Searches for **Heavy Neutral Leptons** with CMS

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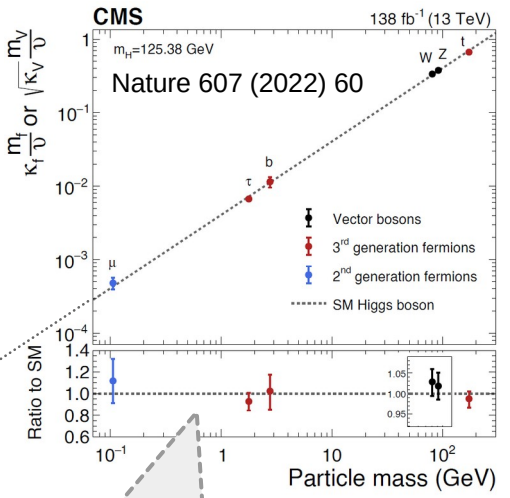
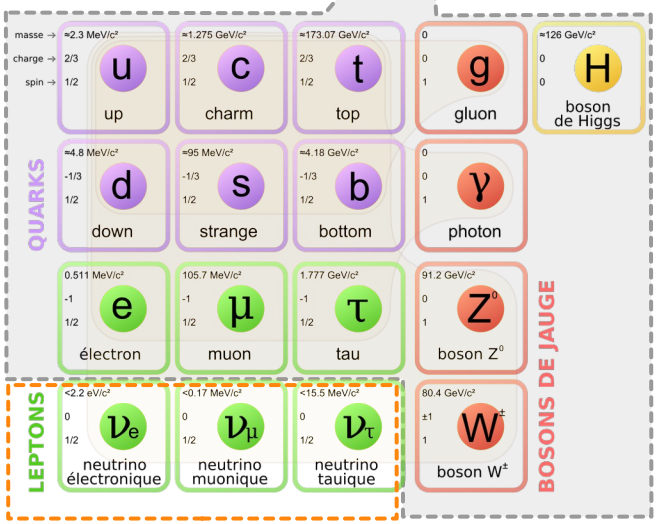
EPS'23

Heavy neutral leptons (HNLs)

- SM neutrinos are weird!
  - tiny mass? flavor oscillations? Higgs interactions?
- extending neutrino sector of SM
  - postulate heavy neutral leptonic particles:
    - Dirac HNL (particle + antiparticle)
    - Majorana HNL (own antiparticle)
  - can mix with SM lepton sector
  - see-saw mechanism
  - dim.-5 effective extension in EFT
- can explain various observed phenomena
  - neutrino oscillations
  - dark matter candidate
  - baryon asymmetry
  - anomalous muon g-2
  - etc …





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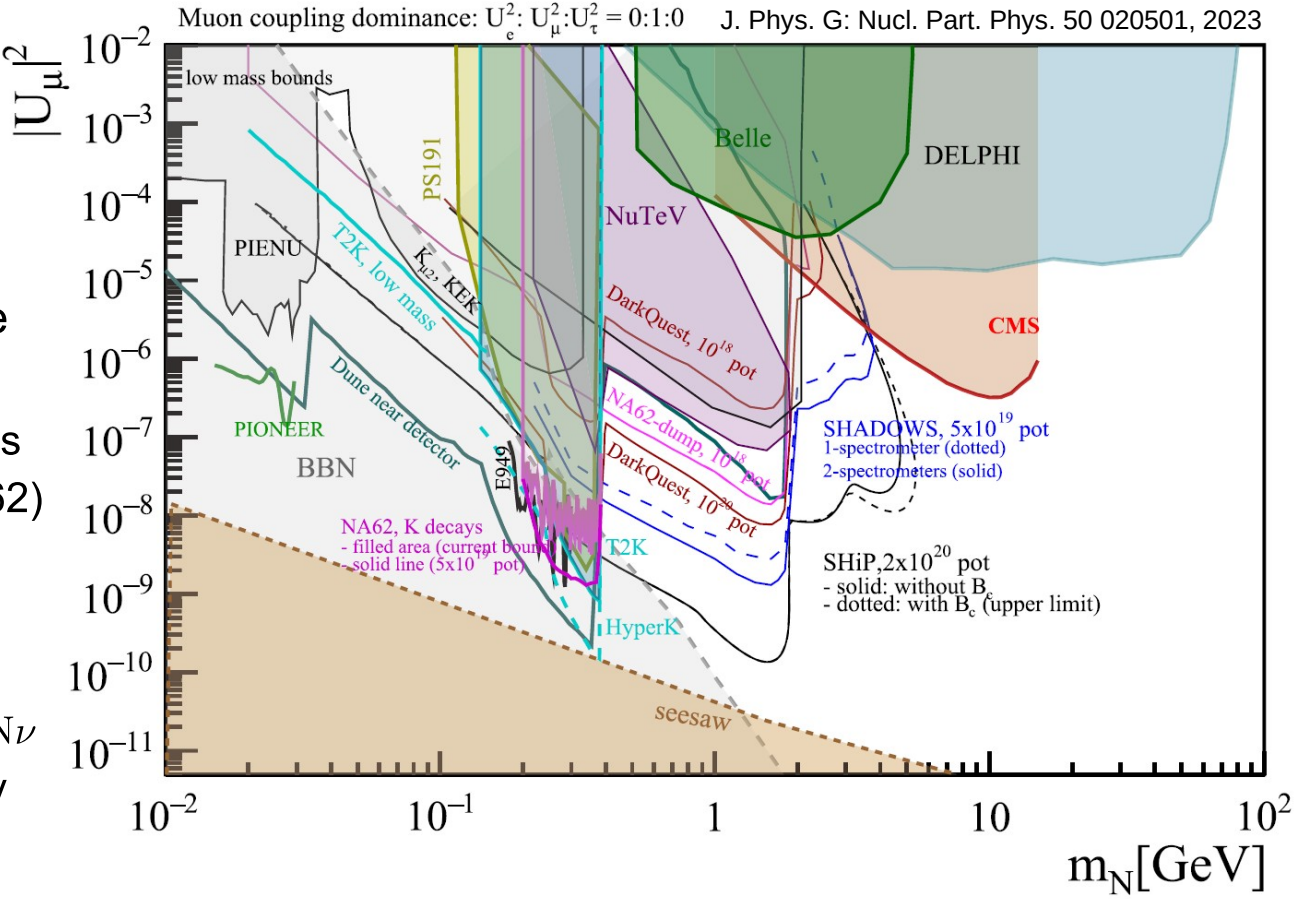
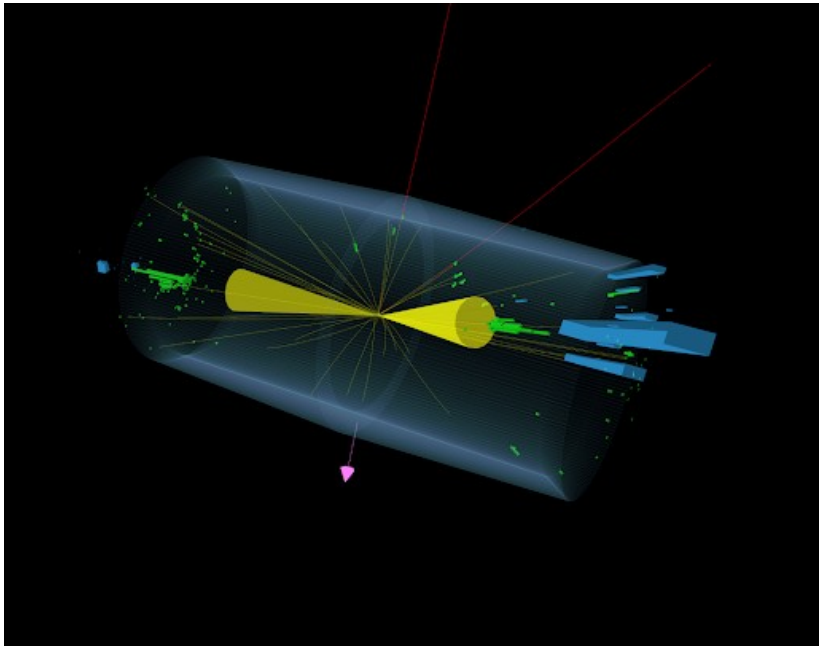
Experimental landscape

- rich set of searches at various experiments ongoing & planned:
  - collider & fixed-target
  - nuclear decays
  - atmospheric/solar neutrinos
- accessible production/decay mode depends on HNL mass
  - below Kaon mass can use decays $\mathrm{K}^{\pm} \to \ell^{\pm}\mathrm{N},\ \mathrm{K}^{\pm} \to \mu\mu\pi$ (e.g. NA62)
  - below B or D meson masses $\mathrm{B}^{\pm}, \mathrm{D}_{\mathrm{s}}^{\pm}, \tau^{\pm} \to \ell^{\pm}\mathrm{N},\ \mathrm{D}^{0} \to \ell^{\pm}\pi^{\mp}\mathrm{N}$ (e.g. Belle, LHCb)
  - below W, Z boson masses: $\mathrm{Z} \to \mathrm{N}\nu$
  - above W, Z boson masses decay to onshell bosons dominant $\mathrm{W}^{\pm} \to \ell^{\pm}\mathrm{N},\ \mathrm{N} \to \ell^{\pm}\mathrm{W}^{\mp}, \nu\mathrm{Z}, \nu\mathrm{H}$



Searches for prompt HNLs

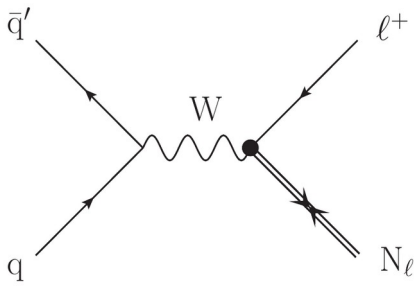
https://cms.cern/news/two-ends-seesaw



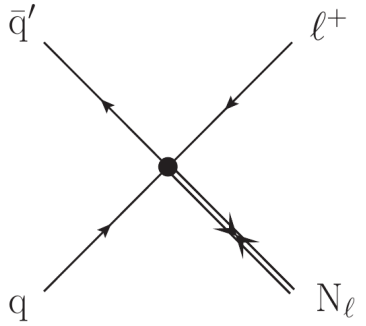
Heavy composite Majorana neutrino

Phys. Lett. B 843 (2023) 137803

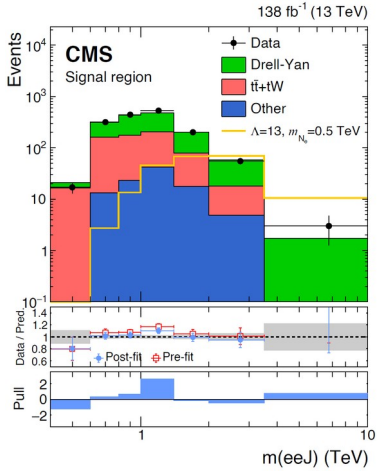
- composite model where leptons & quarks have substructure at energy scale Λ
  $E \ll \Lambda \rightarrow$ effective gauge & contact interactions
- investigate $\mathrm{eeq\bar{q}}$ or $\mu\mu\mathrm{q\bar{q}}$ final states
- same- or opposite-sign lepton pairs
  $p_\mathrm{T} > 150\ (100)\ \mathrm{GeV}$ & isolated
- large radius jet: $p_\mathrm{T} > 190\ \mathrm{GeV}$
  (encapsulates $\mathrm{q\bar{q}}$ from HNL decay)
- limits determined from $m(\ell\ell\mathrm{J})$ distribution
- exclude up to 6.0 (6.1) TeV HNLs with $m_\mathrm{N} = \Lambda$ for electrons (muons)

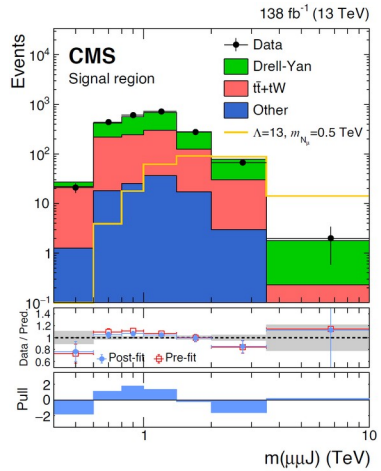


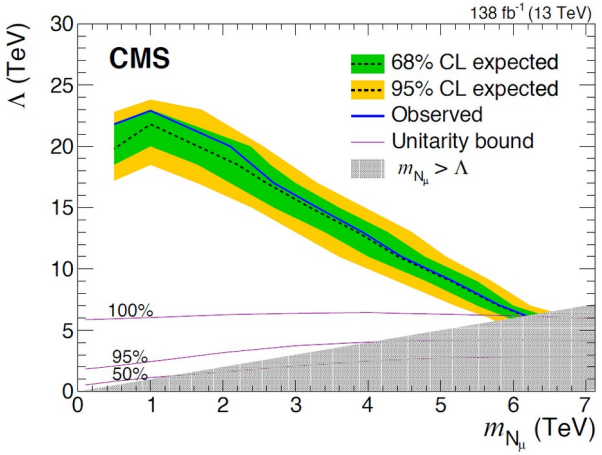
$$\mathcal{L}_\mathrm{GI} = \frac{g f}{\sqrt{2}\Lambda}\overline{N}\sigma^{\mu\nu}(\partial_\mu W_\nu)P_\mathrm{L}\ell + \mathrm{h.c.}$$



$$\mathcal{L}_\mathrm{CI} = \frac{g_*^2 \eta}{\Lambda^2}\bar{q}'\gamma^\mu P_\mathrm{L} q\, \overline{N}\gamma_\mu P_\mathrm{L}\ell + \mathrm{h.c.}$$







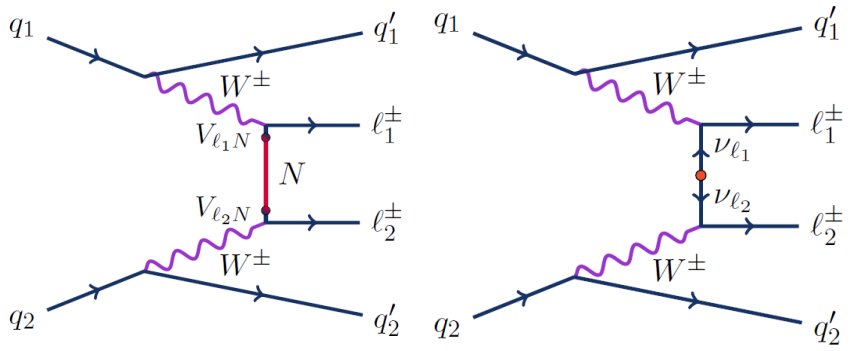
HNLs & Weinberg operator in VBF

Phys. Rev. Lett. 131 (2023) 011803

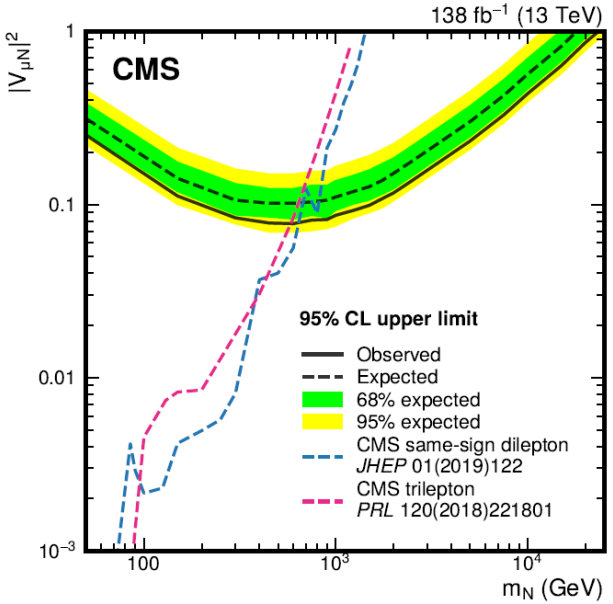
- Weinberg operator (dim-5 Wilson coefficient)

$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda}[\Phi \cdot \overline{L}_\ell^c][L_{\ell'} \cdot \Phi] \quad m_{\ell\ell'} = C_5^{\ell\ell'} v^2/\Lambda$$

- focus on $\mu^\pm\mu^\pm$ events via vector boson fusion
  → access to TeV HNLs; complementary to s-channel



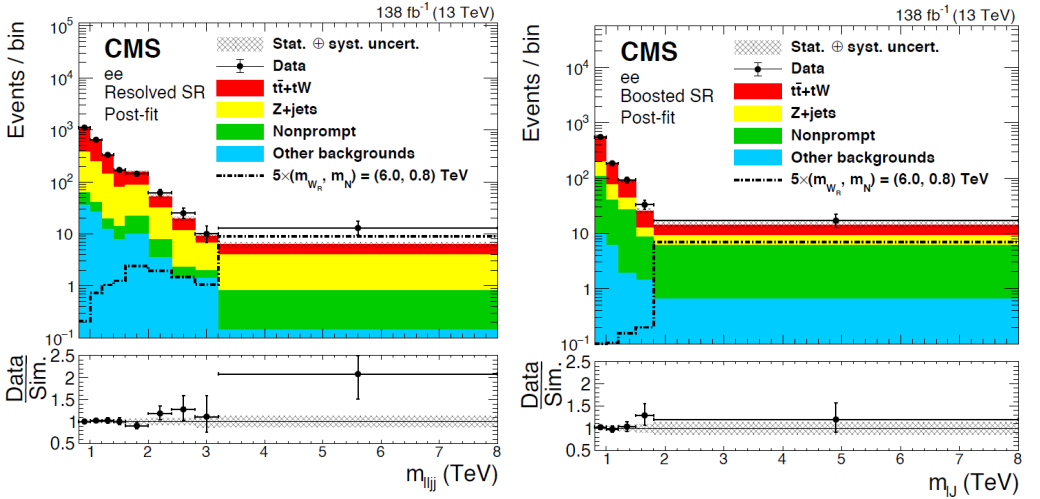
- 2 muons ($p_T > 30$ GeV) & 2 forward jets ($p_T > 30$ GeV)
- VBF selection with $|\Delta\eta_{jj}| > 2.5,\ m_{jj} > 750$ GeV
- non prompt background estimated from
  muon isolation sideband (fake-rate method)
- limit on Weinberg operator translated into
  limit on $m_{\mu\mu} > 10.8\ (12.8)$ GeV [obs (exp)]
- limits on typeI Majorana HNLs determined
  → exceed LHC energy through use of VBF events!

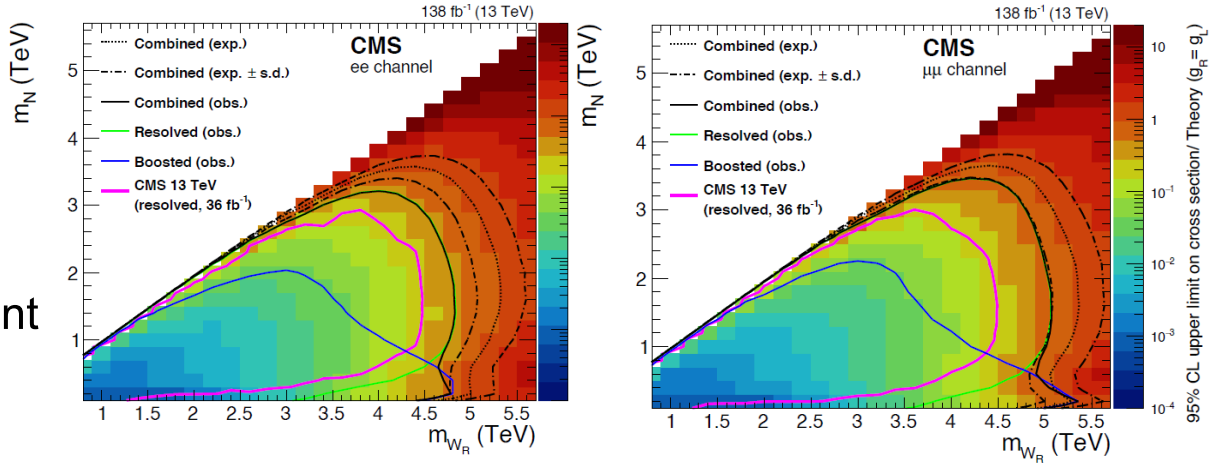


Right-handed W boson & HNLs

JHEP 04 (2022) 047

- left-right symmetric model (LRSM):
  adds $(\mathrm{W}_\mathrm{R}^{\pm}, \mathrm{Z}')$ & $(N_\mathrm{e}, N_\mu, N_\tau)$ to SM
  → W_R boson couple to right-handed HNLs
- $\mathrm{eeq\bar{q}}$ or $\mu\mu\mathrm{q\bar{q}}$ final states with
  leading (subleading) lepton $p_\mathrm{T} > 60(53)$ GeV
- 2 resolved jets $p_\mathrm{T}^j > 40$ GeV or
  1 boosted large radius jet $p_\mathrm{T}^\mathrm{J} > 200$ GeV
- background estimated from simulation
- sensitive observable: $m_{\ell\ell jj}$ or $m_{\ell\mathrm{J}}$
- limits for $m_\mathrm{N} = m_{\mathrm{W}_R}/2$:
  - electrons: $m_{\mathrm{W}_R}/2 > 4.7\ (5.2)$ TeV
  - muons: $m_{\mathrm{W}_R}/2 > 5.0\ (5.2)$ TeV
- electron channel excess most significant
  at $(m_{\mathrm{W}_R}, m_\mathrm{N}) = (6.0, 0.8)$ TeV
  $\Rightarrow 2.95\ (2.78)\sigma$ [local (global)]

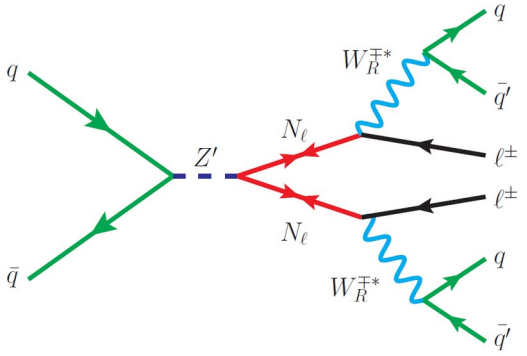


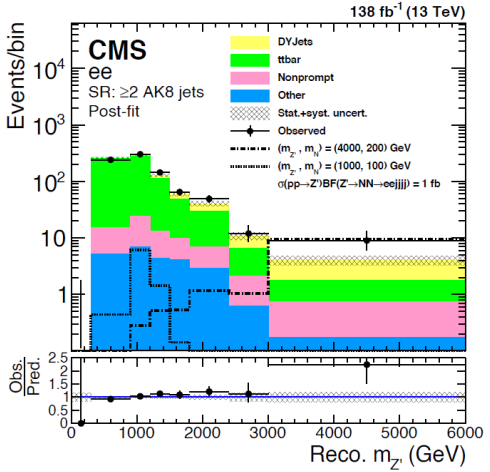


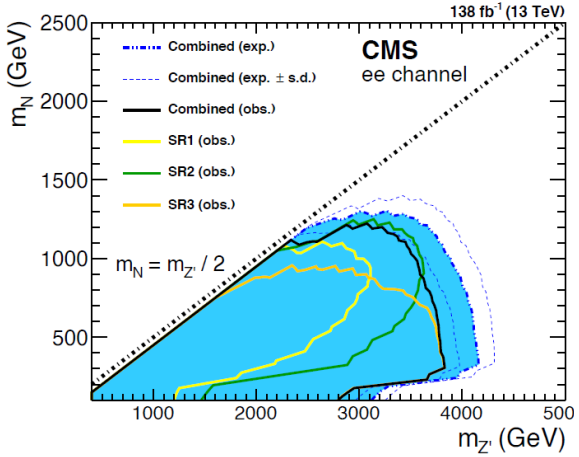
Z' boson decay to HNL pairs

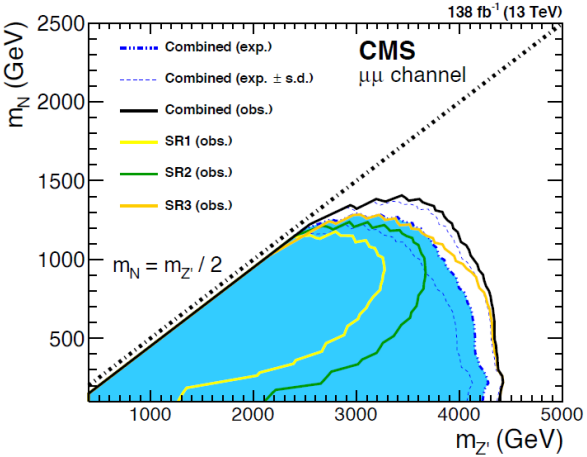
arXiv:2307.06959 [hep-ex]
(submitted to JHEP)

- LRSM model with heavy Z' boson
- OS or SS ee or $\mu\mu$ events ($p_{\mathrm{T}}^{\ell} > 65{-}75$ GeV)
- up to 4 resolved jets ($p_{\mathrm{T}} > 40$ GeV)
- 3 signal regions depending on number of large radius jets ($p_{\mathrm{T}} > 300$ GeV)
- HNL & Z' masses reconstructed from lepton+jets through kinematic considerations
- background estimated from simulation
- limits for $m_{\mathrm{N}} = m_{\mathrm{Z}'}/4$:
  - electrons: $m_{\mathrm{Z}'} > 3.59\ (3.90)$ TeV
  - muons: $m_{\mathrm{Z}'} > 4.10\ (3.86)$ TeV
- electron channel excess most significant at $(m_{\mathrm{Z}'}, m_{\mathrm{N}}) = (4.6, 0.1)$ TeV
  $\Rightarrow 3.32\ (2.28)\sigma$ [local (global)]







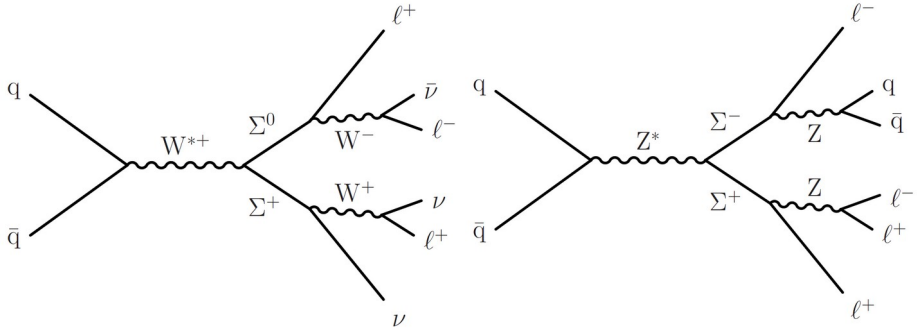


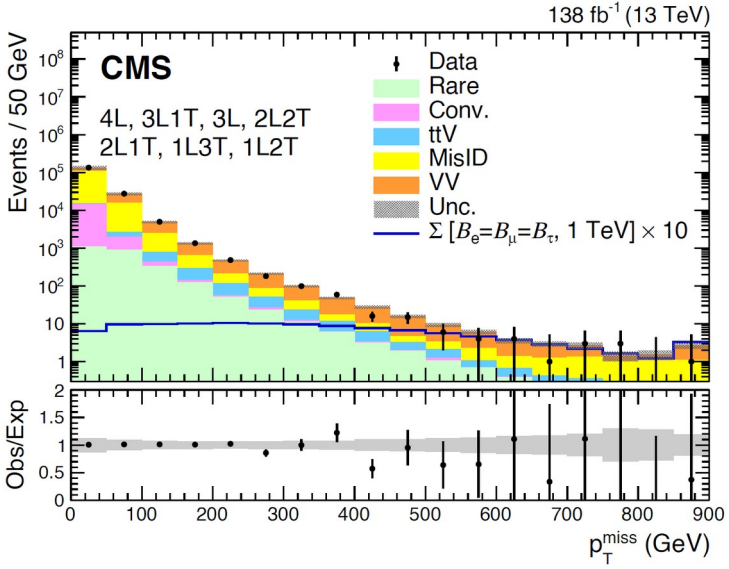
Non-resonant multileptons

Phys. Rev. D 105 (2022) 112007

- generic search for BSM events with 3-4 leptons + jets
- interpretations: TypeIII seesaw; doublet & singlet vector-like leptons; leptoquarks
- electrons/muons: $p_{\mathrm{T}} > 10$ GeV
- hadronic taus: $p_{\mathrm{T}} > 20$ GeV
- jets: $p_{\mathrm{T}} > 30$ GeV (b-tagged)
- 7 signal categories based on $N_L(\mathrm{e}/\mu)$ & $N_T(\tau)$
- further classification based on scalar momentum sums, charge/flavor combinations, jet multiplicity & kinematic properties → model-independent (used for background-only compatibility test)
- BDTs trained to enhance sensitivity for a specific model (used to derive limits)

TypeIII seesaw



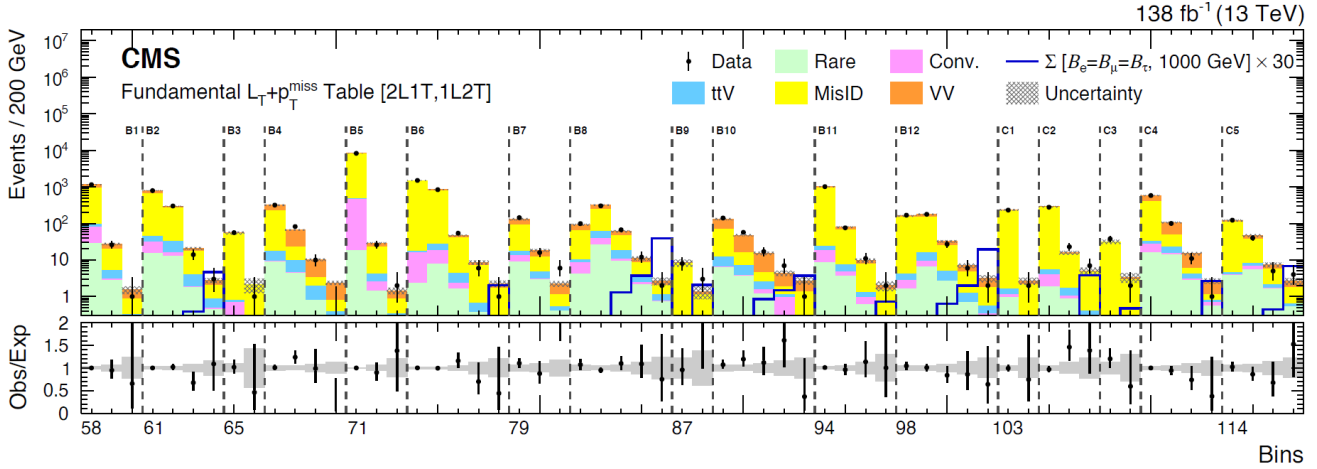


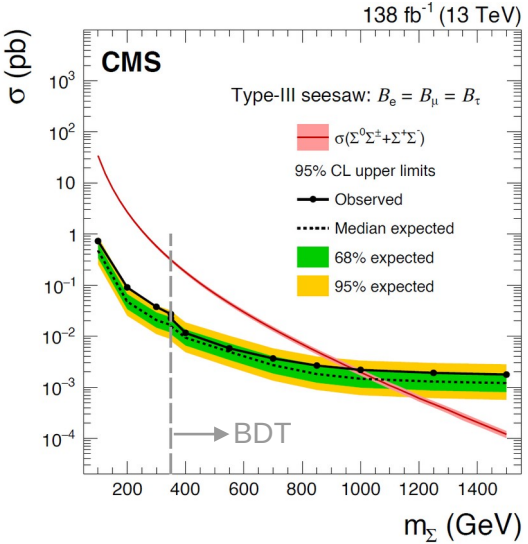
Non-resonant multileptons (2)

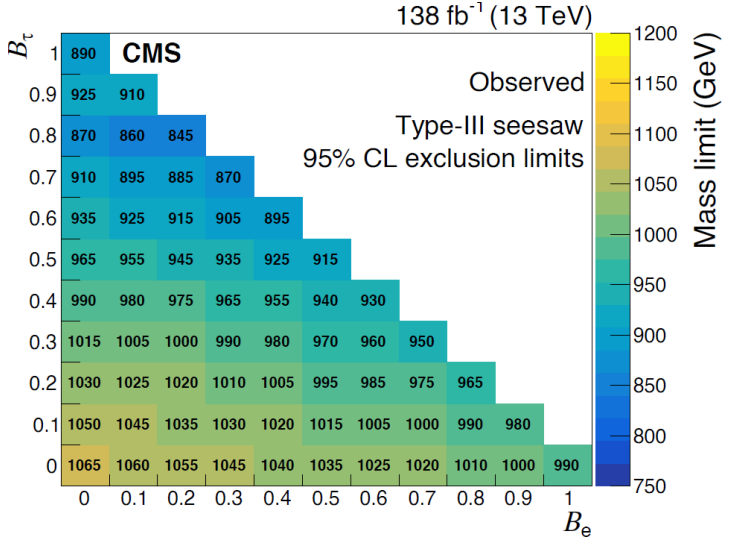
Phys. Rev. D 105 (2022) 112007

- background-only goodness of fit test on $L_{\mathrm{T}} + p_{\mathrm{T}}^{\mathrm{miss}}$ distributions
  $\Rightarrow p = 67\%$
  (good compatibility also for other binning schemes)

- limits on type-III seesaw for flavor-democratic couplings
  $m_{\Sigma} > 980\ (1060)\ \mathrm{GeV}$ [obs(exp)]

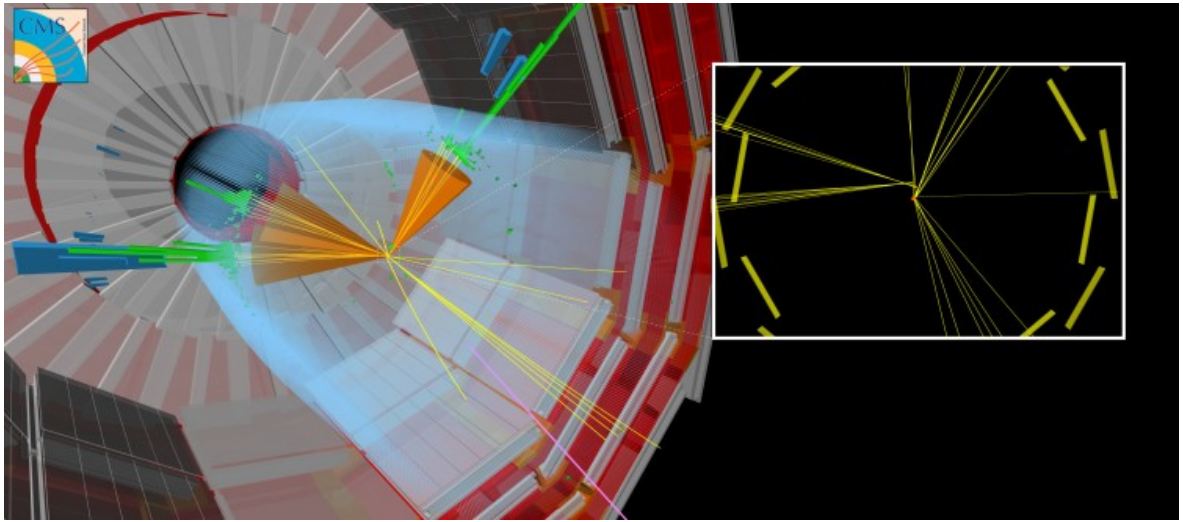






Searches for long-lived HNLs

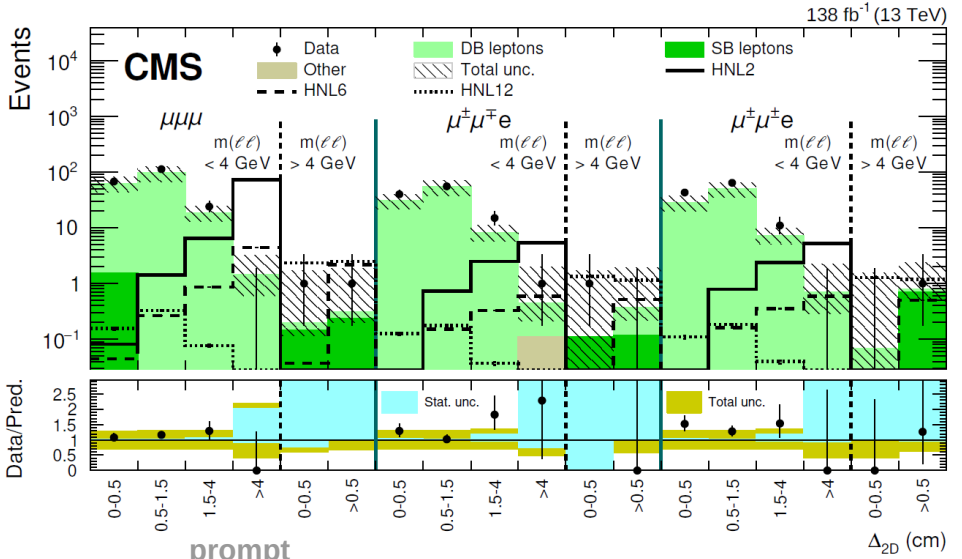
https://cms.cern/news/using-artificial-intelligence-search-new-exotic-particles

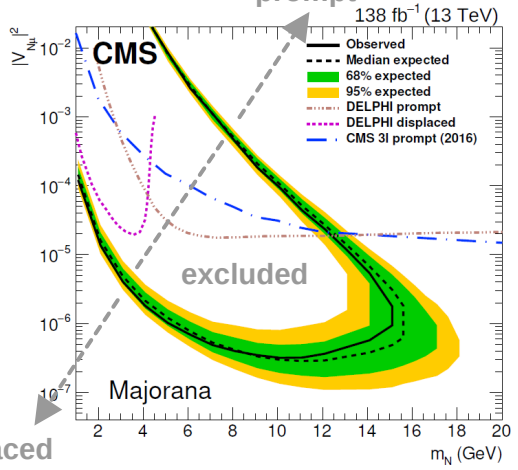


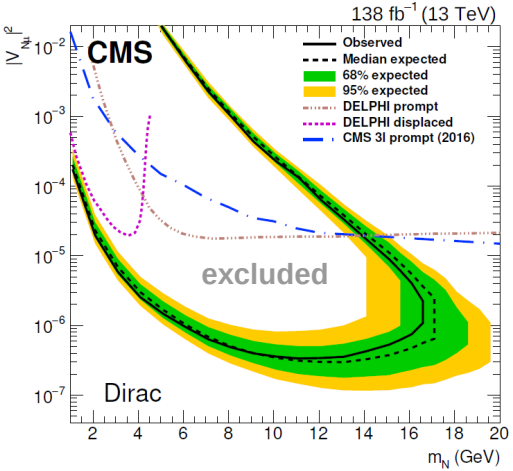
Long-lived HNL in 3 lepton events

JHEP 07 (2022) 081

- HNL-lepton coupling can be arbitrary small $\tau_0 \propto m_{\mathrm{N}}^{-5} \, |V_{\mathrm{N}\ell}|^{-2}$ → long-lived for ~GeV mass
- HNL can travel macroscopic distances away from production vertex → unique signature
- focus on $\mathrm{pp} \to \mathrm{W} \to \ell\mathrm{N}, \; \mathrm{N} \to \ell\ell\nu \;\; (\ell \in \{\mathrm{e}, \mu\})$
  - 1 prompt lepton ($p_{\mathrm{T}} > 25{-}32$ GeV)
  - 2 displaced leptons ($p_{\mathrm{T}} > 5{-}7$ GeV) forming a secondary vertex
- background with 1 or 2 misidentified leptons estimated from data (fake-rate method)
- limits derived on Majorana & Dirac HNLs using displacement of vertex & dilepton mass
- for $m_{\mathrm{N}} = 10$ GeV can exclude
  - $9.1 \times 10^{-7} < |V_{\mathrm{Ne}}|^2 < 1.7 \times 10^{-4}$
  - $3.6 \times 10^{-7} < |V_{\mathrm{N}\mu}|^2 < 2.3 \times 10^{-4}$



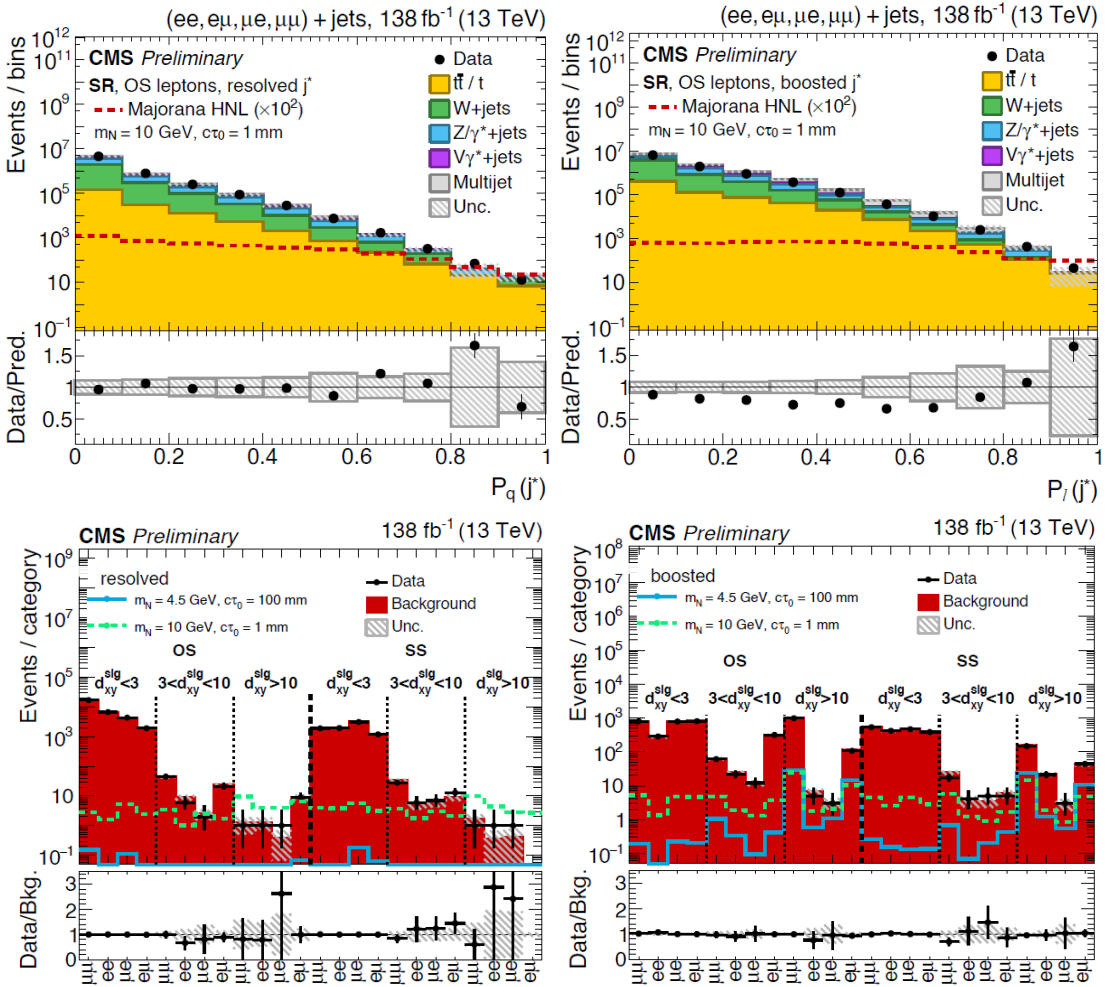




Long-lived HNL in 2 lepton events

CMS-PAS-EXO-21-013

- 2 lepton (electron or muon) events
  $pp \to W \to \ell_1 N,\ N \to \ell_2 q\bar{q}$
  → orthogonal to search in 3 lepton events
- jets $p_T > 20{-}30$ GeV (boosted = ℓ inside)
- special neural network based displaced jet tagger trained on jet constituent features
- domain adaptation uses data from control region → good modeling of output scores
- events categorized in lepton flavor/charge combinations & significance of $d_{xy}(\ell_2)$
- background estimated from data in tagger & $m_{\ell\ell j}$ sideband (ABCD method)

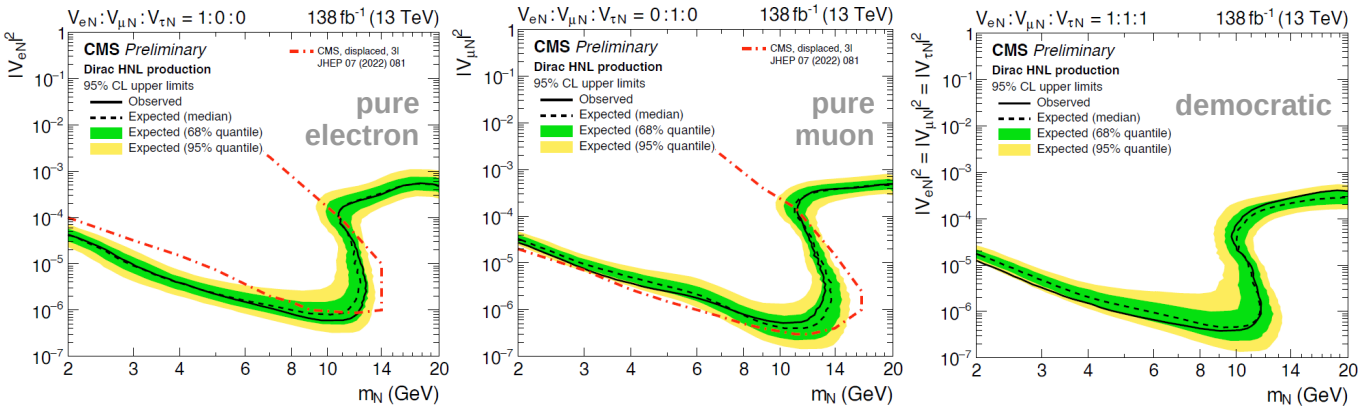


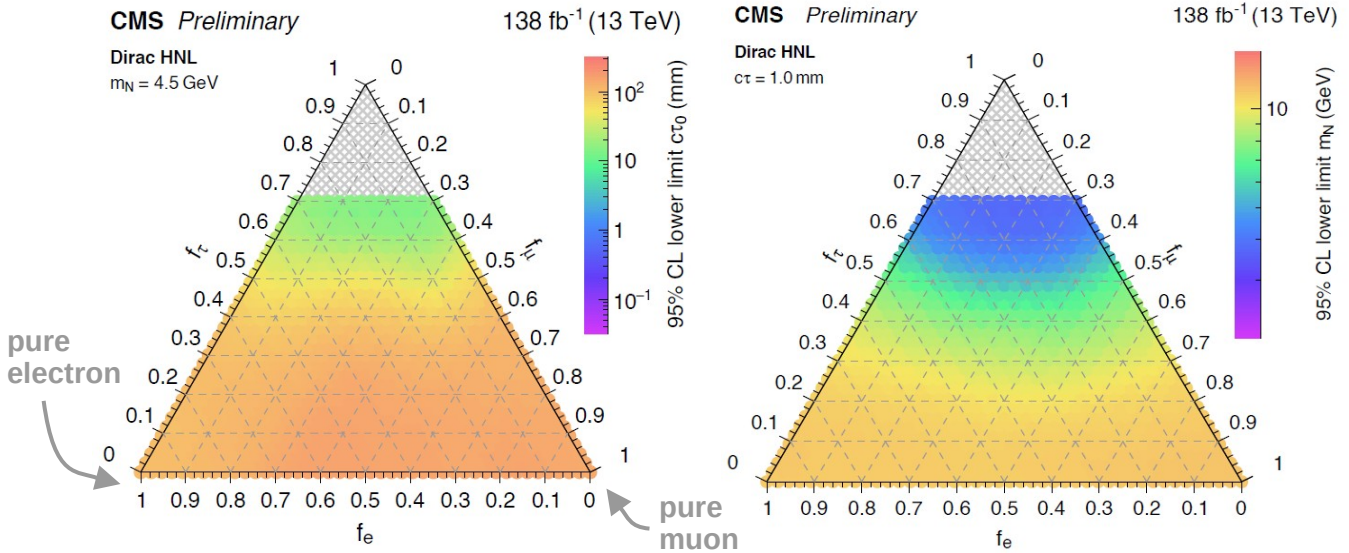
Long-lived HNL in 2 lepton events (2)

CMS-PAS-EXO-21-013

- probe for arbitrary coupling to all 3 lepton generations by reweighting signal simulation
- best limit for $m_{\mathrm{N}} = 10\ \mathrm{GeV}$
  $|V_{\mathrm{N}\mu}|^2 < 5\ (4) \times 10^{-7}$
  [Dirac (Majorana)]

- probe HNL scenarios in relative coupling plane for fixed mass or lifetime
- pure tau coupling to be investigated

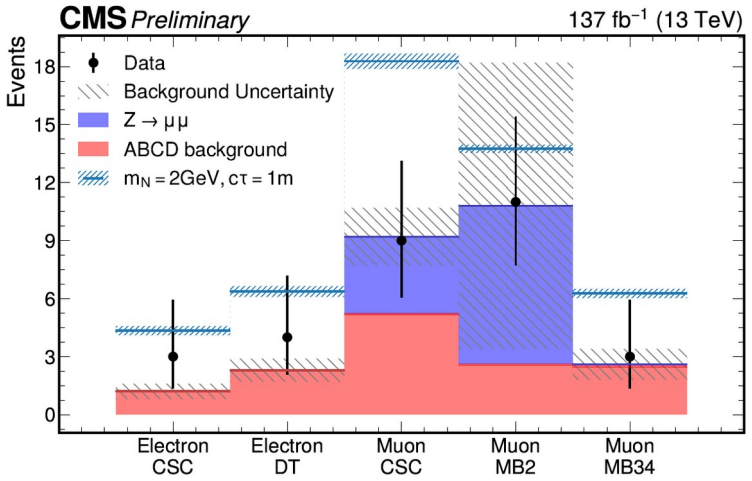




Type I HNLs in muon system

CMS-PAS-EXO-22-017

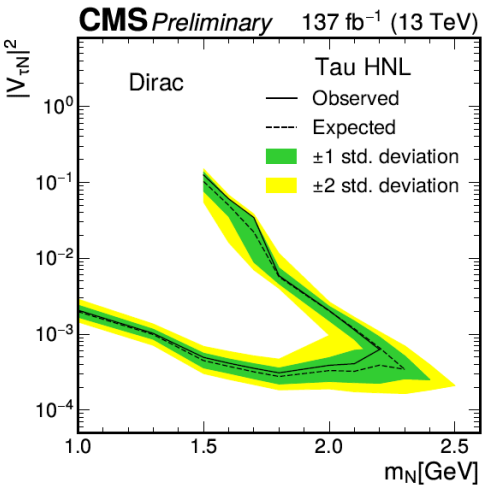
- idea: HNL decays in CMS muon system ($4 < r < 7$ m)
- focus on $\mathrm{pp} \to \mathrm{W} \to \ell\mathrm{N},\ \mathrm{N} \to$ muon system hit cluster (no reconstruction of 2nd lepton from HNL decay)

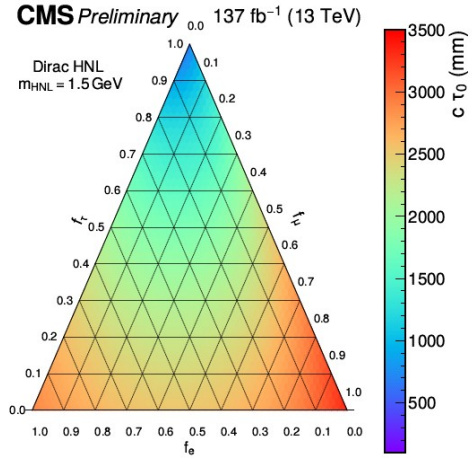


- 1 electron or muon: $p_{\mathrm{T}} > 25{-}35$ GeV
- veto jets overlapping with muon clusters
- events categorized in lepton flavor & muon subsystem
- nonprompt background estimated from data using $\Delta\phi(\ell, \mathrm{cluster})$ & N_{hits} sideband (ABCD)

- limits derived for $1 < m_{\mathrm{N}} < 4$ GeV
  - best electron: $8.6 \times 10^{-6} < |V_{\mathrm{Ne}}|^2$ (@2.6 GeV)
  - best muon: $4.6 \times 10^{-6} < |V_{\mathrm{N}\mu}|^2$ (@2.8 GeV)

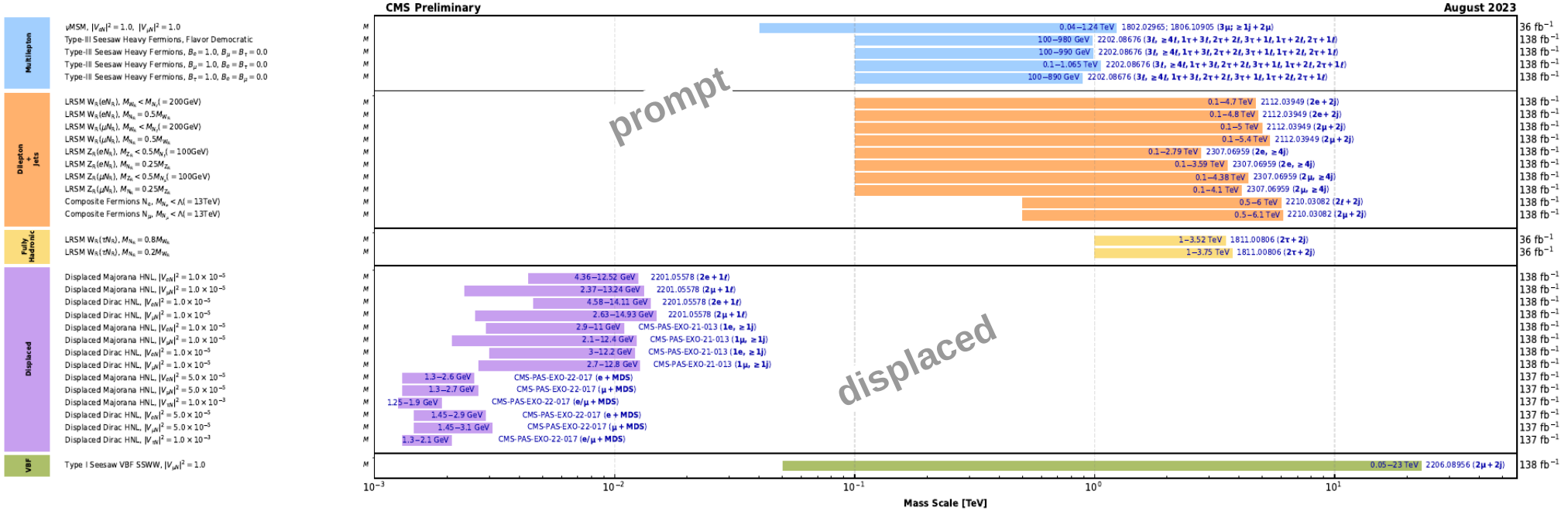
- limits with arbitrary coupling to all 3 lepton generations





HNL results by CMS at glance

- 95% CL limits on HNL mass for various scenarios

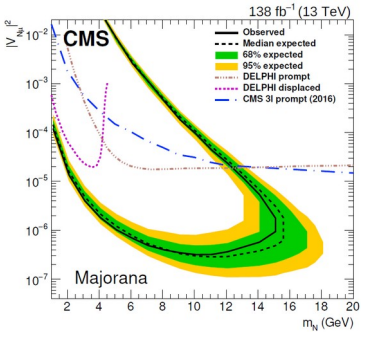


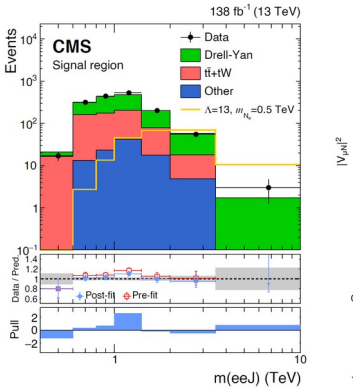
https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#Heavy_Neutral_Lepton_summary_plo

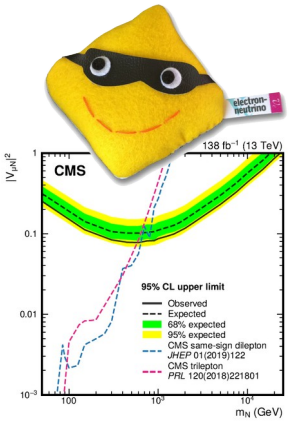
Summary

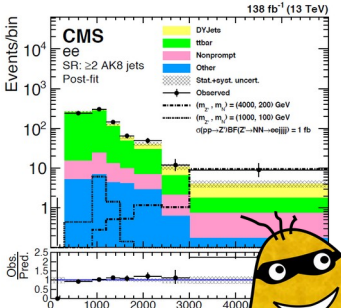
- LHC Run 2 data analyzed!
- rich experimental signatures investigated
  - resolved / boosted jets
  - prompt and/or flavor-violating HNLs
  - vector boson fusion
  - models with right-handed W,Z bosons
  - long-lived, displaced HNLs
- more to explore
  - comprehensive analysis of coupling to 3rd generation
  - complementary production or decay mechanisms
  - displaced signatures

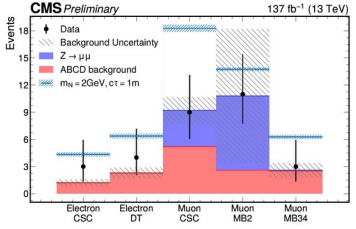
→ stay tuned!

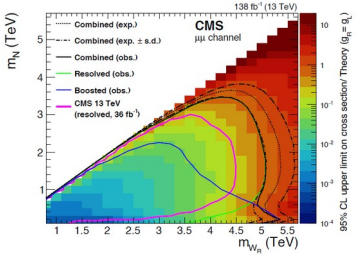


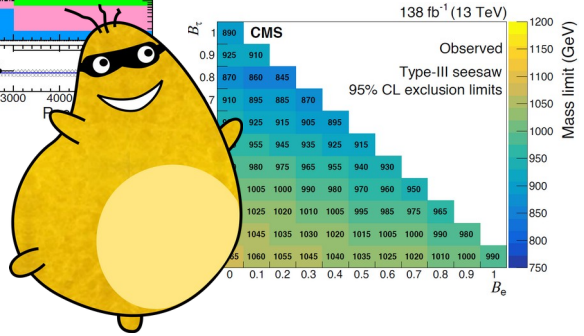


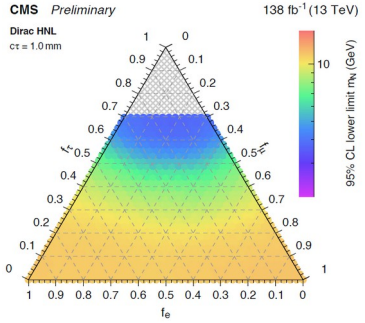












Backup

Type I HNL production/decay

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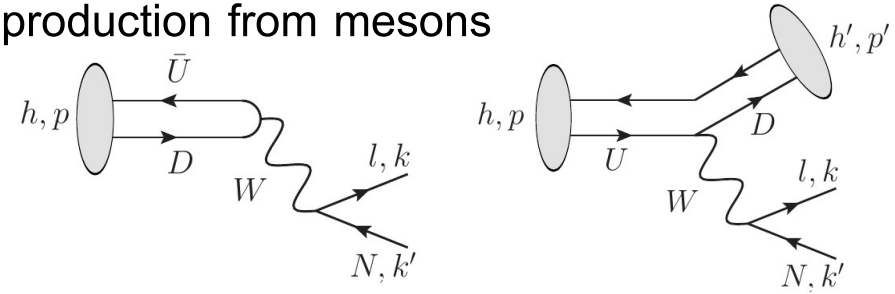
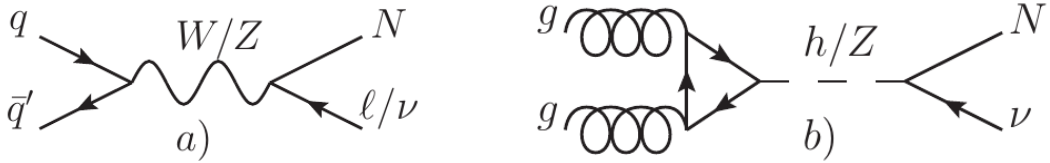
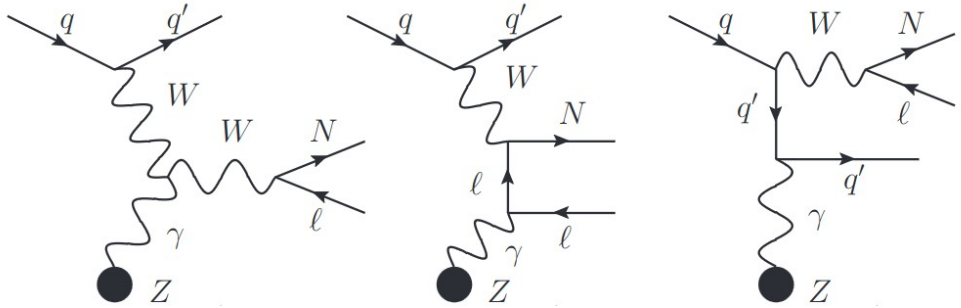
- production from mesons

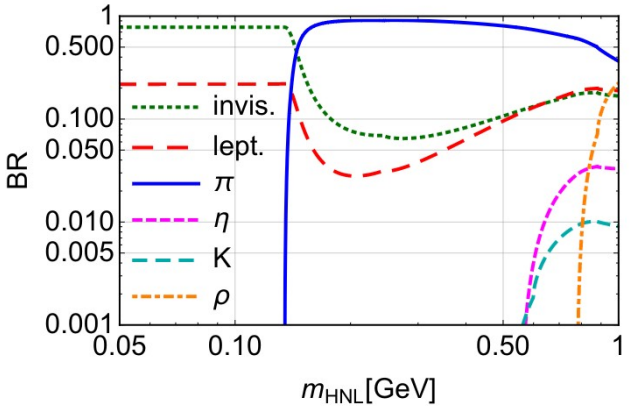


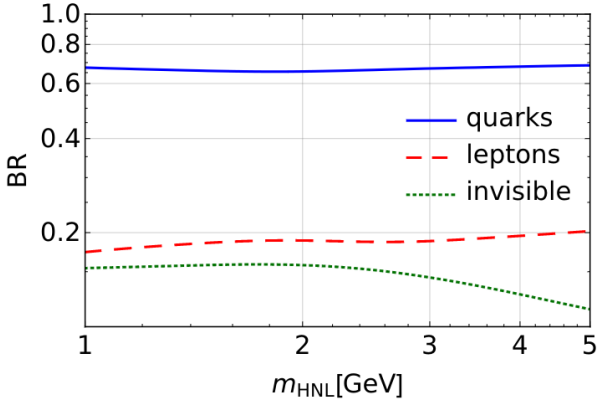
- production from quarks/gluons



- production from proton-nuclei scattering







Heavy right-handed W boson & HNL

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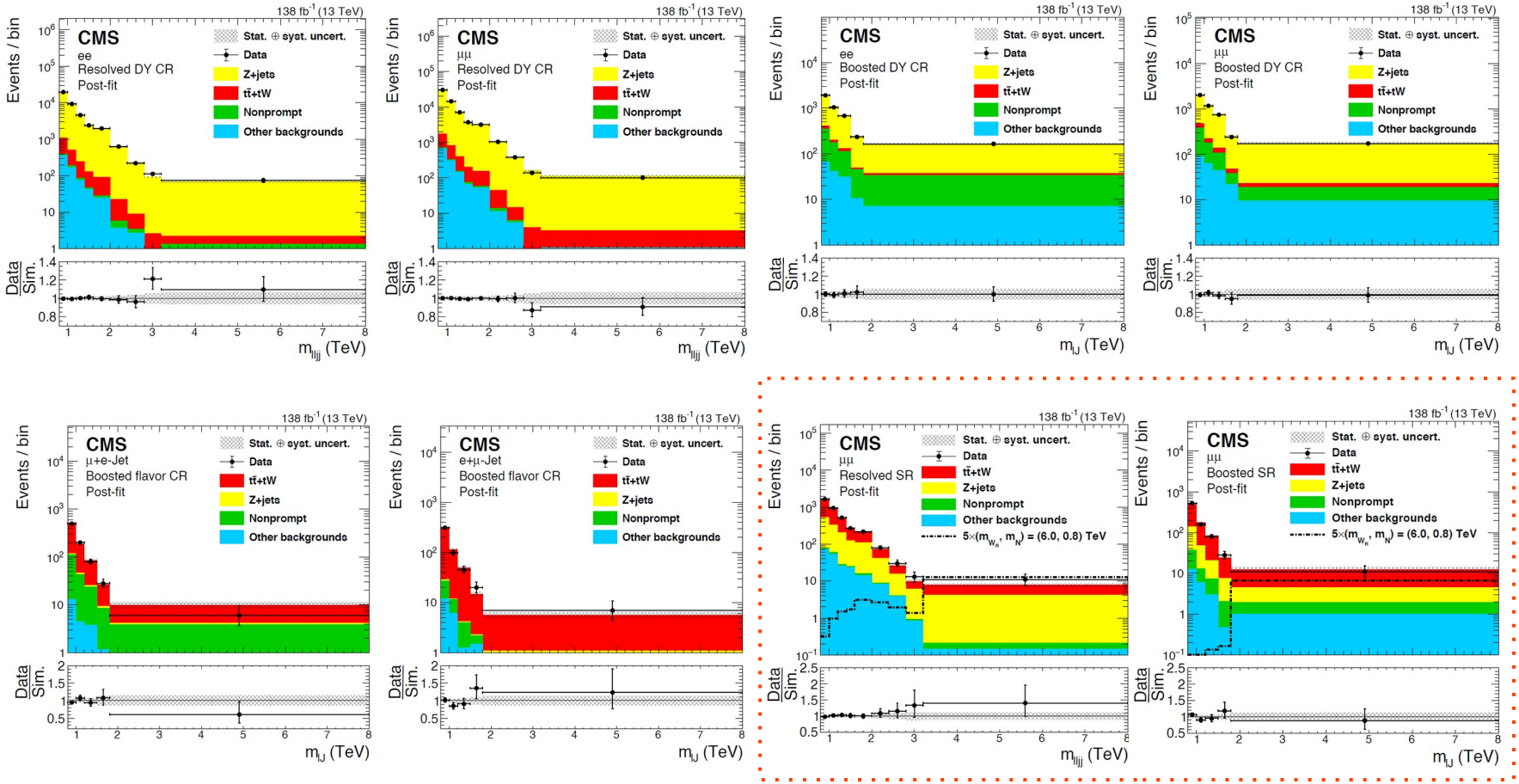
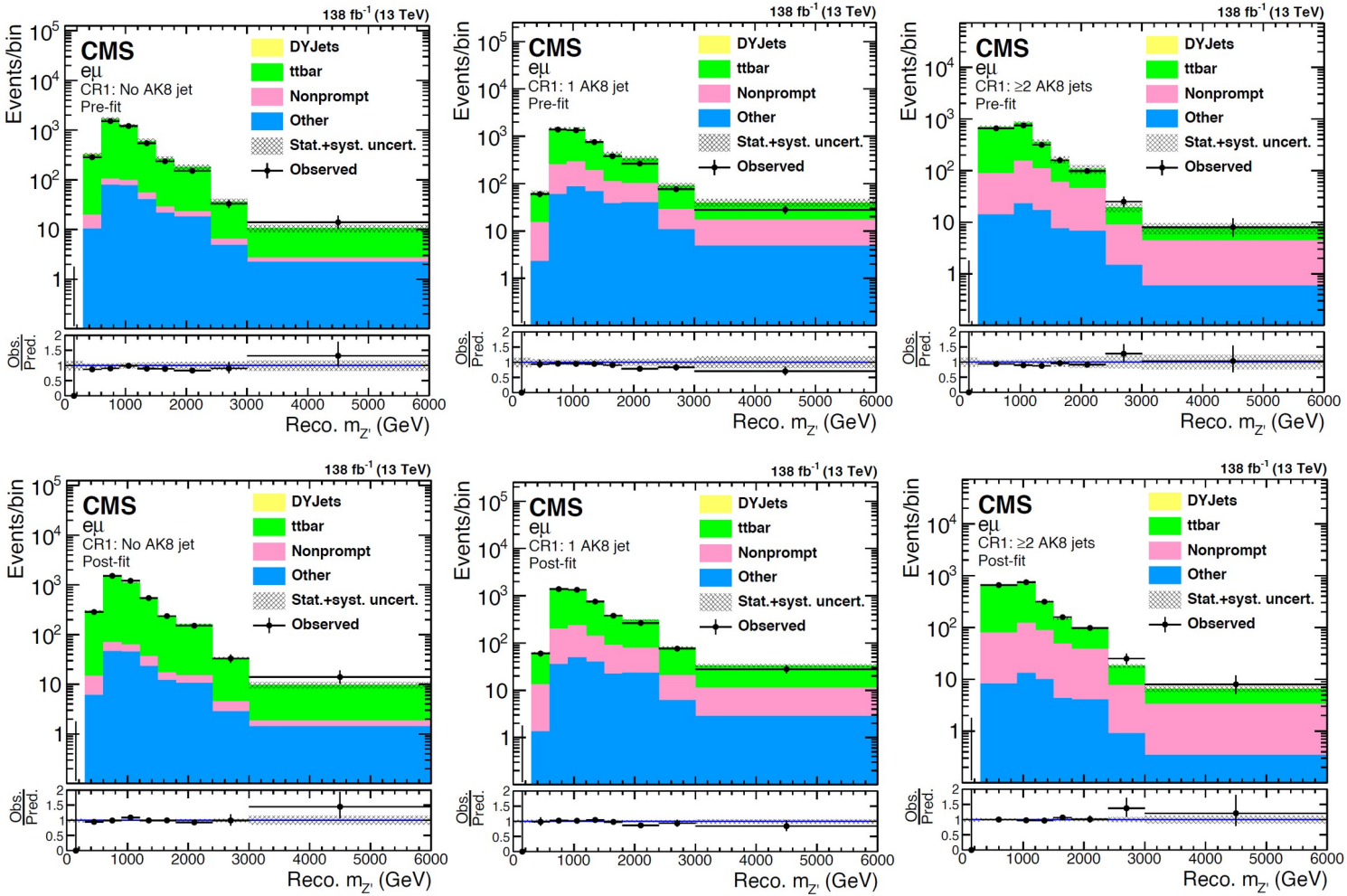


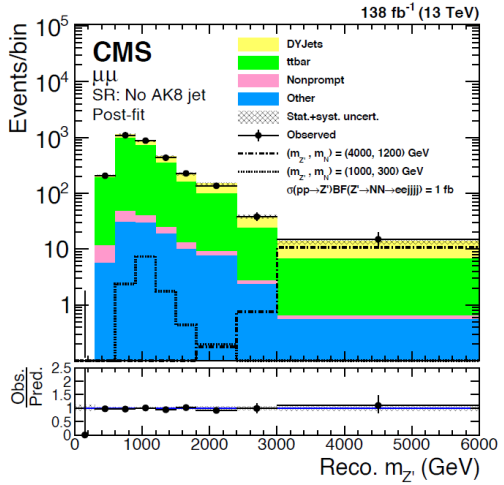
Z' boson decay to HNL pairs: CR

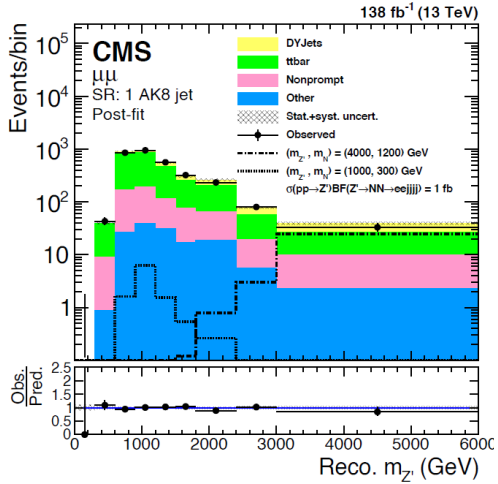
arXiv:2307.06959 [hep-ex]
(submitted to JHEP)

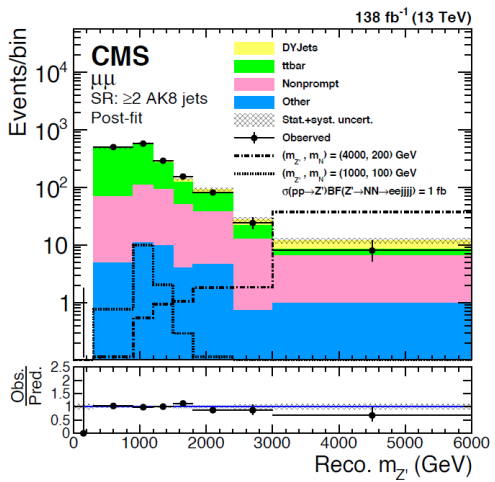


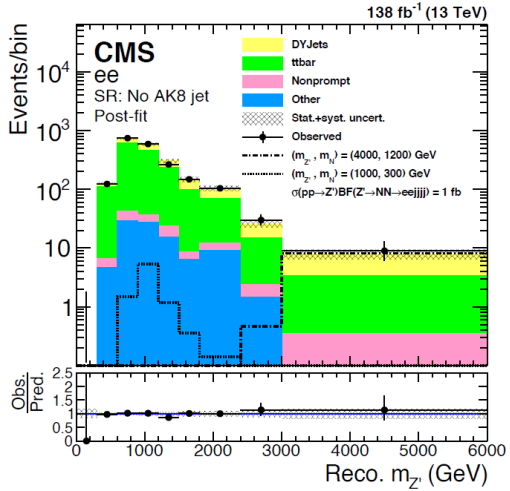
Z′ boson decay to HNL pairs: SR

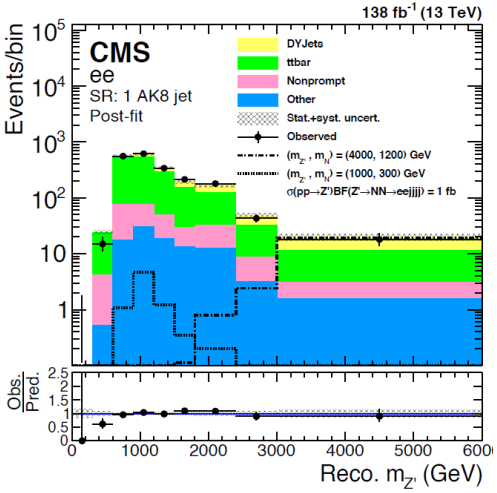
arXiv:2307.06959 [hep-ex]
(submitted to JHEP)

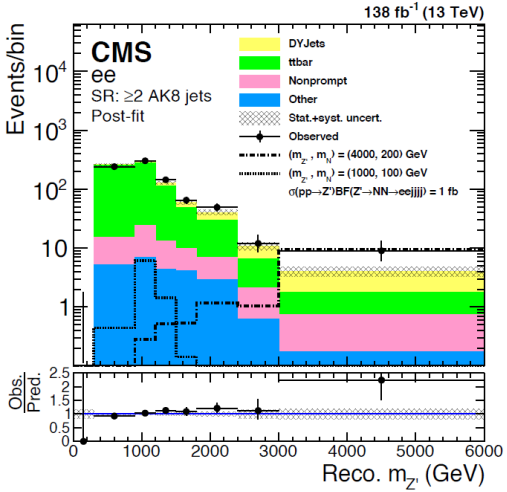






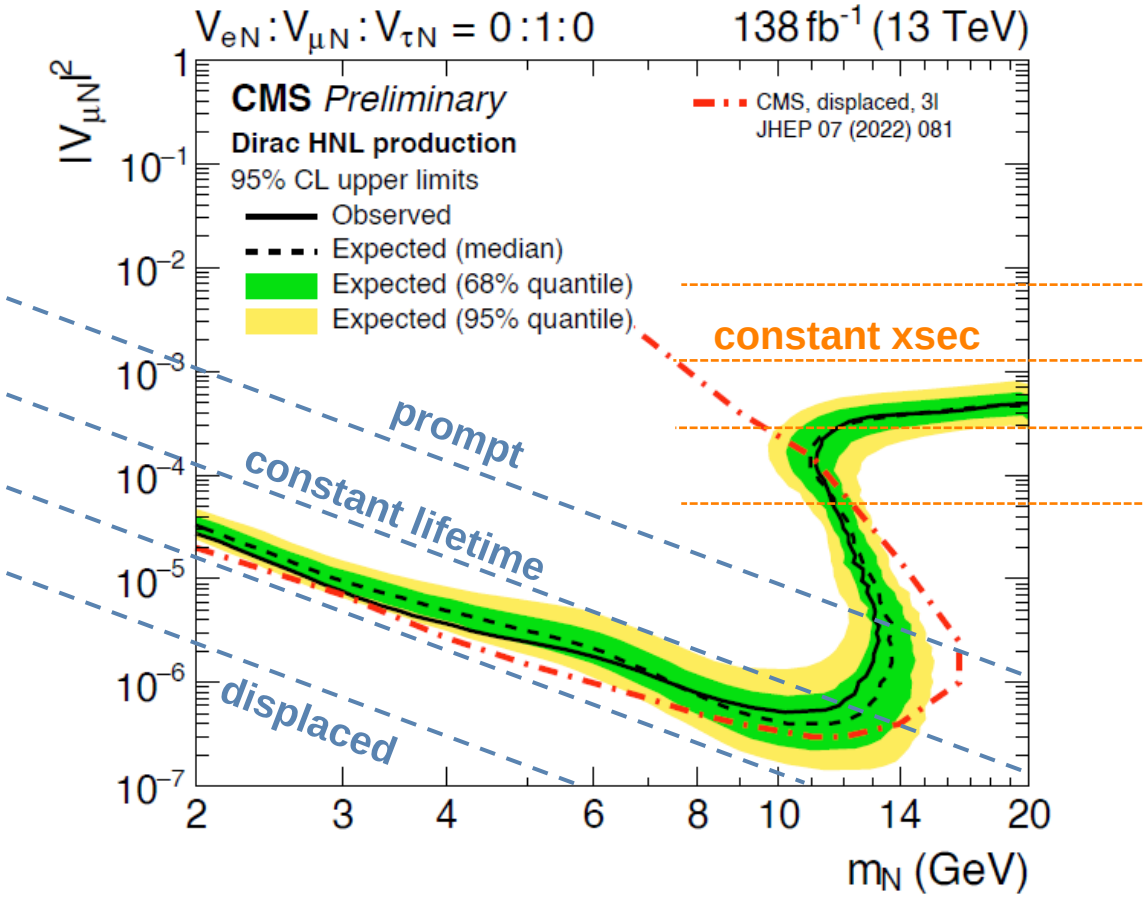






Limit shape

CMS-PAS-EXO-21-013



Displaced jet tagger

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