Heavy Neutrino searches at ATLAS & CMS

Debarati Roy
on behalf of the ATLAS & CMS Collaboration

Standard Model (SM) : Cannot be whole story

- SM :

=> Extremely successful theory.
=> Guided for a series of new particle discoveries.
=> Discovery of Higgs boson by ATLAS & CMS in 2012 again glorifies its success!

- However there exist a couple of experimental observations that SM cannot explain.

=> New Physics can be hiding there!
e.g. Experimental signature of neutrino oscillation concludes neutrino has a very small mass.
=> Several searches performed with LHC data to explain the origin of a very small neutrino mass!

Several theories exist in Beyond Standard Model (BSM) to explain neutrino mass!

- LRSM (Left Right Symmetric Model) :

=> Restores parity by introducing right-handed W, Z bosons (WR, ZR) and right-handed neutrinos (NR – Ne, Nμ, Nτ).

=> Includes the Seesaw mechanism (with heavy right-handed Majorana neutrino (NR) so explains small (SM neutrino) νL masses.

=> Seesaw mechanism couples νL masses to NR through a mass mixing matrix. It allows heavy neutrinos to be GeV-TeV scale and therefore discoverable at LHC .

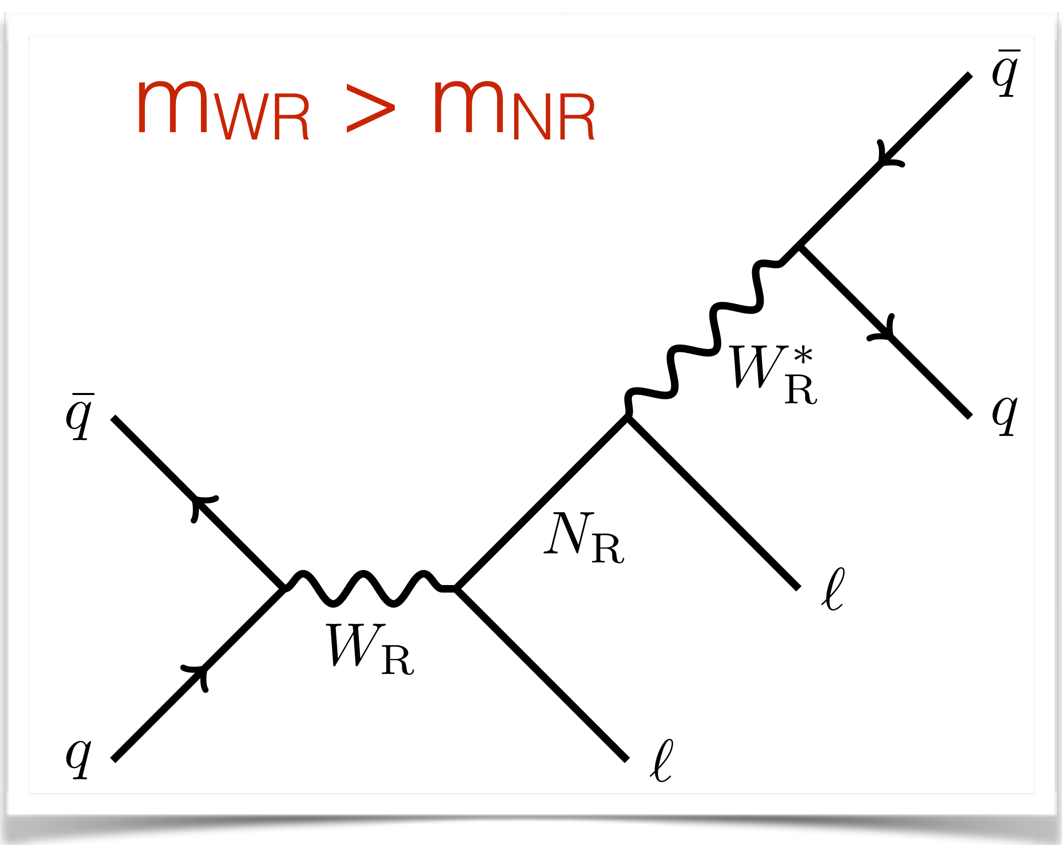
- νMSM (neutrino Minimal Standard Model) :

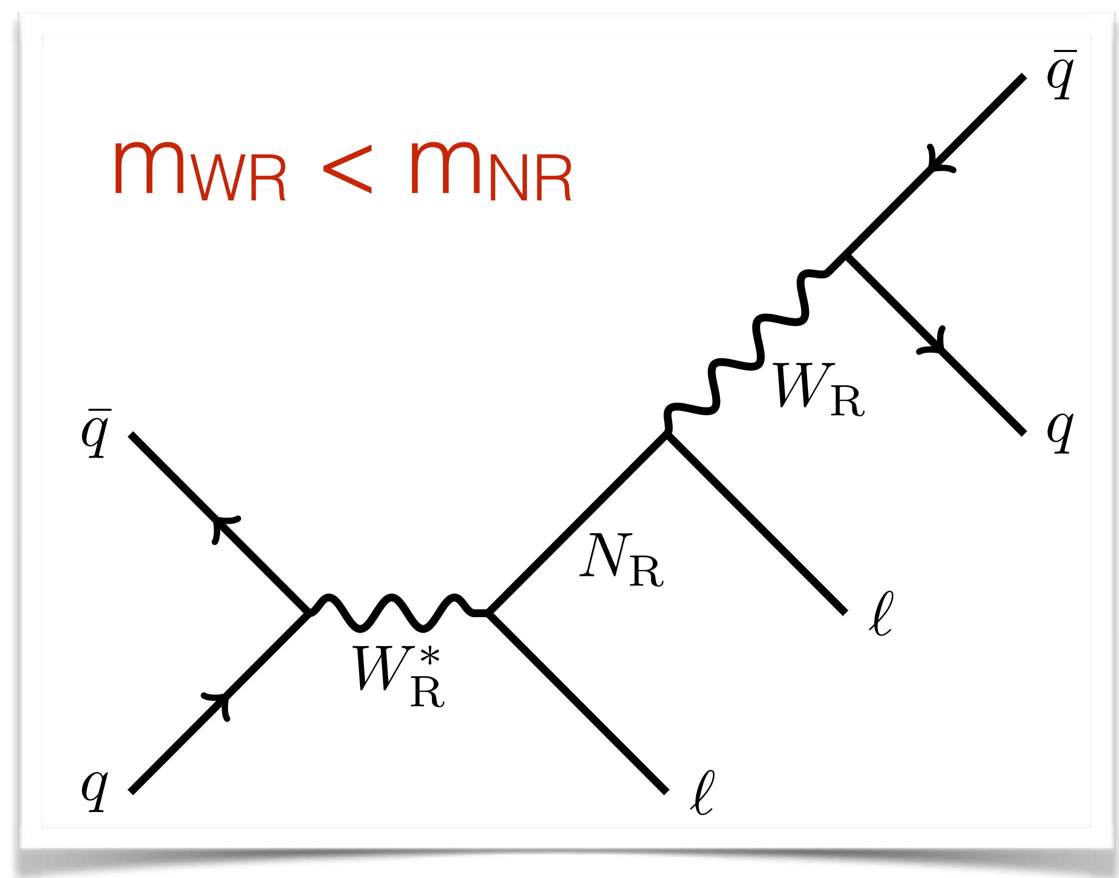
=> Incorporates Seesaw mechanism.
=> Small neutrino masses result from large mass of NR similar to LRSM.
=> Incorporates heavy-neutrino states without additional vector bosons.

ATLAS & CMS latest 13 TeV results shown in this presentation.

Latest heavy neutrino search in ATLAS with 36.1 fb^{-1} of data :

- Based on LRSM theory.
- Type-I seesaw mechanism => Majorana neutrino
- Inverse seesaw mechanism => Dirac neutrino
- Keung–Senjanović (KS) process considered ($m_{NR} <= 2m_{WR}$)





arXiv:1809.11105, submitted to JHEP

Analysis Strategy, Object & Event Selection :

- Always SF (same flavour) leptons (either electron (e) or muon(μ)) selected in final state.

- Exactly 2 leptons (E_T / p_T > 25 / 30 GeV) & 2 jets (p_T > 100 GeV) selected.

- SS (same-sign), OS (opposite-sign) lepton channels cover for both Majorana and Dirac hypotheses with the best sensitivity.

- 50%-50% probability assumed between SS & OS for Majorana case. 100% probability for OS corresponds to Dirac case.

- Dominating backgrounds : OS (ttbar, Z+jet(s)). SS(misidentification, diboson).

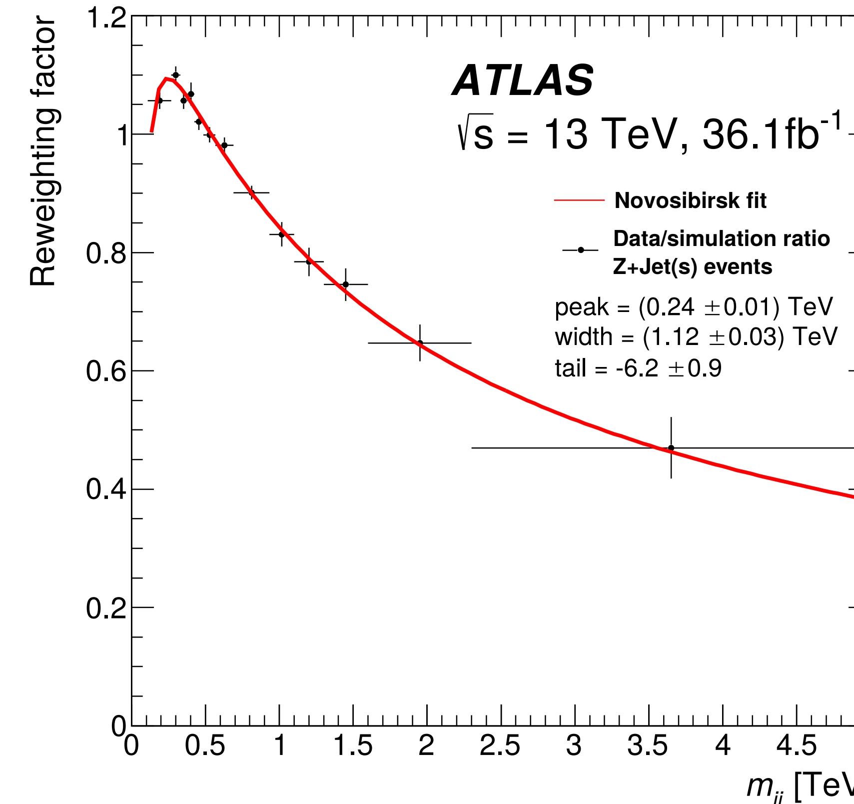
- Signal region (SR) defined mainly to reduce Z+jet(s).

arXiv:1809.11105, submitted to JHEP

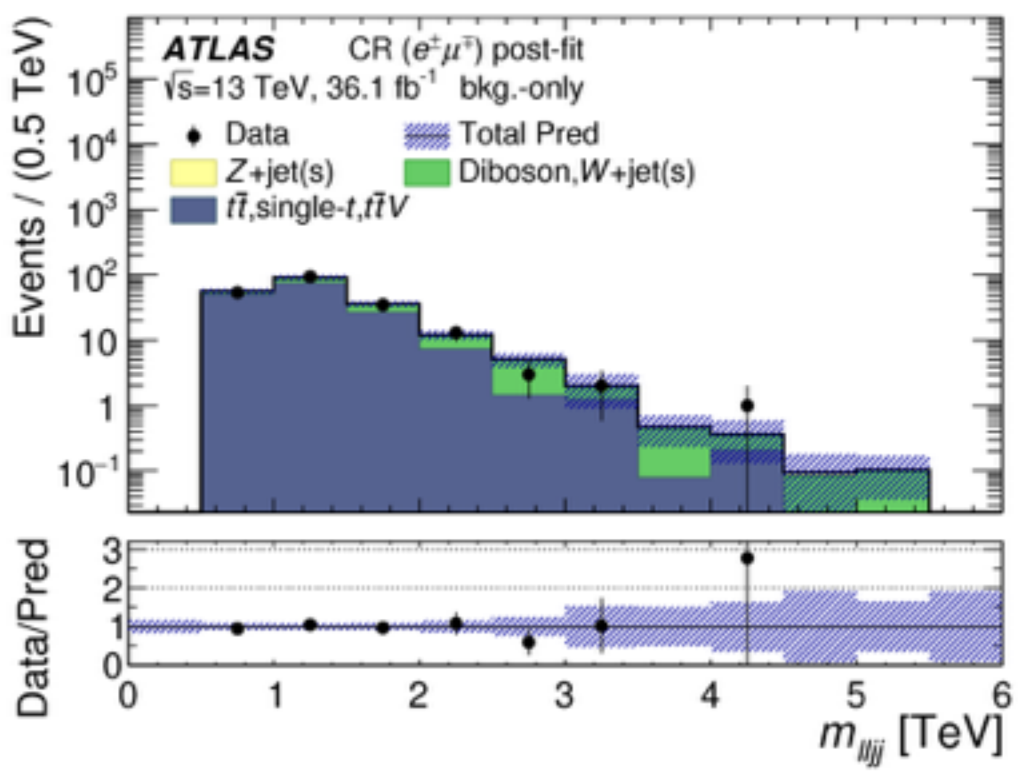
Data-Prediction(Pred) Comparison in Analysis regions :

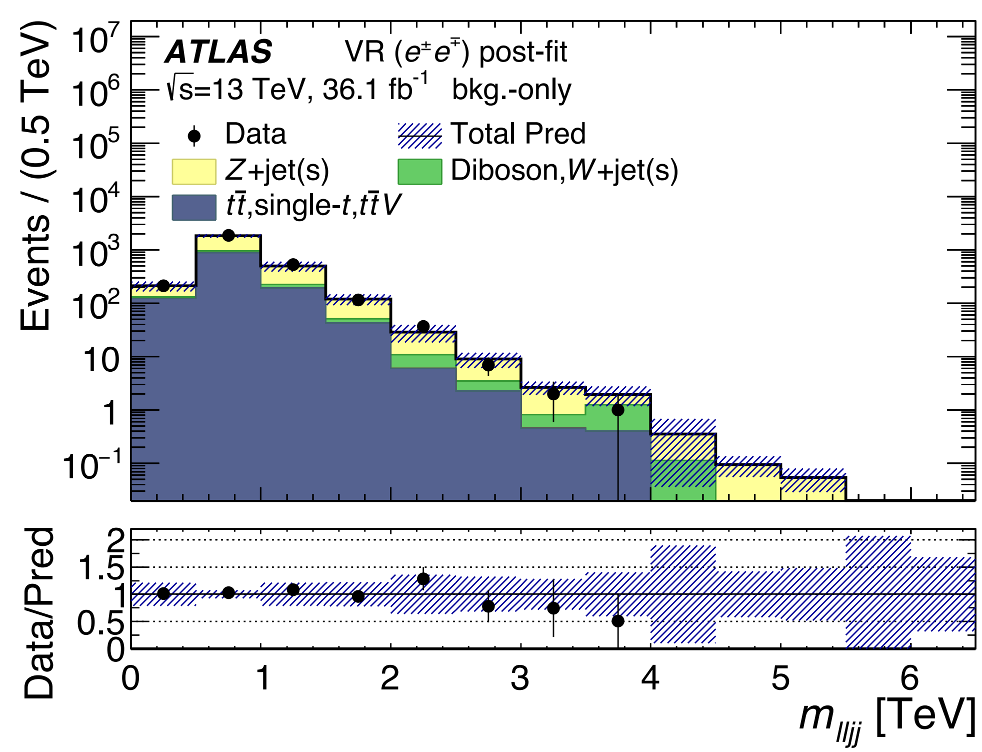
- Several analysis regions studied

Region	Control region			Validation region		Signal region	
Channel	CR($\ell^\pm\ell^\mp$)	CR($\ell^\pm\ell'^\mp$)	CR($\ell^\pm\ell^\pm$)	VR($\ell^\pm\ell^\mp$)	VR($\ell^\pm\ell^\pm$)	SR($\ell^\pm\ell^\mp$)	SR($\ell^\pm\ell^\pm$)
m_{ee} [GeV]	[60, 110]	—	[110, 300]	[110, 400]	[300, 400]	> 400	> 400
$m_{\mu\mu}$ [GeV]	[60, 110]	—	[60, 300]	[110, 400]	[300, 400]	> 400	> 400
$m_{e\mu}$ [GeV]	—	> 400	—	—	—	—	—
H_T [GeV]	> 400	> 400	—	> 400	—	> 400	> 400
m_{jj} [GeV]	> 110	> 110	—	> 110	—	> 110	> 110
Jet p_T [GeV]	> 100	> 100	> 50	> 100	> 50	> 100	> 100



- Data-Pred agreed within uncertainty in CR & VR.
- Z+jet(s) mismodelling in OS addressed with data-driven reweighting factors as a function of m_{jj}.

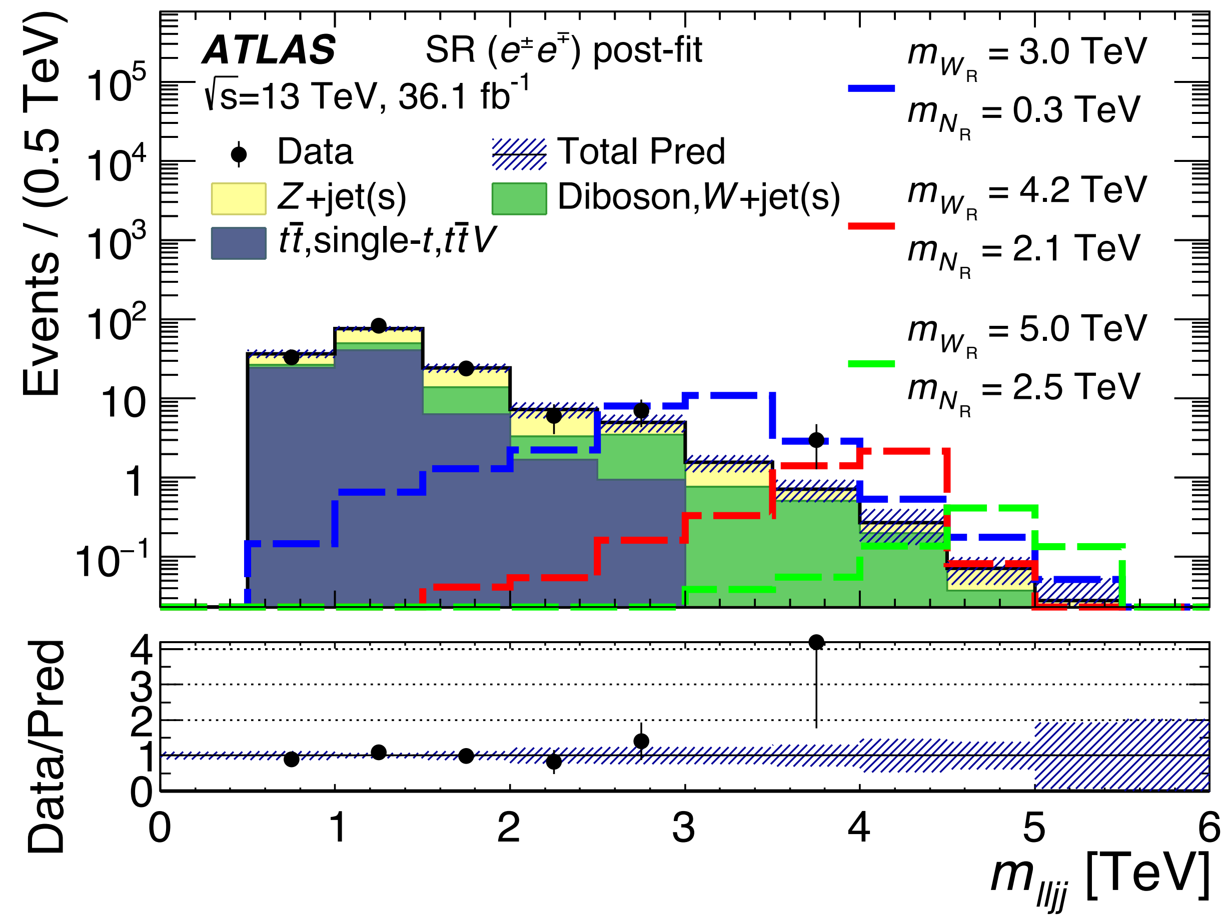


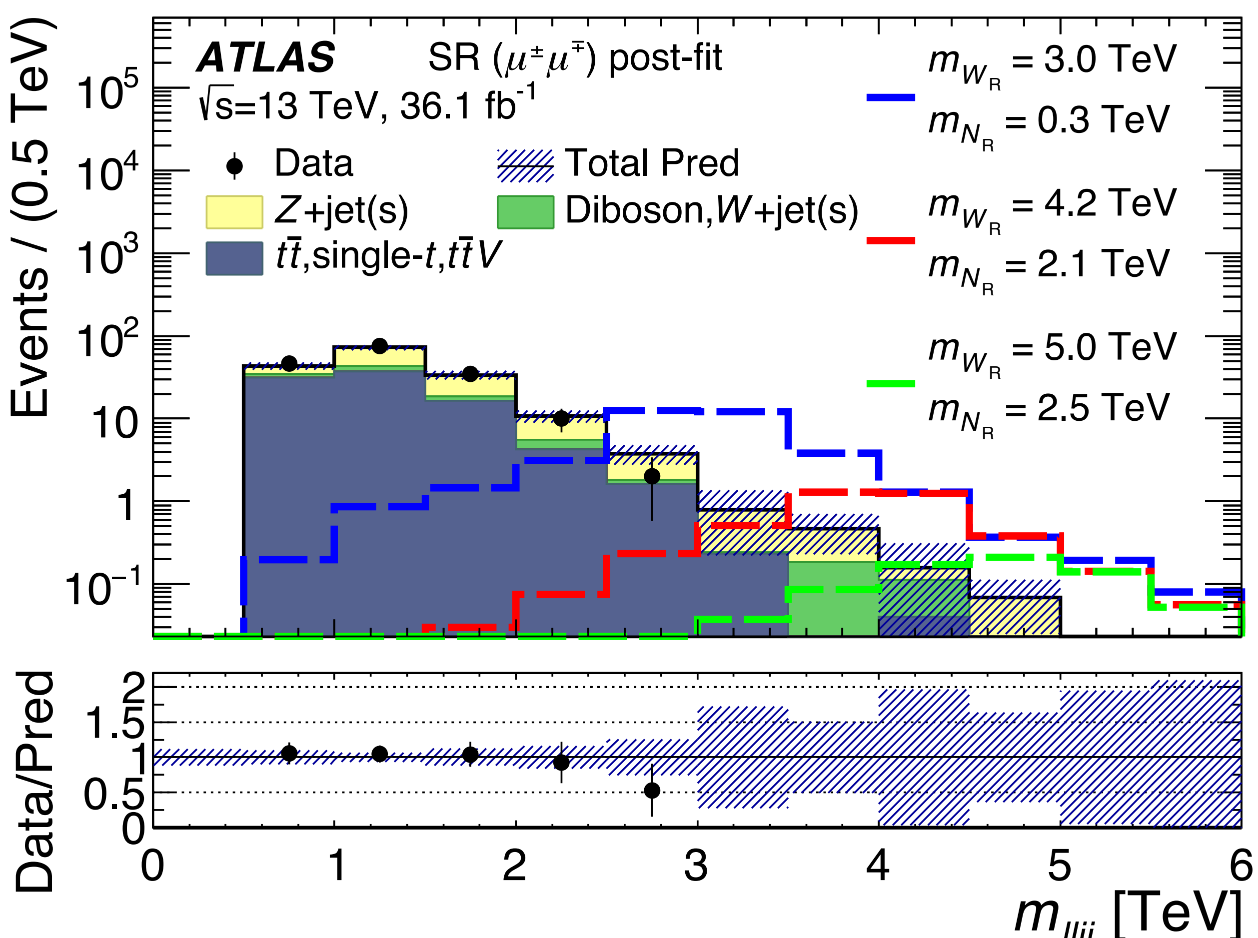


 arXiv:1809.11105, submitted to JHEP

Data-Prediction(Pred) Comparison in SR :

- In SR reasonable agreement found between Data & Pred in both e & μ channels (& in both SS and OS channels).

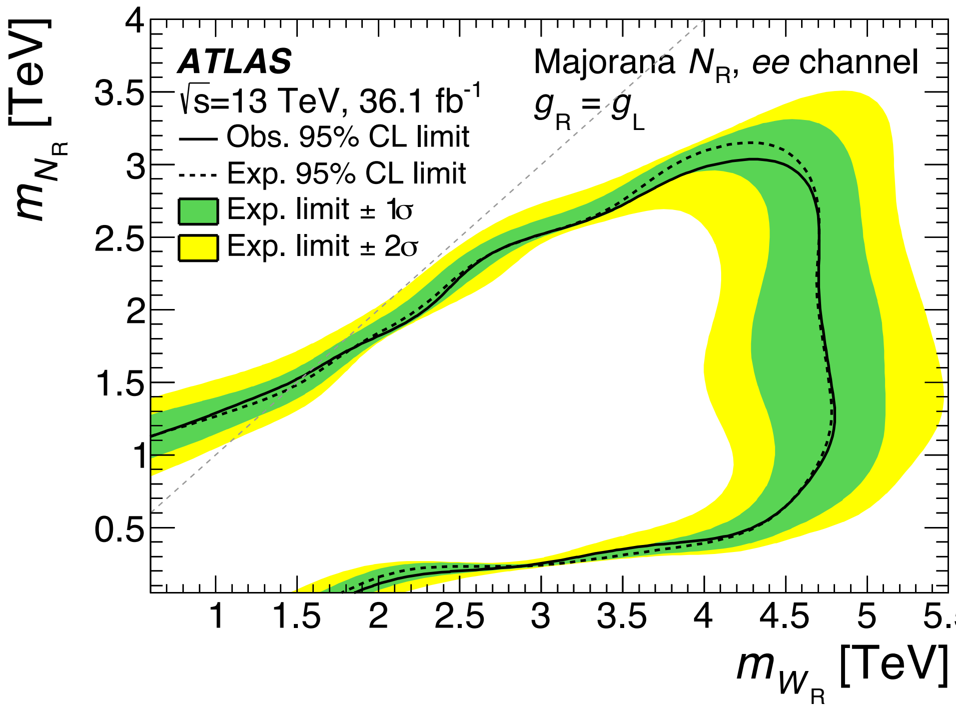


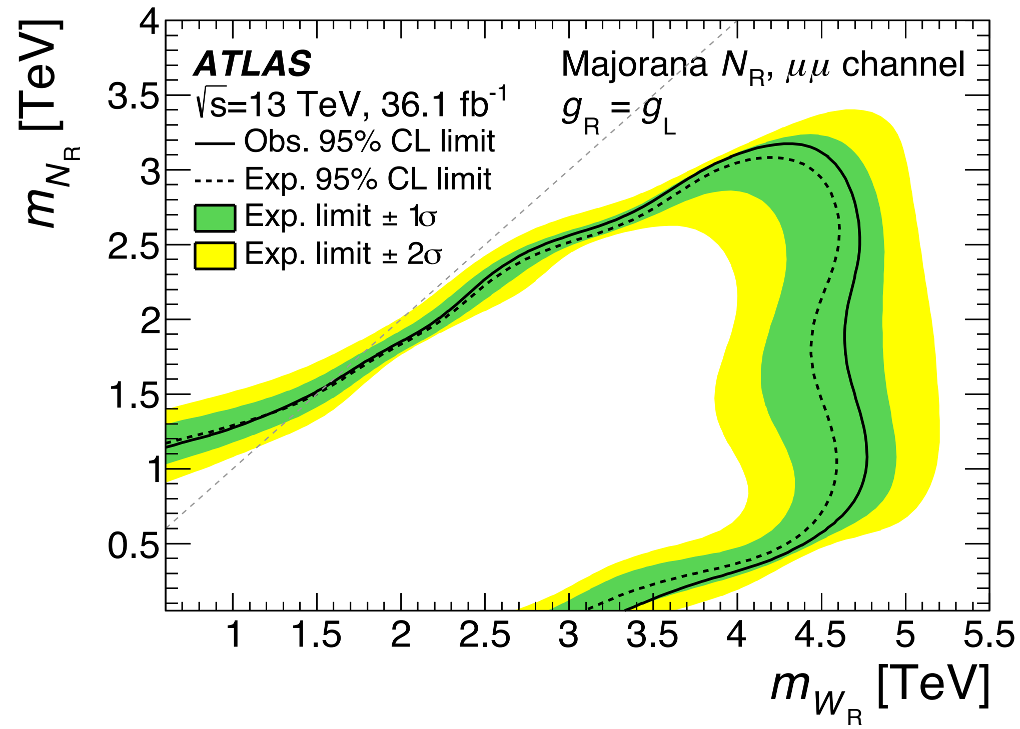


- Almost no data in region with m_{WR} > 3TeV.
- No significant deviation found.

arXiv:1809.11105, submitted to JHEP

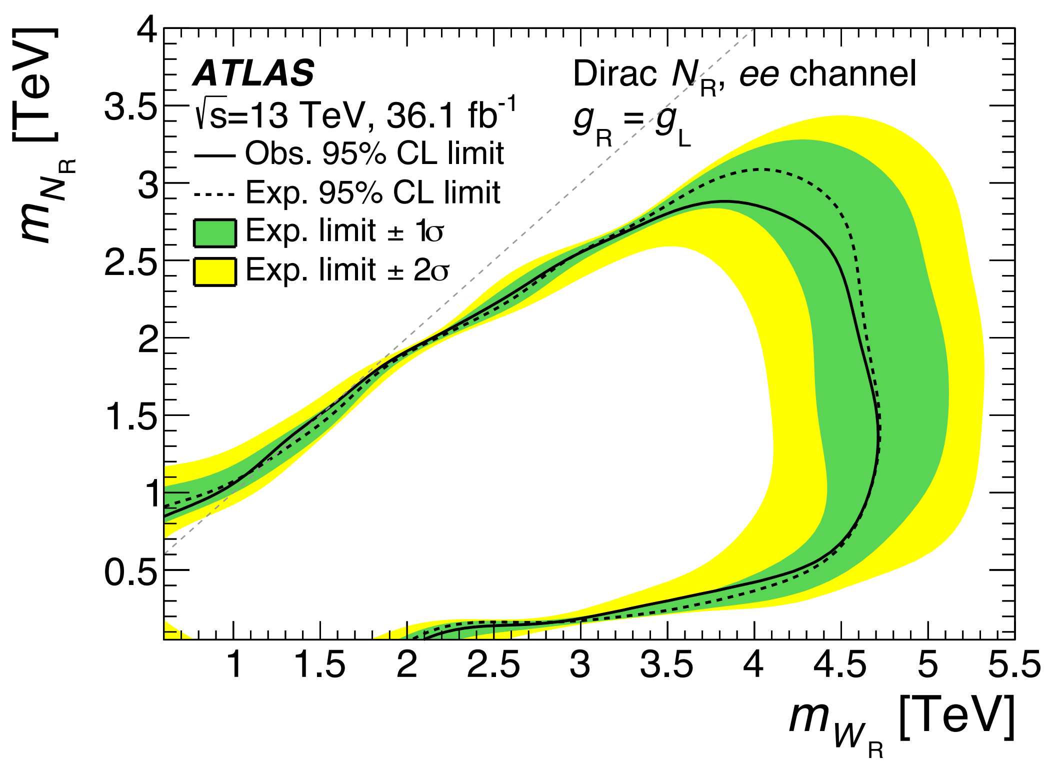
Final Result (Setting up limit) :

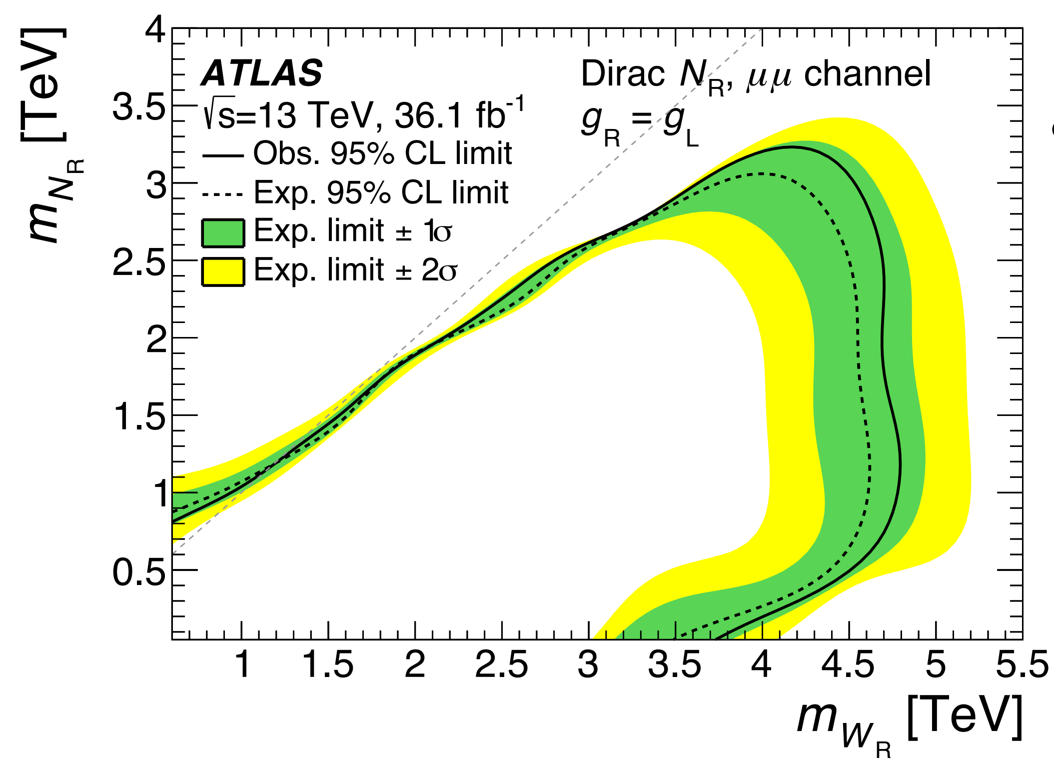




- e, μ channels separately tested for Majorana hypothesis.

m_{WR} up to 4.7 TeV are excluded at 95% CL, for m_{NR} in 0.5–3.0 TeV region for the g_R=g_L assumption.





- e, μ channels separately tested for Dirac hypothesis.

 arXiv:1809.11105, submitted to JHEP

Latest heavy neutrino search in CMS with 35.9 fb^{-1} of data with same final state :

- Based on LRSM theory : $W_R \to \ell N_R \to \ell\ell W_R^* \to \ell\ell q\bar{q}'$, $\ell = e$ or μ.
- No charge requirement on leptons.
- Dominating backgrounds : ttbar, DY+jet(s), tW, diboson.
- Inspired by previous WR search at 8 TeV with a 2.8σ local excess m_{eejj} ~ 2.1 TeV.
- Leading & subleading leptons (p_T > 60 GeV & 53 GeV) & Particle Flow (PF) jets (p_T > 40 GeV) selected.
- Signal region (SR) : m_{lljj} > 600 GeV, m_{ll} > 200 GeV (to reduce Z +jet(s)).

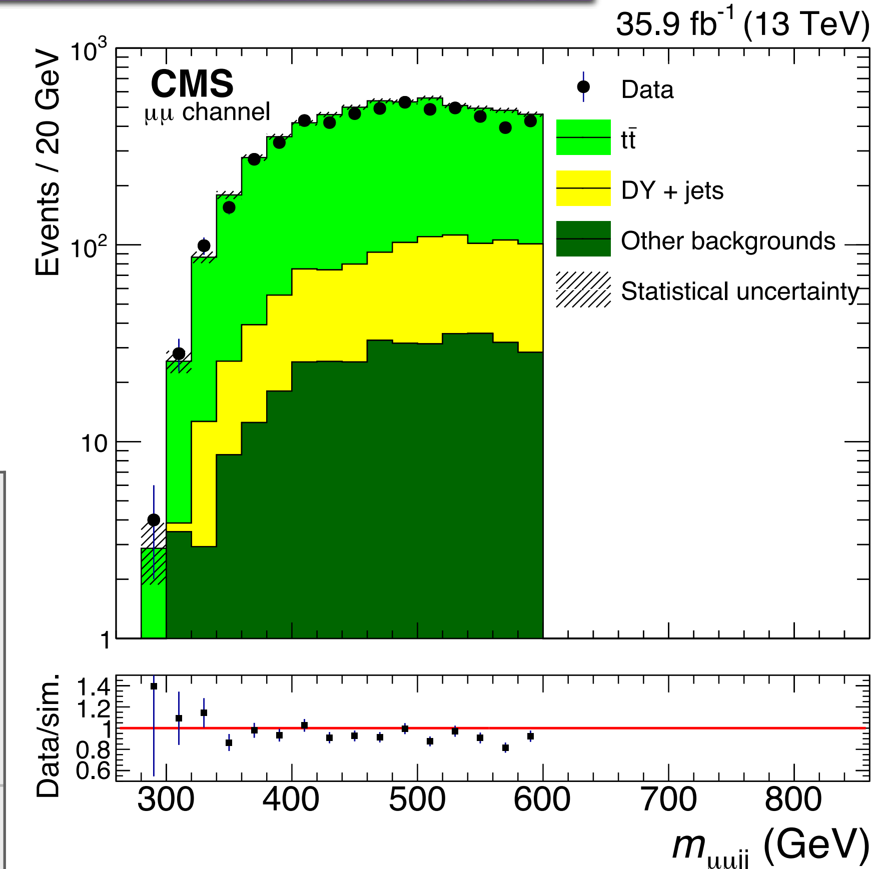
**m_{ij} is invariant mass of objects ij

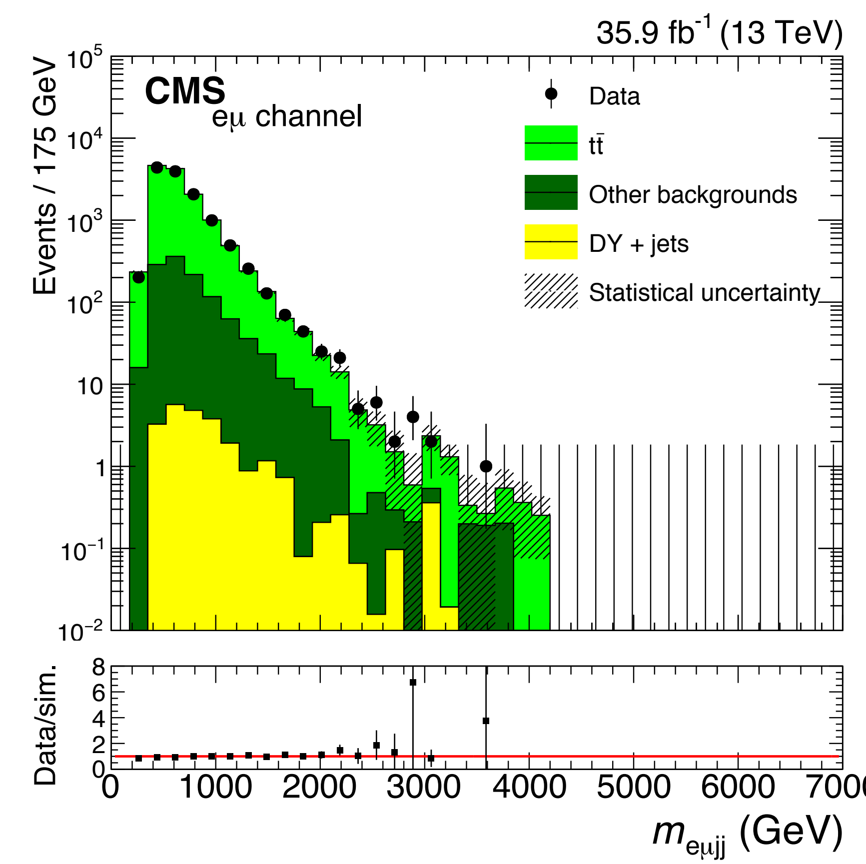
JHEP 05(2018) 148

Data-Simulation(Sim.) Comparison in CR / VR :

- Various Control Region (CR) studied to estimate most dominating backgrounds (DY+jet(s), ttbar).

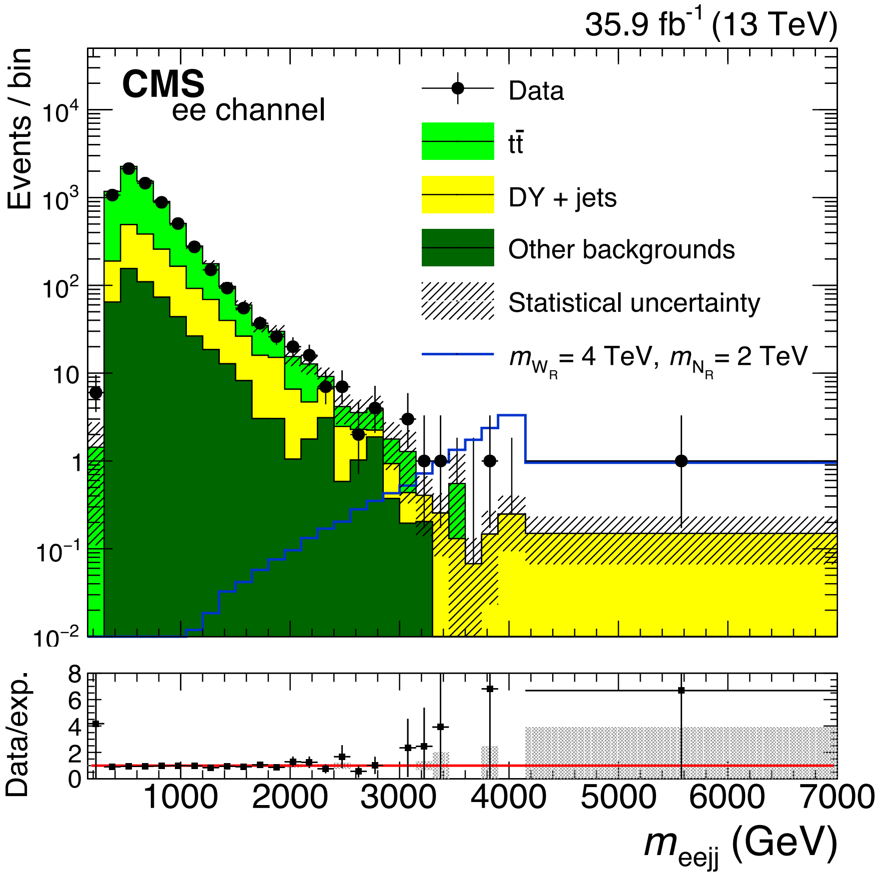
Analysis Regions	Event Selection
CR for DY+jet(s)	2SF, OS e or μ (80 GeV < m_{ll} < 100 GeV), 2 jets, m_{lljj} < 600 GeV
VR for DY+jet(s)	2SF, OS e or μ (m_{ll} > 200 GeV), 2 jets, m_{lljj} < 600 GeV
CR for ttbar	1 e & 1 μ (m_{ll} > 200 GeV), 2 jets, m_{lljj} > 600 GeV

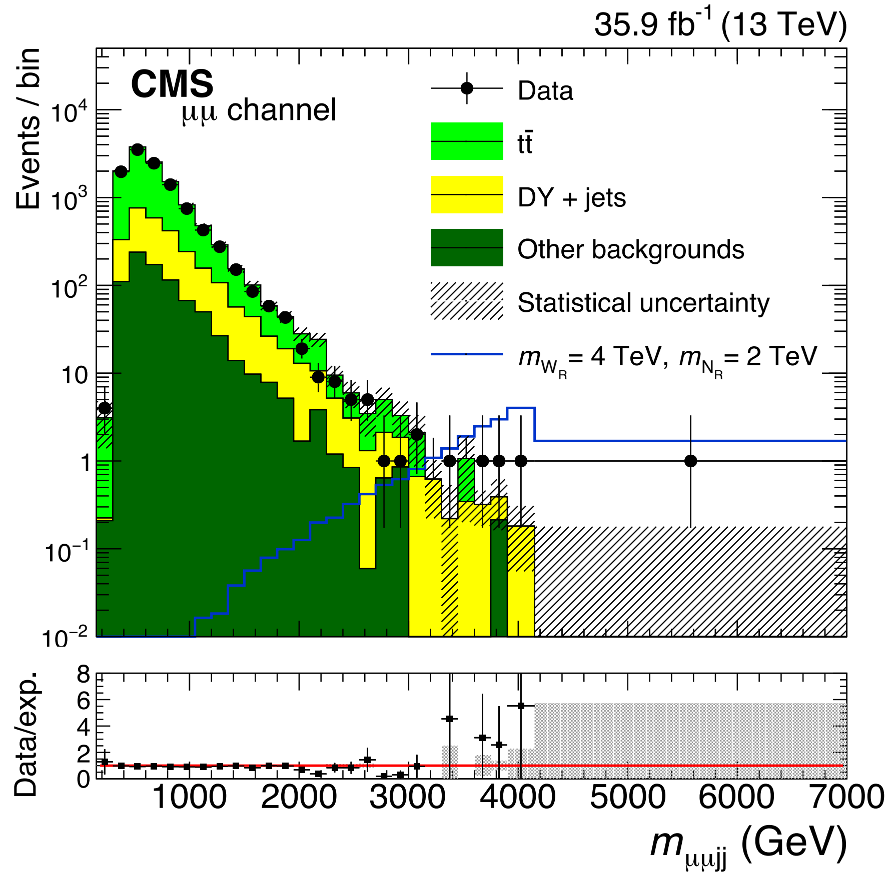




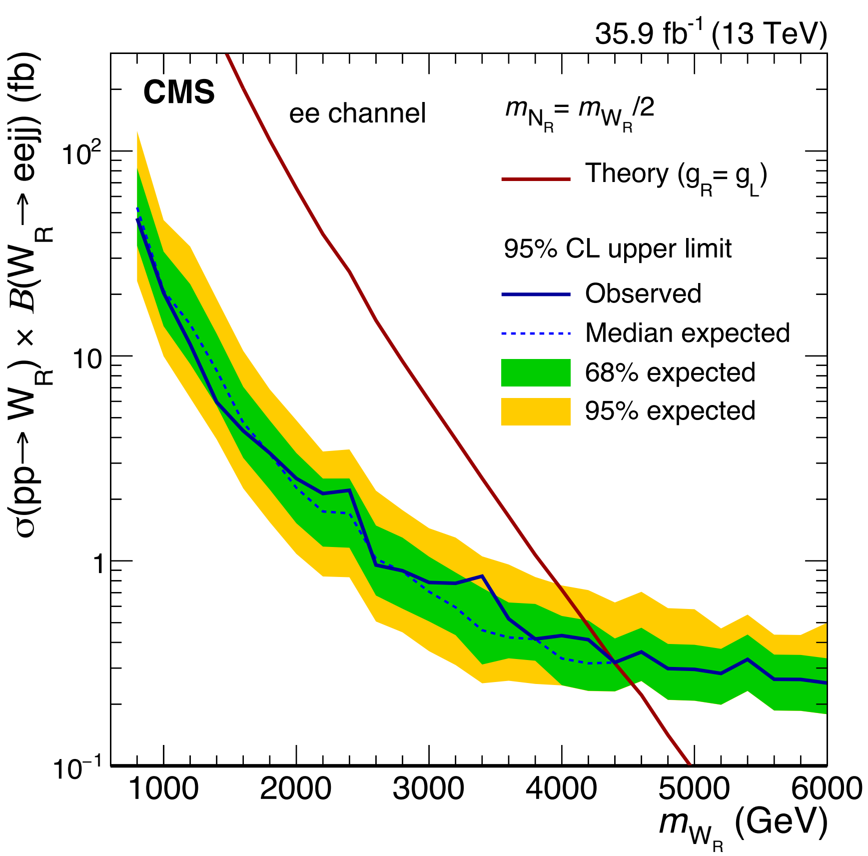
JHEP 05(2018) 148

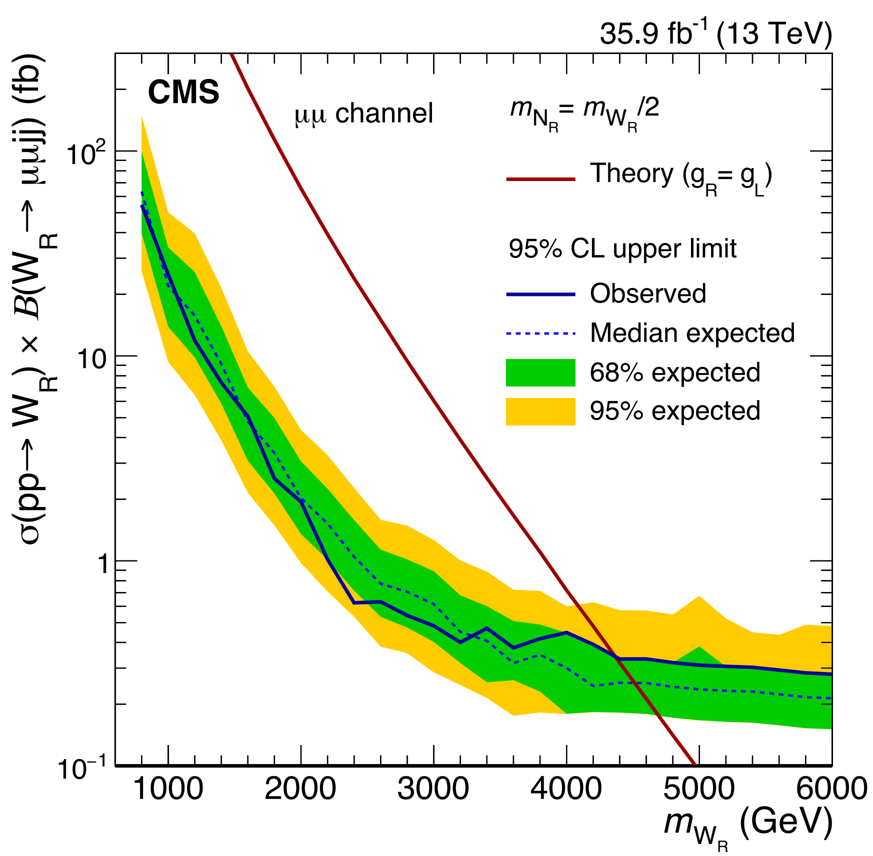
Data-Simulation(Sim.) Comparison in SR & limit estimation :





No significant deviations found in data in SR.





Observed limit at 95% CL on WR mass ~ 4.4TeV for both channels with $m_{NR} = m_{WR}/2$.

JHEP 05(2018) 148

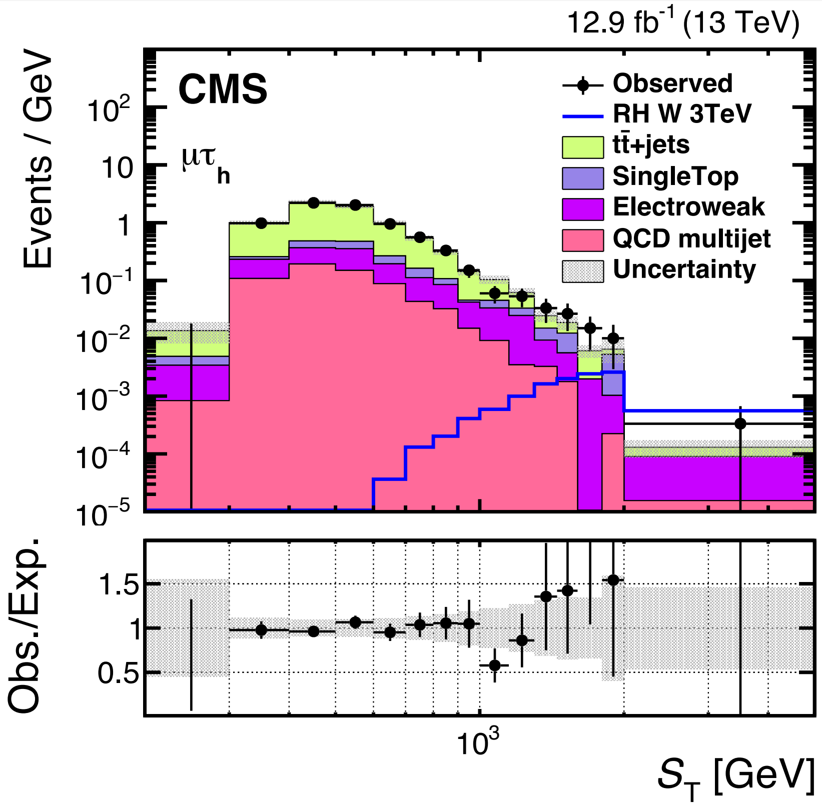
Latest heavy neutrino search in CMS with 12.9 fb^{-1} of data in lepton + jets final state :

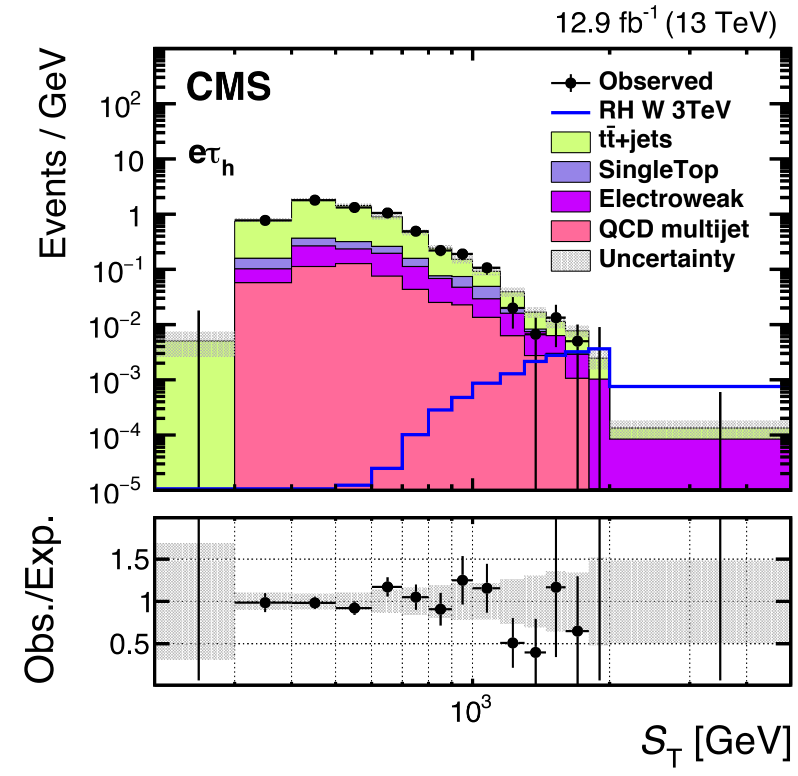
- Based on LRSM theory : $\mathrm{W_R} \to \tau + \mathrm{N}_\tau$, where $\mathrm{N}_\tau \to \tau + \mathrm{W}^*_\mathrm{R} \to \tau + \mathrm{q\bar{q}}$.
- Focussed on 1 $\tau(\tau_l)$ decays to e/μ. Other $\tau(\tau_h)$ decays hadronically.
- PF algorithm utilised to identify individual particles.
- Reconstruction of τ_h (hadrons-plus-strips algorithm), jets, missing energy performed with identified particles as inputs.
- Selection : e or μ with $p_T > 50$ GeV. τ_h with $p_T > 60$ GeV. Transverse momentum imbalance (p_T^{miss}) > 50 GeV. Invariant mass of e/μ + τ_h > 150 GeV.
- Identified e, μ, τ_h required to originate from same vertex with $\Delta R > 0.5$.

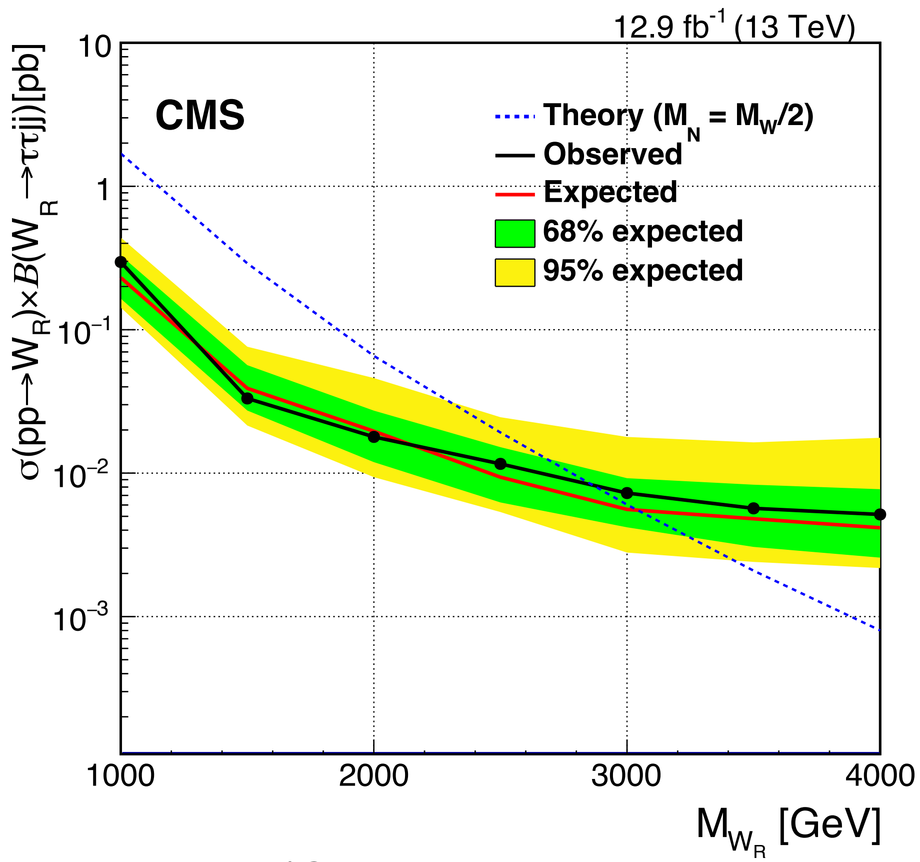
JHEP 07(2017) 121

Observed (in data)-Expected(in simulation) comparison in SR : No deviation from SM found.

- ttbar background validated in e/μ + at least 2 jets final state.
- W+jets background estimated in W -> μν/ eν + at least 3 jets with no b-tagged jet.
- Estimation of multi jet background performed by loosening τ_h ID, Isolation criteria.





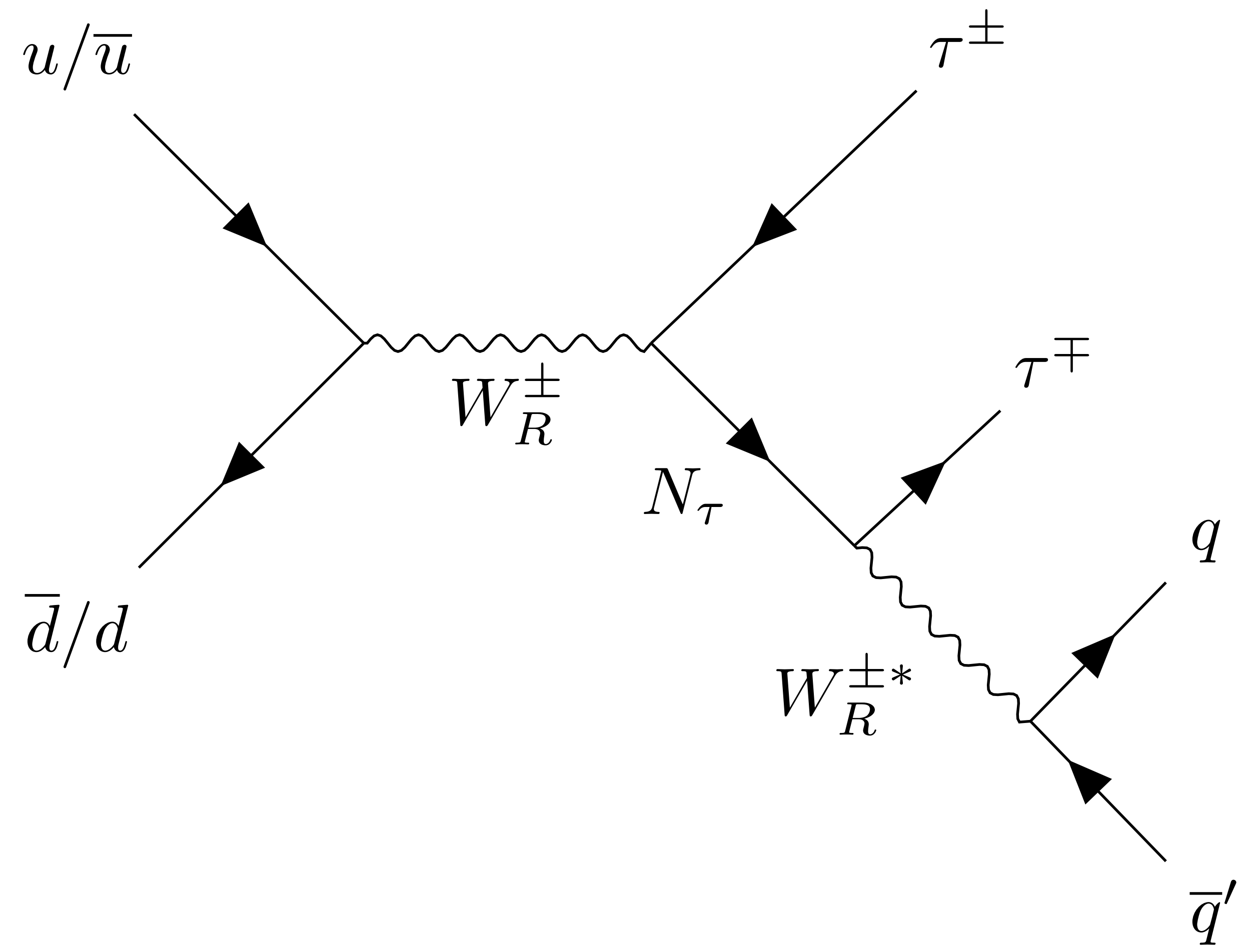


Observed (expected) limit at 95% CL on m_{WR} determined to be 2.9 (3.0)TeV with $m_{NR} = m_{WR}/2$.

JHEP 07(2017) 121

Latest heavy neutrino search in CMS with 35.9 fb^{-1} of data with hadronically decaying τ leptons (τ_h) + jets final state :

- Based on LRSM theory with 2 final state τ leptons decaying hadronically.
- All jets $p_T > 30$ GeV (2 jets with $p_T > 50$ GeV) . $\tau_h > 32$ GeV (2 $\tau_h > 70$ GeV).
- Dominating backgrounds : ttbar, Z+jet(s), multijet.



$$m(\tau_{h,1}, \tau_{h,2}, j_1, j_2, p_T^{miss}) = \sqrt{(E_{\tau_{h,1}} + E_{\tau_{h,2}} + E_{j_1} + E_{j_2} + p_T^{miss})^2 - (\vec{p}_{\tau_{h,1}} + \vec{p}_{\tau_{h,2}} + \vec{p}_{j_1} + \vec{p}_{j_2} + \vec{p}_T^{miss})^2}.$$

$\approx m_{WR}$

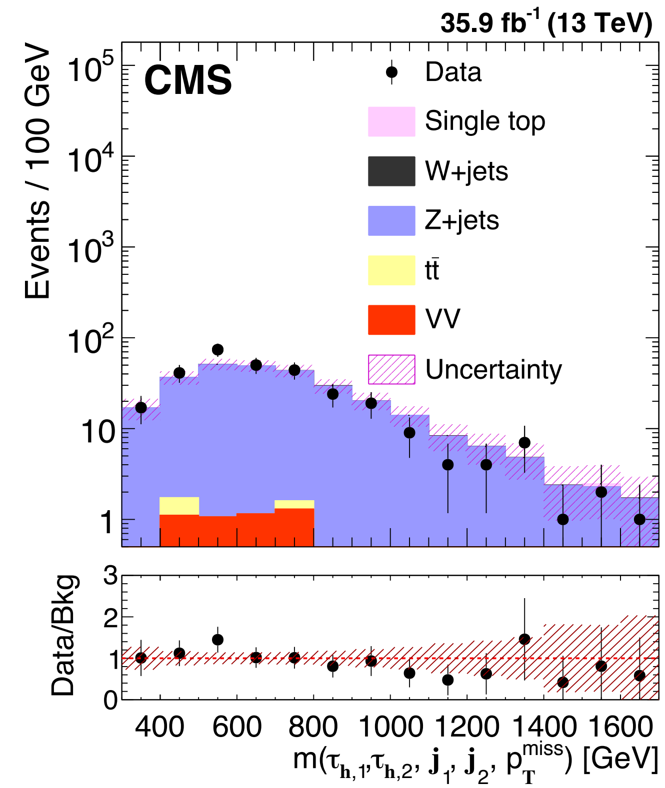
arXiv:1811.00806, Submitted to JHEP

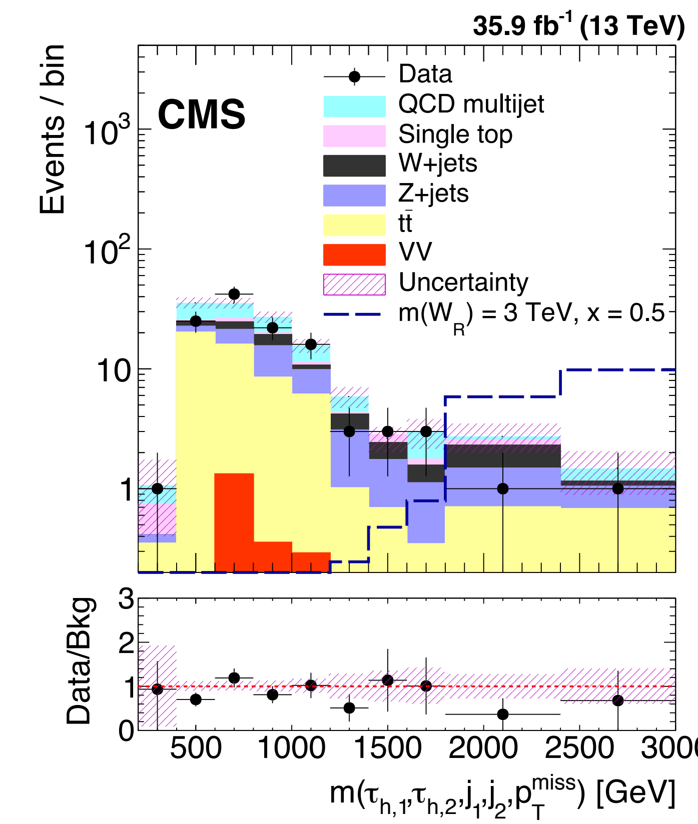
Various Analysis regions comparisons and limit setup :

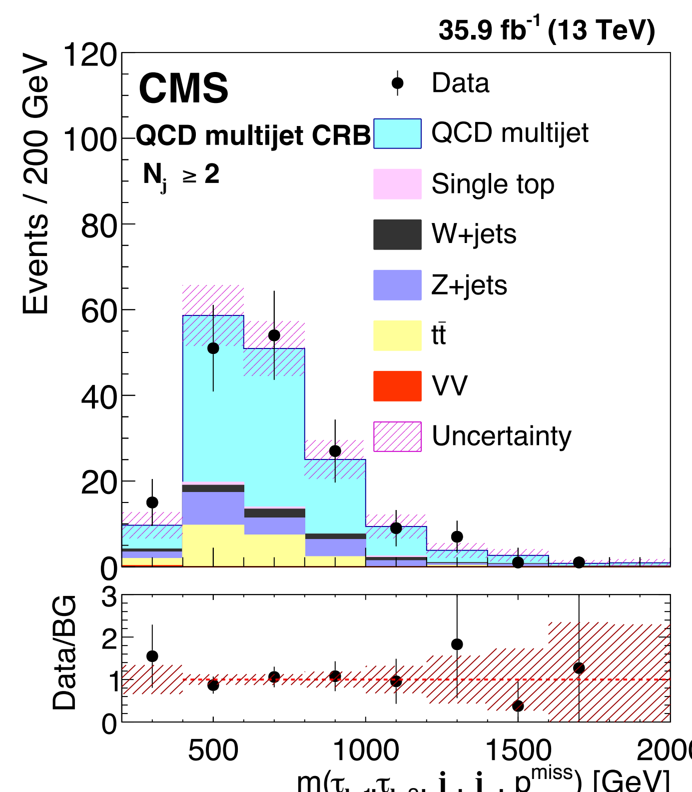
- ttbar CR : 2 muons + at least 1 b-tagged jet with $m_{\mu\mu} < 80$ GeV or $m_{\mu\mu} > 110$ GeV.

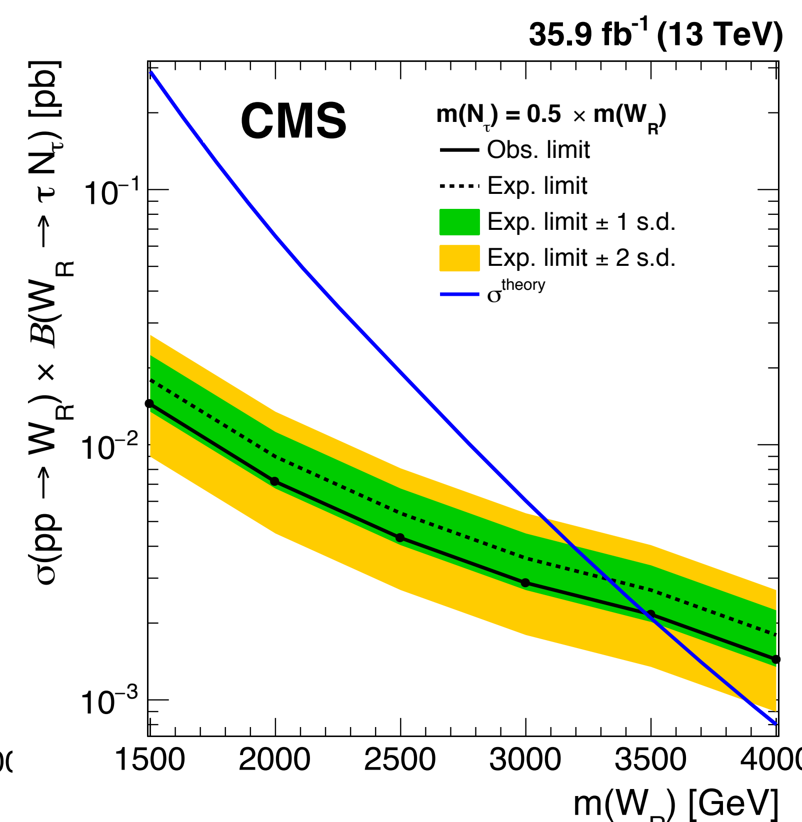
- Z+jet(s) CR : 2 muons with 80 GeV < $m_{\mu\mu} < 110$ GeV.

- Data driven ABCD matrix method used for multijet event estimation : p_T^{miss} (50 GeV) & τ_h isolation as discriminators between signal & QCD jets.





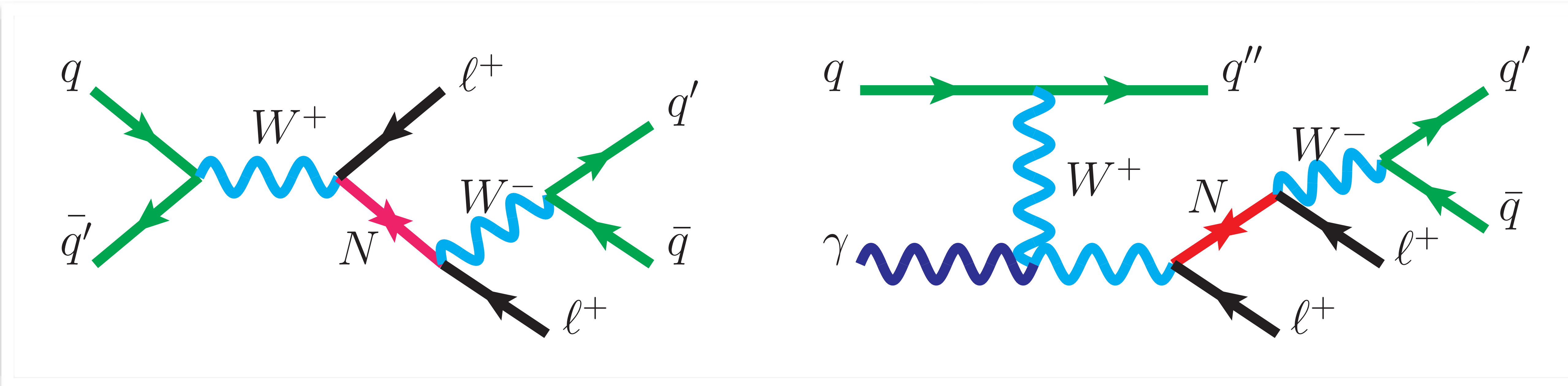




m_{WR} below 3.50 TeV excluded at 95% CL (expected 3.35 TeV).

 arXiv:1811.00806, Submitted to JHEP

Latest heavy neutrino search in CMS with 35.9 fb^{-1} of data νMSM theory :



- Also looked into N production via Wγ fusion.
- Same sign leptons + (at least 2 jets (R = 0.4)/exactly 1 jet (R = 0.4)/at least 1 large jet (R = 0.8) in final state considered.
- No flavour conservation considered (ee or μμ or eμ).
- Limits estimated with matrix element describing mixing of N with SM ν of flavour e or μ.

arXiv:1806.10905, Submitted to JHEP

Various Analysis regions category & object selection :

- Large jet with R = 0.8 required to have $\tau_{21} < 0.6$ and a pruned jet mass between 40 & 130 GeV. (See Pierre-Antoine Delsart's talk later).
- $p_T > 25(15)$ GeV for ee, $> 20(10)$ GeV for $\mu\mu$, 25(10) GeV for $e\mu$.

- Different SR(s) studied based on ($m_N \gtrsim 80$ GeV or $m_N \lesssim 80$ GeV), combination of flavours and small jet or large jet selection :

=> low- & high mass SR1 : number of R = 0.4 jets >= 2, R = 0.8 jets = 0.
=> low-mass SR2 : number of R = 0.4 jets = 1, number of R = 0.8 jets = 0.
=> high-mass SR2 : number of R = 0.8 jets >= 1.

- Several variables used simultaneously for optimized signal selection.

arXiv:1806.10905, Submitted to JHEP

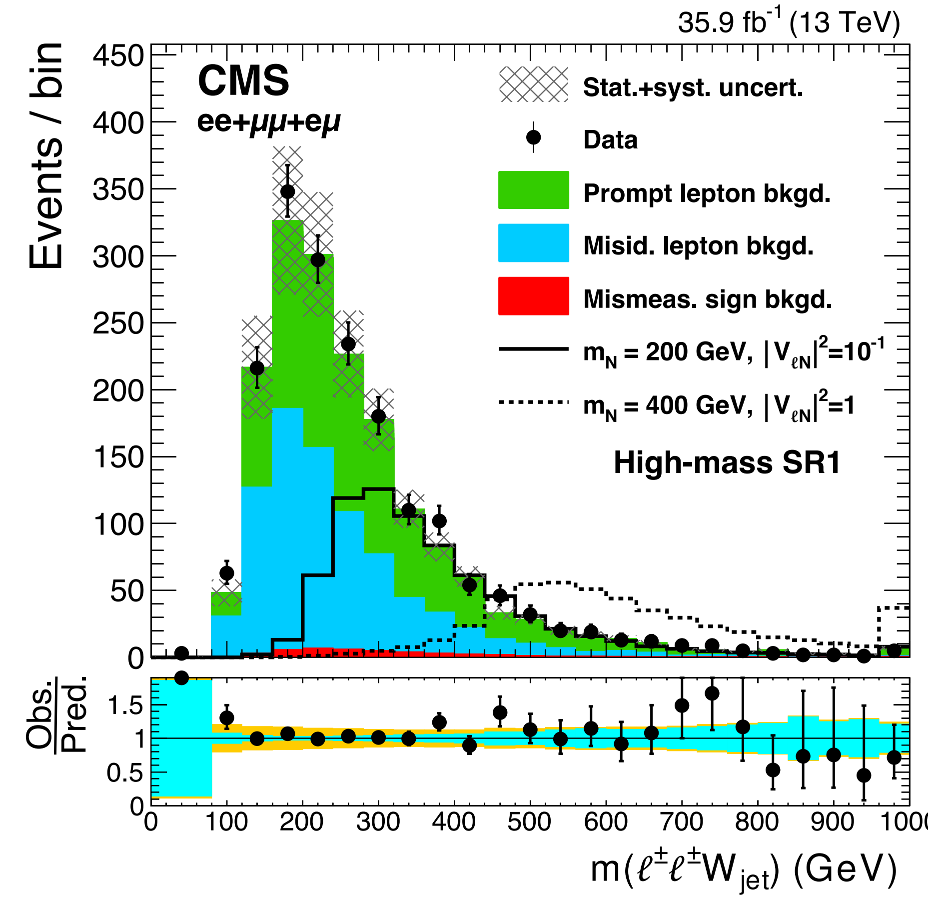
Limit setup with mixing matrix element :

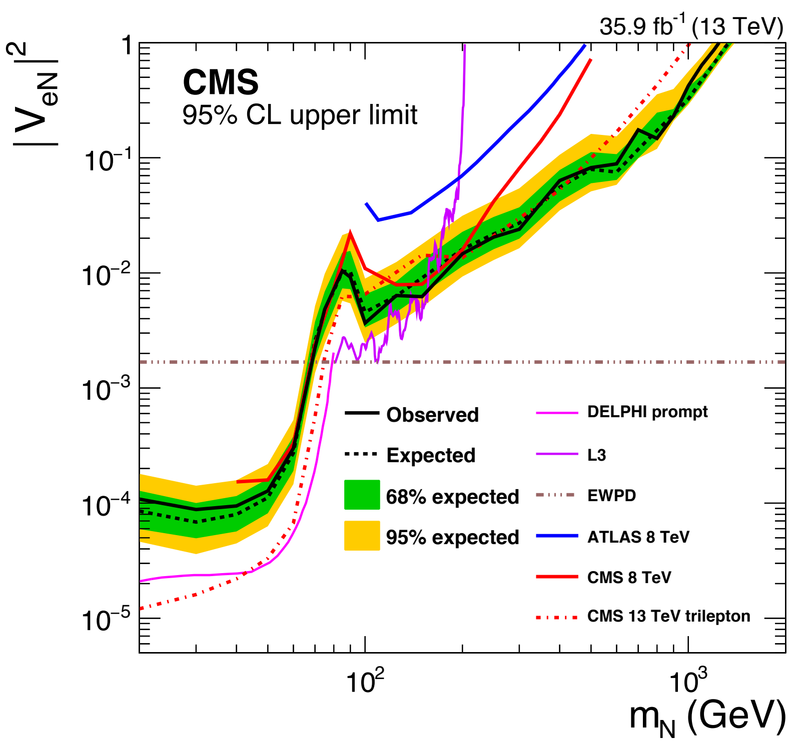
<u>CR(s) classified in following categories</u> :

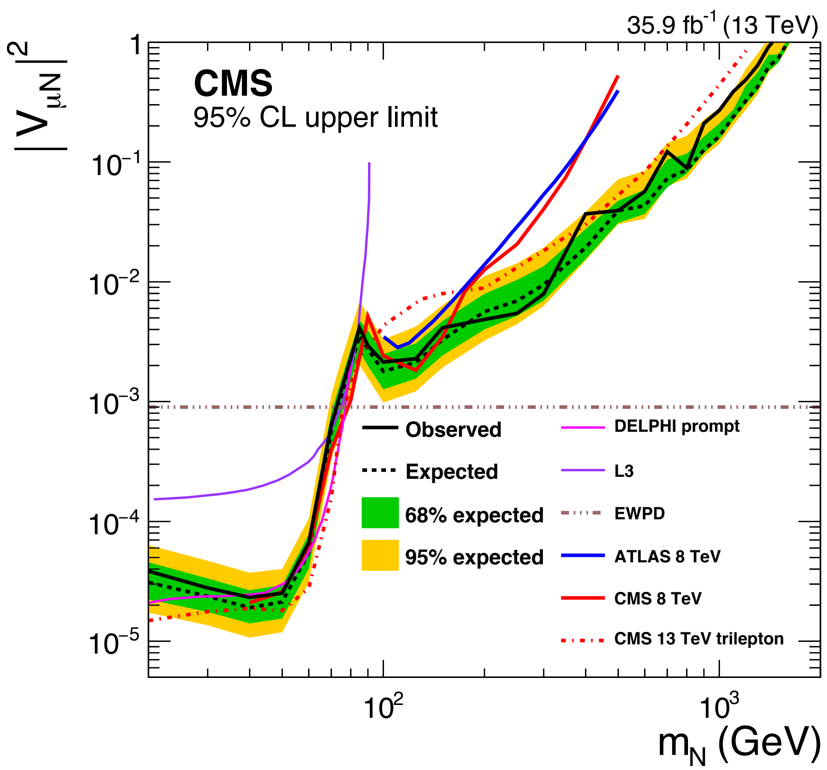
a. Multiple prompt leptons => diboson

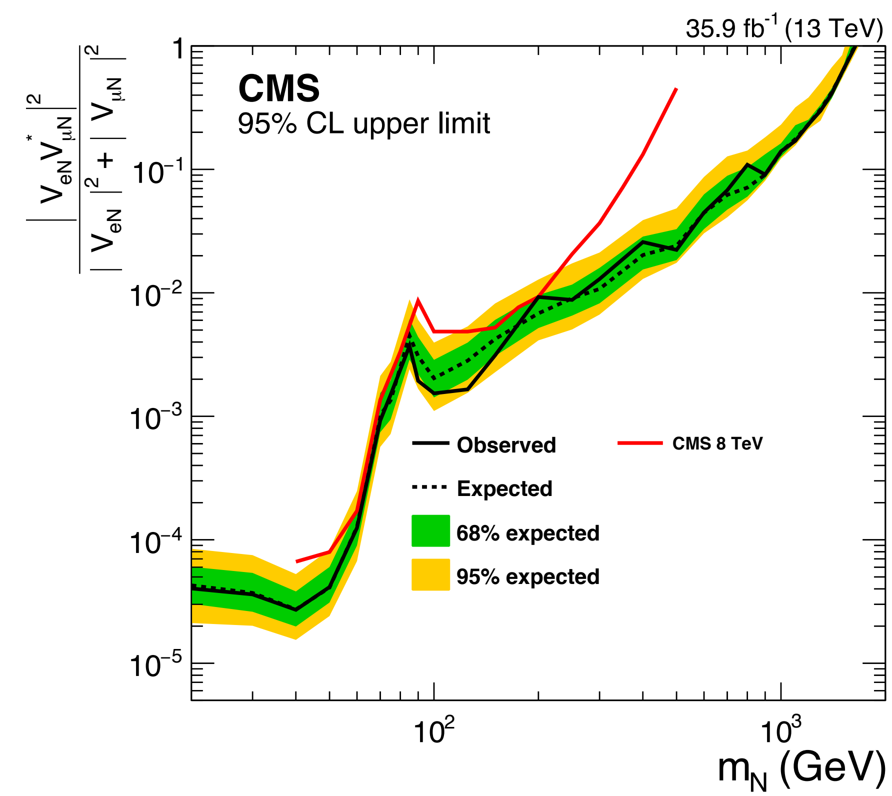
b. Misidentified leptons => W+jets, ttbar

c. Sign mismeasurement => OS 2leptons









For N masses between 20 and 1600 GeV, upper limits on $|V_{ln}|^2$ range between 2.3 * 10^{-5} & 1.0.

<u>arXiv:1806.10905</u>, Submitted to JHEP

Summary & Outlook

- A comprehensive set of searches for heavy neutrinos carried out (ongoing) in both ATLAS & CMS (With Type-III seesaw mechanism heavy neutrino search using 79.8 fb-1 of ATLAS data, glimpses in backup!).

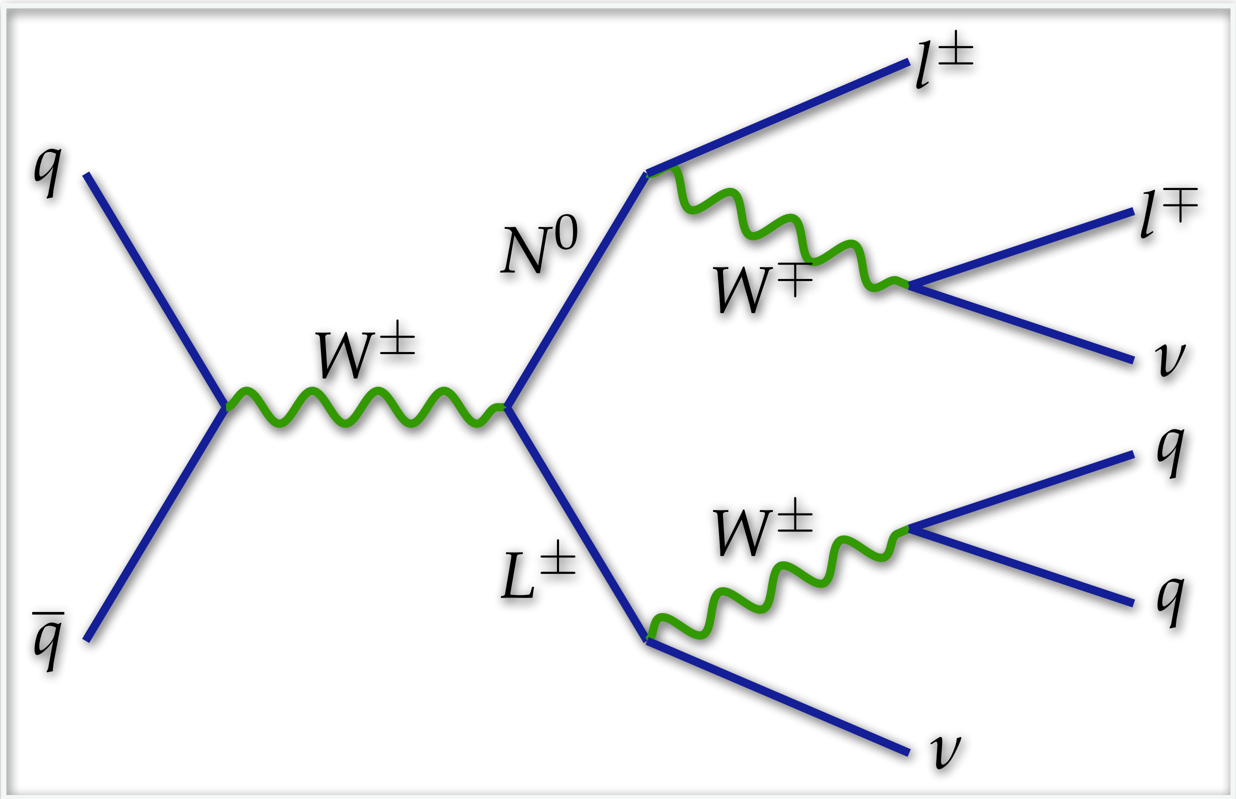
- Until now no consistent deviation from SM prediction found.

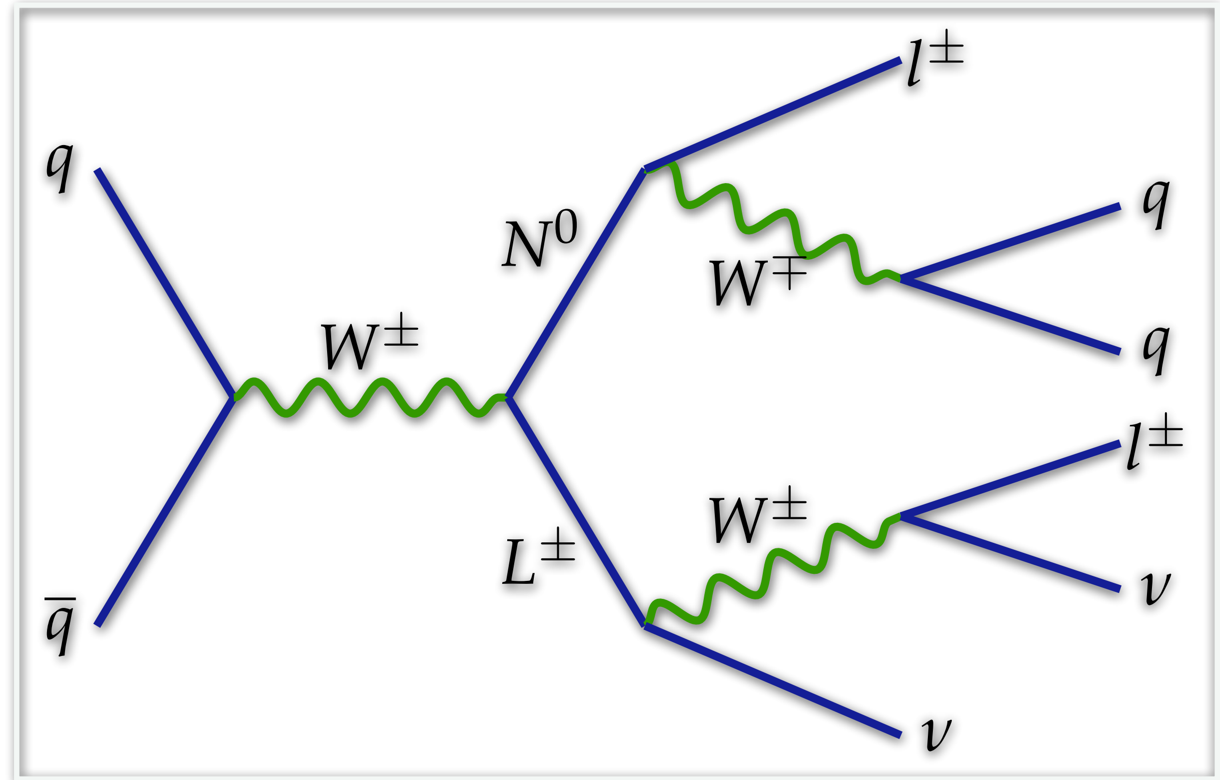
- Searches with same final state performed at various centre of mass energies of LHC (e.g. 7 TeV, 8 TeV 13 TeV) helps in gaining deeper understanding of heavy neutrino theories.

- Exclusion limit reaches to 4.7 TeV m_{WR} with mN_R 0.5–3.0 TeV. However it depends on the specific model used!

- Higher energy boosted scenarios can be explored to gain deeper insights for lower mN_R!

Additional Material



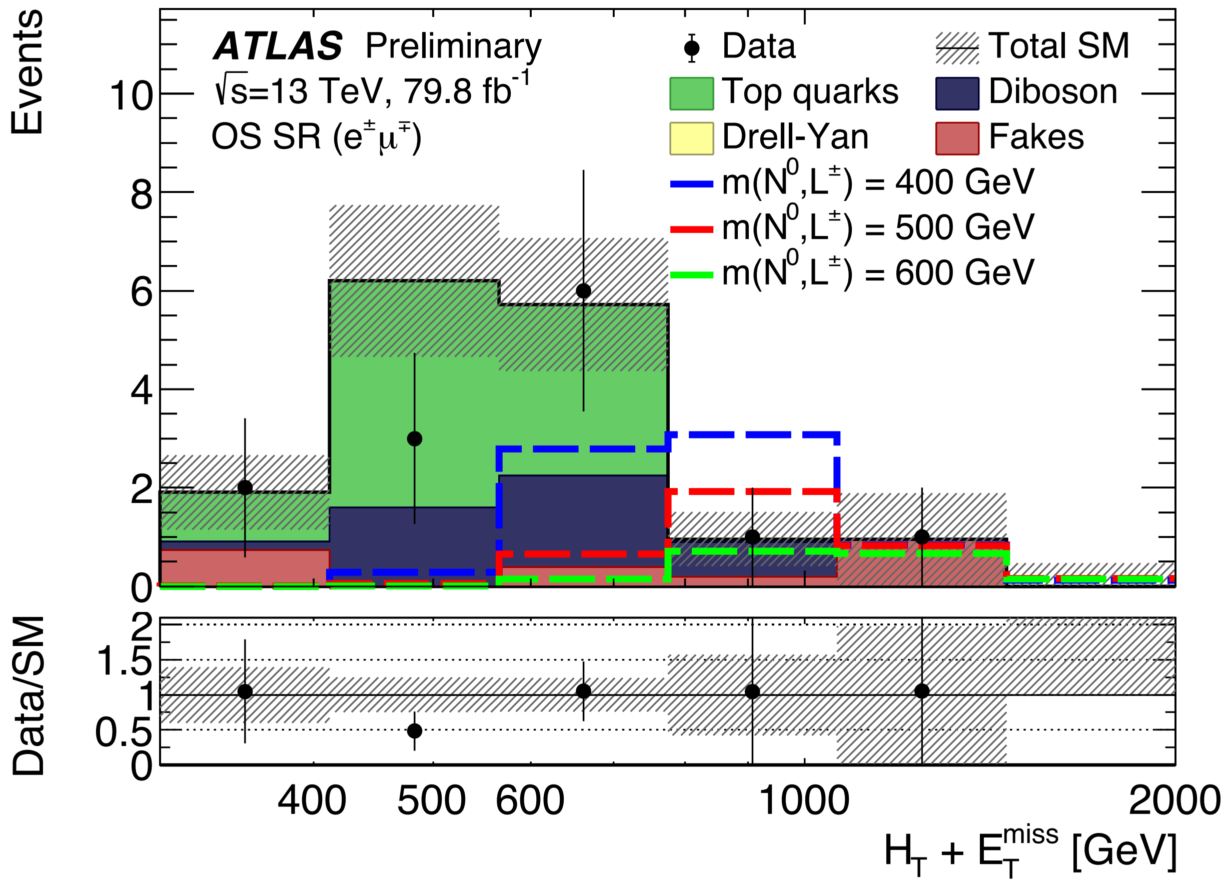


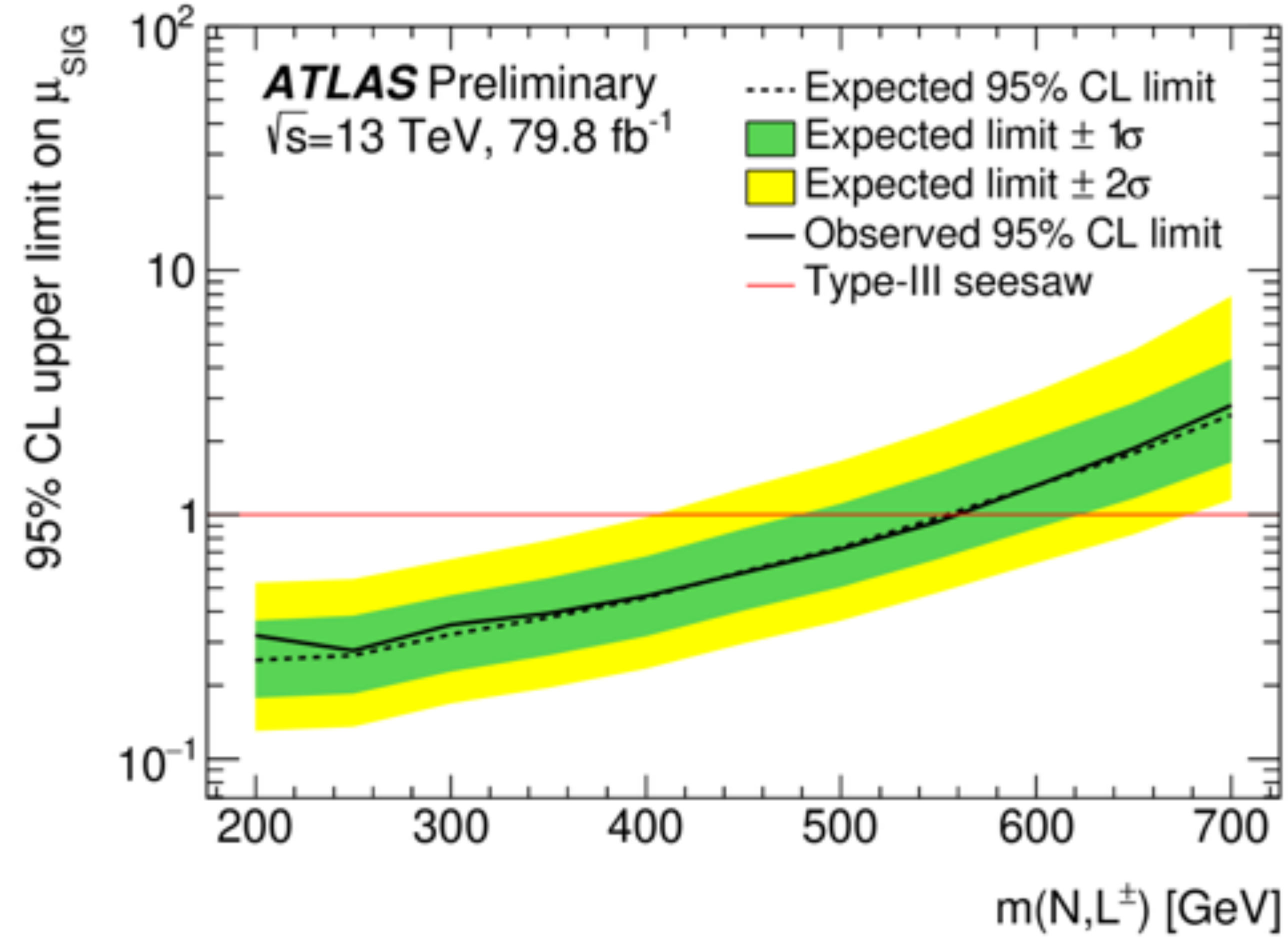
	OS ($\ell^+\ell^- = e^+e^-$, $e^{\pm}\mu^{\mp}$, $\mu^+\mu^-$)				**SS** ($\ell^{\pm}\ell^{\pm} = e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$)			
	Top CR	Z+jets VR	m_{jj} VR	SR	Z+jets VR	m_{jj} VR	m_{jj} CR	SR
N(jet)	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2
N(b-jet)	$\boldsymbol{\geq 2}$	0	0	0	0	0	0	0
m_{jj} [GeV]	$[60, 100)$	$[60, 100)$	$\boldsymbol{[35, 60) \cup [100, 125)}$	$[60, 100)$	$[60, 100)$	$\boldsymbol{[0, 60) \cup [100, 300)}$	$\boldsymbol{[0, 60) \cup [100, 300)}$	$[60, 100)$
$m_{\ell\ell}$[GeV]	$[110, \infty)$	$\boldsymbol{[70, 110)}$	$[110, \infty)$	$[110, \infty)$	$\boldsymbol{[70, 100)}$	$[100, \infty)$	$[100, \infty)$	$[100, \infty)$
Sig($E_{\mathrm{T}}^{\mathrm{miss}}$)	≥ 5	≥ 5	$\boldsymbol{\geq 10}$	$\boldsymbol{\geq 10}$	≥ 5	≥ 5	≥ 5	$\boldsymbol{\geq 7.5}$
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, l)_{\mathrm{min}}$				$\boldsymbol{\geq 1}$				
$p_{\mathrm{T}}(jj)$ [GeV]				$\boldsymbol{[100, \infty)}$				$\boldsymbol{[60, \infty)}$
$p_{\mathrm{T}}(\ell\ell)$ [GeV]				$\boldsymbol{[100, \infty)}$				$\boldsymbol{[100, \infty)}$
$H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$[300, \infty)$	$[300, \infty)$	$[300, \infty)$	$[300, \infty)$		$\boldsymbol{[500, \infty)}$	$\boldsymbol{[300, 500)}$	$[300, \infty)$

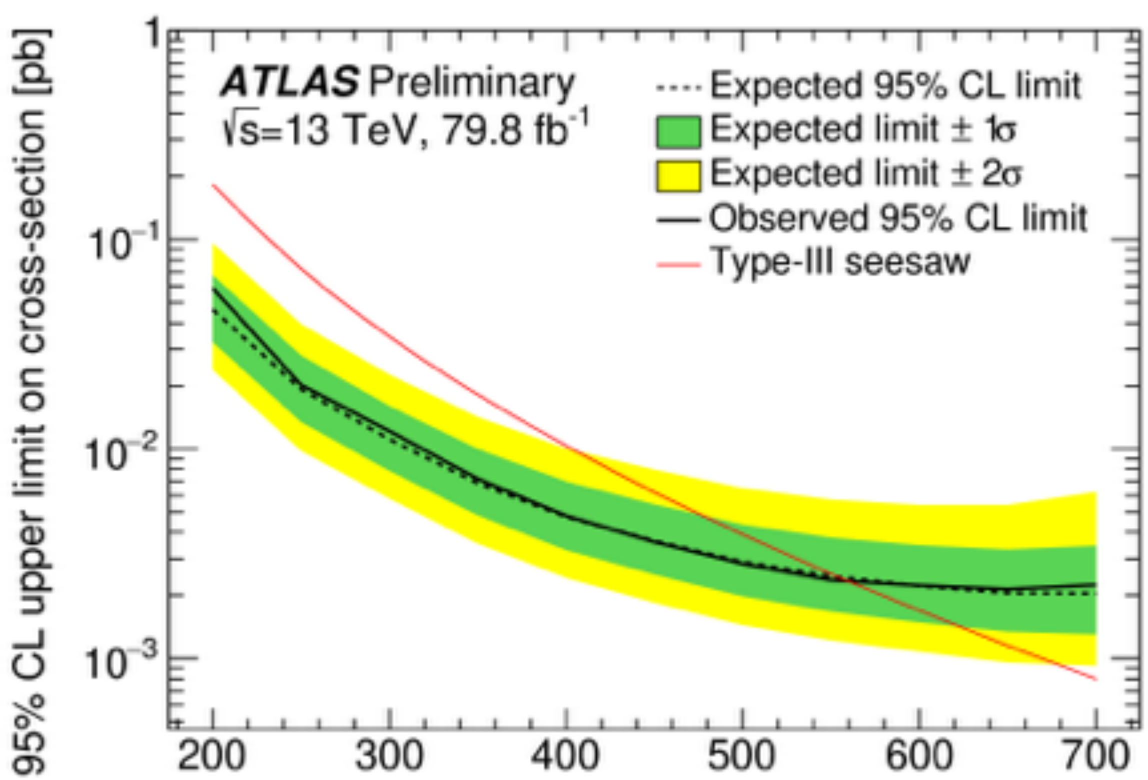
- Final state : 2jets + 2 leptons (SS or OS) + neutrinos
- No flavour conservation considered (ee or μμ or eμ)

ATLAS-CONF-2018-020

Additional Material







Exclusion limit at 95% CL 550 GeV expected and 560 observed.

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