Heavy resonance searches

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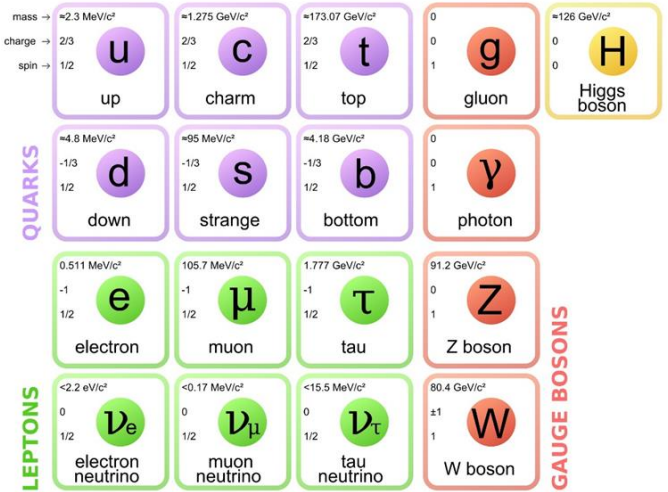
Heavy resonance search at collider experiments

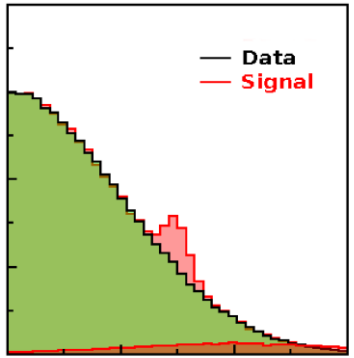
Standard Model (SM) is successful for particle physics

SM shortcomes (Hierarchy problem, Unific.of Gravity, Dark Matter/Energy) indicate the existence of New Physics → **Beyond Standard Model (BSM)** theories

Heavy resonance search is a good way to probe new physics

- Heavy resonances are predicted in many new physics models:
  - Two-Higgs-doublet model (A, $H^{\pm}$, …)
  - Heavy Vector triplet (W′, Z′)
  - Many more…
- A straight-forward way to observe new physics/particles:
  - Featured kinematics (e.g., "invariant mass") could make a bump on a rather flat SM background spectrum, indicating an unknown resonance particle
  - High energy collider like LHC makes it possible to search for "heavy" resonances at high energy





$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$

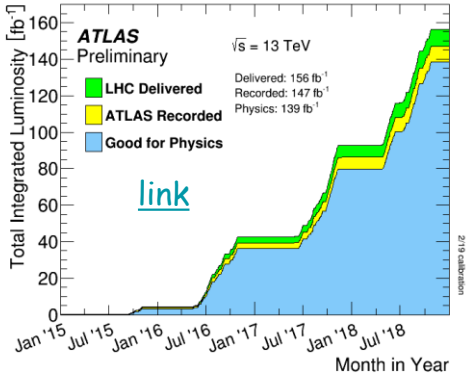
ATLAS/CMS heavy resonance searches results

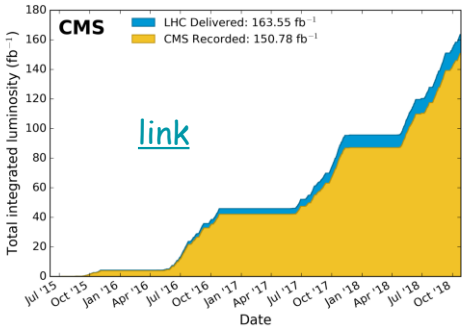
Results shown today are based on LHC Run2 pp collision data at $\sqrt{s}$= 13 TeV.

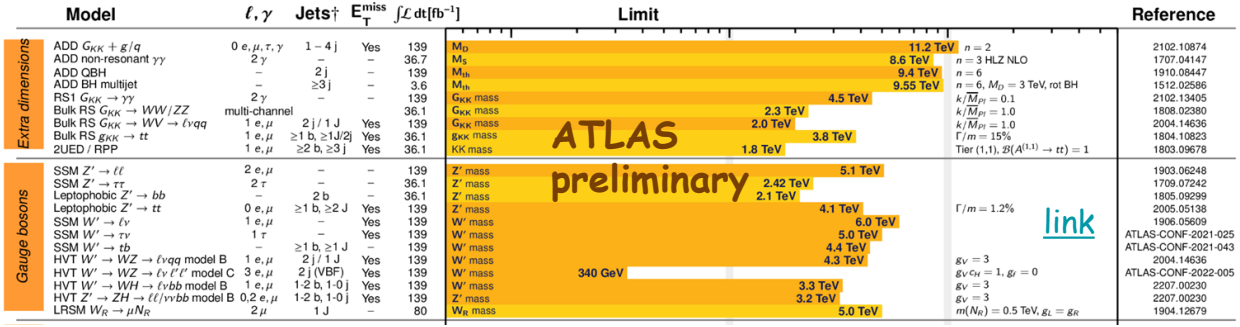
~140 fb^{-1} good-for-physics data collected

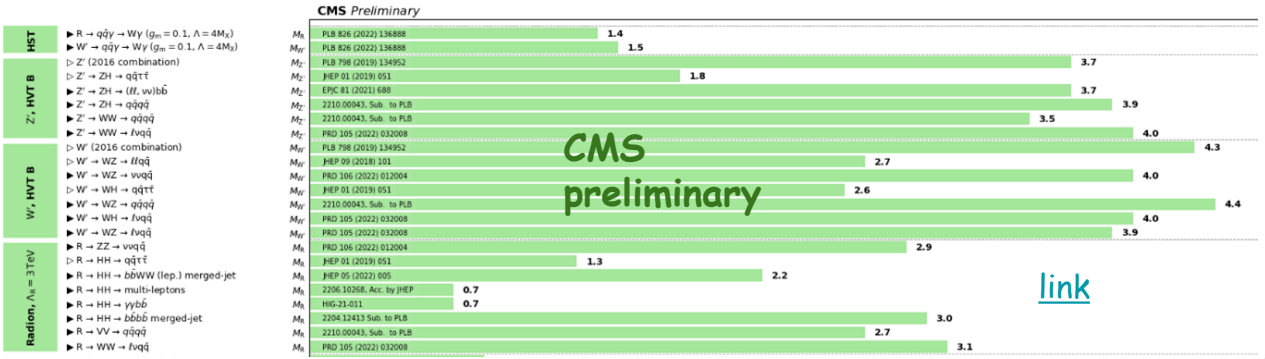
Many new results since last LHCP, covering wide range of models

Only part of the latest ATLAS/CMS results will be shown today





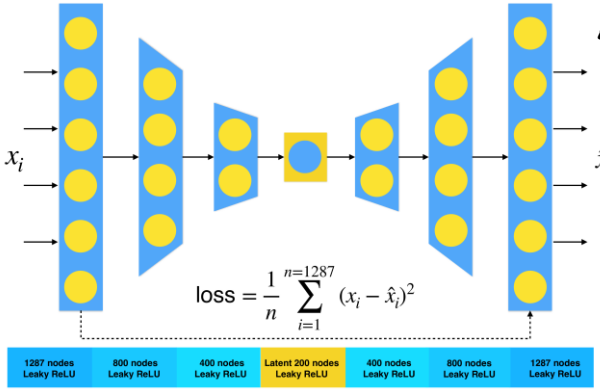




Anomaly detection in jet+Y

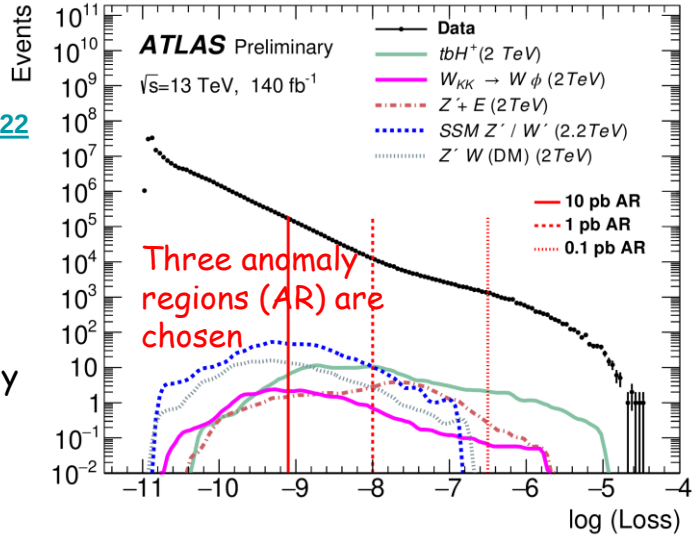
Two-body final states: jet+Y, where Y can be a lepton (electron or muon), a photon, or another jet

ATLAS-CONF-2023-022



AutoEncoder (AE):

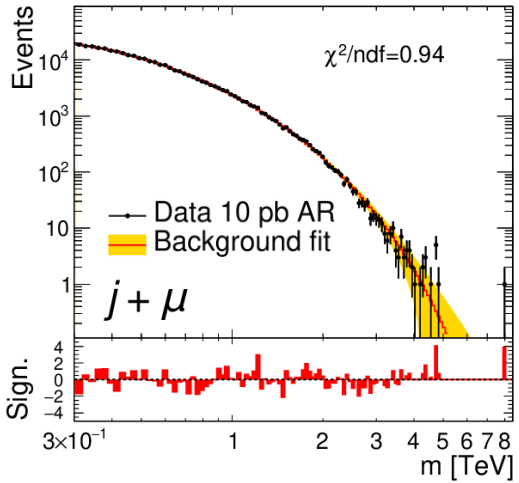
- Commonly used with unsupervised learning
- Trained with 1% randomly selected events
- Alerts to anomalous events with high loss

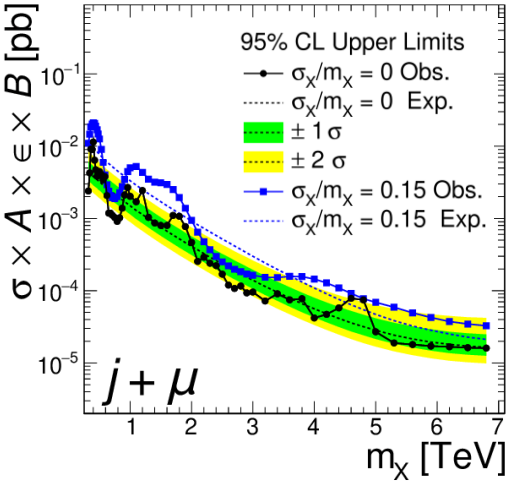


Invariant mass spectra in each anomaly region are examined for any localized excesses

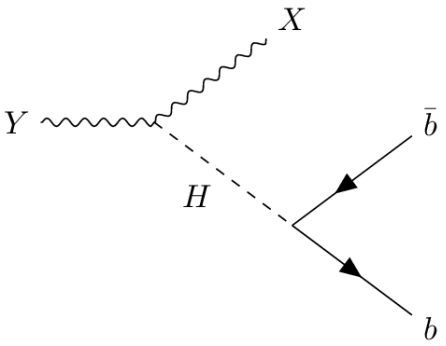
Largest excess reported by BumpHunter at $m_{j\mu}$ = 4.8 TeV with %0 width in 10 pb AR: local significance of 2.9σ

No significant resonance-like signal found





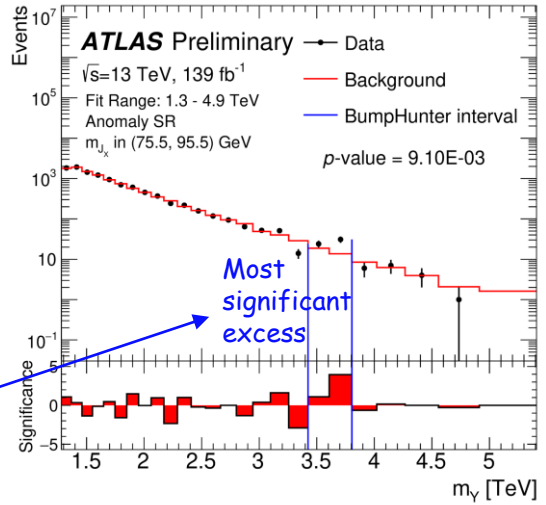
Generic $Y \to XH$ in hadronic final states



Two large-R jets: J_H (one with larger D_{Hbb}) + J_X

$$D_{H_{bb}} = \ln \frac{p_{\text{Higgs}}}{f_{\text{top}} \cdot p_{\text{top}} + (1 - f_{\text{top}}) \cdot p_{\text{multijet}}}$$

ATLAS-CONF-2022-045



Largest excess found in the anomaly SR with a global significance of 1.47σ

No significant deviations from SM.

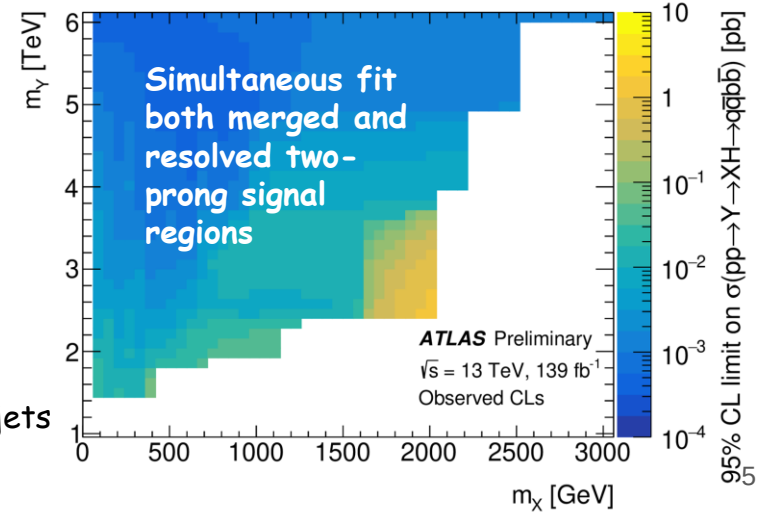
Three signal regions:

- **Anomaly Region:** Anomaly Score > 0.5 → defined using a variational recurrent neural network (VRNN)
- **Two-prong Merged Region**
- **Two-prong Resolved Region**

> Target the benchmark $X \to q\bar{q}$ decay

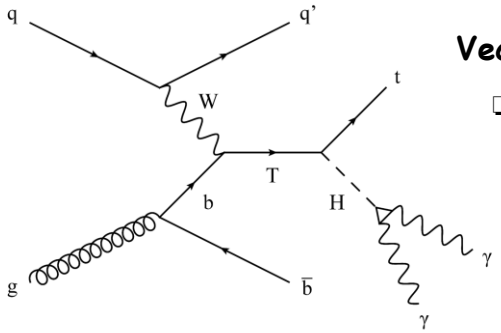
Merged: m_Y built by two large-R jets

Resolved: m_Y computed with large-R Higgs jet and the two small-R X jets



Vector-like quark $T' \rightarrow tH$

arXiv:2302.12802



Vector-like quark (VLQ):

- Hypothetical spin-1/2, colored particles whose left- and right-handed components transform in the same way under the SM gauge group

Γ/M_T, : relative decay width

κ_T : coupling to third generation quarks

Leptonic category:

- pair of photons and at least one electron or muon
- at least one b-tagged jet

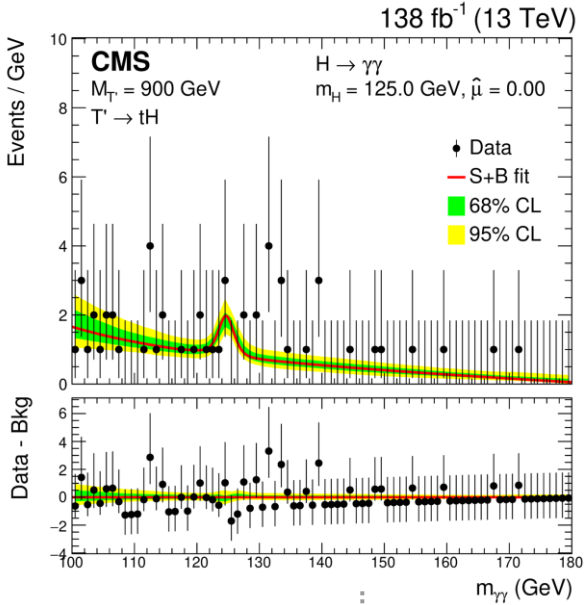
Hadronic category:

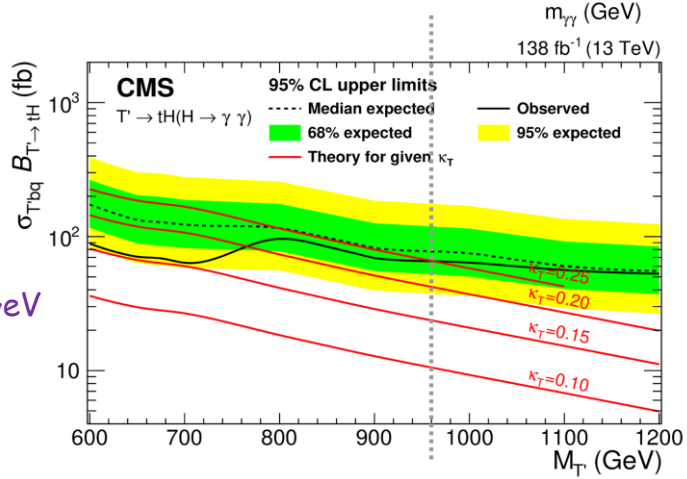
- pair of photons and no lepton
- three jets, of which at least one is b-tagged

First T' search by the LHC experiments in $H \rightarrow \gamma\gamma$

No statistically significant excesses

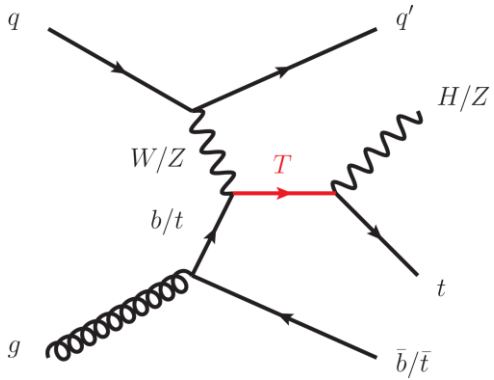
T' excluded up to a mass of 960 GeV for $\kappa_T = 0.25$ and $\Gamma/M_T, < 5\%$





Vector-like quark $T \rightarrow Ht/Zt$

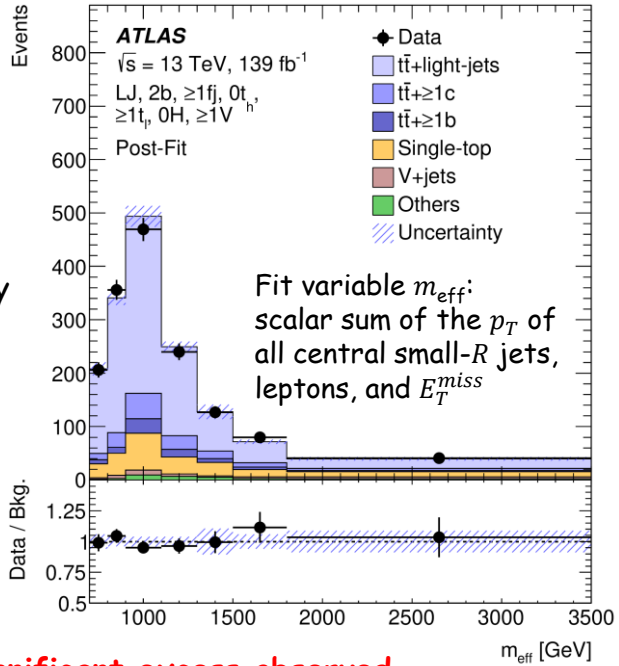
arXiv:2305.03401

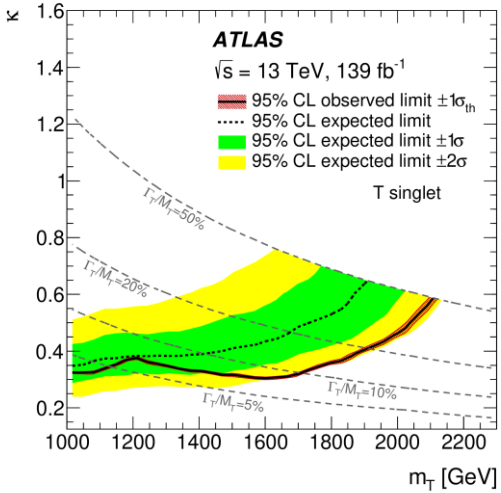


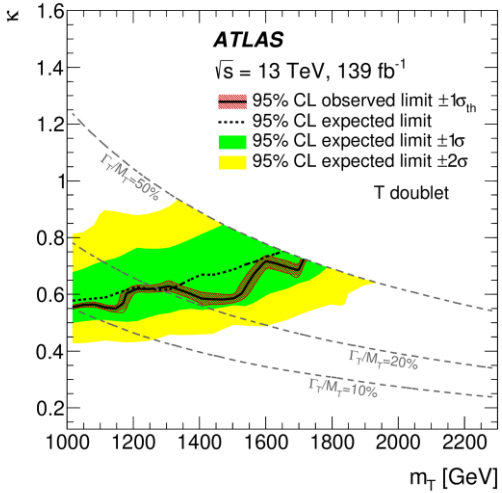
VLQs may exist as SU(2) singlets (T) or (B), doublets (X T) or (T B), or triplets

Topology:

- $T \rightarrow$ leptonically decaying t + hadronically decaying H or Z
- Small-R (b)jets
- Reclustered (RC) jets built from small-R jets: 't-tagged', 'H-tagged' or 'V-tagged'







No significant excess observed

singlet T:

$m_T < 2.1$ TeV excluded for $\kappa \geq 0.6$

$\kappa > 0.3$ excluded for $m_T = 1.6$ TeV

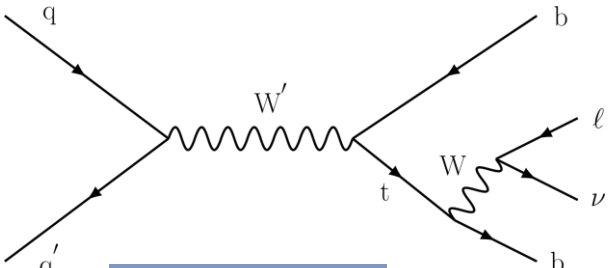
doublet T:

$m_T < 1.68$ TeV excluded for $\kappa \geq 0.75$

$\kappa > 0.55$ excluded for $m_T = 1.0$ TeV

κ: universal coupling strength

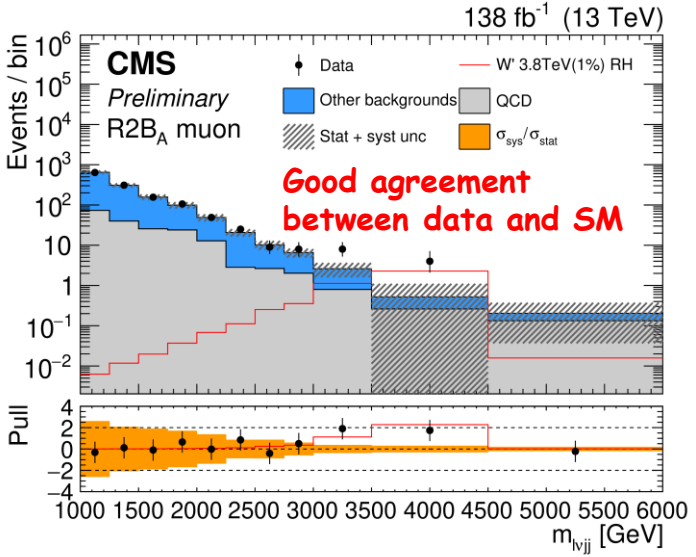
$W' \to bt$ in leptonic final states



CMS-PAS-B2G-20-012

Z' and W':
predicted in many BSM models

- ✓ One muon or electron
- ✓ At least two AK4 jets

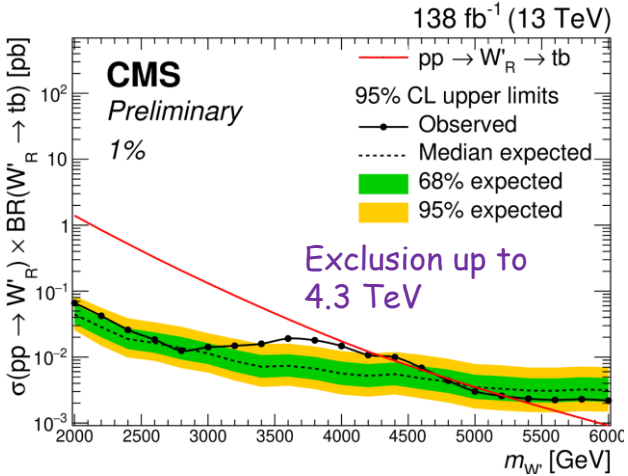


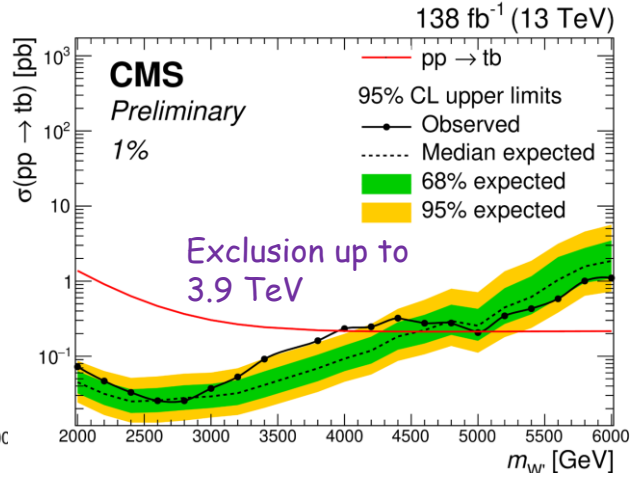
Largest local (global) significance of 2.6(2.0)σ for a W' at 3.8 TeV with a relative width of 1%

Criteria to determine jet from top decay

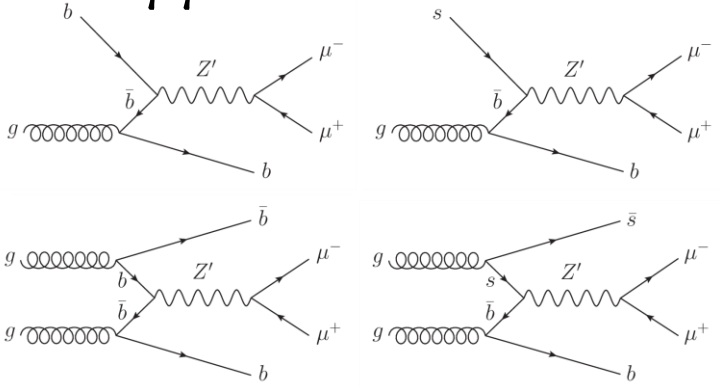
- ❑ M_{lvj} closest to top mass
- ❑ closest to lepton
- ❑ subleading

Categorization based on b-tagging condition of top jet and W' jet





$Z' \to \mu\mu b$ search

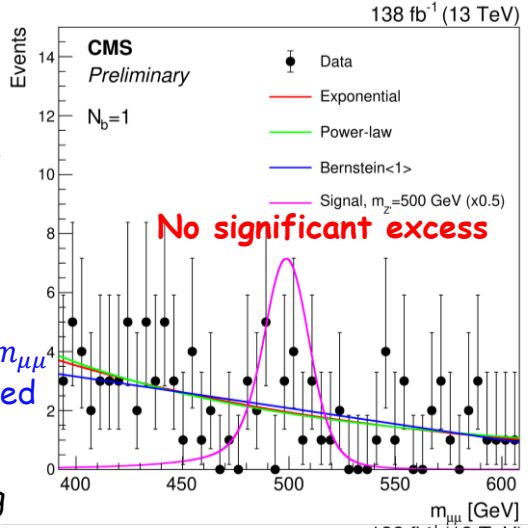


CMS-PAS-EXO-22-016

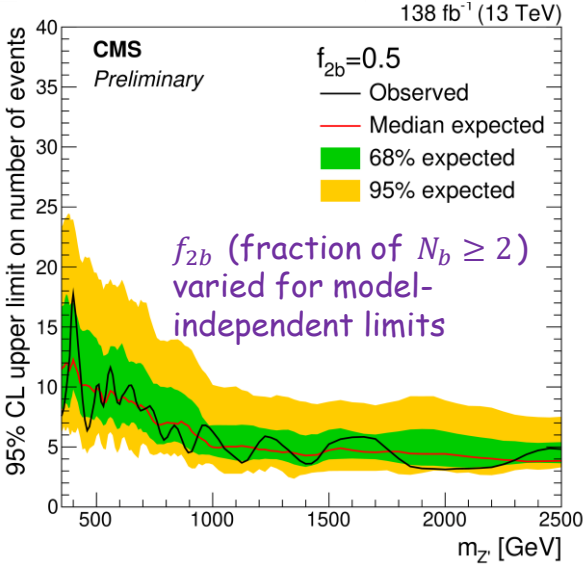
Inclusive Z' search suffers from large Drell-Yan background

→ **Presence of b-jets required in this search**

Signal and background $m_{\mu\mu}$ distribution parametrized



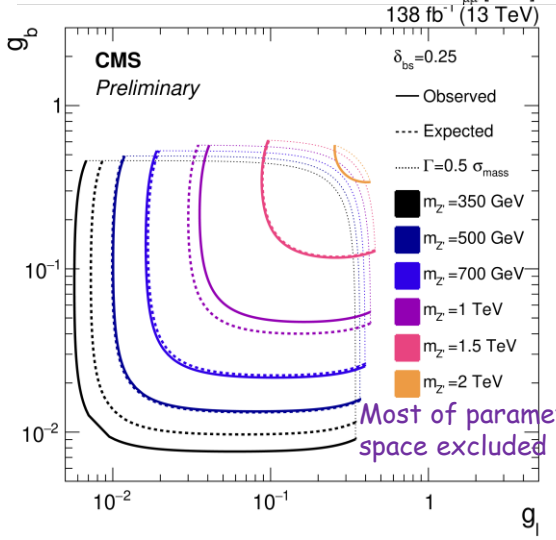
$t\bar{t}$ background reduced by two orders of magnitude by requiring $\min(m_{\mu b}) > m_{top}$



Categorization: $N_b = 1$ and $N_b \geq 2$

Interpretation for the lepton flavor-universal model:

- $g_\nu = g_\ell$
- g_b scales both $Z'bb$ and $Z'sb$ interactions
- δ_{bs} solely scales the $Z'sb$ interaction
- Restricted to $\Gamma(Z') < \sigma_{mass}/2$



LFV $e\mu$ or $\ell\tau$ resonance search

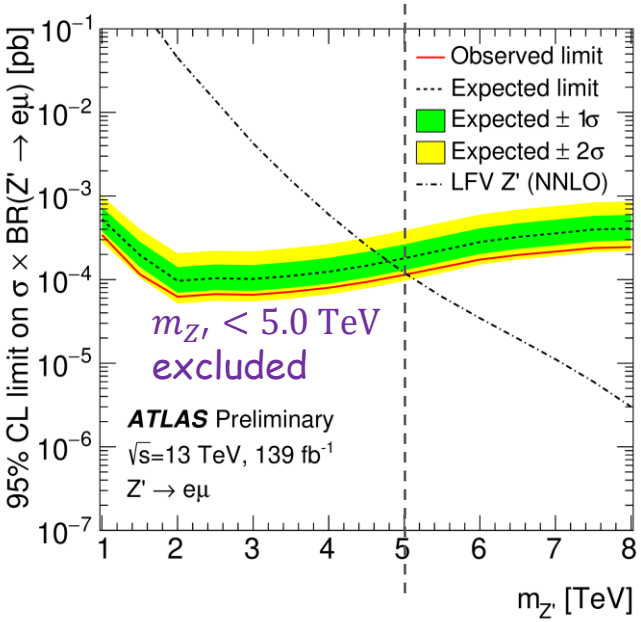
EXOT-2019-20

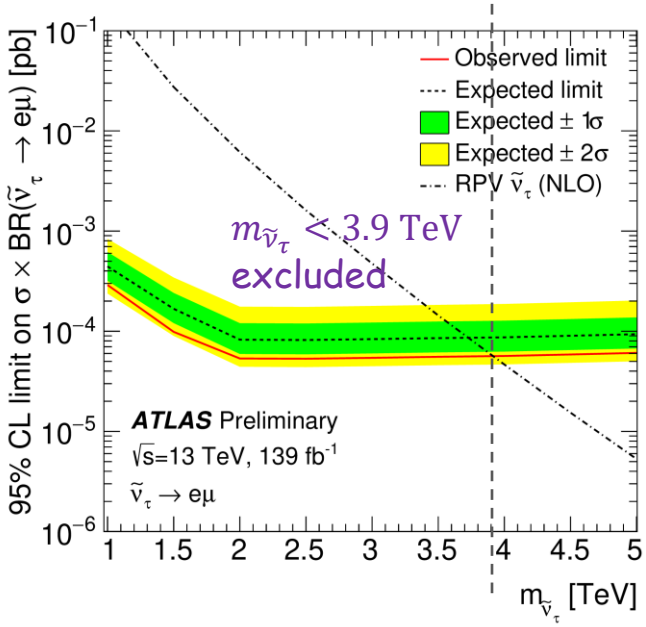
Lepton-flavour-violation (LFV):
predicted in many BSM models

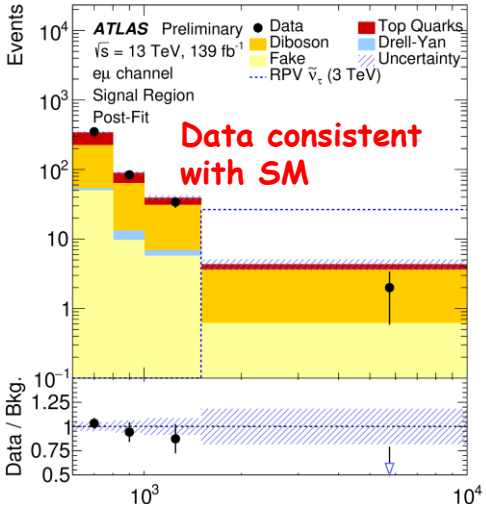
- from Z' decay
- from τ-sneutrino ($\tilde{\nu}_\tau$) decay — RPV SUSY

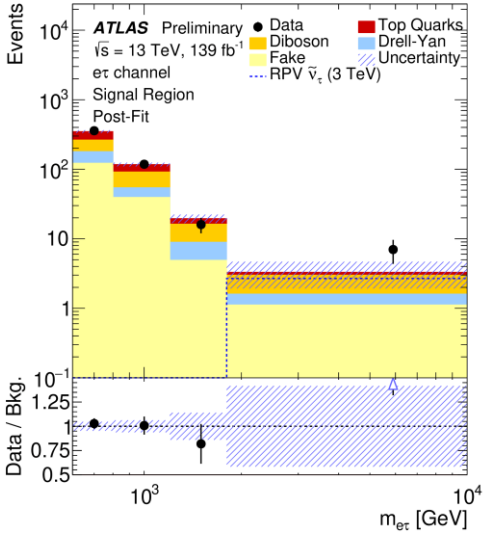
Exactly two opposite-sign leptons:

- $e\mu$, $e\tau_{\text{had}}$ or $\mu\tau_{\text{had}}$
- ν_τ reconstructed from E_T^{miss} and direction of τ_{had}
- back-to-back in φ

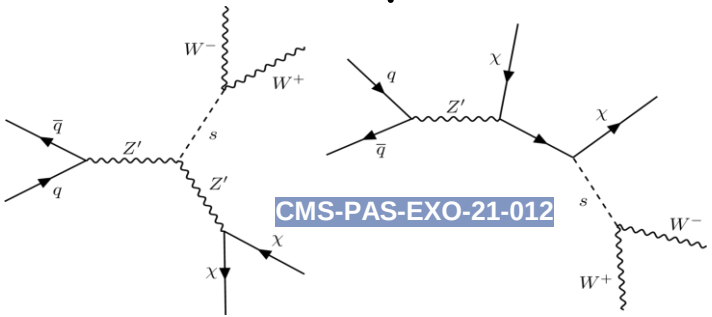








Dark matter particles search with W^+W^- + E_T^{miss}



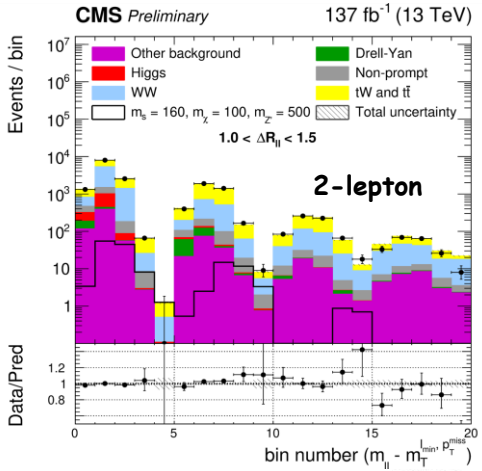
Dark Higgs boson singlet s:

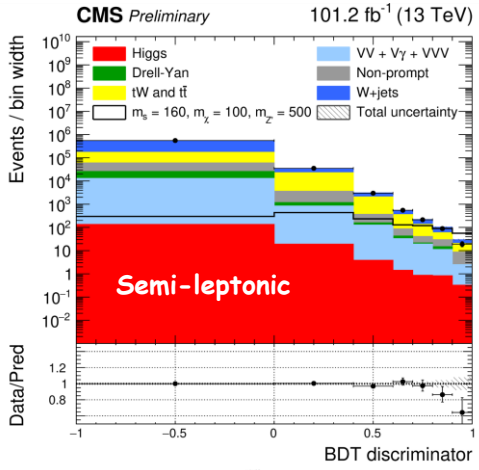
- A Majorana DM particle

Massive spin-1 vector boson Z':

- Decays to stable χ

a new U(1) local gauge symmetry





First time the CMS explores the dark Higgs model

No significant deviation from SM

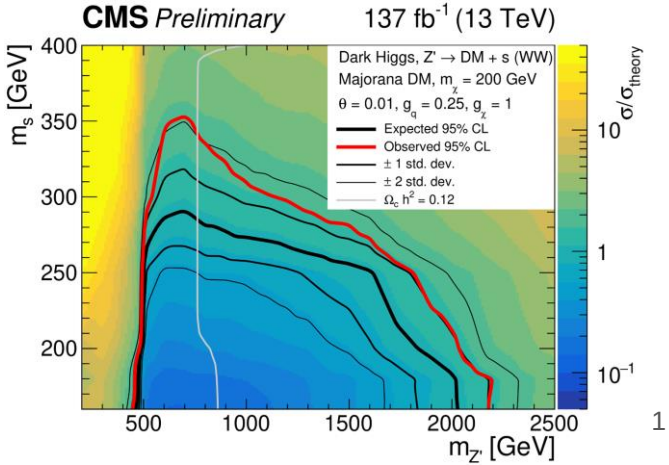
2-lepton channel:

- $e\mu$, μe
- opposite-sign
- $E_T^{miss} > 20$ GeV

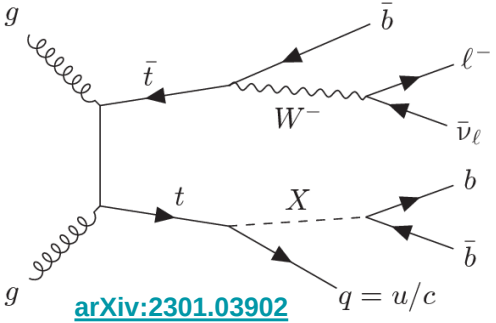
Semi-leptonic channel:

- one lepton
- at least 2 jets
- $E_T^{miss} > 60$ GeV

For $m_\chi = 200$ GeV:
excludes $m_s < 350$ GeV for $m_{Z'} = 700$ GeV
excludes $m_{Z'} < 2200$ GeV for $m_s = 160$ GeV



FCNC $t \to qX$ decays



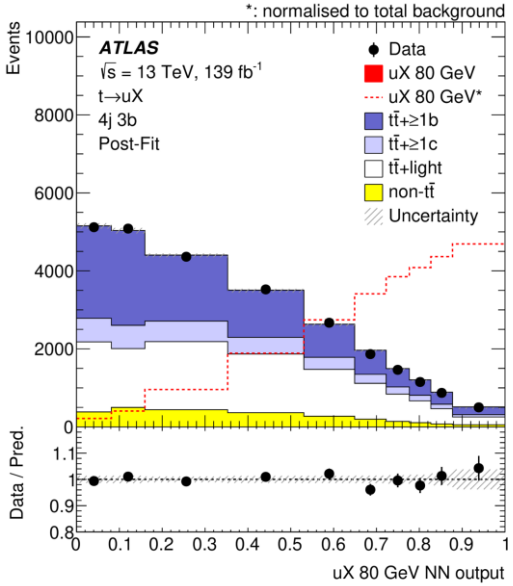
arXiv:2301.03902

Flavour-changing neutral-current (FCNC):

- Do not exist at tree level in the SM
- Predicted in many BSM theories, e.g., Froggatt-Nielsen mechanism

X: non-SM Higgs field

No significant excess above the SM

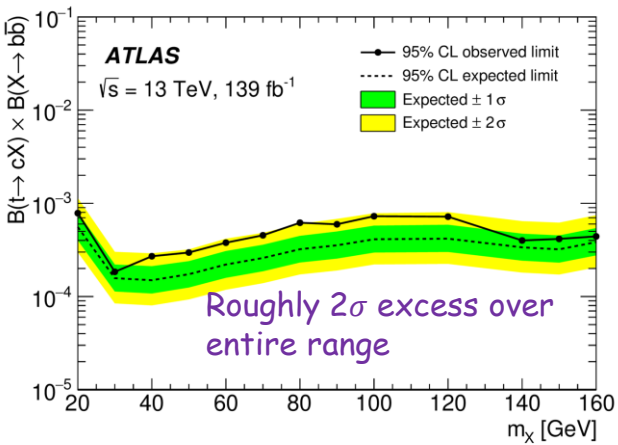


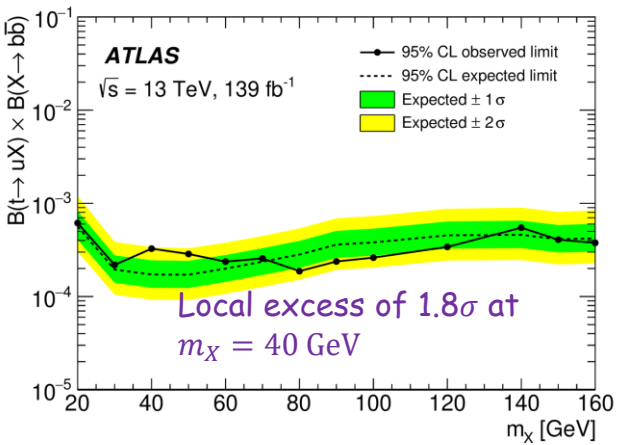
Exactly one electron or muon

At least four jets

Categorised by number of jets (j) and b-jets (b): 4j 3b, 5j 3b and 6j 3b

Neural Network score used for signal extraction fit





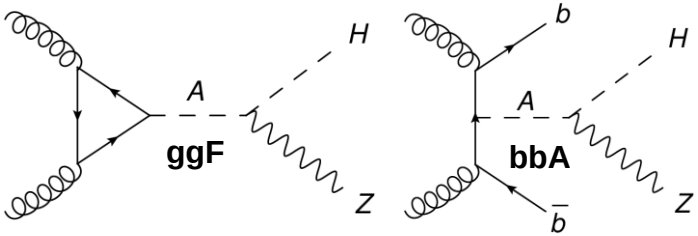
2HDM $A \to ZH \to \ell\ell tt$ or $vvbb$

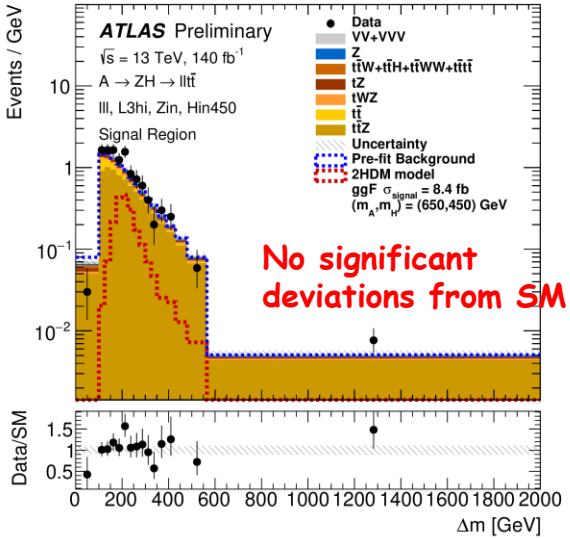
Two-Higgs-doublet model (2HDM):

ATLAS-CONF-2023-034

- Five Higgs bosons after electroweak symmetry breaking: h, H, A, H^+, H^-
- h is the common higgs boson
- $m_A > m_H$ is favoured

$\tan\beta$: ratio of the vacuum expectation value of the two doublets





No significant deviations from SM

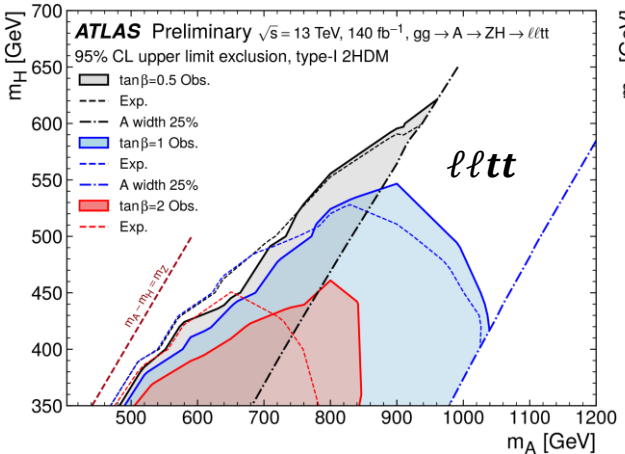
Largest local signifcance of 2.85σ at $(m_A, m_H) = (650, 450)$ GeV for $\ell\ell tt$

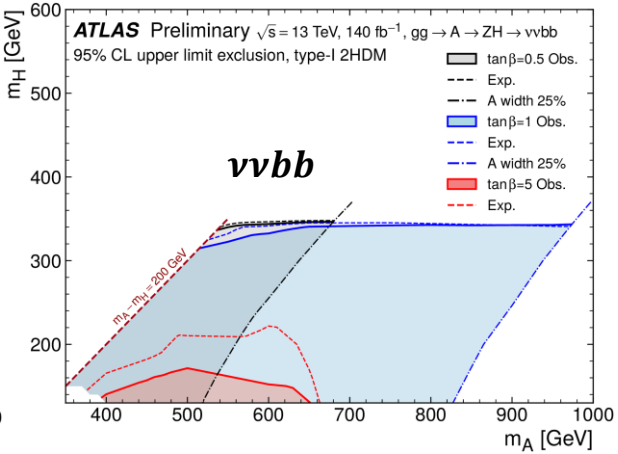
$vvbb$: $Z \to vv$ and $H \to bb$

- ✓ $p_T^V \left(E_T^{miss}\right) > 150$ GeV
- ✓ at least 2 jets, exactly 2 b-tagged (gg fusion) or >2 b-tagged (b-associated)
- ✓ **First time for LHC at high m_{bb}**

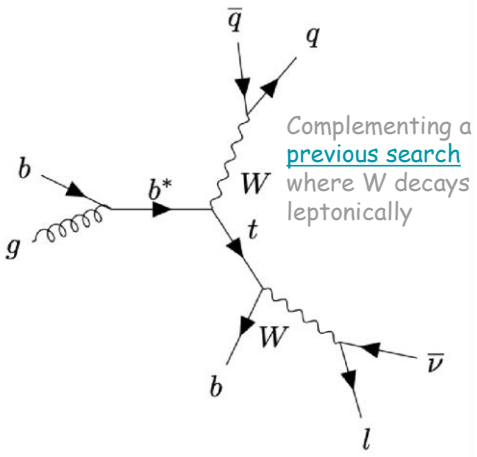
$\ell\ell tt$: $Z \to \ell\ell$ and $H \to tt$ → semi-leptonic

- ✓ 3 leptons: eee, $ee\mu$, $e\mu\mu$, $\mu\mu\mu$
- ✓ at least 4 jets and exactly 2 b-tagged
- ✓ **First time for LHC 13TeV**





Excited $b^* \to Wt$



- ✓ exactly one lepton (either electron or muon)
- ✓ at least one b-tagged AK4 jet (b jet)
- ✓ exactly one W-tagged AK8 jet (W jet).

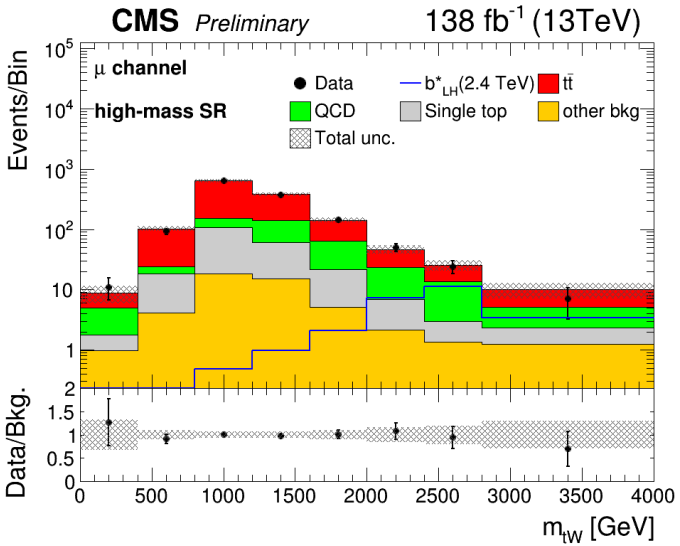
High-/Low- mass signal regions defined based on p_T^{miss} and p_T^W

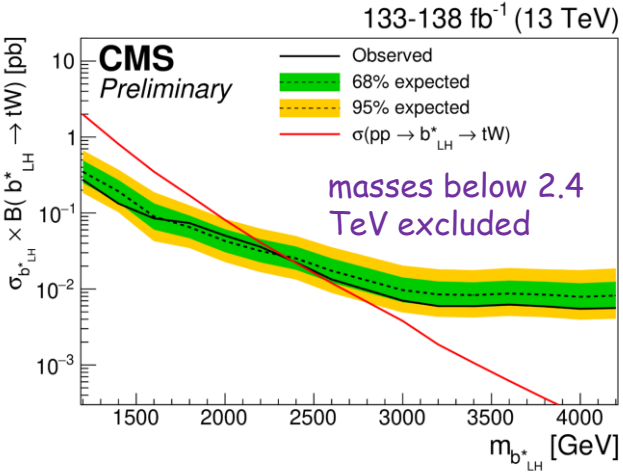
CMS-PAS-B2G-21-005

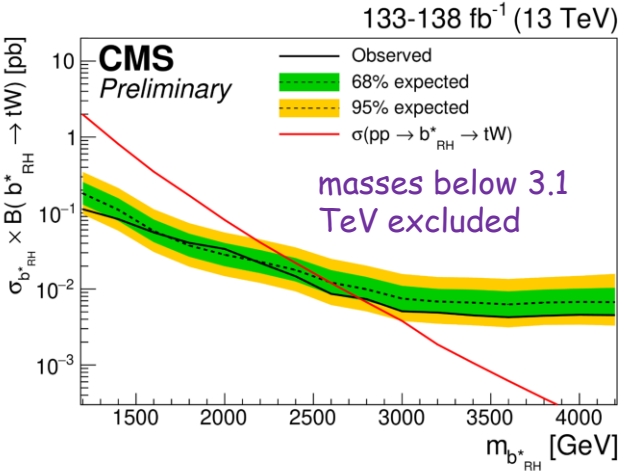
Excited b^* quark:

- In compositeness models, excited states of quarks can have masses of the order of 1 TeV
- Right-Handed (RH), Left-Handed (LH) or Vector-Like (VL) scenarios are studied

No significant excess found







Generic trijet resonances search

CMS-PAS-EXO-22-008

First generic search for new particles decaying to three hadronic jets

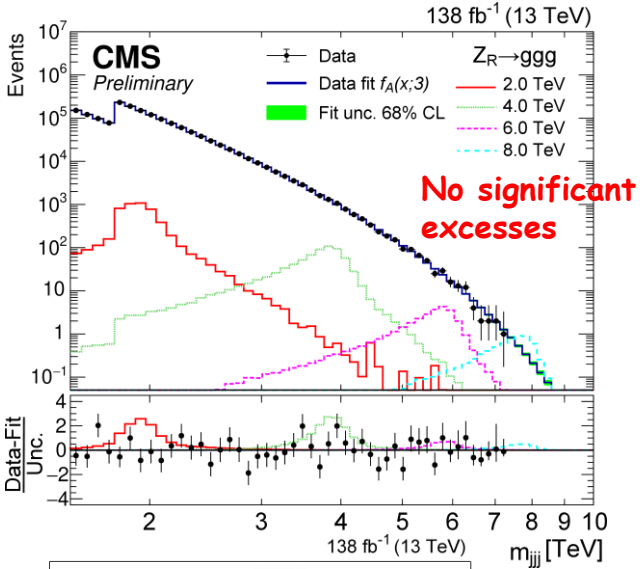
- Kaluza-Klein gluon (G_{KK}) to three gluons via radion: $X \to Y(gg)g$
- Excited quark q^* to three quarks via vector boson: $X \to Y(qq)q$

ρ_m: mass ratio between Y and X

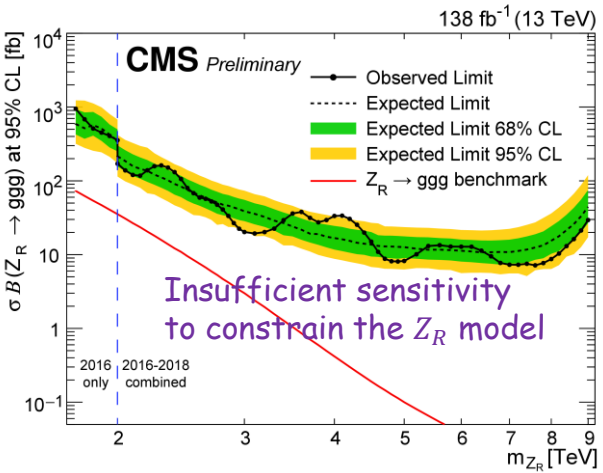
First search in range ρ_m 0.2 to 0.8

- Right-handed Z boson (Z_R) directly to three gluons: $X \to 3g$
  a) nominal ($\Gamma_X \sim 3\%$)
  b) narrow ($\Gamma_X \sim 0.01\%$)

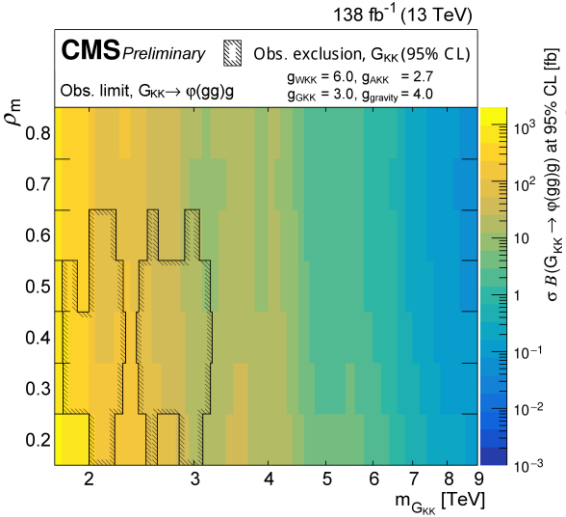
largest local significance of 2.1(2.2)σ at 4.1 TeV for nominal (narrow) width →

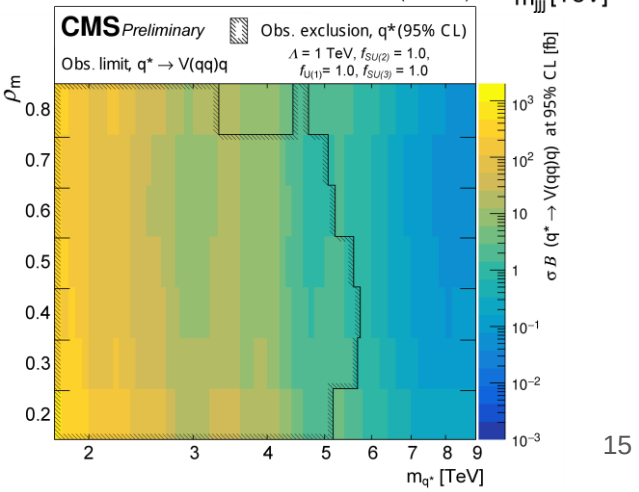


No significant excesses



Insufficient sensitivity to constrain the Z_R model



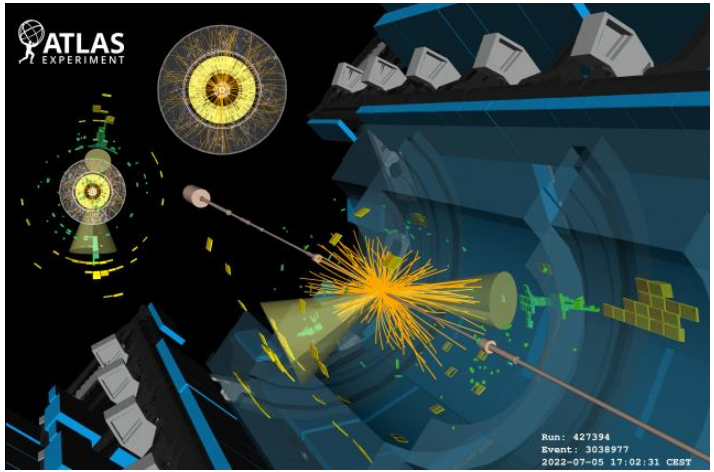


Summary

- ✓ Heavy resonance search remains an active area of research
- ✓ New models and particles beyond the Standard Model explored at ATLAS and CMS, yet no significant deviation beyond Standard Model is observed
- ✓ New Techniques such as Machine Learning are developed and implemented in the analyses
- ✓ Extended exclusion limits on BSM theories

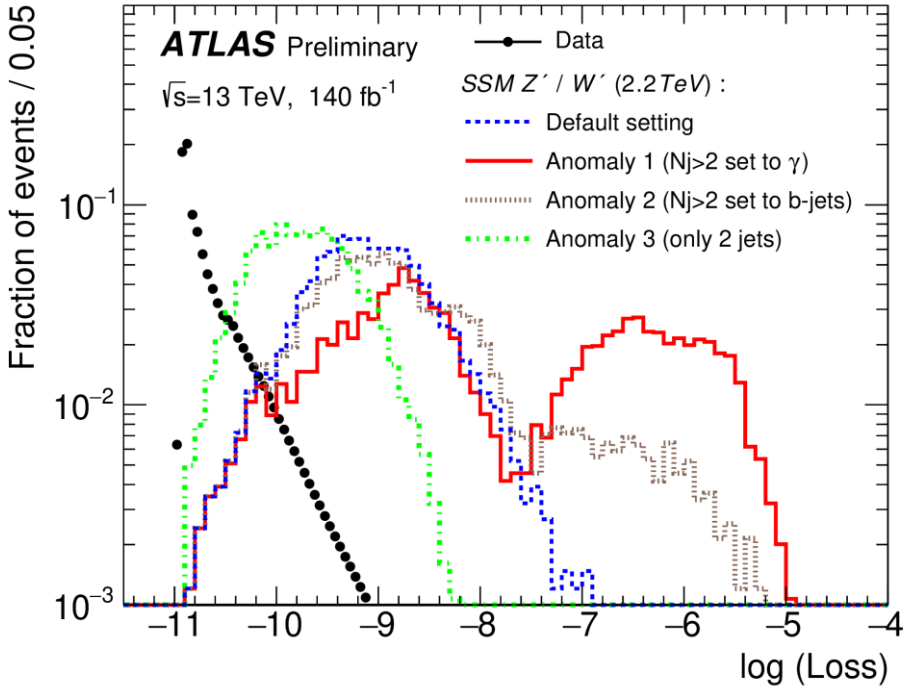
Future Prospects:

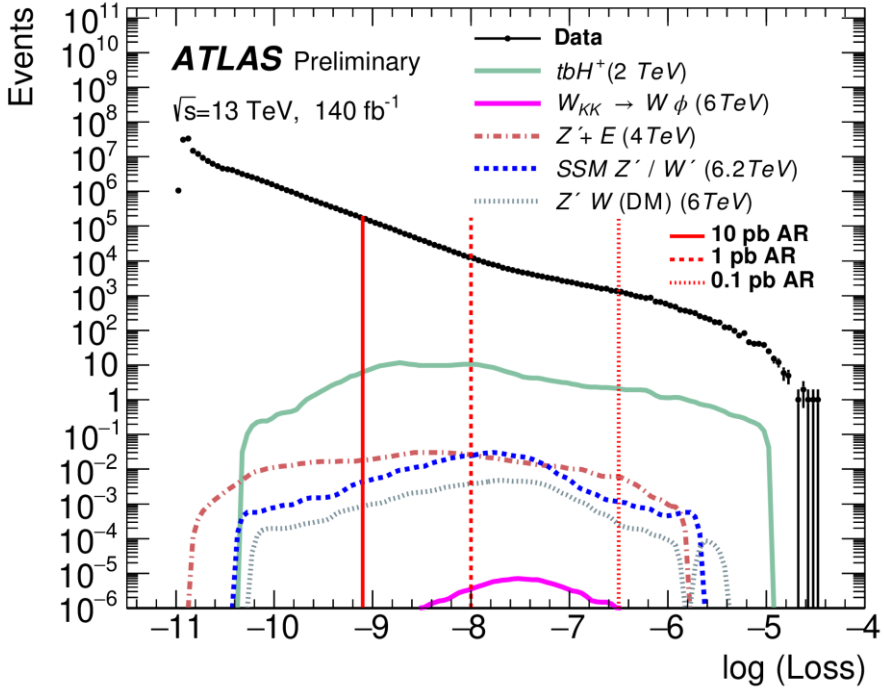
- ☐ Continued data analysis in Run-3
- ☐ Further development of analysis techniques
- ☐ Exploring new theoretical frameworks



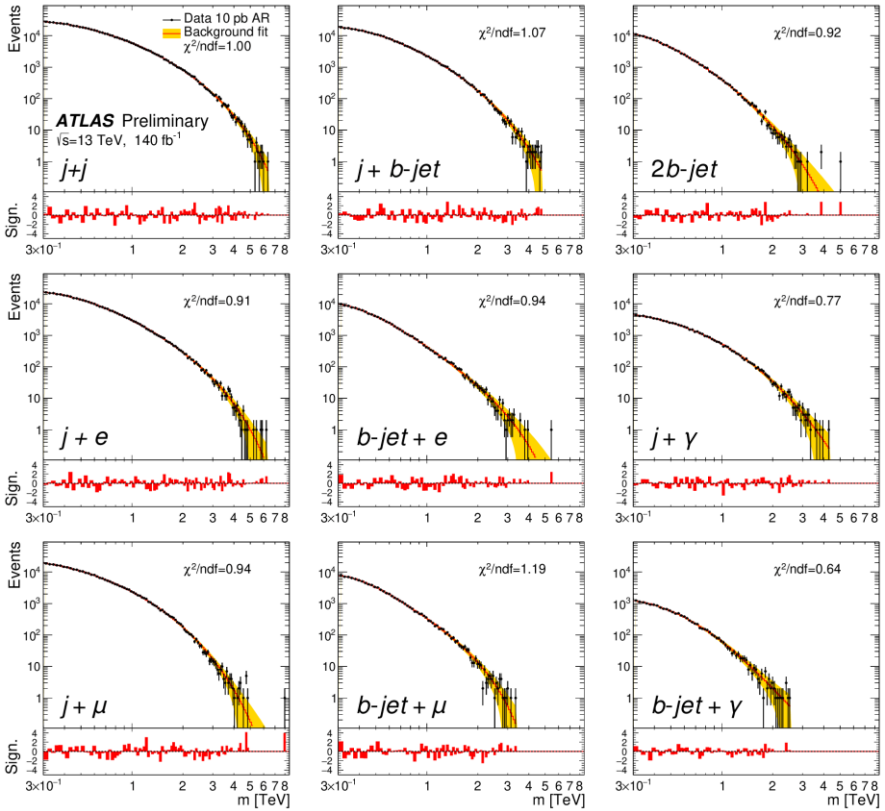
Back up

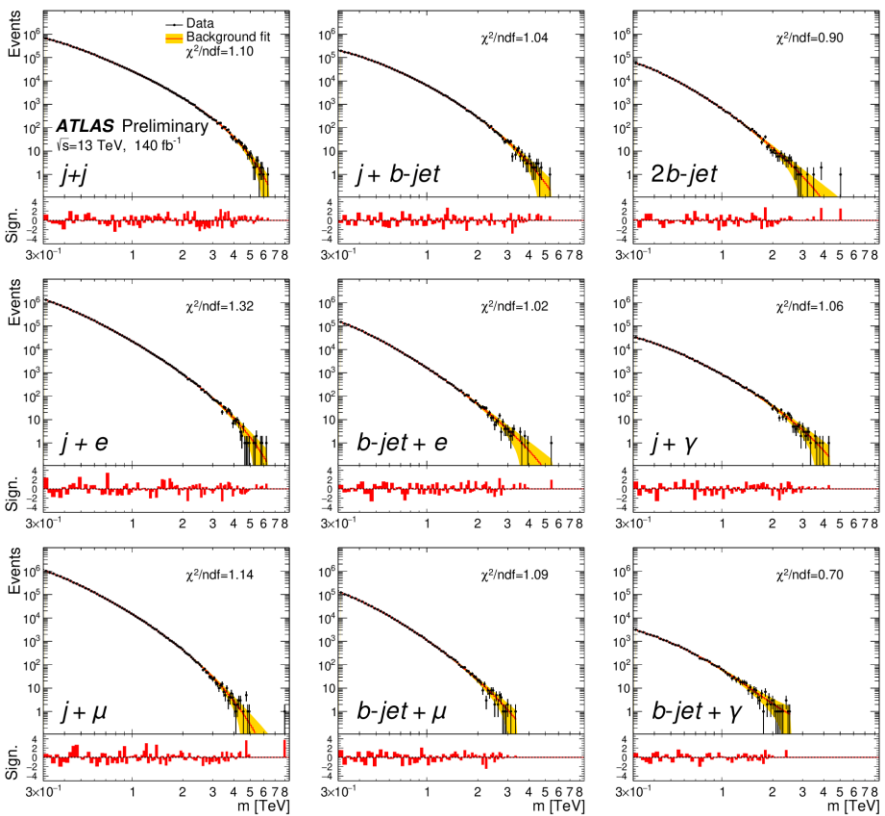
Anomaly detection in jet+Y



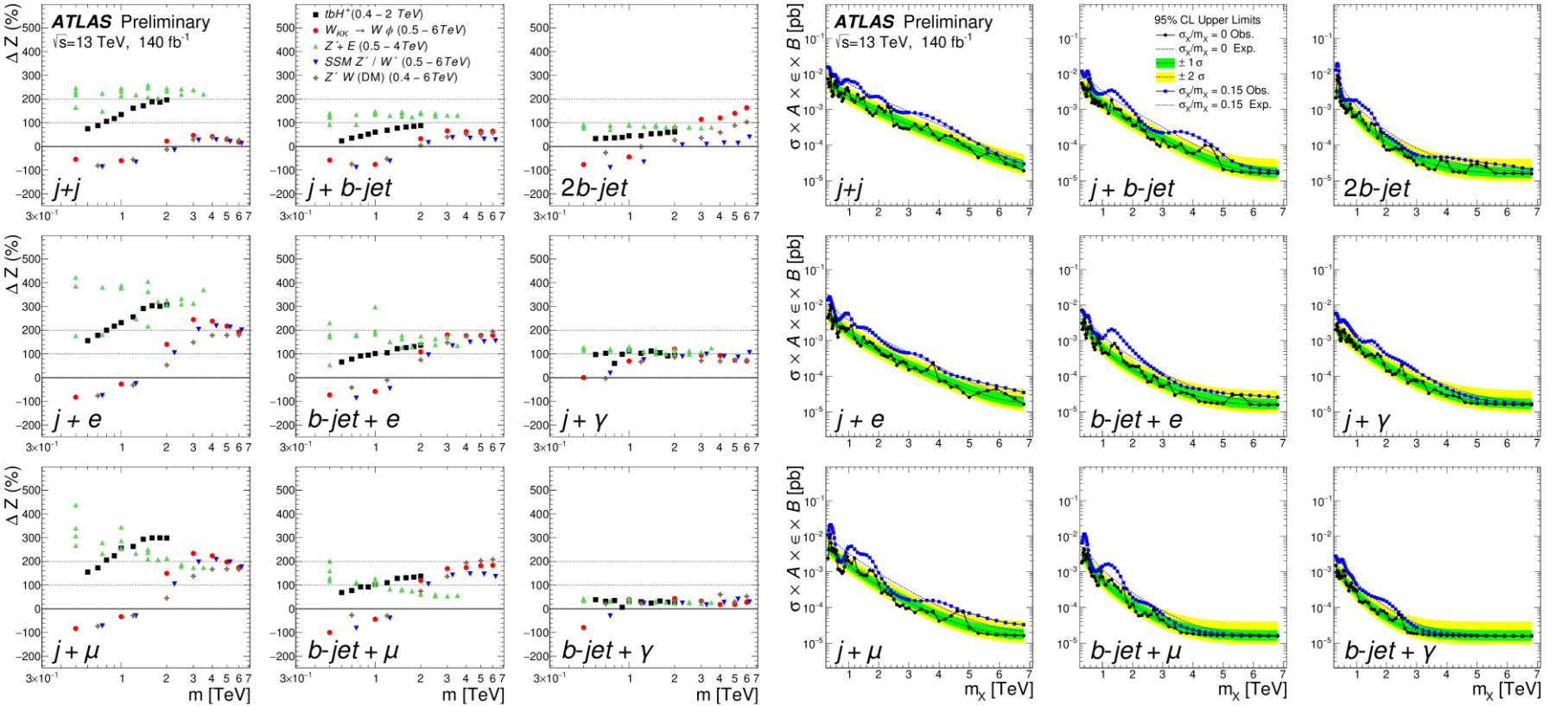


Anomaly detection in jet+Y





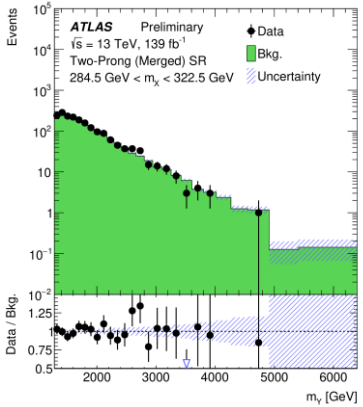
Anomaly detection in jet+Y

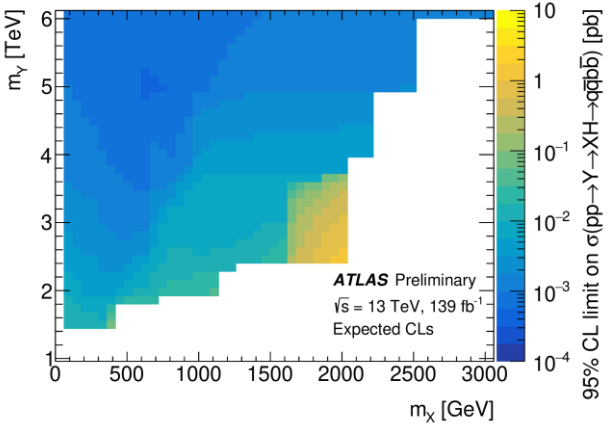


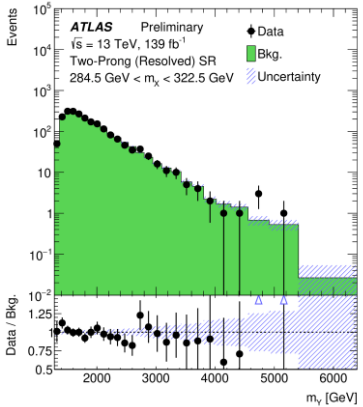
Generic $Y \rightarrow XH$ in hadronic final states

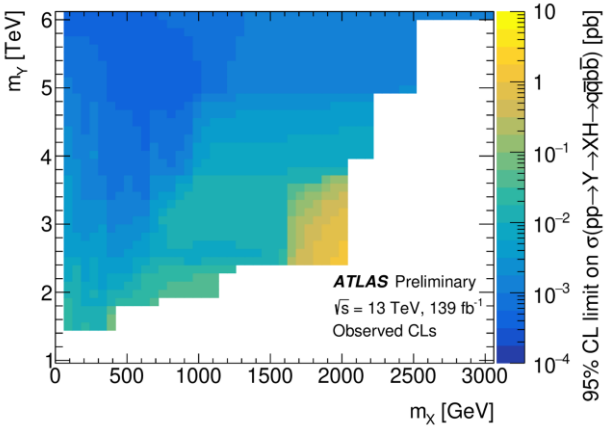
Parameter	Preselection requirements				
m_{JJ} [GeV]	> 1300				
$p_{\mathrm{T}}(J_1)$ [GeV]	> 500				
m_J [GeV]	$m_{J_1} > 50 \parallel m_{J_2} > 50$				
$D_{H_{bb}}$	> -2				
	Signal regions				
	Merged		Resolved		Anomaly
m_H [GeV]	(75, 145)				
$D_{H_{bb}}$	> 2.44				
D_2^{trk}	< 1.2		> 1.2		-
$\lvert\Delta y_{j_1,j_2}\rvert$	-		< 2.5		-
p_{T}^{bal}	-		< 0.8		-
Anomaly Score	-		-		> 0.5
	Background estimation regions				
	CR0	HSB0	HSB1	LSB0	LSB1
m_H [GeV]	(75, 145)	(145, 200)		(65, 75)	
$D_{H_{bb}}$	< 2.44	< 2.44	> 2.44	< 2.44	> 2.44

- ✓ Signal regions are built by selecting two large-R jets with additional criteria to enrich the presence of Higgs and X particles → Larger D_{Hbb} as J_H and the other as J_X
- ✓ Orthogonal resolved reconstruction is used to recover sensitivity where the X is less boosted
- ✓ requiring at least four j in the event
- ✓ mY computed with large-R Higgs jet and the two small-R X jets



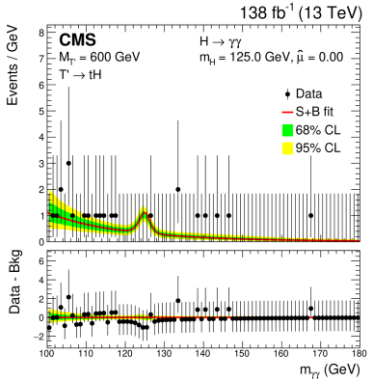


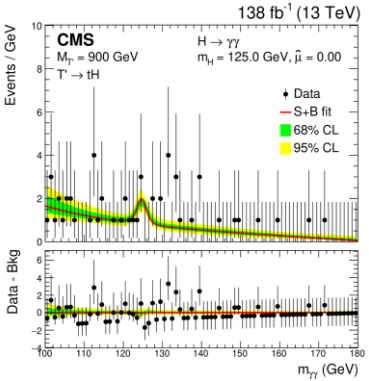


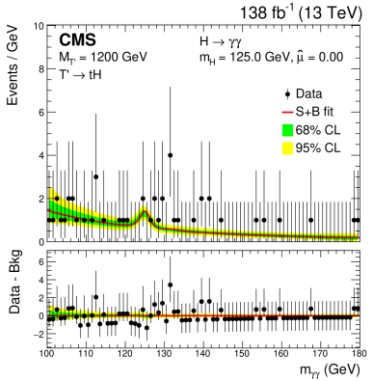


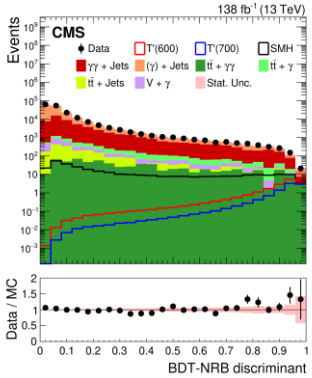
Vector-like quark $T' \rightarrow tH$

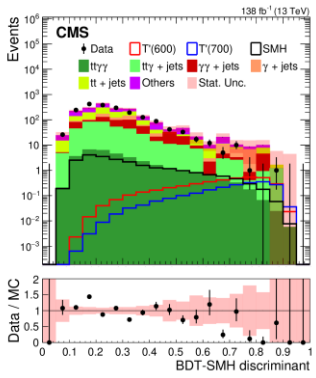
BDT	I	II	III
$M_{T'}$(GeV)	[600, 700]	[700, 1000]	[1000, 1200]
Hadronic analysis			
BDT-NRB score	> 0.94	>0.96	>0.95
BDT-SMH score	>0.80	>0.80	>0.80
m_{tH} window (GeV)	[480, 800]	[550, 1150]	[650, 1600]
Leptonic analysis			
BDT score	>0.60	>0.40	>0.40
m_{tH} window (GeV)	[480, 800]	[550, 1150]	[650, 1600]

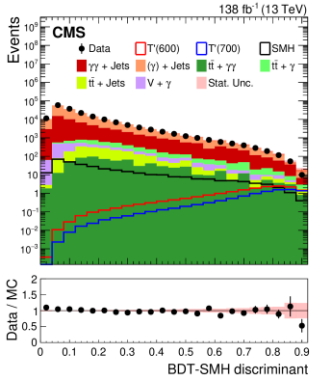


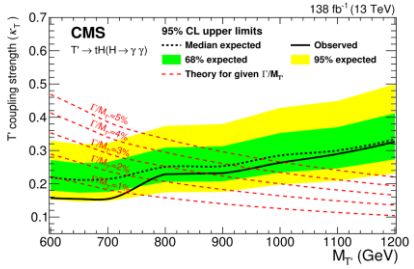


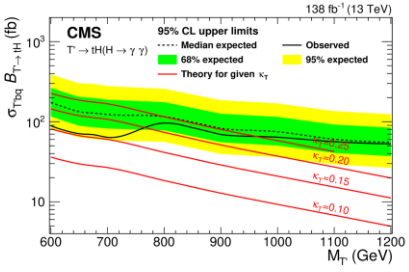












*Previous results on pair production exclude T' masses below 1.48 TeV at 95% confidence level (CL), assuming branching fractions of 50, 25 and 25% for bW, tZ, and tH decays, respectively

Vector-like quark $T \to Ht/Zt$

Preselection requirements
Single-lepton or $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
=1 isolated e OR μ
$\geq$3 jets
$\geq$1 b-tagged jets
$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W} > 60$ GeV
$m_{\mathrm{eff}} > 600$ GeV

Events categorized in terms of multiplicities of:

1.jet,

2.b-tagged jet ,

3.forward jet,

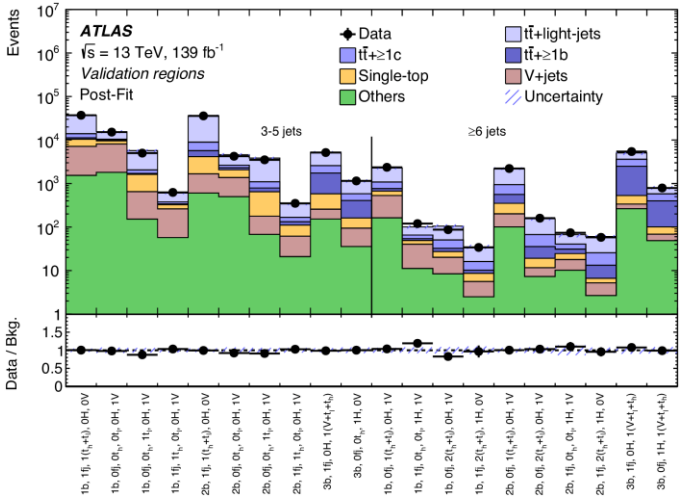
4.V-tagged jet,

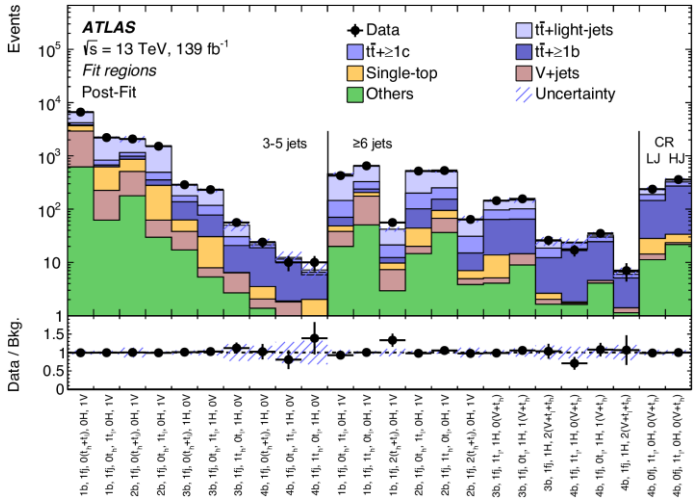
5.Higgs-tagged jet,

6.hadronic top-tagged jet,

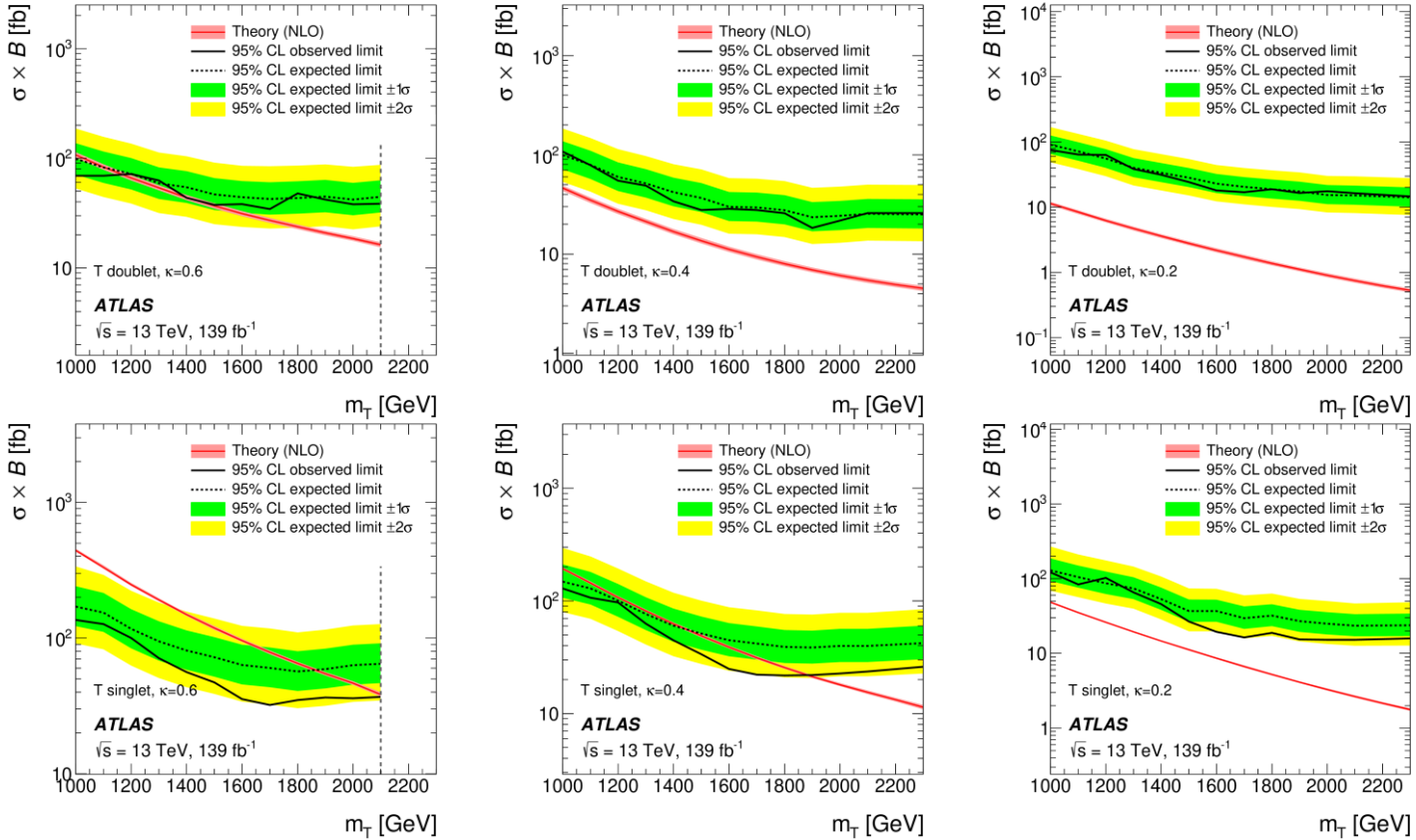
7.leptonic top-quark candidate

Fit regions			
Jet mult.	b-tag mult.	Region	Targeted signal / bkg
3–5	1	LJ, 1b, $\geq$1fj, 0(t_h+t_l), 0H, $\geq$1V	$T(\to Zt)qb$
		LJ, 1b, $\geq$1fj, 0t_h, $\geq$1t_l, 0H, $\geq$1V	
	2	LJ, 2b, $\geq$1fj, 0(t_h+t_l), 0H, $\geq$1V	
		LJ, 2b, $\geq$1fj, 0t_h, $\geq$1t_l, 0H, $\geq$1V	
	3	LJ, 3b, $\geq$1fj, 0(t_h+t_l), $\geq$1H, 0V	$T(\to Ht)qb$
		LJ, 3b, $\geq$1fj, 0t_h, $\geq$1t_l, $\geq$1H, 0V	
		LJ, 3b, $\geq$1fj, $\geq$1t_h, 0t_l, $\geq$1H, 0V	
	$\geq$4	LJ, $\geq$4b, $\geq$1fj, 0(t_h+t_l), $\geq$1H, 0V	
		LJ, $\geq$4b, $\geq$1fj, 0t_h, $\geq$1t_l, $\geq$1H, 0V	
		LJ, $\geq$4b, $\geq$1fj, $\geq$1t_h, 0t_l, $\geq$1H, 0V	
		LJ, $\geq$4b, 0fj, $\geq$1t_l, 0H, 0(V+t_h)	$t\bar{t}$+$\geq$1b, $t\bar{t}$+$\geq$1c
≥6	1	HJ, 1b, $\geq$1fj, 0t_h, 1t_l, 0H, $\geq$1V	$T(\to Zt)qt$
		HJ, 1b, $\geq$1fj, $\geq$1t_h, 0t_l, 0H, $\geq$1V	
		HJ, 1b, $\geq$1fj, $\geq$2(t_h+t_l), 0H, $\geq$1V	
	2	HJ, 2b, $\geq$1fj, 0t_h, 1t_l, 0H, $\geq$1V	
		HJ, 2b, $\geq$1fj, $\geq$1t_h, 0t_l, 0H, $\geq$1V	
		HJ, 2b, $\geq$1fj, $\geq$2(t_h+t_l), 0H, $\geq$1V	
	3	HJ, 3b, $\geq$1fj, 1t_l, $\geq$1H, 0(V+t_h)	$T(\to Ht)qt$
		HJ, 3b, $\geq$1fj, 0t_l, $\geq$1H, 1(V+t_h)	
		HJ, 3b, $\geq$1fj, $\geq$1H, $\geq$2(V+t_l+t_h)	
	$\geq$4	HJ, $\geq$4b, $\geq$1fj, 1t_l, $\geq$1H, 0(V+t_h)	
		HJ, $\geq$4b, $\geq$1fj, 0t_l, $\geq$1H, 1(V+t_h)	
		HJ, $\geq$4b, $\geq$1fj, $\geq$1H, $\geq$2(V+t_l+t_h)	
		HJ, $\geq$4b, 0fj, $\geq$1t_l, 0H, 0(V+t_h)	$t\bar{t}$+$\geq$1b, $t\bar{t}$+$\geq$1c



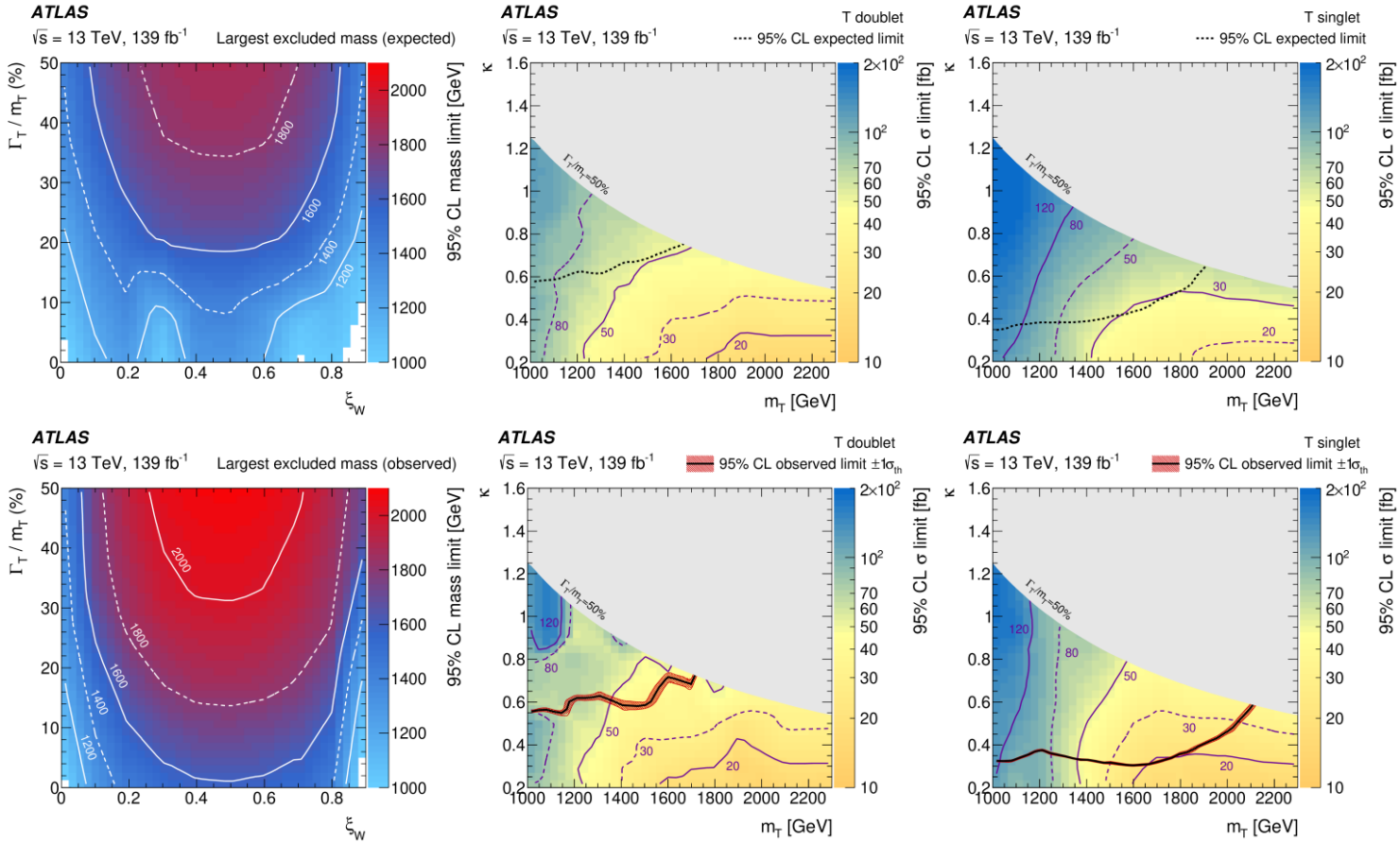


Vector-like quark $T \rightarrow Ht/Zt$



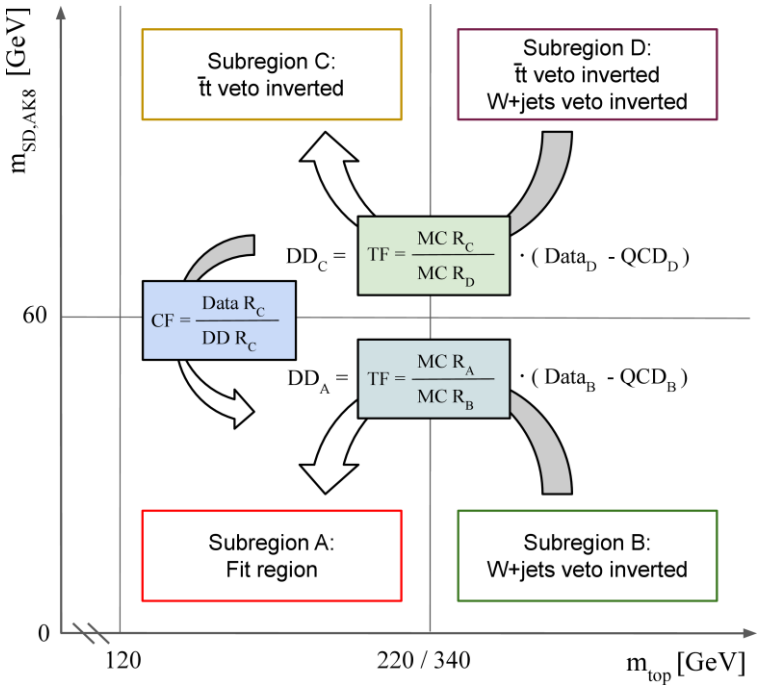
*Previously a combination of all ATLAS pair production analyses using the data collected by the ATLAS detector in 2015 and 2016 delivered the most stringent limits to date on pair-produced vector-like quarks, with masses observed to be excluded below 1.31 TeV for T and 1.03 TeV for B for any combination of decay modes

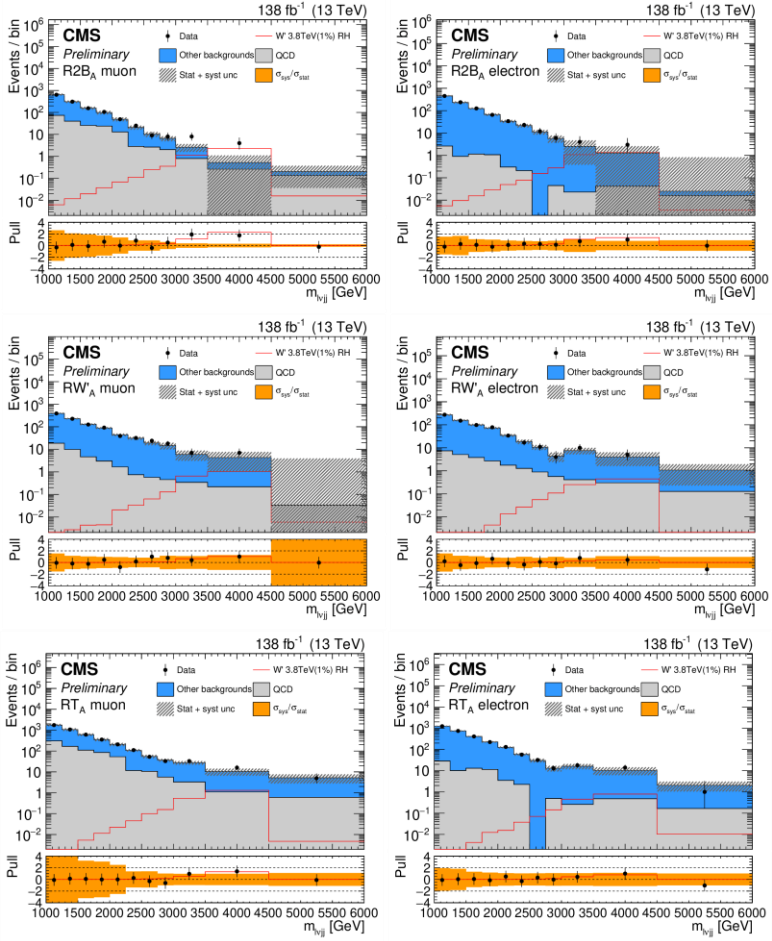
Vector-like quark $T \rightarrow Ht/Zt$



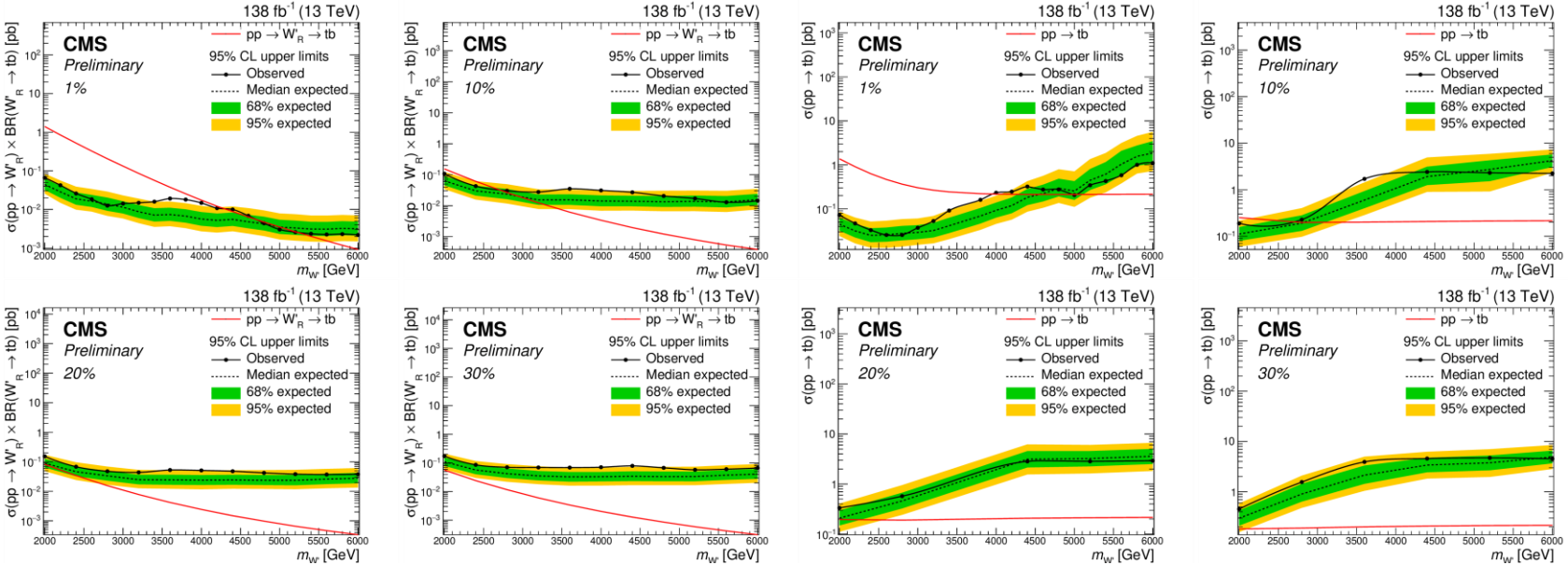
$W' \to bt$ in leptonic final states

number of b jets	jet_{top} is a b-tagged jet	$\text{jet}_{W'}$ is a b-tagged jet	type of category (label)
0	no	no	Control region (R0)
	Signal-enriched regions		
1	yes	no	top jet region (RT)
1	no	yes	W' jet region (RW′)
≥ 2	yes	yes	region with 2 b-jets (R2B)

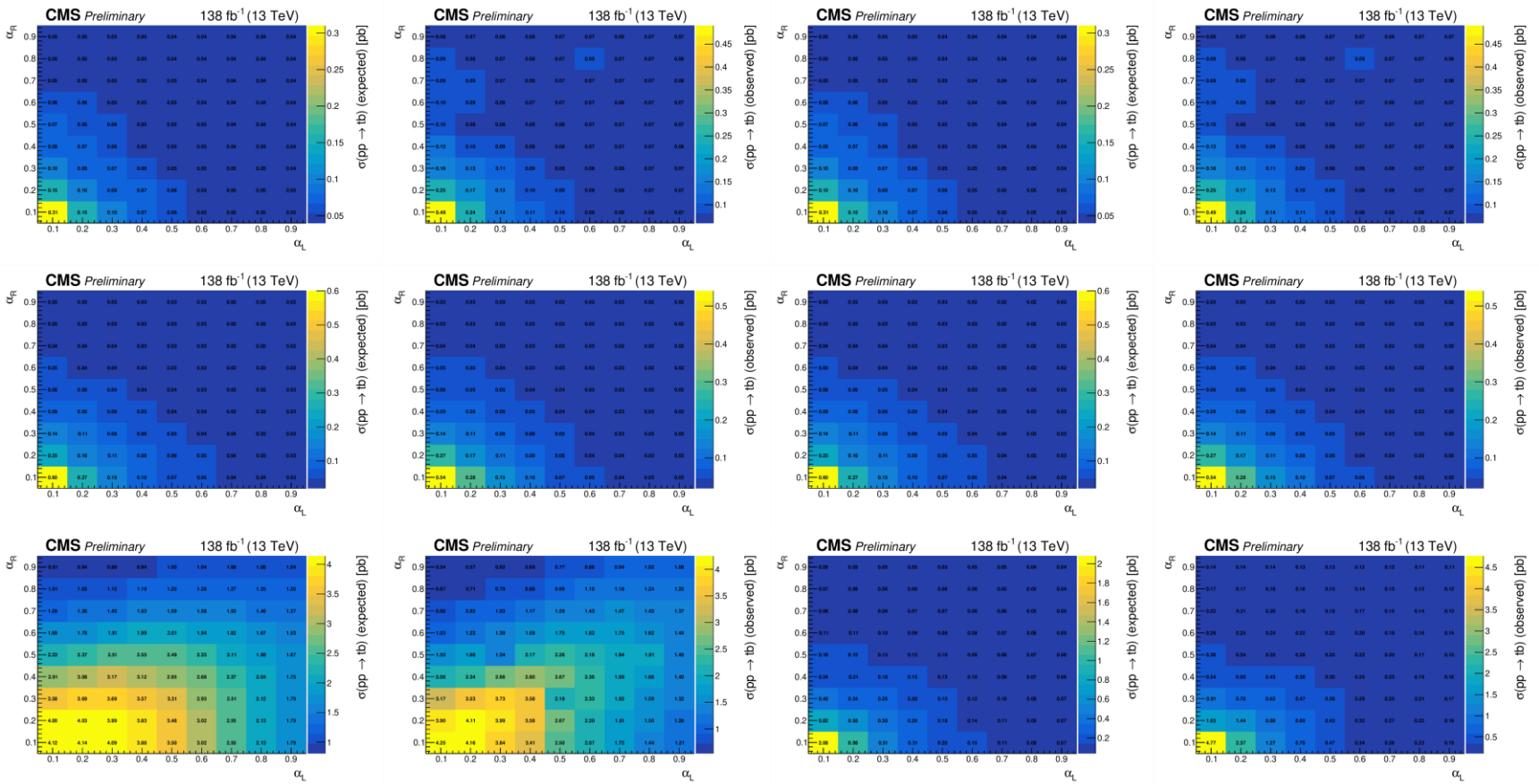




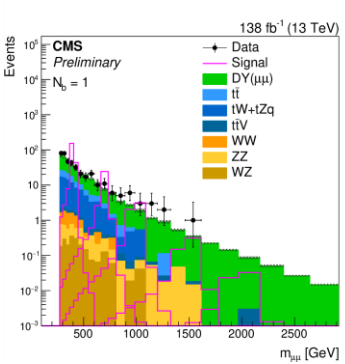
$W' \to bt$ in leptonic final states

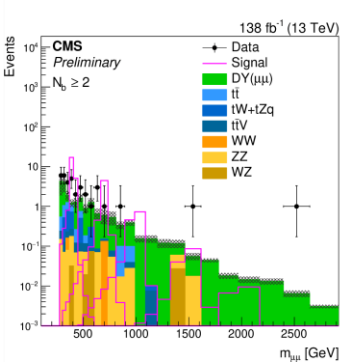


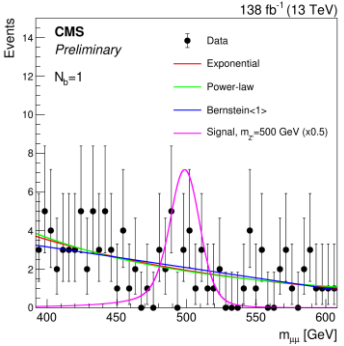
$W' \to bt$ in leptonic final states

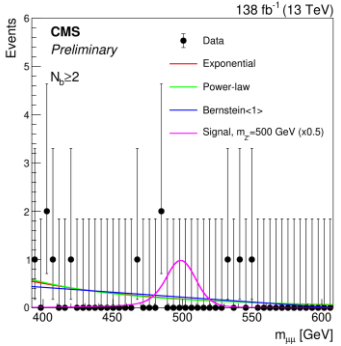


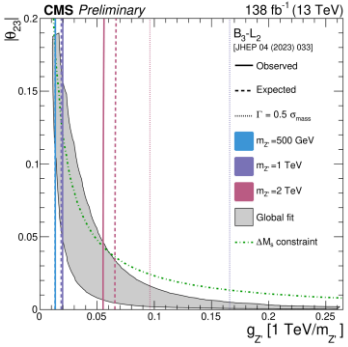
$Z' \to \mu\mu b$ search

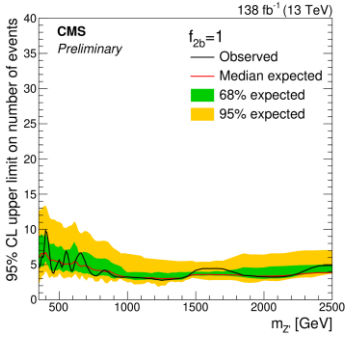


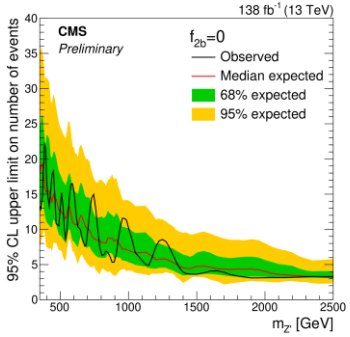


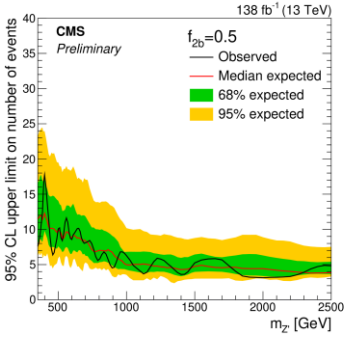


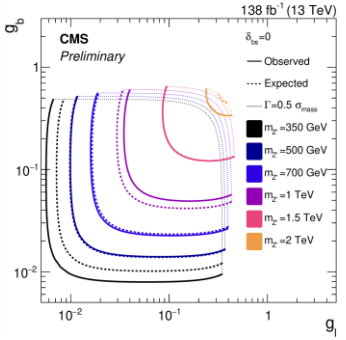


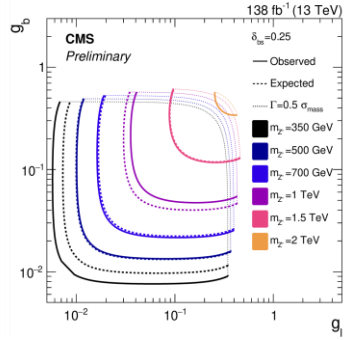




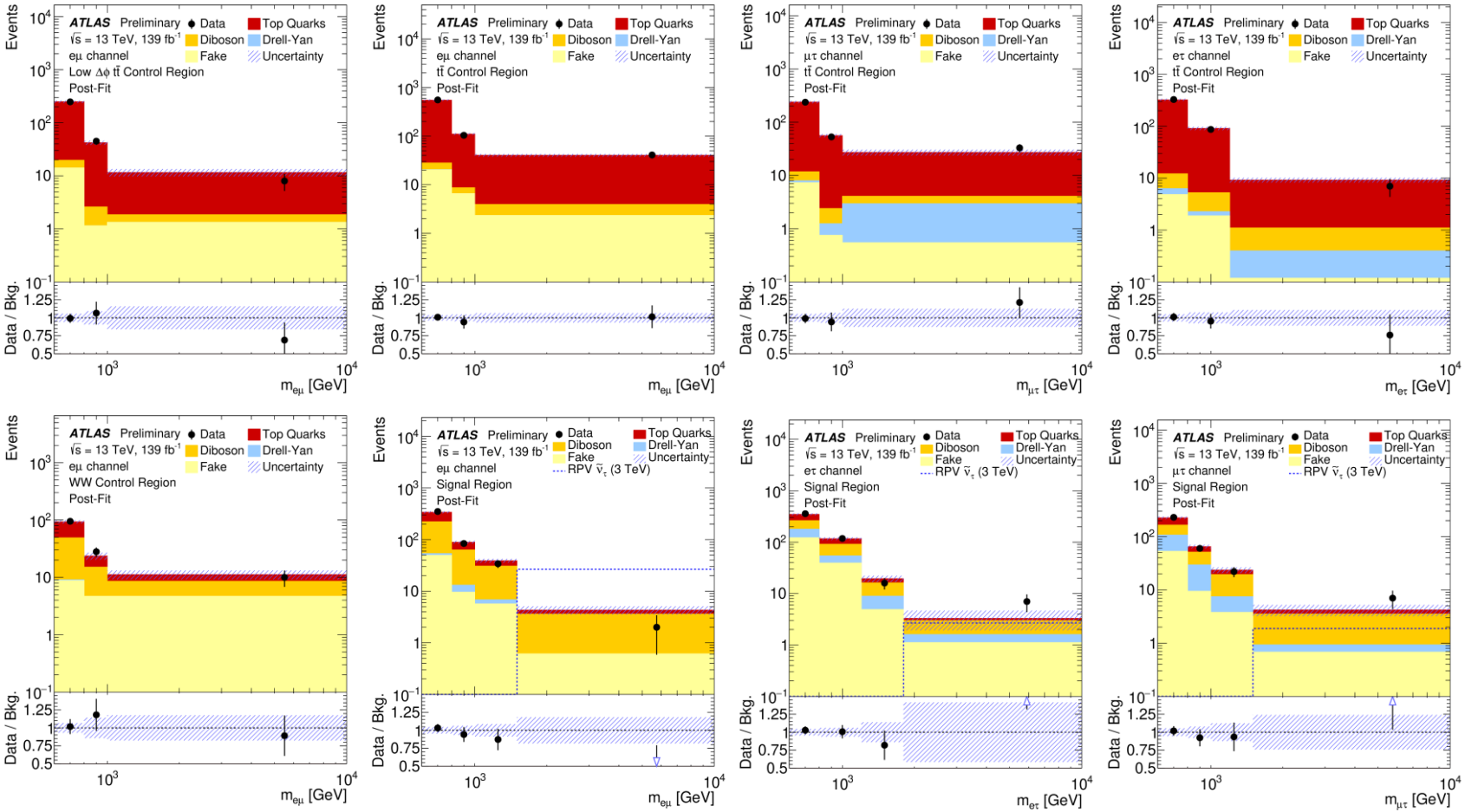




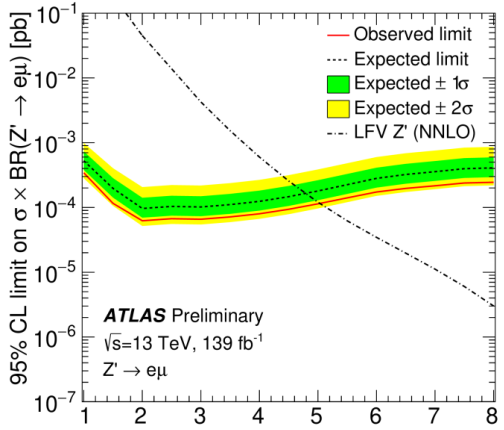


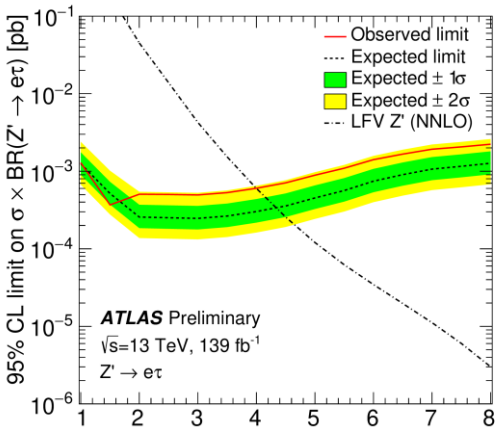


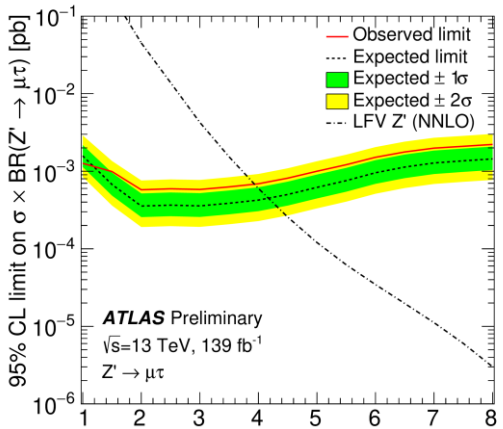
LFV $e\mu$ or $\ell\tau$ resonance search

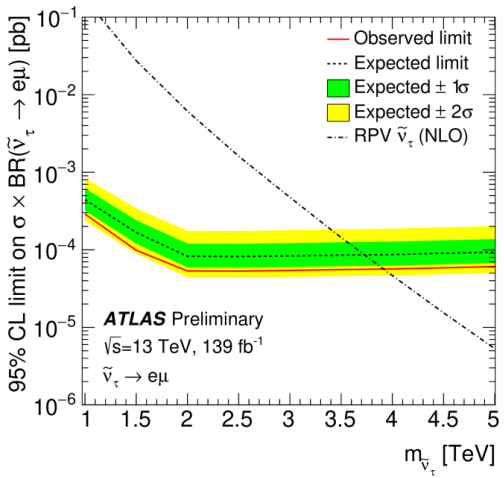


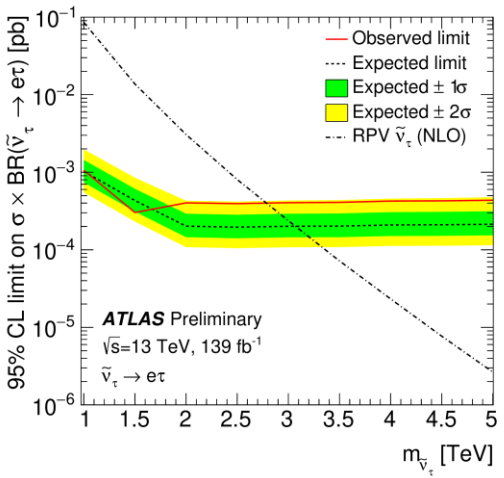
LFV $e\mu$ or $\ell\tau$ resonance search

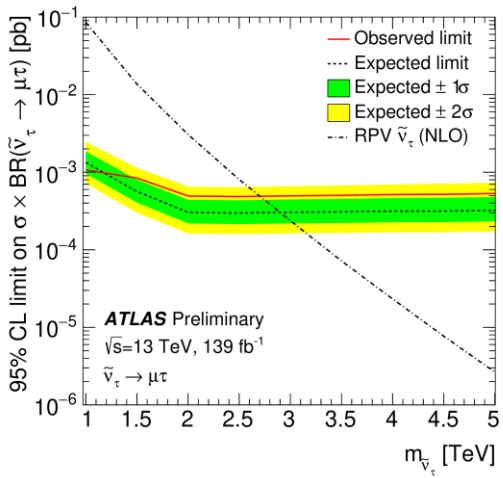












Dark matter particles search with W^+W^- + E_T^{miss}

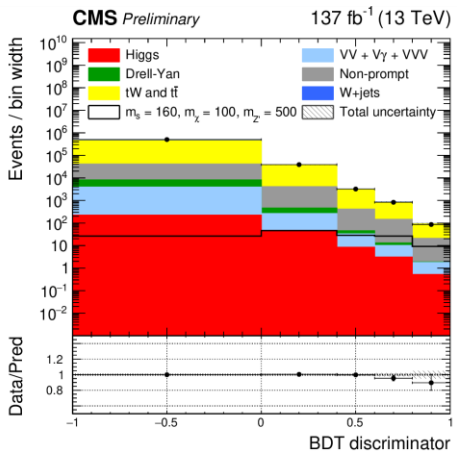
Semi-leptonic channel

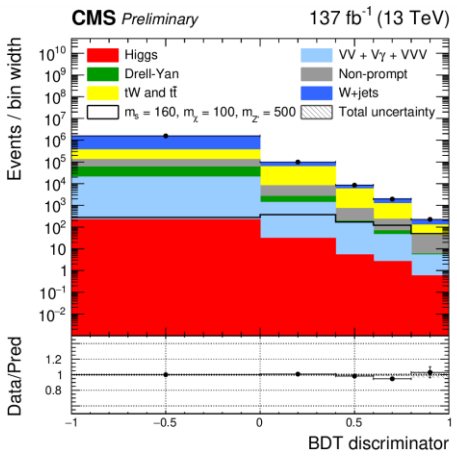
Quantity	Selection
Number of leptons	1
Additional leptons	0
Number of jets	≥ 2
Non W-candidate b-tagged jets	0
m_{jj}	$> 65\,\mathrm{GeV}, < 105\,\mathrm{GeV}$
$p_{\mathrm{T}}^{\mathrm{miss}}$	$> 60\,\mathrm{GeV}$
$p_{\mathrm{T}}^{\ell\mathrm{jj}}$	$> 60\,\mathrm{GeV}$
$m_{\mathrm{T}}^{\ell,p_{\mathrm{T}}^{\mathrm{miss}}}$	$> 80\,\mathrm{GeV}$
$\Delta R_{\ell,\mathrm{jj}}$	< 3
$\Delta\phi_{\ell,\mathrm{jj}}$	< 1.8
$\Delta\phi_{\ell\mathrm{jj},p_{\mathrm{T}}^{\mathrm{miss}}}$	> 2

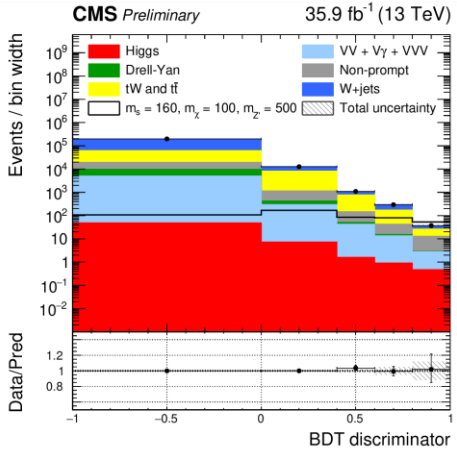
Two-lepton channel

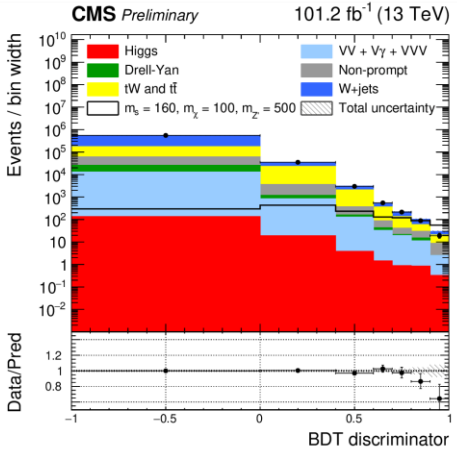
Quantity	Selection
Number of leptons	2
Lepton flavors	$\mathrm{e}\mu$, $\mu\mathrm{e}$
Lepton charges	Opposite
Additional leptons	0
$p_{\mathrm{T}}^{\ell\,\mathrm{max}}$	$> 25\,\mathrm{GeV}$
$p_{\mathrm{T}}^{\ell\,\mathrm{min}}$	$> 20\,\mathrm{GeV}$
$m_{\ell\ell}$	$> 12\,\mathrm{GeV}$
$p_{\mathrm{T}}^{\ell\ell}$	$> 30\,\mathrm{GeV}$
$p_{\mathrm{T}}^{\mathrm{miss}}$	$> 20\,\mathrm{GeV}$
$min(p_{\mathrm{T}}^{\mathrm{miss,PF\,proj}}, p_{\mathrm{T}}^{\mathrm{miss,track\,proj}})$	$> 20\,\mathrm{GeV}$
$m_{\mathrm{T}}^{\ell\ell,p_{\mathrm{T}}^{\mathrm{miss}}}$	$> 50\,\mathrm{GeV}$
$\Delta R_{\ell\ell}$	< 2.5
Number of b-tagged jets	0

Dark matter particles search with W^+W^- + E_T^{miss}



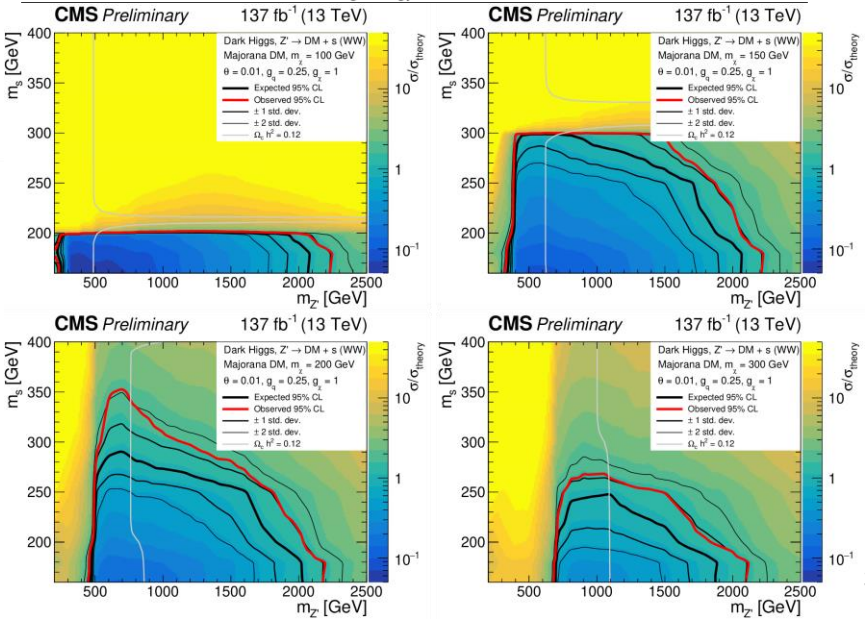




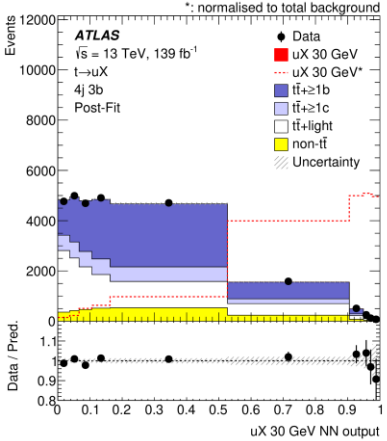


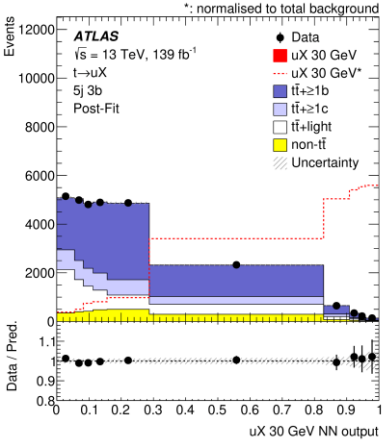
Variable	Definition
p_T^{jj}	p_T of the vectorial sum of the W candidate jets
$p_T^{\ell jj}$	p_T of the vectorial sum of the visible particles
p_T^{miss}	Size of the missing transverse momentum vector
$\Delta\eta_{\ell,jj}$ and $\Delta\phi_{\ell,jj}$	$\Delta\eta$ and $\Delta\phi$ between the lepton and the di-jet system
$\Delta\eta_{j,j}$ and $\Delta\phi_{j,j}$	$\Delta\eta$ and $\Delta\phi$ between the W candidate jets
$\Delta\eta_{\ell,p_T^{miss}}$ and $\Delta\phi_{\ell,p_T^{miss}}$	$\Delta\eta$ and $\Delta\phi$ between the lepton and $\vec{p}_T^{miss}$
$\Delta\phi_{\ell jj,p_T^{miss}}$	$\Delta\phi$ between the vectorial sum of the visible particles and $\vec{p}_T^{miss}$
$min(p_T^{\ell}, p_T^{j2})/p_T^{miss}$	Minimum of the lepton p_T and the trailing jet p_T, divided by p_T^{miss}
$max(p_T^{\ell}, p_T^{j2})/p_T^{miss}$	Maximum of the lepton p_T and the leading jet p_T, divided by p_T^{miss}
$max(p_T^{\ell}, p_T^{j1})/m_{\ell jj p_T^{miss}}$	Maximum of the lepton p_T and the leading jet p_T, divided by the invariant mass of the vectorial sum of the visible particles and the p_T^{miss} where the missing energy is considered to be massless

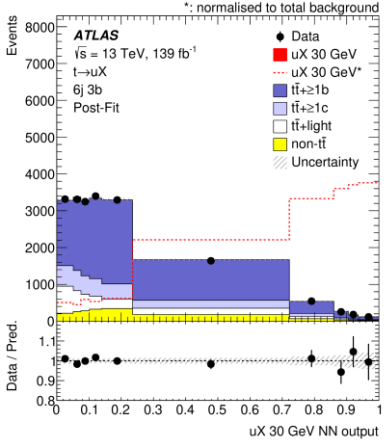
BDT input variables

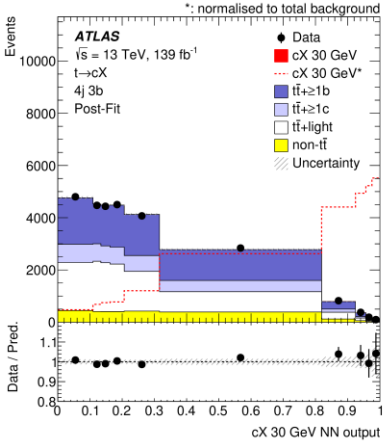


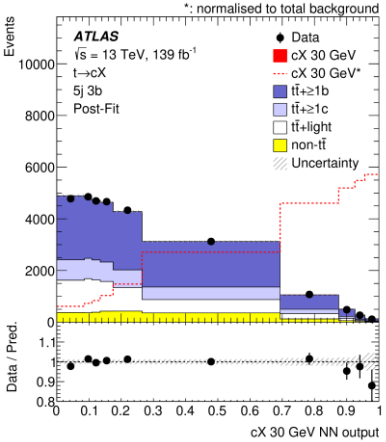
FCNC $t \to qH$ decays

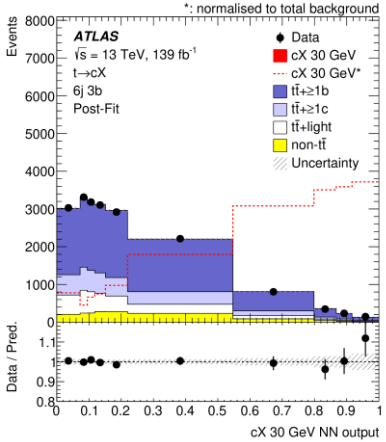




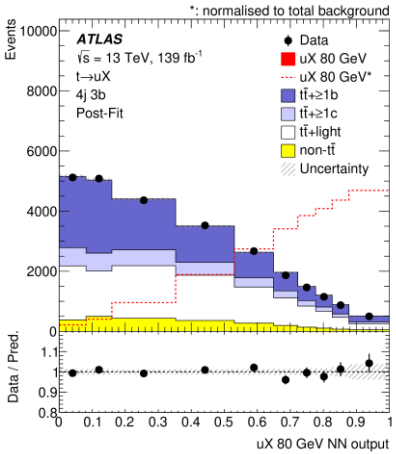


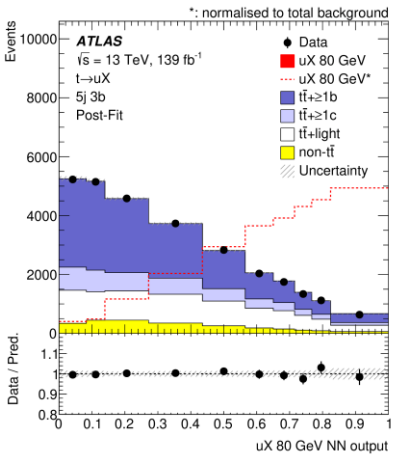


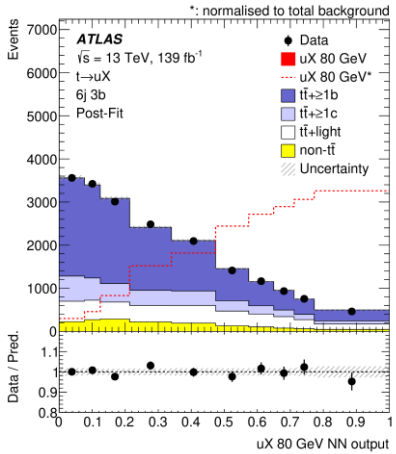


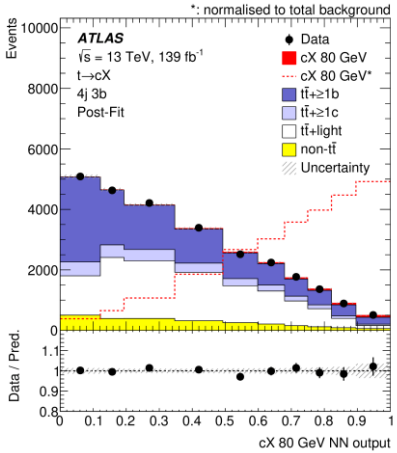


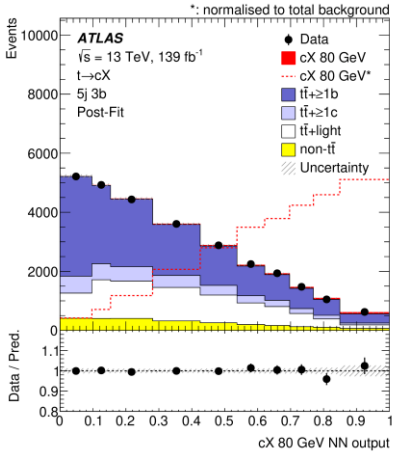
FCNC $t \to qH$ decays

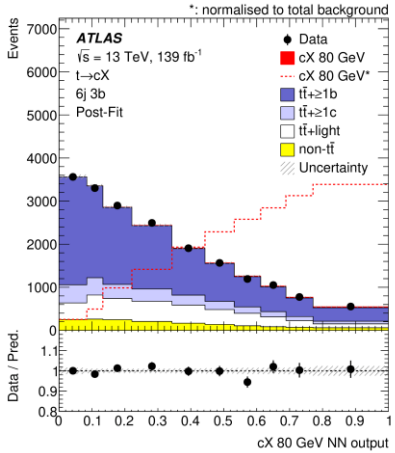




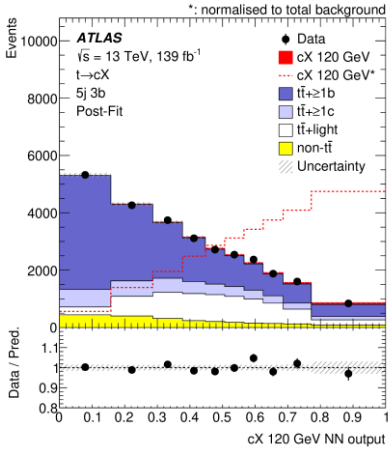


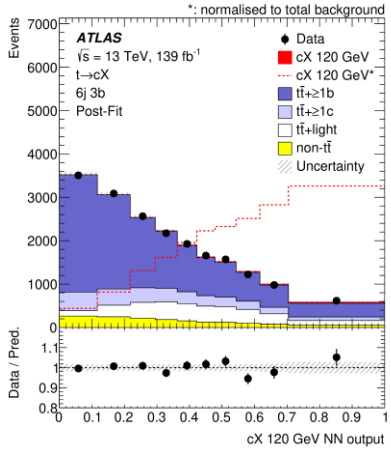


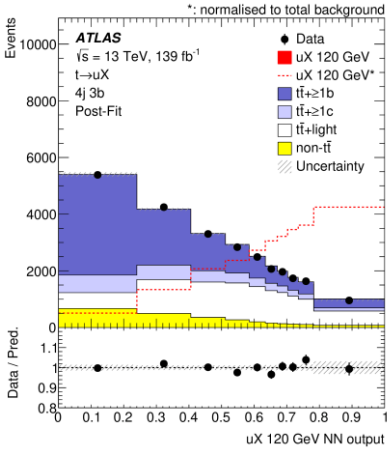


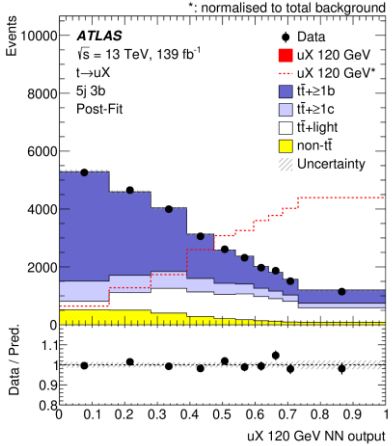


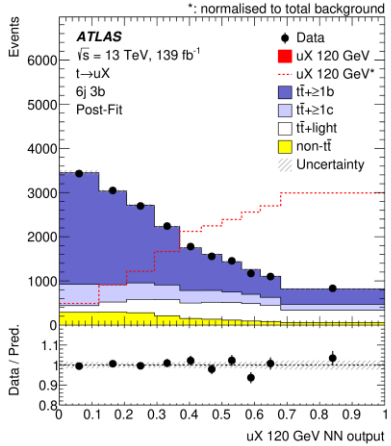
FCNC $t \to qH$ decays

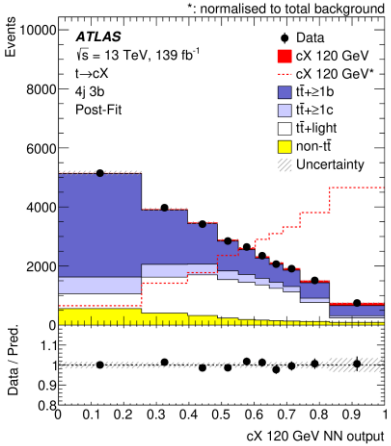












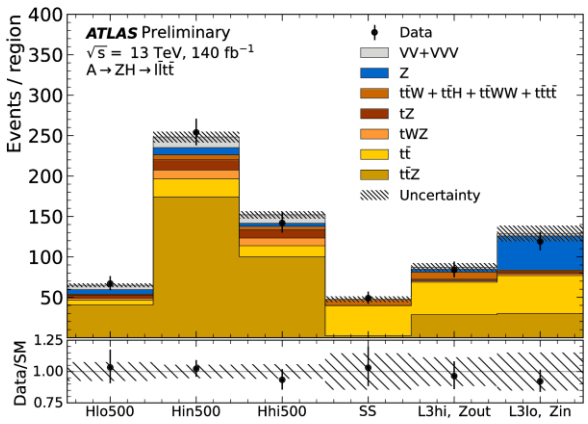
2HDM $A \to ZH \to \ell\ell tt$ or $vvbb$

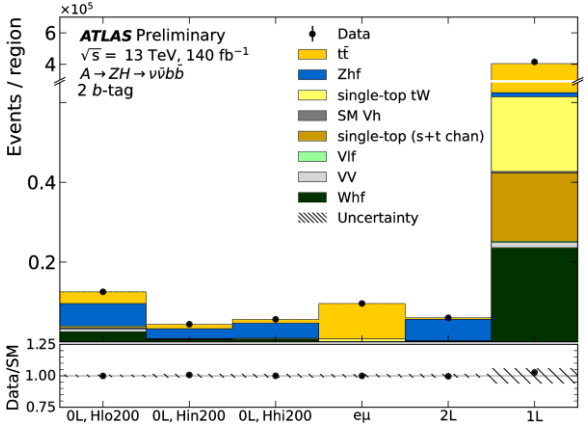
Cut	Regions				
	ss (CR)	L3hi_Zout (VR)	Hlo / Hhi (CR)	Hin (SR)	L3lo_Zin (VR)
N leptons	3				
p_{T} (ℓ_1)	> 27 GeV				
N jets	≥ 4				
N b-jets	2				
$\lvert\eta^{\mathrm{ZH-r.fr.}}_{H-\mathrm{cand}}\rvert$	$< 2.2 + 0.0004 \cdot m_H^{\mathrm{cand}} - 0.0011 \cdot m_A^{\mathrm{cand}}$				
p_{T} (ℓ_3)	> 13 GeV				> 7 GeV & < 13 GeV
Lepton flavour	$ee\mu/\mu\mu e$	$eee/ee\mu/\mu\mu e/\mu\mu\mu$			
OSSF lepton pairs	0	≥ 1			
$\lvert m_Z^{\mathrm{cand}} - m_Z\rvert$	< 20 GeV	> 10 GeV & < 20 GeV	< 10 GeV		
$\lvert m_H^{\mathrm{cand}} - m_H^{\mathrm{hypo}}\rvert$	$m_H^{\mathrm{hypo}} < 500$ GeV	-	$> 0.32 \cdot m_H^{\mathrm{hypo}}$	$< 0.32 \cdot m_H^{\mathrm{hypo}}$	-
	$m_H^{\mathrm{hypo}} > 500$ GeV		$> 0.24 \cdot m_H^{\mathrm{hypo}}$	$< 0.24 \cdot m_H^{\mathrm{hypo}}$	

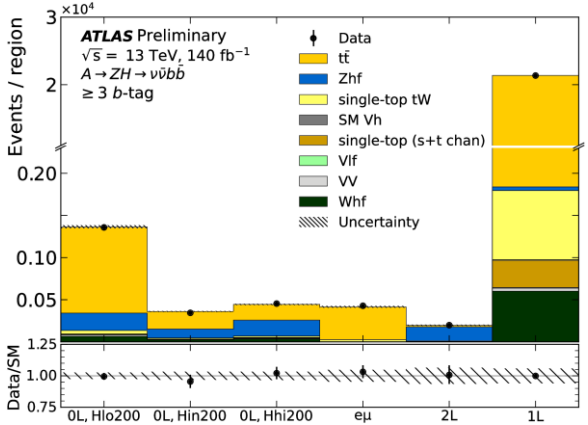
$\ell\ell tt$

Cut	Regions				
	2L (CR)	eμ (CR)	1L (VR)	Hlo / Hhi (CR)	Hin (SR)
N jets	2-5				
N b-jets	> 2				
m_H^{cand}	> 50 GeV				
N hadronically decaying τ-leptons	0				
$p_{\mathrm{T}}(V)$	> 150 GeV				
$\min_i \Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_i^{\mathrm{jet}})$	$> \pi/10$				
$\Delta R(b_1, b_2)$	< 3.3 (2 b-jets)				
	< 3.5 (≥ 3 b-jets)				
N leptons	2		1	0	
Lepton flavour	$ee/\mu\mu$	$e\mu$	e/μ	-	
$p_{\mathrm{T}}(\ell_1)$	> 27 GeV			-	
$\lvert m_Z^{\mathrm{cand}} - m_Z\rvert$	< 10 GeV	-			
$\mathcal{S}_{\mathrm{MET}}$	< 5	-	> 3	> 10	
$m_{\mathrm{top}}^{\mathrm{near}}$	-			> 180 GeV	
$m_{\mathrm{top}}^{\mathrm{far}}$	-			> 200 GeV	
$\lvert m_H^{\mathrm{cand}} - m_H^{\mathrm{hypo}}\rvert$	-			$> 0.2 \cdot m_H^{\mathrm{hypo}}$	$< 0.2 \cdot m_H^{\mathrm{hypo}}$

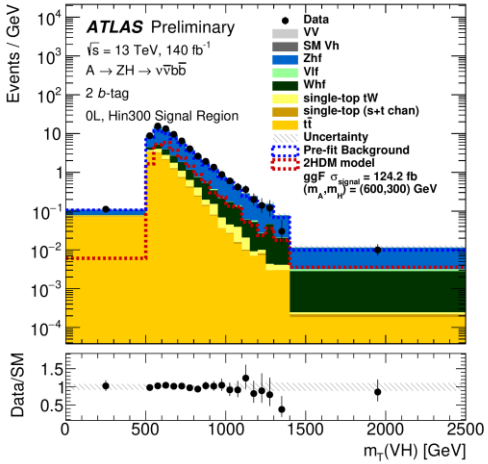
$vvbb$

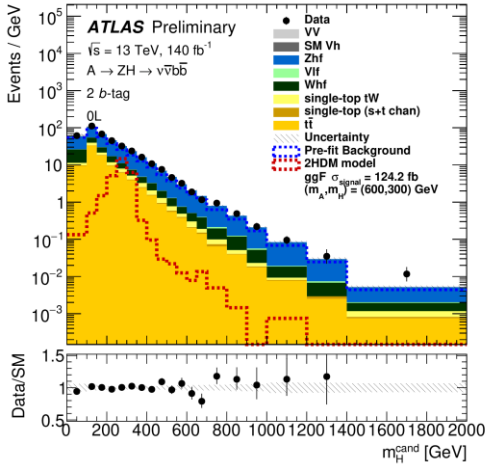


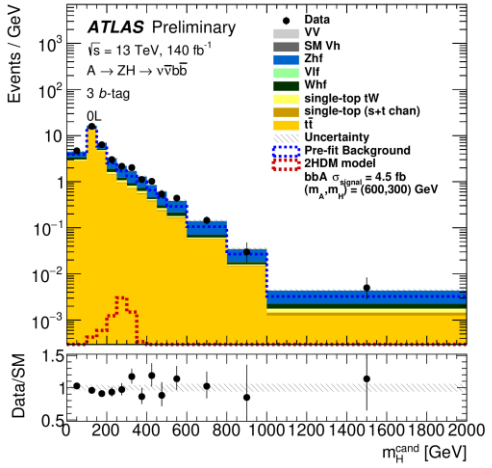


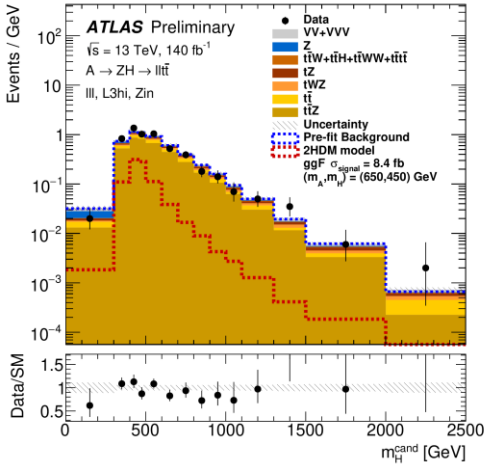


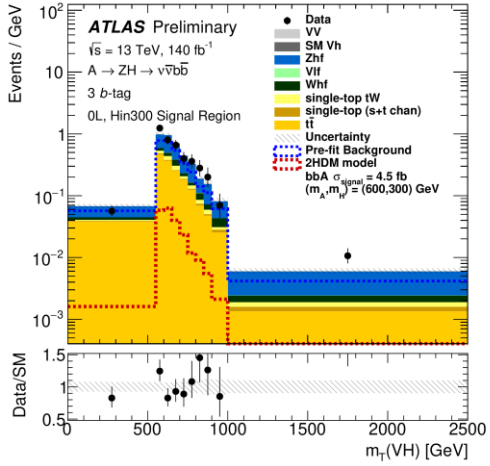
2HDM $A \to ZH \to \ell\ell tt$ or $vvbb$

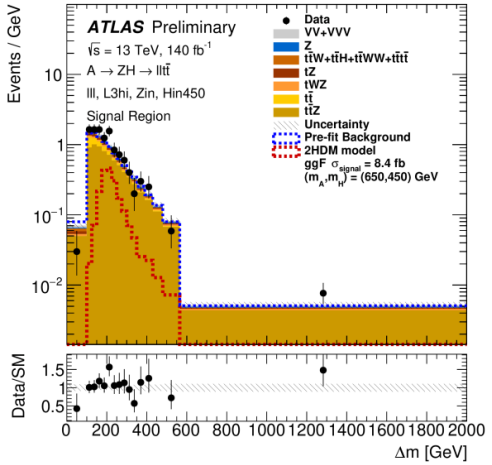






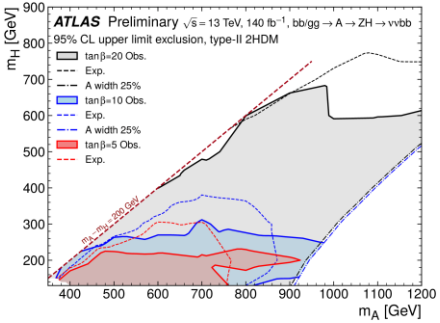


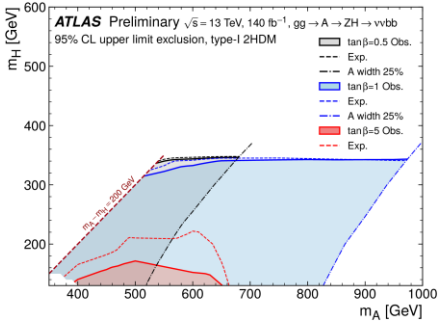


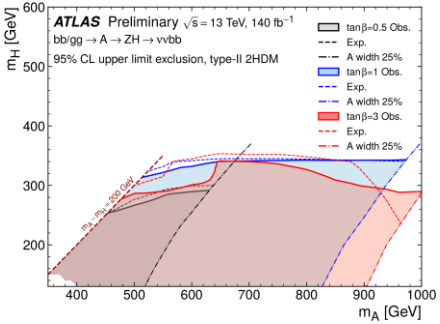


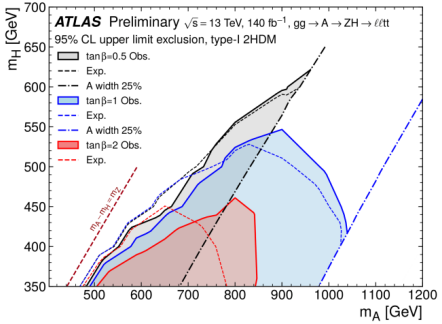
2HDM $A \to ZH \to \ell\ell tt$ or $vvbb$

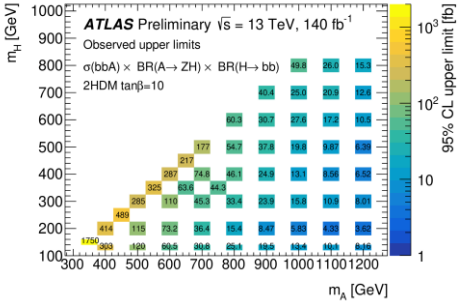
Previous $\ell\ell bb$ result: Eur. Phys. J. C 81, 396 (2021)

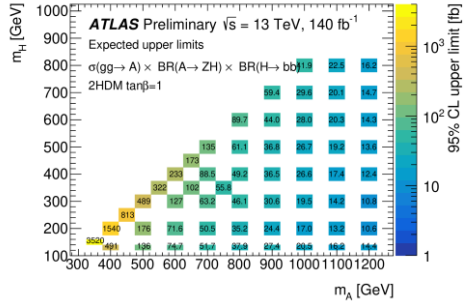


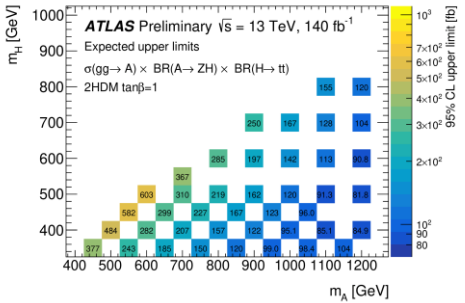


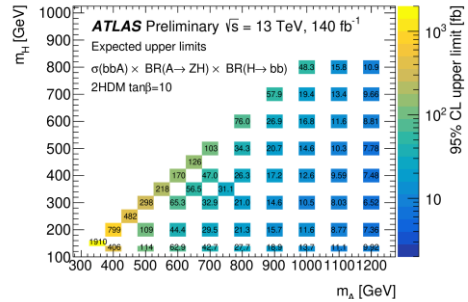


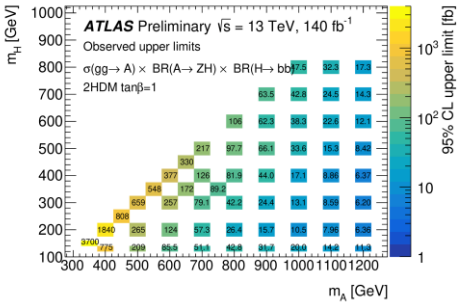


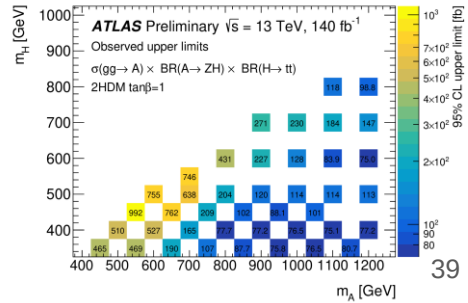




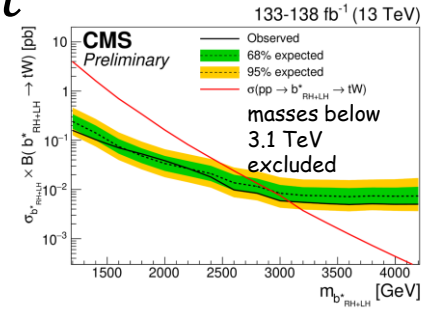


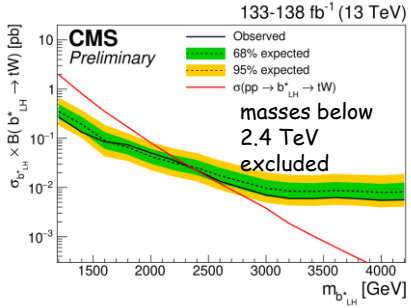


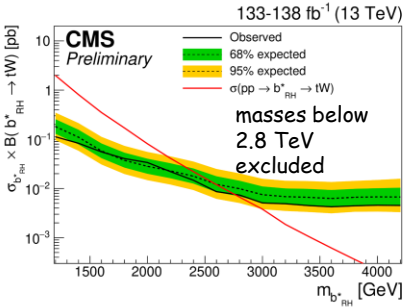


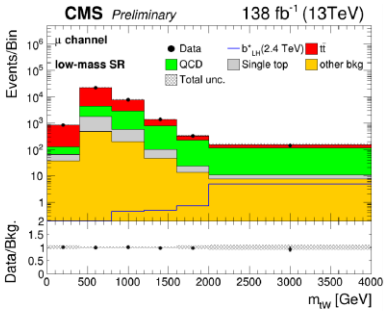


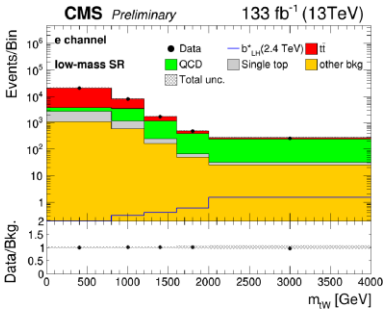
Excited $b^* \rightarrow Wt$

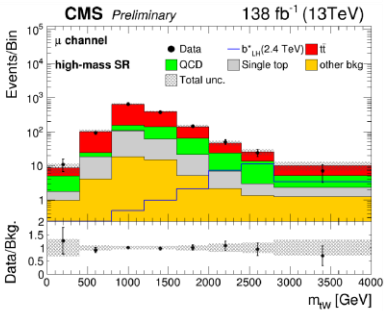


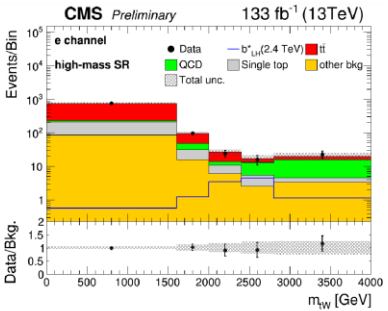


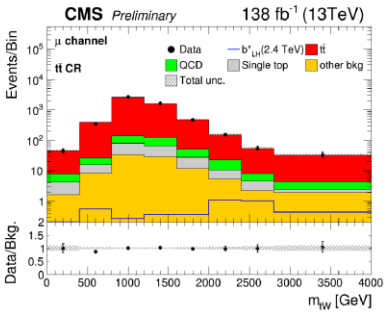


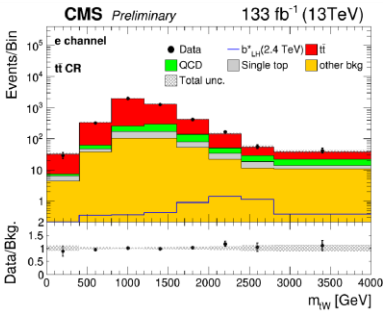












*Previous searches for an excited bottom quark in the tW decay mode have been performed at $\sqrt{s}$ = 8 TeV by the ATLAS and CMS Collaborations. These searches excluded b∗ quark masses at 95% confidence level (CL) below 1.4, 1.4 and 1.5 TeV for the LH, RH and VL hypotheses

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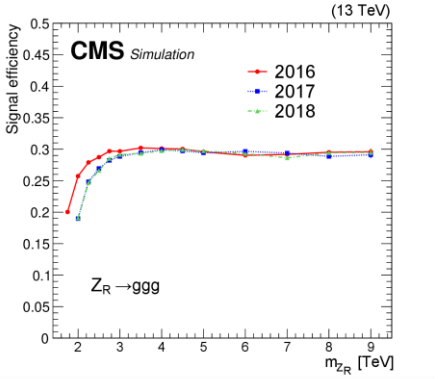

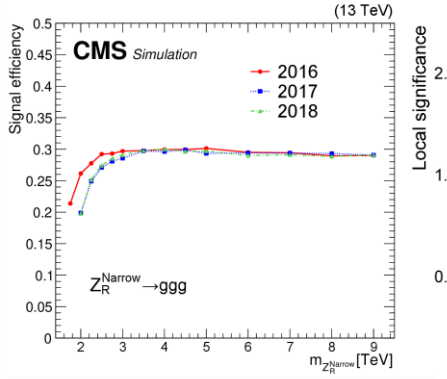

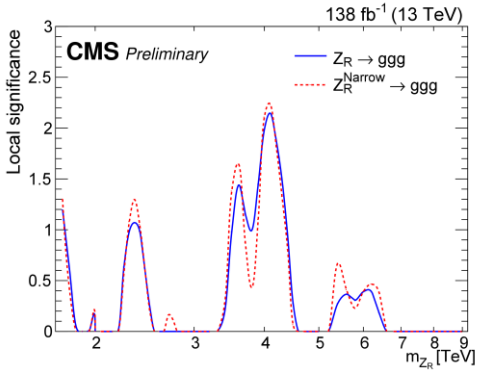

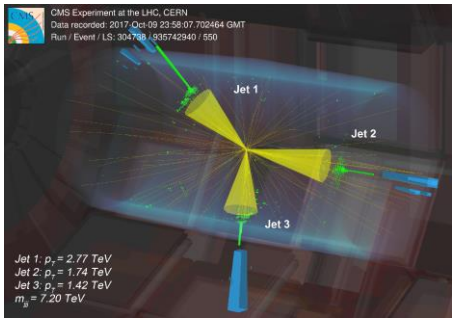

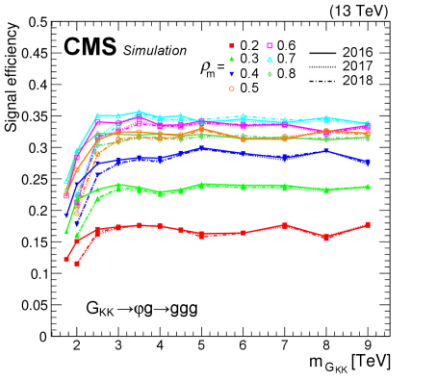

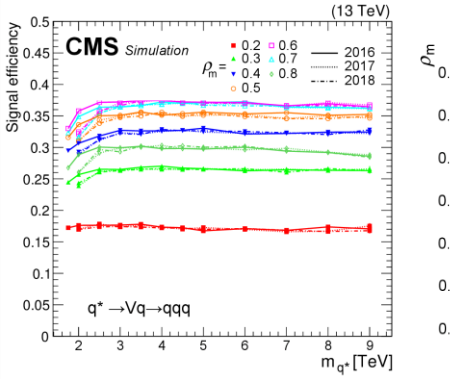

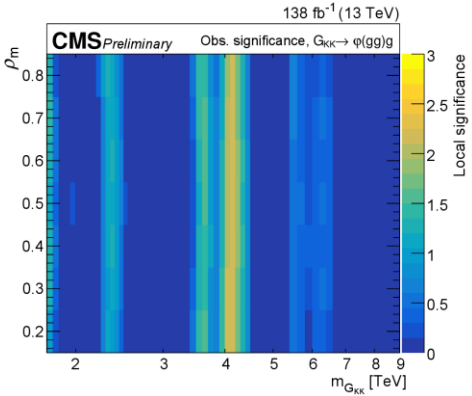

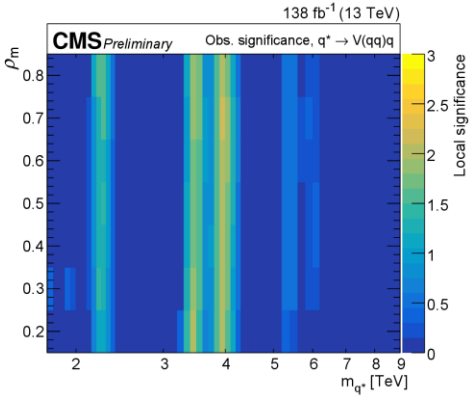

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