Searches for Heavy Neutrinos and Lepton Number Violation using the CMS at the LHC

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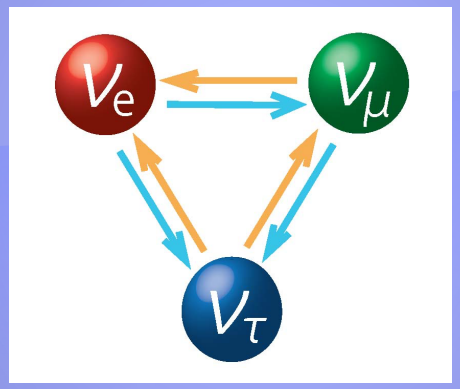
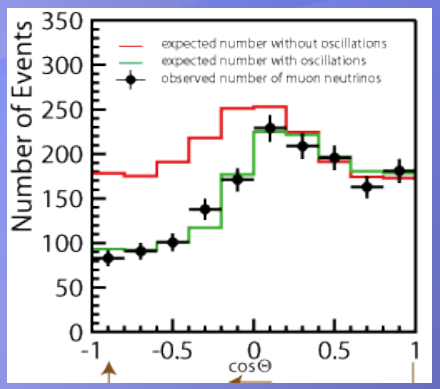
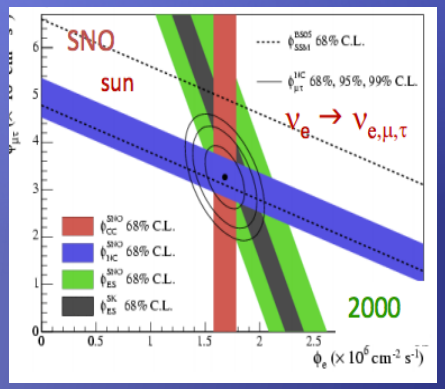
On behalf of the CMS collaboration

NuFact 2016, Aug. 21-26, 2016, ICISE @ Quy Nhon

Neutrino Oscillation

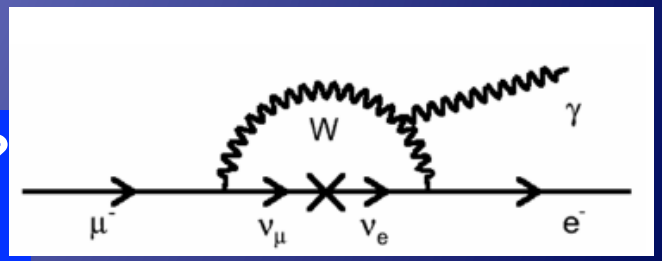




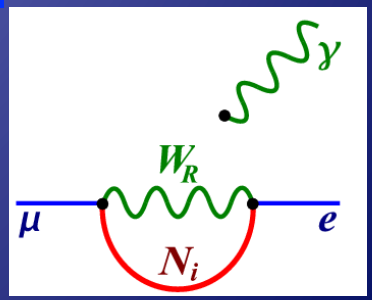


- Lepton Number Violation (LNV)
- Non-zero neutrino mass

- Is the Charged Lepton Number Violated ?
  $\mu \rightarrow e\gamma$



- Does the righted-handed N exist?

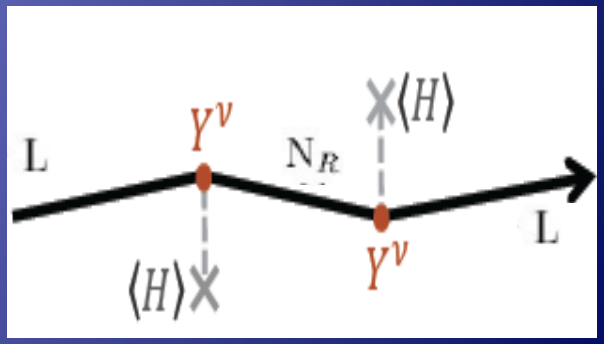


Physics Beyond SM

- SM induced LNV for charged lepton is so small, $Br(\mu \to e\gamma) \sim 10^{-50}$, many news physics models can enhance this decay
  - RPV SUSY, Extra-dim, GUT, models with Majorana N etc
  - Look for $\mu \to e\gamma$, and $Z, H, Z' \to e\mu, \mu\tau$

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

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



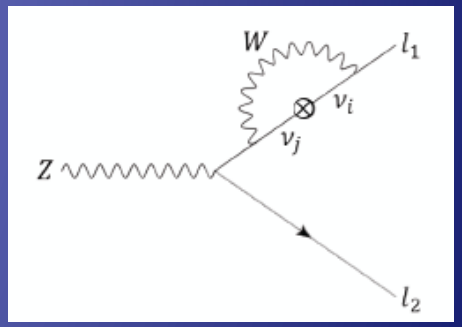
  - Seesaw Mechanism (type I, II, III)

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

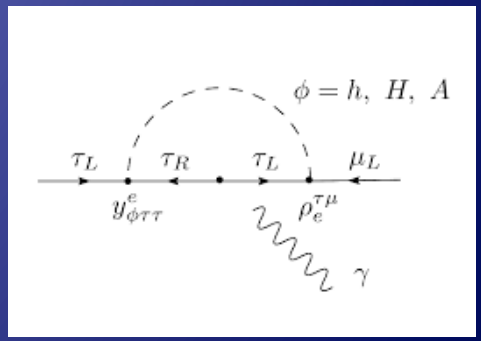
$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \qquad M_{W_R} \gg M_{W_L}$$

Searches for the LNV at the LHC

- Z decay, Z → eμ
  - Neutrino oscillation predicts LNV, but Br(Z→eμ)<10^{-60}
  - Indirect from μ→3e: Br(Z→eμ)<5×10^{-13}
  - Can be enhanced by the BSM
  - Searches for heavy states
    - RPV SUSY sneutrino
    - Quantum Black Hole with extra-dim

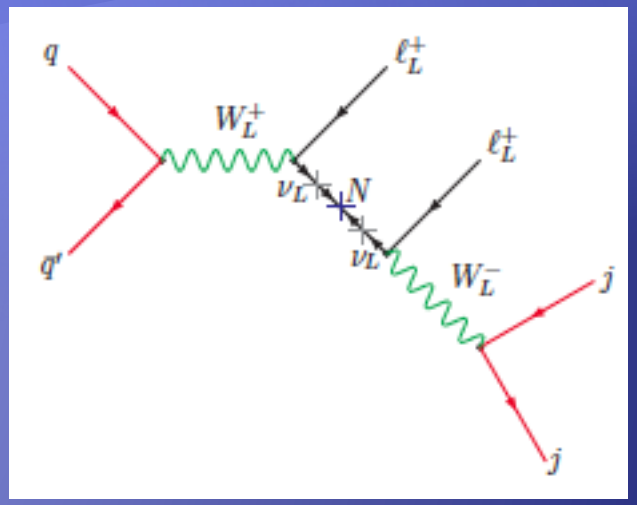


- Higgs decay, H→ e/μτ
  - B(H→ eμ) < O(10^{-8}) from μ→eγ
  - B(H→ e/μτ) < O(10%) from μτ→e/μγ
  - Direct Search promising



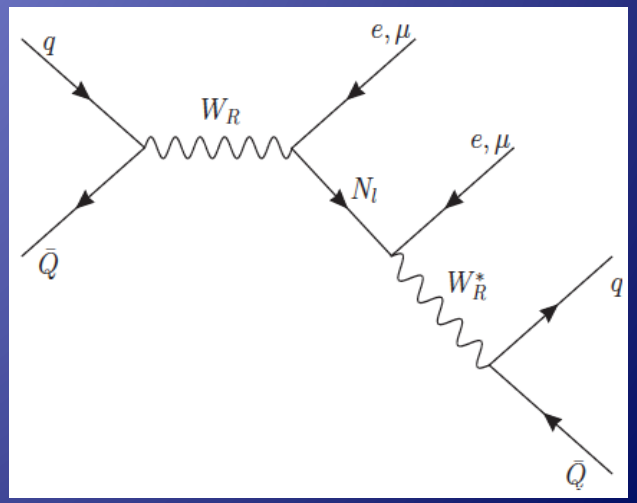
Searches for Heavy N at the LHC

- **Type 1:**
  - Resonant production via s-channel W* or W(real)
  - probe light-heavy mixing
  - Majorana: 50% same-sign
  - Cross section depends
  - on $|V_{IN}|^2$ and m_N



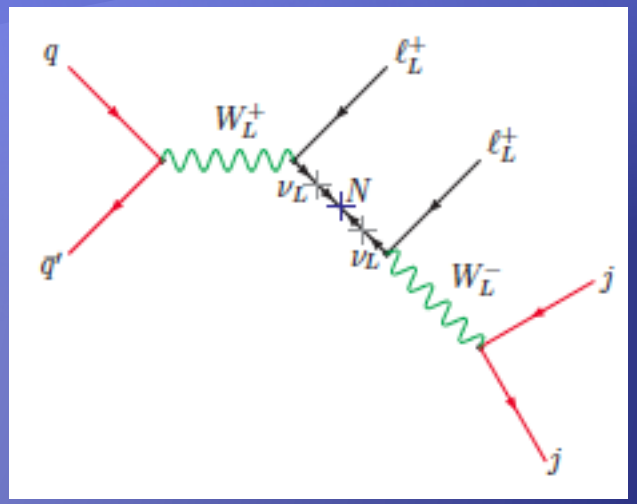
Signal: 2 leptons + 2 jets + no $\not{p}_T$

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



Heavy N productions

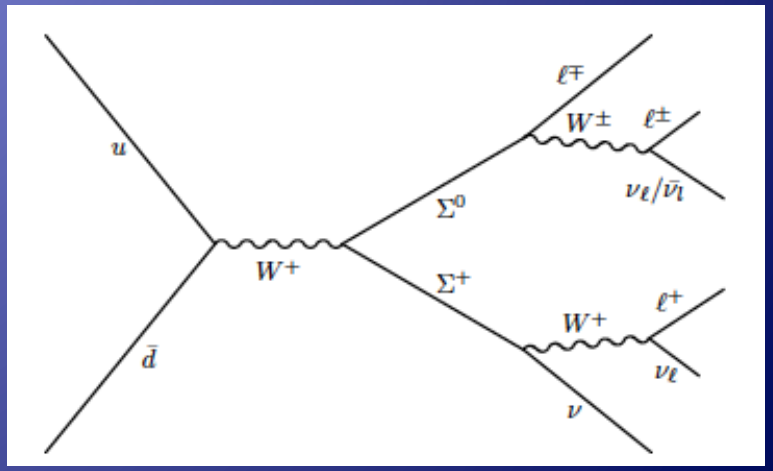
- **Type 1:**
  - Resonant production via s-channel W* or W(real)
  - probe light-heavy mixing
  - Majorana: 50% same-sign)
  - Cross section depends
  - on $|V_{lN}|^2$ and m_N



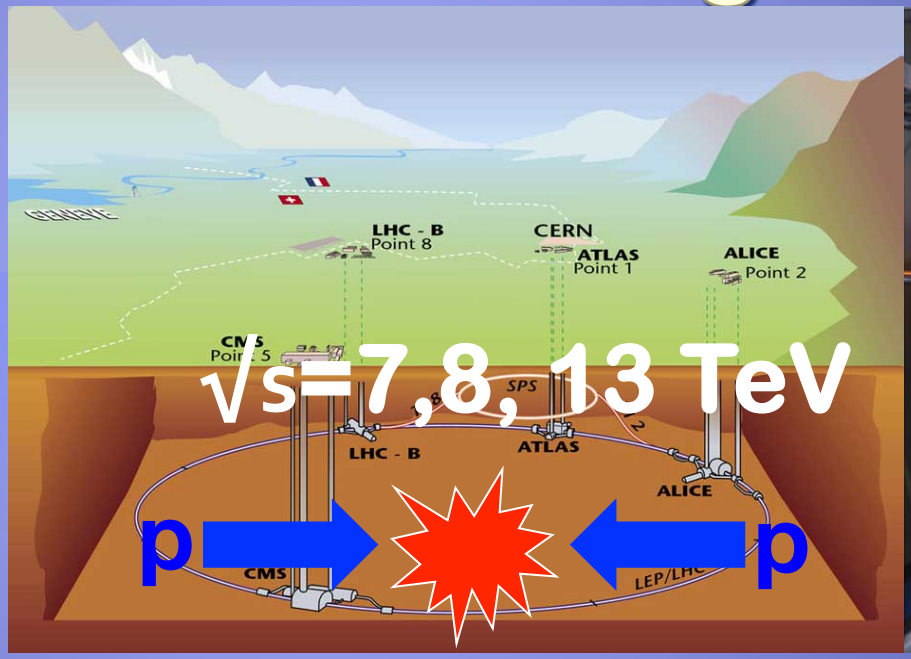
Signal: 2 leptons + 2 jets + no $\not{p}_T$

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

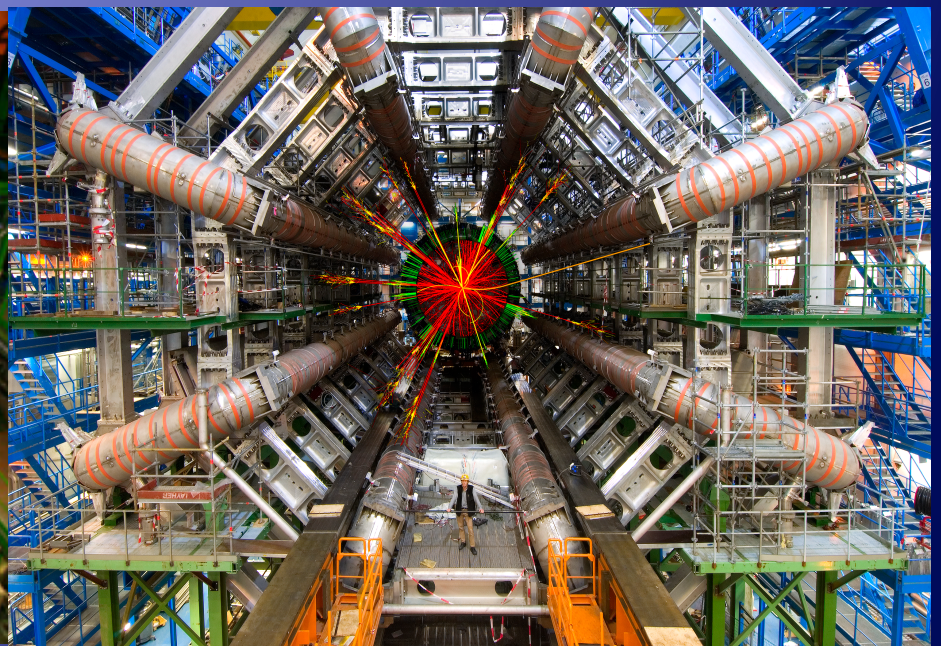
- **Type III:**
  - Production of Σ^0, $\Sigma^{+/-}$ via s-channel W*



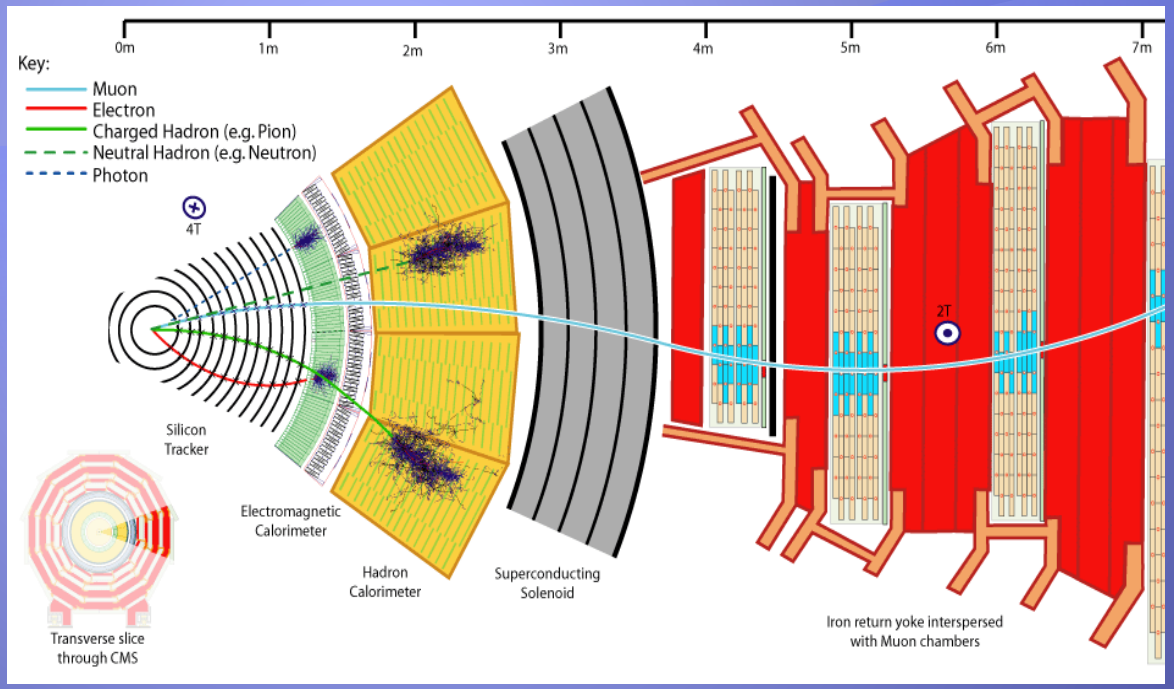
Use the Large Hadron Collider!

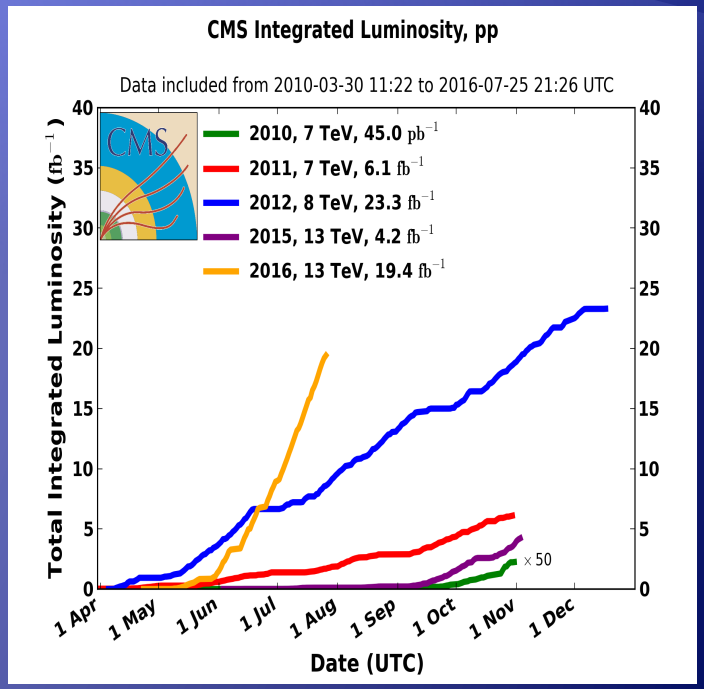


$\sqrt{s}$=7,8, 13 TeV



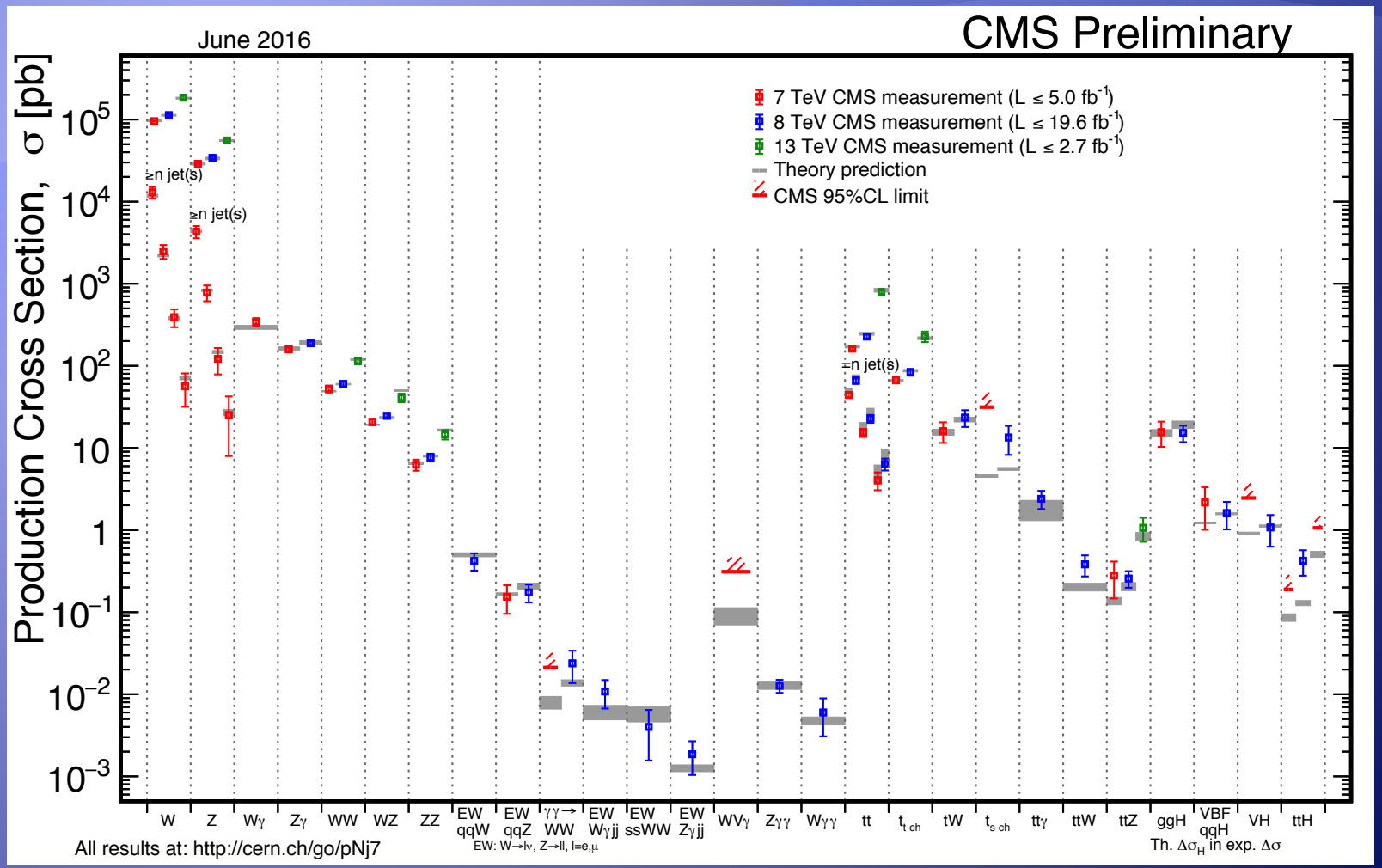
Detectors and Data





- High precision multipurpose detectors
- Excellent electron, muon, photon, jets IDs with good energy resolution
- Impressive data-taking

Before Searching for New Physics

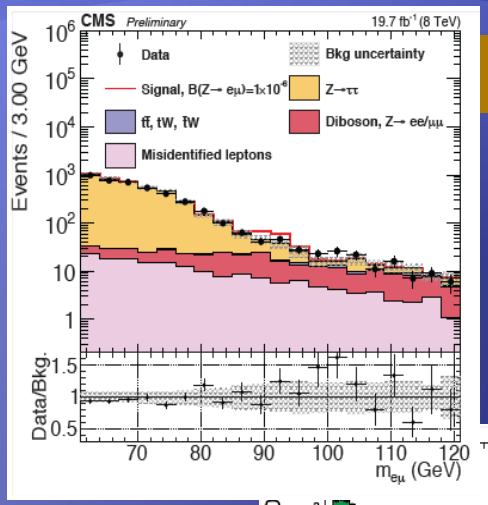


- **Impressive agreements with the SM**

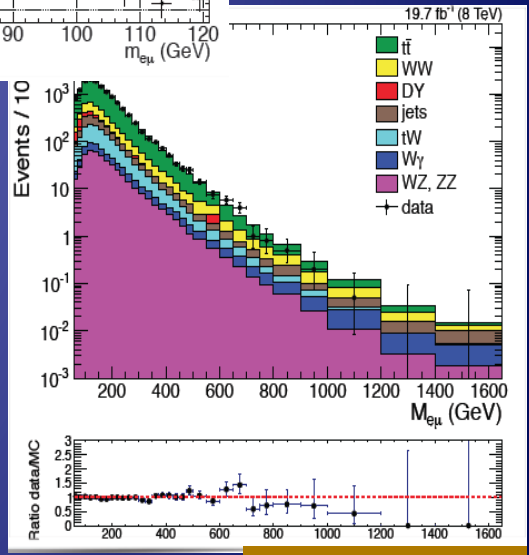
Results @ NuFact15

- Z→eμ
  - The most strong direct limit:
    $Br(Z \to e\mu) < 7.3 \times 10^{-7}$
- Heavy state→eμ
  - τ sneutrino: m < 1.28 (2.11) TeV
    for $\lambda_{132}=\lambda_{311}=0.01$ ($\lambda_{132}=0.05$, $\lambda_{311}=0.1$)
  - Black hole: m< 1.99-3.66 TeV for n_{extra_dim}=0-6
- H→μτ
  - 2.4σ deviation from the SM observed
  - Limits on branching ratio
  - & LFV Yukawa coupling

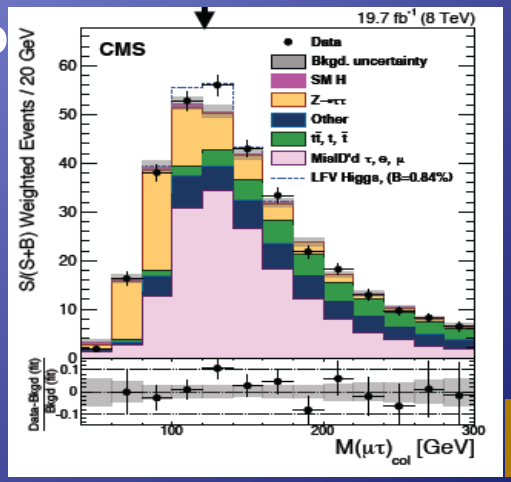
  $Br(H \to \mu\tau)$ <1.51%
  (0.75% expected)



EXO-13-005



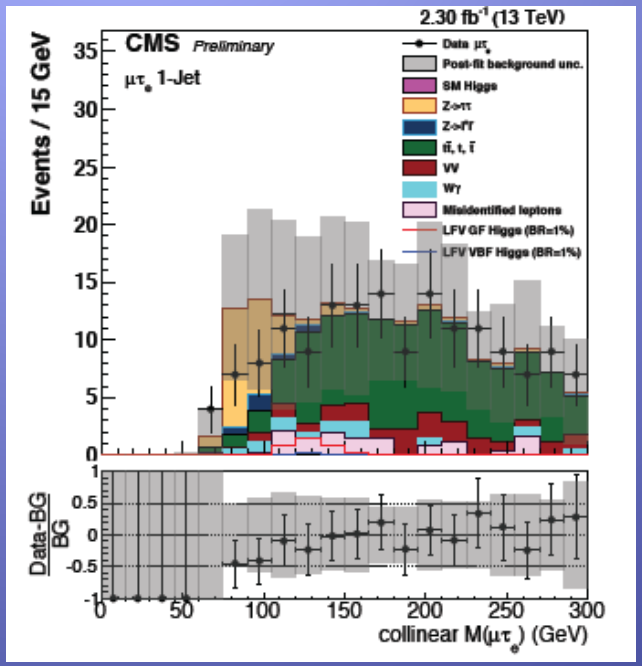
EXO-13-002

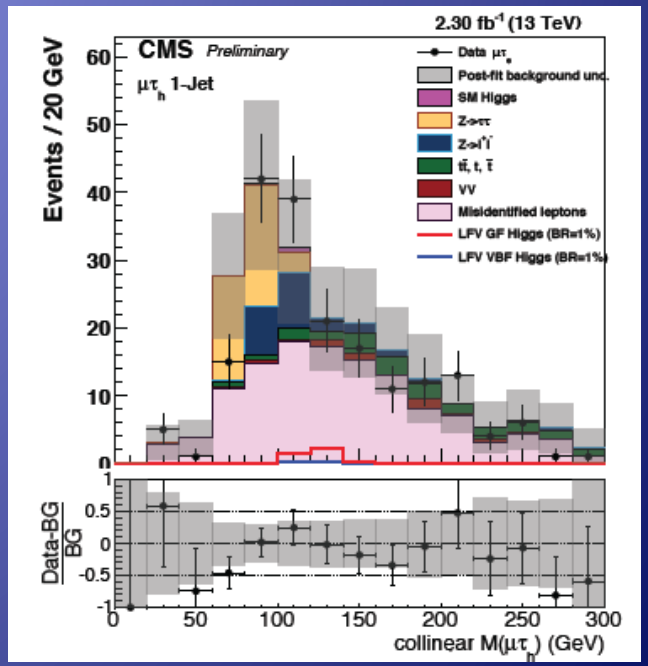


PLB749, 347 (2015)

Update on H→μτ

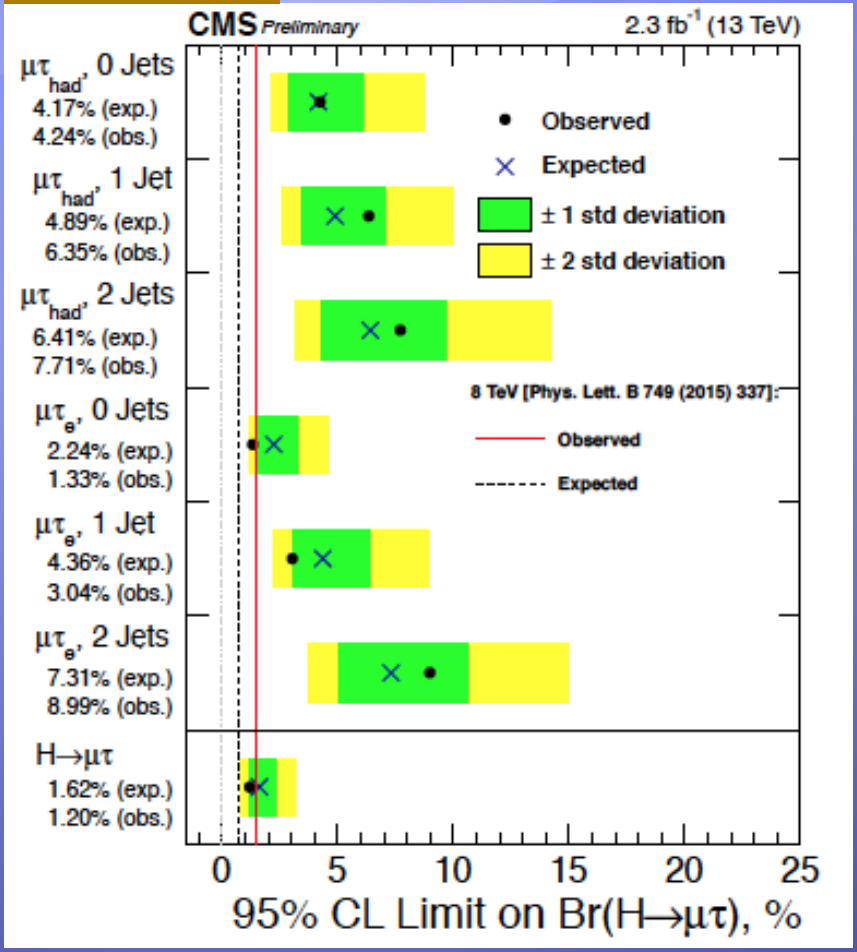
- A small 2.4s excess @ 8 TeV data
- Analyze the 2015 13 TeV data
  - 2 channels: e/μ τ(e/μ), e/μ τ(had) with 3 categories (0, 1, 2 jets)
  - Large bkgds: large systematics
  - Template fits to the collinear mass distribution





Update Results on H→μτ

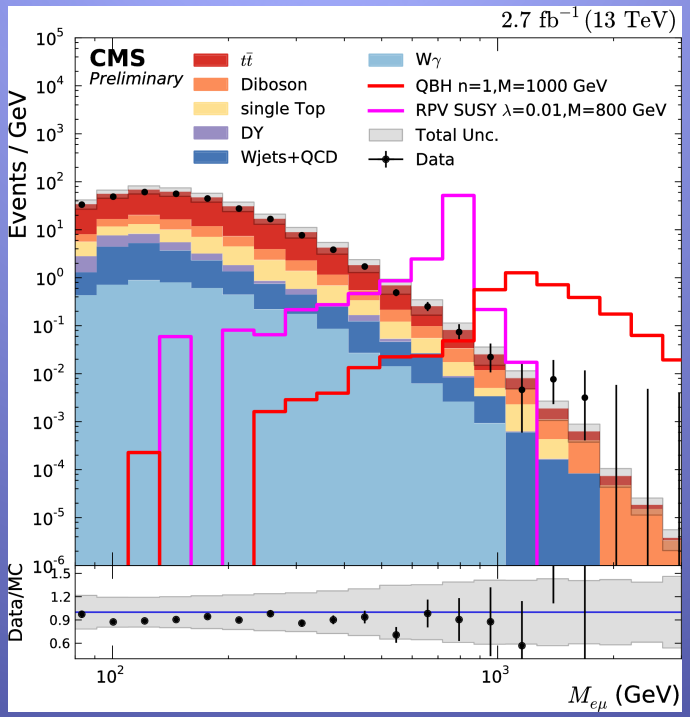
HIG-16-005

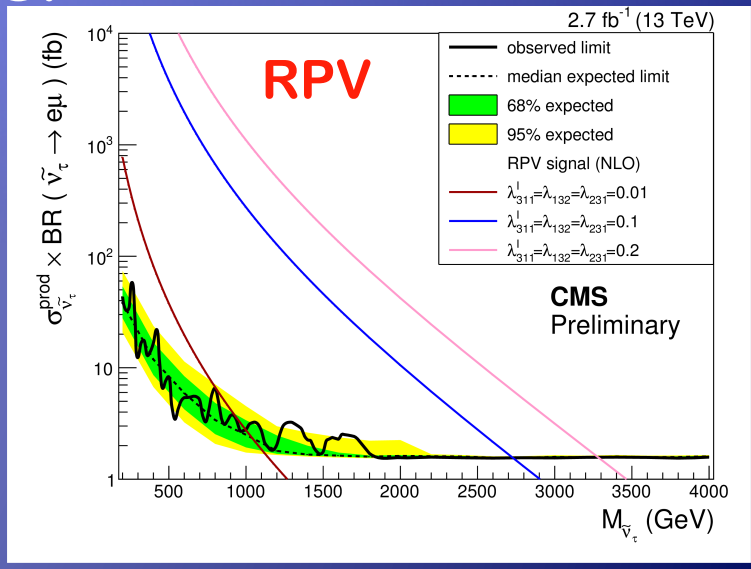


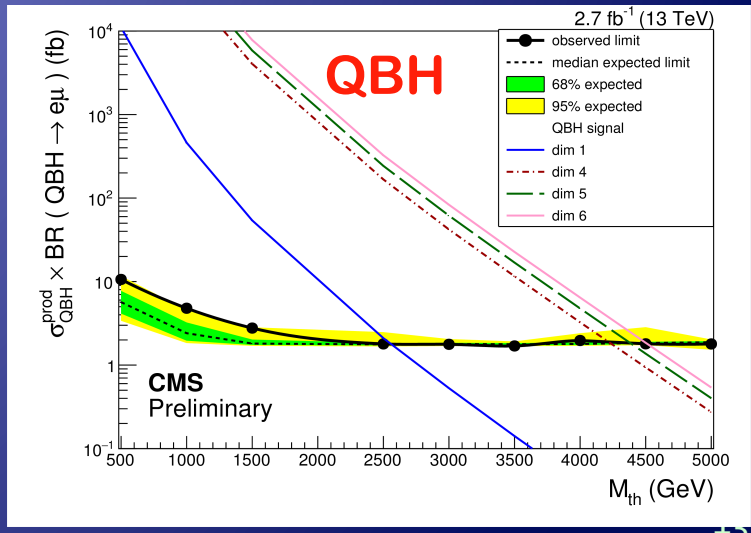
Set on the upper limits on Br(H→μτ)<1.20% (1.62% expected): not reached the Run 1 sensitivity

Search for heavy X→ eμ

- RPV SUSY with τ sneutrino as LSP
  - Iso. high pT e/μ with 35/53 Gave
  - e-μ pair with highest invariant mass
  - **Shape based limits:**
    - **RPV: 3.3 TeV, QBH: 4.5 TeV (n=6)**

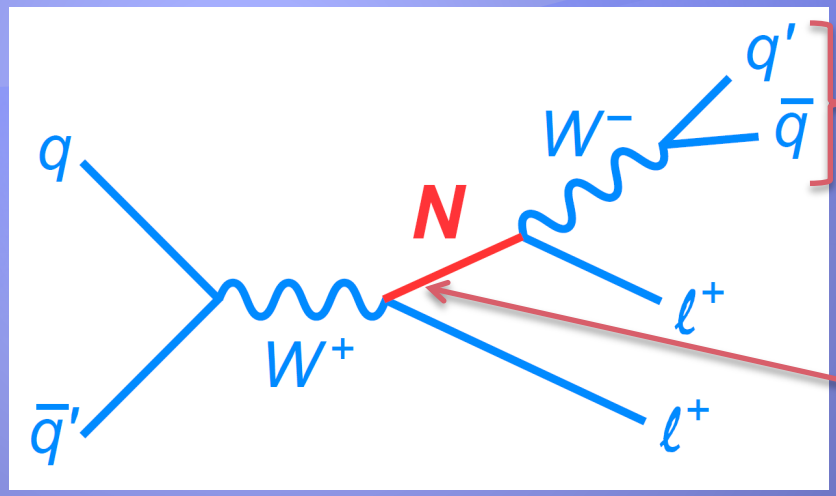






EXO-16-001

Searches in Type I Seesaw



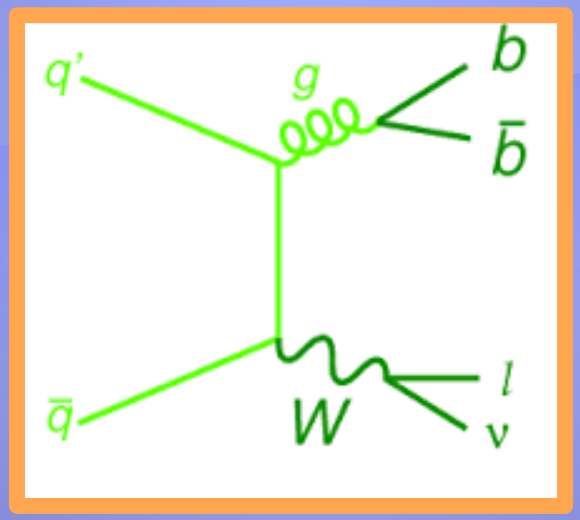
two jets from W
m(jj) = m(W)

Majorana Neutrino
Same-Sign 50% of events

- Final states: dileptons + 2 jets + no missing transverse energy (MET)
  - Lepton Pt > 20, 15 GeV leton pt cuts,
  - Jets Pt> 20 Gave, no MET (<30 Gave)
- Use only same sign leptons channels

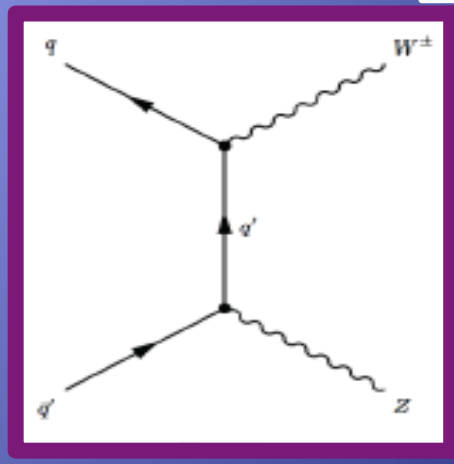
- Challenges:
  - Small signal cross sections but large bkgds from QCD jets
  - Understanding of Z+jets bkgd, but with a lepton-charge flip

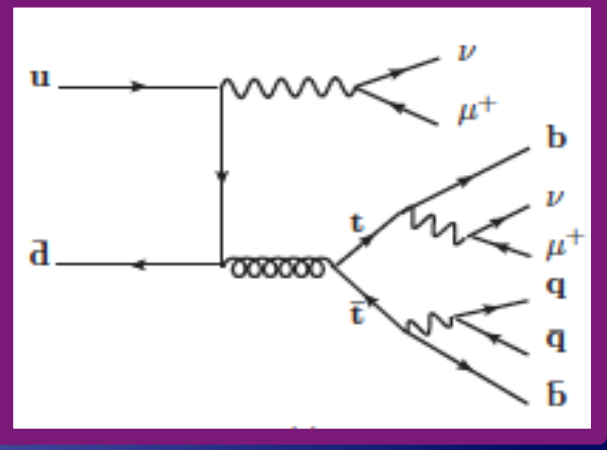
Backgrounds: ee/μμ/eμ+2 jets

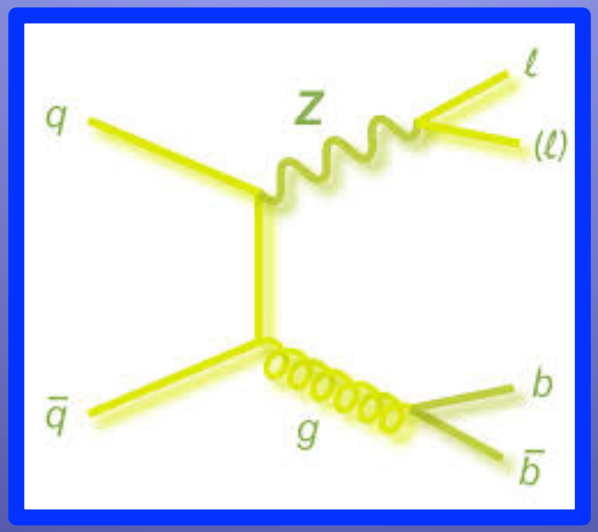


Fake leptons: "data"
W(e,μ)+jets:
dominant bkgd

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







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

Results @ CMS

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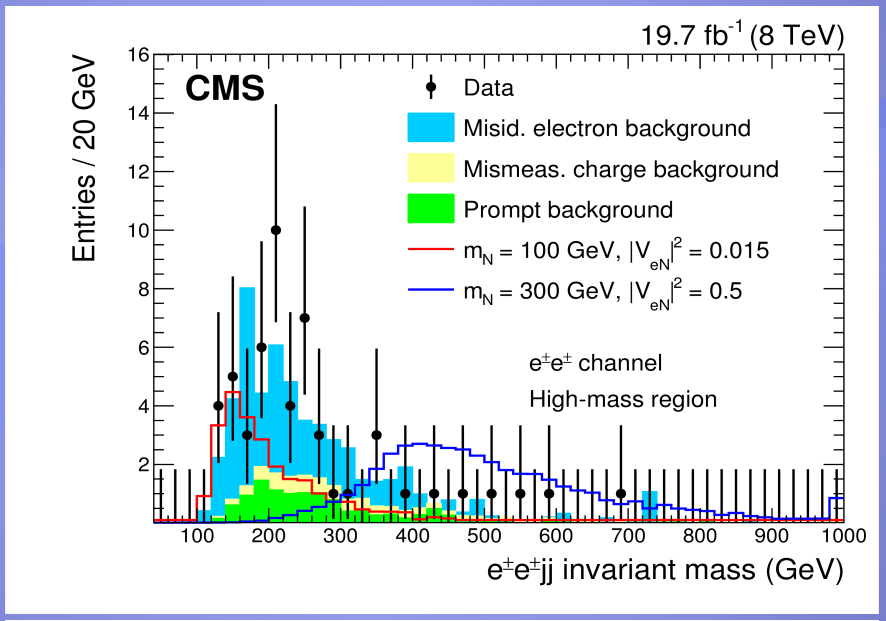

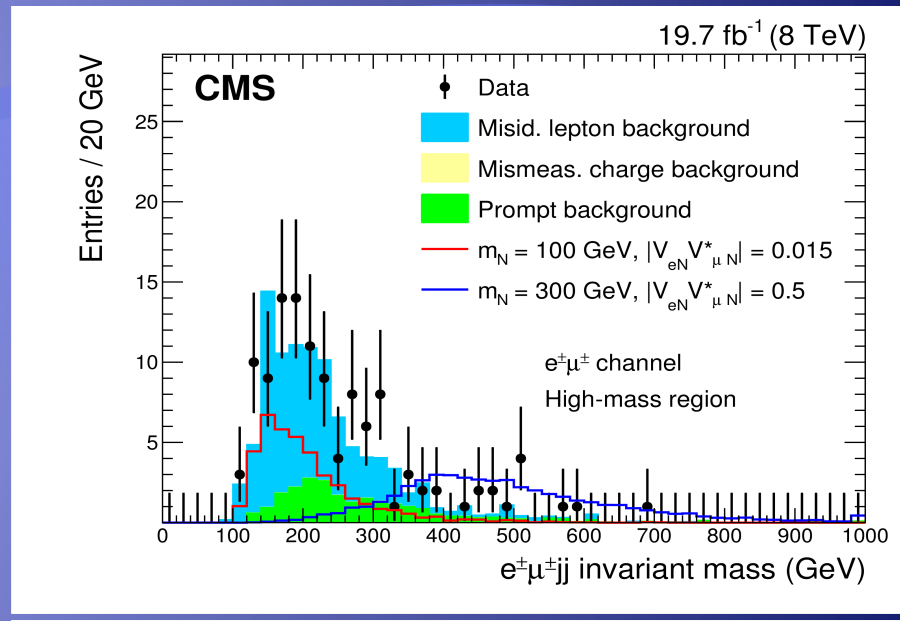

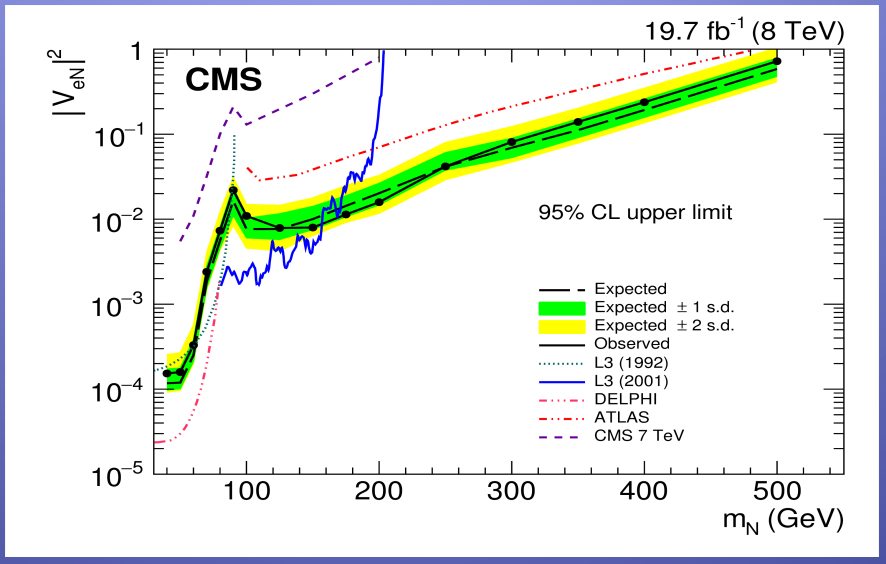

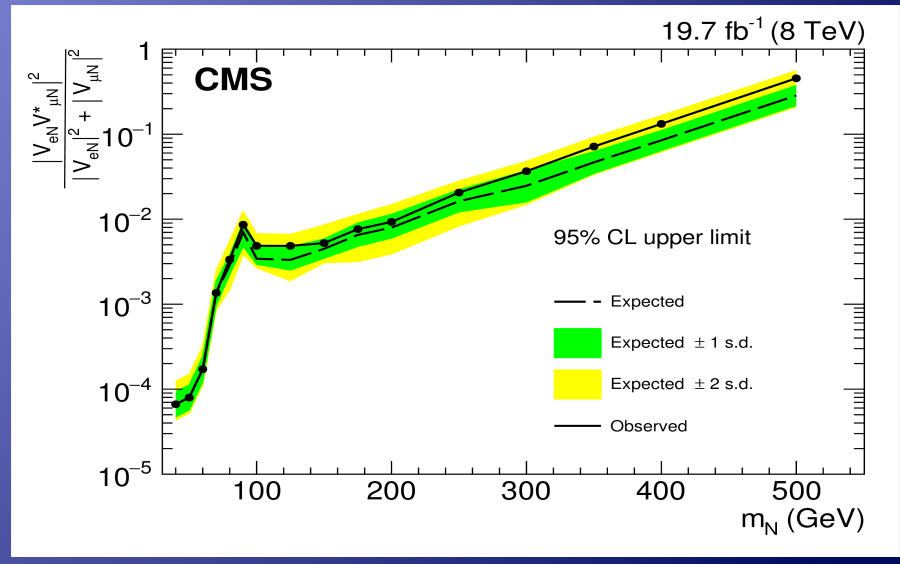

Results on Mixing

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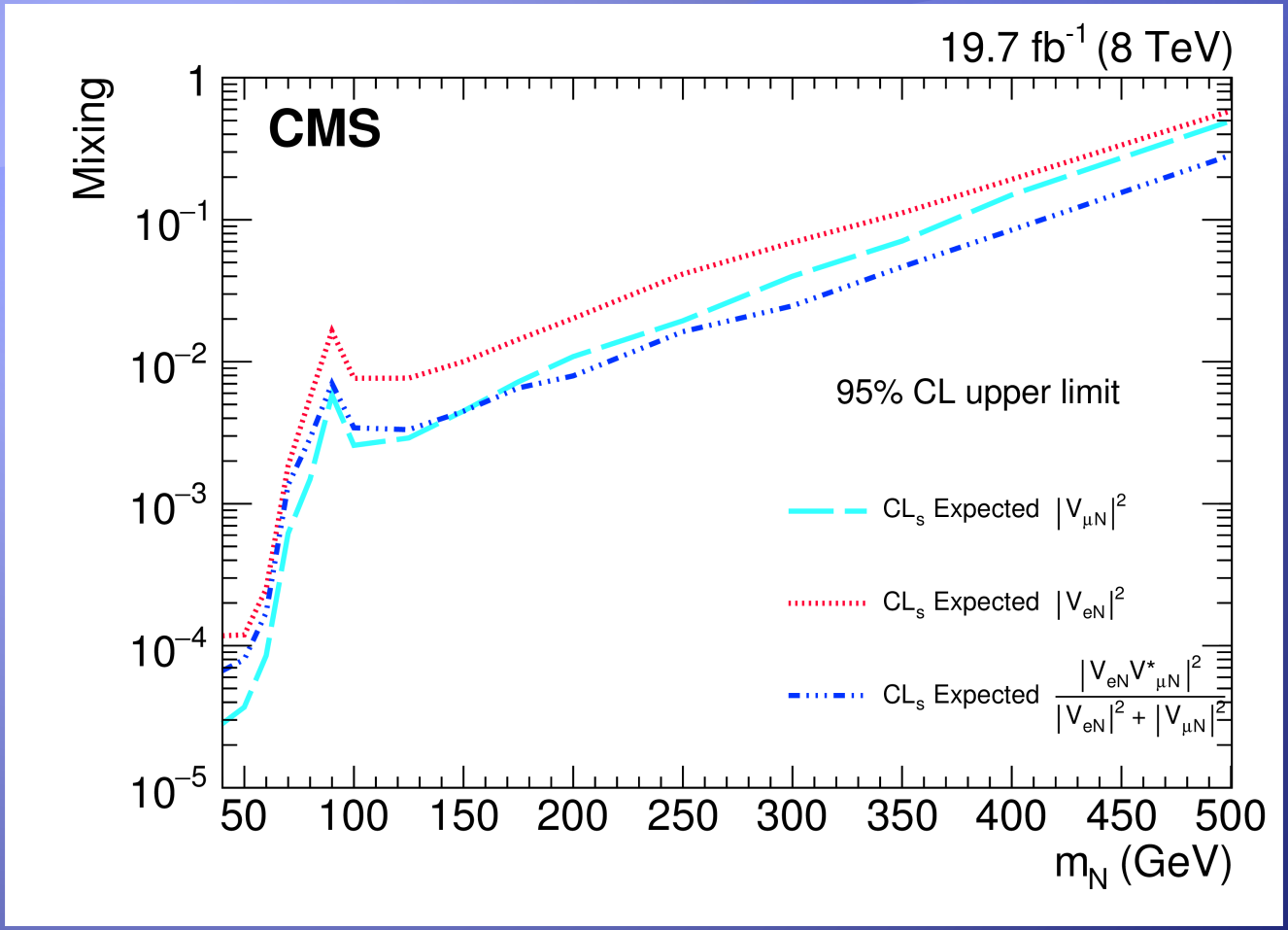
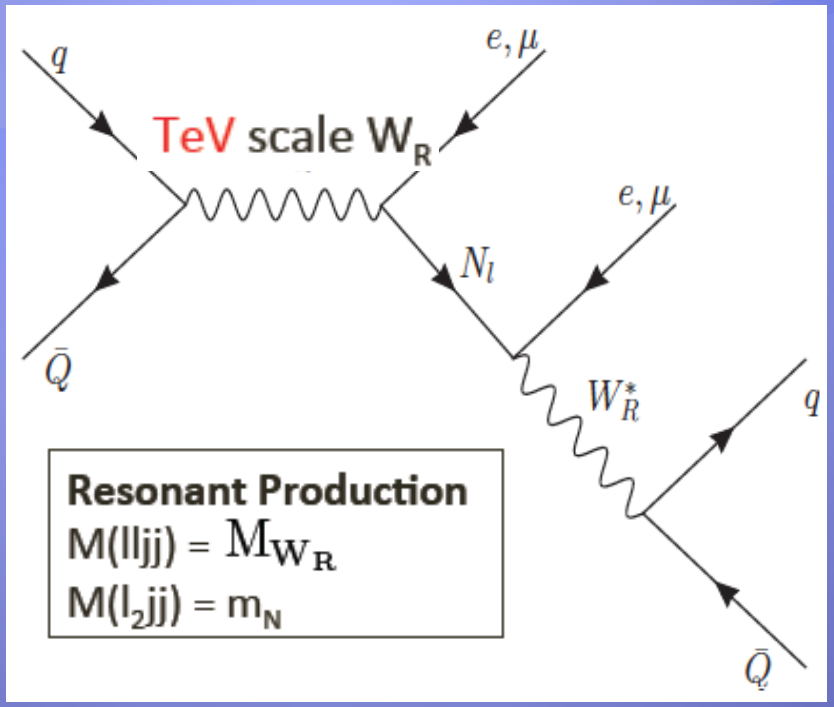
PLB 748, 144 (2015)



- LHC provides the world best 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

Searches in the LRSM



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),

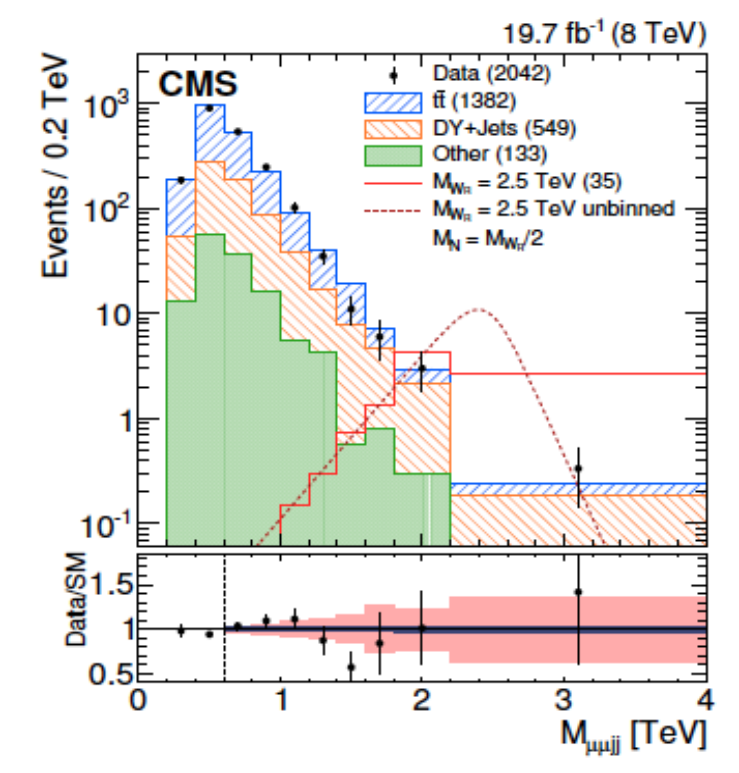
- M(lljj) (i.e m(W_R)) > 600 GeV.

➢ **Challenges:**

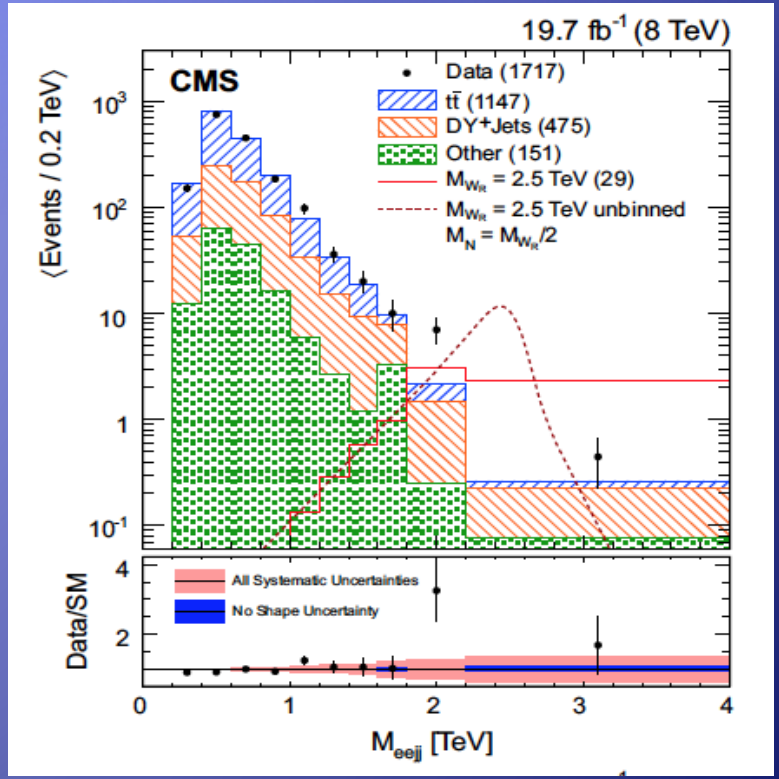
- **For m_N<<m_{WR}, jets and lepton from N decays overlap → standard isolation will kill signals**
- **Same challenges as Type I in terms of bkgds**

Results @ CMS

Di-muon channel



Di-electron channel

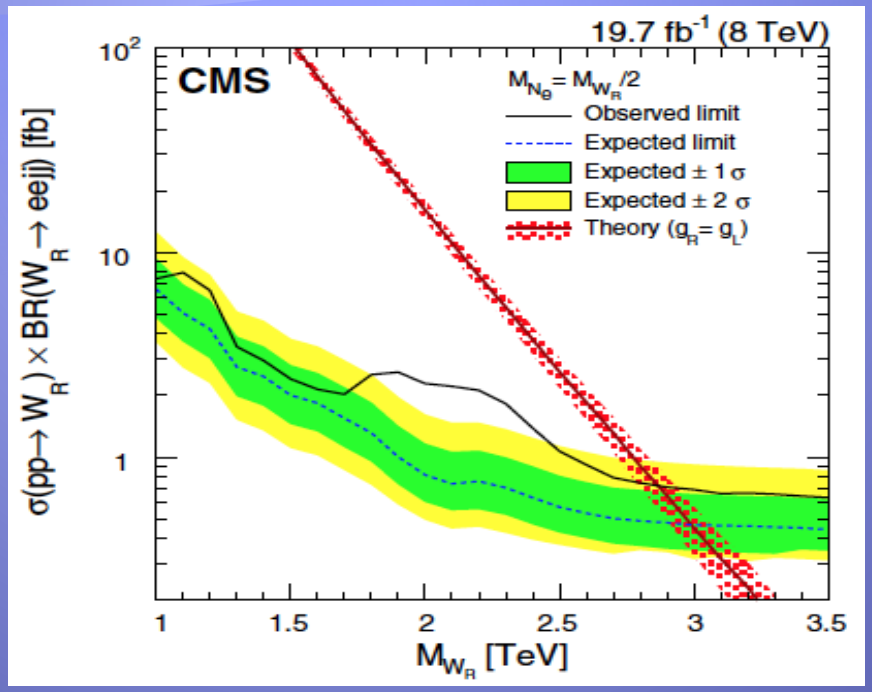


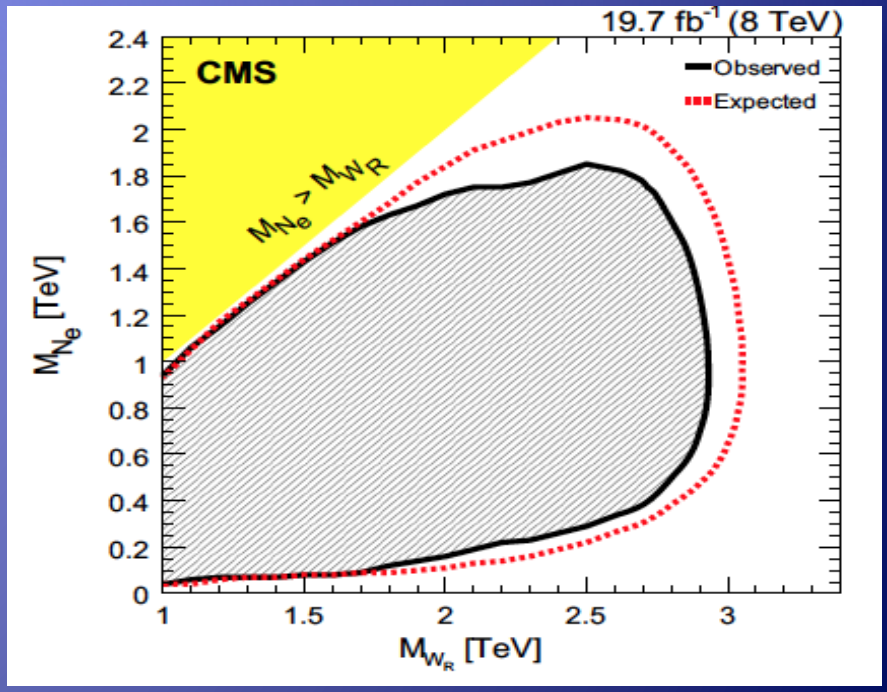
EPJ C74 (2014) 3149

- **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

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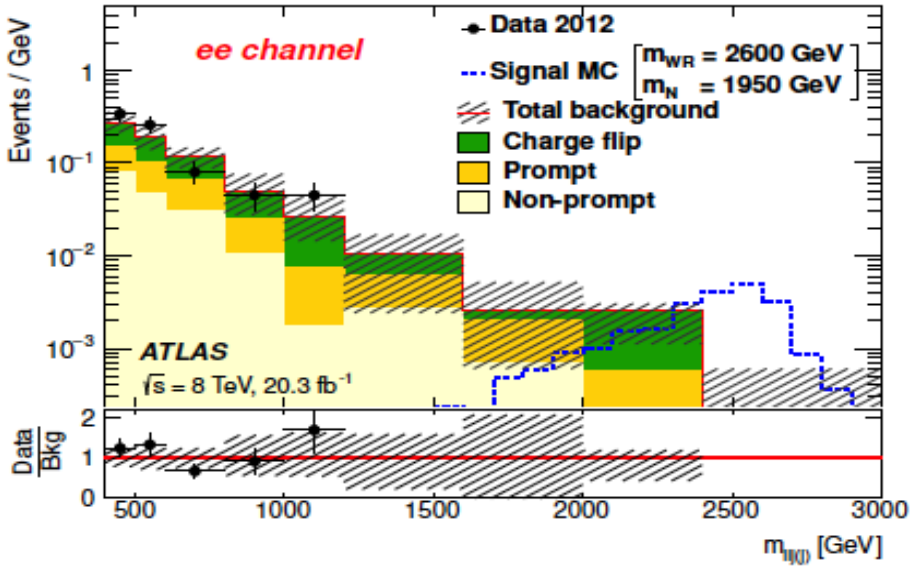
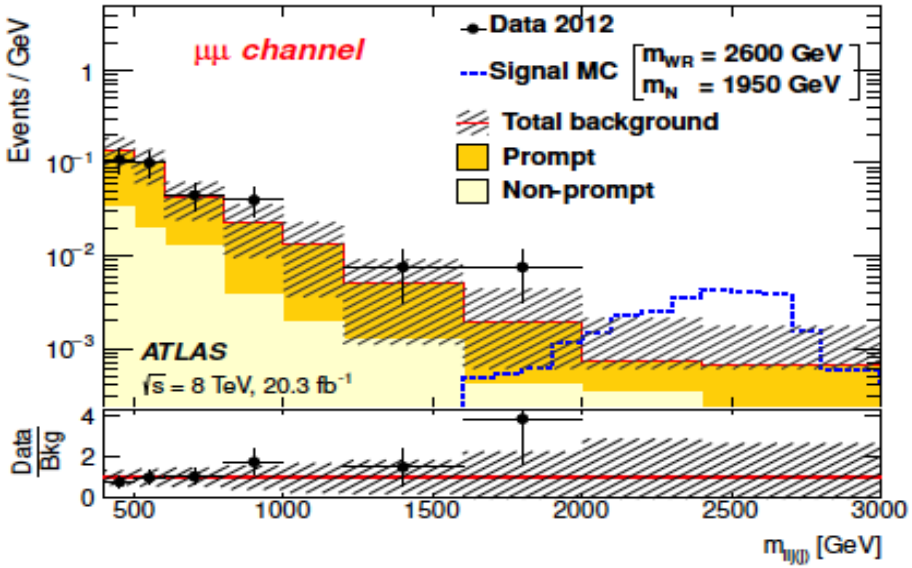




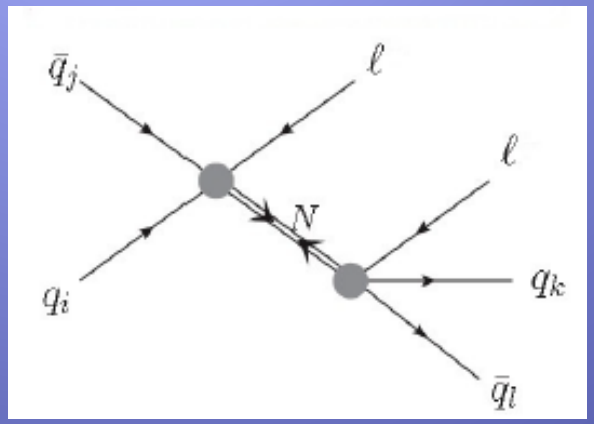
Invariant mass (lljj)

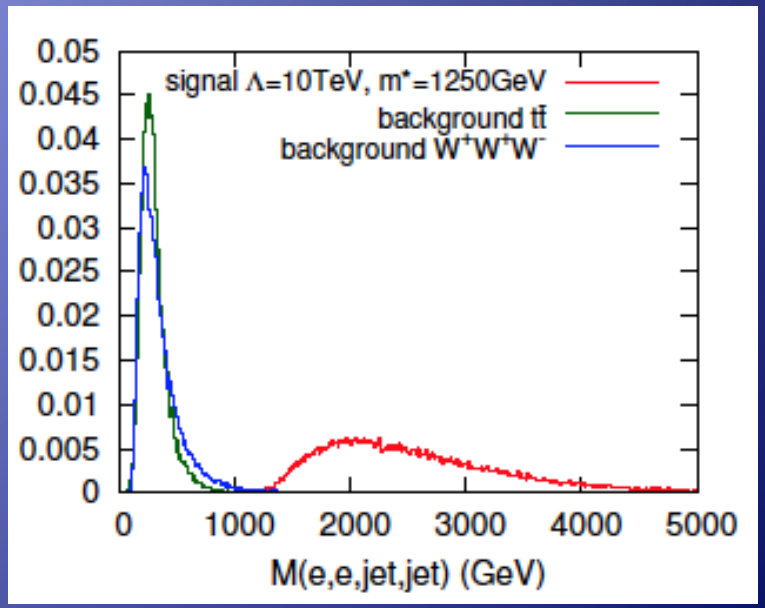
- No excess in ee channel (SS)
- OS channel?

Searches at 13 TeV

- A 2.8σ excess in eejj channel but no excess in dimuon 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]





Searches at 13 TeV

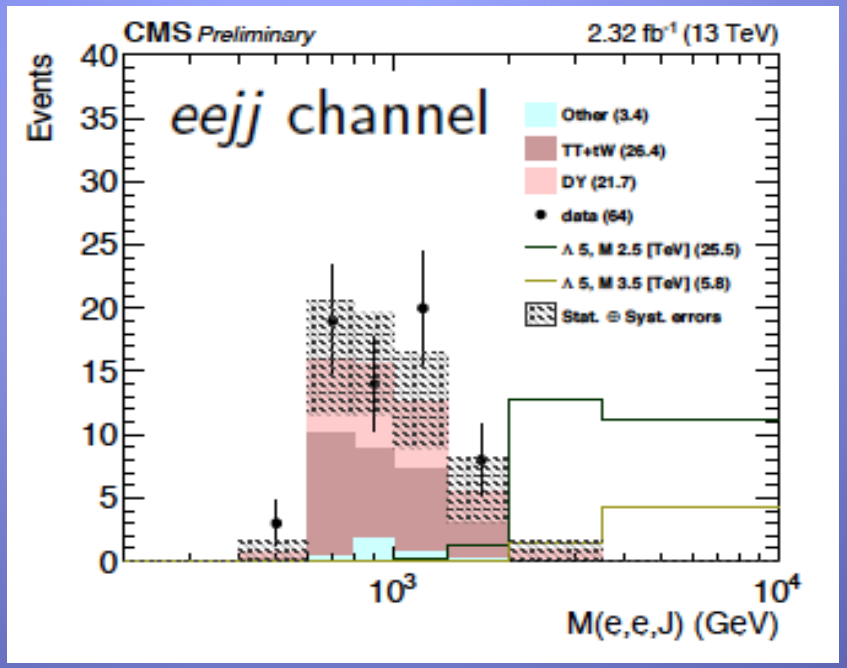
Di-electron channel

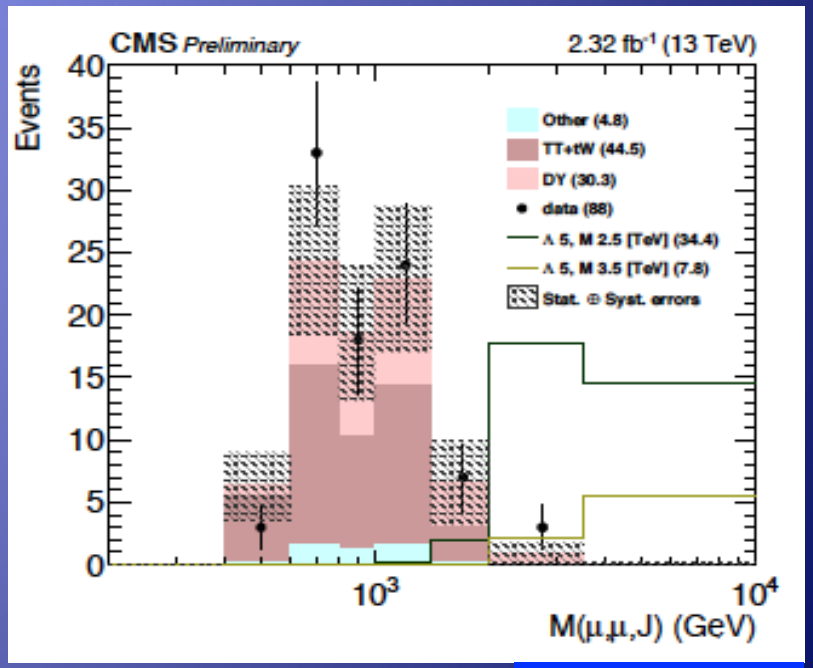
- p_T(e): 110, 35 GeV
- *m*(ee or μμ)>300 GeV,

Di-muon channel

p_T(μ)>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

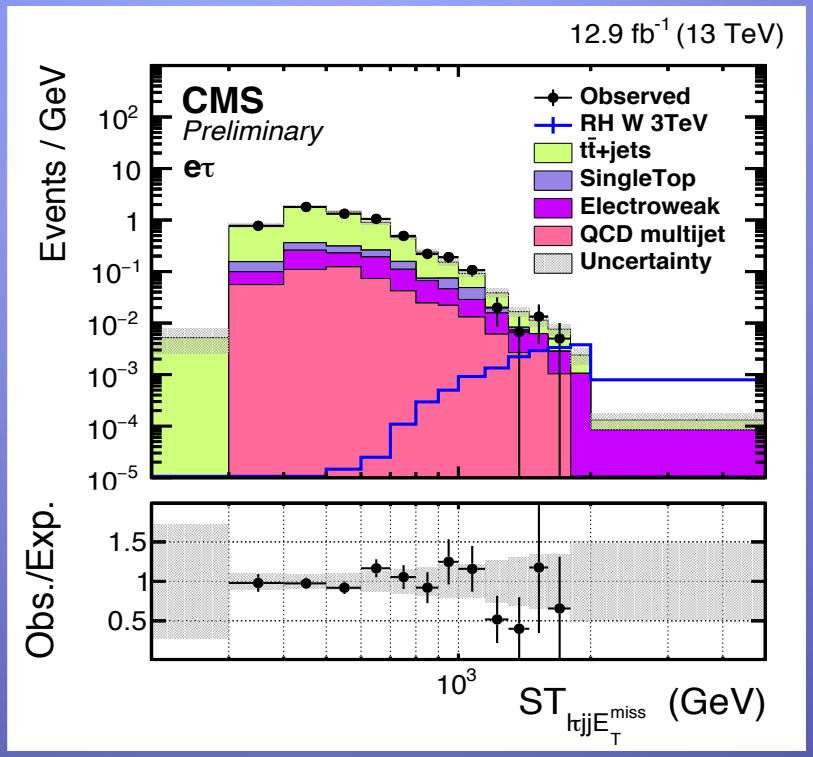
- A 2.8σ excess in eejj channel but no excess in dimuon channel
  - Any broad excess in 3rd generation?

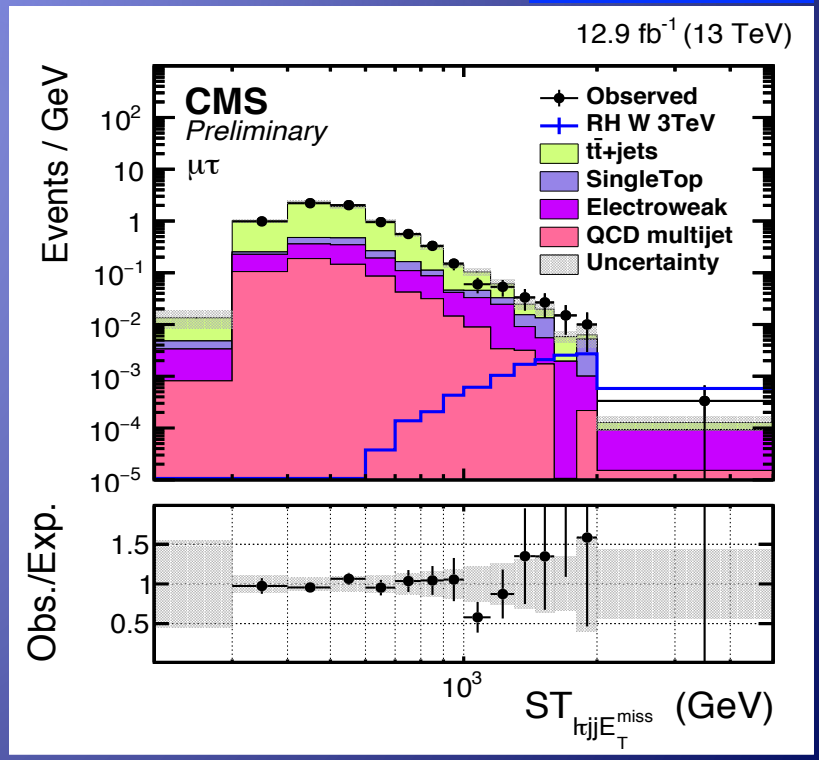
- Searches in $\tau\tau$:
  - All hadronic channel, $\tau(h)\tau(h)$ using 2.1 fb^{-1} at 13 TeV
    → Largest branching ratio, but a large QCD tau-fake
  - Lepton+hadronic channel: $\tau(e)\tau(h)$, $\tau(\mu)\tau(h)$
    → Relatively clean events, but a small branching ratio,
    → thus use 12.9 fb^{-1} at 13 TeV

Results in τ(l)τ(h) channel

- 2016 data: 12.9 fb^{-1}
- p_T(e or μ) > 50 GeV, $p_T(\tau_h)$ > 60 GeV, MET> 50 GeV
- m(eτ_h or μτ_h) > 150 GeV, m(jτ_h) > 250 GeV,
- 2 jets with p_T>50 GeV

EXO-16-023



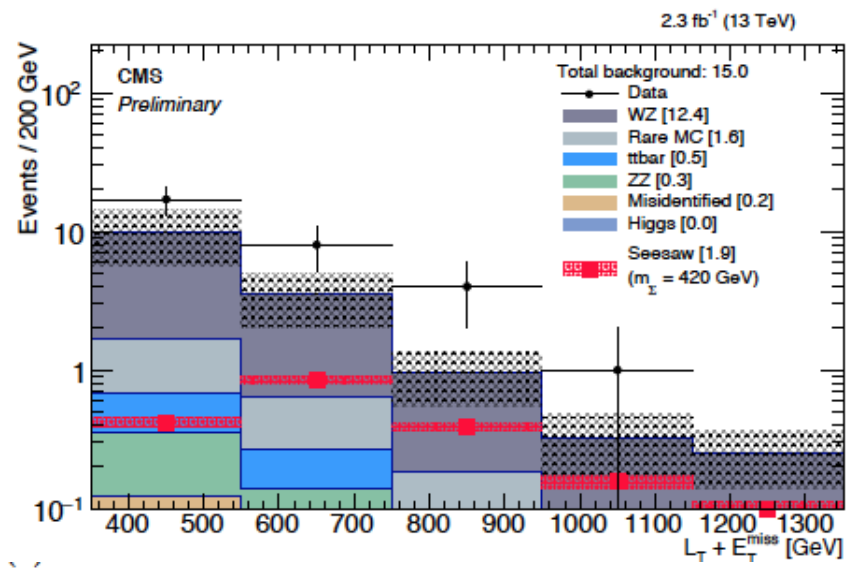


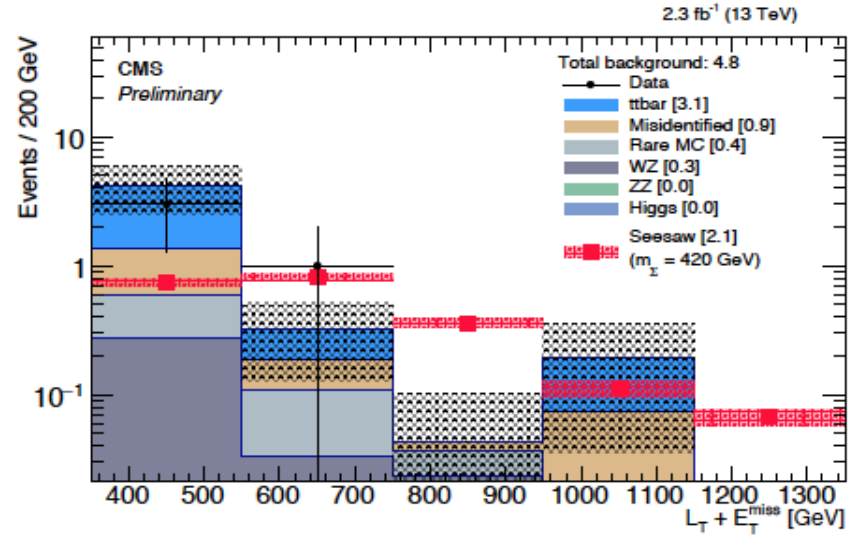
$$S_T = p_T(\ell) + p_T(\tau_h) + p_T(jet_1) + p_T(jet_2) + E_T^{miss}$$

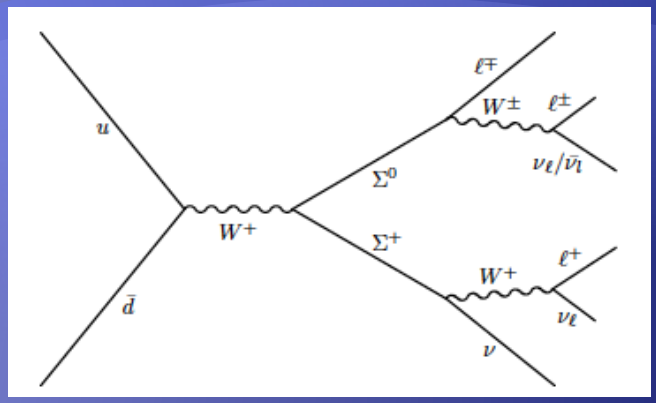
No excess in data, exclude W_R up to 3.2 TeV

Type III Results @ CMS

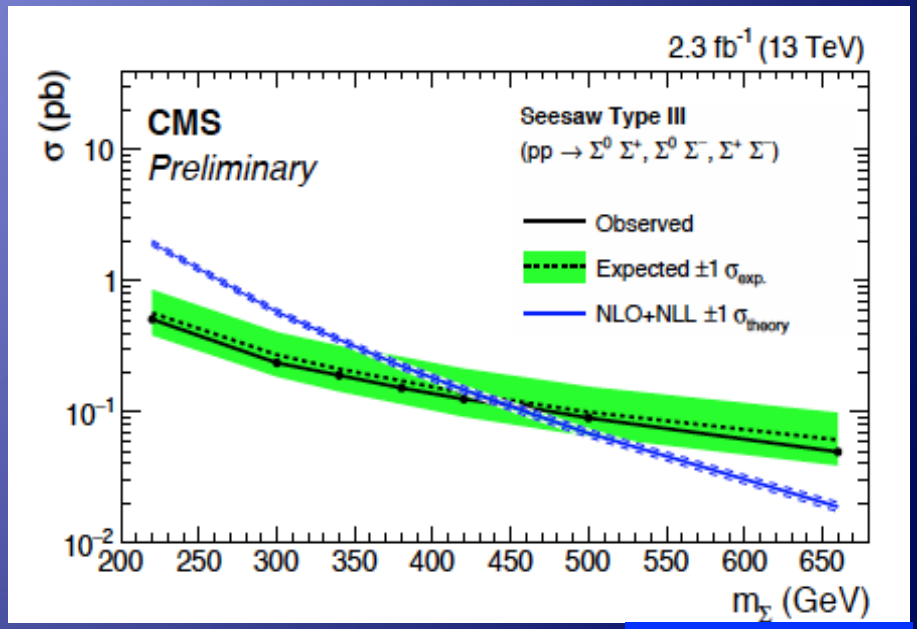
(3 or 4 leptons)







- 2015 data: 2.3 fb^{-1}



EXO-16-002

Summary

- Neutrino Oscillations attracts many interesting searches at the LHC
  - Lepton Number Violation decays: Z, H, Z' → eμ & H→e/μτ
  - Searches for heavy neutrinos
    - Test various Seesaw models and LRSM to explain small ν mass can tested:
- CMS has searched for the LNV decays and heavy neutrinos, but with no excess seen in data
  - H→μτ : not confirmed by the first 13 TeV data
  - RPV sneutrino > 3.3 TeV, QBH>4.5 TeV (n=6)
  - Upper limits are set on $|V_{lN}|^2$, exclude W_R mass up to 4.35 TeV (e), 4.5 TeV (μ) and 3.2 TeV (τ)
- Searches will be explored using the full 13 TeV data from many different channels