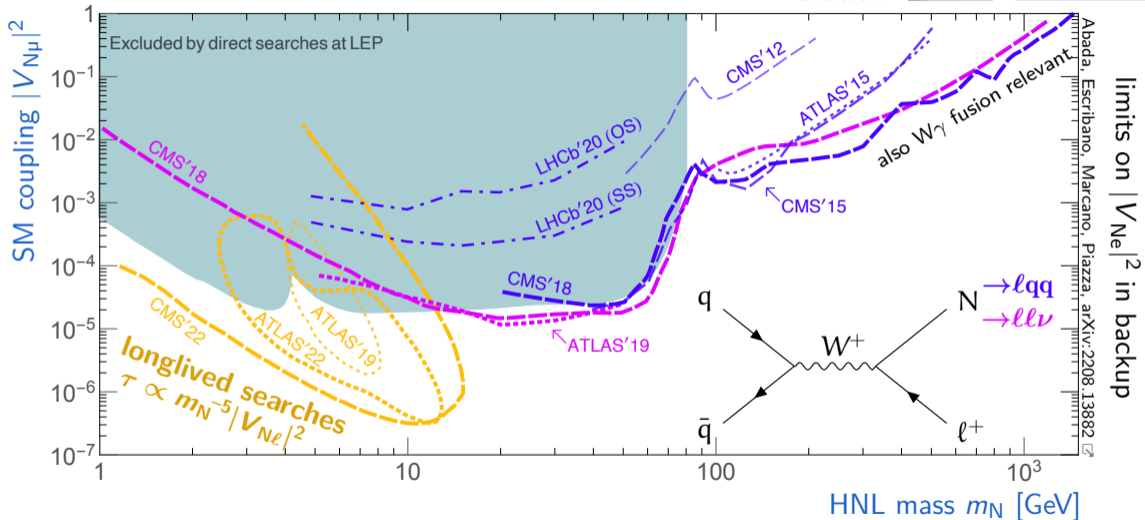
- type-I seesaw: right-handed HNLs
 - Majorana or Dirac nature
 - properties: mass m_N , SM coupling $|V_{N\ell}|^2$
- type-III seesaw: N + heavy charged L
- left-right symmetry: N + new bosons
- ...



At the Large Hadron Collider (LHC)

- can be produced in proton-proton collisions through various processes
- ATLAS & CMS experiments well equipped to search for HNLs
 - excellent reconstruction of leptons, jets, missing momentum; also displaced
 - large data set of $\sim 140 \text{ fb}^{-1}$ at $\sqrt{s} = 13 \text{ TeV}$
- today: selection of very recent results

HNLs in DY production: overview

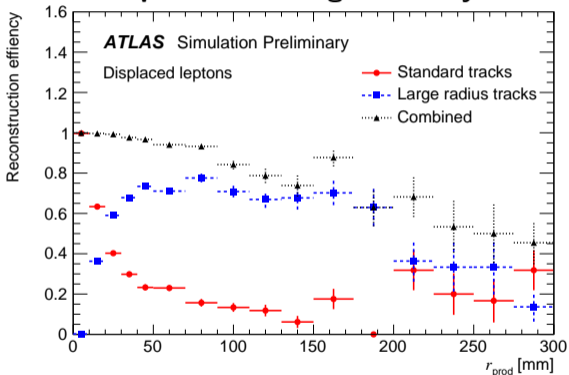


Longlived HNLs in DY production: tracking

ATL-PHYS-PUB-2017-014 [↗](#), JHEP 07 (2022) 081 [↗](#)

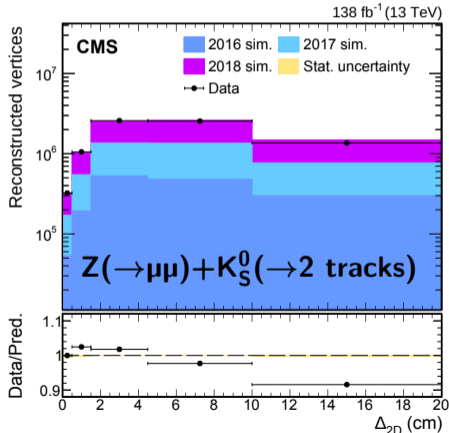


Displaced tracking efficiency



dedicated tracking iterations for displaced particles

Data-to-simulation corrections



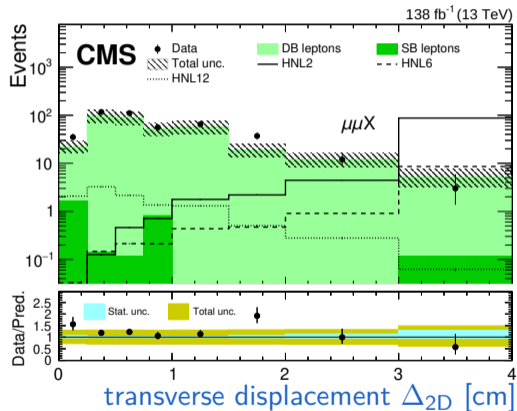
HNL searches at the LHC | Joscha Knolle, FIPs2022

Longlived HNLs in DY production: event yields (CMS)

JHEP 07 (2022) 081 [↗](#)



- prompt lepton (e/μ) with $p_T(e) > 32/35$ GeV or $p_T(\mu) > 25$ GeV
- two OS displaced leptons that form a displaced secondary vertex
- event categories: $m(\ell_2\ell_3)$ & Δ_{2D}
- background: displaced ℓ are misidentified hadrons, from hadron decays, or from conversions
 - double-background (DB): correlated, e.g. in B decay chain
 - single-background (SB)
- estimation from data sideband

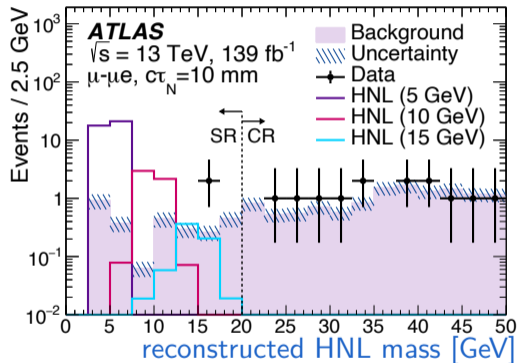


Longlived HNLs in DY production: event yields (ATLAS)

arXiv:2204.11988 (accepted by PRL) [↗](#)



- prompt lepton (e/μ) with $p_T > 28$ GeV
- two OS displaced leptons that form a displaced secondary vertex
- reconstruction of HNL mass using:
 - W mass constraint
 - primary to secondary vertex vector as HNL flight direction
- random track crossing background estimated with “shuffled events”:
 - displaced vertex from sideband events without prompt lepton
 - prompt lepton from signal region events with SS displaced leptons

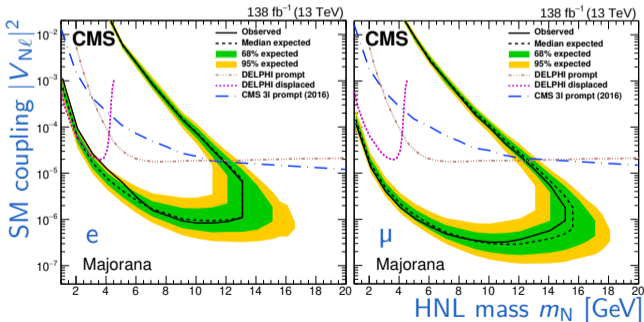


Longlived HNLs in DY production: limits

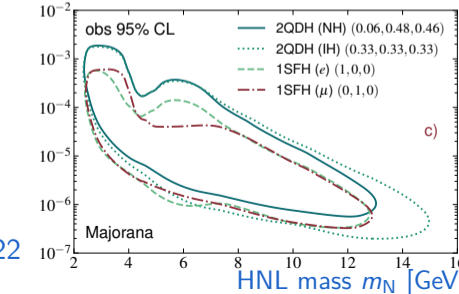
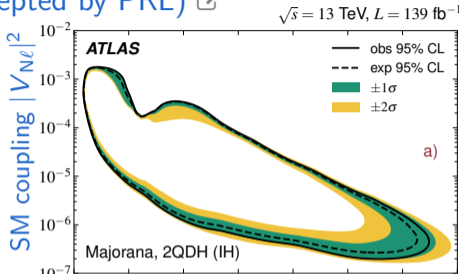
JHEP 07 (2022) 081 [↗](#), arXiv:2204.11988 (accepted by PRL) [↗](#)



- CMS: limits in single-coupling scenario only
- ATLAS: also limits for 2QDH(NH/IH) model
2 quasi-degenerate HNLs, IH: $|V_{Ne}|^2 = |V_{N\mu}|^2 = |V_{N\tau}|^2$
- significantly improves over prompt searches



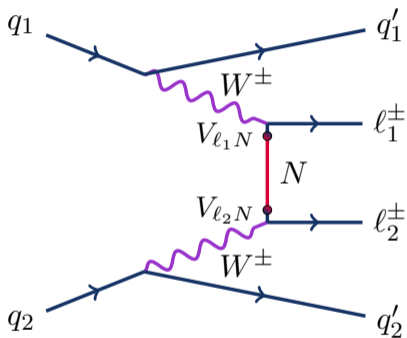
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also Dirac limits from ATLAS & CMS

HNLs in t -channel VBF production

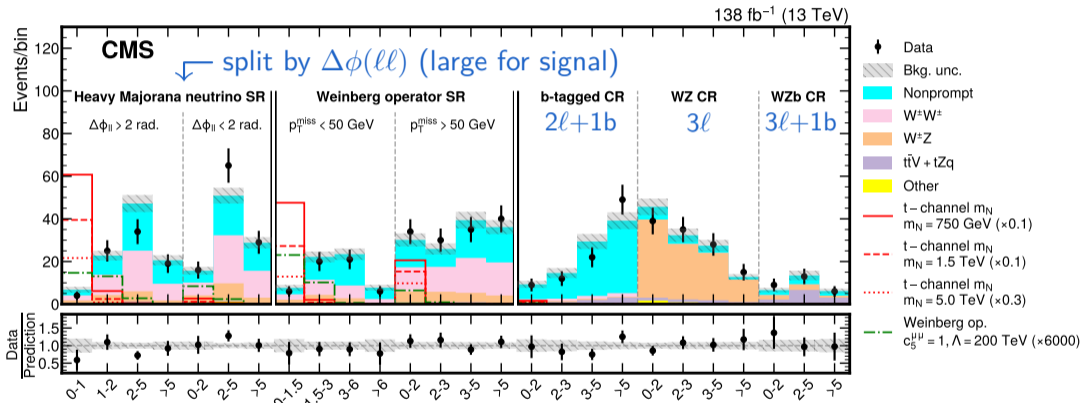
arXiv:2206.08956 (submitted to PRL) [↗](#)



- Majorana HNL with couplings only to muons
- t -channel production through vector boson fusion (VBF) process
- cross section compared to s -channel DY:
 - less sensitive to m_N
 - more sensitive to $|V_{Ne}|^2$
- event selection: two same-sign muons, two (forward) jets, large rapidity gaps
- backgrounds: nonprompt leptons (from data), diboson, top+boson

HNLs in t -channel VBF production: event yields

arXiv:2206.08956 (submitted to PRL) [↗](#)



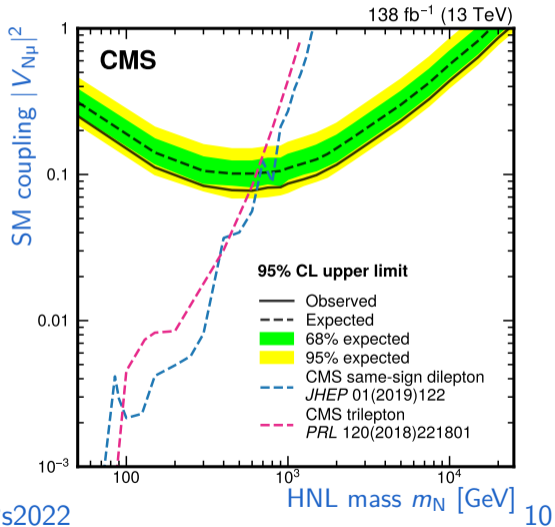
$H_T(\text{jets})/p_T(\mu_1)$: hadronic activity relative to leptonic activity (small for signal)



HNLs in t -channel VBF production: limits

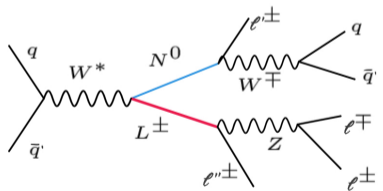
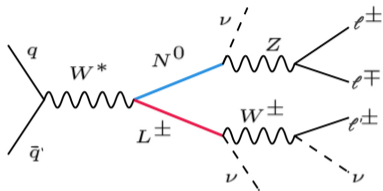
arXiv:2206.08956 (submitted to PRL) [↗](#)

- simultaneous fit to signal and control regions, nonprompt-lepton and WZ background constrained
- limits on HNL–muon coupling in mass range 50 GeV–25 TeV
- better sensitivity than DY searches above 650 GeV
- first direct limits above 2 TeV
- also interpreted in terms of Weinberg operator



Heavy leptons in type-III seesaw

arXiv:2202.02039 (accepted by EPJC) [↗](#)



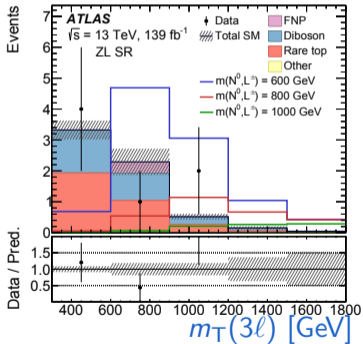
- type-III seesaw: extra fermionic $SU(2)_L$ triplet
 \Rightarrow new heavy neutral & charged leptons N^0, L^\pm
- consider N^0, L^\pm to be mass degenerate
- DY production of $N^0 L^\pm$ and $L^\pm L^\mp$ pairs,
 subsequent decays to multiple leptons
- strategy: 3ℓ and 4ℓ events categorized by decay
 scenarios: Z candidate or not, many or few jets
- reducible backgrounds: nonprompt leptons,
 charge-misidentified electrons (from data)
- irreducible backgrounds: diboson, $t\bar{t}$ +boson

Heavy leptons in type-III seesaw: event yields

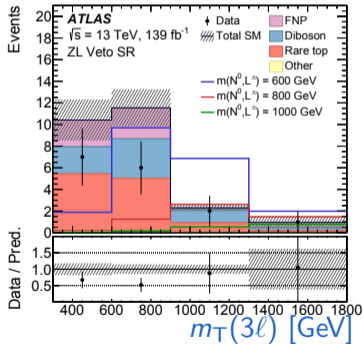
arXiv:2202.02039 (accepted by EPJC) 

- signal regions: 3ℓ with or without Z, 3ℓ with ≤ 1 jets, 4ℓ with charge sum 0 or ± 2
- control and validation regions: diboson, rare top, fake and nonprompt leptons (FNP)

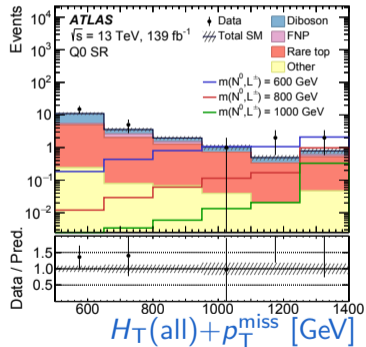
3ℓ with Z candidate



3ℓ without Z candidate



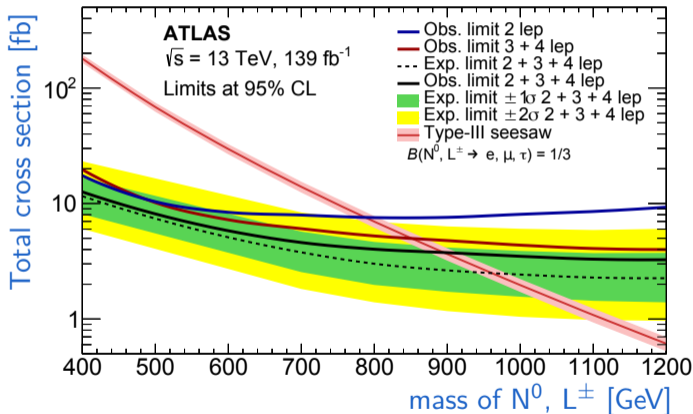
4ℓ with charge sum 0



Heavy leptons in type-III seesaw: limits

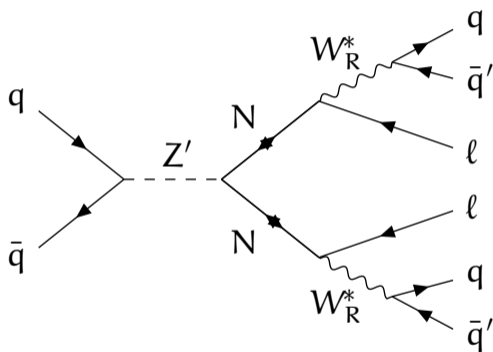
arXiv:2202.02039 (accepted by EPJC) [↗](#)

- simultaneous fit to signal and control regions
 - 3ℓ : $m_T(3\ell)$
 - 4ℓ : $H_T(\text{all}) + E_T^{\text{miss}}$
- also combination with 2ℓ +jets channel
Eur. Phys. J. C 81 (2021) 218 [↗](#)
- heavy leptons excluded up to 910 GeV
- 3ℓ channel dominates above 500 GeV



HNL pair production in Z' decays

CMS-PAS-EXO-20-006 [↗](#)

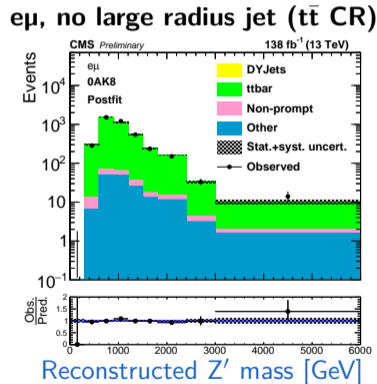
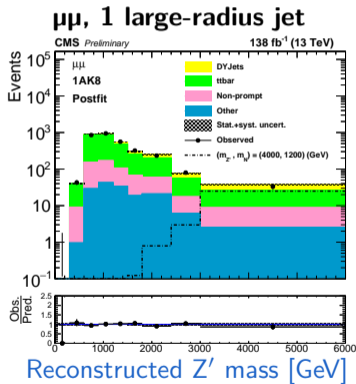
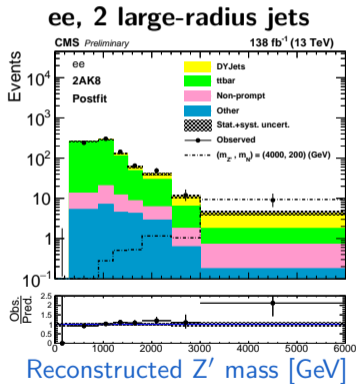


- left-right symmetry model (LRSM):
 $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
 \Rightarrow three additional bosons W_R^\pm and Z'
 \Rightarrow three HNLs
 (\Rightarrow extended Higgs sector, e.g. $H^{\pm\pm}$ [↗](#))
- search for high-mass Z' with low to medium mass gap to HNL \Rightarrow highly boosted HNL decay products
- strategy: combine resolved decays (isolated $\ell+2$ jets) and boosted decay (nonisolated ℓ +large-radius jet)
- only prompt backgrounds: $t\bar{t}$ and DY

HNL pair production in Z' decays: event yields

CMS-PAS-EXO-20-006 [↗](#)

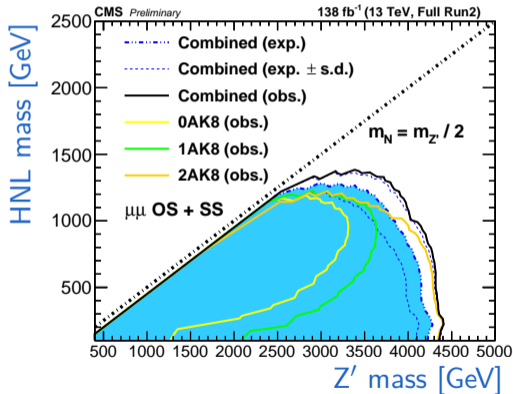
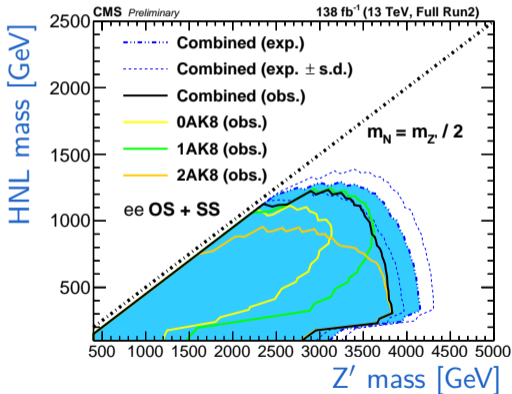
- dilepton events, categorized by lepton flavor and number of large-radius jets (0–2)
- Z' mass reconstructed from HNL decays: $\ell+2$ jets and/or large-radius jet



HNL pair production in Z' decays: limits

CMS-PAS-EXO-20-006 [↗](#)

- simultaneous fit to signal and control regions, $t\bar{t}$ and DY background constrained
- for lowest HNL mass (100 GeV, highest boost): exclusion of Z' up to 2.8 and 4.4 TeV



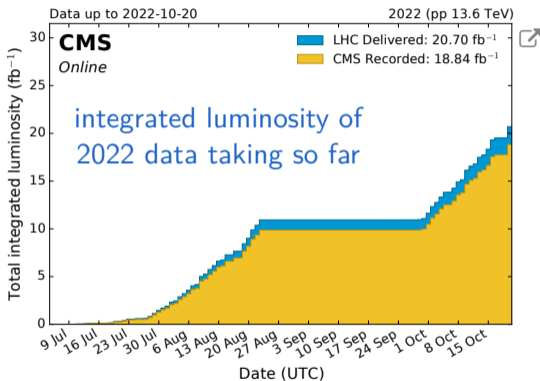
Summary



Exciting Run 2 results on HNLs

- ATLAS & CMS have good sensitivity to various HNL models with GeV and TeV masses
- selection of recent results shown today
 - displaced HNLs with ATLAS & CMS
 - t -channel HNLs in VBF with CMS
 - type-III seesaw heavy leptons with ATLAS
 - HNL pairs in Z' decays with CMS
- more results with 13 TeV data to come
 - many “top-up” analyses with full data set in preparation
 - machine-learning methods in investigation for better sensitivity






Run 3 has started!



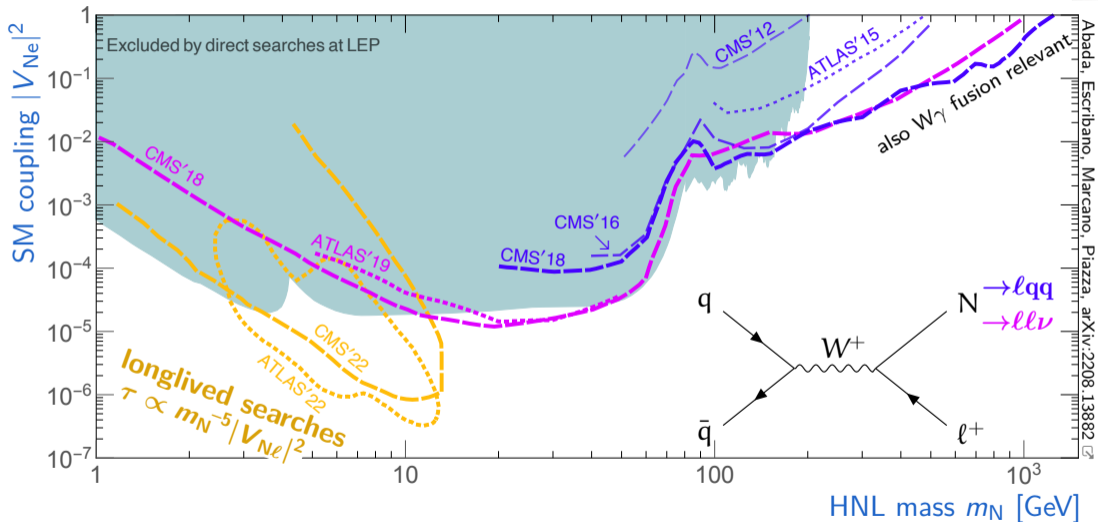
⇒ stay tuned for first results at 13.6 TeV!

References



-  CMS Collaboration, “Search for long-lived heavy neutral leptons with displaced vertices in proton-proton collisions at $\sqrt{s} = 13$ TeV”, JHEP 07 (2022) 081 [↗](#)
-  ATLAS Collaboration, “Search for type-III seesaw heavy leptons in leptonic final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, arXiv:2202.02039 (accepted by EPJC) [↗](#)
-  ATLAS Collaboration, “Search for heavy neutral leptons in decays of W bosons using a dilepton displaced vertex in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”, arXiv:2204.11988 (accepted by PRL) [↗](#)
-  CMS Collaboration, “Probing heavy Majorana neutrinos and the Weinberg operator through vector boson fusion processes in proton-proton collisions at $\sqrt{s} = 13$ TeV”, arXiv:2206.08956 (submitted to PRL) [↗](#)
-  CMS Collaboration, “Search for Z' bosons decaying to pairs of heavy Majorana neutrinos in proton-proton collisions at $\sqrt{s} = 13$ TeV”, CMS-PAS-EXO-20-006, CERN 2022 [↗](#)

HNLs in DY production: overview (e)



Abada, Escrivano, Marciano, Piazza, arXiv:2208.13882