

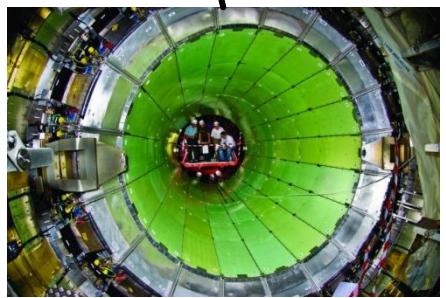
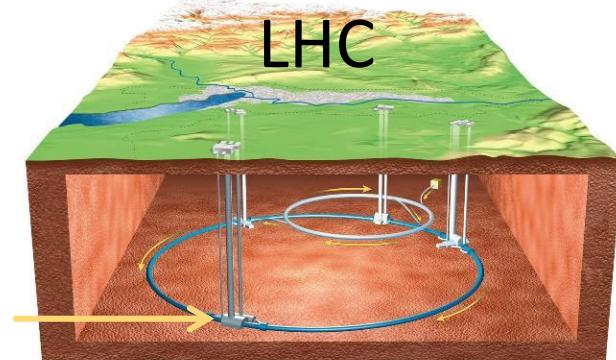
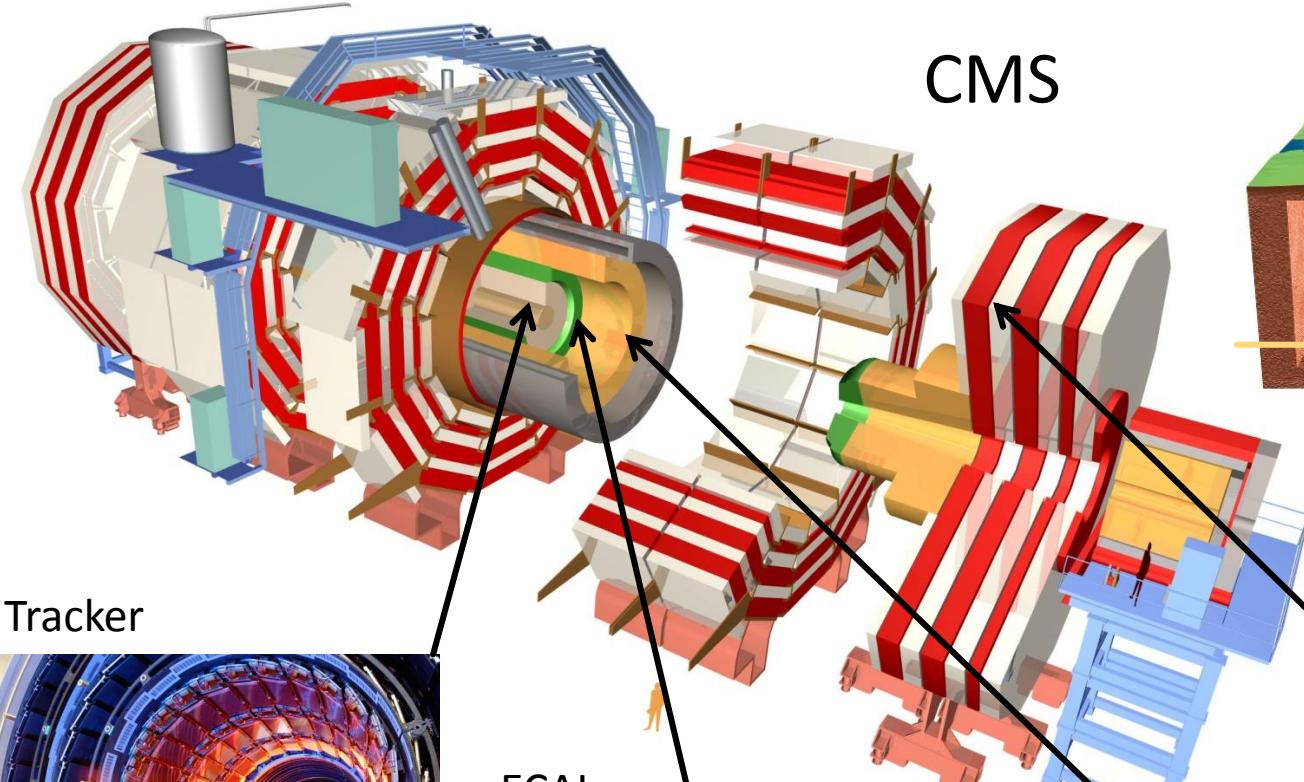
# Search for right-handed neutrinos at CMS

Joe Pastika for the CMS Collaboration



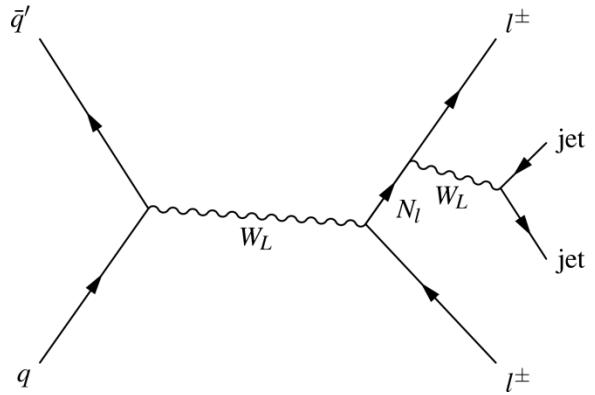
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# Compact Muon Solenoid

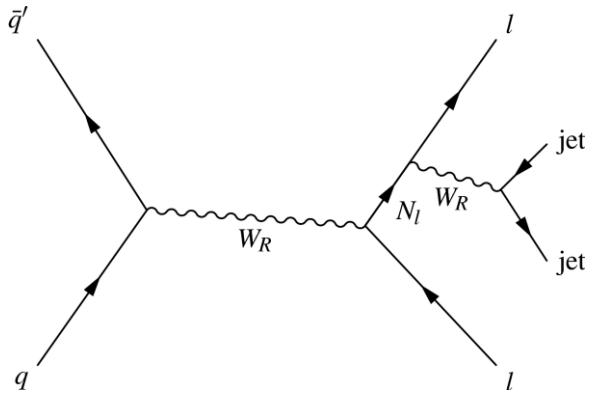


Muon Chambers

# CMS Search Methods



Search for heavy neutrinos  
produced through mixing  
with SM  $W_L$

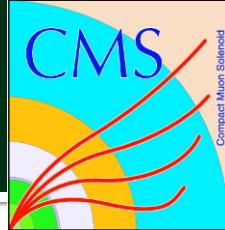


Search for heavy neutrinos  
produced through Beyond  
the SM  $W_R$

[arXiv:1501.05566](https://arxiv.org/abs/1501.05566) [hep-ex]  
Submitted to Phys. Lett. B

DOI: [10.1140/epjc/s10052-014-3149-z](https://doi.org/10.1140/epjc/s10052-014-3149-z)

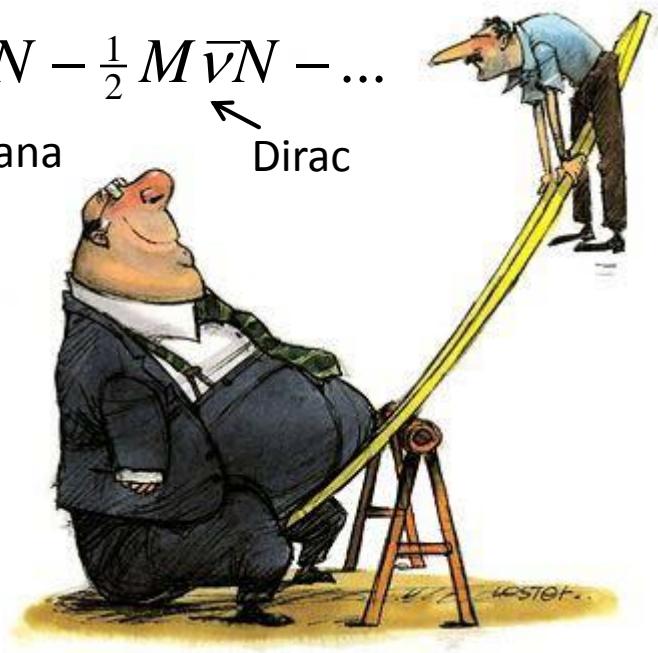
# See-saw Mechanism



$$L = -\frac{1}{2} \begin{pmatrix} \bar{\nu} & \bar{N} \end{pmatrix} \begin{pmatrix} B' & M \\ M & B \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix} + h.c. = -\frac{1}{2} \underset{\substack{\uparrow \\ \text{Majorana}}}{B} \bar{N} N - \frac{1}{2} \underset{\substack{\leftarrow \\ \text{Dirac}}}{M} \bar{\nu} N - \dots$$

Assuming  $B \gg M \gg B'$  we have mass eigenvalues of

$$\lambda_+ \cong B \quad \text{and} \quad \lambda_- \cong -\frac{M^2}{B}$$



$$\nu_s = \begin{pmatrix} \nu_{s1} \\ \nu_{s2} \\ \vdots \end{pmatrix}$$

Type-I

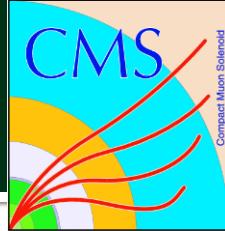
$$\Delta = \begin{pmatrix} \Delta^{++} \\ \Delta^+ \\ \Delta^0 \end{pmatrix}$$

Type-II

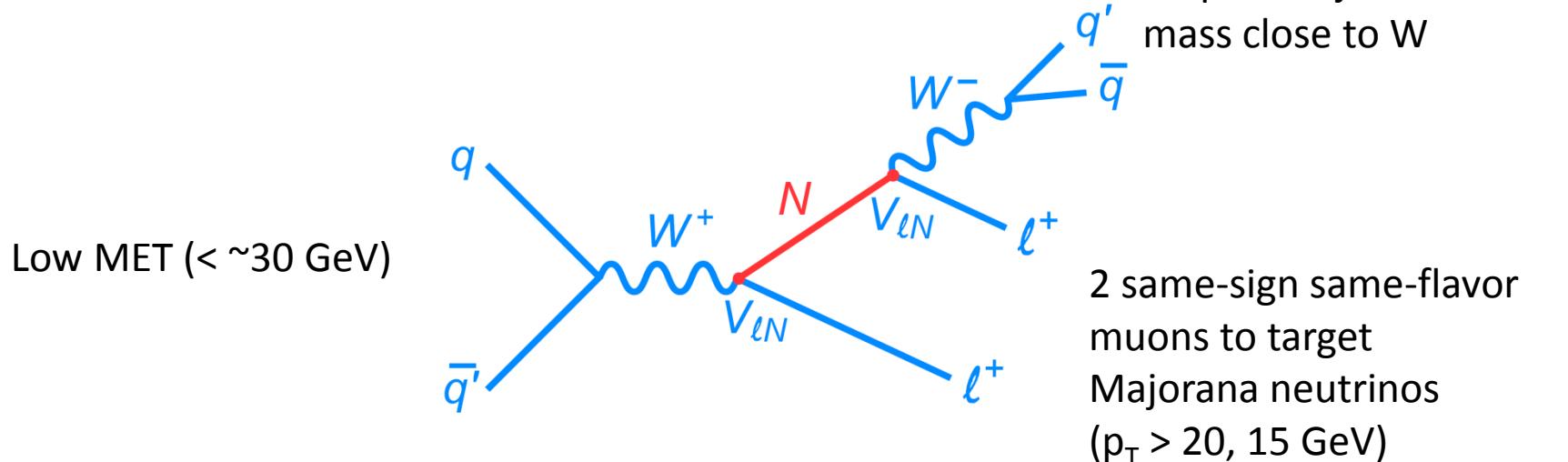
$$\Sigma = \begin{pmatrix} \Sigma^+ \\ \Sigma^0 \\ \Sigma^- \end{pmatrix}$$

Type-III

# Majorana Selection Overview



Select 2 same-sign muons and 2 jets,  
But reject events with additional leptons



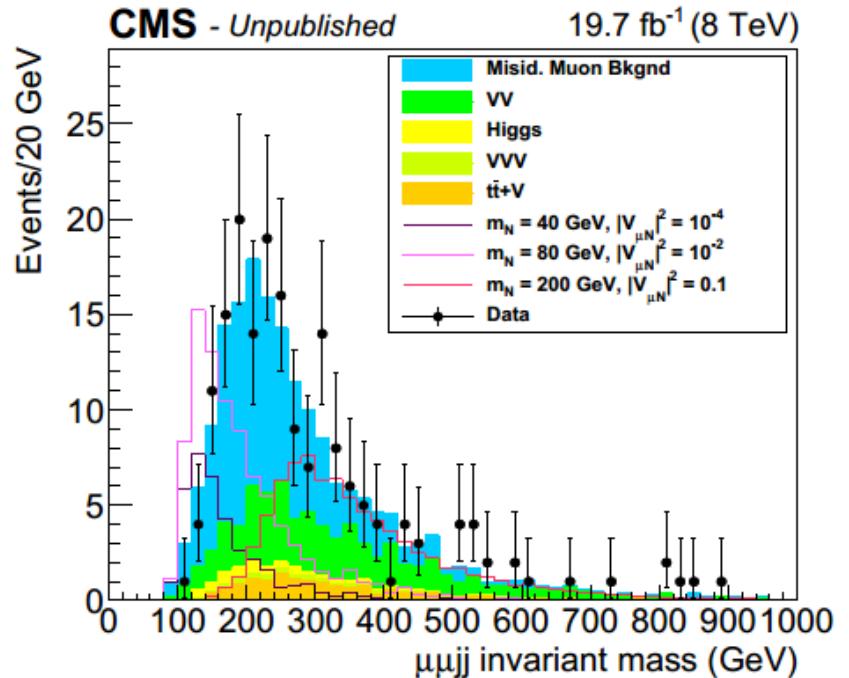
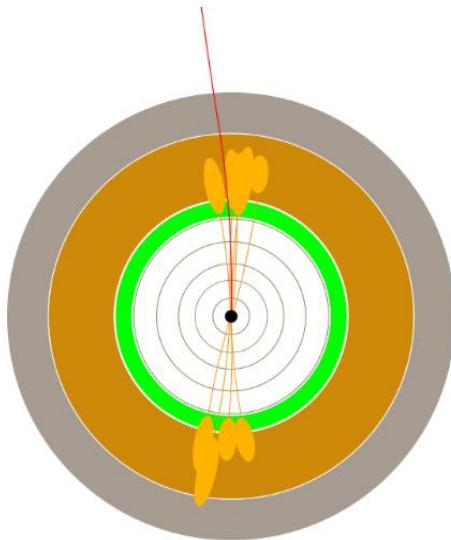
$M(l\bar{l}jj)$ ,  $p_{T\mu 1}$ , and  $p_{T\mu 2}$  lower limits are optimized

# Majorana Background Estimation



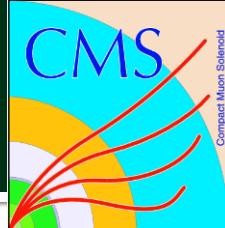
Largest background source is mis-reconstructed muons

Muon “fake” rate  
estimated in di-jet events

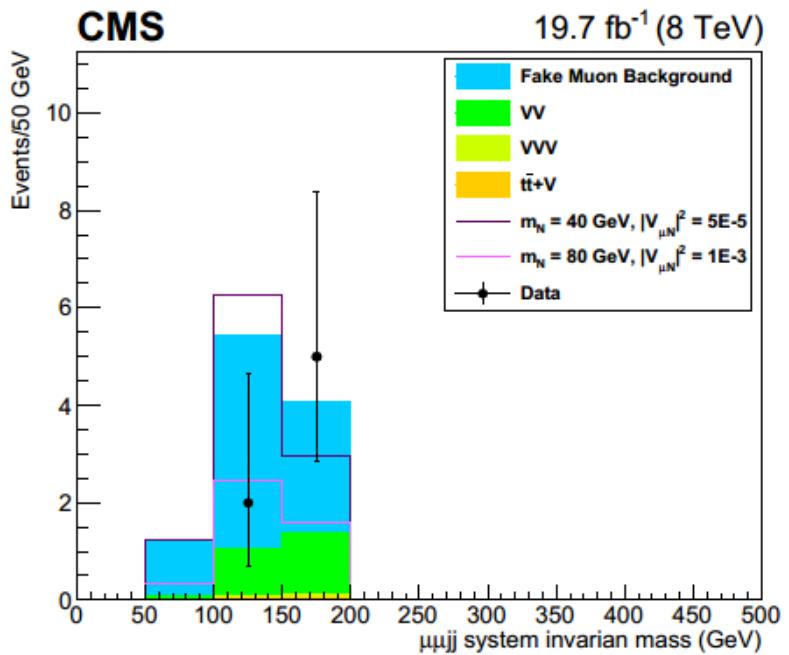


Other backgrounds are estimated from MC.

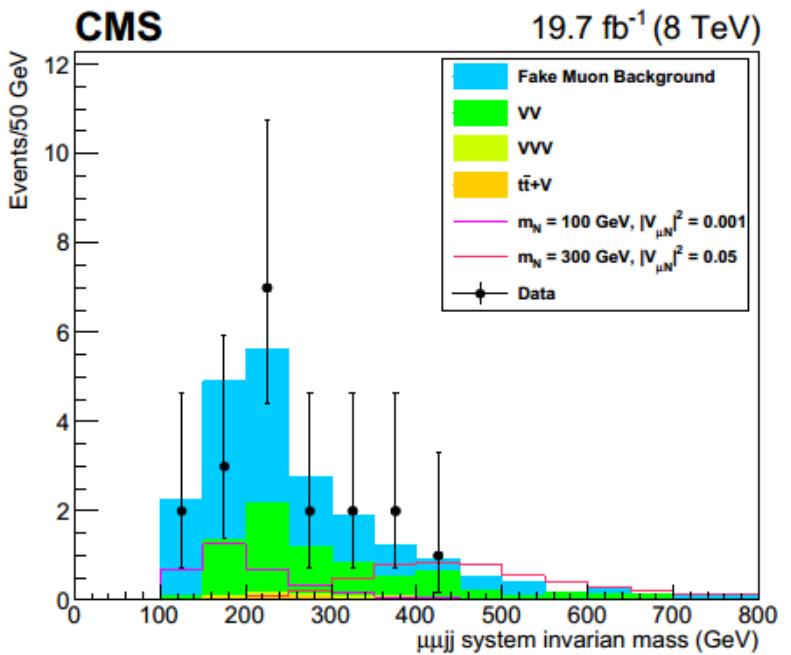
# Majorana Results



Low Mass Selection  
 $M(N) < 90 \text{ GeV}$



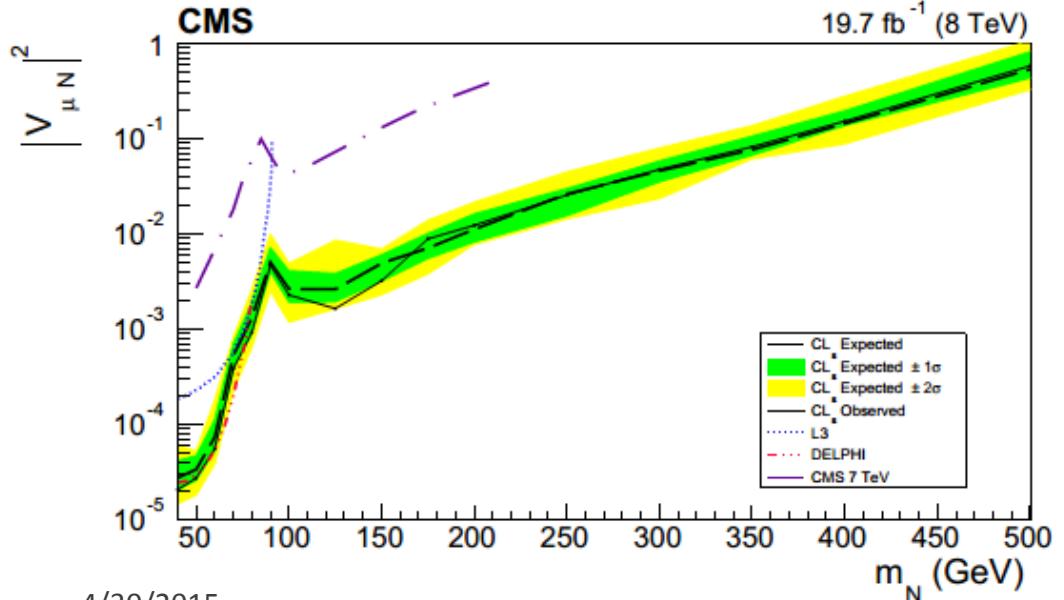
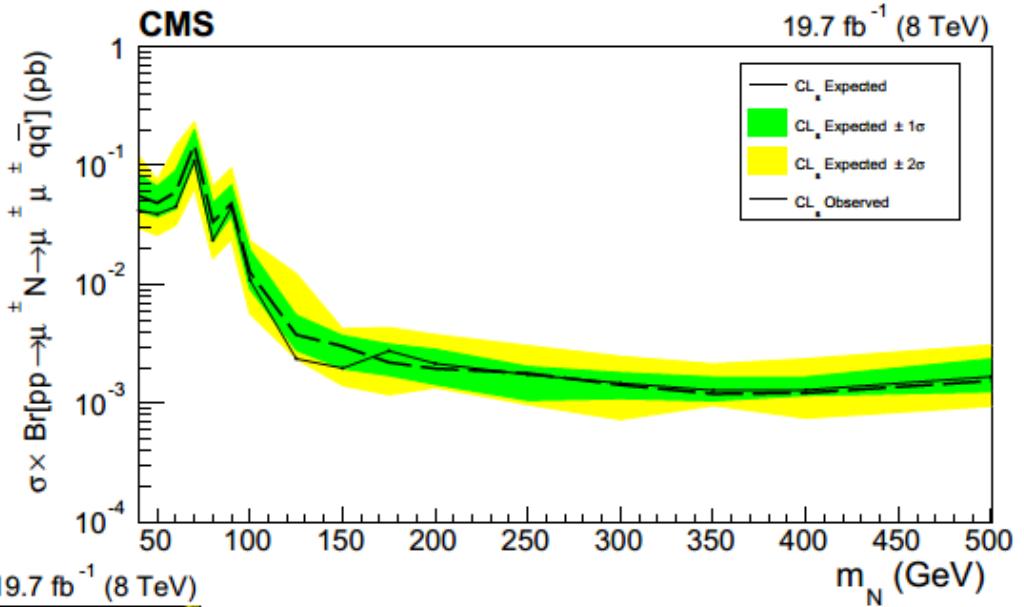
High Mass Selection  
 $M(N) > 90 \text{ GeV}$



# Majorana Limits

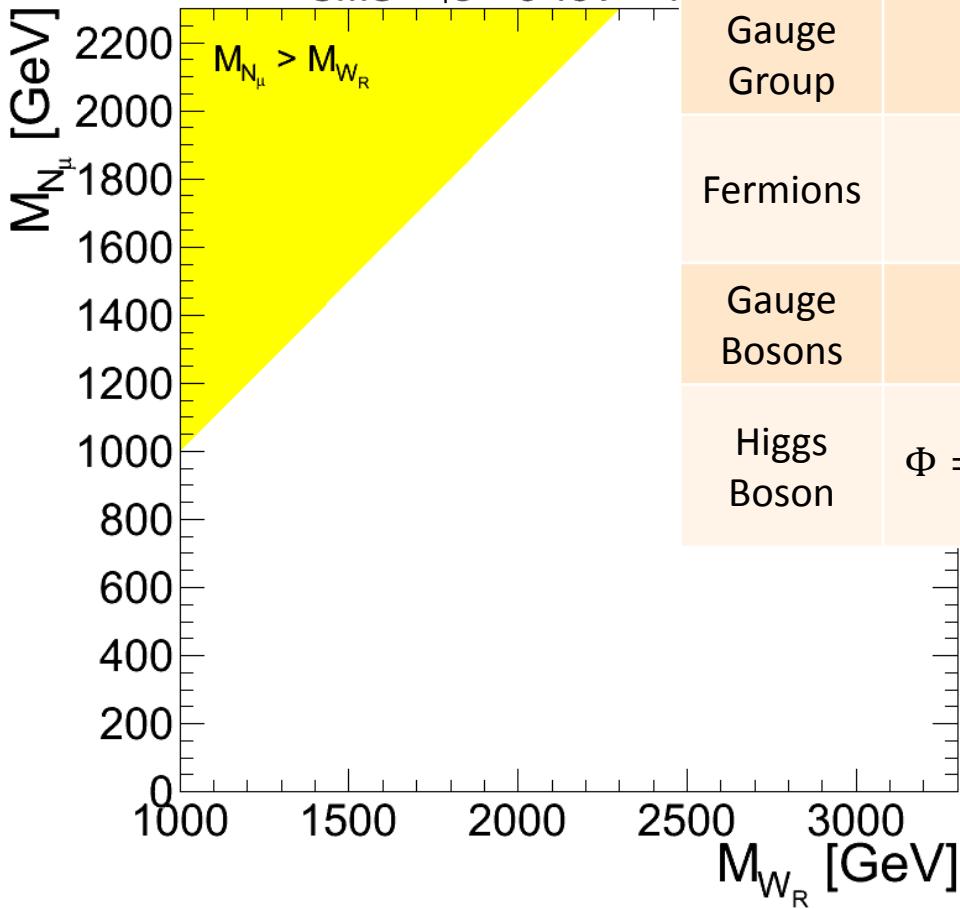
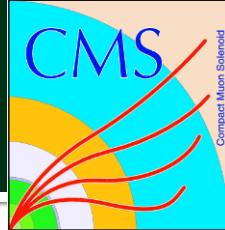


Cross-section Limits  
(assuming unitary mixing)

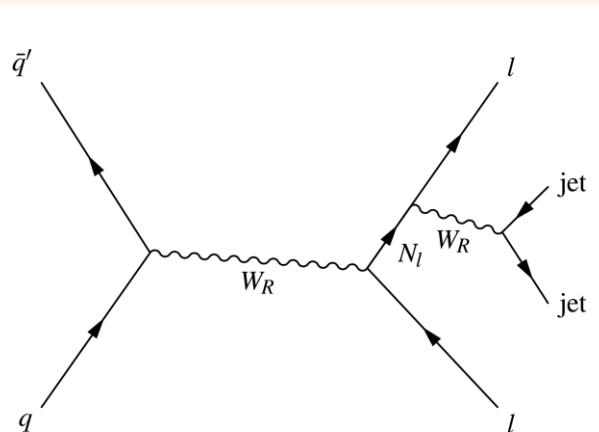


Majorana neutrino mixing  
parameter

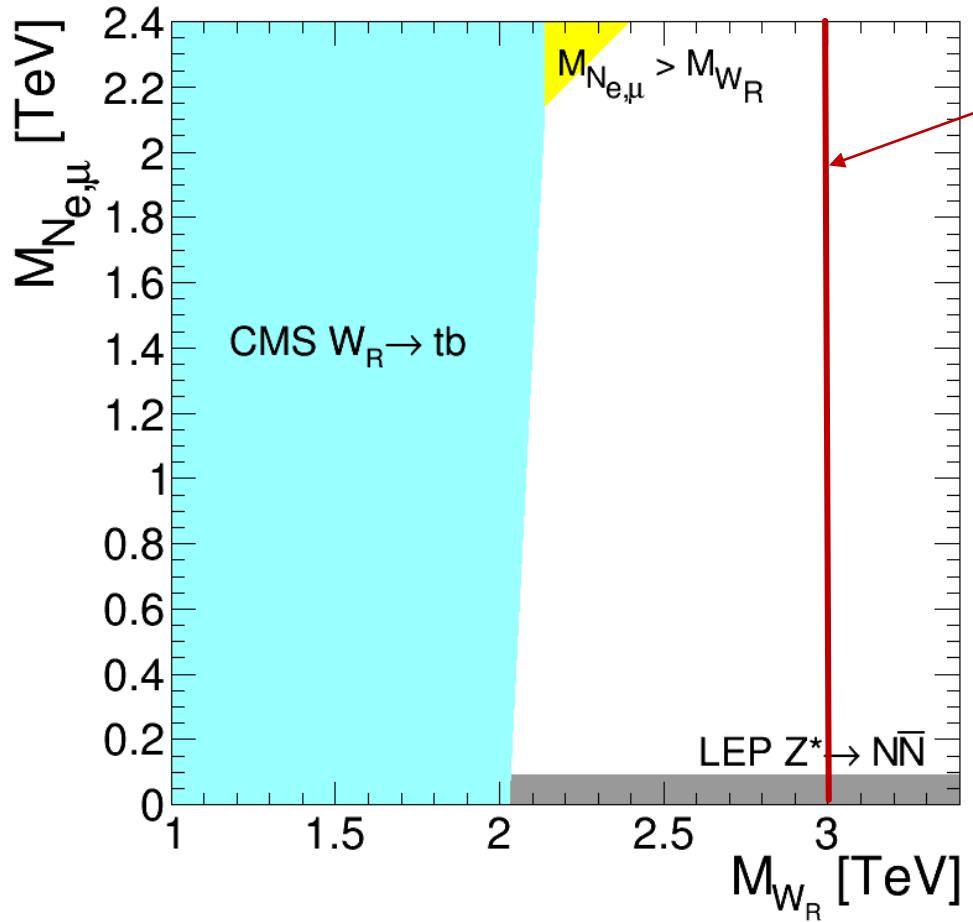
# $W_R$ and Left-Right Symmetry



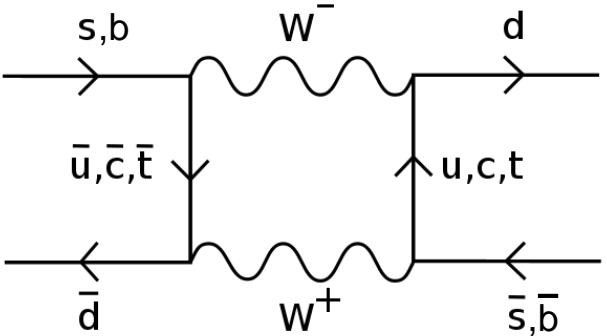
	Left-Right Symmetric Standard Model
Gauge Group	$SU(3) \times SU(2)_L \times \textcolor{red}{SU(2)_R} \times U(1)$
Fermions	$Q_L = (u^i, d^i)_L, L_L = (l^i, \nu^i)_L$ $Q_R = (u^i, d^i)_R, L_R = (l^i, \textcolor{red}{N^i})_R$
Gauge Bosons	$g^{ij}, W_L^\pm, \textcolor{red}{W_R^\pm}, Z_0, \textcolor{red}{Z'}, \gamma$
Higgs Boson	$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}, \Delta_{L,R} = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}_{L,R}$



# Pre-existing Limits



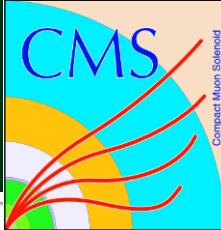
Indirect limits from K & B mixing  
 $M(W_R) > 3.0$  TeV



Direct Limits from  

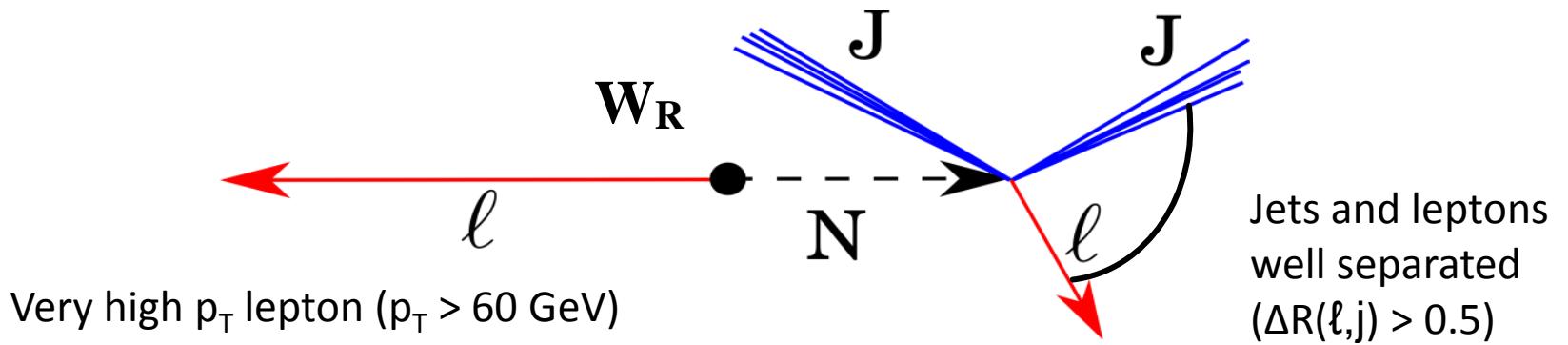
- $W' \rightarrow tb$  search
- $Z^* \rightarrow N\bar{N}$

# $W_R$ Selection Overview



Highest  $p_T$  same flavor leptons (e or  $\mu$ ), jets used to assemble the  $W_R$  candidate

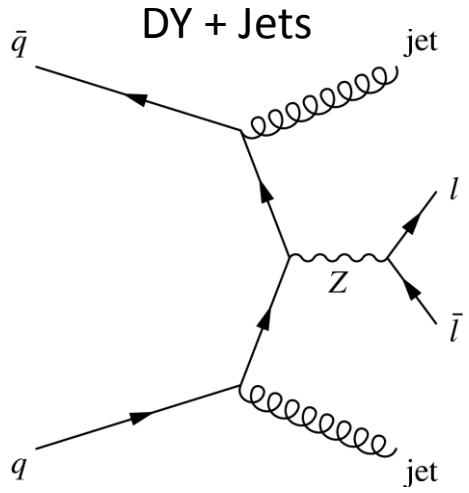
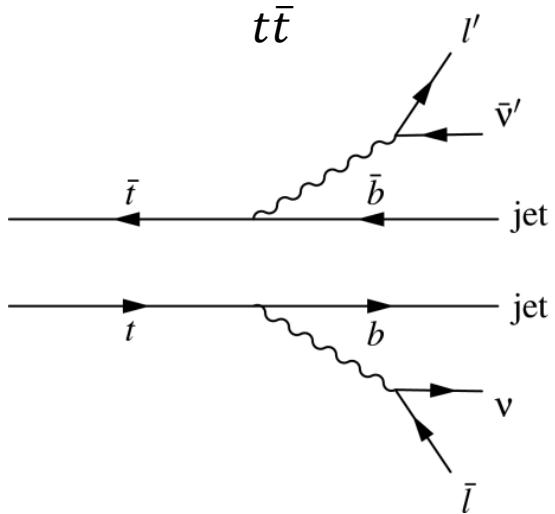
Remaining lepton and jets  $p_T > 40$  GeV



$$\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

Variable of merit in the search:  $\ell\ell jj$  mass

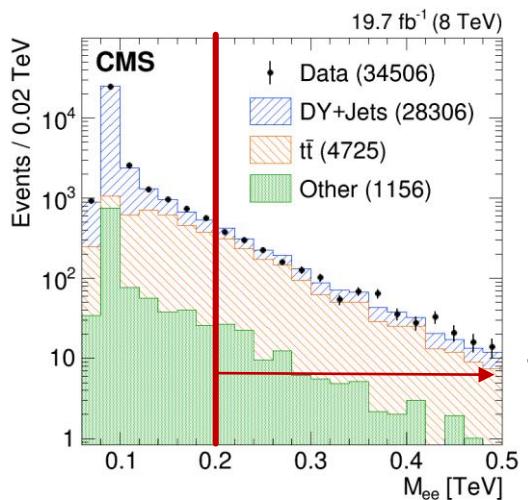
# $W_R$ Background Estimation



$t\bar{t}$  background estimated from  $e\mu jj$  final state

Normalized to  $eejj$  and  $\mu\mu jj$  final states  
independently

Other backgrounds estimated directly from MC

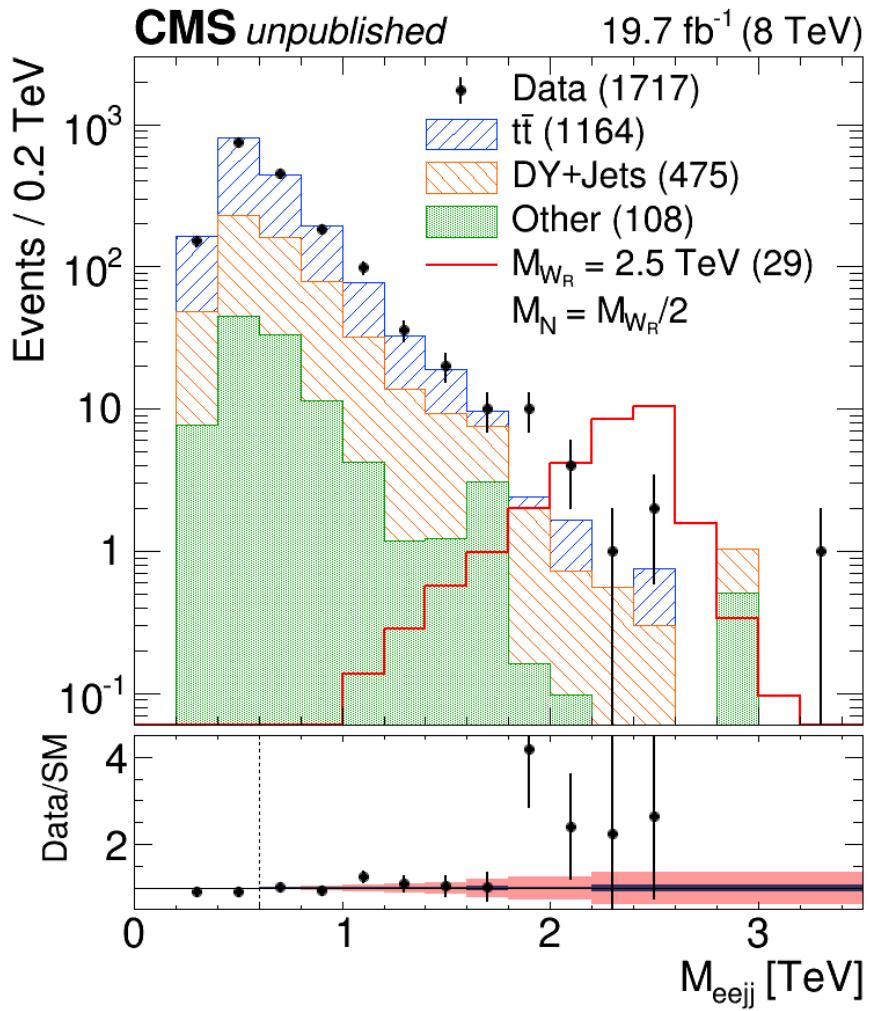


Signal Region  
 $M_{ll} > 200$  GeV

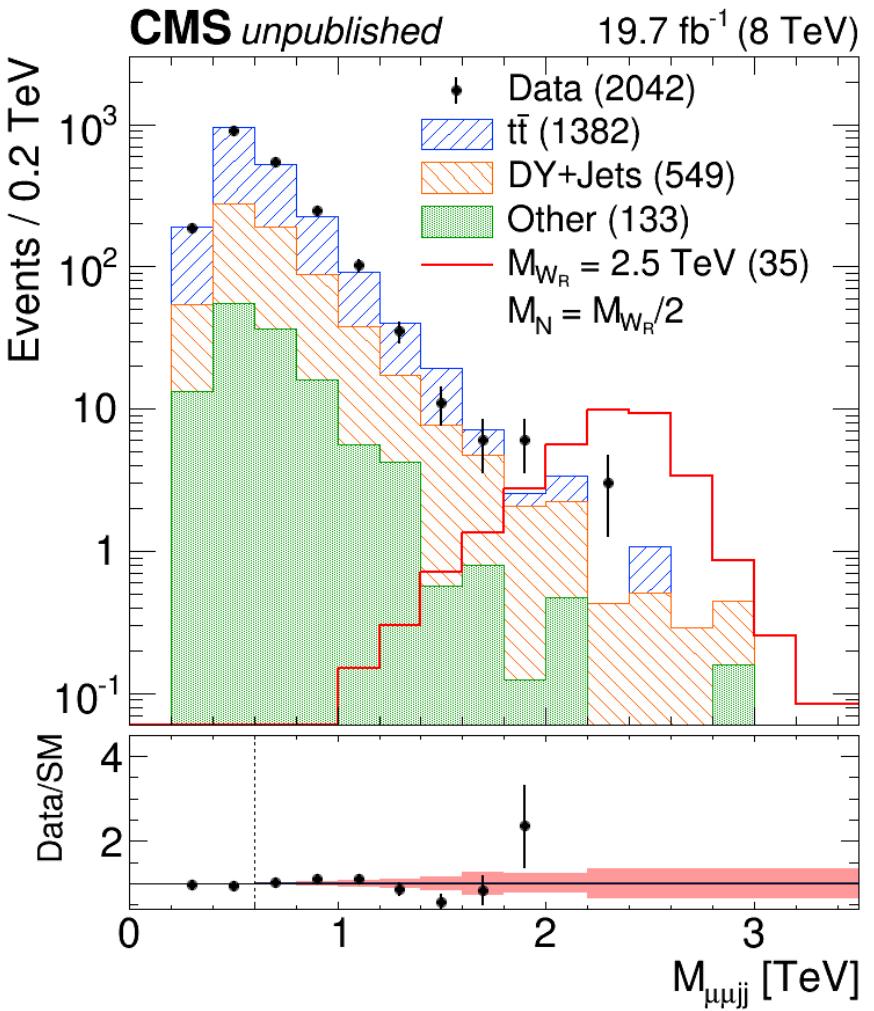
# $W_R$ Results



## Electron



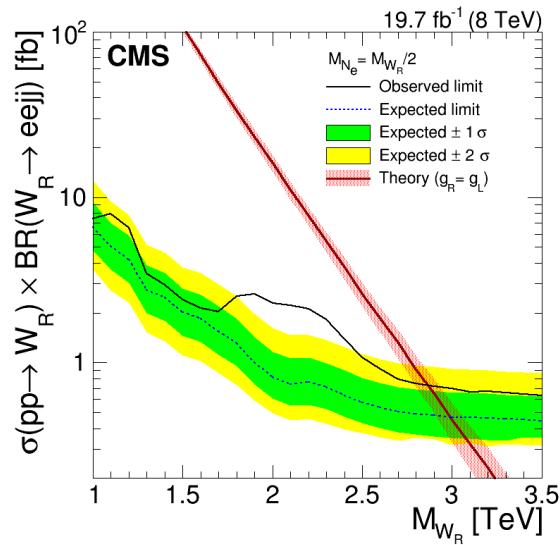
## Muon



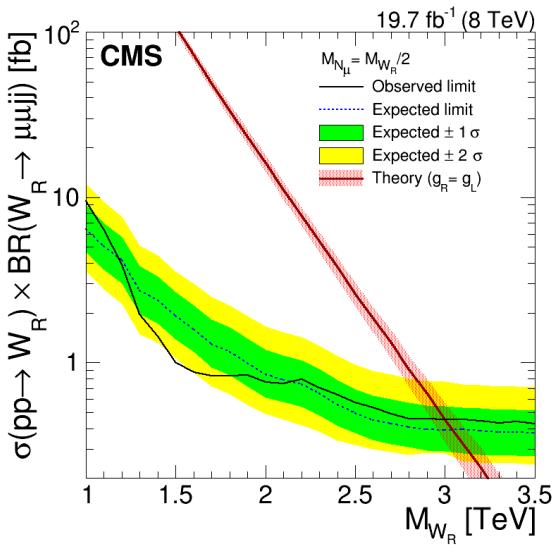
# $W_R$ Limits



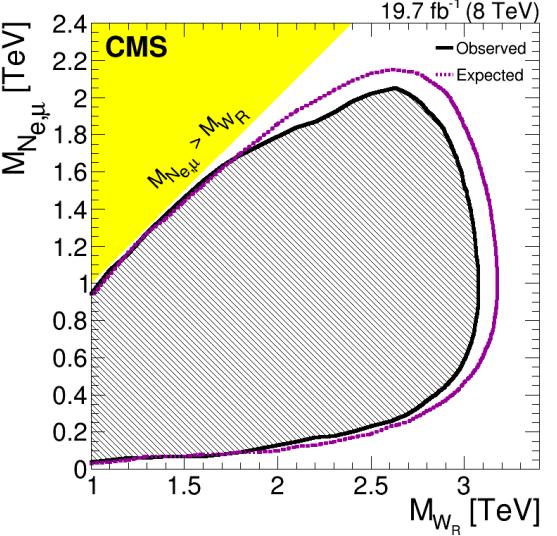
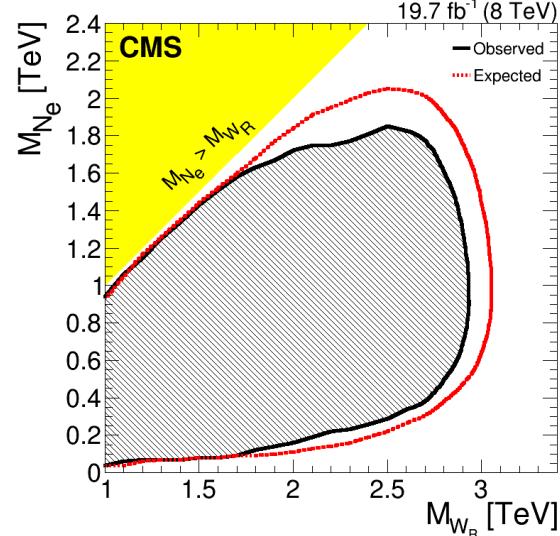
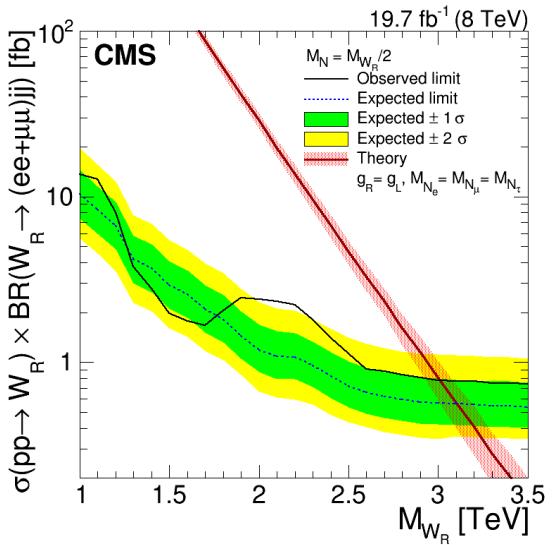
## Electron



## Muon



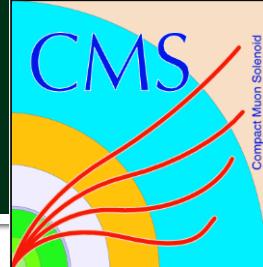
## Combined



# Conclusions



- CMS conducted two searches for a heavy right-handed neutrinos
  - Search for majorana neutrinos
    - No significant deviation from expectations seen
    - Excludes new territory for low mass N
  - Search for  $W_R$ 
    - Muon channel sees no disagreement with SM predictions
    - Electron channel shows  $2.8\sigma$  deviation from SM at 2.1 TeV
    - Maximum exclusion to  $\sim 3$ TeV in  $M(W_R)$
- With increased energy and luminosity coming next month this may be an exciting channel

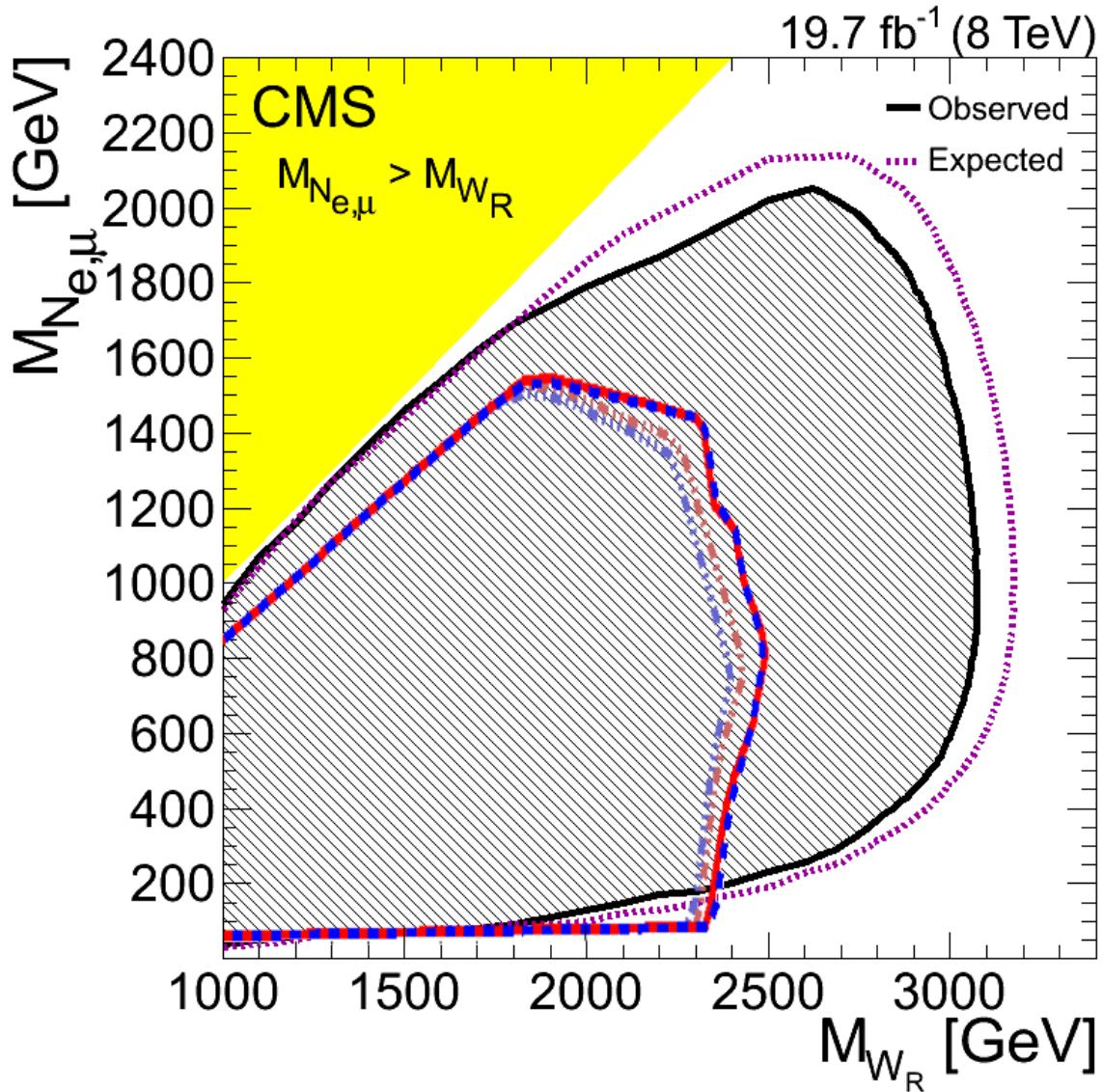


# Backup Slides



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# $W_R$ Comparison to ATLAS

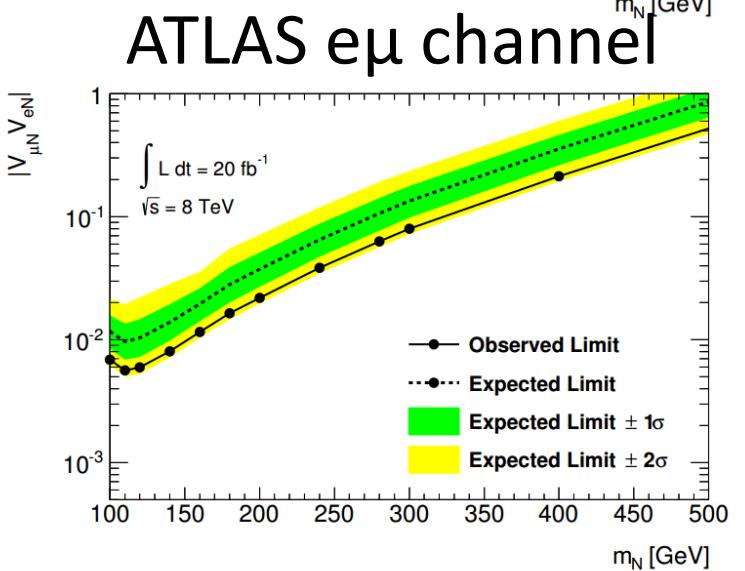
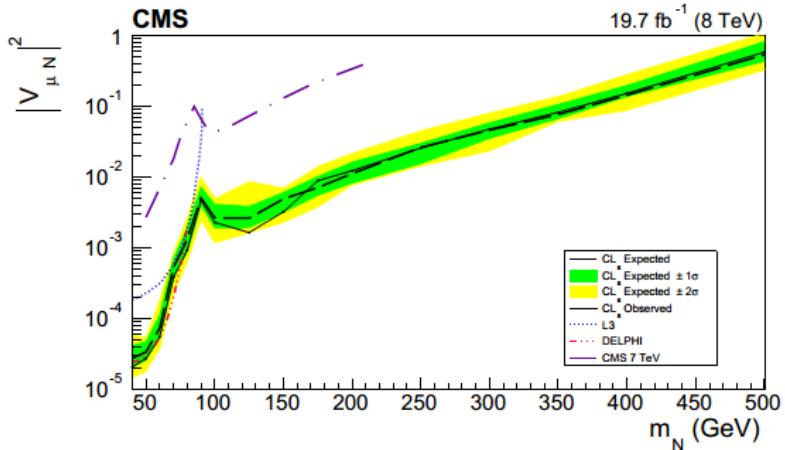
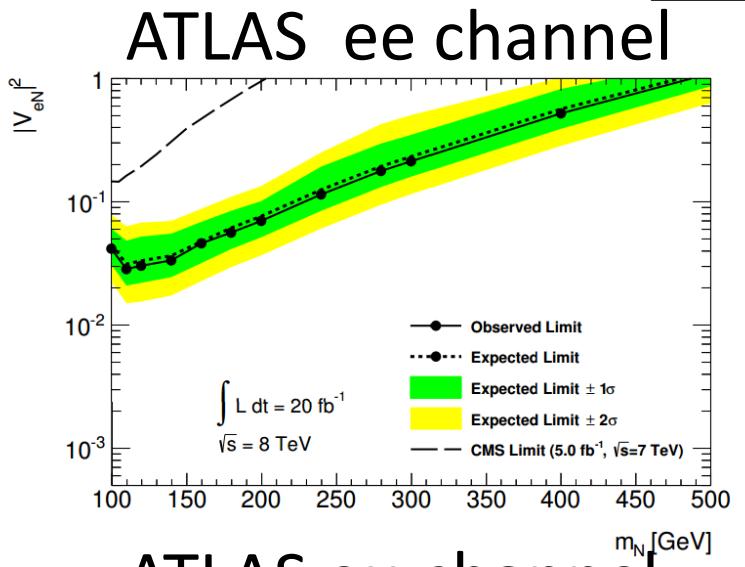
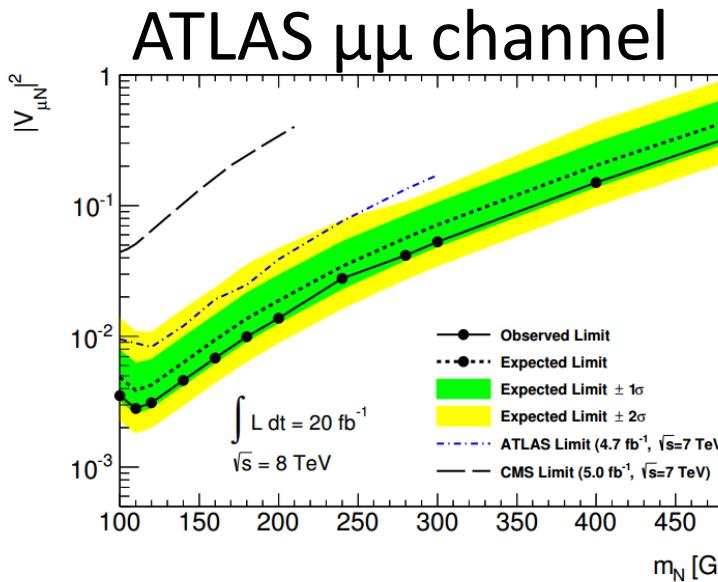


- 2.1  $\text{fb}^{-1}$  @ 7 TeV
- 2 leptons ( $> 25$  GeV)
- 1 or 2 jets ( $> 20$  GeV)
- $M(l\bar{l}) > 110$  GeV
- $\Delta R > 0.5$  between lepton and jet
- $M(l\bar{l}j(j)) > 400$  GeV
- Split into SS and OS
- OS :  $S_t > 400$  GeV
- [Doi:10.1140/epjc/s10052-012-2056-4](https://doi.org/10.1140/epjc/s10052-012-2056-4)

- ..... With mixing, ee+μμ+eμ, Expected
- - - With mixing, ee+μμ+eμ, Observed
- - - No mixing, ee+μμ, Expected
- - - No mixing, ee+μμ, Observed

**ATLAS**  
**SS+OS**

# Majorana Comparison to ATLAS



CMS working on ee and e $\mu$  channels