Neutrinos at LHC

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On behalf of ATLAS & CMS collaborations

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LHC Days in Split

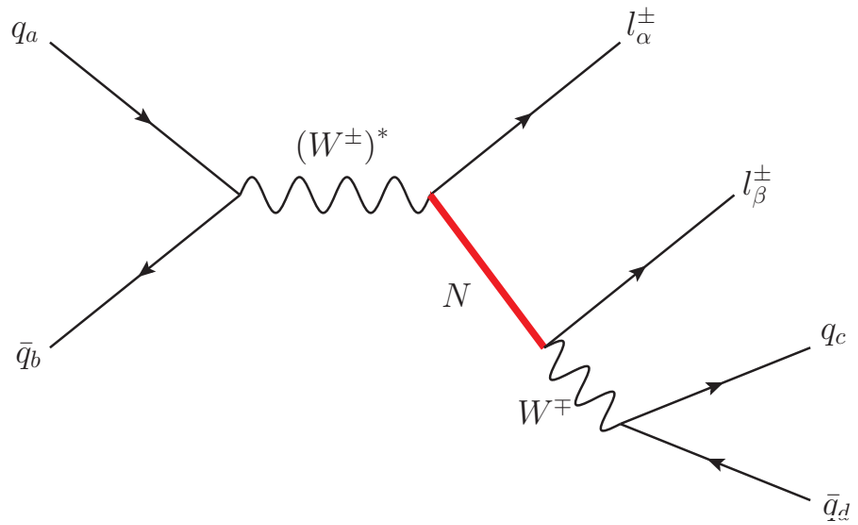
Heavy Majorana Neutrinos

- **Minimal Type-I seesaw mechanism (mTISM)**
  - The small mass of the known neutrinos can be explained:

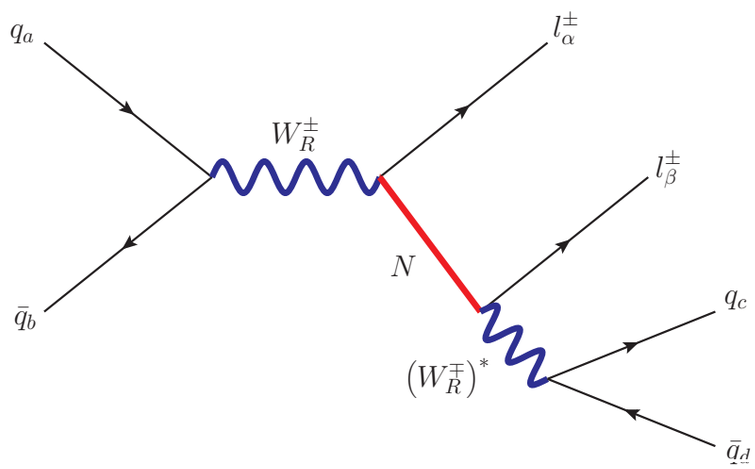
$$m_\nu \sim \frac{m_d^2}{M_N}$$

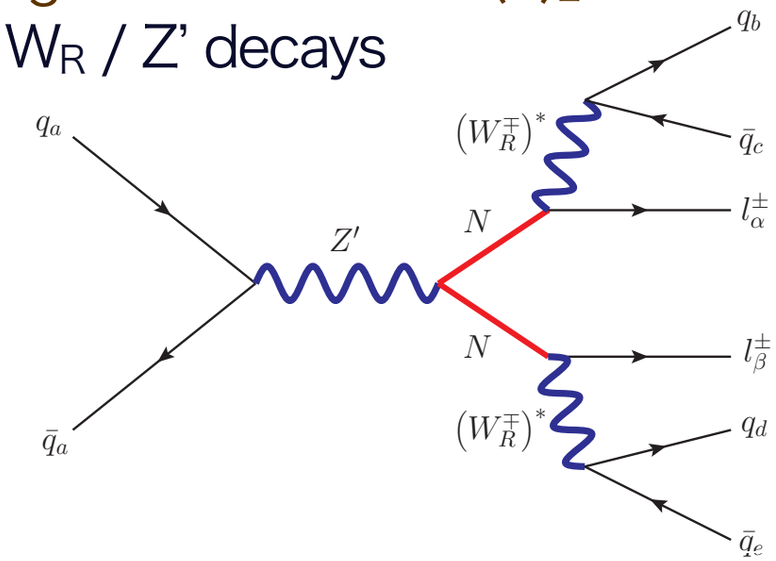
m_ν : Neutrino mass
m_d : Dirac mass
M_N : Heavy neutrino mass

    - ✓ **if all neutrinos are Majorana particles**
  - Simplest model with right-handed neutrinos
  - Production of **Heavy Majorana Neutrinos** (**HMN**)
    - W decays
  - Parameters
    - M_N , $V_{\ell N}$ (mixing between SM and heavy neutrinos)



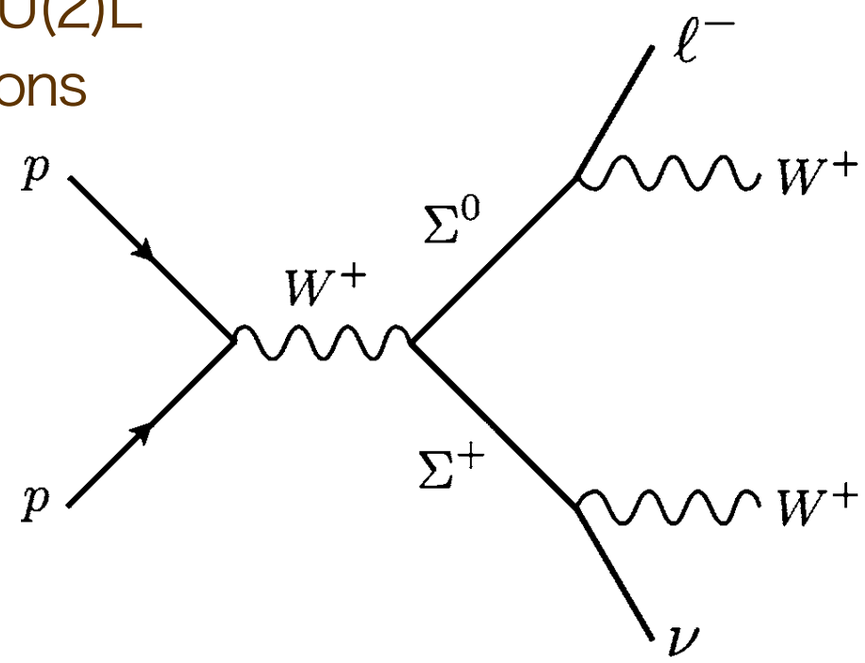
- **Left-Right Symmetric Model (LRSM)**
  - $SU(2)_R$ assumed to be the right-handed analogue of the SM $SU(2)_L$
    - Increased sensitivity with N production via W_R / Z' decays



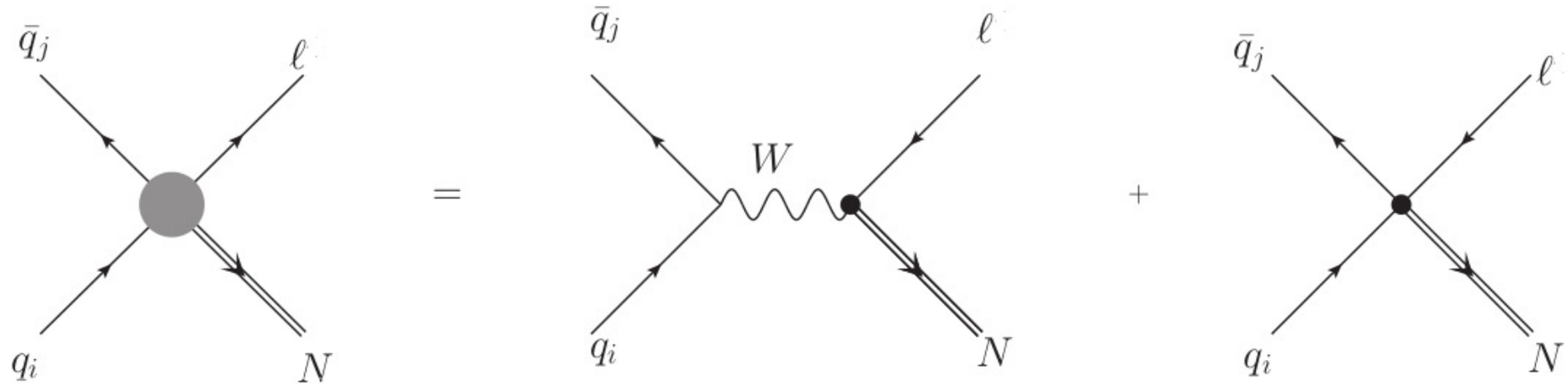


Other models for HMN

- **Type-III seesaw mechanism**
  - At least two extra triplets of fermionic fields with zero hyper-charge in the adjoint representation of SU(2)L that generate neutrino masses and couple to gauge bosons



- **Composite model for quark/lepton**
  - From Gauge and Contact interactions
  - Motivated from the excess with M_{eejj} ~ 2 TeV
    - CMS: Eur.Phys.J.C74,3149
  - and m_{jj} ~ 5 TeV resonance
    - CMS: PhysRevLett.116.071801
    - ATLAS: Phys.Let.B.2016.01.032

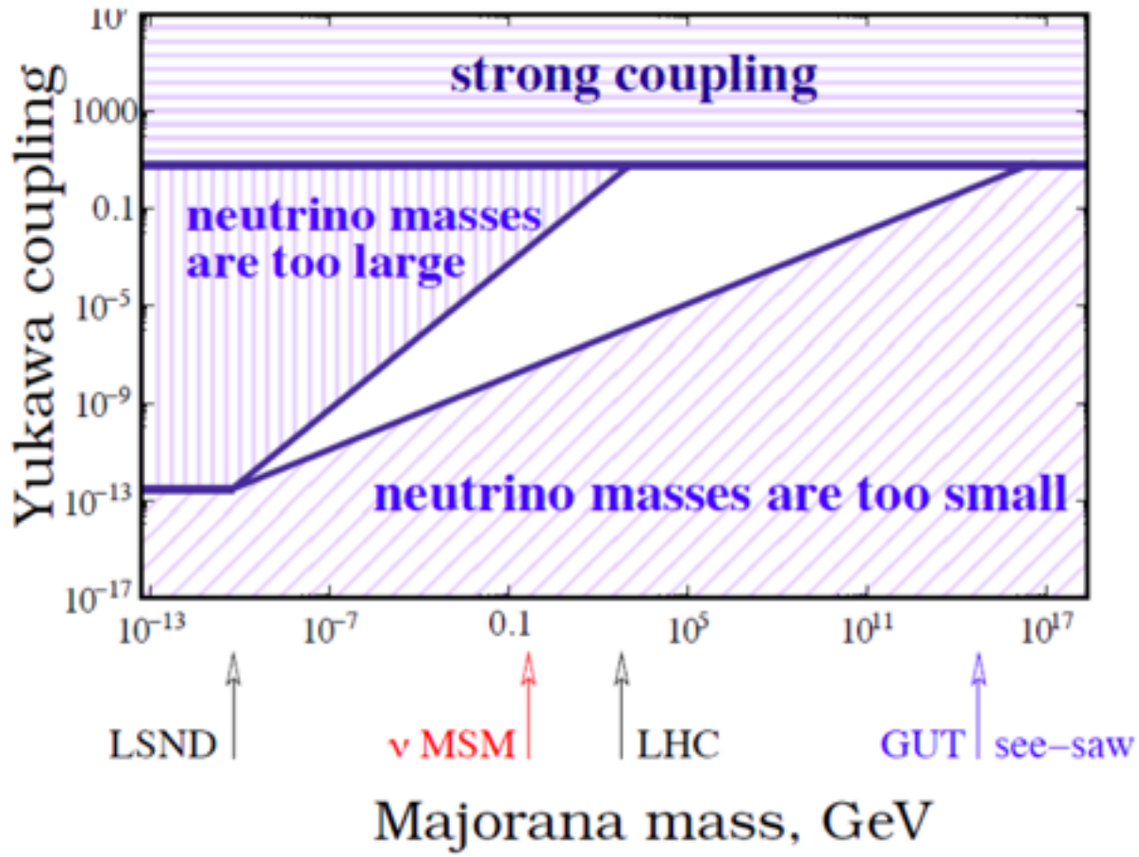


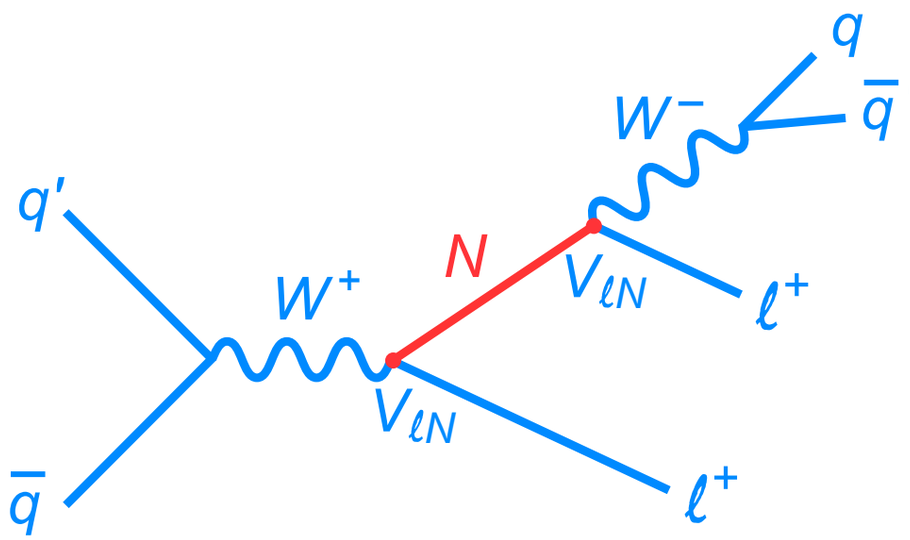
Experimental searches for HMN

- Mass range
  - Wide possibilities
    - $M_N < M_W$ or $M_N \geqq 300$ GeV from cosmology

- Experiments
  - $M_N < M_K$
    - NA62
  - $M_N < M_B$
    - LHCb, Belle2
  - $M_N < M_Z$
    - future lepton colliders
  - **$M_N > M_Z$**
    - **ATLAS / CMS** in LHC

- Basic signals
  - same sign di-lepton + 2 jets
    - M_{jj} to be $\sim M_W$

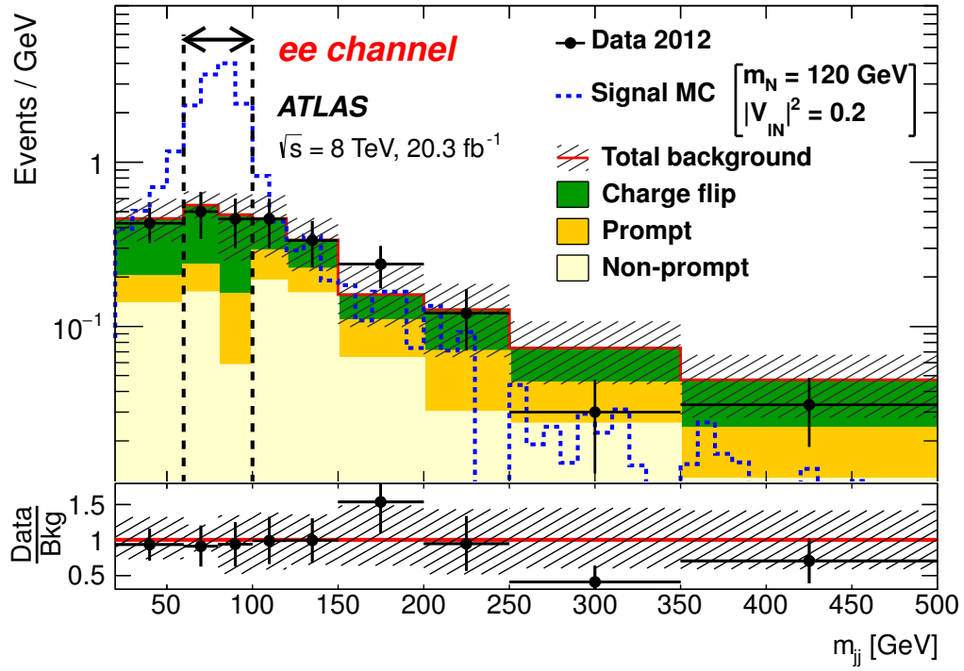


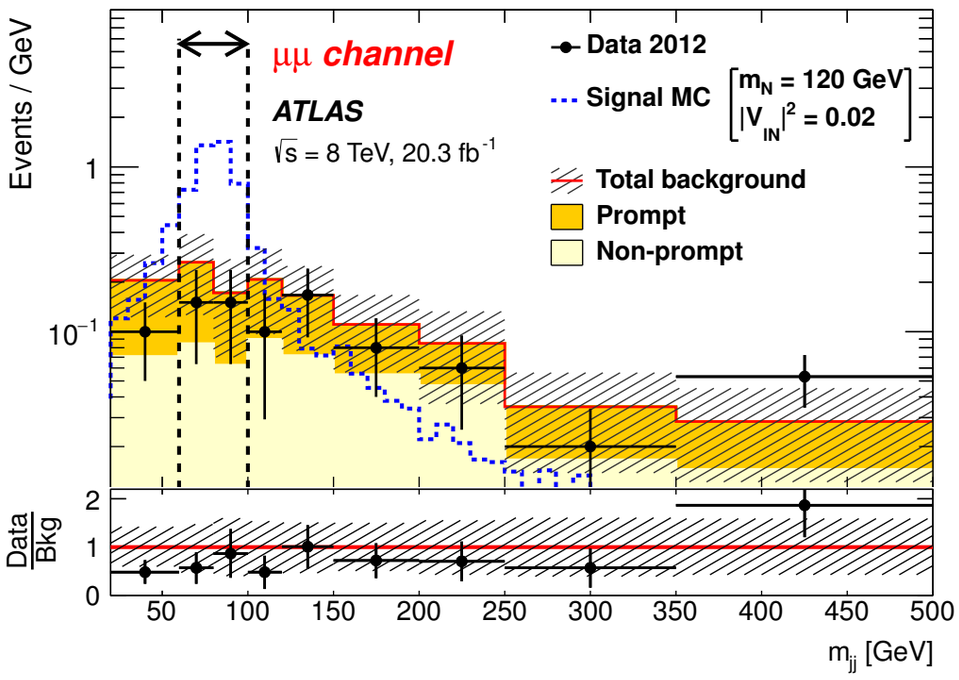


ATLAS: HMN search in mTISM at 8 TeV

JHEP07(2015)162

- Full Run1 data : 20/fb
- Event selections
  - SS ee/μμ + 2 jets
  - $p_T(\ell 1) > 25$ GeV
  - $p_T(\ell 2) > 20$ GeV
  - MET < 40 GeV
  - $60 < M_{jj} < 100$ GeV
- Backgrounds
  - QCD multi-jets
    - leptons from b-decays
  - W+jets
    - leptonic decay + fake lepton
  - Z+jets
    - leptonic + charge flip
  - ttbar, single top
  - di-boson
- Result
  - no excess observed
    - 95 % CL limits set



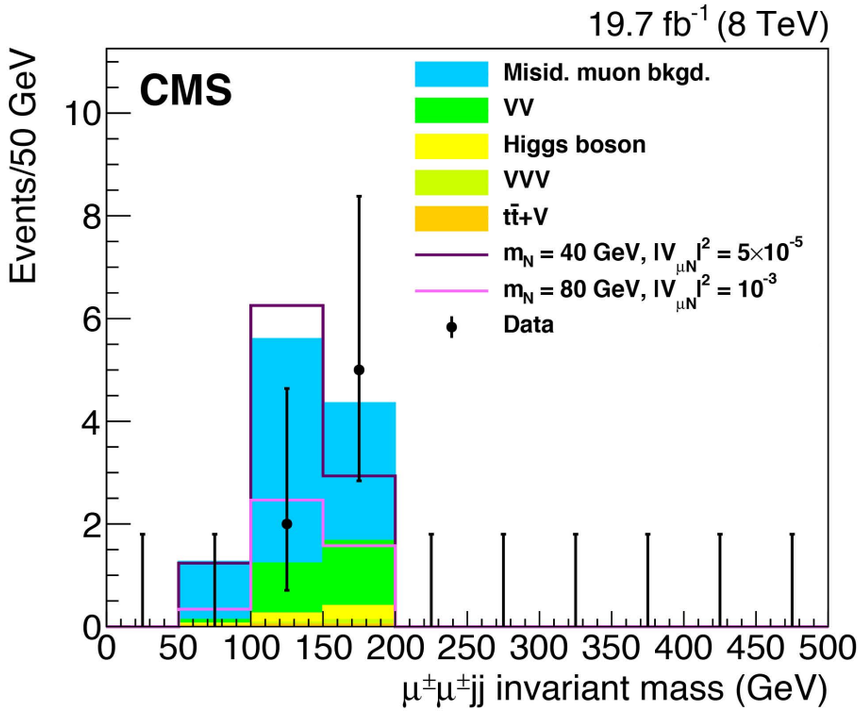


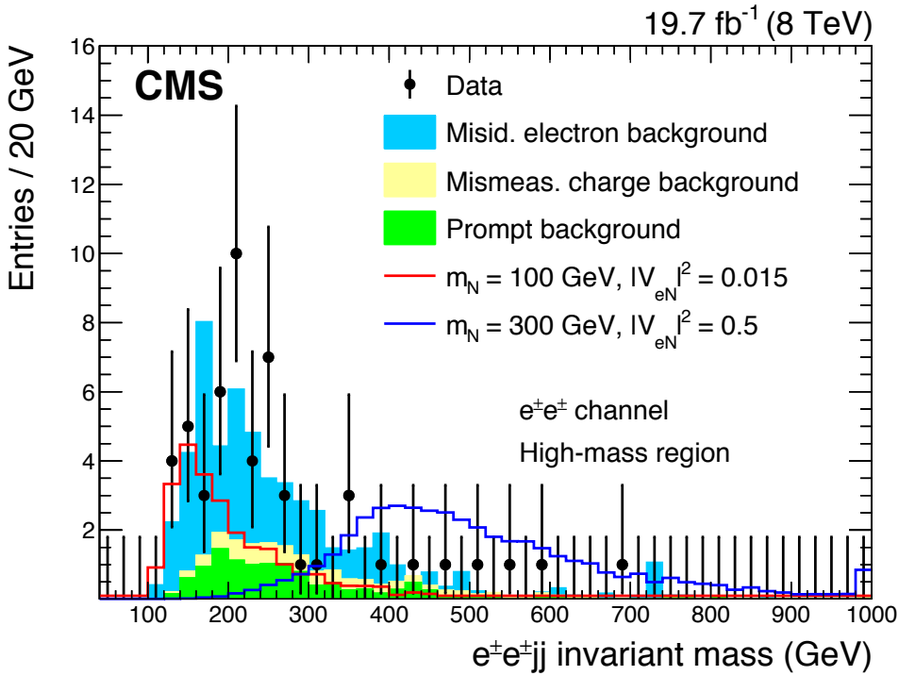
CMS: HMN search at 8 TeV

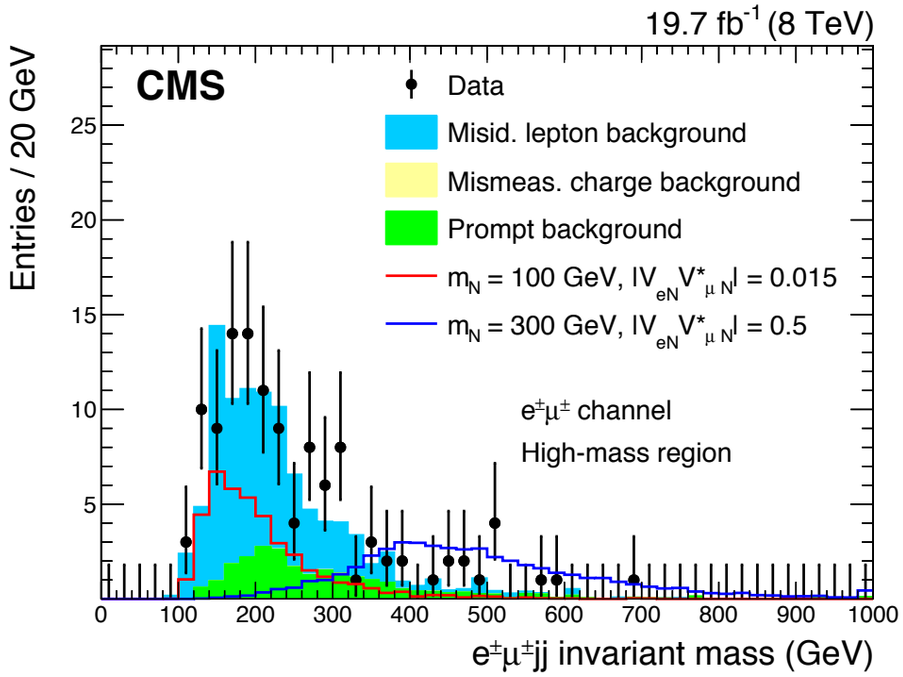
JHEP04(2016)169,
Phys.LetB748 144

- Event selections
  - SS ee/μμ + 2 jets
  - $p_T(\ell 1) > 20$ GeV
  - $p_T(\ell 2) > 15$ GeV
  - MET < 30(35 for μμ) GeV
  - 50 < Mjj < 110 GeV

- Result
  - No excess observed

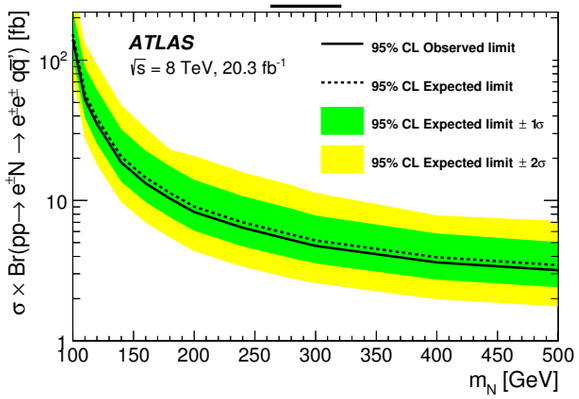
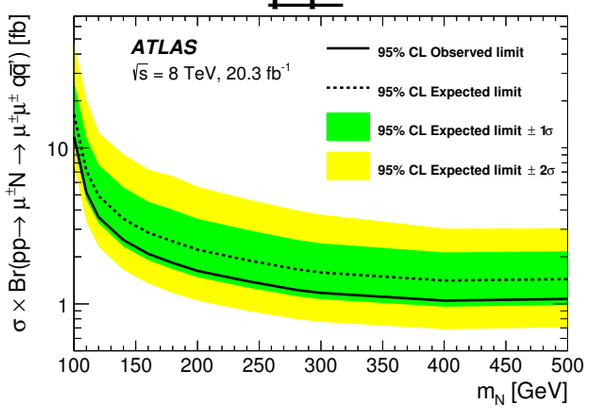
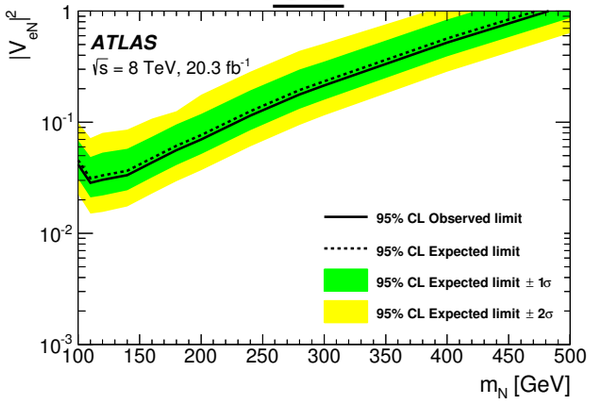
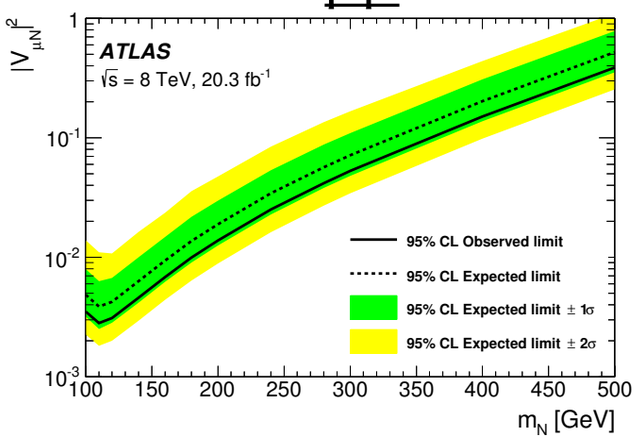
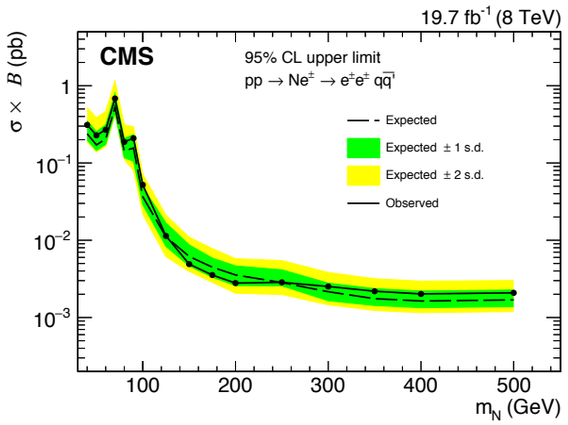
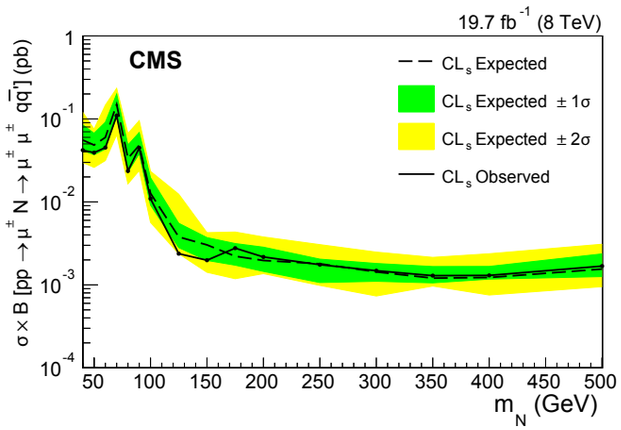
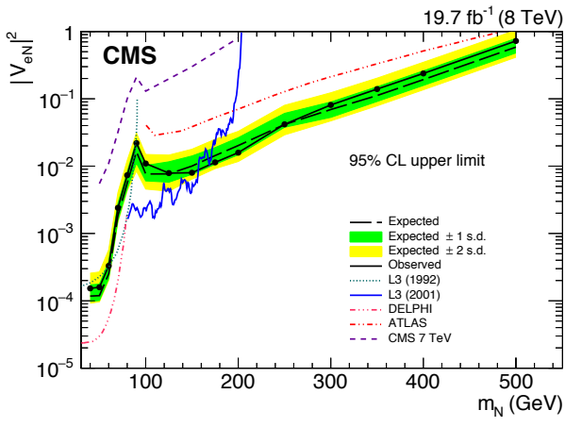
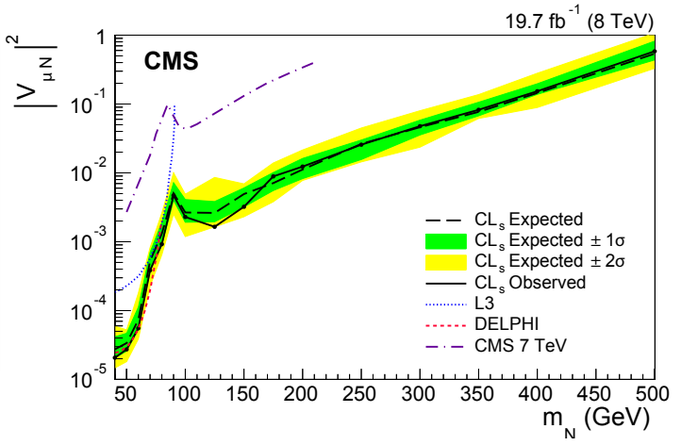






ATLAS & CMS: limits on HMN

- Run1 results
  - production cross sections : σ
  - mixing parameters : $V_{\ell N}$
    - ✓ assuming that only one HMN contributes to σ

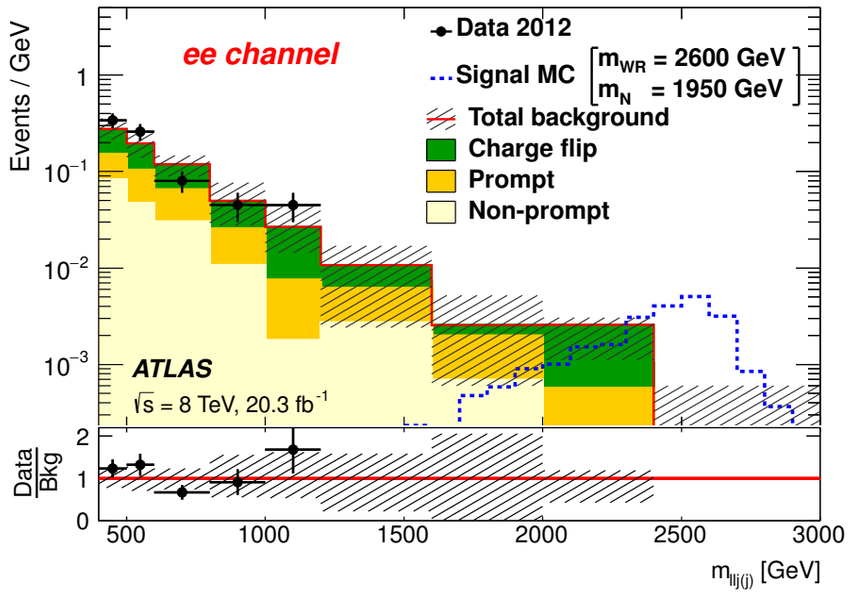
	$\sigma \times BR$		$\lvert V_{\ell N}\rvert^2$	
	ee	μμ	ee	μμ
ATLAS				
CMS				

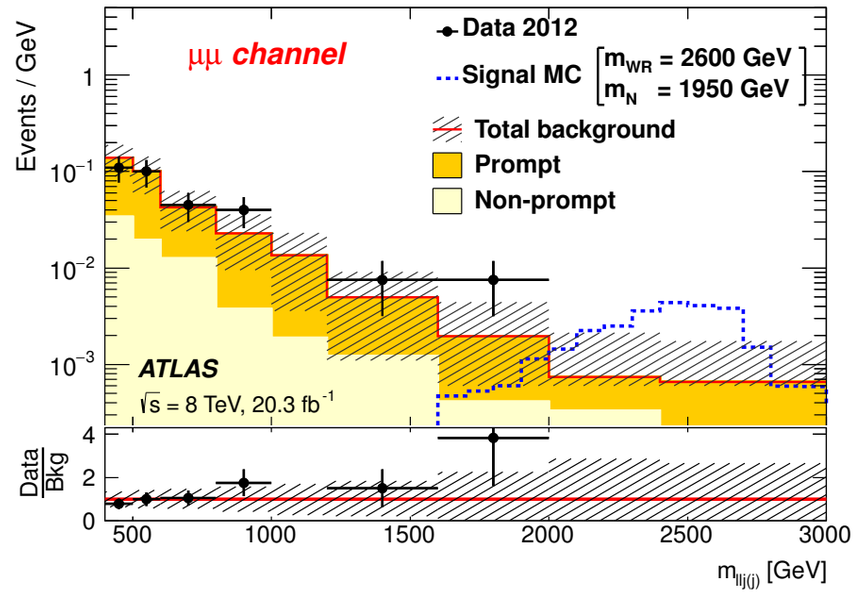
ATLAS: LRSM

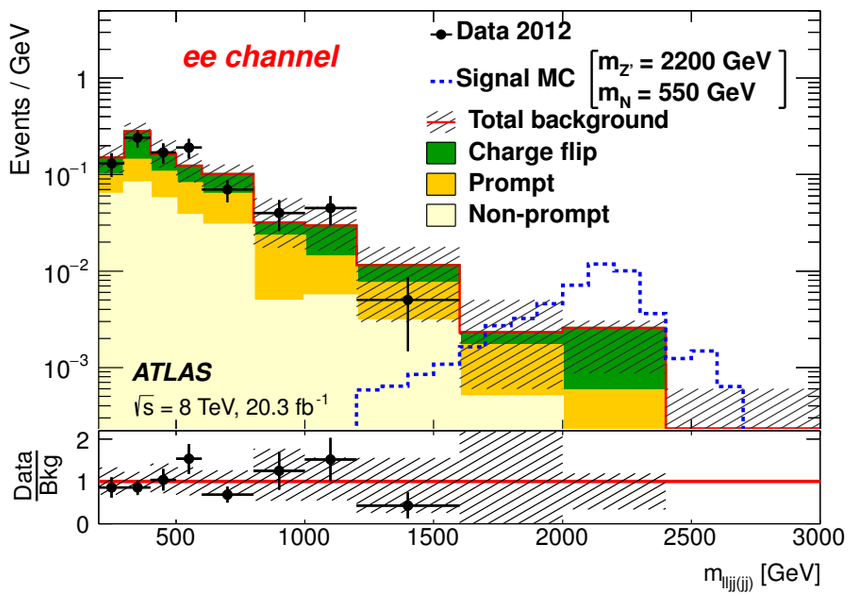
JHEP07(2015)162

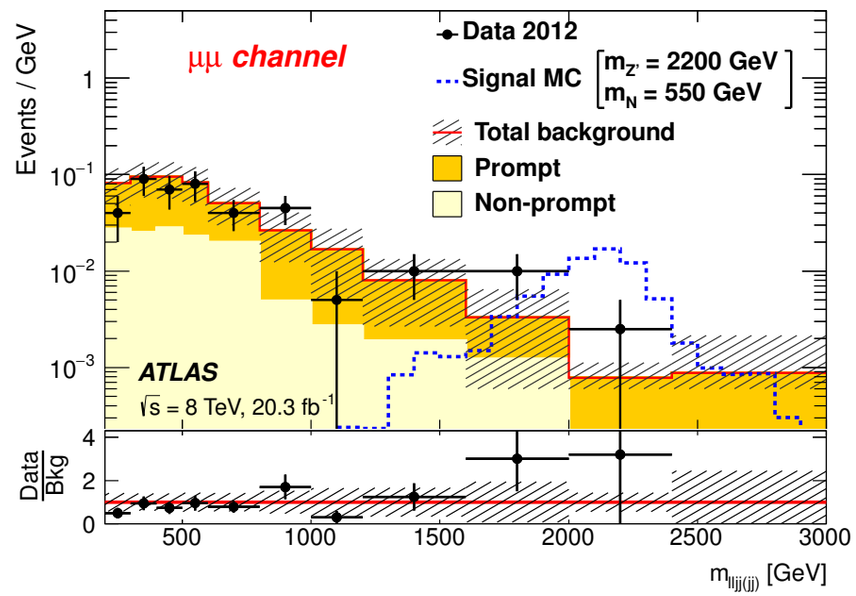
- Event selections
  - same lepton selections as in mTISM analysis
    - + M $_{\ell\ell}$ > 110 GeV
  - W_R search
    - $\ell\ell$ + ≥1 jet
      - 2 jets from W decays can be merged
    - M$\ell\ell$j(j) > 400 GeV
  - Z' search
    - $\ell\ell$ + ≥ 2 jets
    - M$\ell\ell$jj(jj) > 200 GeV

- Results
  - No excess observed





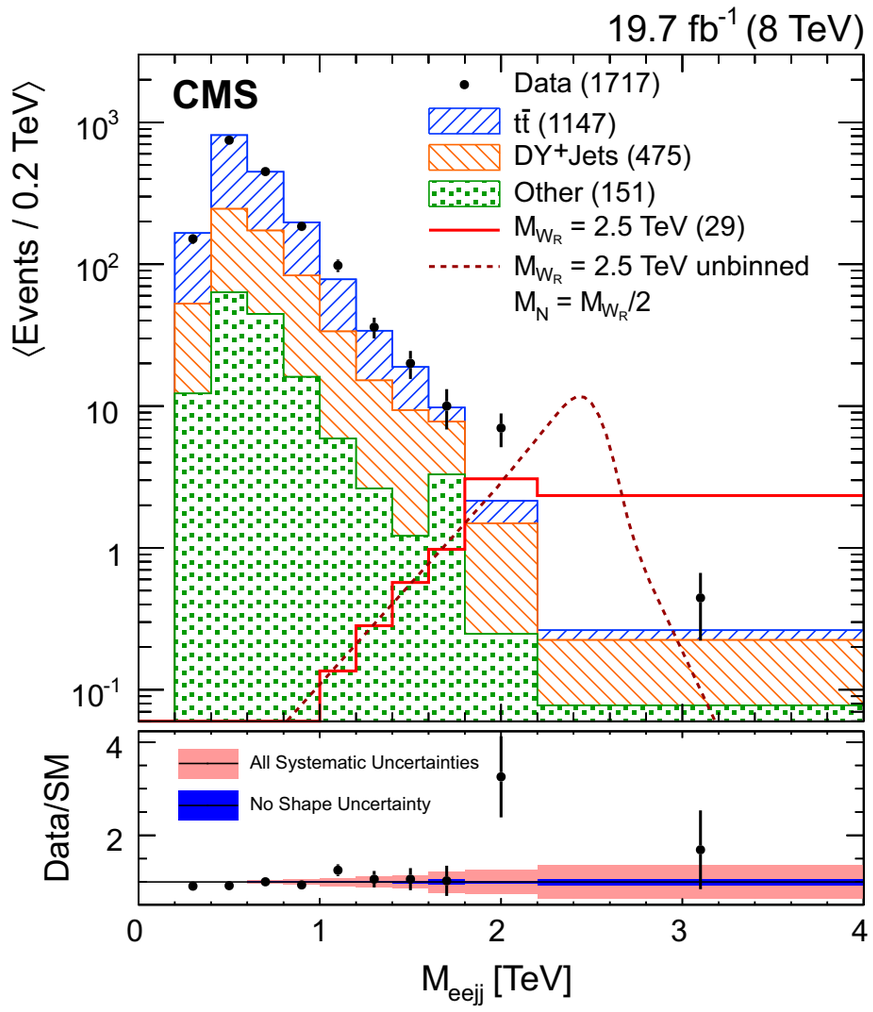


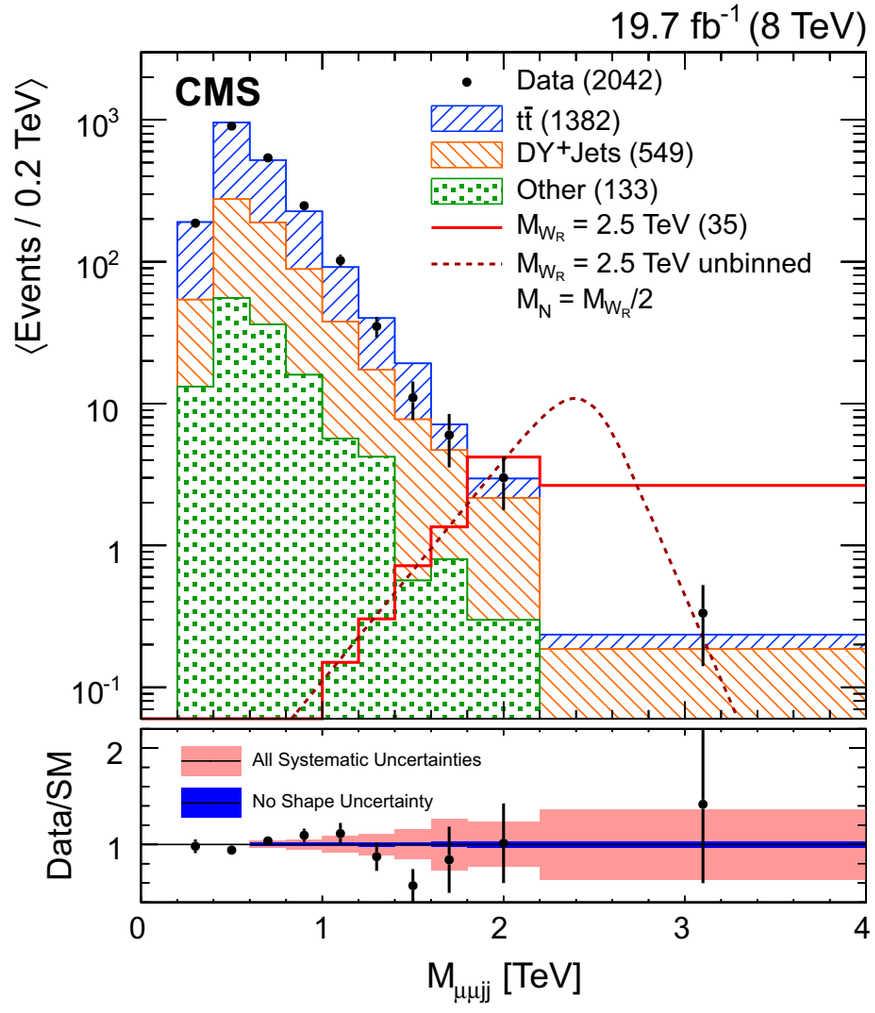


CMS: LRSM

- Event selections
  - ee/μμ [with no charge requirement] + 2 jets
  - $p_T(\ell 1) > 60$ GeV, $p_T(\ell 2) > 40$ GeV
  - $p_T(\text{jet}) > 40$ GeV, $M_{\ell\ell} > 200$ GeV
- Results
  - $2.8\,\sigma$ excess at $M_{eejj} \sim 2$ TeV
  - No excess in the muon channel

Eur.Phys.J.C74,3149





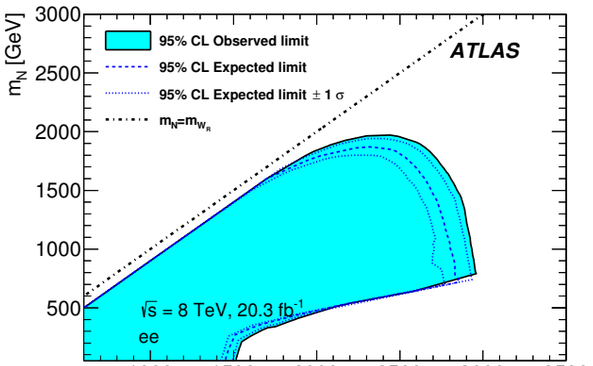
ATLAS & CMS: LRSM

- Model independent limits on M_N

ATLAS

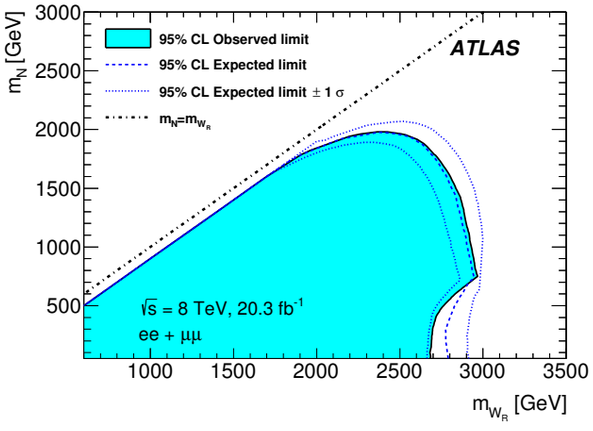
W_R

ee

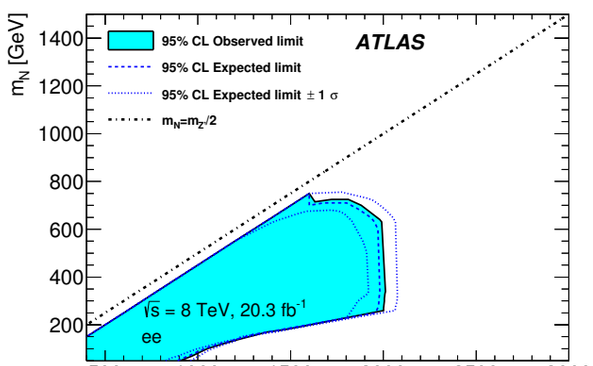


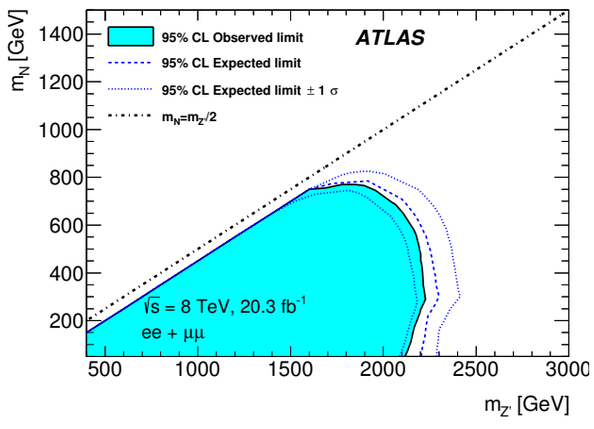
μμ

eμ



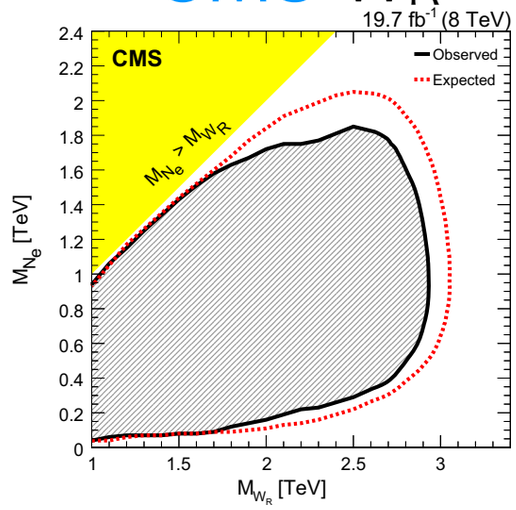
Z'



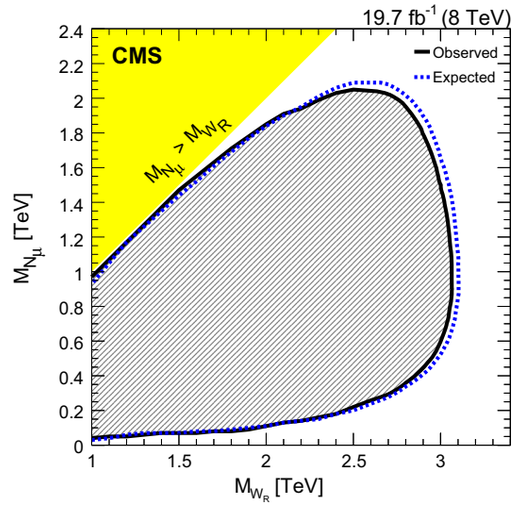


CMS W_R

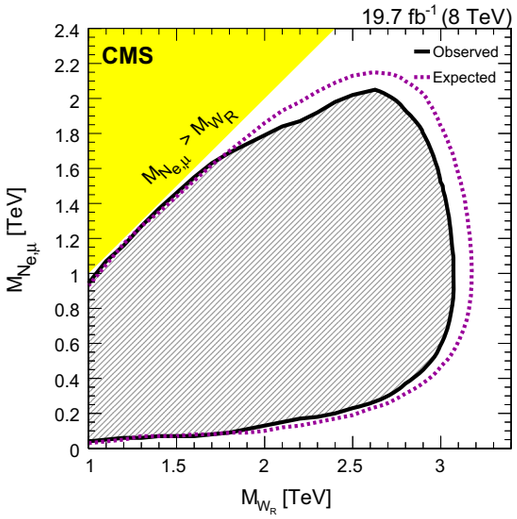
ee



μμ



eμ

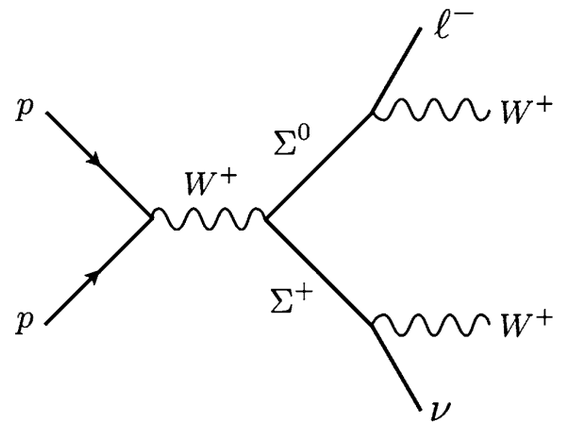


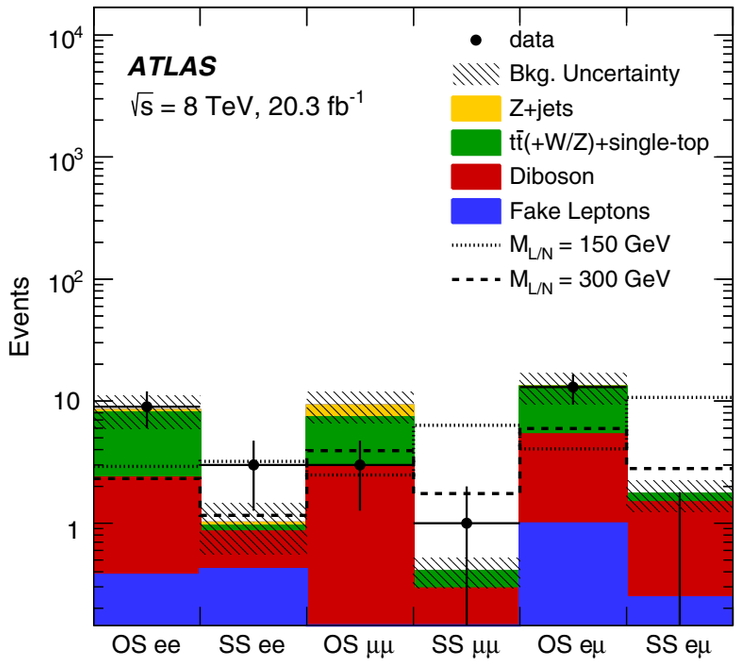
ATLAS: Type-III seesaw model at 8 TeV

- Signature
  - OS or (SS) di-leptons + 2jets
    - $p_T(\ell 1) > 100(70)$ GeV, $p_T(\ell 2) > 25(40)$ GeV
    - $m_{\ell\ell} > 130$ (90) GeV
    - $p_T(\text{jet1}) > 60$ (40) GeV, $p_T(\text{jet2}) > 30$ (25) GeV
  - MET > 110(100) GeV

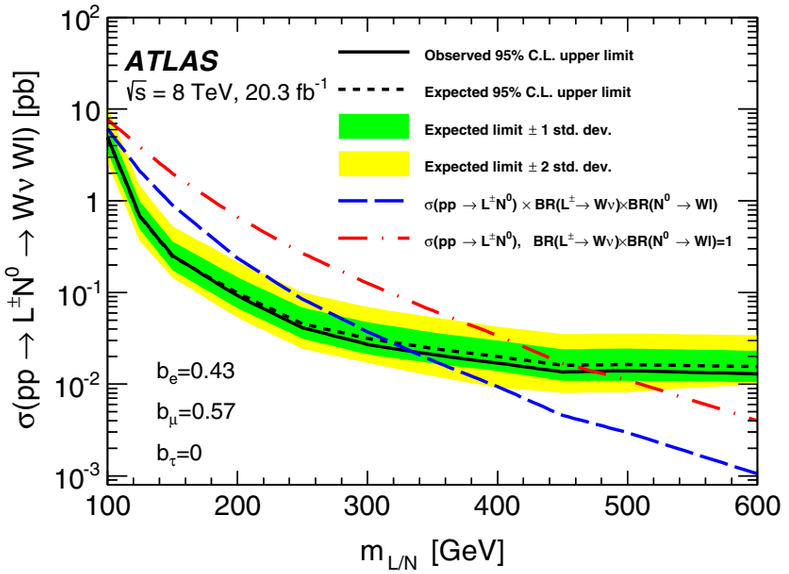
- Run1 result
  - No excess observed
  - 95 % CL limit set

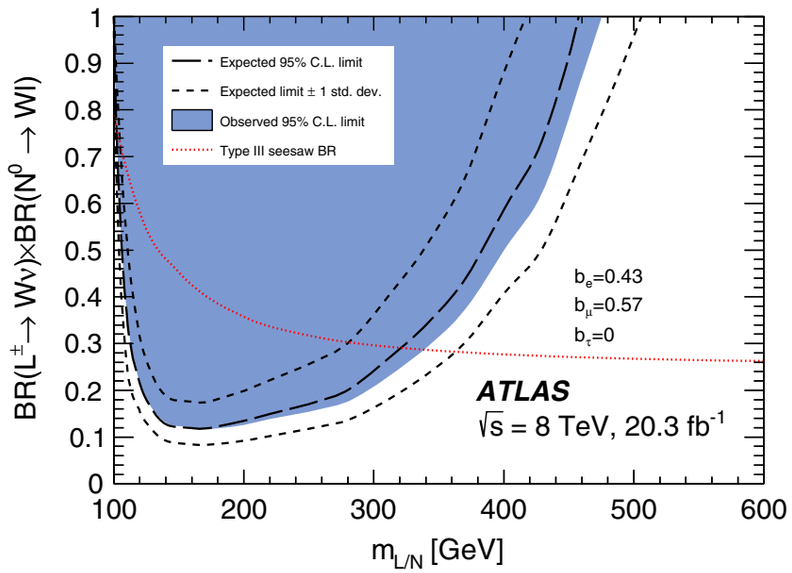
$$b_\alpha = |V_\alpha|^2 / (|V_e|^2 + |V_\mu|^2 + |V_\tau|^2)$$





Phys.Rev.D 92.032001

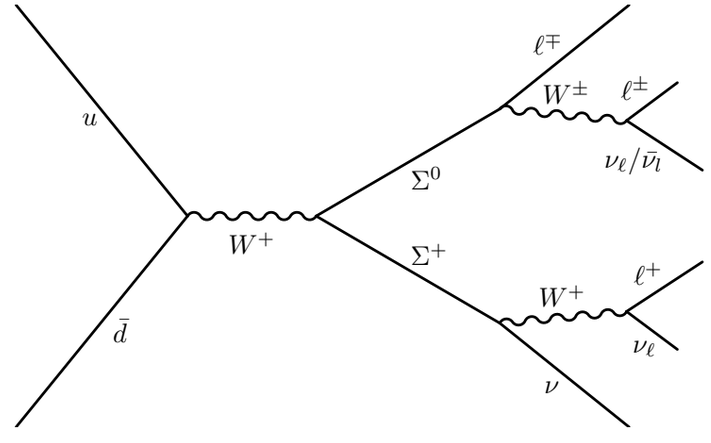




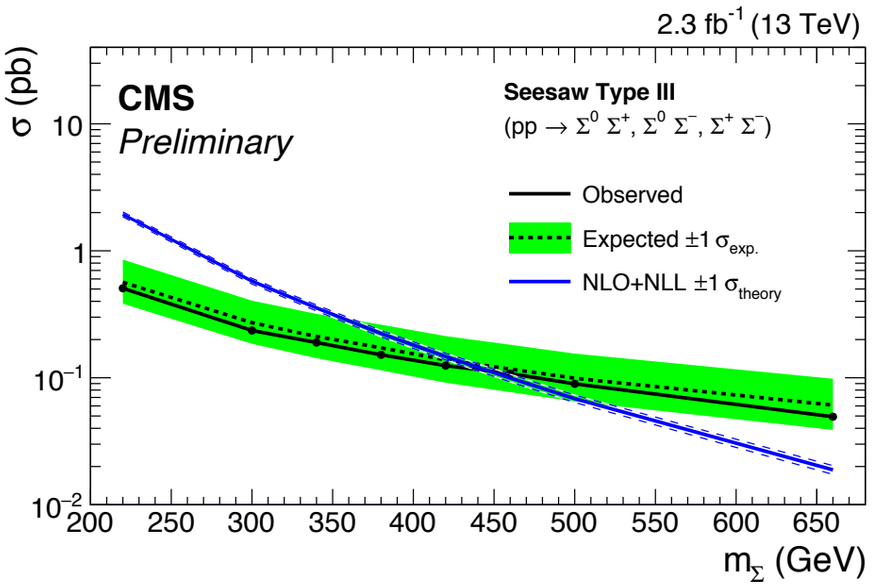
CMS: Type-III seesaw model at 13 TeV

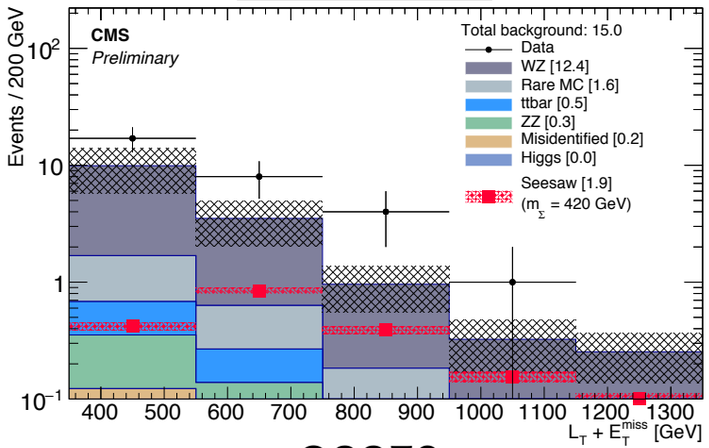
EXO-16-002

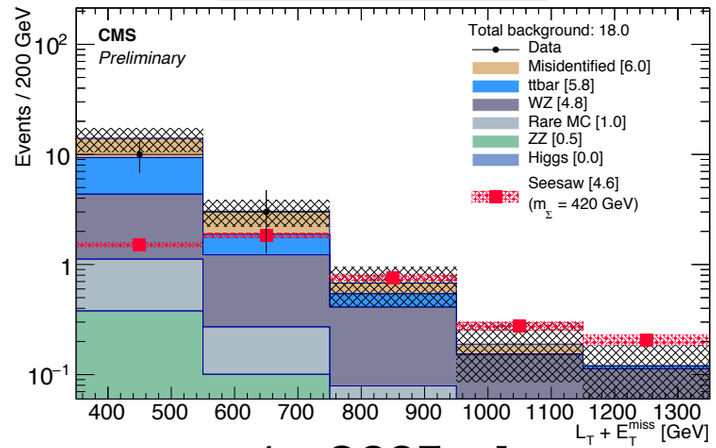
- Signature
  - ≥3 leptons(e or μ) with p_T > 20, 15, 10 GeV
  - Categorization : Sign / Flavor
    - $\mu^+\mu^-\mu^-$ / $\mu^+\mu^-e^-$: OS-SF1
    - $\mu^+\mu^+e^-$: OS-SF0
    - $\mu^+\mu^-e^+e^-$: OS-SF2
  - $m_{\ell\ell}$(OS leptons) > 12 GeV

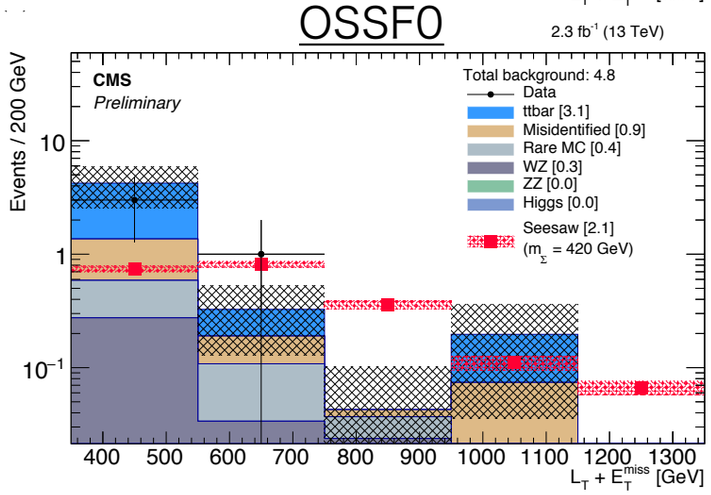


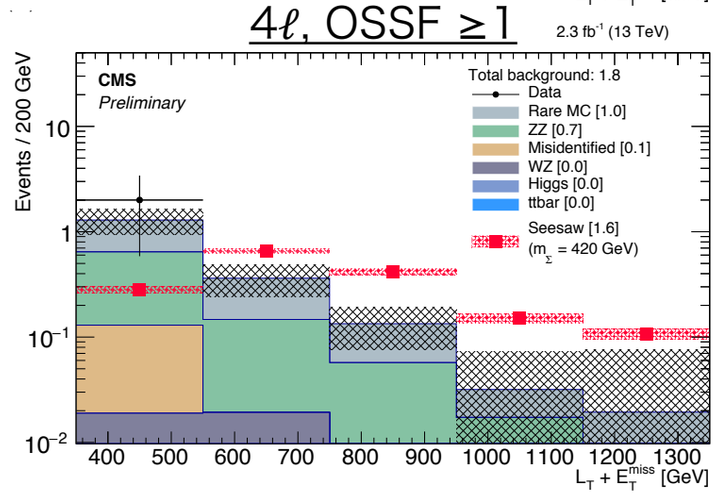
- Run2 result with ∫L = 2.3/fb
  - No excess observed







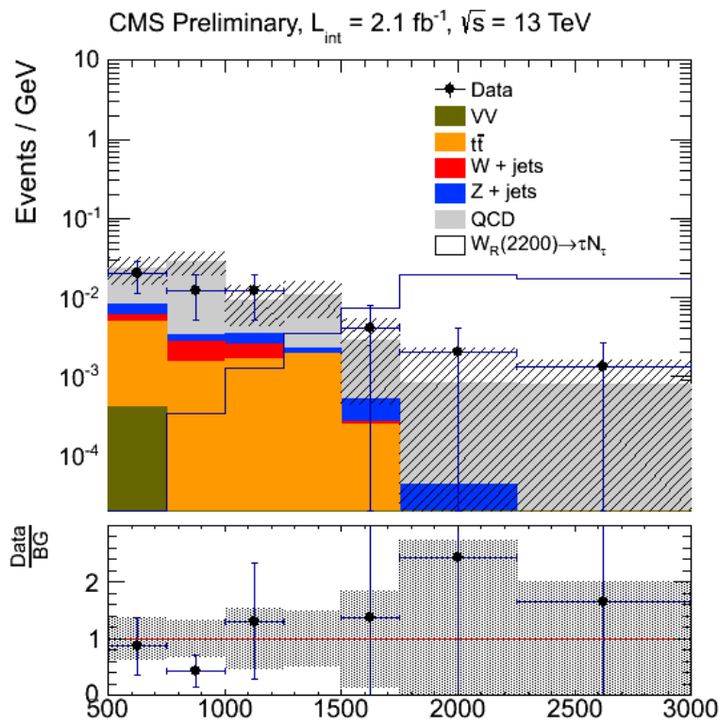




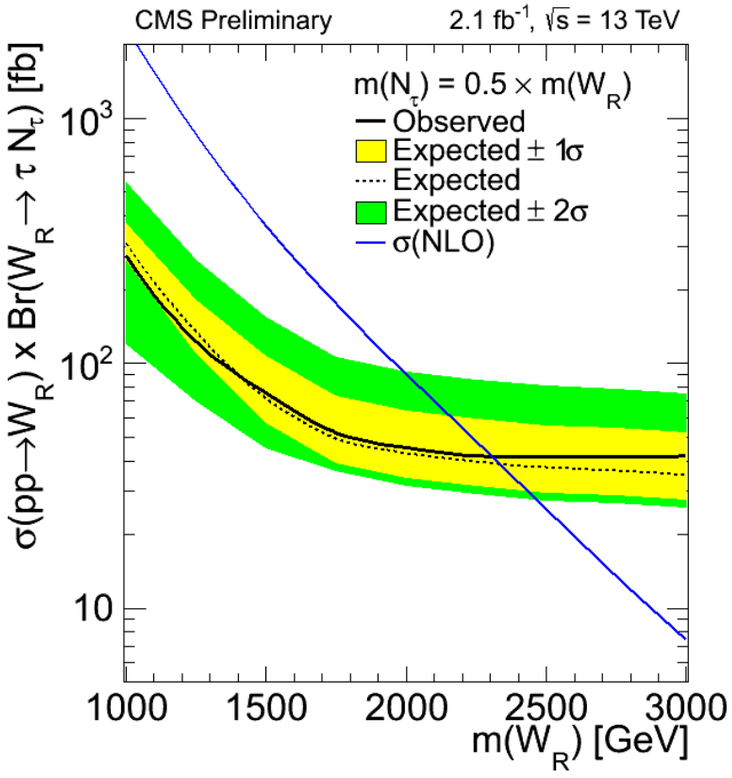
CMS: LRSM HMN search at 13 TeV

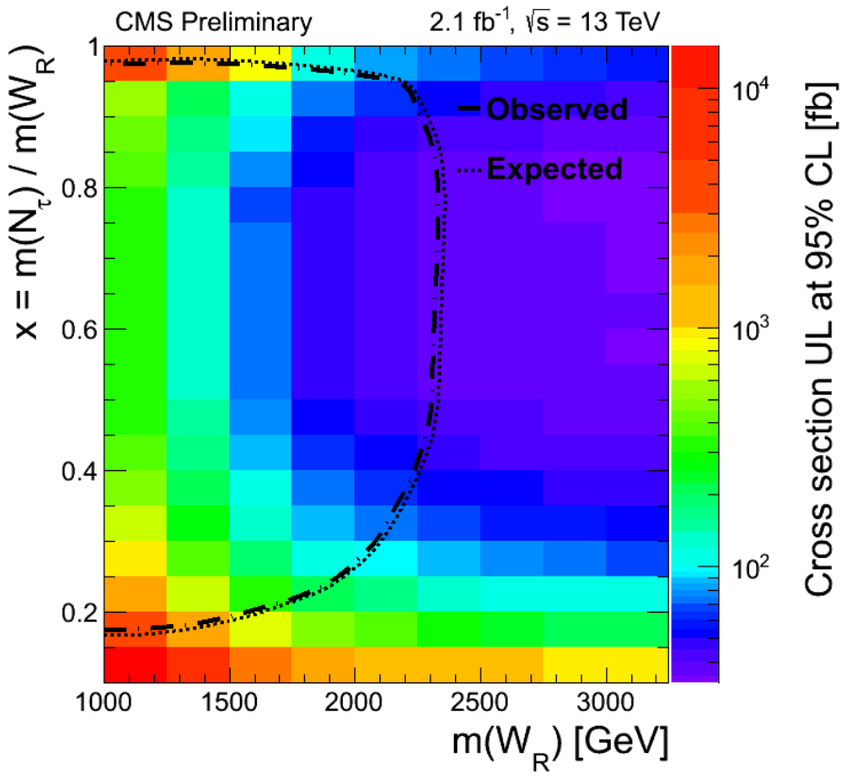
EXO-16-023

- With 2 hadronic taus
  - Event selections
    - pre-selection for two τ candidates
      - pT(τ_h)| > 35 GeV in |η(τ_h)|< 2.1
    - 2 τ selections
      - pT(τ_h) > 70 GeV
      - $\Delta R_{\tau\tau} > 0.4$
      - Same-sign
    - 2jets w/ pT > 50 GeV in |η| < 2.4
    - MET > 50 GeV (in τ decays)
    - $M_{\tau\tau} > 100$ GeV



- Result with $\int L$ = 2.3/fb in 2015
  - No excess observed

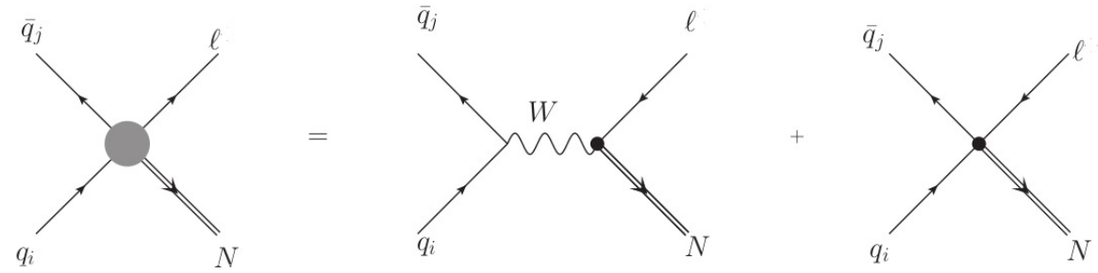




CMS: Composite N search at 13 TeV

EXO-16-026

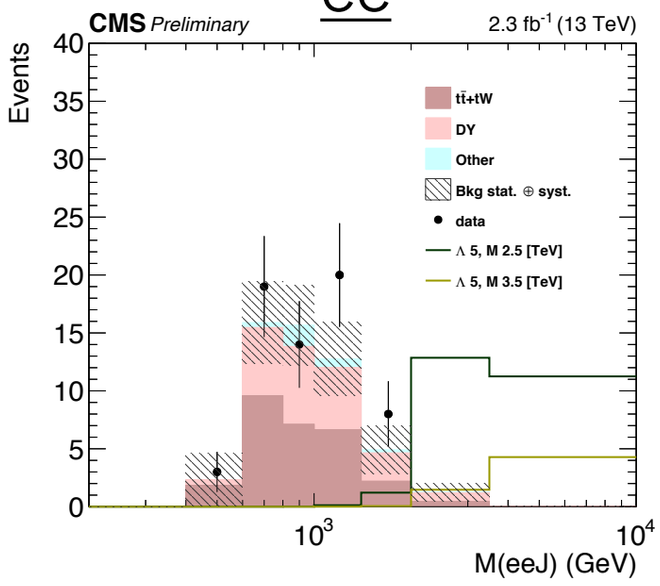
- Composite model for q/ℓ
  - Signals
    - $\ell\ell$ + wide jet (Anti-Kt R=0.8)



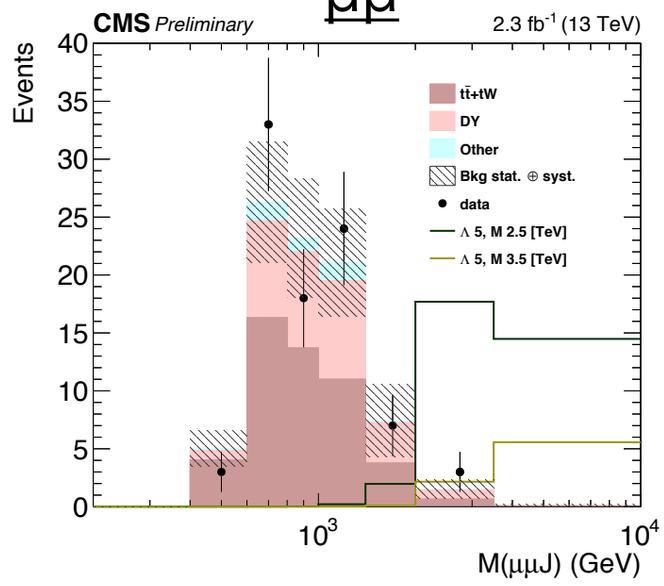
- Event selections
  - SS two leptons
    - p_T(e1) > 110 eV
      p_T(e2) > 35 GeV
    - p_T(μ1) > 53 eV
      p_T(μ2) > 30 GeV
      - ✓ $|\eta| < 2.4$
  - p_T(J) > 190 GeV

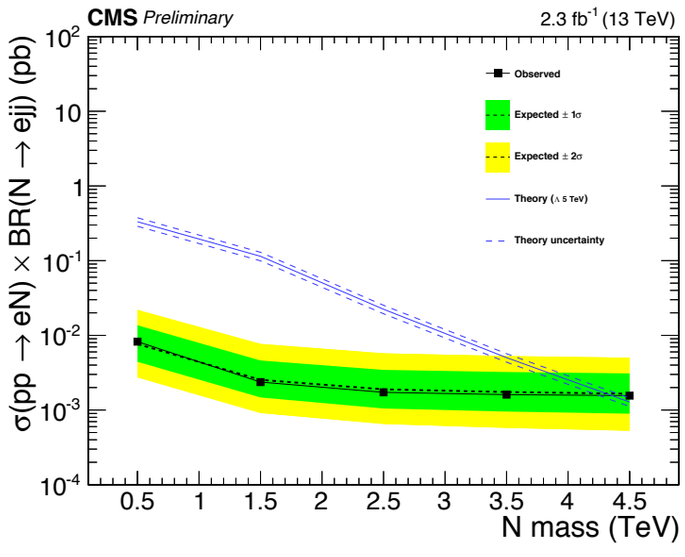
- Run2 result with $\int L = 2.3/fb$
  - No excess observed

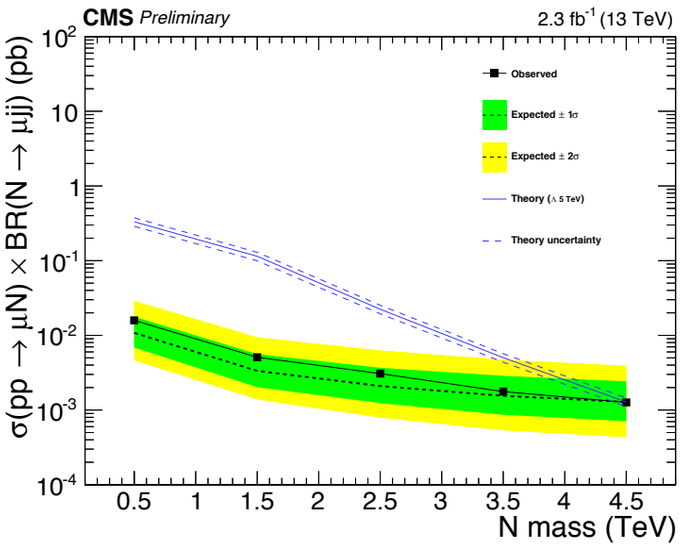
ee



μμ







Summary

- Heavy Majorana Neutrinos
  - Models, searches
    - Minimal Type-I seesaw mechanism
    - Left-right symmetric model
      - ✓ Signals free from SM backgrounds : **same sign di-lepton**
    - Type-3 seesaw model
    - Composite model

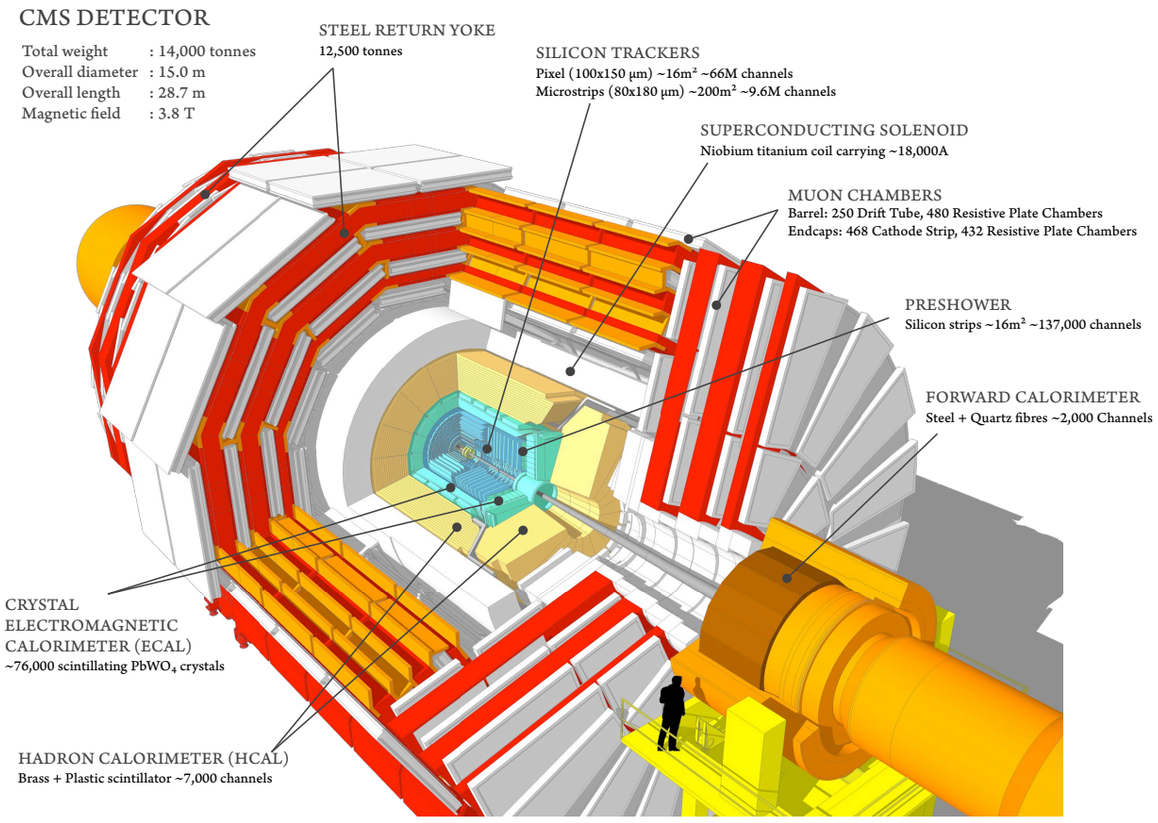
  - Results
    - No statistically significant excess observed in Run1 data taken with ATLAS or CMS
    - First results from CMS in Run2 at $\sqrt{s}$ = 13 TeV

      - ✓ **Much more data coming in Run2 for more strict limits, or discoveries. Stay tuned!**

Backup

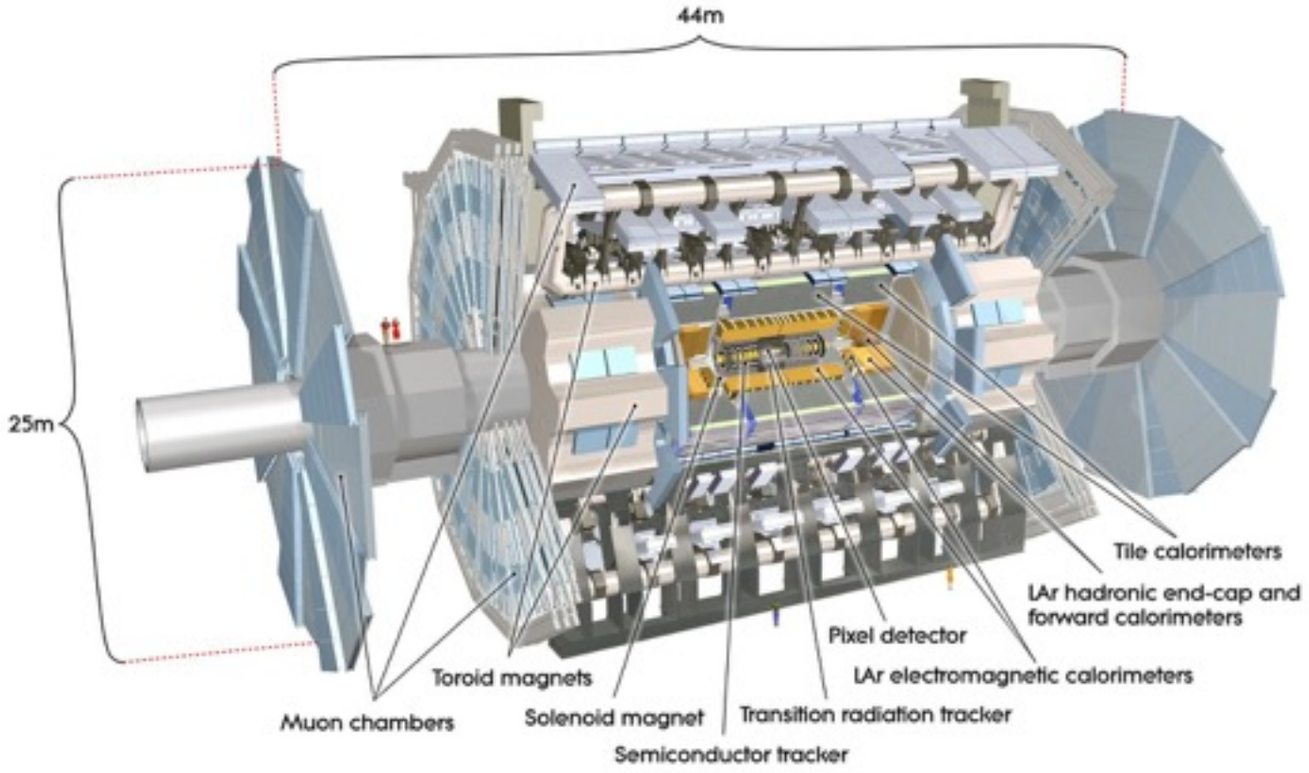
Experimental apparatuses

The CMS detector



CMS Document 11514

The ATLAS detector



CERN-GE-0803012

References

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  - http://dx.doi.org/10.1007/JHEP07(2015)162
    - “Search for heavy Majorana neutrinos with the ATLAS detector in pp collisions at √s = 8 TeV”
  - http://dx.doi.org/10.1103/PhysRevD.92.032001
    - “Search for type-III seesaw heavy leptons in pp collisions at √s = 8 TeV with the ATLAS detector”
  - http://dx.doi.org/10.1140/epjc/s10052-012-2056-4
    - Search for heavy neutrinos and right-handed W bosons in events with two leptons and jets in pp collisions at √s = 7 TeV with the ATLAS detector
  - http://dx.doi.org/10.1007/JHEP09(2015)108
    - “Search for heavy lepton resonances decaying to a Z boson and a lepton in pp collisions at √s = 8 TeV with the ATLAS detector”

- CMS results
  - CMS-PAS-EXO-16-002, https://cds.cern.ch/record/2140978
    - “Search for Type-III Seesaw Heavy Fermions with Multi-lepton Final States using 2.3/fb of 13 TeV proton-proton Collision Data”
  - CMS-PAS-EXO-16-023, https://cds.cern.ch/record/2205270
    - “Search for the third-generation scalar leptoquarks and heavy right-handed neutrinos in $\tau_\ell \tau_h$jj final states in pp collisions at 13 TeV”
  - CMS-PAS-EXO-16-026, https://cds.cern.ch/record/2205277
    - “Search for heavy composite Majorana neutrinos produced in association with a lepton and decaying into a same-flavour lepton plus two quarks at √s= 13 TeV with the CMS detector”
  - http://link.springer.com/article/10.1007/JHEP04(2016)169
    - “Search for heavy Majorana neutrinos in e±e±+ jets and e±μ±+ jets events in proton-proton collisions at √s = 8 TeV”
  - http://dx.doi.org/10.1016/j.physletb.2015.06.070
    - “Search for heavy Majorana neutrinos in $\mu\pm\mu\pm$ + jets events in proton–proton collisions at √s = 8 TeV”
  - http://dx.doi.org/10.1140/epjc/s10052-014-3149-z
    - “Search for heavy neutrinos and W bosons with right-handed couplings in proton–proton collisions at √s = 8 TeV”
  - http://link.aps.org/doi/10.1103/PhysRevLett.116.071801
    - “Search for Narrow Resonances Decaying to Dijets in Proton-Proton Collisions at √s =13 TeV