

57th Rencontres de Moriond - March 18 2023

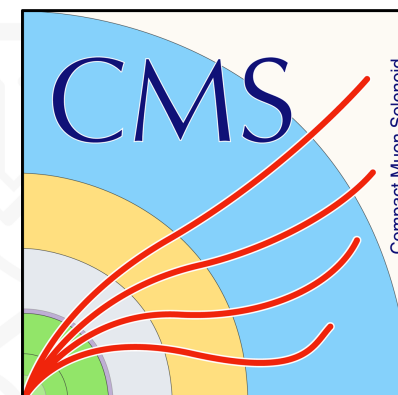
Searches for Vector-Like Quarks and Leptons, Heavy Neutral Lepton with the CMS and ATLAS Detectors

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On behalf of the ATLAS and CMS

Collaborations

20 - 03 - 2023



Heavy Neutral Leptons (HNLs)

- ✓ Extension to the SM by 3 R-H neutrinos (seesaw mechanism)
- ✓ Explain dark matter, Baryon asymmetry and **neutrino masses**
- ✓ Can couple to the 3 lepton generation i.e. LFC and LFV
- ✓ Can have Dirac(Majorana) nature LNC(LNC + LNV)

✓ The proper lifetime $\tau \propto \frac{1}{m_N^5 \sum_{e,\mu,\tau} |V_{eN}|^2}$

[arXiv: 1305.4172](https://arxiv.org/abs/1305.4172)

Vector-like quarks (VLQs) :

- ✓ Vector-like quarks (VLQs) are spin half fermions and coloured
- ✓ Transform the same way as SM quarks under the strong force but singlet under the weak force.
- ✓ Natural solution to the hierarchy problem
→ **the smallness of the Higgs boson mass**

[arXiv:1301.5516](https://arxiv.org/abs/1301.5516)

Vector-like leptons (VLLs)

- ✓ Same electric charge and spin as SM leptons
- ✓ Interact with both left- and right-handed particles through the weak force.
- ✓ Explanation to neutrino masses and the nature of dark matter
- ✓ Potential solution to the hierarchy problem
→ **the smallness of the Higgs boson mass**

[arxiv:1312.5329](https://arxiv.org/abs/1312.5329)

→ Solution to SM limitations: HNLs, VLQs and VLLs hypothetical particles offer explanation of the smallness of Higgs boson mass and neutrinos masses.

CMS and ATLAS results with **full run 2** dataset corresponding to $\sim 138 \text{ fb}^{-1}$.

All results can be found:

- **ATLAS:** [Exotics Physics Searches Publications](#)
- **CMS:** [Beyond 2nd Generation : Preliminary](#) , [Publications](#) , [Exotica : Preliminary](#) , [Publications](#)

Analysis	Topology	Released	Experiment
EXOT-2019-39	Search for W_R and $N_\ell - 1/2 \ell^\pm + \text{jets}$	March 23	ATLAS
EXO-21-013	Search for long-lived HNLs in $2 \ell^\pm + \text{jet}$	March 23	CMS
EXOT-2019-08	VLQ pair production $T\bar{T}$ and $B\bar{B}$ single lepton	December 22	ATLAS
EXOT-2018-58	VLQ pair production $T\bar{T}$ and $B\bar{B}$ 2l + multi-leptons	October 22	ATLAS
B2G-20-011	VLQ pair production $T\bar{T}$ and $B\bar{B}$ - 1 - 2 and multi-lepton	September 22	CMS
B2G-21-007	VLQ single production, $T \rightarrow tH$ and $H \rightarrow \gamma\gamma$	July 22	CMS
EXOT-2020-07	VLL pair production	March 23	ATLAS
EXO-21-002	VLL pair production	February 22	CMS



Search for right-handed W_R bosons and heavy neutrino N_ℓ



- Left-Right symmetry model (LRSM) : Extension to the SM

by an $SU(2)_R$.

[EXOT-2019-39](#)

- Majorana and Dirac N_ℓ nature and exclusive coupling to

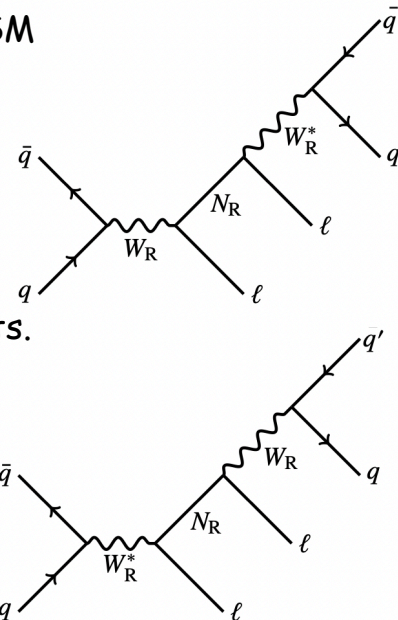
3 ℓ generation.

- SF 2ℓ : $2\mu, 2e$ + jets events also events 1ℓ : $1e$ + jets.

- 2ℓ OS(OS + SS) for Dirac(Majorana).

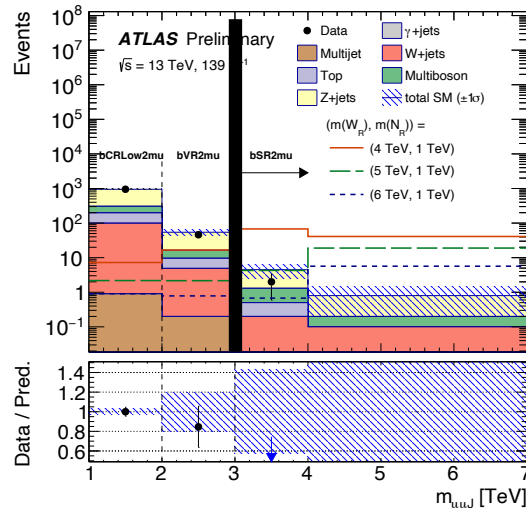
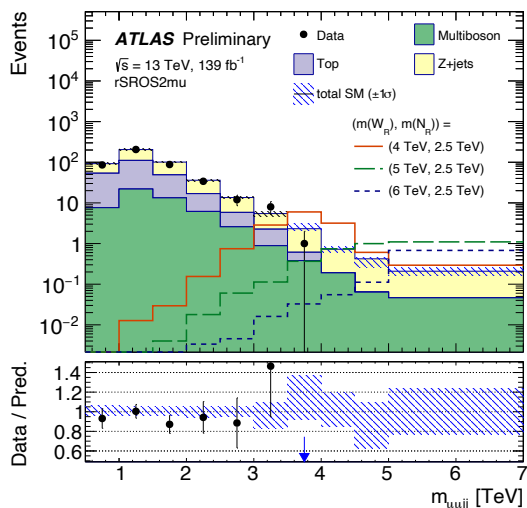
- 2 event topology : boosted and resolved

$$\Delta M = m_{W_R} - m_{N_R} > 4 (< 4) \text{ TeV respectively.}$$

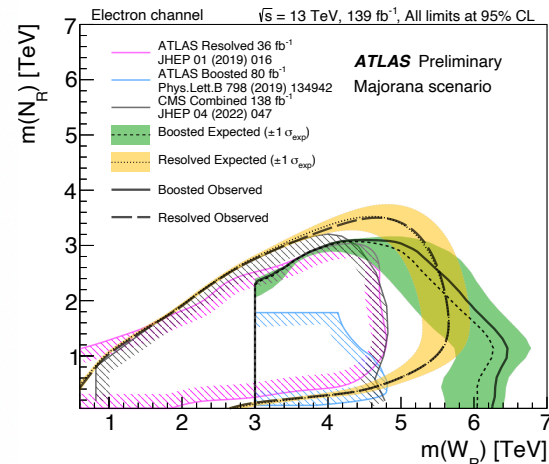


SR: 2μ OS resolved

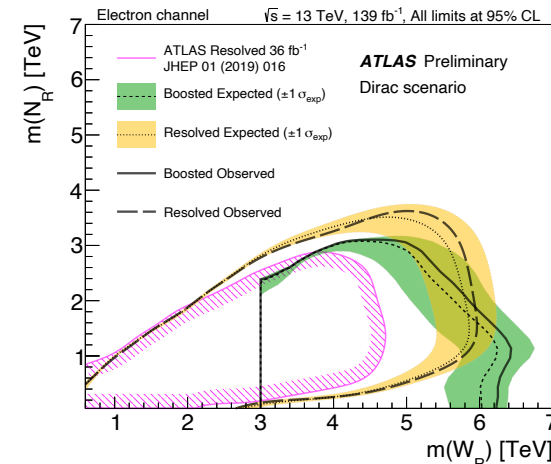
SR: 2μ OS boosted



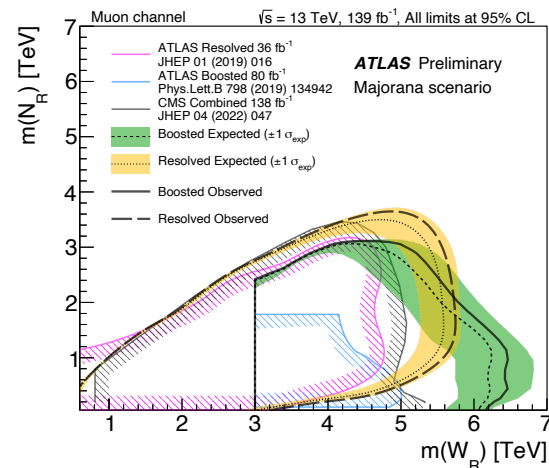
Majorana: electron channel



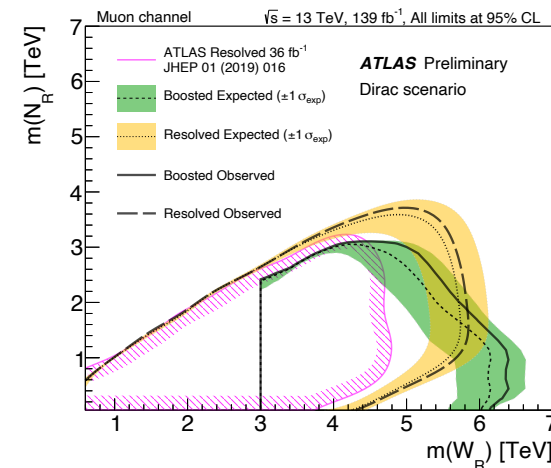
Dirac: electron channel



Majorana: muon channel



Dirac: muon channel

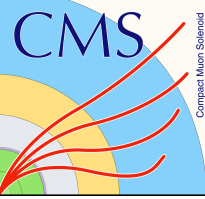


Exceeds CMS results : EXO-20-002 ~ 5 to 5.5 TeV

→ stricter constraints



Search for long-lived HNLs in $2 \ell + \text{jet}$ final state



Probe Dirac and Majorana HNLs

Inclusive coupling to the 3 ℓ generation

prompt ℓ_1 + displaced ℓ_2 and j^*

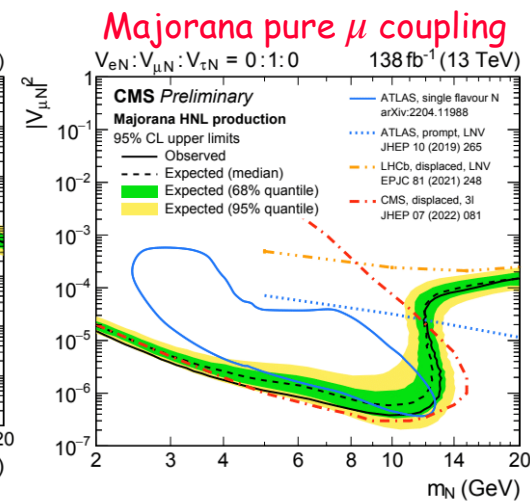
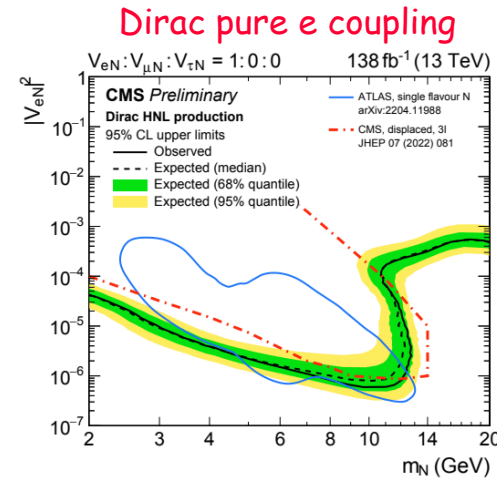
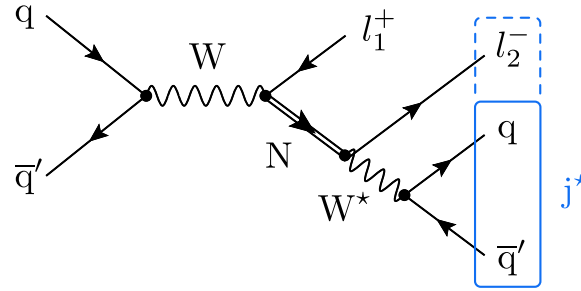
low mass region \rightarrow displaced decays

Broad categorisation (48 category):

- ℓ_2, j^* topology : **boosted or resolved**
- $\ell_1 \ell_2$ flavour(charge) combination i.e SF/OF(OS/SS)
- The 2D displacement sign. from PV: $d_{xy}^{sig}(\ell_2) = d_{xy}(\ell_2)/d_{xy}^{err}(\ell_2)$

A displaced jet tagger (deep NN) to maximise sensitivity to a broad $c\tau_0$.

EXO-21-013



\rightarrow Exceeds ATLAS results specially at low mass region

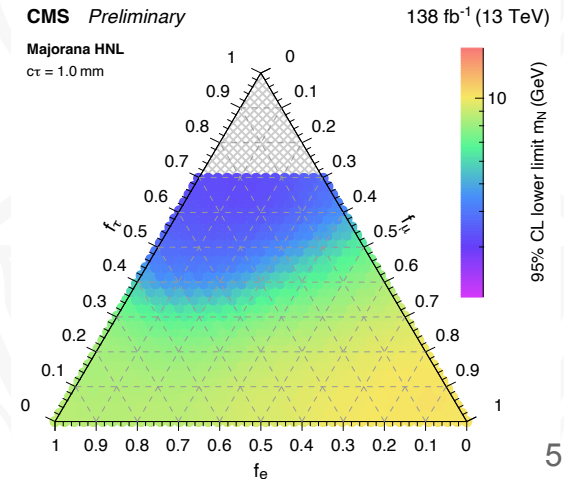
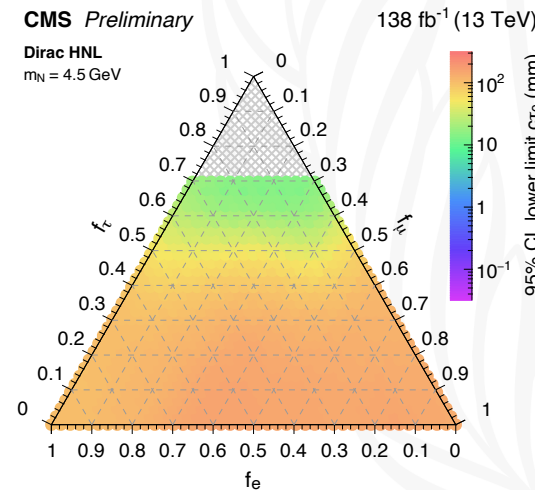
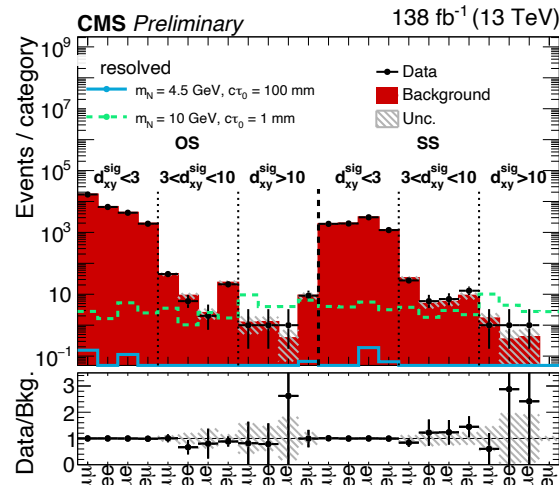
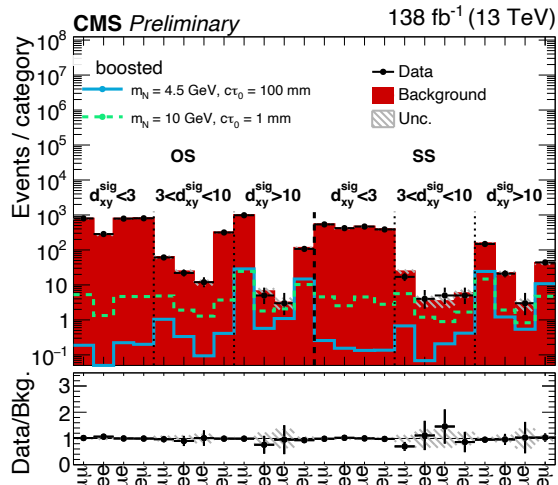
Relative coupling to the 3 lepton generation

Max excl. $c\tau_0$ for fixed m_N

Max excl. m_N for fixed $c\tau_0$

#yields SR:boosted

#yields SR:resolved



Search for pair production of vector-like T and B with $Z \rightarrow \ell\ell$

- $T\bar{T}$ where at least one $T \rightarrow Zt$ or $B \rightarrow Zb$ ($Z \rightarrow \ell\ell$ and $t \rightarrow bW$)

- MCBOT trained to tag jets from H, top or V(Z/W).

[EXOT-2018-58](#)

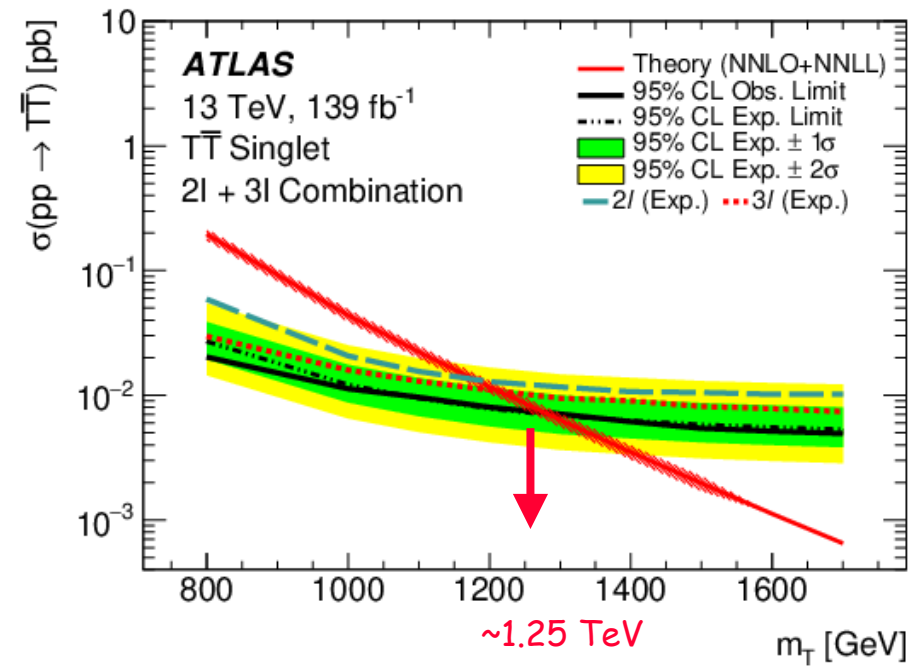
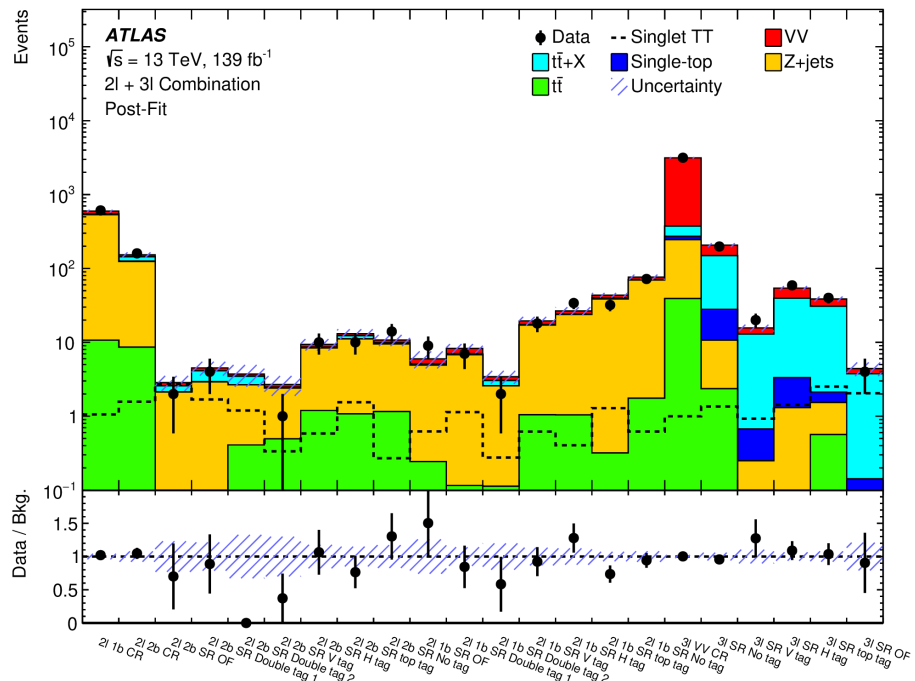
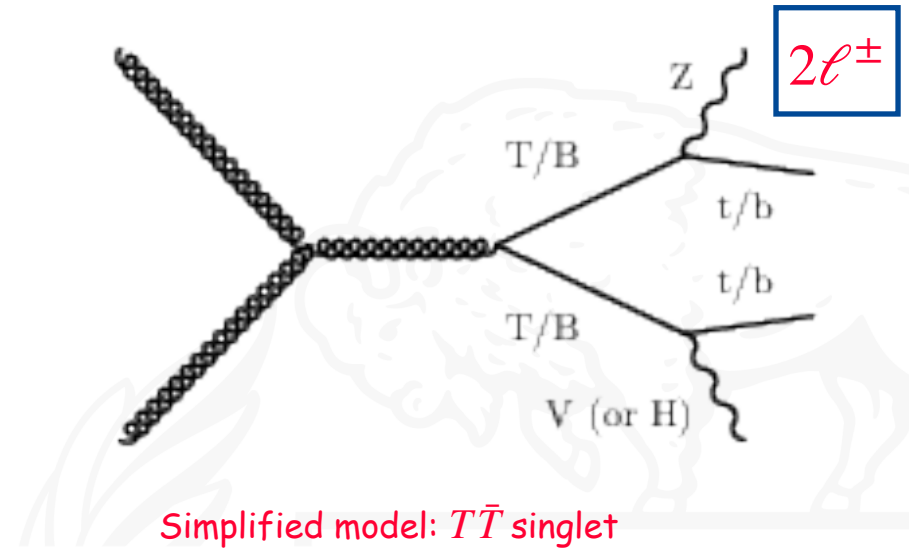
2 lepton category:

2 subcategories : = 1 b-jet or ≥ 2 b-jets

7 subcategories - presence of (W, Z, H or top)

3 lepton category:

5 subcategories - presence of (W, Z, H or top)

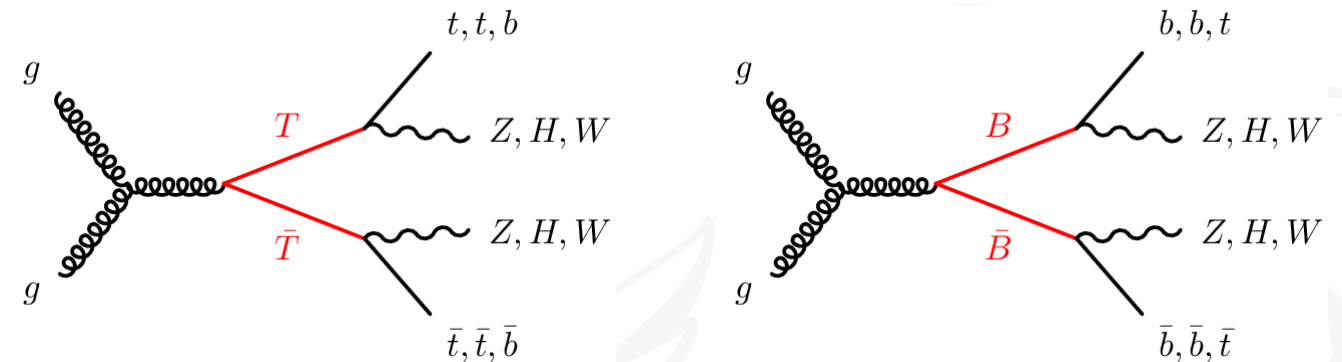


Search for pair production of Vector-Like T and B - $1\ell + \text{MET}$

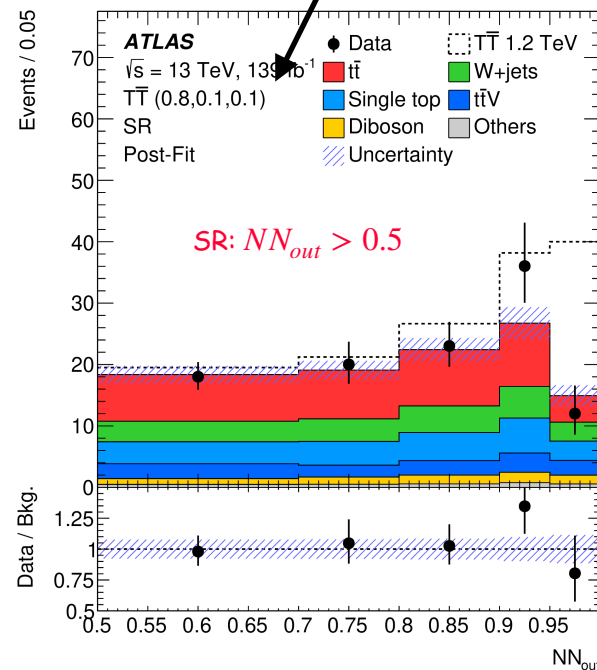
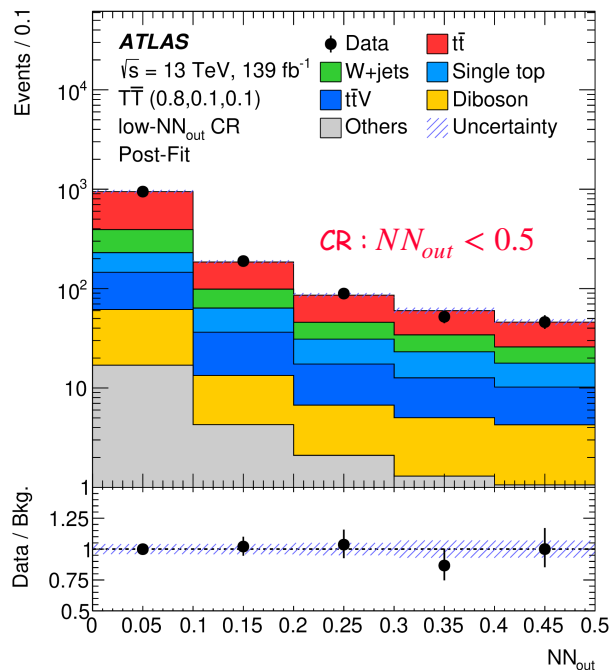
EXOT-2019-08

1 lepton category:

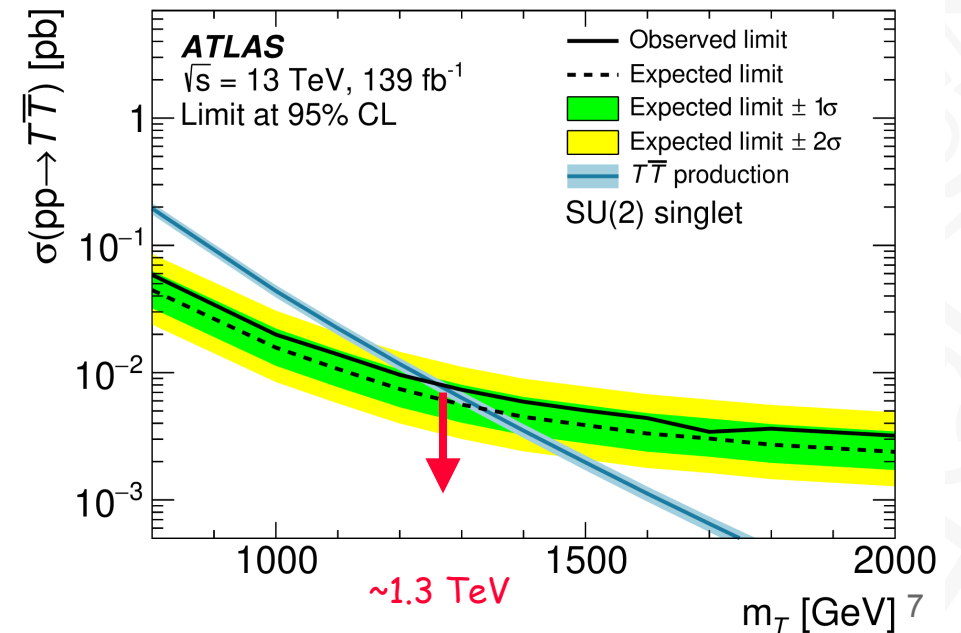
- Events with $1\ell + \text{MET}$ in the final state i.e. $\ell = e, \mu$
- Most sensitive to $T \rightarrow tZ, t \rightarrow \ell\nu b, Z \rightarrow \nu\nu$
- $B \rightarrow Wt \rightarrow \tau_{\text{had}}\nu_\tau \ell b$
- NNs to discriminate S/B SR \rightarrow high NNs score.



$\mathcal{B}(Zt, Ht, Wb)$



Simplified model: $T\bar{T}$ singlet



Search for pair production of Vector-Like T and B

B2G-20-011

$T\bar{T}$ and $B\bar{B}$: $T \rightarrow bW, T \rightarrow tH, T \rightarrow tZ$ $B \rightarrow tW, B \rightarrow bH, B \rightarrow bZ$

- Single ℓ ($T\bar{T}$ or $B\bar{B}$, $B \rightarrow tW$)

H/Z/t/b ident. by deepAK8 \rightarrow reco. VLQ candidate

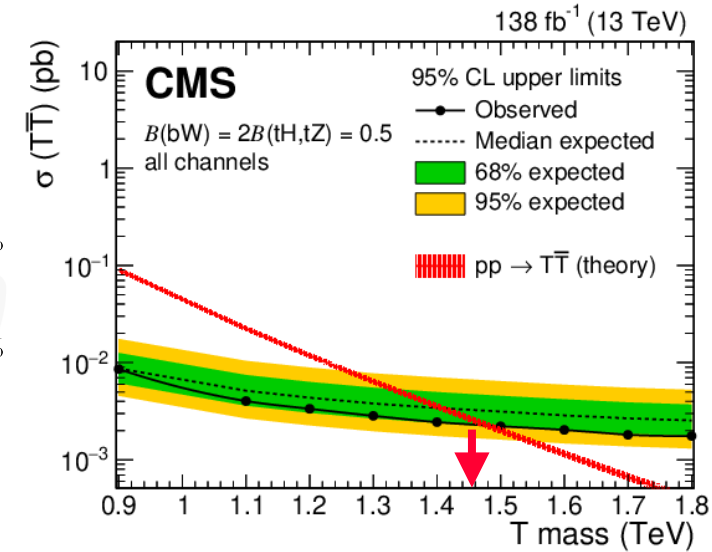
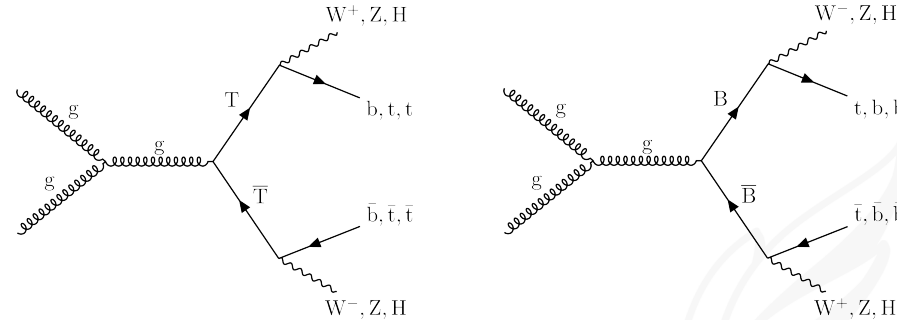
MLP: 3 outputs (signal, $t\bar{t}$ and W+jets) to separate S/B.

- SS 2ℓ : ($T \rightarrow tH (H \rightarrow WW)$ or $B \rightarrow tW$)

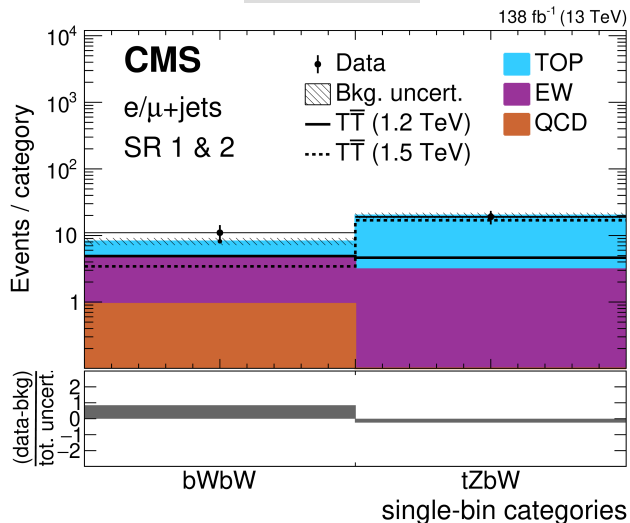
Subcategories based on $\ell_1\ell_2$ flavour: $\mu\mu, e\mu, ee$

- Multi ℓ : ($T \rightarrow tZ, B \rightarrow tW$).

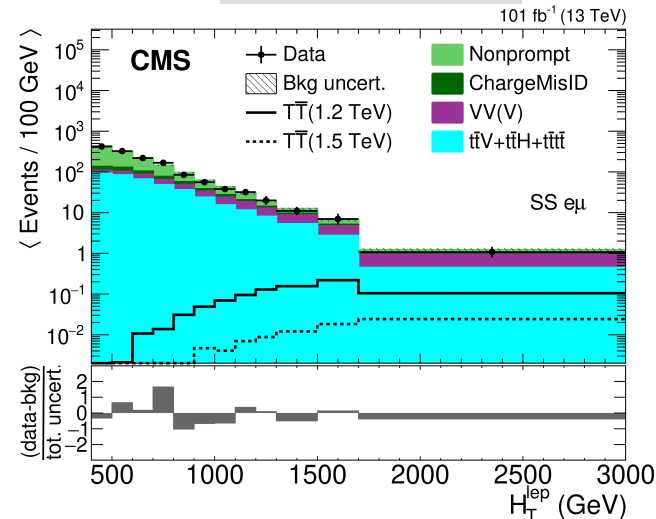
Subcategories based on $\ell_1\ell_2\ell_3$ flavour: $eee, ee\mu, e\mu\mu, \mu\mu\mu$



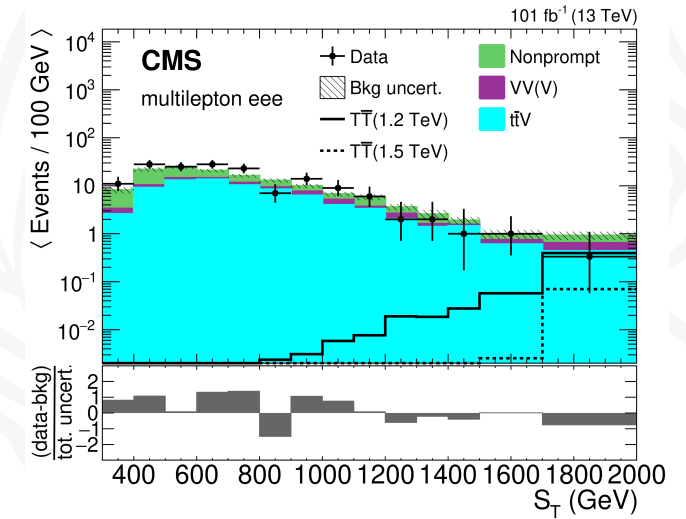
SR - 1 lep



SR - 2 lep SS: $e\mu$

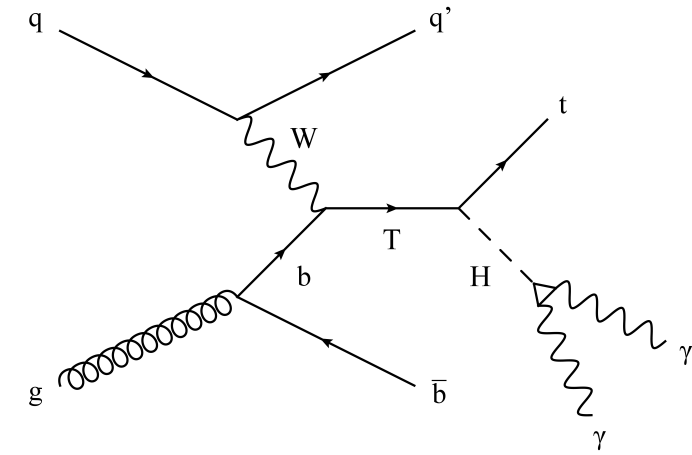


SR - Multi-lep: eee



Search for Single production of $T \rightarrow Ht \rightarrow \gamma\gamma t$

[B2G-21-007](#)



-Events with $T \rightarrow Ht, H \rightarrow \gamma\gamma, t \rightarrow wb$

- 2 category : leptonic/hadronic decay of t

$1\ell + 2\gamma + 1b$ jet

$0\ell + 2\gamma + 3$ jets (1b at least)

- 2 BDTs as S/B discriminant - 1 per category. (BDT-SMH)

- 1 BDT for non resonant background in hadronic category.

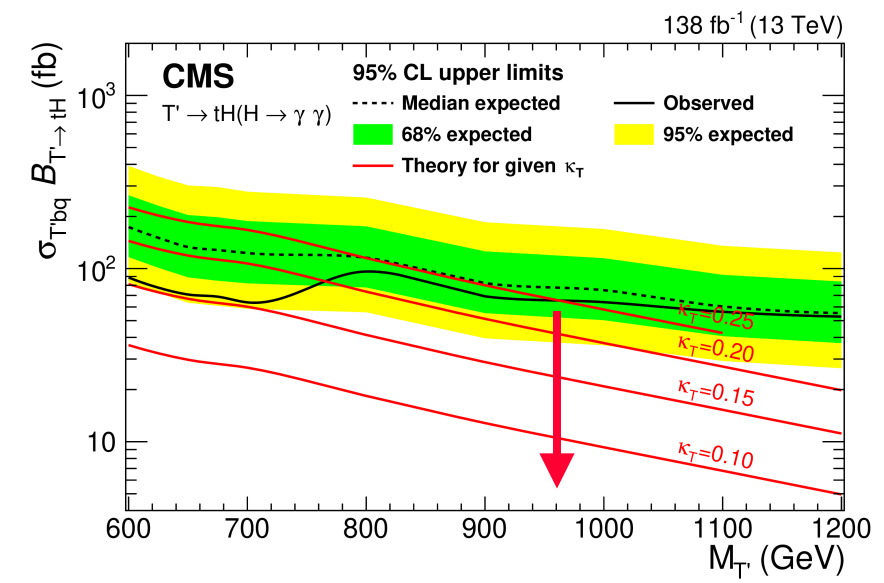
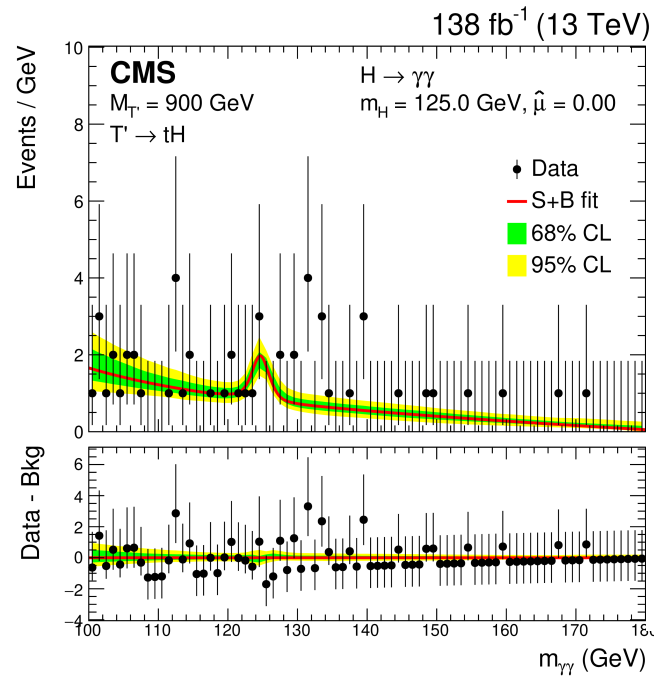
(BDT-NRB)

→ BDT-SMH and BDT-NRB trained on 3 $m_{T'}$ regions:

$m_{T'} \in [600 - 700], [700, 1000]$ and $[1000, 1200]$

S eff. $\sim 75(96)$ % - leptonic(hadronic)

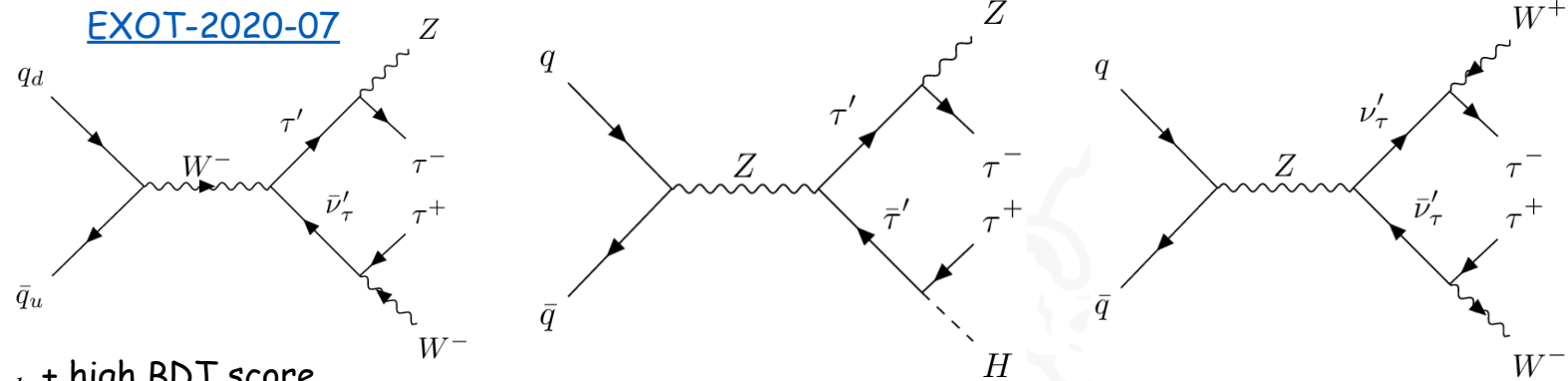
B eff. ~ 10 % both.



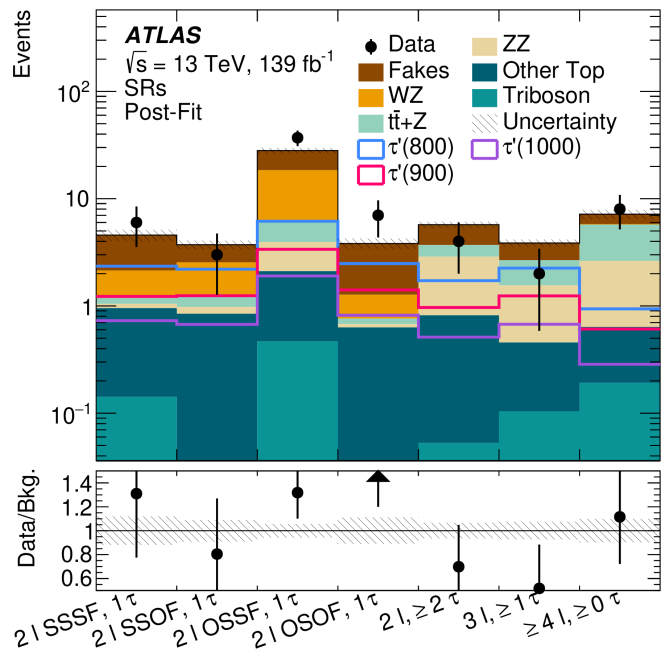
~ 950 GeV

Search for third-generation vector-like lepton

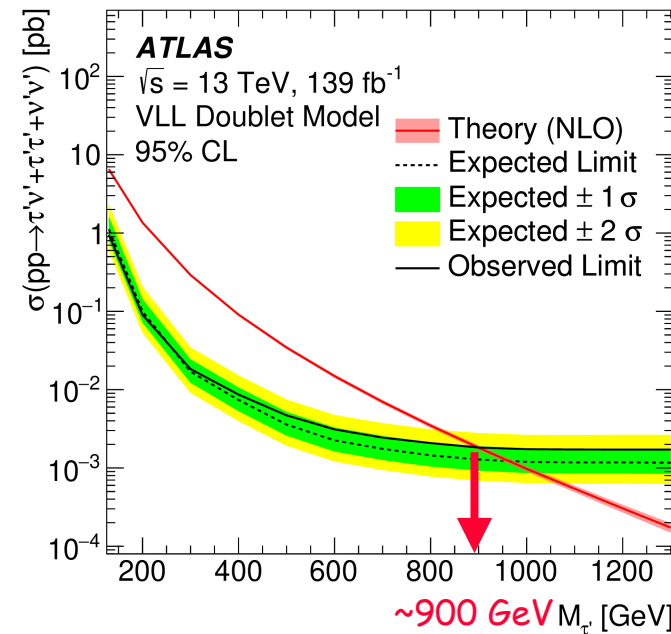
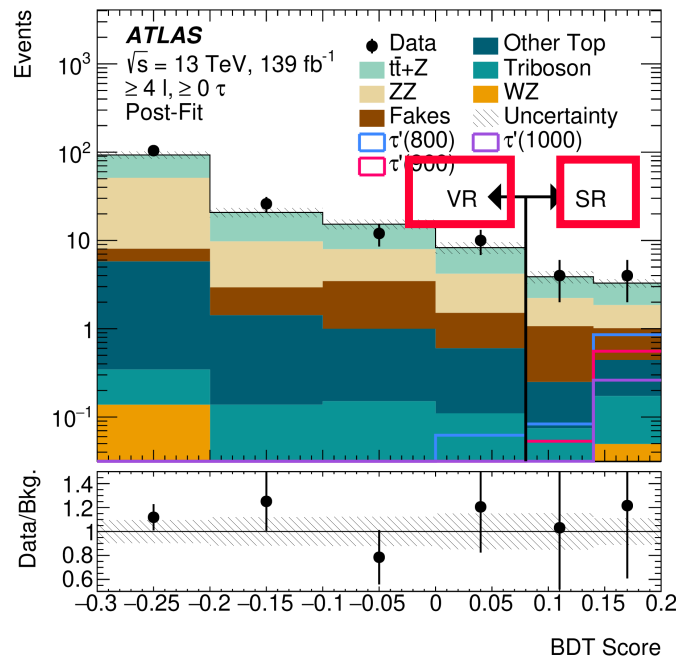
- Doublet vector-like lepton model ($\tau', \nu_{\tau'}$)
- Couple only to the 3rd lepton generation.
- Events with multi-lepton in final state
- BDTs to maximise signal significance
- 7 SRs: $\#\ell$, charge(flavour) combination and $\#\tau_{had}$ + high BDT score.
- 7 VR: low BDTs score.



7 SRs : #yields

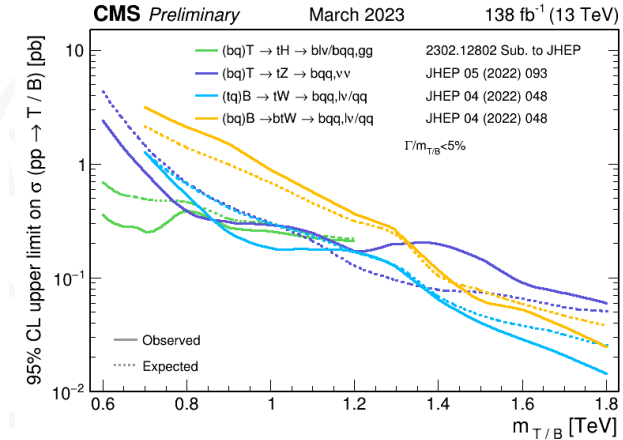


$\geq 4\ell + 0\tau_{had}$

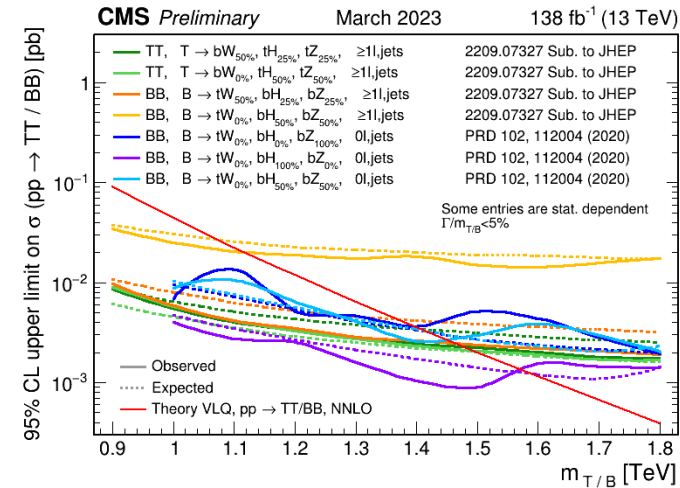


CMS results excl. up to $m_{\tau'} 1000 \text{ GeV}$

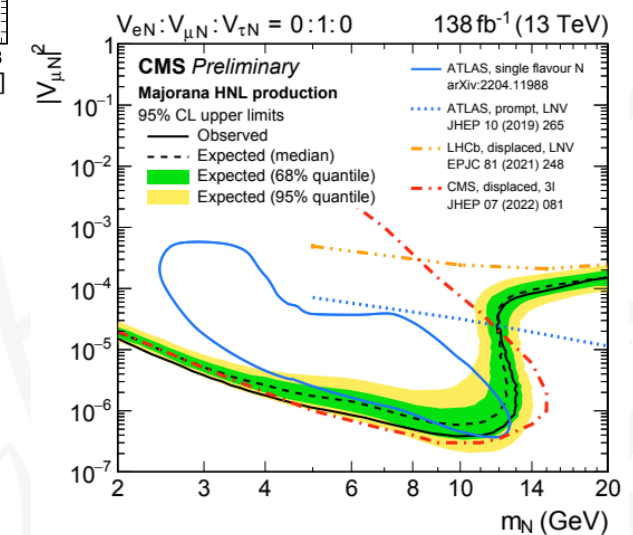
VLQ Single Production



VLQ Pair production



HNL pure μ coupling



- Only new analysis published since last Moriond were shown
- All single and pair VLQ production performed with the run2 dataset are summarised
- Similarly, low mass HNLs summarised together with ATLAS results.
- Several techniques used to maximise sensitivities.
- No evidence of new physics is observed **YET !**
- Many phase spaces (not yet excluded) have to be explored → We need more data !
- Run 3 has only started ~ 35 fb⁻¹ for ATLAS and CMS of collected data

The best is yet to come!

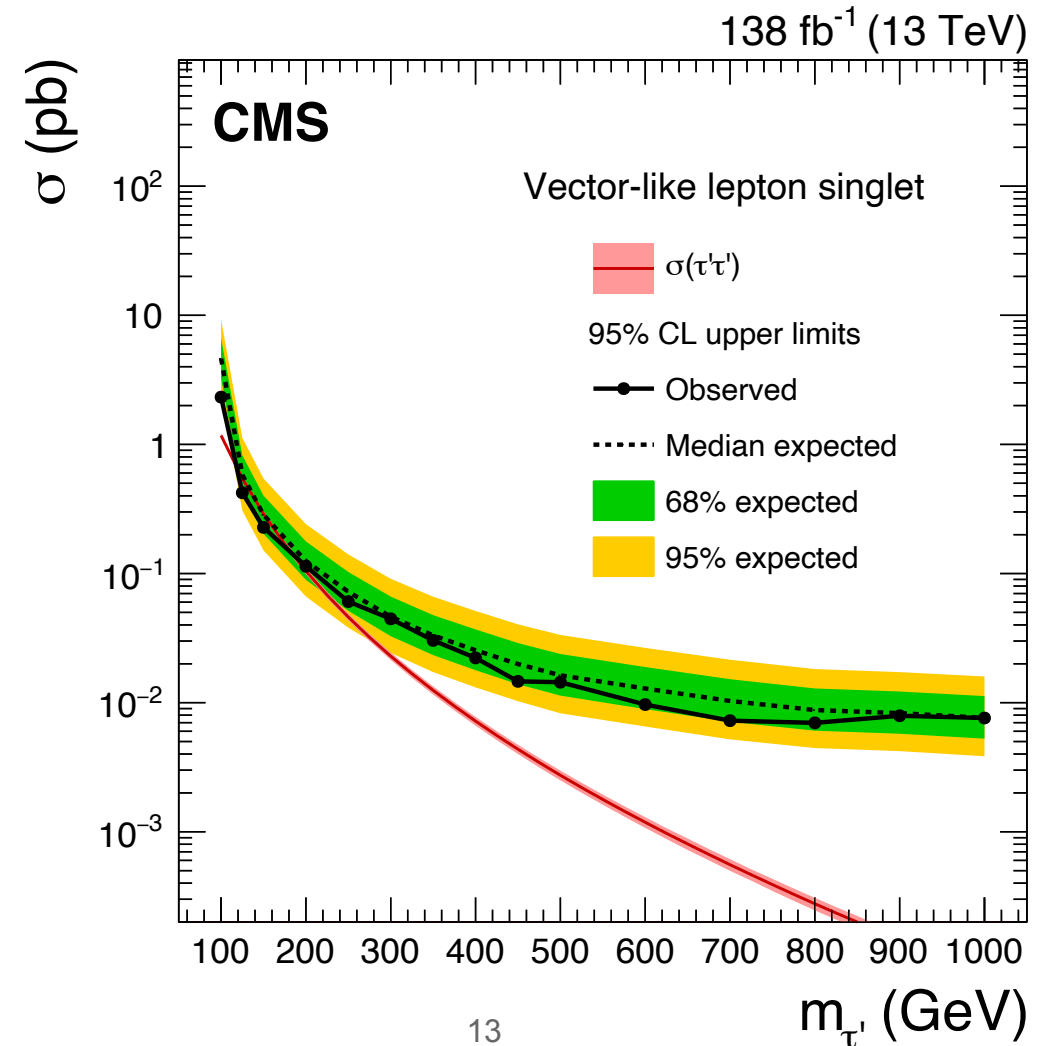
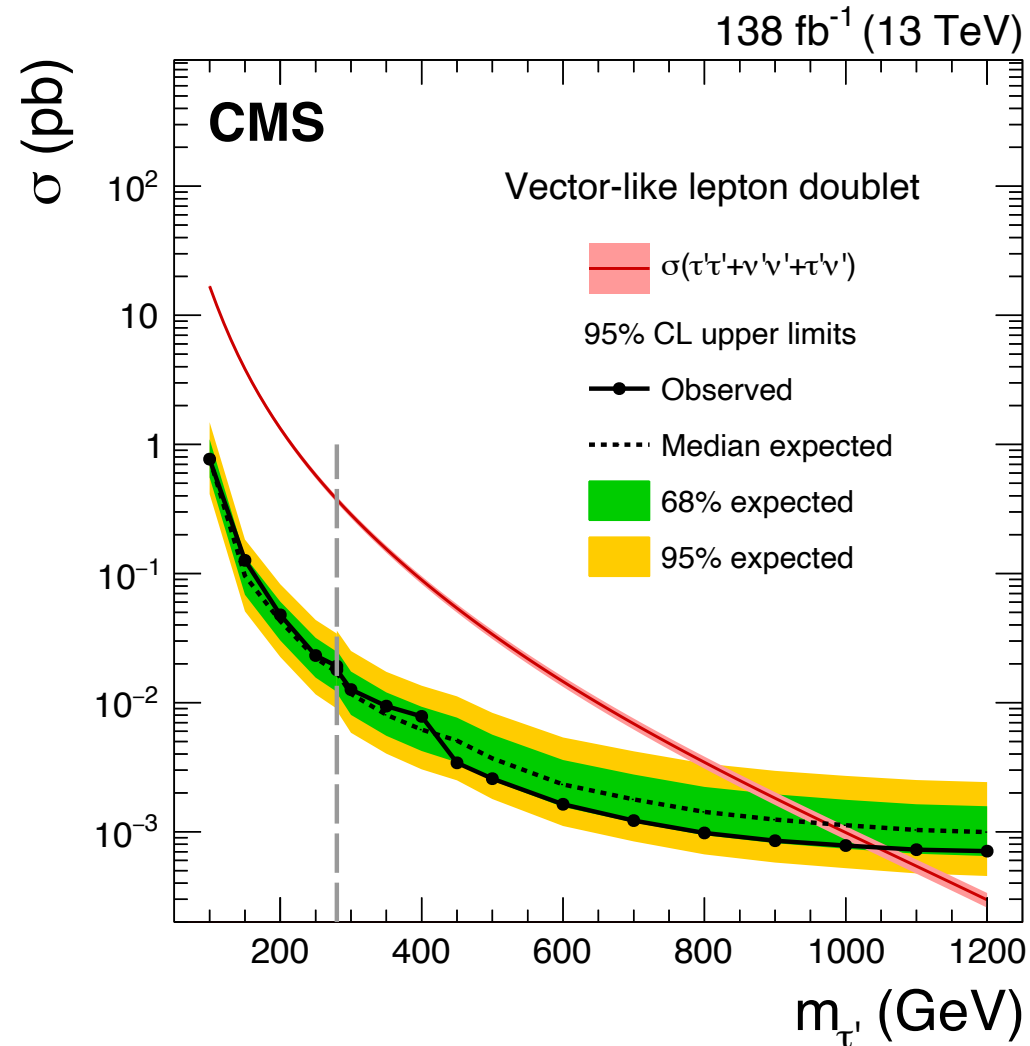
Backup



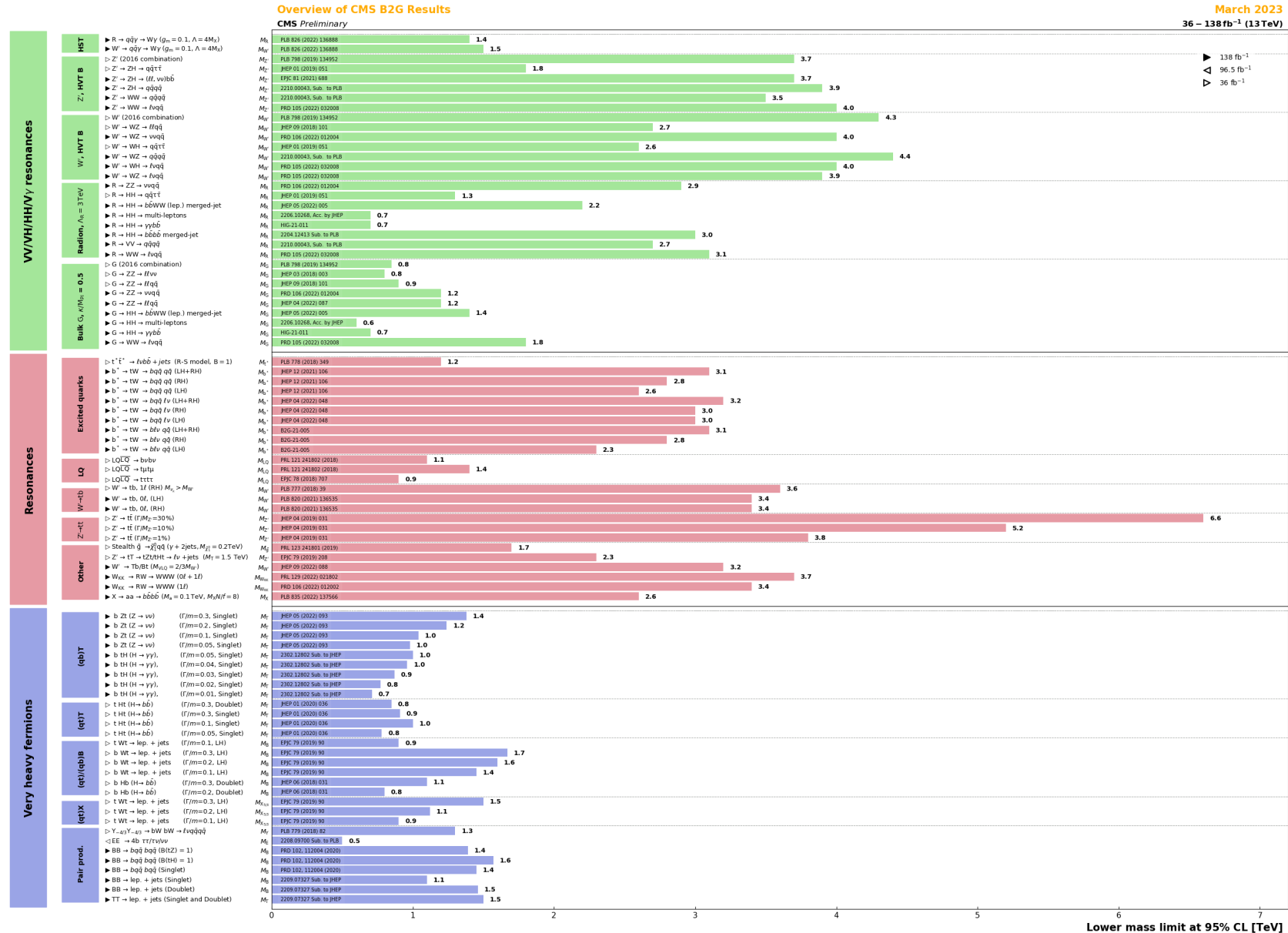
Vector-like Leptons

- Inclusive nonresonant multilepton probes of new phenomena

[EXO-21-002](#)



Backup: Summary of CMS B2G results including VLQs



Summary of ATLAS Heavy particles results including VLQs and HNL



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary
 $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$
 $\sqrt{s} = 13 \text{ TeV}$

Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference		
Extra dimen.	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	1-4 j	Yes	139	M_0 11.2 TeV $n=2$	2102.10874	
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_0 8.6 TeV $n=3$ HLZ NLO	1707.04147	
	ADD QBH	-	2j	-	139	M_n 9.4 TeV $n=6$	1910.08447	
	ADD BH multijet	-	$\geq 3j$	-	3.6	M_n 9.55 TeV $n=6, M_0 = 3 \text{ TeV, rot BH}$	1512.02586	
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	G_{KK} mass 4.5 TeV $k/\overline{M}_{Pl} = 0.1$	2102.13405	
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV $k/\overline{M}_{Pl} = 1.0$	1808.02380	
	Bulk RS $G_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	36.1	g_{KK} mass 3.8 TeV $\Gamma/m = 15\%$	1804.10823	
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3j$	Yes	36.1	KK mass 1.8 TeV Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	1803.09678	
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass 5.1 TeV	1903.06248
		SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass 2.42 TeV	1709.07242
Leptophobic $Z' \rightarrow bb$		-	2b	-	36.1	Z' mass 2.1 TeV	1805.09299	
Leptophobic $Z' \rightarrow tt$		$0 e, \mu$	$\geq 1 b, \geq 2J$	Yes	139	Z' mass 4.1 TeV $\Gamma/m = 1.2\%$	2005.05138	
SSM $W' \rightarrow \ell\nu$		$1 e, \mu$	-	Yes	139	W' mass 6.0 TeV	1906.05609	
SSM $W' \rightarrow \tau\nu$		1τ	-	Yes	139	W' mass 5.0 TeV	ATLAS-CONF-2021-025	
SSM $W' \rightarrow tb$		-	$\geq 1 b, \geq 1J$	-	139	W' mass 4.4 TeV	ATLAS-CONF-2021-043	
HVT $W' \rightarrow WZ$ model B		$0-2 e, \mu$	$2j/1J$	Yes	139	W' mass 340 GeV	2004.14636	
HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell'\ell'$ model C		$3 e, \mu$	$2j$ (VBF)	Yes	139	W' mass 4.3 TeV $g_V = 3$	2207.03925	
HVT $Z' \rightarrow WW$ model B		$1 e, \mu$	$2j/1J$	Yes	139	Z' mass 3.9 TeV $g_V = 3$	2004.14636	
LRSM $W_R \rightarrow \mu N_R$	2μ	1J	-	80	W_R mass 5.0 TeV $m(N_R) = 0.5 \text{ TeV, } g_L = g_R$	1904.12679		
CI	CI $qqqq$	-	2j	-	37.0	Λ 21.8 TeV η_{LL}	1703.09127	
	CI $\ell\ell qq$	$2 e, \mu$	-	-	139	Λ 35.8 TeV η_{LL}	2006.12946	
	CI $eebs$	$2e$	1b	-	139	Λ 1.8 TeV $g_* = 1$	2105.13847	
	CI $\mu\mu bs$	2μ	1b	-	139	Λ 2.0 TeV $g_* = 1$	2105.13847	
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	Λ 2.57 TeV $ C_{4l} = 4\pi$	1811.02305	
	DM	Axial-vector med. (Dirac DM)	-	2j	-	139	m_{med} 3.8 TeV	ATL-PHYS-PUB-2022-036
Pseudo-scalar med. (Dirac DM)		$0 e, \mu, \tau, \gamma$	1-4 j	Yes	139	m_{med} 376 GeV	2102.10874	
Vector med. Z' -2HDM (Dirac DM)		$0 e, \mu$	2b	Yes	139	$m_{Z'}$ 3.0 TeV $\tan\beta=1, g_Z=0.8, m(\chi)=100 \text{ GeV}$	2108.13391	
Pseudo-scalar med. 2HDM+a		multi-channel	-	-	139	m_a 800 GeV $\tan\beta=1, g_s=1, m(\chi)=10 \text{ GeV}$	ATLAS-CONF-2021-036	
LQ	Scalar LQ 1 st gen	$2e$	$\geq 2j$	Yes	139	LQ mass 1.8 TeV $\beta = 1$	2006.05872	
	Scalar LQ 2 nd gen	2μ	$\geq 2j$	Yes	139	LQ mass 1.7 TeV $\beta = 1$	2006.05872	
	Scalar LQ 3 rd gen	1τ	2b	Yes	139	LQ_3^+ mass 1.49 TeV $\mathcal{B}(LQ_3^+ \rightarrow br) = 1$	2303.01294	
	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 2j, \geq 2b$	Yes	139	LQ_3^+ mass 1.24 TeV $\mathcal{B}(LQ_3^+ \rightarrow \tau\nu) = 1$	2004.14060	
	Scalar LQ 3 rd gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 j, \geq 1 b$	-	-	139	LQ_3^+ mass 1.43 TeV $\mathcal{B}(LQ_3^+ \rightarrow tr) = 1$	2101.11582	
	Scalar LQ 3 rd gen	$0 e, \mu, \geq 1 \tau, 0-2j, 2b$	-	-	139	LQ_3^+ mass 1.26 TeV $\mathcal{B}(LQ_3^+ \rightarrow b\nu) = 1$	2101.12527	
	Vector LQ mix gen	multi-channel	$\geq 1j, \geq 1b$	Yes	139	LQ_3^+ mass 2.0 TeV $\mathcal{B}(U_1 \rightarrow t\nu) = 1, Y\text{-M coupl.}$	ATLAS-CONF-2022-052	
	Vector LQ 3 rd gen	$2 e, \mu, \tau$	$\geq 1b$	Yes	139	LQ_3^+ mass 1.96 TeV $\mathcal{B}(LQ_3^+ \rightarrow br) = 1, Y\text{-M coupl.}$	2303.01294	
Vector-like fermions	VLQ $TT \rightarrow Zt + X$	$2e/2\mu \geq 3e, \mu$	$\geq 1 b, \geq 1j$	-	139	T mass 1.46 TeV	2210.15413	
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV	1808.02343	
	VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS)/2e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	1807.11883	
	VLQ $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3j$	Yes	139	T mass 1.8 TeV	ATLAS-CONF-2021-040	
	VLQ $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	Y mass 1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_Y(Wb) = 1$	1812.07343	
	VLQ $B \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1j, \geq 1J$	-	139	B mass 2.0 TeV	ATLAS-CONF-2021-018	
	VLL $\tau' \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1j$	Yes	139	τ' mass 898 GeV	2303.05441	
	Exctd ferm.	Excited quark $q^* \rightarrow qg$	-	2j	-	139	q^* mass 6.7 TeV	1910.08447
Excited quark $q^* \rightarrow q\gamma$		1γ	1j	-	36.7	q^* mass 5.3 TeV	1709.10440	
Excited quark $b^* \rightarrow bg$		-	1b, 1j	-	139	b^* mass 3.2 TeV	1910.08447	
Excited lepton τ^*		2τ	$\geq 2j$	-	139	τ^* mass 4.6 TeV	2303.09444	
Other		Type III Seesaw	$2,3,4 e, \mu$	$\geq 2j$	Yes	139	N^0 mass 910 GeV	2202.02039
	LRSM Majorana ν	2μ	2j	-	36.1	N_R mass 3.2 TeV	1809.11105	
	Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$	$2,3,4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	2101.11961	
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2,3,4 e, \mu$ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV	2211.07505	
	Multi-charged particles	-	-	-	139	multi-charged particle mass 1.59 TeV	ATLAS-CONF-2022-034	
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV	1905.10130	

*Only a selection of the available mass limits on new states or phenomena is shown.

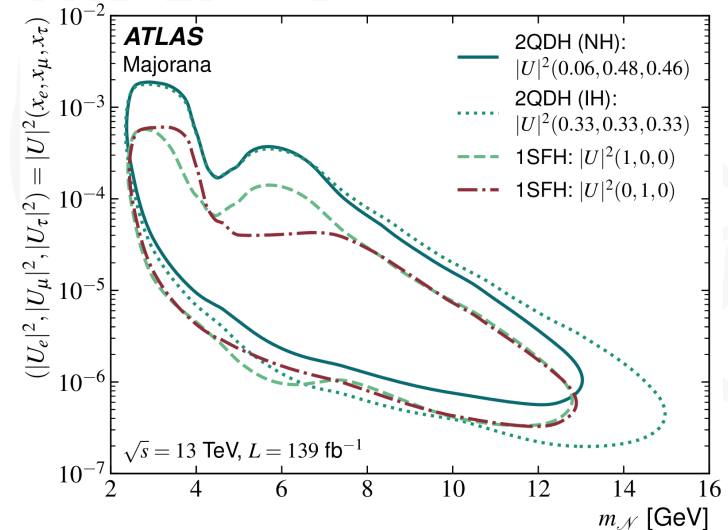
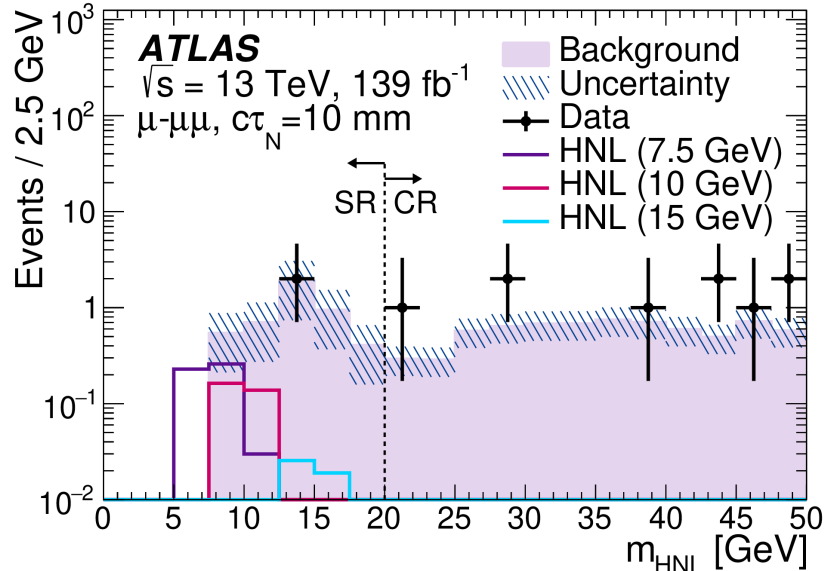
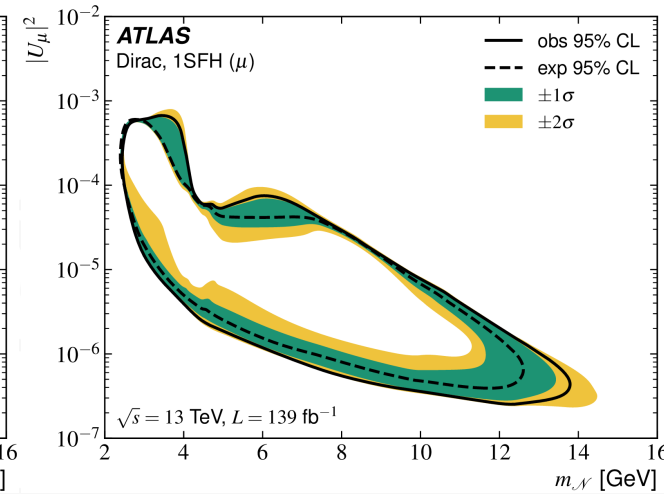
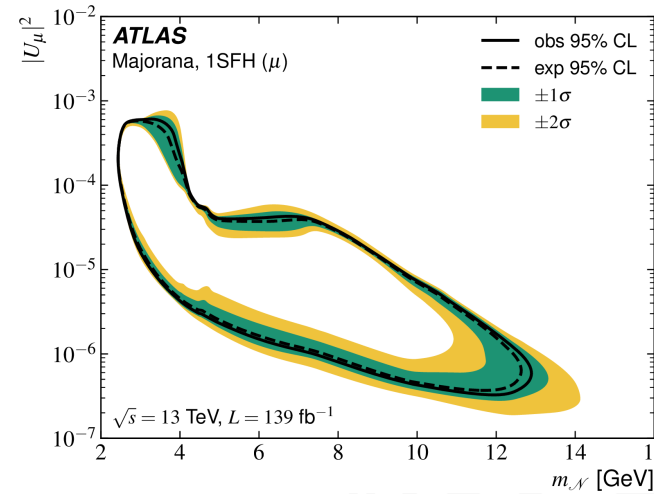
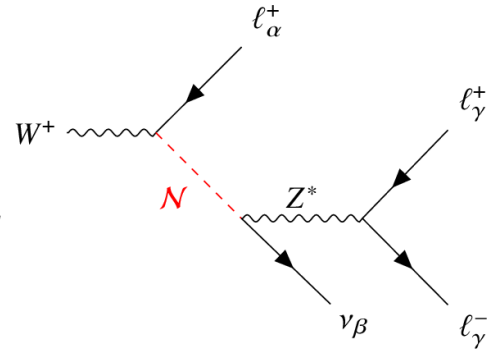
†Small-radius (large-radius) jets are denoted by the letter j (J).



Search for HNLs using a dilepton displaced vertex

EXOT-2019-29

- Type-I seesaw mechanism
- Dirac or Majorana nature.
- Long-lived : $\tau \propto m_N^{-5} \times |V_{\ell N}|^{-2}$
- $N \rightarrow \ell W^* \rightarrow \ell \ell \nu$ or $N \rightarrow Z^* \nu \rightarrow \ell \ell \nu$
- Displaced vertex (mass) reconstruction
- SR $m_{HNL} \in [0,20]$ CR $m_{HNL} \in [20,50]$ GeV
- SRs binned in leptons flavour : $\mu - \mu\mu, \mu - \mu e, e - ee, e - e\mu, \mu - ee, e - \mu\mu$
- Background estimated in data from CRs



Search for Single production of $T \rightarrow t Z$ $Z \rightarrow MET + t \rightarrow$ Jets final state.

$T \rightarrow tZ$ where $t \rightarrow Wb \rightarrow q' \bar{q} b$ and $Z \rightarrow \nu \bar{\nu}$.

Say how you do identify jets parent particle

High MET, High multiplicity of jets and Leptons veto

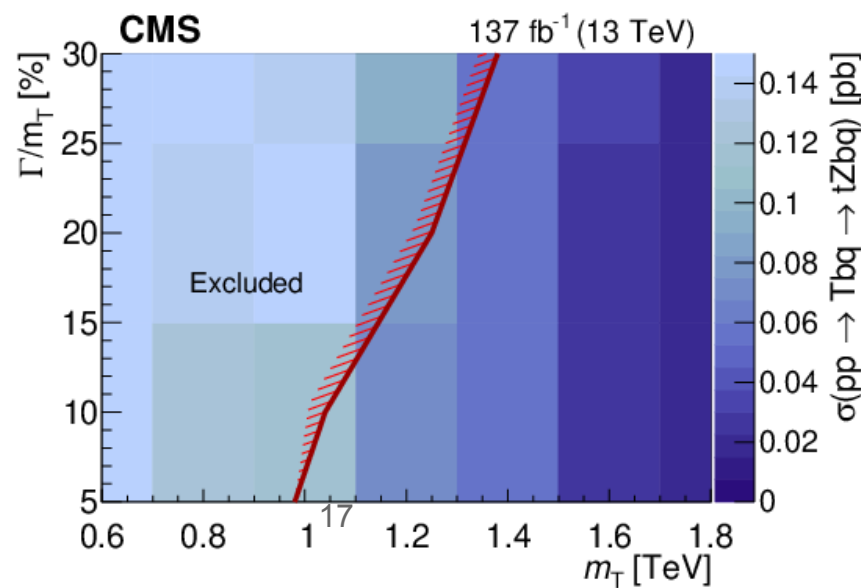
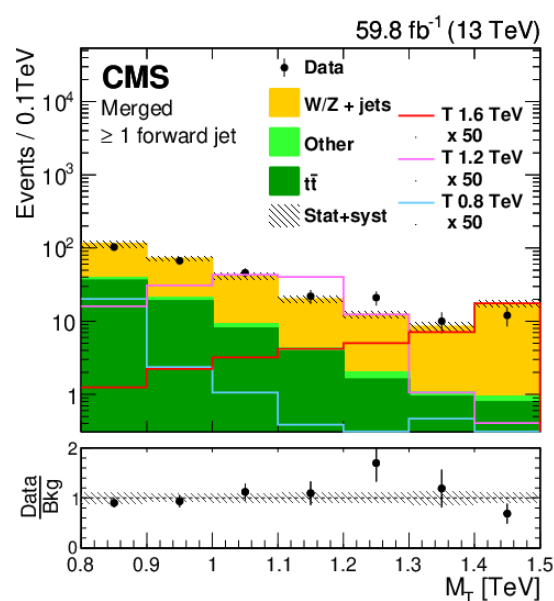
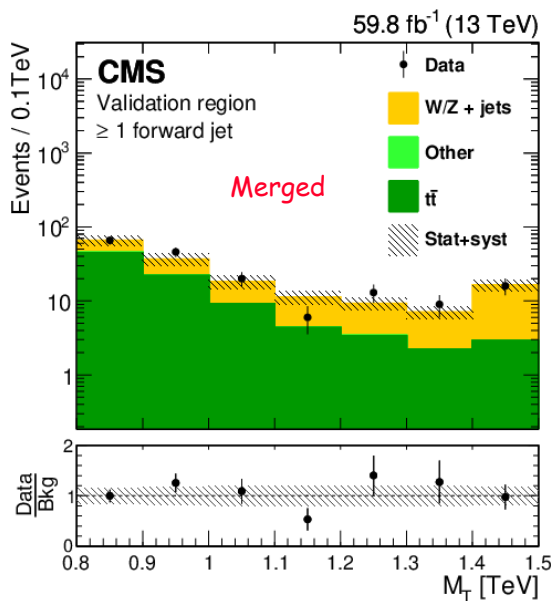
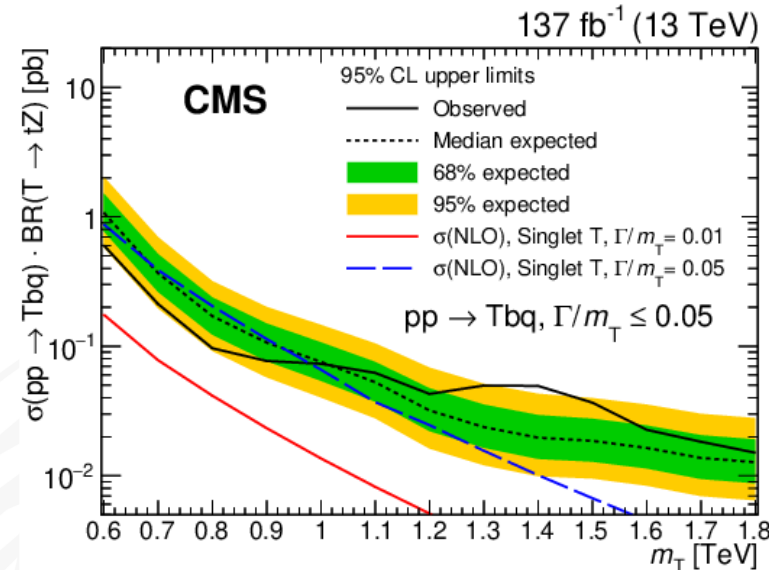
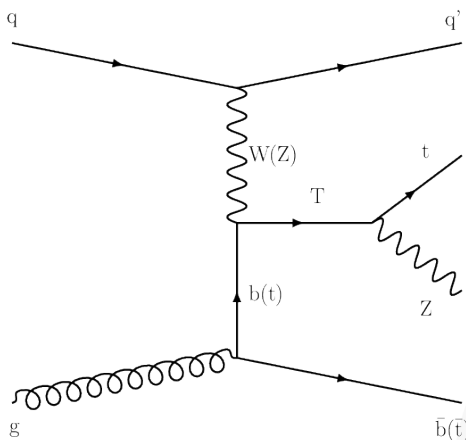
3 categories based on top quark identification :

- **Merged:** 1 single large-Radius (0.8) jet.
- **Partially Merged:** 1 W + b jet.
- **Resolved:** 3 small-Radius (0.4) jet.

2 categories: # forward jet 0 or 1

→ in total $3 \times 2 = 6$

B2G-19-004



Search for Single production of $T \rightarrow t Z(H) - t \rightarrow \text{leptons} + Z \rightarrow \text{hadrons} - \text{ATLAS}$

-b-assoc. production of single VL T

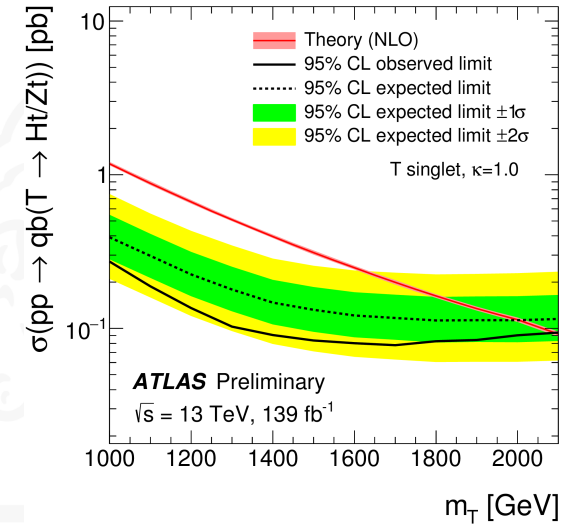
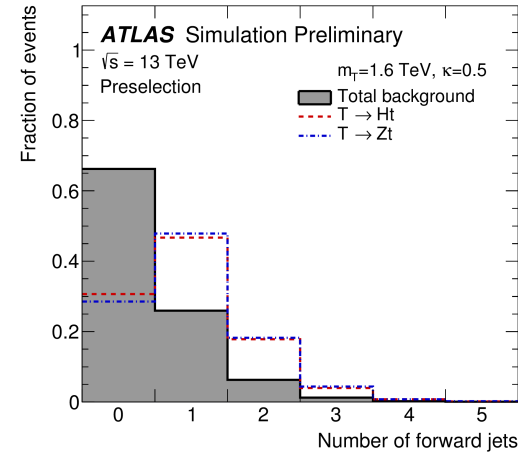
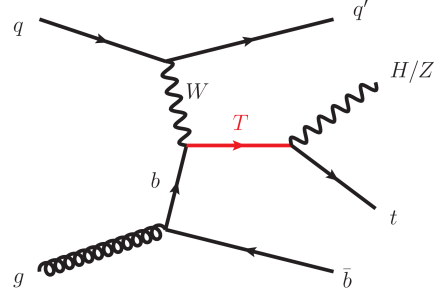
$$\left. \begin{aligned} - T \rightarrow tH, H \rightarrow b\bar{b} \\ - T \rightarrow tZ, Z \rightarrow q\bar{q} \end{aligned} \right\} + qb$$

-top quark decays leptonically $\rightarrow 1$ lepton ($e \mu$).

-1 forward jet for signal purity.

-Jets tagged as b, t_ℓ, t_h, H and Z jets using reclustered large-radius jets.

ATLAS-CONF-2021-040

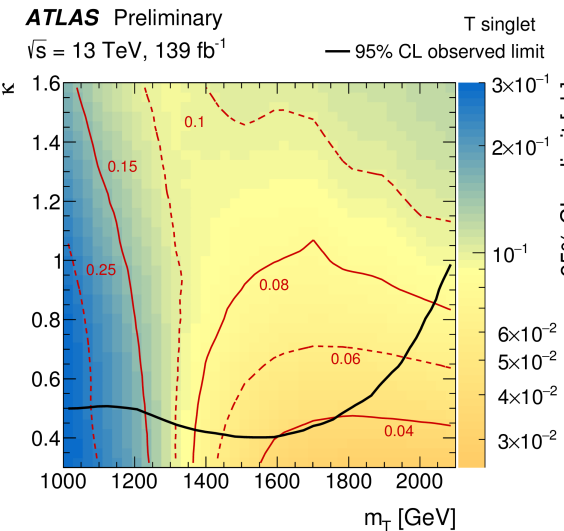
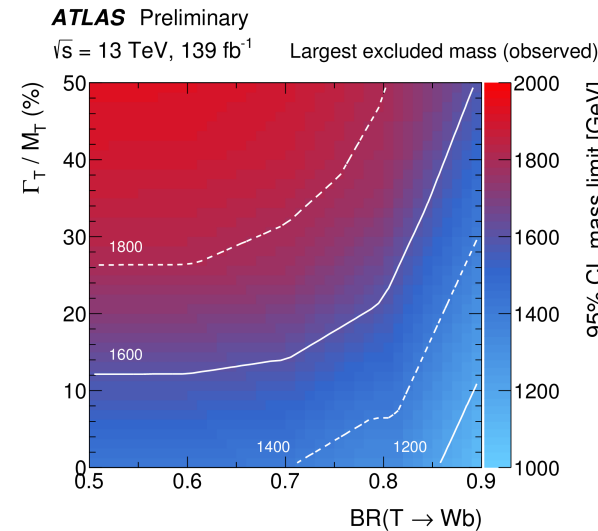
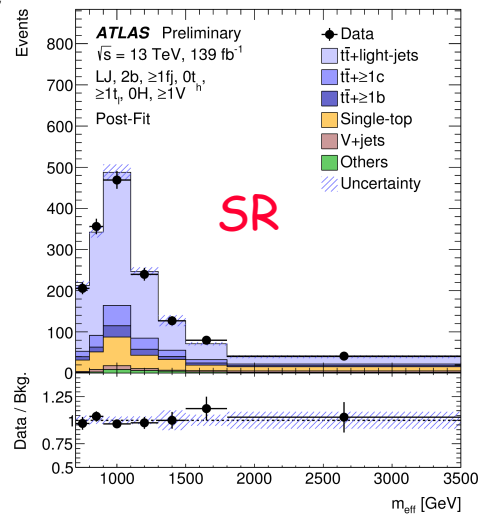
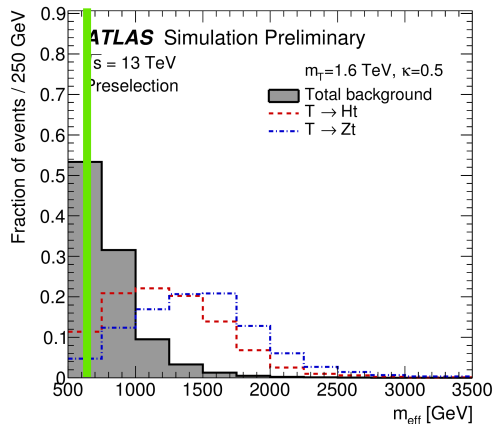


4 regions split in
 24 fit regions
 and 20 Validation Regions (VRs).

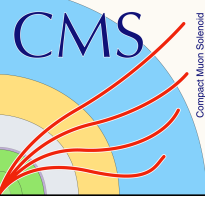
Baseline selections on jet and b -tag multiplicity

Jet multiplicity	b -tag multiplicity	Channel name	Targeted signal
3-5	1-2	LJ, 1-2b	$T \rightarrow Zt$
3-5	≥ 3	LJ, $\geq 3b$	$T \rightarrow Ht$
≥ 6	1-2	HJ, 1-2b	$T \rightarrow Zt$
≥ 6	≥ 3	HJ, $\geq 3b$	$T \rightarrow Ht$

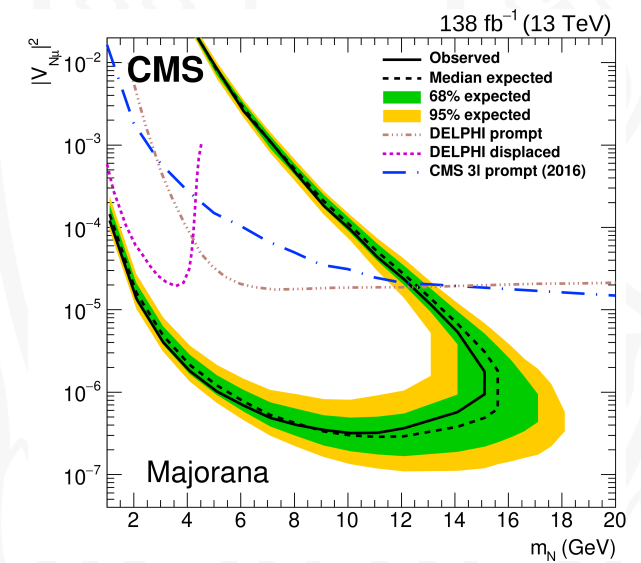
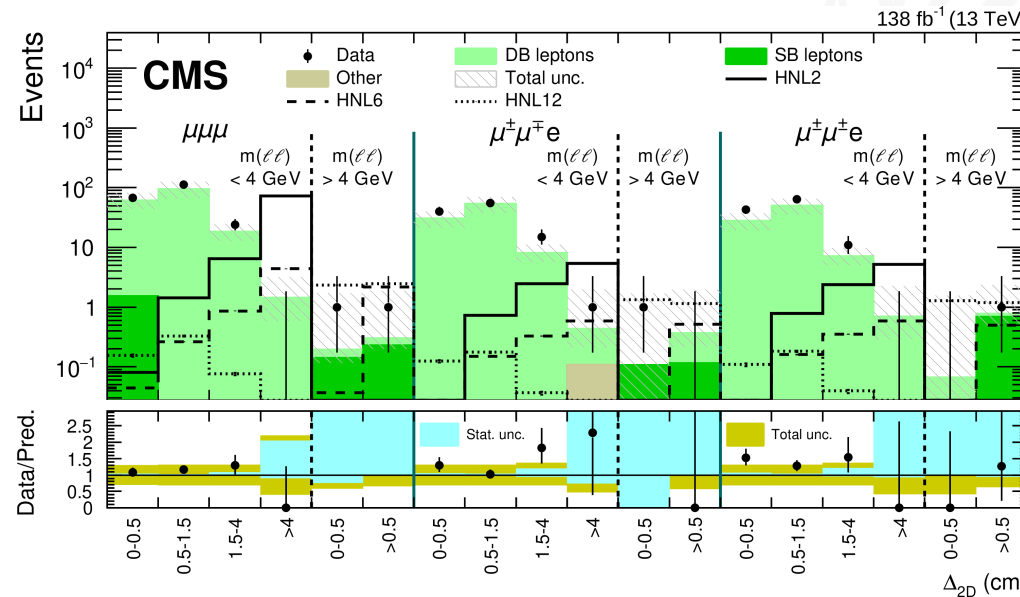
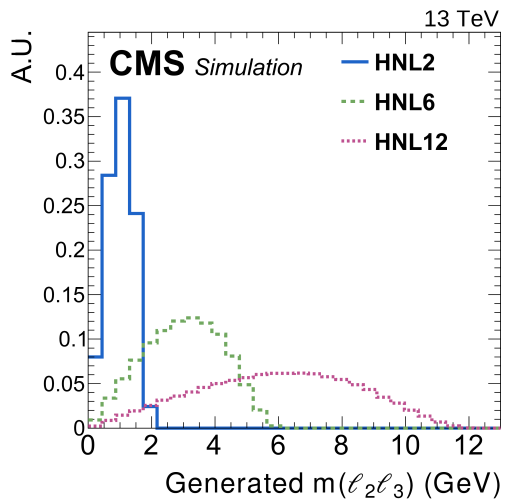
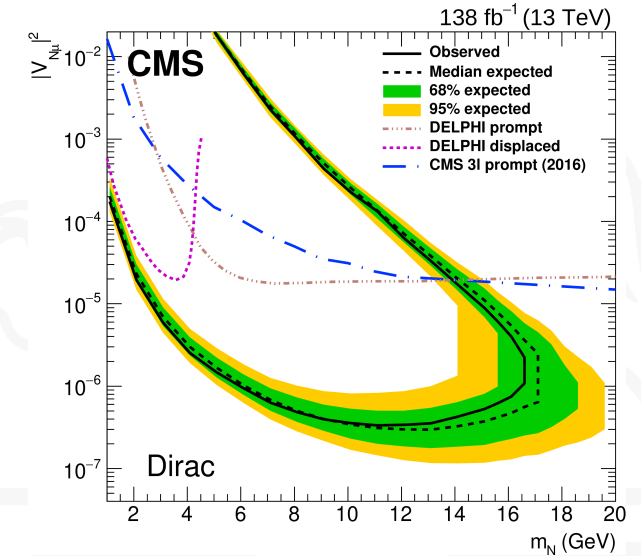
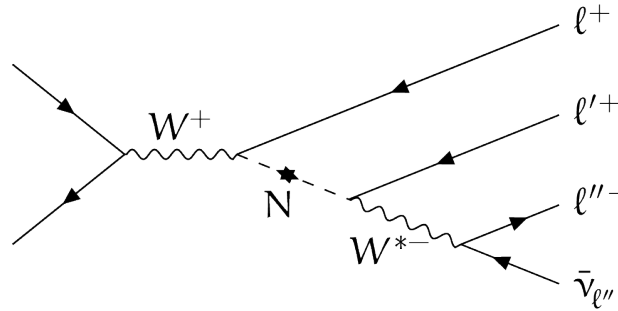
$-m_{eff}$: discriminate $m_{eff} = \sum_{\text{central jets}} p_T^j + \sum_{\text{leptons}} p_T^\ell + E_T^{miss}$



Search for HNLs in three leptons final states with displaced vertices. CMS



- Type-I seesaw mechanism
- Produced through mixing with active SM ν .
- Dirac - Majorana are considered.
- $N \rightarrow \ell W^* \rightarrow \ell \ell \nu$ or $N \rightarrow Z^* \nu \rightarrow \ell \ell \nu$
- Displaced vertex (mass) reconstruction of 2 ℓ : $\Delta_{2D}(m_{\ell\ell})$
- SRs binned in : leptons flavour i.e. $\mu - \mu\mu, \mu - \mu e, e - ee, e - e\mu$, (OS - SS), $m_{\ell\ell}$ and Δ_{2D} :
- Background estimated in data from CRs



Search for right-handed W_R bosons and heavy neutrino N_ℓ

- Similar to Z' search, LRSM is considered.

- Looking for $W_R \rightarrow \ell N_\ell$ where $N_\ell \rightarrow \ell q \bar{q}'$

- 2 Leptons ($\mu\mu, ee$) and $\#jets \geq 1$.

- 2 categories based on the topology of N_ℓ decays.

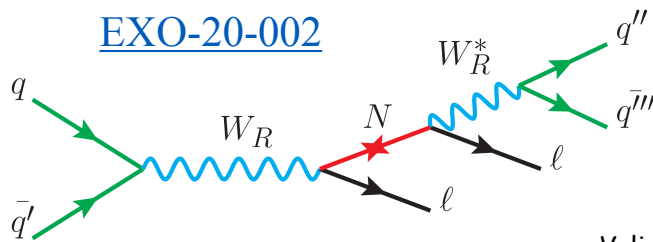
- **Resolved:** 2 leptons + AK4 jets ≥ 2 **Boosted:** 2 leptons + AK8 jets ≥ 1

- Reconstruction of $m_{\ell\ell}, m_{N_\ell}$ and $m_{W_R} = m_{\ell\ell j}(m_{\ell j})$ for resolved (boosted).

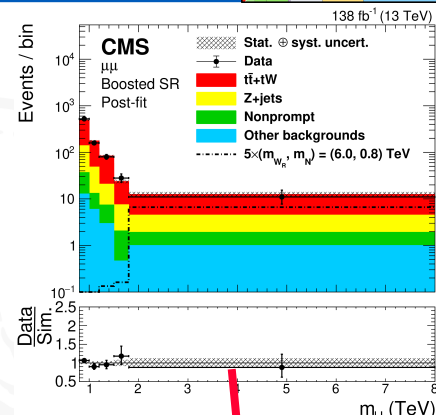
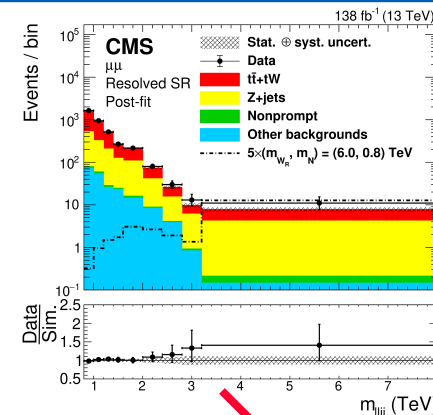
- $m_{\ell\ell}$: to reduce background ($T\bar{T}, DY+jets$) - define CRs/VRs and SRs

- Corrections tested in validation regions

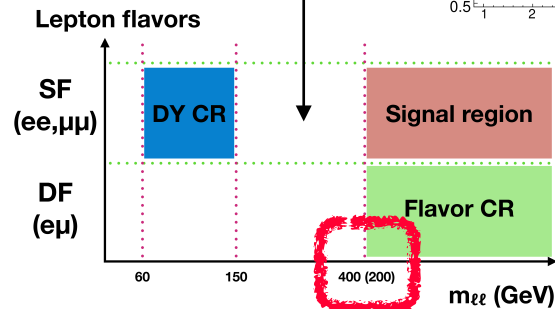
- m_{W_R} : Search deviations with respect to the SM background.



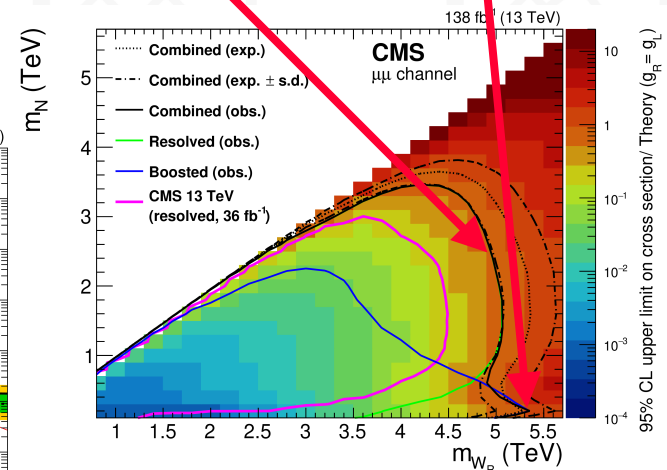
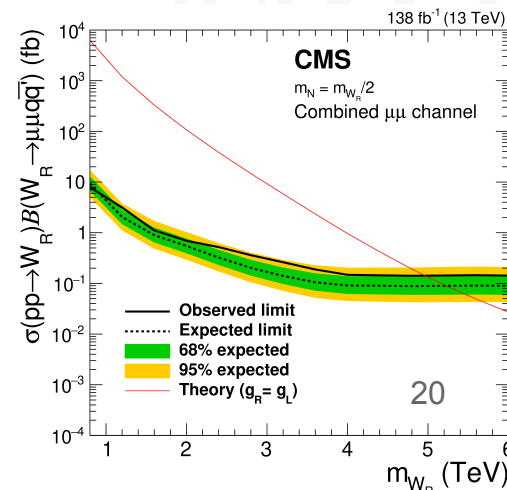
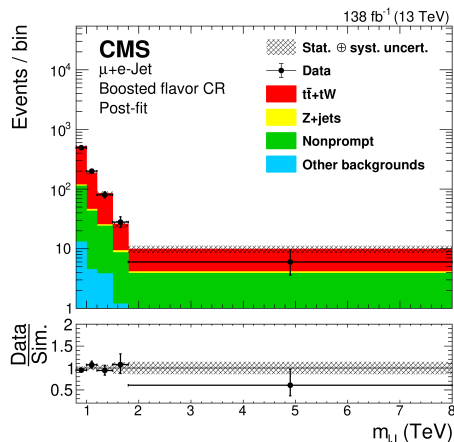
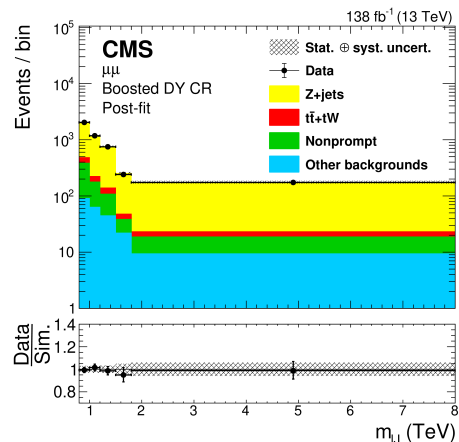
EXO-20-002



Validation region



Resolved(boosted)



Search for Z' bosons decaying to pair of Heavy Majorana neutrinos $N_\ell N_\ell$

- Left-Right symmetry model (LRSM) : Extension to the SM by an SU_R .

- New particles: W_R^\pm , Z' and 3 ν_R denoted N_ℓ , ($\ell = e, \mu, \tau$)

- Focus on Z' and N_ℓ .

- Same flavour leptons (e or μ) and # large-radius jets ≥ 2 .

- 3 categories based on the events topology (boosted/resolved)

AK4 jets ≥ 4 + #tight leptons = 2 + #AK8 jets=0
 # Ak4 jets ≥ 2 + #tight leptons ≥ 1 + #AK8 jets = 1
 - + - + AK8 jets ≥ 2 .

- Reconstruction of m_{N_ℓ} and $m_{Z'}$: key variables.

- $m_{\ell\ell} \geq 150$ GeV, $m_{Z'} > 300$ GeV (background rejection)

- SM dominant backgrounds $T\bar{T} + DY \Rightarrow$ CRs

