Searches for Electroweak-Scale Heavy Neutrinos at the LHC

Un-ki Yang

Seoul National University

On behalf of the ATLAS and CMS collaborations

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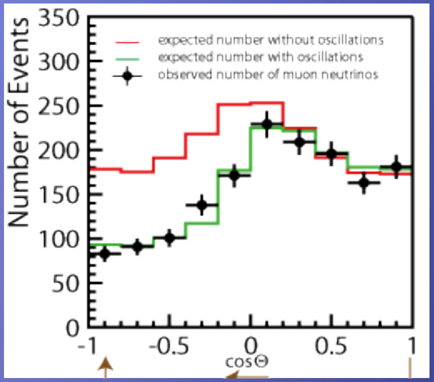
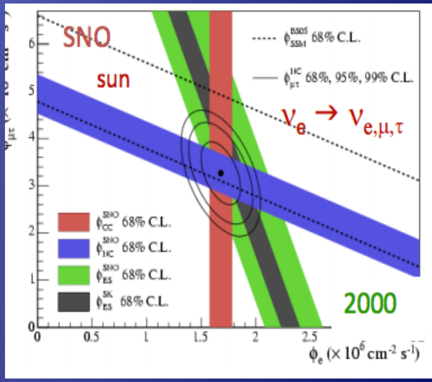
Why Heavy Neutrinos?

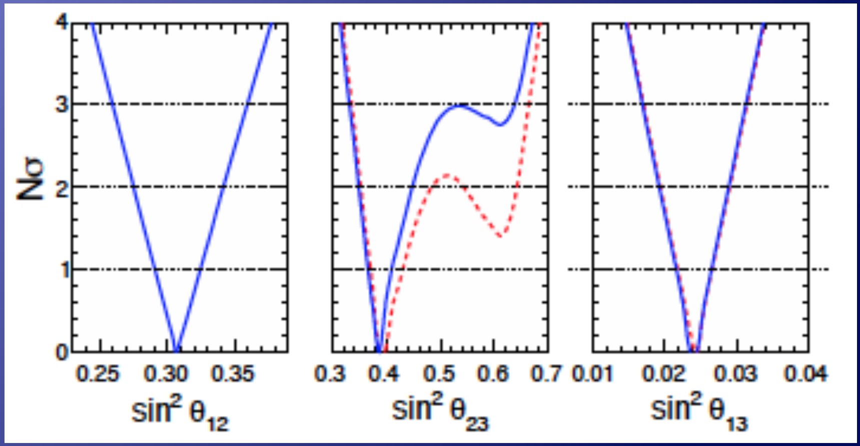
- Neutrinos oscillates between
  all three flavours
  → at least two massive neutrions





- First conclusive experimental evidence for BSM physics

- Sum of light neutrino masses
  < 0.3 eV from cosmology



- Small neutrino mass can be naturally explained by the SeaSaw mechanism with Majorana heavy neutrinos

SeaSaw mechanism

Standard seesaw mechanism:

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

$$m_\nu \approx \frac{m_D^2}{M}.$$

- Normally means for M_ν that M_N >> TeV (i.e., not interesting at the LHC)

But there are frameworks with smaller heavy neutrino

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

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

→ TeV scale heavy neutrinos

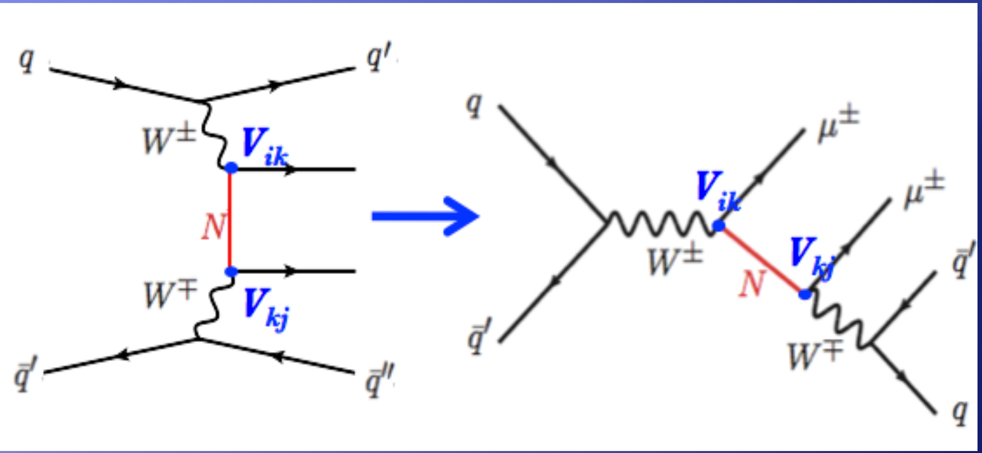
[Pilaftsis '92; Kersten, Smirnov '07; Ibarra, Molinaro, Petcov '10; Mitra, Senjanović, Vissani '11; ...]

With a more fundamental theory

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

Minimal Type-1 Seesaw Model

- Search for heavy neutrino production at LHC in Lepton Number Violating (LNV).: equivalent to neutrino-less double beta decay



- Single heavy neutrinos, pair production of heavy neutrinos

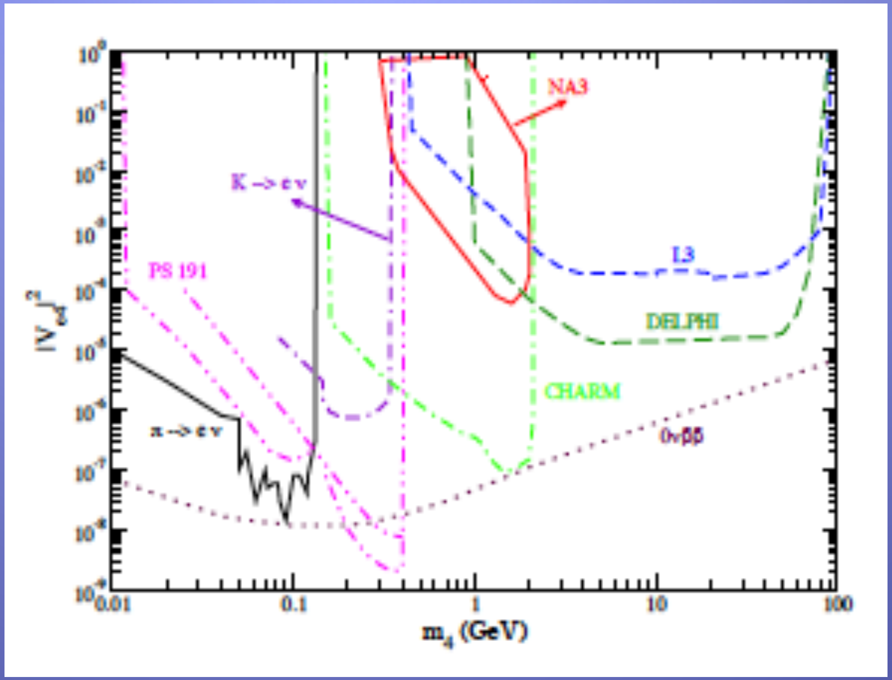
Signal: 2 leptons + 2 jets + no $\not{p}_T$

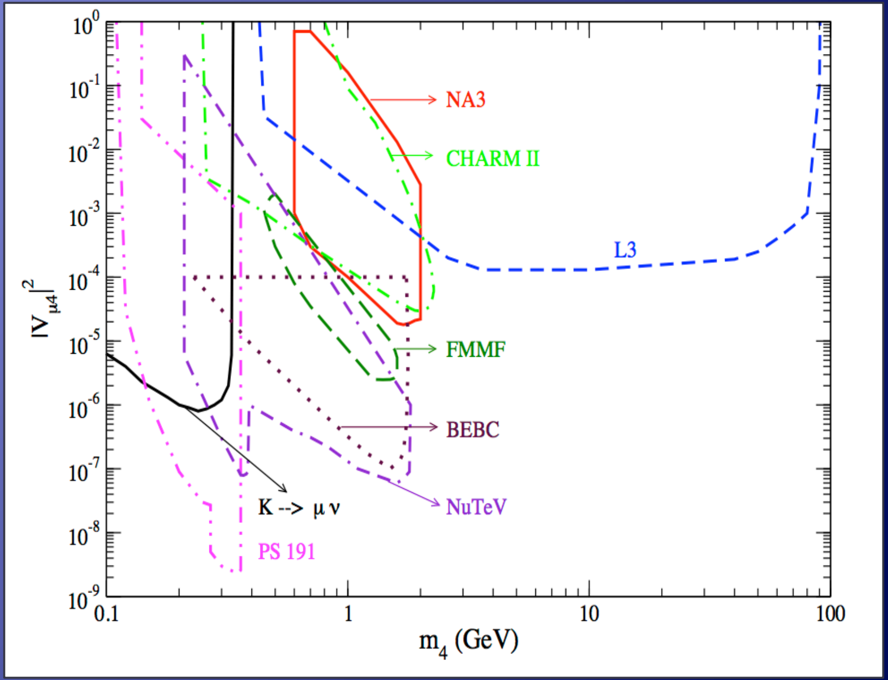
LNV signatures: $pp \to e^+e^+,\ e^+\mu^+,\ e^-e^-$

LFV signatures: $pp \to e^+\mu^-,\ e^-\mu^+,\ e^-\tau^+$

Previous Constraints on Mixing

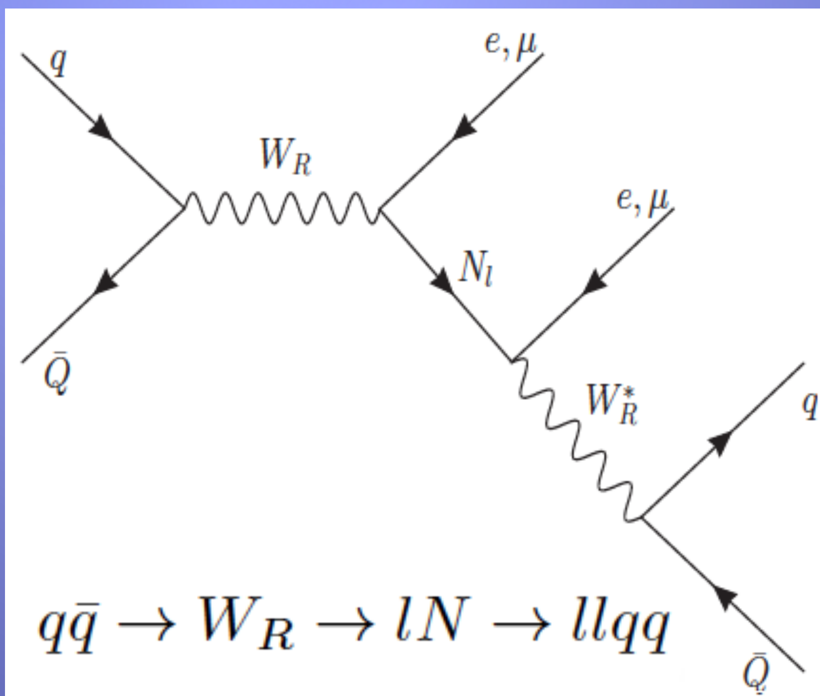
- Use rare leptonic decays of pion/kaons.
- As well as direct searches at LEP





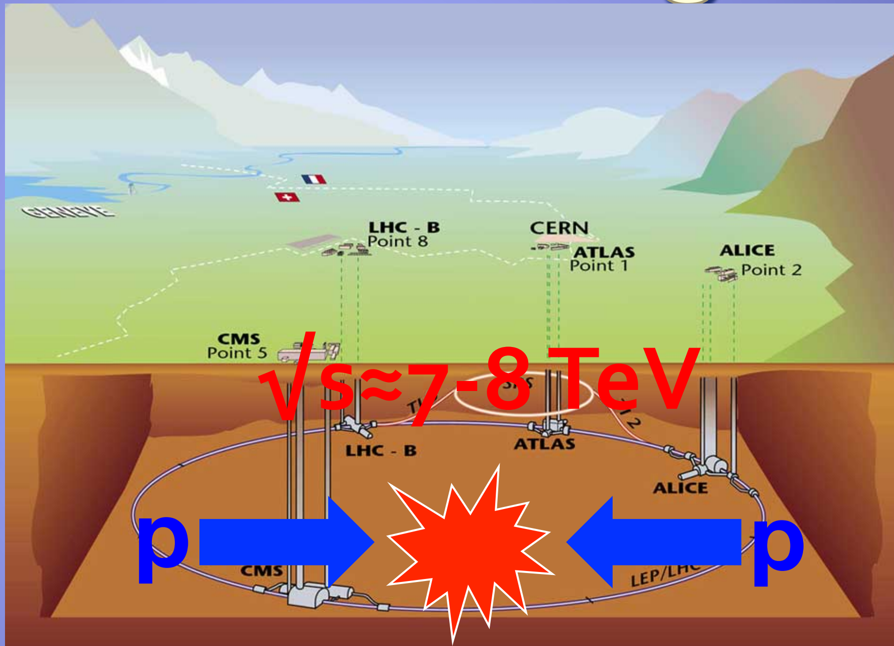
[Atre, Han, Pascoli, Zhang '09]

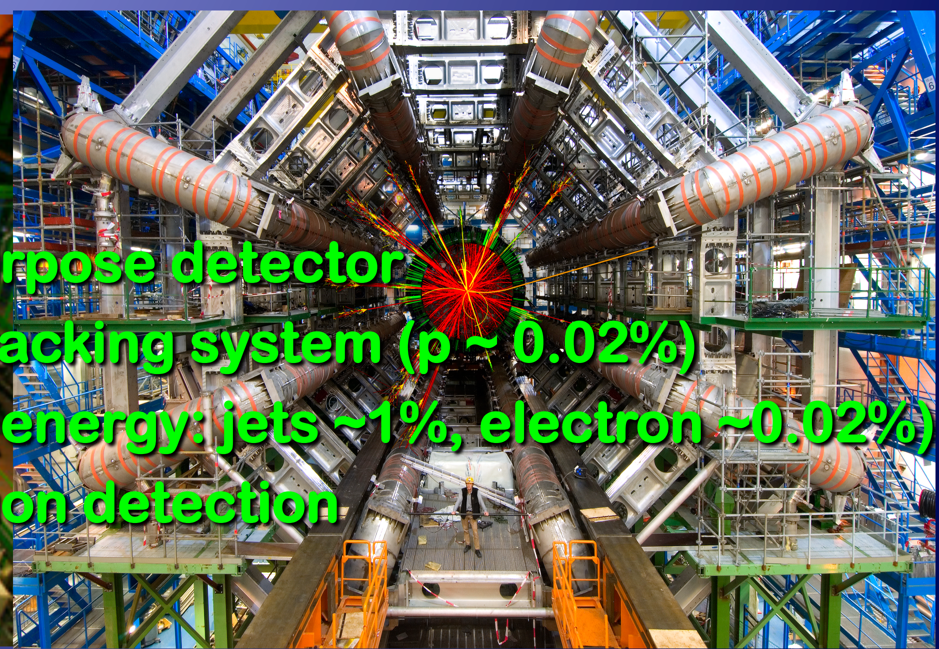
Heavy Neutrinos in the Left-Right Symmetric Model (LRSM)



- A high energy gauge theory that can explain parity violation in weak sector
- Includes 3 (TeV scale) gauge bosons (2W$_R$ and Z')
- Naturally introduces heavy right-handed neutrinos, N$_l$ (m$_N$, m$_{WR}$ and m$_{Z'}$ are free parameters)
- Promising signature at LHC

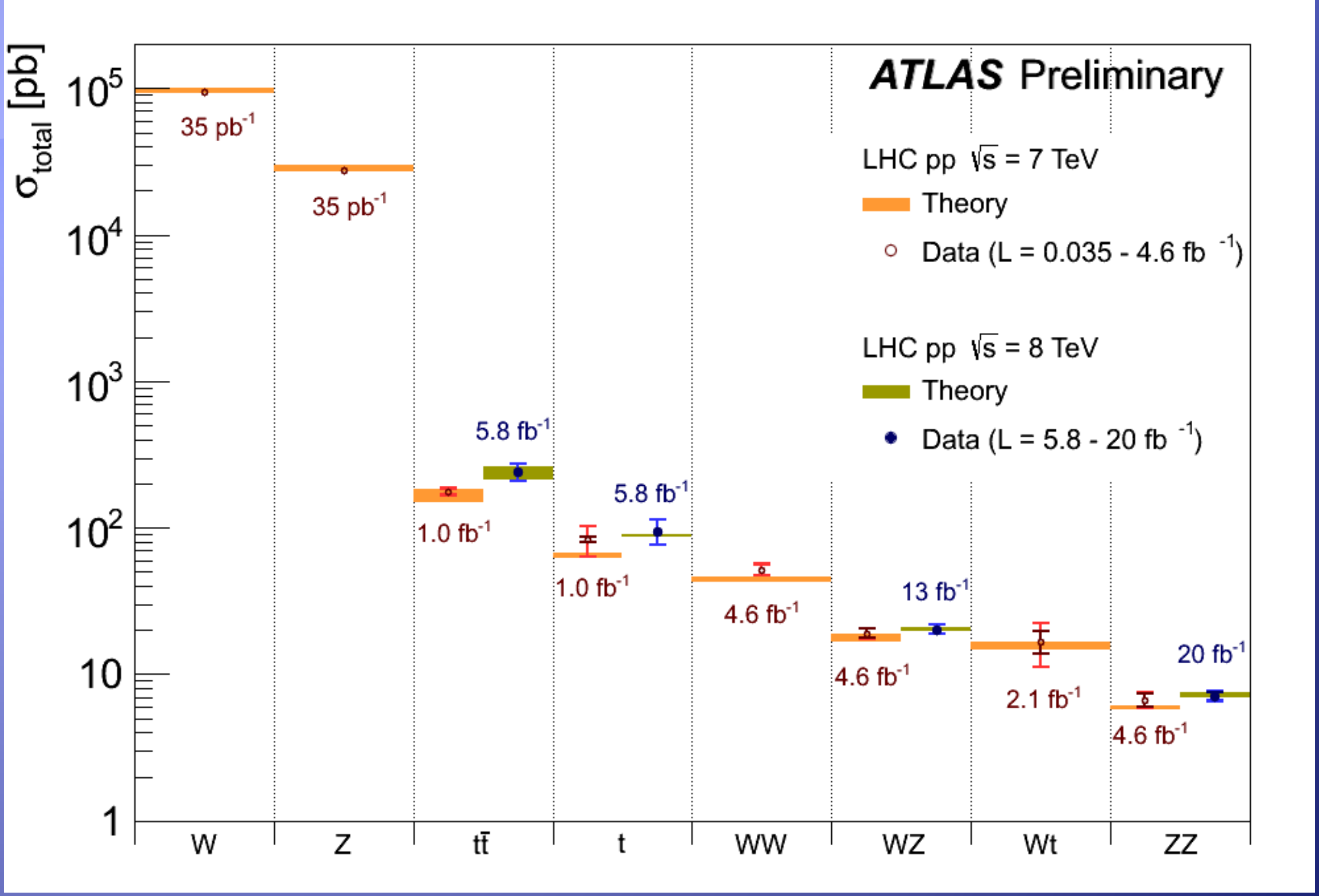
Use the Large Hadron Collider!!!





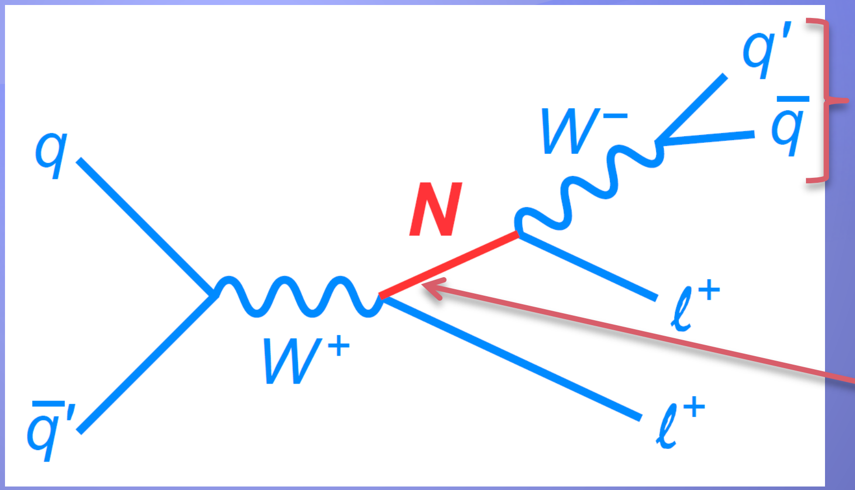
- High precision multipurpose detector
- Excellent vertex and tracking system (p ~ 0.02%)
- Excellent calorimetry (energy: jets ~1%, electron ~0.02%)
- Large coverage for muon detection

Before Searching for New Physics



- **Impressive agreement with the SM across orders of magnitude**

Searches in Minimal Type-1 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 mis-identified leptons from multijet QCD events
  - Understanding charge misidentification rate for electron: important from Z+jets bkgd

Event Selection

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

CMS Event Selection:	ATLAS Event Selection:
- 20/10 GeV lepton pt cuts.	- 20/20 GeV lepton pt cuts.
- Di-lepton Triggers	- Single lepton trigger
- MET < 50 GeV.	- MET < 35 GeV
- Third letpton veto	- Veto on third **loose** lepton
	- 55 < M(jj) < 120 GeV

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

Backgrounds and systematics

Backgrounds

Misidentified Lepton:

$b\bar{b}$ / $t\bar{t}$ / W+jets (uses data)

Charge mis-reconstruction:

Z+jet (data and MC) only in electron channel.

Prompt:

WZ, ZZ, SS WW, V+ $t\bar{t}$ (MC)

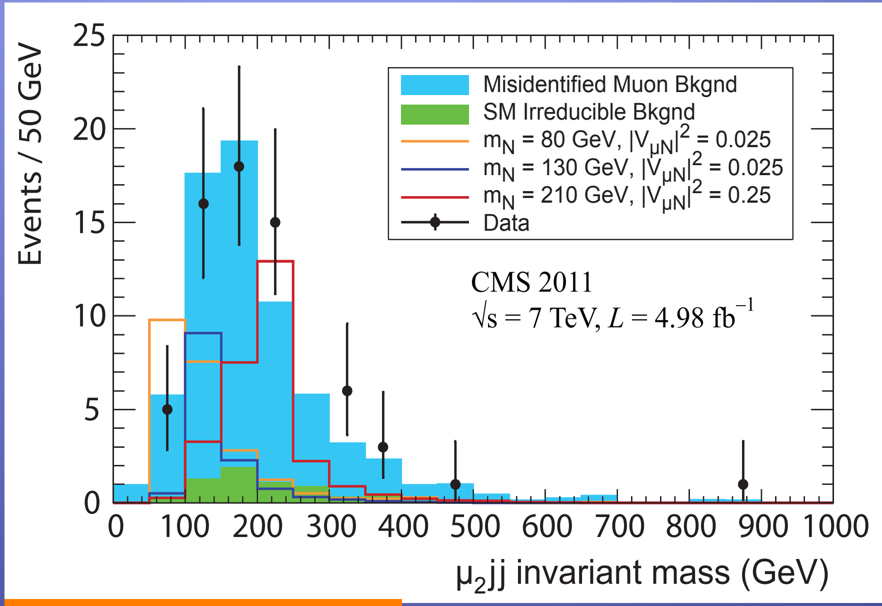
Main Systematics

QCD background (35-50%).

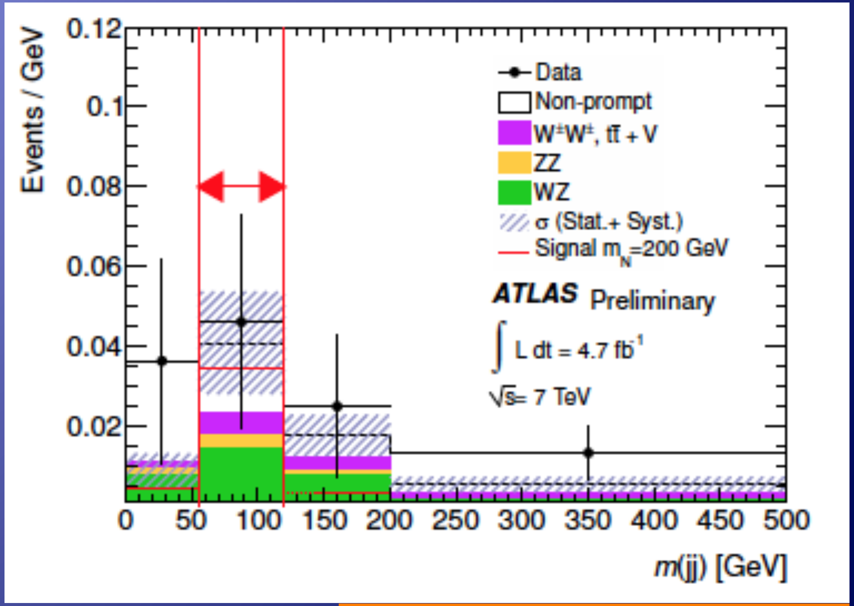
Charge misID 25%. (CMS only)

Jet Energy Uncertainty

Largest background is misidentified lepton in CMS (blue), WZ in ATLAS (Green).



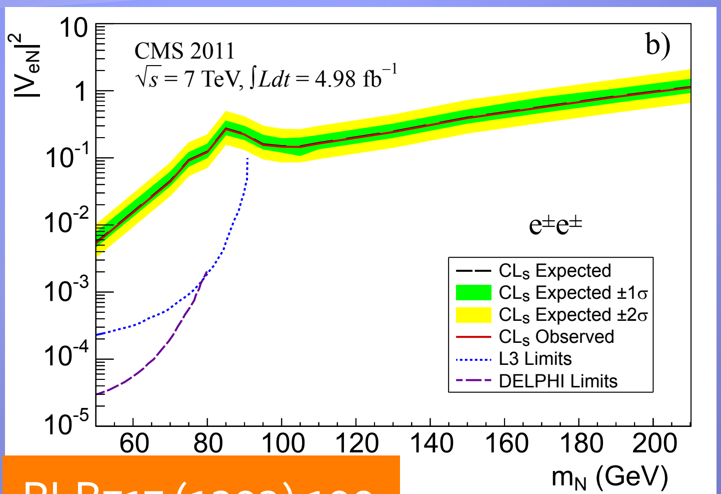
PLB717 (1202) 109



ATLAS-CONF-2013-019

Results

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



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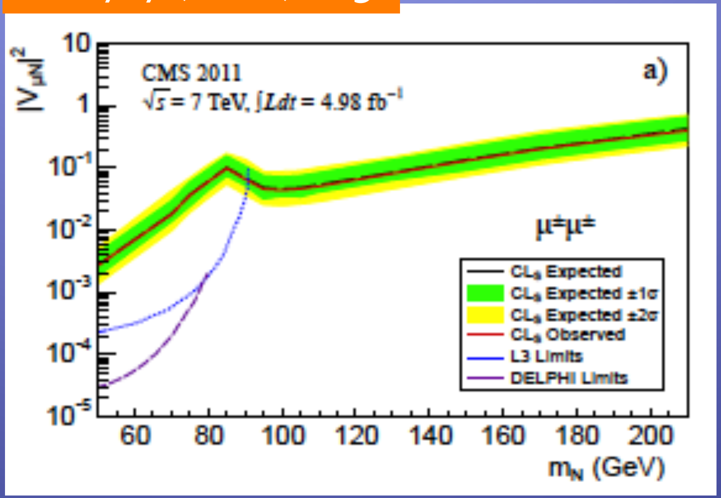
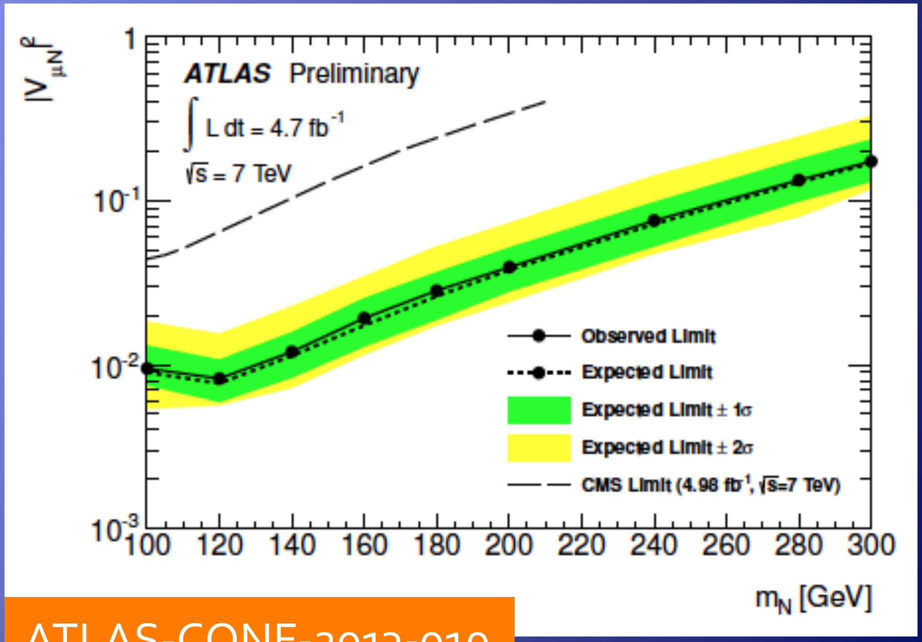
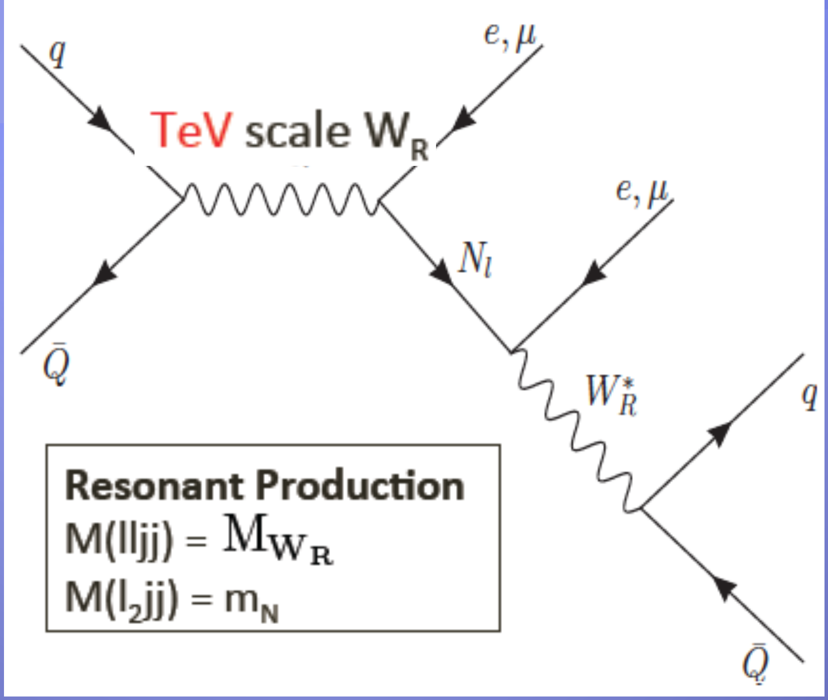




ATLAS-CONF-2013-019

- First direct limits for m_N>90 GeV from LHC
- Updated results with the full 8 TeV data will be available soon

Searches in Left-Right Symmetric Model (LRSM)



FINAL STATE
2 Leptons
2 Jets
No Missing Energy

Same Final state as SeaSaw-1 but very different kinematics (higher energy final state)

- **Challenges:**
  - **For m_N<<m_{WR}, jets and lepton from N decay overlap → standard isolation will kill signals**
  - **Same challenges as SeeSaw Type-1 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.

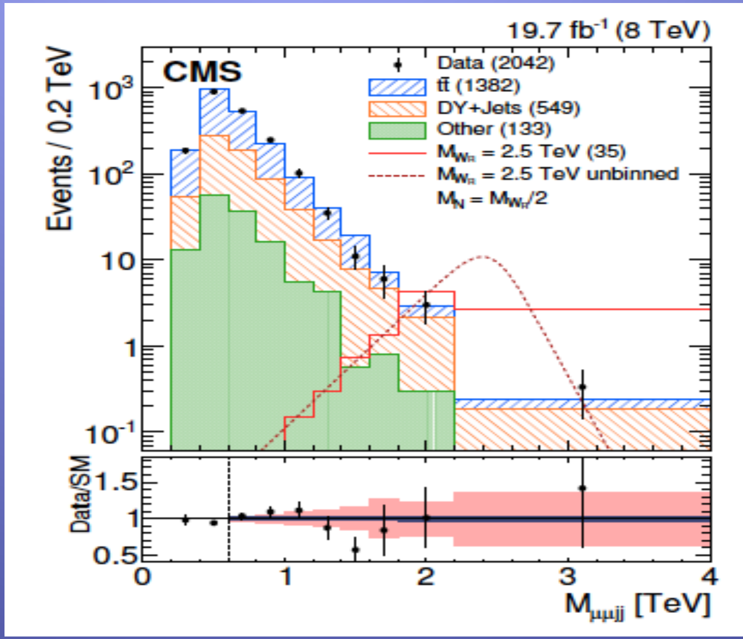
*** Signal efficiency drops as m_N increases as N is boosted!**

- **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)**

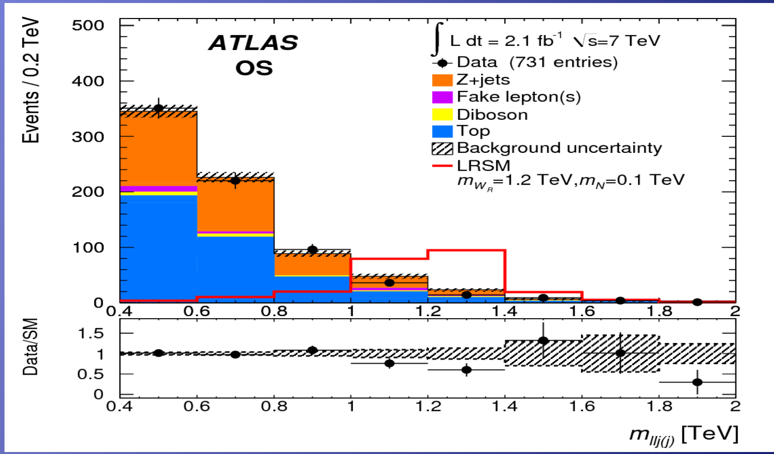
Backgrounds & Systematics

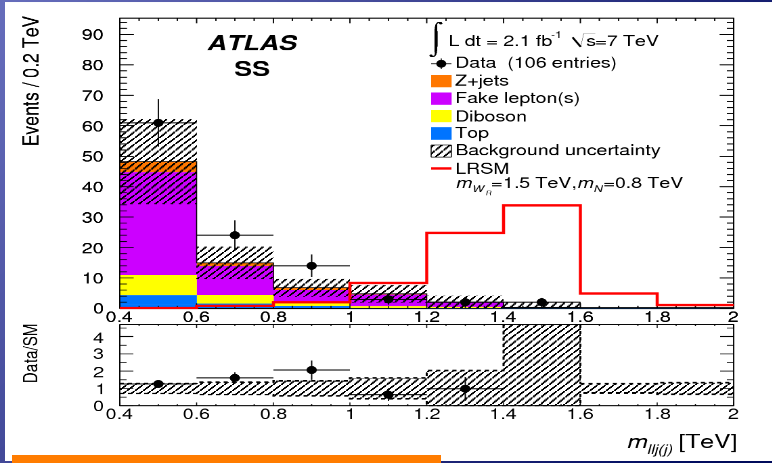
Dominant Backgrounds	CMS	ATLAS
Z+jets	Data + MC	MC
ChargeFlip	MC	Data
Lepton MisID	Data	Data
$t\bar{t}$ (fully leptonic)	Data + MC	Data + MC

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



arXiv:1407.3683

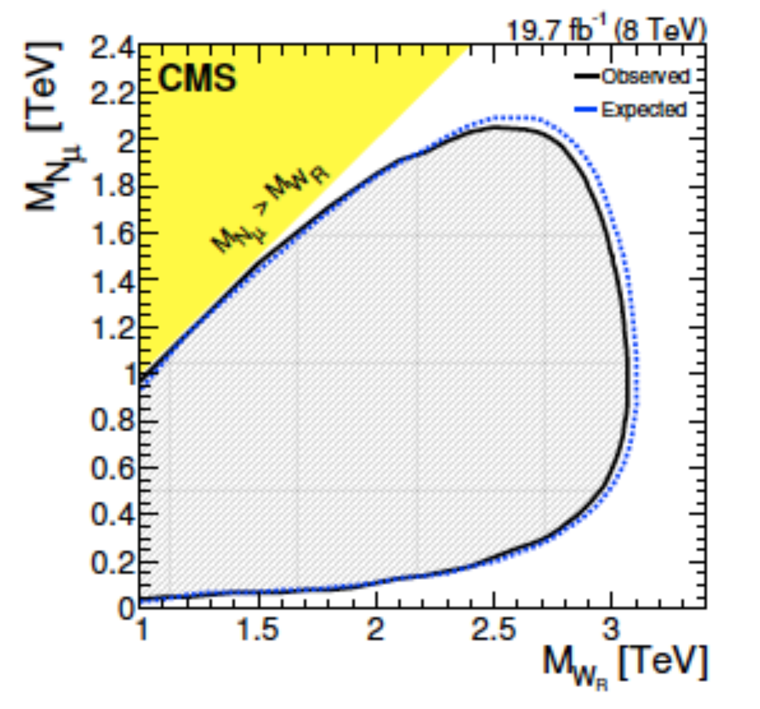


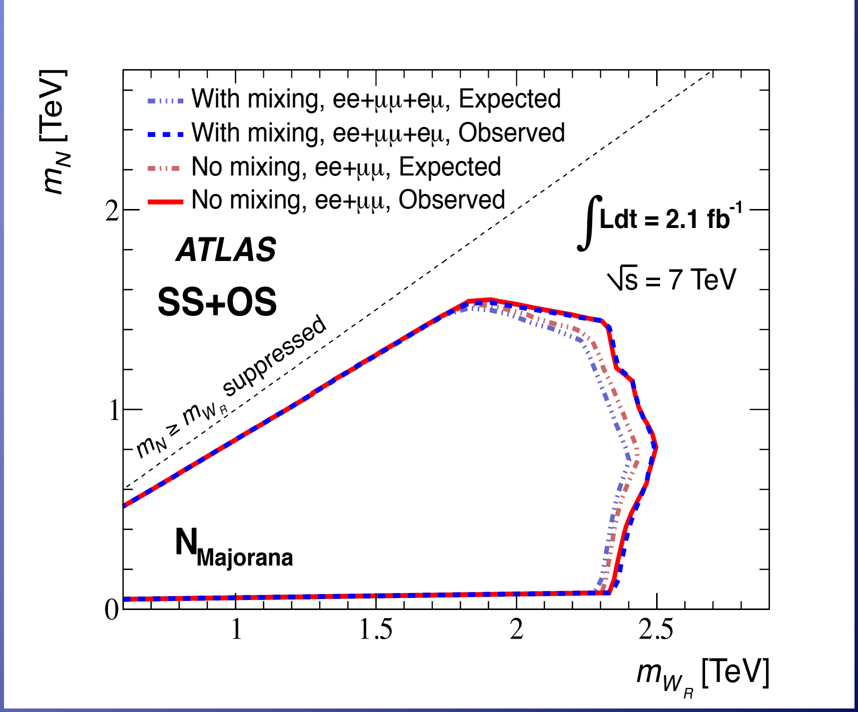


EPJ C72 (2012) 2056

Limits in the LRSM

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





CMS @ 8 TeV
Best sensitivity in 8 TeV
Muon: exclude up to 3.0 TeV

ATLAS @ 7 TeV
Best sensitivity in OS+SS channels
Exclude up to 2.5 TeV

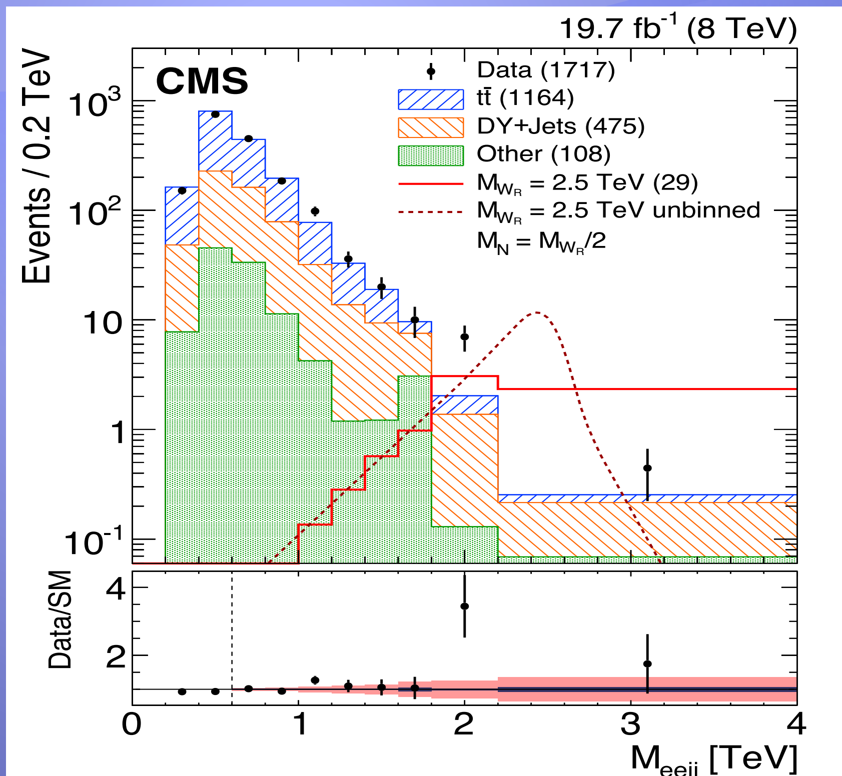
arXiv:1407.3683

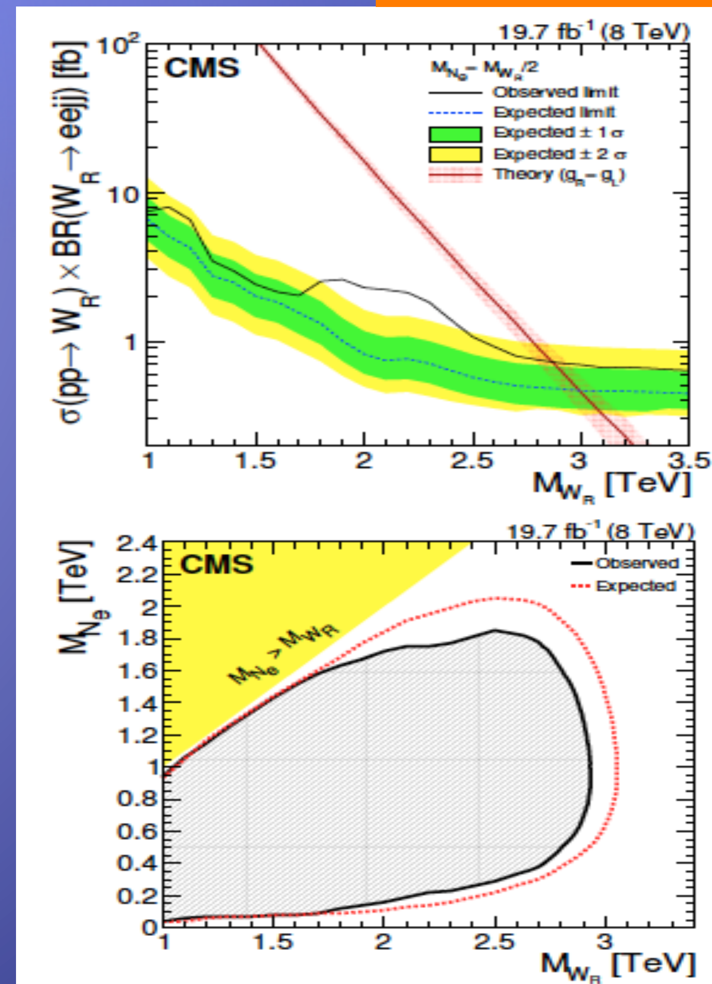
EPJ C72 (2012) 2056

Limits in the LRSM

- An interesting excess in electron channel?

arXiv:1407.3683





- A local significance, 2.8σ effect
- But it doesn't to be consistent with the LRSM

- It will be interesting to see the ATLAS result!

Conclusion

- ATLAS and CMS have searched for heavy neutrinos in the event sample containing 2 leptons, 2 jets and no missing transverse energy
- 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 neutrino and lepton verses m_N
- Updated results with full 2012 dataset will be available soon
- With high-Lum 300 fb^{-1} data by 2017 (a factor of 4 larger Xsection at m_N=500 GeV), systematic searches in different channels will be performed: MORE EXCITING TIME

Backup

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* '91; 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

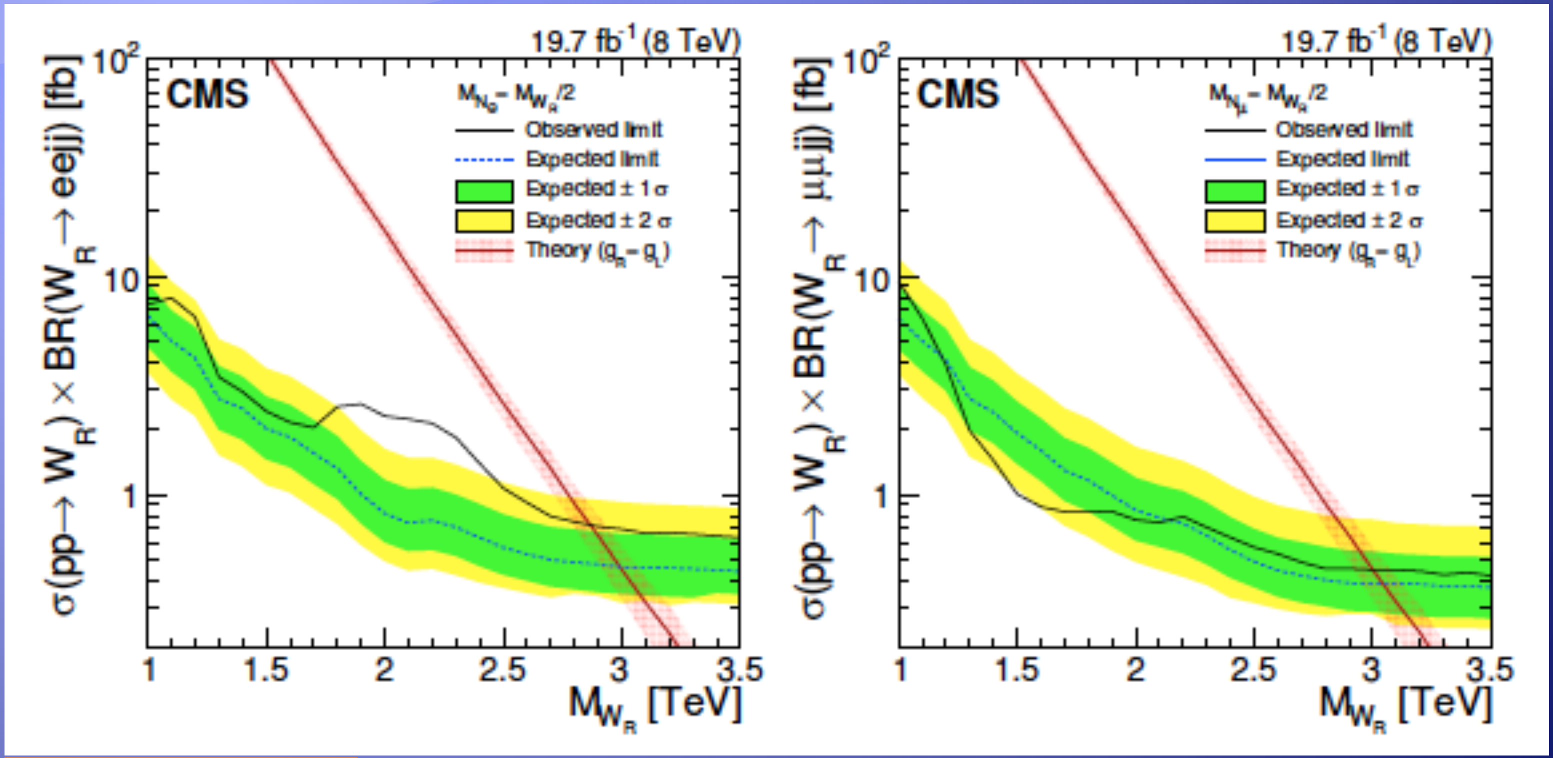
$$\left|\sum_{i=1}^{n} \frac{V_{eN_i}^2}{m_{N_i}}\right| < 5 \times 10^{-8} \ \ \mathrm{GeV}^{-1}.$$

- 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]

CMS Limits in the LRSM

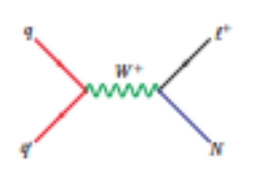


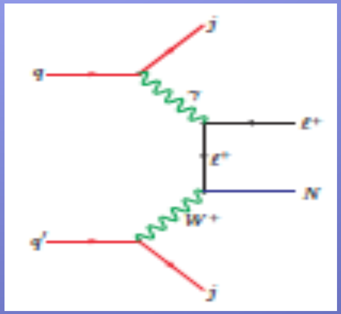
arXiv:1407.3683

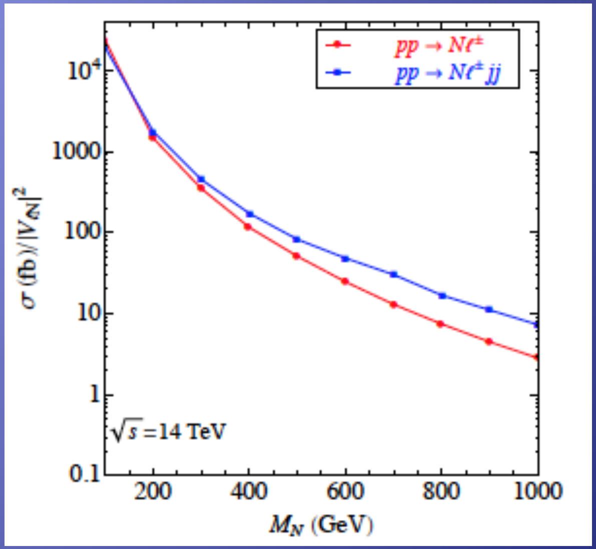
Prospects

- **Both ATLAS and CMS groups plan to update the results using the full dataset by this summer**
- **The LHC searches have been based on only the s-ch W-exchange diagram, but the t-ch. is found to be a comparable contribution**

Dev, Pilaftsis, Yang: PRL 2014







- **Even with 5/fb of 14 TeV data, the limit will be improved by the factor of five**