Searches for Heavy Neutral Leptons at the LHC

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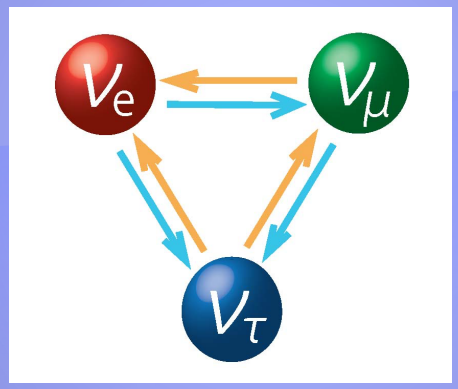
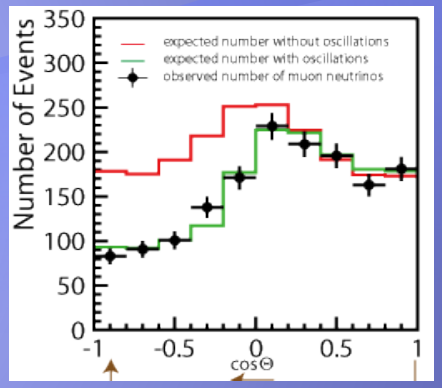
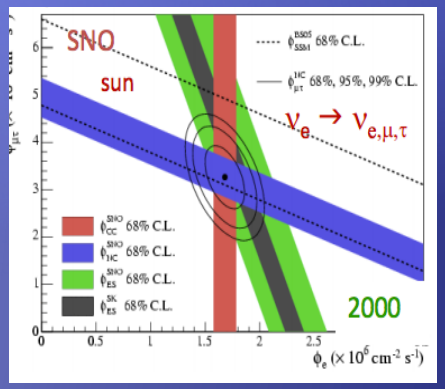
On behalf of the ATLAS and CMS collaborations

NEUTRINO 2020, June 22 – July 2, Chicago

Why Heavy Neutral Lepton? (heavy neutrino)

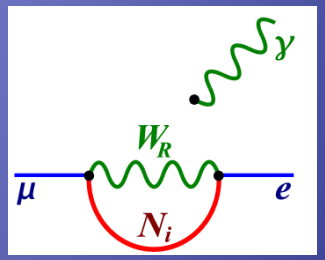


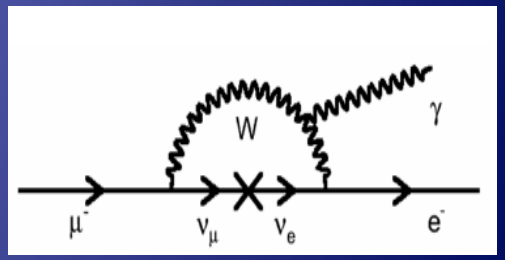




- **Neutrino Oscillation!**

- **Small neutrino mass**
- **Right-handed neutrino**





- **Origin of neutrino mass**

- **Heavy Neutral Leptons (LNV, if Majorana)**
- **Charged Lepton Flavor Violation**

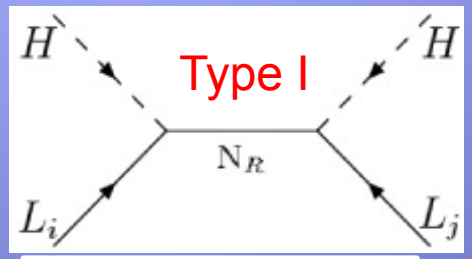
- **Bayron asymmetry through Leptogenesis**

Neutrino: Physics Beyond SM

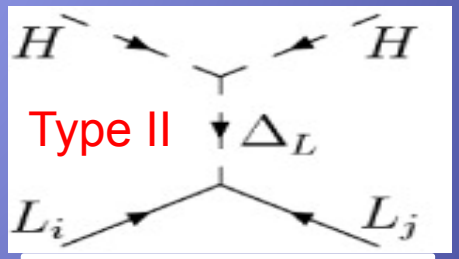
- A natural way to generate LNV and neutrino mass
  - Introduce an effective operators to the SM

$$\sim \frac{Y_L}{\Lambda_L} LLH^2$$

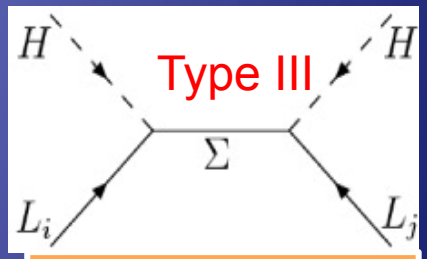
  - Seesaw Mechanism (type I, II, III)



Singlet Fermion (N_R)



Scalar triplet (Δ^{++}, Δ^{+} ,Δ)



Triplet Fermion (Σ^0, $\Sigma^{+/-}$)

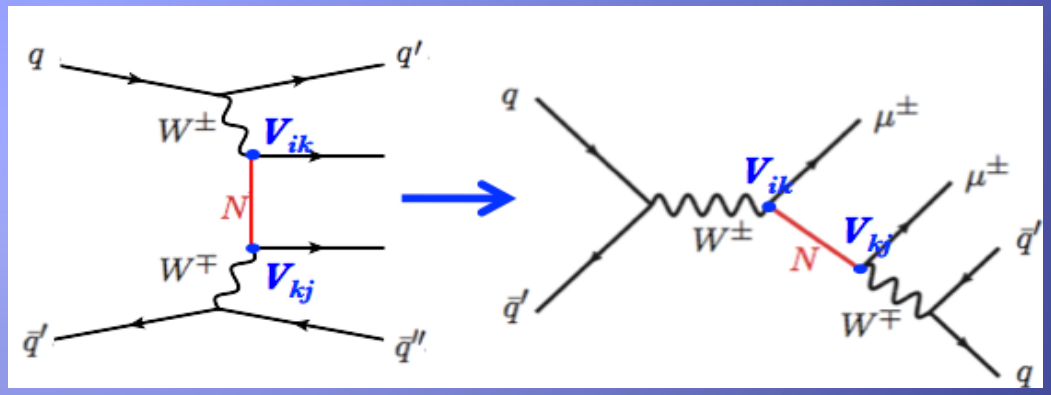
- Physics behind the Seesaw? Left-Right Symmetry model (LRSM) offers the Seesaw scale and heavy neutral lepton (HNL)

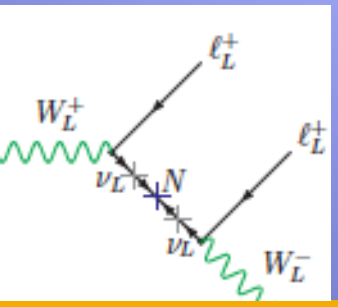
$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

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

Search for HNL at the LHC

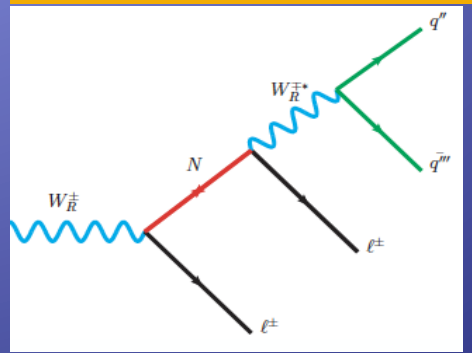
- Direct production of HNL (*N*)
  - Complementary program to the 0νββ

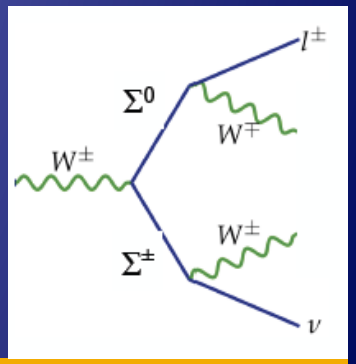




1. Type-I seesaw
- Right-handed N_R
- Only mix with SM ν

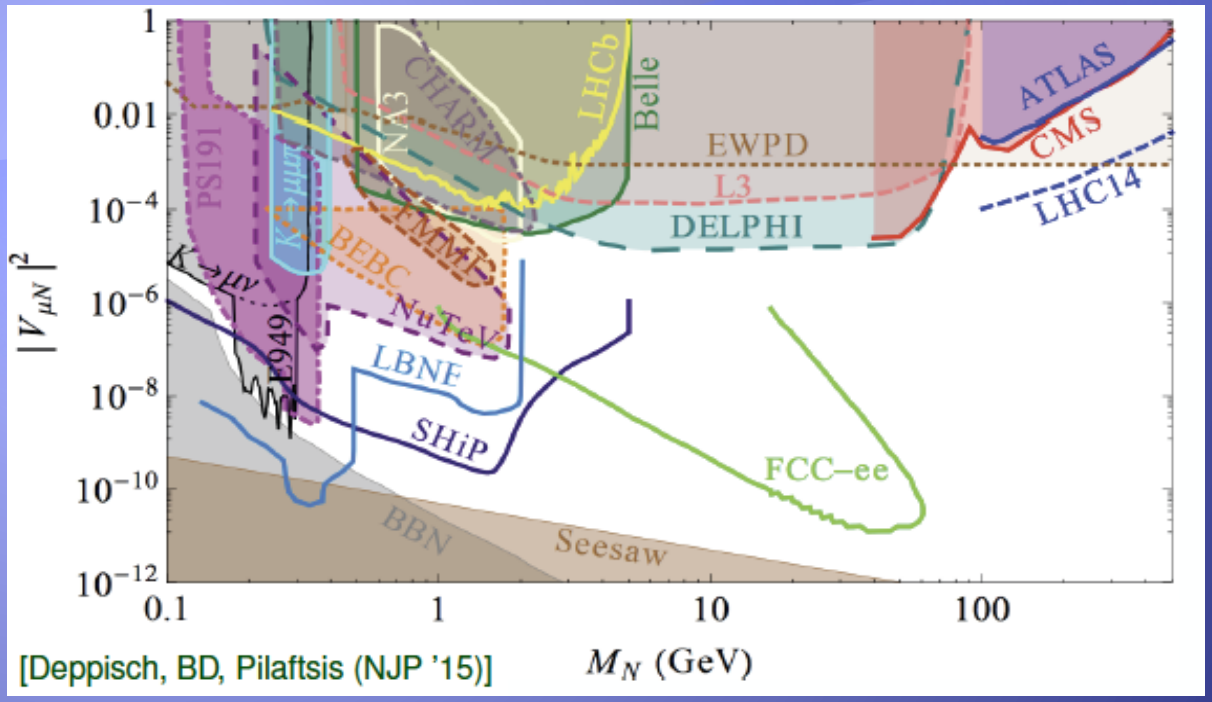
2. LRSM
- Right-handed N_R
- N_R couple to RH bosons, W_R,Z_R





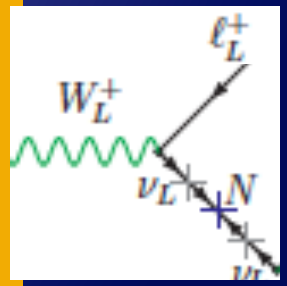
3. Type-III seesaw
- at least two $SU(2)_L$ triplets (Σ^0, $\Sigma^{+/-}$) couple to SM gauge bosons

HNL Searches for 40 yrs

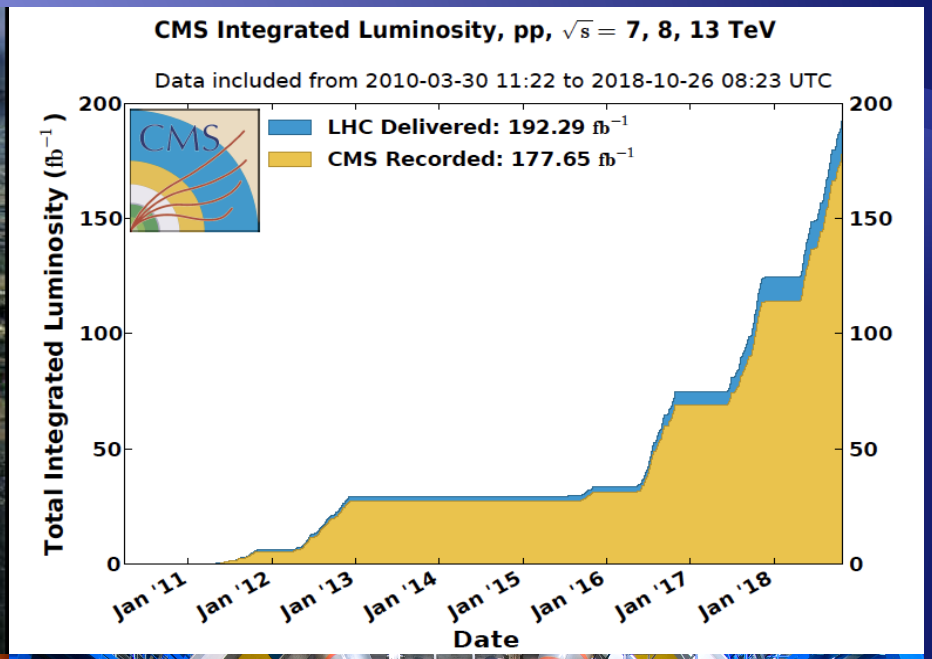


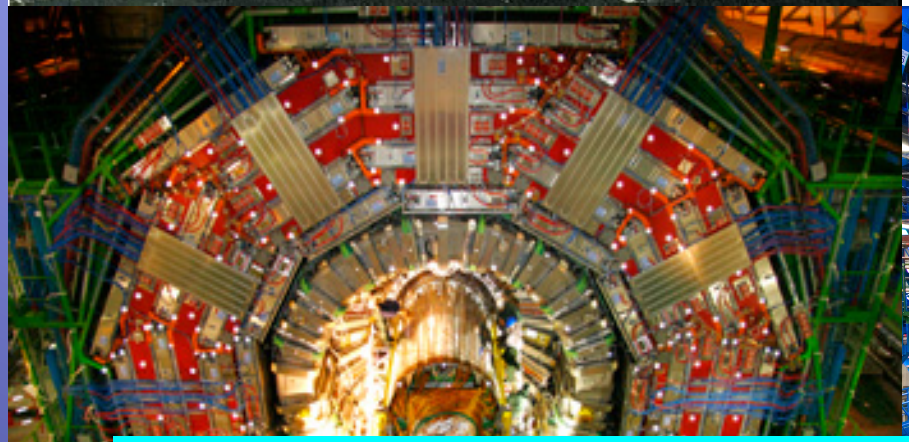
[Deppisch, BD, Pilaftsis (NJP '15)]

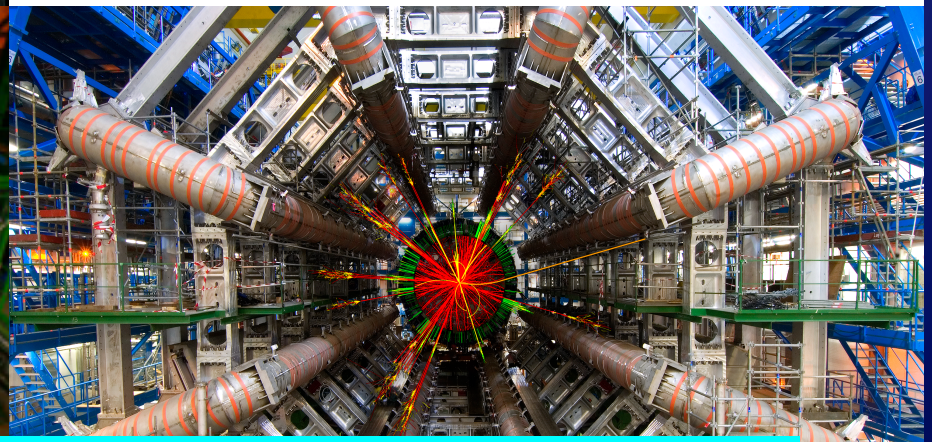
- m_N< ~500 MeV: $K\to\mu N$
- m_N< ~2 GeV: $N\to\mu\pi,\ \mu K$ (NuTeV, NA62)
- m_N< ~5 GeV: $D,B\to\mu\mu\pi$ (Belle, LHCb, SHiP)
- m_N< ~90 GeV: $Z\to\mu N$ (LEP), and LHC
- m_N> ~90 GeV: LHC (ALTAS, CMS)
- *Results since Neutrino 2018*



Use the Large Hadron Collider!



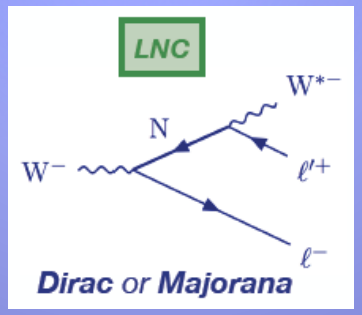


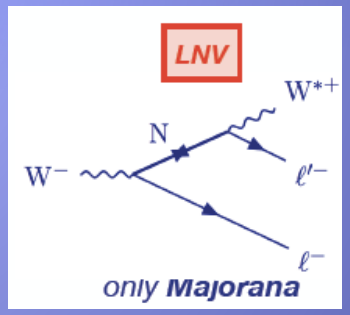


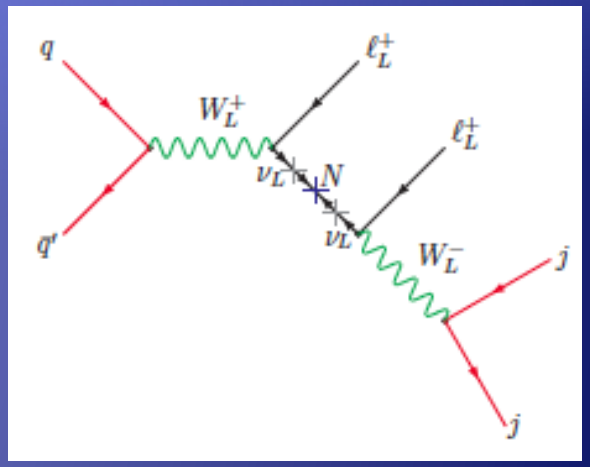
- Multi-purpose detectors at LHC: ATLAS & CMS
- Great LHC performance and impressive data taking

Type-I HNL Searches

- Resonant production via s-channel W or W*
  - m_N and $\nu - N$ mixing angle, $|V_{lN}|^2$
  - Conserving or violating lepton number







- *N* decays

Trilepton (3*l* + ν)
- Low background
- No m_N peak

Dilepton (2*l* + 2q)
- Large background, but relatively small for (LNV) with same lepton charge
- Measurable m_N peak

Search in Dilepton

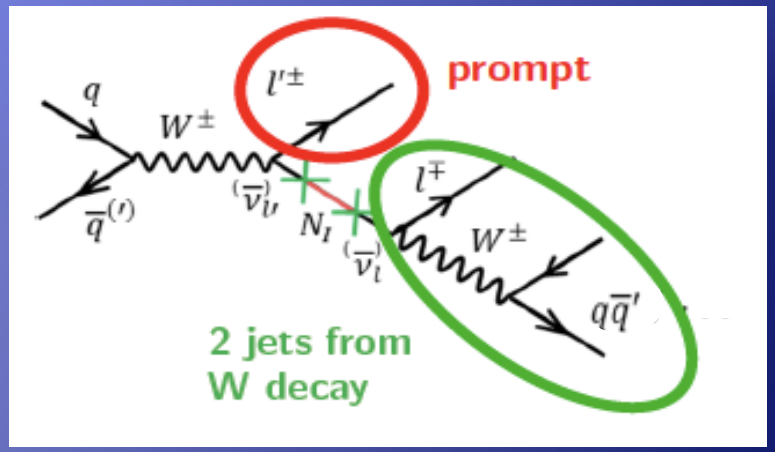
- *N* with mass 20 GeV ~ TeV
  - 2 same-sign hi-pt leptons (LNV only)
  - 2 jets or 1 boosted jet (large con jet)
  - Flavor combinations

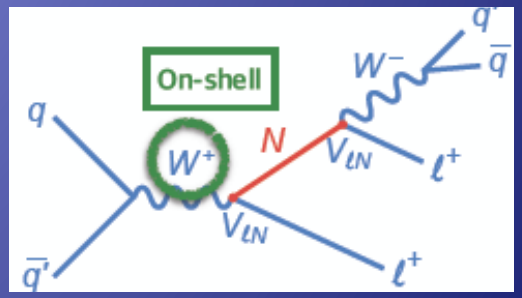
$$e^\pm e^\pm, \quad \mu^\pm \mu^\pm, \quad e^\pm \mu^\pm$$

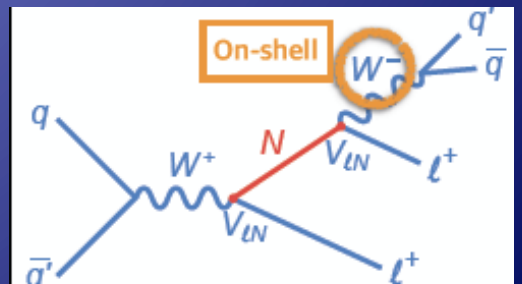
$$\downarrow \qquad \downarrow \qquad \downarrow$$

$$|V_{eN}|^2, \quad |V_{\mu N}|^2, \quad \frac{|V_{eN} V_{\mu N}^*|^2}{|V_{eN}|^2 + |V_{\mu N}|^2}$$

  - Separate searches for low mass ($m_N < m_W$) vs high mass ($m_N > m_W$) regions



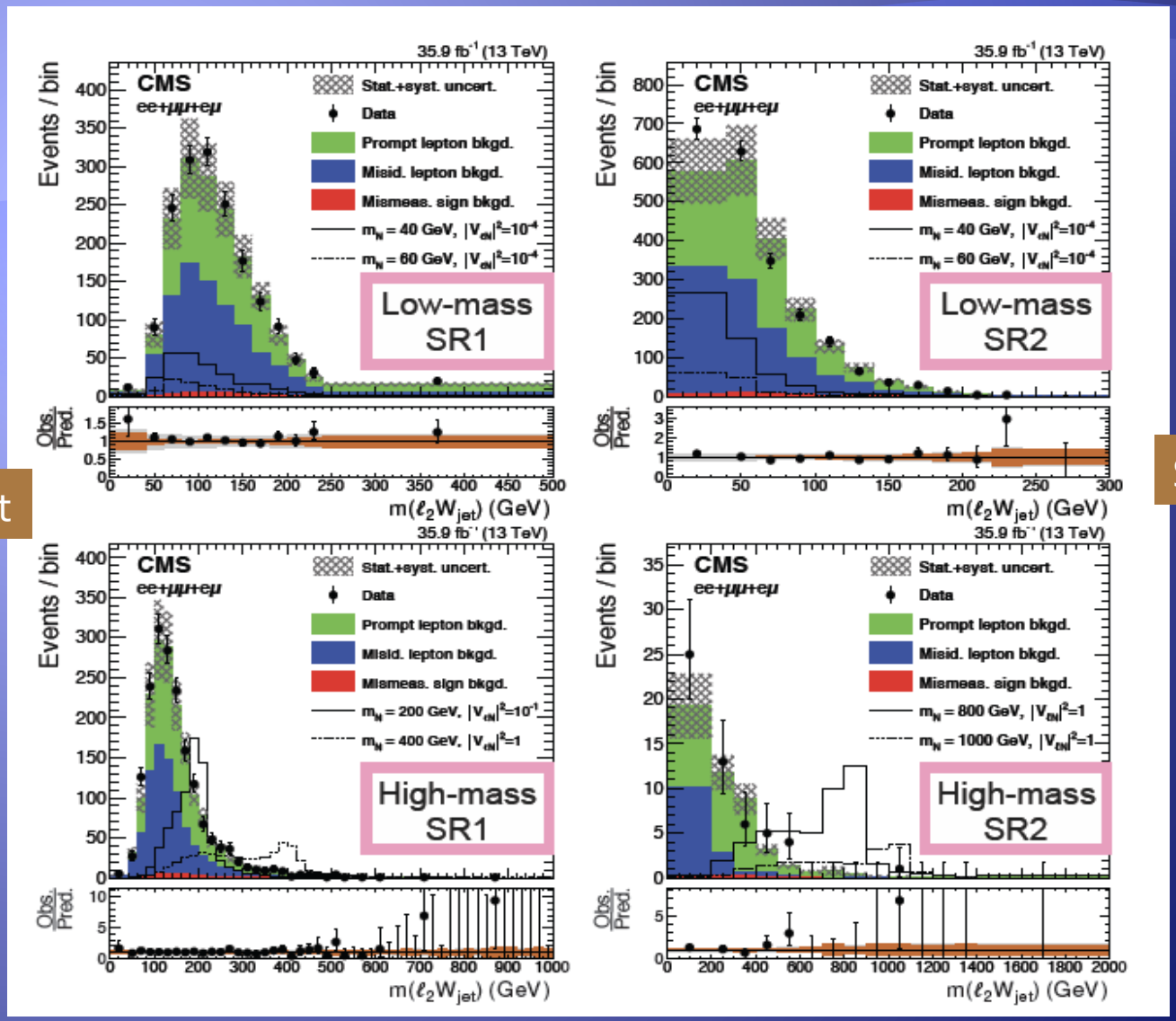




CMS Results at 13 TeV

SR1: W: 2 jet

SR2: W: 1 jet



No significant deviation from the SM

Results on the Mixing

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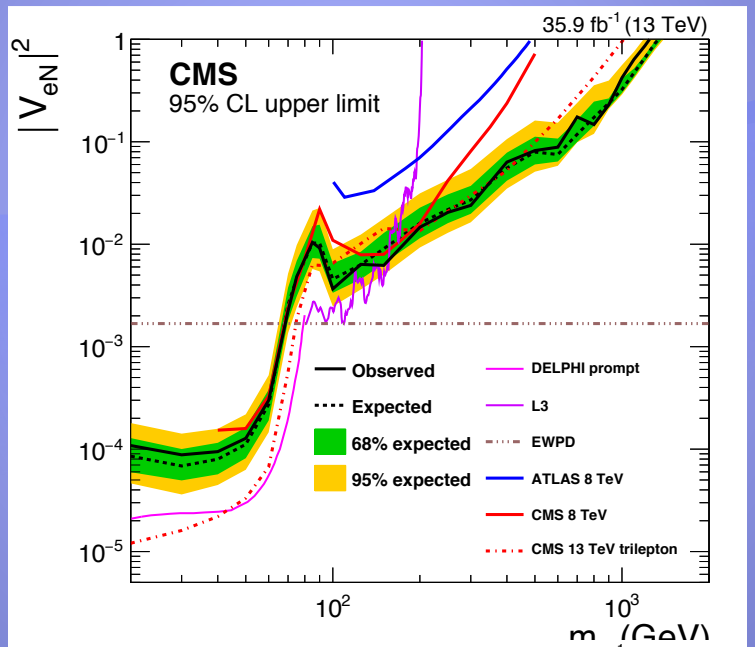
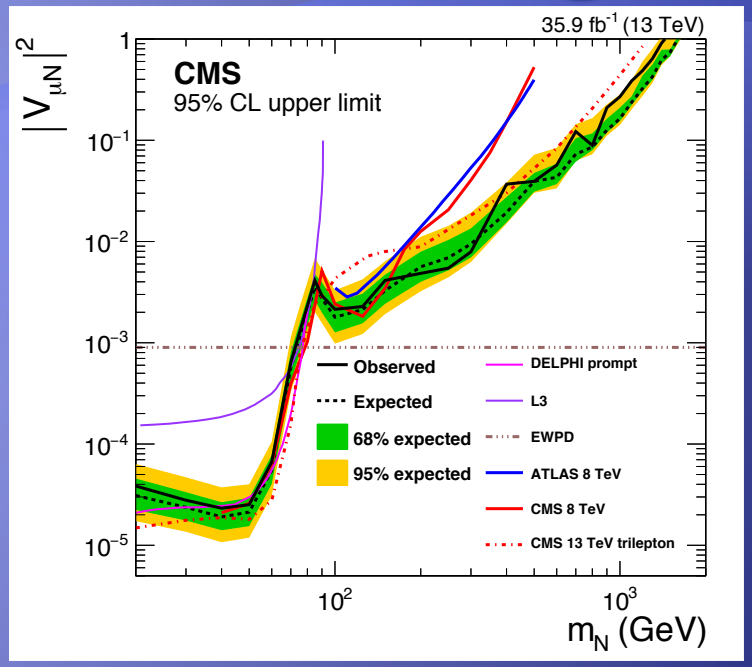
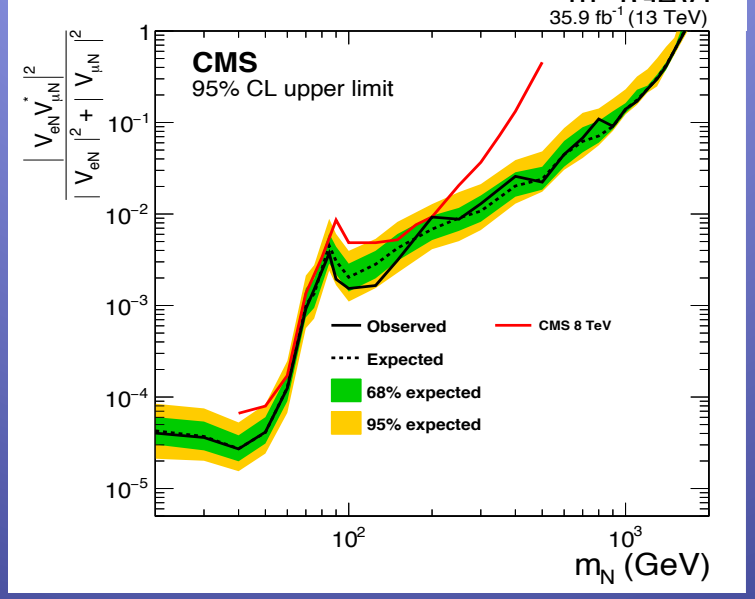




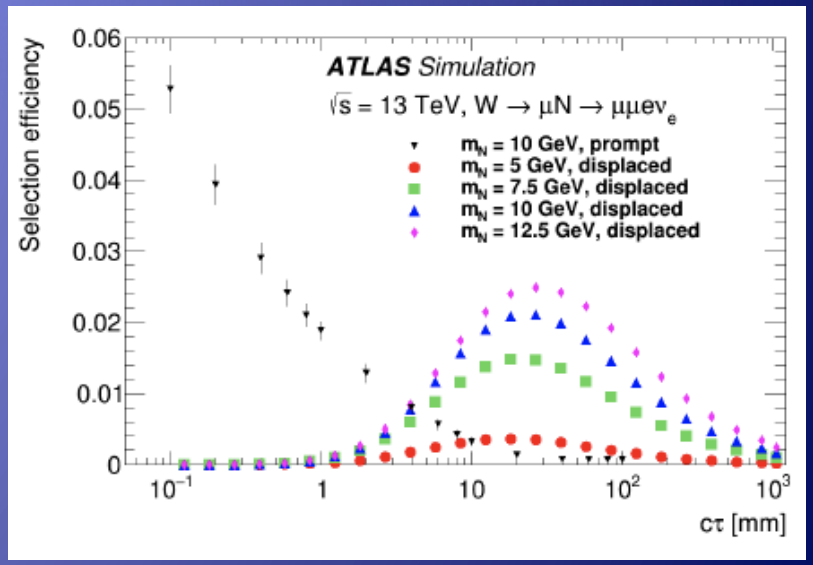


- LHC provides the best direct limits on $|V_{eN}|^2$, $|V_{\mu N}|^2$, and $|V_{eN}{}^*V_{\mu N}|$ for high mass region
- Significant improvement to the previous searches
  - CMS limits down to 20 GeV, and up to 1.2 TeV
  - Lepton flavor mixing case by CMS

Searches in trilepton

- In dilepton+2 jets: difficulty to explore small m_N region due to jet pt cut (hard to select jets below 20 GeV, but lepton is easier)
- In trilepton channel: smaller BR
- it is promising with high-statistics
- At small m_N , N has a longer lifetime

$$\tau \sim m_N^{-5} \, |V_\ell|^{-2}$$



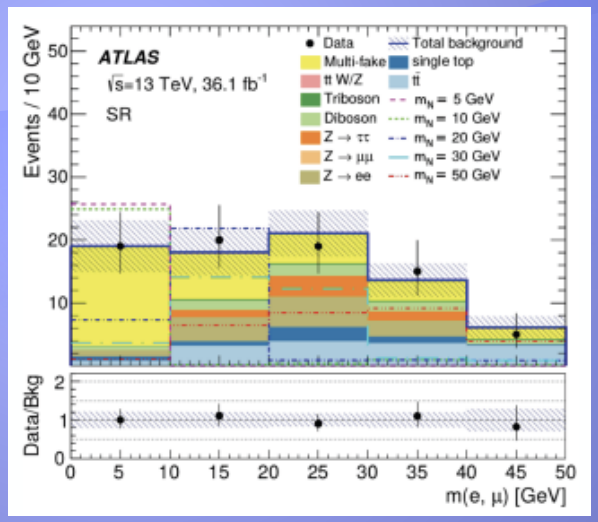
- ATLAS
- Focused on the region of high sensitivity (4.5 – 50 GeV)
- Low mass with prompt muon + diplaced vertex (4-300 mm)
- Use same-sign dilepton with no b-jet

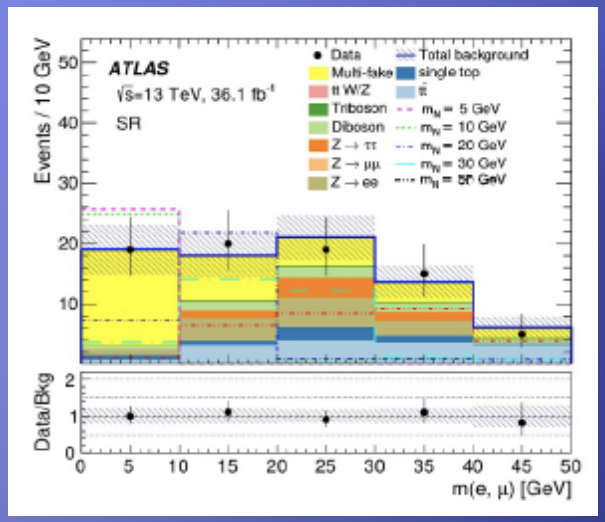
- CMS
- A broad range,: 1– 1200 Gave
- 33 categories by lepton pt, 2l and 3 l mass, missing Et

Results from ATLAS

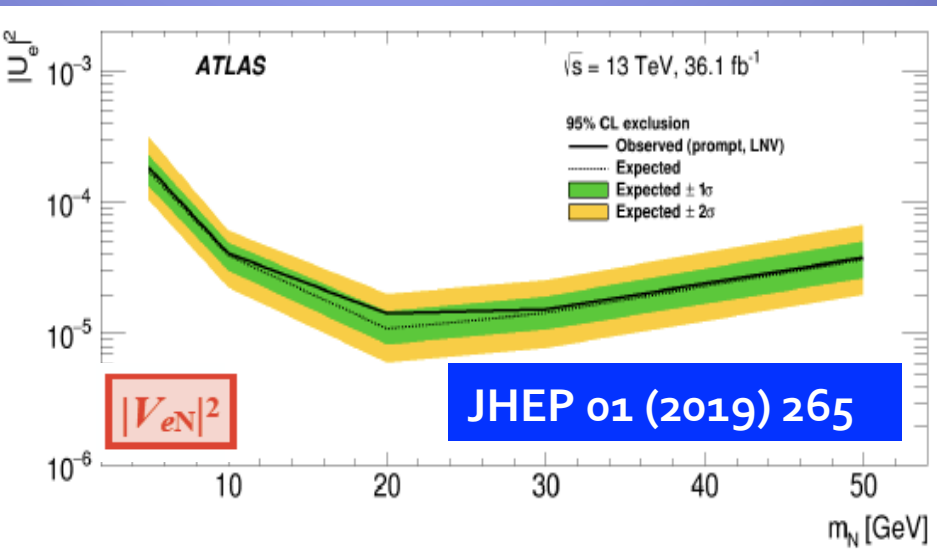
- Tri-lepton channel for 4.5 – 50 GeV

$e^{\pm}e^{\pm}\mu^{\mp}$





$\mu^{\pm}\mu^{\pm}e^{\mp}$



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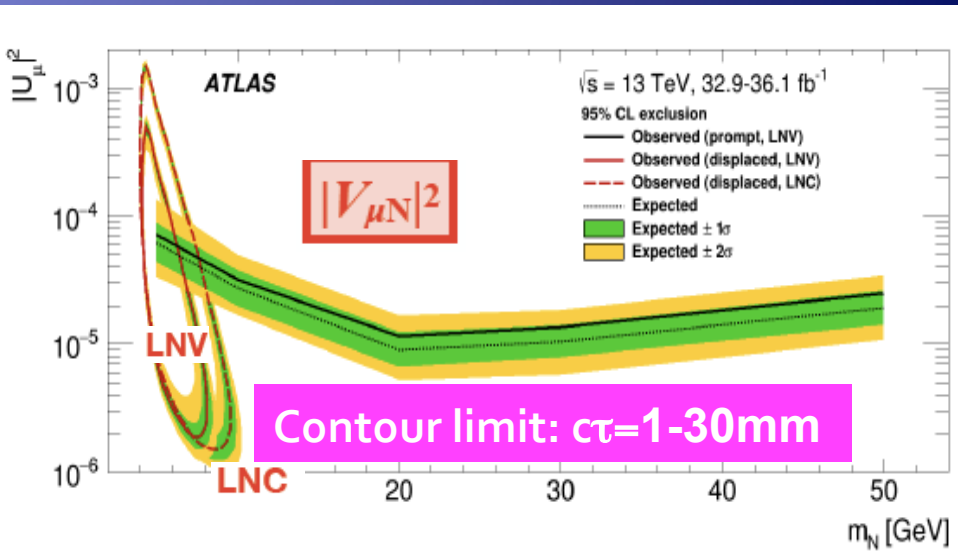
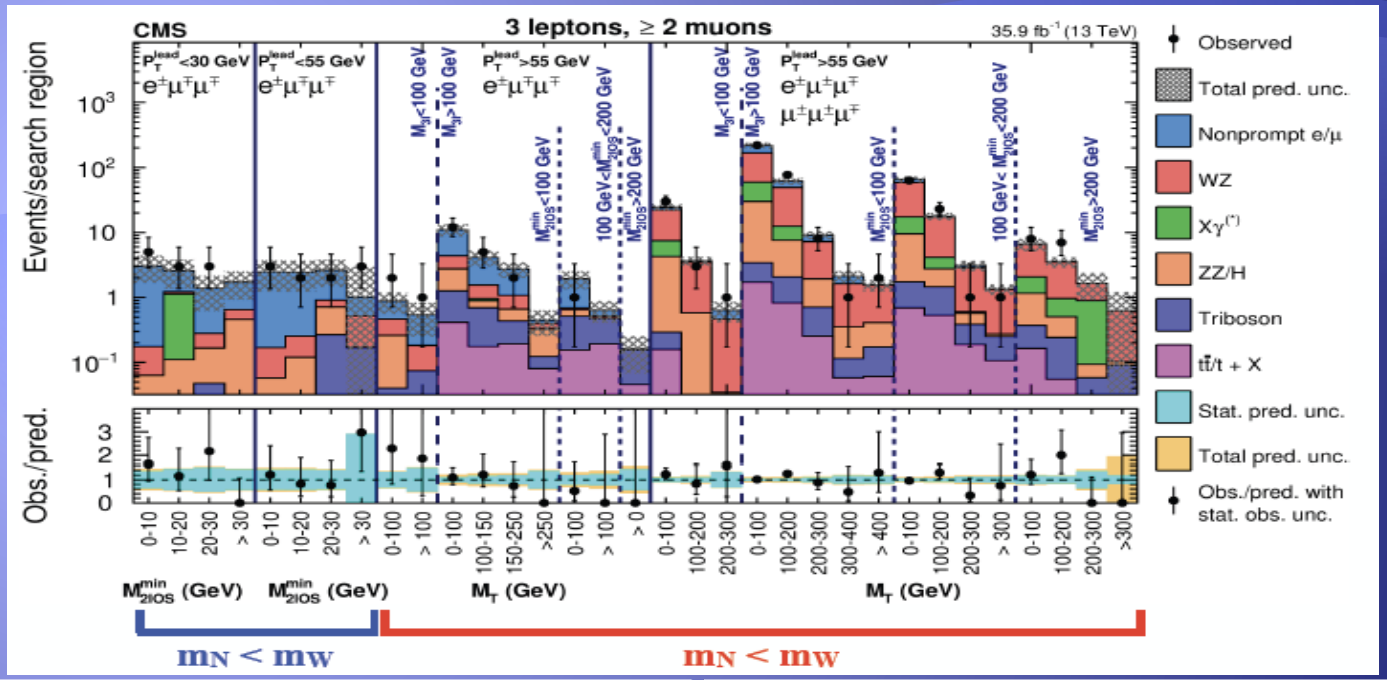
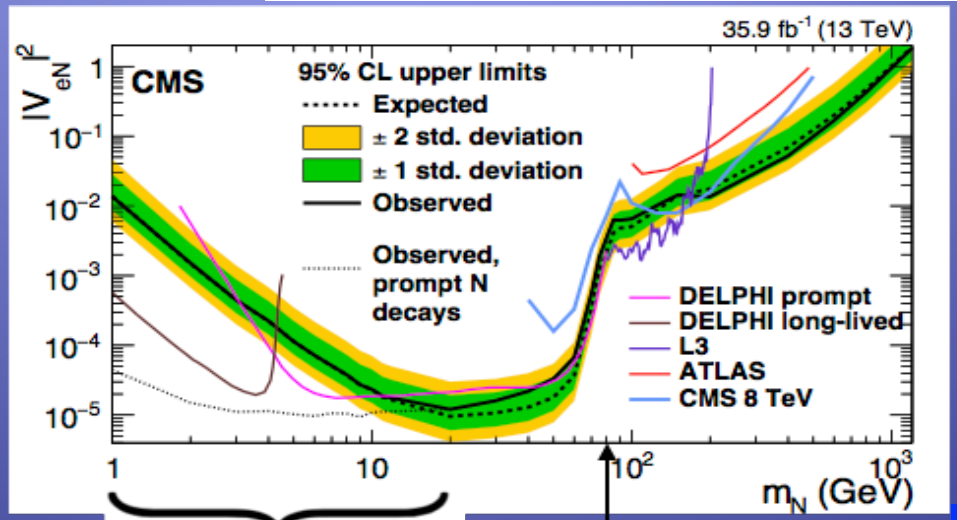
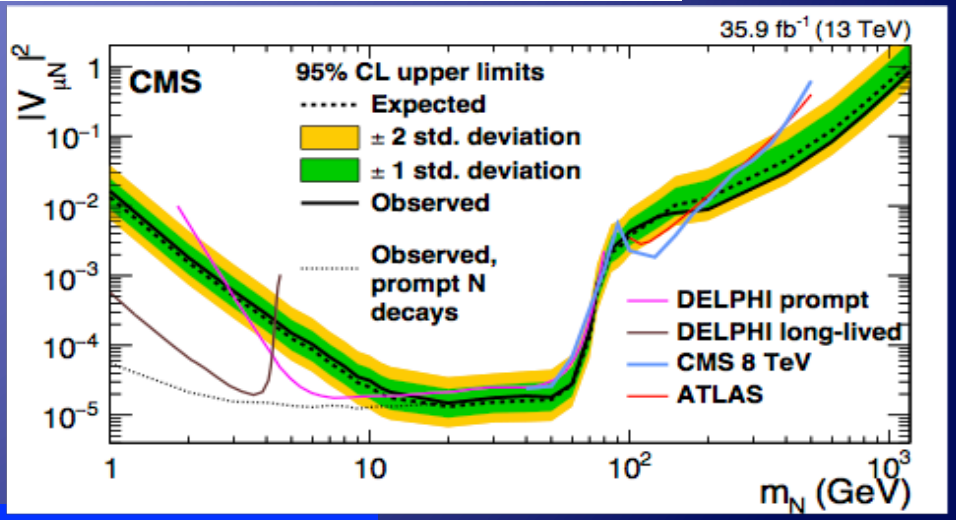


Contour limit: cτ=1-30mm

Results from CMS

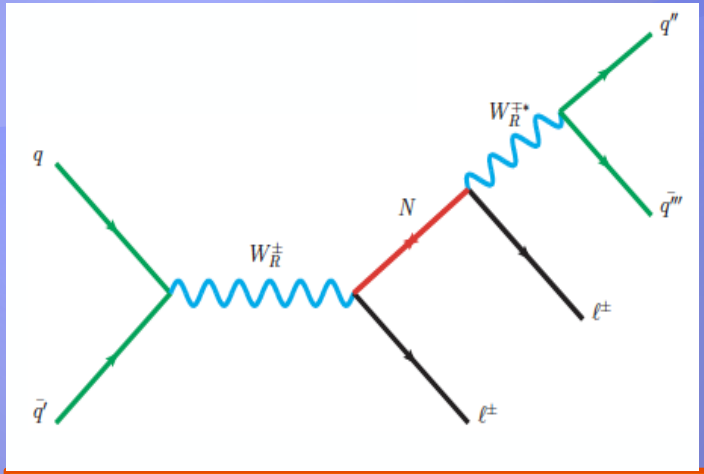






PRL 120.221801

Searches in the LRSM



Same Final state as type-I
But different kinematics

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

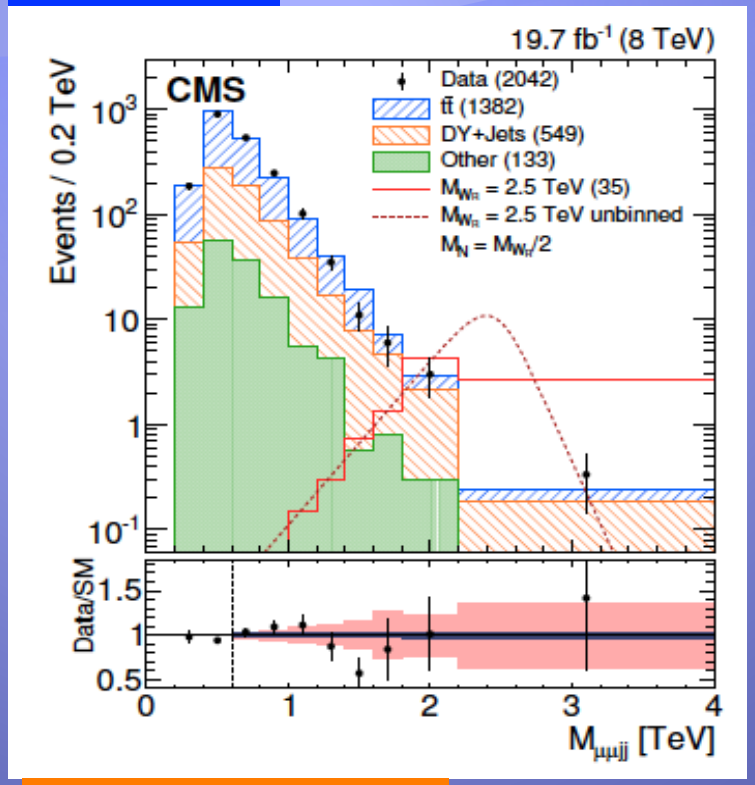
- **Challenges:**
  - For $m_N \ll m_{WR}$, jets and lepton from N decays overlap
    → standard lepton isolation will kill signal
    → use boosted jet to resolve lepton and jet

- **ATLAS**
  - Separate OS and SS pairs fro Majorana/Dirac
  - Kinematic shape analysis m(jjll), m(jj)

- **CMS**
  - No distinction for OS & SS
  - For each W_R mass hypothesis, a counting experiment in m(jjll) window

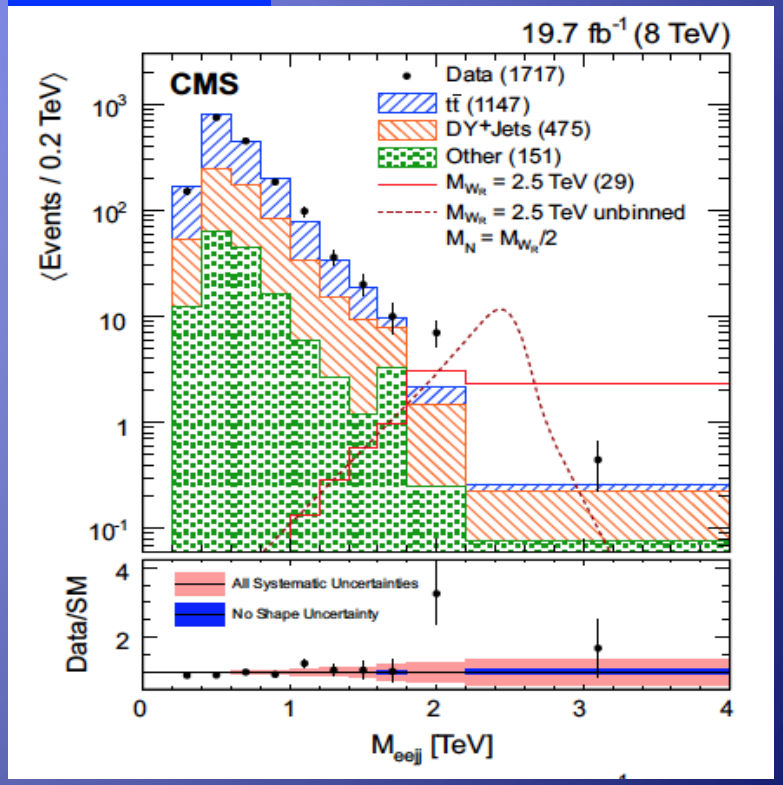
Run 1 results from CMS

μμ channel



EPJ C74 (2014) 3149

ee channel



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

Update result with 13 TeV

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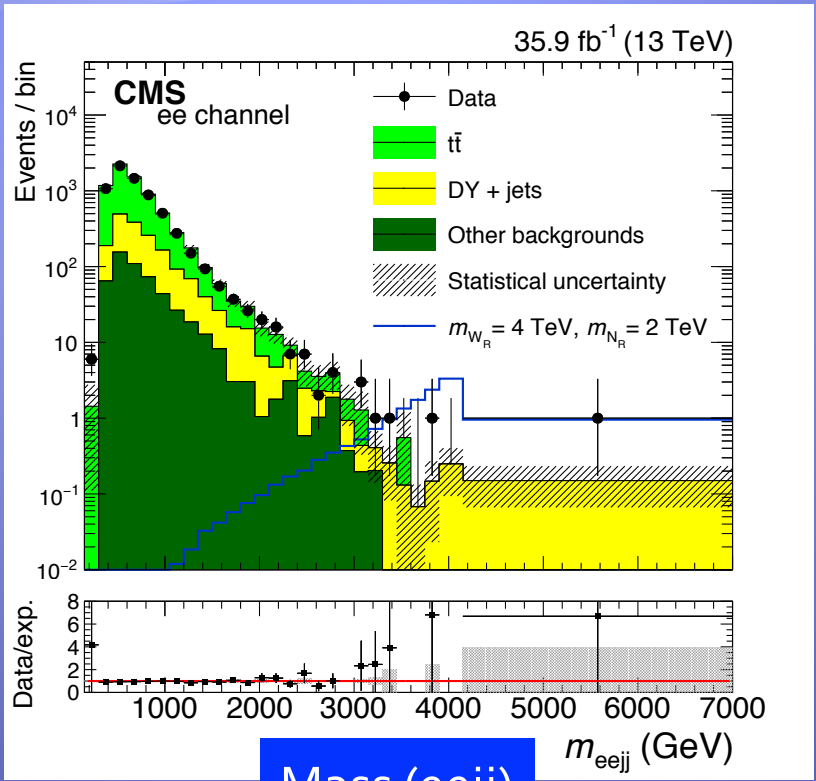
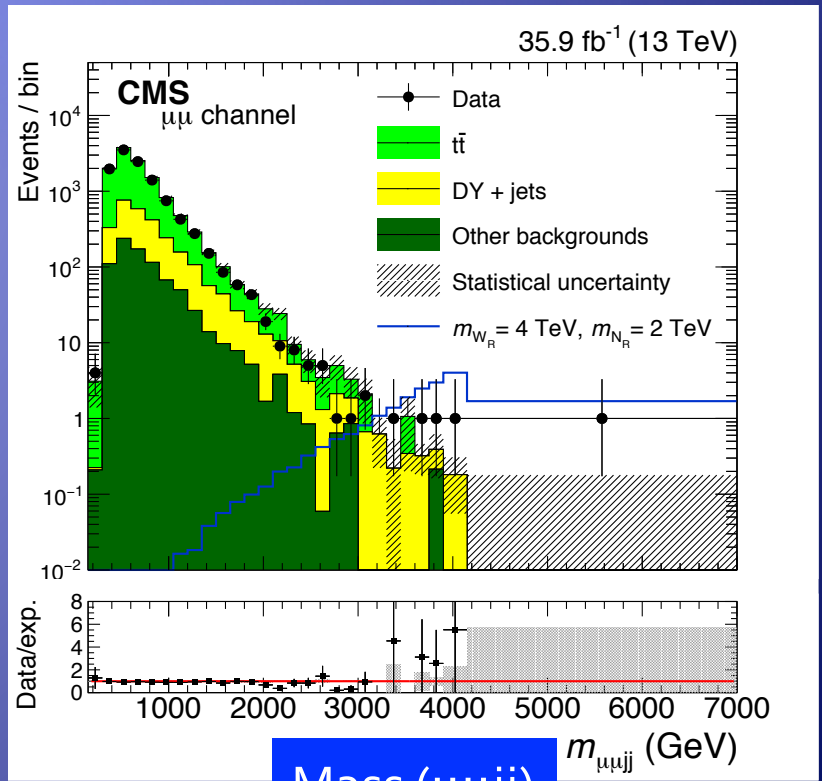


Mass (eejj)



Mass (μμjj)

- **No excess in signal region**

Limits in the LRSM

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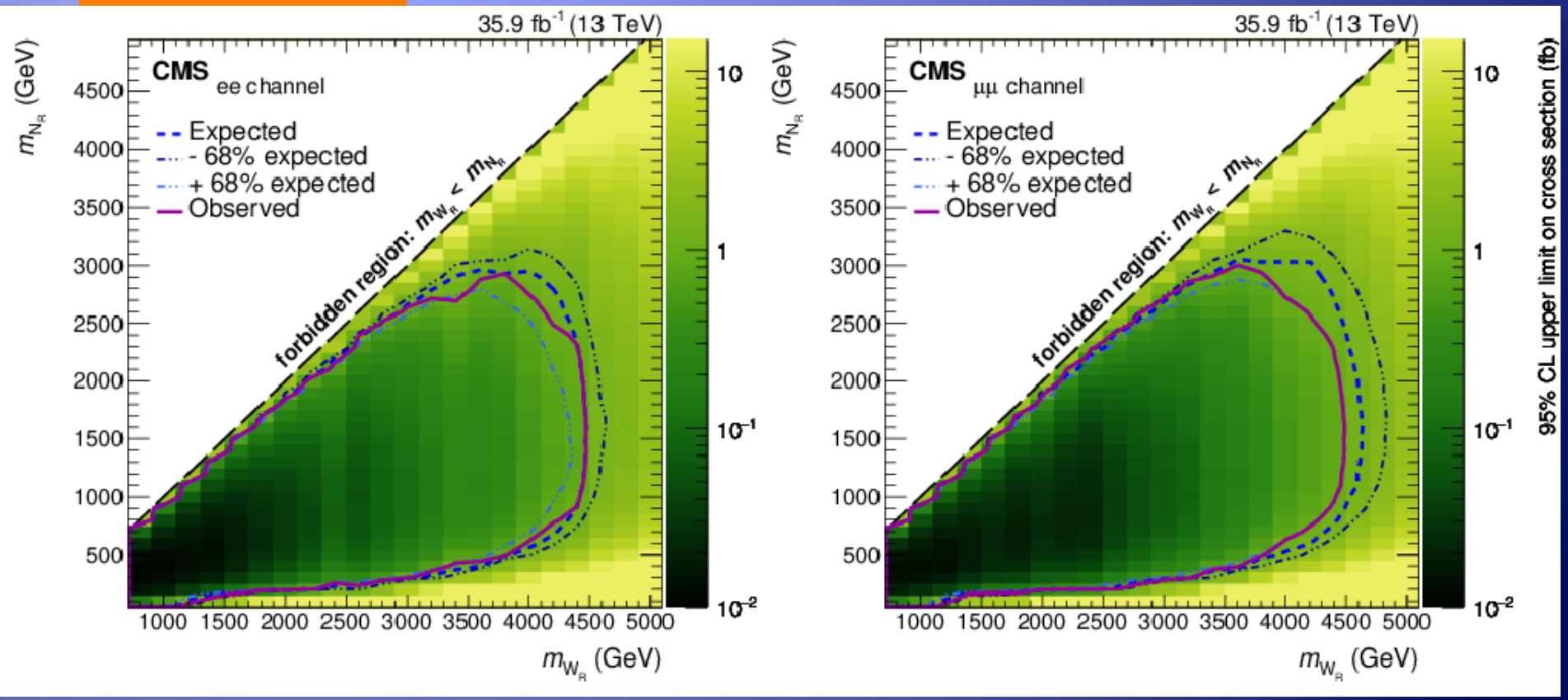
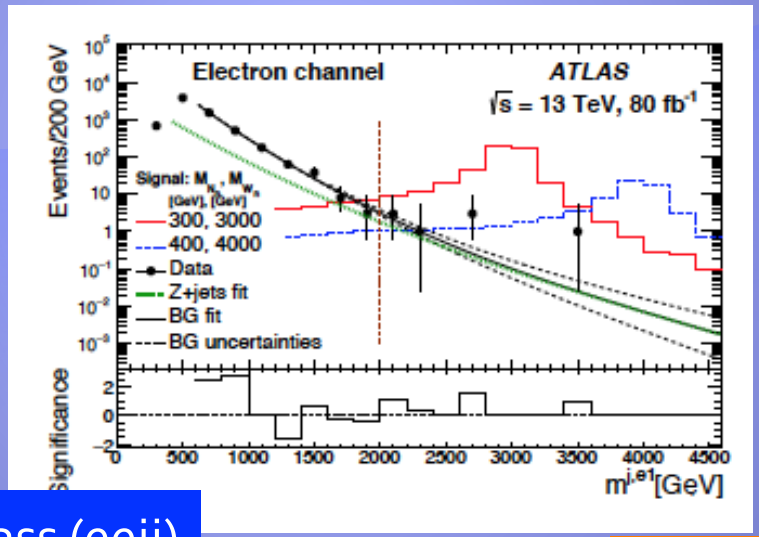
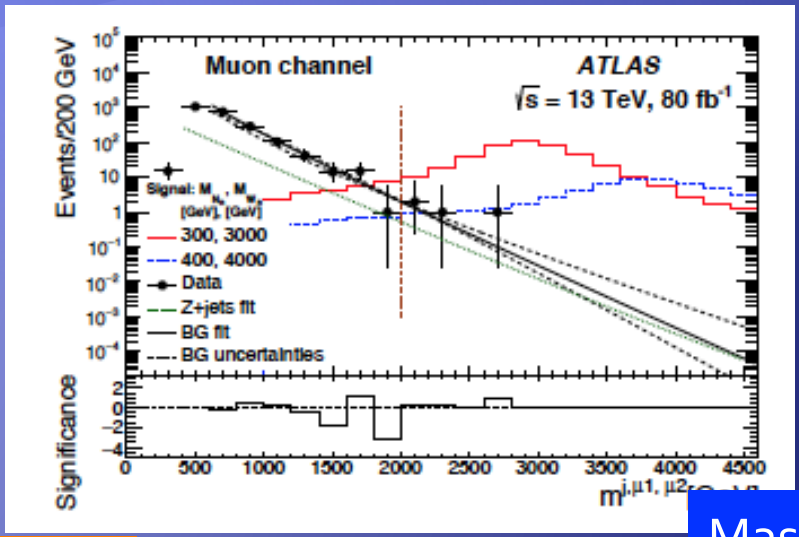


- The exclusion of W_R up to 4.4 TeV

Update result with 13 TeV

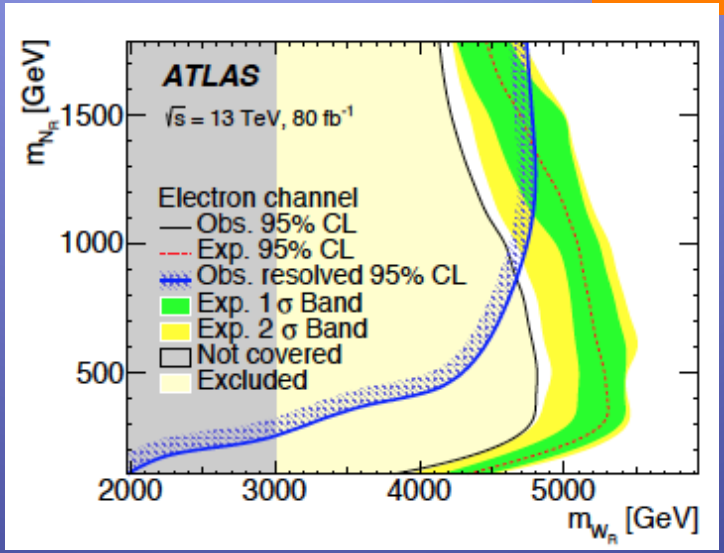


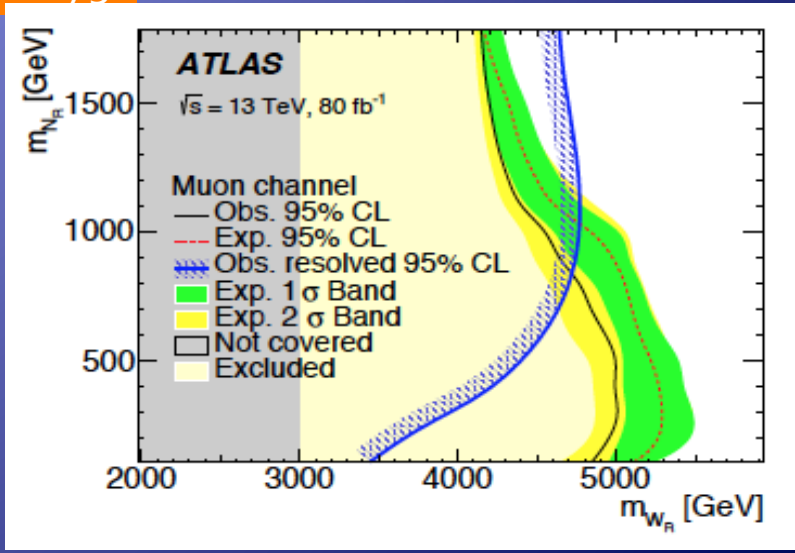
Mass (eejj)



Mass (μμjj)

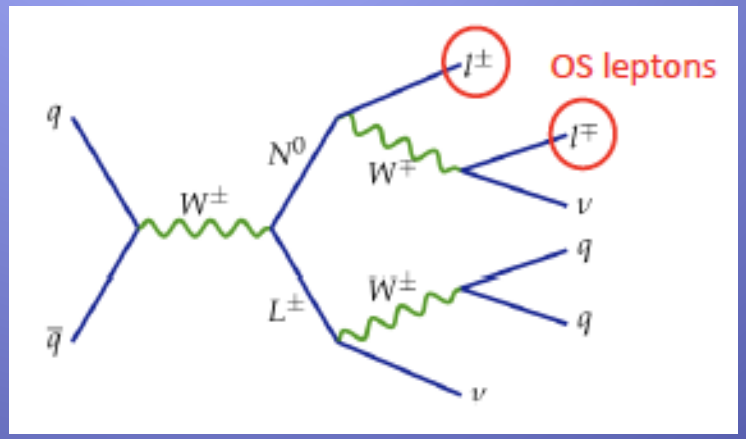
arXiv.1904.12679

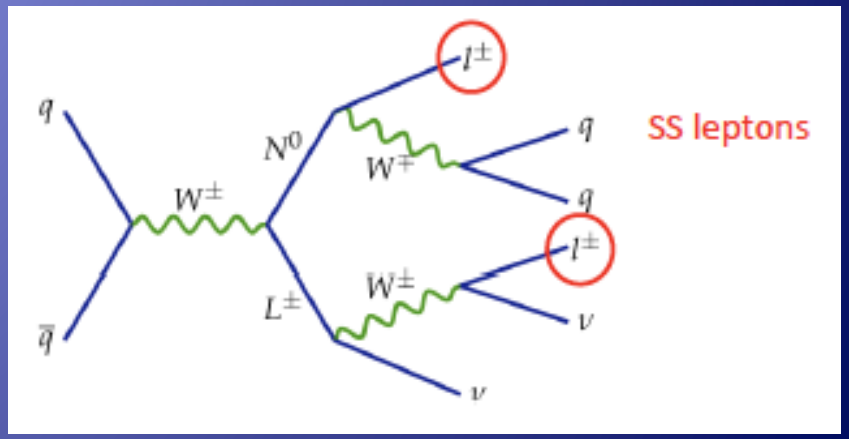




Search for Type III Seesaw

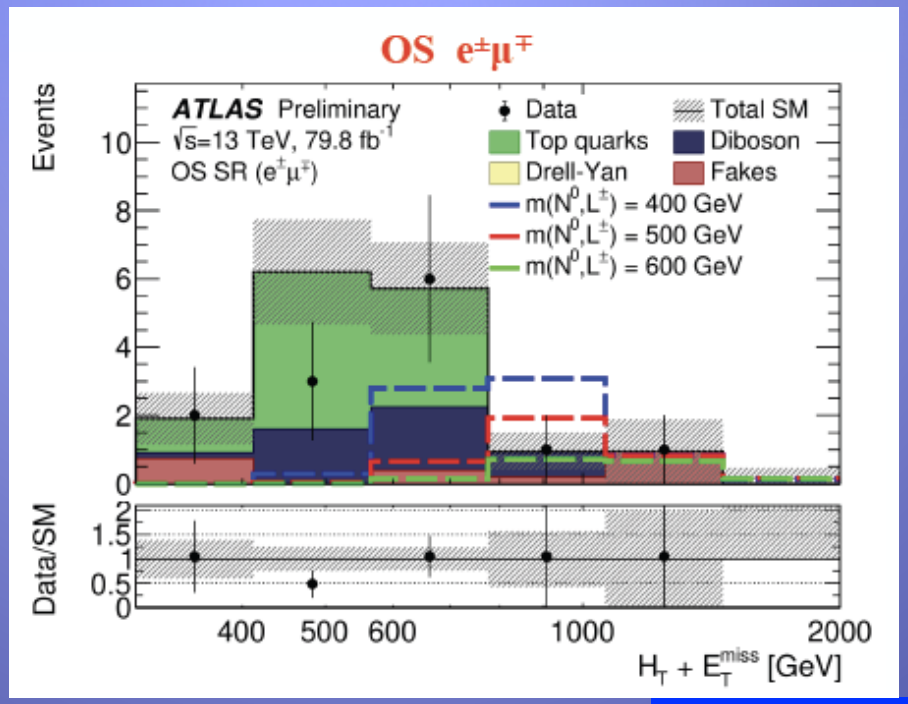
- Look for decay of new heavy fermions (N^0, L^+, L^-)
- ATLAS: OS or SS leptons + 2 jets (2018)
- CMS: 3 or 4 leptons with MET (2017)
- Both used MET + H_T(scalar sum) as search variable

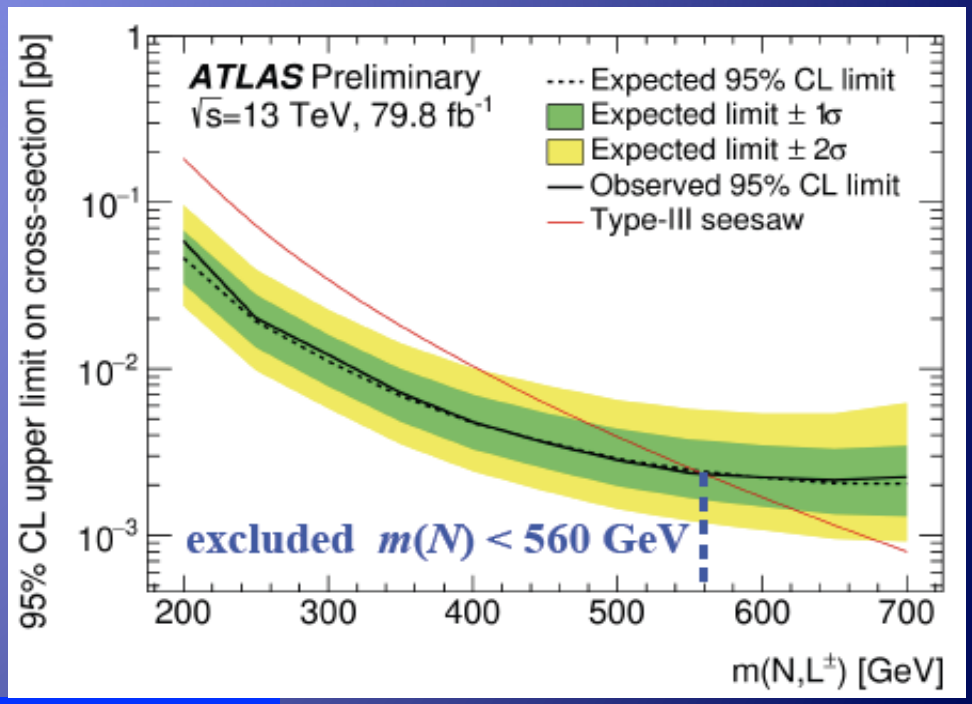




ATLAS Search for Type III

- Used MET + H_T(scalar sum) as search variable

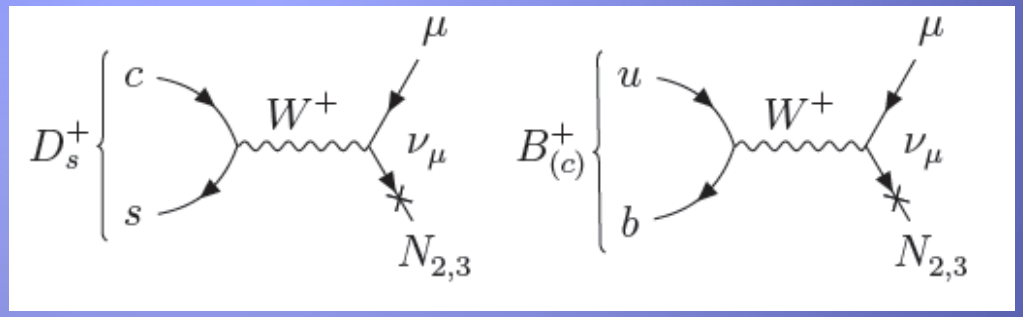


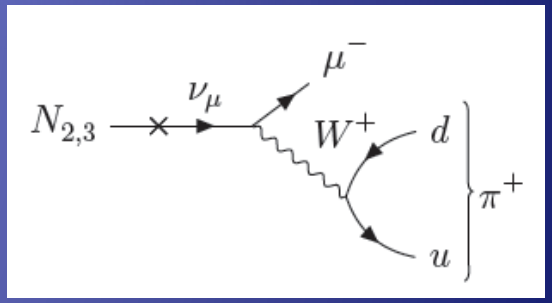


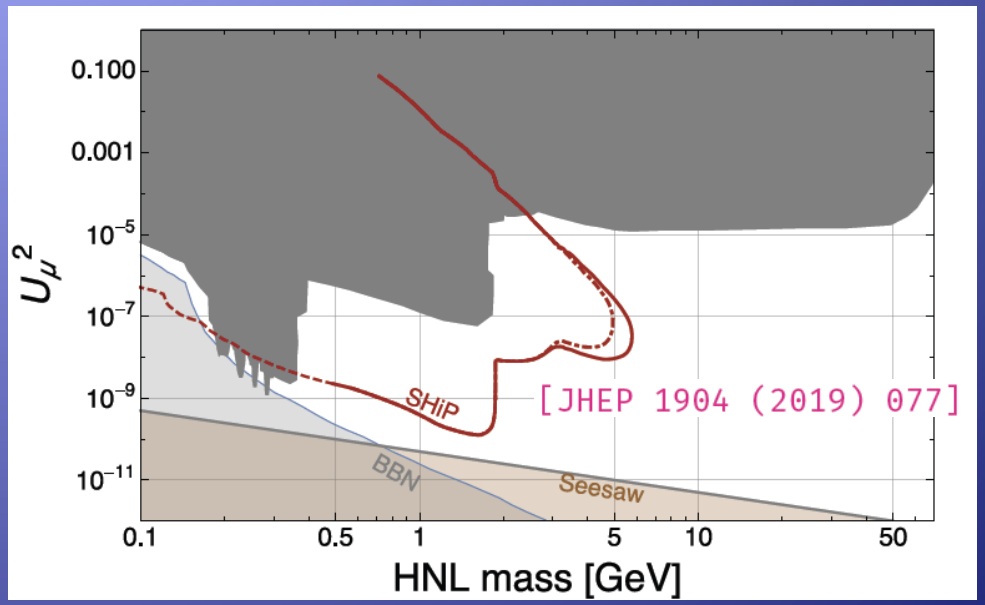
ATLAS-CONF-2018-020

Future SHiP

- SHiP experiment looks for NHL (N) from charmed or B mesons decays
- SHiP can reconstruct exclusive decays







Summary

- Neutrino oscillations attracts many interesting searches at the LHC: the origin of neutrino mass
  - Searches for HNL provides tests for various Seesaw models and LRSM

- LHC has searched for heavy neutral leptons but with no excess seen in data
  - Upper limits are set on $|V_{IN}|^2$
  - Exclusion on W_R mass up to 4.5 TeV

- Searches will be explored using the full 13 TeV data from many different channels
- SHiP will explore in low mass region near future

Backup

SS Dimuon + 2 jets event observed in the CMS detector