Test of Neutrino Mass Models at CMS

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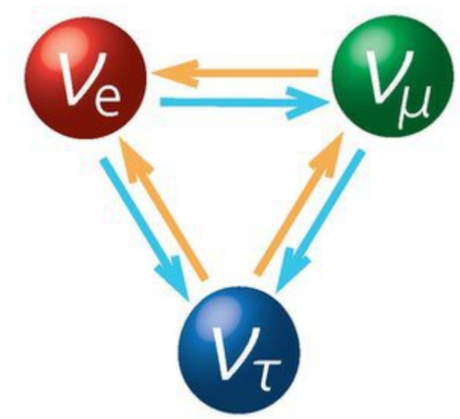
Introduction

✓ The Standard Model (SM) neutrinos (ν) were assumed to be massless

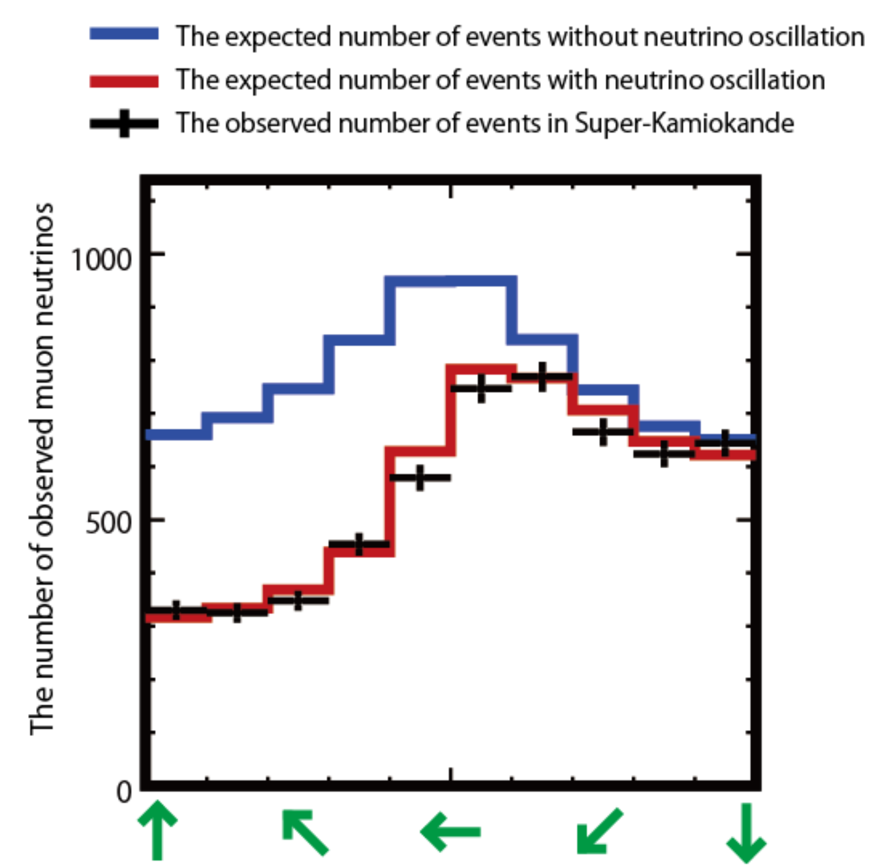
✓ It is now well known that neutrinos have mass due to the discovery of neutrino oscillations and this could be the hint for physics beyond SM

- What is the origin of neutrino masses?
- Does the right-handed (RH) neutrino exist?
- How can baryogenesis be explained?

  And more …

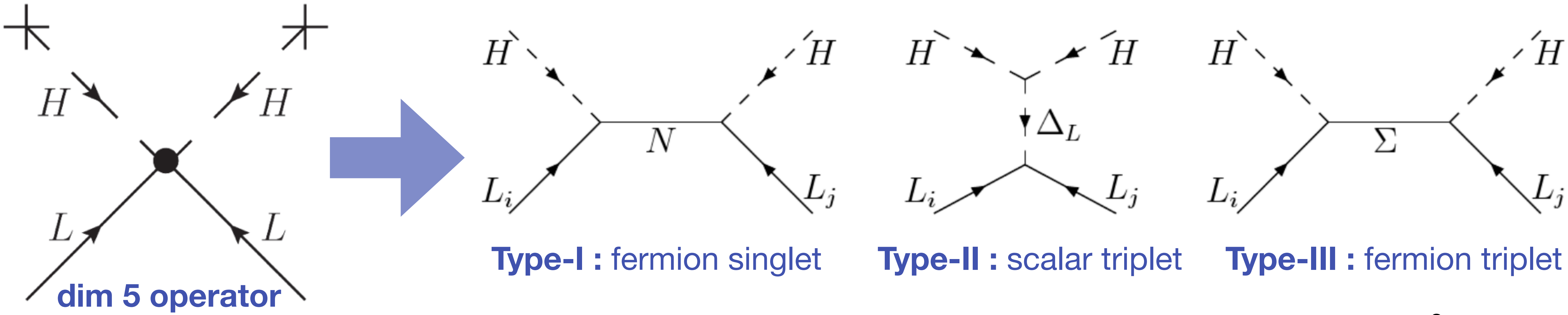


✓ One plausible answer for these questions would be …



✓ Seesaw Model : natural way to generate neutrino masses

✓ Open up dim 5 operator in tree level : fermion singlet, scalar triplet, fermion triplet



✓ Smallness of neutrino masses can be explained by existence of N $m_\nu = y\frac{v^2}{m_N}$

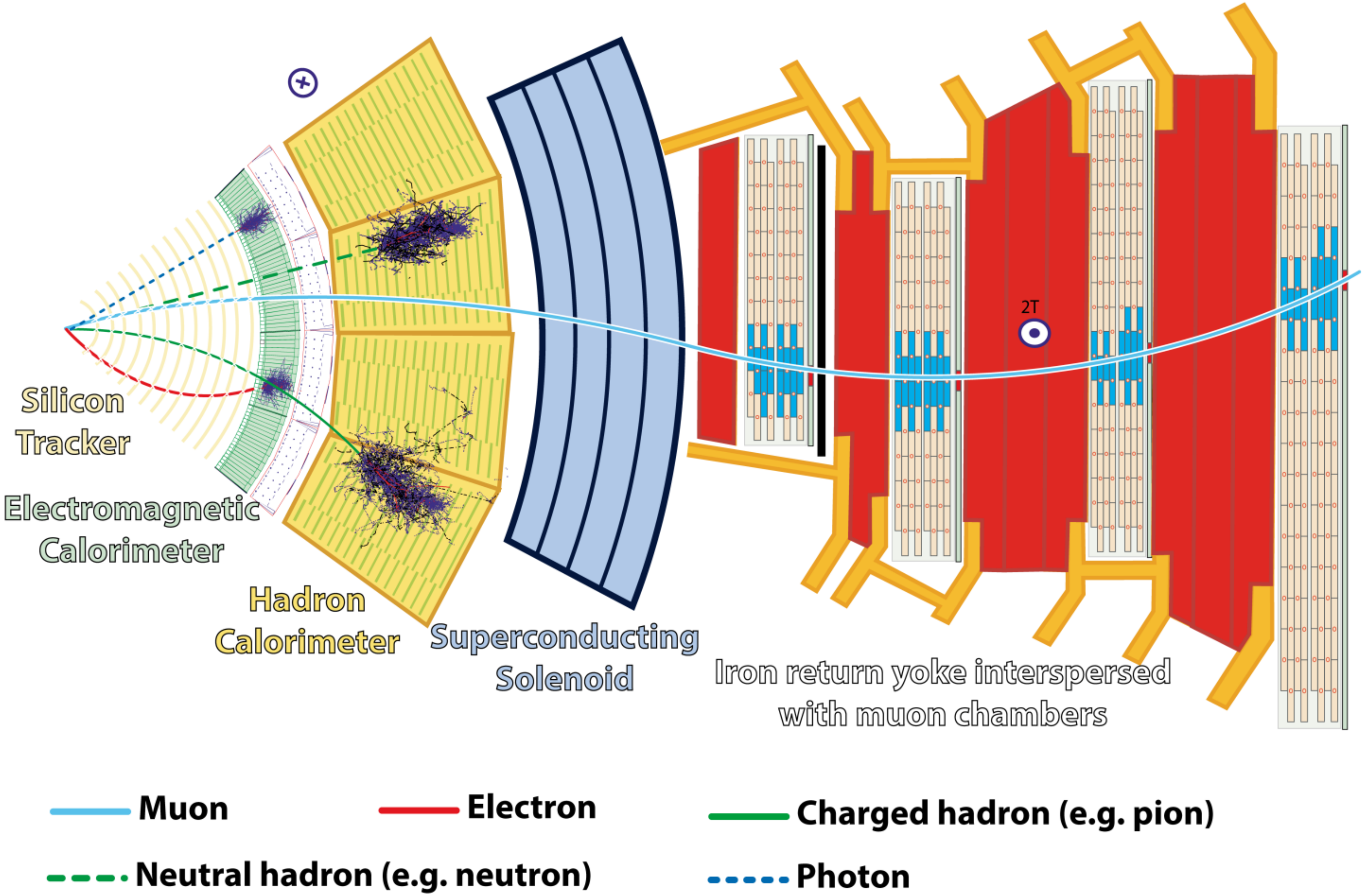
✓ Mechanism of neutrino mass generation in Left-Right Symmetric Model (LRSM) is introduced via Seesaw Model after electroweak spontaneous symmetry breaking

✓ Inverse Seesaw Model, Zee-Babu Model, Scotogenic Model, and more …

Some of the heavy neutrino searches are done along with leptoquark (LQ) or some other models due to its common final states, but this talk will strictly stick to the searches for N only covering 8 and 13 TeV studies from CMS

* N : heavy right-handed neutrinos

Compact Muon Solenoid



Outline

8 TeV Searches

Type-I Seesaw Model
Left-Right Symmetric Model

13 TeV Searches

Composite Model
Type-I & III Seesaw Model
Left-Right Symmetric Model

8 TeV Searches

Type I Seesaw Model

8 TeV

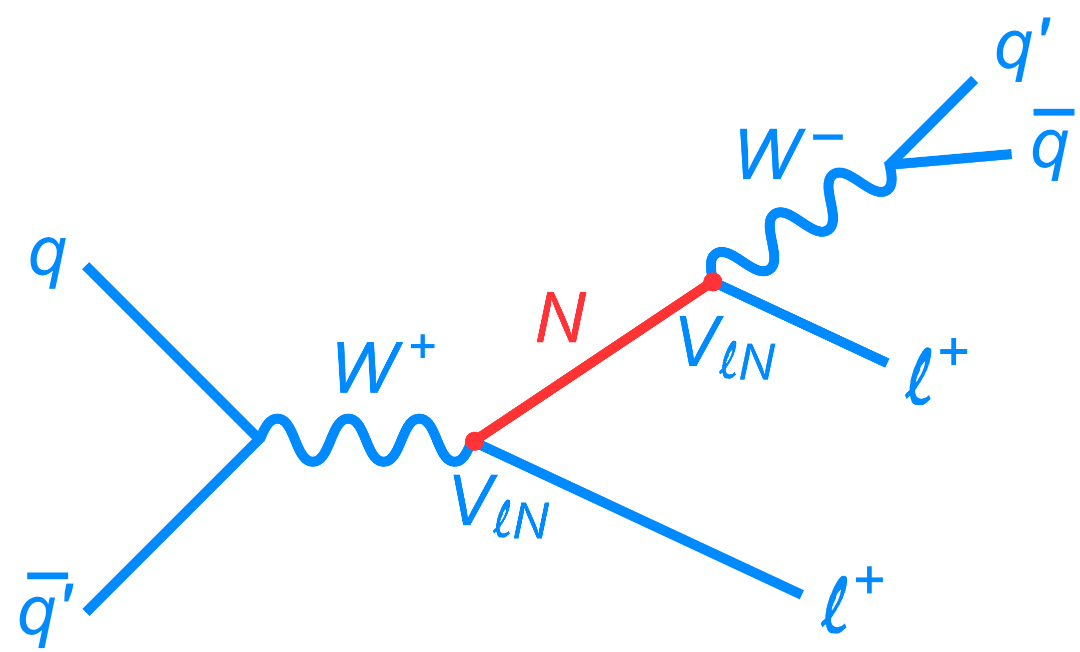
- ✓ Simplest model : N with no new interactions
  - ✓ N mixes with SM neutrinos via mixing angle $V_{\ell N}$
- ✓ If Majorana N, lepton number violation is possible
  - ✓ Same-sign (SS) signals have advantage over opposite-sign (OS) signals due to significantly low backgrounds
- ✓ Limits set on $|V_{\ell N}|^2$ and cross section

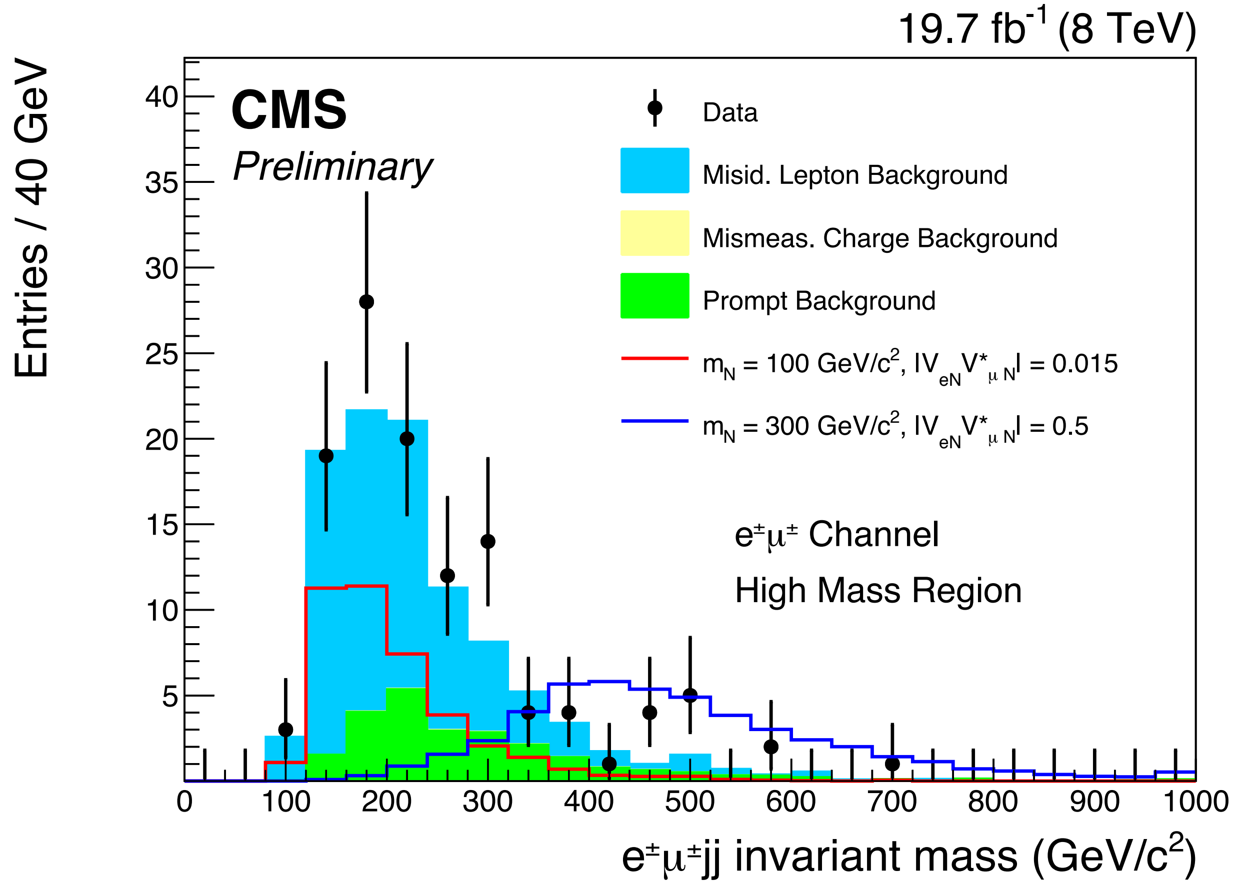
Event Selection

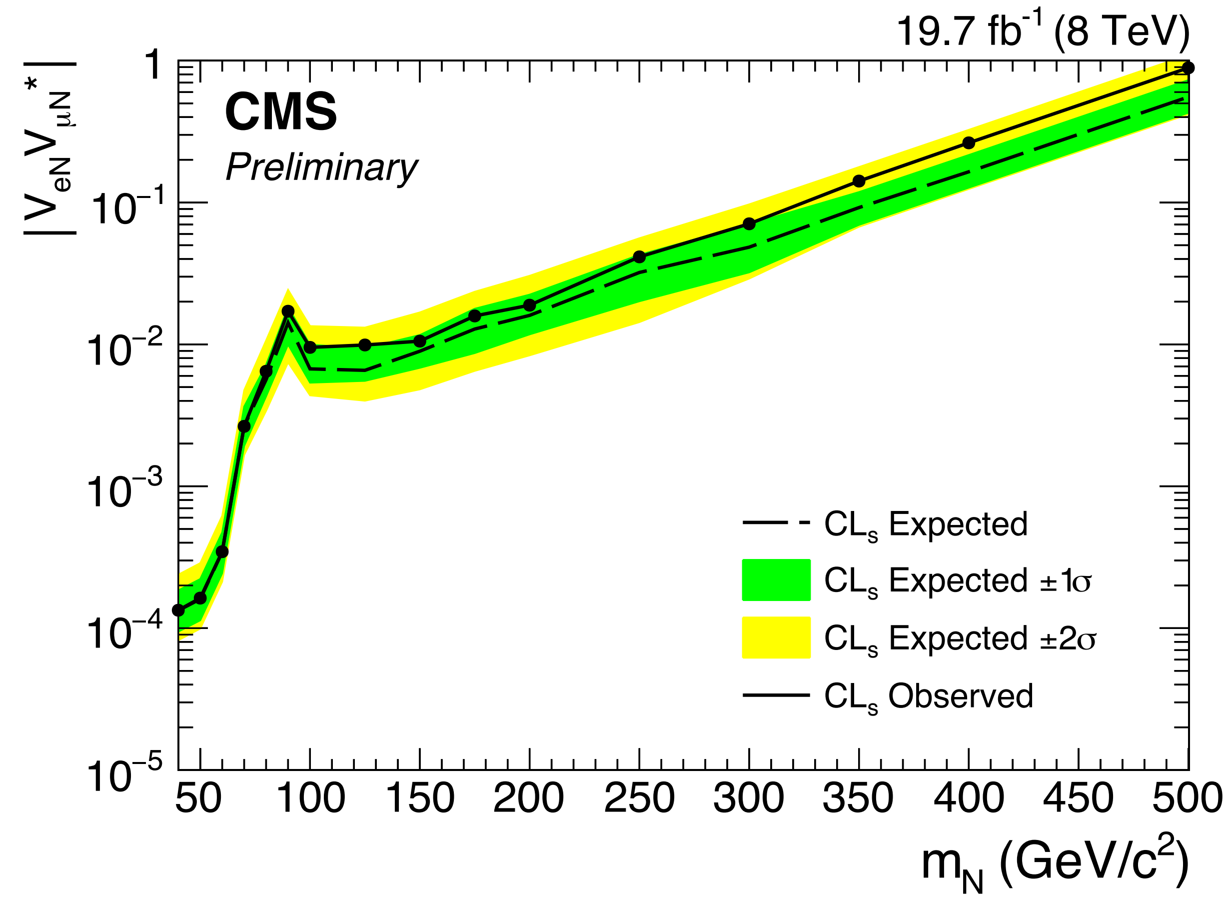
- 2 leptons (ℓ) : μμ, ee, eμ
  - same-sign pair
  - $p_T(\ell_1,\ell_2)$>25,15 GeV
- at least 2 jets (j) with p_T(j)>20 GeV
- different cuts on MET, m(jj), m(ℓjj), and m($\ell\ell$jj)

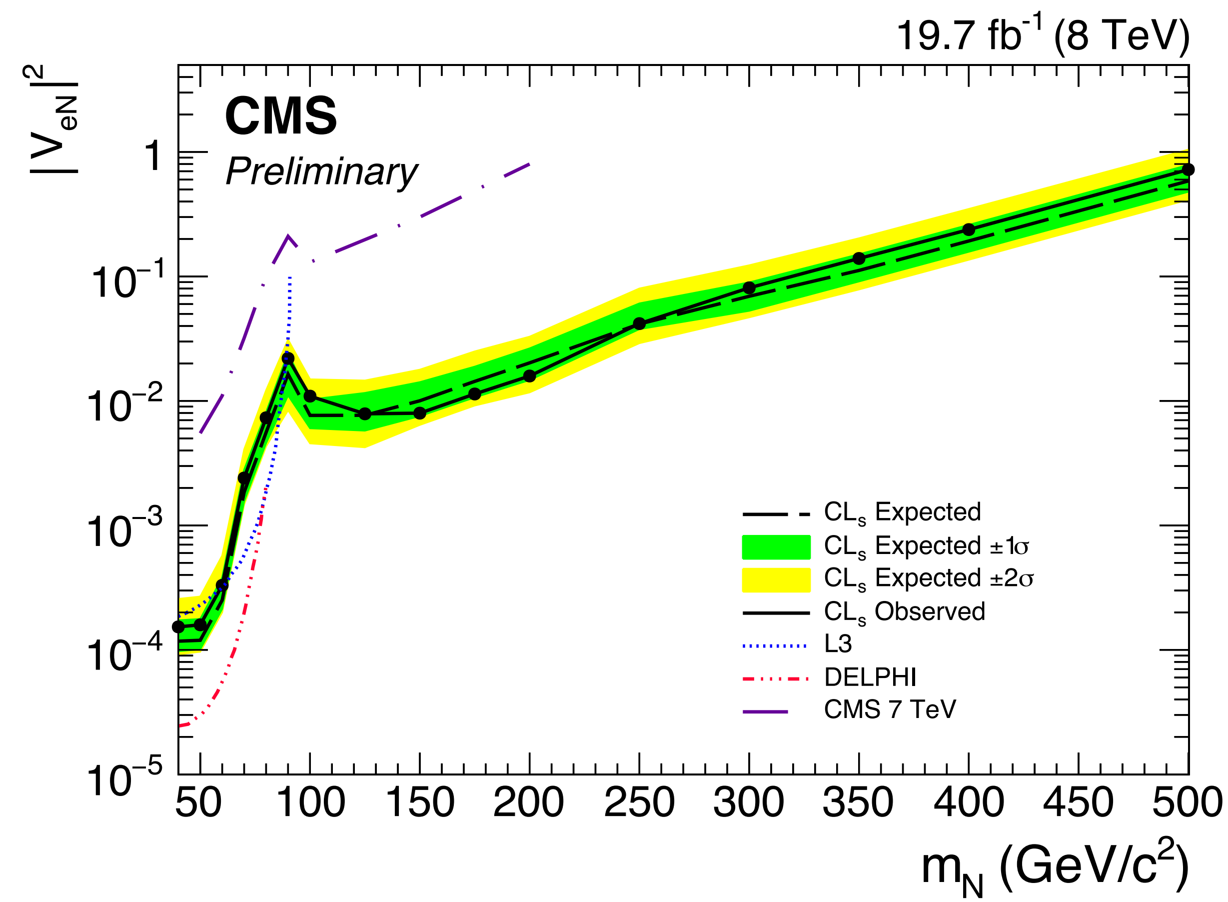
Major Backgrounds

- prompt : WZ, ZZ
- nonprompt : Wjets, QCD
- charge-mismeasured (only for ee)









- ✓ Used full 8 TeV run data
- ✓ No excess above SM prediction
- ✓ Limits set up to m(N)=500 GeV
- ✓ First to set direct limits on $|V_{eN}V_{\mu N}^*|$

Phys.Lett.B748(2015)144
JHEP04(2016)169

Left-Right Symmetric Model

8 TeV

✓ $SU(2)_R$ added to SM, predicts 3 new gauge bosons ($W_R^{\pm}$ and Z’) along with 3 heavy right-handed partners of SM neutrinos

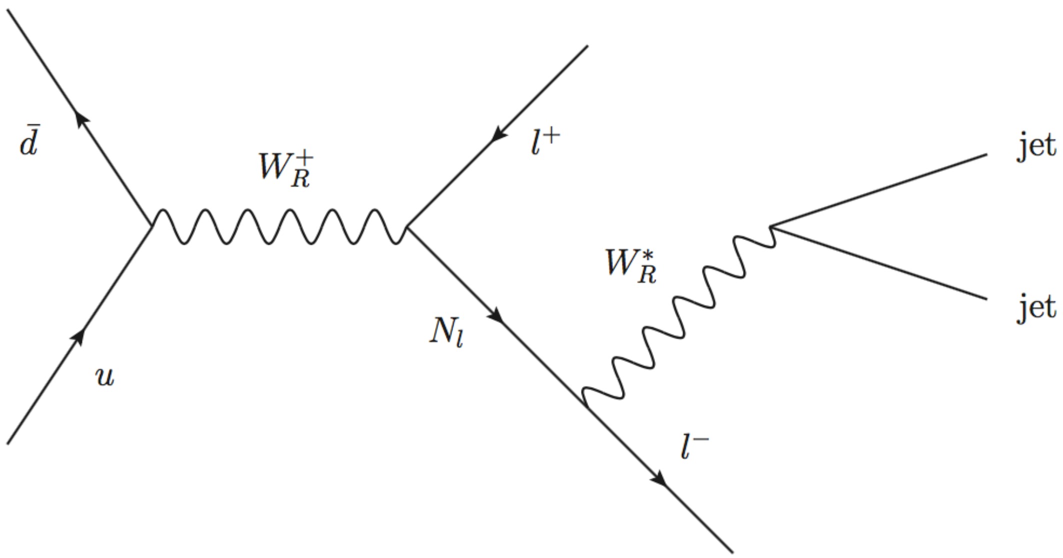
- ✓ Different kinematics from Type-I Seesaw Model

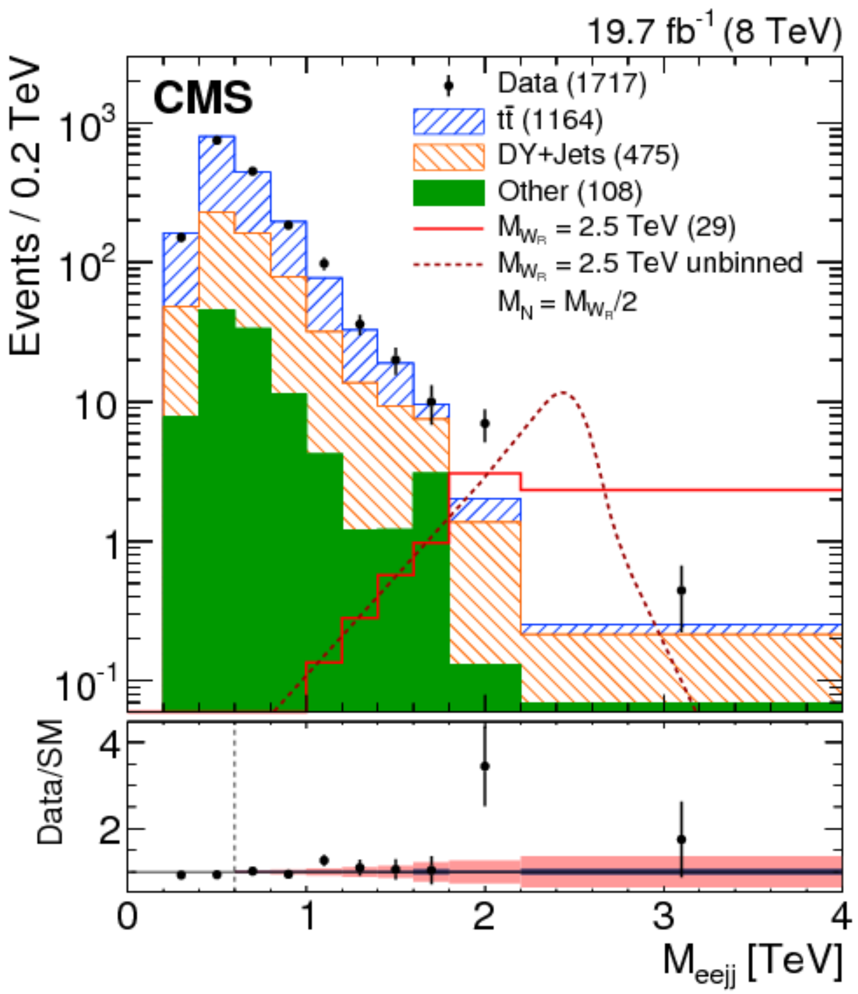
✓ 2D ($m(W_R)$, m(N)) limits set on cross section

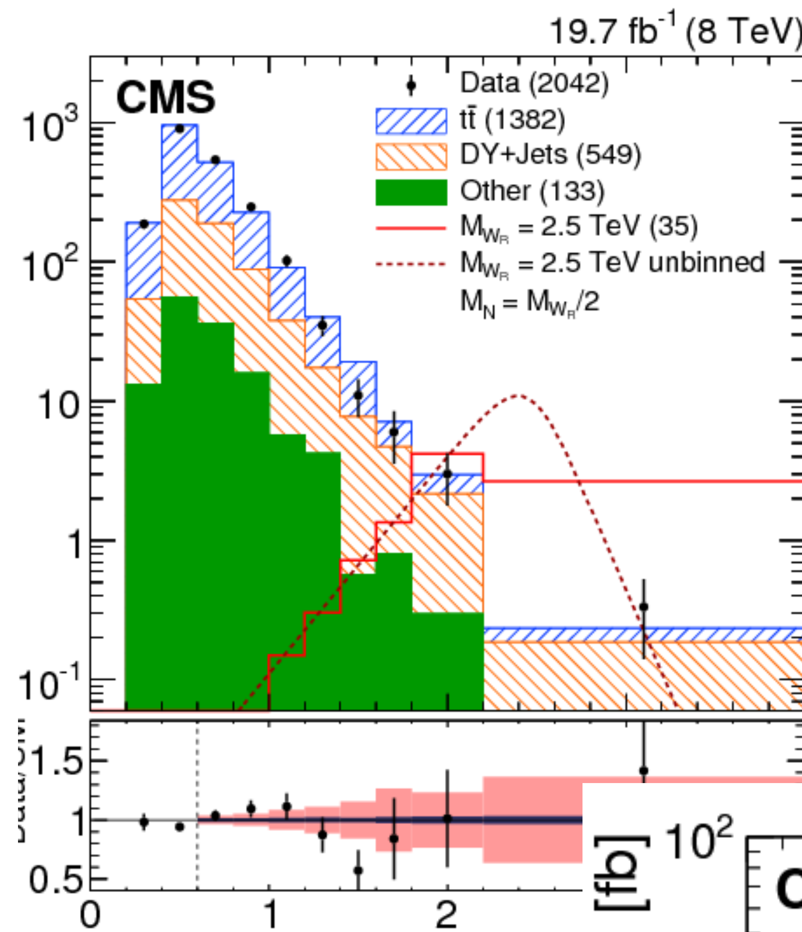
✓ *13 TeV results are in backup slides*

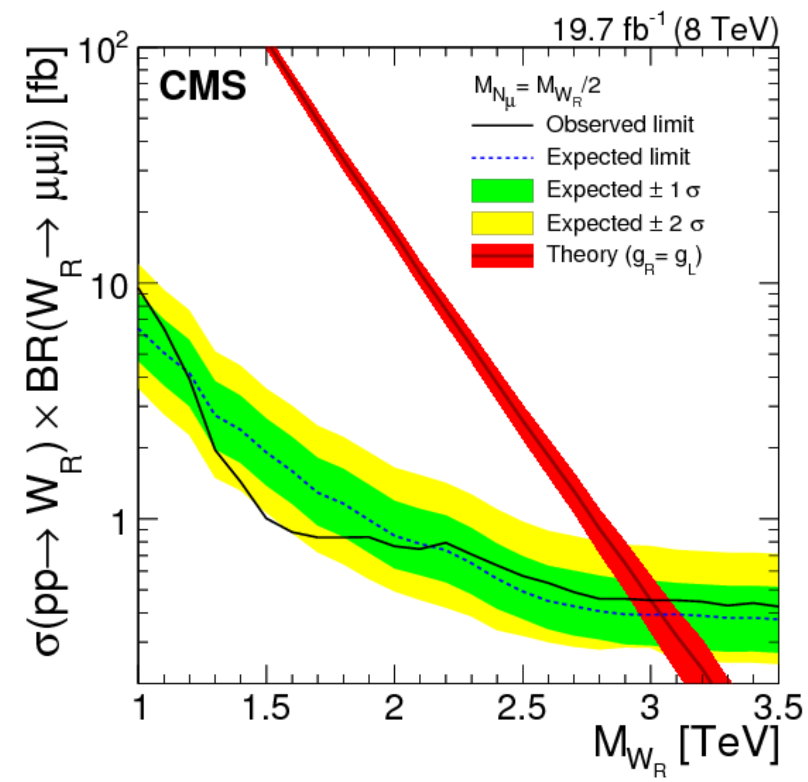
Event Selection
- 2 leptons : μμ, ee
    - no charge requirements, high p_T
- at least 2 jets with $p_T(j)>40$ GeV
- $m(\ell\ell)>200$ GeV, $m(\ell\ell jj)>600$ GeV

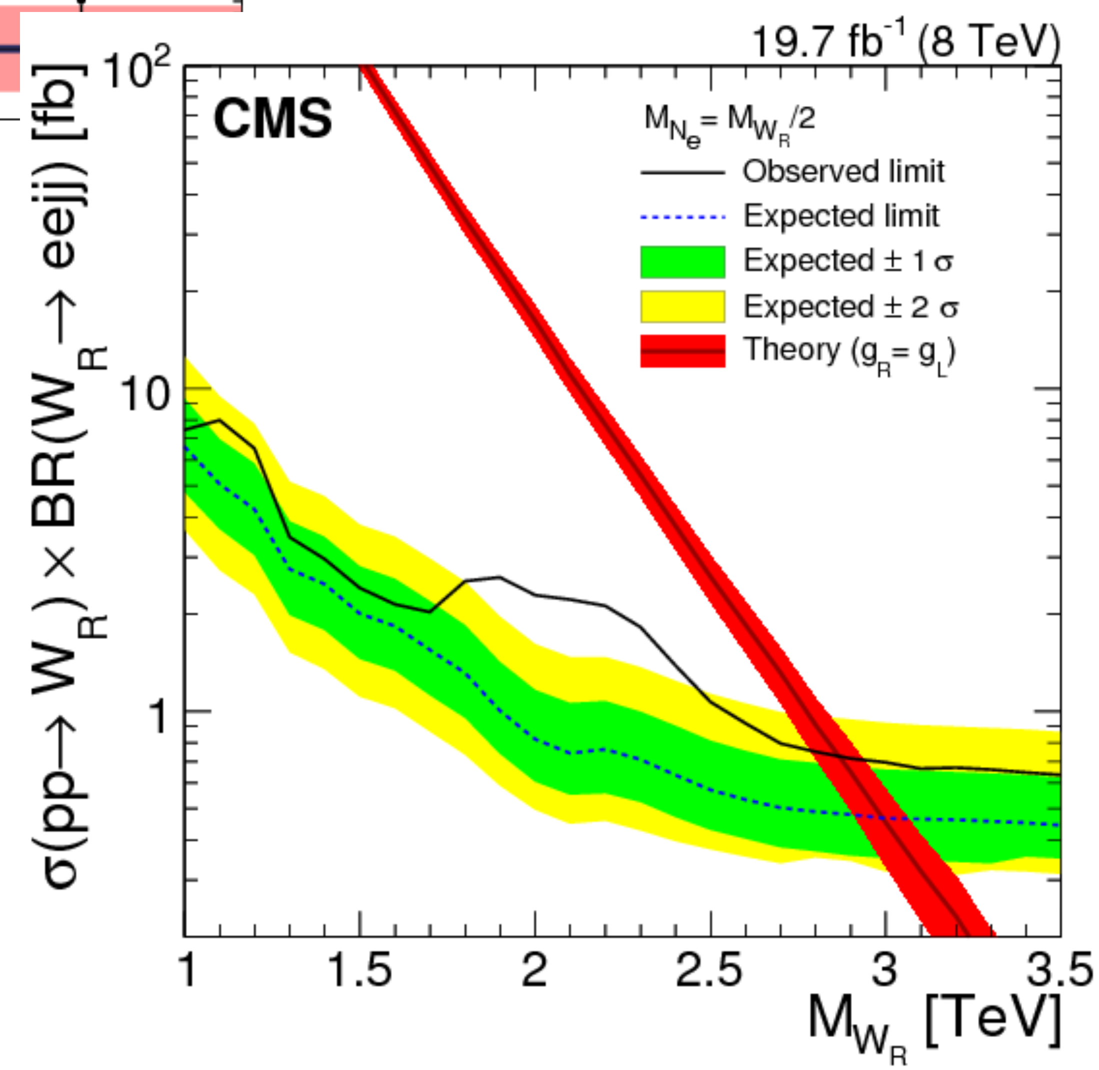
Major Backgrounds
- prompt : DYjets, $t\bar{t}$
- nonprompt contributions negligible











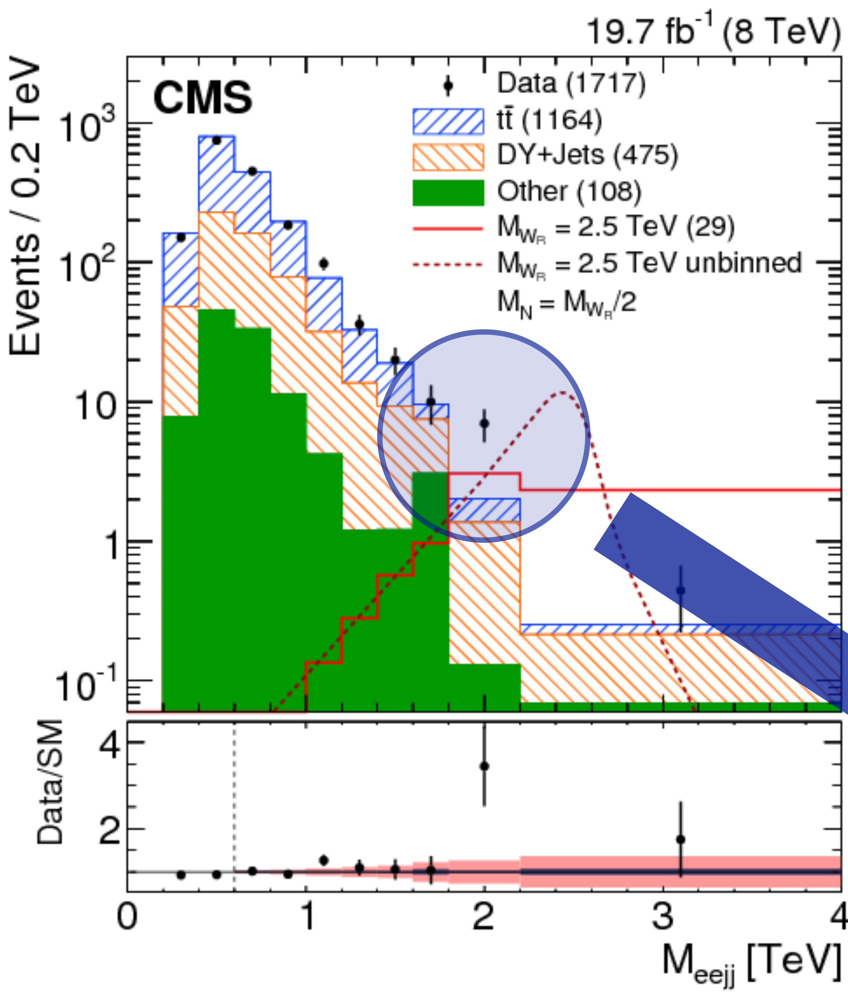
✓ Used full 8 TeV run data

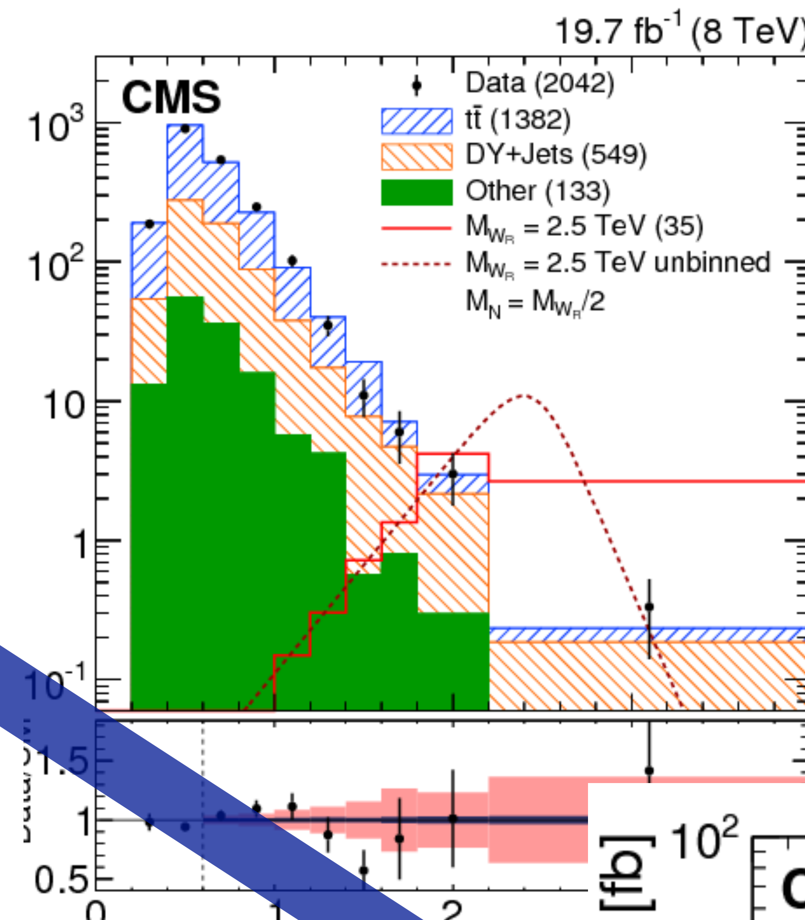
✓ 2.8σ excess at m(eejj)~2 TeV

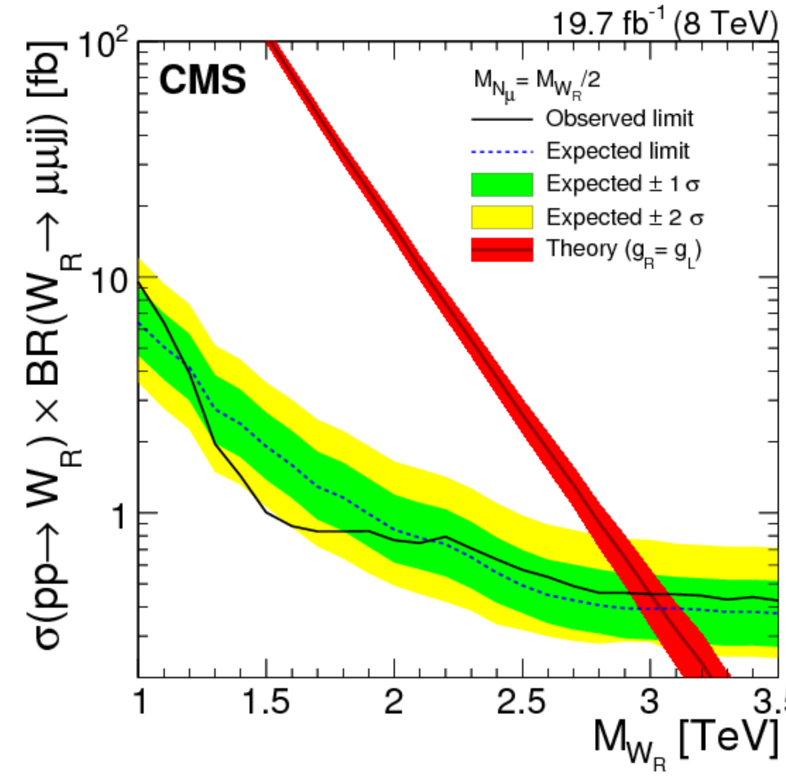
✓ 2.5σ excess also seen from Leptoquark analysis but only in e channel (eejj, eνjj)

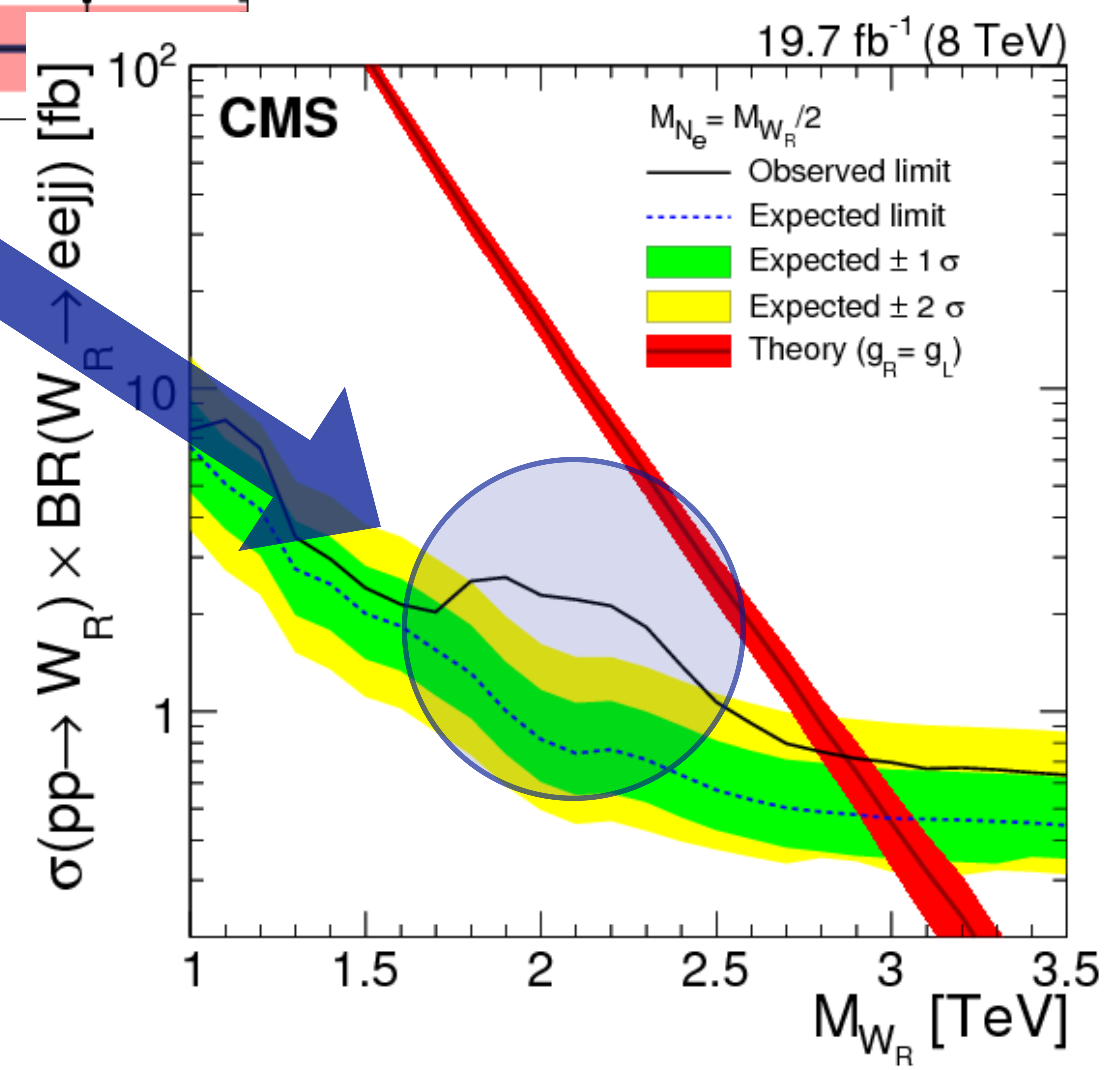
✓ SS analysis from ATLAS : no excess

Eur.Phys.J.C74(2014)3149









- ✓ Used full 8 TeV run data
- ✓ 2.8σ excess at m(eejj)~2 TeV
- ✓ 2.5σ excess also seen from Leptoquark analysis but only in e channel (eejj, eνjj)
- ✓ SS analysis from ATLAS : no excess

Eur.Phys.J.C74(2014)3149

13 TeV Searches

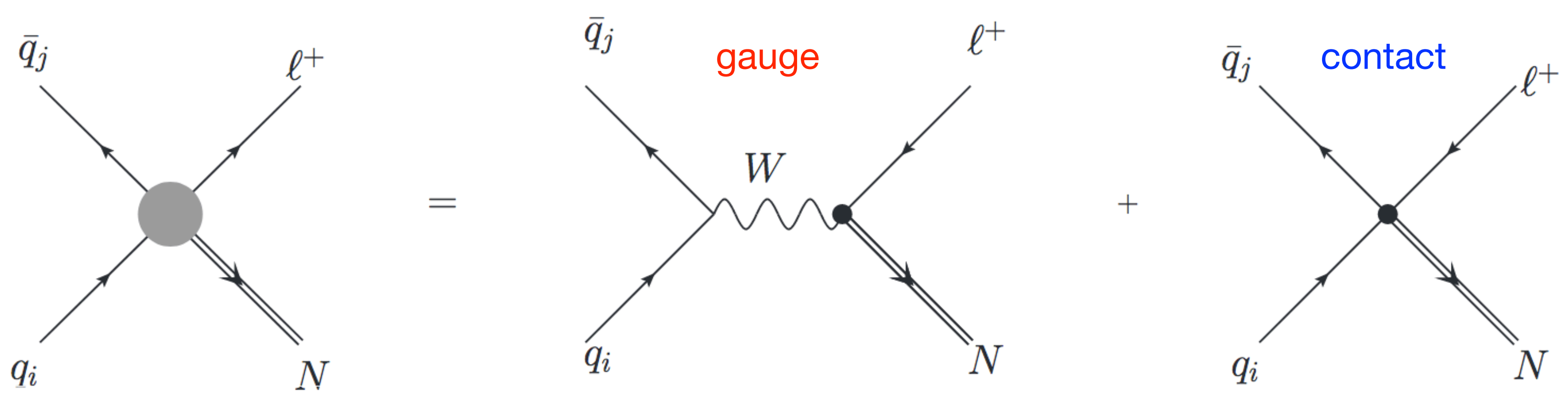
Composite Model

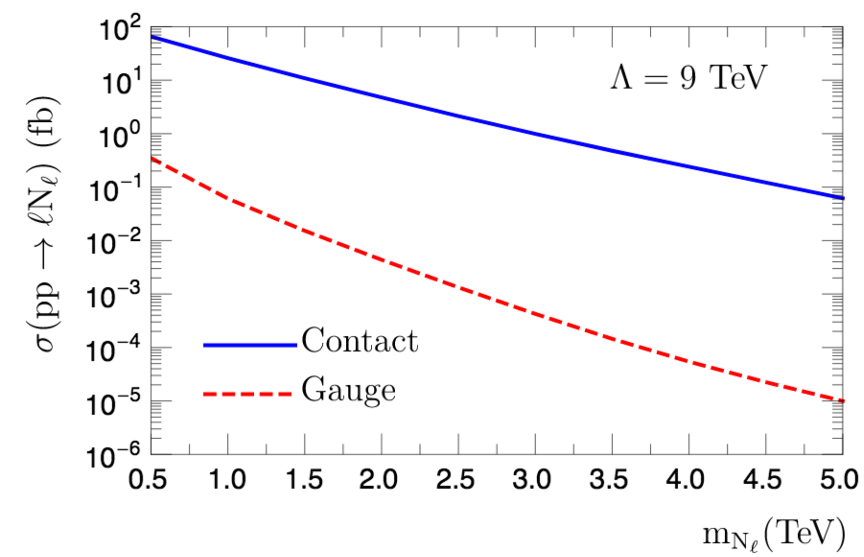
13 TeV CMS

- ✓Fermions are bound states of "preons" which can manifest itself at some compositeness scale Λ
- ✓Heavy composite Majorana neutrino (excited state of fermions) and contact interaction (unknown internal dynamics from compositeness) are expected
- ✓Composite model is able to explain
  - ✓Why only ee channel showed excess above SM at 8 TeV
    - ✓Excited μ state is heavier than excited e state
  - ✓Why only CMS (OS+SS) saw excess while ATLAS (SS) could not
    - ✓*Answers in backup slides*
- ✓Limits set on cross section, compositeness scale

✓Use large-radius (AK8) jet (J) unlike previous $\ell\ell qq$ channel searches considering 2 separated (AK4) jets

✓Effective for gauge boson mediated decay where W is boosted (radius is large enough to contain merged pair of partons from W)



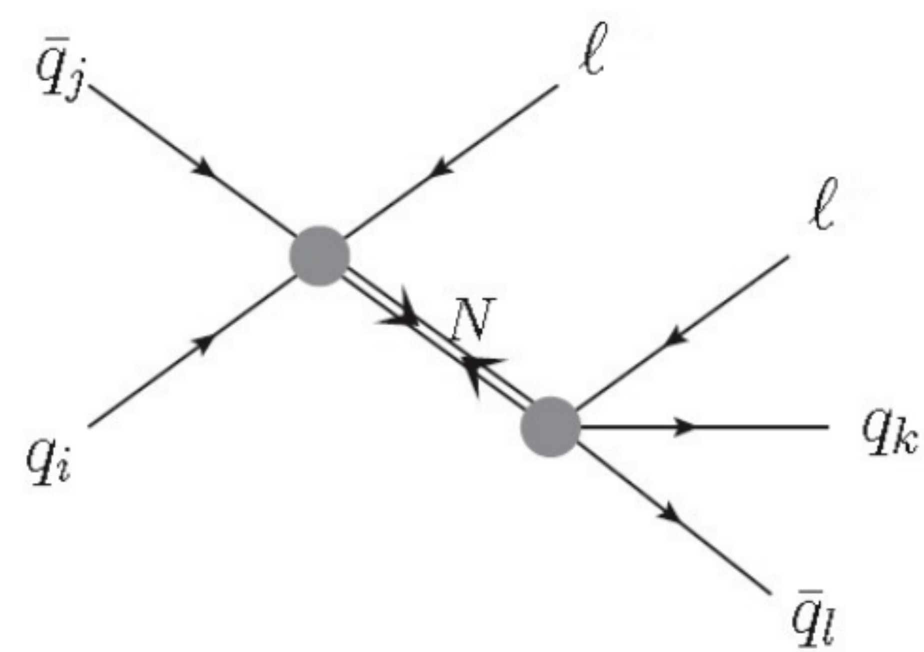


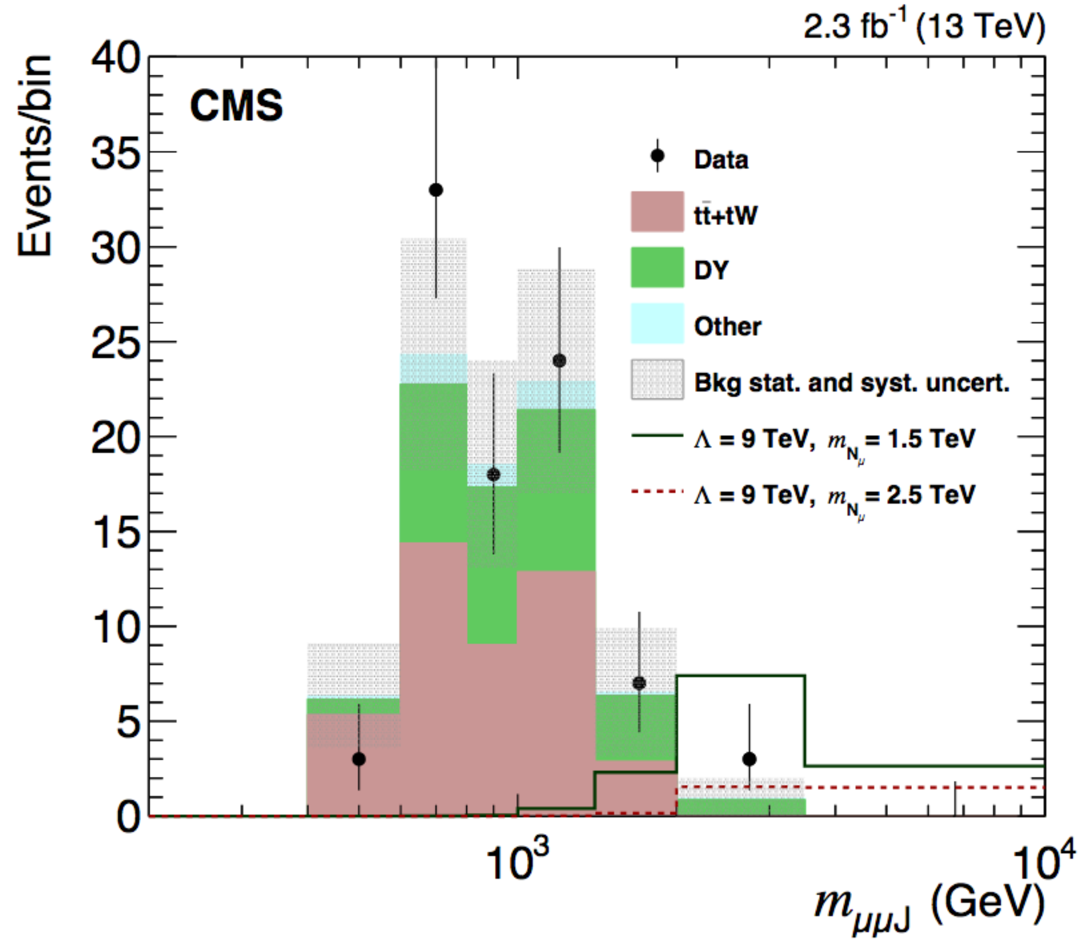
Event Selection

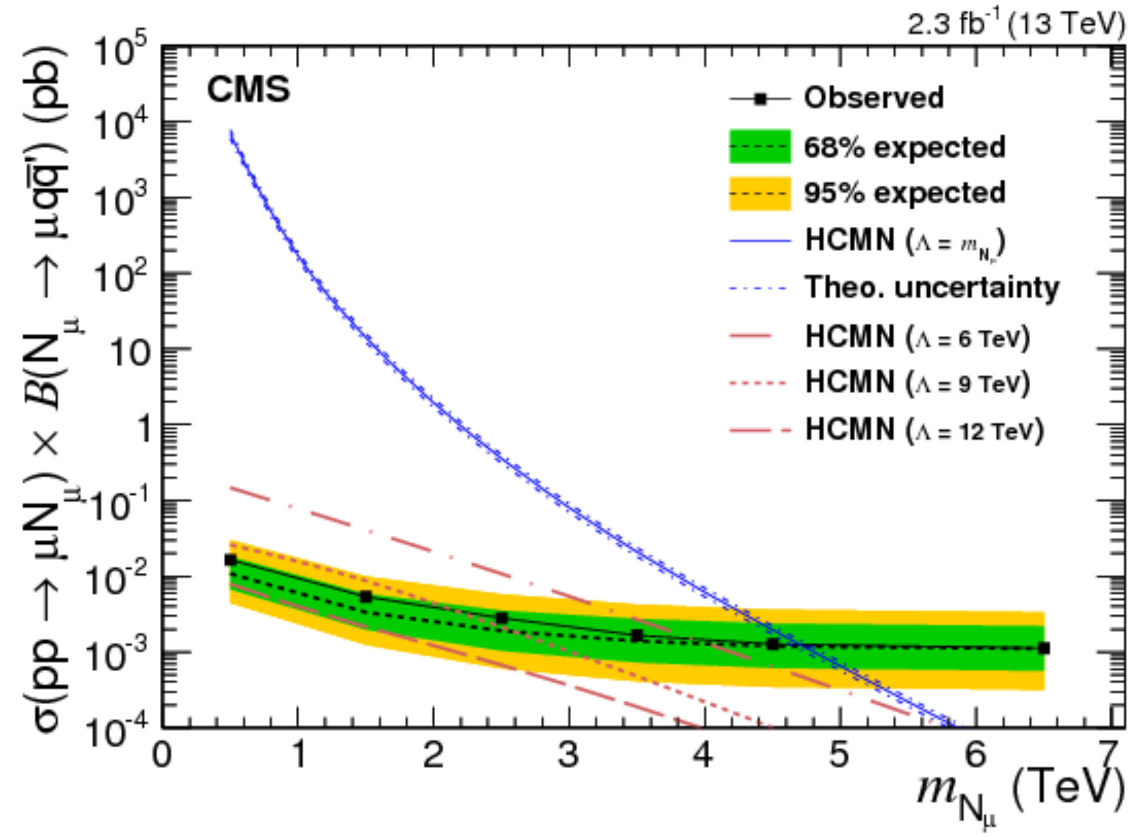
- 2 leptons : μμ, ee
  - no charge requirements, high p_T
- p_T(J)>190 GeV
- m(ℓℓ)>300 GeV

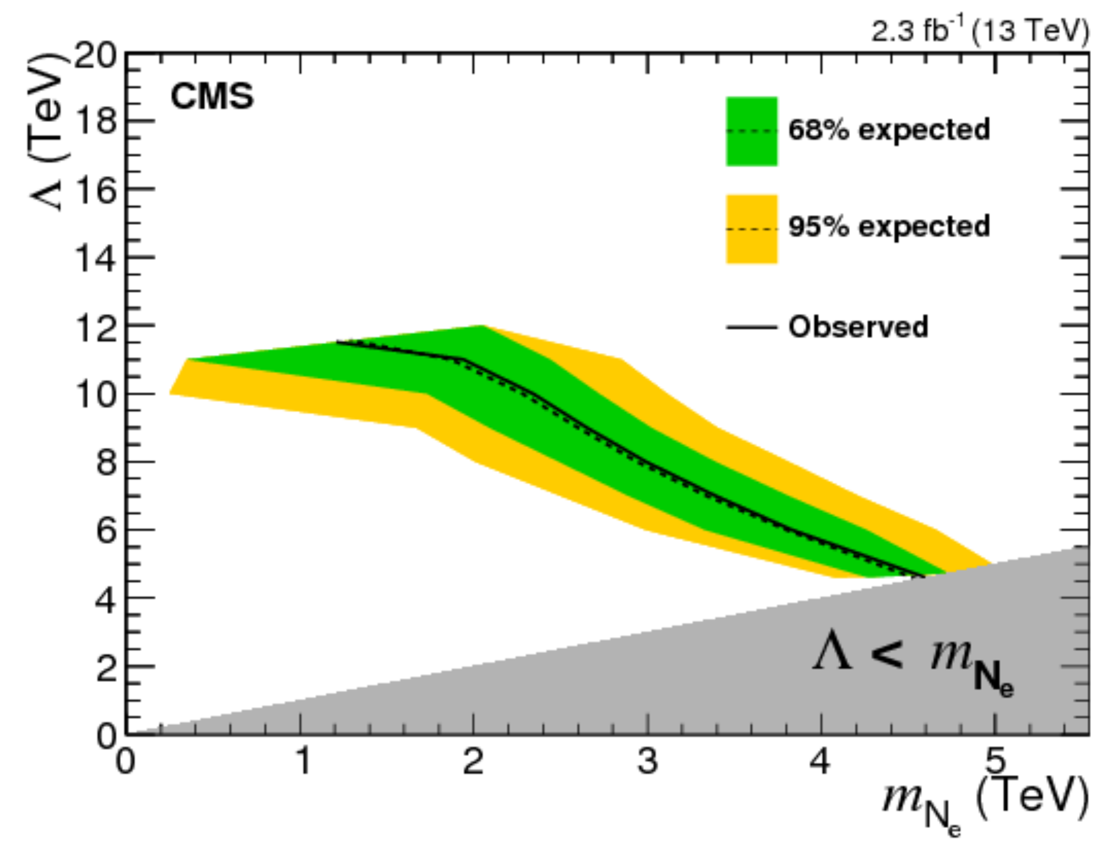
Major Backgrounds

- prompt : DYjets, $t\bar{t}$, single t
- other nonprompt contributions negligible









- ✓ Used 2015 13 TeV run data
- ✓ No excess above SM prediction
- ✓ m(N)=Λ : excluded up to 4.6 TeV
- ✓ First to utilise large-radius jet signature in searches for heavy neutrino

Phys.Lett.B775(2017)315

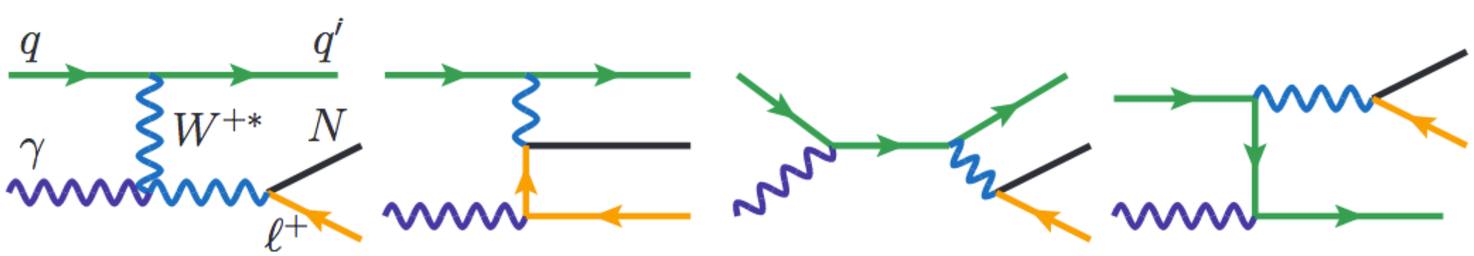
Type I Seesaw Model : 2 leptons

✓ Photon-induced (VBF) processes as signals which gives higher cross sections for high mass N

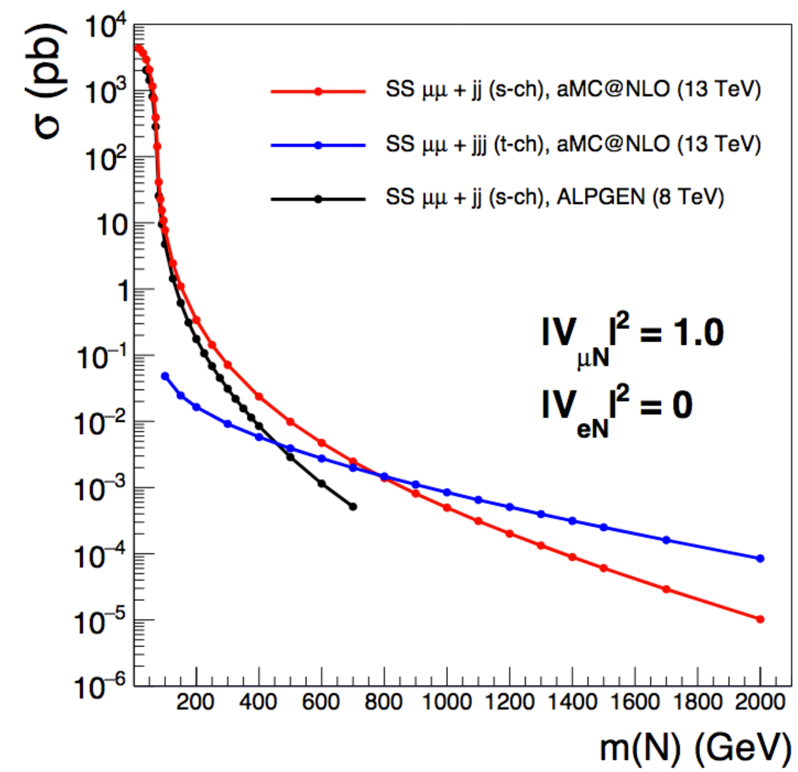
✓ Added single jet signal regions, unlike using only 2 jet events, implementing ideas from composite model

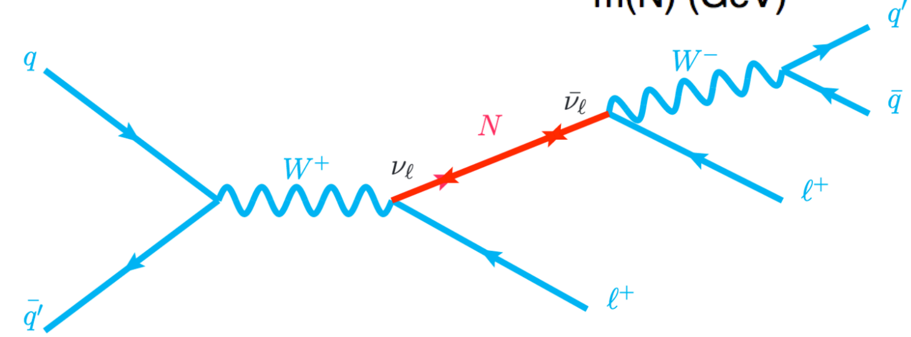
Signal Regions

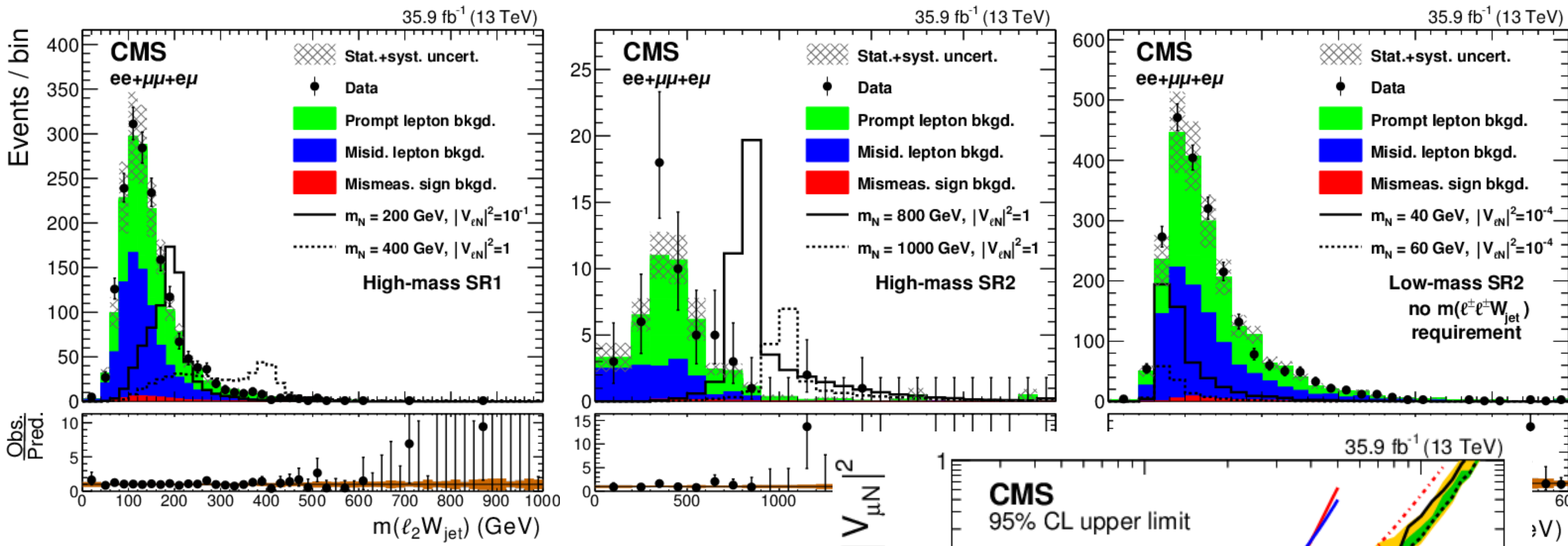
- low N mass SR1 : 2 SS leptons + 2 jets
- low N mass SR2 : 2 SS leptons + 1 jet
  - absence of secondary jet due to pT cut
- high N mass SR1 : 2 SS leptons + 2 jets
- high N mass SR2 : 2 SS leptons + 1 large jet
  - merged partons from boosted W

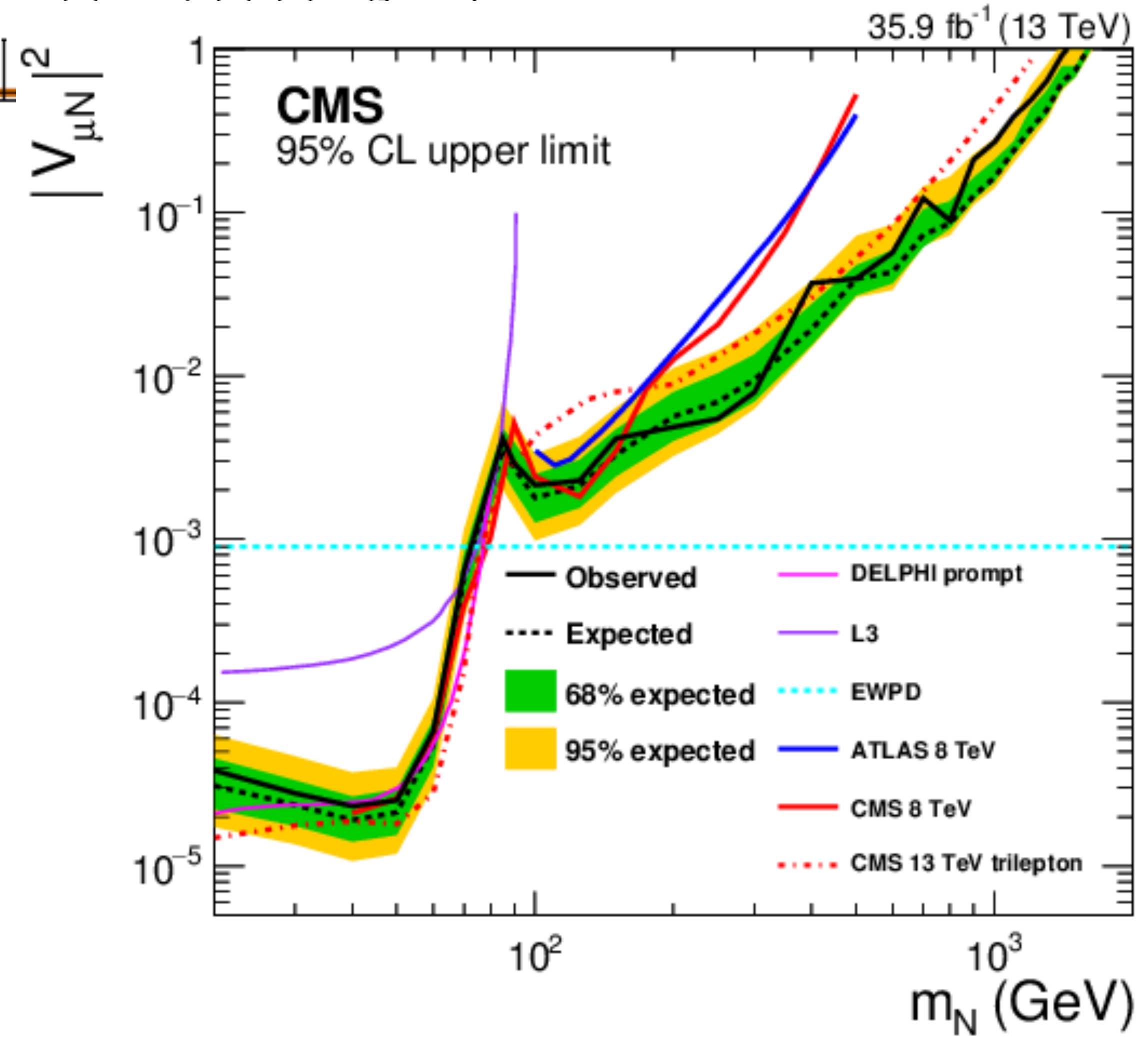


photon-induced processes









- ✓ Used 2016 13 TeV run data
- ✓ No excess above SM prediction
- ✓ Limits set up to m(N)=1200 GeV
- ✓ N production from photon-induced (VBF) channel and signal regions using single jet events updated from 8 TeV analysis

JHEP01(2019)122

Type I Seesaw Model : 3 leptons

13 TeV

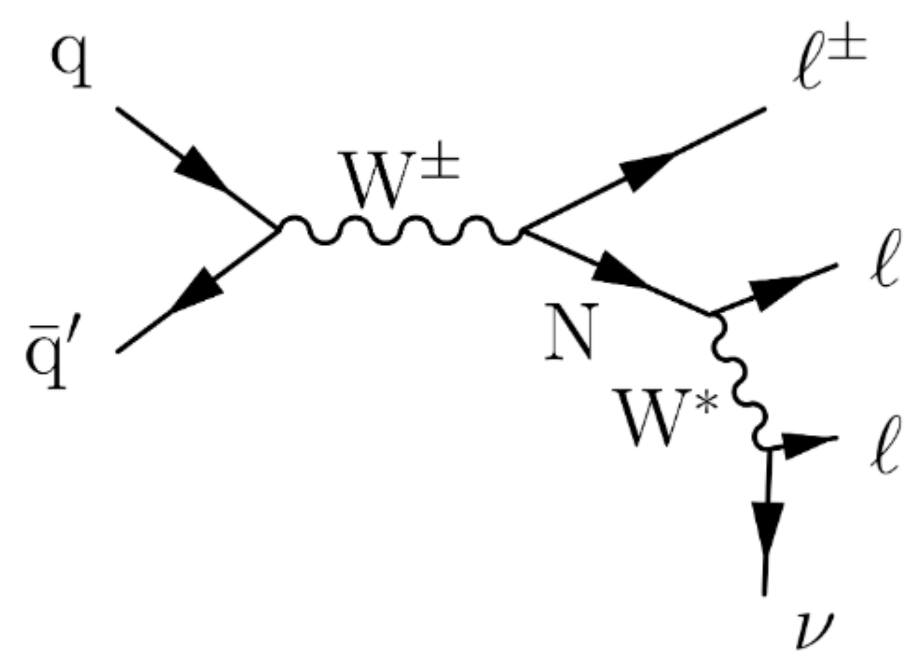
- ✓ 3 leptons channel : W from N decaying leptonically
  - ✓ Smaller branching fraction compared to 2 leptons channel
  - ✓ Advantage for low mass N : lower p_T cuts for leptons than jets
- ✓ Assume that N mixes with only one flavour
  - ✓ Probe $|V_{\mu N}|^2$: use μμμ and μμe events assuming $|V_{eN}|^2 = 0$
  - ✓ Probe $|V_{eN}|^2$: use μee and eee events assuming $|V_{\mu N}|^2 = 0$

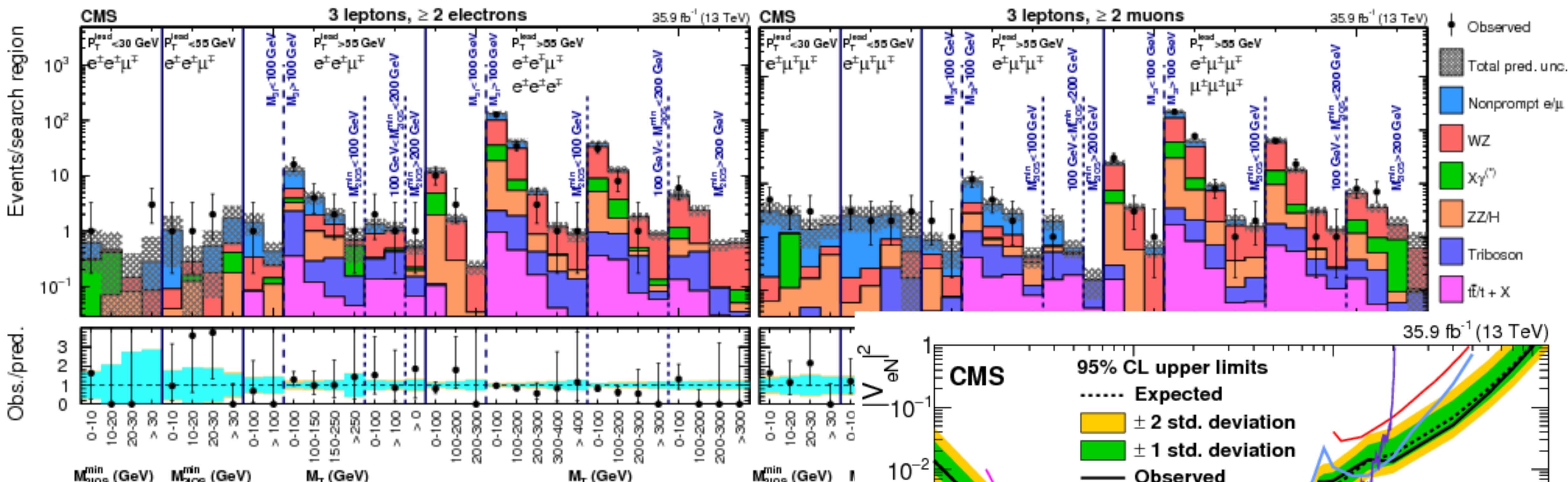
Event Selection

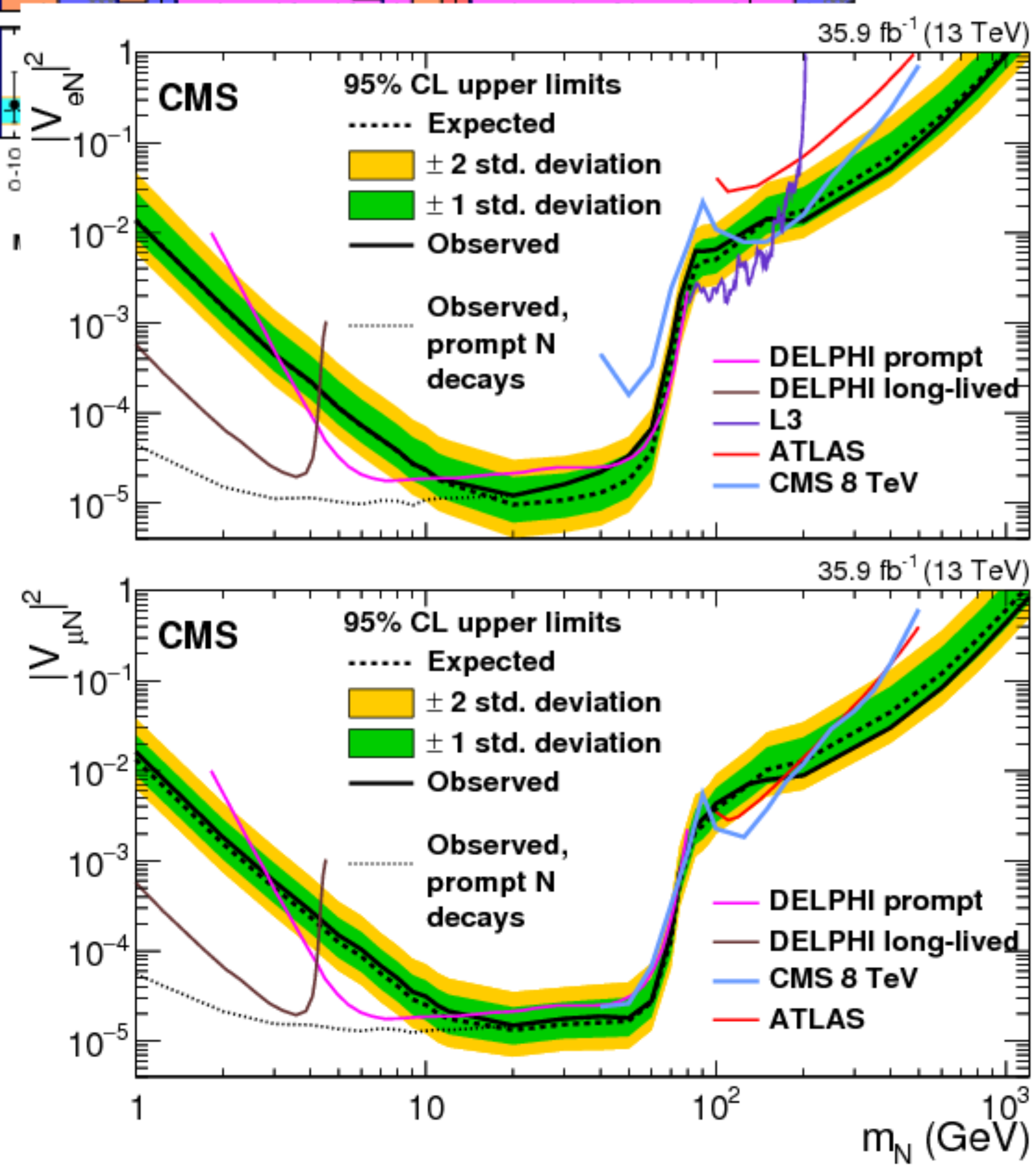
- 3 leptons : μμμ, μμe, μee, eee
  - charge sum=±1
  - $p_T(\ell_1,\ell_2,\ell_3)$>15,10,5 GeV
- |m(OSSF ℓℓ, ℓℓℓ)-91|>15 GeV
- multiple signal regions : 33 categories
  - OSSF, $p_T(\ell_1)$, m(OS ℓℓ), m(ℓℓℓ), m_T(ℓ,MET)

Major Backgrounds

- WZ, Vγ, ZZ, nonprompt backgrounds depending on the signal region







- ✓ Used 2016 13 TeV run data
- ✓ No excess above SM prediction
- ✓ Limits set up to m(N)=1100 GeV
- ✓ First to search for N in 3 leptons channel, and for low masses (m(N)<40 GeV) at LHC

Phys.Rev.Lett.120,221801(2018)

Left-Right Symmetric Model : ττ

13 TeV CMS

✓2 searches for N in LRSM with ττ final states

$\tau_\ell\tau_h$ channel	$\tau_h\tau_h$ channel
High misidentification rate of τ_h from jets	m_T is larger than when there is τ_ℓ ($\tau \rightarrow \ell\nu\nu$)
Clear triggering of events by requiring a lepton	Larger branching fraction of τ decaying hadronically

✓τ decay always involve ν : intrinsic MET inevitable

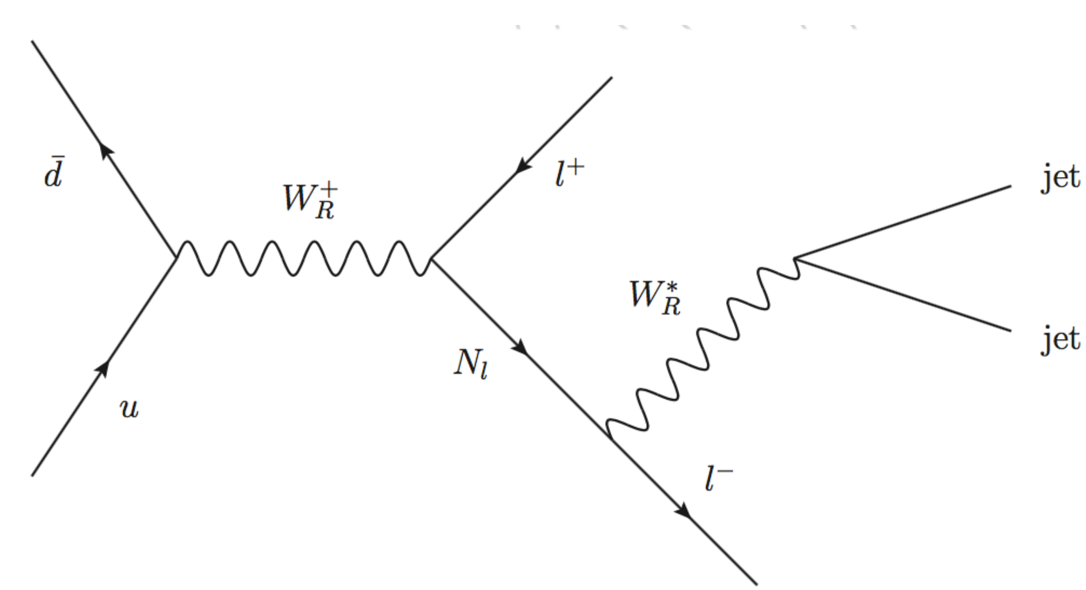
✓Use S_T or m_T as discriminating variables against SM

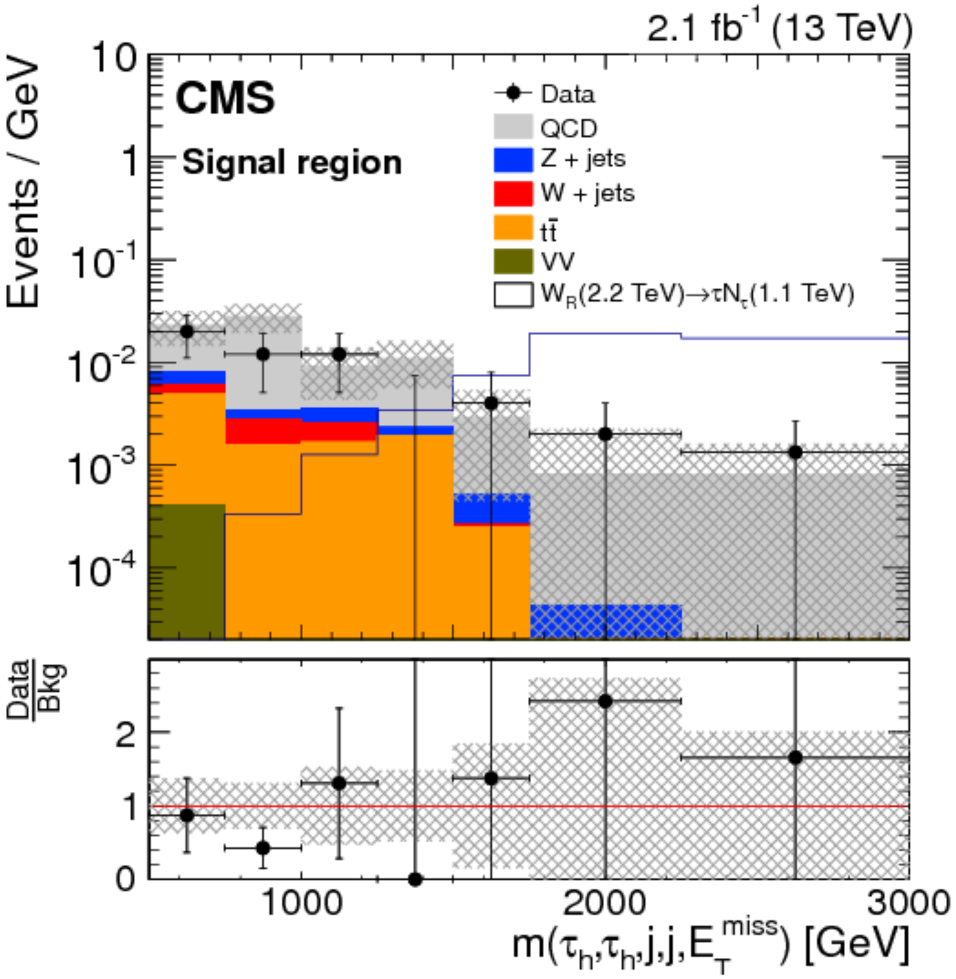
Event Selection

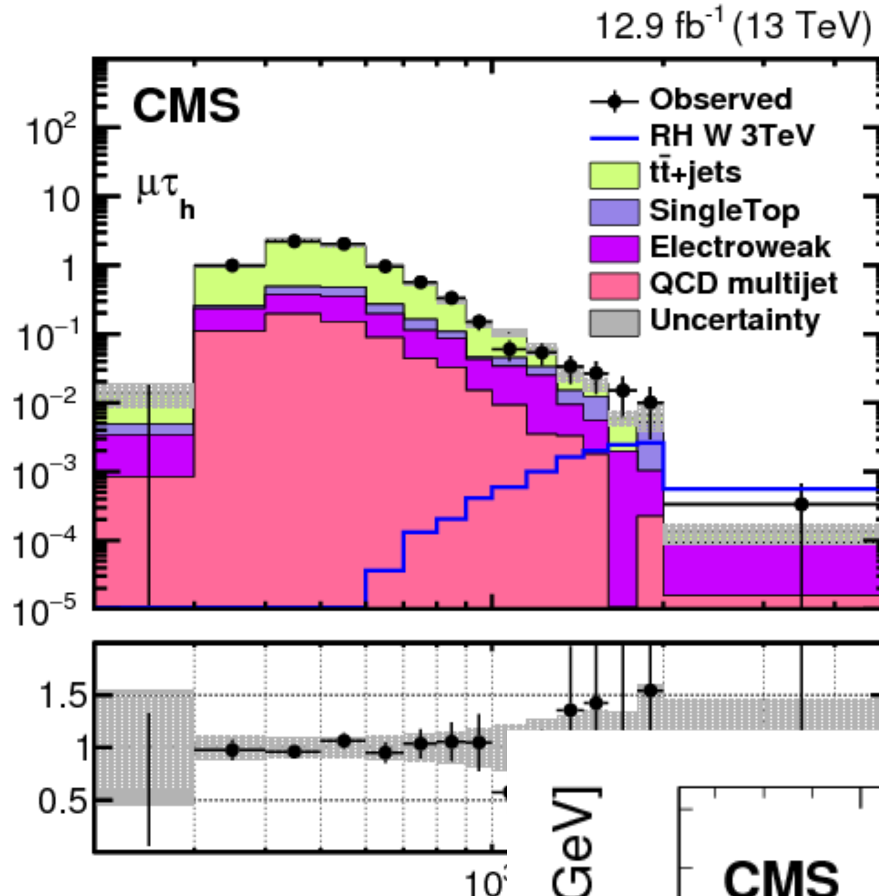
- 2 leptons : eτ, μτ, and ττ (τ : hadronic)
  - OS for eτ, μτ, no requirement for ττ
  - high p_T leptons and τs
- at least 2 jets with $p_T(j)>50$ GeV
- MET>50 GeV, cuts on m(τj) or m(ττ)

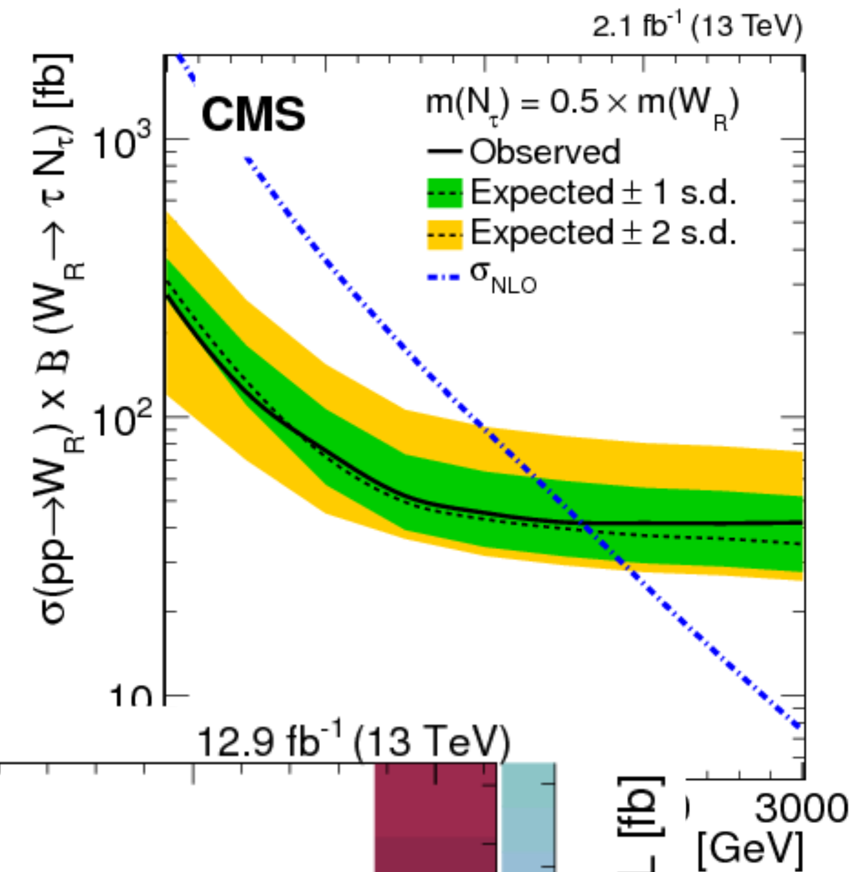
Major Backgrounds

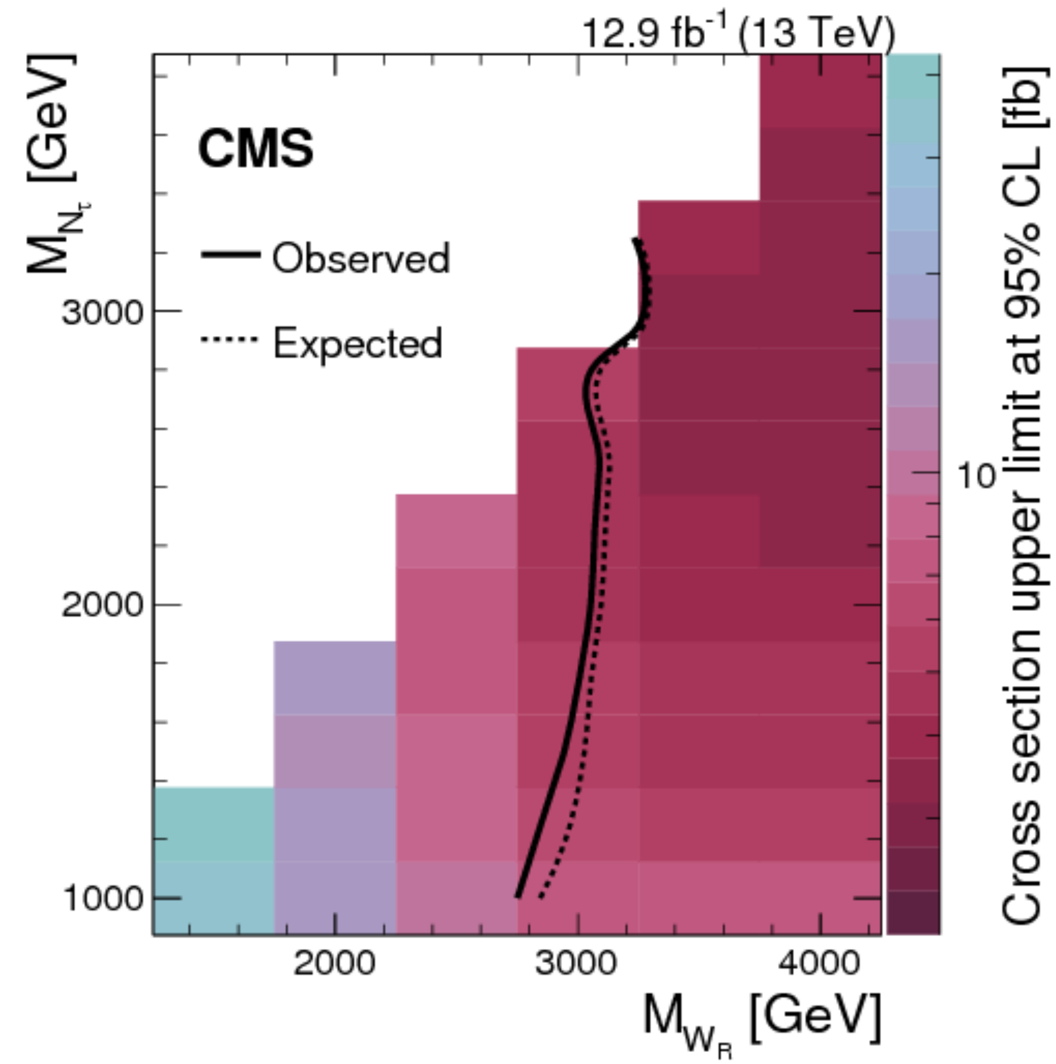
- nonprompt, DYjets for ττ
- $t\bar{t}$, single top for eτ, μτ











- ✓ Used 2015 or 2016 13 TeV run data
- ✓ No excess above SM prediction
- ✓ $m(N)=m(W_R)/2$: excluded up to 1.45 GeV
- ✓ $\tau_h\tau_h$: first search for N with τ τ final state

JHEP07(2017)121
JHEP03(2017)077

Type-III Seesaw Model

13 TeV CMS

✓ Masses of SM neutrino arise from the mediation of new massive fermions, SU(2) triplet of Dirac charged leptons $\Sigma^{\pm}$ and heavy Majorana neutral lepton Σ^0

✓ Σ can decay to W, Z, and H bosons

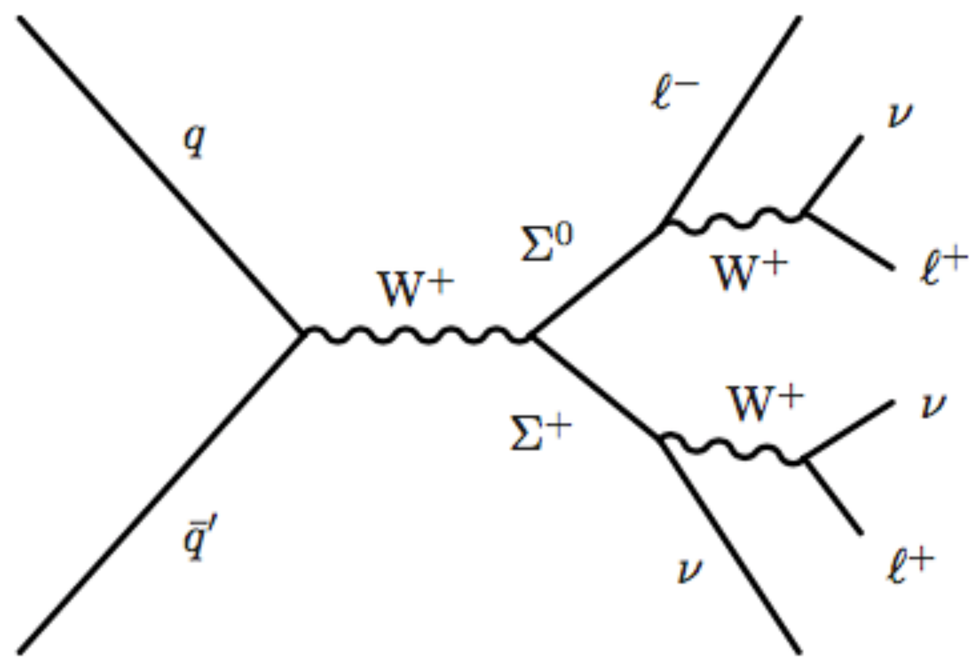
- ✓ 27 different productions and decay processes from $\Sigma^0\Sigma^{\pm}$, $\Sigma^{\pm}\Sigma^{\mp}$
- ✓ e.g. $\Sigma^+\Sigma^0 \to W^+\nu W^+\ell^- \to \ell^+\nu\nu\ell^+\nu\ell^-$: signals with multiple leptons

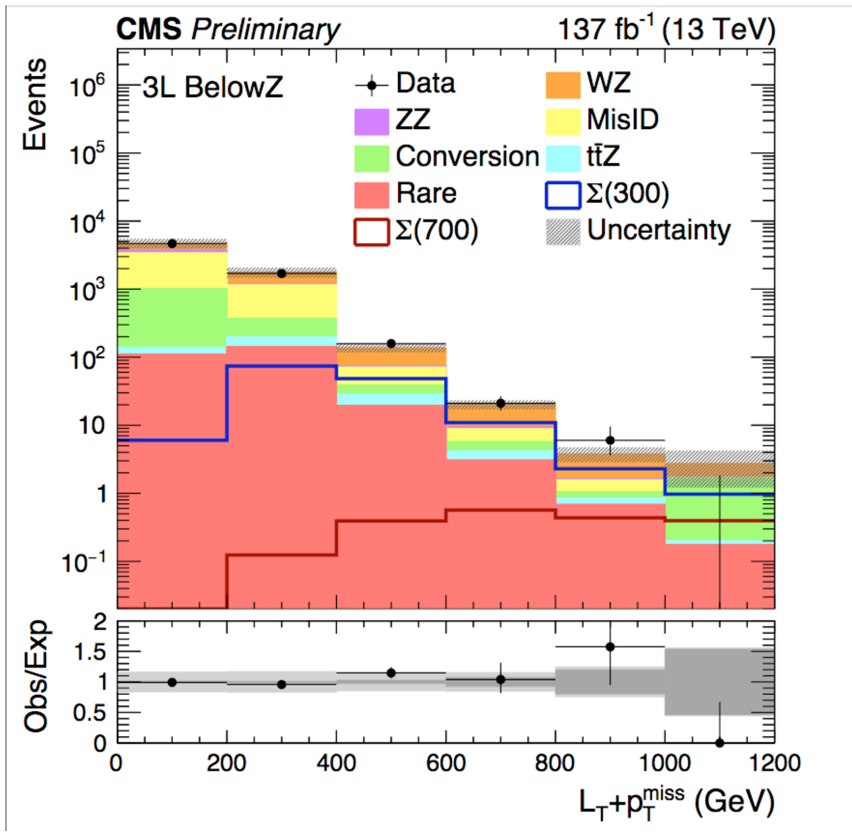
Event Selection

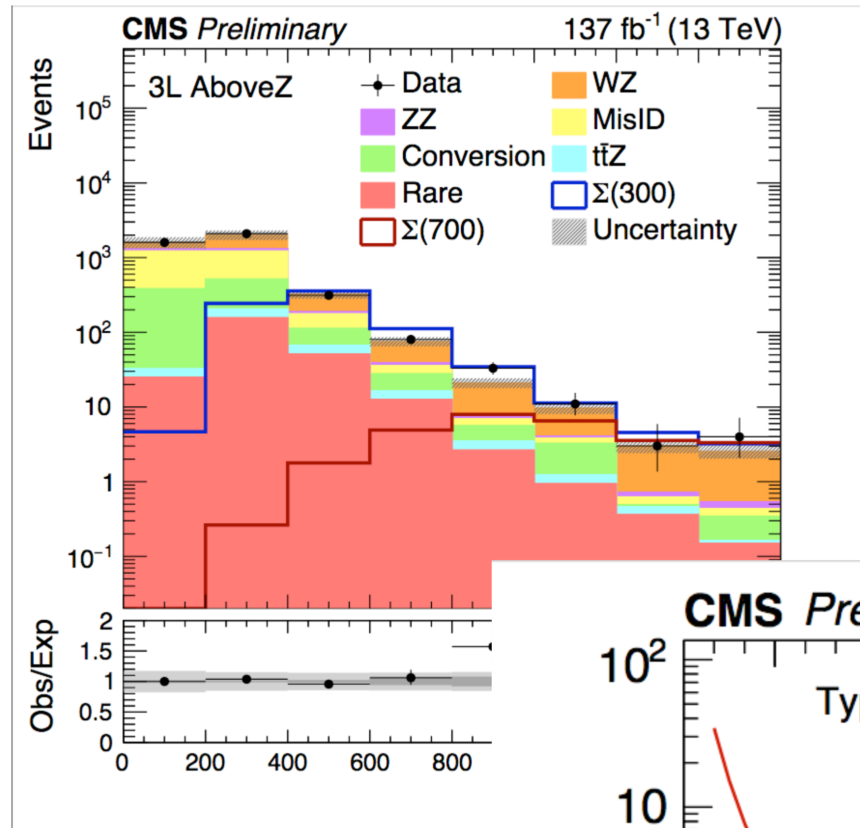
- at least 3 leptons
  - charge sum=±1 or 0
  - $p_T(\ell_1,\ell_2,\ell_3(,\ell_4))$>26,10,10(,10) GeV
- |m(OSSF $\ell\ell$, $\ell\ell\ell$) - 91|>15 GeV
- multiple signal regions : 40 categories
  - N(ℓ), OSSF, m(OSSF $\ell\ell$), MET, S_T or M_T

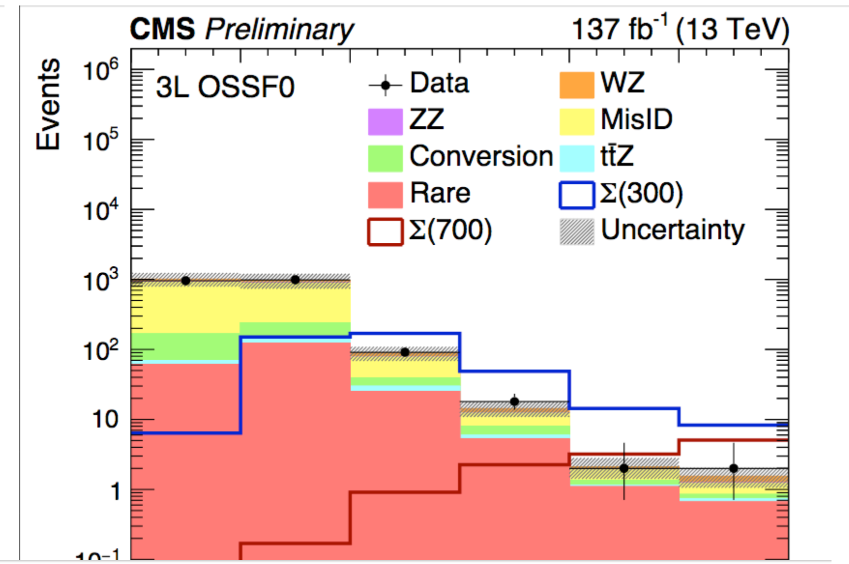
Major Backgrounds

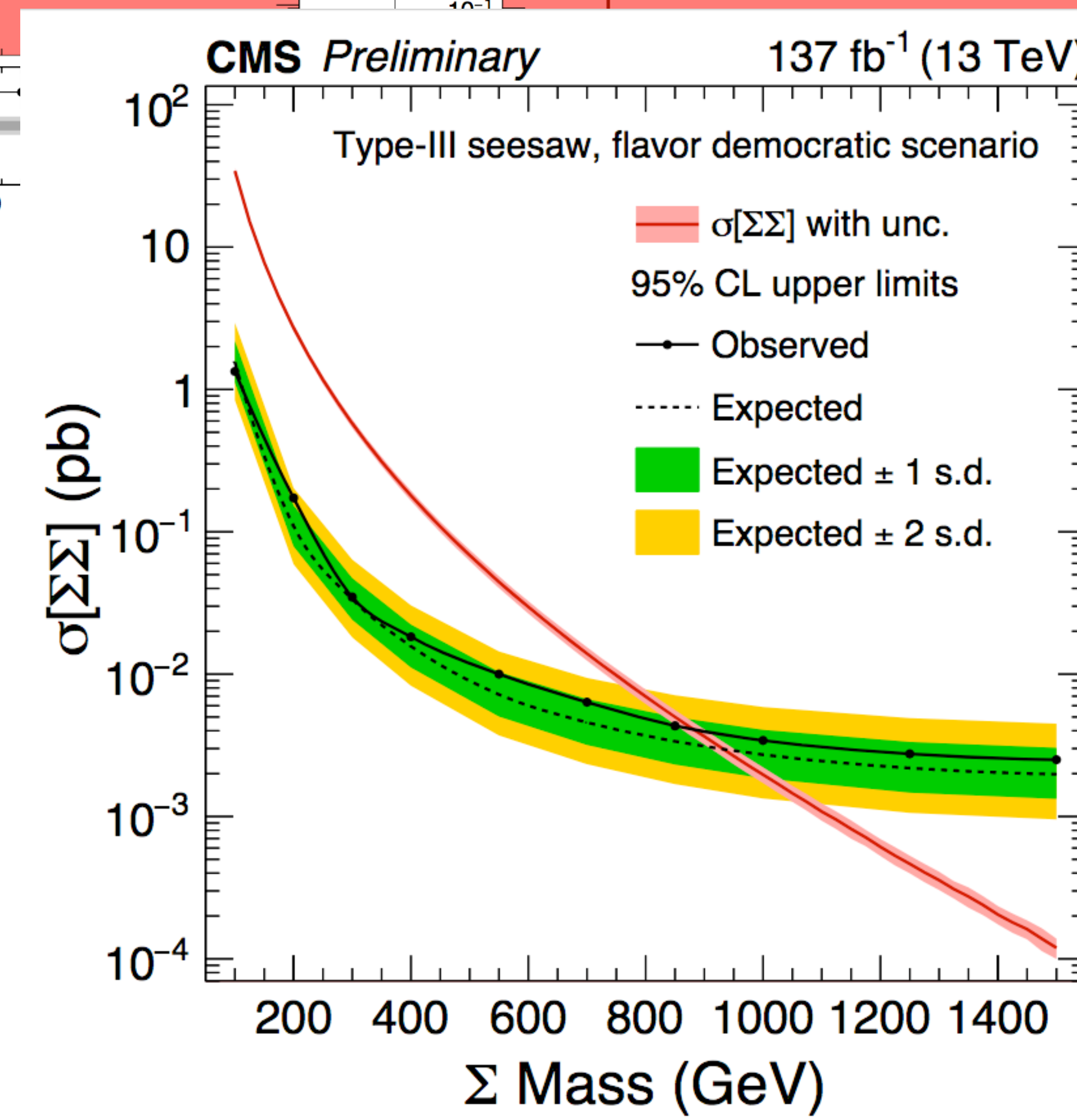
- WZ, Vγ, ZZ, ttV, nonprompt backgrounds depending on the signal region











- ✓ Used full 13 TeV run data
- ✓ No excess above SM prediction
- ✓ Excluded up to m(Σ)=880 GeV
- ✓ Not yet published in journal

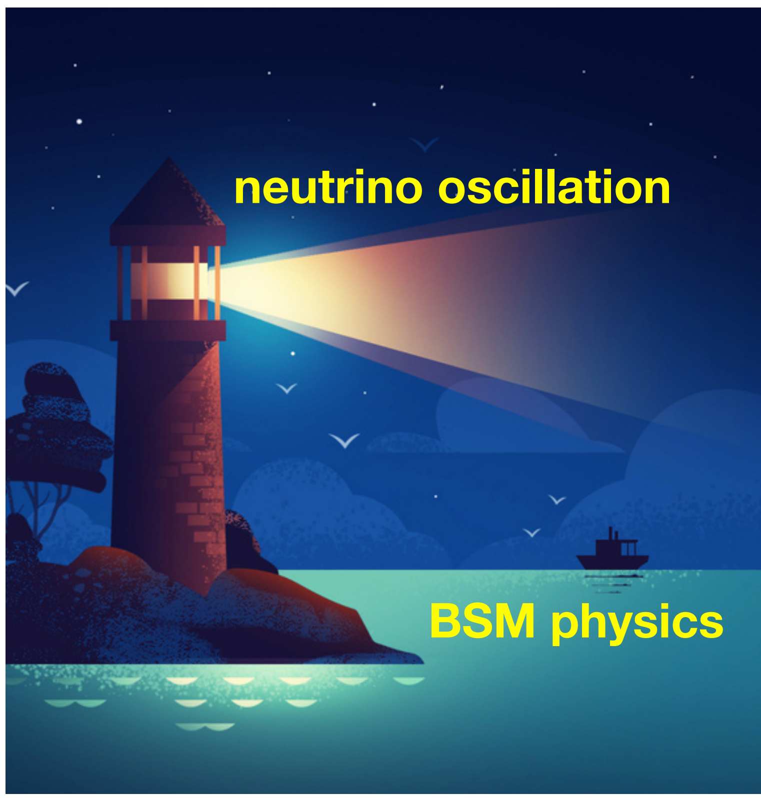
CMS-PAS-EXO-19-002

Summary

✓**Discovery of neutrino oscillation motivated many interesting searches at LHC**

- ✓Are neutrinos Dirac or Majorana particles?
- ✓What is the mechanism that neutrinos obtain mass?

✓**Various models for neutrino searches have been tested at CMS**



Up to date results from CMS

Composite Model : excluded up to m(N)=4.6 TeV for m(N)=Λ

Type-I Seesaw Model

- 2 leptons : limits on $|V_{\ell N}|^2$ set up to m(N)=1200 GeV
- 3 leptons : limits on $|V_{\ell N}|^2$ set down to m(N)=1 GeV

Type-III Seesaw Model : excluded up to 880 GeV for flavour democratic case

Left-Right Symmetric Model

- ττ : excluded up to m(N)=1.45 TeV for m(N)=m(W_R)/2
- ee/μμ : excluded up to m(N)=2.2 TeV for m(N)=m(W_R)/2 (*backup slides*)

✓**More searches to come with new features using full 13 TeV run data from CMS**

- ✓Type-I Seesaw Model : N from pure VBF, long-lived N
- ✓Left-Right Symmetric Model : boosted N from WR, pair production of N from Z'

Backup Slides

Composite Model

A search for physics beyond the standard model in the final state with two same-flavour leptons (electrons or muons) and two quarks produced in proton-proton collisions at $\sqrt{s} = 13$ TeV is presented. The data were recorded by the CMS experiment at the CERN LHC and correspond to an integrated luminosity of 2.3 fb^{-1}. The observed data are in good agreement with the standard model background prediction. The results of the measurement are interpreted in the framework of a recently proposed model in which a heavy Majorana neutrino, N_ℓ, stems from a composite-fermion scenario. Exclusion limits are set for the first time on the mass of the heavy composite Majorana neutrino, m_{N_ℓ}, and the compositeness scale Λ. For the case $m_{N_\ell} = \Lambda$, the existence of N_e (N_μ) is excluded for masses up to 4.60 (4.70) TeV at 95% confidence level.

Composite Model

✓ Predominance of excess from OS on SS

✓ Processes giving OS from pp→e^+L^{--}→ e^+e^-jj

✓ Additional neutrino with similar but slightly different mass makes interference between the 2 states and depresses SS (arXiv:1508.02277, arXiv:1509.05387)

Type-I Seesaw Model : 2 leptons

A search is performed for a heavy Majorana neutrino (N), produced in leptonic decay of a W boson propagator and decaying into a W boson and a lepton, with the CMS detector at the LHC. The signature used in this search consists of two same-sign leptons, in any flavor combination of electrons and muons, and at least one jet. The data were collected during 2016 in proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}. The results are found to be consistent with the expected standard model background. Upper limits are set in the mass range between 20 and 1600 GeV in the context of a Type-I seesaw mechanism, on $|V_{\mathrm{eN}}|^2$, $|V_{\mu\mathrm{N}}|^2$, and $|V_{\mathrm{eN}}V^*_{\mu\mathrm{N}}|^2/(|V_{\mathrm{eN}}|^2 + |V_{\mu\mathrm{N}}|^2)$, where $V_{\ell\mathrm{N}}$ is the matrix element describing the mixing of N with the standard model neutrino of flavor $\ell = \mathrm{e}, \mu$. For N masses between 20 and 1600 GeV, the upper limits on $|V_{\ell\mathrm{N}}|^2$ range between 2.3×10^{-5} and unity. These are the most restrictive direct limits for heavy Majorana neutrino masses above 430 GeV.

Type-I Seesaw Model : 3 leptons

A search for a heavy neutral lepton N of Majorana nature decaying into a W boson and a charged lepton is performed using the CMS detector at the LHC. The targeted signature consists of three prompt charged leptons in any flavor combination of electrons and muons. The data were collected in proton-proton collisions at a center-of-mass energy of 13 TeV, with an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$. The search is performed in the N mass range between 1 GeV and 1.2 TeV. The data are found to be consistent with the expected standard model background. Upper limits are set on the values of $|V_{\mathrm{eN}}|^2$ and $|V_{\mu\mathrm{N}}|^2$, where $V_{\ell\mathrm{N}}$ is the matrix element describing the mixing of N with the standard model neutrino of flavor ℓ. These are the first direct limits for N masses above 500 GeV and the first limits obtained at a hadron collider for N masses below 40 GeV.

Left-Right Symmetric Model : ττ

A search is performed for third-generation scalar leptoquarks and heavy right-handed neutrinos in events containing one electron or muon, one hadronically decaying τ lepton, and at least two jets, using a $\sqrt{s} = 13$ TeV pp collision data sample corresponding to an integrated luminosity of 12.9 fb^{-1} collected with the CMS detector at the LHC in 2016. The number of observed events is found to be in agreement with the standard model prediction. A limit is set at 95% confidence level on the product of the leptoquark pair production cross section and β^2, where β is the branching fraction of leptoquark decay to a τ lepton and a bottom quark. Assuming $\beta = 1$, third-generation leptoquarks with masses below 850 GeV are excluded at 95% confidence level. An additional search based on the same event topology involves heavy right-handed neutrinos, N_R, and right-handed W bosons, W_R, arising in a left-right symmetric extension of the standard model. In this search, W_R bosons are assumed to decay to a tau lepton and N_R followed by the decay of the N_R to a tau lepton and an off-shell W_R boson. Assuming the mass of the right-handed neutrino to be half of the mass of the right-handed W boson, W_R boson masses below 2.9 TeV are excluded at 95% confidence level. These results improve on the limits from previous searches for third-generation leptoquarks and heavy right-handed neutrinos with τ leptons in the final state.

Left-Right Symmetric Model : ττ

A search for new particles has been conducted using events with two high transverse momentum (p_T) τ leptons that decay hadronically, at least two high-p_T jets, and missing transverse energy from the τ lepton decays. The analysis is performed using data from proton-proton collisions, collected by the CMS experiment in 2015 at $\sqrt{s} = 13\,\mathrm{TeV}$, corresponding to an integrated luminosity of $2.1\,\mathrm{fb}^{-1}$. The results are interpreted in two physics models. The first model involves heavy right-handed neutrinos, N_ℓ ($\ell = e, \mu, \tau$), and right-handed charged bosons, W_R, arising in a left-right symmetric extension of the standard model. Masses of the W_R boson below 2.35 (1.63) TeV are excluded at 95% confidence level, assuming the N_τ mass is 0.8 (0.2) times the mass of the W_R boson and that only the N_τ flavor contributes to the W_R decay width. In the second model, pair production of third-generation scalar leptoquarks that decay into $\tau\tau$bb is considered. Third-generation scalar leptoquarks with masses below 740 GeV are excluded, assuming a 100% branching fraction for the leptoquark decay to a τ lepton and a bottom quark. This is the first search at hadron colliders for the third-generation Majorana neutrino, as well as the first search for third-generation leptoquarks in the final state with a pair of hadronically decaying τ leptons and jets.

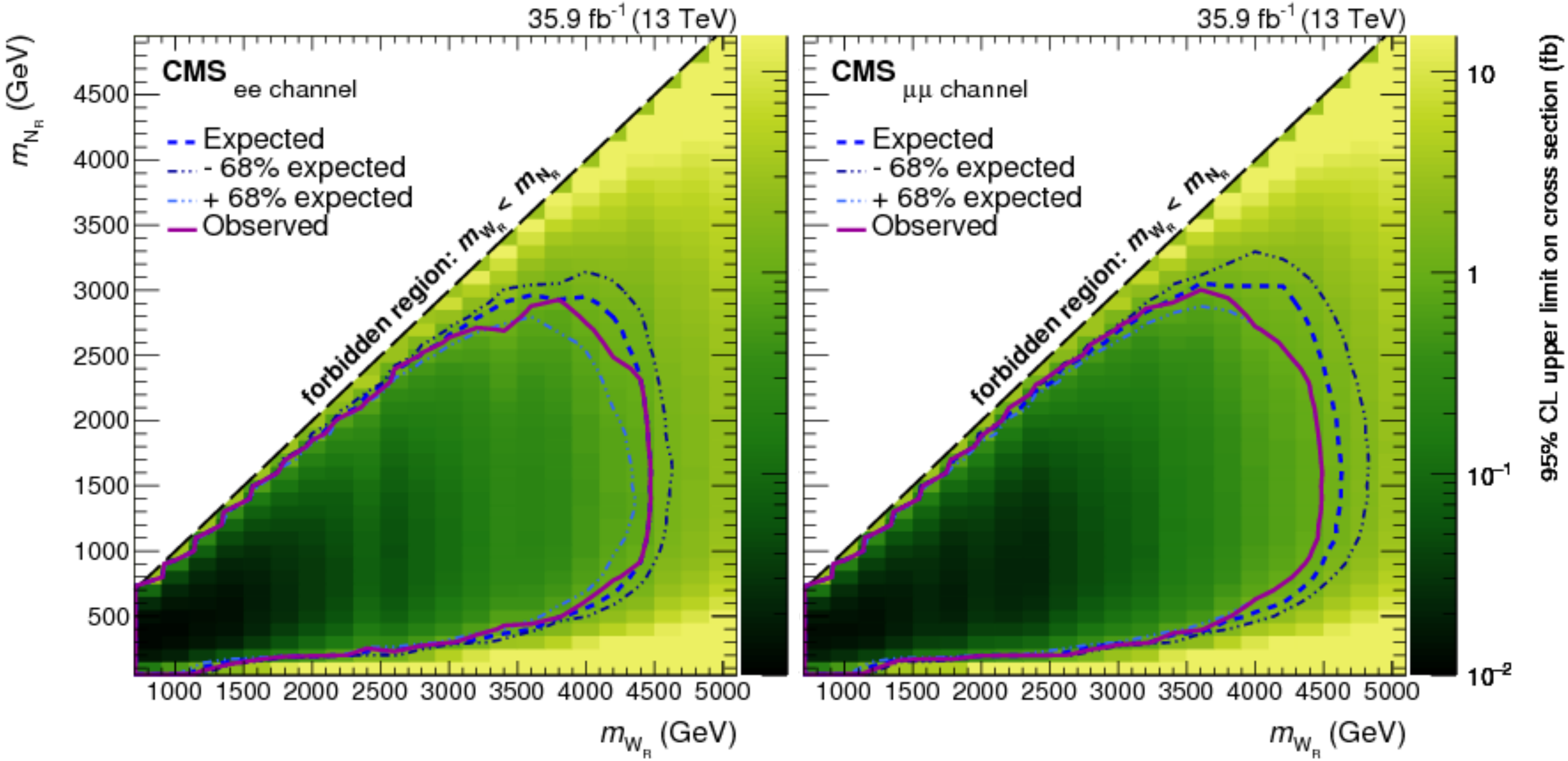
Left-Right Symmetric Model : ee/μμ

A search for a heavy right-handed W boson (W_R) decaying to a heavy right-handed neutrino and a charged lepton in events with two same-flavor leptons (e or μ) and two jets, is presented. The analysis is based on proton-proton collision data, collected by the CMS Collaboration at the LHC in 2016 and corresponding to an integrated luminosity of 35.9 fb^{-1}. No significant excess above the standard model expectation is seen in the invariant mass distribution of the dilepton plus dijet system. Assuming that couplings are identical to those of the standard model, and that only one heavy neutrino flavor N_R contributes significantly to the W_R decay width, the region in the two-dimensional (m_{W_R}, m_{N_R}) mass plane excluded at 95% confidence level extends to approximately $m_{W_R} = 4.4$ TeV and covers a large range of right-handed neutrino masses below the W_R boson mass. This analysis provides the most stringent limits on the W_R mass to date.

Left-Right Symmetric Model : ee/μμ

13 TeV

✓ Same approach as 8 TeV analysis



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Type III Seesaw Model

A search for new physics in events with three or more electrons or muons is presented. The data sample corresponds to 137 fb^{-1} of integrated luminosity in pp collisions at $\sqrt{s} = 13$ TeV collected by the CMS experiment at the CERN LHC in 2016, 2017, and 2018. The targeted signal models are pair production of type-III seesaw heavy fermions and associated production of a light scalar or pseudoscalar boson with a pair of top quarks, in final states with at least three leptons. The heavy fermions may produce non-resonant excesses in the tails of the transverse mass as well as the sum of leptonic transverse momenta and missing transverse energy, whereas light scalars or pseudoscalars may create resonant dilepton mass spectra in multilepton events with or without b quark jets. The observations are found to be consistent with expectations from standard model processes. The results exclude heavy fermions of the type-III seesaw model with masses below 880 GeV for the lepton flavor democratic scenario. Assuming a Yukawa coupling of unity strength to top quarks, the branching ratio of new scalar (pseudoscalar) bosons to dielectrons and dimuons above 0.003 (0.03) and 0.04 (0.03) are excluded for masses in the range of $15 - 75$ GeV and $108 - 340$ GeV, respectively.

Photos/Illustrations

https://www.stockillustrations.com/image/2054-young-woman-and-man-on-seesaw
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