DE LA RECHERCHE À L'INDUSTRIE

Search for Majorana neutrinos at the LHC

present and perspectives

XXIII Roma Tre Topical Seminar | Matthias Saimpert

Monday 13 December 2021

www.cea.fr

OUTLINE

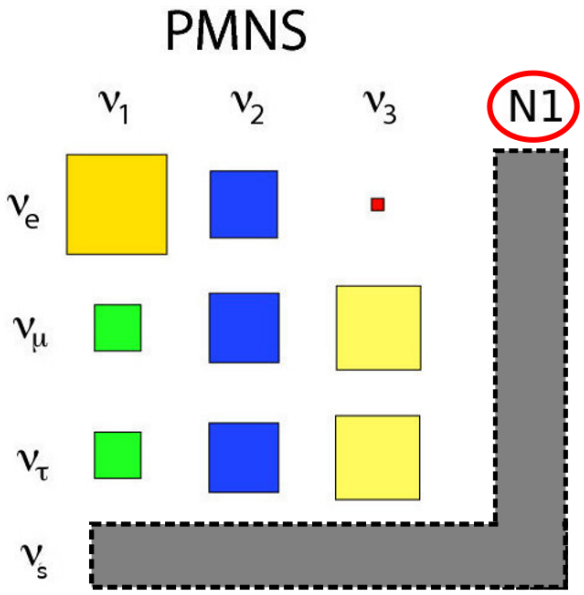
Models & Signatures

Main backgrounds & Current sensitivity

Perspectives & Recent developments

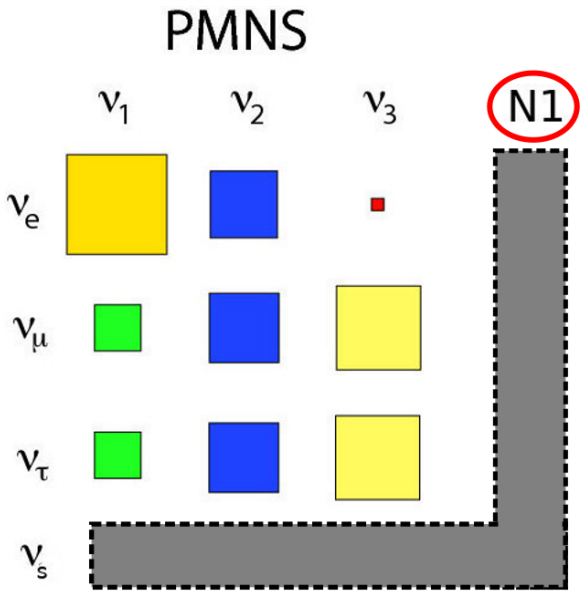
Future colliders

HEAVY NEUTRAL LEPTONS



- **Heavy Neutral Lepton (HNL) = heavy, sterile, Majorana neutrino**

HEAVY NEUTRAL LEPTONS



- **Heavy Neutral Lepton (HNL) = heavy, sterile, Majorana neutrino**
  - seesaw mechanism → neutrino mass
  - zero couplings → dark matter
  - CP violation → baryon asymmetry

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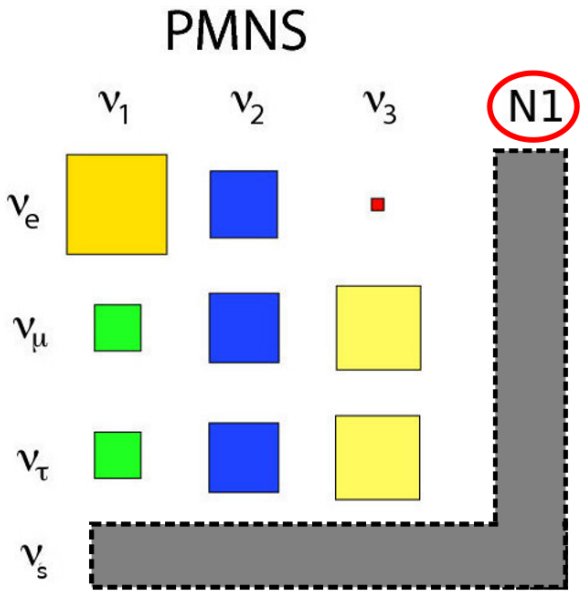

The LHC is an **everything** factory

Particle	Produced in 140 fb^{-1} at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.8 million	
Top quark	275 million	
Z boson	8 billion	($\to \ell\ell$, 270 million per flavour)
W boson	26 billion	($\to \ell\nu$, 2.8 billion per flavour)
Bottom quark	~160 trillion	(significantly reduced by acceptance)

reference

- **Heavy Neutral Lepton (HNL) = heavy, sterile, Majorana neutrino**
  - seesaw mechanism $\to$ neutrino mass
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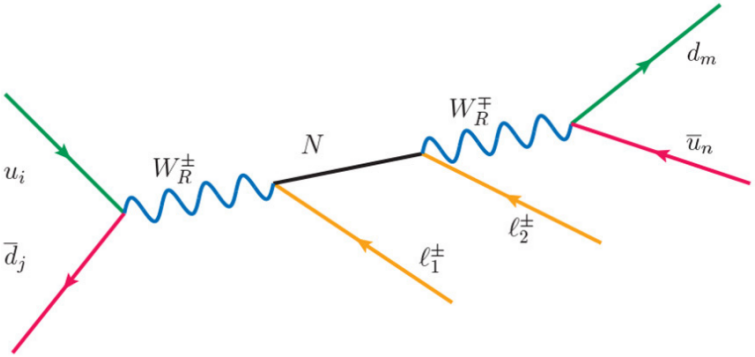
- **At LHC, can be singly produced in the numerous W decays**
  - other possibilities : Z, Higgs, mesons and τ decays

SIGNAL MODELS

HNL predicted in many models → benchmarks defined



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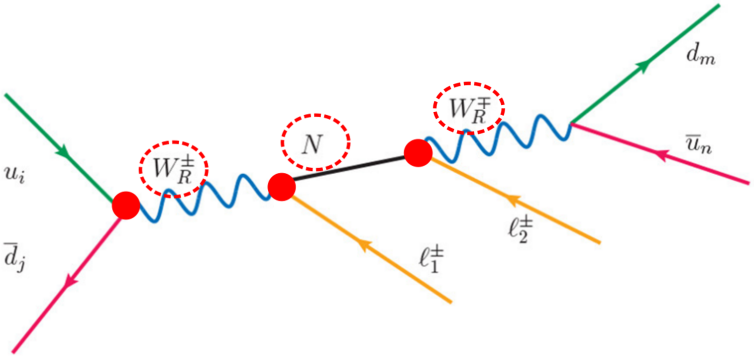

- **'UV complete',** ex : left-right symmetric models (LRSM),
  - HNLs, $W_R^\pm$, Z_R, additional scalars
  - relevant new particles : 1 HNL, $W_R^\pm$ (others set to large mass)
  - relevant parameters : g_R, m_{W_R}, m_N

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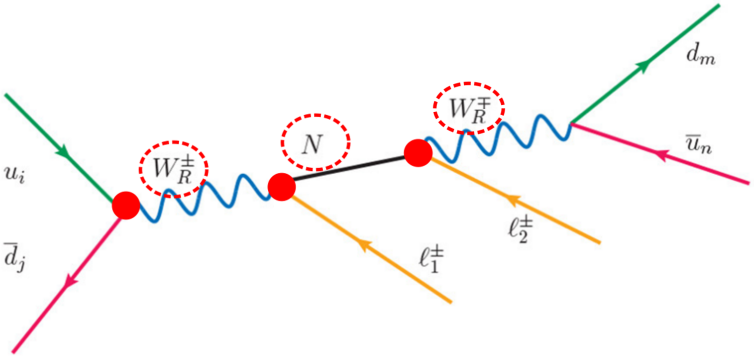

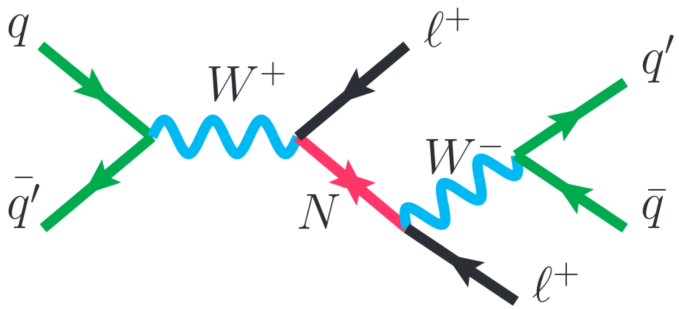

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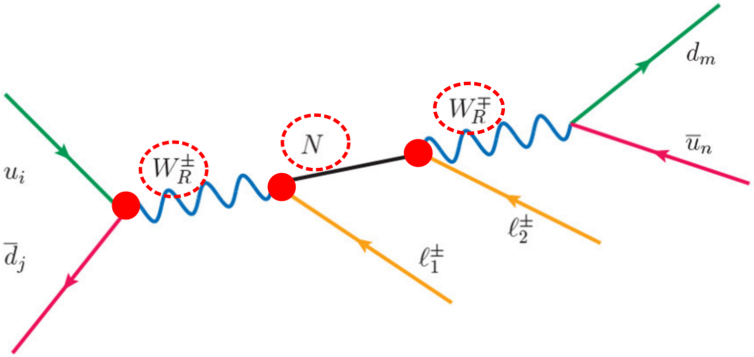
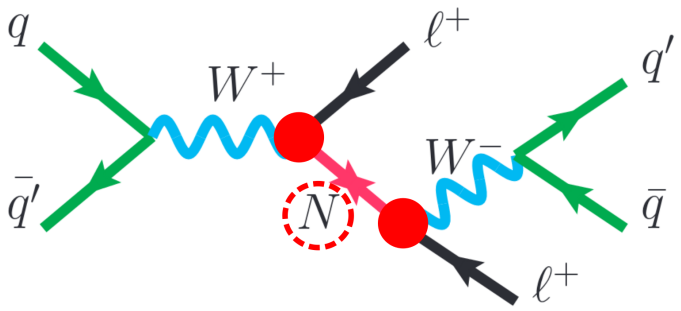
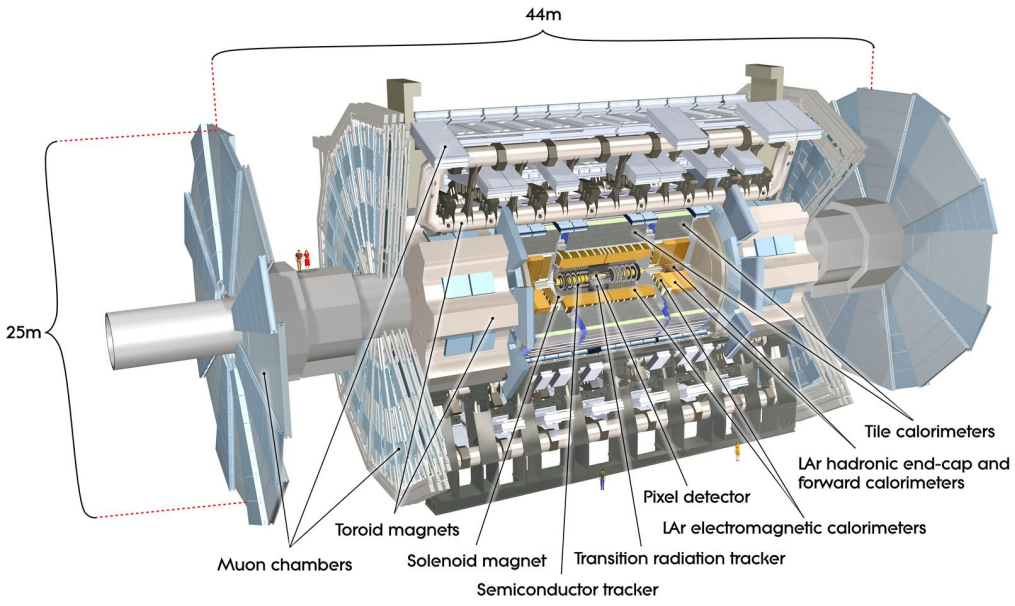


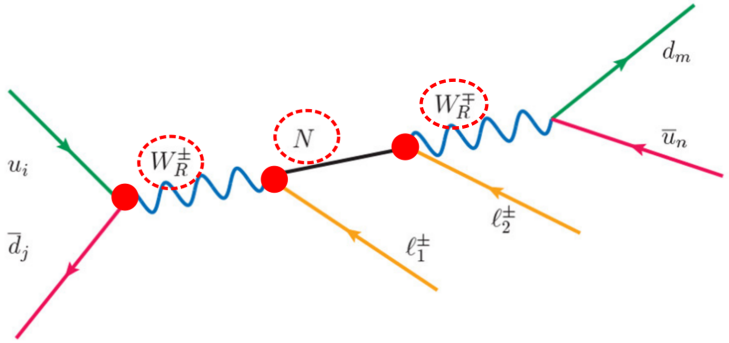


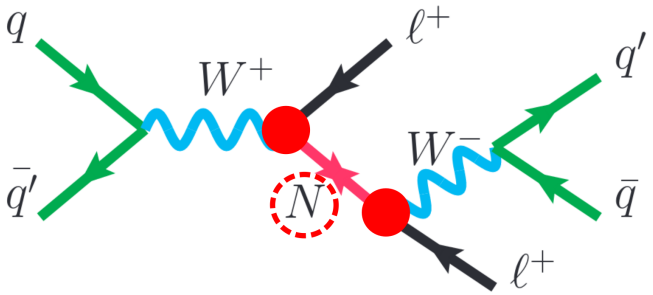
- **'UV complete',** ex : left-right symmetric models (LRSM),
  - HNLs, $W_R^\pm$, Z_R, additional scalars
  - relevant new particles : 1 HNL, $W_R^\pm$ (others set to large mass)
  - relevant parameters : g_R, m_{W_R}, m_N
- **'Minimal',** ex : phenomenological type-I seesaw,
  - HNLs + mass mixing parameters
  - relevant new particles : 1 HNL (others set to large mass)
  - relevant parameters : m_N, $V_{\ell N}$ (one flavor at a time)

SIGNATURES @ ATLAS, CMS

ATLAS/CMS detectors at CERN : proton collisions @ 13 TeV, $\sim$ 140 fb^{-1} $\times$2 collected







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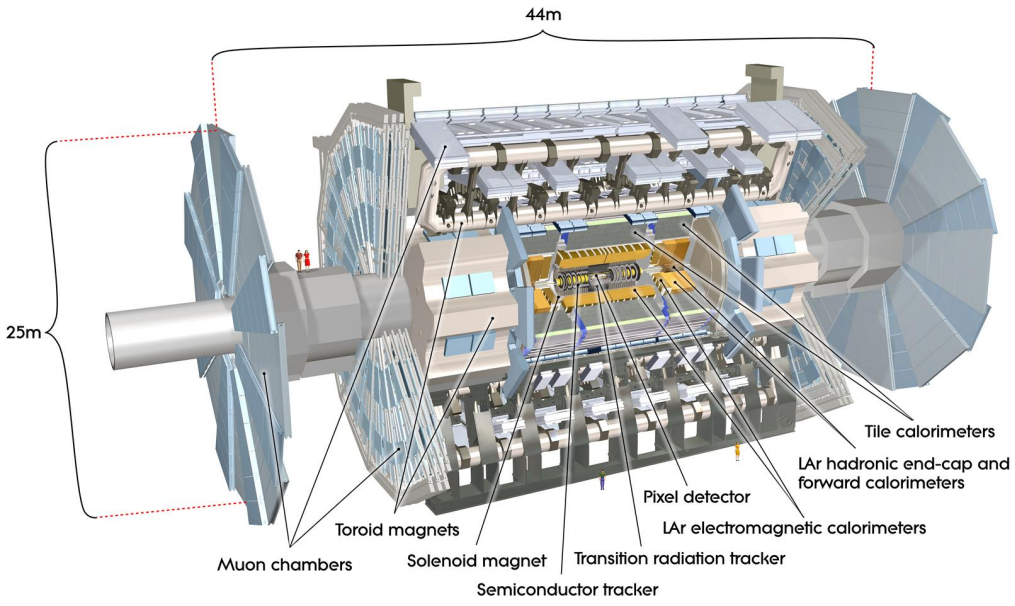

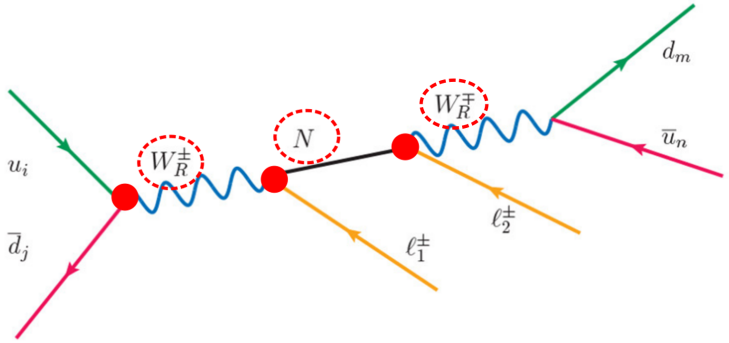

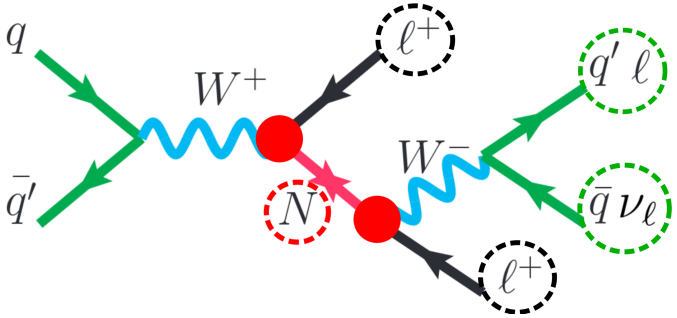

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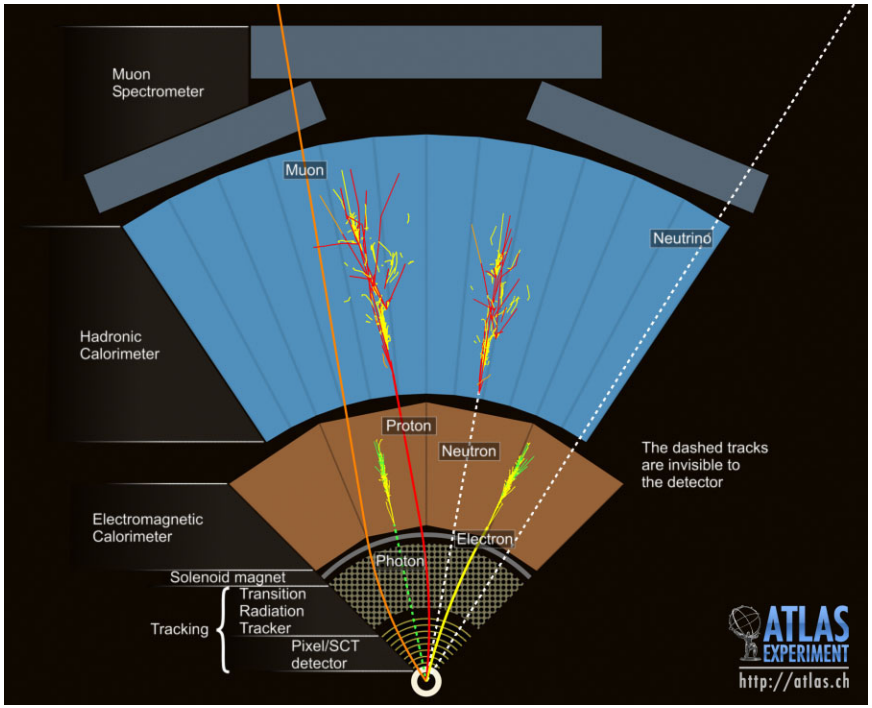
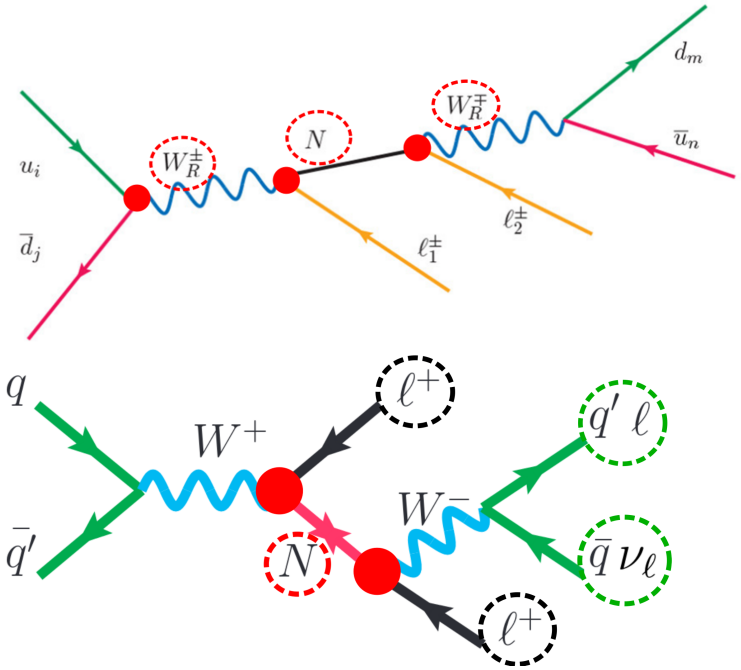
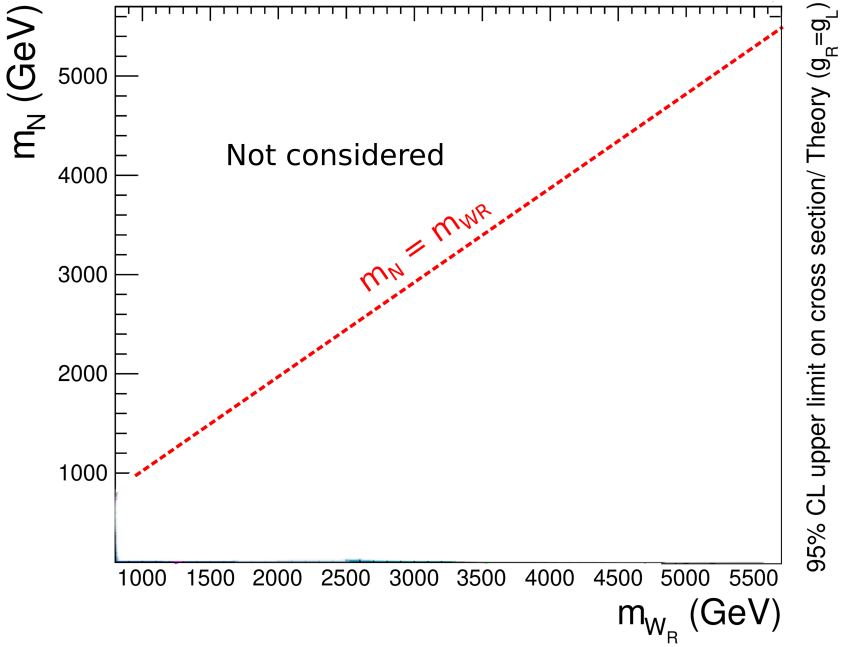




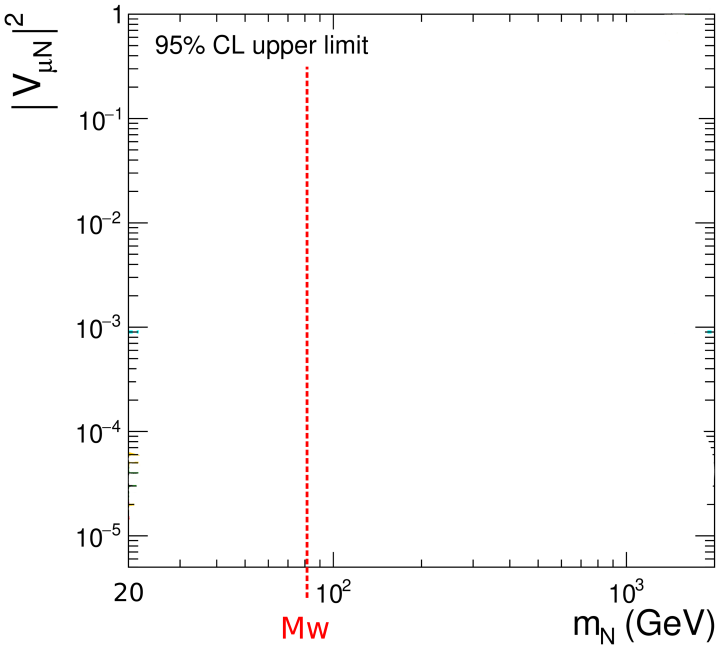
- **Final state :** '2 same-sign leptons + 2 jets' **or** '3 leptons' **(e or μ)**
  - tracker reconstructs **trajectories/sign** of charged particles ($\sim$ 600 per event !)
  - calorimeters collects **energy deposits** of e/γ and collimated jets of hadrons
  - outer spectrometer allows to identify muons by matching inner detector tracks

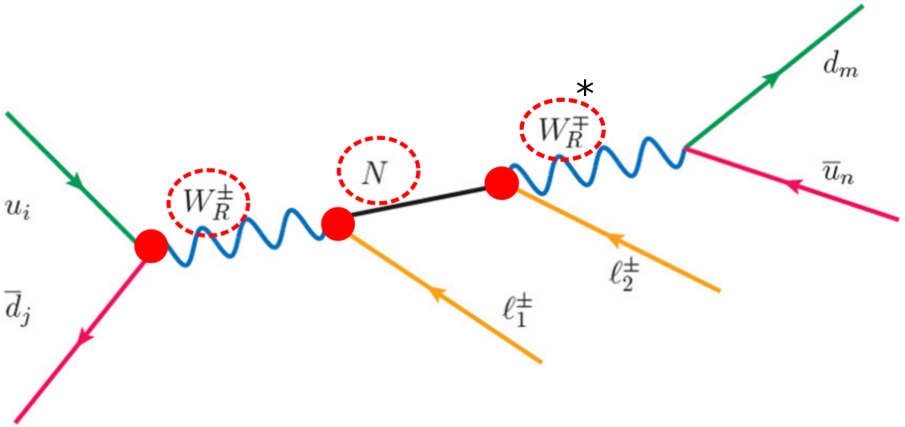
SIGNATURES & PARAMETER SPACE

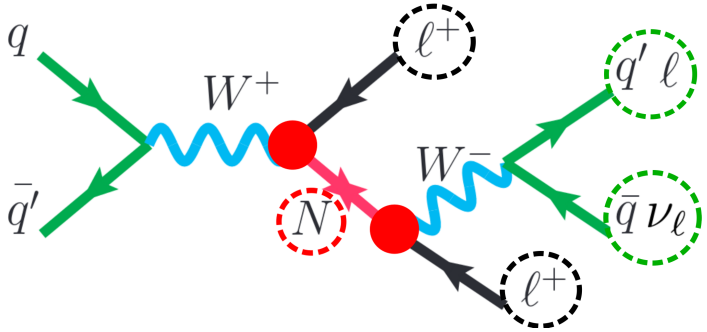
LRSM ($g_R = g_L$, m_{W_R}, m_N)



Type-I seesaw (m_N, $V_{\ell N}$)







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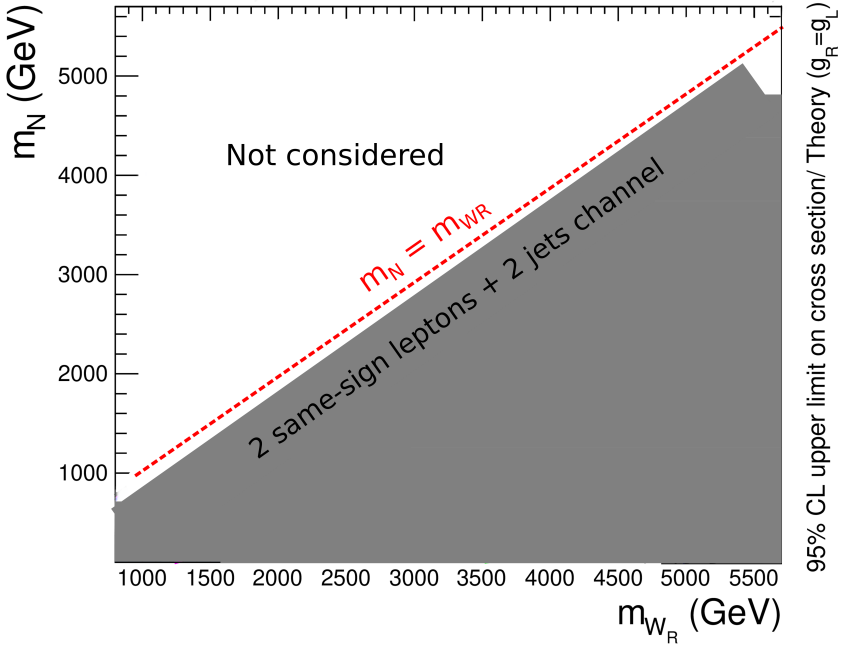

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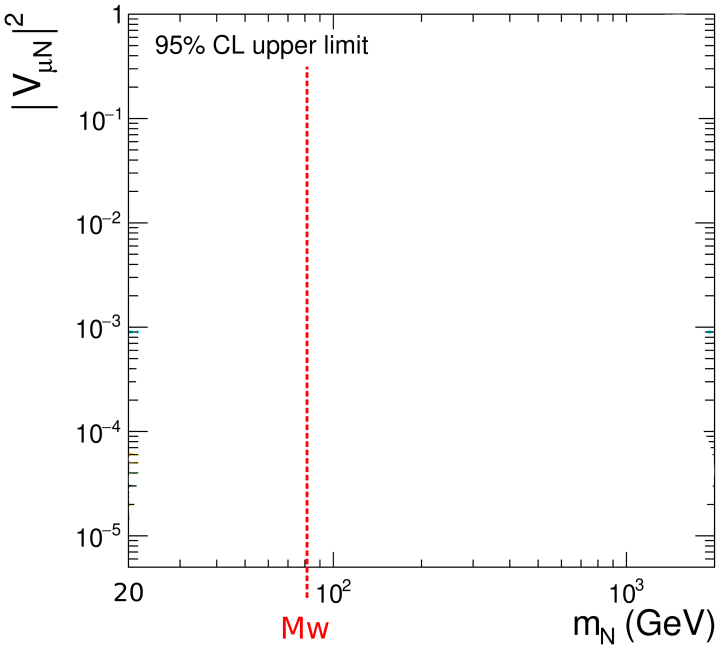

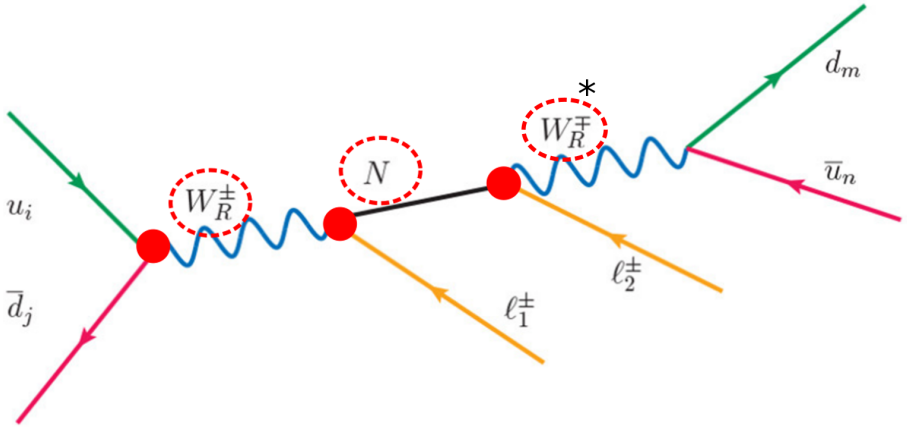

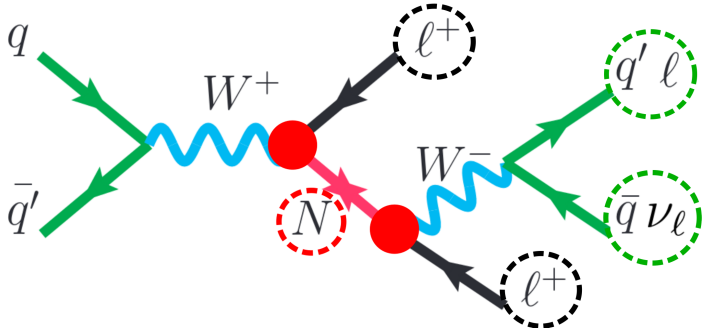

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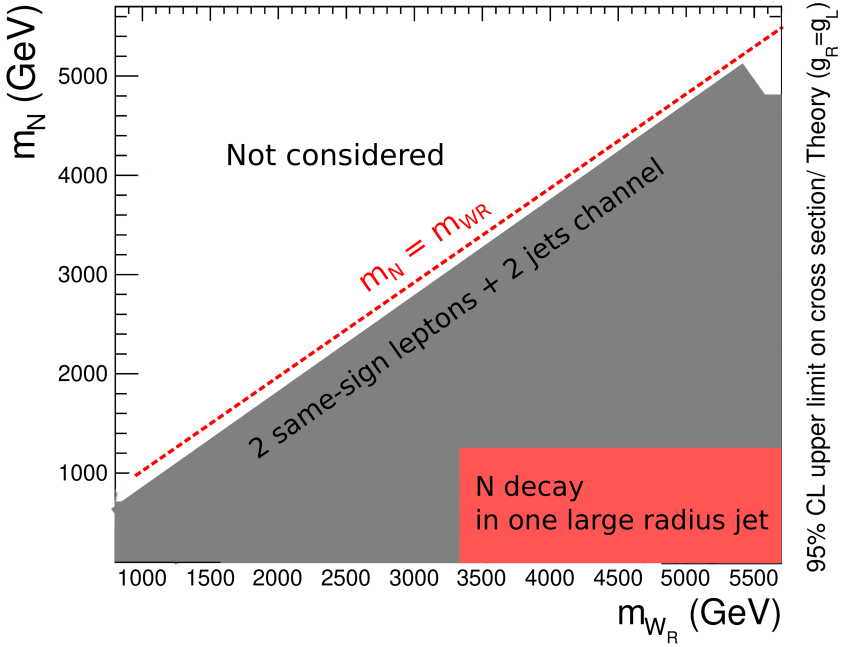

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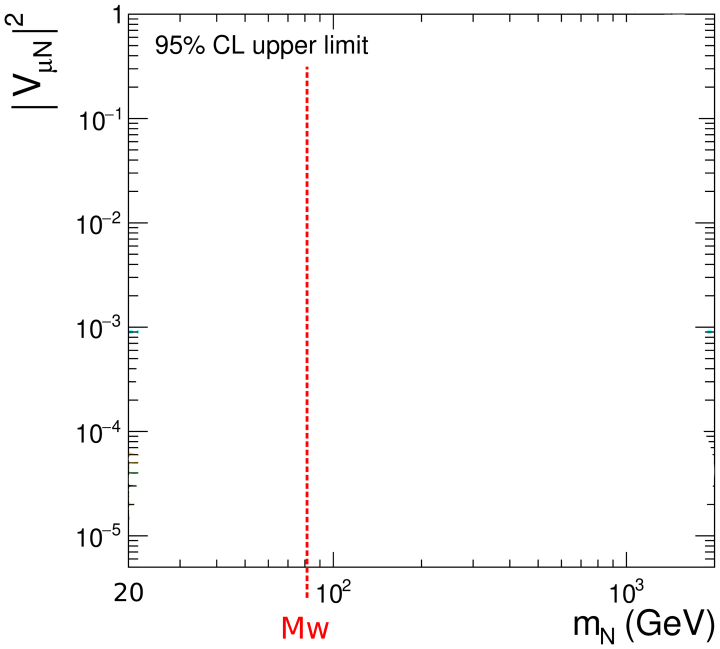

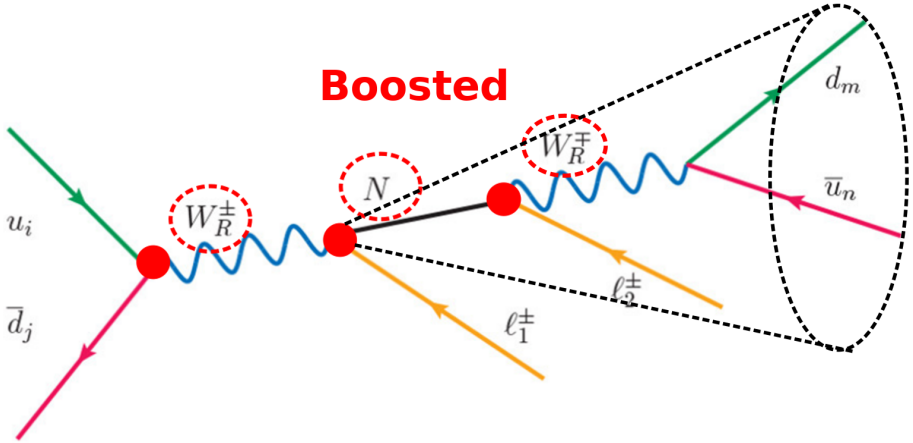

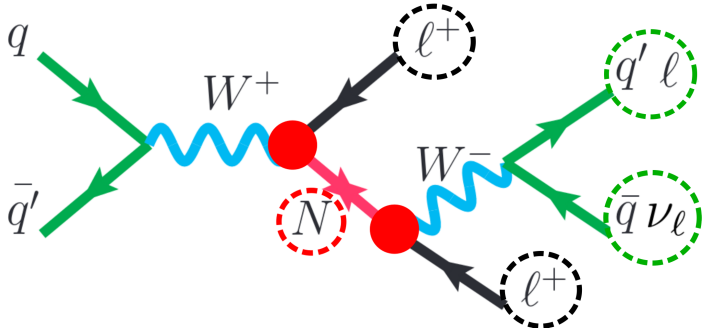

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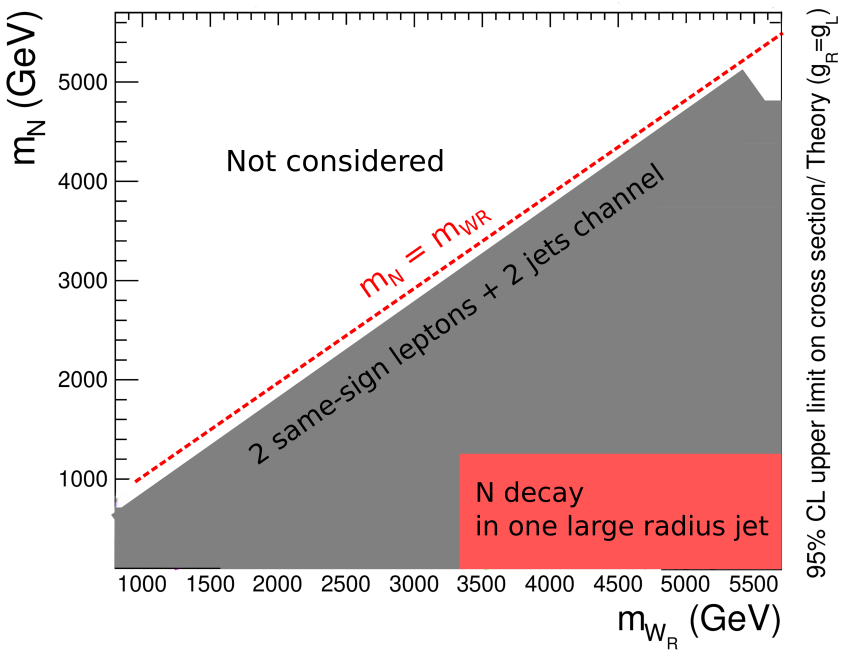

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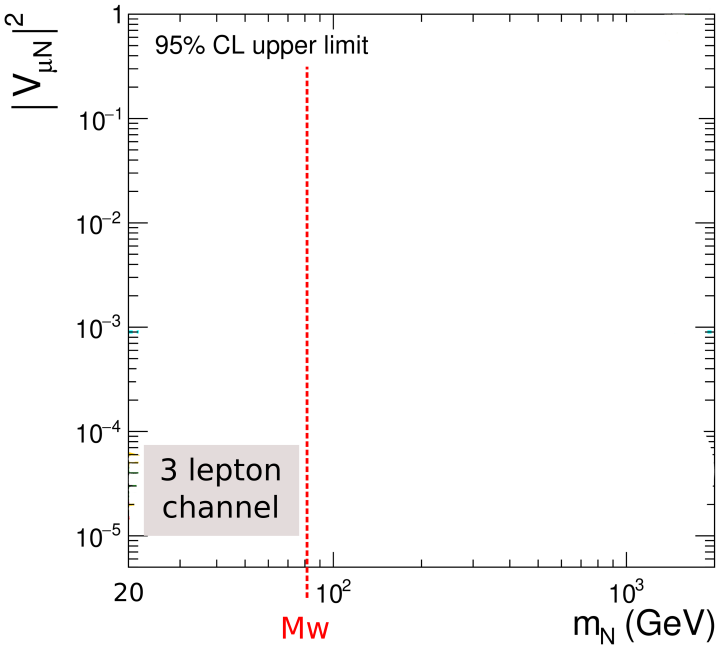

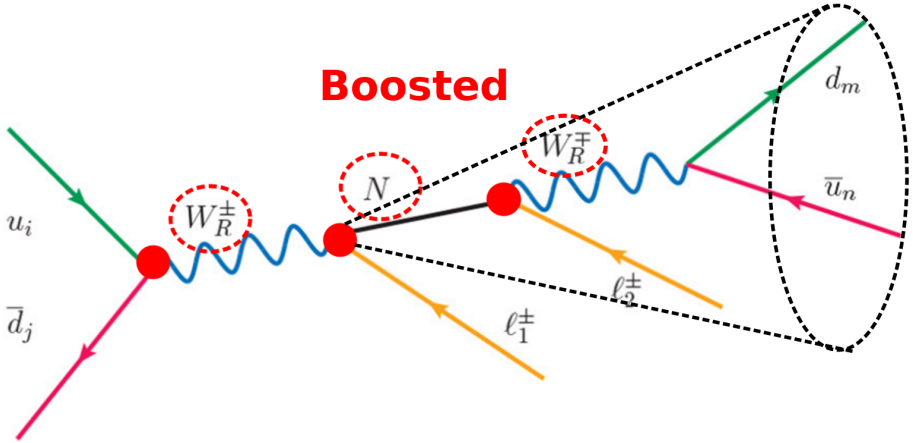

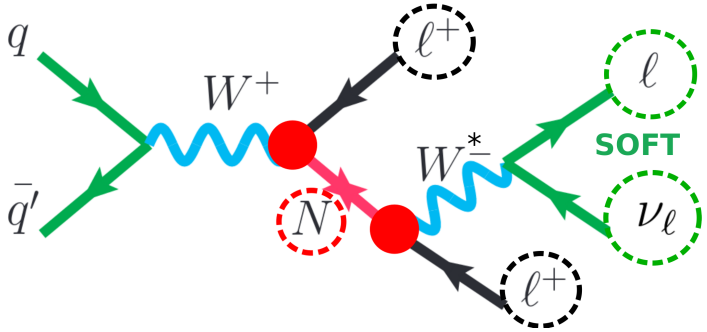

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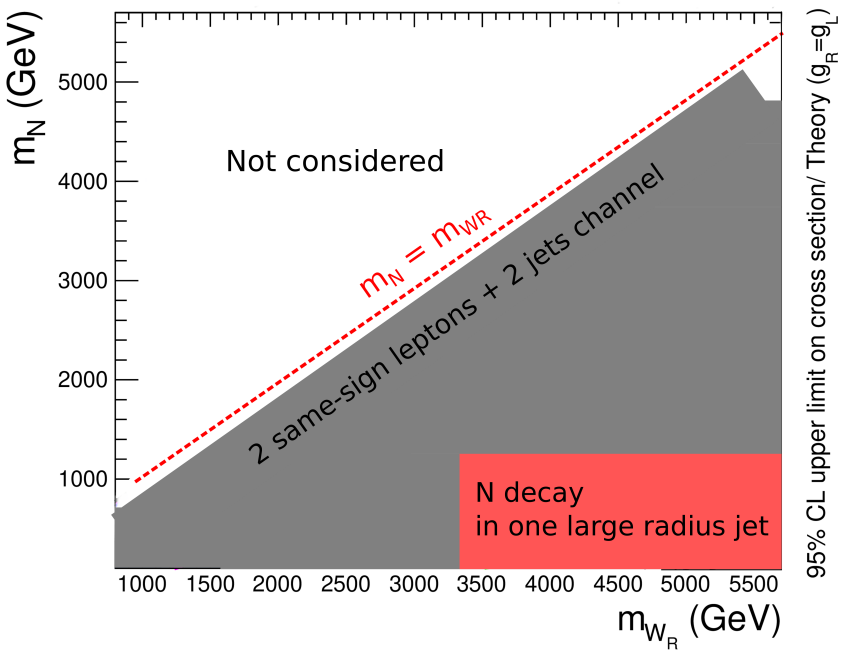

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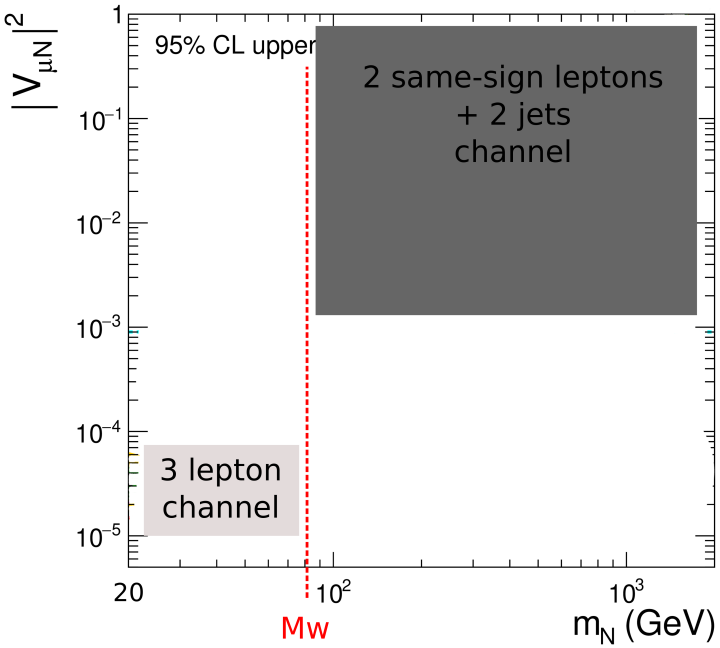

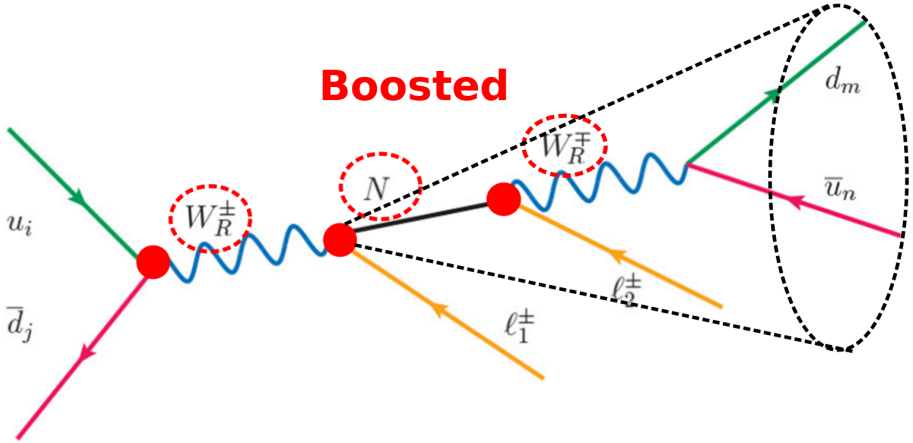

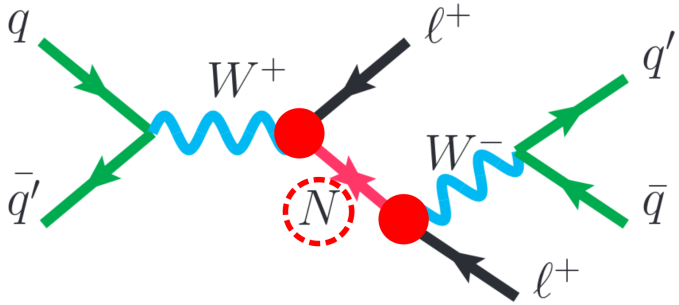

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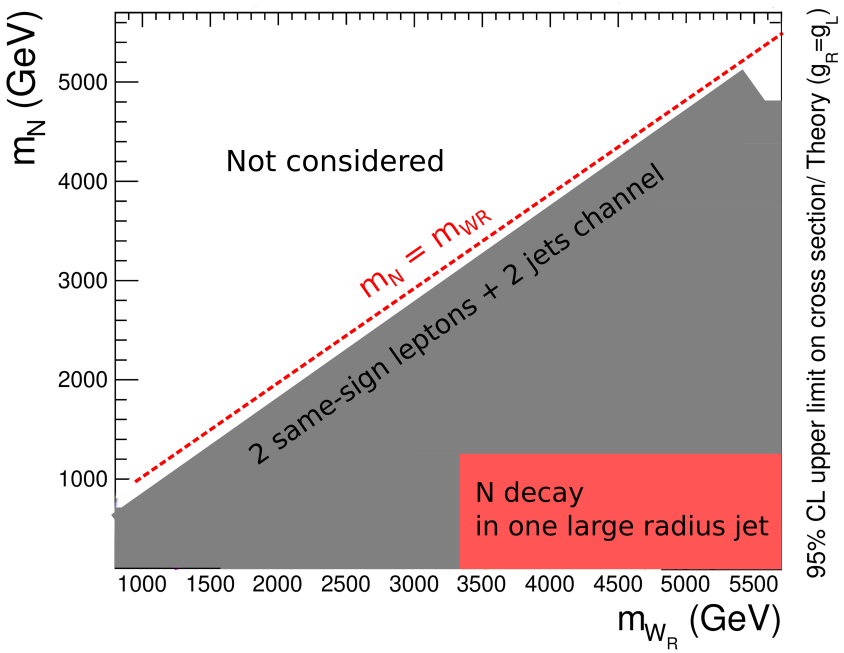

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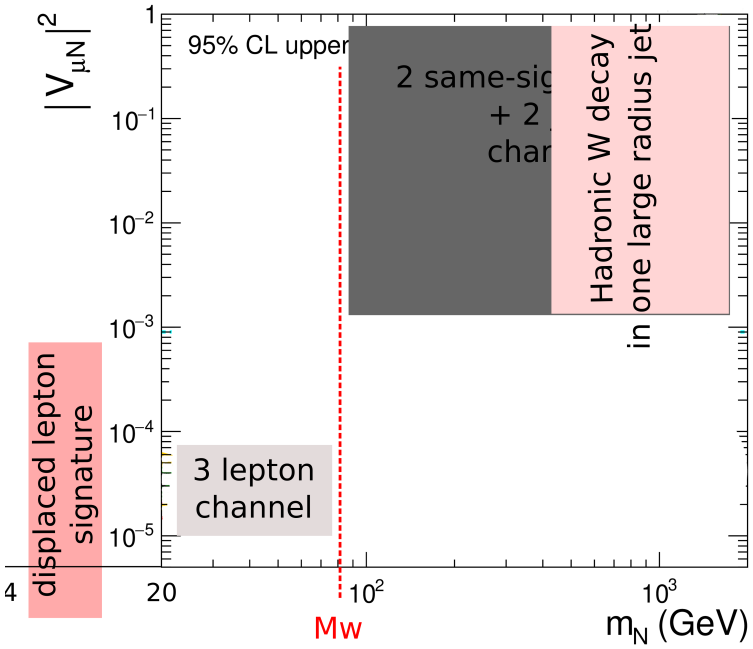

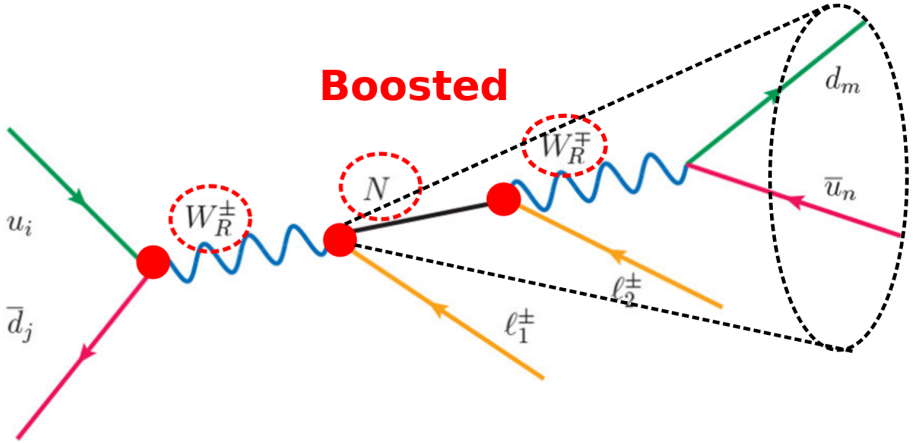

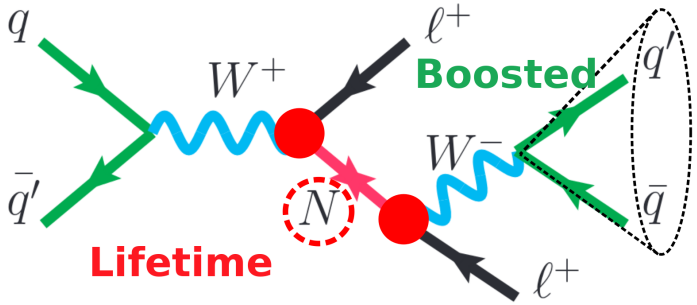

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2L-SS + JETS SIGNATURES : ANALYSIS

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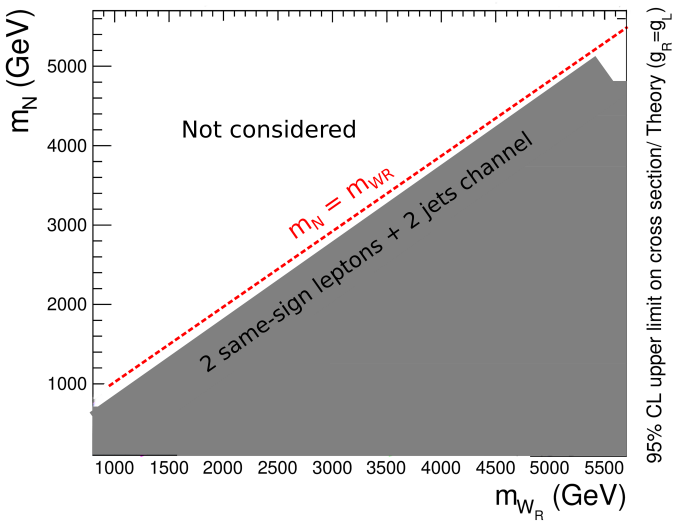

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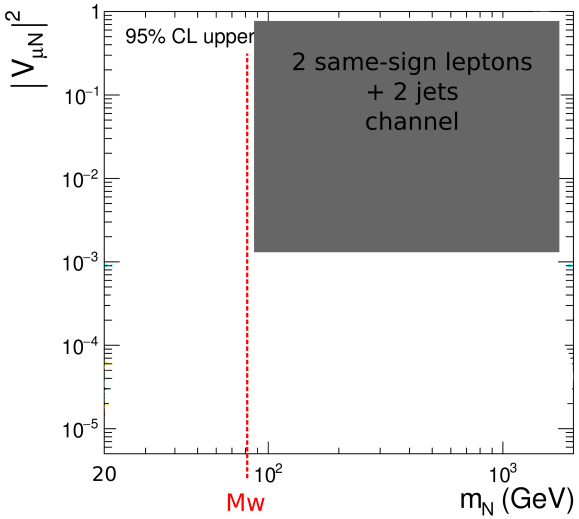
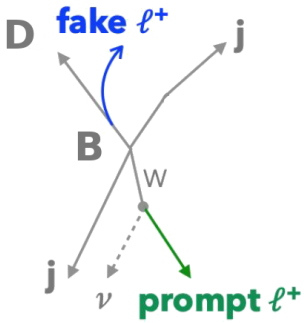
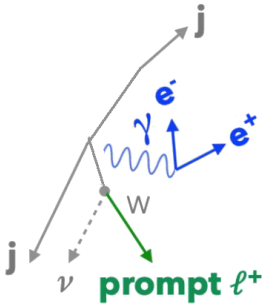


- **Many delicate instrumental backgrounds**
  - fake ℓ from B hadrons and $\gamma \to \ell\ell$
  - e channels : ℓ sign mismeasurement
- **Other background :** $WZ \to \ell\nu\ell\ell$ with 1 missed ℓ

Semileptonic b-decay

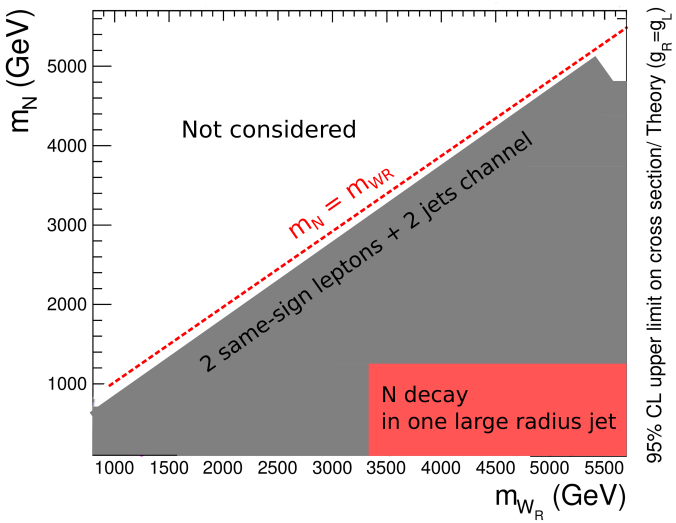


Photon conversions

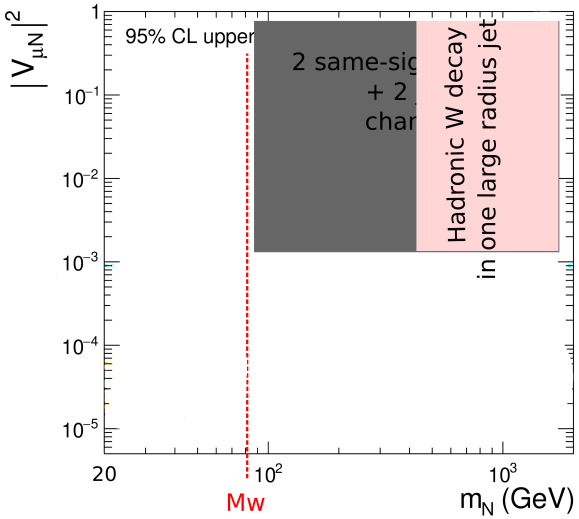


2L-SS + JETS SIGNATURES : ANALYSIS

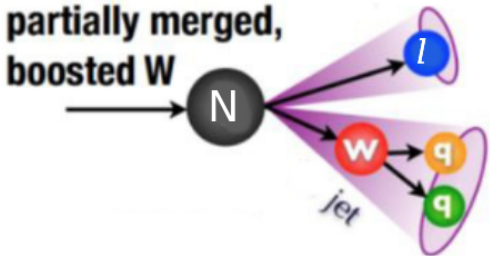
LRSM ($g_R = g_L$, m_{W_R}, m_N)

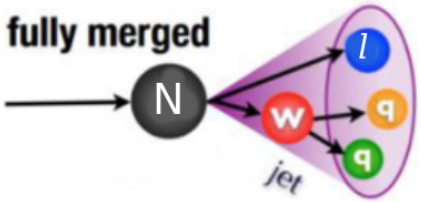


Type-I seesaw (m_N, $V_{\ell N}$)



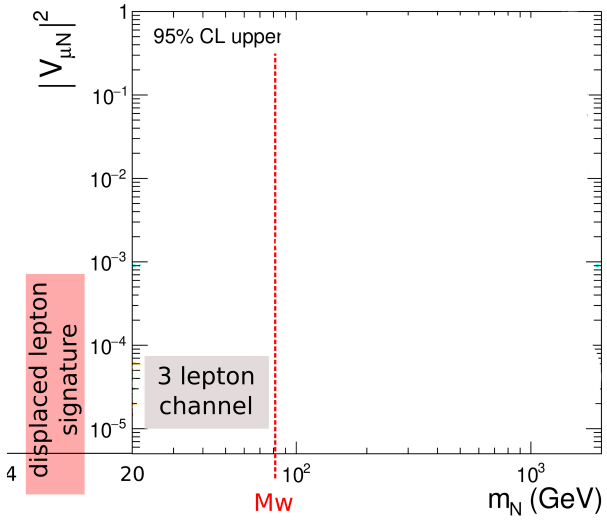
- **Many delicate instrumental backgrounds**
  - fake ℓ from B hadrons and $\gamma \to \ell\ell$
  - e channels : ℓ sign mismeasurement
- **Other background :** $WZ \to \ell\nu\ell\ell$ with 1 missed ℓ
- **Boosted regions**
  - low acceptance $\to$ use special reconstruction



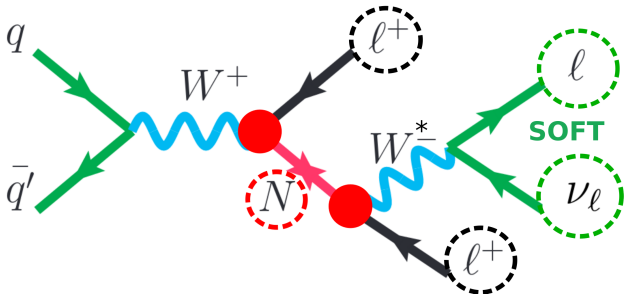


3L SIGNATURES : ANALYSIS

Type-I seesaw (m_N, $V_{\ell N}$)

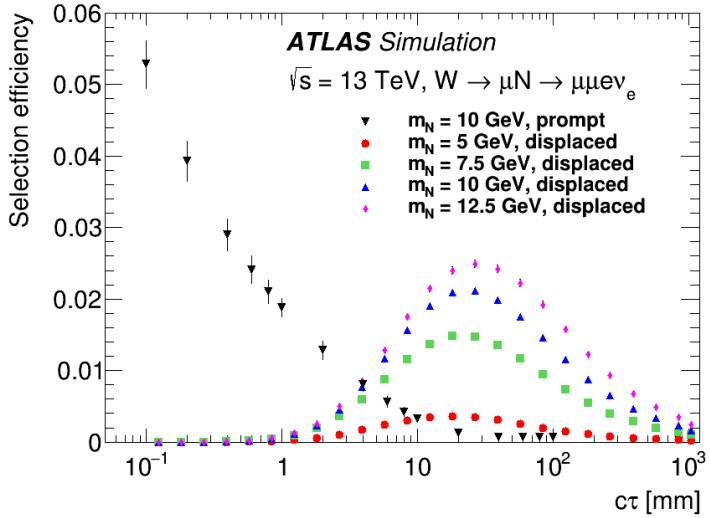


- **Similar but lower backgrounds**
- Lower signal cross section compensated by higher selection efficiency at low m_N (soft W decays)



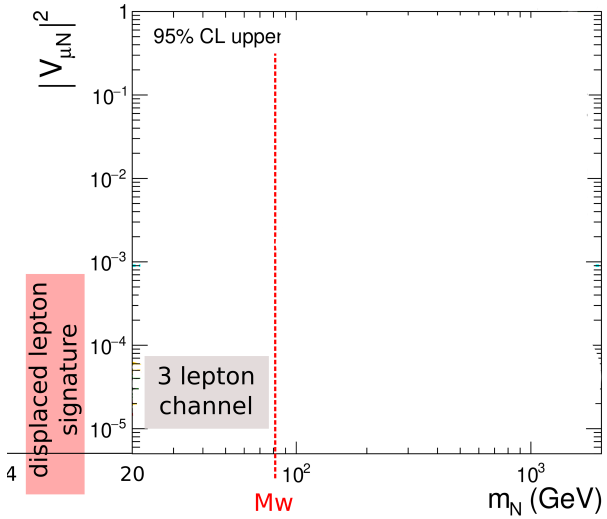
3L SIGNATURES : ANALYSIS

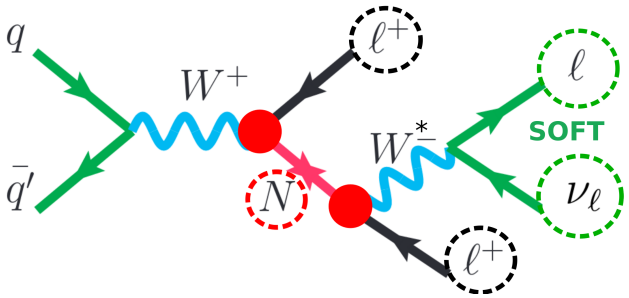
Large radius tracking @ ATLAS



JHEP 10 (2019) 265

Type-I seesaw (m_N, $V_{\ell N}$)

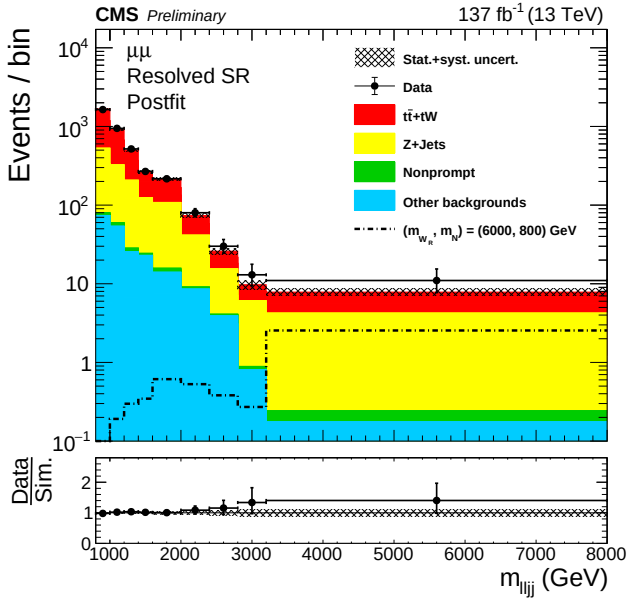




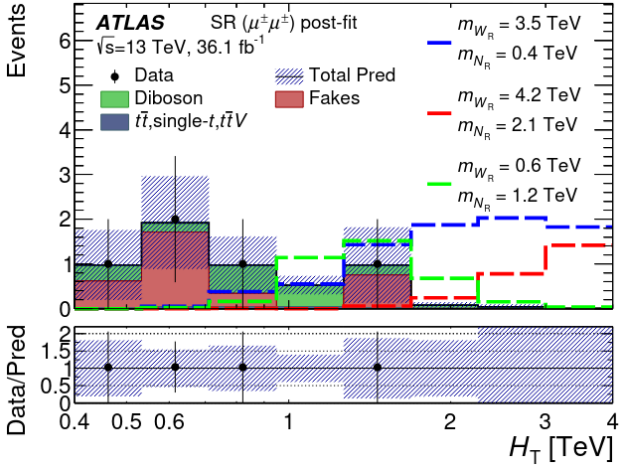
- **Similar but lower backgrounds**
- Lower signal cross section compensated by higher selection efficiency at low m_N (soft W decays)
- **$m_N < 20$ GeV $\rightarrow$ displaced vertices $\mathcal{O}$(1cm)**
- low acceptance $\rightarrow$ use special reconstruction

EXCLUSION OVERVIEW @ ATLAS & CMS

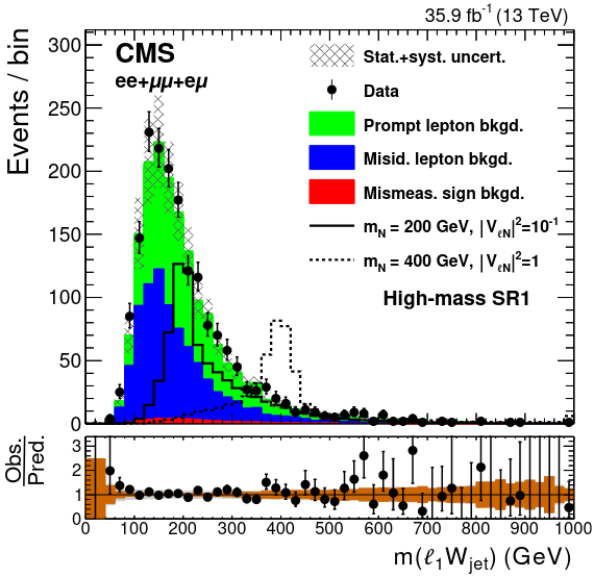
CMS-PAS-EXO-20-002 - LRSM (2LSS + jets)



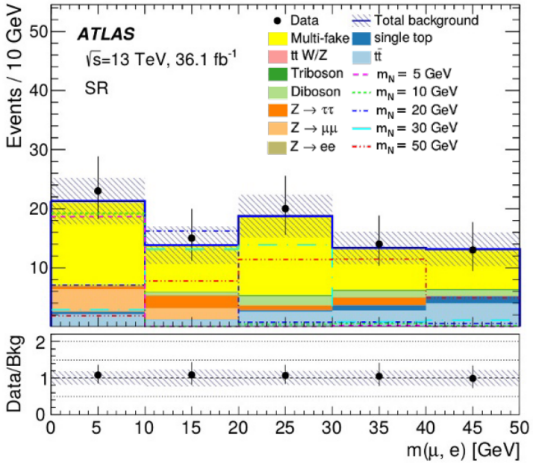
JHEP 01 (2019) 016 - LRSM (2LSS + jets, resolved)



JHEP 01 (2019) 122 - Type-I seesaw (2LSS)

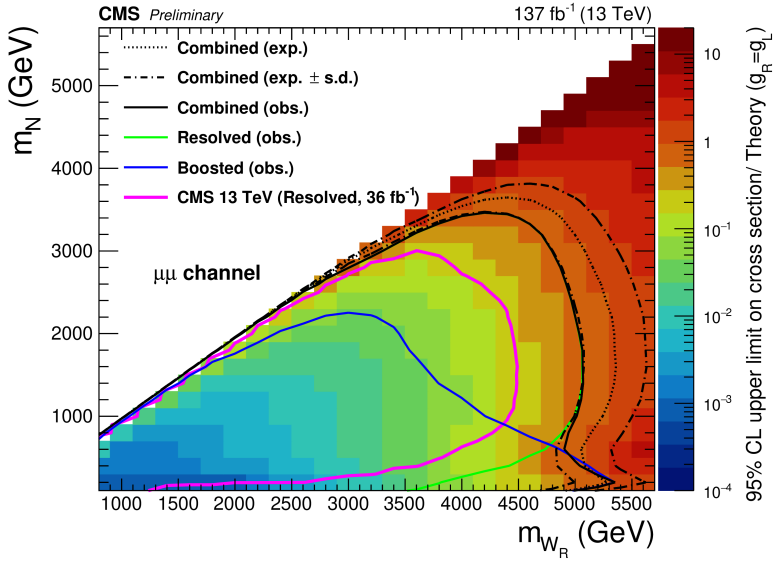


JHEP 10 (2019) 265 - Type-I seesaw (3L, displaced)

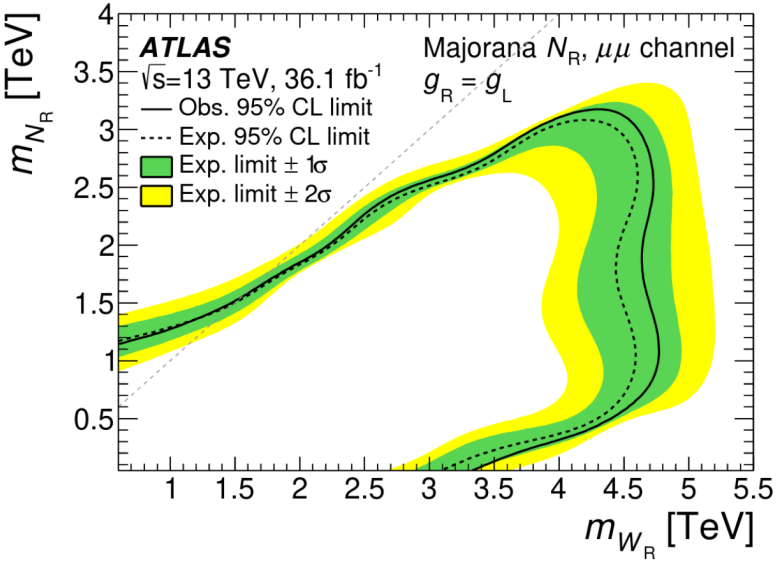


EXCLUSION OVERVIEW - MUONS

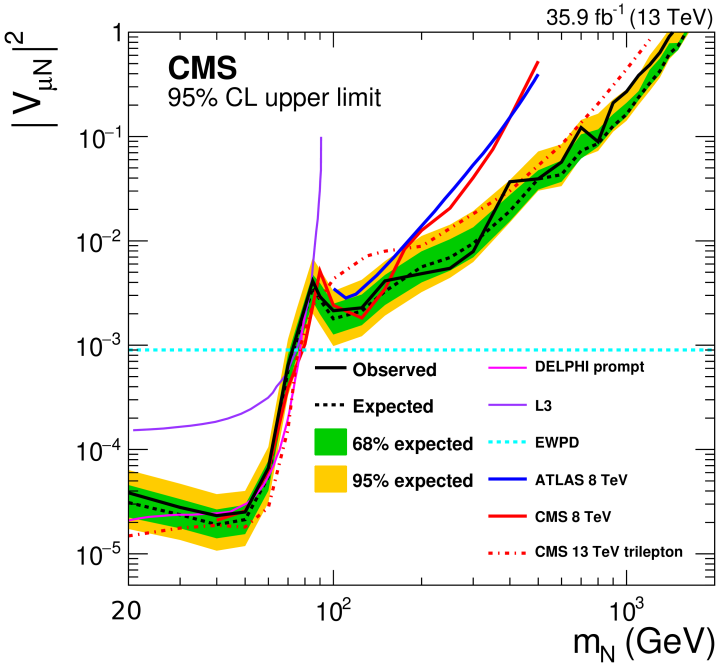
CMS-PAS-EXO-20-002 - LRSM (2LSS + jets)



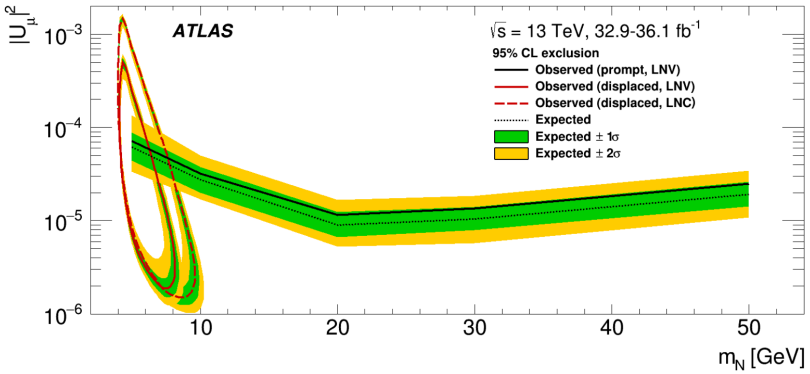
JHEP 01 (2019) 016 - LRSM (2LSS + jets, resolved)



JHEP 01 (2019) 122 - Type-I seesaw (2LSS)

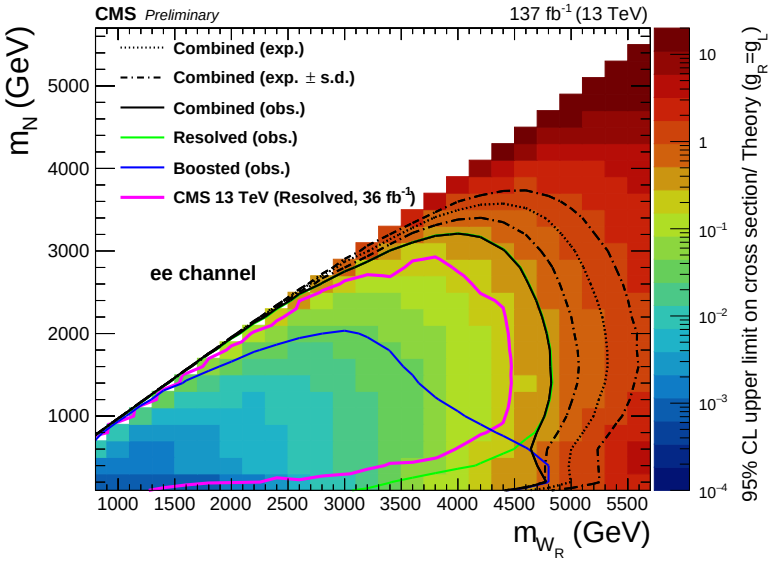


JHEP 10 (2019) 265 - Type-I seesaw (3L)

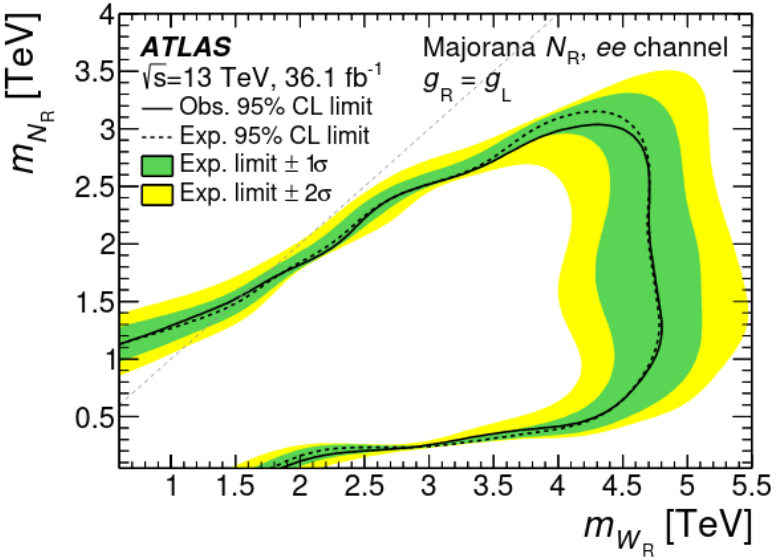


EXCLUSION OVERVIEW - ELECTRONS

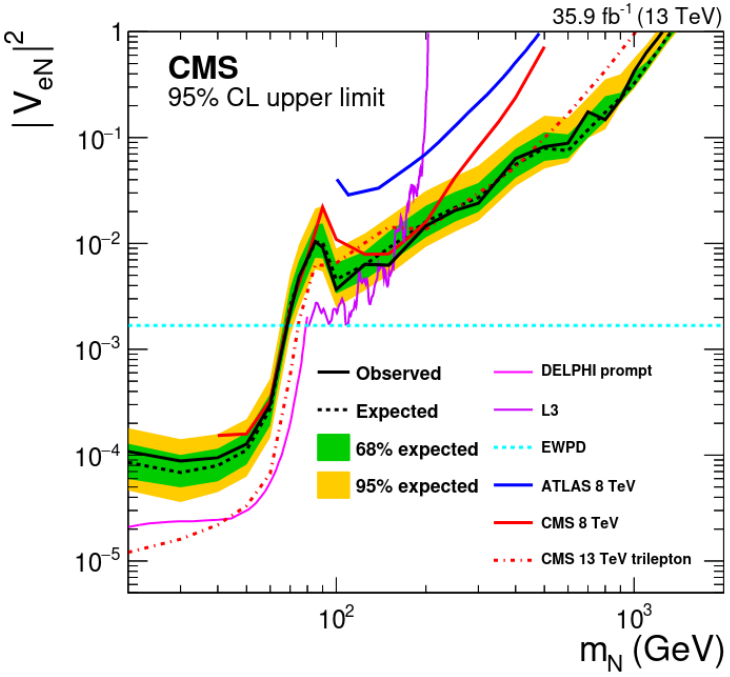
CMS-PAS-EXO-20-002 - LRSM (2LSS + jets)



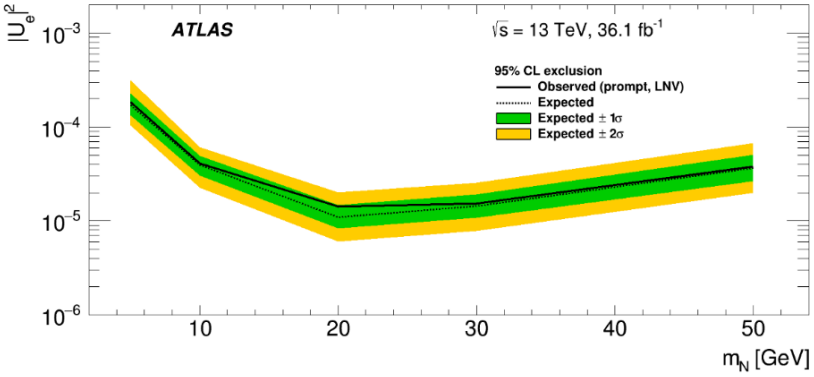
JHEP 01 (2019) 016 - LRSM (2LSS + jets, resolved)



JHEP 01 (2019) 122 - Type-I seesaw (2LSS)



JHEP 10 (2019) 265 - Type-I seesaw (3L, displaced)



OUTLINE

Models & Signatures

Main backgrounds & Current sensitivity

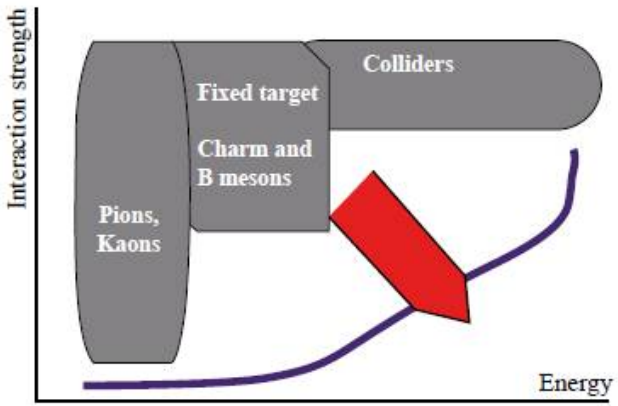
Perspectives & Recent developments

Future colliders

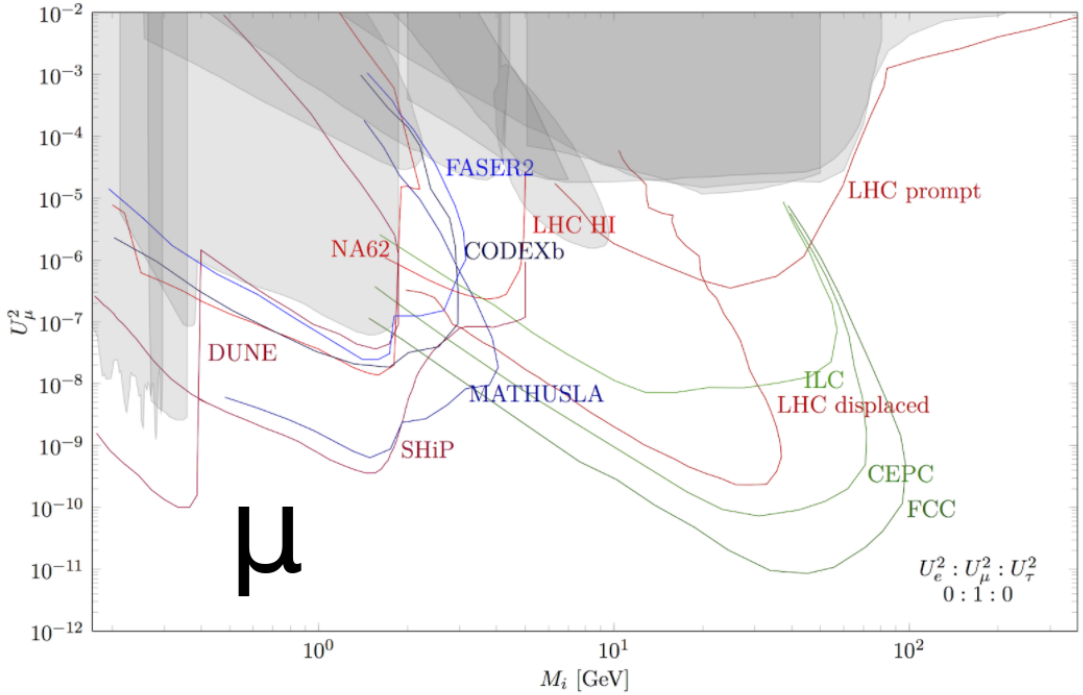
COLLIDER SENSITIVITY COMPARISON

Type-I seesaw (m_N, $V_{\ell N}$)

reference



reference, current (gray areas), future runs/exp. (lines)



- **NA62/LHC currently provide strongest direct constraints for $m_N > m_K$**
  - difficult to probe low mixing for $m_N > m_W$ though
- Many new experiments planned, but only colliders can access directly $m_N > 10$ GeV

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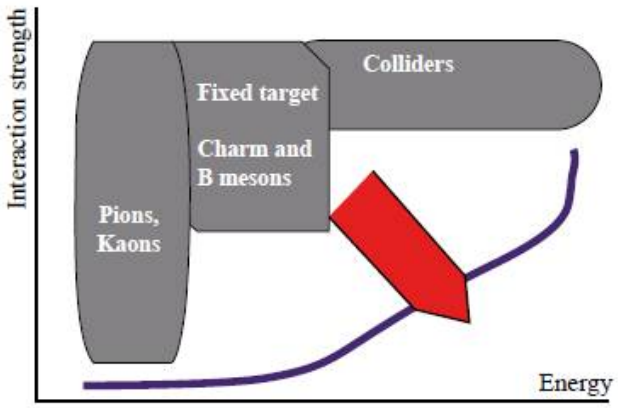

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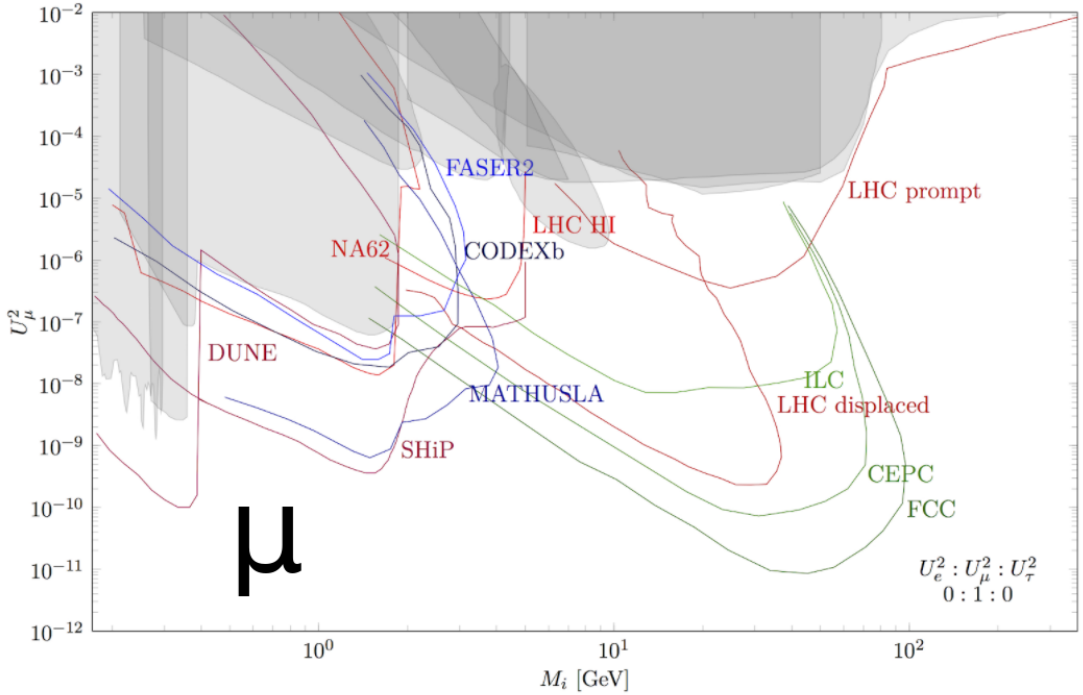

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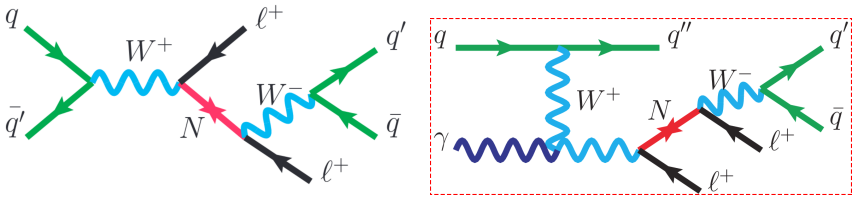
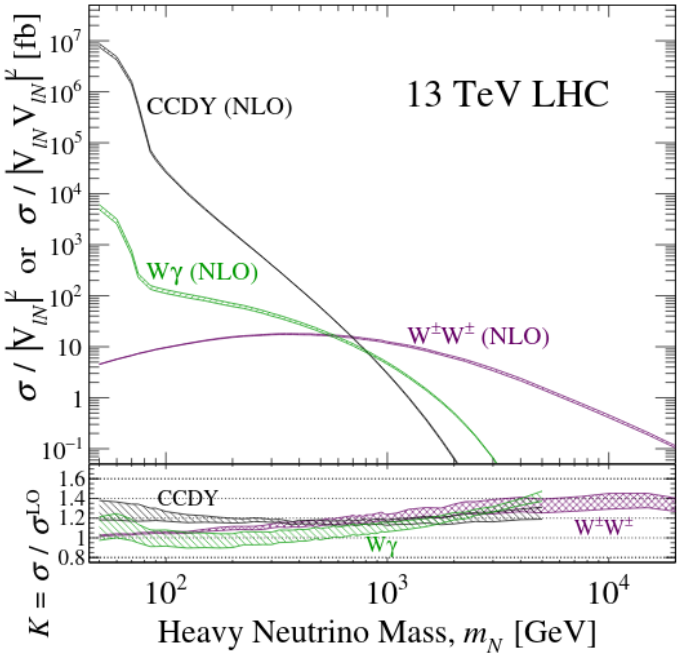
  - difficult to probe low mixing for $m_N > m_W$ though
- Many new experiments planned, but only colliders can access directly $m_N > 10$ GeV
- $0\nu\beta\beta$ experiments irrelevant for μ,τ ; electrons sensitivity $\sim V_{eN}^2 = 10^{-8}$-10^{-6}
  New J.Phys. 17 (2015) 7, 075019

SENSITIVITY @ TEV M_N : $W\gamma$ / WW FUSION

Type-I seesaw (m_N, $V_{\ell N}$)

JHEP 02 (2015) 072





Recent findings at high m_N :

- ***W*γ fusion sizable :** unchanged signature → need to update signal samples
  - included in latest CMS results, not yet in ATLAS

SENSITIVITY @ TEV M_N : $W\gamma$ / WW FUSION

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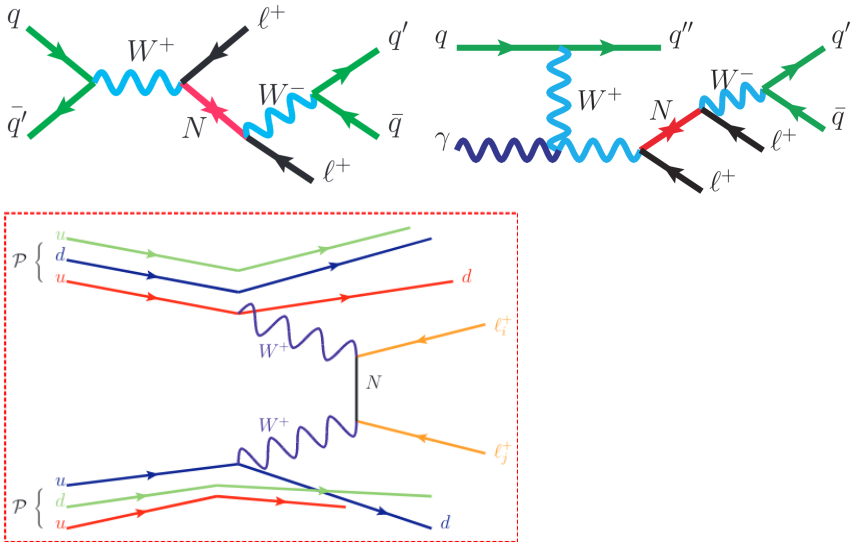
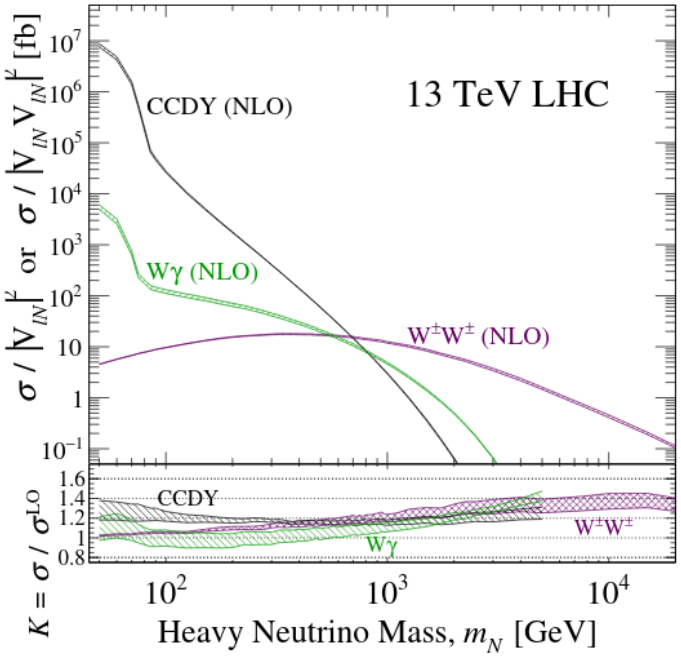
JHEP 02 (2015) 072 Phys. Rev. D 103, 055005 (2021)





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  - $\sigma \propto V_{\ell N}^4$ → small mixings hard to reach

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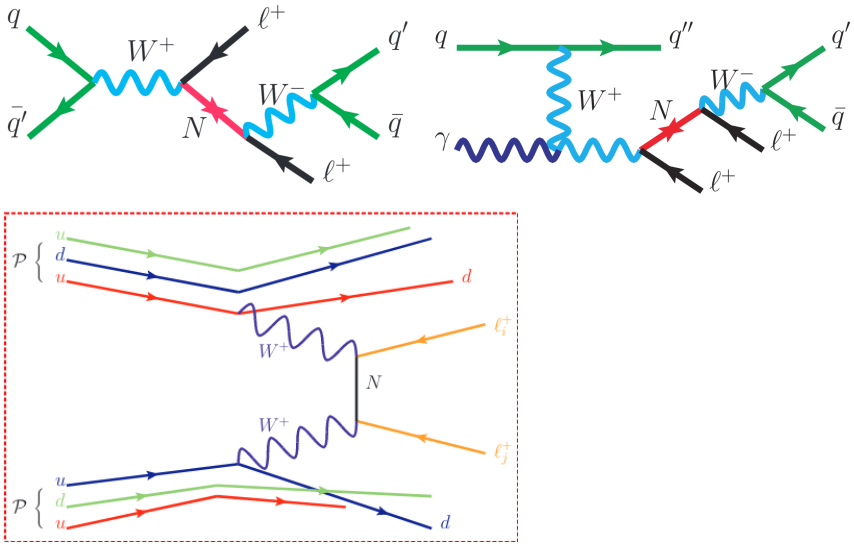

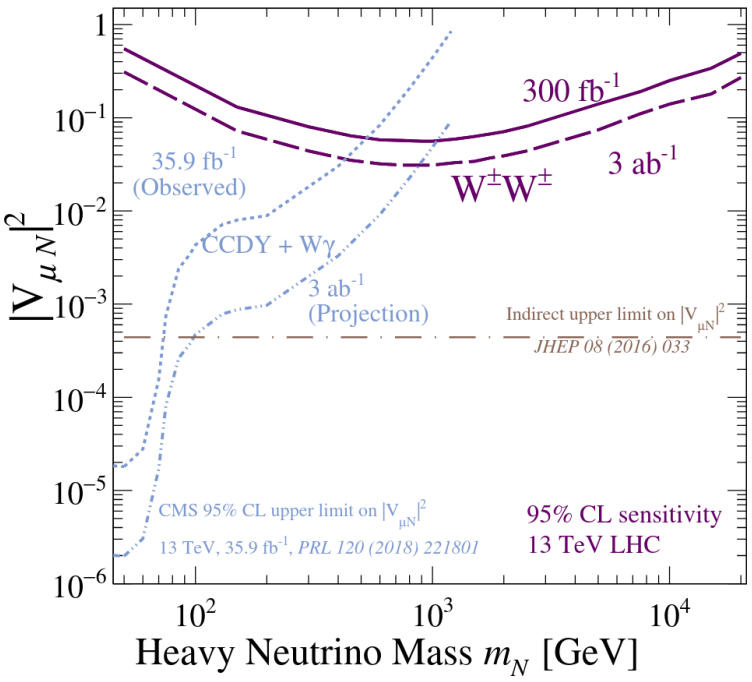

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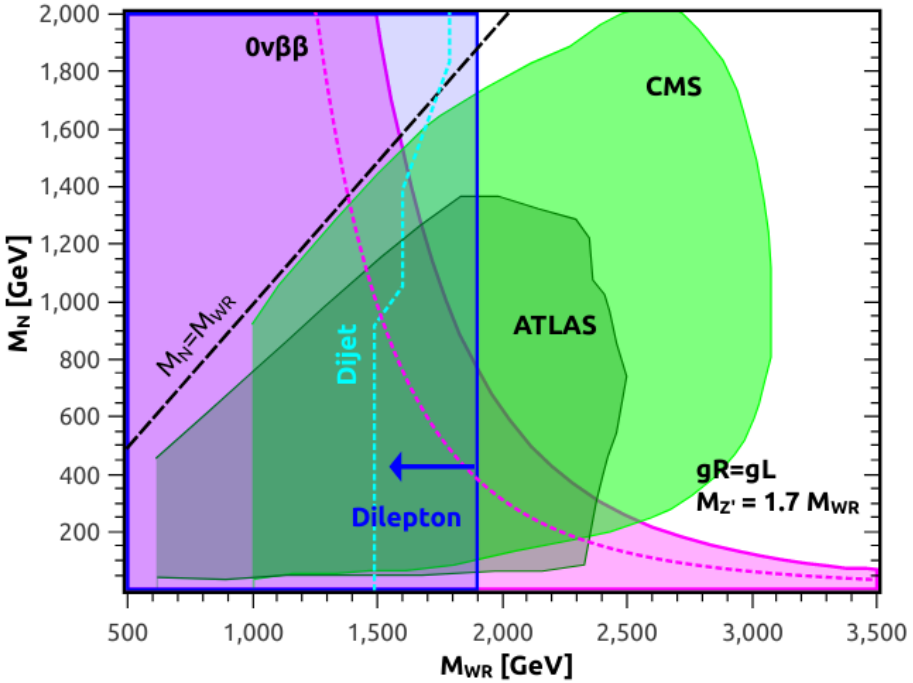
COLLIDER SENSITIVITY COMPARISON

LRSM ($g_R = g_L$, m_{W_R}, m_N)

- W_R and Z_R probed at LHC also via hadronic/leptonic decays
- Indirect constraints from $0\nu\beta\beta$ can also be derived when W_R, Z_R couple to electrons

$\rightarrow$ strong constraints at low m_{W_R}

Phys.Lett.B 762 (2016) 190-195



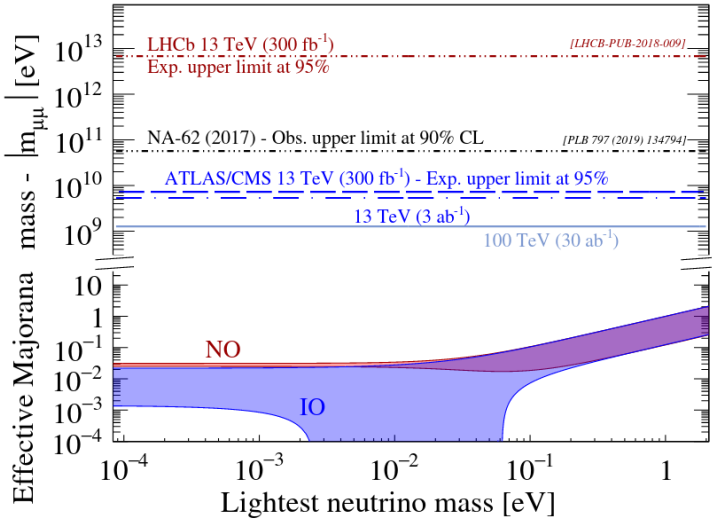
- **ATLAS/CMS LRSM searches bring unique sensitivity at high m_{W_R}**
- (ATLAS/CMS results shown here from LHC Run 1 $\rightarrow$ outdated, for illustration)

NEW EFFECTIVE MODELS (MULTI-TEV)

Weinberg operator (SMEFT, dim 5)

Phys. Rev. D 103, 115014 (2021)

$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda}\left[\Phi\cdot\overline{L}_\ell^c\right]\left[L_{\ell'}\cdot\Phi\right] + \text{H.c.}$$



- Probing the Weinberg operator at the LHC $\rightarrow m_{\ell\ell'} = C_5^{\ell\ell'} v^2/\Lambda$
- make link with ν data and $0\nu\beta\beta$ experiments trivial
- ATLAS/CMS more sensitive than LHCb/NA62, not competitive with ν data

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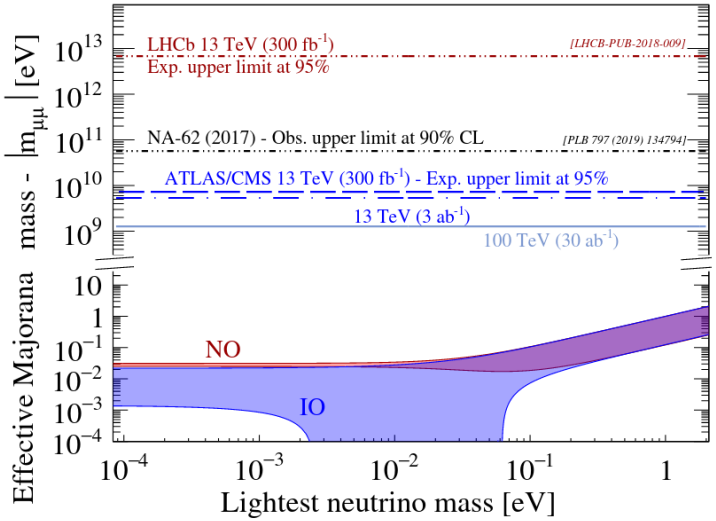
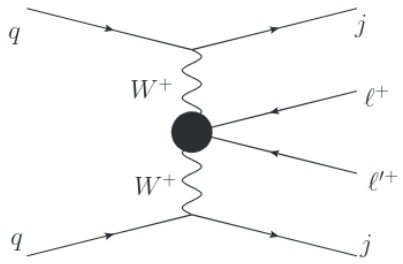


Dimension 7/9 operators

Phys.Rev.D 101 (2020)
e.g. describe Type-I seesaw at large m_N



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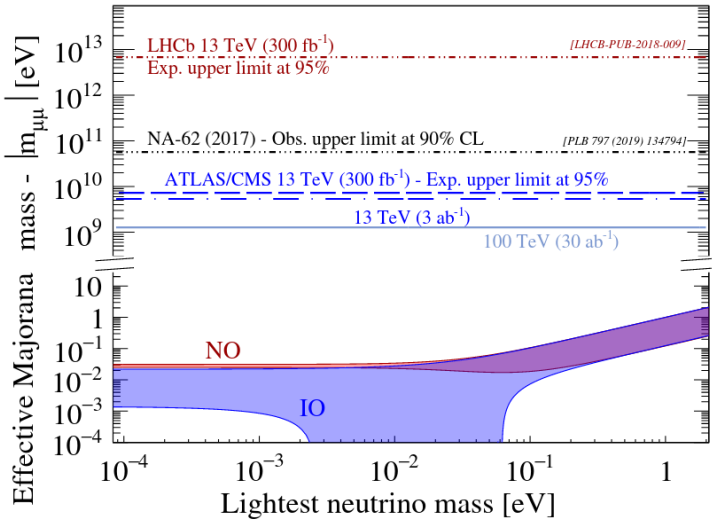

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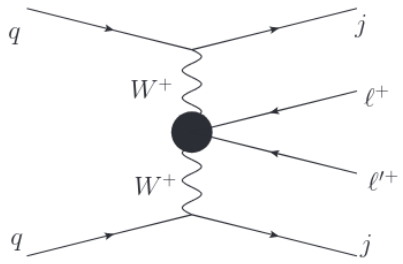

$\rightarrow$ establish systematic way to probe lepton number violation across experiments

- Probing the Weinberg operator at the LHC $\rightarrow m_{\ell\ell'} = C_5^{\ell\ell'} v^2/\Lambda$
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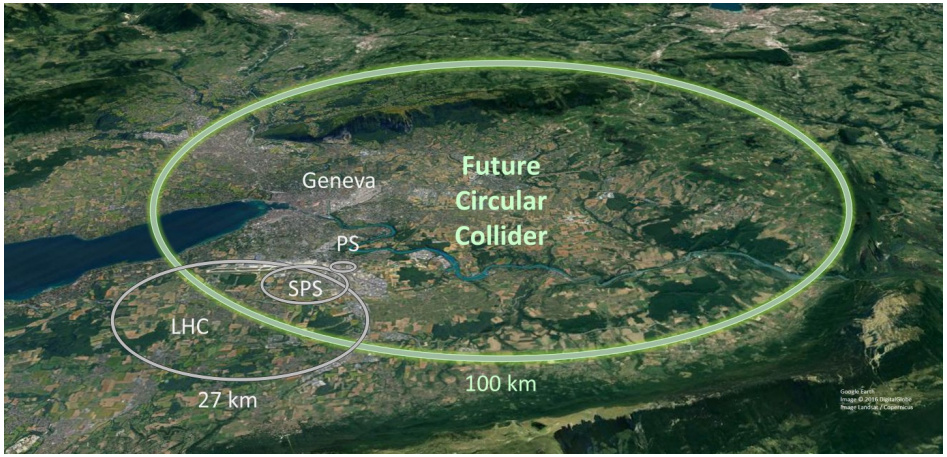
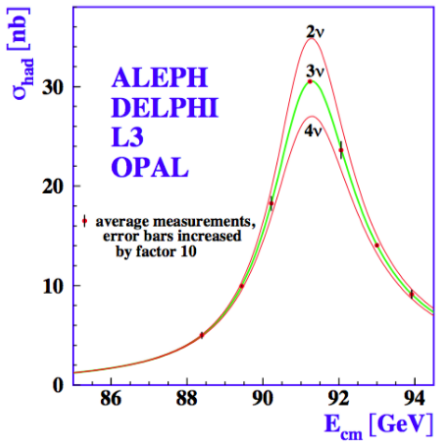
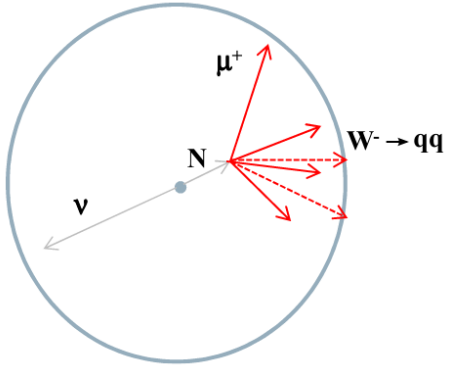
HNL SEARCHES AT FCC-EE

arXiv:1906.02693v1





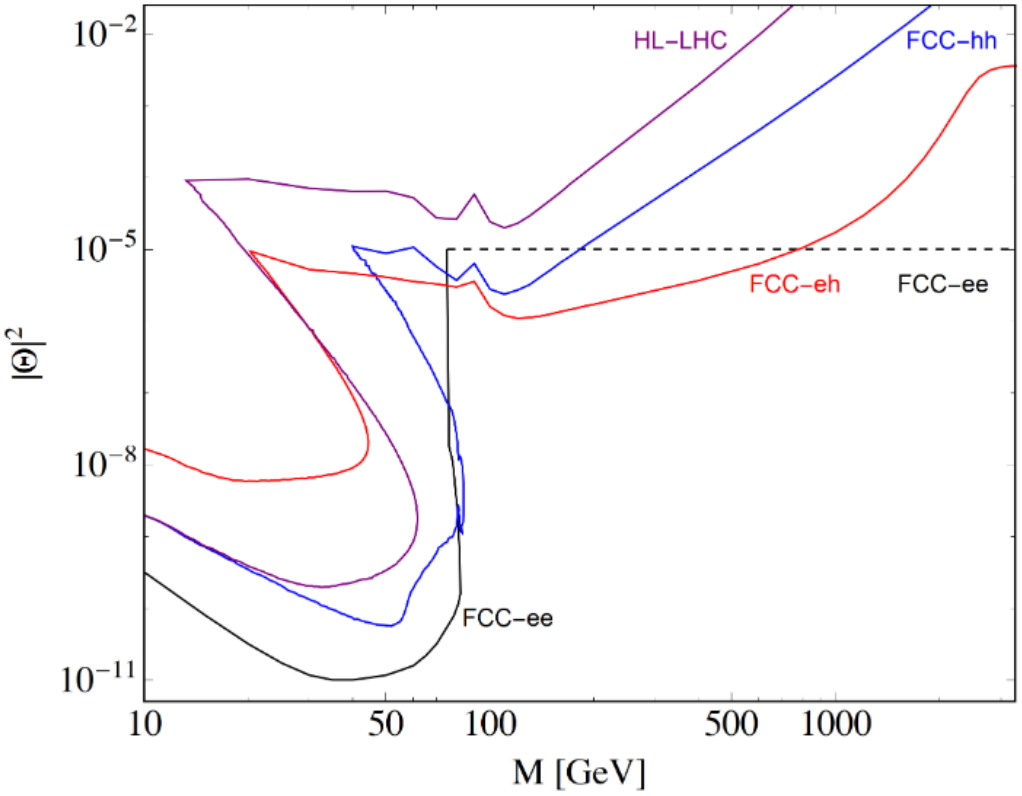


- **Future ee collider at CERN being evaluated (would start operations in $\sim$ 2040)**
  - center-of-mass energy considered : Z peak, WW, ZH, $t\bar{t}$ threshold
- **LEP-type precision measurements with 10^5 more statistics**
  - indirect constraints from Z boson line shape improved by 10-20
  - direct HNL production in Z boson decays : $Z \to \nu + N$ with $N \to W\ell$ or $Z\nu$

Nucl.Part.Phys.Proc. 273-275 (2016) 1883-1890

HNL SEARCHES AT FCC-EE

CERN-ACC-2019-0007



- **Solid lines :** direct searches
- **Dashed line :** indirect constraints from precision EW measurements

NOT FURTHER DISCUSSED BUT RELEVANT

- Searches with τ and multi-flavor final states @ LHC
- Searches for Type-III seesaw @ LHC (heavy charged leptons)
- Belle II and LHCb sensitivity
- ...

MAJORANA NEUTRINOS @ LHC

- **LHC has unique sensitivity to probe Majorana neutrinos**
  - access to high masses and mixing with 2nd/3rd generation
- Lepton final states with tricky instrumental backgrounds
- Recent findings demonstrate sensitivity in multi-TeV range
- New tools establish systematics way to probe lepton number violation at colliders and other experiments
- Future *ee* collider at Z peak would allow to significantly increase sensitivity

Additional Material

Commissariat à l'énergie atomique et aux énergies alternatives
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DPhP
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ATLAS

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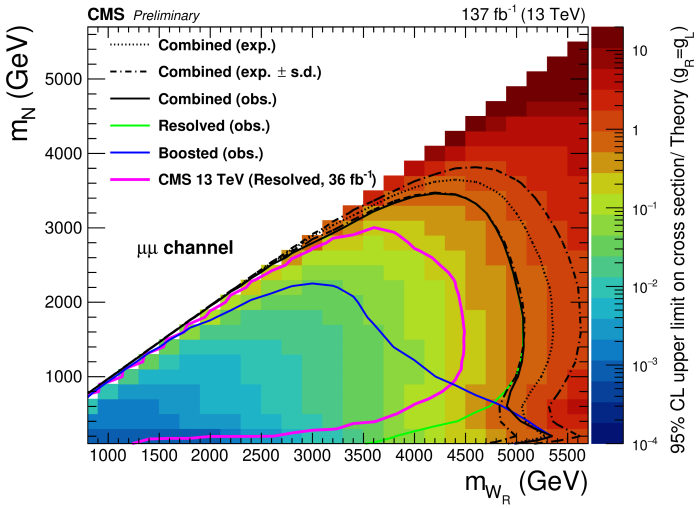
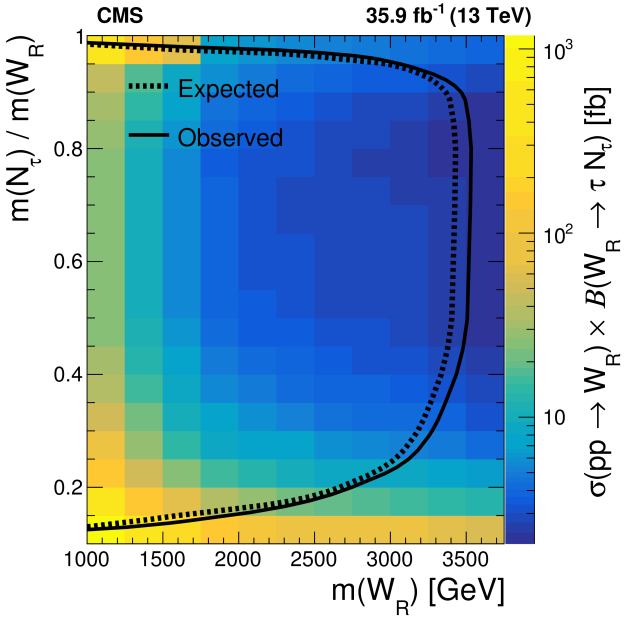
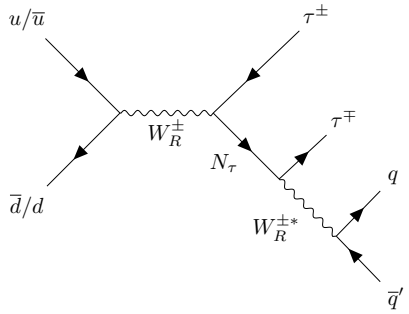
ADDITIONAL SIGNATURES

τ-lepton and multi-flavor final states



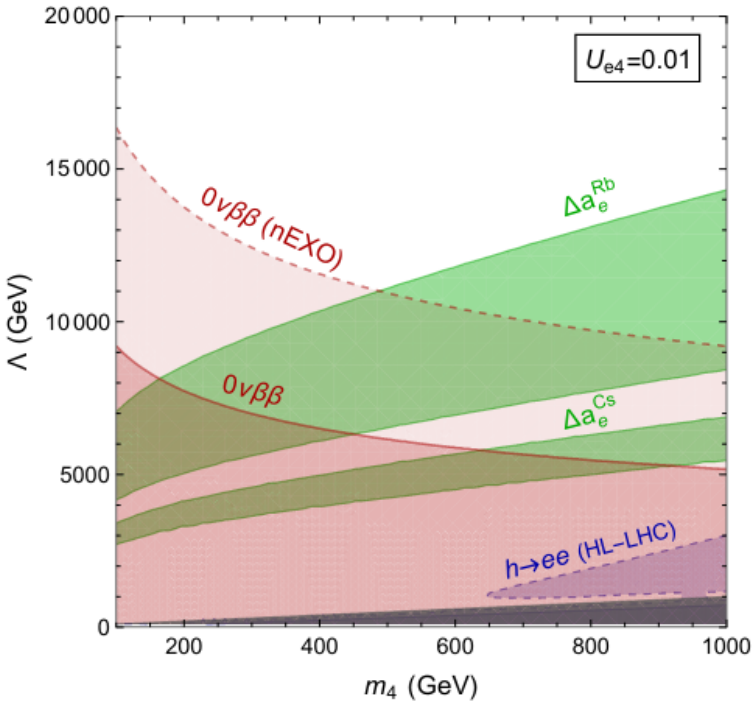


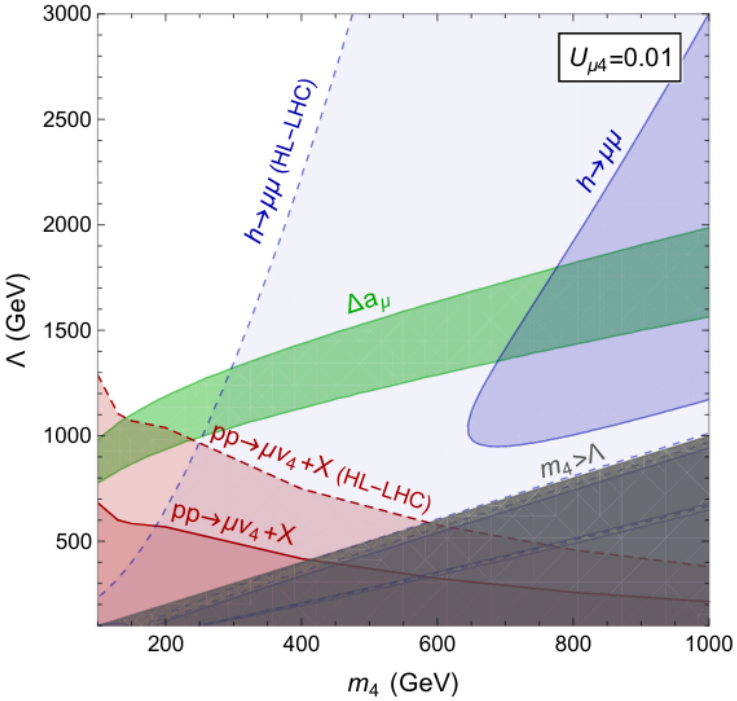
Ex : LRSM, but similar picture for seesaw and effective models



- **Scenarios with HNL/tau mixing much less constrained**
  - not disfavored by theory, not covered by nuclear experiments
  - no dedicated ATLAS analysis, only few CMS analyses, e.g. JHEP 03 (2019) 170
- **Further exploration of multi-flavor final states ($e\mu$, $e\tau$, ...)**
  - possible hint for lepton flavor violation in g-2/flavor anomalies, arXiv:2104.03691
  - ex : V_{eN}, $V_{\tau N} \neq 0$, no published ATLAS/CMS analysis

EFT-BASED STUDIES





- Low energy anomalies can be traced back to certain types of EFT operators
- EFT operators can then be probed in wide range of data (searches, precision measurements), in many types of experiments
- Concrete example for the anomalous magnetic moments of charged leptons detailed in JHEP 08 (2021) 103