

Search for heavy neutrinos in final states with two leptons and jets with the ATLAS detector

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On behalf of the ATLAS Collaboration



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Theoretical Models

Minimal Type-I Seesaw Mechanism (mTISM)

- Simplest extension of SM to include right-handed heavy neutrinos
- If heavy neutrinos are Majorana particles, they can account for light neutrino masses via Type-I Seesaw mechanism:

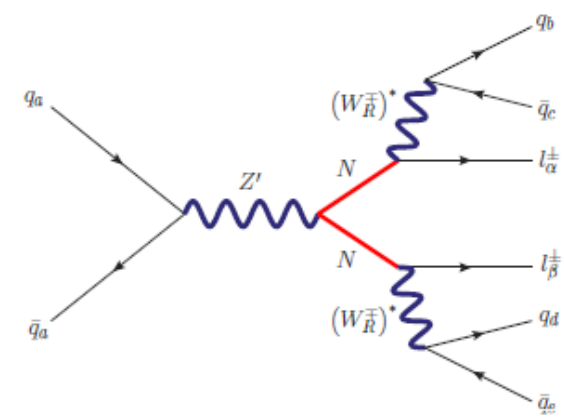
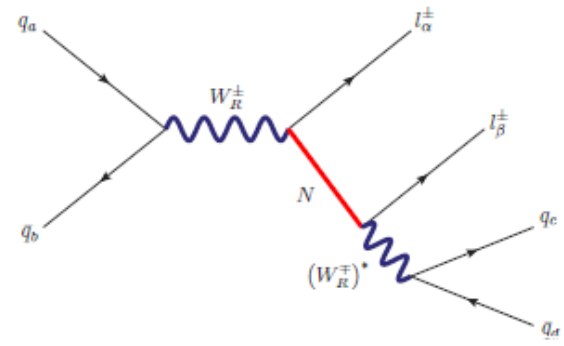
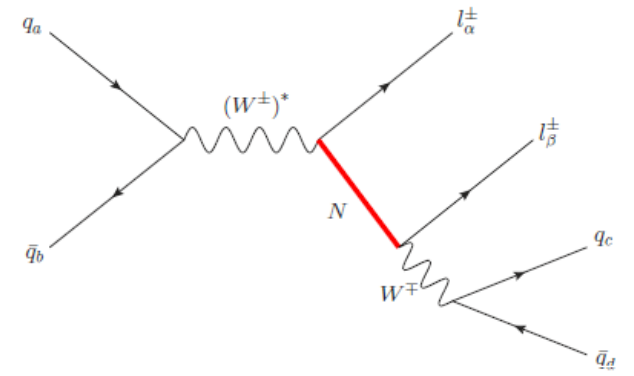
$$m_\nu \sim \frac{(m_\nu^D)^2}{m_N} \leq 1eV$$

- m_ν : light neutrino mass
- m_ν^D : Dirac mass for charged fermion of the same generation
- m_N : heavy neutrino mass

- Free parameters:
 - m_N, V_{IN} (mixing between heavy Majorana and SM neutrinos)

Left-Right Symmetric Model (LRSM)

- In SM weak interaction parity conservation is violated, introduce $SU(2)_R$ to restore which contains W_R, Z', N_R , thus imply gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.
- Include seesaw mechanism to give N_L tiny mass when N_R has a large Majorana mass.
- Free parameters: $m_{WR}, m_{Z'}, m_N$
- **Mass of N_R is assumed to be below that of W_R in this analysis**



Analysis Strategy

- **Dataset:**

- 7 TeV: 2.1 fb^{-1} ; 8 TeV: 20.3 fb^{-1}

- **Characteristic signature:**

- two same/opposite sign e/ μ .
- Multi-jets depending on models
- no significant missing ET



- **Background:**

- SS channel(smaller SM background than OS channel):
 - Prompt SS leptons: Diboson(WZ, ZZ)...
 - Prompt OS leptons(charge-flip): Drell-Yan, ttbar...
 - Fake and non-prompt SS leptons: W+jets, ttbar, QCD multi-jets...
- OS channel: Drell-Yan and ttbar dominate

- **Discriminant variables:**

- mTISM: invariant mass of two highest-pT jets (m_{jj})
- LRSM: invariant mass of decay products of heavy gauge bosons ($m_{ll(jj)}, m_{lljj(jj)}$)

Final state lepton pair we can explore for various cases:

	Majorana	Dirac
'with-mixing'	OS+SS (ee, $\mu\mu$, e μ)	OS (ee, $\mu\mu$, e μ)
'no-mixing'	OS+SS (ee, $\mu\mu$)	OS (ee, $\mu\mu$)

8 TeV: focuses on SS & 'no-mixing' 7 TeV: all above studied

Note: 'mixing' refers to mixing between different flavors of heavy neutrino

8 TeV: set limits on both mTISM and LRSM models

7 TeV: set limits on LRSM

7 TeV:

Selection	Jet	Electron	Muon
p_T	$> 20\text{GeV}$	$> 25\text{GeV}$	$> 25\text{GeV}$
$ \eta $	< 2.8	$< 2.47 \&\& (1.37 < \eta < 1.52)$	< 2.4

- LRSM:
 - OS/SS lepton pair
 - at least 1 jet
 - $m_{ll} > 110\text{ GeV}$
 - $m_{ll(j)} > 400\text{ GeV}$
 - OS: scalar sum of ET of two lep and two leading jet larger than 400 GeV

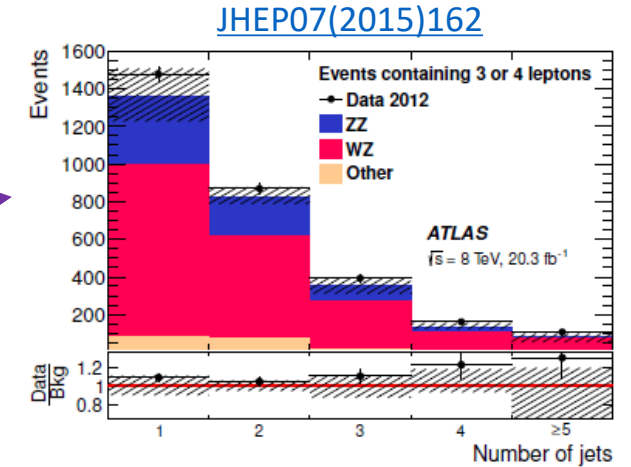
8 TeV: Selection criteria optimized separately for each model while a **common object selection** is used:

Selection	Jet	Electron	Muon
p_T	$> 20\text{GeV}$	$p_T(l1) > 25\text{GeV}, p_T(l2) > 20\text{GeV}$	
$ \eta $	< 2.8	$< 2.47 \&\& (1.37 < \eta < 1.52)$	< 2.5

- mTISM:
 - SS ee/ $\mu\mu$ + at least 2 jets
 - $60 < m_{jj} < 100\text{ GeV}$
 - MET $< 40\text{ GeV}$
 - $m_{ll} > 40\text{ GeV}$
 - ee channel: $|m_{ll} - m_z| > 20\text{ GeV}$

- LRSM:
 - W_R search:
 - SS ee/ $\mu\mu$ + at least 1 jet
 - $m_{ll} > 110\text{ GeV}$
 - $m_{ll(j)} > 400\text{ GeV}$
 - Z' search:
 - SS ee/ $\mu\mu$ + at least 2 jets
 - $m_{ll} > 110\text{ GeV}$
 - $m_{ll(jj)} > 200\text{ GeV}$

- SS channel:
 - Prompt SS leptons background:
 - Minor background directly taken from MC
 - 8TeV: WZ and ZZ background estimated using MC samples, with uncertainty on normalization derived in dedicated control region
 - Charge-flip background:
 - Muons: Found to be negligible
 - Electrons:
 - Performing fit using events under Z peak in data, get correction factor by comparing charge-flip rate measured in data and MC
 - Charge-flip rate increases ~ 100 times from central region to forward region
 - Fake background:
 - Data-driven method, fake factor derived from data in control regions
- OS channel (7 TeV):
 - Drell-Yan background estimated using MC with normalization derived in control region
 - Fake lepton background evaluated with the same data-driven method as for SS channel
 - Other backgrounds are directly accounted for using MC



7 TeV:

- SS ee and eμ channel: dominant uncertainty from fake lepton background estimation
- OS channel: dominant ones come from uncertainties on Drell-Yan and top background
- PDF uncertainty of LRSM signal ~9%

8 TeV:

- breakdown of relative uncertainty on the total background (given in %) in:

mTISM signal region

	ee	μμ
<u>Non-prompt</u>	± 7	± 14
<u>Charge-flip</u>	± 7	—
<u>Prompt normalisation</u>	± 2	± 10
<u>MC statistics</u>	± 14	± 8
<u>Jet energy scale</u>	+8/-22	+7/-12
E_T^{miss}	+2/-3	+6/-3
Jet energy resolution	± 4	± 3
Jet vertex fraction	+2/-6	+4/-5
Lepton uncertainties	± 2	+2/-3
Luminosity	± 2	± 1
Total	+20/-29	+21/-24

LRSM signal region

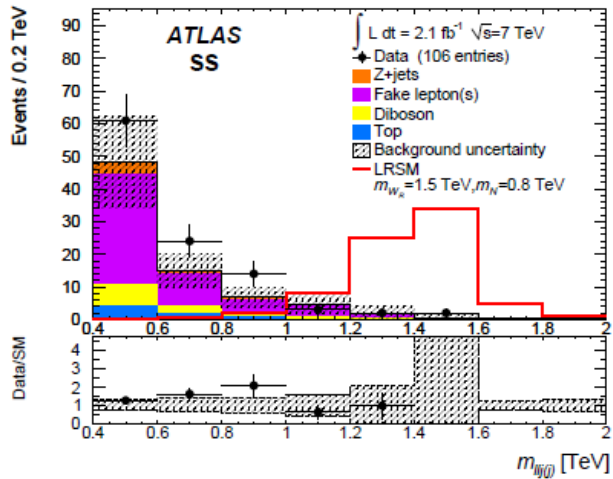
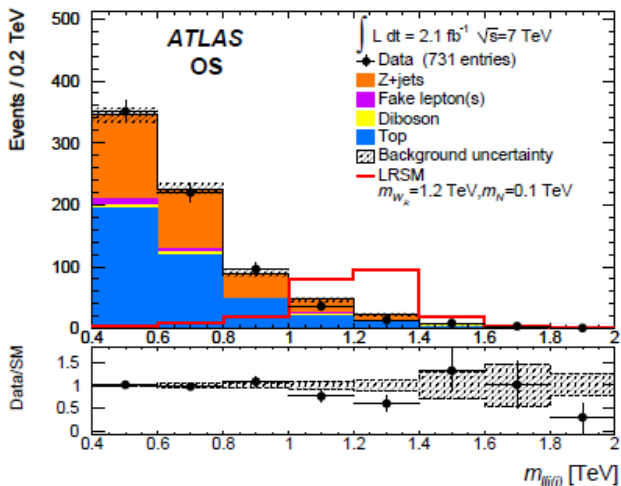
[JHEP07\(2015\)162](#)

	ee		μμ	
	W _R	Z'	W _R	Z'
<u>Non-prompt</u>	± 12	± 15	+10/-9	+13/-11
<u>Charge-flip</u>	+5/-4	+4/-3	—	—
<u>Prompt normalisation</u>	± 5	+5/-4	± 18	± 14
<u>MC statistics</u>	± 7	± 6	± 5	± 4
<u>Jet energy scale</u>	+8/-9	+5/-4	± 5	+5/-4
Jet energy resolution	± 0.9	± 0.6	± 1.2	± 0.2
Jet vertex fraction	± 1	± 2	+0.9/-0.1	+2.4/-1.1
Lepton uncertainties	+2/-1	+2.7/-1	± 2	± 2
Luminosity	± 1	+1.5/-1	± 1	± 1
Total	± 18	± 18	± 21	+20/-19

- Parton shower uncertainty on signal efficiency ~5%
- PDF uncertainty on signal acceptance is ~5% for mTISM signal and ~7% for LRSM signal

Signal Region

7 TeV:

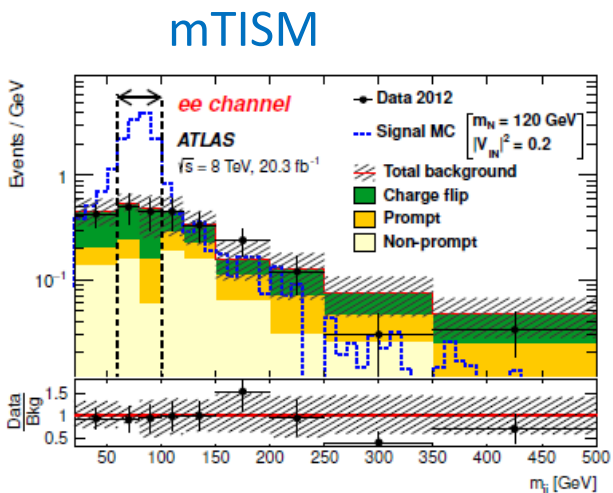


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OS Chan.	ee	$\mu\mu$	$e\mu$	Total
Total bkg	254.8 ± 25.8	279.7 ± 27.6	210.9 ± 33.4	745 ± 77
Observed	246	241	244	731
SS Chan.	ee	$\mu\mu$	$e\mu$	Total
Total bkg	48.4 ± 16.1	$4.4^{+2.1}_{-1.3}$	24.6 ± 7.6	77 ± 21
Observed	59	8	39	106

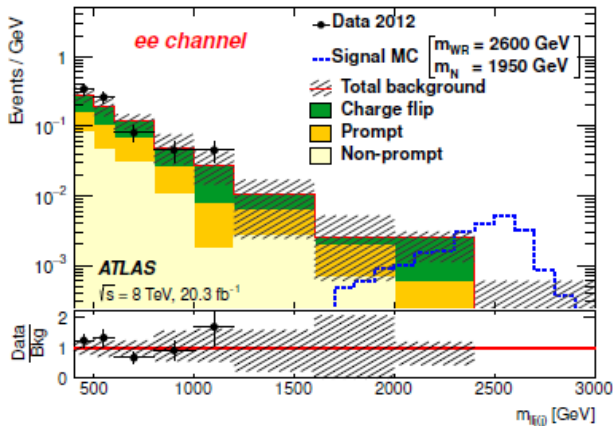
8 TeV:

[JHEP07\(2015\)162](https://arxiv.org/abs/1507.06748)



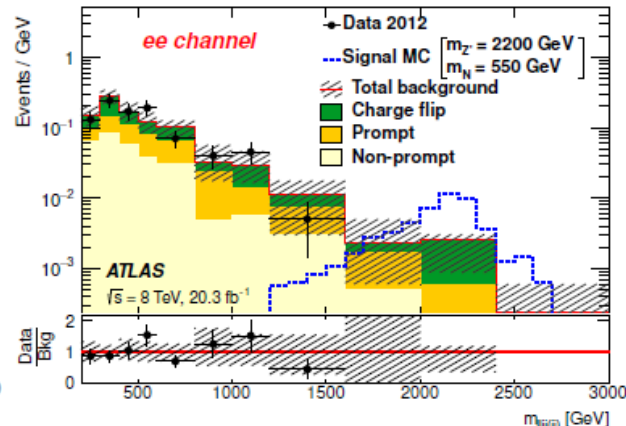
SS Chan.	ee	$\mu\mu$
Total bkg	21^{+4}_{-6}	8.7 ± 2.0
Observed	19	6

LRSM W_R



SS Chan.	W_R ee	W_R $\mu\mu$	Z' ee	Z' $\mu\mu$
Total bkg	93 ± 16	43 ± 9	111^{+16}_{-14}	60^{+13}_{-12}
Observed	94	44	106	55

LRSM Z'

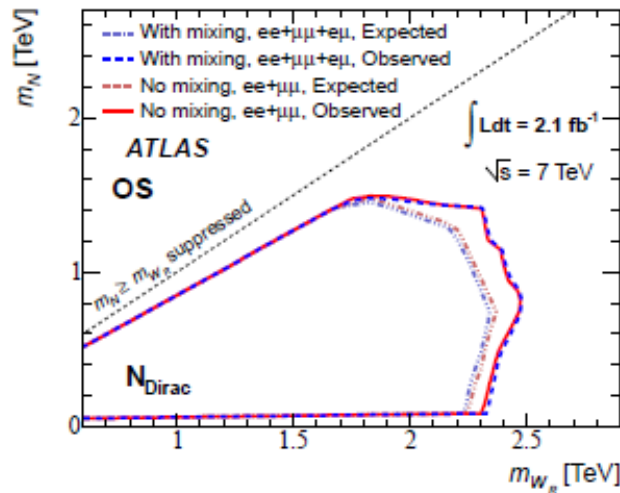
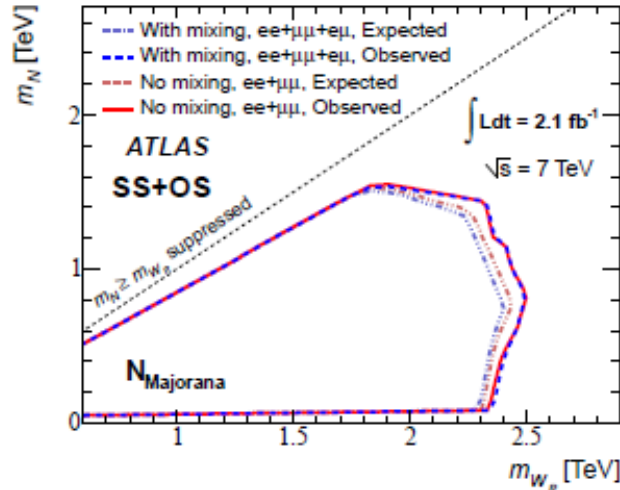


8 TeV No obvious deviation from SM observed

7 TeV

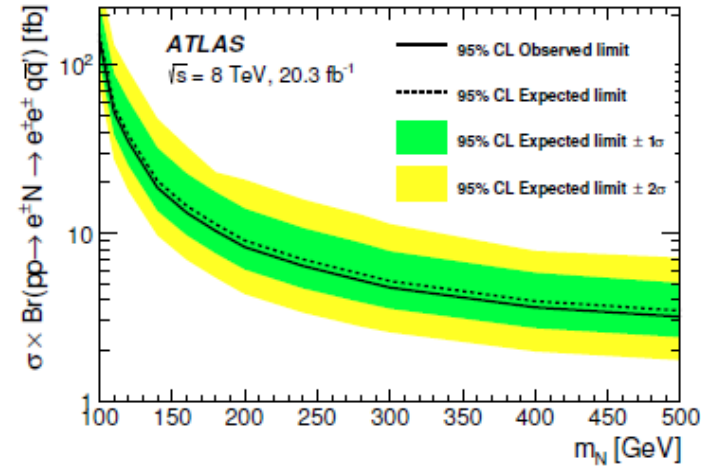
7 TeV LRSM:

Eur.Phys.J. C72 (2012) 2056

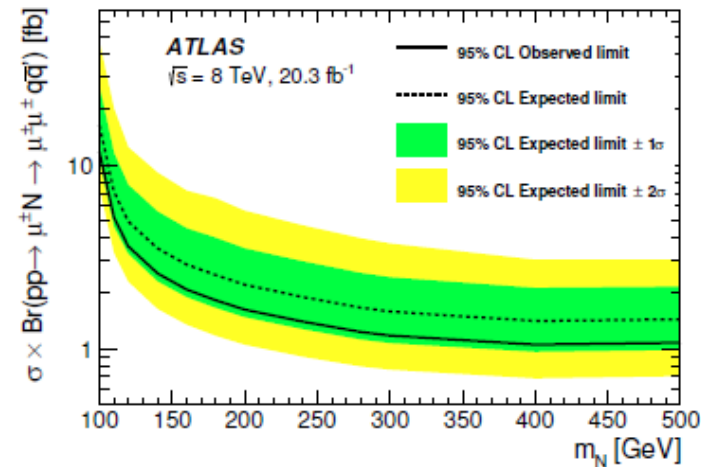


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mTISM:



(a)

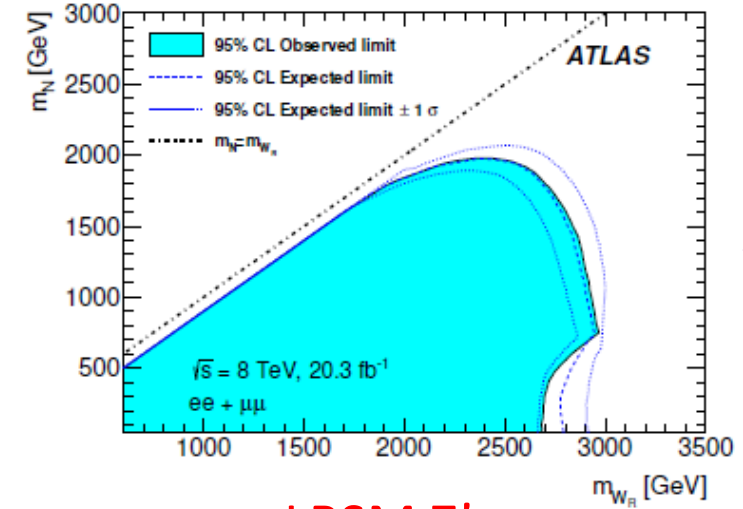


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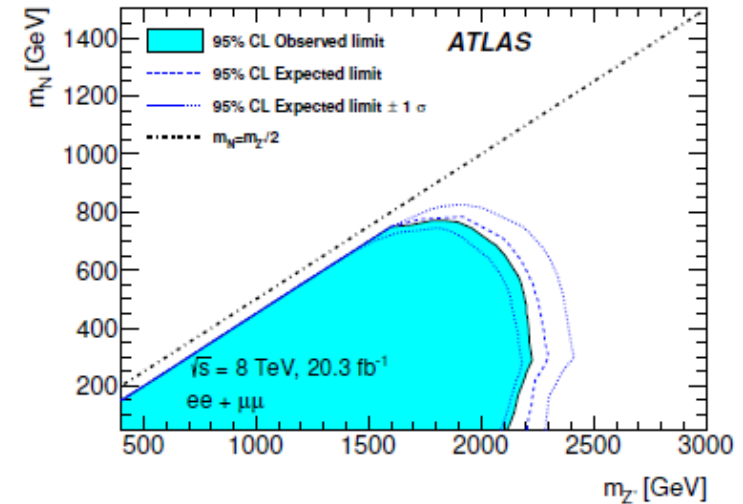
8 TeV

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LRSM W_R:



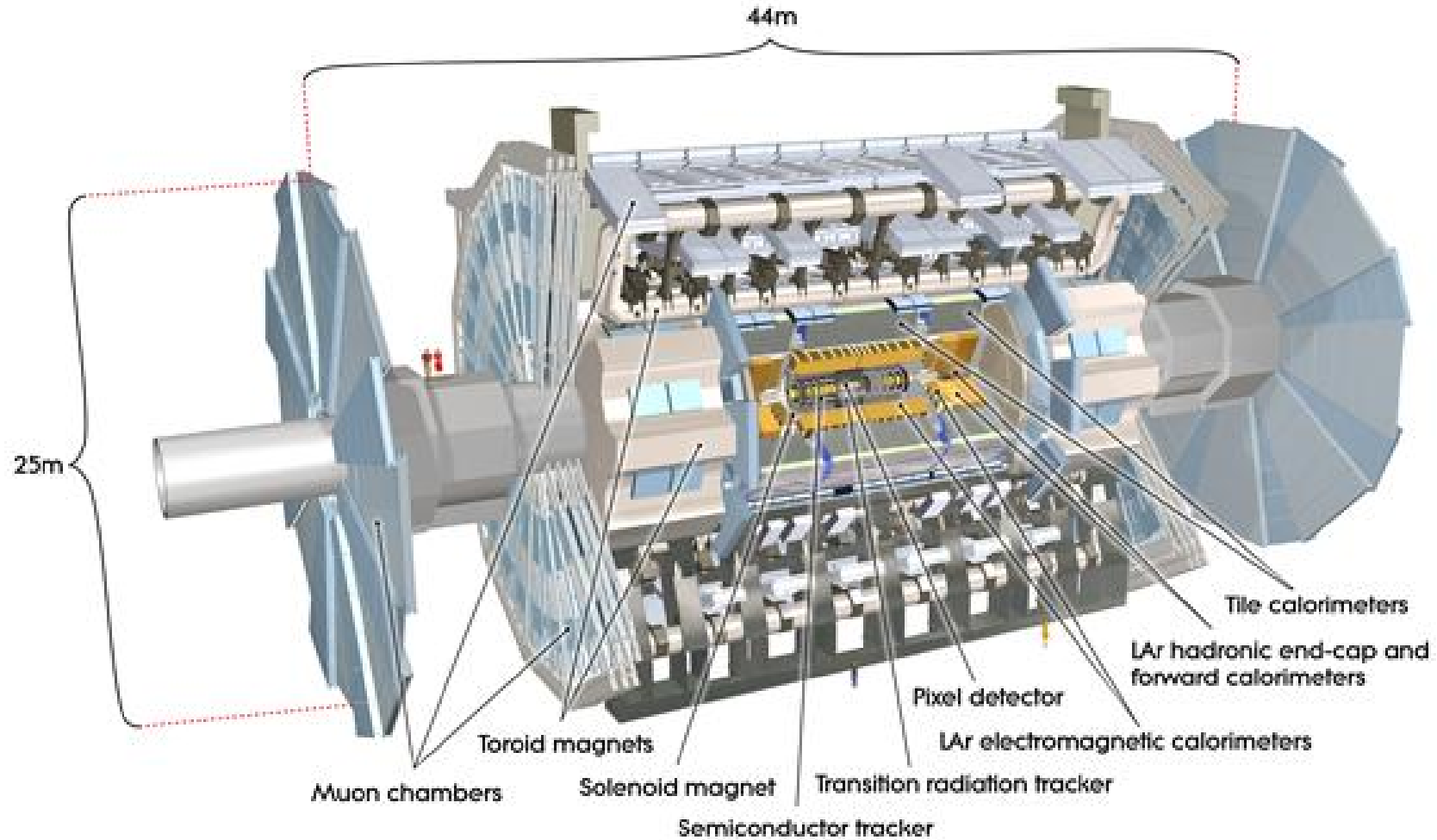
LRSM Z':



Assume heavy neutrinos of electron and muon flavors degenerated

- Searches for heavy Majorana or Dirac neutrinos and heavy gauge bosons with ATLAS detector presented, **no significant excess** beyond SM prediction observed
 - **7 TeV** analysis set limit on LRSM model, W_R bosons with masses below ≈ 1.8 TeV (≈ 2.3 TeV) are excluded for mass differences between the W_R and N masses larger than 0.3 TeV (0.9 TeV).
 - **8 TeV** analysis set limit on both mTISM and LRSM models:
 - **mTISM**: heavy neutrino mass is excluded up to 500 GeV
 - **LRSM**: limits are set on heavy neutrino mass in the range 50 to 2000 GeV for heavy gauge boson masses above 400 GeV
- An update on the ATLAS Run-1 result is expected in the near future with Run-2 data which is not yet public at this moment.

Backup Slides



- In Standard Model:
 - The neutrino is neutral.
 - The neutrino is left-handed and massless
 - The neutrino only interacts weakly
 - Three active flavors

- But:

✓ Neutrino oscillation has been found



What does it implies?

- Neutrinos are massive
- Neutrinos are mixing between flavor classification and mass classification

Oscillation probability

$$P_{osc} = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

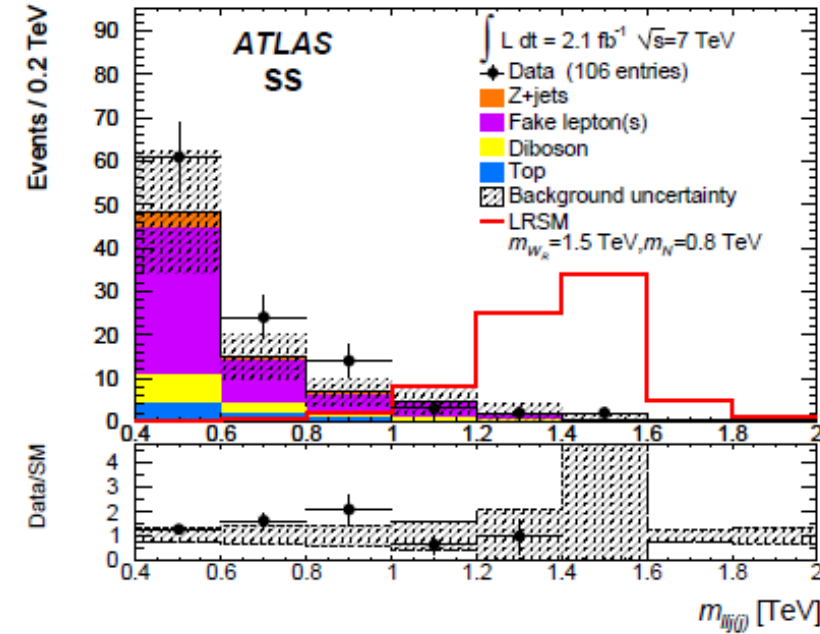
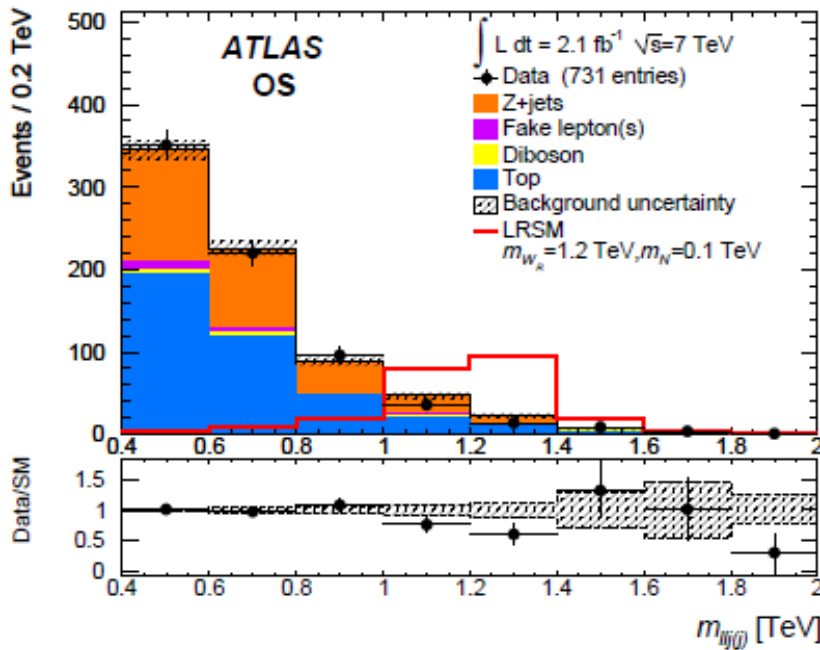
8 TeV Background and Signal Simulation

Process	OS/SS	Generator	Parton shower	PDF set		
Background processes						
Wt	OS	MC@NLO	HERWIG	CT10		
$t\bar{t}$						
Z		SHERPA	SHERPA			
$W^\pm W^\mp$						
WZ	SS				MADGRAPH	MSTW 2008
ZZ						
$W^\pm W^\pm jj$		PYTHIA	CTEQ6L1			
$t\bar{t} + W/Z$						
Signal processes						
$W^\pm \rightarrow \ell^\pm N$	SS	ALPGEN	PYTHIA	CTEQ6L1		
$W_R^\pm \rightarrow \ell^\pm N$		PYTHIA		MSTW 2008		
$Z' \rightarrow NN$						

Table 1. Overview of primary MC samples used for the simulation of signal and background processes. The category labelled ‘OS/SS’ refers to whether the process leads to pairs of opposite-sign (OS) or same-sign (SS) leptons. As described in section 5.2, OS MC samples are used in the prediction of the charge-misidentification background.

No significant deviation from SM is observed.

[Eur.Phys.J. C72 \(2012\) 2056](#)



Distribution of reconstructed W_R mass

Signal region yields: 7 TeV

OS channel:

Physics Processes	e^+e^-			$\mu^+\mu^-$			$e^+\mu^\mp$			Total		
Z/ γ^* +jets	136.1	\pm	12.5	173.2	\pm	15.1	0.8	\pm	0.8	310	\pm	20
Diboson	4.3	\pm	1.8	7.3	\pm	1.9	5.9	\pm	1.6	18	\pm	3
Top	103.1	\pm	12.3	100.9	\pm	12.0	199.4	\pm	23.3	403	\pm	46
Fake lepton(s)	12.5	\pm	8.1	-0.2	\pm	0.7	6.1	\pm	4.2	18	\pm	9
Total Background	256.0	\pm	26.2	281.2	\pm	27.9	212.3	\pm	33.8	750	\pm	78
Observed events	248			245			247			740		
$m_{\ell\ell(j)} \geq 400$ GeV												
Total Background	254.8	\pm	25.8	279.7	\pm	27.6	210.9	\pm	33.4	745	\pm	77
Observed events	246			241			244			731		

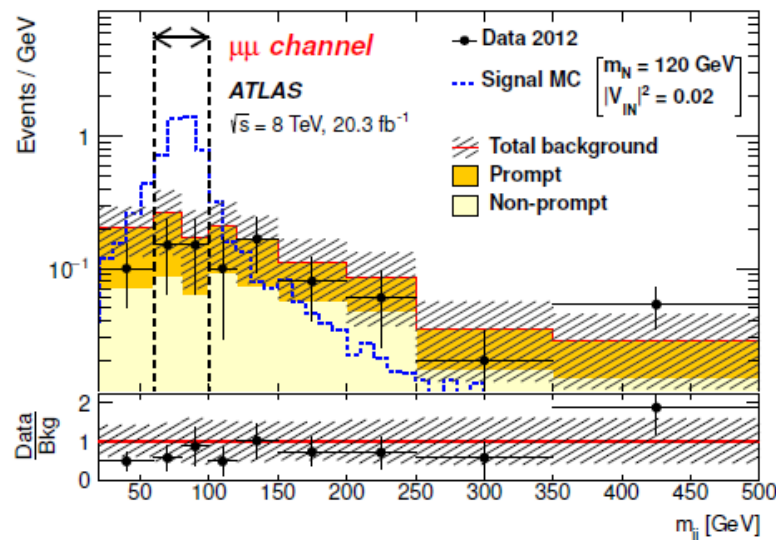
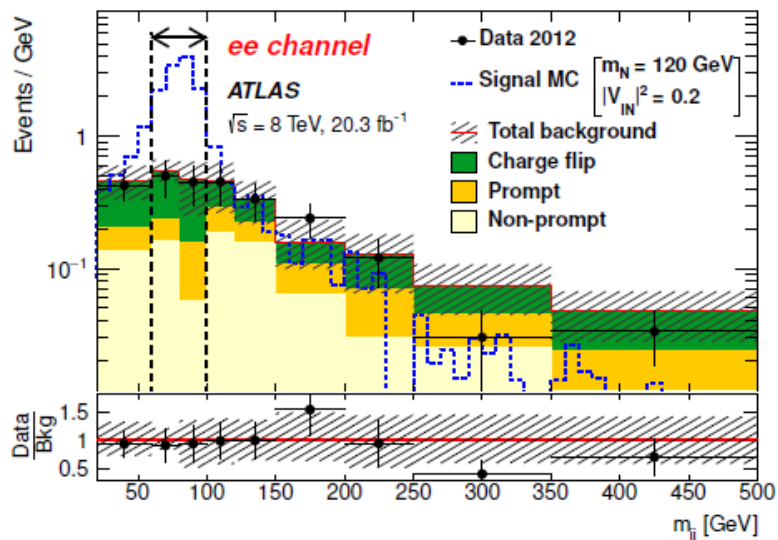
SS channel:

Physics Processes	e^+e^+			$\mu^+\mu^+$			$e^+\mu^+$			Total		
Z/ γ^* +jets	26.1	\pm	5.6	0.0	\pm	$\frac{1.6}{0}$	1.2	\pm	0.7	27	\pm	6
Diboson	12.7	\pm	2.3	7.2	\pm	1.7	18.8	\pm	3.0	39	\pm	6
Top	5.8	\pm	1.3	0.7	\pm	0.3	6.8	\pm	1.6	13	\pm	3
Fake lepton(s)	93.6	\pm	35.7	3.1	\pm	1.6	53.8	\pm	20.3	151	\pm	50
Total Background	138.3	\pm	36.5	11.0	\pm	$\frac{2.9}{2.5}$	80.7	\pm	20.8	230	\pm	52
Observed events	155			14			99			268		
$m_{\ell\ell(j)} \geq 400$ GeV												
Total Background	48.4	\pm	16.1	4.4	\pm	$\frac{2.1}{1.3}$	24.6	\pm	7.6	77	\pm	21
Observed events	59			8			39			106		

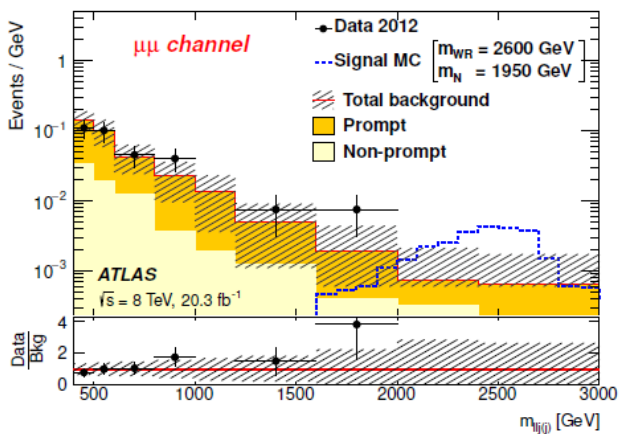
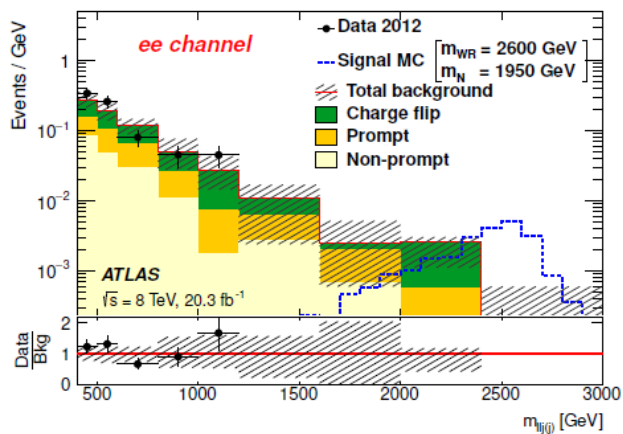
No significant deviation from SM is observed.

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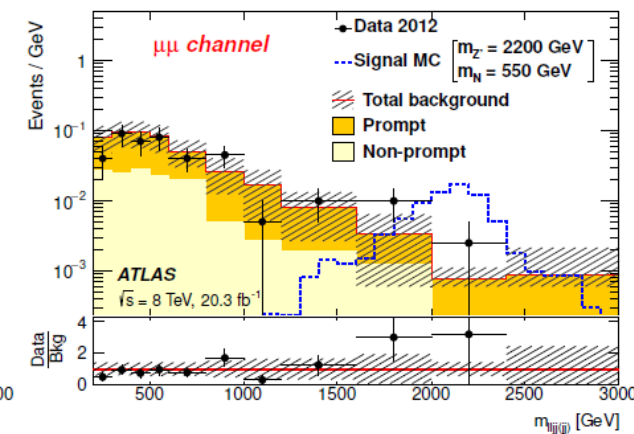
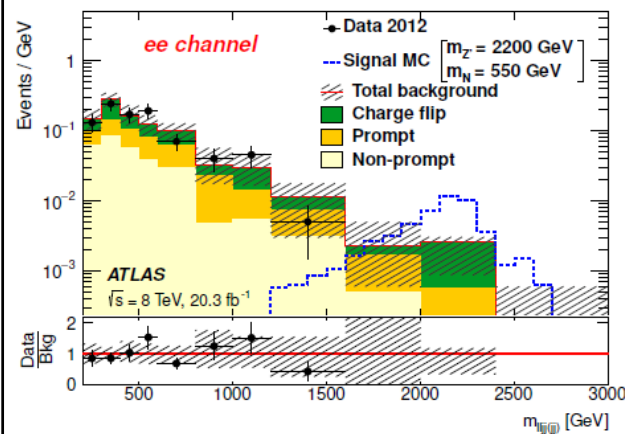
mTISM:



LRSM W_R :



LRSM Z' :



Signal region yields: 8 TeV

mTISM:

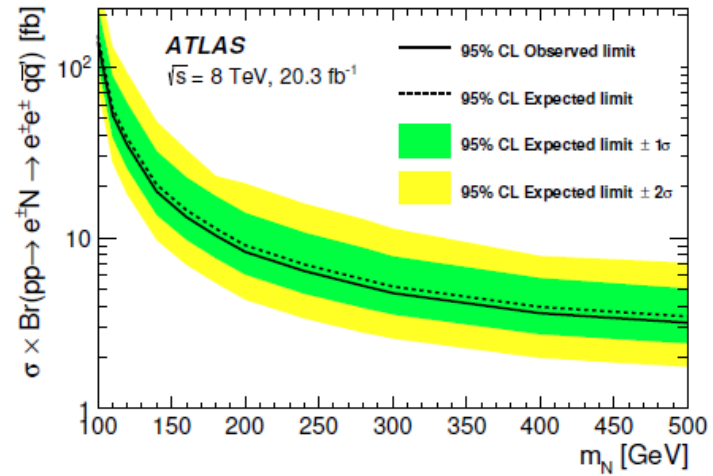
	ee	$\mu\mu$
Prompt	$3.5^{+0.9}_{-1.7}$	$5.8^{+1.3}_{-1.7}$
Charge-flip	13^{+3}_{-6}	< 0.02
Non-prompt	4.3 ± 1.8	2.9 ± 1.3
Total background	21^{+4}_{-6}	8.7 ± 2.0
Data	19	6
Signal ($m_N = 120$ GeV)	18	6.6
Signal ($m_N = 240$ GeV)	30	5.3

LRSM:

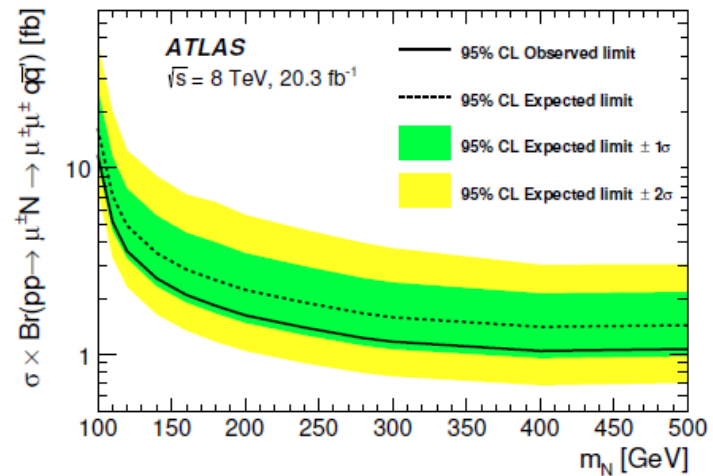
	ee		$\mu\mu$	
	W_R	Z'	W_R	Z'
Prompt	26 ± 5	34 ± 6	33 ± 8	42 ± 10
Charge-flip	44 ± 11	44^{+10}_{-8}	< 0.03	< 0.03
Non-prompt	23 ± 11	33^{+11}_{-10}	9.8^{+5}_{-4}	17^{+8}_{-7}
Total background	93 ± 16	111^{+16}_{-14}	43 ± 9	60^{+13}_{-12}
Data	94	106	44	55
Signal	2.4	5.2	2.9	7.7

mTISM:

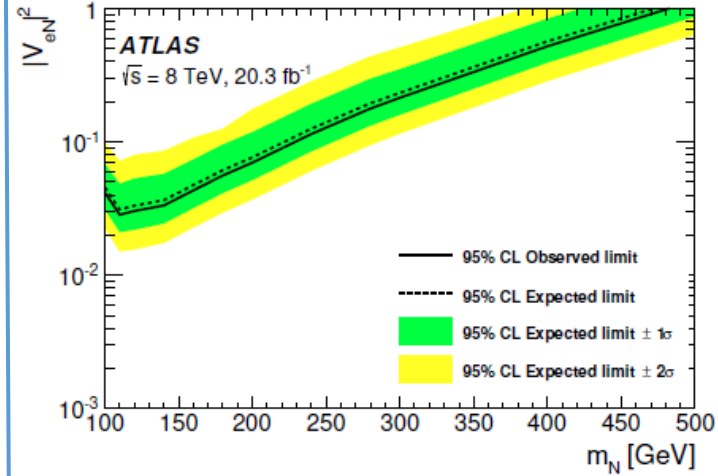
Cross-section x BR



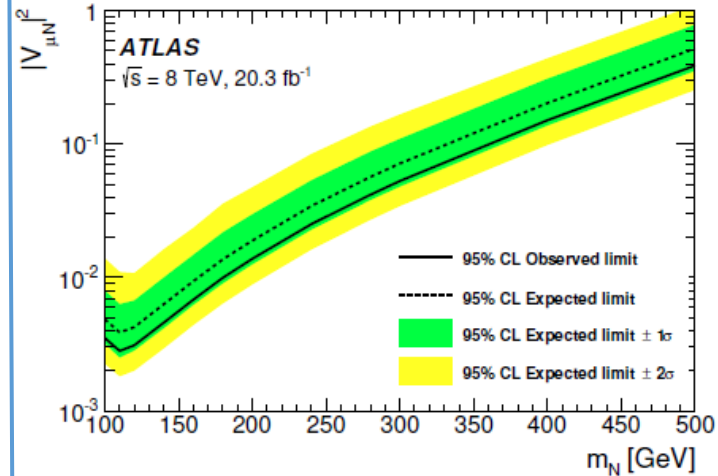
(a)



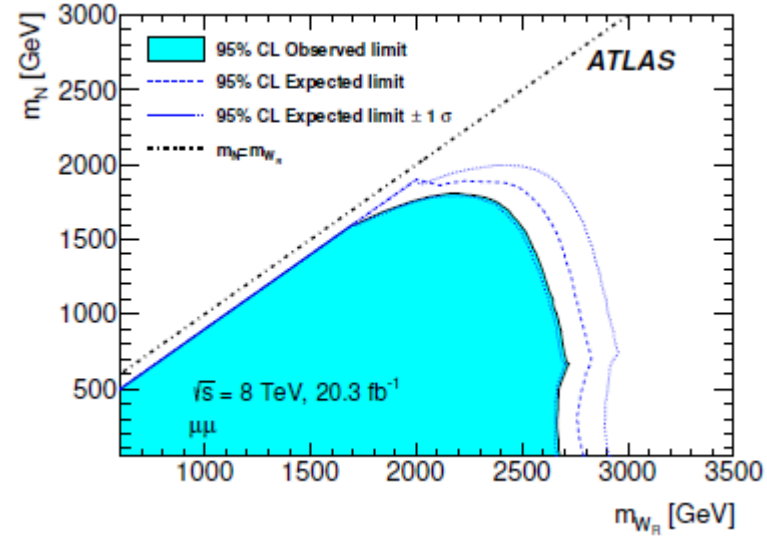
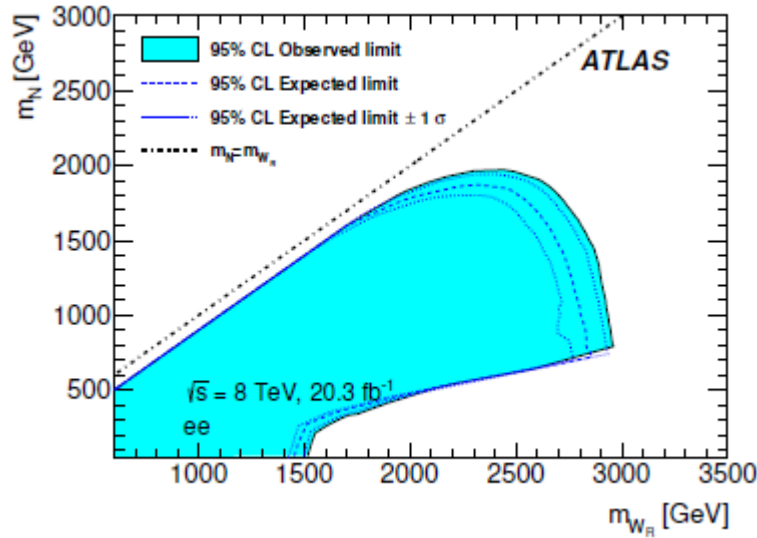
$|V_{IN}|^2$



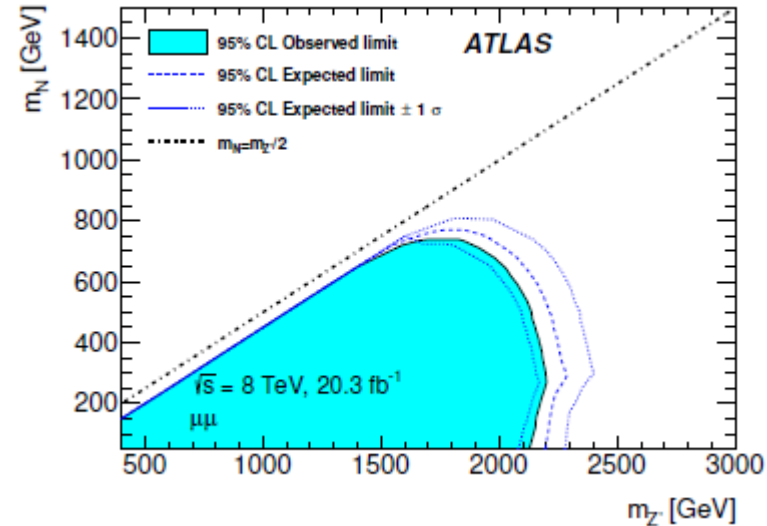
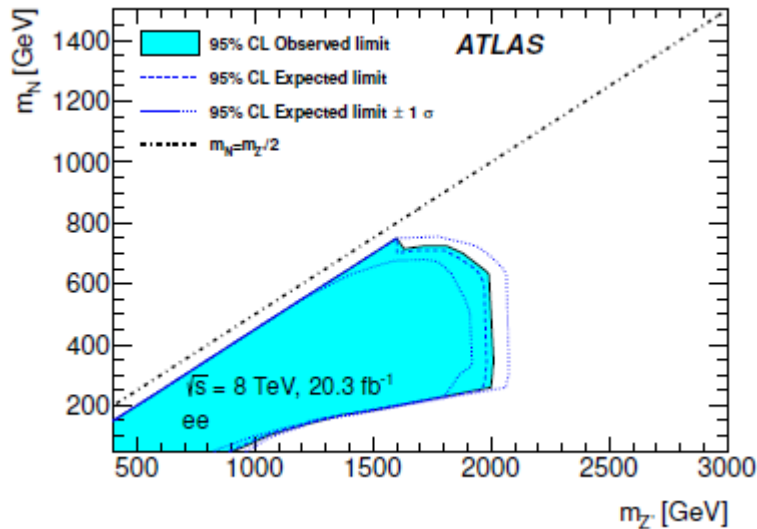
(b)



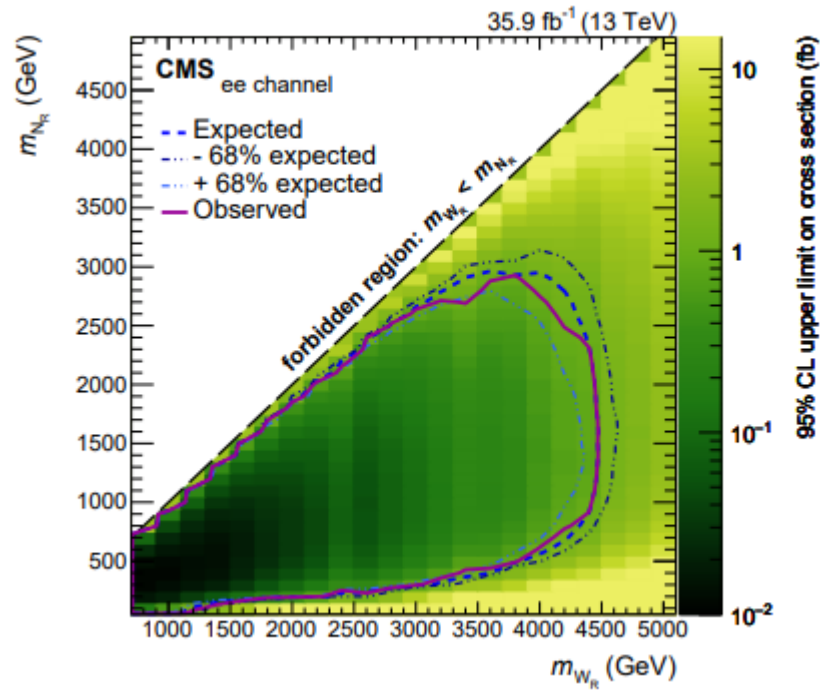
LRSM W_R :



LRSM Z' :



Electron channel



Muon channel

