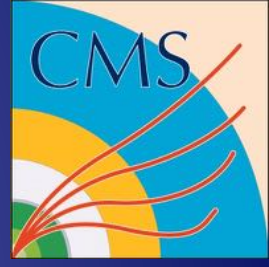




# New Results on Heavy Neutrino Searches at the LHC

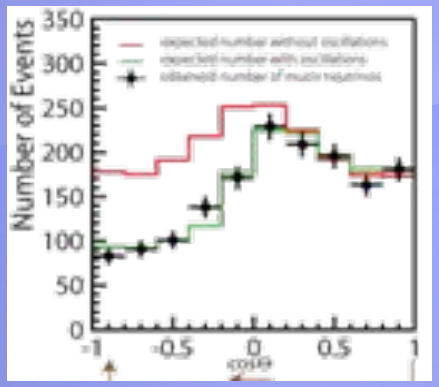
**Un-ki Yang**

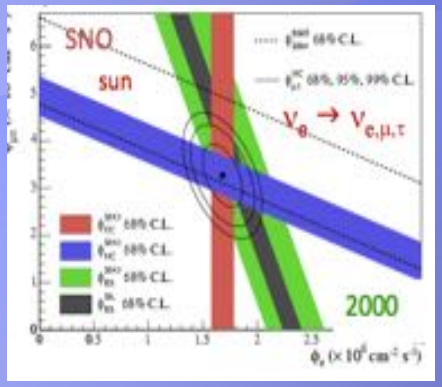
**Seoul National University**

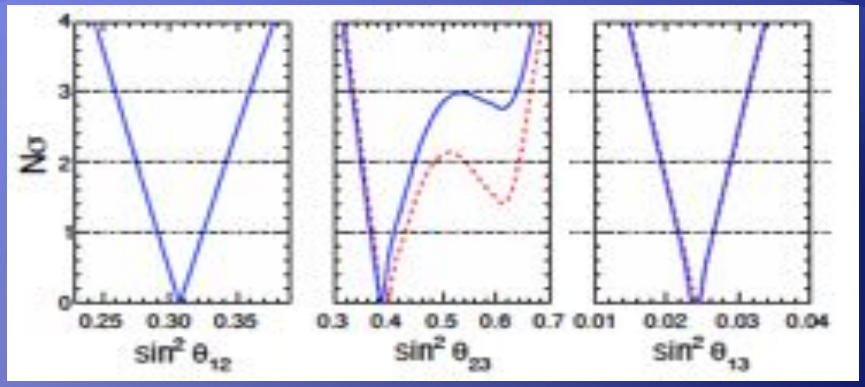

**On behalf of the ATLAS and CMS collaborations**

**WIN 2015, June 8-13, 2015, MPIK Heidelberg,**

# Why Heavy Neutrinos?



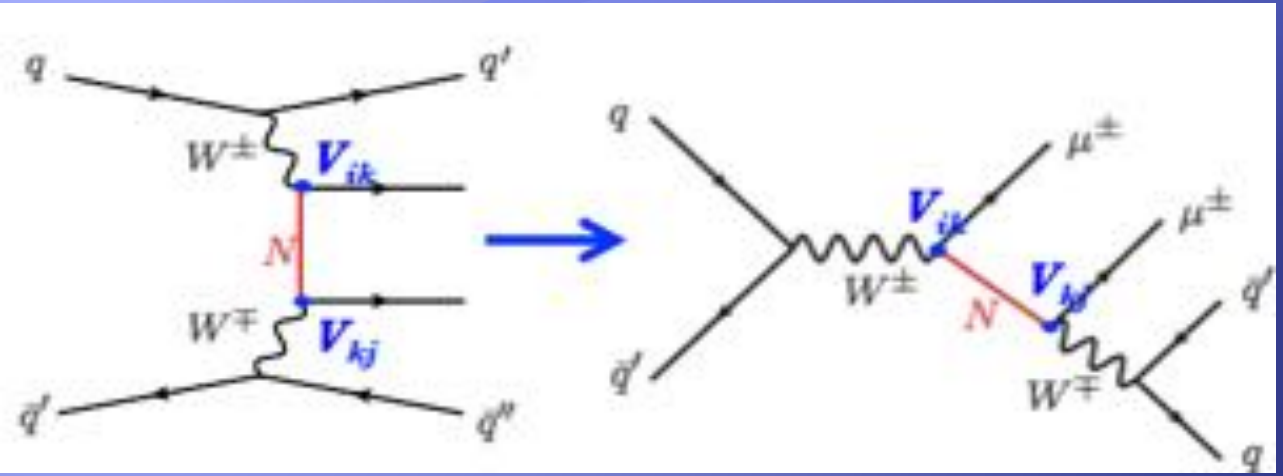




- Small neutrino mass → heavy neutrino ($N_R$) by "SeaSaw

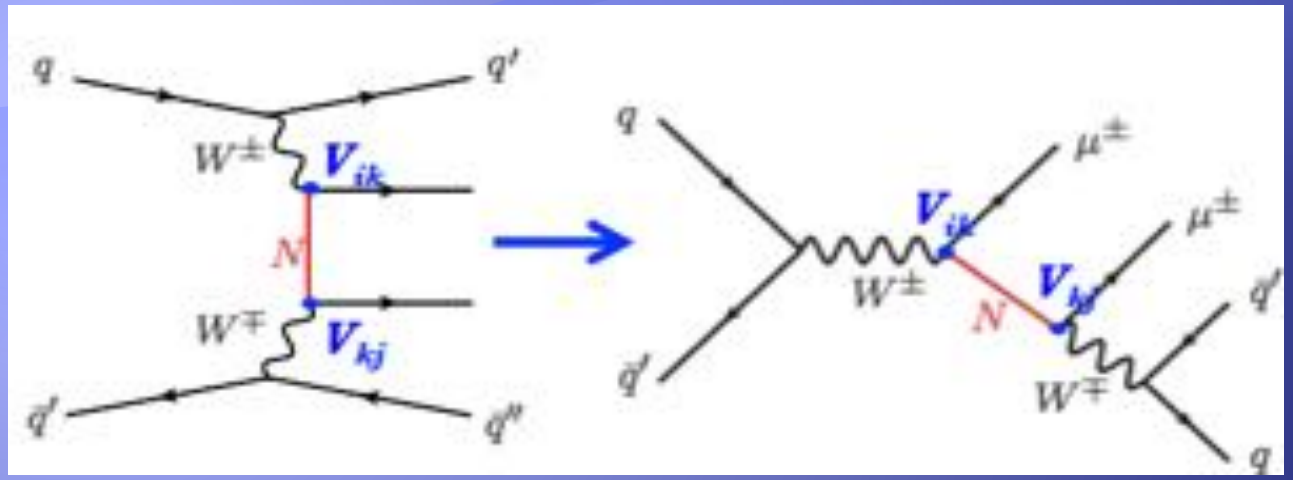
- Type I : weak-singlet fermion (N)
- Type III : weak-triplet fermion ($\Sigma^0$, $\Sigma^{+/-}$)
- 'Left-Right Symmetric Model' (**LRSM**): $SU(2)_R$ symmetry to the SM: N, $W_R$ , Z'

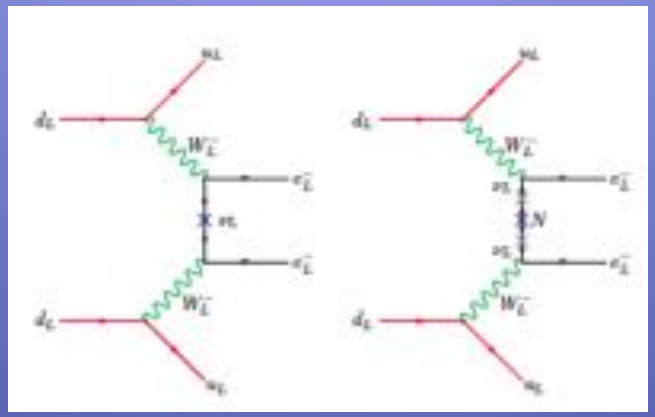
"reference in backup"

# Heavy Neutrinos at the LHC?



# Heavy Neutrinos at the LHC?

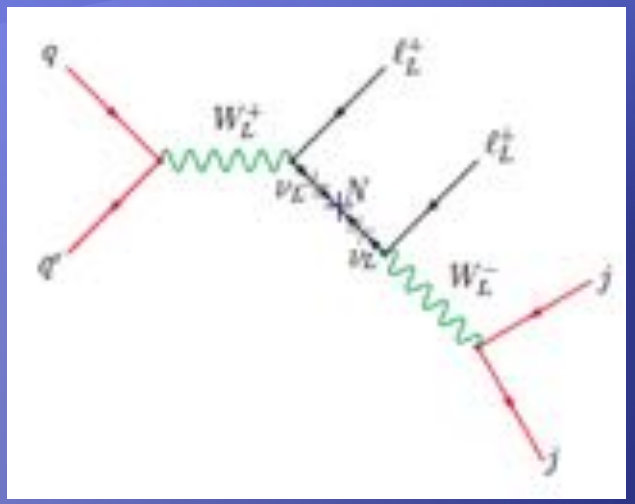


- LHC: direct production of heavy N
  - Same-sign two leptons + 2 jets
  - Type I: probe light-heavy mixing
  - LRSM: a resonance $W_R$ production
- $0\nu\beta\beta$ : does not fully probe the light-heavy mixing

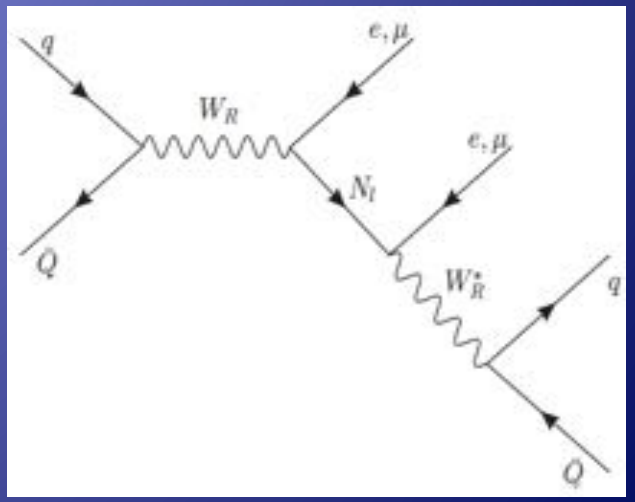
# Heavy N productions

- **Type 1:**
  - **Resonant production via s-channel W* or W(real)**
  - **Majorana can decay to positive or negative lepton (50% same-sign)**
  - **Cross section depends on $|V_{IN}|^2$ and mass**



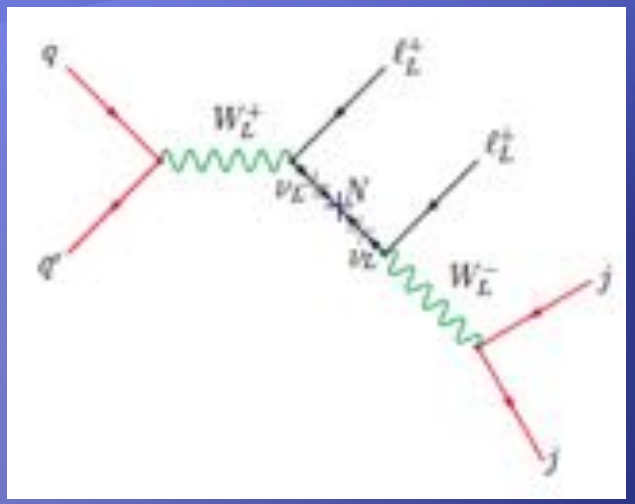

**Signal:** 2 leptons + 2 jets + no $\not{p}_T$

- **LRSM:**
  - **TeV scale gauge bosons ($2W_R$ and Z')**



# Heavy N productions

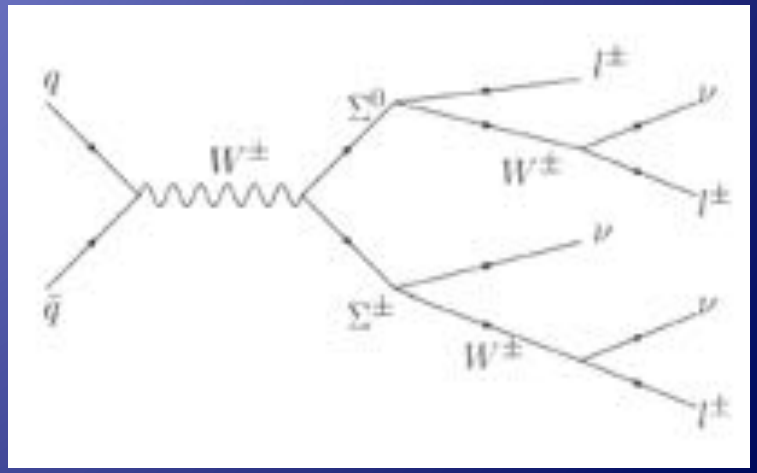
- **Type 1:**
  - **Resonant production via s-channel W* or W(real)**
  - **Majorana can decay to positive or negative lepton (50% same-sign)**
  - **Cross section depends on $|V_{lN}|^2$ and mass**



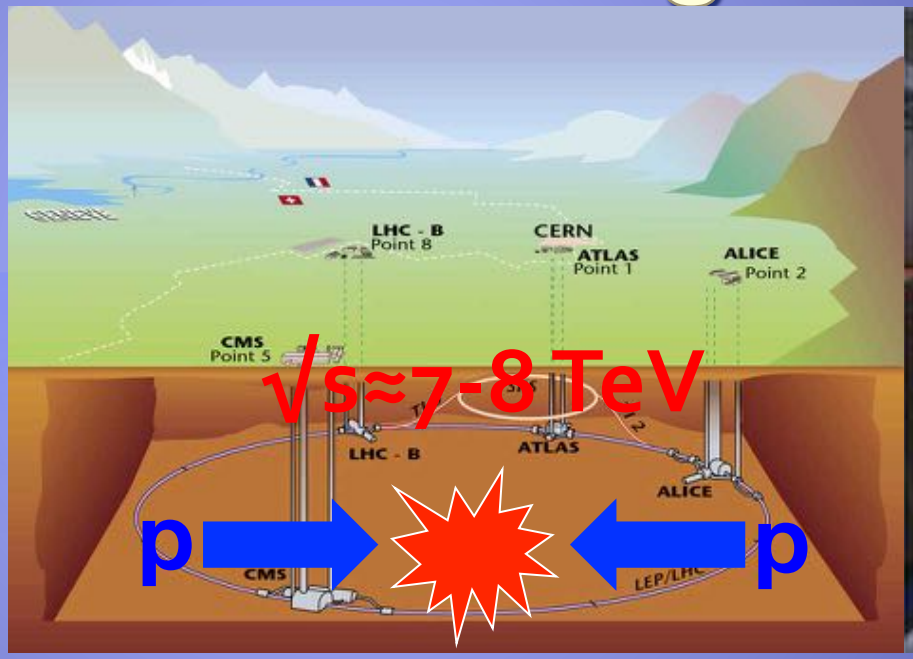

**Signal:** 2 leptons + 2 jets + no $\not{p}_T$

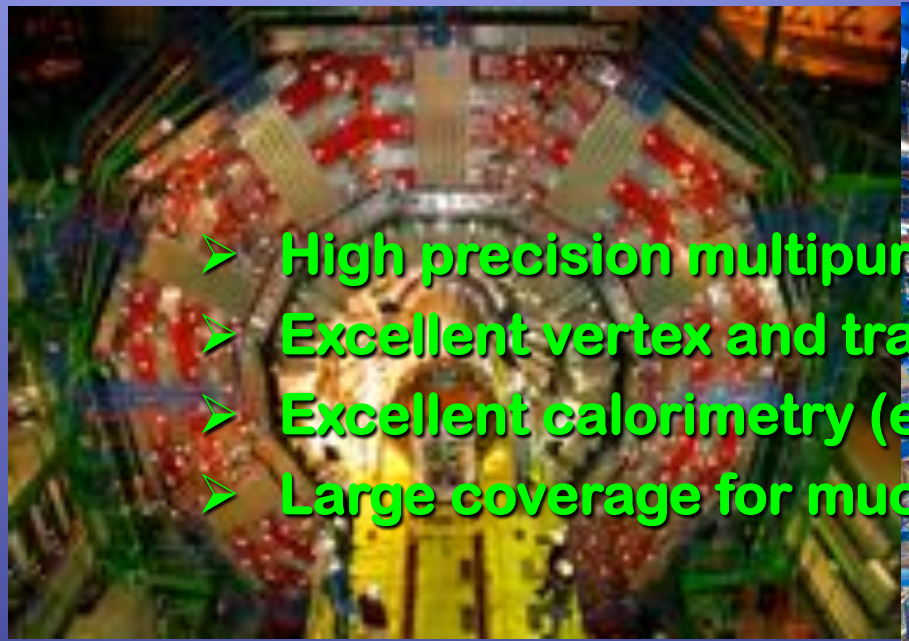
- **LRSM:**
  - **TeV scale gauge bosons ($2W_R$ and Z')**

- **Type III:**
  - **Production of $\Sigma^0$, $\Sigma^{+/-}$ via s-channel W***

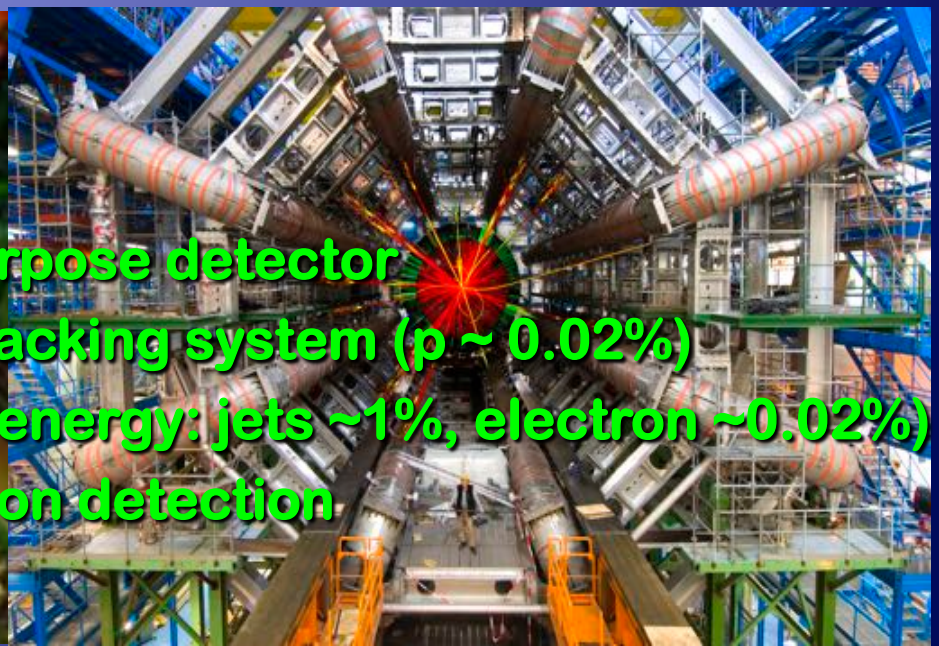


# Use the Large Hadron Collider!!!

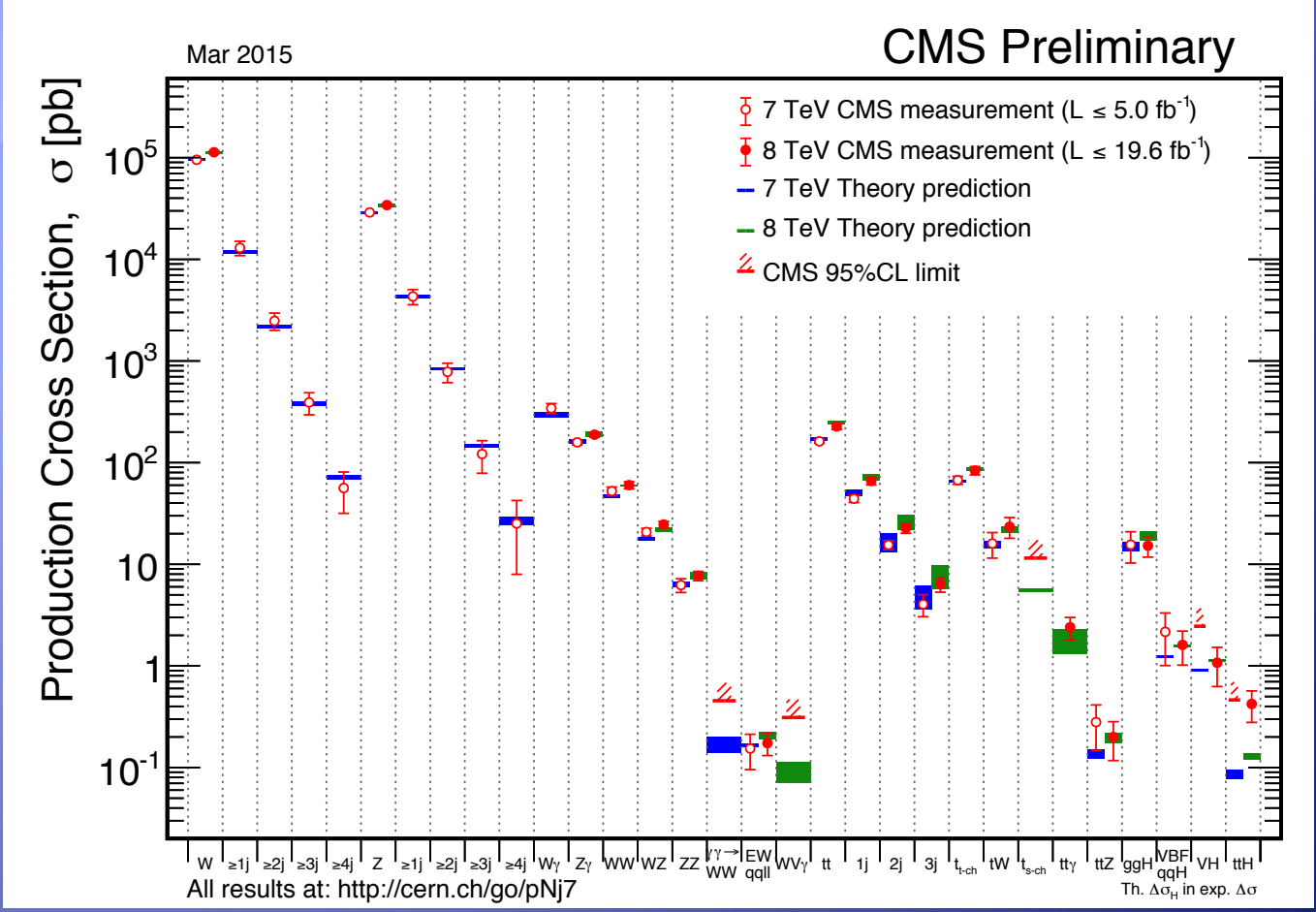


- High precision multipurpose detector
- Excellent vertex and tracking system (p ~ 0.02%)
- Excellent calorimetry (energy: jets ~1%, electron ~0.02%)
- Large coverage for muon detection

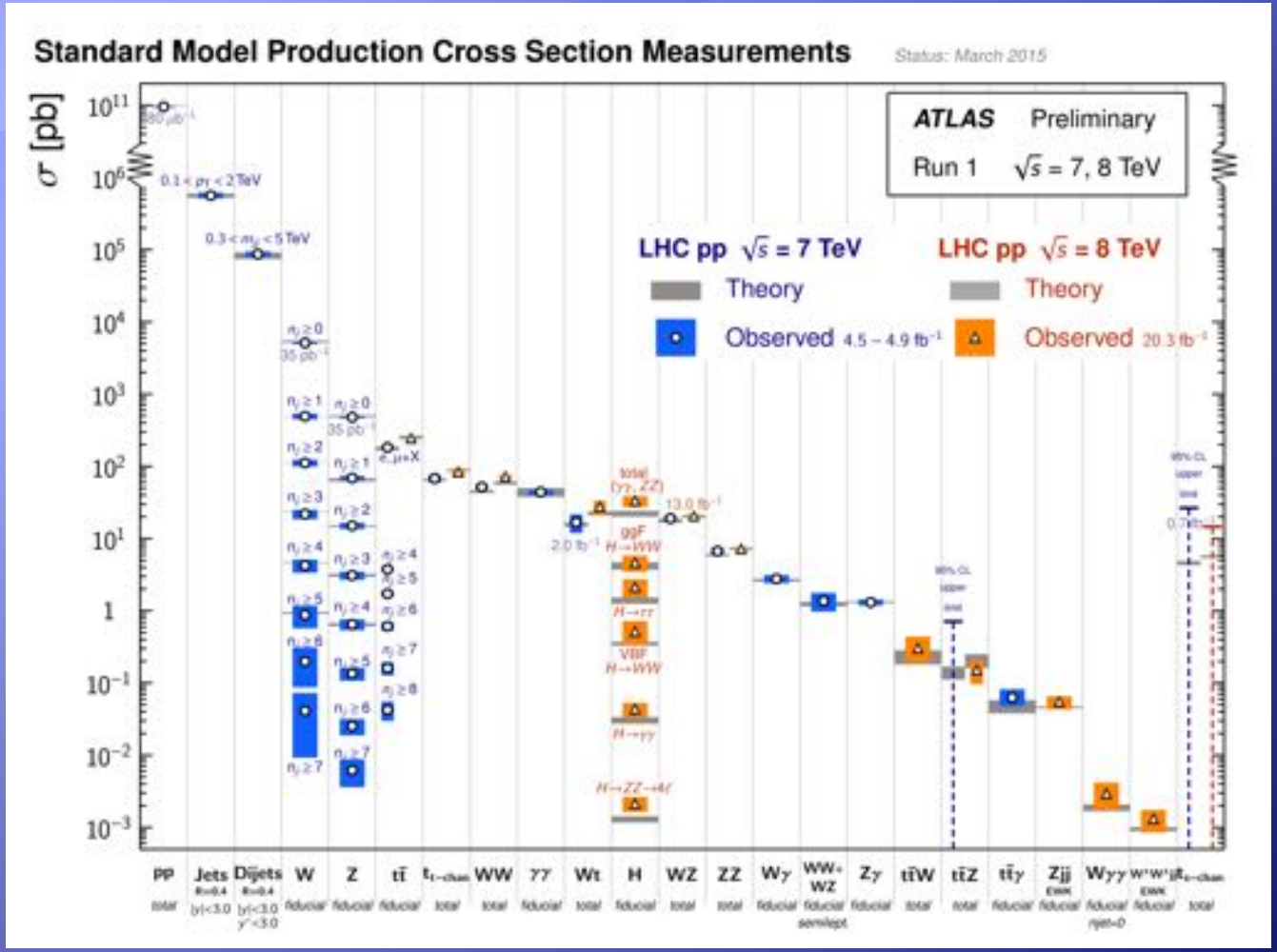


# Before Searching for New Physics at CMS



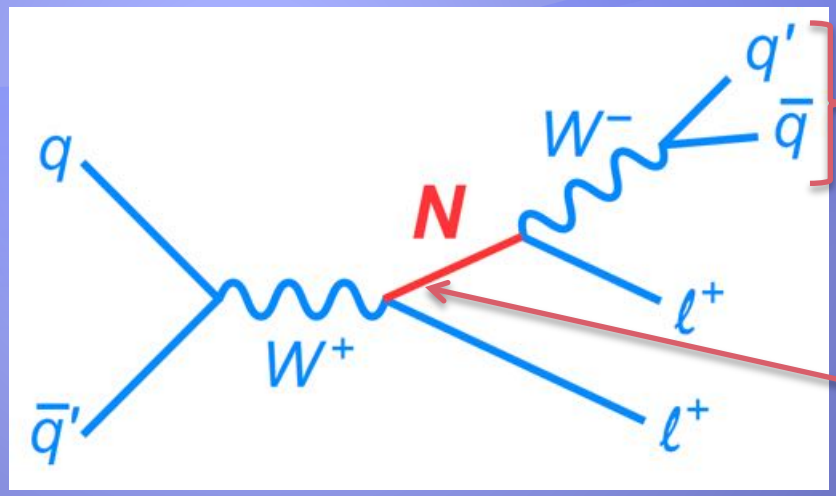

- **Impressive agreement with the SM**

# Before Searching for New Physics at ATLAS




- **Another impressive agreement**

# Searches in Type I Seasaw



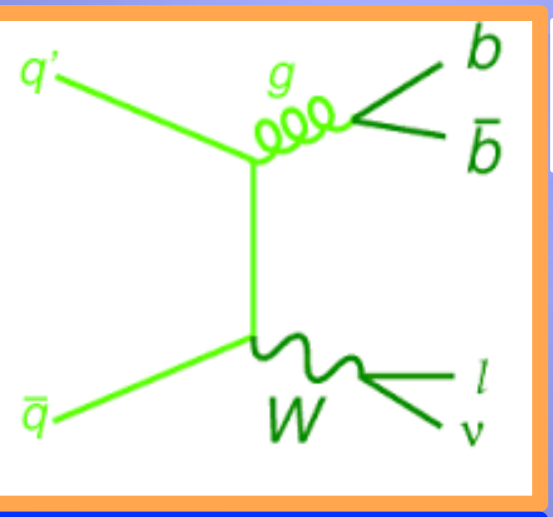

two jets from W decay, m(jj) = m(W)

**Majorana Neutrino**
**Same Sign 50% of events**

- Final states: dileptons + 2 jets + no missing transverse energy (MET)
- Use only same sign leptons channels: due to a large Z+jets bkgds

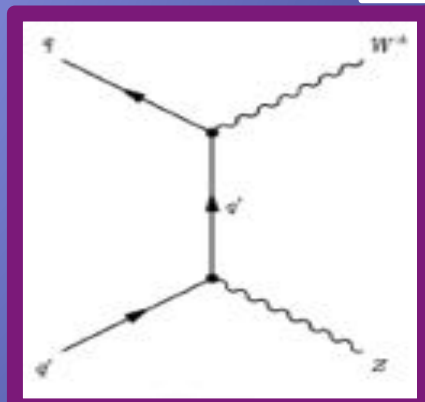
- Challenges:
  - Small signal cross sections but large bkgds from from QCD jets
  - Understanding of Z+jets bkgd, but with a lepton-charge flip

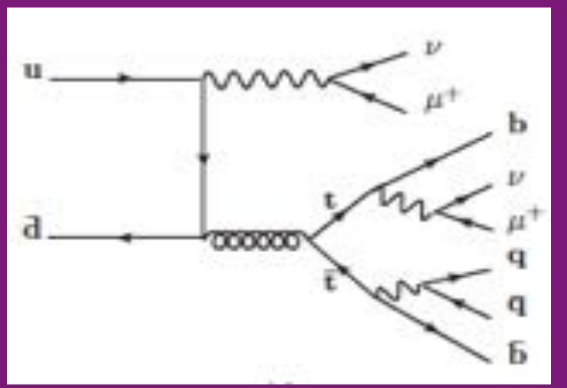
# Backgrounds

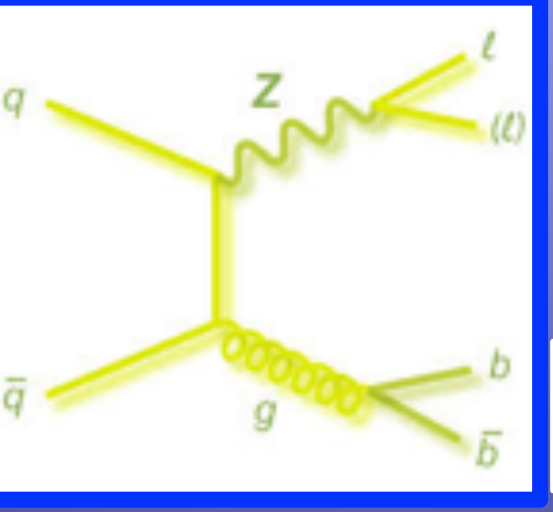



**Fake leptons: "data"**
**W(e,μ)+jets, multijets**

**SM prompt lepton; MC**
**dibosons(VV), tt+V**






**Charge-flip: "data+MC"**
**Z(ll)+2jets**

# Event Selection

- **Common Selection**
  - 2 same sign leptons (isolated)
  - Njets: at least two jets
- **Difference in selection**

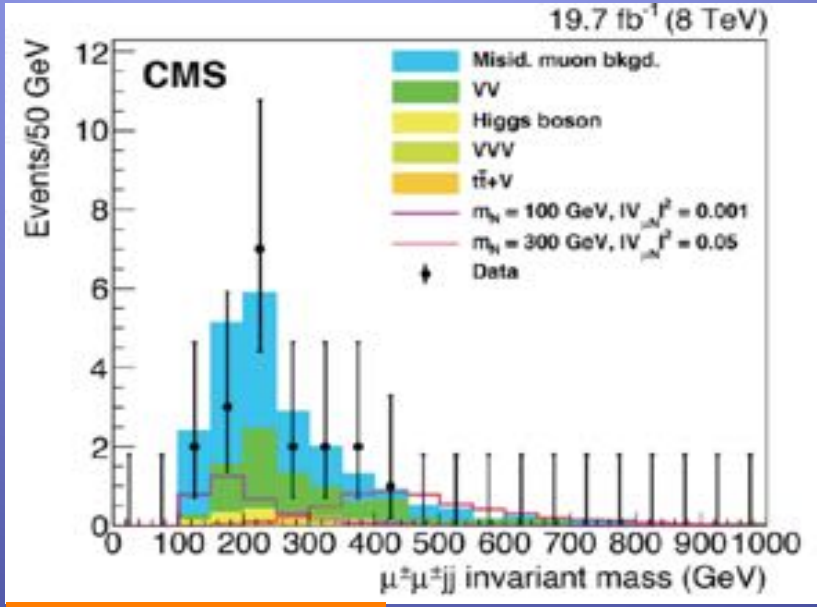
- **CMS**
  - 20/15 GeV lepton pt cuts
  - Dilepton triggers
  - Search for m(N)>40 GeV
  - Use m(ljj) for signals

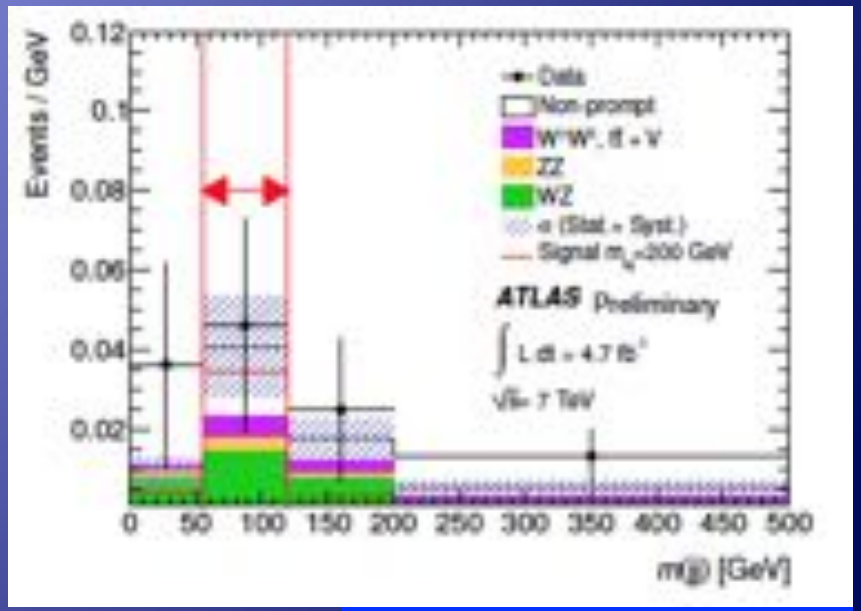
- **ATLAS**
  - 25/20 GeV lepton pt cuts
  - Single lepton trigger
  - Search for m(N)>100 GeV
  - Use m(jj) for signals

- **Remarks**
  - CMS: di-lepton trigger→ lower pt cut→ increase acceptance for low $m_{N,}$ but more QCD bkgds
  - 3rd lepton veto: remove WZ/ZZ bkgds
  - ATLAS: mass of two leading jets to be near $m_W$

# Backgrounds and systematics

- **Main systematics**
  - **Fake-lepton (non-prompt): ~30-50%**
  - **Charge mis-Id: 20% (e)**
  - **Jet Energy Uncertainty**
  - **Largest:**
    **non-prompt (CMS), WZ(ATLAS)**



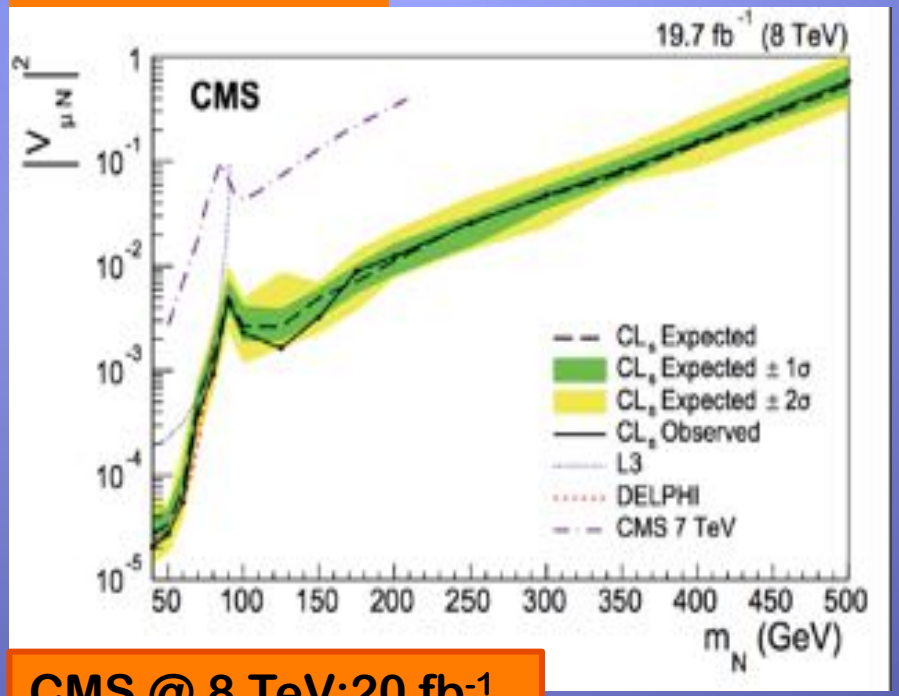

arXiv:1501.05566

ATLAS-CONF-2013-019

# Results

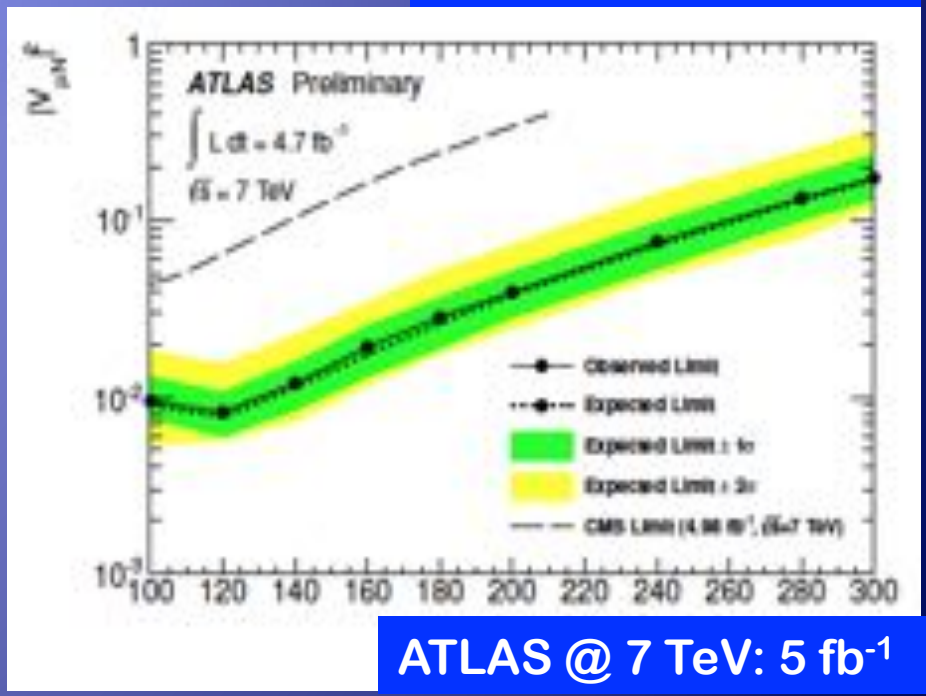
- No excess observed: both ATLAS & CMS limits on cross sections and coupling parameter $|V_{lN}|^2$

arXiv:1501.05566




CMS @ 8 TeV:20 fb$^{-1}$

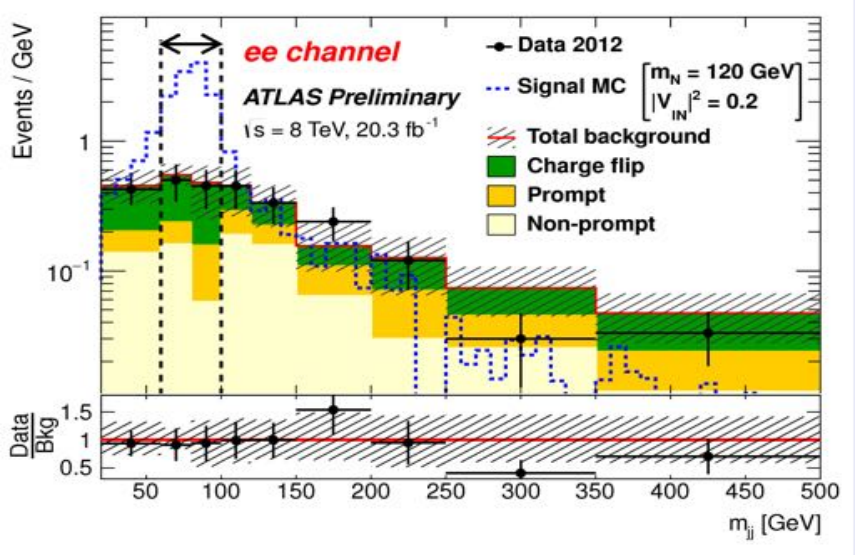
ATLAS-CONF-2013-019

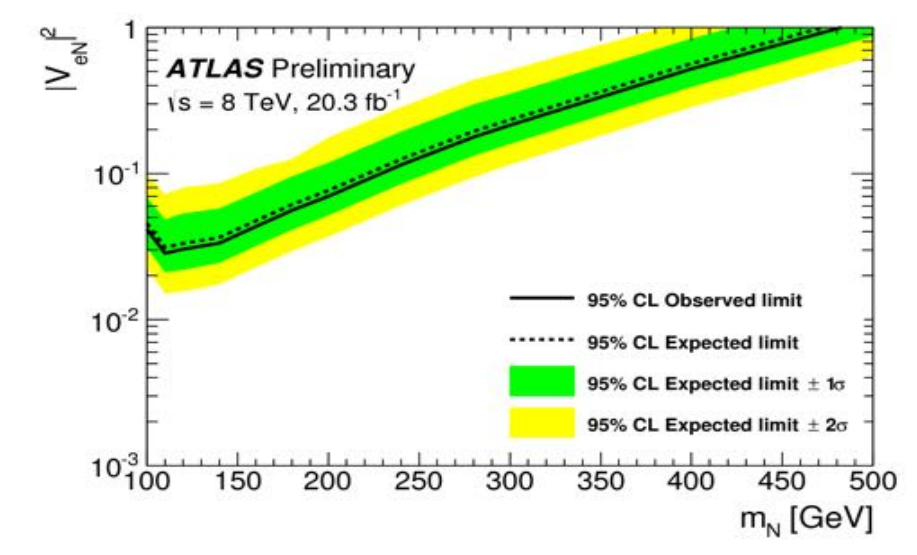


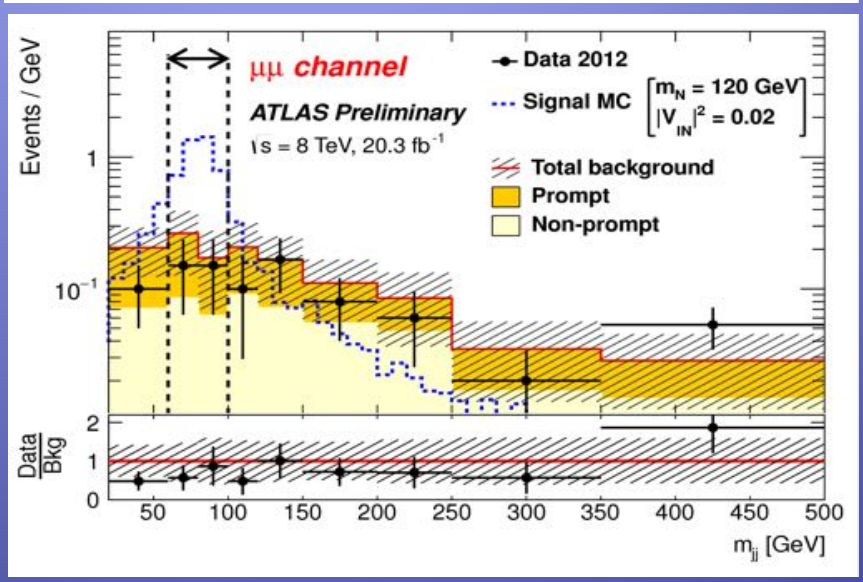

ATLAS @ 7 TeV: 5 fb$^{-1}$

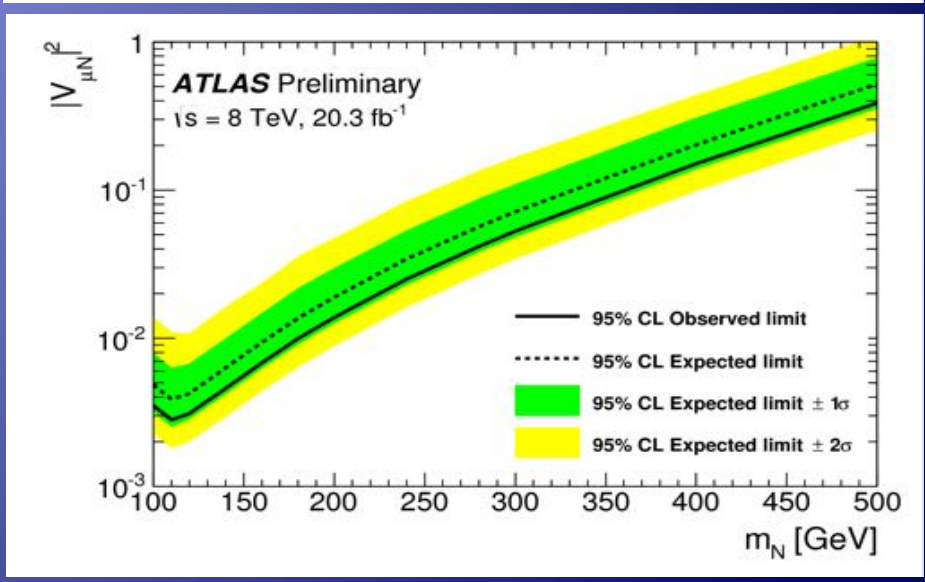
- LHC provides the world best limits on $|V_{\mu N}|^2$ for m(N)>90 GeV
- Updated results with the full 8 TeV data will be available soon

# Fresh ATLAS Results (this week)



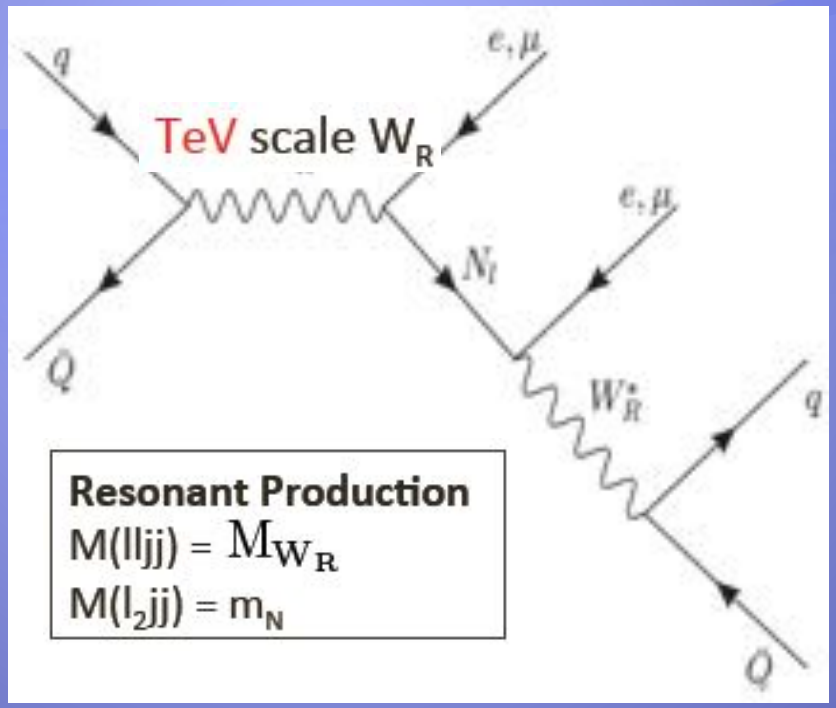




- **No excess, the limits are comparable to the CMS results**

# Searches in LRSM




**Resonant Production**
$M(lljj) = M_{W_R}$
$M(l_2jj) = m_N$

**FINAL STATE**
2 Leptons
2 Jets
No Missing Energy

**Same Final state as type I but very different kinematics (higher energy final state)**

- **Challenges:**
  - For $m_N << m_{WR}$, jets and lepton from N decays overlap → standard isolation will kill signals
  - Same challenges as Type I in terms of bkgds

# Event Selection

**CMS Baseline Selection:**

- 2 Isolated* leptons (e/mu),

No charge requirement on leptons.

- Lepton 1/2 pt > 60/40 GeV,
- Njet ≥ 2 *,
- M(ll) > 200 GeV,

**(remove SM backgrounds),**

- M(lljj) (i.e $m(W_R)$) > 600 GeV.

**ATLAS Baseline Selection:**

- 2 SS/OS isolated leptons,
- Njet ≥ 1,
- Lepton pt > 25 GeV,
- M(ll) > 110 GeV **remove Z's**
- $S_T$ > 400 GeV ($S_T$ is sum of lepton + jet momenta),
- m(lljj) (i.e $m(W_R)$) > 400 GeV.

*** Signal efficiency drops as $m_N$ increases as N is boosted!**

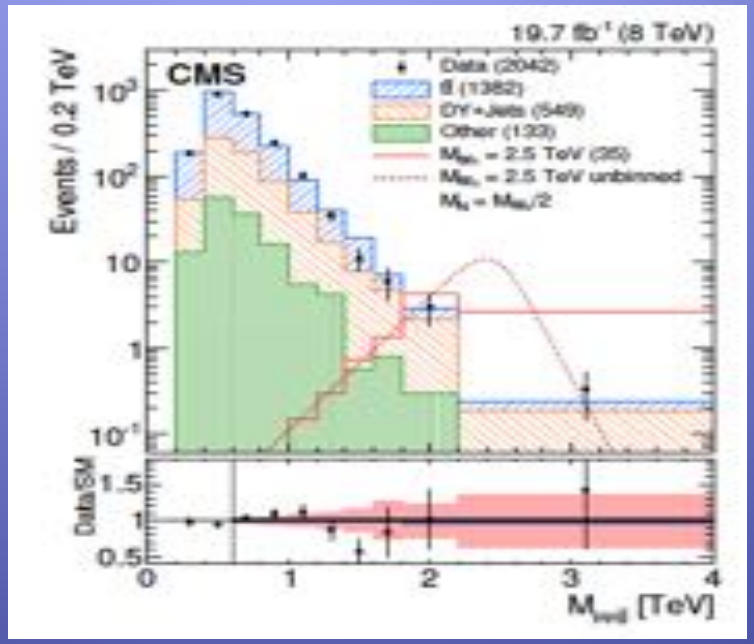
- **Remarks**
  - **With higher energy final state, a large Z backgrounds can be removed. SS/OS are used**
  - **CMS: tighter cuts to reduce more SM bkgds**

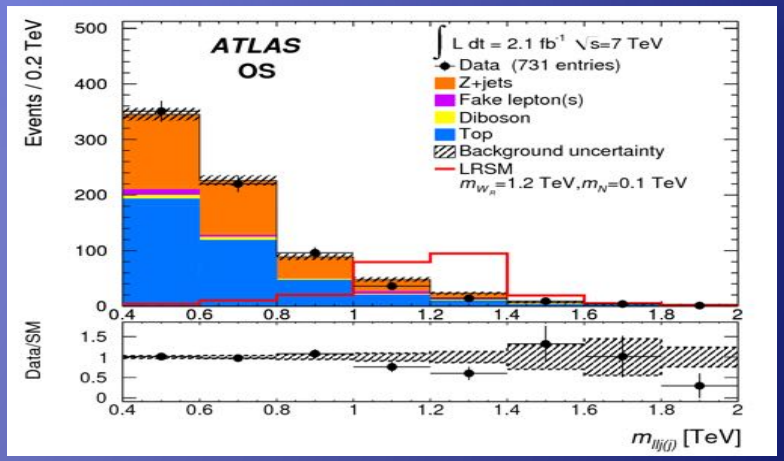
    **→ better for signal with large $m_N$**
  - **ATLAS: try to recover signals with boosted N ( 1 jet events )**

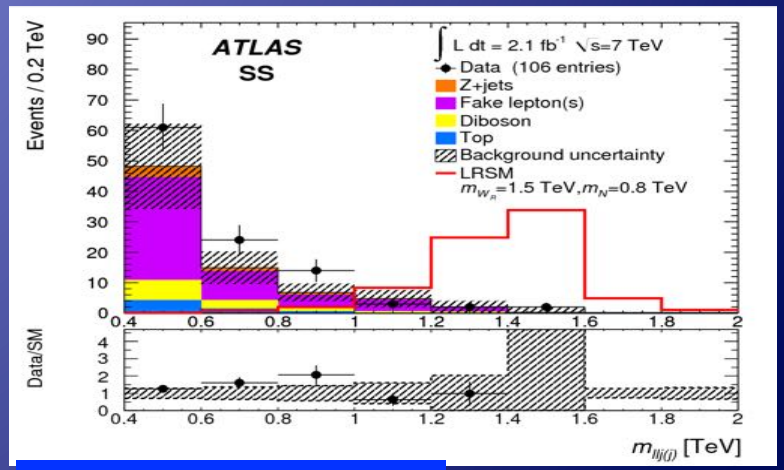
# Backgrounds & Systematics

| Dominant Backgrounds | CMS | ATLAS |
|---|---|---|
| Z+jets | Data + MC | MC |
| ChargeFlip | MC | Data |
| Lepton MisID | Data | Data |
| $t\bar{t}$ (fully leptonic) | Data + MC | Data + MC |

Dominant Systematic
CMS: Background shape
ATLAS: Lepton MisID (SS) / Jet Energy (OS)



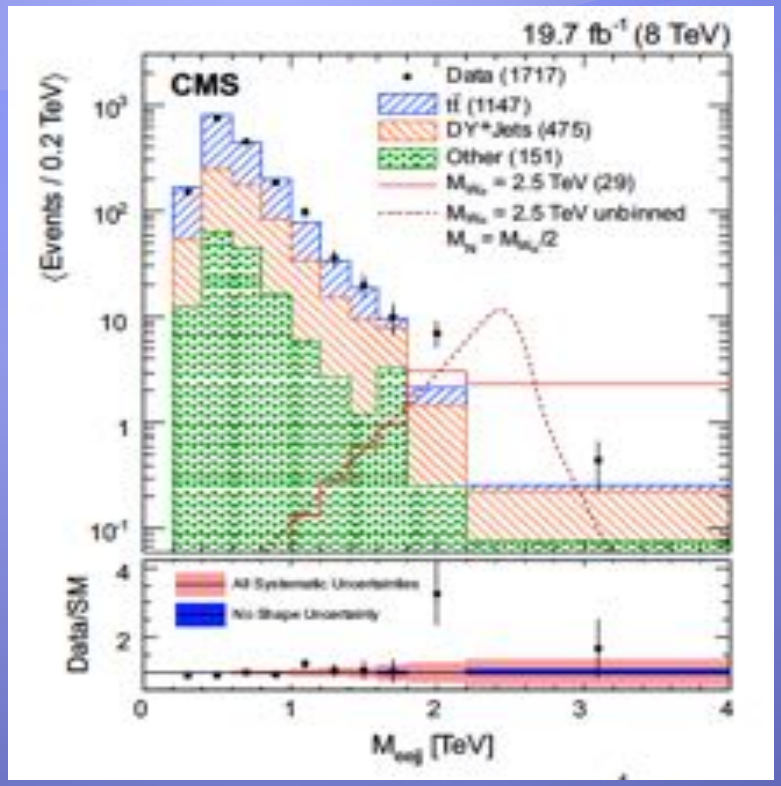

EPJ C74 (2014) 3149

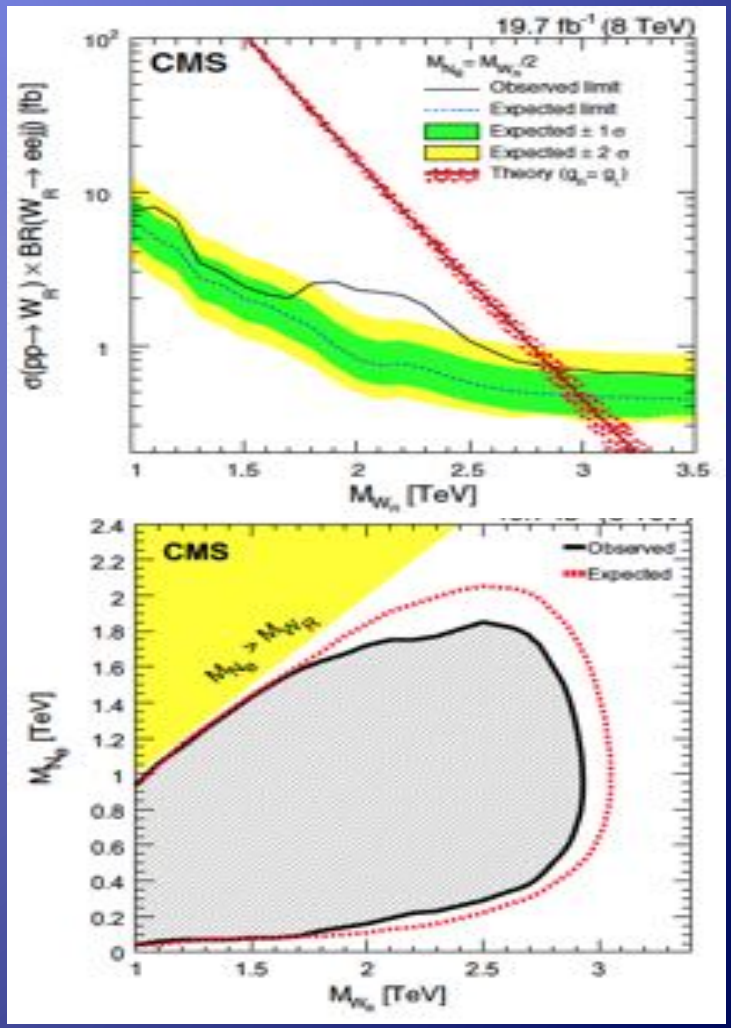
EPJ C72 (2012) 2056

# Limits in the LRSM

- An interesting excess in electron channel?

EPJ C74 (2014) 3149

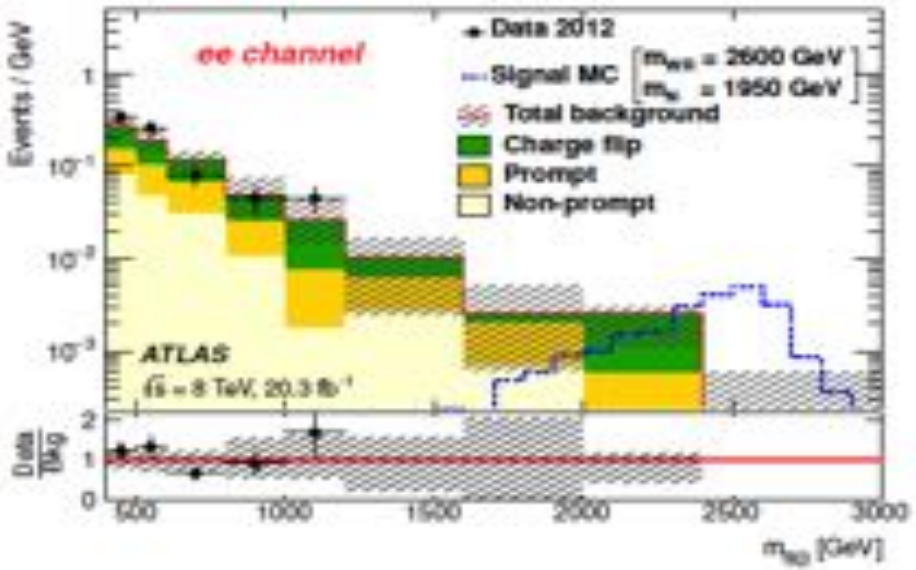


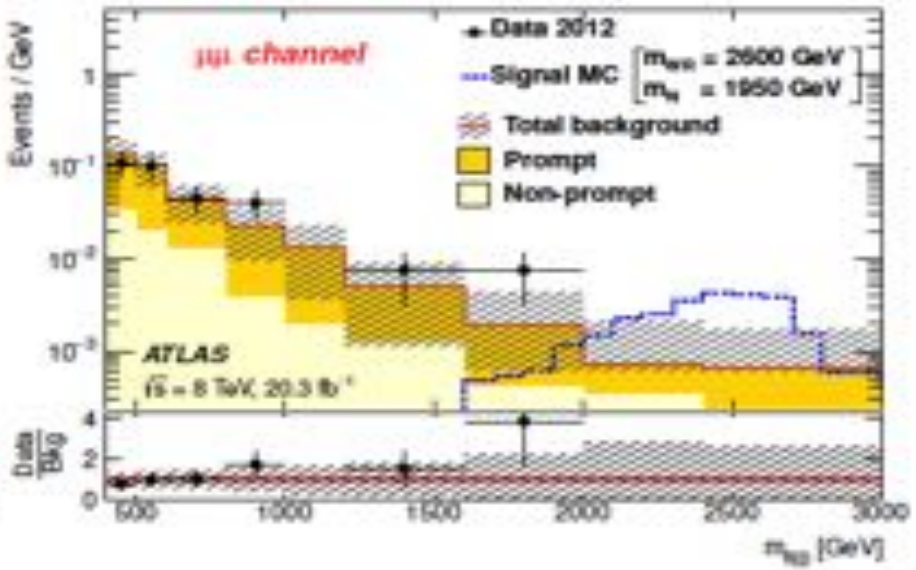




- A local significance, 2.8σ effect
- Consistency with the LRSM?

- It will be interesting to see the ATLAS result!

# Fresh ATLAS Results (this week)



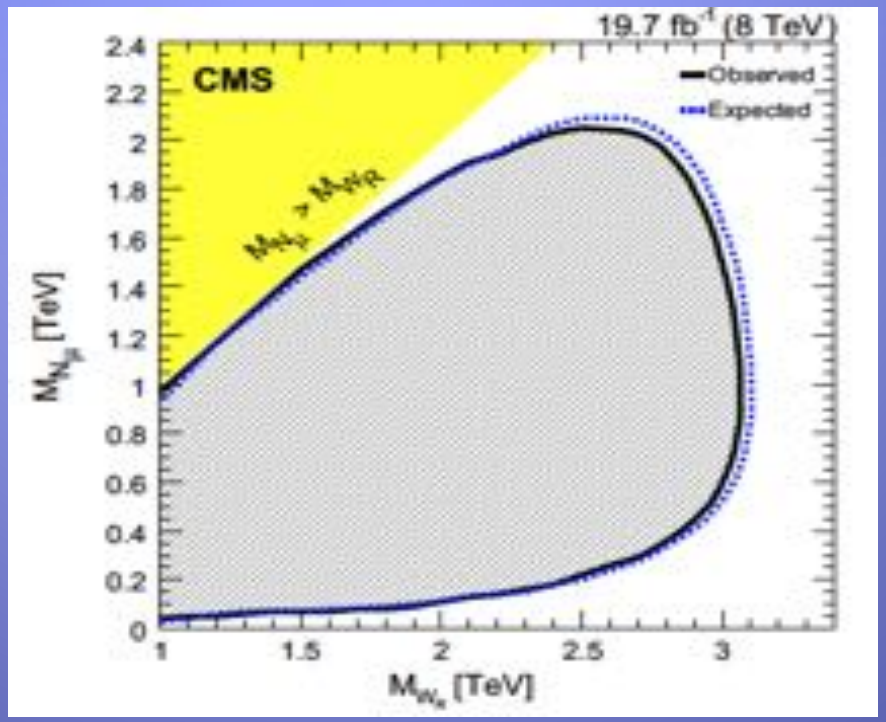



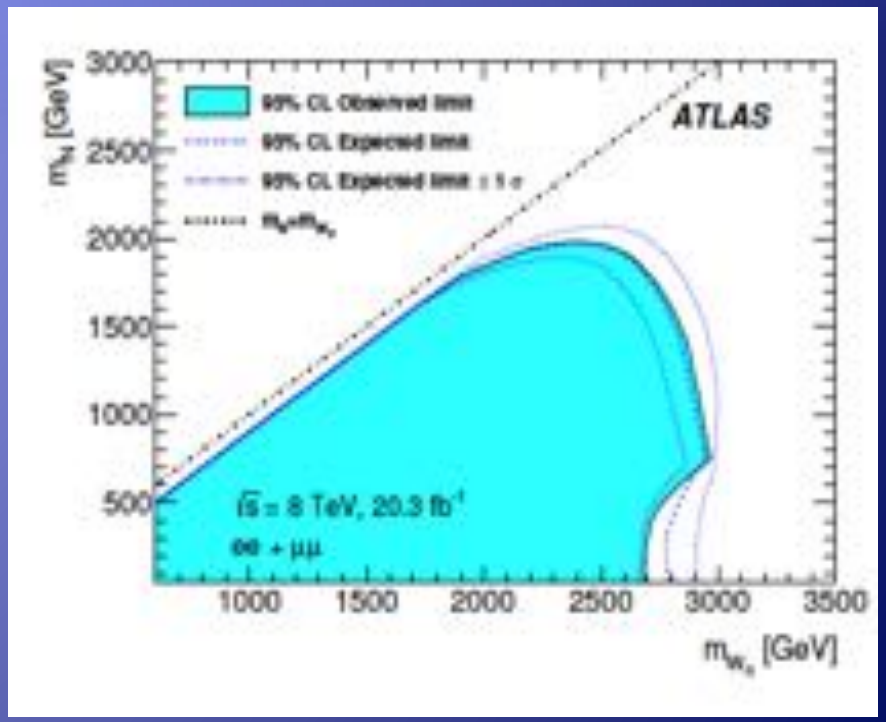

## Invariant mass (lljj)

- No excess in ee channel
- OS channel?

# Limits in the LRSM

- Both use the shape of reconstructed $W_R$ mass
- Exclusion in $m_N$ and $m_{WR}$ plane



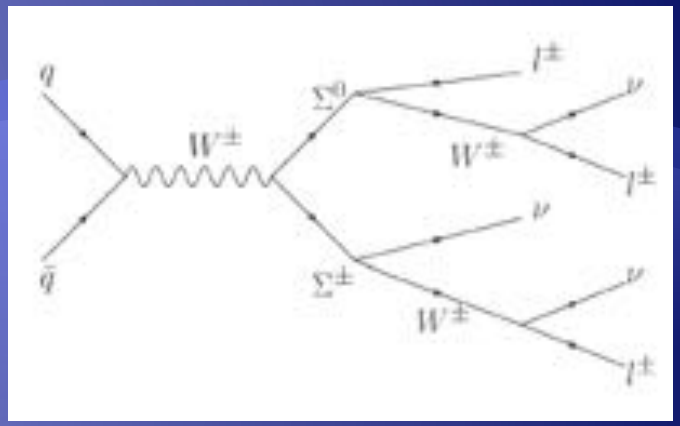



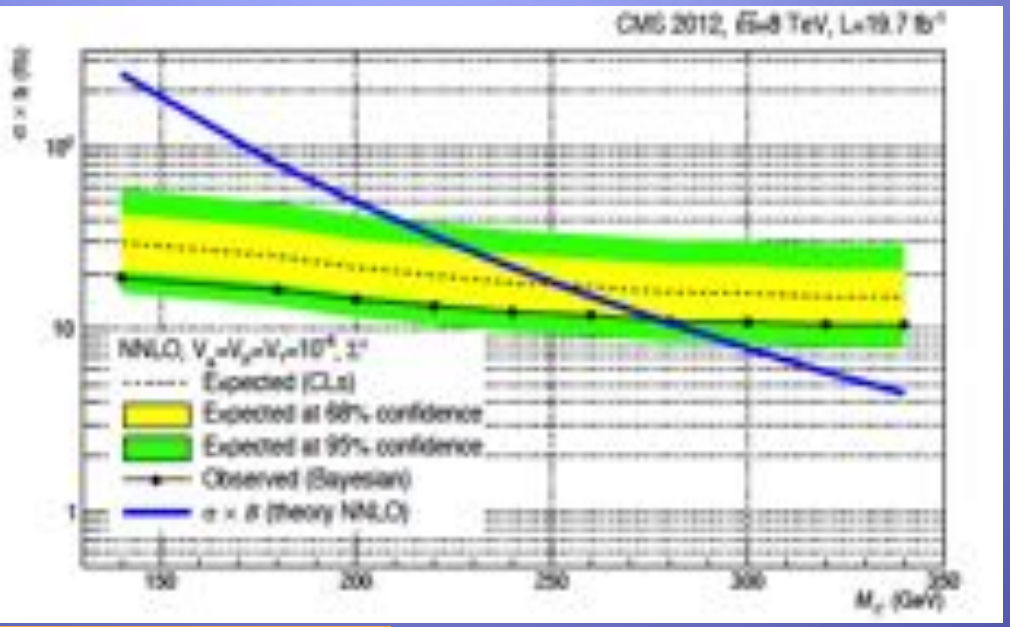

**CMS @ 8 TeV (OS+SS)**
**Best sensitivity in 8 TeV**
**Muon: exclude up to 3.0 TeV**

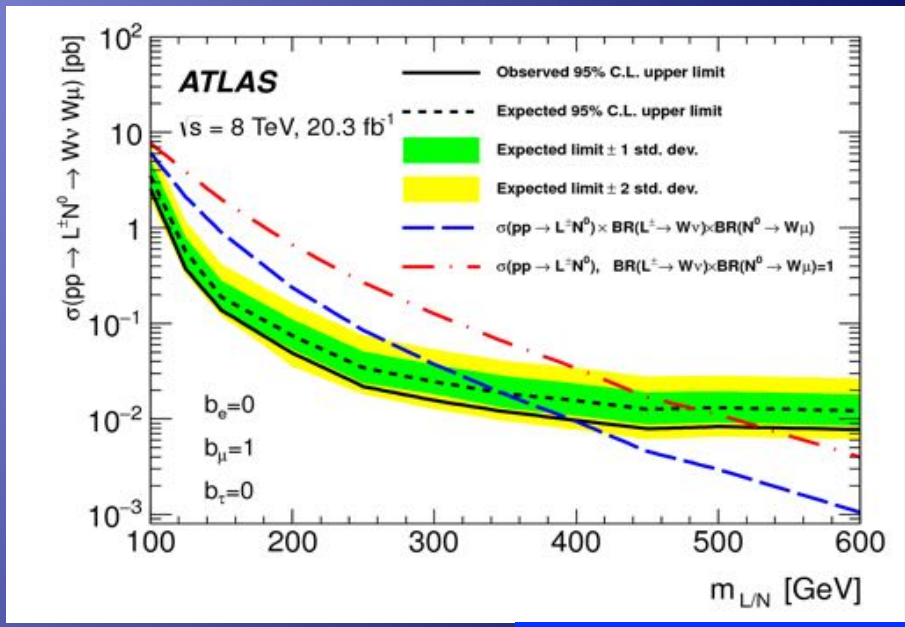
**ATLAS @ 8 TeV**
**Best sensitivity in SS channels**
**Exclude up to 3.0 TeV**

EPJ C74 (2014) 3149

# Type III Results (tri-leptons)




CMS-EXO-14-001

arXiv:1506.01839

# Summary

- ATLAS and CMS have searched for heavy neutrinos in 2 leptons, 2 jets and no missing transverse energy

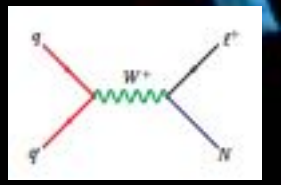
- But with no excess seen in data, 95% CL have been set
  - LRSM: on the mass of heavy neutrino (up to 2 TeV) and $W_R$ mass (up to 3.0 TeV)
  - SeaSaw type-1: on the coupling of heavy and light neutrino as a function of $m_N$

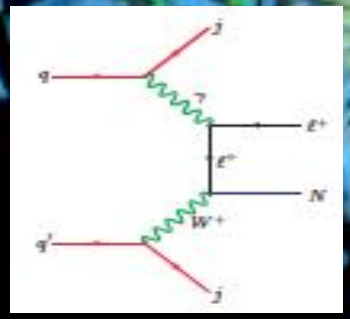
- Fully updated CMS results (type I) with full 2012 dataset (ee,e$\mu$) will be available soon

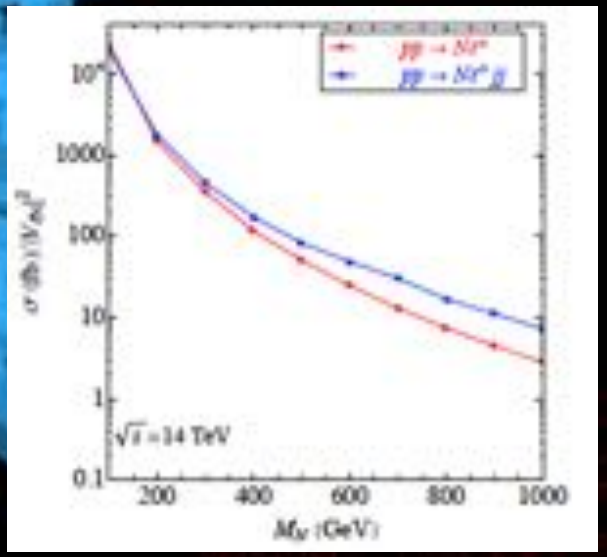
# Prospects

- 13 TeV collisions for Run 2 just started last week!!!
- With high-Lum ((~150 $fb^{-1}$) data by 2018 ( a factor of 4 larger cross section at mN=500 GeV), systematic searches in different channel will be performed: EXCITING TIME

- t-channel for heavy N by $W\gamma$ is found to be a comparable contribution too




- Even with 5 $fb^{-1}$ of 14 TeV data, the limit can be improved by the factor of five

Dev, Pilaftsis, Yang: PRL 112 (2014) 081801

# Backup

# SeaSaw mechanism

**Standard seesaw mechanism:**

- Majorana mass terms can be added to the SM Lagrangian 'for free'

$$m_\nu \simeq \frac{m_D^2}{M}$$

- Normally means for $M_\nu$ that $M_N >>$ TeV (i.e., not interesting at the LHC)

**But there are frameworks with smaller heavy neutrino mass**

- one attractive model, minimal Type-1 Seesaw mechanism (no extra gauge boson)

→ TeV scale heavy neutrinos

$$m_\nu^{\text{light}} \sim \frac{m_D^2}{m_N} \sim 0.1\ \text{eV}$$

[Pilaftsis '92; Kersten, Smirnov '07; Ibarra, Molinaro, Petcov '10; Mitra, Senjanović, Vissani '11; ...]

**With a more fundamental theory**

- 'Left-Right Symmetric Model' (**LRSM**) which adds a chiral $SU(2)_R$ symmetry to the SM (extra new bosons)

# Previous Constraints on Mixing

- Electroweak precision data constraints using global fit to tree level processes involving light neutrino experiments.

$$\sum_i |V_{eN_i}|^2 \leq 3.0 \times 10^{-3},\ \sum_i |V_{\mu N_i}|^2 \leq 3.2 \times 10^{-3},\ \sum_i |V_{\tau N_i}|^2 \leq 6.2 \times 10^{-3}$$

[Langacker, London '88; Bhattacharyya *et al.* '92; Pilaftsis '95; del Aguila, de Blas, Perez-Victoria '08]

- Additional stringent bounds are set on the coupling $V_{eN}$ between N and electrons set by double neutrino-less beta decay experiments

$$\left| \sum_{i=1}^{n} \frac{V_{eN_i}^2}{m_{N_i}} \right| < 5 \times 10^{-8}\ \text{GeV}^{-1}$$

- LFV constraints for mixing involving 2 leptons

$$\left| \sum_i V_{eN_i} V_{\mu N_i}^* \right| \leq 10^{-4},\ \left| \sum_i V_{eN_i} V_{\tau N_i}^* \right| \leq 10^{-2},\ \left| \sum_i V_{\mu N_i} V_{\tau N_i}^* \right| \leq 10^{-2}$$

[Korner, Pilaftsis, Schilcher '93; Ilakovac, Pilaftsis '94; Tommasini *et al.* '95; Illana, Riemann '00]