Experimental Search for Heavy Neutral Leptons at LHC

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Particle Physics from Early Universe to Future Colliders
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GHENT UNIVERSITY

Heavy Neutral Leptons

- Neutrino oscillations suggest $\mathrm{m}(\boldsymbol{\nu}) > \mathbf{0}$
- Not naturally included in SM
- Minimal extensions (**ie. $\boldsymbol{\nu MSM}$, Left-Right Symmetric Models**) with additional heavy leptons
- **Seesaw mechanism** to give masses to SM neutrinos

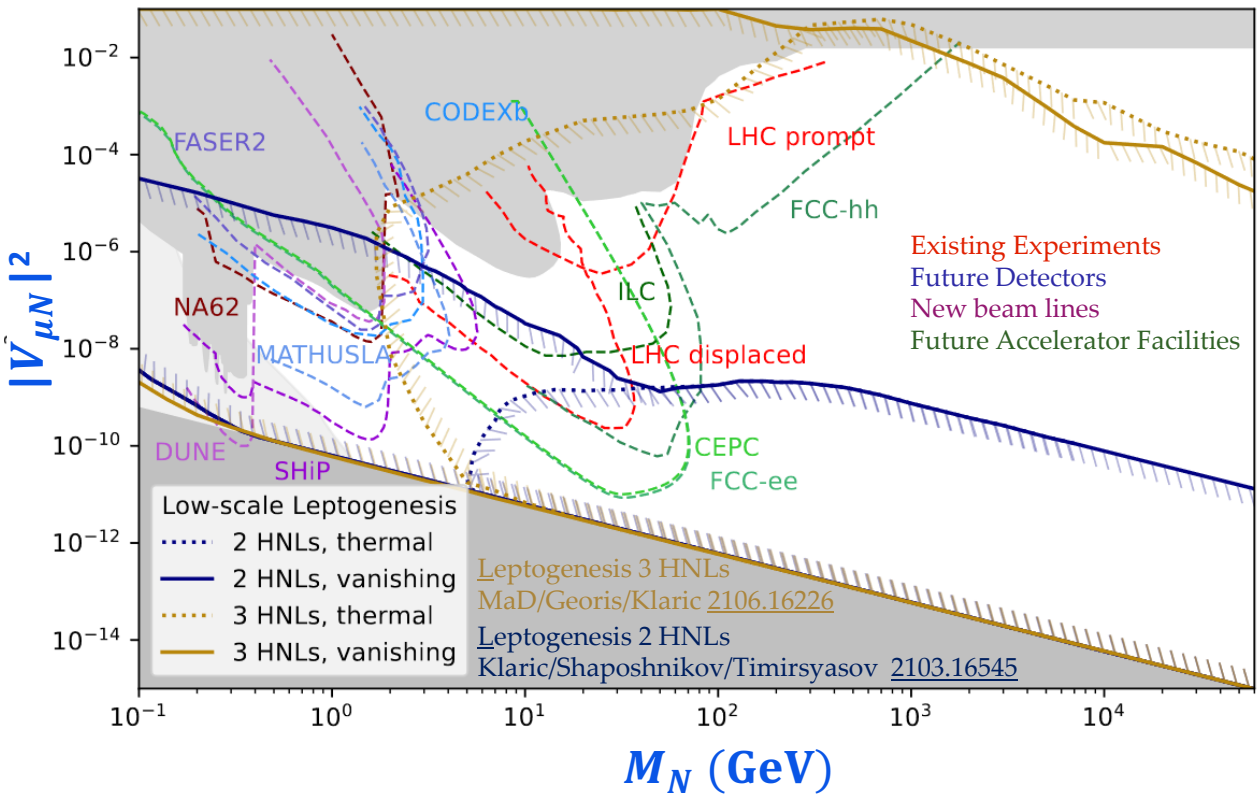
A biased selection of results, mainly CMS & ATLAS

- **Type-I Seesaw Model**
  - Multiple searches with rich phenomenology
  - Prompt and displaced decays
- **Type-III Seesaw Model**
  - Heavy charged/neutral leptons up to ~880 GeV
- **Left-Right Symetric Models**
  - Right-handed W or Z' decaying to HNL
  - Most stringent limits on m_{WR} $m_{Z'}$ m_N

All with full Run-II data

Type-I Seesaw: landscape

- Parameter space ($|V_{\nu N}|^2$, M_N) is very wide
- Complementary experiments to probe HNL: fixed target, B-factories, LEP, LHC



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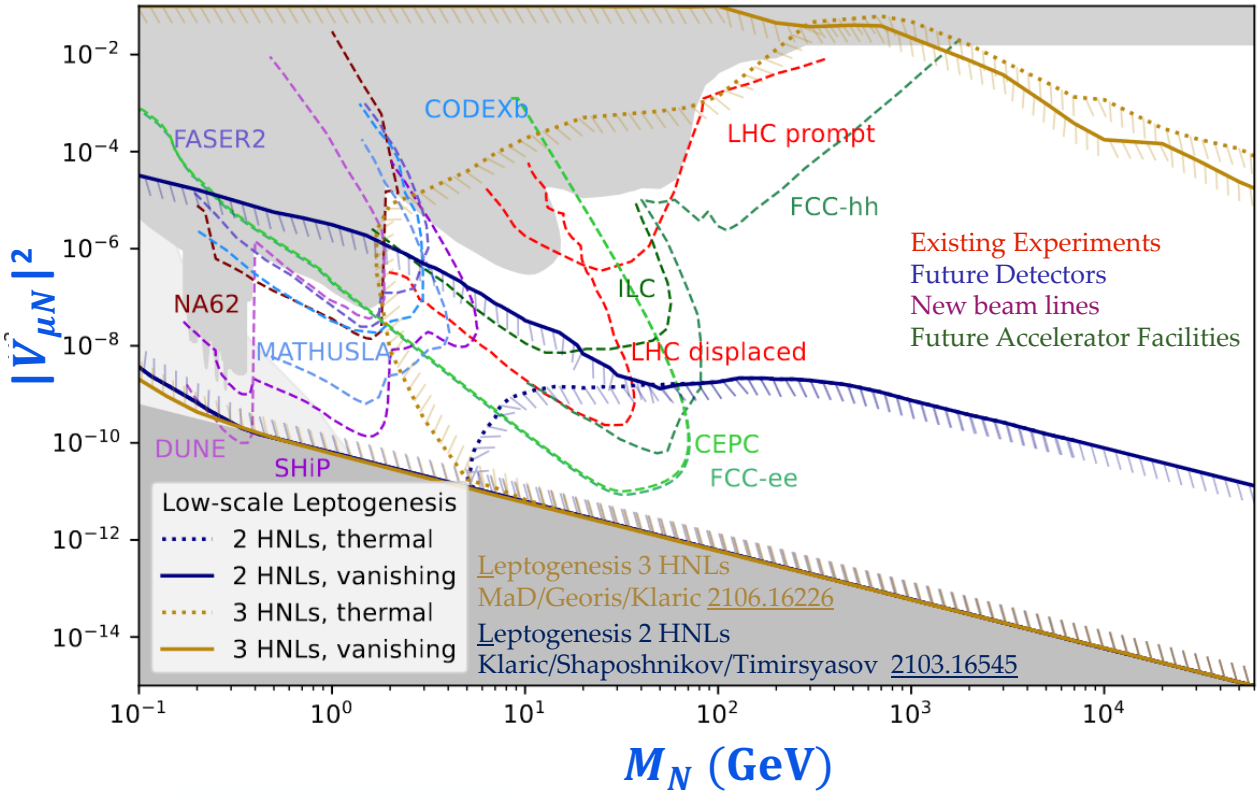
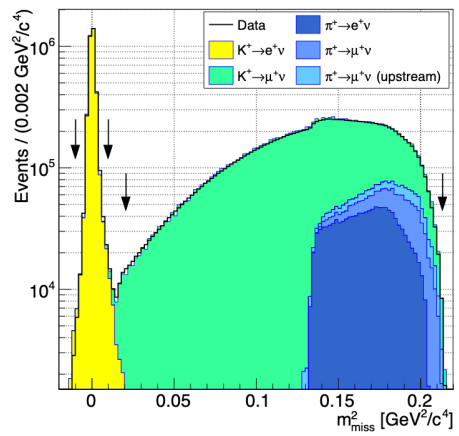
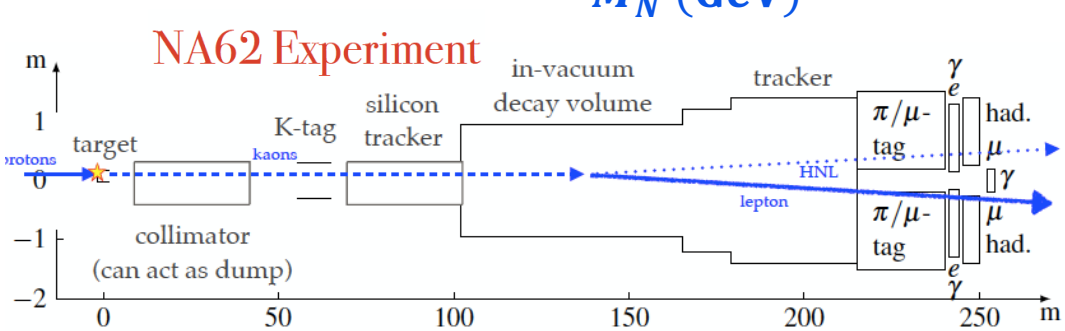


- $M_N < M_{\text{kaon}}$ is pretty much excluded, explored by fixed target experiments, eg. NA62.





$K^+ \to \mu^+ N$

$K^+ \to e^+ N$

Look for: $m^2_{miss} = P^2_K - P^2_\ell = m^2_N$

Type-I Seesaw: landscape

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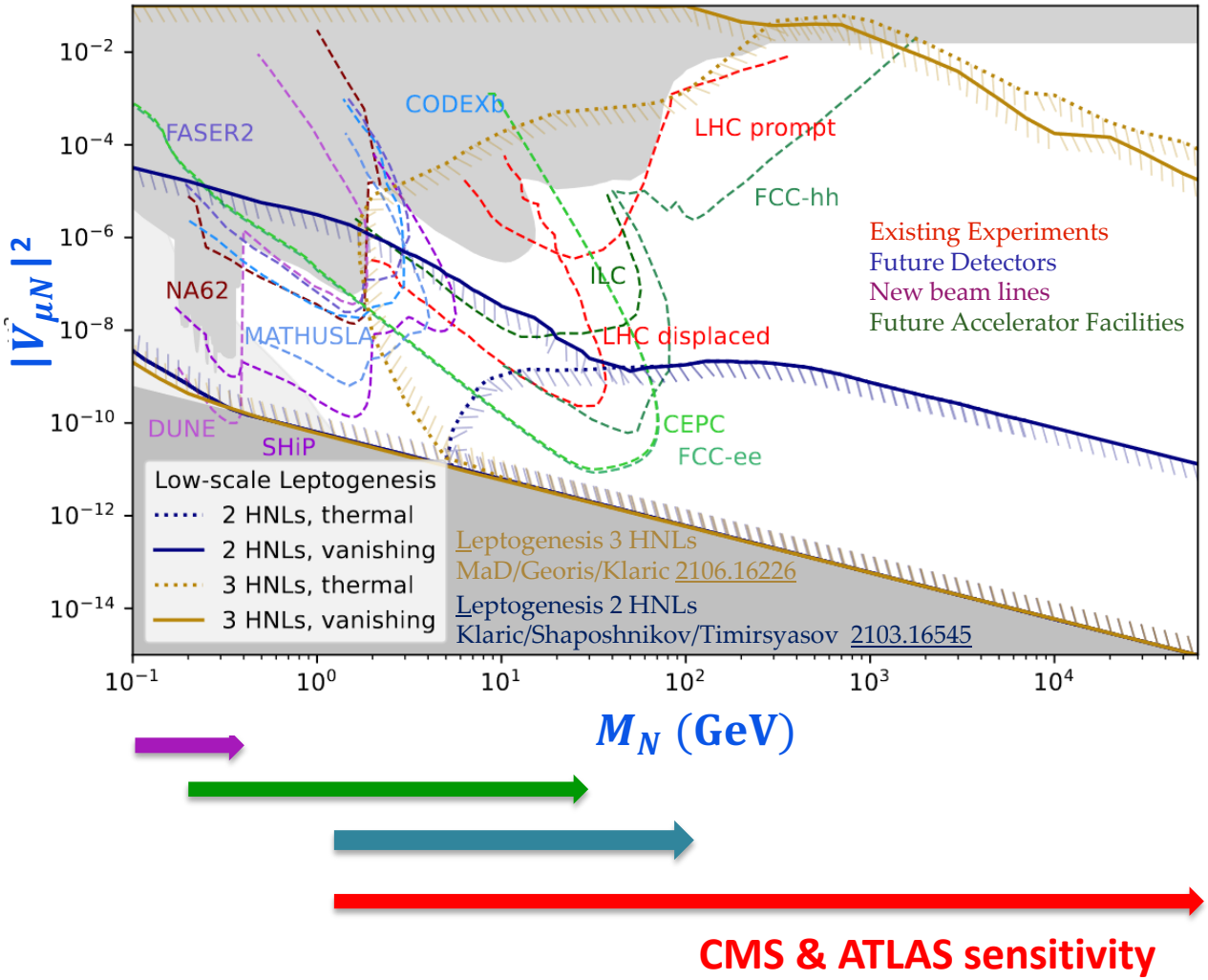
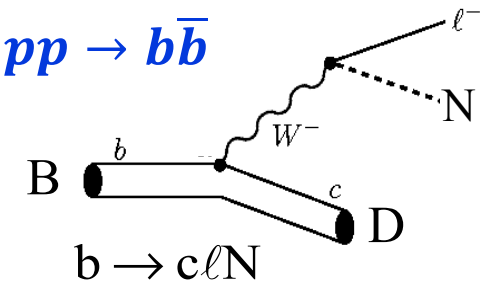


- $M_N < M_{\text{kaon}}$ is pretty much excluded, explored by fixed target experiments, eg. NA62.
- $M_N < M_{B,D}$ explored LHCb, Belle, SHIP
- $M_N < M_Z$ results from LEP
- M_N [1GeV – TeV] LHCb/CMS/ATLAS

HNL production at LHC

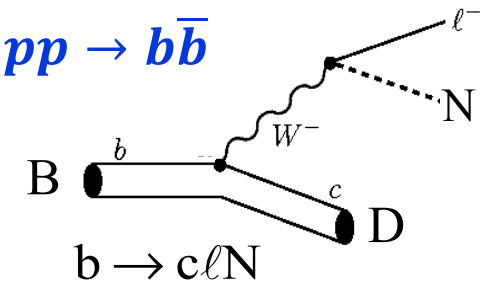
- $pp \to b\bar{b}$



- Large cross section
- Experimentally very challenging → no trigger
- B-parking data ~10^{10} →being analyzed

HNL production at LHC

- $pp \to b\bar{b}$



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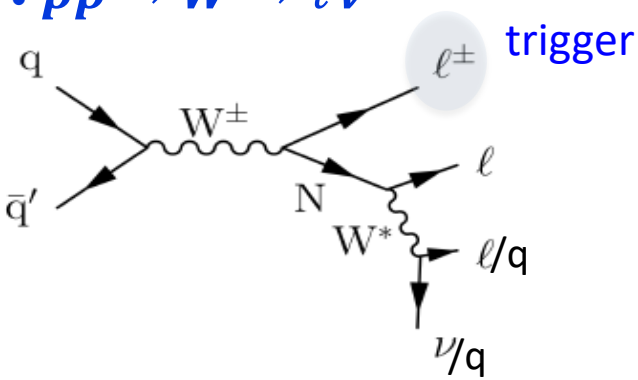
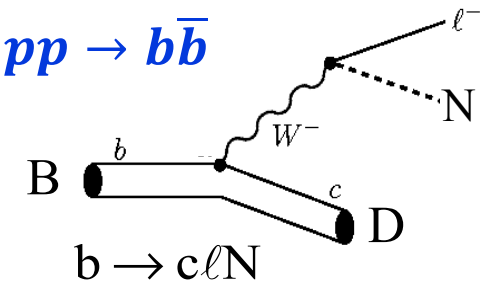
- $pp \to W \to \ell\nu$



- Lower x-section but cleaner exp. signature
- In Run2 ($W \to \ell\nu$) ~9x10^9 events
- Tri-leptons (3ℓ) and di-lepton+di-jets($2\ell 2q$)

HNL production at LHC

- $pp \to b\bar{b}$



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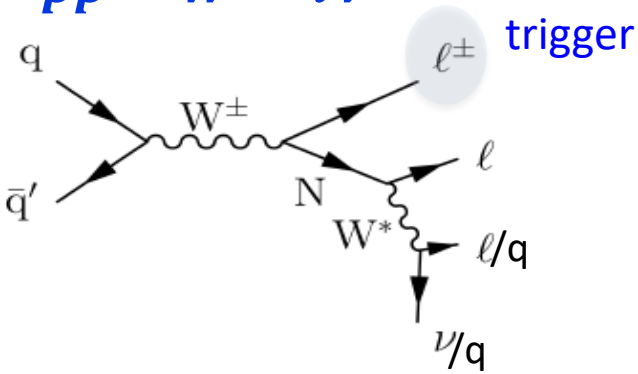

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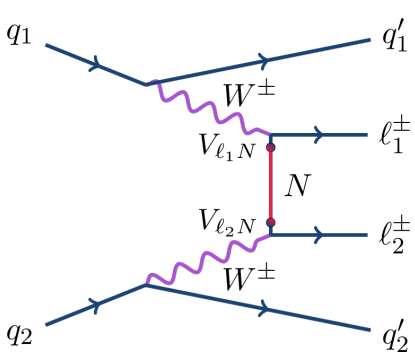
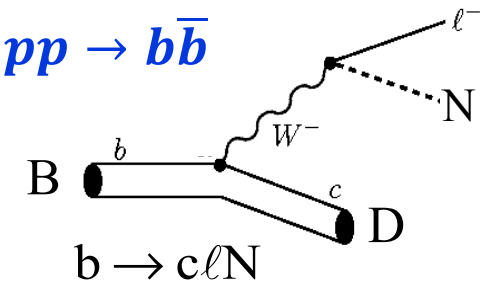
- $pp \to qq\ell^\pm\ell^\pm$



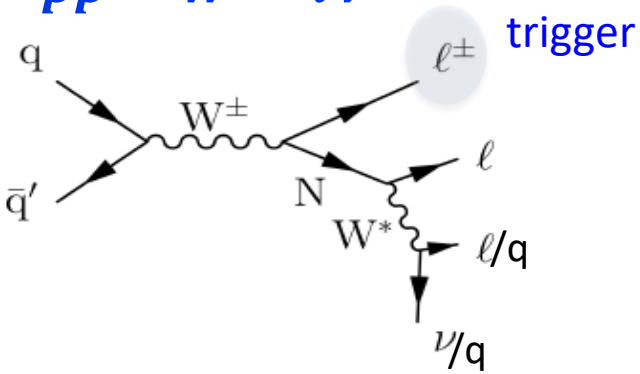
- HNL in t-channel
- SS di-leptons & two forward jets
- Low background, sensitive to high-HNL mass

HNL production at LHC

- $pp \to b\bar{b}$



- $pp \to W \to \ell\nu$



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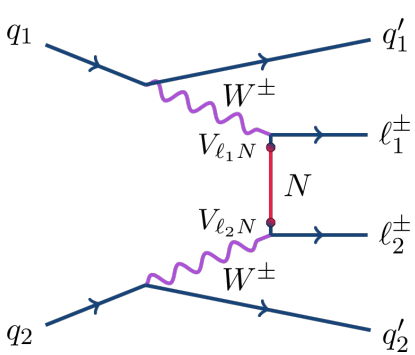
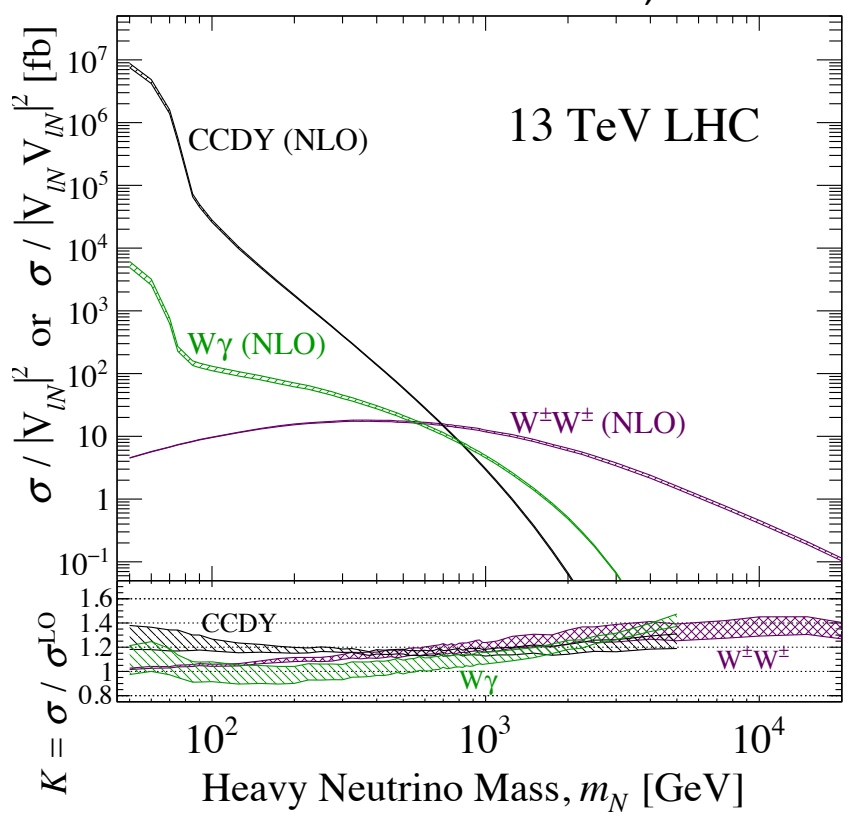


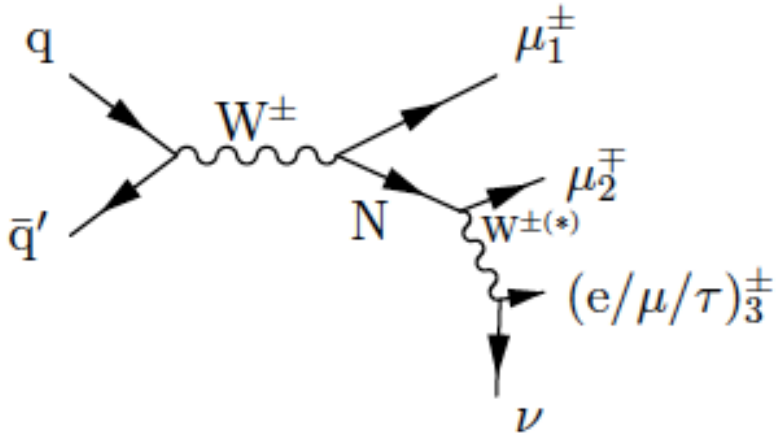
2011.02547, Fuks et.al



HNL search with displaced leptons

Trilepton final states with one coupling: e.g. $V_{\mu N} \neq 0$

LNC decay



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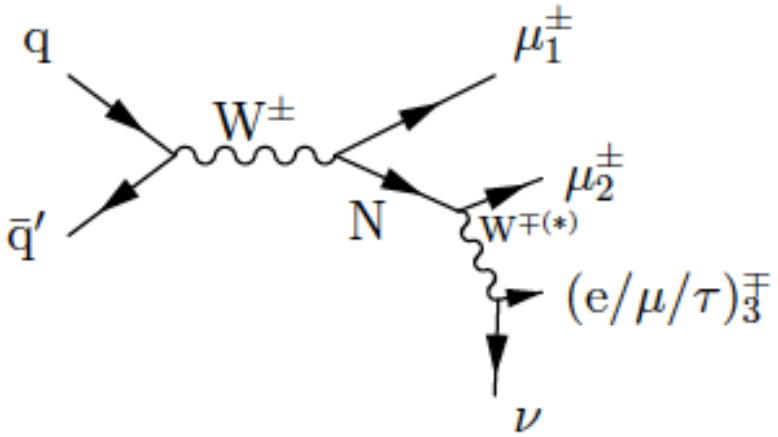
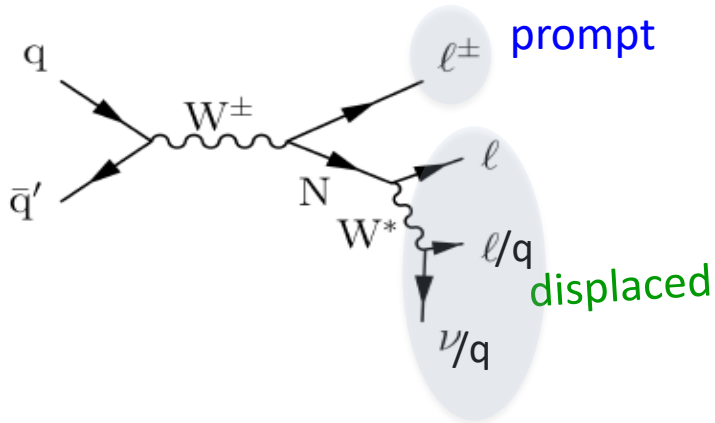


- Always an Opposite-sign-same-flavor (OSSF) lepton pair
- High background

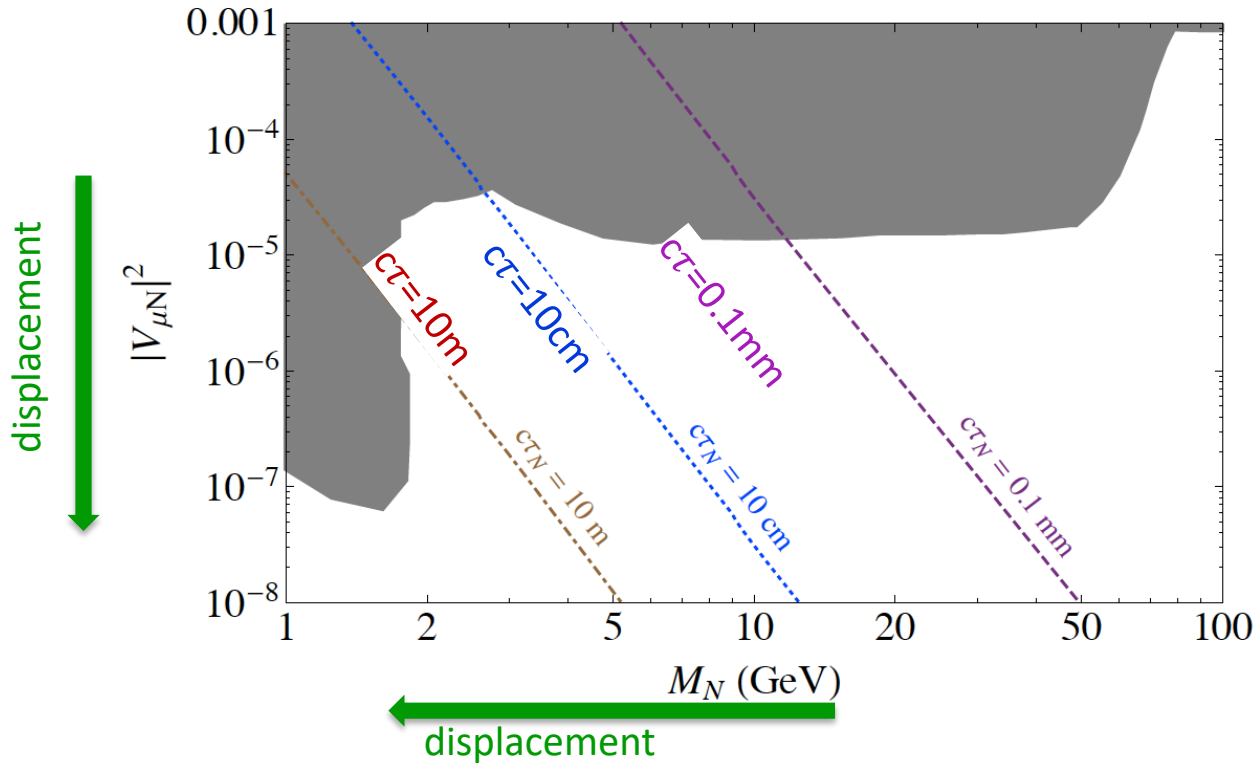
- With and w/o OSSF pair
- Low background

HNL production at LHC



Flight distance of HNL can be macroscopic

$$\tau \propto |V_{\ell N}|^{-2}\, m_N^{-5}$$



HNL search with displaced leptons

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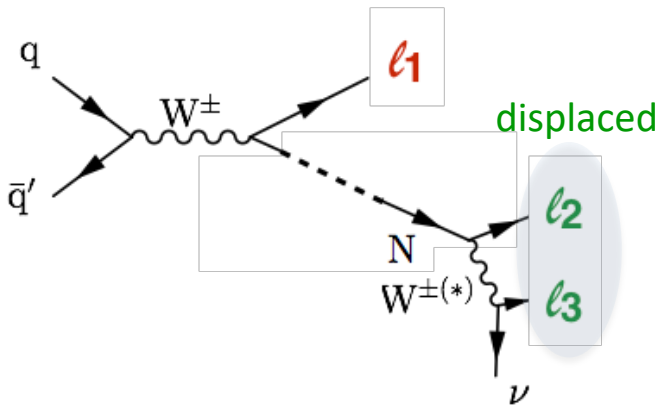
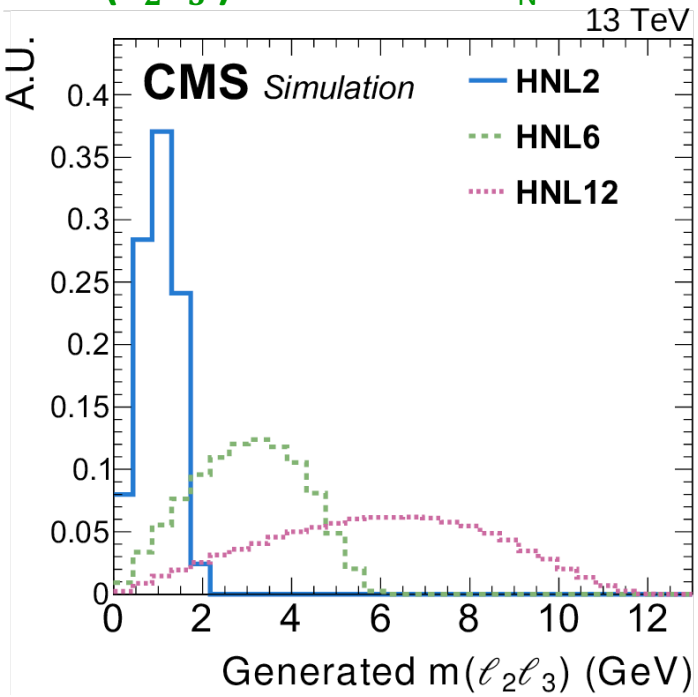
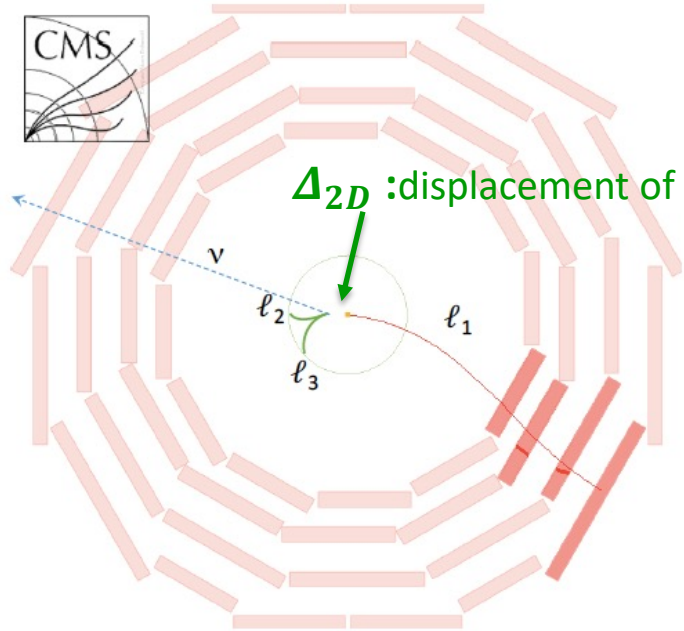


- ℓ_1 prompt & high p_T
- ℓ_1 and ℓ_2 same flavor (LFC)
- eee, μμμ, $\mu^{\pm}\mu^{\mp}e$, $e^{\pm}e^{\mp}\mu$, $e^{\pm}e^{\pm}\mu$, $\mu^{\pm}\mu^{\pm}e$
- test Dirac/Majorana hypotheses
- $M(\ell_1, \ell_2, \ell_3) < M_W$
- $M(\ell_2, \ell_3) \sim M_N$

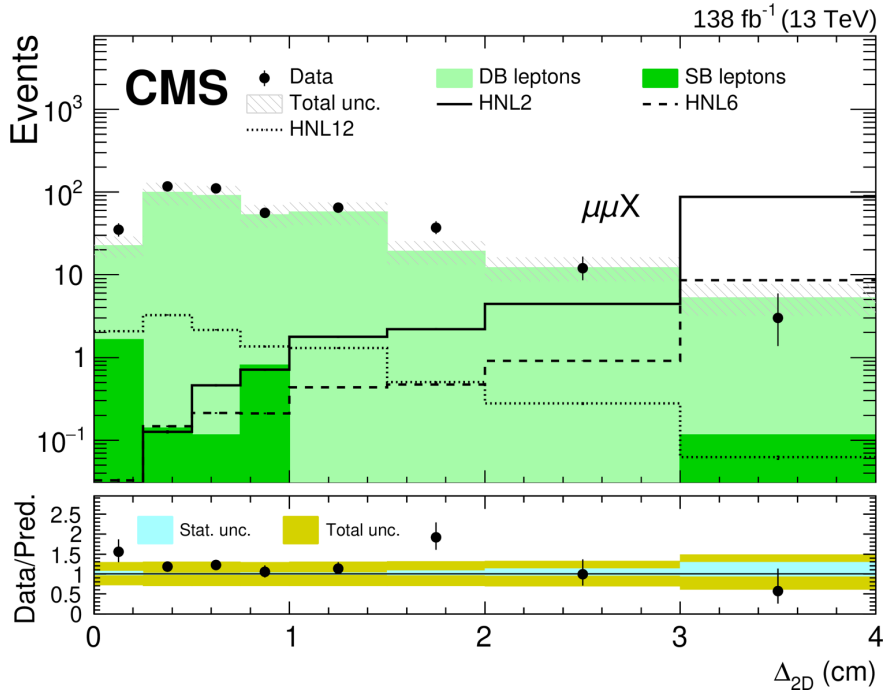
$M(\ell_2\ell_3)$ sensitive to M_N

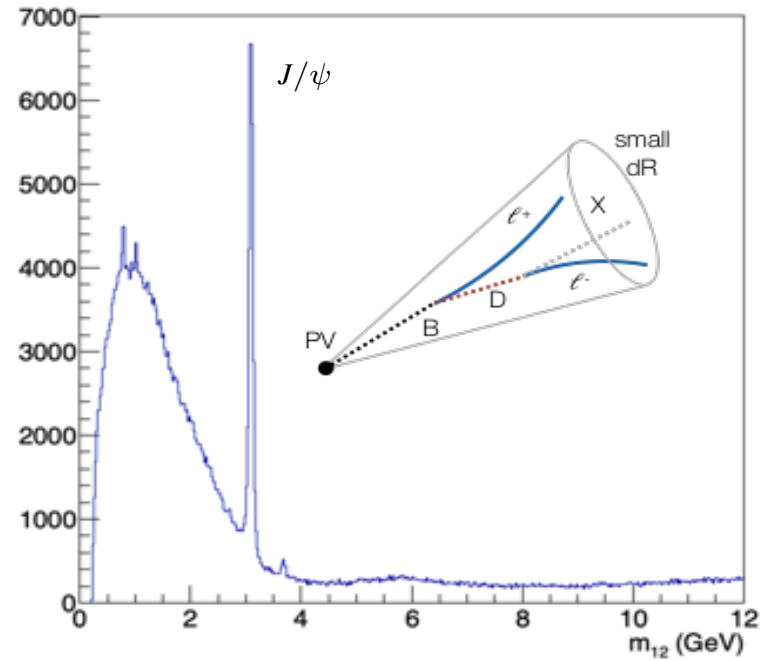




Understanding the backgrounds

Δ_{2D} :displacement of the vertex





- **Main backgrounds** are due to "misidentified" leptons with various origin
- Data-driven estimation is mandatory!

Results in search regions

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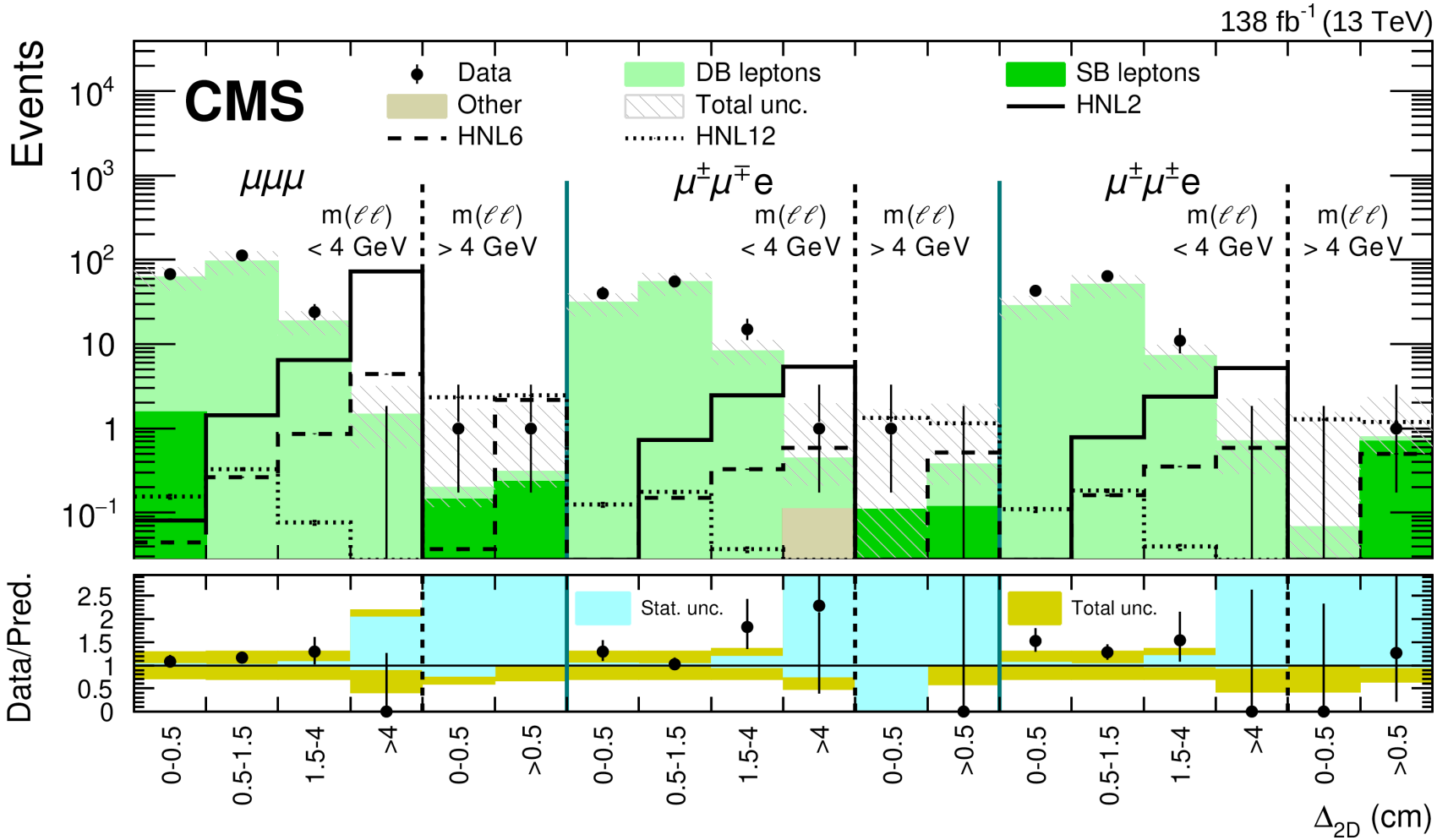


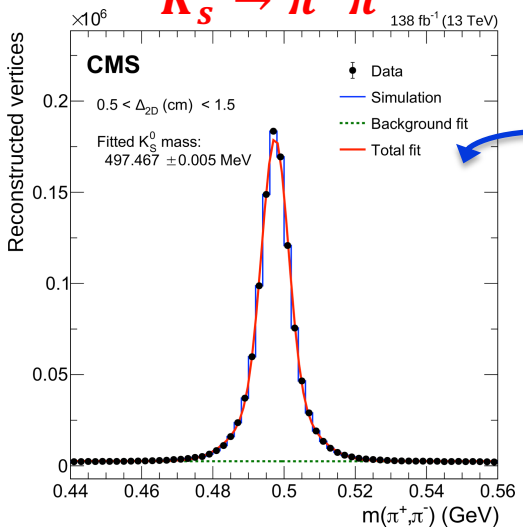
Data agrees with the predicted data within the uncertainties

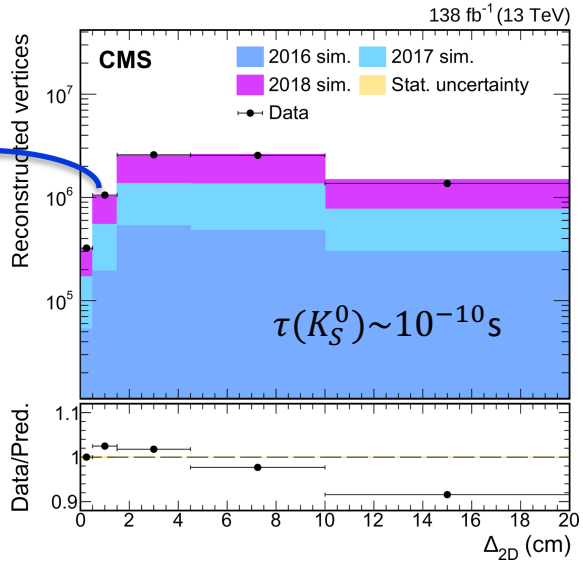
Signal efficiency validation

Displaced Vertex reconstruction:

- Events with K_S^0 and Λ^0
- Displaced vertices using tracks that from M(K_S^0) or M(Λ^0)
- Spot any mismodeling in the simulation

$K_S^0 \rightarrow \pi^+\pi^-$





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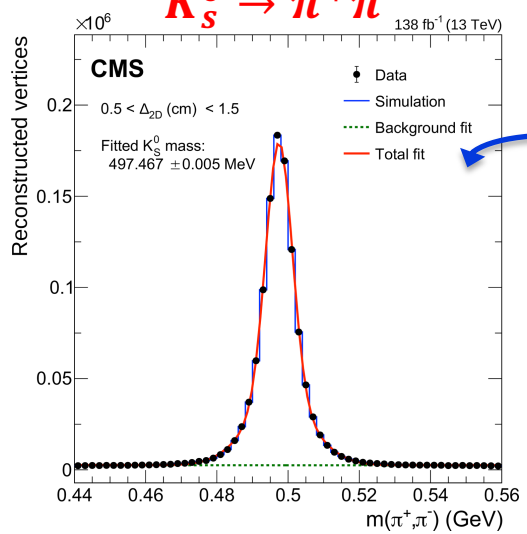
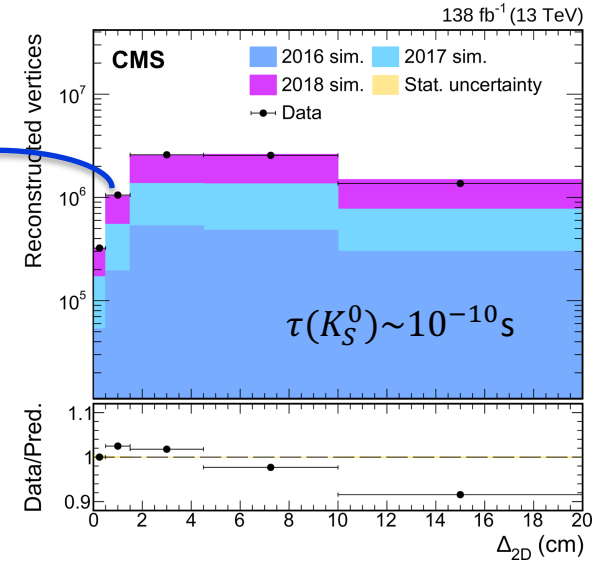
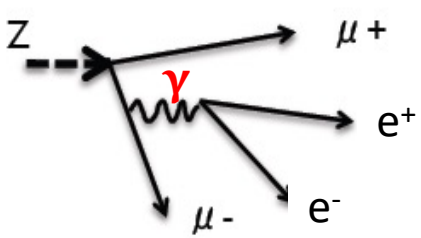
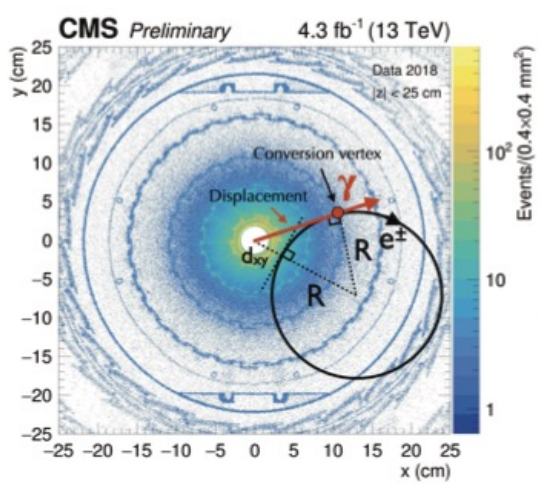




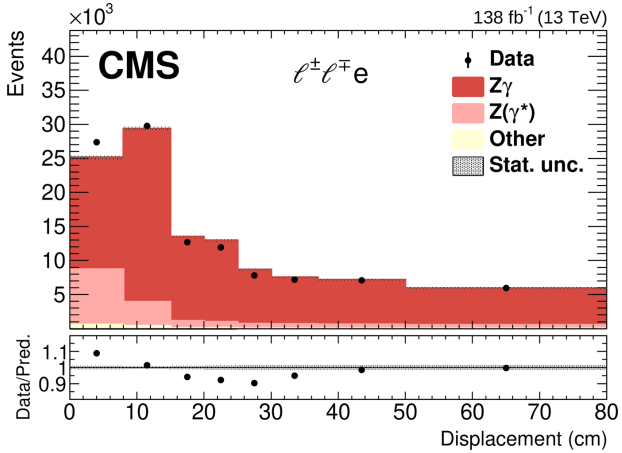
Displaced lepton reconstruction:

- J/ψ → $\mu\mu$
- γ conversions in $Z \to \mu\mu\gamma$





$Z \to \mu\mu\gamma, (\gamma \to e^+e^-)$

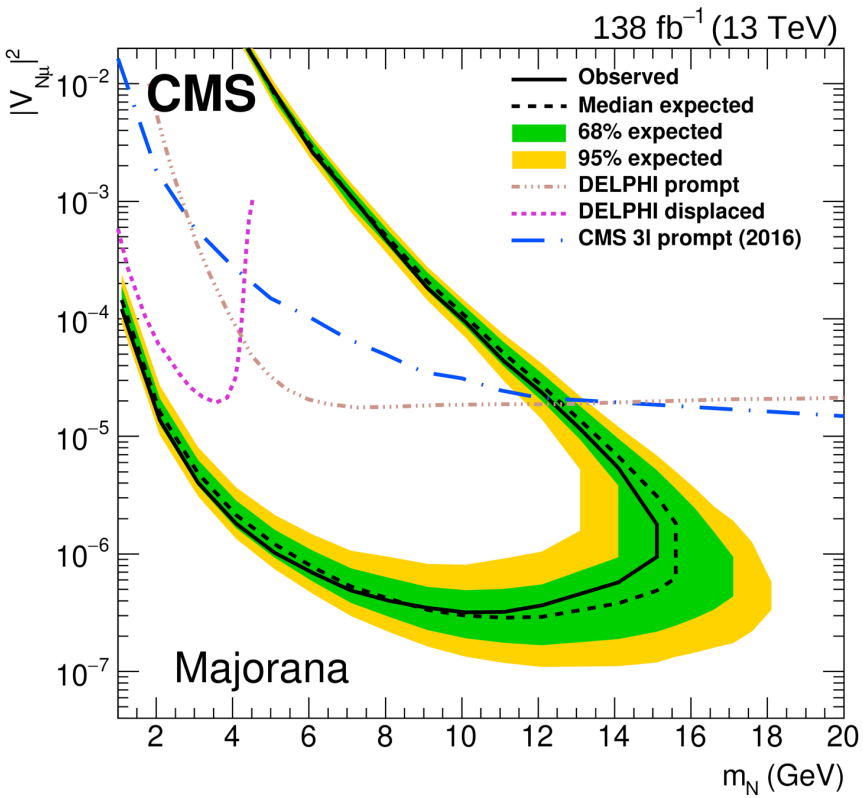


Calibrate HNL simulation using data/MC agreement found in these studies

Interpretation in Majorana HNL

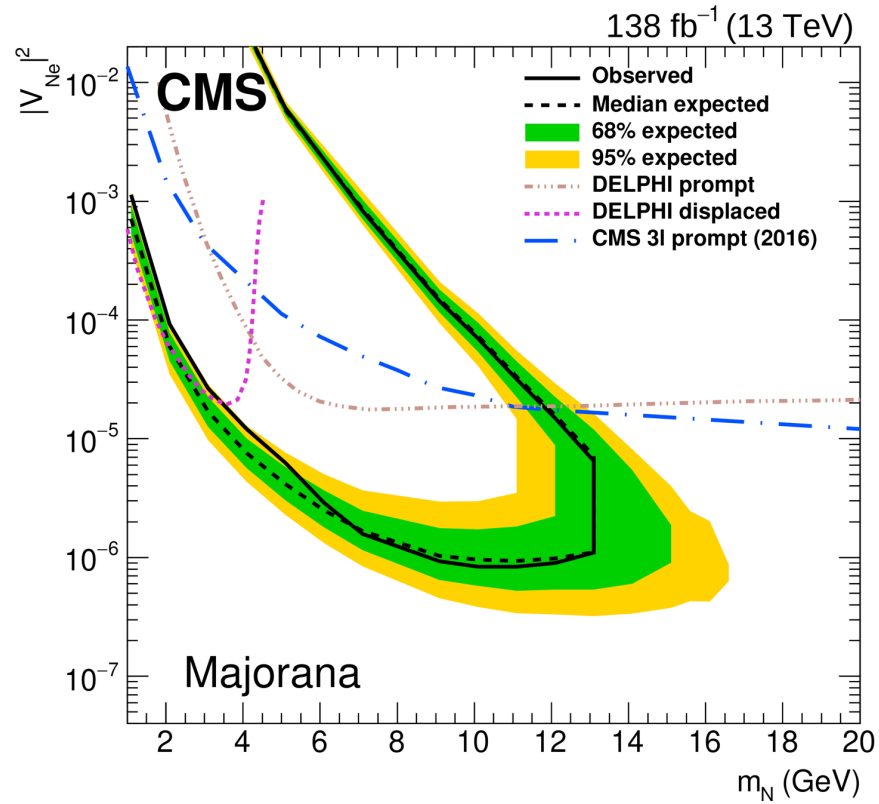
Sensitivity to $|V_{\mu N}|^2$

μμμ, μ±μ∓e± and μ±μ±e∓;



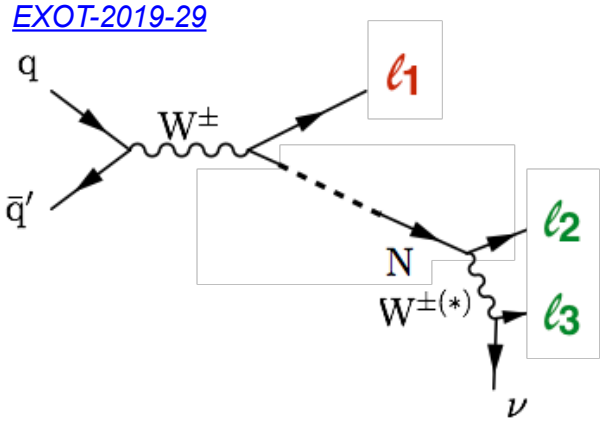
Sensitivity to $|V_{eN}|^2$

eee, e±e∓μ± and e±e±μ∓.



HNL search in ATLAS

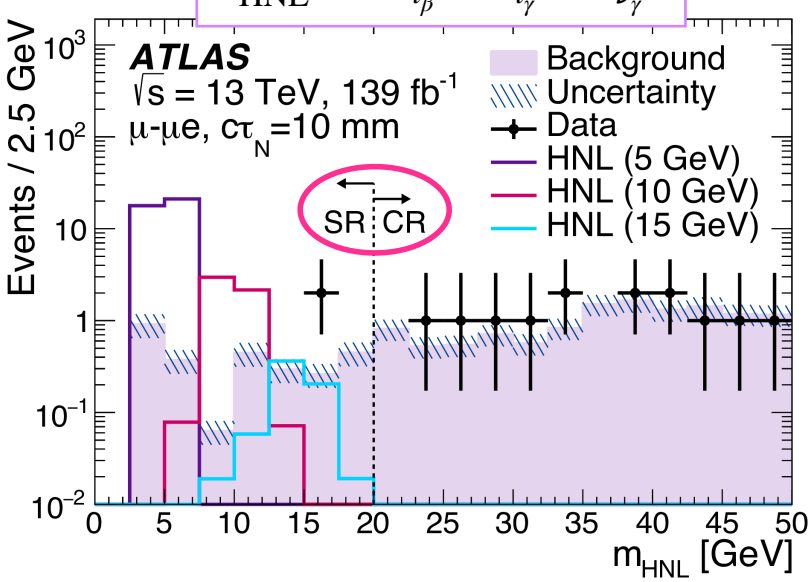
EXOT-2019-29



- Similar strategy to CMS, except LFV (mixed HNL couplings) are also taken into account: ℓ_1 and ℓ_2 maybe OF
- LNC & LNV hypotheses tested

HNL mass reconstruction using M_W hypot.

$$m^2_{\mathrm{HNL}} = (P_{l_\beta} + P_{l_\gamma} + P_{\nu_\gamma})^2$$



HNL search in ATLAS

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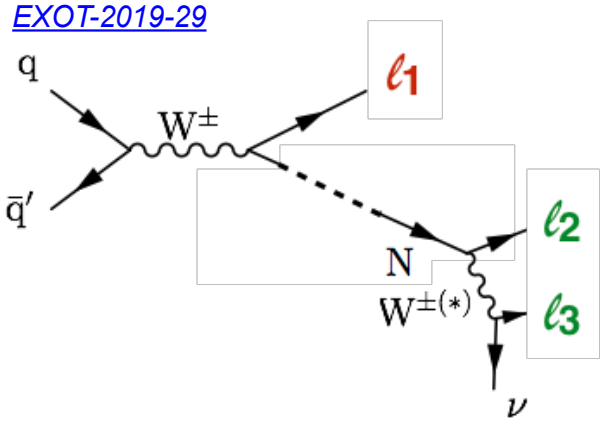

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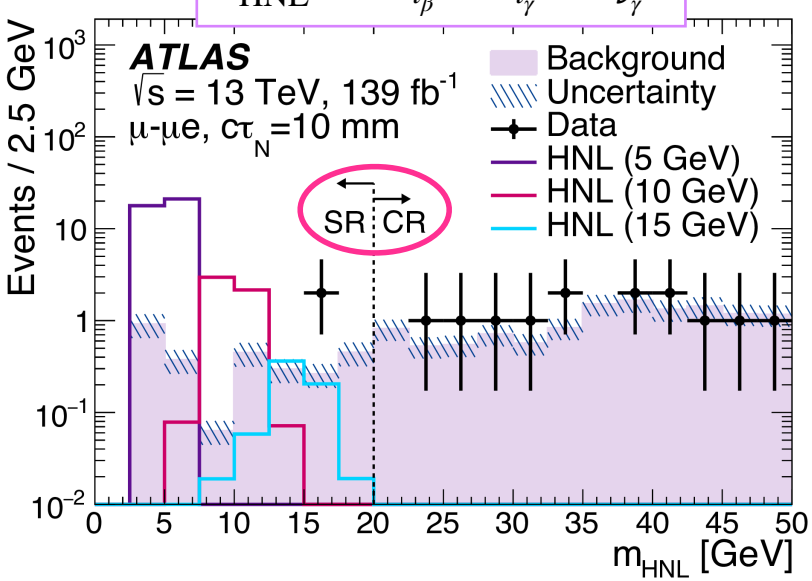
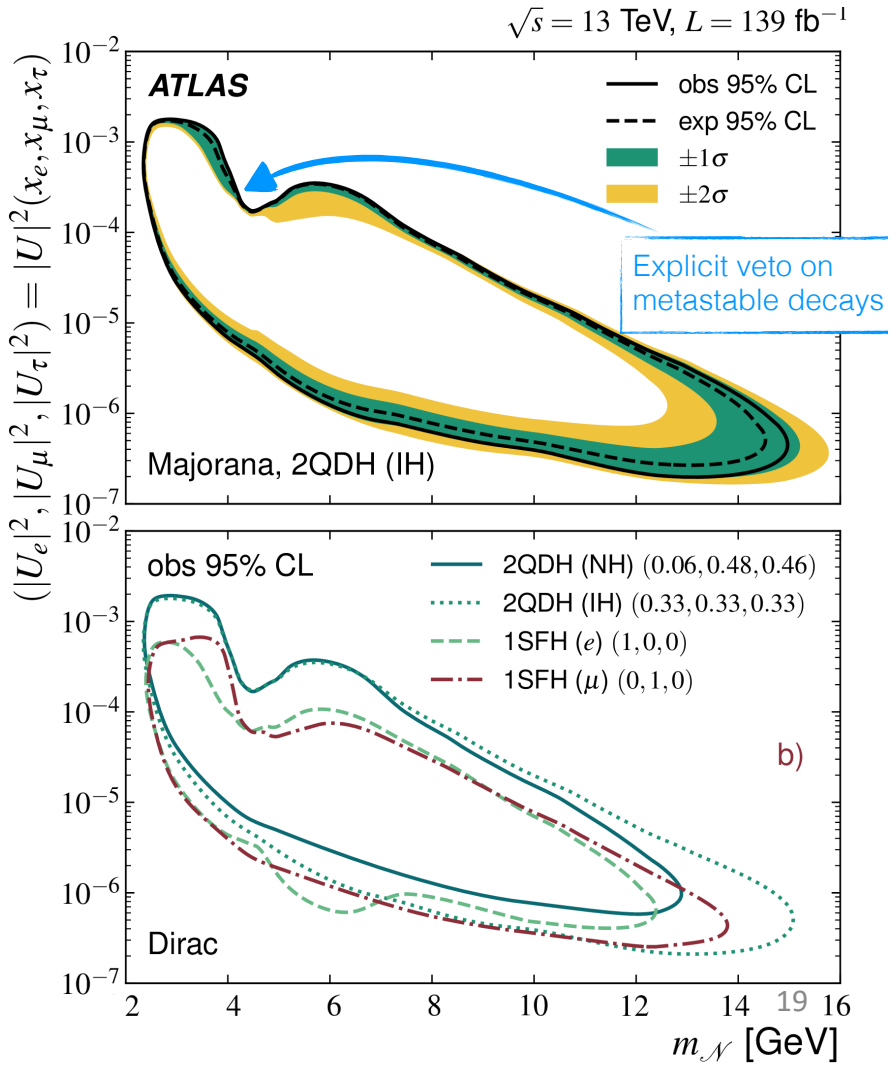
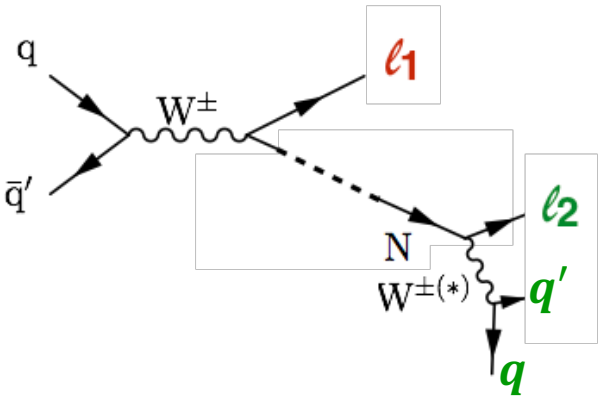


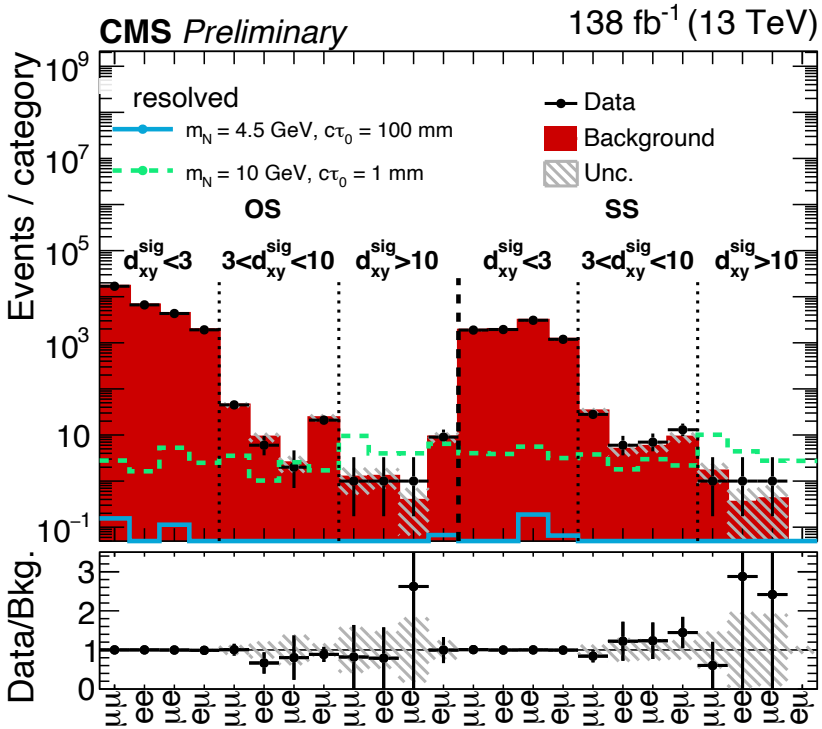


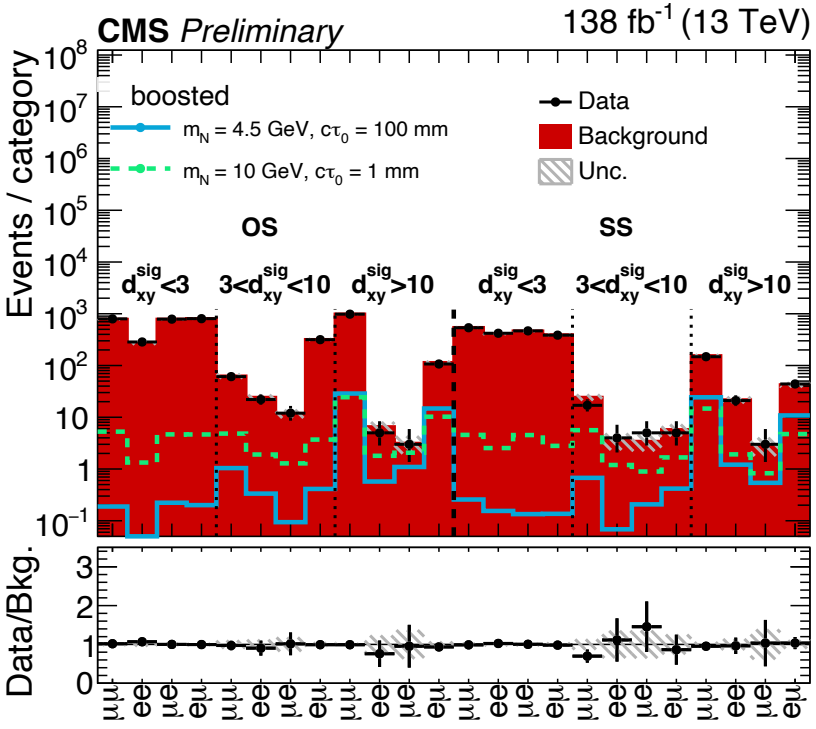
HNL search in CMS

EXO-21-013



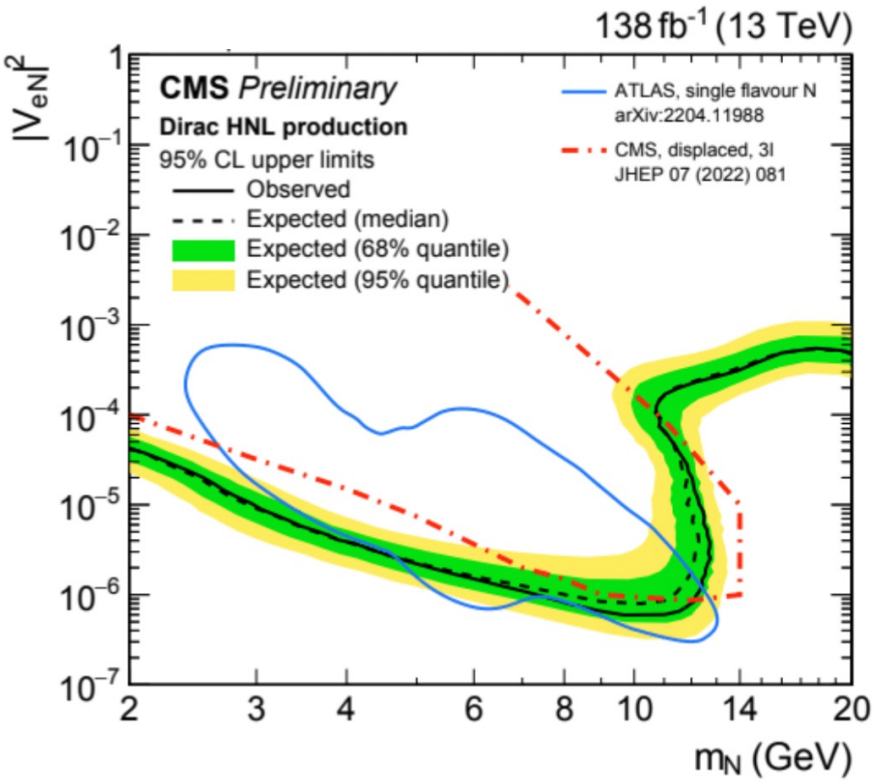
- 2 SS/OS dilptons $(ee, \mu\mu, e\mu, \mu e)$ + jet events
- $p_T(e, \mu) > 5{,}3\ GeV$
- Boosted (resolved) regime
- Deep neural network to tag displaced jet
- Search observable: Impact parameter significance
- 48 categories to be sensitive to various HNL scenarios simultaneously



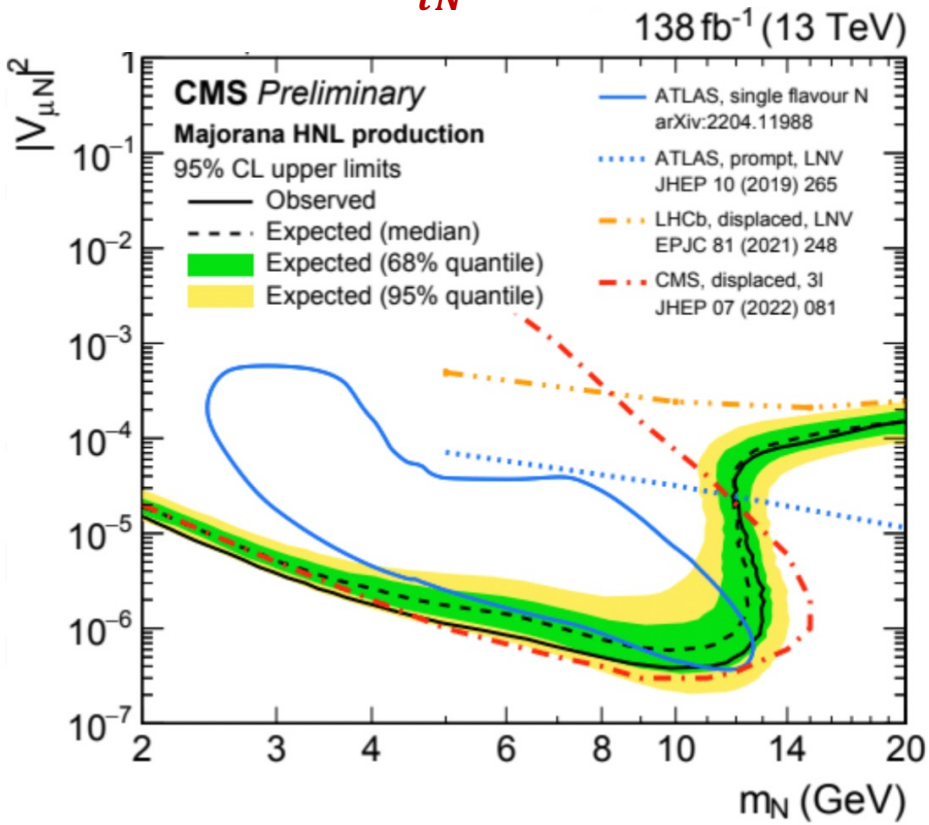


HNL search in CMS & ATLAS

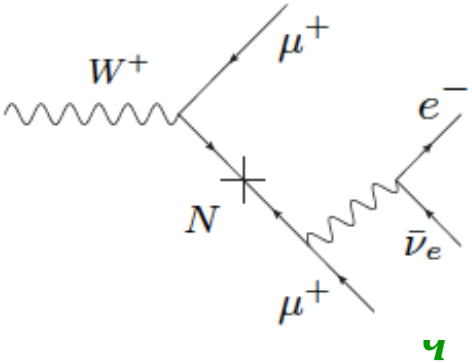
$V_{eN} \neq 0$
$V_{\mu N} = 0$
$V_{\tau N} = 0$



$V_{eN} = 0$
$V_{\mu N} \neq 0$
$V_{\tau N} = 0$



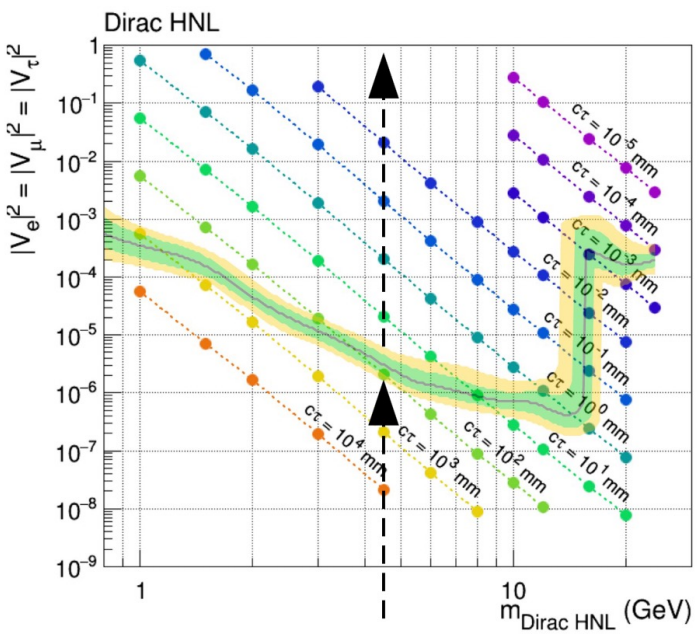
A more realistic interpretation

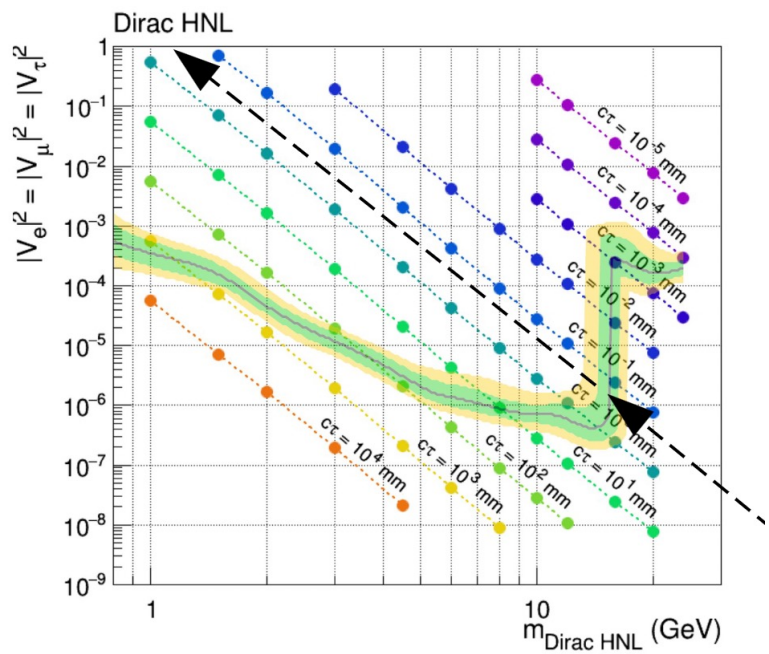


- Typically consider the coupling of N to one neutrino flavour at a time.
- First time symultaneous couplings to $\nu_e \nu_\mu \nu_\tau$ is considered

Lifetime of N: $\tau_N \propto \left|V_{\nu N}\right|^{-2} m_N^{-5}$

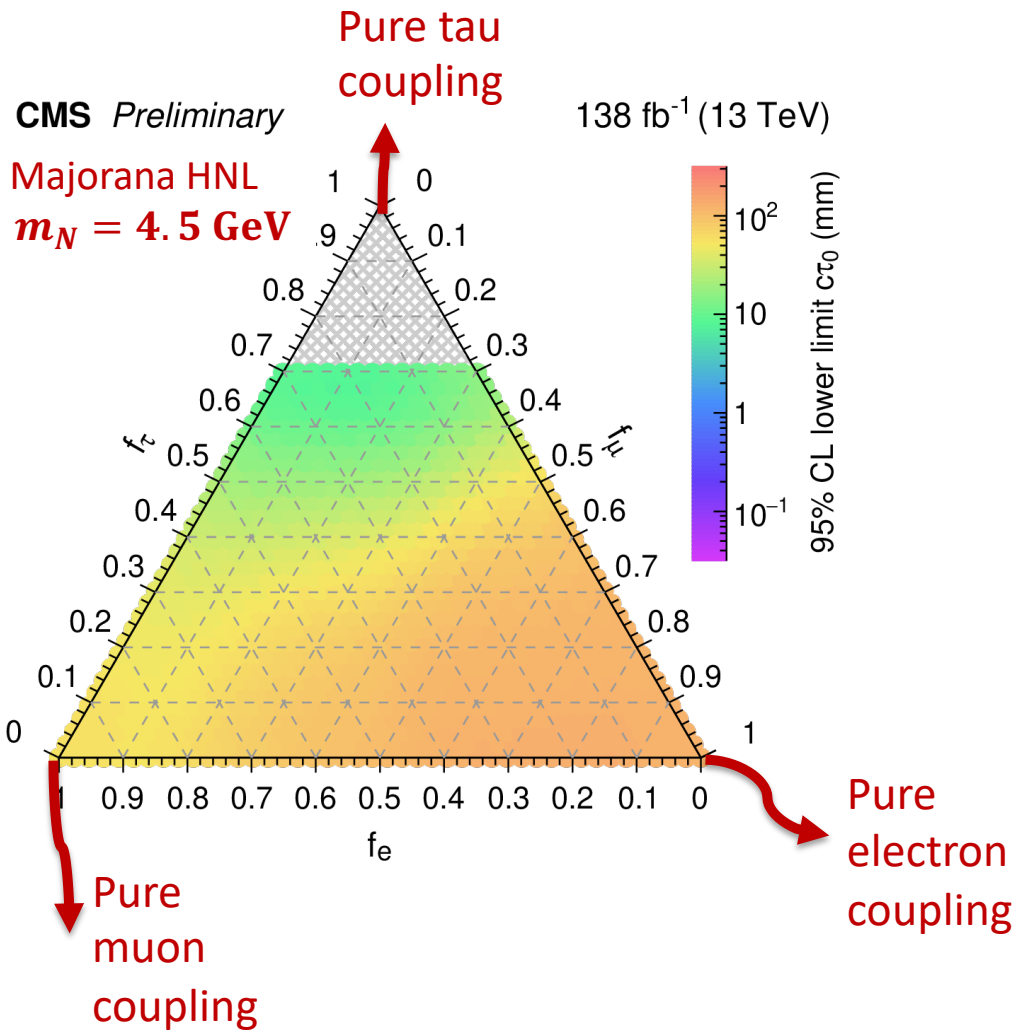
$$\Gamma_N(m_N, V_{eN}, V_{\mu N}, V_{\tau N}) = \underbrace{A_e(m_N) \times |V_{eN}|^2}_{=\Gamma_e} + \underbrace{A_\mu(m_N) \times |V_{\mu N}|^2}_{=\Gamma_\mu} + \underbrace{A_\tau(m_N) \times |V_{\tau N}|^2}_{=\Gamma_\tau}$$



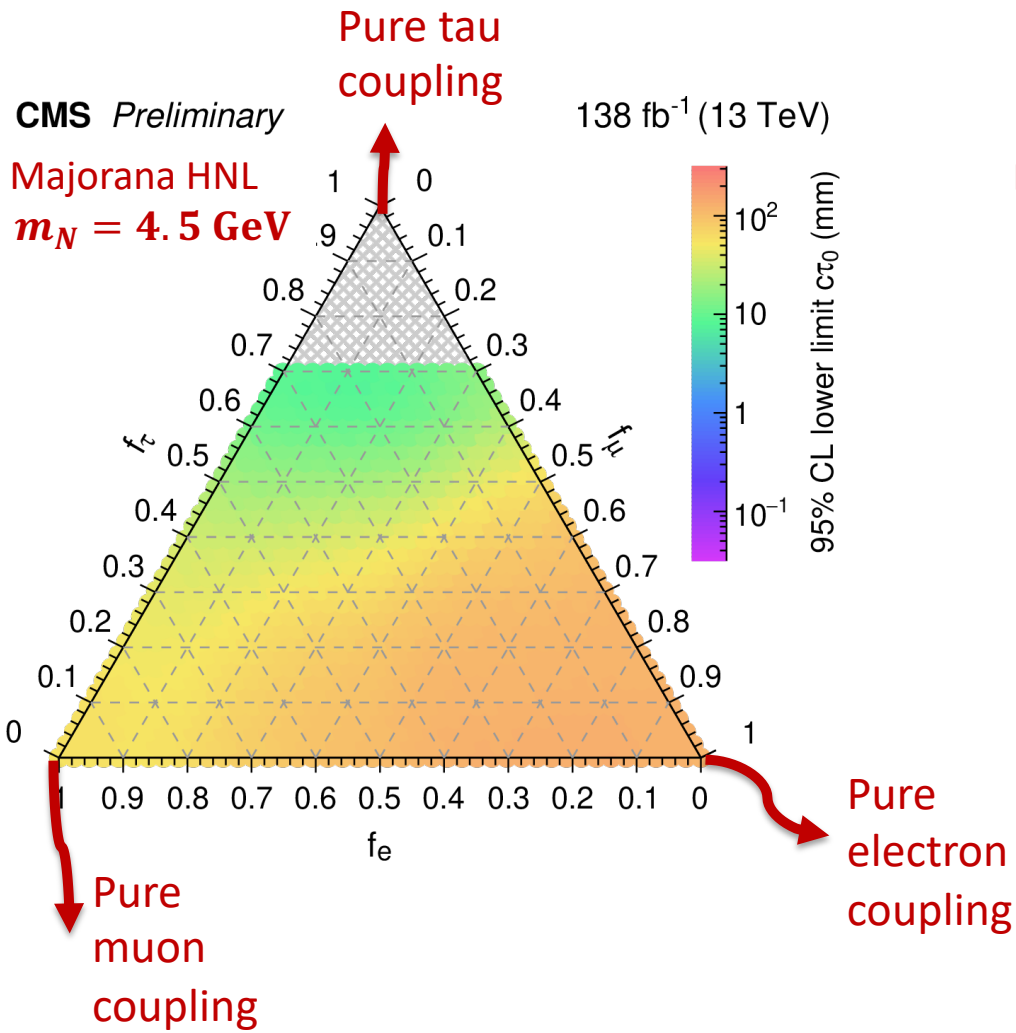


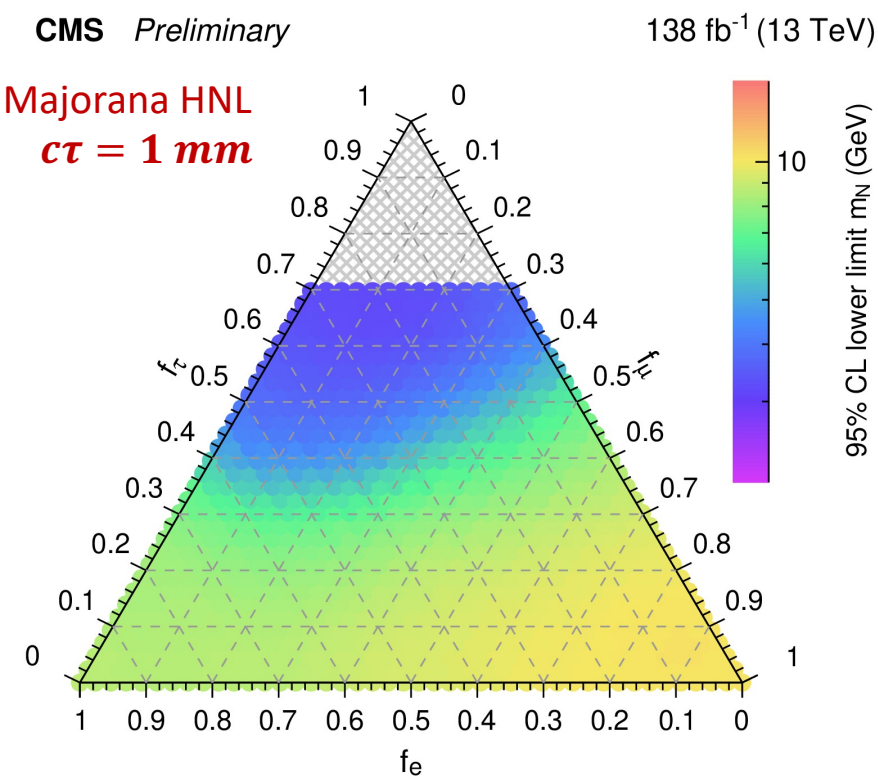
A more realistic interpretation

EXO-21-013



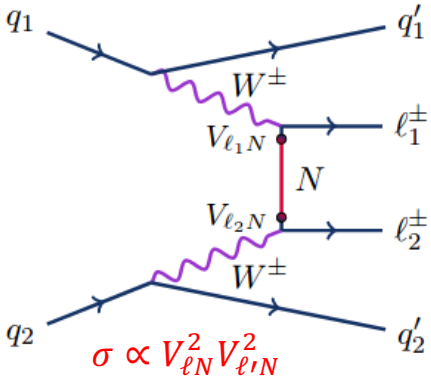
A more realistic interpretation



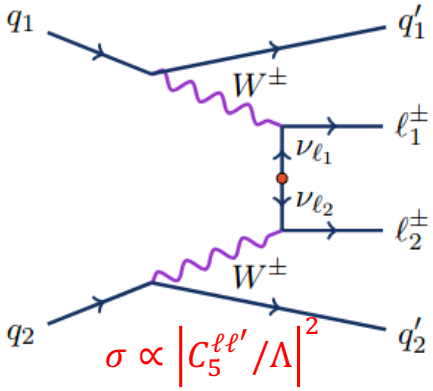


HNL search via VBF production

Type-1 Seesaw



Weinberg operator Dim 5



Experimental signature:

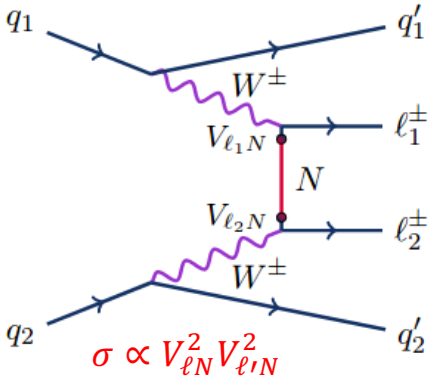
- Same-sign muons + VBF jets
- Complementary to DY HNL production→ larger x-section at high mass

Backgrounds:

- Main: WZ and non-prompt leptons estimated using CRs.
- Others: WW, ZZ, tZq, ttW, ttZ, and VVV

HNL search via VBF production

Type-1 Seesaw



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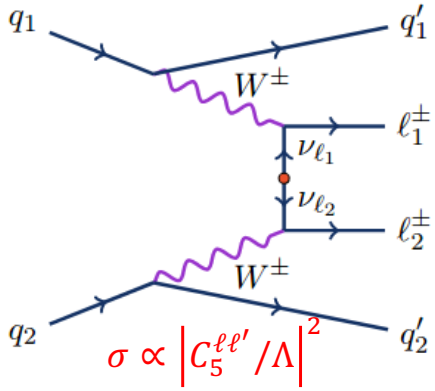

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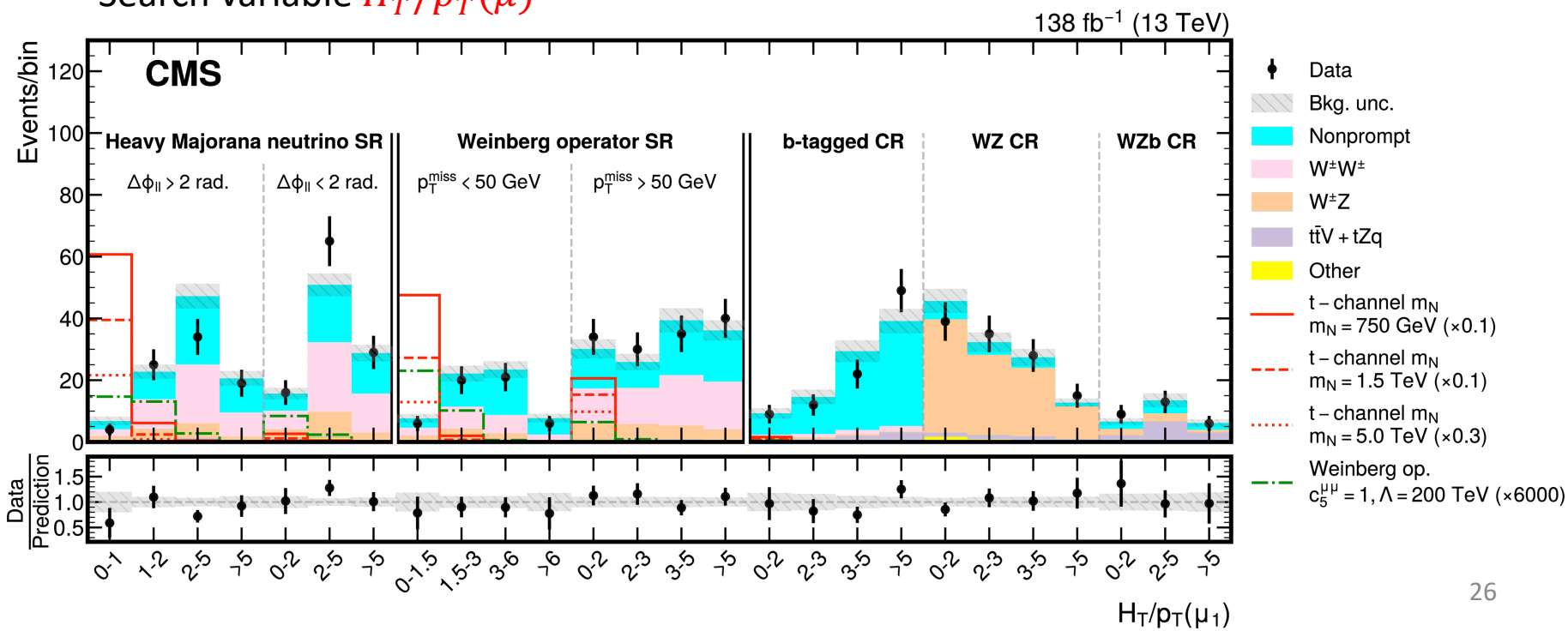
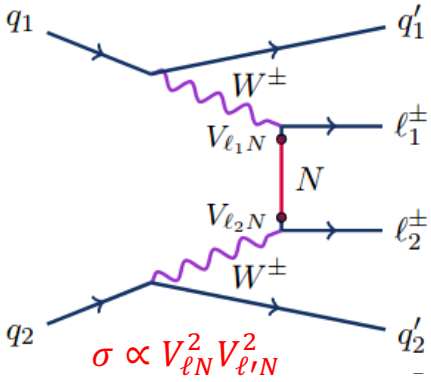
Search variable $H_T/p_T(\mu)$



HNL search via VBF production

Type-1 Seesaw



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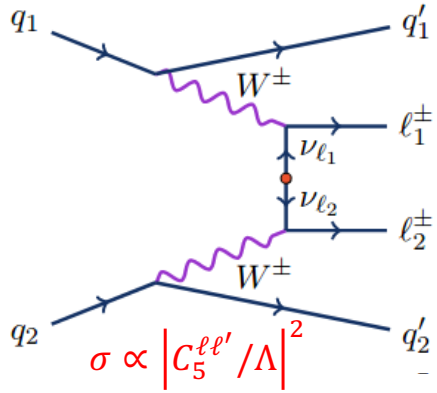
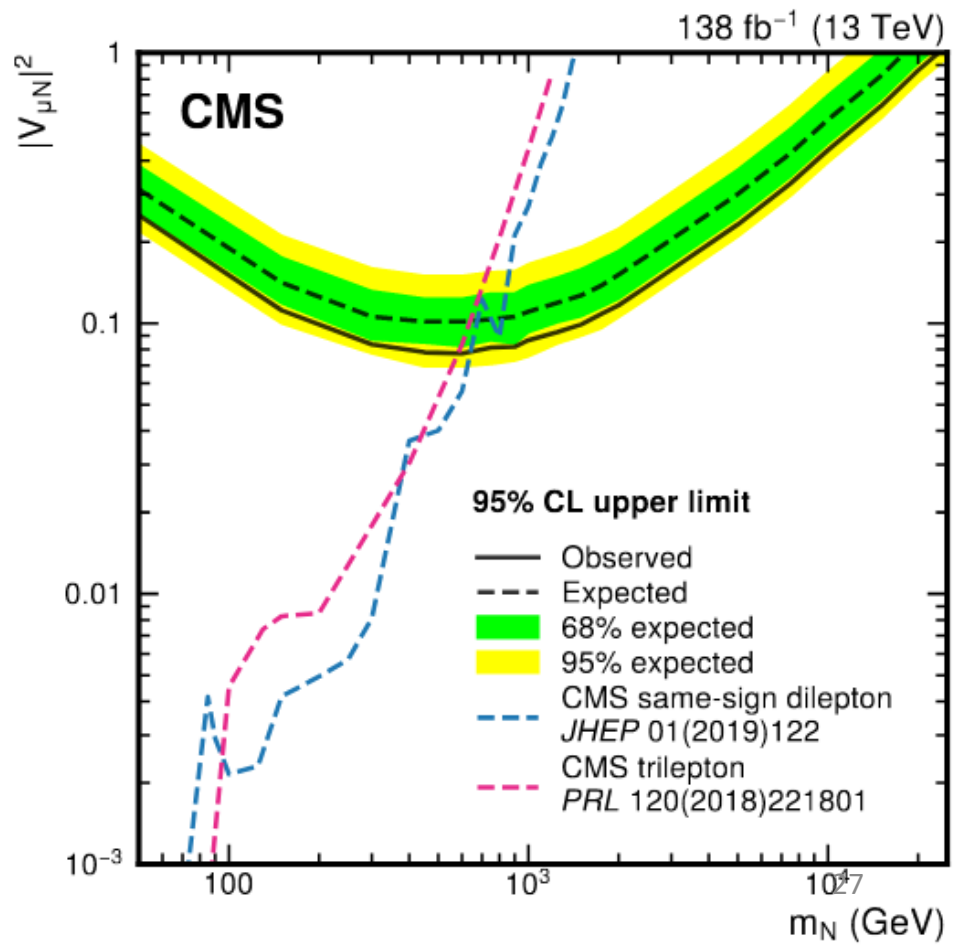
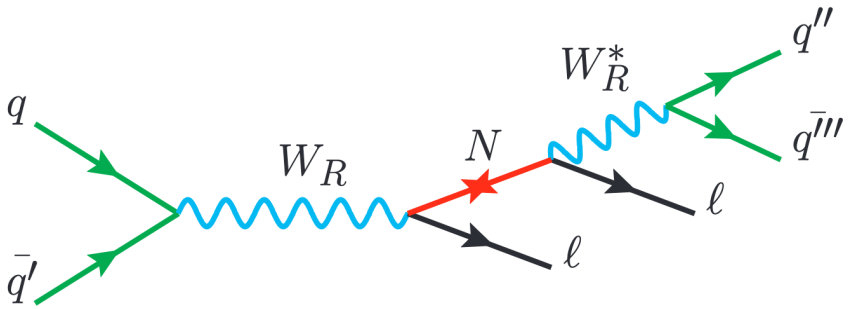


- First search for Majorana HNL at masses up to 23 TeV, most stringent limits beyond 650 GeV
- First test of Weinberg operator at collider: exclude effective Majorana neutrino mass ($C_5^{\ell\ell'} \sim |m_{\mu\mu}|$) up to obs(exp)10.8(12.8) GeV



Left-Right Symmetric models, W_R

EXO-20-002



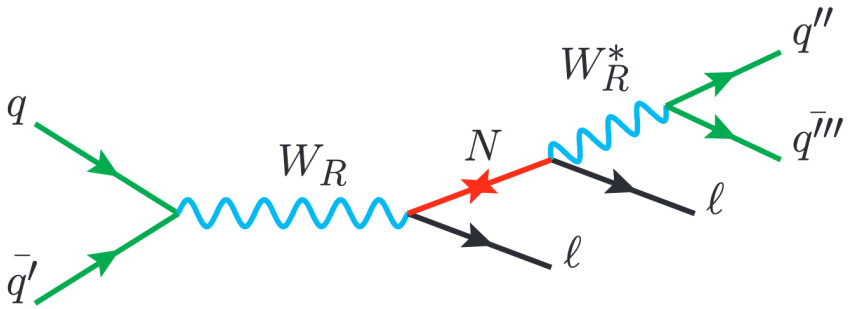
Experimental signature:

- Two high pT same flavor leptons ($ee, \mu\mu$)
- Dirac&Majorana
- Fully **reconstruct** M_{W_R}
- **boosted/resolved jets**
- for low M_N boosted jet includes the lepton
- Search observables:

$$m(\ell\ell jj)\ m(\ell J),$$

Left-Right Symmetric models, W_R

EXO-20-002



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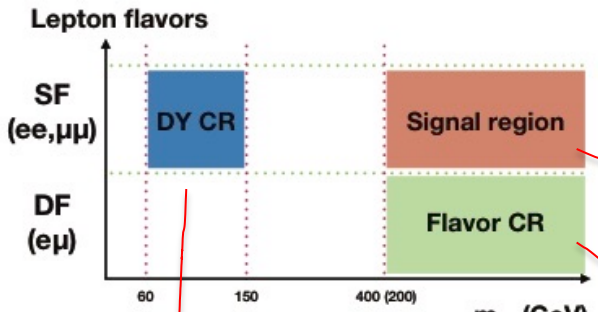
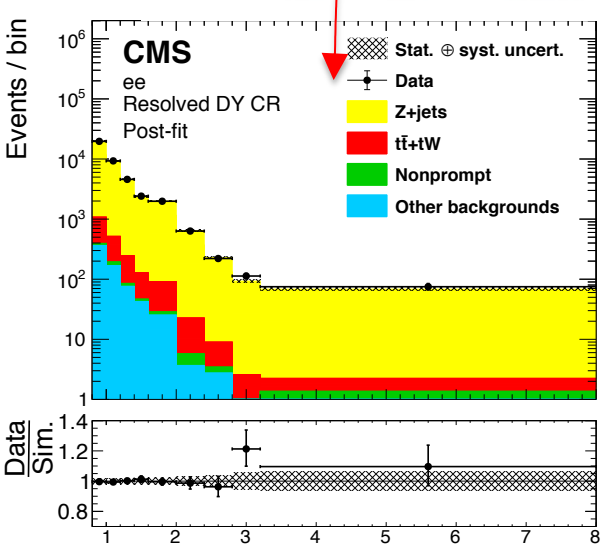
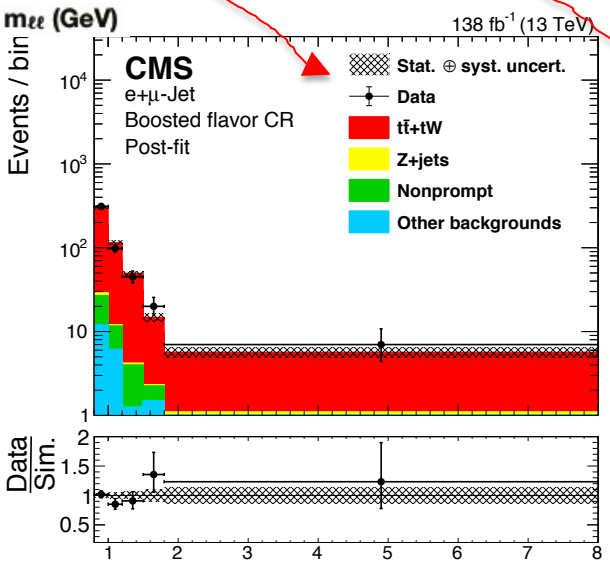
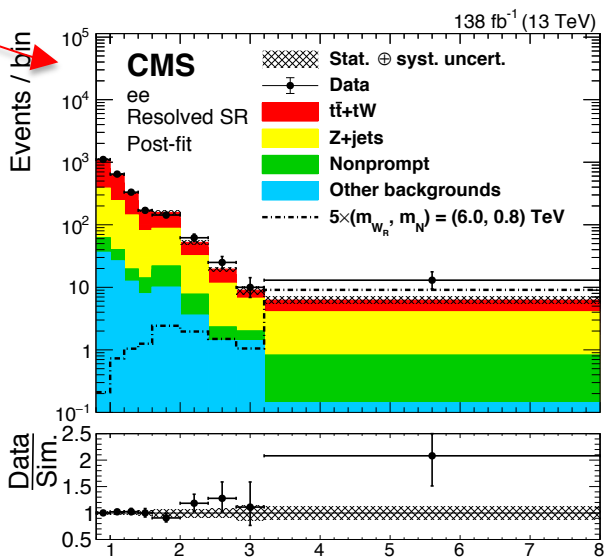




$m(\ell\ell jj)$ TeV



$m(\ell J)$ TeV

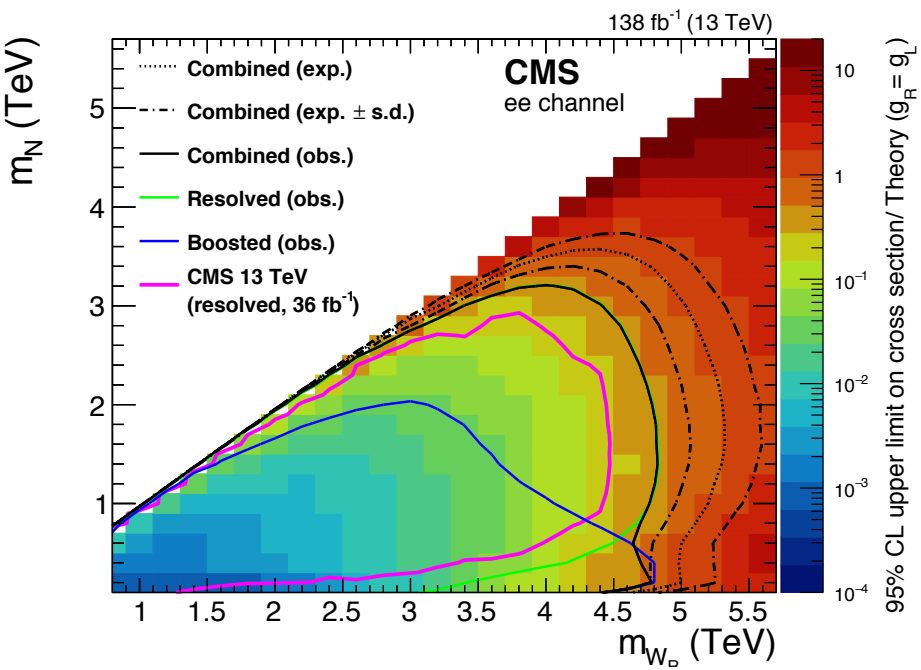


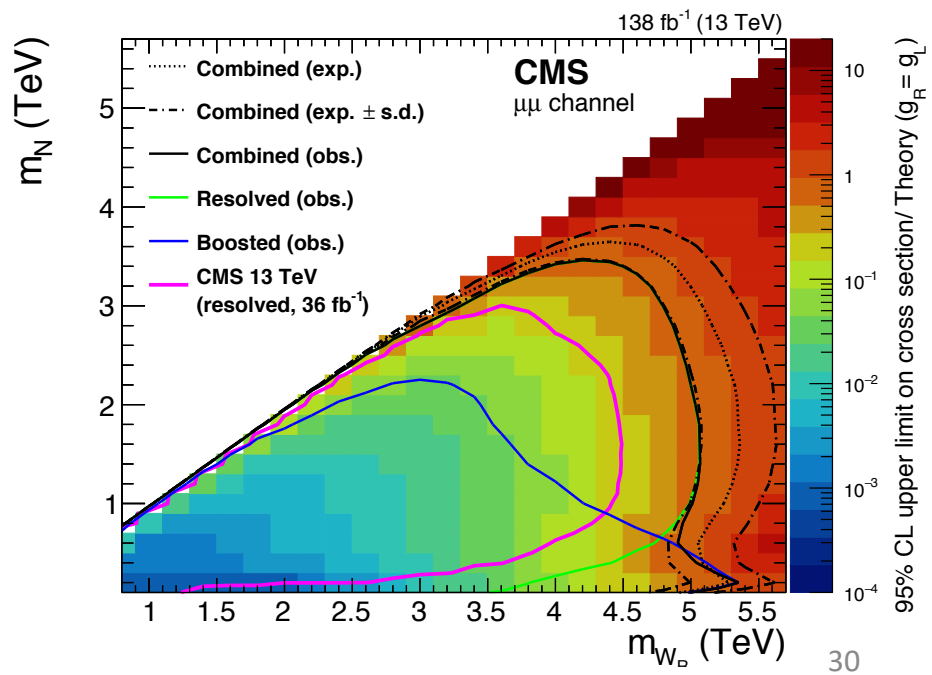
$m(\ell\ell jj)$ TeV

Left-Right Symmetric models, W_R

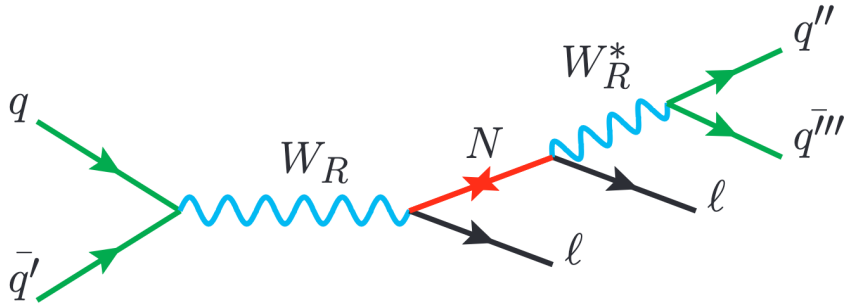
EXO-20-002

- 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(μ) TeV
- At $m_N = 0.2$ TeV, excluded m_{W_R} up to 4.8(e) and 5.4(μ) TeV
- Boosted category provides big improvement with low m_N





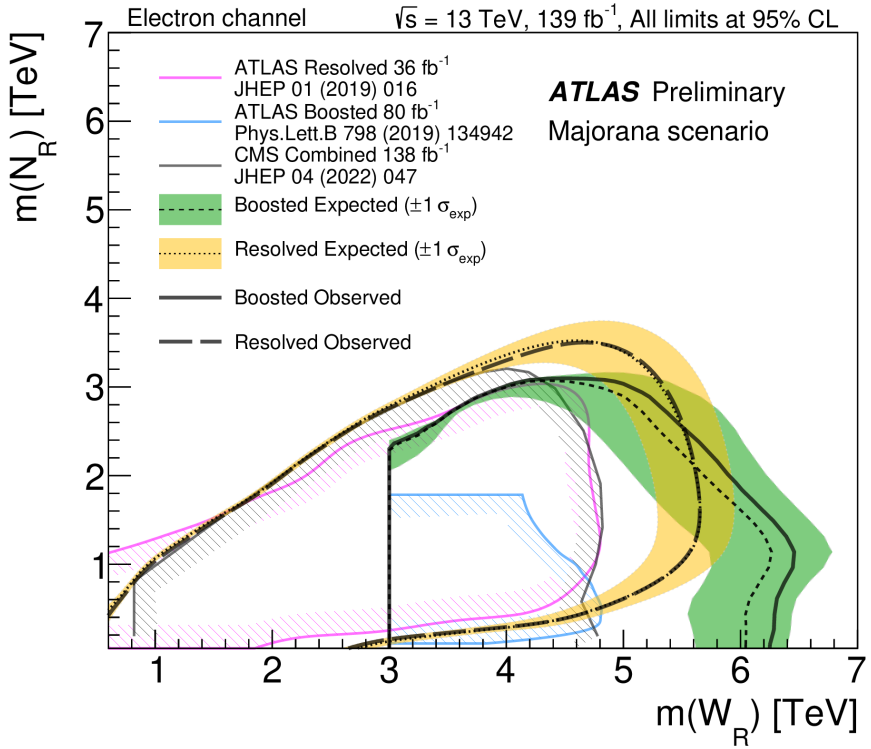
Left-Right Symmetric models, W_R

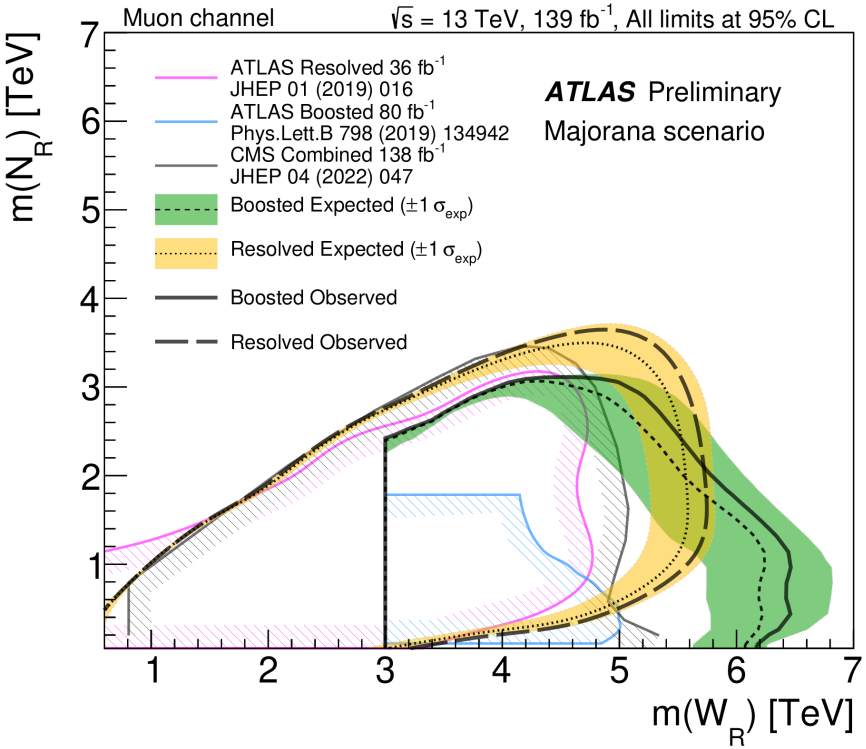


- Similar search by ATLAS
- More rigurous search regions for boosted & resolved scenarios

  $\Delta(m) = m(W_R) - m(N)$

  $m(\ell\ell jj)\ m(\ell J), m(\ell\ell J), m(jj)$
- No significant excess (only 1.6 σ)

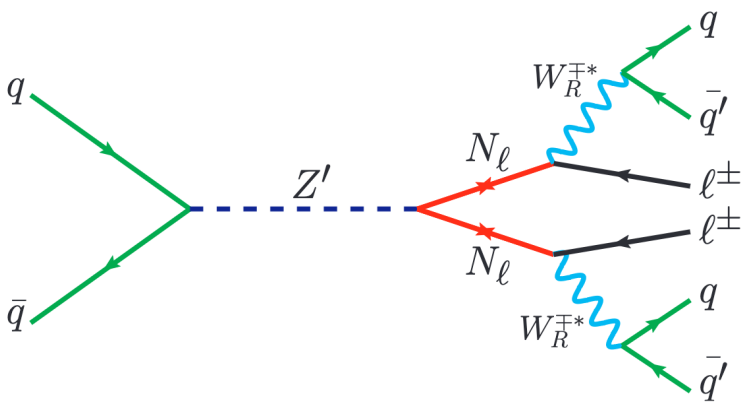




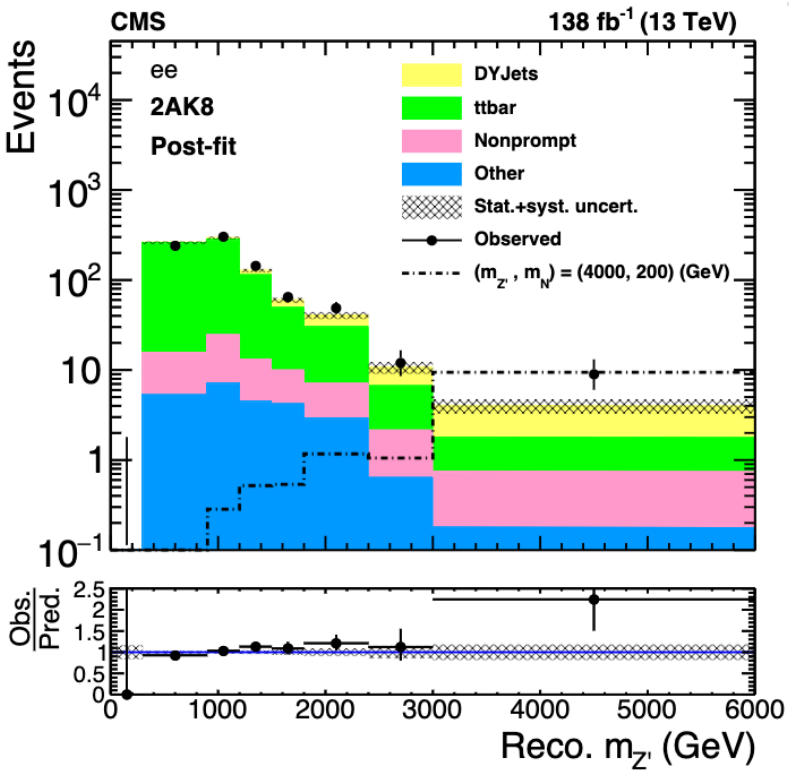
- Exceeds the sensitivity of CMS in particular for large $\Delta(m)$
- For $m(N) < 50\ GeV$, **N becomes long lived** (M. Nemevek et. al, arXiv:1801.05813)

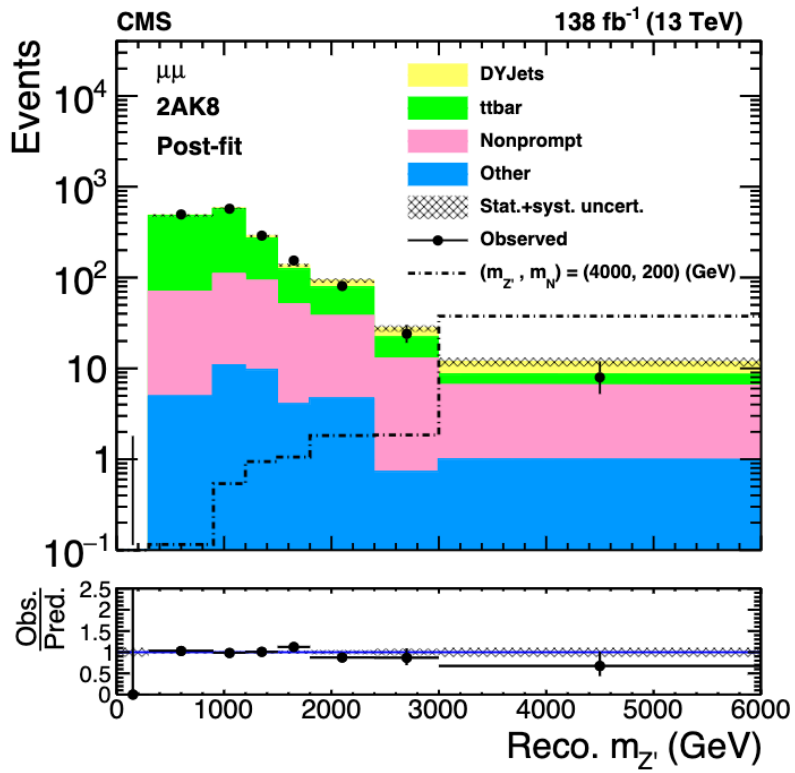
Left-Right Symmetric models, Z'

PAS-EXO-20-006



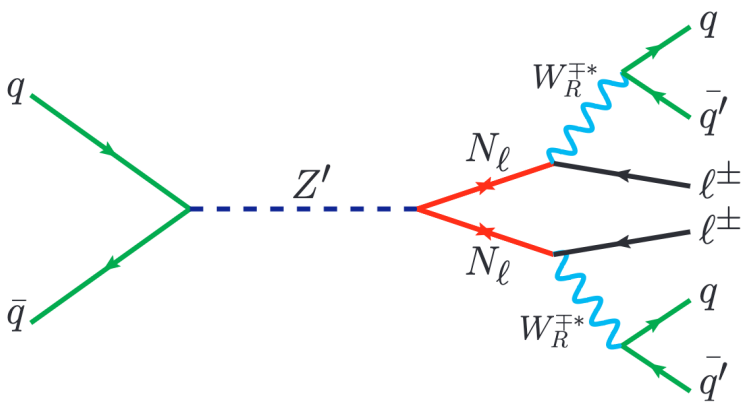
- LRSM model with Z'(400 GeV - 4.4 TeV) decaying to right-handed neutrinos (100 GeV - $m_{Z'}/2$)
- OS and SS lepton pair(ee or $\mu\mu$) + jets
  $\rightarrow$ categories for 0,1 and 2+ large-radius jets(AK8)
  $\rightarrow$ cover boosted and resolved scenarios
- reconstruct $M_{Z'}$
- No significant excess is observed



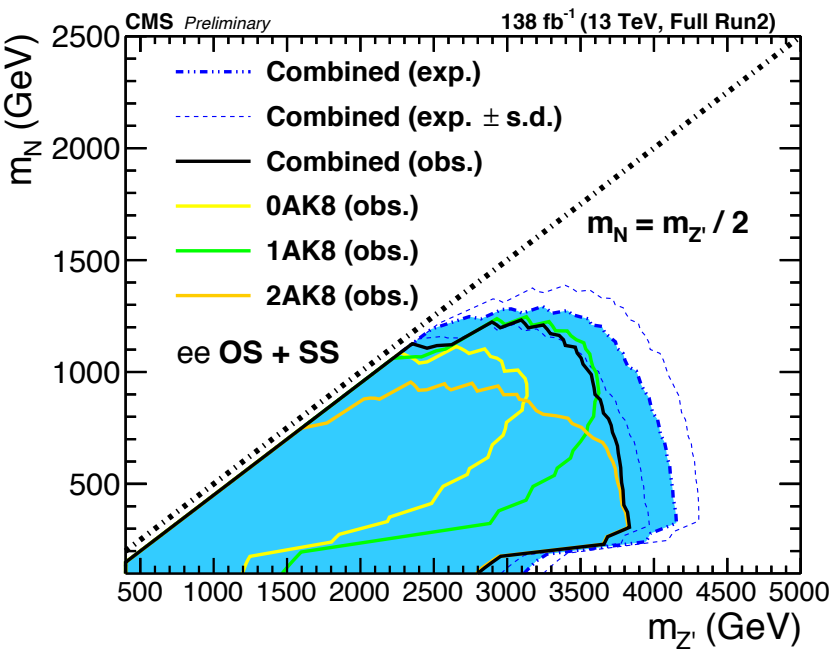


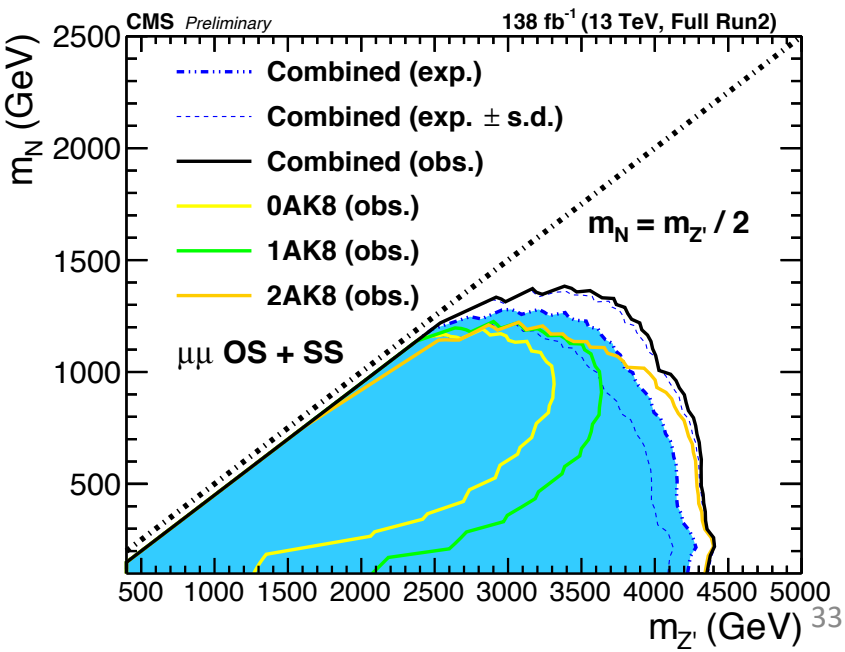
Left-Right Symmetric models, Z'

PAS-EXO-20-006



- LRSM model with Z'(400 GeV - 4.4 TeV) decaying to right-handed neutrinos (100 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
- reconstruct $M_{Z'}$
- 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

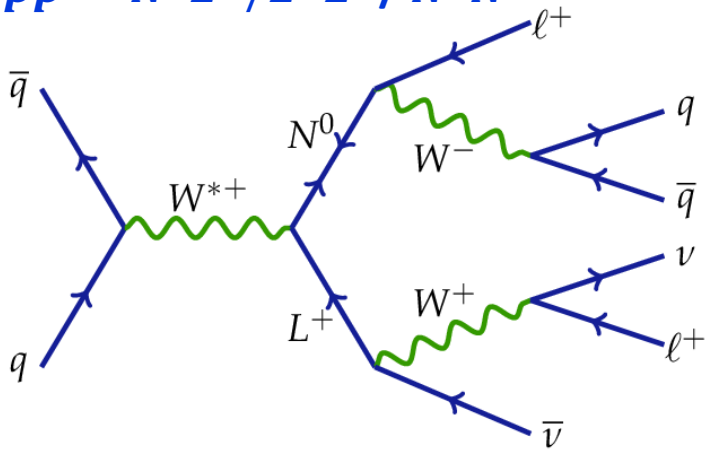




Search for Type-III Seesaw

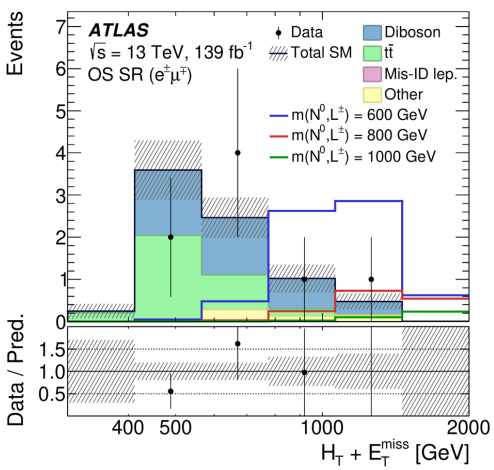
Eur. Phys. J. C 81 (2021) 218

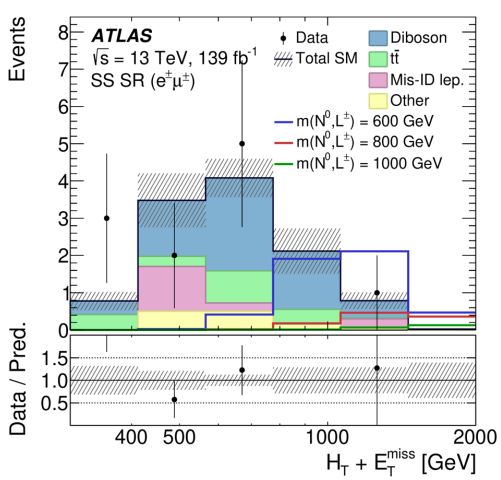
$pp \rightarrow N^0 L^{\pm} / L^{\pm} L^{\pm} / N^0 N^0$

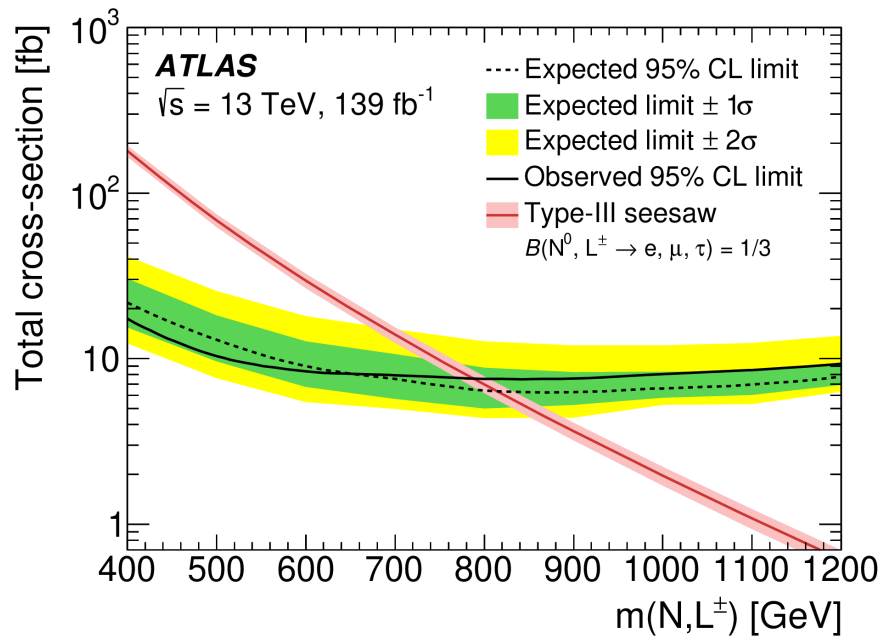


- extra triplet of heavy fermionic fields which couple to EW gauge bosons
- S-channel production of $N^0 L^{\pm}$
- Two leptons with same or opposite charge
- 2 jets and large missing E_T

Main search observables:



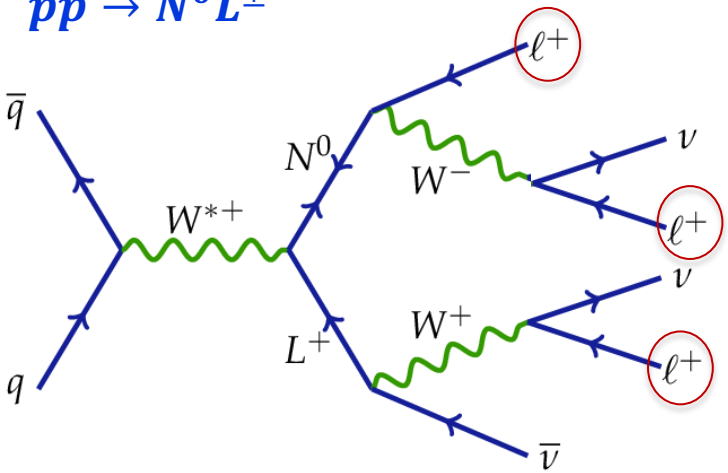




Search for Type-III Seesaw

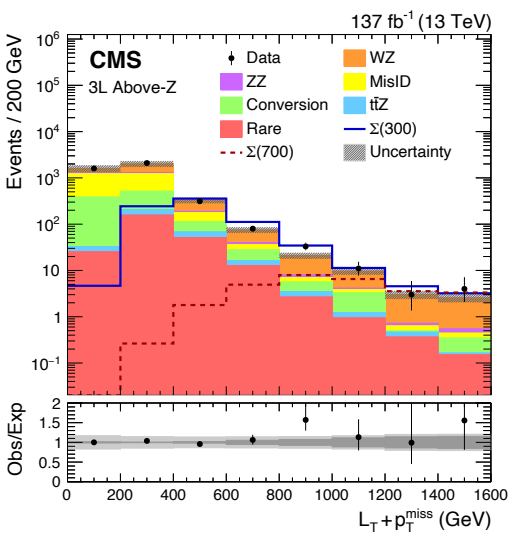
JHEP 03 (2020) 051

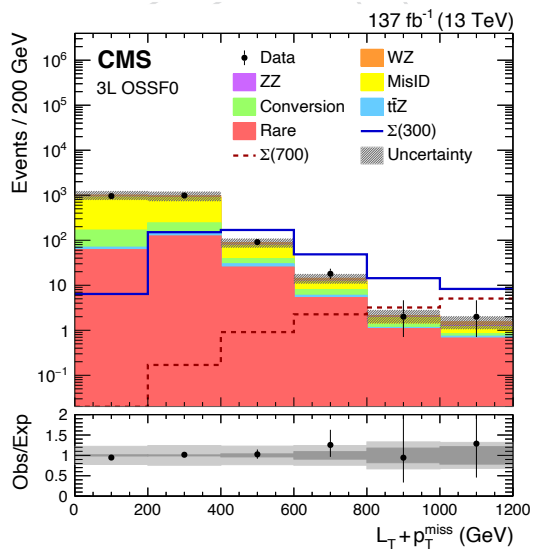
$pp \to N^0 L^\pm$

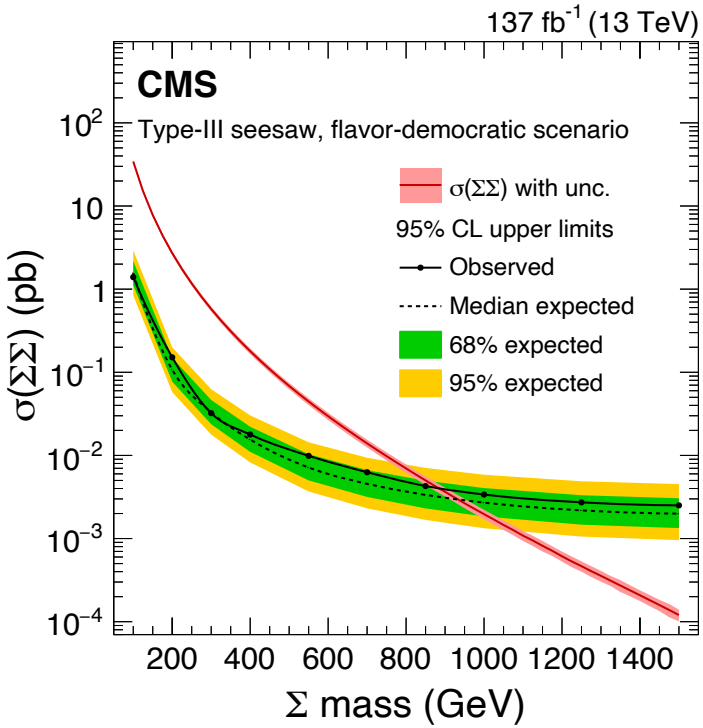


- S-channel production of $N^0 L^\pm$
- Multi-leptons, lower backgrounds
- ~40 exclusive search regions

$$L_T = sum\{p_T^{lepton}\}$$

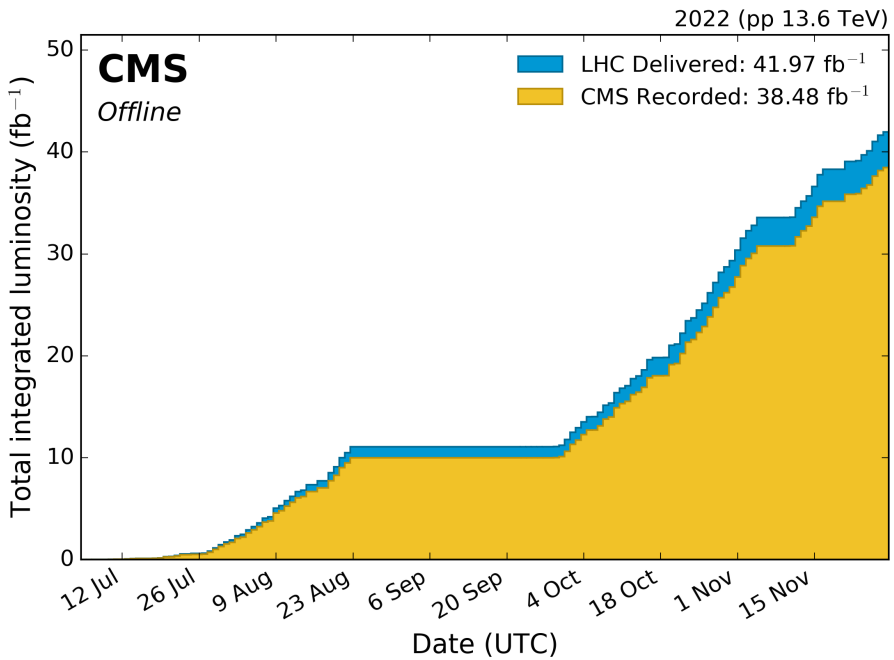






Summary & Outlook

- Heavy Neutral Leptons are well motivated and has a rich set of experimental probe
- Run II data is exhausted for low hanging parameter space
  - A few analyses still in the pipeline with RunII data

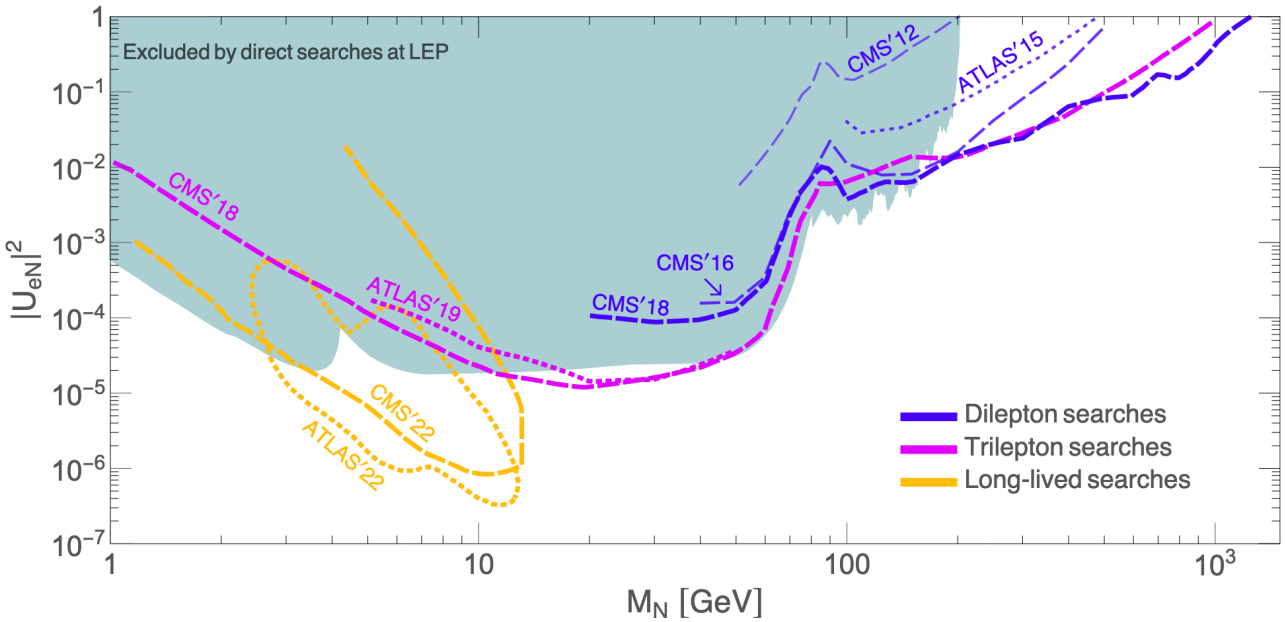


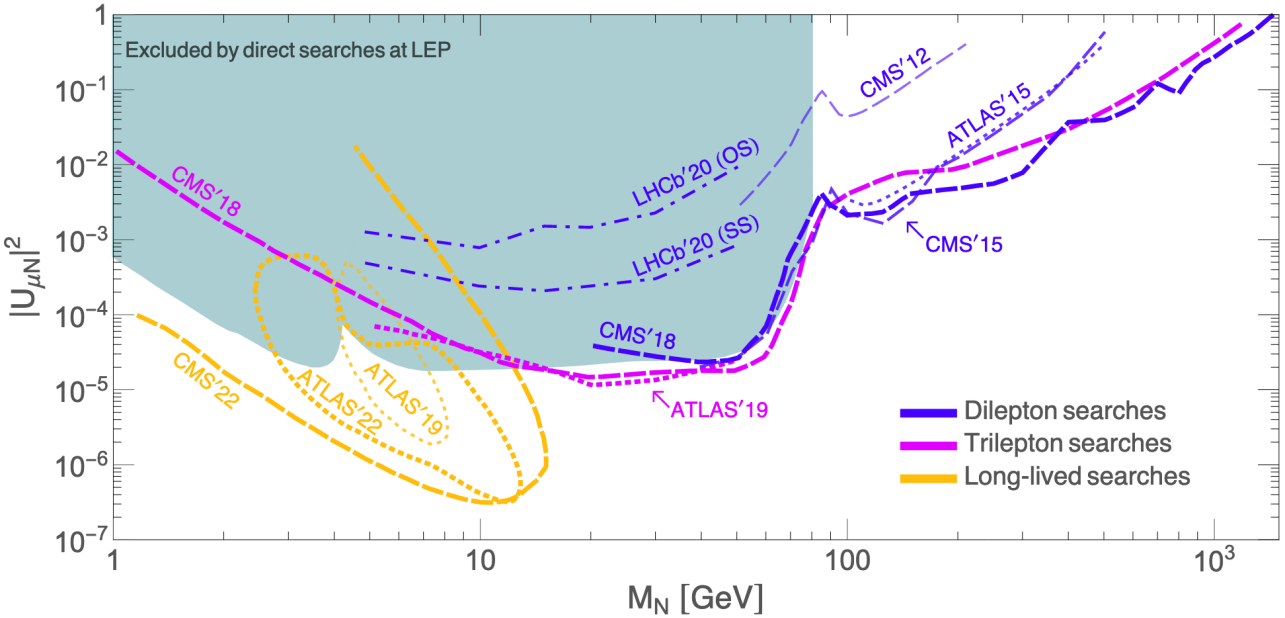
- Run 3 will improve further on existing techniques, new triggers and new analyses…

backup

HNL search in CMS & ATLAS

Abada, Escribano, Marcano, Piazza 2208.13882





- Both experiments extend the reach towards low couplings
- Some differences in sensitivity → expected!