

Searches for Heavy Neutral Leptons in CMS

Recent results

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Why Heavy Neutral Leptons?

Motivation for HNL searches at CMS

- Explanation for low masses of SM ν
→ Seesaw mechanism
- Majorana HNL allow for Lepton Number Violation
→ Leptogenesis and baryogenesis
→ Matter-antimatter asymmetry
- Dark matter candidate in specific circumstances
- Appealing because simple and 'obvious' addition to SM
- Appears in a large variety of models, there is still uncovered phase space
- Kinematics highly dependent on m_N and model specifics, leading to variety of searches

Three Generations of Matter (Fermions) spin $\frac{1}{2}$											
		I		II		III					
mass →		2.4 MeV	1.27 GeV	173.2 GeV							
charge →		$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$							
name →		u	c	t							
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	
Quarks		up	charm	top							
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	
	down	strange	bottom								
	-1/3	-1/2	-1/2								
Leptons		ν_e	ν_μ	ν_τ							
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	
	0.511 MeV	~GeV	~GeV	~GeV							
	-1	-1	-1	-1							
	e	μ	τ								
	electron	muon	tau								
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	

Bosons (Forces) spin 1

g	0	0	0	0	0	0	0	0	0	0	0
gluon											
γ	0	0	0	0	0	0	0	0	0	0	0
photon											
Z^0	0	0	0	0	0	0	0	0	0	0	0
weak force											
W^\pm	±1	0	0	0	0	0	0	0	0	0	0
weak force											
H	126 GeV	0	0	0	0	0	0	0	0	0	0
Higgs boson											
spin 0											

New Heavy Neutral Lepton searches

Lots of activity around HNLs in CMS over the past year

- Heavy Composite Majorana Neutrino
 - Test of composite-fermion model
 - Longlived HNL in type-1 Seesaw Model
 - displaced signature very sensitive for low HNL masses $\sim \text{GeV}$
 - Heavy Majorana Neutrinos (and Weinberg operator) through Vector boson fusion
 - reaches very high HNL mass, up to 23 TeV
 - Right-handed W decaying to HNL
 - Most stringent limits on m_{W_R} to date
 - Z' decaying to HNL
 - Most stringent limits in $m_{Z'}$ vs m_N plane
- All with full Run 2 data

Heavy Composite Majorana Neutrino

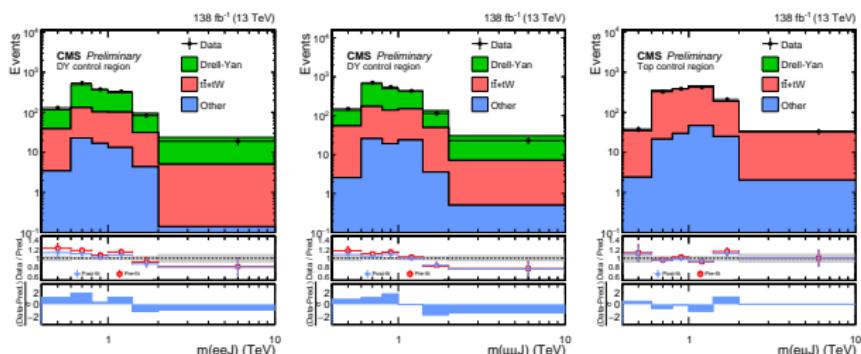
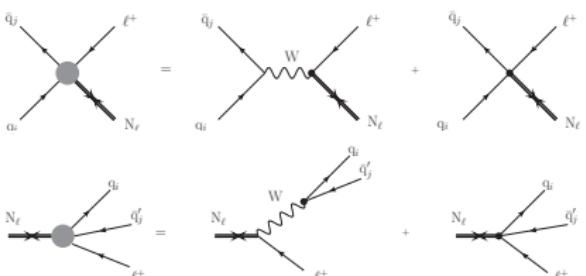
PAS-EXO-20-011

Composite-fermion model

- Heavy Majorana neutrino as an excited state of ν
- Include both gauge and **contact-interactions**
- $m_N = [0.5, 8] \text{ TeV}$, $\Lambda = [1, 20] \text{ TeV}$
- Optimized with **unitarity bounds** in mind

high- p_T dileptons + large-radius jet

- ee or $\mu\mu$, $p_T^l > 150$ (100) GeV, $m(l\bar{l}) > 300$ GeV
- 1 large-radius jet (anti- k_T with $R=0.8$)



Shape analysis in $m(l\bar{l}J)$

- Drell-Yan and Top as main backgrounds, estimated from simulation
- Dedicated control regions

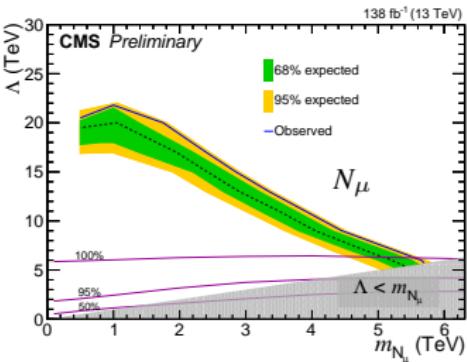
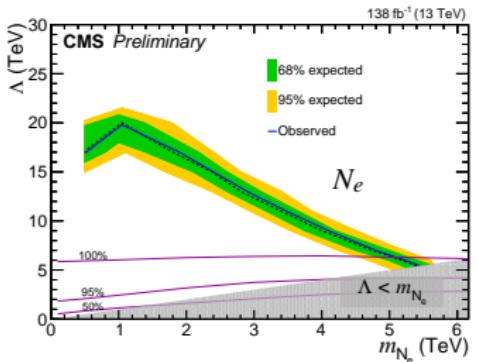
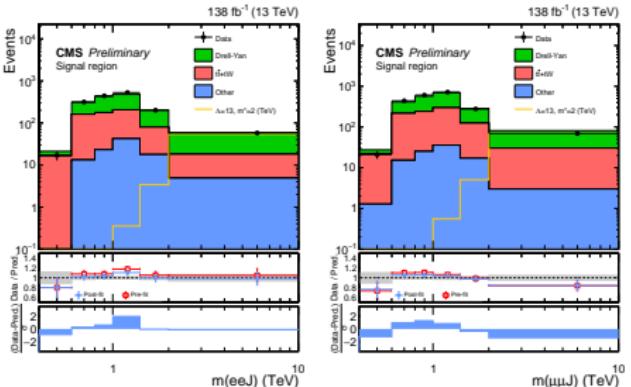
Heavy Composite Majorana Neutrino

Uncertainty

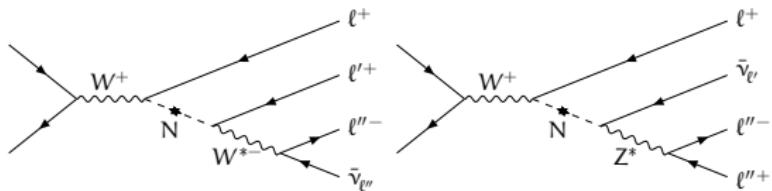
- dominated by statistical unc. from limited size of MC samples for background estimation

Results

- No significant excess observed
- At $\Lambda = m_N$, $N_e(N_\mu)$ excluded up to 5.5(5.7) TeV (1 TeV improvement)
- With unitarity bounds, up to 5.1(5.5) TeV



Long-lived HNL with displaced vertex



Type-1 Seesaw HNL model

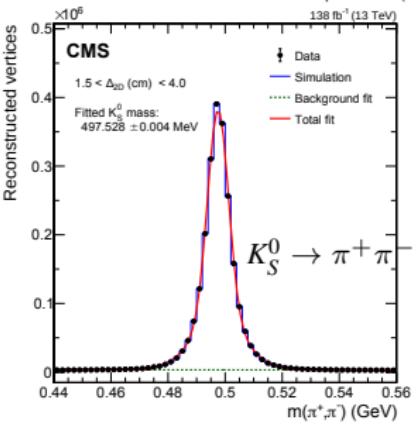
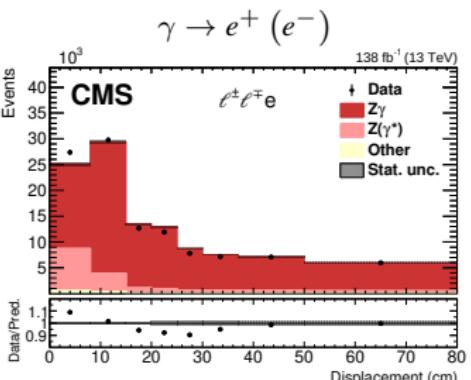
- Produced via $\nu - N$ mixing with coupling strength $|V_{IN}|^2$
- Naturally becomes longlived for $m_N < 20$ GeV
 $\rightarrow \tau_N \sim |V_{IN}|^{-2} M_N^{-5}$
- Consider LNV (Majorana) and LNC final states

Prompt lepton + Displaced vertex with 2 leptons

- Focus on displacements **within CMS tracker**
 \rightarrow well reconstructed displaced leptons
- reconstruct **vertex** from displaced lepton pair
 Δ_{2D} = transverse displacement of vertex

Validation of displaced reconstruction

- Displaced e : asymmetric photon conversions
- Displaced μ : J/ψ and K_S^0 decays



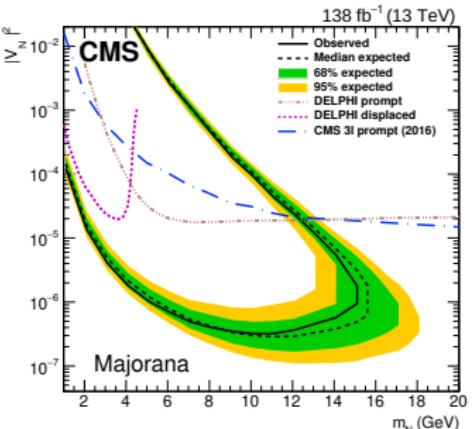
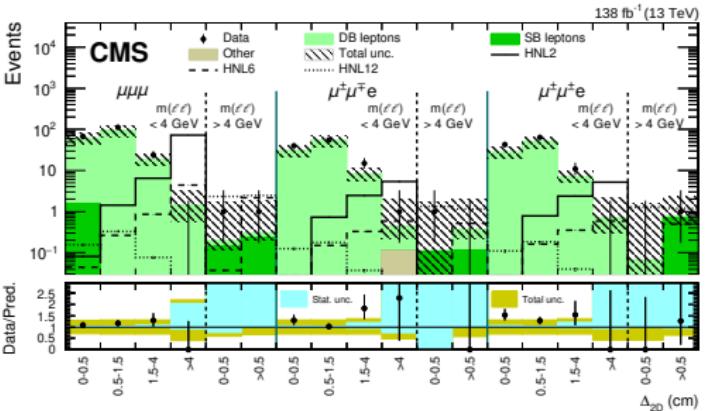
Long-lived HNL with displaced vertex

Data-driven Background Estimation

- Tight-to-loose ratio with lepton isolation
- Single Background(SB) leptons = uncorrelated sources for the leptons
- Double Background(DB) leptons = leptons produced in same decay chain → close together

Results

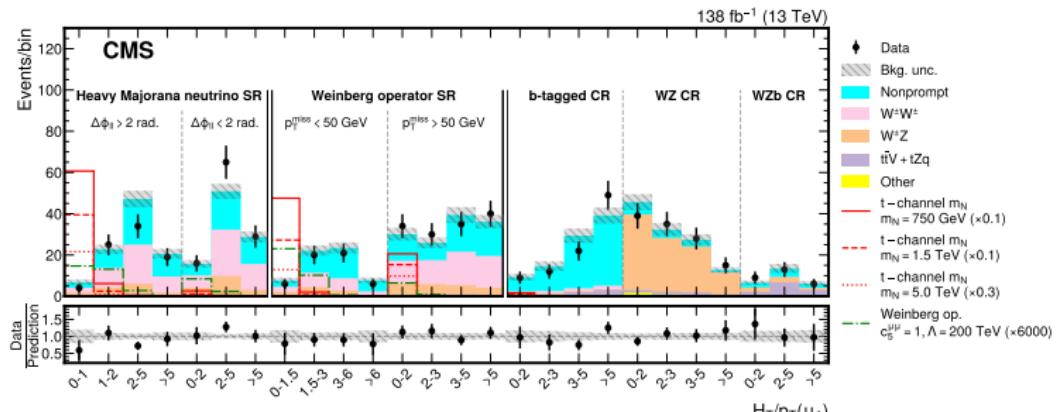
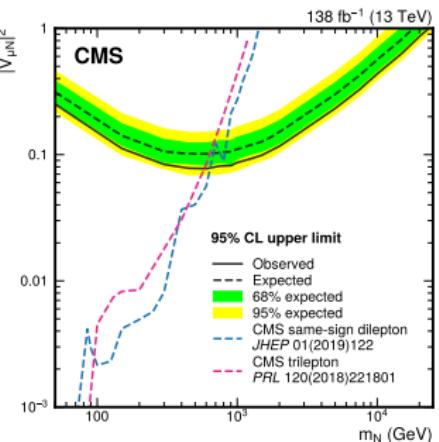
- No significant excess observed
- Dirac and Majorana interpretation
- Consider N coupling purely to e or μ
- Towards high couplings, HNL becomes prompt and exclusion curve closes



HNL and Weinberg operator through VBF

Covered in E. Tziaferis talk this morning:
New physics in final states with jets

- Type-1 Seesaw HNL model
- Same-sign muons + VBF jets
- Large new mass-range excluded up to 23 TeV
 → Thanks to VBF production and optimization
- Most stringent limits beyond 650 GeV
- First test of Weinberg operator at collider: exclude effective $\mu\mu$ Majorana neutrino mass up to 10.8 GeV



W_R to Heavy Neutral Leptons

EXO-20-002

Left-right symmetric model

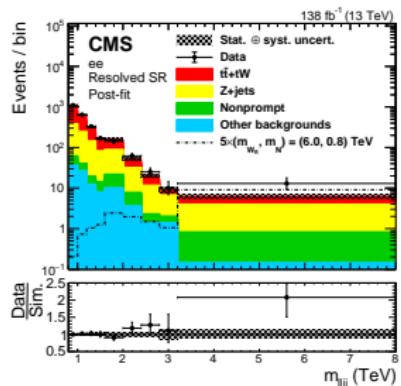
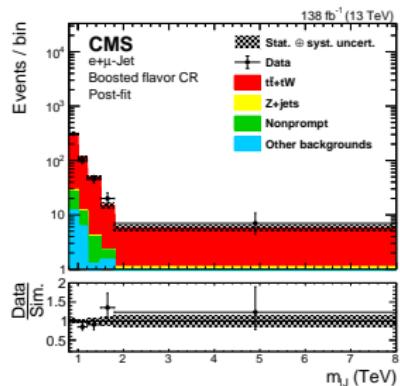
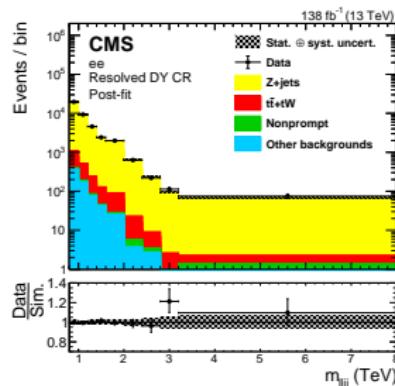
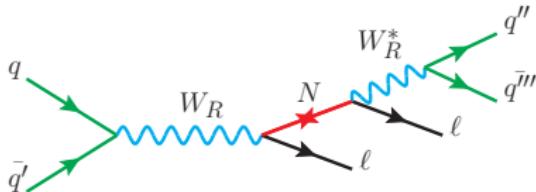
- Explain parity violation in the SM
- Resolved and boosted scenarios based on mass difference $m_{W_R} - m_N$

Resolved: 2 leptons + 2 jets

- Isolated high- p_T jets and leptons

Boosted: 2 leptons + 1 Large-radius jet

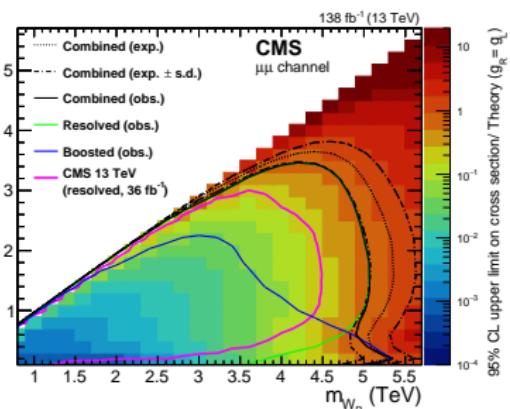
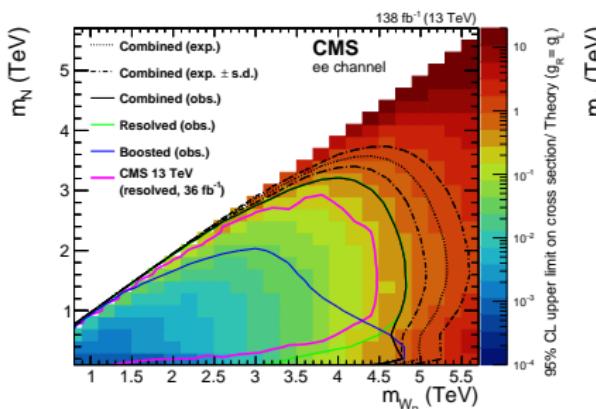
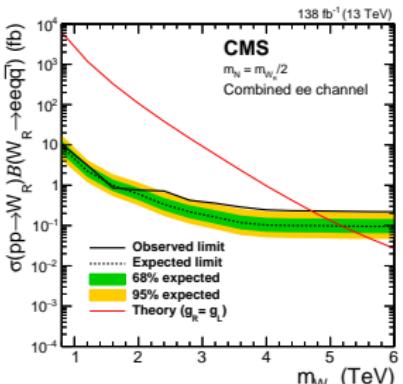
- Second lepton inside large-radius jet (anti- k_T with $R=0.8$)
- Lepton subjet fraction algorithm checks consistency of jet with three subjets (ℓ, q, q')
 → Shape analysis in reconstructed m_{W_R}



W_R to Heavy Neutral Leptons

Results

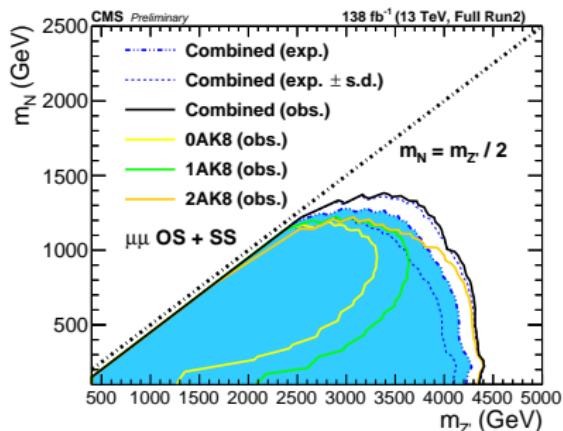
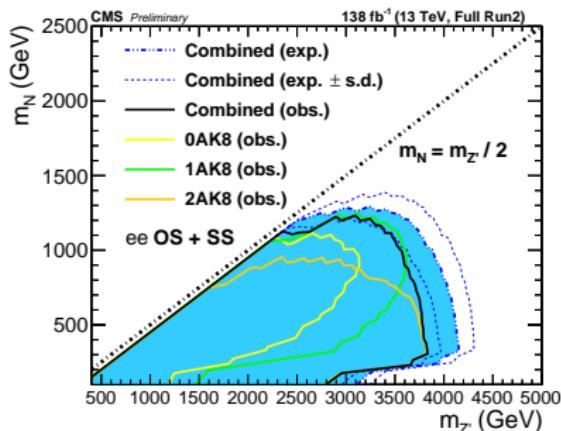
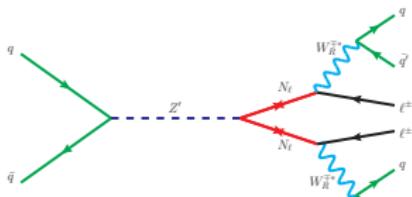
- No significant excess is observed
- But slight excess in ee channel: highest local(global) significance of $2.95\sigma(2.78\sigma)$ for $(m_{W_R}, m_N) = (6.0, 0.8)$ TeV
- At $m_N = m_{W_R}/2$, excluded m_{W_R} up to $4.7(e)$ and $5.0(\mu)$ TeV
- At $m_N = 0.2$ TeV, excluded m_{W_R} up to $4.8(e)$ and $5.4(\mu)$ TeV
- Boosted category provides big improvement with low m_N
- Most stringent limits on W_R mass to date



$Z' \rightarrow \text{HNL pair}$

PAS-EXO-20-006

- LRSM model with $Z'(400 \text{ GeV} - 4.4 \text{ TeV})$ decaying to right-handed neutrinos ($100 \text{ GeV} - m_{Z'}/2$)
- OS and SS lepton pair (ee or $\mu\mu$) + jets
 → categories for 0, 1 and 2+ large-radius jets (AK8)
 → cover boosted and resolved scenarios
- Shape analysis in reconstructed $m_{Z'}$
- No significant excess is observed
- For $m_N = m_{Z'}/4$, exclude $m_{Z'}$ up to 3.87 TeV (e and μ)
- Most stringent limits to date in $m_{Z'}$ vs m_N plane

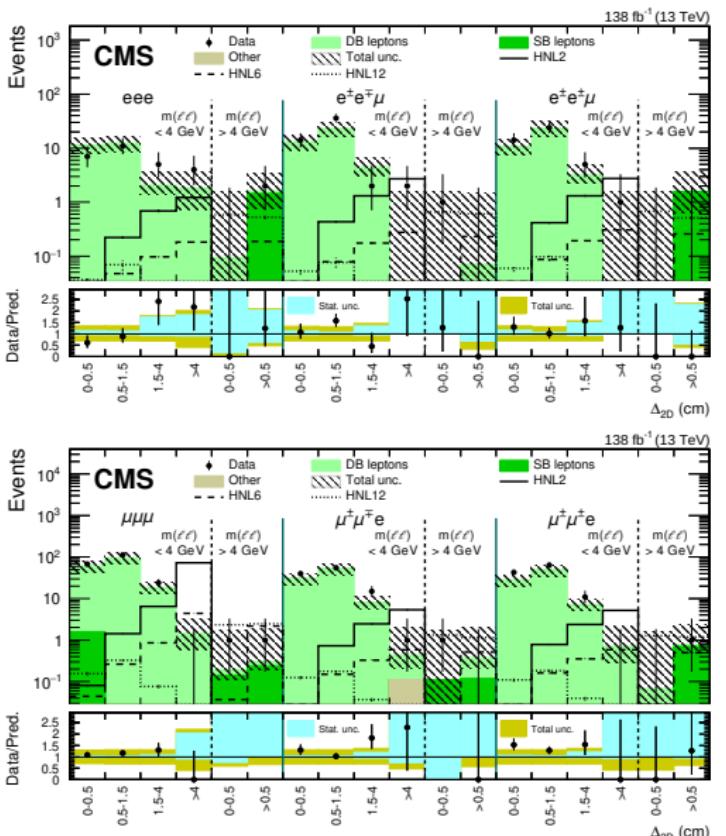


Conclusion

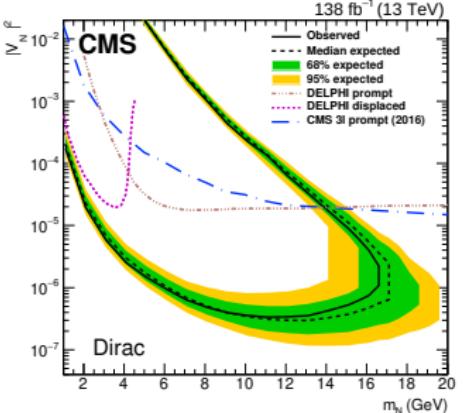
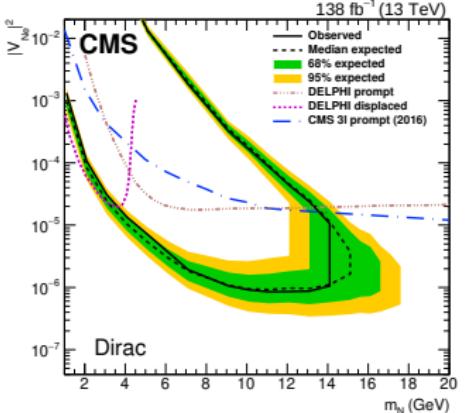
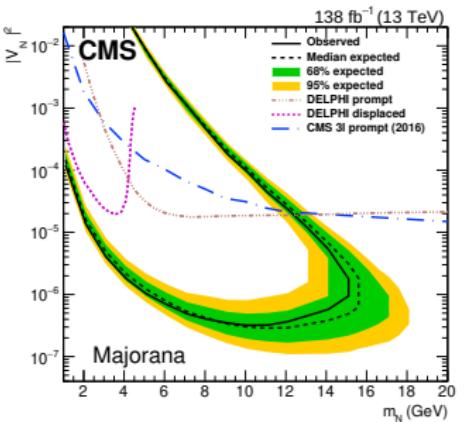
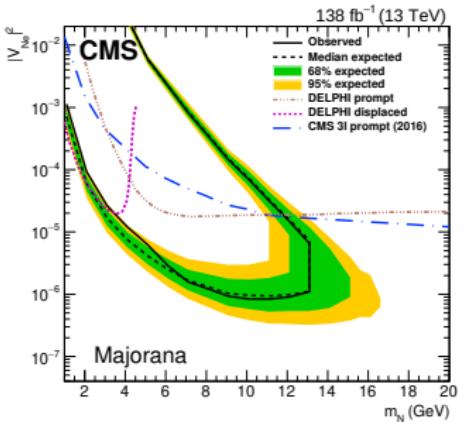
- Heavy Neutral Leptons remain a **very active** topic of research
- CMS achieves impressive constraints in these Heavy Neutral Lepton searches with **full Run 2 data**
- Several HNL analysis still in the pipeline with Run 2 data
- **Run 3 will improve further** on existing techniques
 - New triggers
 - New reconstruction techniques
 - More creative ideas
- Exciting times for HNL enthusiasts!

Backup

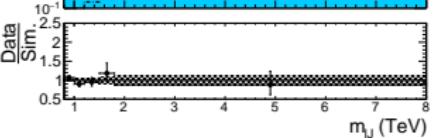
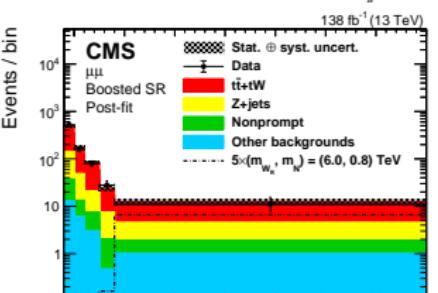
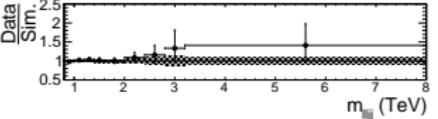
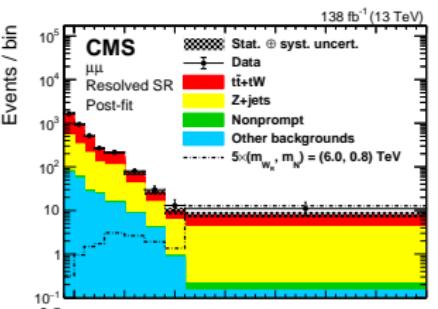
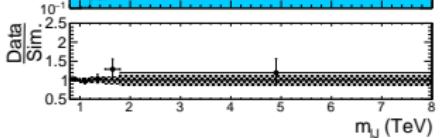
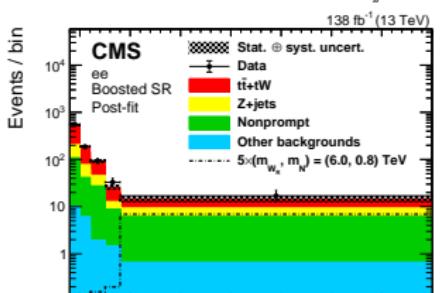
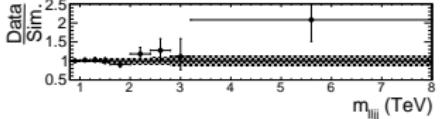
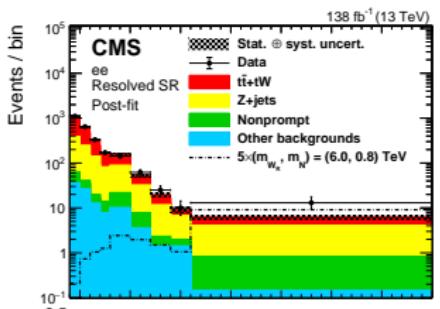
Longlived HNL: Signal Region yields



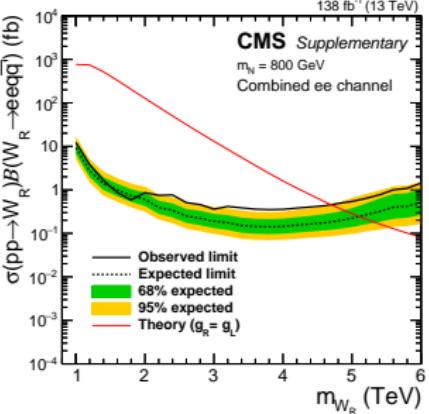
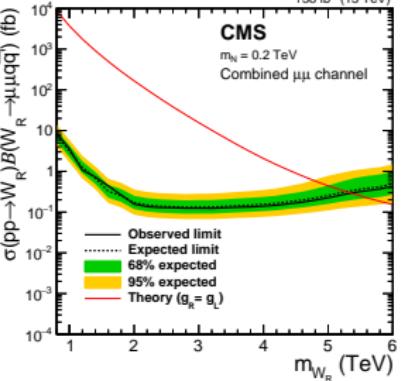
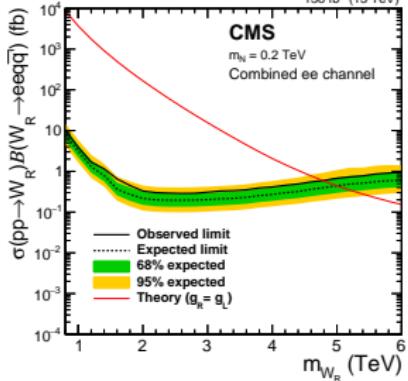
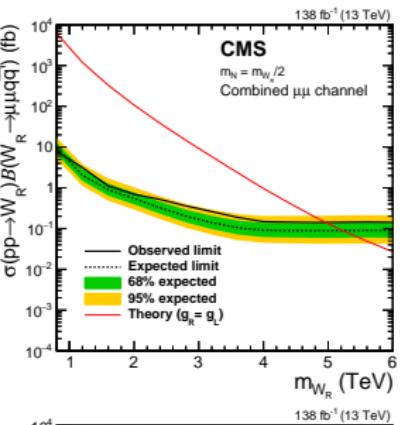
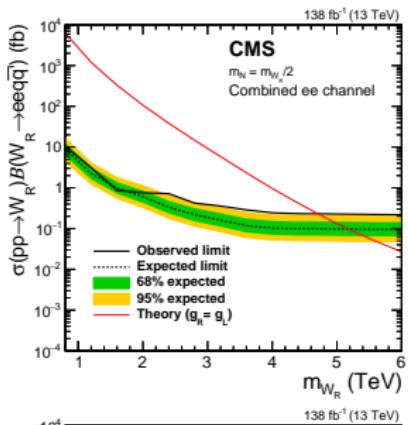
Longlived HNL: Limits



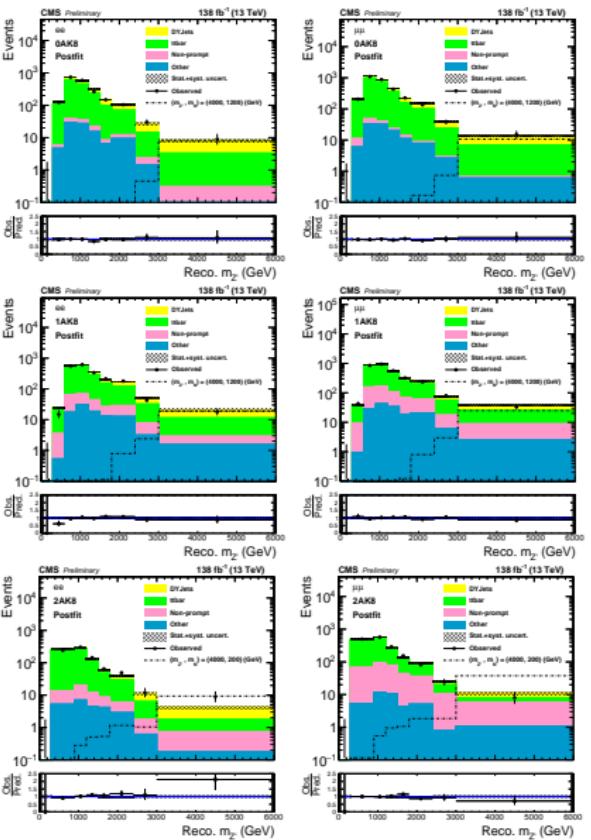
W_R to HNL: Signal Region yields



W_R to HNL: 1D Limits



$Z' \rightarrow \text{HNL pair: Signal Region}$



$Z' \rightarrow \text{HNL pair: 1D Limits}$

