Experimental Search for Heavy Neutral Leptons at LHC

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Baryon, Lepton Number
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Heavy Neutral Leptons

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

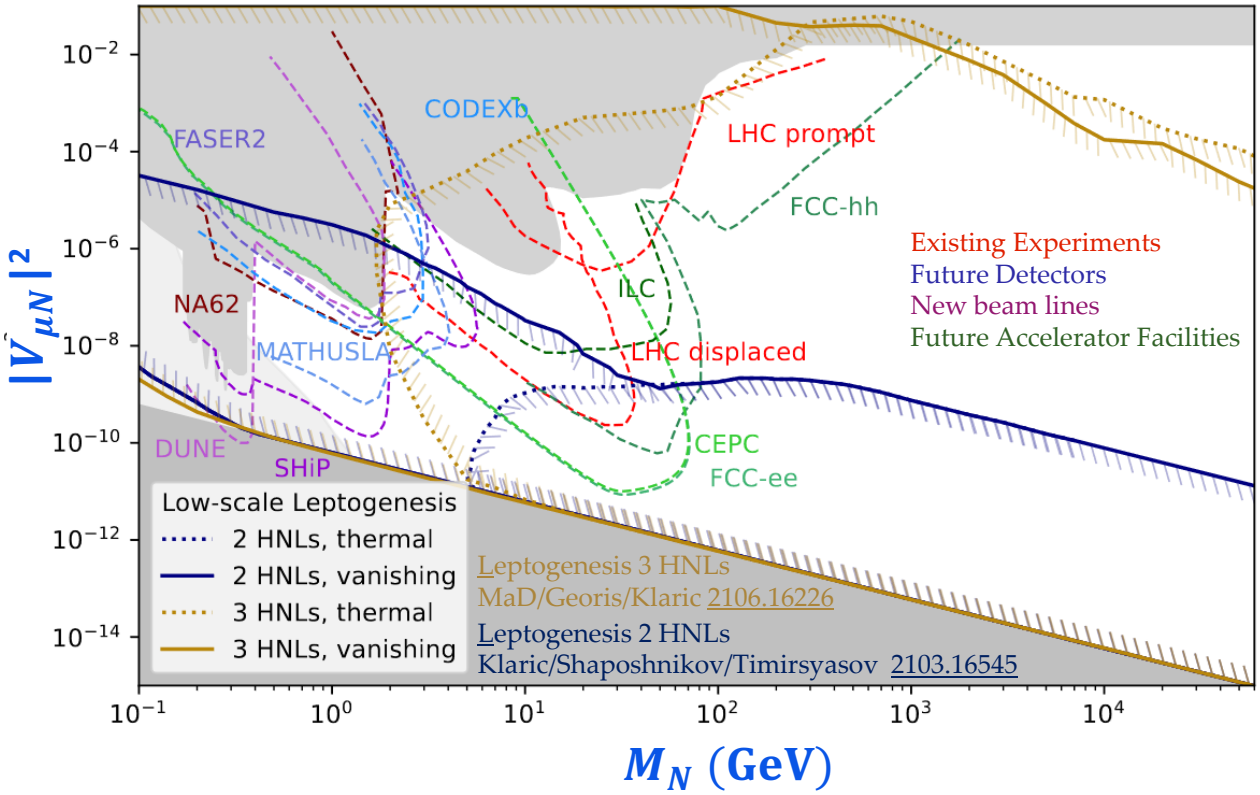
A biased selection of results, mainly CMS

- **Type-I Seesaw Model**
  - Multiple searches with rich phenomenology
  - Prompt and displaced decays
  - A few new results!
- **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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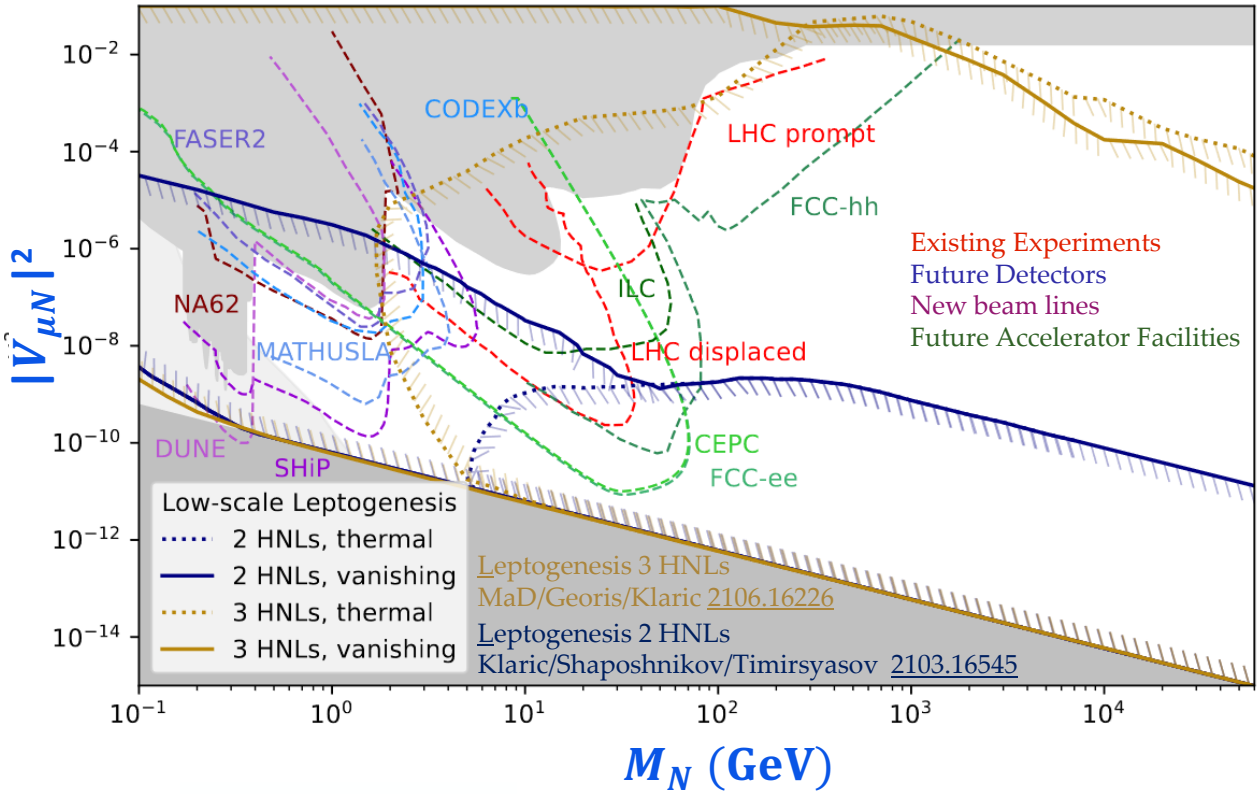
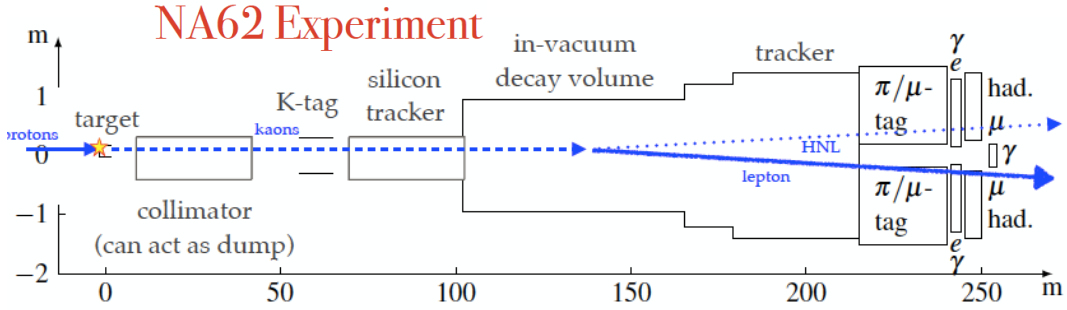
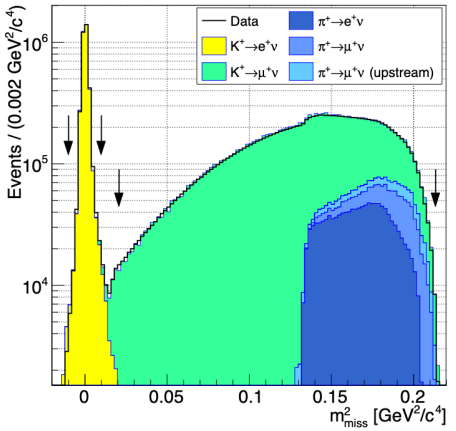


- $M_N < M_{\text{kaon}}$ is pretty much excluded, explored by fixed target experiments, eg. NA62.



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

$K^+ \to e^+ N$



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

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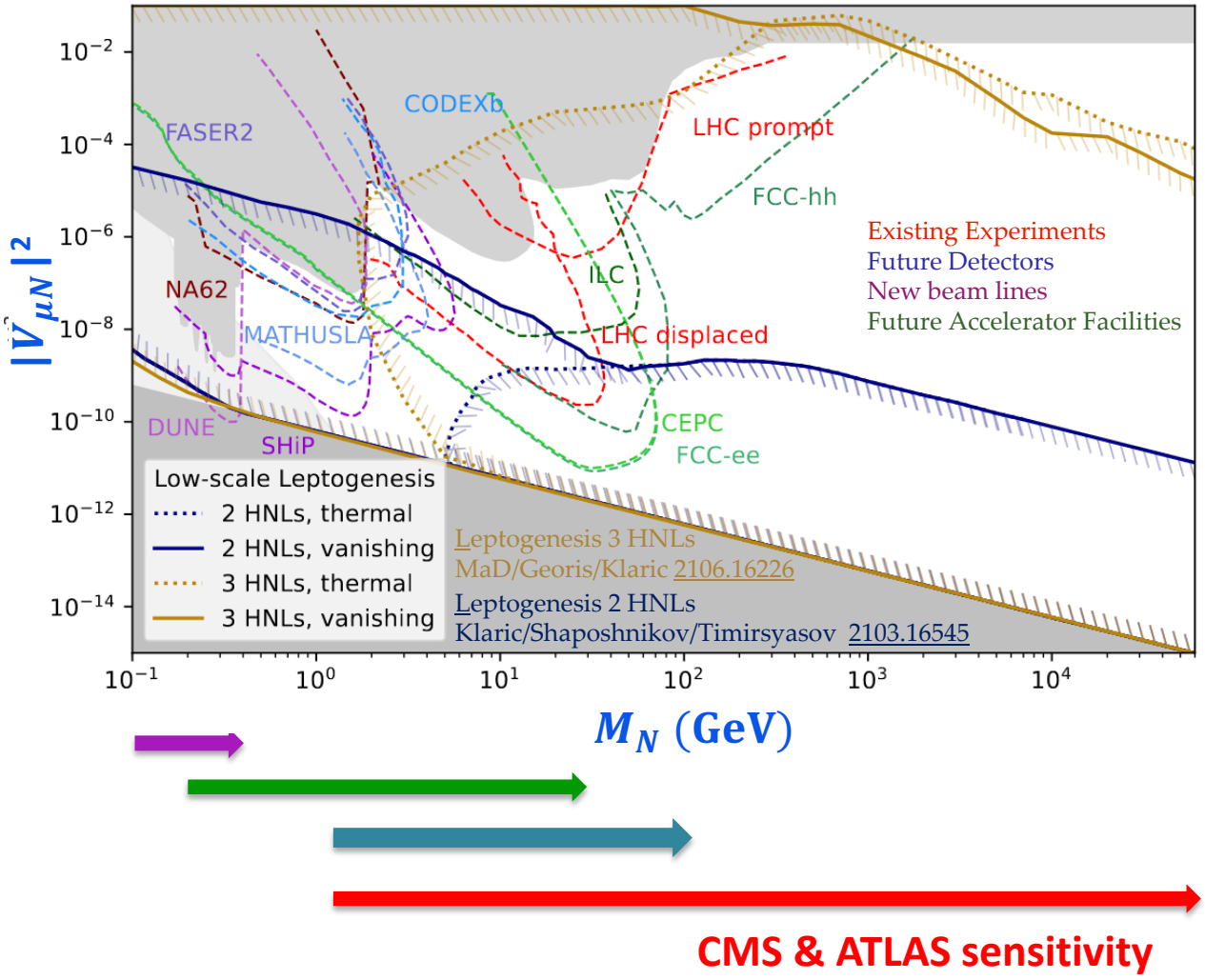
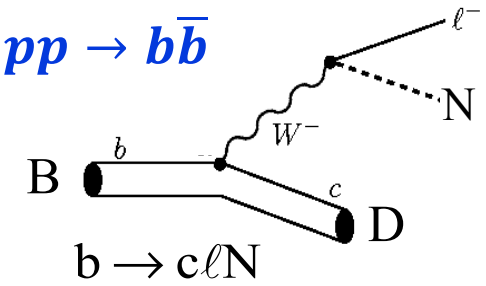


- $M_N < M_{\text{kaon}}$ is pretty much excluded, explored by fixed target experiments, eg. NA62.
- $M_N < M_{B,D}$ explored LHCb, Belle, SHIP
- $M_N < M_Z$ results from LEP
- M_N [1GeV – TeV] LHCb/CMS/ATLAS

HNL production at LHC

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



- Large cross section
- Experimentally very challenging → no trigger
- B-parking data ~10^{10} →New results!

HNL production at LHC

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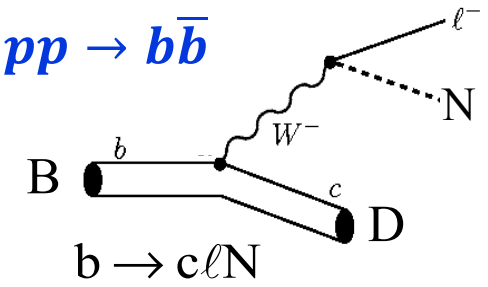

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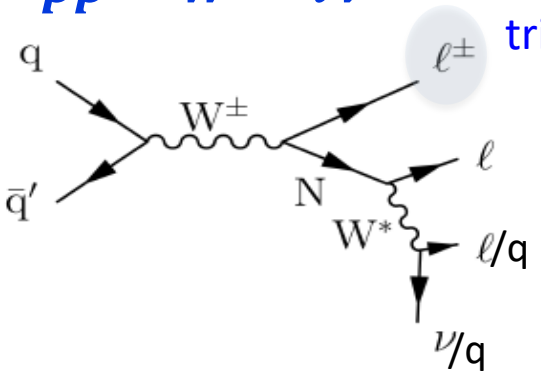
- $pp \to W \to \ell\nu$



- Lower x-section but cleaner exp. signature
- In Run2 ($W \to \ell\nu$) ~9x10^9 events
- Tri-leptons (3ℓ) and SS dilepton+jets
- New results!

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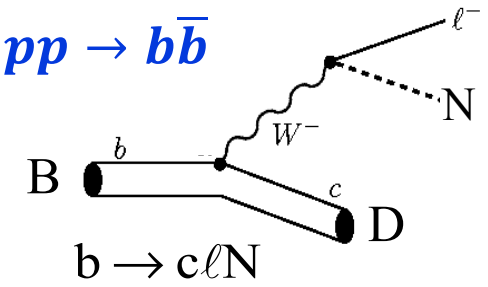

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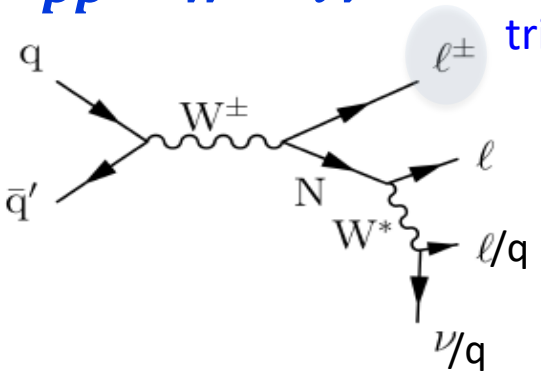

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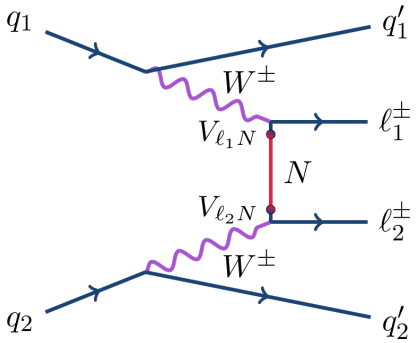
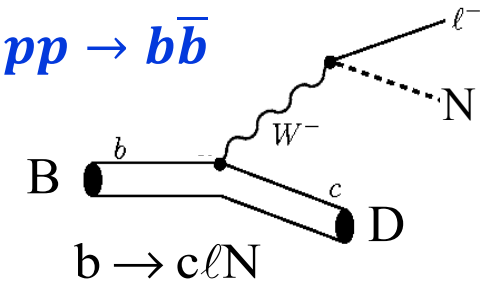
- $pp \to qq\ell^\pm\ell^\pm$



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

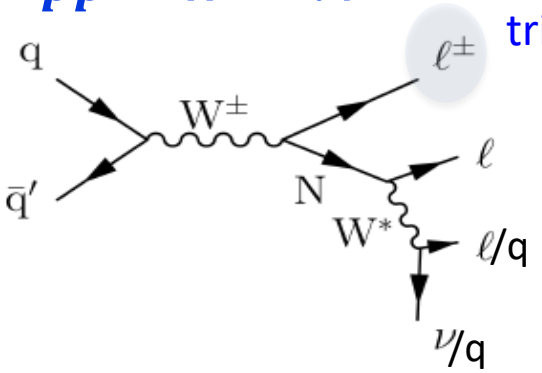
HNL production at LHC

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

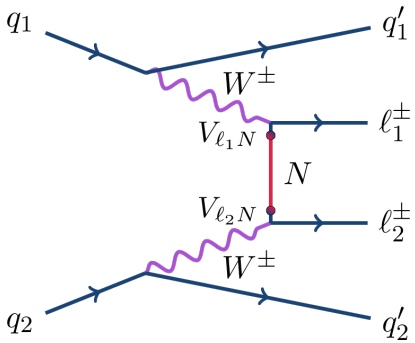


- $pp \to W \to \ell\nu$

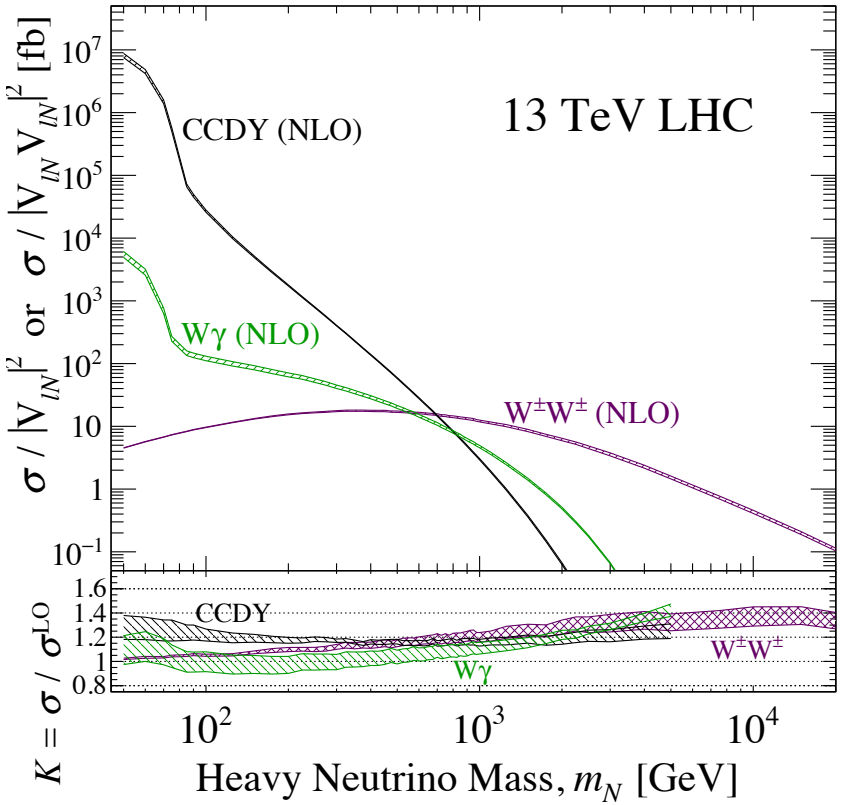
trigger



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

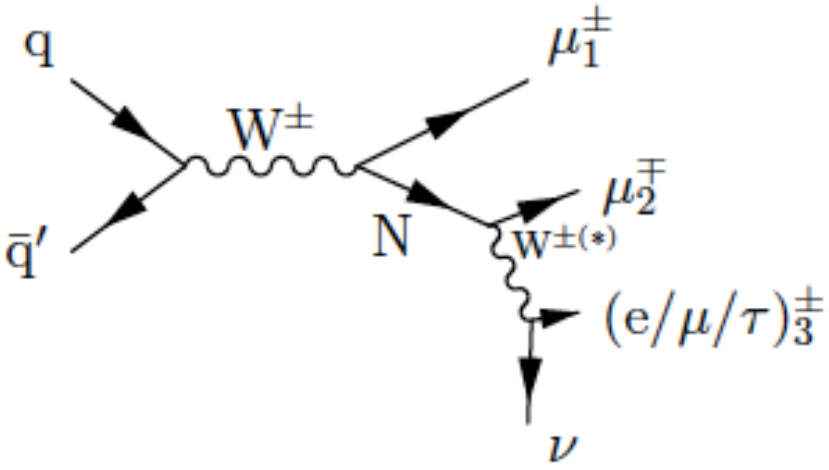


2011.02547, Fuks et.al



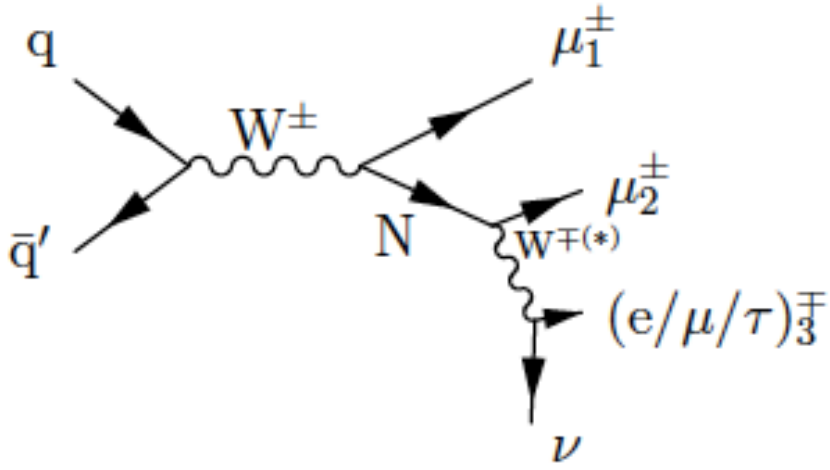
HNL search with displaced leptons

LNC decay



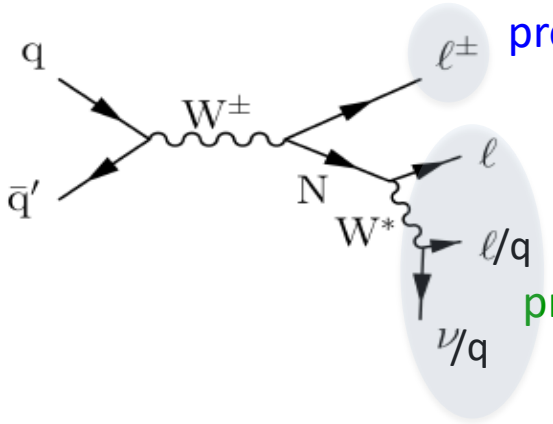
- Always an Opposite-sign-same-flavor (OSSF) lepton pair
- High background

LNV decay



- With and w/o OSSF pair
- Low background

HNL production at LHC

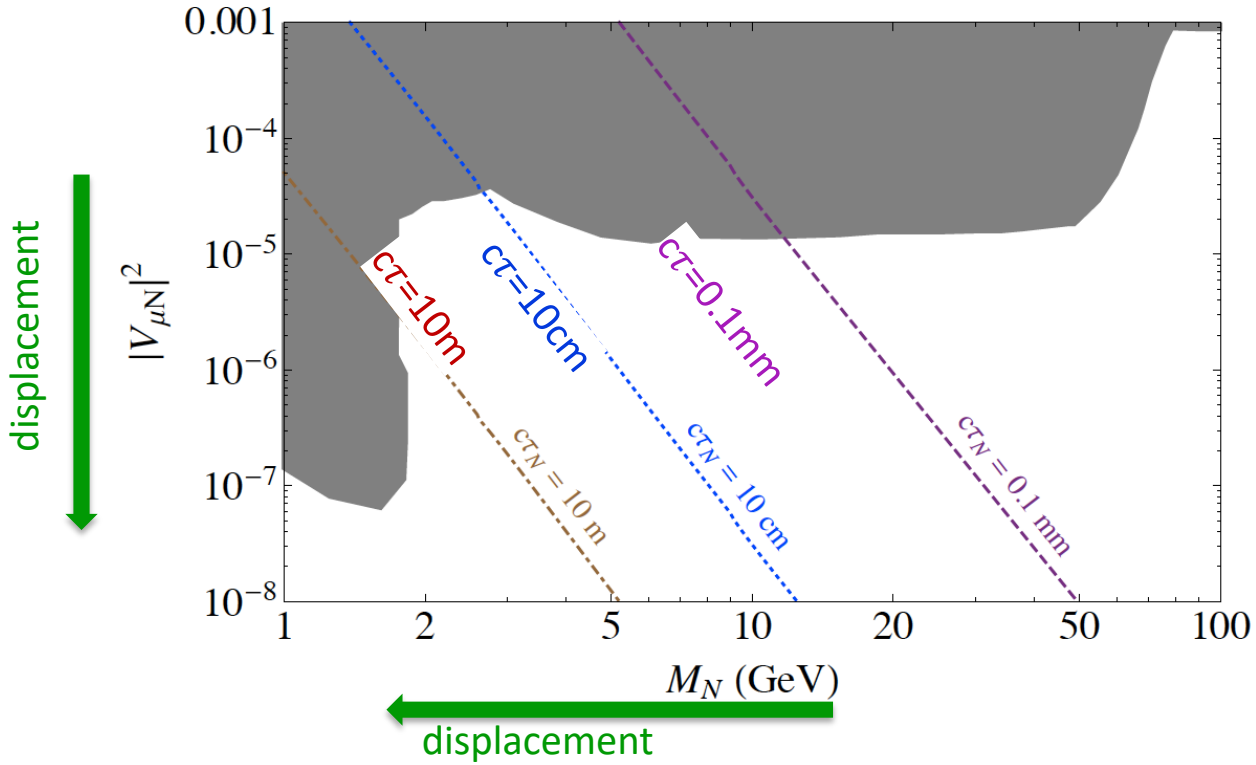


prompt

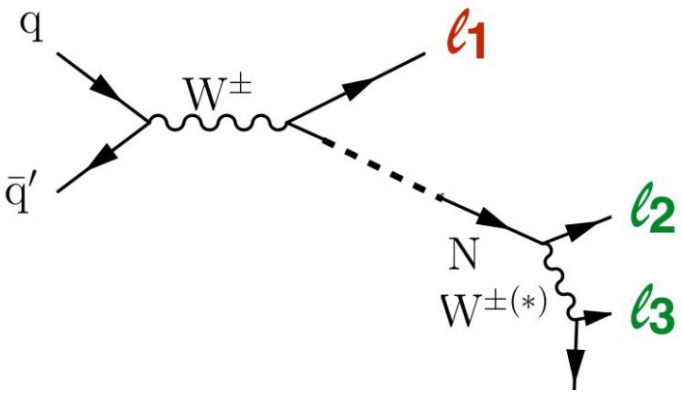
prompt/displaced

Flight distance of HNL can be macroscopic

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



HNL search with prompt leptons



eee, μμμ, $\mu^{\pm}\mu^{\mp}e$, $e^{\pm}e^{\mp}\mu$, $e^{\pm}e^{\pm}\mu$, $\mu^{\pm}\mu^{\pm}e$ + hadronic tau
test Dirac/Majorana hypotheses

arXiv:2403.00100

- BDT's trained in 5 mass regions:
  - Low mass: 10-40 and 50-75 GeV
  - High mass: 85-100, 100-200 and 200-400 GeV

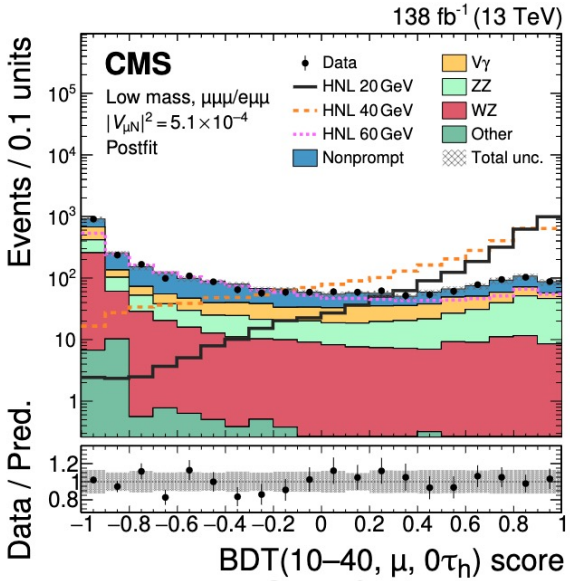
Low mass region

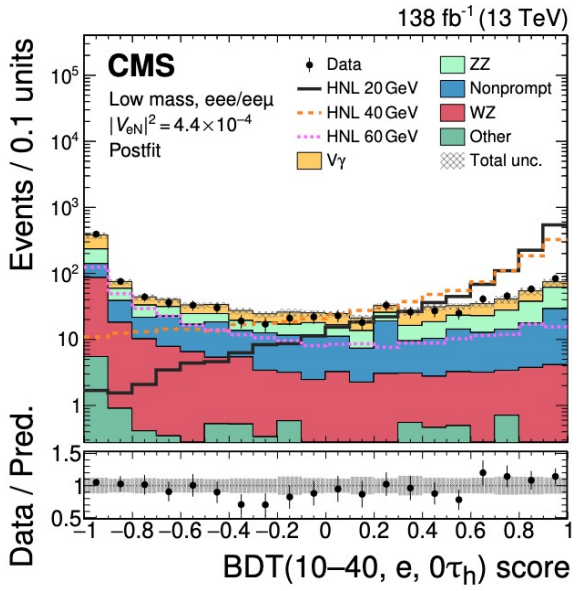
- Training only for events in SR Lb (OSSF present)
- Separate trainings for:
  - e-coupling
  - mu-coupling
  - tau-coupling: light lepton channels
  - tau-coupling: llτ channels

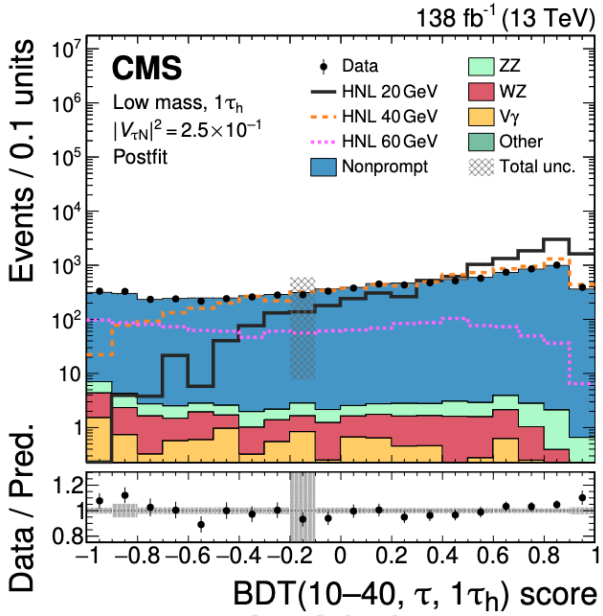
Exhausted list of chategories!!!

High mass region

- Training for all events (OSSF and no OSSF)
- Separate trainings for:
  - e-coupling
  - mu-coupling
- No trainings for tau-coupling







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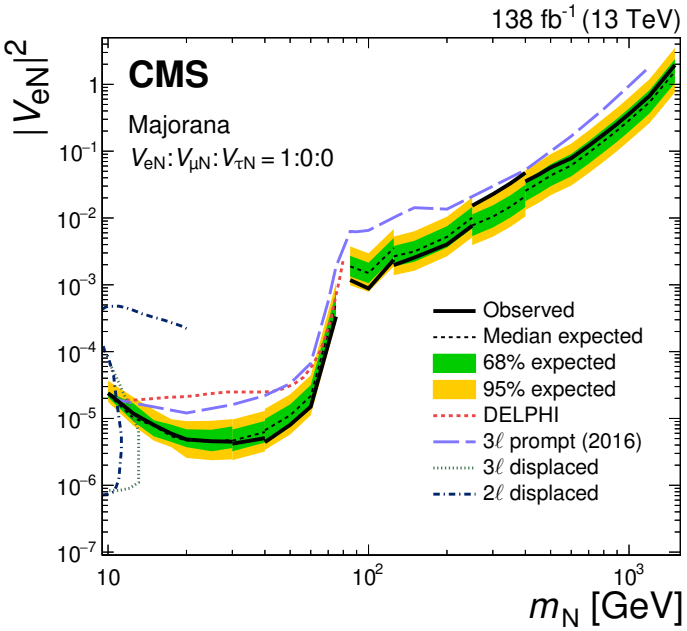

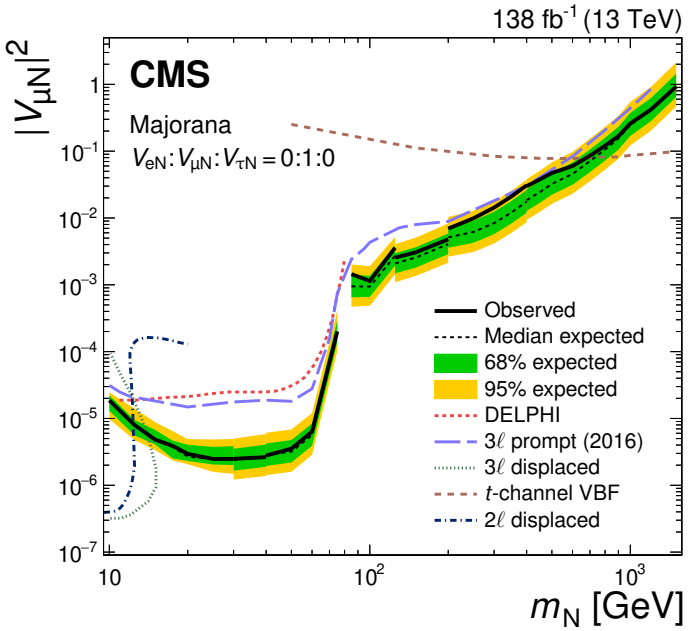

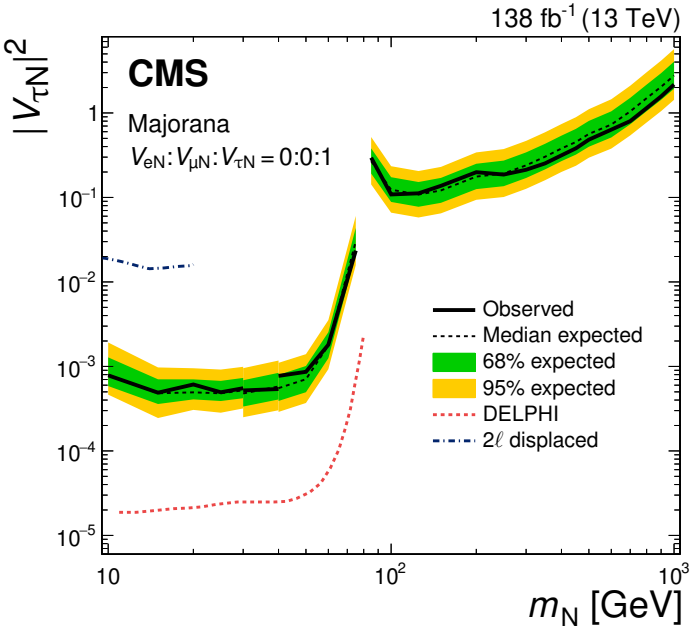

HNL search with displaced leptons

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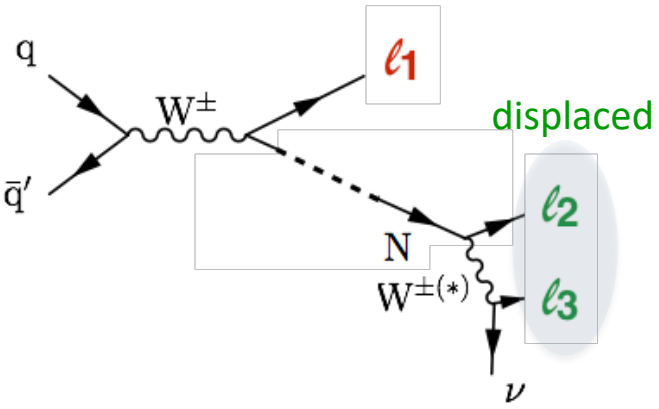
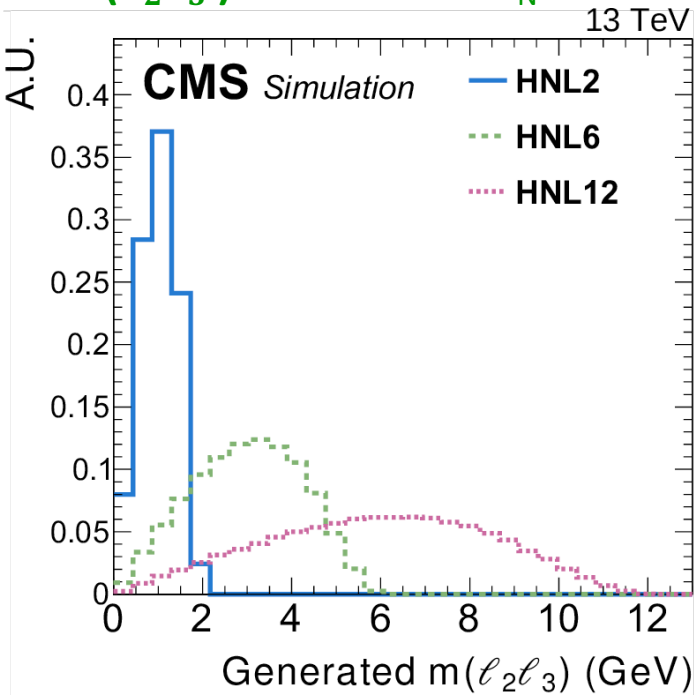
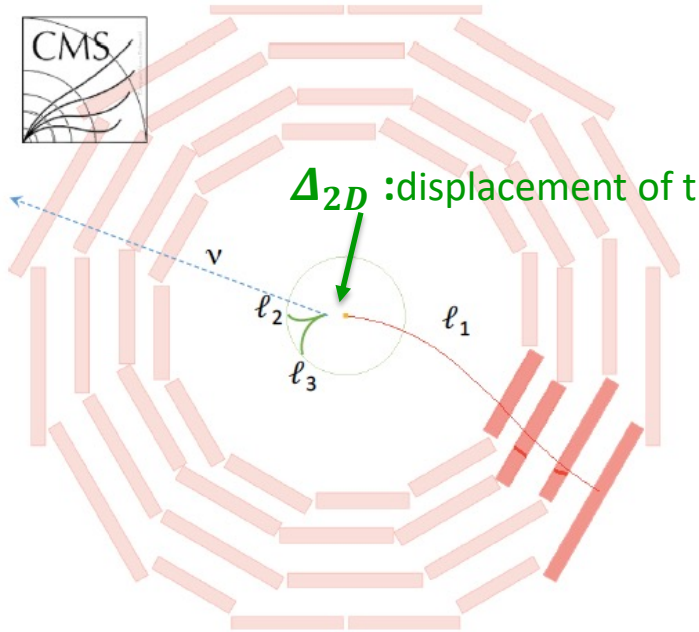


- ℓ_1 prompt & high p_T
- ℓ_1 and ℓ_2 same flavor (LFC)
- eee, μμμ, $\mu^{\pm}\mu^{\mp}e$, $e^{\pm}e^{\mp}\mu$, $e^{\pm}e^{\pm}\mu$, $\mu^{\pm}\mu^{\pm}e$
- test Dirac/Majorana hypotheses
- $M(\ell_1, \ell_2, \ell_3) < M_W$
- $M(\ell_2,\ell_3) \sim M_N$

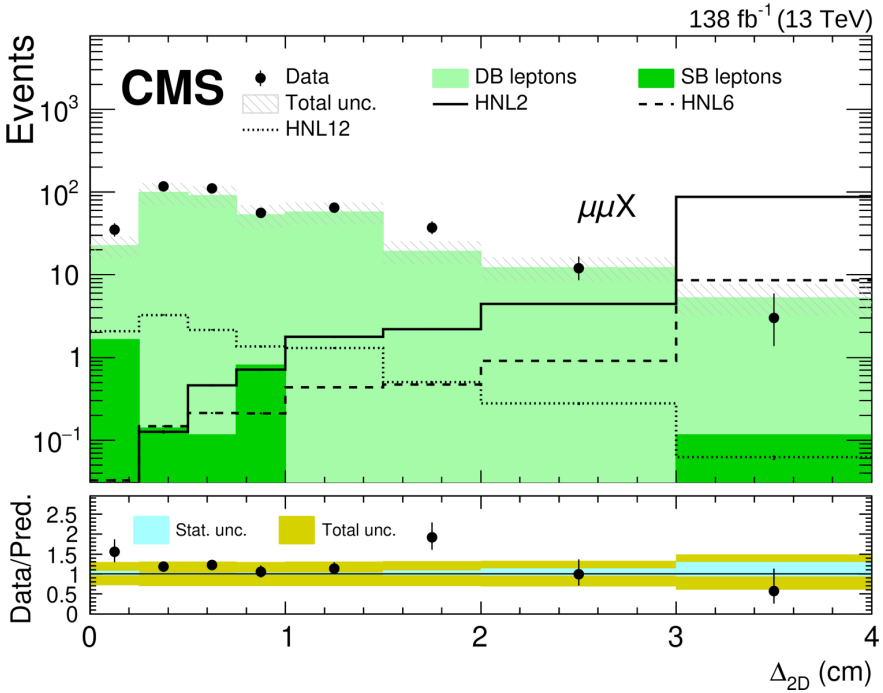
$M(\ell_2\ell_3)$ sensitive to M_N

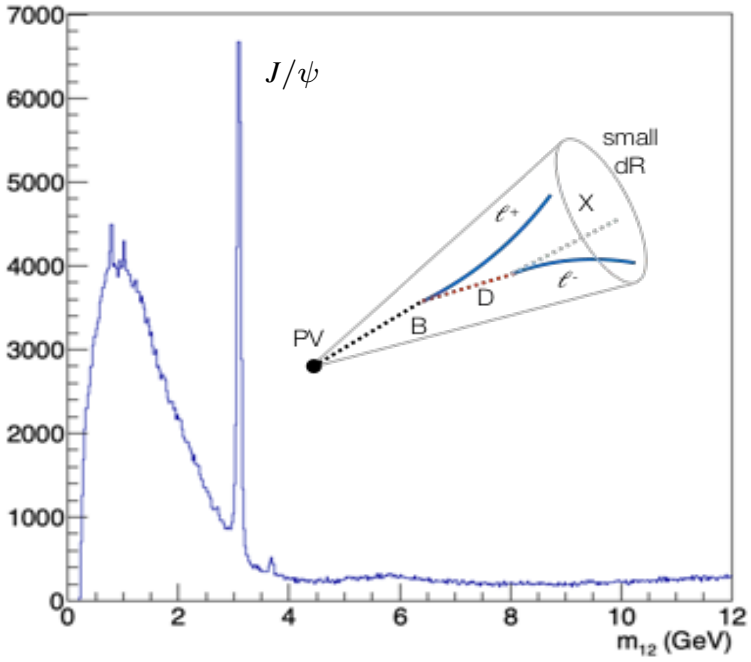




Understanding the backgrounds

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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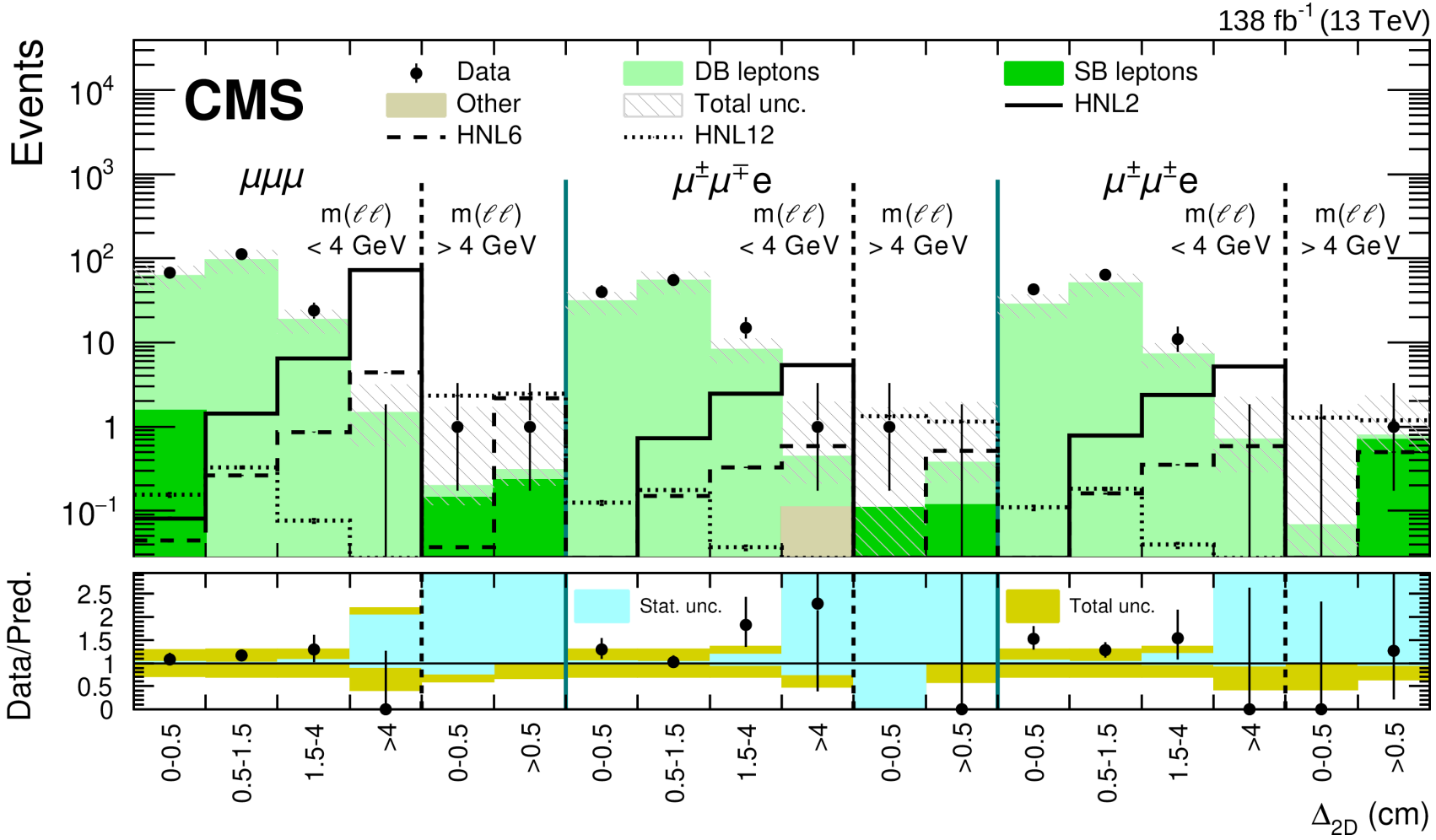
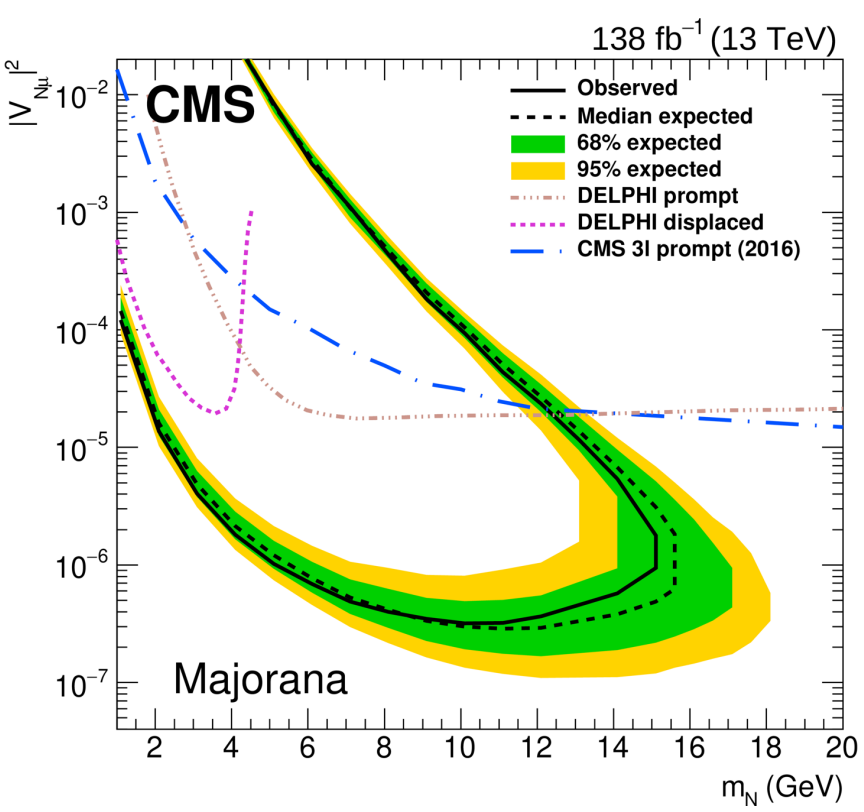


Data agrees with the predicted data within the uncertainties

Interpretation in Majorana HNL

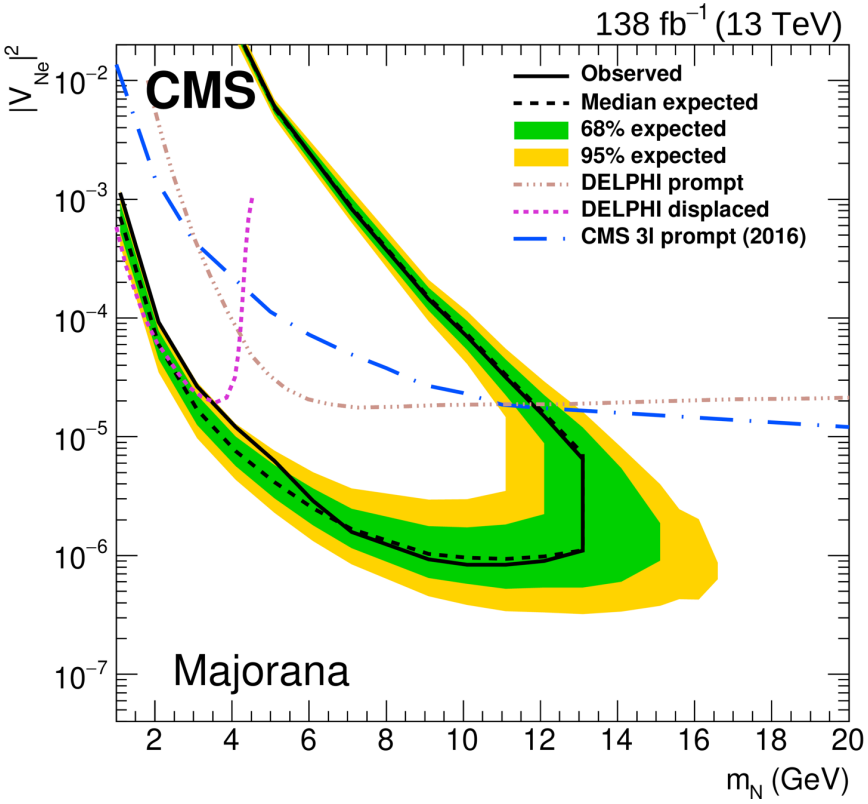
Sensitivity to $|V_{\mu N}|^2$

μμμ, μ±μ∓e± and μ±μ±e∓;

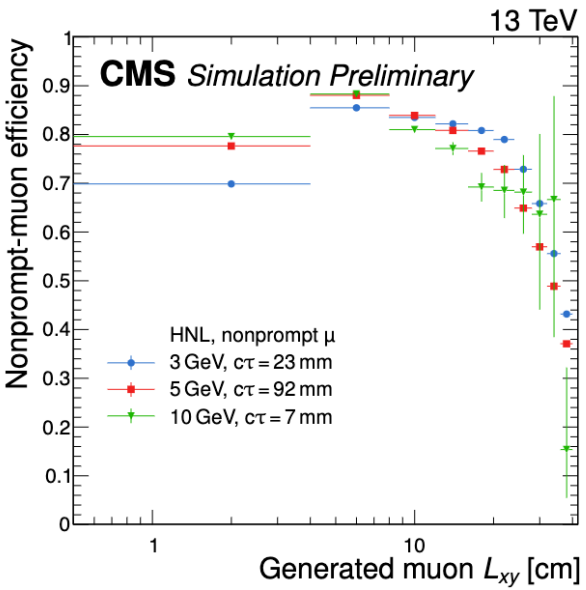


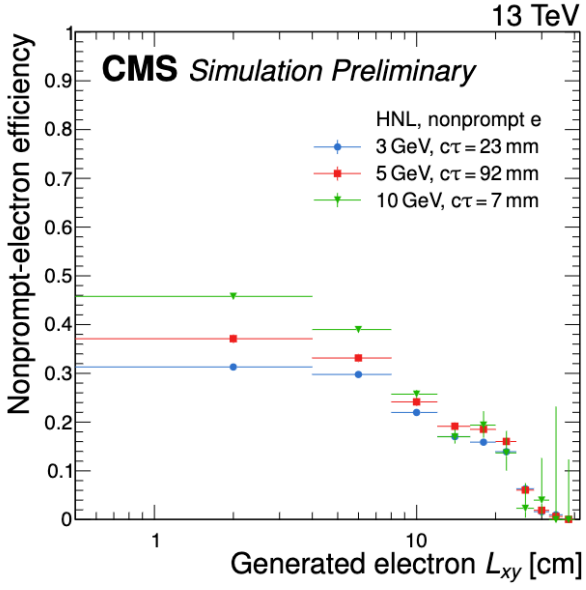
Sensitivity to $|V_{eN}|^2$

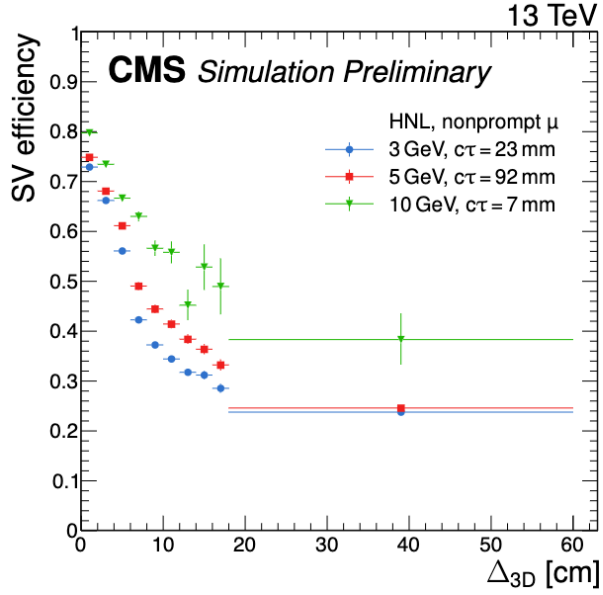
eee, e±e∓μ± and e±e±μ∓.

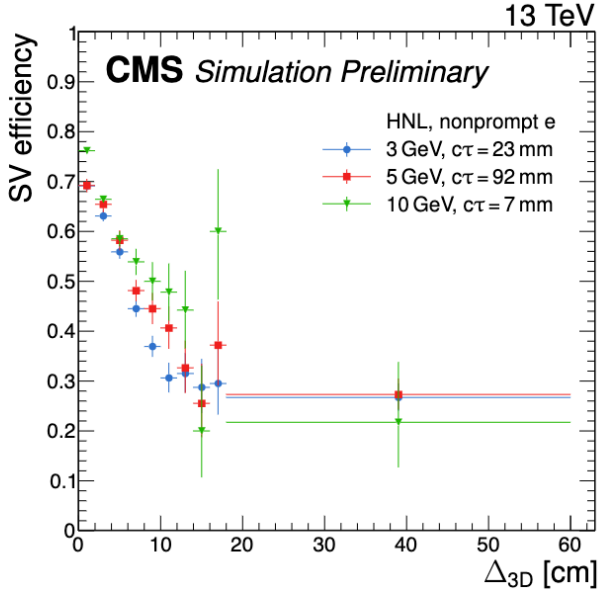


Displaced lepton and vertex reconstruction







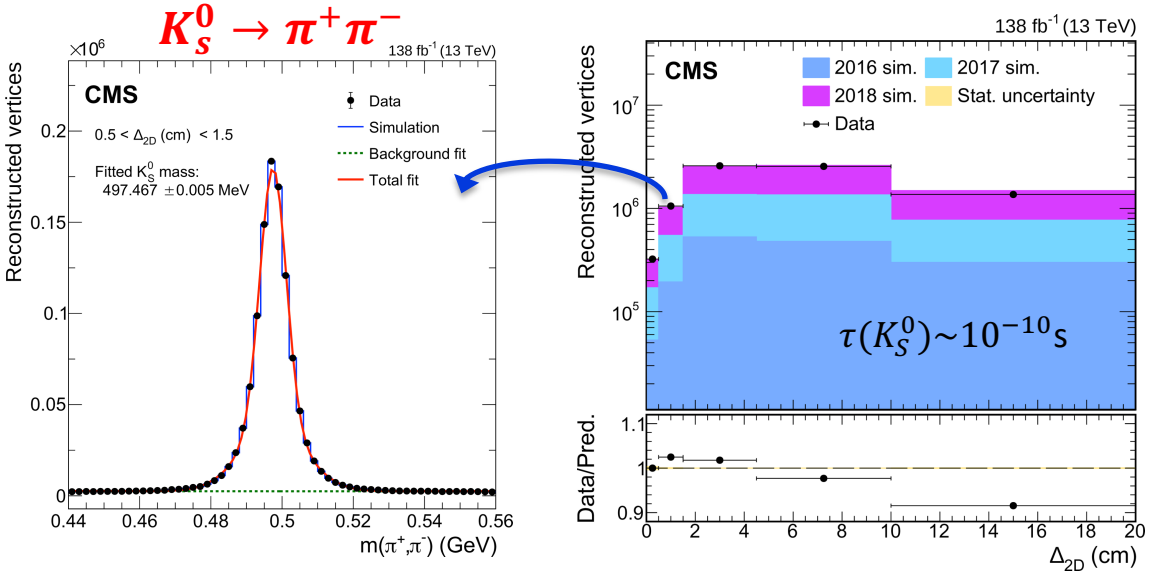


Signal efficiencies are based on simulation, but how realistic it is ? What are the uncertainties associated to this ?

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



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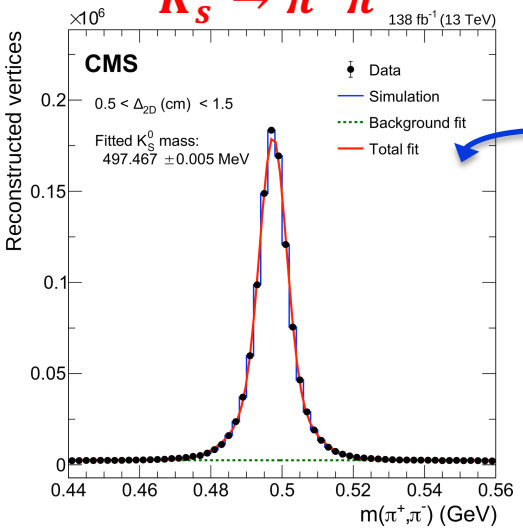
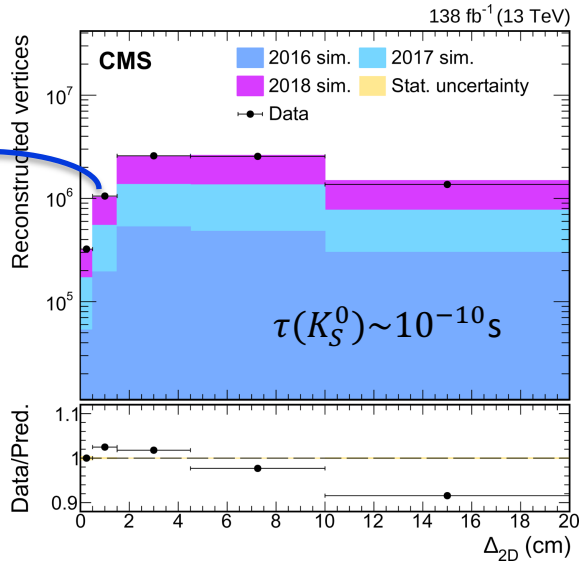
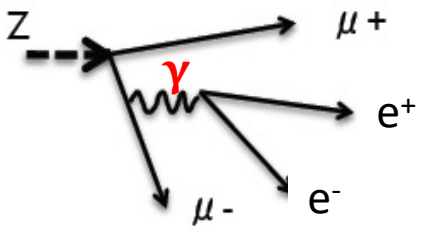
$K_S^0 \to \pi^+\pi^-$

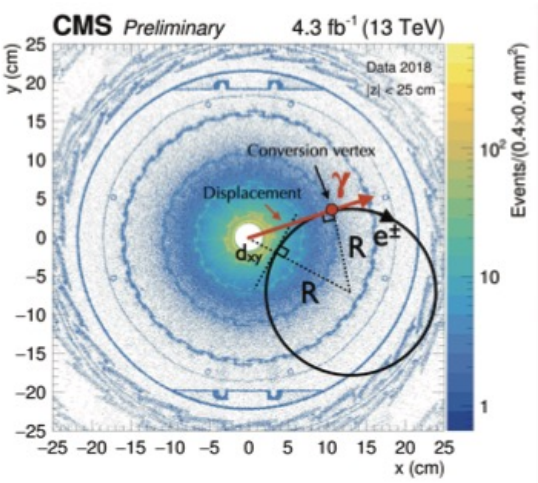




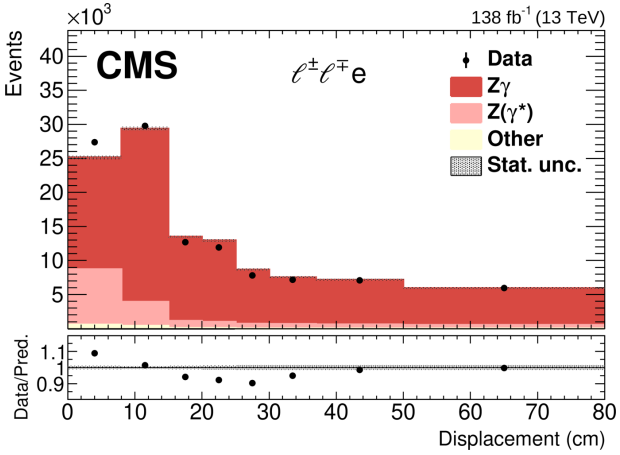
Displaced lepton reconstruction:

- J/ψ → μμ
- 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

HNL search in CMS

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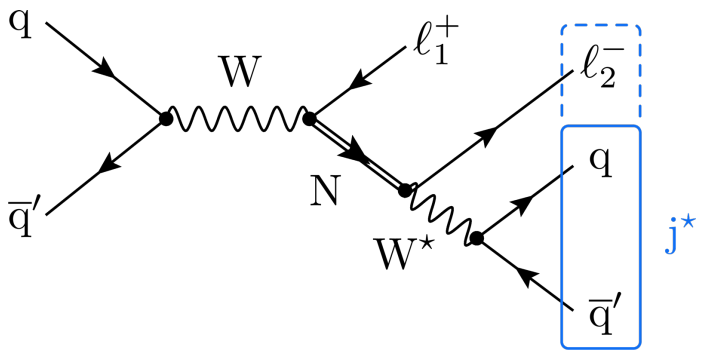
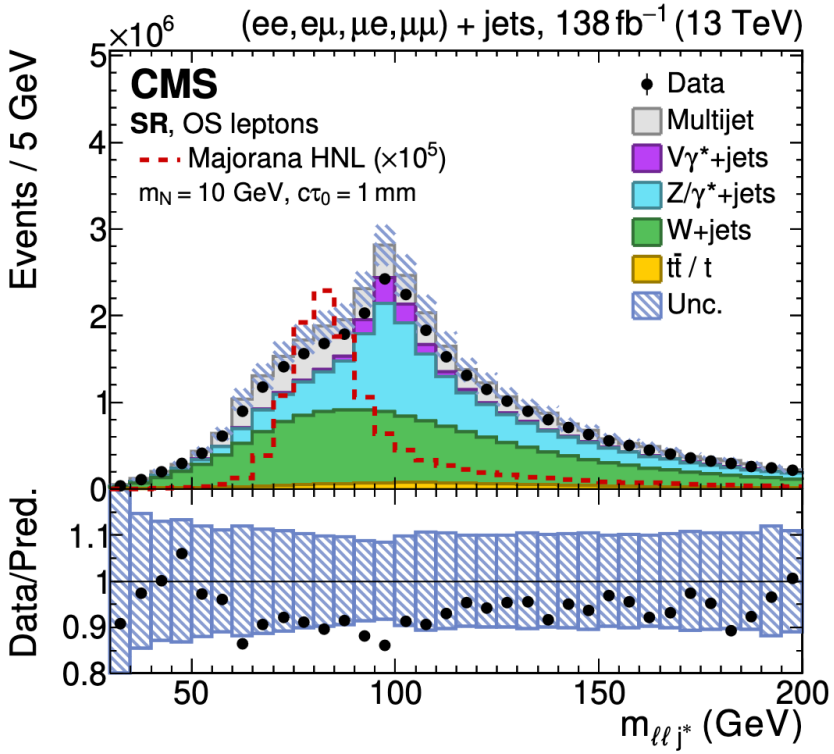
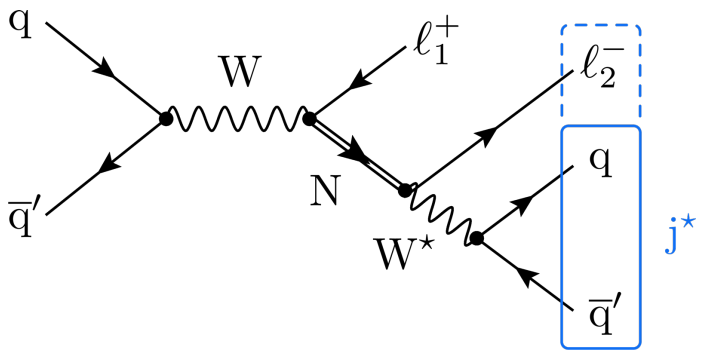


- 2 SS/OS dilptons $(ee, \mu\mu, e\mu, \mu e)$ + jet events
- $p_T(e,\mu) > 5{,}3\ GeV$
- Boosted (resolved) regime
- Deep neural network to tag displaced jet
- Search observable: Impact parameter significance
- 48 categories to be sensitive to various HNL scenarios simultaneously

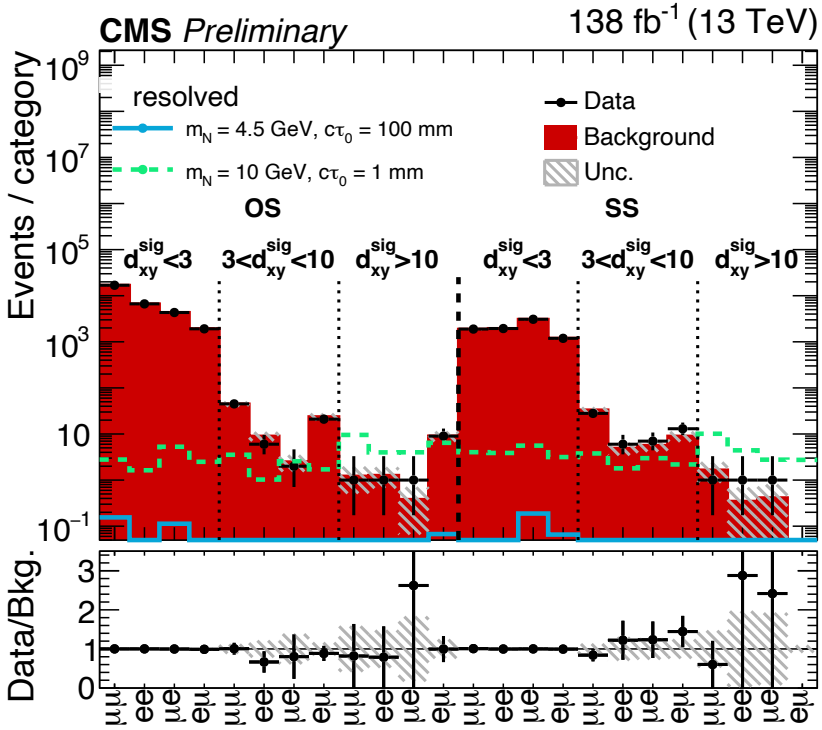


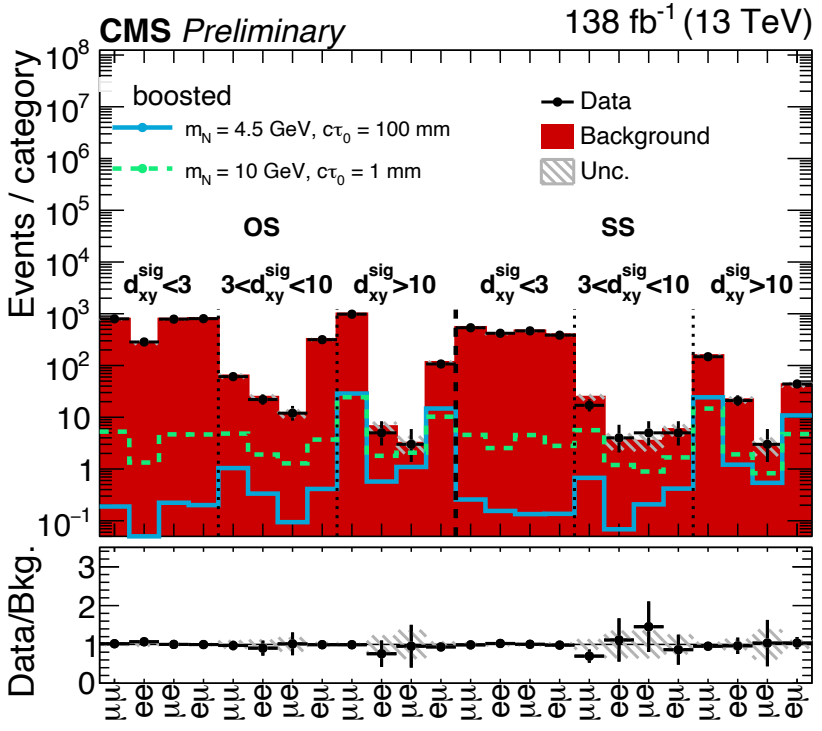
HNL search in CMS

JHEP 03 (2024) 105



- 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

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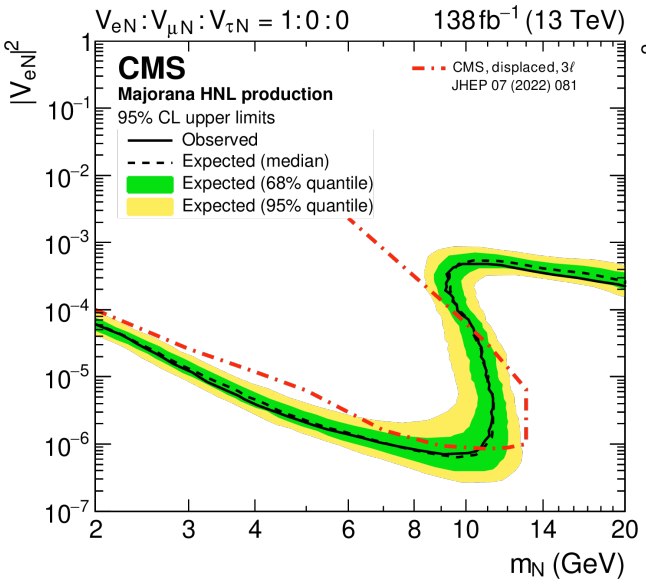
$V_{eN} \neq 0$
$V_{\mu N} = 0$
$V_{\tau N} = 0$



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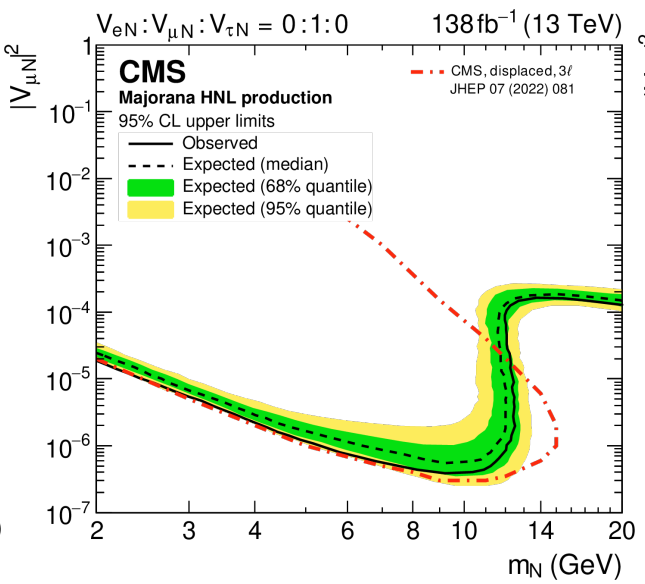

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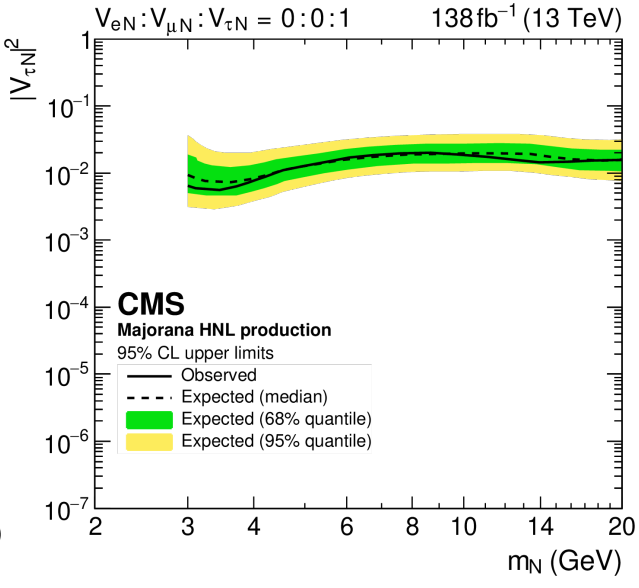
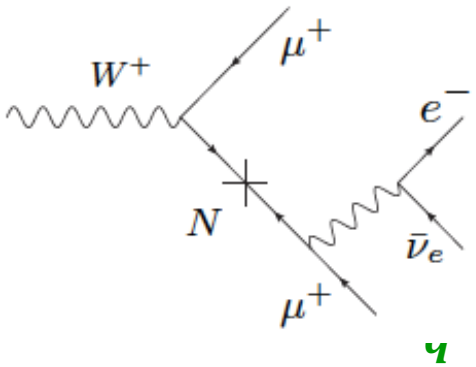


A more realistic interpretation

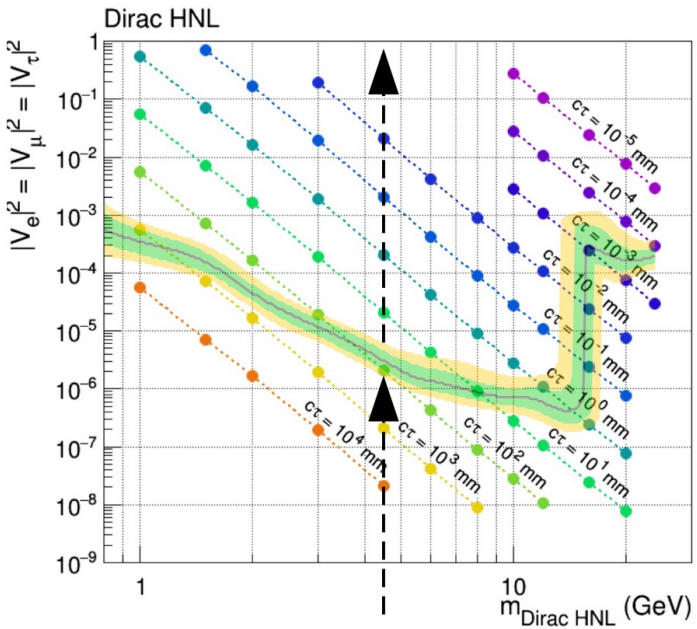
JHEP 03 (2024) 105

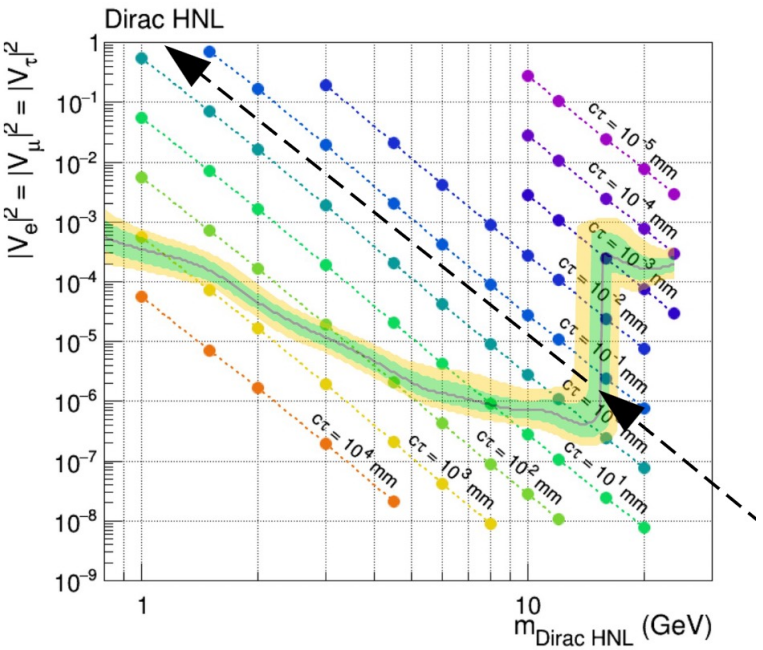


- Typically consider the coupling of N to one neutrino flavour at a time.
- First time symultaneous couplings to $\nu_e \nu_\mu \nu_\tau$ is considered

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

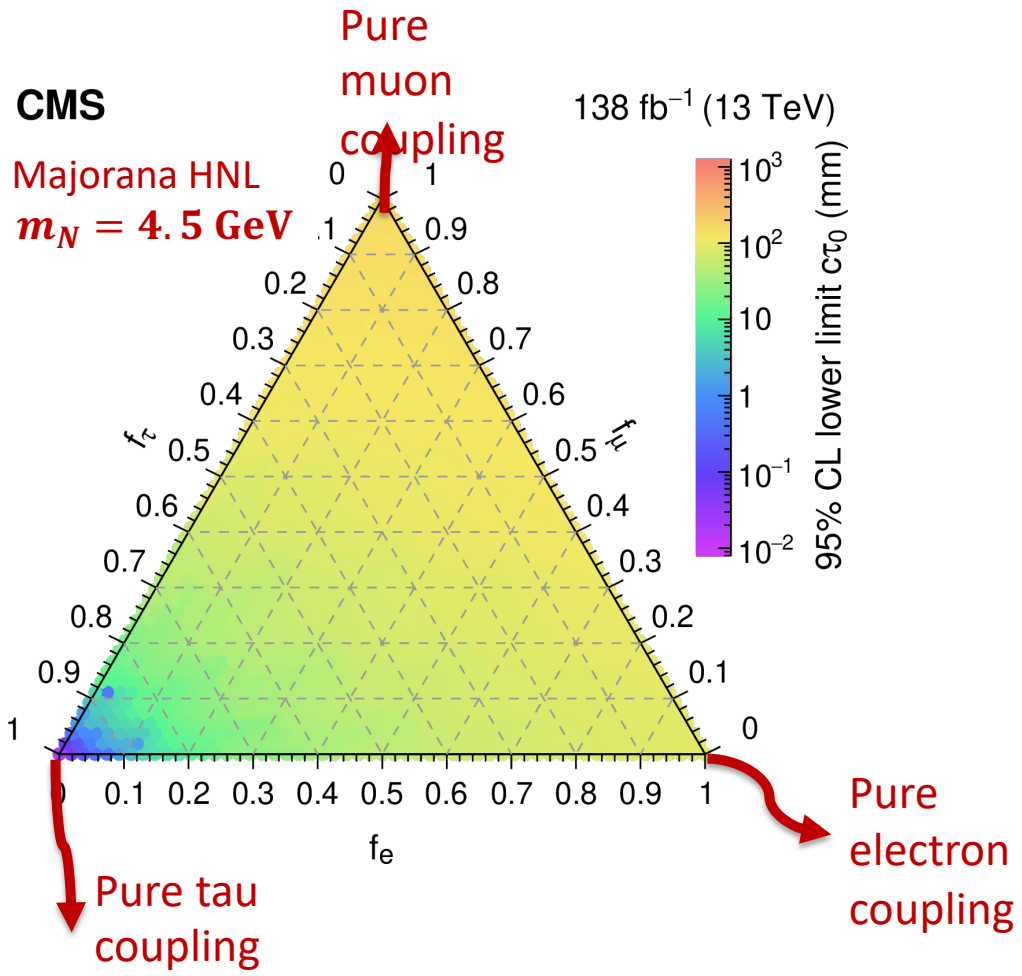
$$\Gamma_N(m_N, V_{eN}, V_{\mu N}, V_{\tau N}) = \underbrace{A_e(m_N) \times |V_{eN}|^2}_{=\Gamma_e} + \underbrace{A_\mu(m_N) \times |V_{\mu N}|^2}_{=\Gamma_\mu} + \underbrace{A_\tau(m_N) \times |V_{\tau N}|^2}_{=\Gamma_\tau}$$





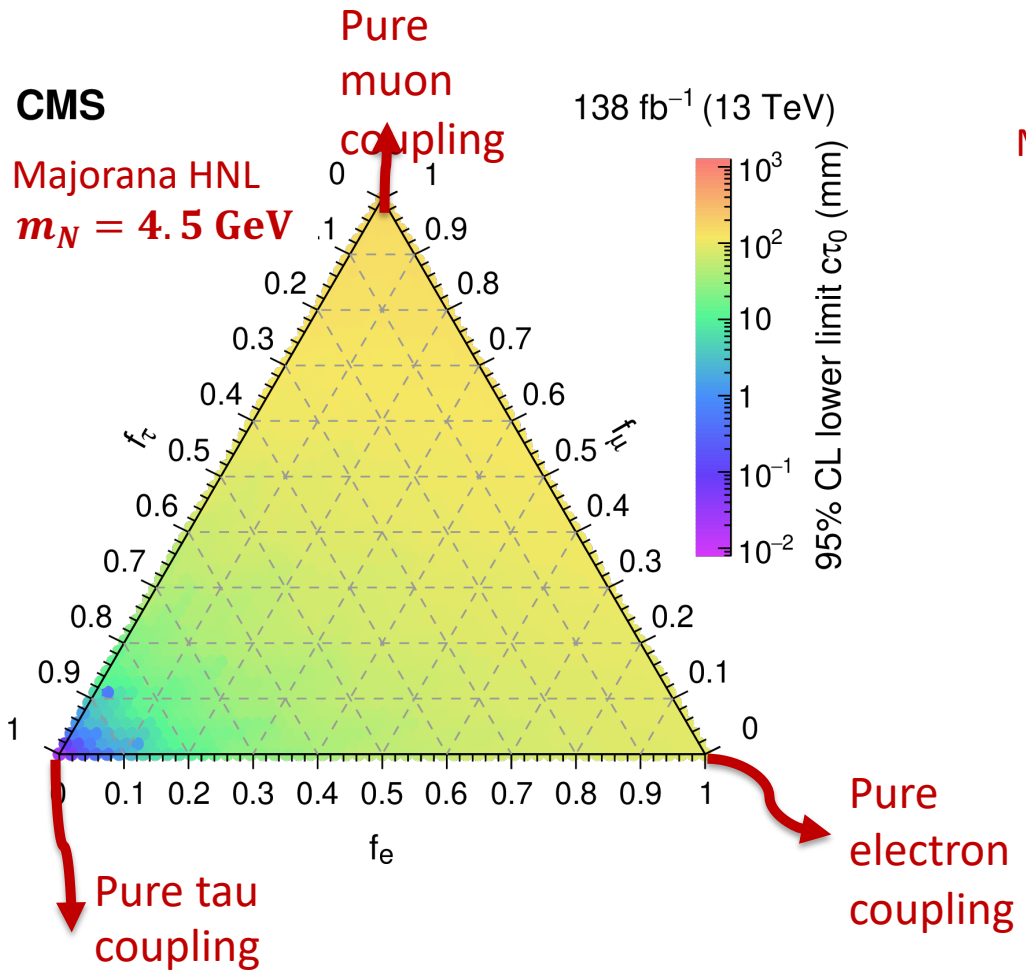
A more realistic interpretation

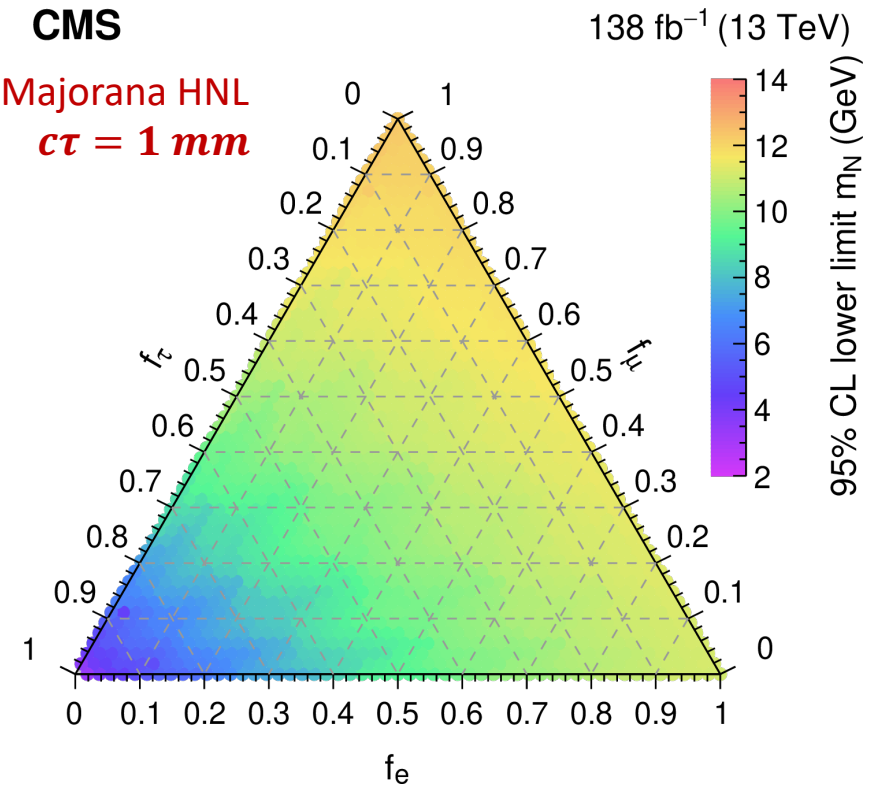
JHEP 03 (2024) 105



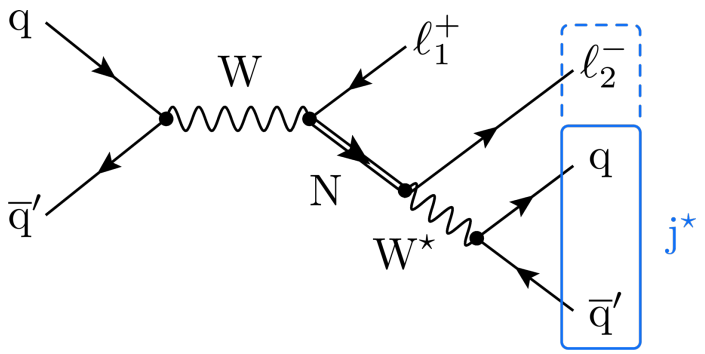
A more realistic interpretation

JHEP 03 (2024) 105





A new result 2ℓ + displaced jet



Event selection criteria
$N(\text{prompt } \ell_1) = 1$
$N(\text{nonprompt } \ell_2) = 1$
$N(\text{jets}) = 1$
$\Delta R(\ell_2, \text{jet}) < 0.7$

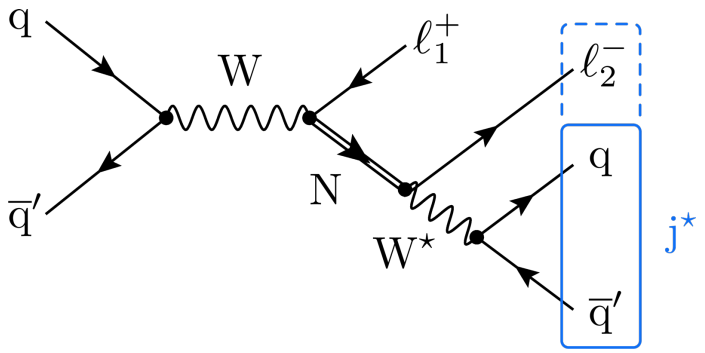
$\ell_2 \in \text{SV}$

$m(\ell_1\ell_2) > 10\,\text{GeV}$

$\Delta\phi(\ell_1, \ell_2) > 0.4$

$m(\mu^{\pm}\mu^{\mp}) \notin [85,95]\,\text{GeV}$

A new result 2ℓ + displaced jet



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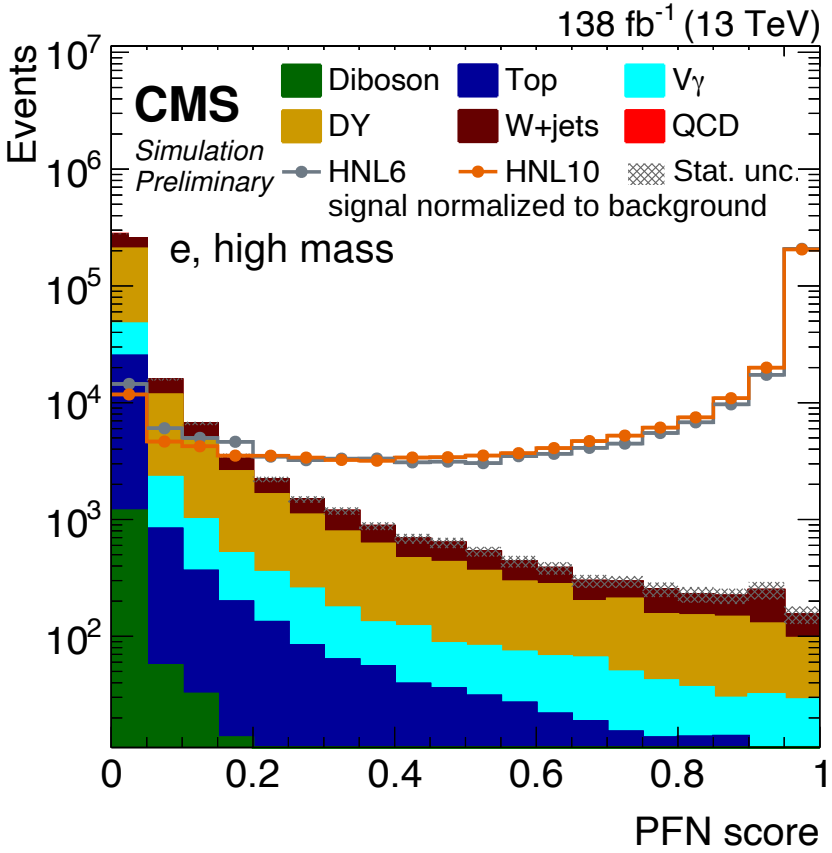
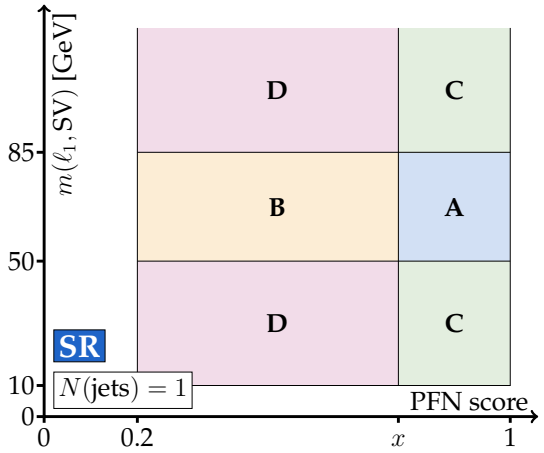


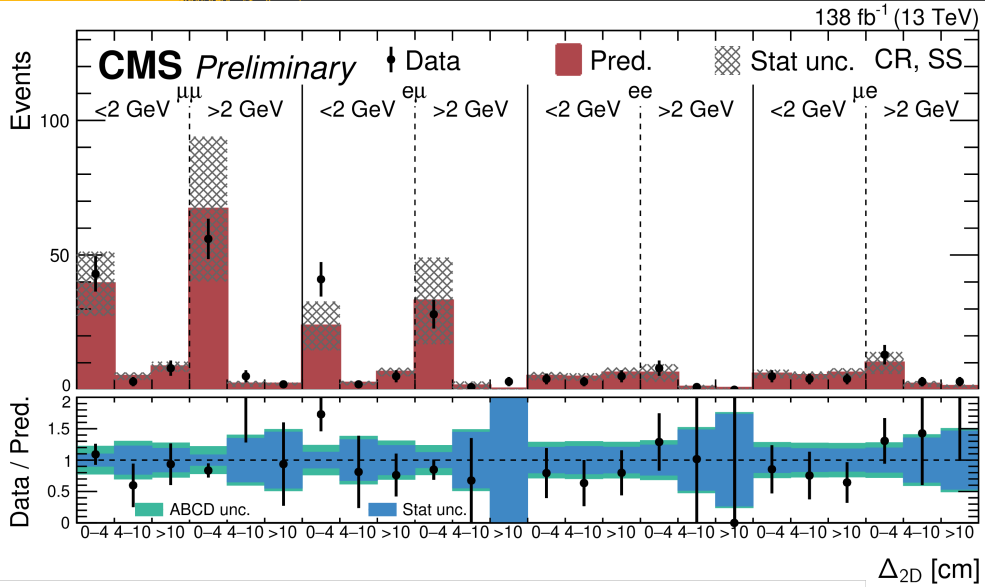


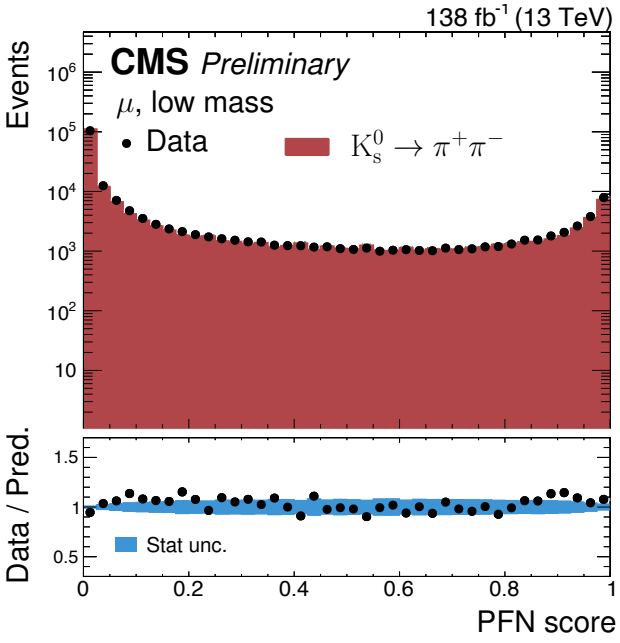
$m(\ell_1, \text{SV})$ ~M(W)

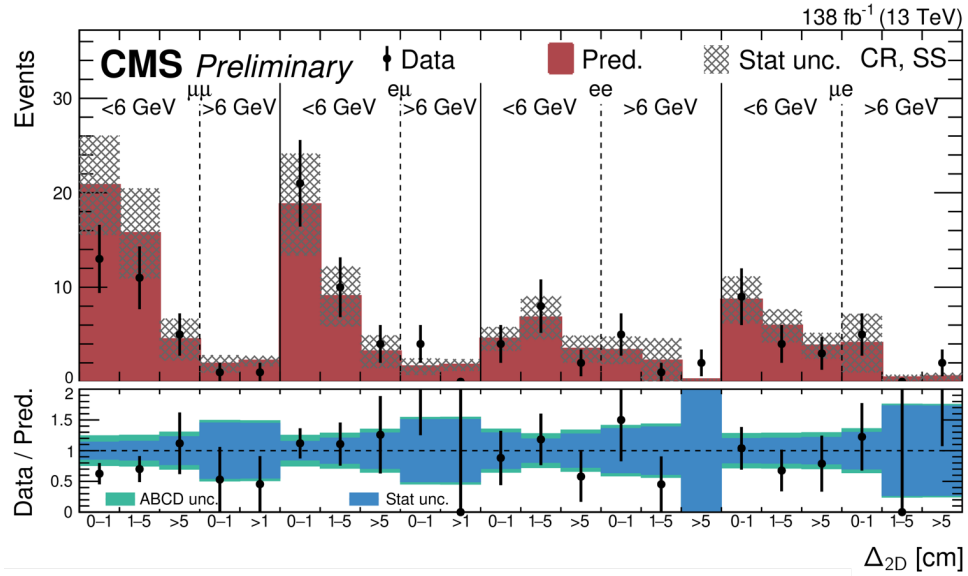
Search regions defined in Δ_{2D} and $m(SV)$

- Train a Particle Flow Network to distinguish signal from background
- Great discrimonation power
- BUT! How to predict the background ?
- How to validate the PFN performance ?

Validating PFN in data control regions

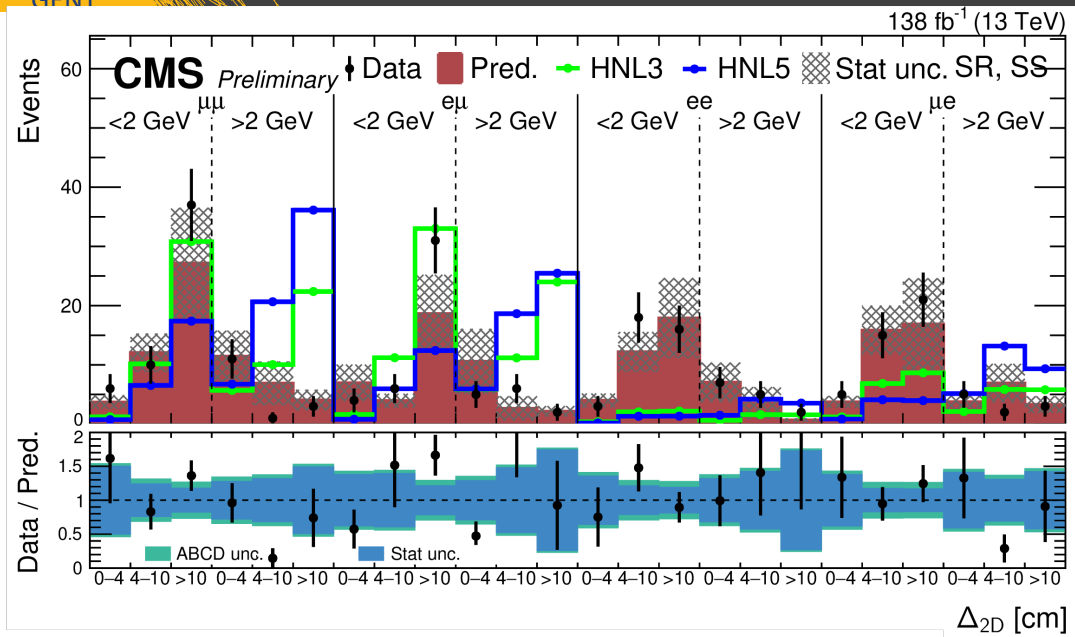




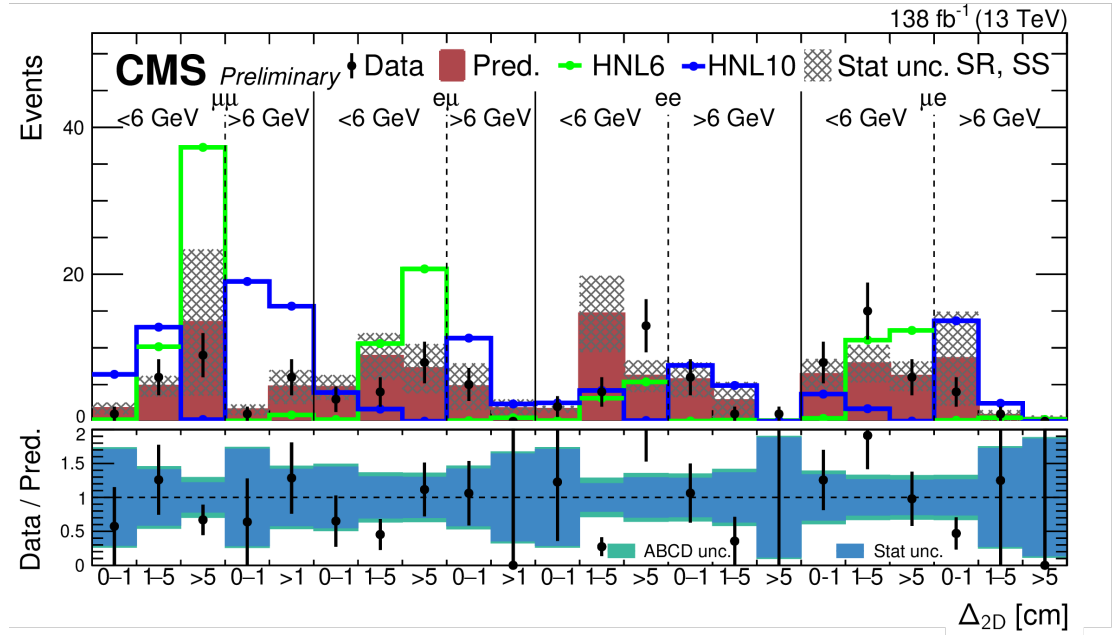


***Njet* > 1 and K_short events for validation**

A new result 2ℓ + displaced jet

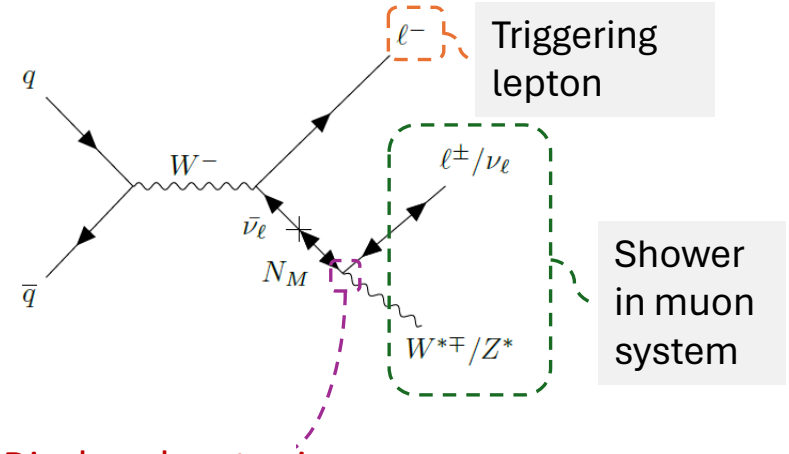


Low mass m(SV)< 6 GeV



Low mass M(SV)> 6 GeV

HNL search in Muon detector

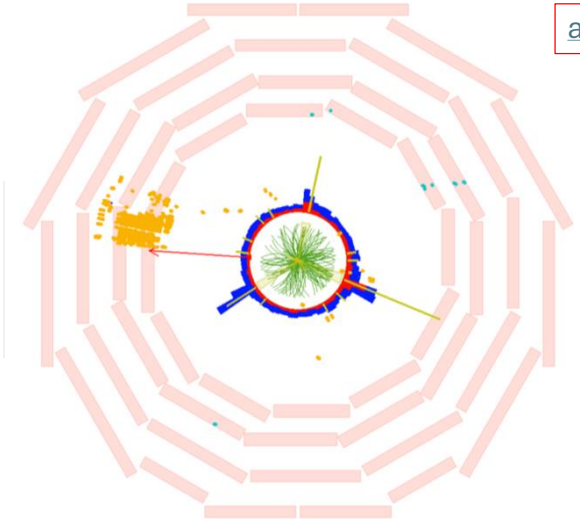


Displaced vertex in muon system, 4-10m from the PV

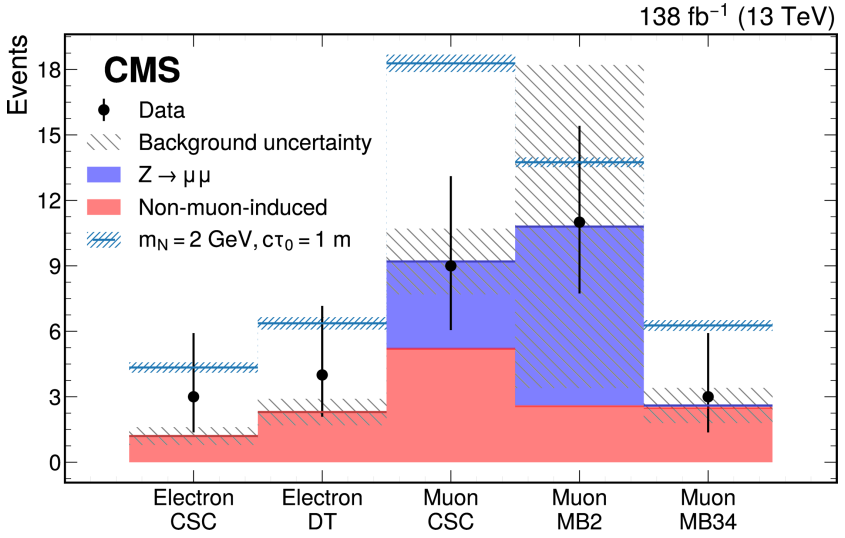
Muon Detector Shower (MDS)

Accepted by PRD

arXiv:2402.18658



- Lifetime sensitivity range of 0.1-10 m
- masses ranging from 1 to approximately 3.5 GeV.
- sensitive to HNL mixing to all three generations of leptons
- Veto events with jets with significant signals in the inner detector suppresses SM background by 10^7

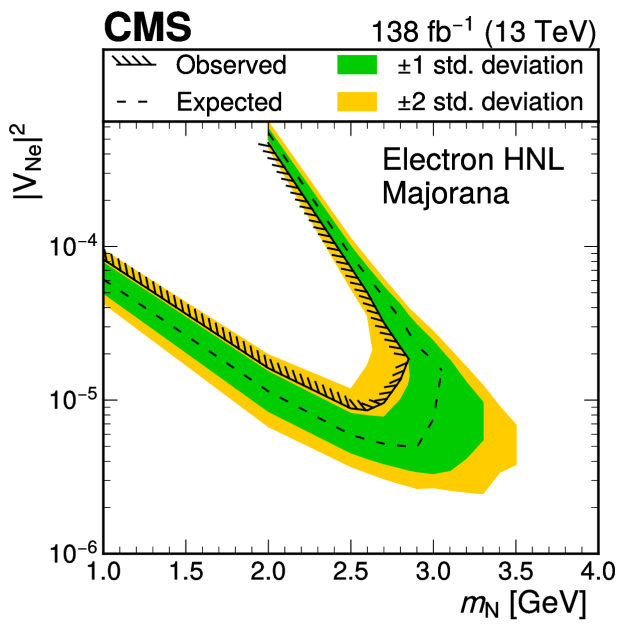


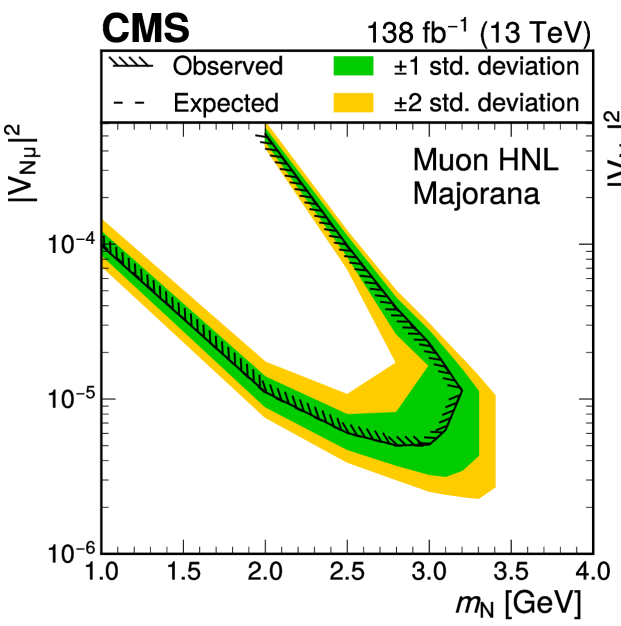
- **Background** contributions
  - **Non muon-induced** (e.g. prompt lepton from W + soft hadron from PU)
  - **Muon-induced** (e.g. $Z \rightarrow \mu\mu$ event + μ bremsstrahlung)

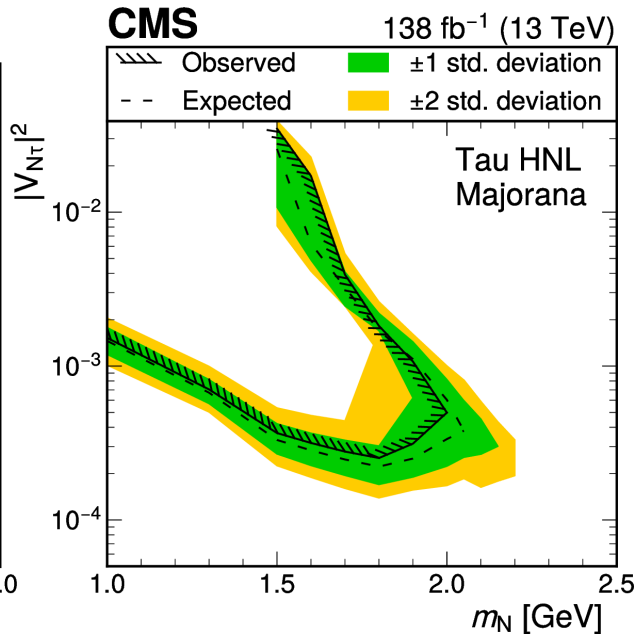
HNL search in Muon detector

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**

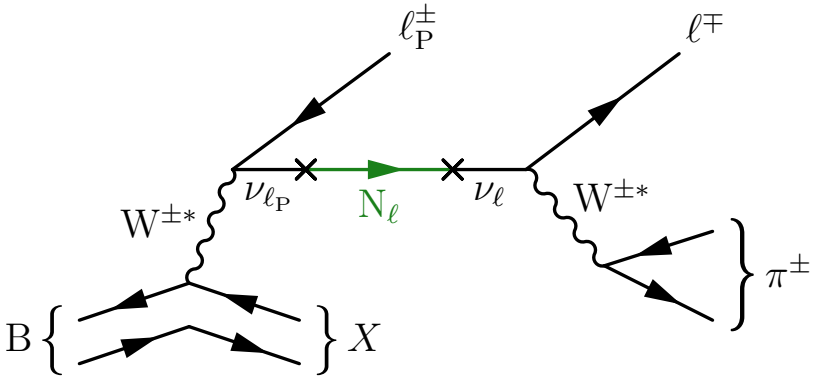
- **Most stringent limits** to date in $|V_e|^2$ in the **2.1-3.0 GeV** mass range
- **Most stringent limits** to date in $|V_\mu|^2$ in the **1.9-3.3 GeV** mass range







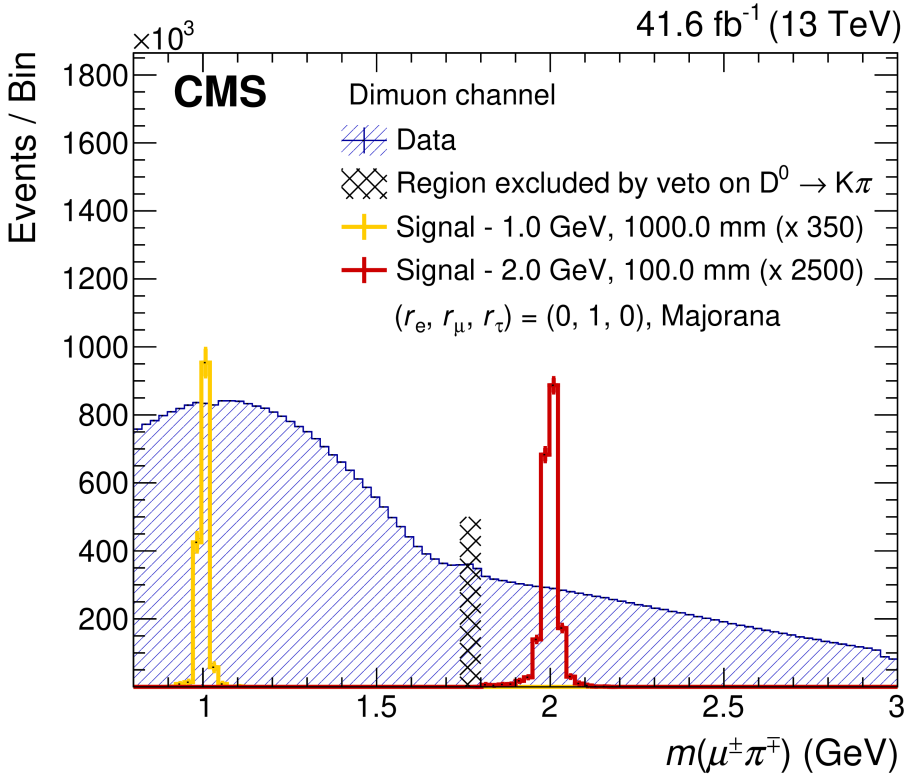
HNL search in B decays

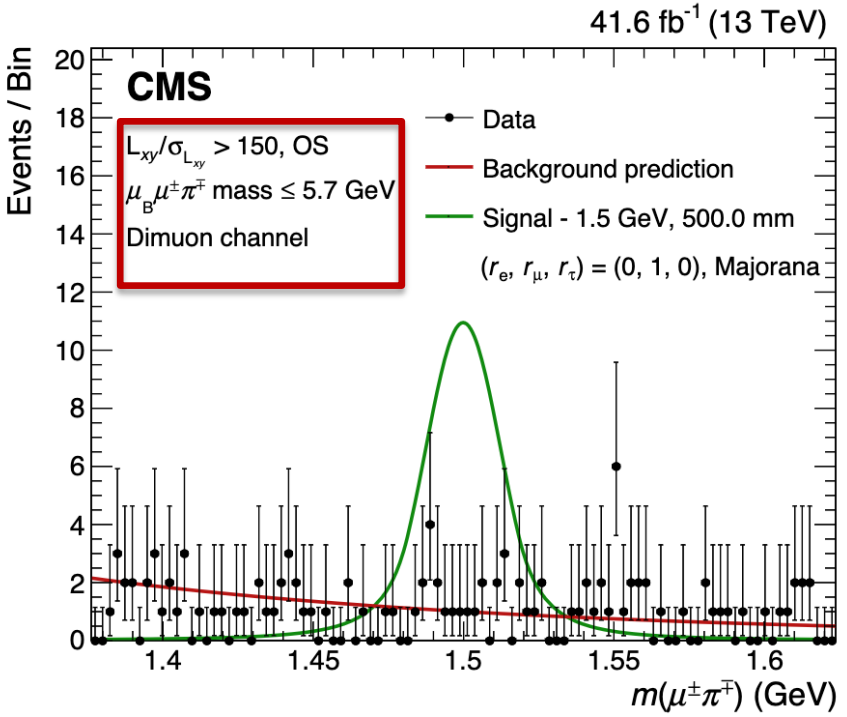


- Long awaited result…
- B-Parking dataset from 2018
- ~10 billion B mesons
- 2 SS/OS dilptons $(ee, \mu\mu, e\mu, \mu e)$ + π
- $p_T(e, \mu) > 5{,}3\ GeV$
- Sensitivity at low mass and $10^{-2} < c\tau_N < 10^4$ mm

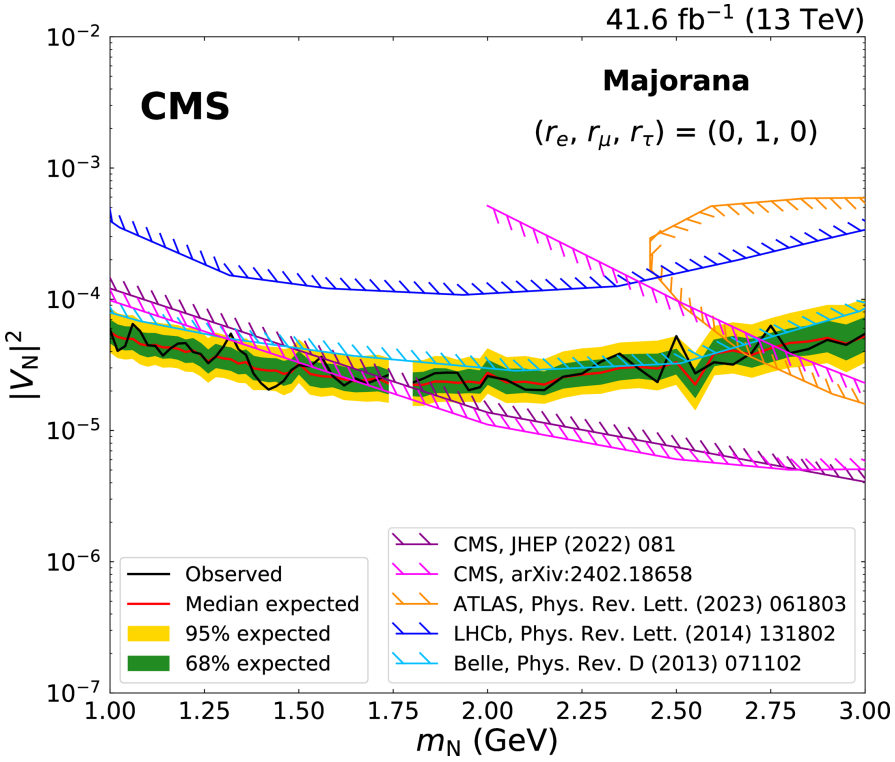
Submitted to JHEP

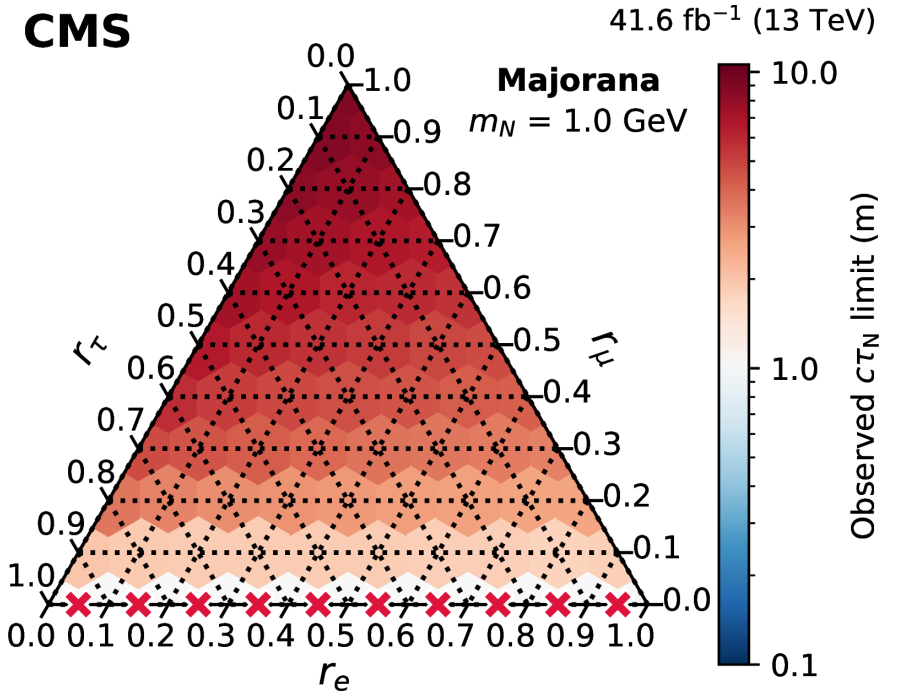
arXiv:2403.04584





HNL search in B decays

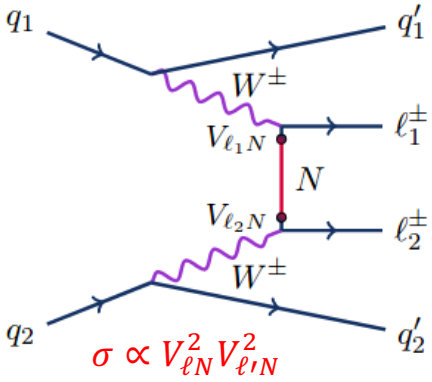




- **Most stringent limits** on $|V_N|^2$ in the **1-1.7 GeV** mass range at **collider experiments**
- **Best sensitivity** reached for $|V_\mu|^2$ thanks to excellent muon identification efficiency
- **Extended previous CMS limits** up to a **factor 2** in the **1-2 GeV** mass region

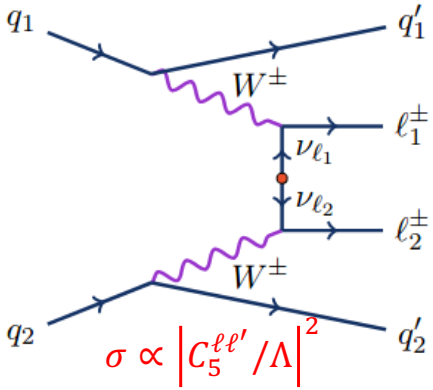
HNL search via VBF production

Type-1 Seesaw



$\sigma \propto V_{\ell N}^2 V_{\ell' N}^2$

Weinberg operator Dim 5



$\sigma \propto \left| C_5^{\ell\ell'} / \Lambda \right|^2$

Experimental signature:

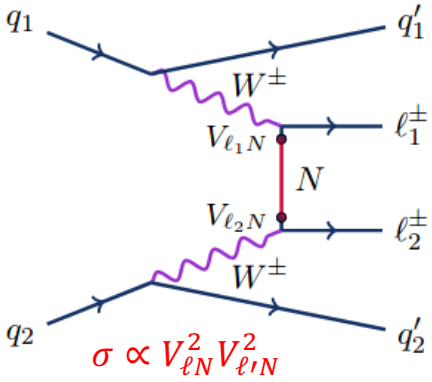
- Same-sign muons + VBF jets
- Complementary to DY HNL production→ larger x-section at high mass

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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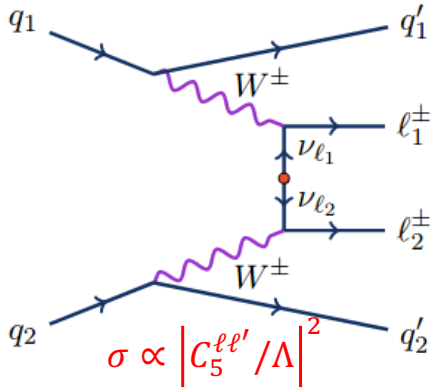
Weinberg operator Dim 5



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Experimental signature: PRL 131 (2023)

- Same-sign muons + VBF jets
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Backgrounds:

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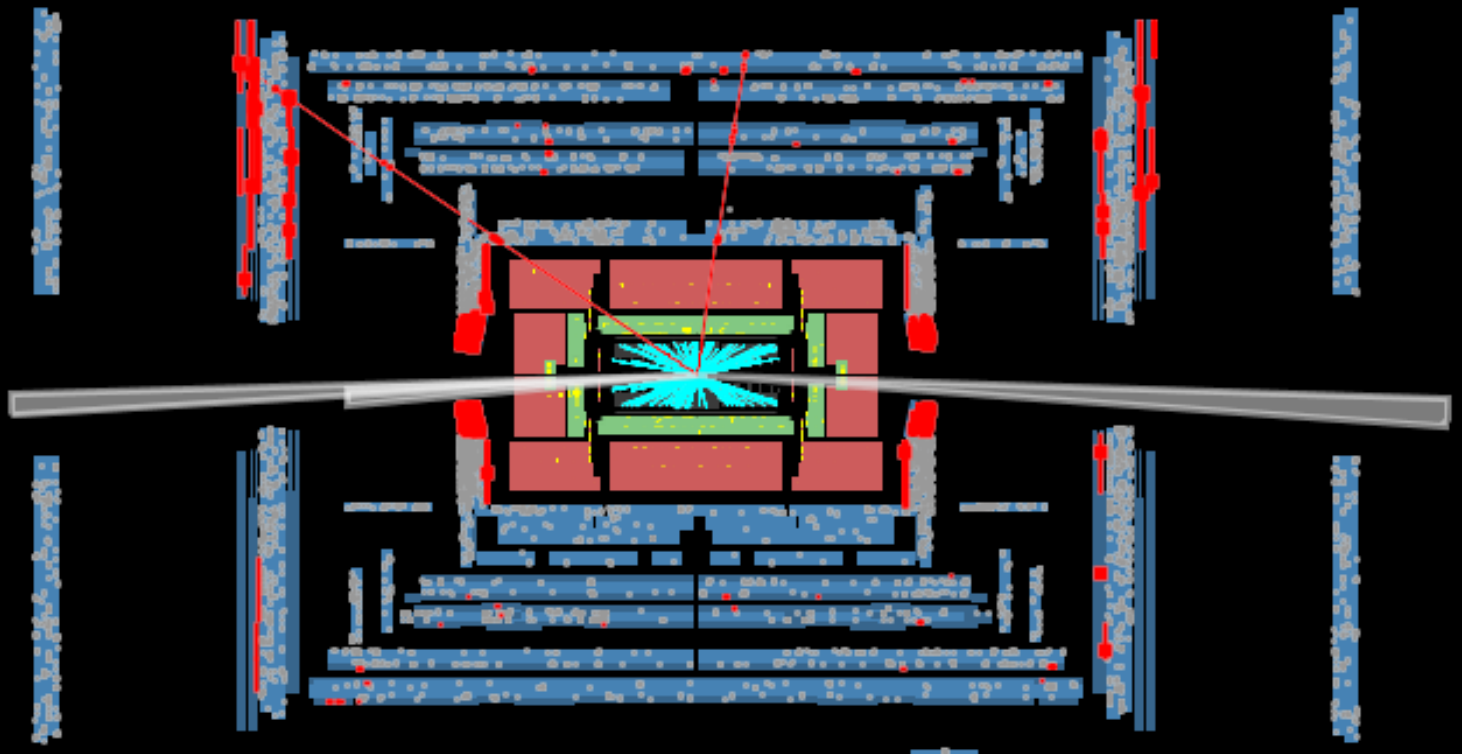
- Others: WW, ZZ, tZq, ttW, ttZ, and VVV

ATLAS EXPERIMENT

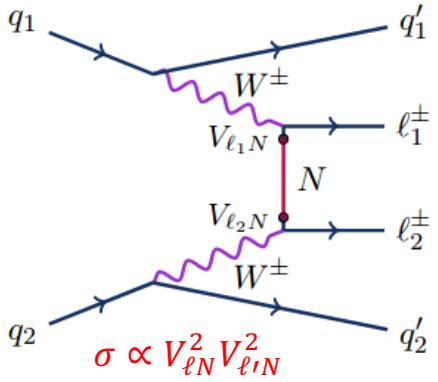


Same-Sign $\mu\mu$

$p_T^{\mu_1} = 139.7$ GeV
$p_T^{\mu_2} = 118.7$ GeV
$m_{jj} = 2582$ GeV
$\Delta Y_{jj} = 6.39$

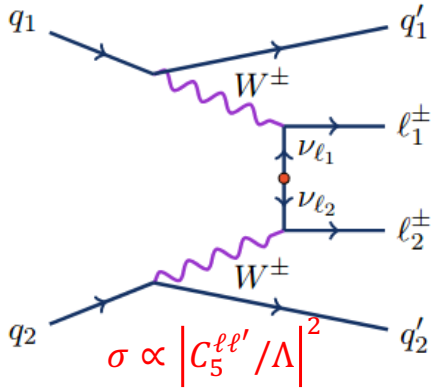
HNL search via VBF production

Type-1 Seesaw



$\sigma \propto V_{\ell N}^2 V_{\ell' N}^2$

Weinberg operator Dim 5



$\sigma \propto \left| C_5^{\ell\ell'}/\Lambda \right|^2$

Experimental signature:

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Backgrounds:

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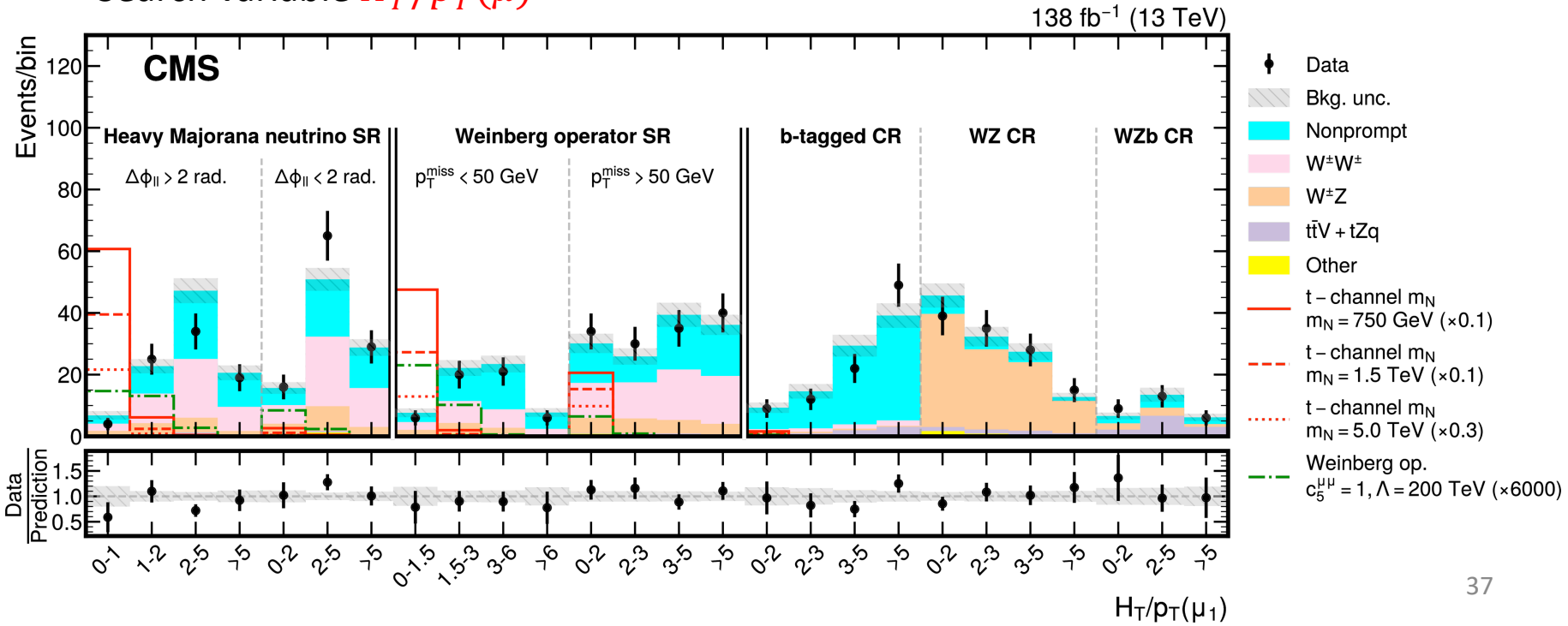
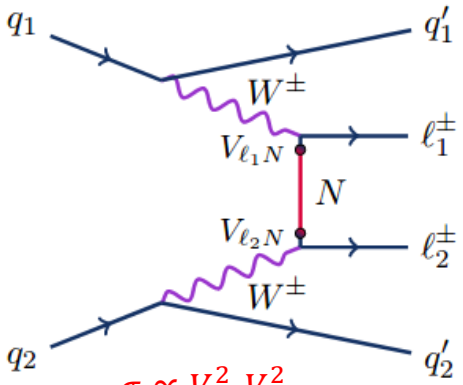
Search variable $H_T/p_T(\mu)$



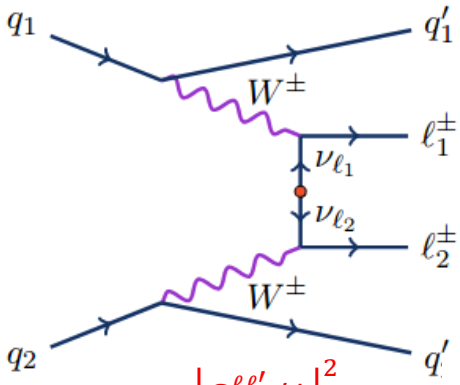
HNL search via VBF production

Type-1 Seesaw



$\sigma \propto V_{\ell N}^2 V_{\ell' N}^2$

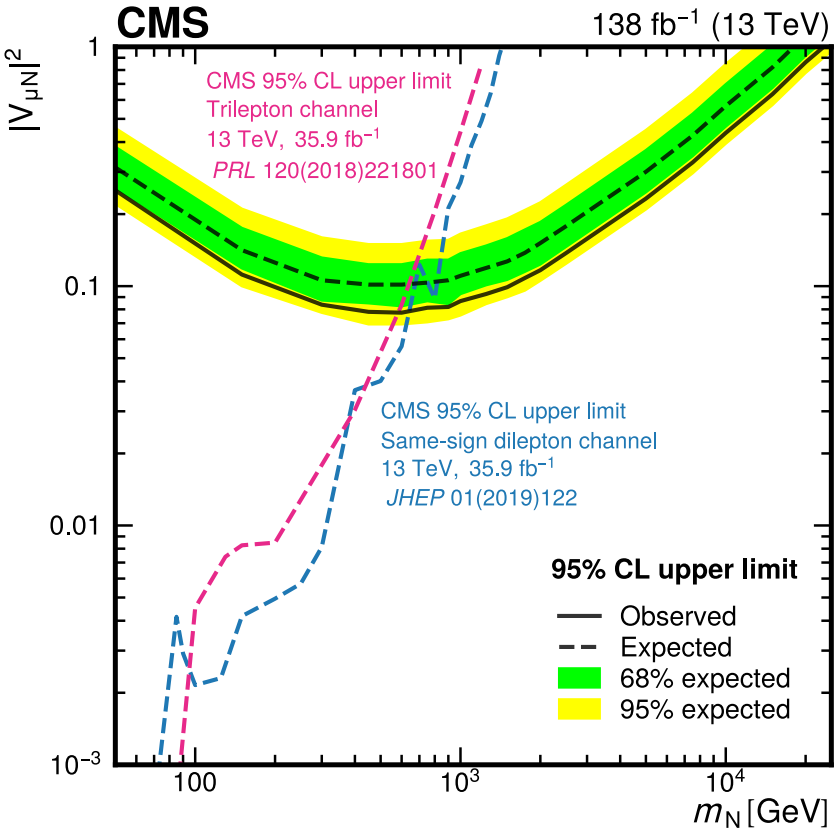
Weinberg operator Dim 5



$\sigma \propto \left| C_5^{\ell\ell'}/\Lambda \right|^2$

PRL 131 (2023)

- 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



HNL (Type I) search summary

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-095
2024/05/29

CMS-EXO-23-006

Review of searches for vector-like quarks, vector-like leptons, and heavy neutral leptons in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ at the CMS experiment

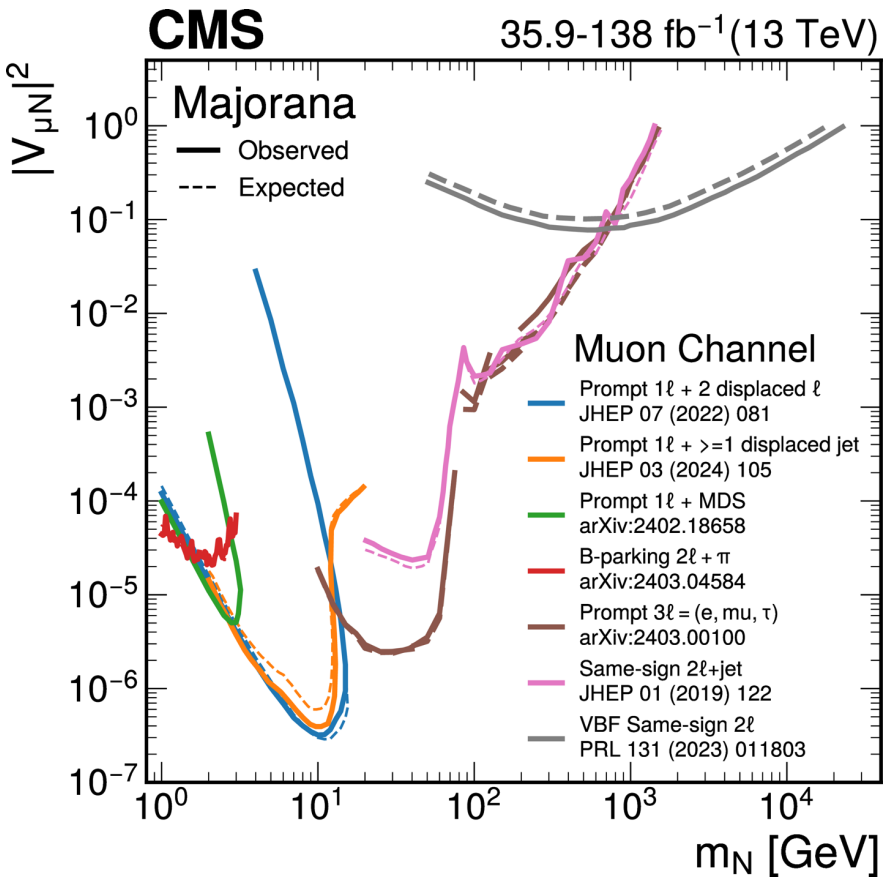
The CMS Collaboration*

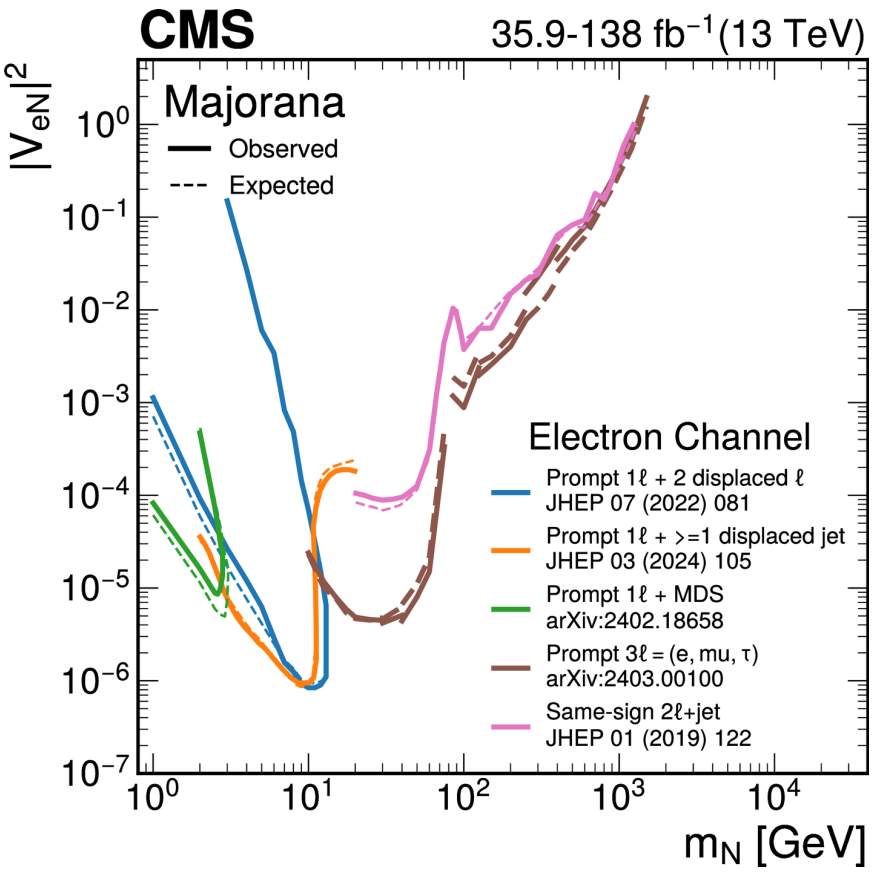
Abstract

The LHC has provided an unprecedented amount of proton-proton collision data, bringing forth exciting opportunities to address fundamental open questions in particle physics. These questions can potentially be answered by performing searches for very rare processes predicted by models that attempt to extend the standard model of particle physics. The data collected by the CMS experiment in 2015–2018 at a center-of-mass energy of 13 TeV help to test the standard model at the highest precision ever and potentially discover new physics. An interesting opportunity is presented by the possibility of new fermions with masses ranging from the MeV to the TeV scale. Such new particles appear in many possible extensions of the standard model and are well motivated theoretically. They may explain the appearance of three generations of leptons and quarks, the mass hierarchy across the generations, and the nonzero neutrino masses. In this report, the status of searches targeting vector-like quarks, vector-like leptons, and heavy neutral leptons at the CMS experiment is discussed. A complete overview of final states is provided together with their complementarity and partial combination. The discovery potential for several of these searches at the High-Luminosity LHC is also discussed.

Submitted to Physics Reports

HNL (Type I) search summary

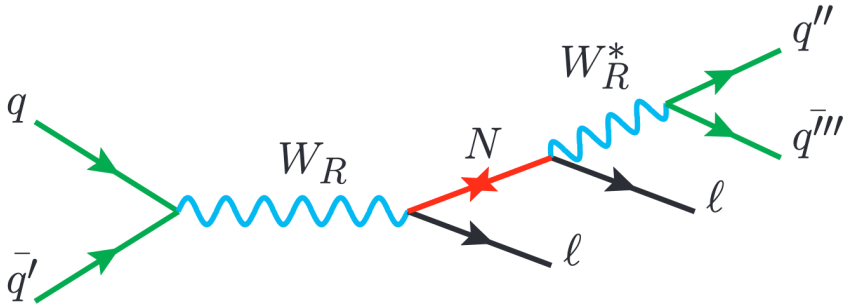




prompt 3ℓ provides most stringent limits over wide mass range

displaced 2ℓ particularly important for long-lived scenarios with 10–20 GeV

Left-Right Symmetric models, W_R



EXO-20-002

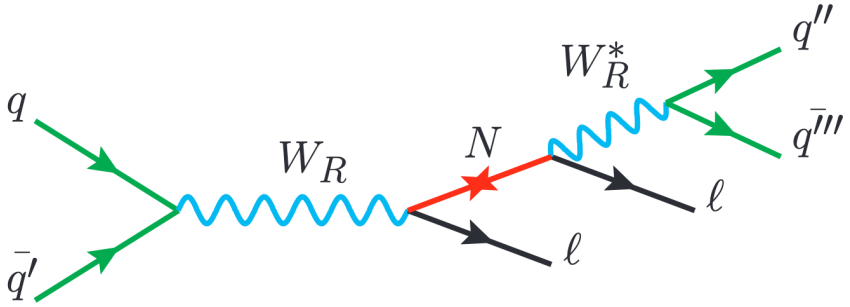
Experimental signature:

- 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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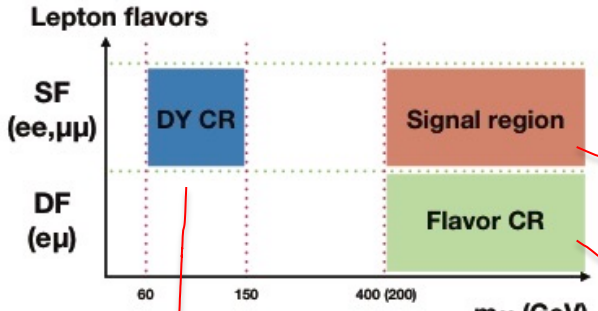
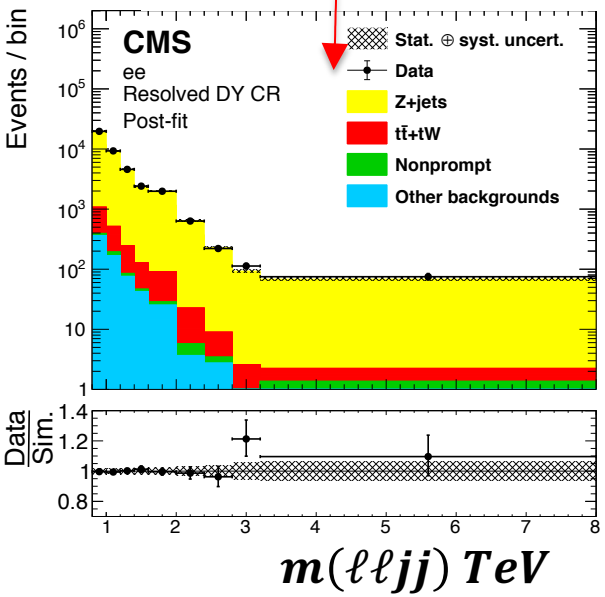
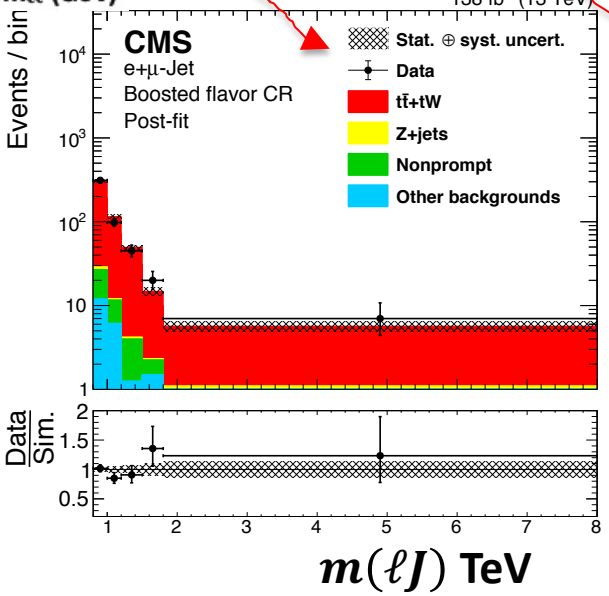
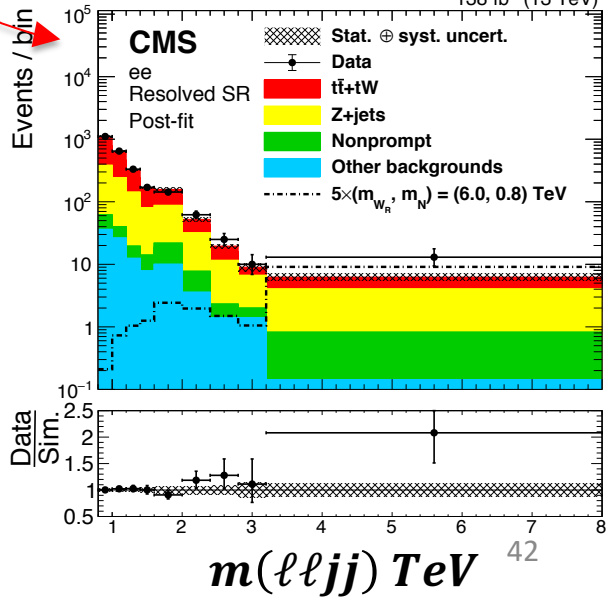




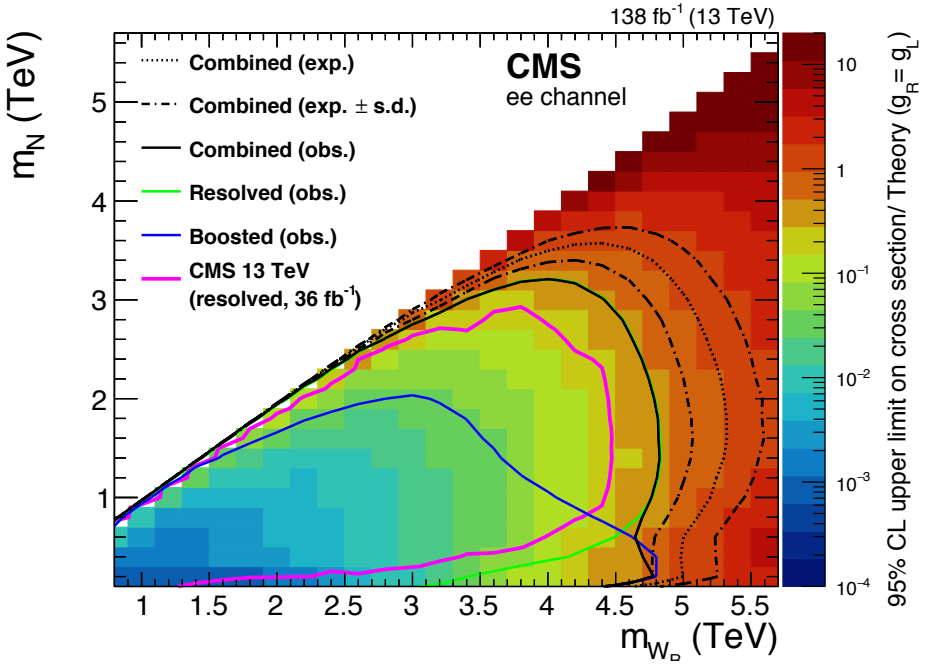


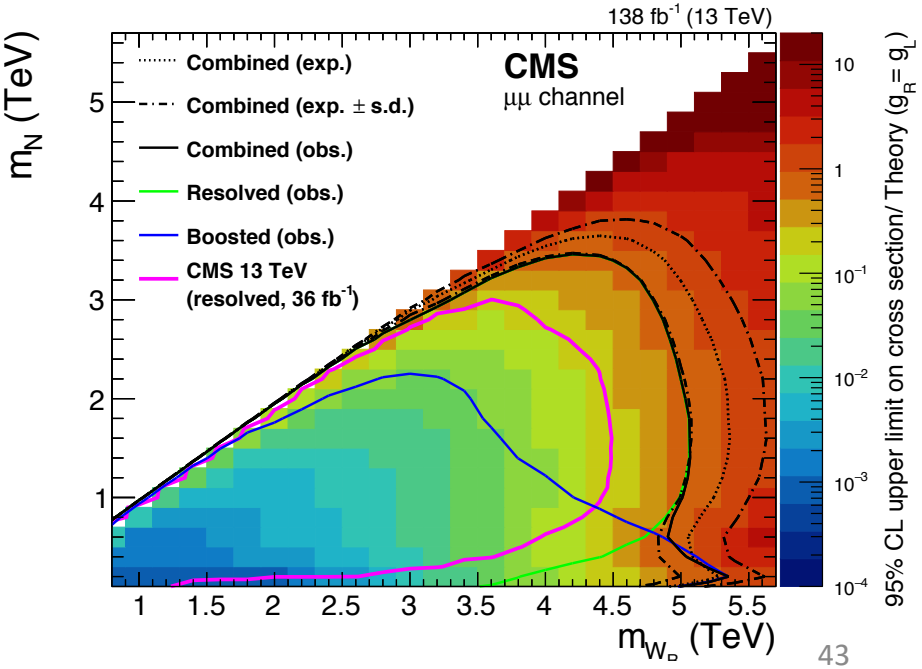


Left-Right Symmetric models, W_R

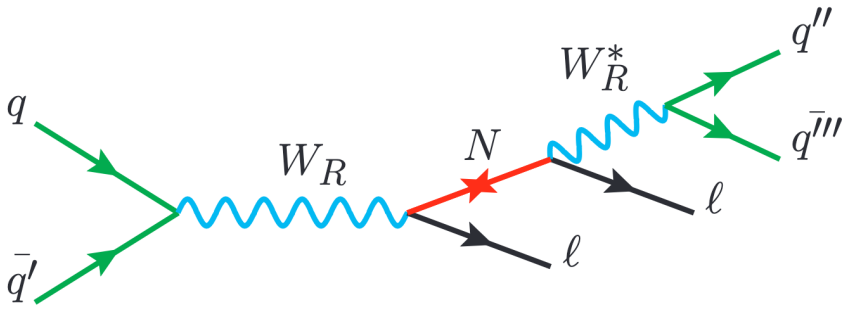
EXO-20-002

- 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

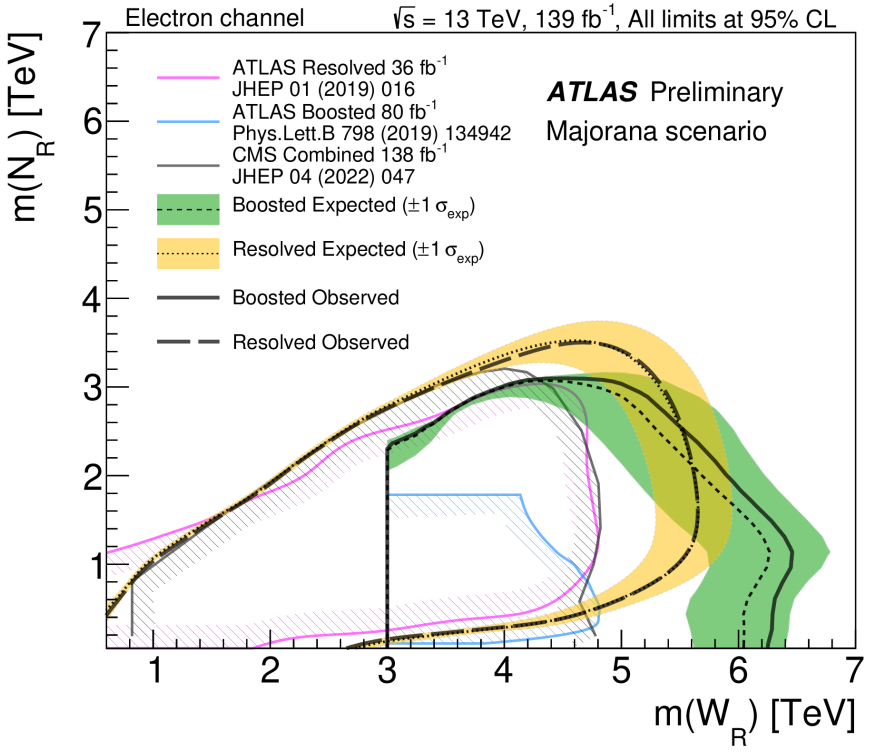


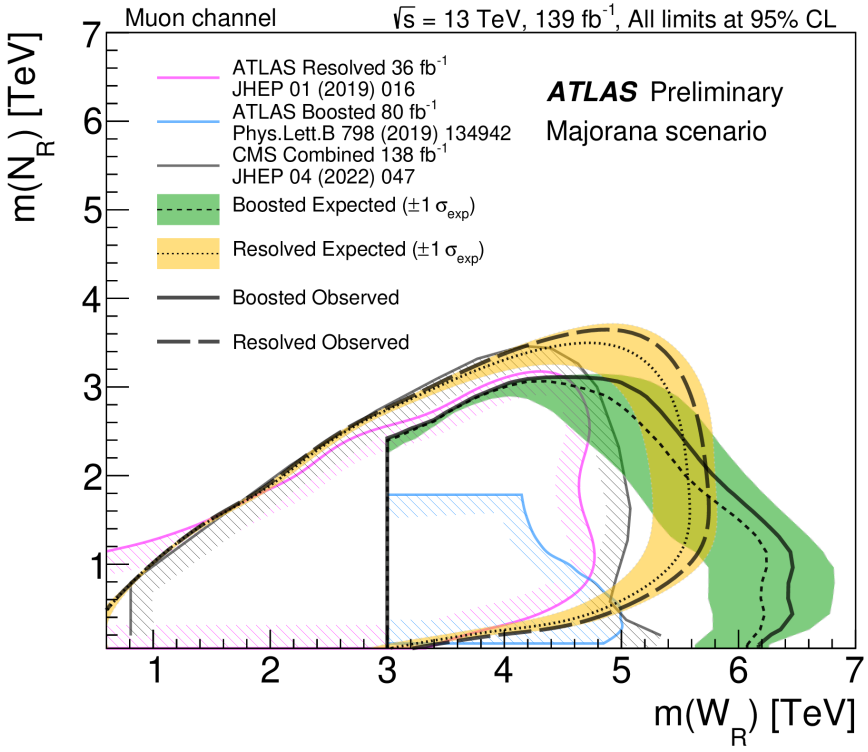
- Similar search by ATLAS
- More rigurous search regions for boosted & resolved scenarios

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

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

- No significant excess (only 1.6 σ)

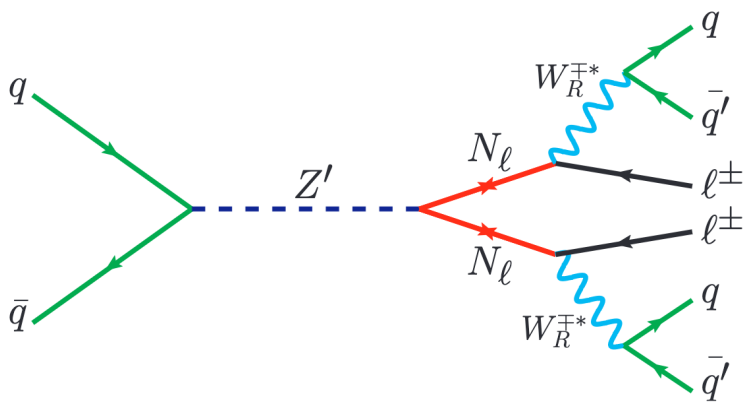




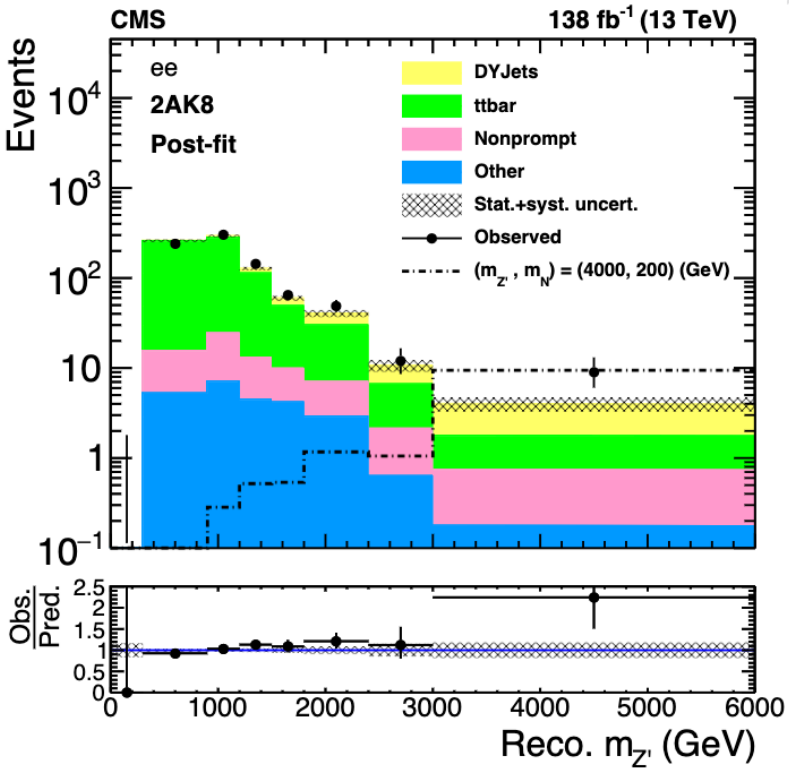
- Exceeds the sensitivity of CMS in particular for large $\Delta(m)$
- For $m(N) < 50\ GeV$, **N becomes long lived** (M. Nemevek et. al, arXiv:1801.05813)

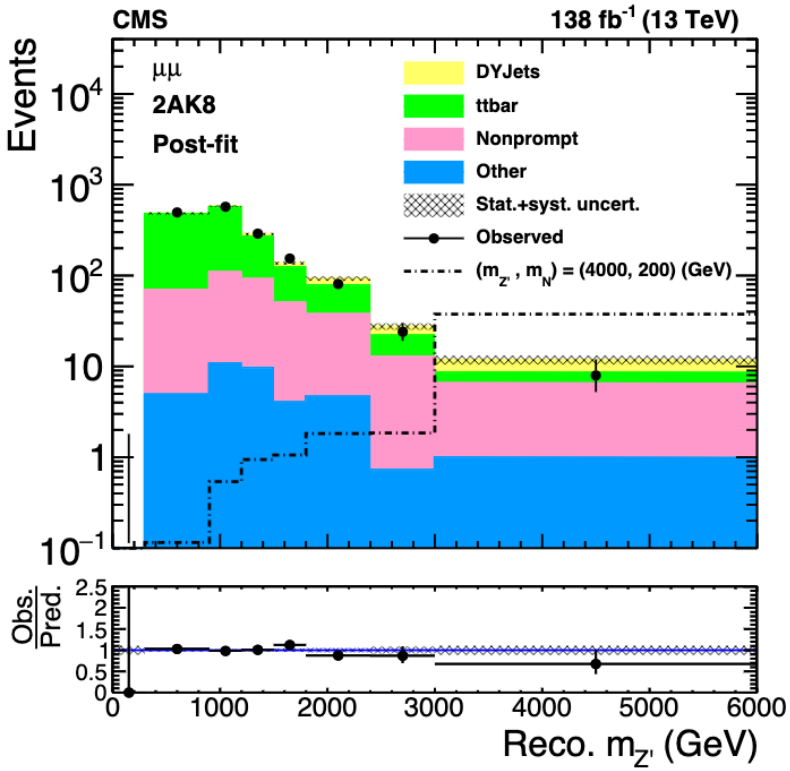
Left-Right Symmetric models, Z'

PAS-EXO-20-006



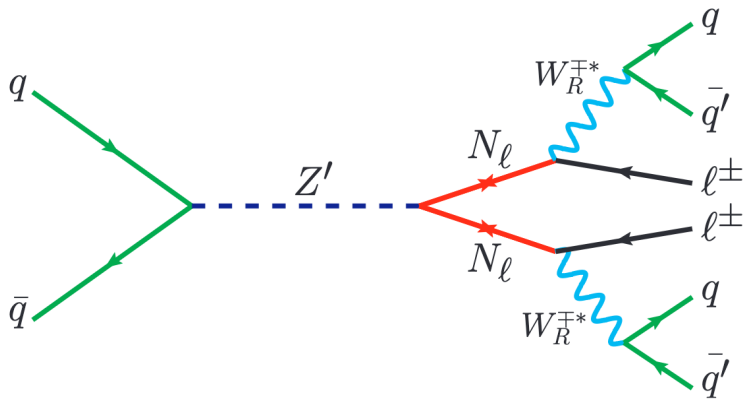
- LRSM model with Z' (400 GeV - 4.4 TeV) decaying to right-handed neutrinos (100 GeV - $m_{Z'}/2$)
- OS and SS lepton pair(ee or $\mu\mu$) + jets
  → categories for 0,1 and 2+ large-radius jets(AK8)
  → cover boosted and resolved scenarios
- reconstruct $M_{Z'}$
- No significant excess is observed





Left-Right Symmetric models, Z'

PAS-EXO-20-006



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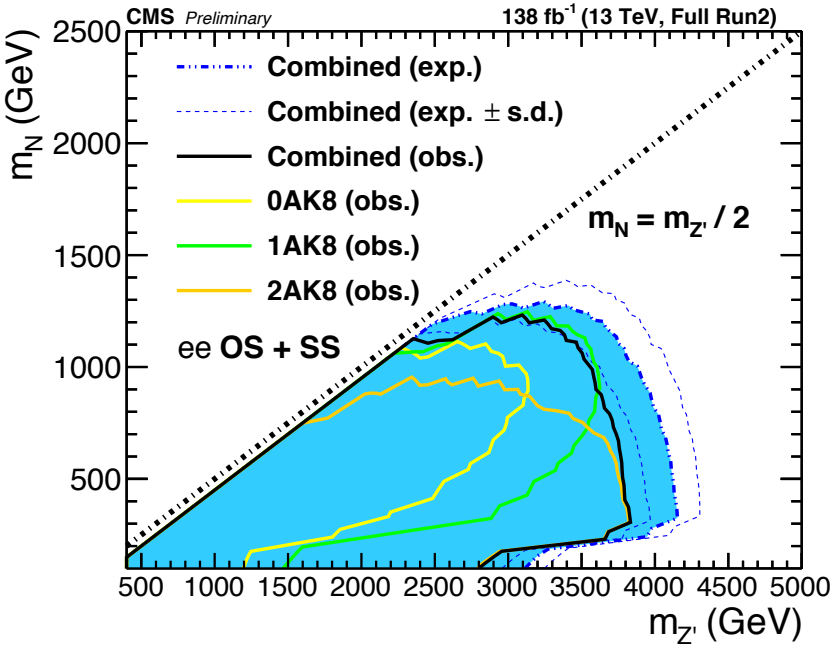
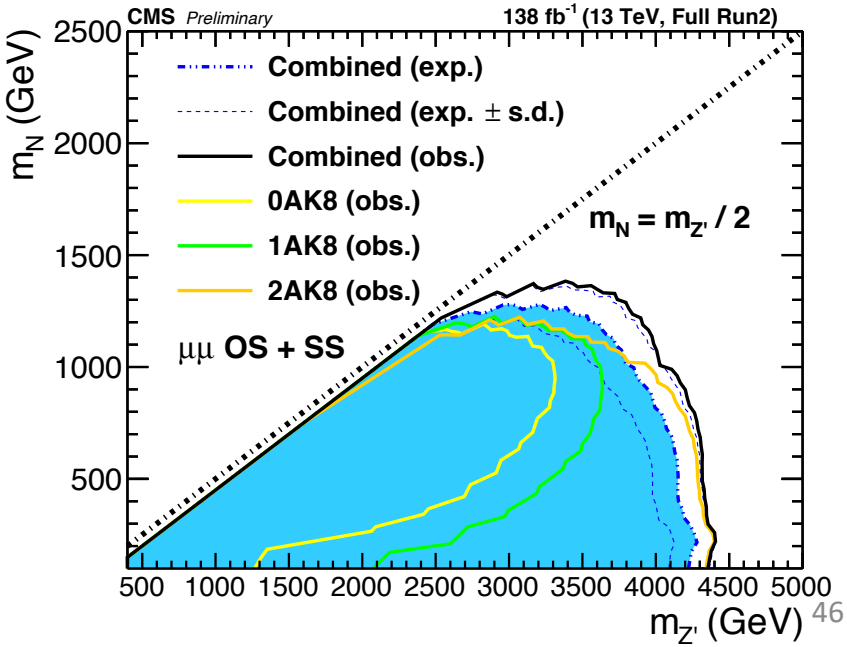
- OS and SS lepton pair(ee or $\mu\mu$) + jets
  → categories for 0,1 and 2+ large-radius jets(AK8)
  → cover boosted and resolved scenarios
- reconstruct $M_{Z'}$
- No significant excess is observed
- For $m_N = m_{Z'}/4$, exclude $m_{Z'}$ up to 3.87 TeV (e and μ)
- Most stringent limits to date in $m_{Z'}$ vs m_N plane

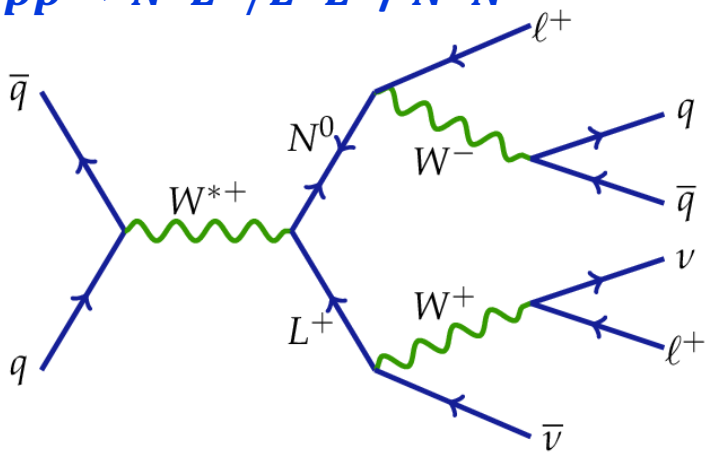




Search for Type-III Seesaw

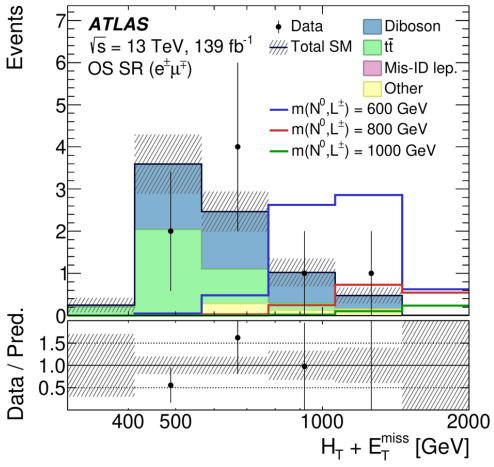
Eur. Phys. J. C 81 (2021) 218

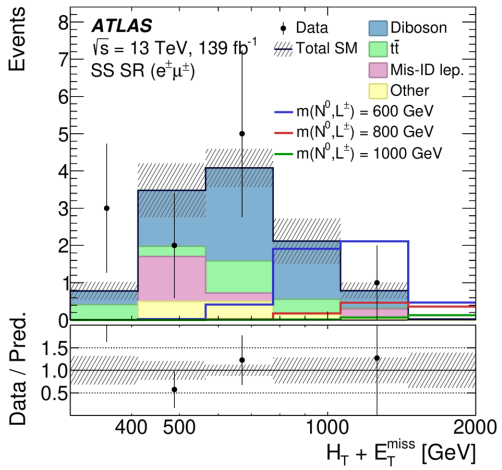
$pp \rightarrow N^0L^\pm / L^\pm L^\pm / N^0N^0$

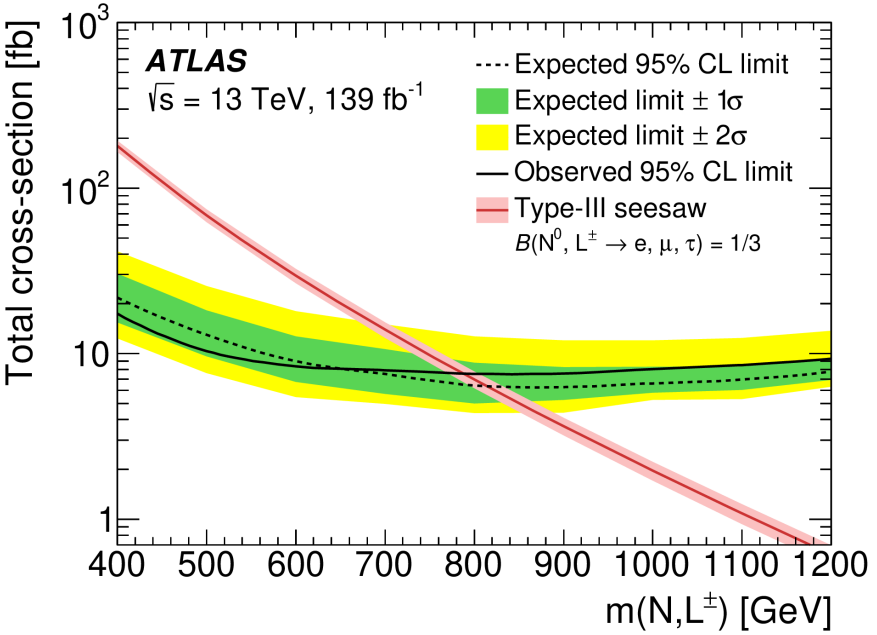


- extra triplet of heavy fermionic fields which couple to EW gauge bosons
- S-channel production of $N^0L^\pm$
- Two leptons with same or opposite charge
- 2 jets and large missing $\boldsymbol{E_T}$

Main search observables:



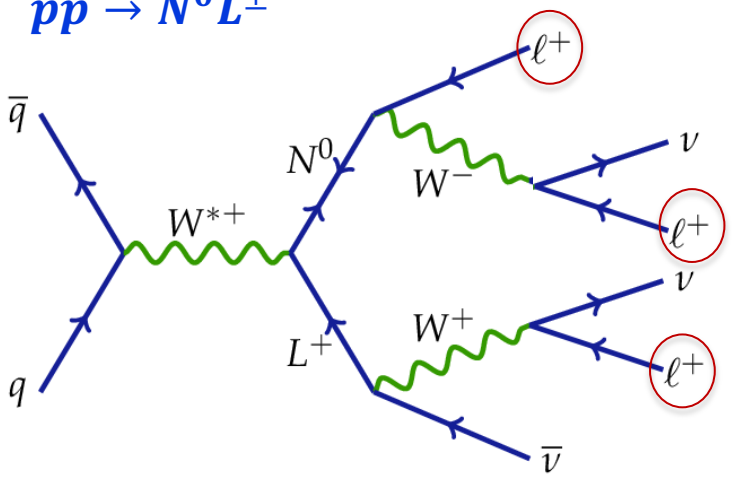




Search for Type-III Seesaw

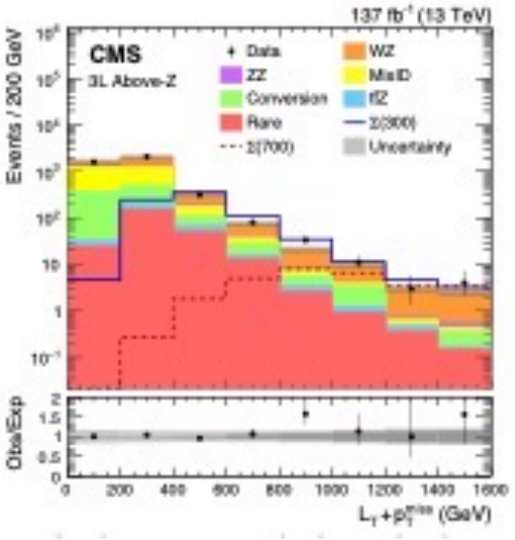
JHEP 03 (2020) 051

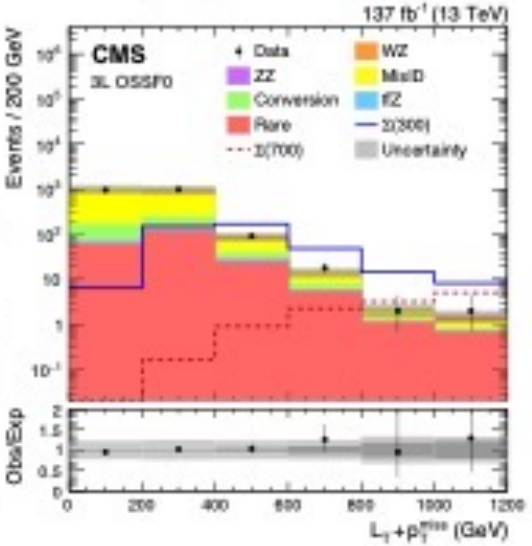
$pp \rightarrow N^0 L^{\pm}$

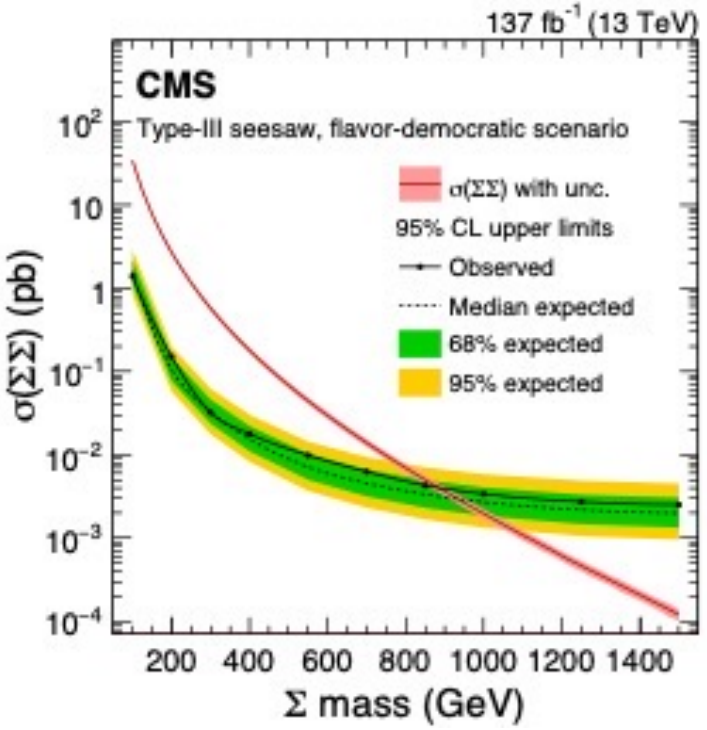


- S-channel production of $N^0 L^{\pm}$
- Multi-leptons, lower backgrounds
- ~40 exclusive search regions

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

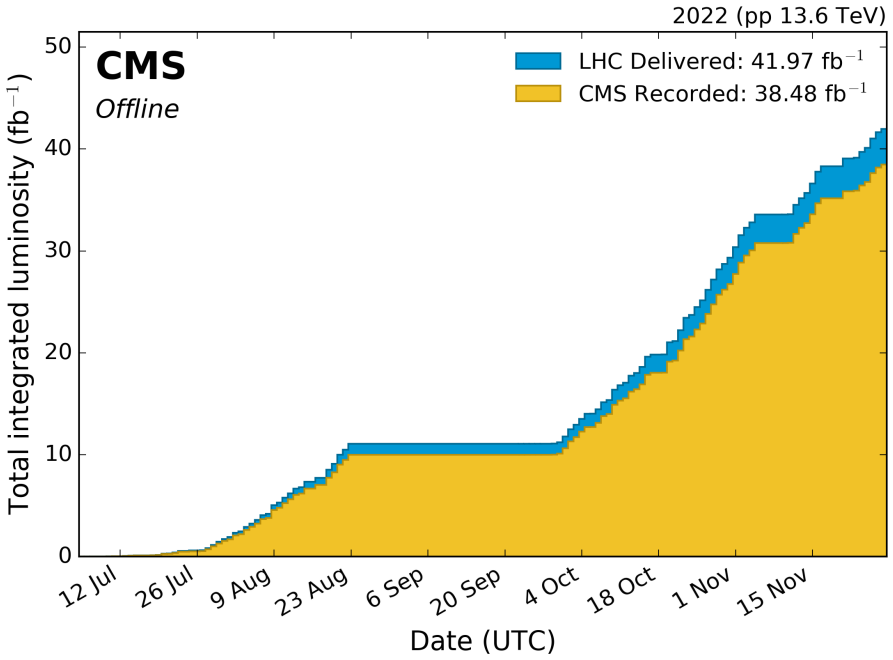






Summary & Outlook

- 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

Search for heavy neutral leptons in $W^+ \to \mu^+\mu^\pm$jet decays

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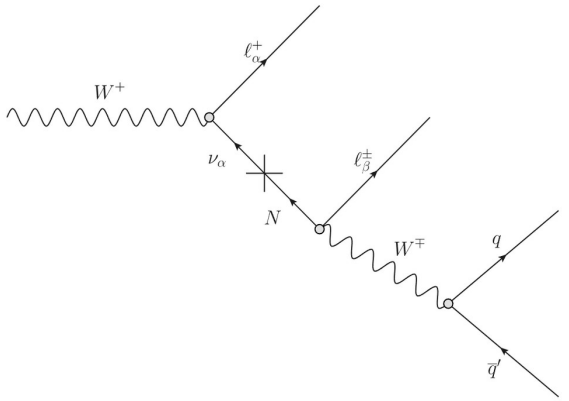
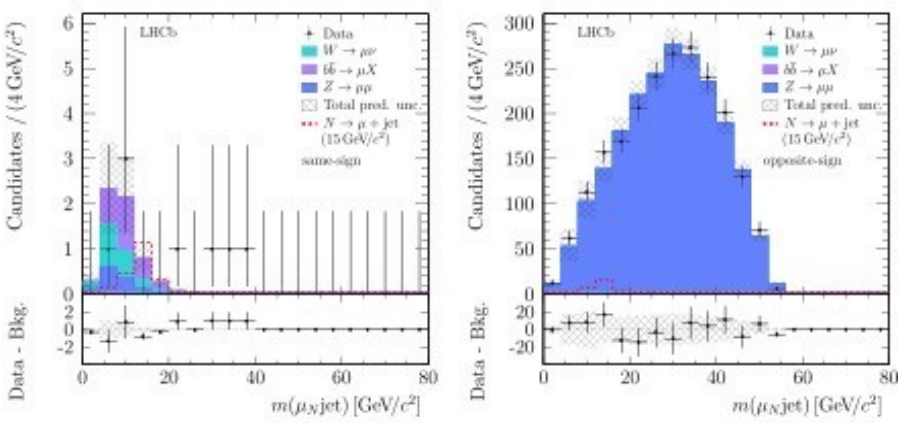
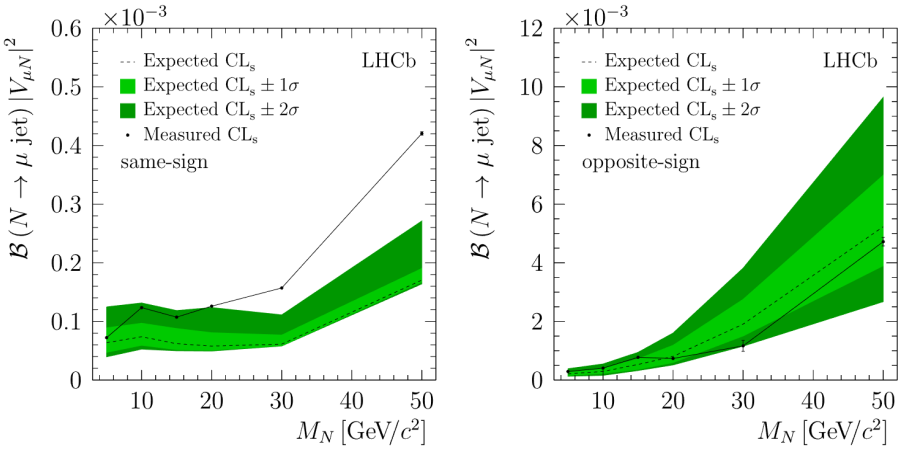
- Prompt HNL decays, allowing for Majorana.
- Background normalised via $W \to \mu\nu$ and $Z \to bb$
- Constrained to prompt in order to suppress heavy-flavour background.

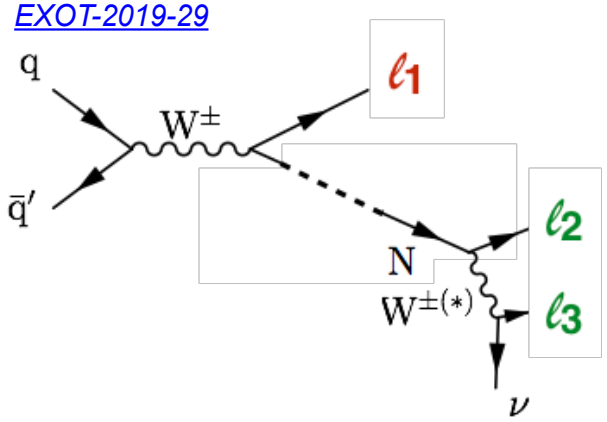






HNL search in ATLAS

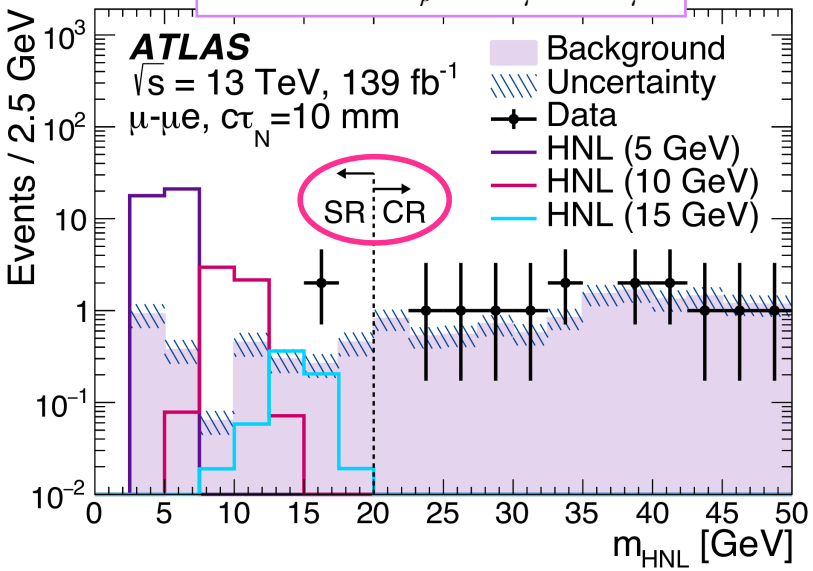
EXOT-2019-29



- 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

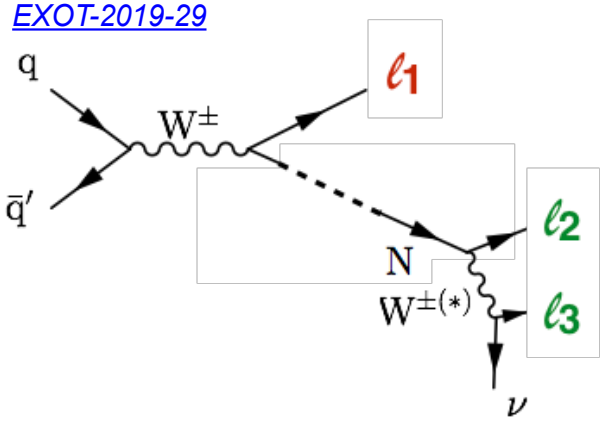
HNL mass reconstruction using M_W hypot.

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



HNL search in ATLAS

EXOT-2019-29



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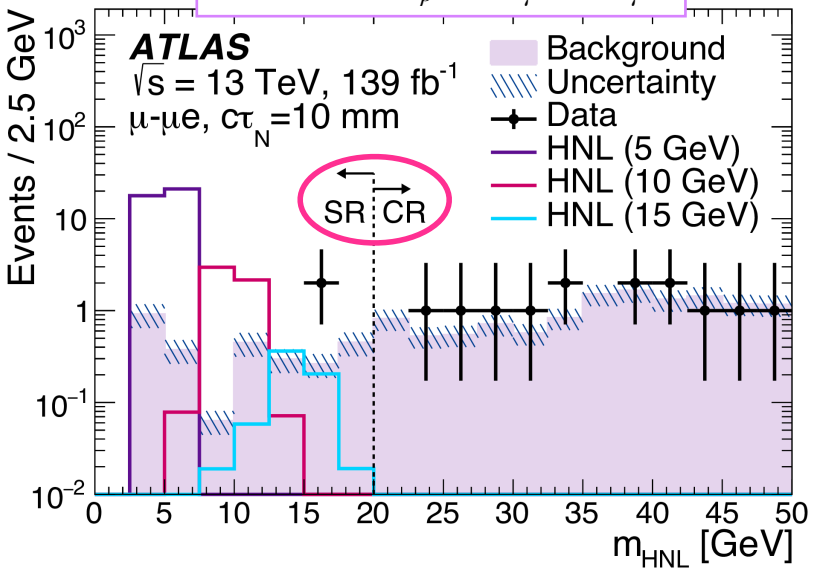
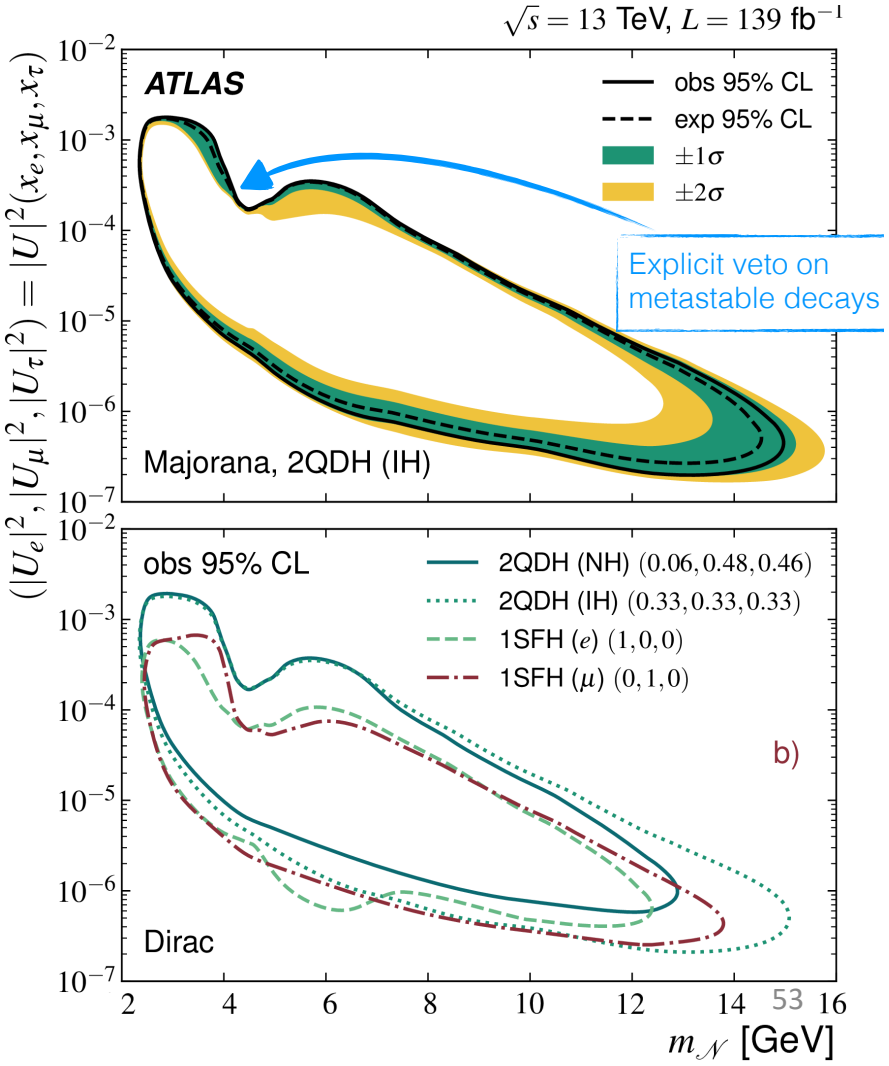
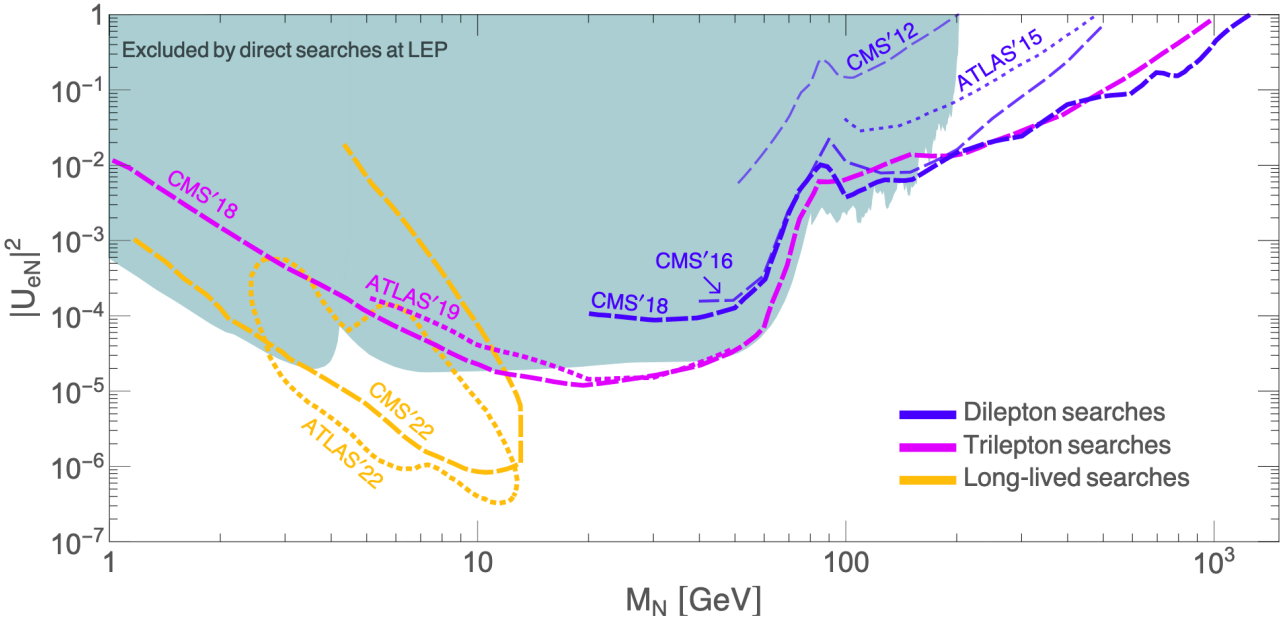
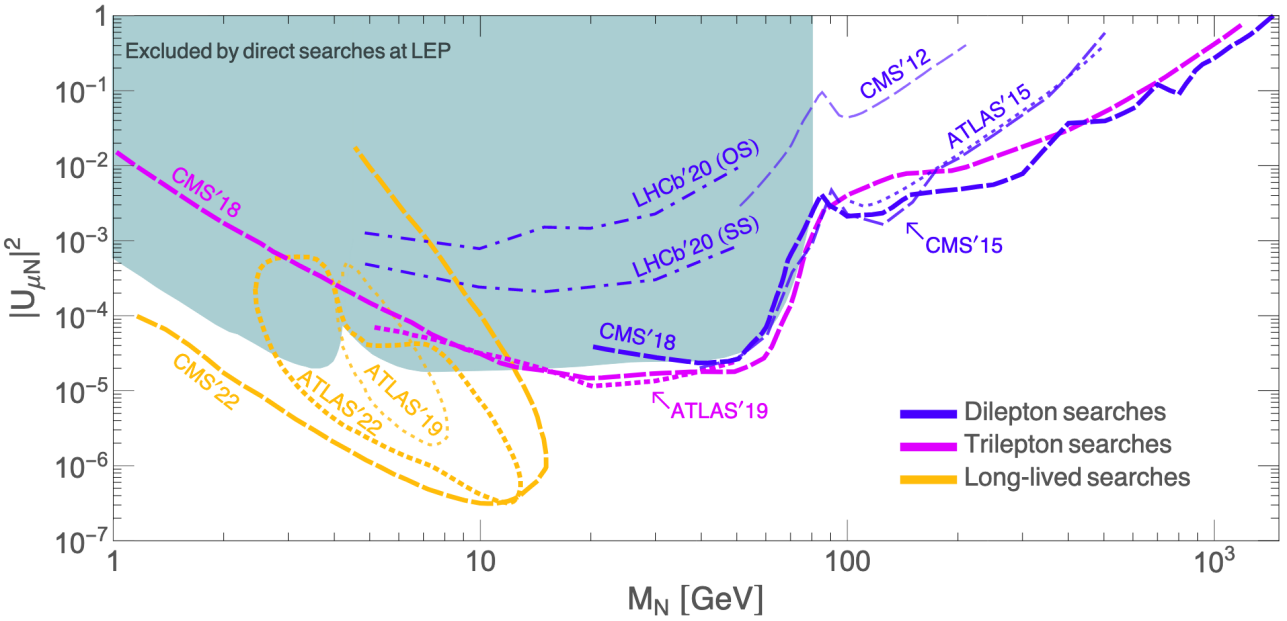




HNL search in CMS & ATLAS

Abada, Escribano, Marcano, Piazza 2208.13882





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