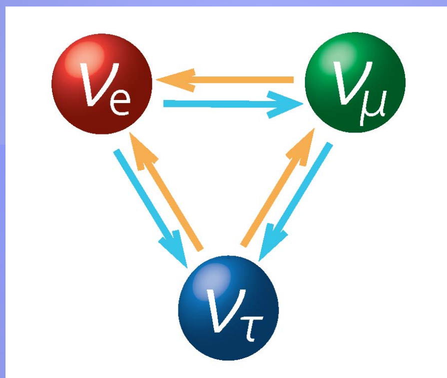
LHC Searches for Neutrino Physics I

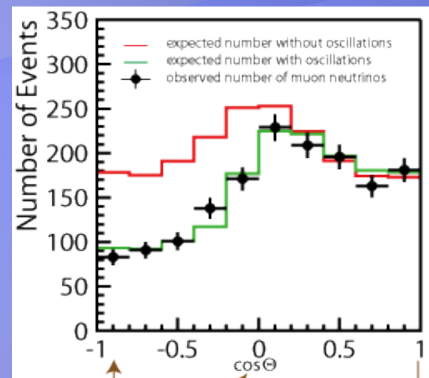
Un-ki Yang

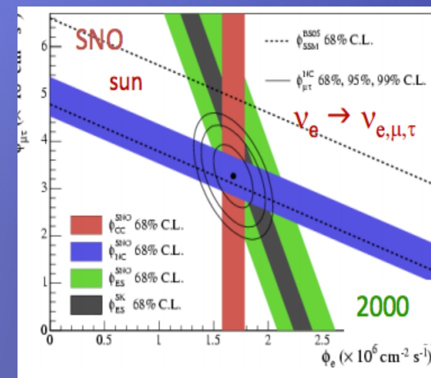
Seoul National University

ACFI Workshop, July 18-20, 2017, U of Mass. at Amherst

Neutrino Oscillation



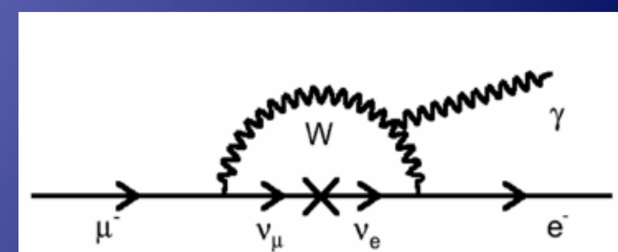


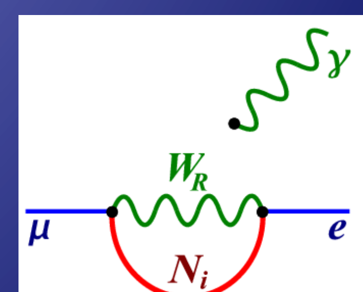


- Neutrino oscillations
- Small neutrino mass

- Lepton Number Violation (LNV)
- Heavy right-handed neutrino

- Beyond the Standard Model



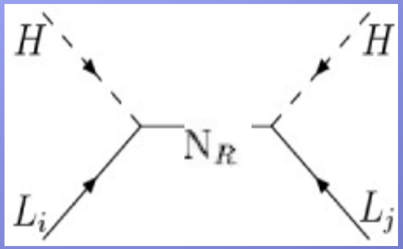


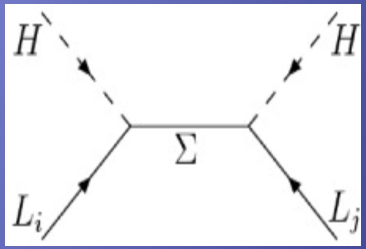
Neutrino: Physics Beyond SM

- A natural way to generate LNV and neutrino mass
  - Introduce an effective operators to the SM

$$\frac{Y_L}{\Lambda_L} LLH^2 + \frac{Y_B}{\Lambda_B^2} qqqL + \ldots$$

  - Seesaw Mechanism (type I, II, III)





Type I: weak-singlet

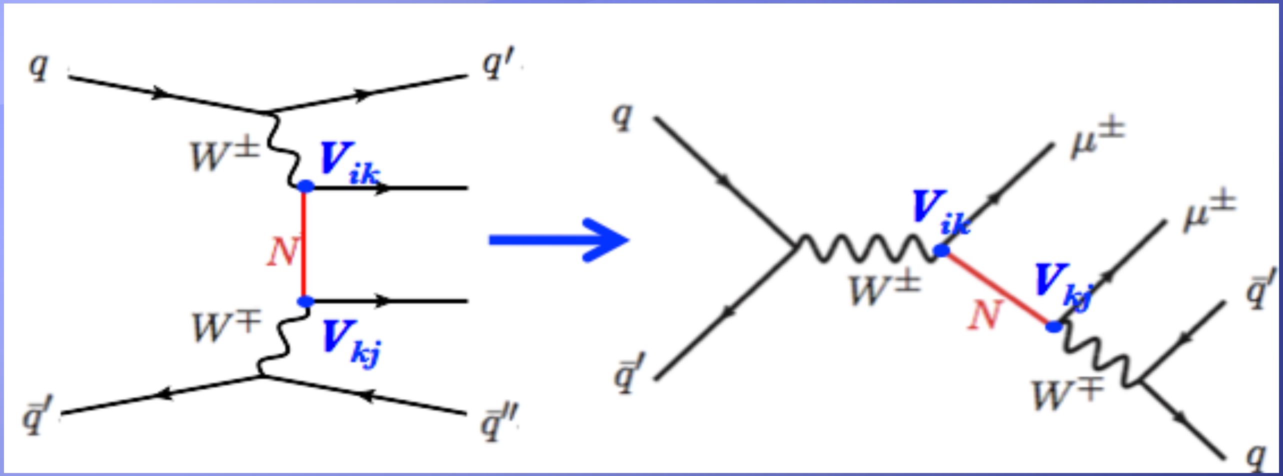
Type III: weak-triplet

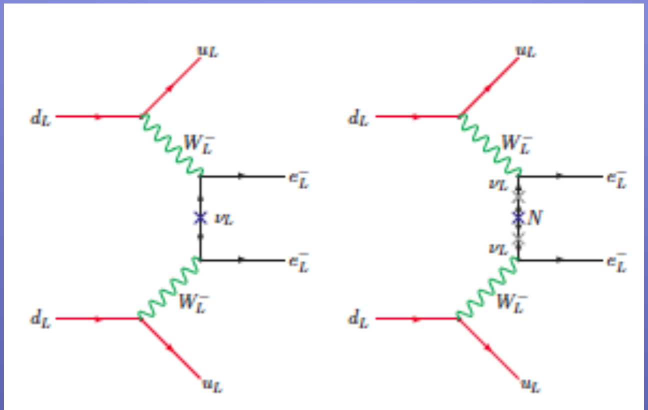
- Physics behind the Seesaw? Left-Right Symmetry model offers the Seesaw scale and heavy neutrinos

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

$$M_{W_R} \gg M_{W_L}$$

Heavy Neutrinos at the LHC?

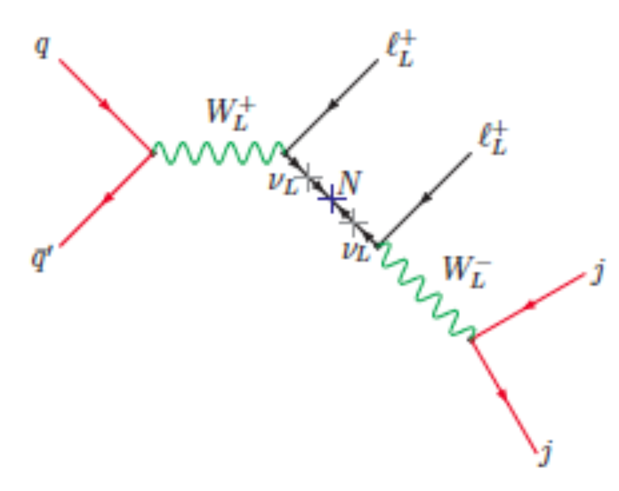




- LHC: direct production of heavy N
  - Same-sign two leptons + 2 jets
  - Type I: probe light-heavy mixing
  - LRSM: a resonance W_R production
- $0\nu\beta\beta$: does not fully probe the light-heavy mixing

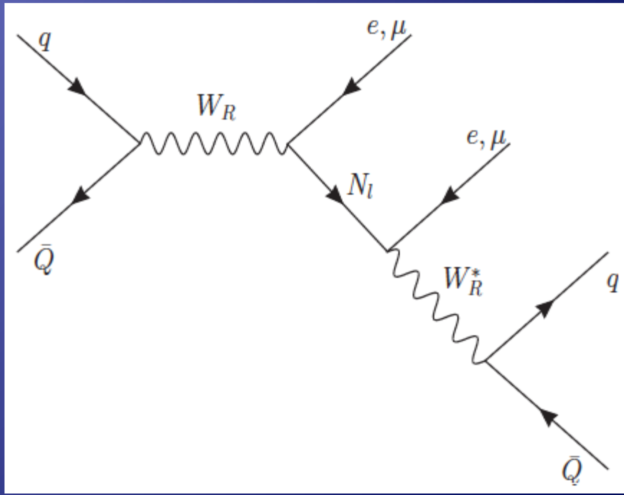
Heavy N productions

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



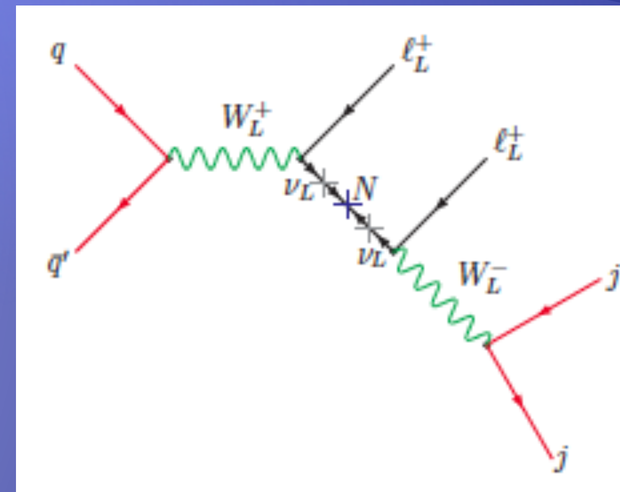
Signal: 2 leptons + 2 jets + no $\not{p}_T$

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



Heavy N productions

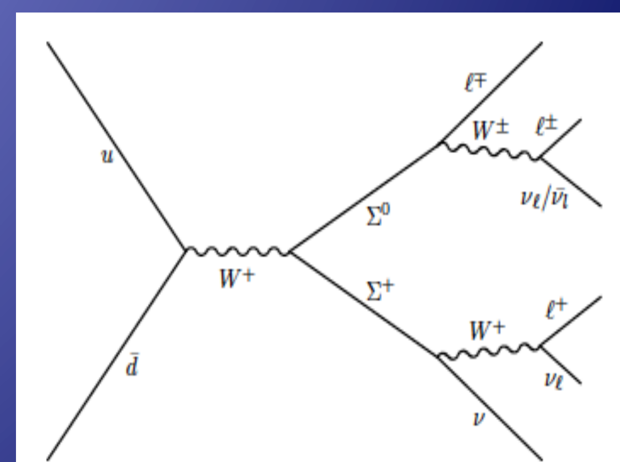
- **Type 1:**
  - Resonant production via s-channel W* or W(real):
  - Majorana: positive or negative lepton (50% same-sign)
  - Cross section depends on $|V_{lN}|^2$ and m_N



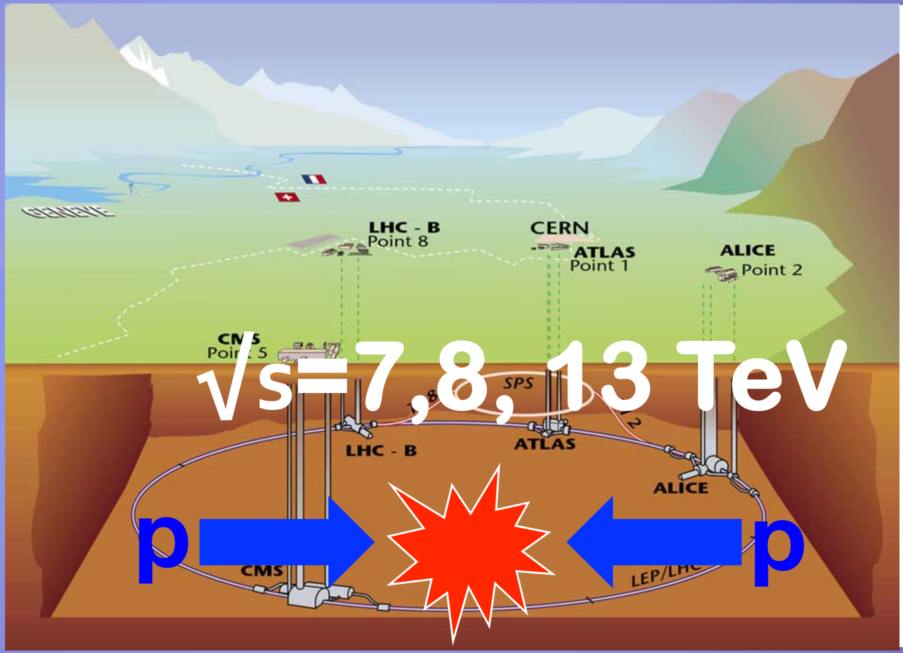
Signal: 2 leptons + 2 jets + no $\not{p}_T$

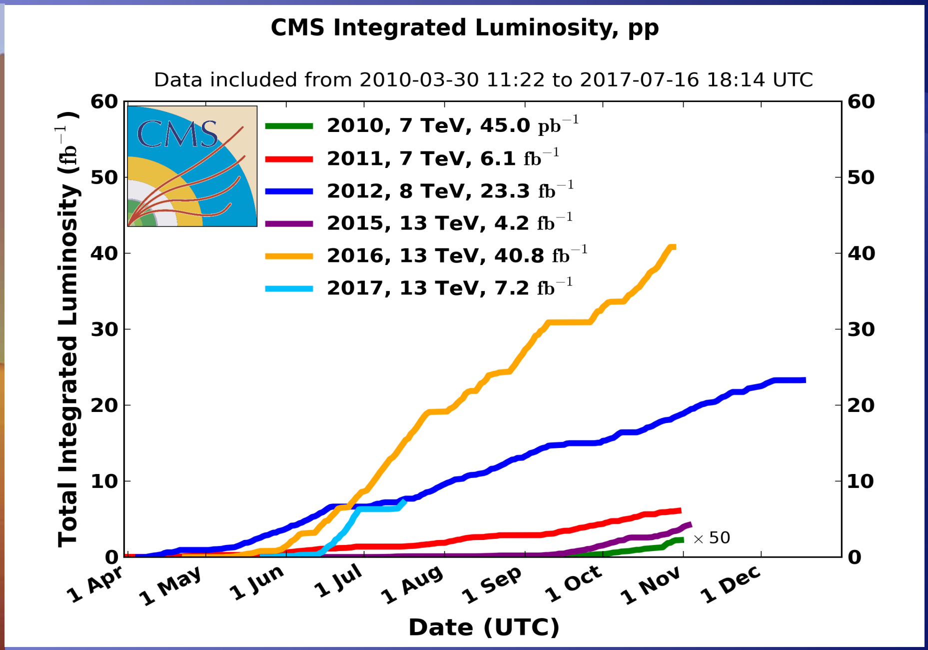
- **LRSM:**
  - TeV scale gauge bosons ($2W_R$ and Z')

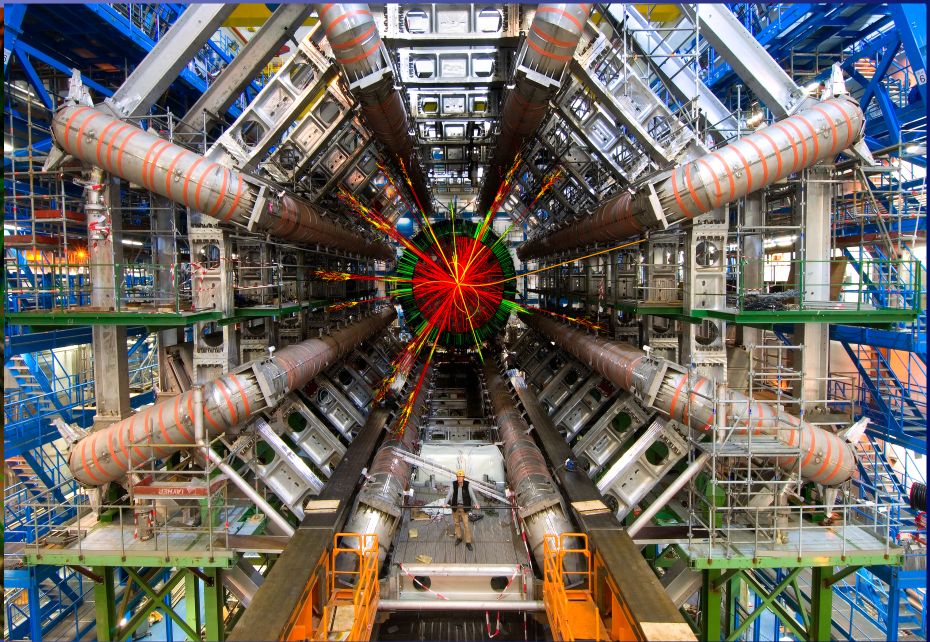
- **Type III:**
  - Production of Σ^0, $\Sigma^{+/-}$ via s-channel W*



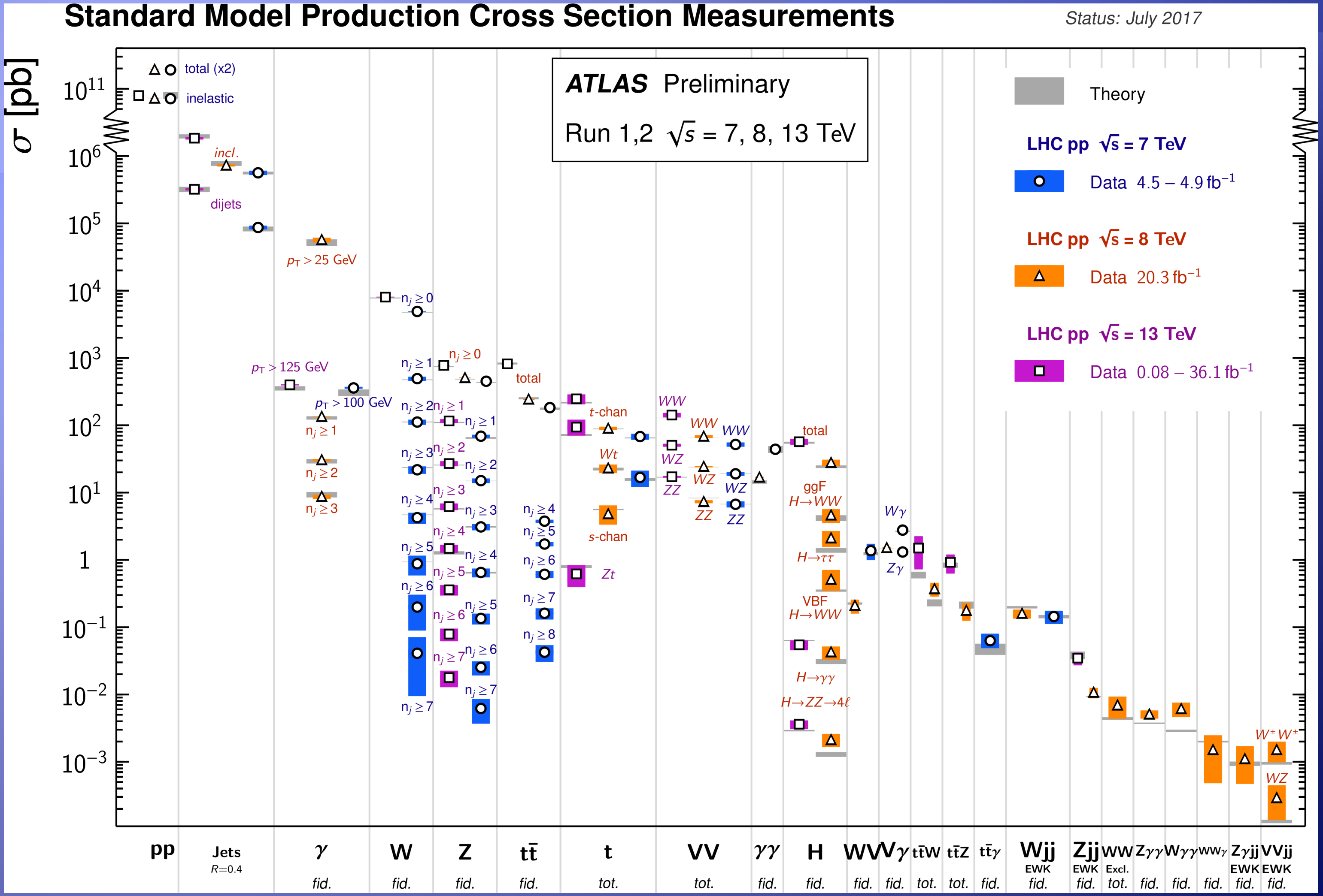
We use the LHC





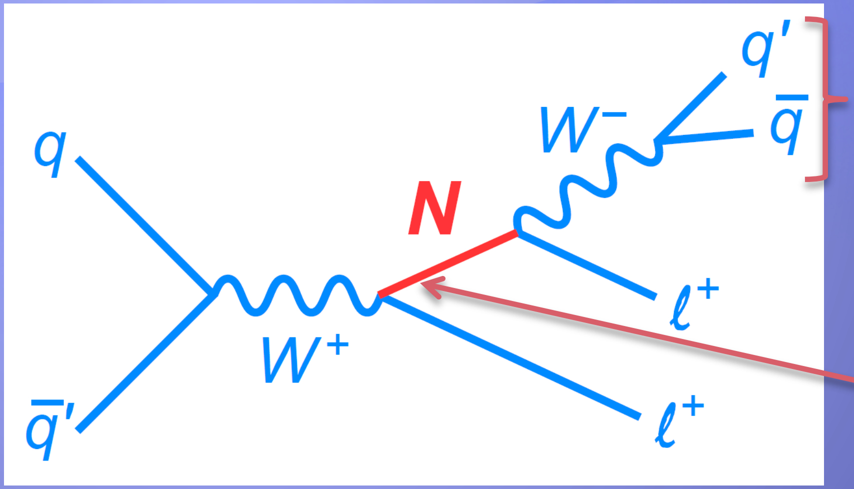


Before Searching for New Physics



- Impressive agreements with the SM

Search for Type I Seesaw



two jets from W
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 QCD jets
  - Understanding of Z+jets bkgd, but with a lepton-charge flip

Event Selection

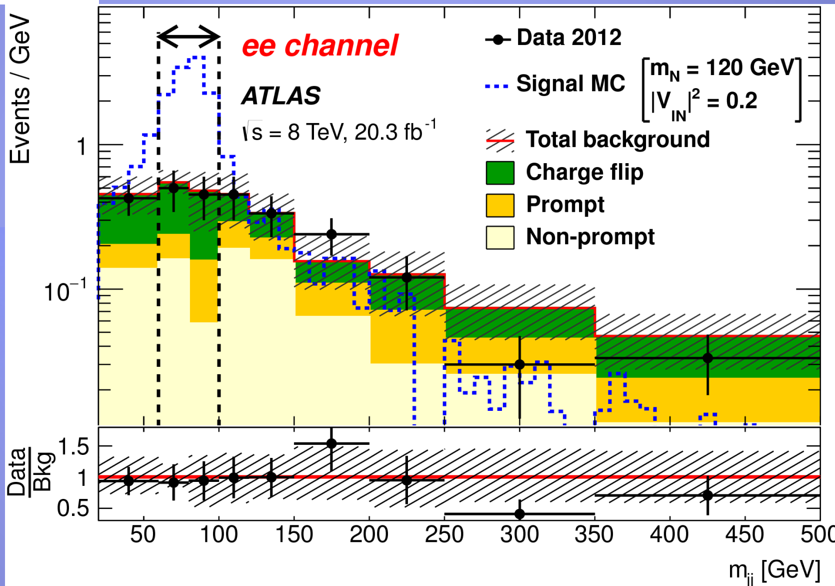
- Common Selection
  - 2 same sign leptons (isolated)
  - Njets: at least two jets
- Difference in selection

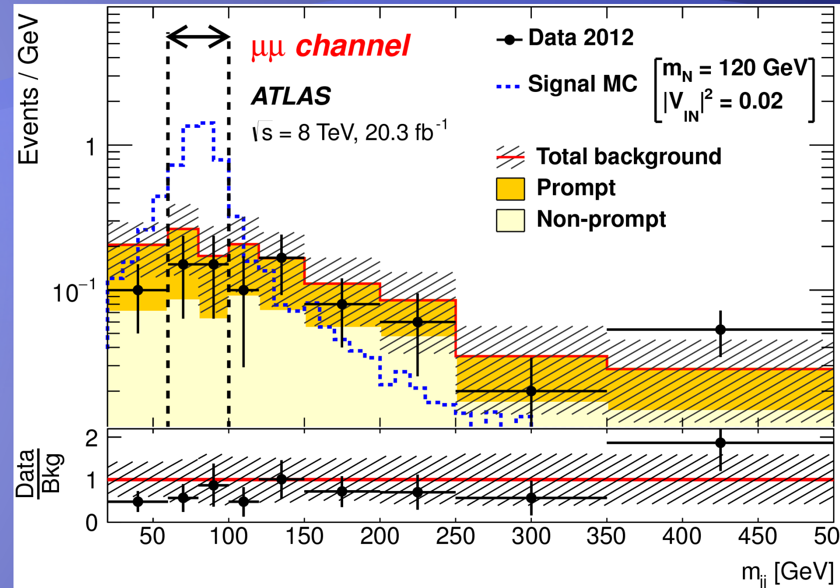
CMS	ATLAS
20/15 GeV lepton pt cuts	25/20 GeV lepton pt cuts
Di-lepton triggers	Single lepton trigger
Search for m(N)>40 GeV	Search for m(N)>100 GeV
Use m(ljj),m(lljj) for signals	Use m(jj) for signals

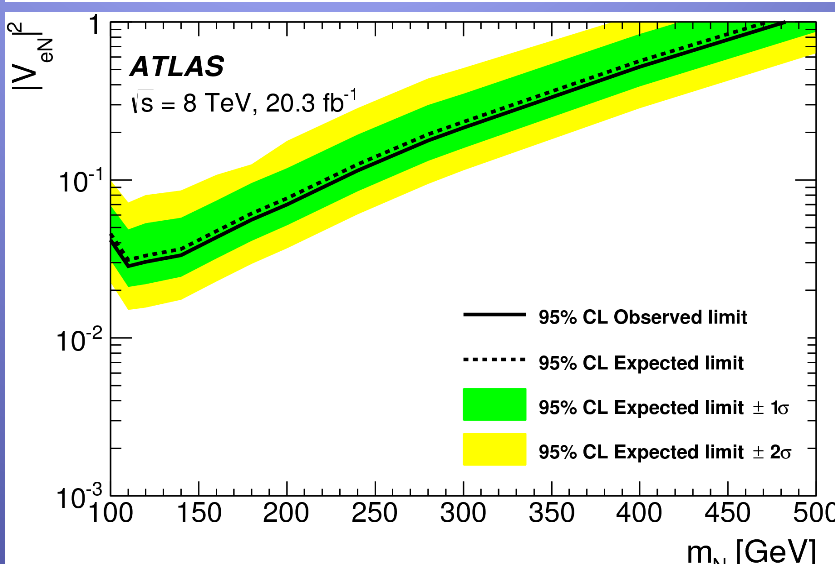
- Remarks
  - CMS: di-lepton trigger→ lower pt cut→ increase acceptance for low $m_{N,}$ but more bkgds
  - 3rd lepton veto:
  - ATLAS: mass of two leading jets to be near m_W

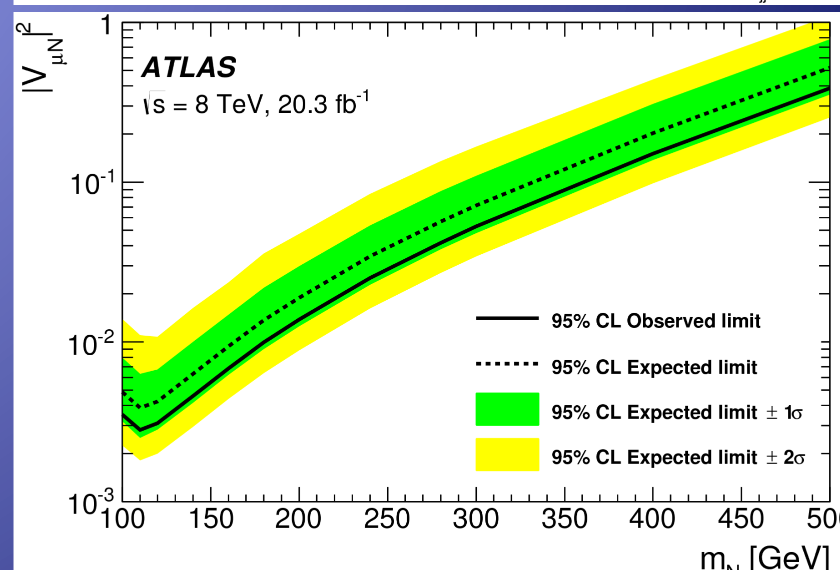
Results @ ATLAS

JHEP 1507 (2015) 162





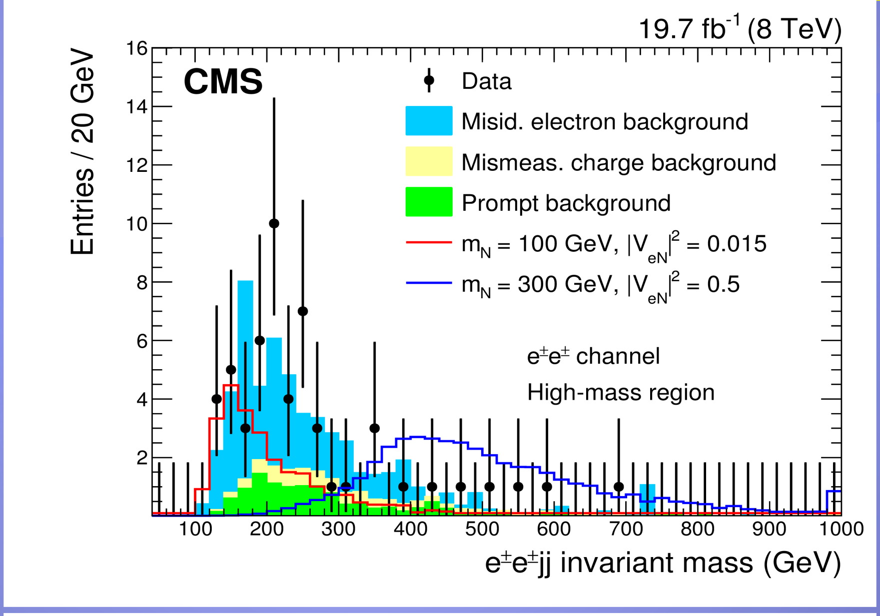


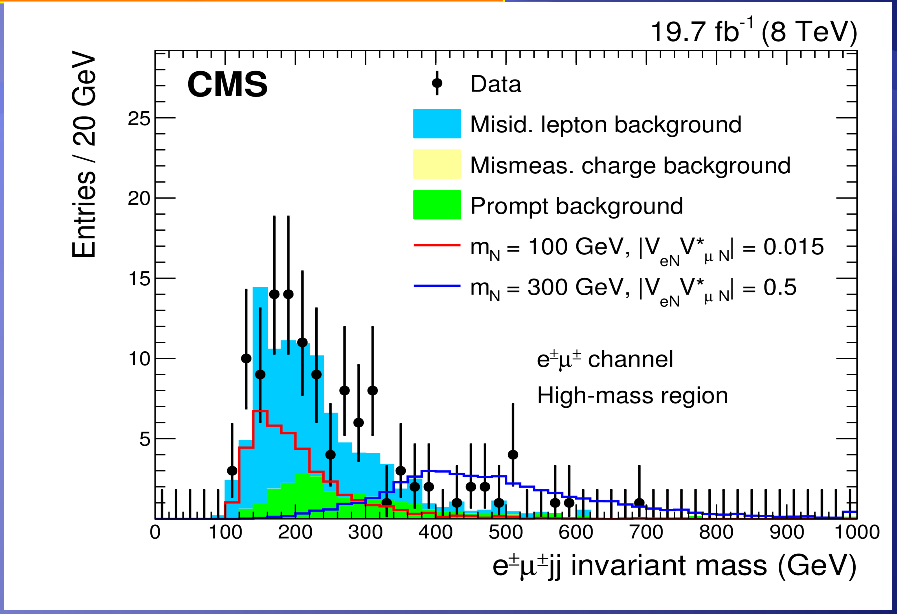


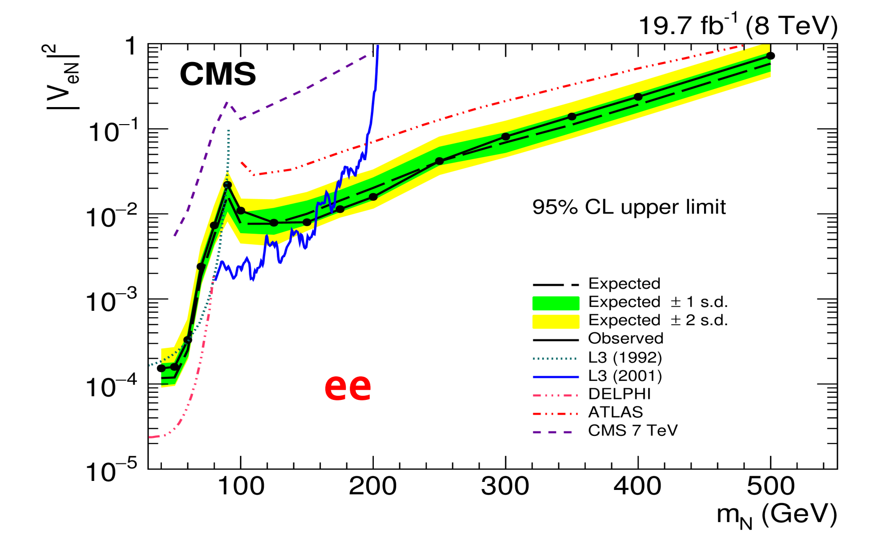
- No excess, upper limits on $|V_{eN}|^2$ and $|V_{\mu N}|^2$

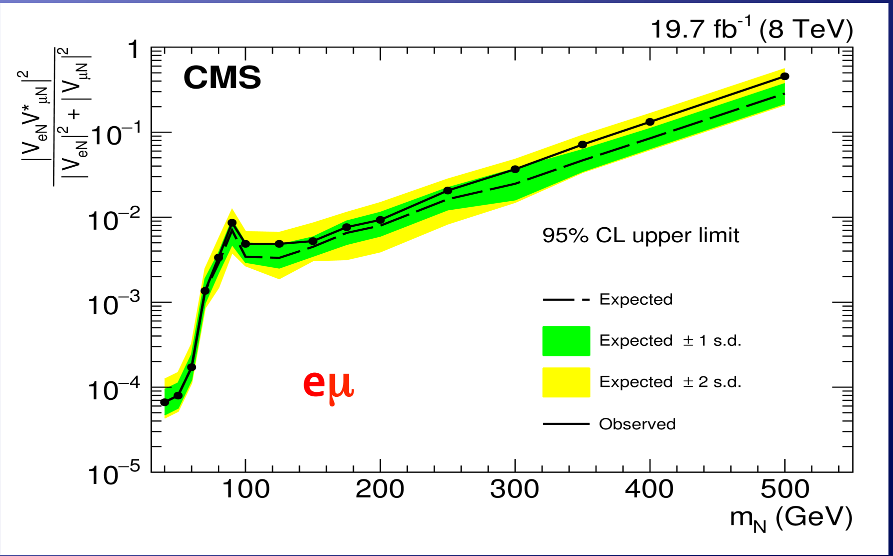
Results@CMS

JHEP 04 (2016) 169





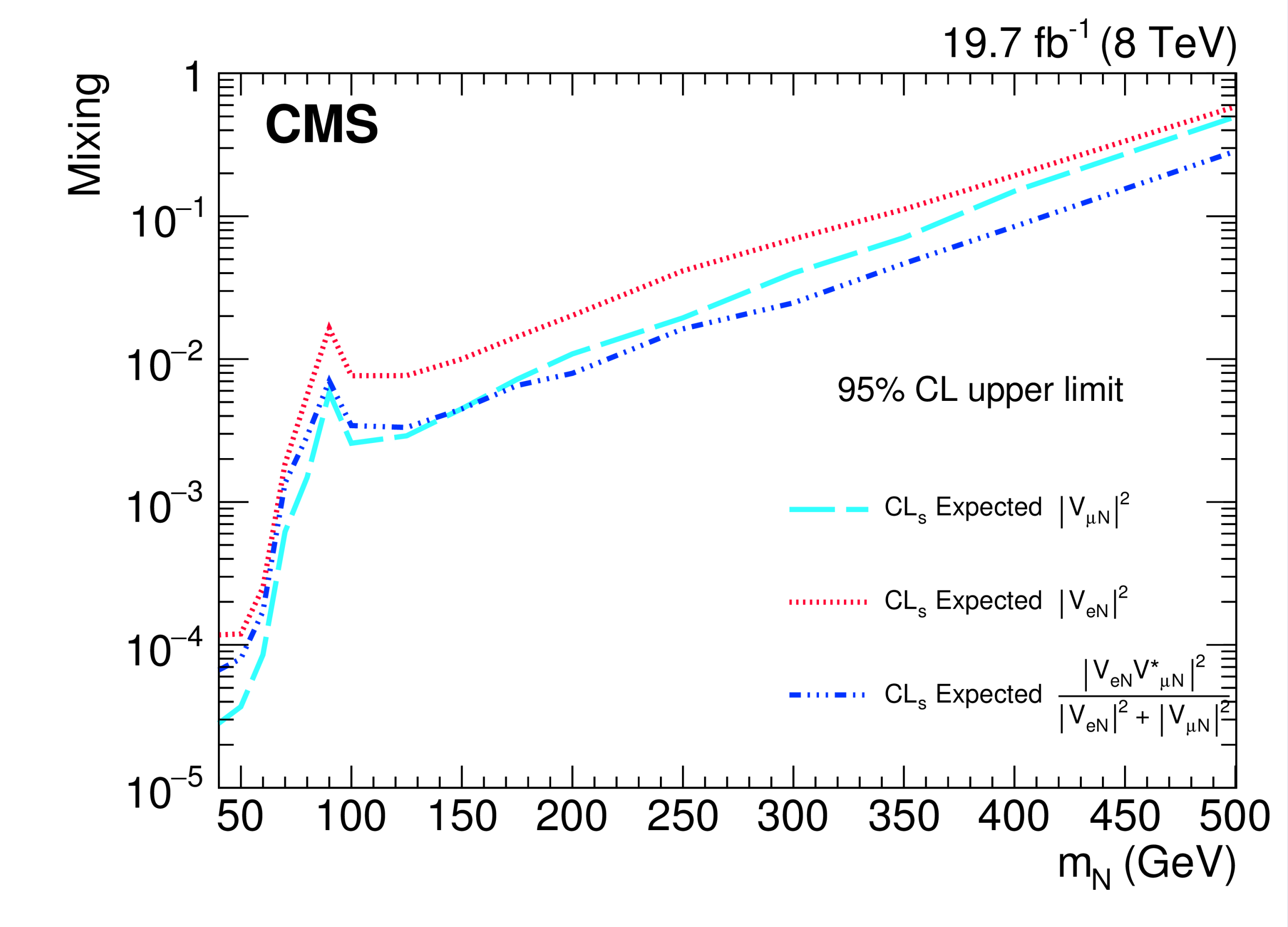




Results on Mixing

JHEP 04 (2016) 169

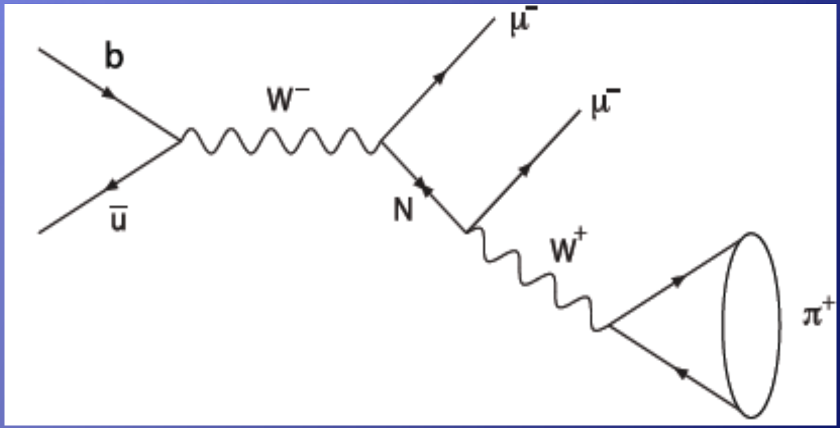
PLB 748, 144 (2015)

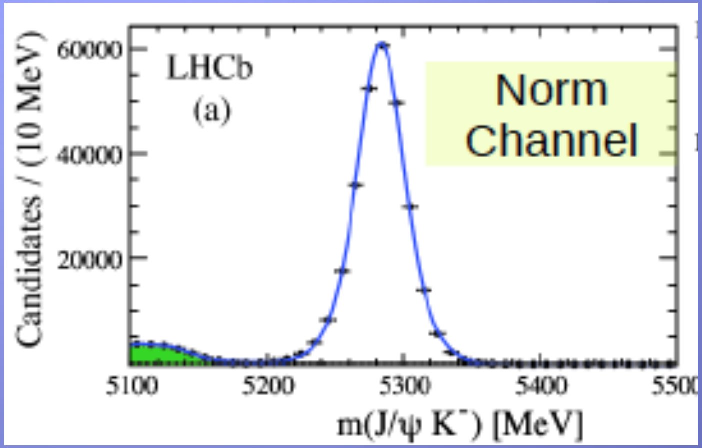


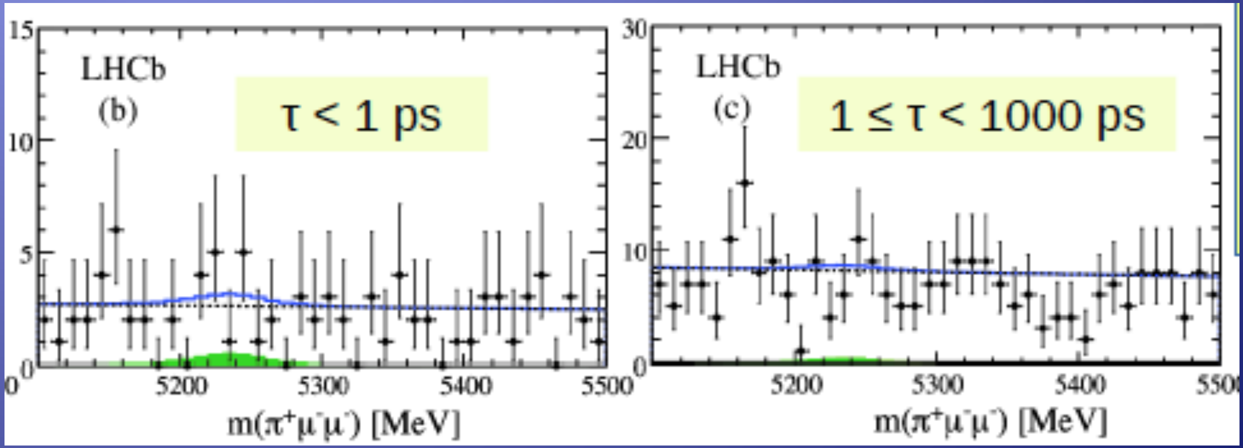
- **LHC provides the best direct limits on $|V_{\mu N}|^2$ for m_N>90 GeV**
- **The first direct limit on $|V_{eN} V_{\mu N}^*|$ for m_N>40 GeV**

Search for Type I Seesaw at LHCb

- For $0.25 < m_N < 5\ GeV$
- Searches in $B^- \to \pi^+ \mu^- \mu^-$
  - Normalize to $B^- \to J/\psi K^-$

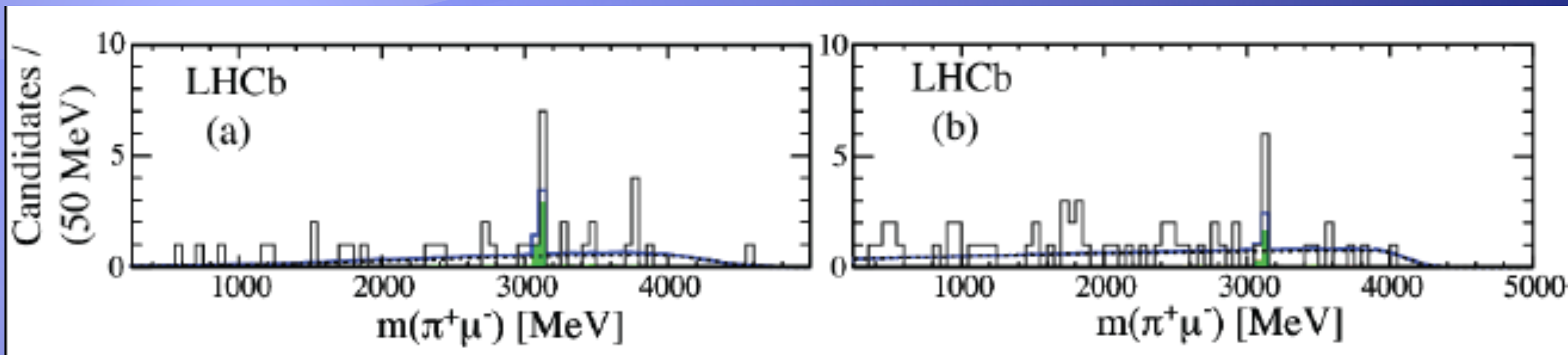


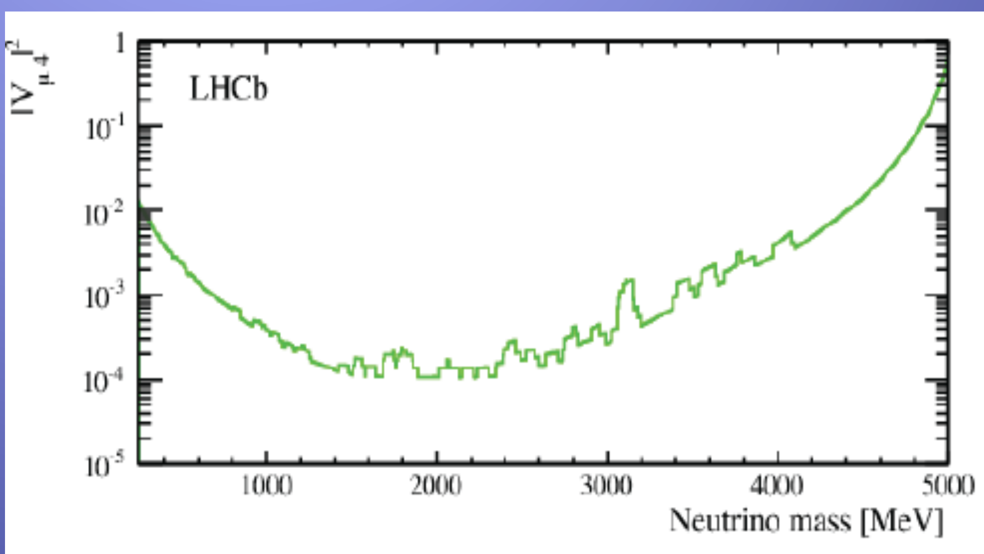




Search for Type I Seesaw at LHCb

- No signal found





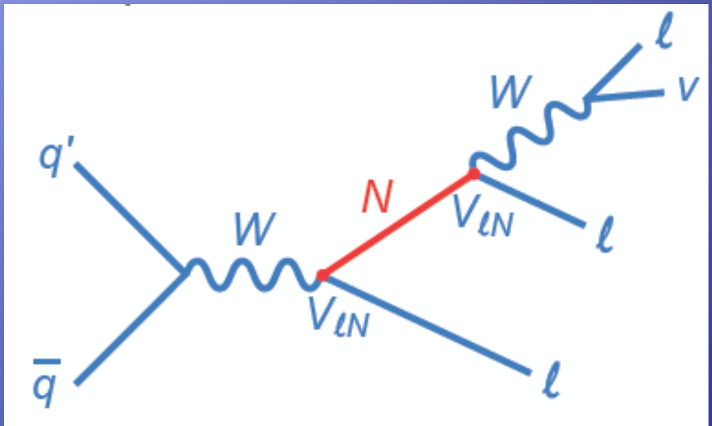
$$Br(B^- \to \pi^+ \mu^- \mu^-) = \frac{G_f^4 f_B^2 f_\pi^2}{128\pi\hbar} \tau_B m_B^5 |V_{ub} V_{ud}|^2 |V_{\mu 4}|^4 \left(1 - \frac{m_4^2}{m_B^2}\right) \frac{m_4}{\Gamma_{N_4}}$$

PRL 112, 131802

- Set limits on $|V_{\mu N}|^2$ for m_N<5 GeV

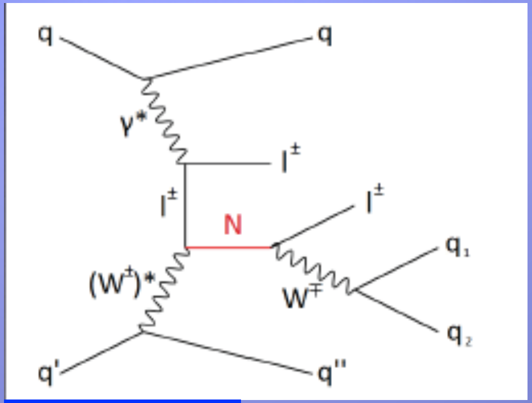
Seesaw Type I in tri-lepton channel

- In di-lepton+2 jets: difficulty to explore small m_N region due to jet pt cut, use tri-lepton channel
- Tri-lepton channel: smaller BR, but no jet
  - Promising with high-statistics
  - CMS results using the full 13 TeV data will be available by this summer
    - Search is down down to $m_N \sim 1$ GeV
    - Our sensitivity is reached to $|V_{lN}|^2 \sim 10^{-5}$ at very low mass

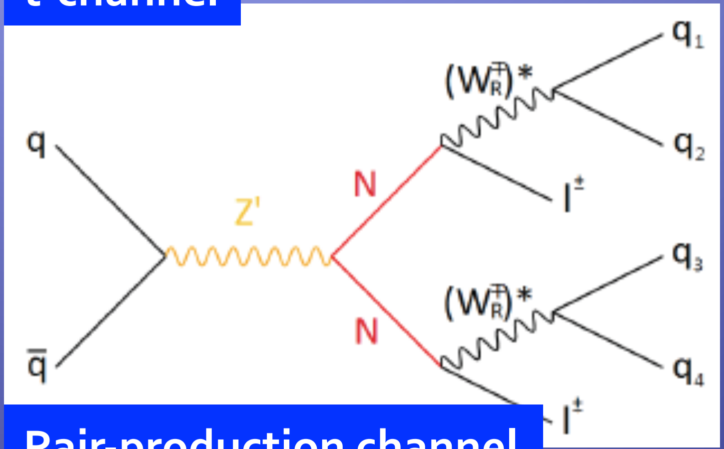


Extension to more channels

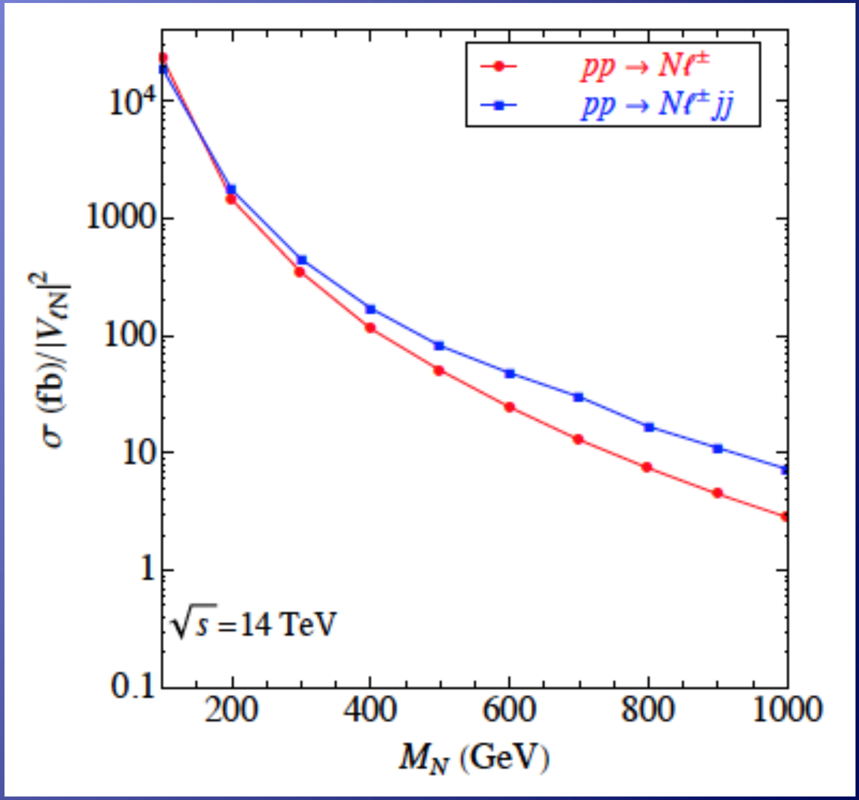
- 3 new channels are being analyzed
  - t-channel, and pair production channels: dilepton + 4 jets
  - OS dilepton at high heavy N mass



t-channel



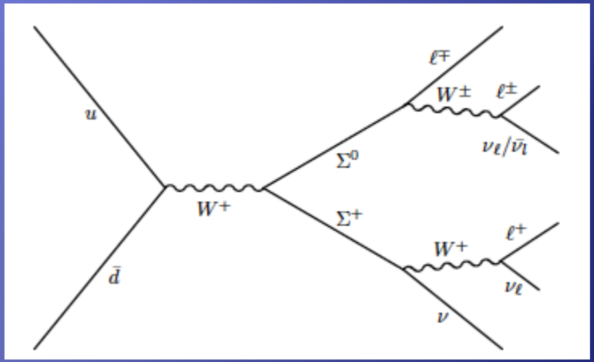
Pair-production channel



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

Search for Type III Seesaw

- Look for decay of new heavy fermions $\Sigma^+\Sigma^- / \Sigma^0\Sigma^\pm$
- 3 or 4 leptons with MET



$$\Sigma^\pm \to W^\pm \nu,\ \Sigma^\pm \to Z\ell^\pm,\ \Sigma^\pm \to H\ell^\pm$$
$$\Sigma^0 \to W^\pm \ell^\mp,\ \Sigma^0 \to Z\nu,\ \Sigma^\pm \to H\nu$$

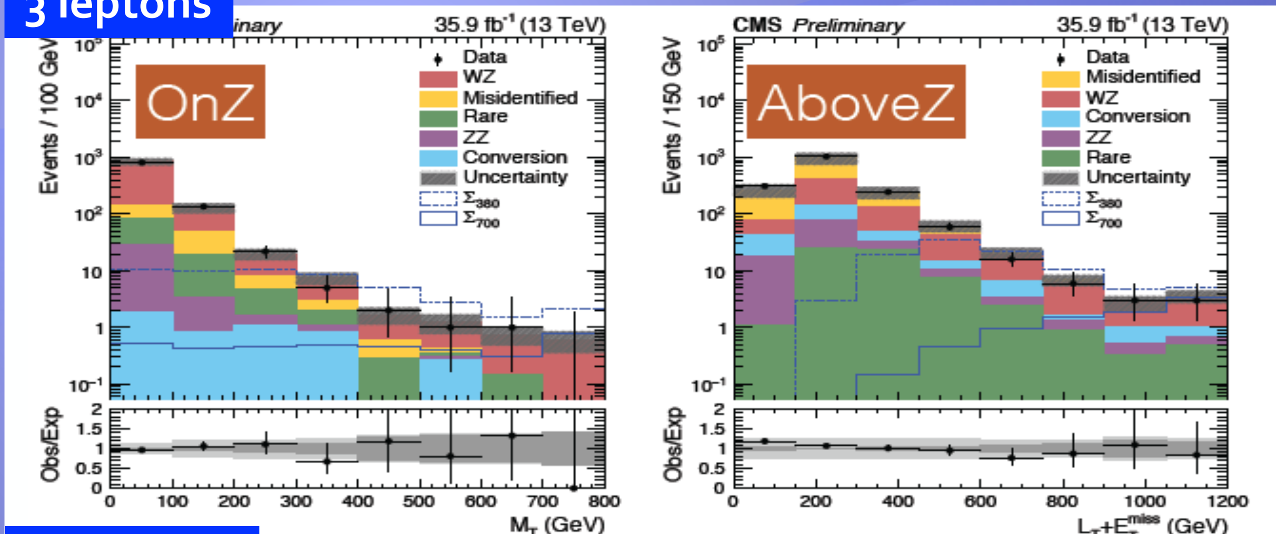
- Assume $m(\Sigma^\pm) = m(\Sigma^0)$

  $V_{\mu N} = V_{eN} = V_{\tau N}$

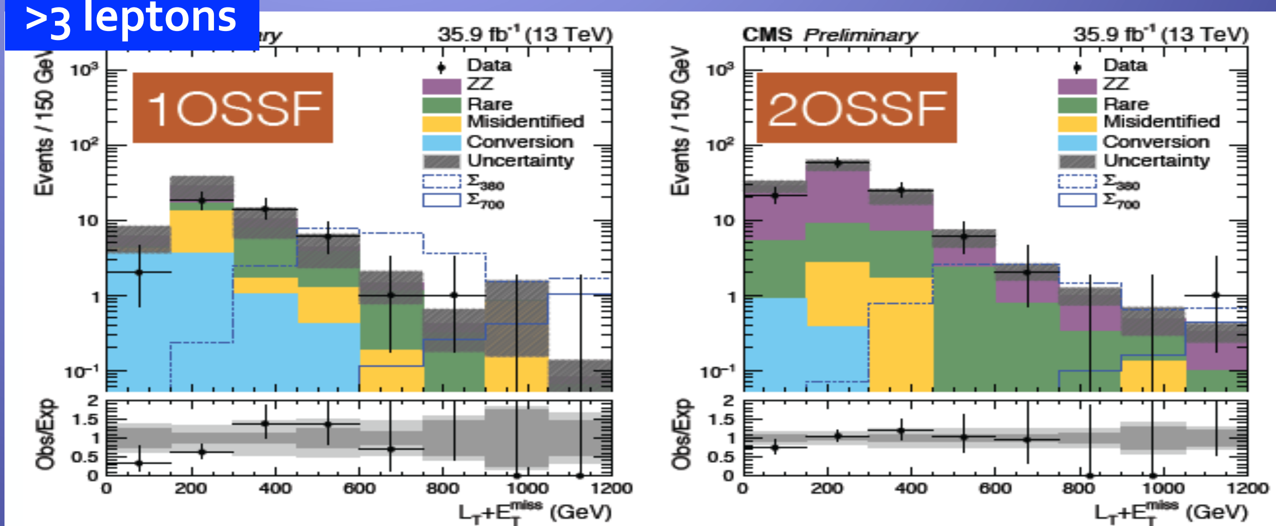
N_{leptons}	OSSF	Kinematic Variable	CR-veto
3	on-Z	M_T	$E_T^{\text{miss}} > 100\,\text{GeV}$
	above-Z	$L_T + E_T^{\text{miss}}$	-
	below-Z	$L_T + E_T^{\text{miss}}$	$E_T^{\text{miss}} > 50\,\text{GeV}$
	none	$L_T + E_T^{\text{miss}}$	-
≥ 4	1 pair	$L_T + E_T^{\text{miss}}$	-
	2 pairs	$L_T + E_T^{\text{miss}}$	$E_T^{\text{miss}} > 50\,\text{GeV}$ if on-Z

Search for Seesaw Type III

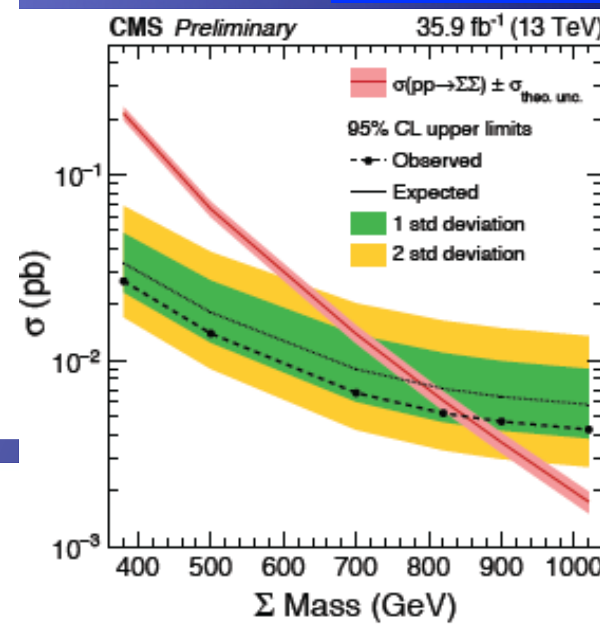
3 leptons



>3 leptons



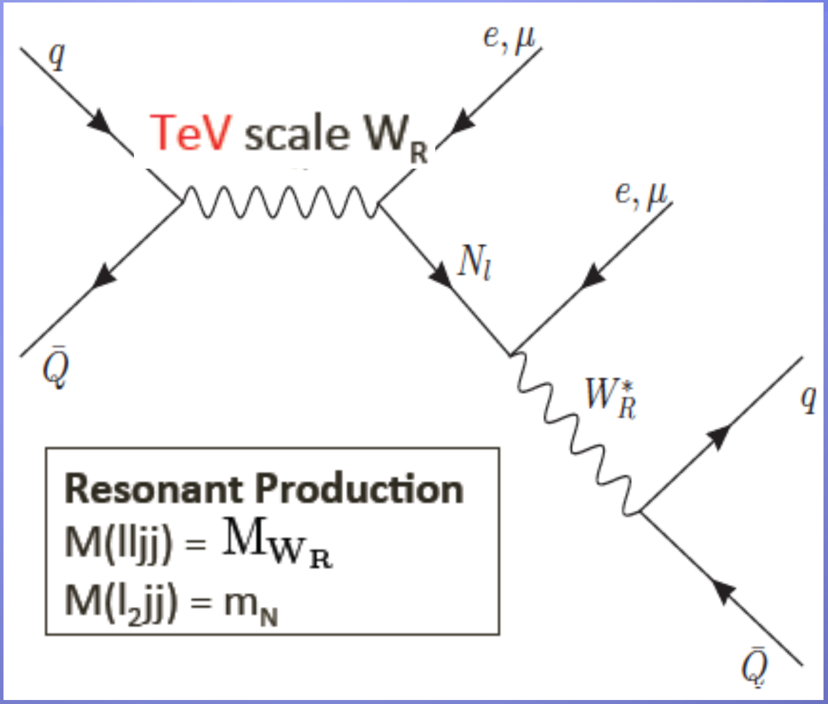
EXO-17-006



- Exclude m(Σ) up to 850 GeV

$V_{\mu N} = V_{eN} = V_{\tau N} = 10^{-6}$

Searches in the LRSM



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

Same Final state as type I but very different kinematics

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),

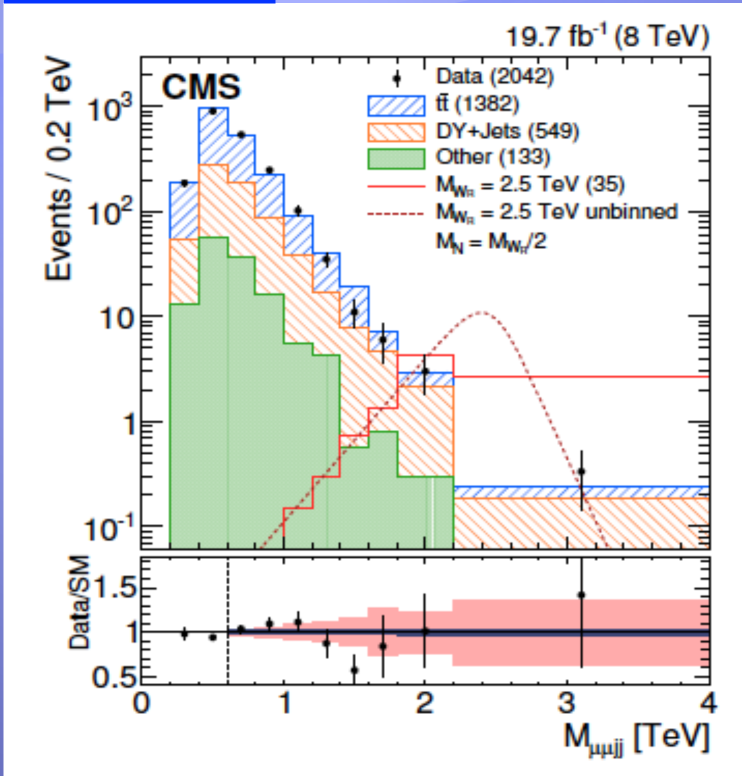
- M(lljj) (i.e $m(W_R)$) > 600 GeV.

➢ Challenges:

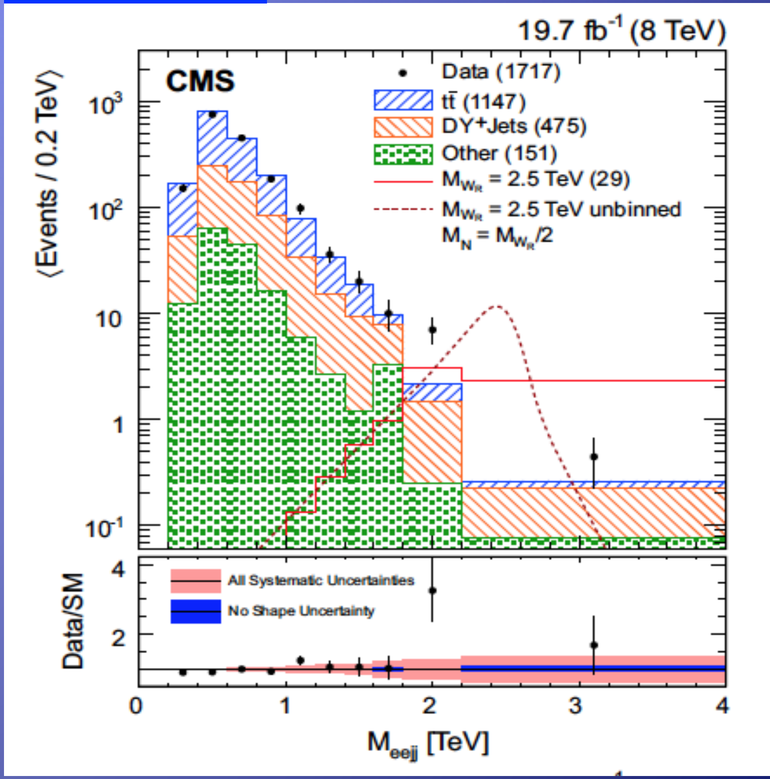
- For $m_N << m_{WR}$, jets and lepton from N decays overlap → standard isolation will kill signals
- Same challenges as Type I in terms of bkgds

Results @ CMS

μμ channel



ee channel

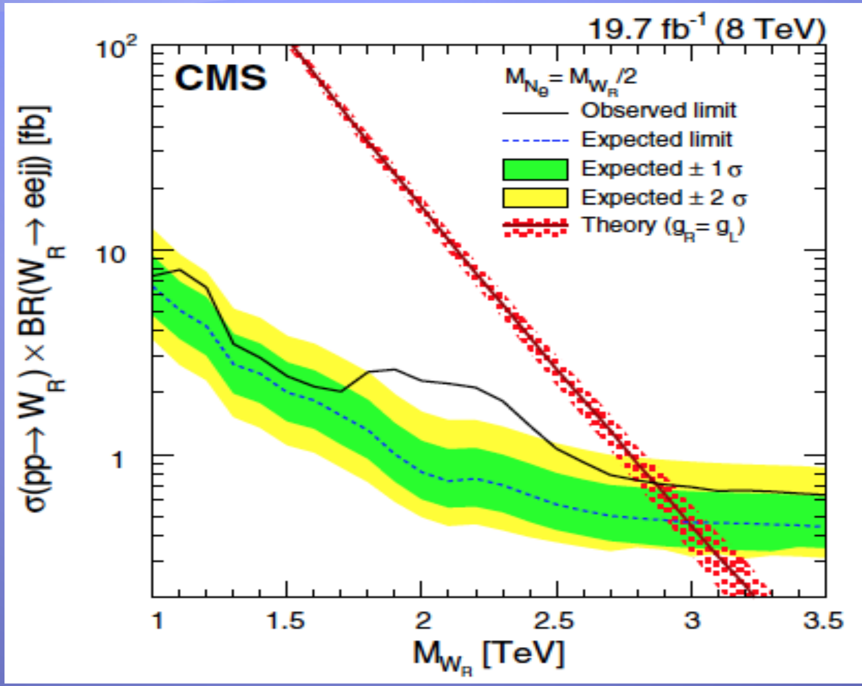


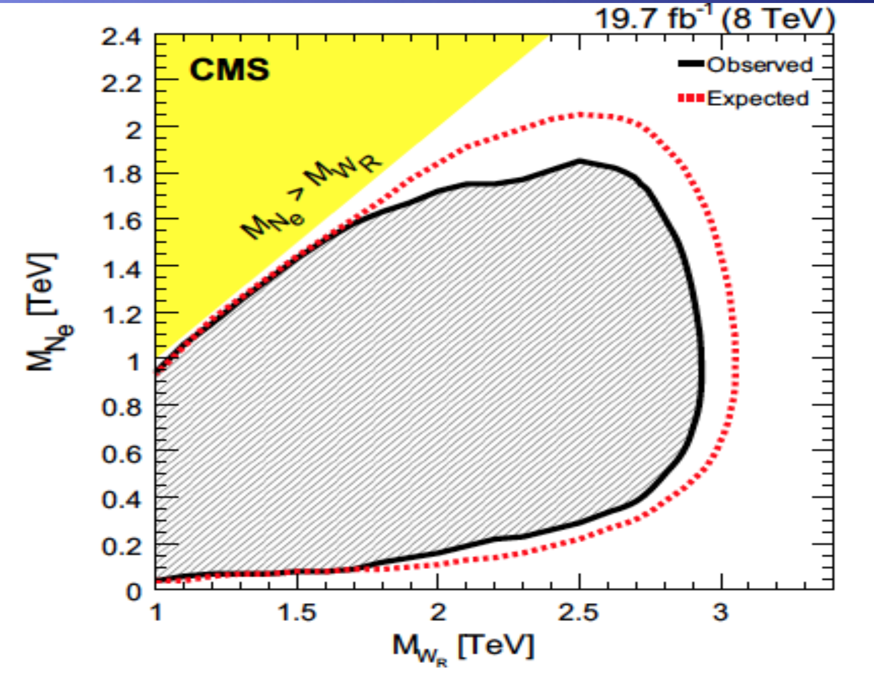
EPJ C74 (2014) 3149

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

Limits in the LRSM

EPJ C74 (2014) 3149

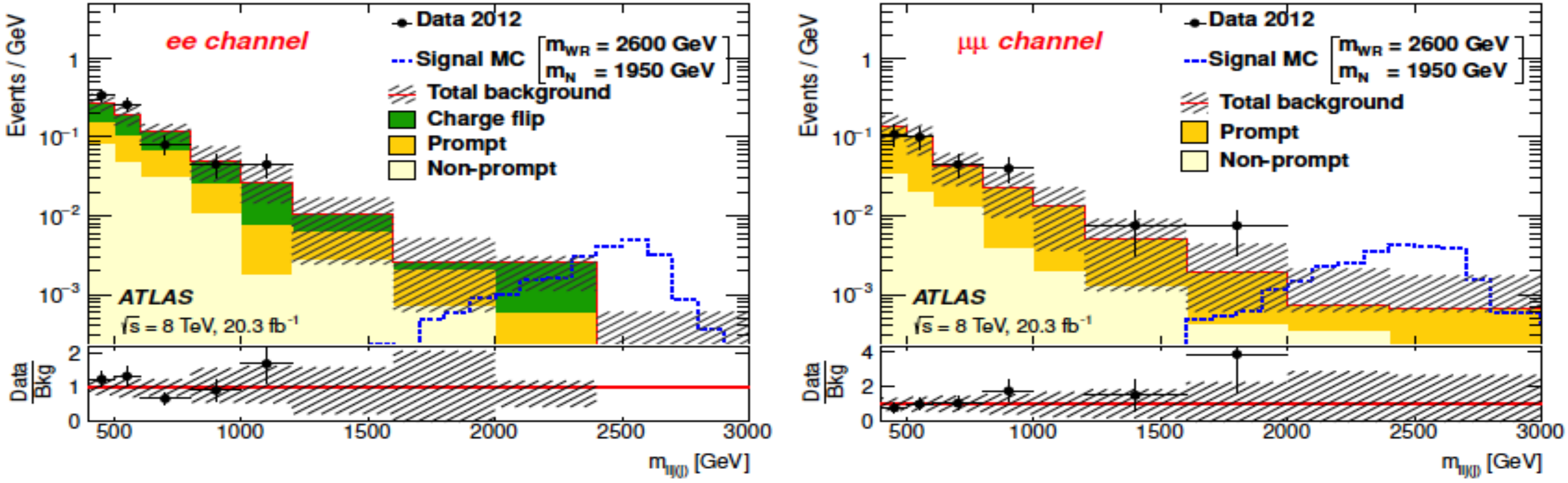




- **What about the results from ATLAS?**

Results @ ATLAS

JHEP 1507 (2015) 162



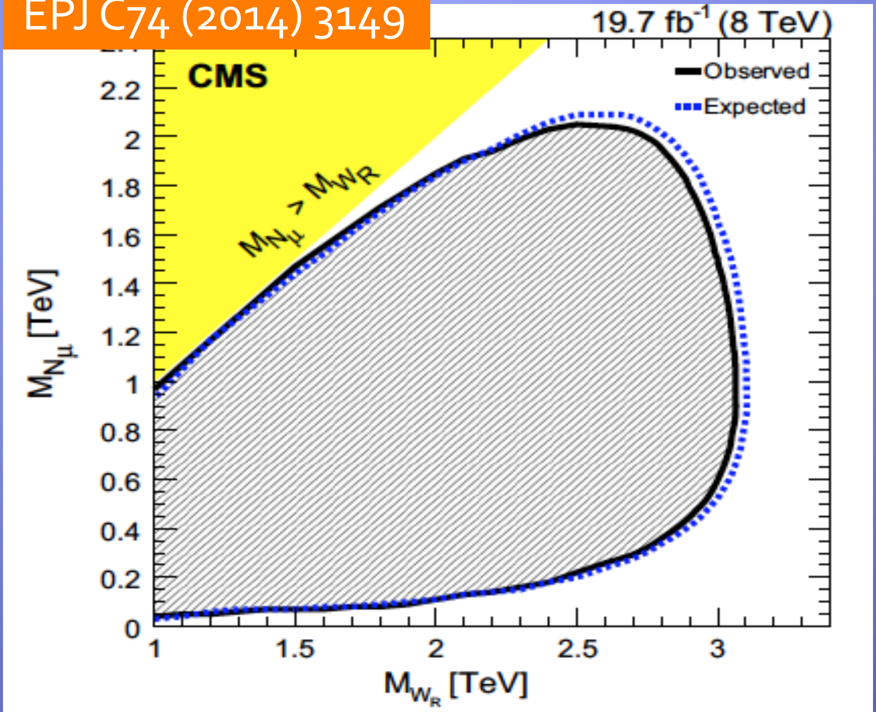
Invariant mass (lljj)

- No excess in ee channel (SS)
- OS channel?

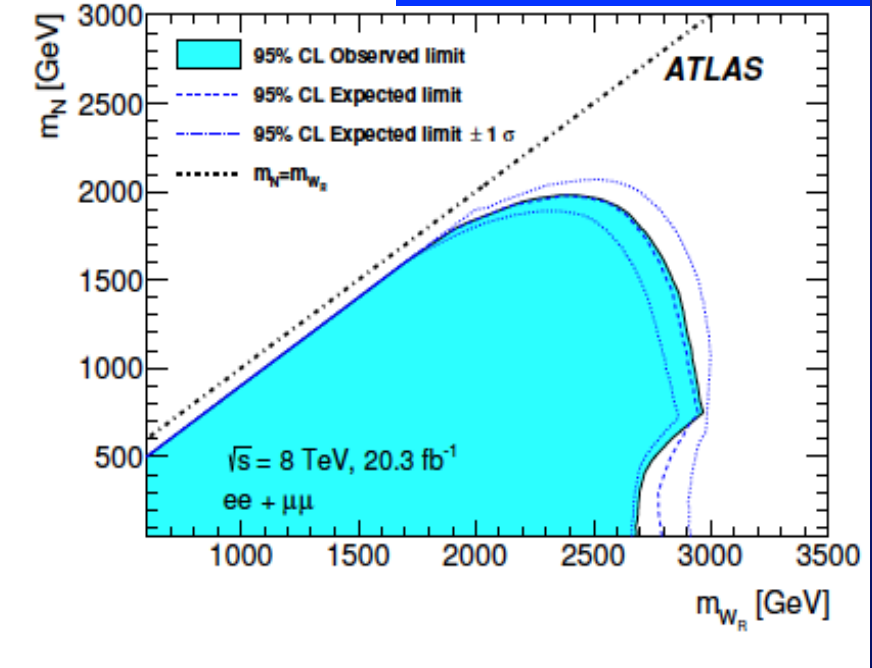
Limits in the LRSM

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

EPJ C74 (2014) 3149



JHEP 1507 (2015) 162



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

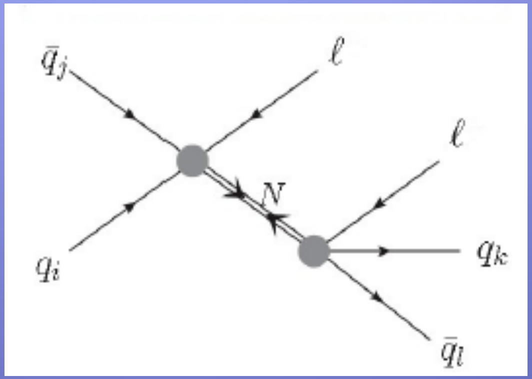
ATLAS @ 8 TeV (SS)
Best sensitivity in SS channels
Exclude up to 3.0 TeV

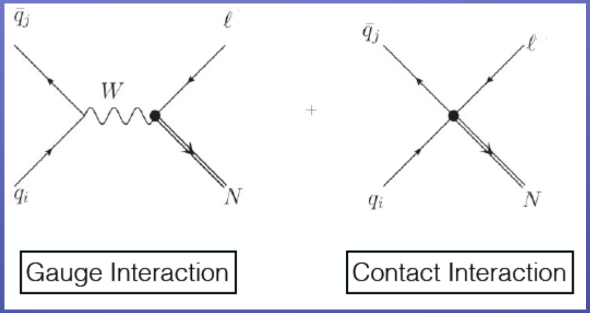
- **With the full 2016 data, limit is expect to up to 4.5 TeV**

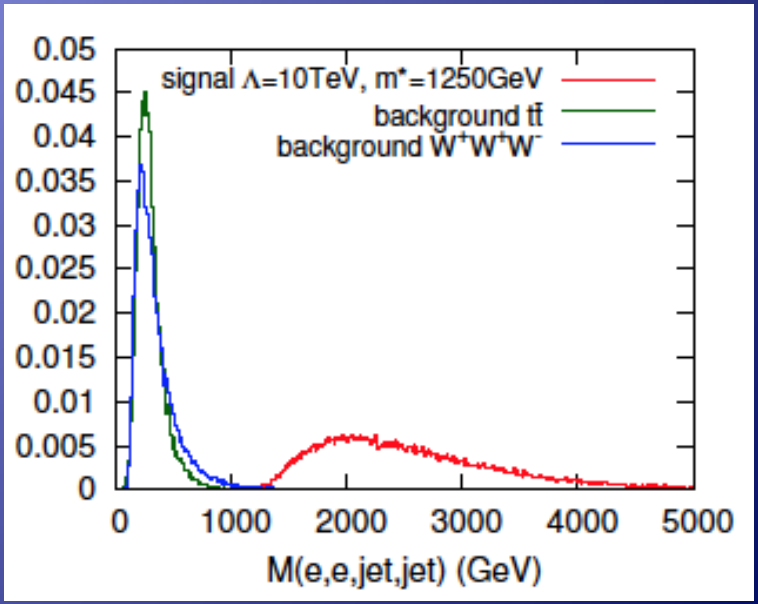
Search for Composite Model

- Composite model: an explanation to mass hierarchy issue in SM
- Can explain the 2.8σ excess in ee channel but no excess in $\mu\mu$ channel
  - A composite model of lepton and quarks with contact interaction, Λ
  - Excited μ state heavier than excited *e* state

arXiv:1508.02277 [hep-ph]







Search for Composite Model

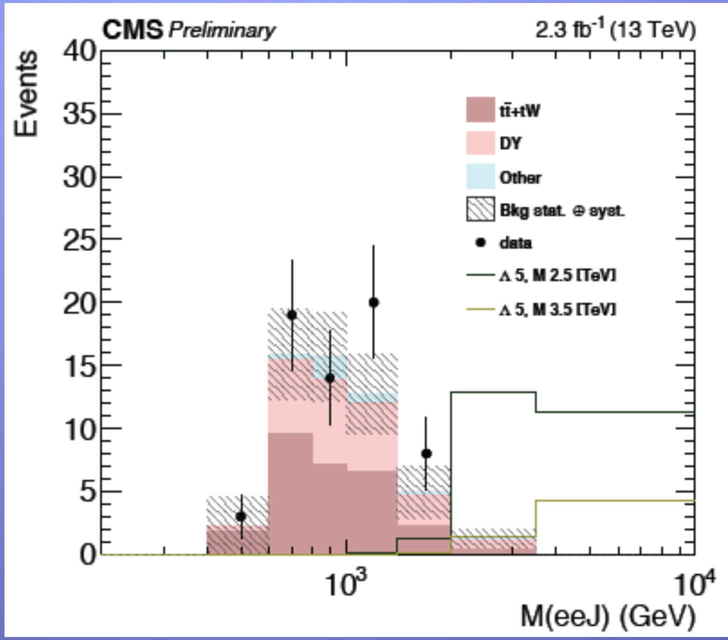
ee channel

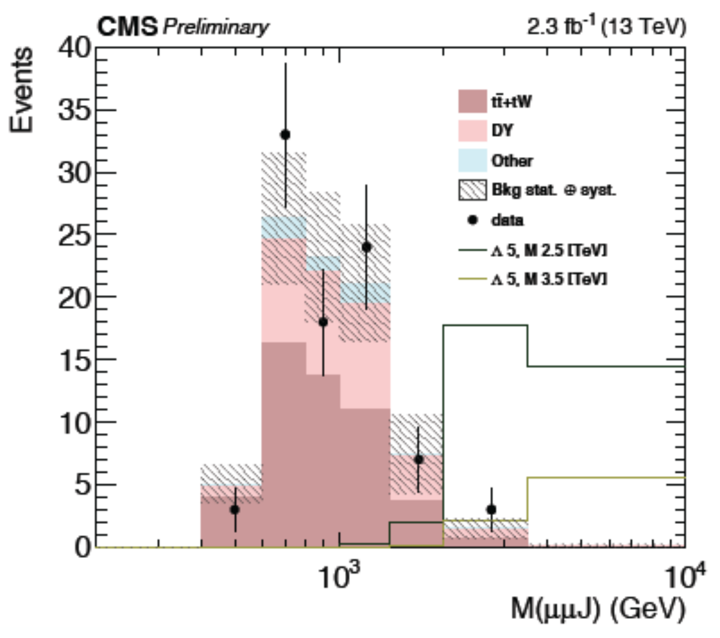
- $p_T(e)$: 110, 35 GeV
- m(ee or $\mu\mu$)>300 GeV,

$\mu\mu$ channel

$p_T(\mu)$>53, 30 GeV

>=1 fat jet with p_T(jet)> 190 GeV





EXO-16-026

- Upper limits at 95% CL on the cross section *Br
- Exclude a Composite Majorana Neutrino of mass up to 4.35 (e), 4.50(μ) TeV

Searches in $\tau\tau$ channel

- A 2.8σ excess in eejj channel but no excess in dimuon channel
  - Any broad excess in 3rd generation?

- Searches in $\tau\tau$:
  - All hadronic channel, $\tau(h)\tau(h)$
    → Largest branching ratio, but a large QCD tau-fake
  - Lepton+hadronic channel: $\tau(e)\tau(h)$, $\tau(\mu)\tau(h)$
    → Relatively clean events, but a small branching ratio,

→ **Wait for the Next Talk by Prof. Teruki Kamon**

Summary

- Neutrino oscillations attract many interesting searches at the LHC
  - Nature of neutrino: Majorana or Dirac can be tested at high energy scale, LHC
  - Tests of Seesaw models to explain small ν mass: heavy N
    - ✓ Different Seesaw types
    - ✓ Left-Right Symmetry model
    - ✓ Composite model
- Searches by ATLAS, CMS, and LHCb show no excess seen in data: set upper limits are set on $|V_{lN}|^2$, exclude W_R mass up to 4.5 TeV
- Searches will be explored using the full 13 TeV data, and will be extended to additional channels (t-channel, pair N production, and long-lived N)