



Searches for Exotic Heavy Resonances with the ATLAS detector

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On behalf of ATLAS Collaboration

Lake Louise Winter Institute 2024



The UNIVERSITY of OKLAHOMA

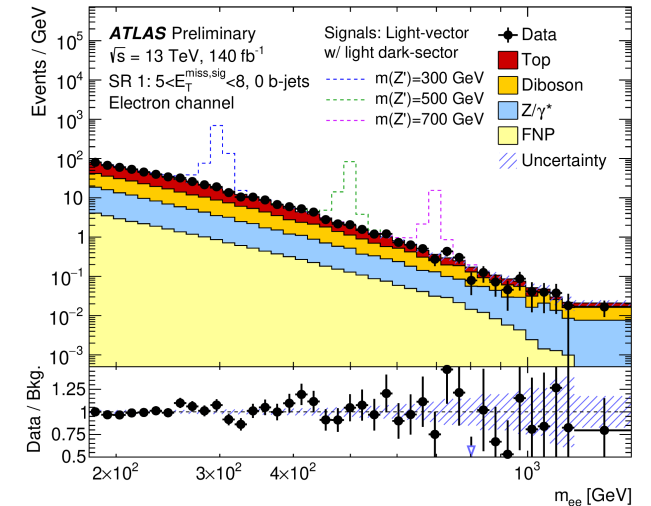
DEPARTMENT OF PHYSICS AND ASTRONOMY



Heavy resonances at the LHC



- Many Beyond Standard Model theories predict the existence of additional particles
- Heavy resonances are predicted in many new physics models
 - Heavy vector triplet (W' , Z')
 - Vector like quarks
- Would appear as a bump on flat Standard Model (SM) prediction
 - Indicates an unknown resonance particle
- LHC allows to explore ever higher masses

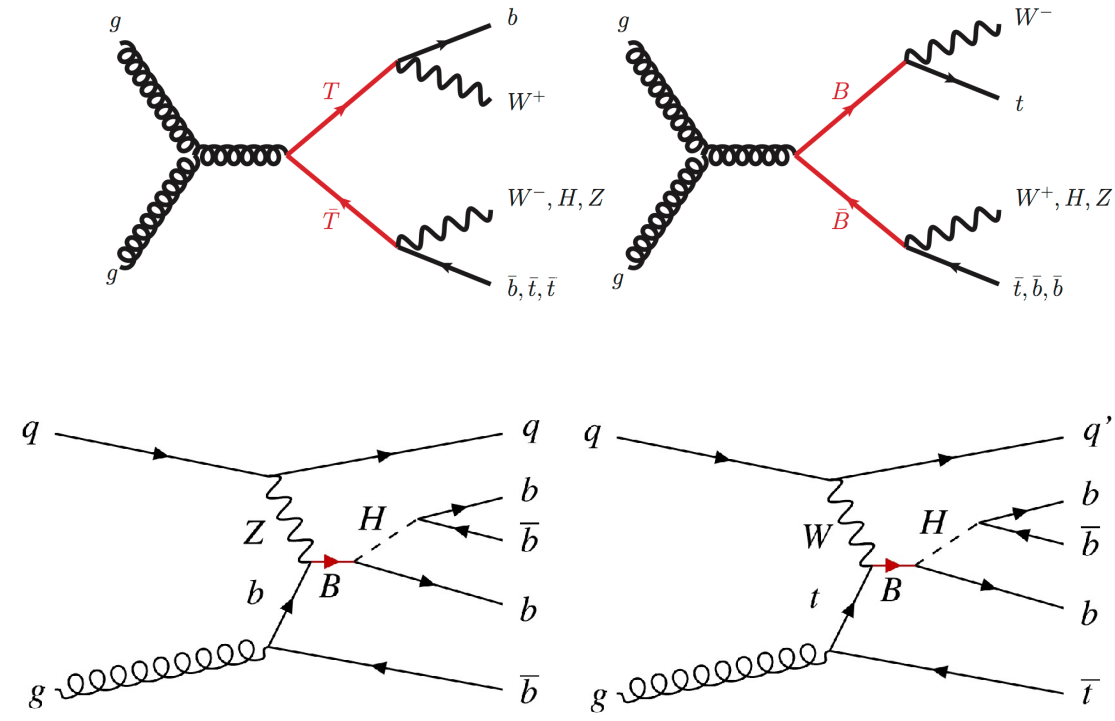




VLQ at the LHC



- Vector Like Quarks (VLQ) are predicted to be spin-1/2 particles that transform as a triplet under color gauge symmetry and whose left- and right-handed components both have the same electroweak quantum numbers
- Couple to the SM fermions via Yukawa couplings
 - ➔ Interact principally with the third-generation SM quarks
- Vector-like T and B quarks
 - Vector-like equivalents of the third-generation SM quarks
 - Electric charge $Q(T) = 2/3$ and $Q(B) = -1/3$,
 - Can exist as singlets, doublets or triplets
- X and Y VLQs
 - Charges $Q(X) = 5/3$ and $Q(Y) = -4/3$ respectively
 - Can exist either in gauge doublets along with a T or B quark or in gauge triplets along with both the T and B quarks
- At the LHC, VLQs are expected to be produced either in pairs, via the strong interaction, or singly, via the exchange of an intermediate electroweak gauge boson

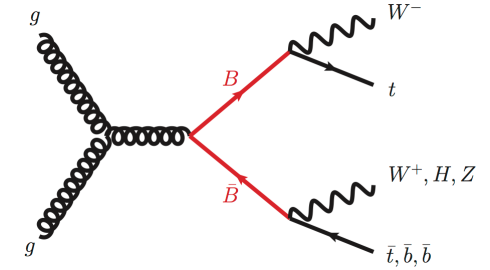
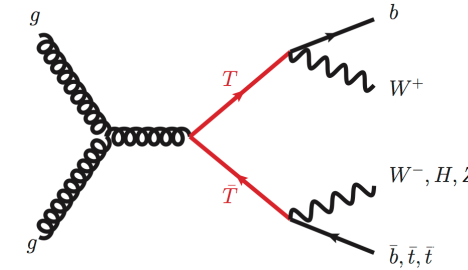




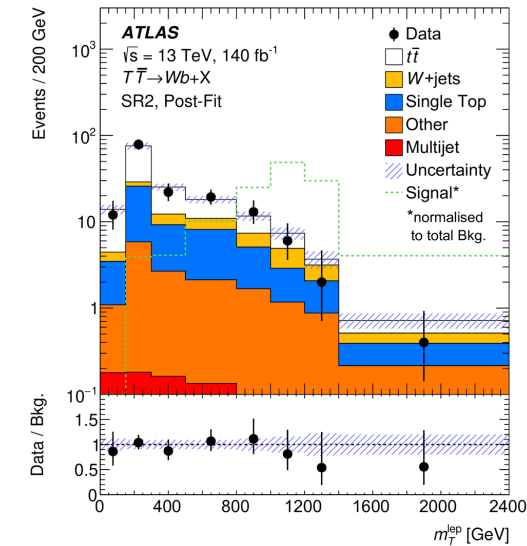
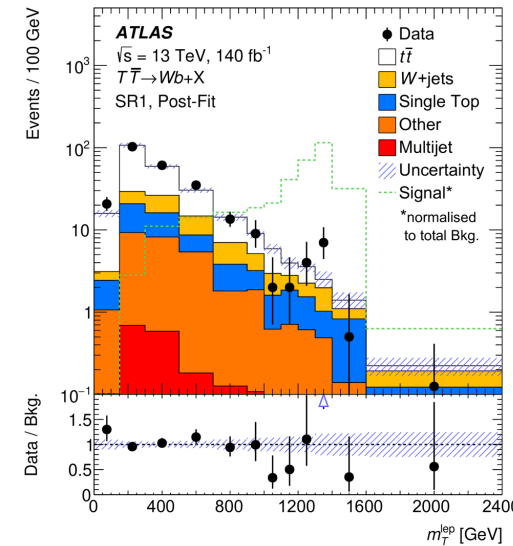
VLQ pair production search in the $Wb+X$ final state



- Optimised for vector-like T-quarks that decay into a W-boson and a b-quark
 - One W-boson decaying leptonically and the other hadronically
- Also considered models
 - Vector-like B-quark
 - Vector-like Y-quarks, which decay exclusively into a W boson and a b -quark
- Event selection:
 - High p_T electron or muon
 - Large E_T^{miss}
 - Large radius jet identified as W-boson
 - Multiple small radius jets: at least one of them is b-tagged
- Important discriminant used to define Signal Region and Control Region, S_T : scalar sum of the p_T of the selected small-radius jets, the lepton p_T and the E_T^{miss}



[arxiv:2401.17165](https://arxiv.org/abs/2401.17165)

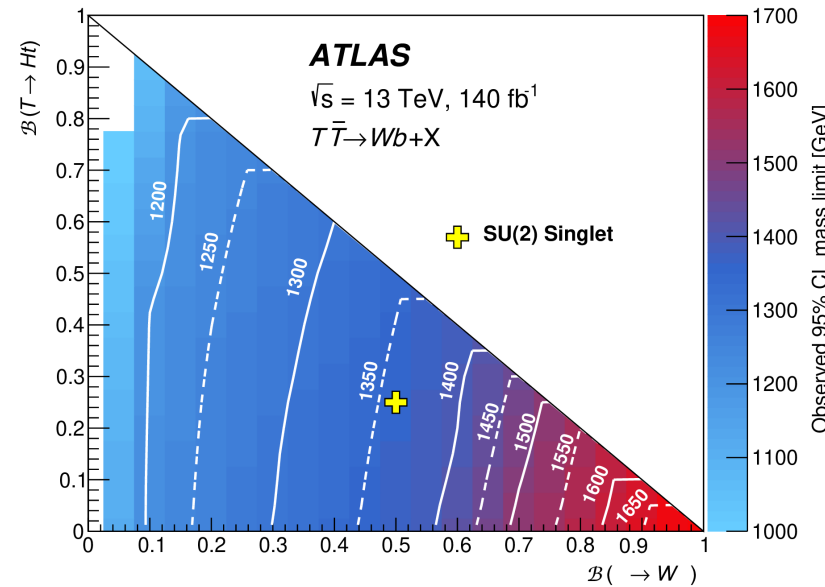
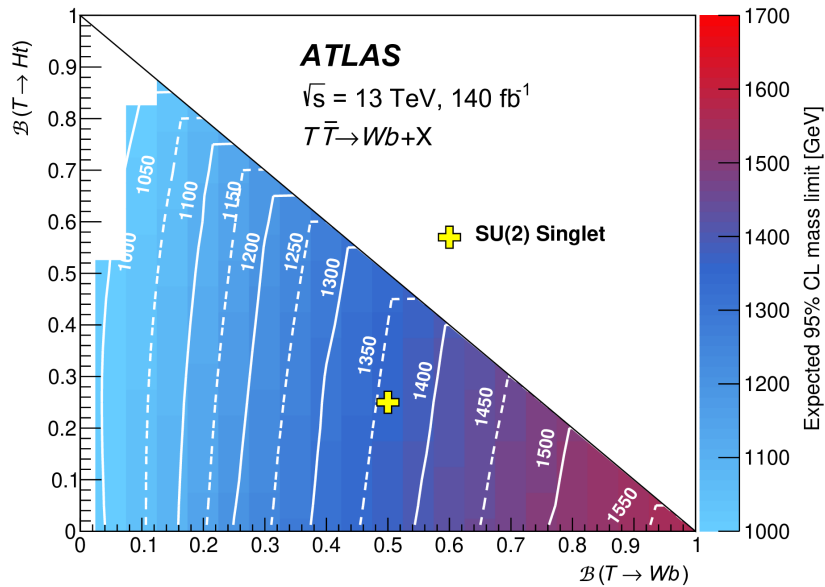
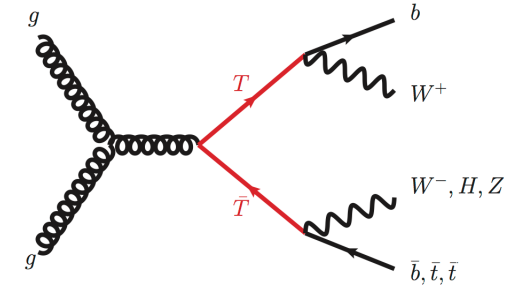




VLQ pair production search in the $Wb+X$ final state



- VLQs can decay via a flavor-changing neutral current or a charged current
 - $\rightarrow T$ has three possible decays: $T \rightarrow Wb/Zt/Ht$
- Expected and observed 95% CL lower limits on the mass of the T -quark in the branching-ratio plane of $B(T \rightarrow Wb)$ versus $B(T \rightarrow Ht)$



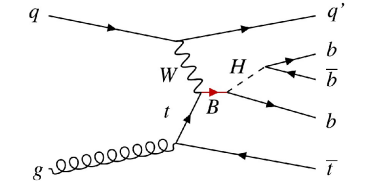
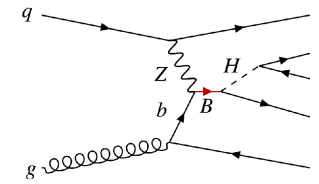
[arxiv:2401.17165](https://arxiv.org/abs/2401.17165)



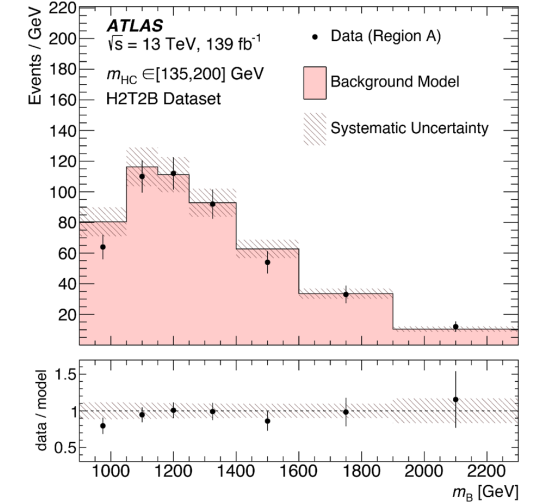
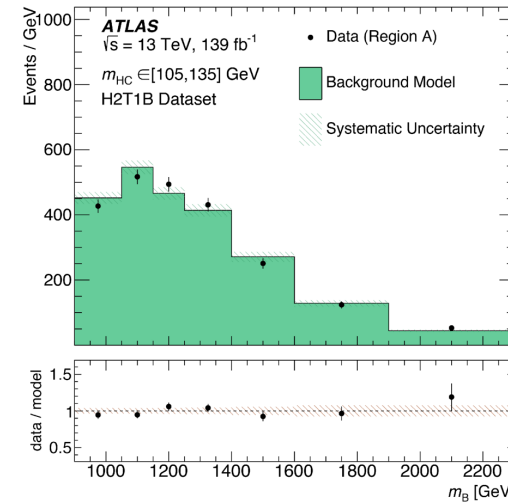
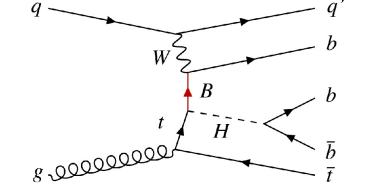
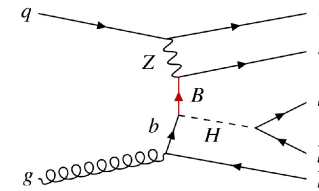
Search for vector-like $B \rightarrow bH$ with $H \rightarrow bb$



- Vector-like B quark can be produced in the resonant s -channel
 - Either the electroweak interaction of an initial-state b -quark and a Z boson (leading production mode for a vector-like B singlet)
 - Or of an initial-state t -quark and a W boson
- Strongly non-resonant single vector-like B quark production arises through t -channel processes
 - Mostly results in low-mass off-shell B quarks falling well outside the acceptance of the trigger selection employed by the analysis
- Event preselection:
 - At least 1 large- R jet, $p_T > 480$ GeV
 - No leptons & no $\gamma\gamma$ pairs with $m_{\gamma\gamma} \in [105, 160]$ GeV
 - At least 2 track-jets associated with the large- R jet, at least one of them b -tagged
 - At least 1 small- R jet with $p_T > 300$ GeV
 - $\Delta R(\text{small-}R \text{ jet, large-}R \text{ jet}) > 2.0$
- Data-driven background estimate



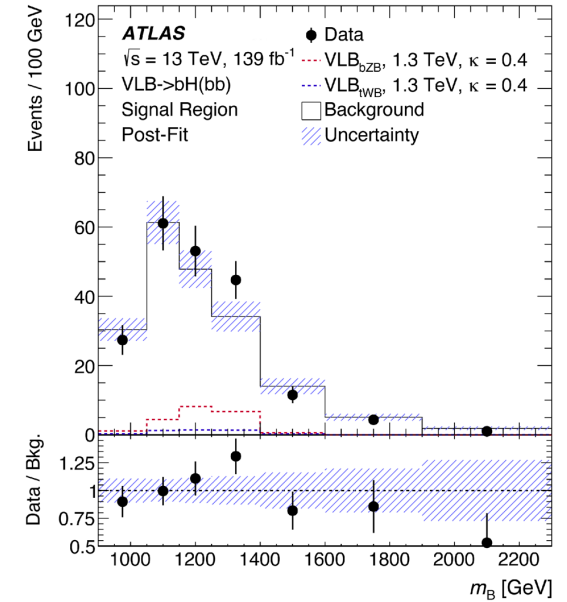
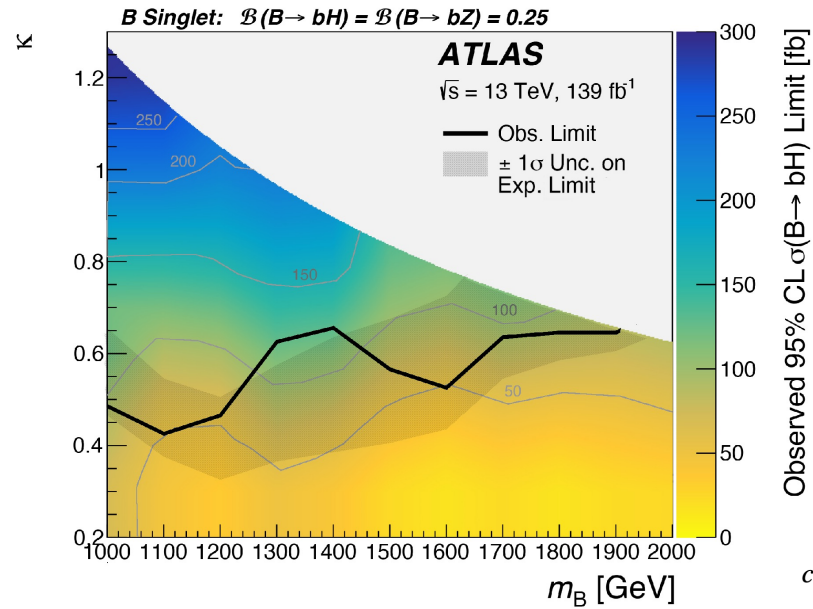
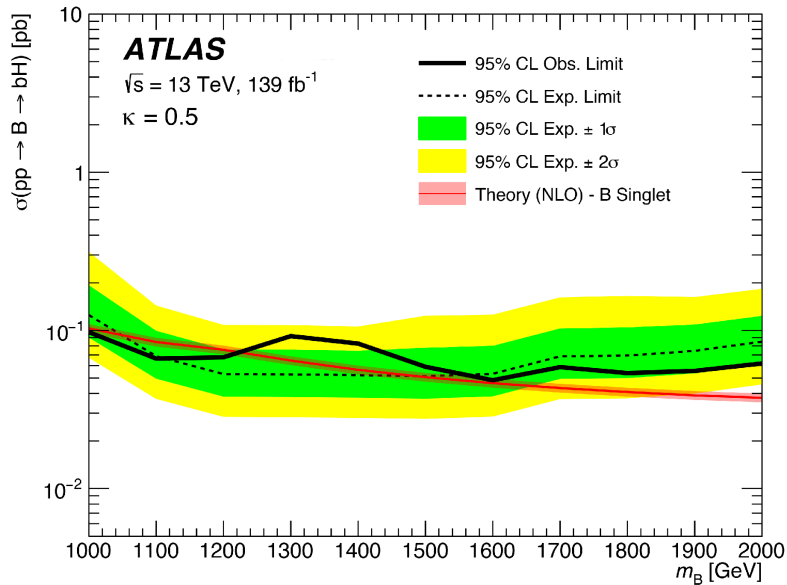
[JHEP11\(2023\)168](#)





Search for vector-like $B \rightarrow bH$ with $H \rightarrow bb$

- Results are interpreted as limits on the single-production cross-section
 - For fixed $K = 0.5$
 - Also as a function of the resonance mass and coupling strength κ



Theoretical scenarios determined by the couplings c_W , c_Z and c_H between the B quark and the SM W , Z and Higgs bosons

$$c_W = \kappa \sqrt{\frac{2\xi_W}{\rho_W}}, \quad c_Z = \frac{m_Z}{m_W} \times \kappa \sqrt{\frac{2\xi_Z}{\rho_Z}}, \quad c_H = \frac{1}{2} \frac{g_W m_B}{m_W} \times \kappa \sqrt{\frac{2\xi_H}{\rho_H}}$$

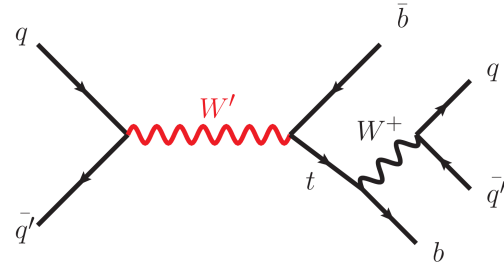
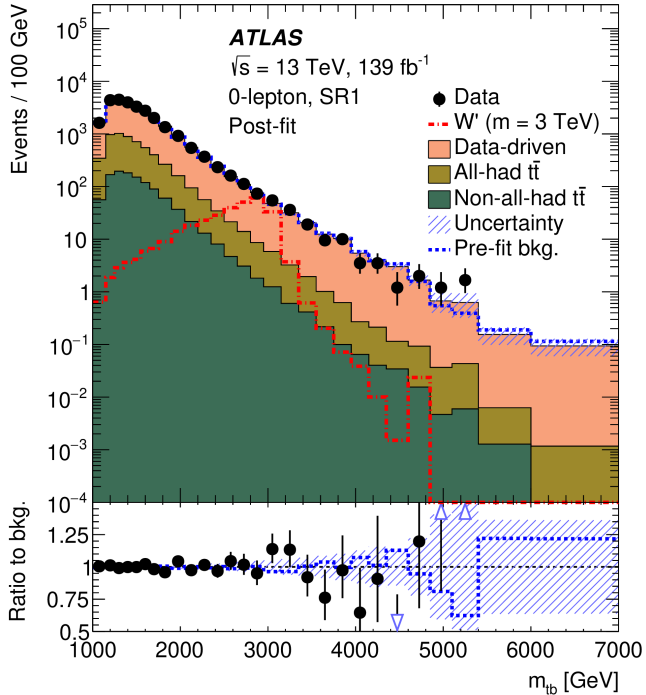


Search for $W' \rightarrow tb$ in 0/1-lepton channel



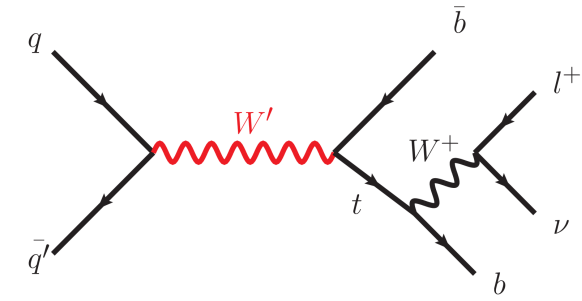
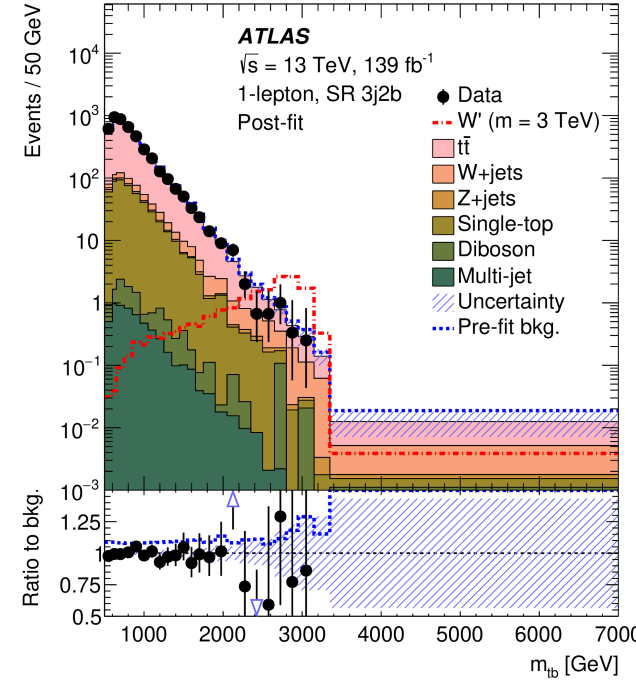
[JHEP12\(2023\)073](#)

- Many models (extra dimensions, strong dynamics, or a composite Higgs boson), predict new vector charged-current interactions
 - Some models predict W' bosons that preferentially couple to third-generation particles



Hadronic channel

- One large- R jet that is top-tagged
- Small- R jet that is b -tagged
- Lepton (e, μ) veto



Single lepton channel

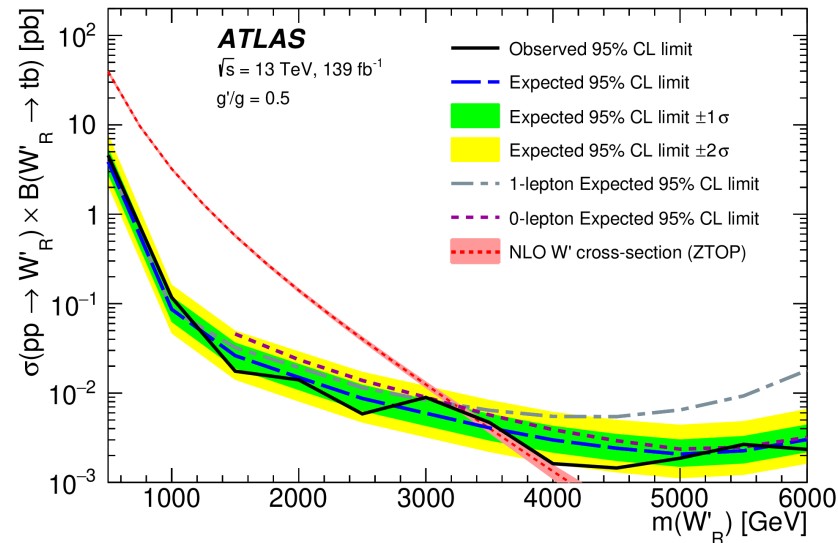
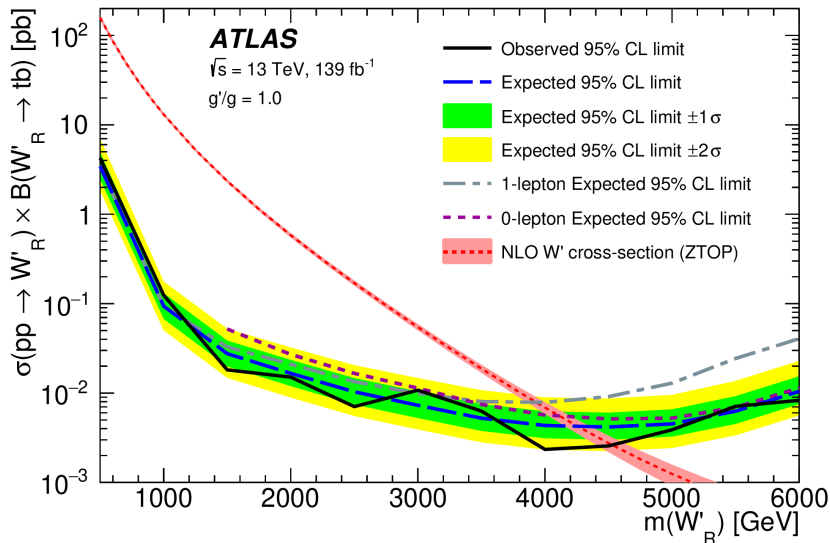
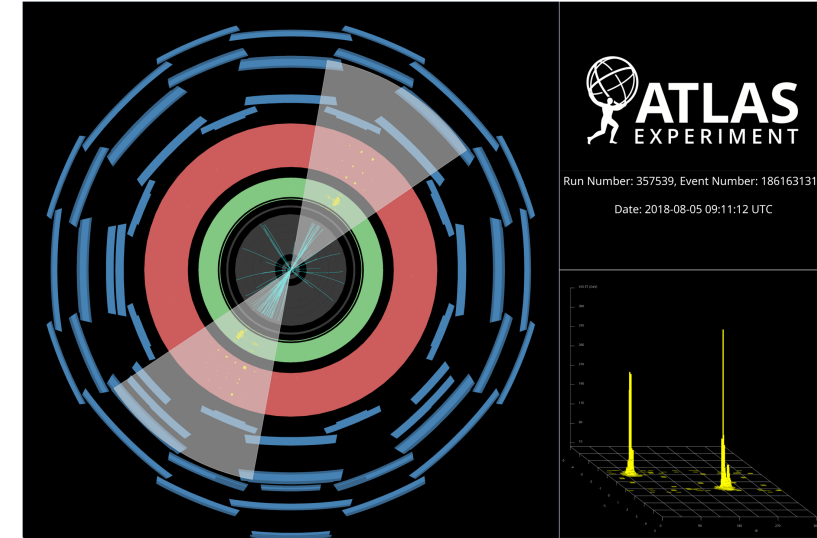
- One lepton (e, μ)
- Large $E_{T, \text{miss}}$
- Neutrino reconstruction
- W -boson is reconstructed as the sum of the lepton and the neutrino
- Top quark is reconstructed by combining the W boson with one of the jets, without considering b -tagging



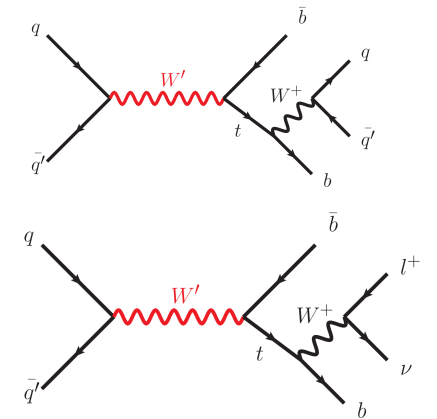
Search for W' to tb 0/1-lepton



- Good agreement between the background prediction and data observed in all regions
- Results interpreted as limits on W' mass



[JHEP12\(2023\)073](#)



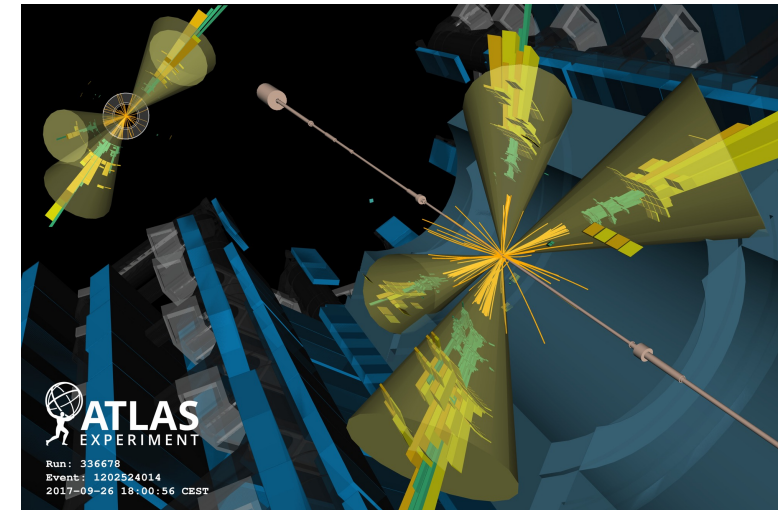
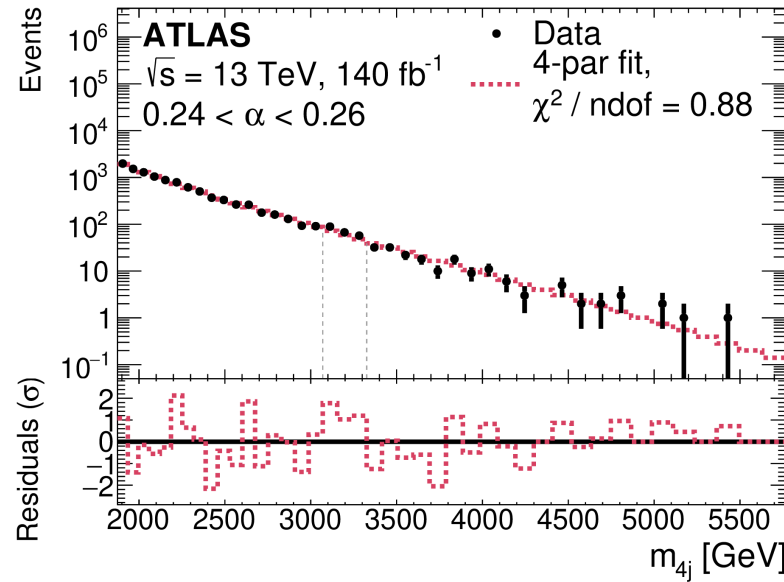
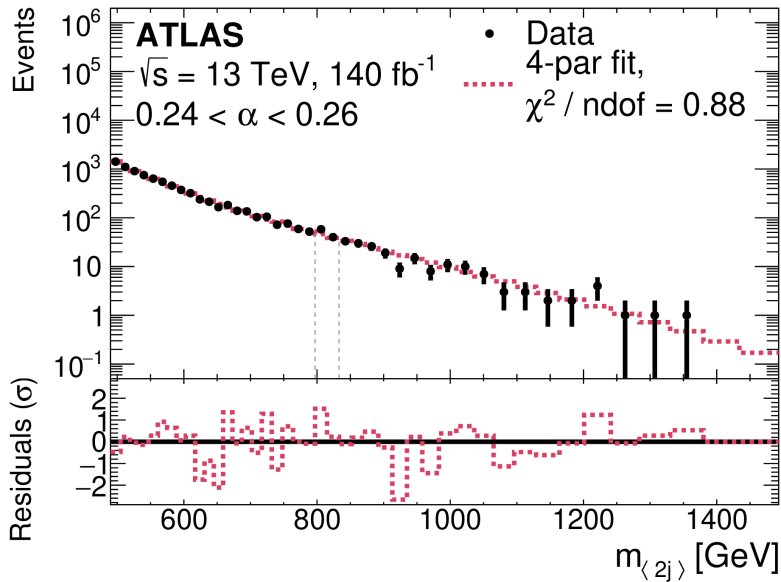
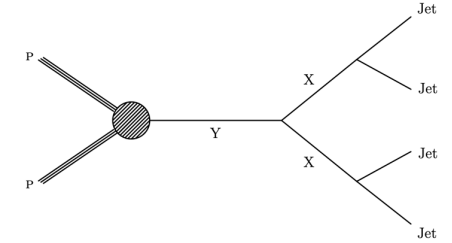


Paired dijet resonance



- Generic massive resonance Y that decays into two pairs of intermediate resonances X with the same mass, each decaying into two partons and so typically producing a pair of dijet system
- Resonances are searched for in the invariant mass of the tetrajet system, and in the average invariant mass of the pair of dijet systems
- Data-driven background estimate is obtained by fitting the tetrajet and dijet invariant mass distributions with a four-parameter dijet function

[Phys. Rev. D 108 \(2023\) 112005](#)

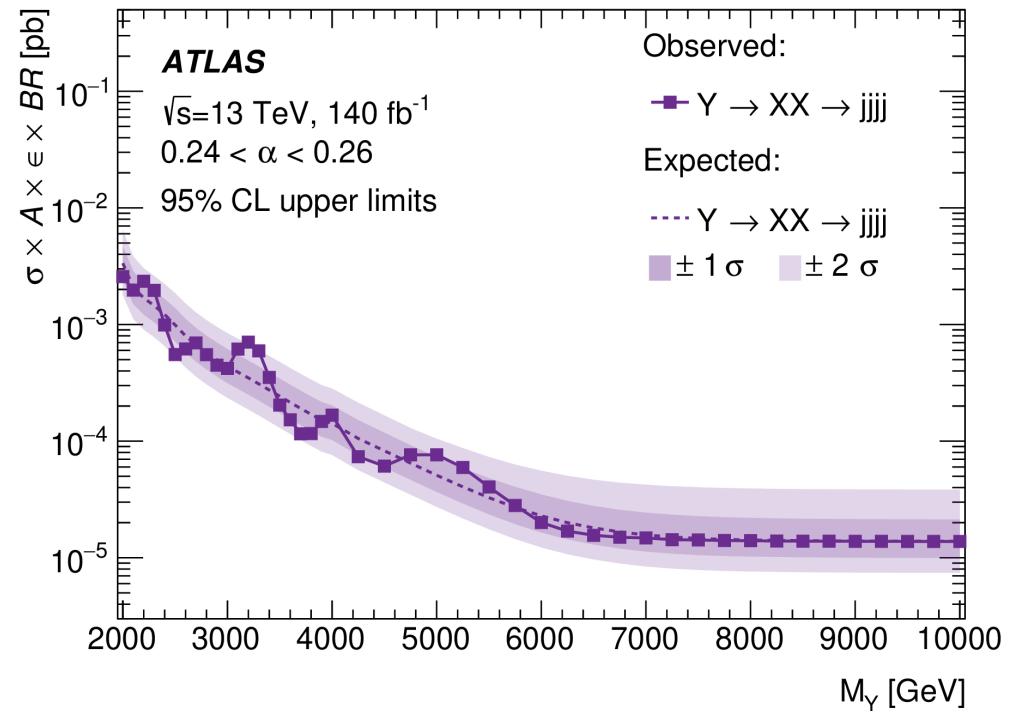
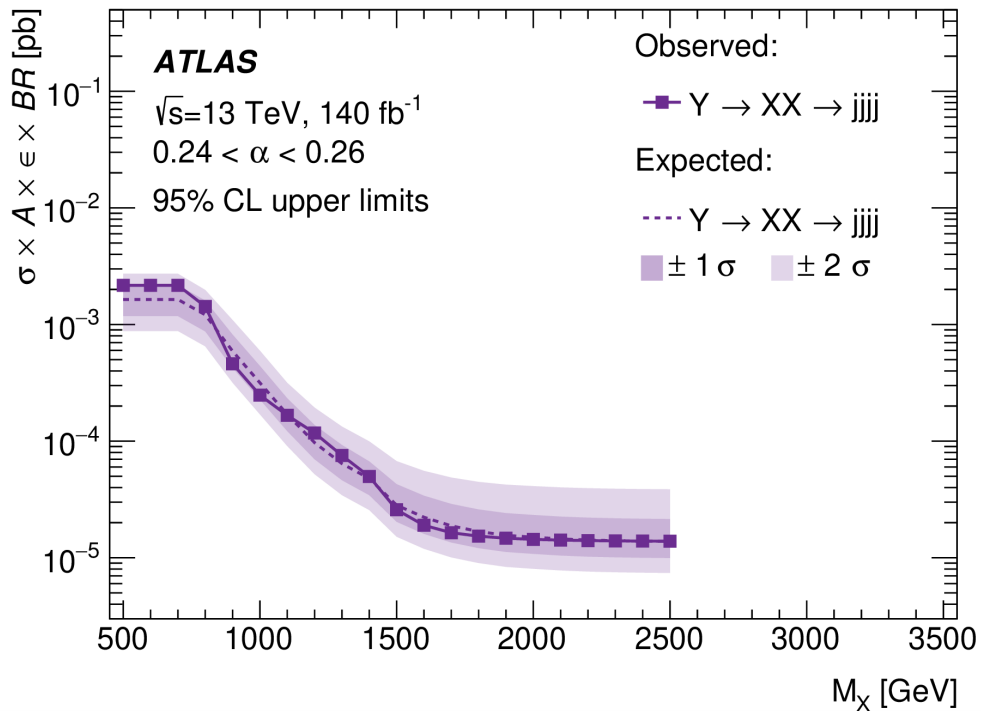




Paired dijet resonance



- 95% CL upper limits on the allowed cross-sections of these particles as a function of their mass [Phys. Rev. D 108 \(2023\) 112005](https://arxiv.org/abs/2205.01231)
- Several representative $\alpha = \langle m_{2j} \rangle / m_{4j}$ regions

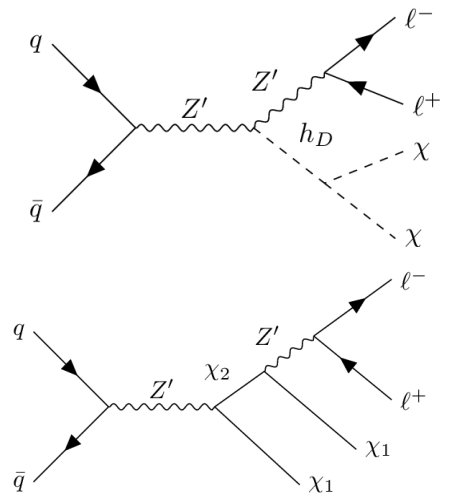




Exclusive dilepton + E_T^{miss}



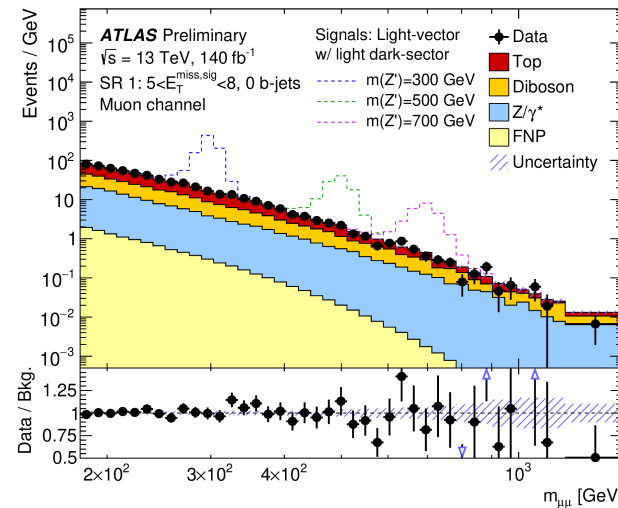
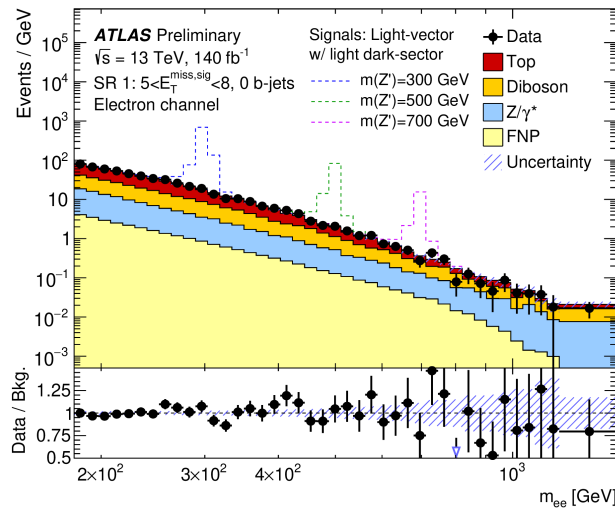
- Dark matter particles produced in association with a new neutral vector boson
- Decays of the Z' boson to same-flavor light leptons ($e^+e^-/\mu^+\mu^-$)
- Dark-Higgs model: a dark-sector Higgs boson h_D can be radiated from the Z' boson and decay to a pair of dark matter particles ($\chi\chi$)
- Light-vector case: the Z' boson has an off-diagonal coupling to the χ_1 and χ_2 dark-sector particles
 - Heavier state χ_2 decays to a lighter dark matter candidate χ_1 and a Z'



ATLAS-CONF-2023-045

- Event selection:
 - Same flavor opposite sign leptons
 - Large E_T^{miss}
 - Three SR based on $E_T^{\text{miss, sig}}$

$$E_T^{\text{miss, sig}} = \frac{|\mathbf{p}_T^{\text{miss}}|}{\sqrt{\sigma_L^2(1 - \rho_{LT}^2)}}$$



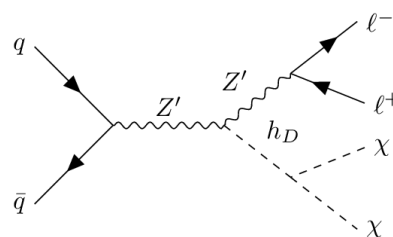
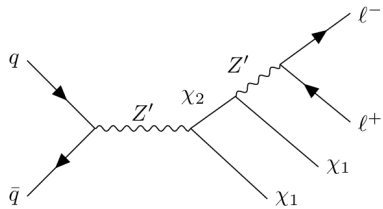


Exclusive dilepton + E_T^{miss}

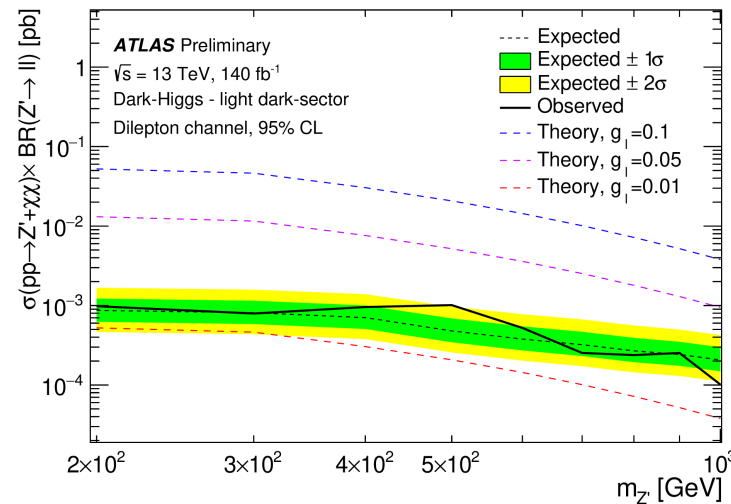
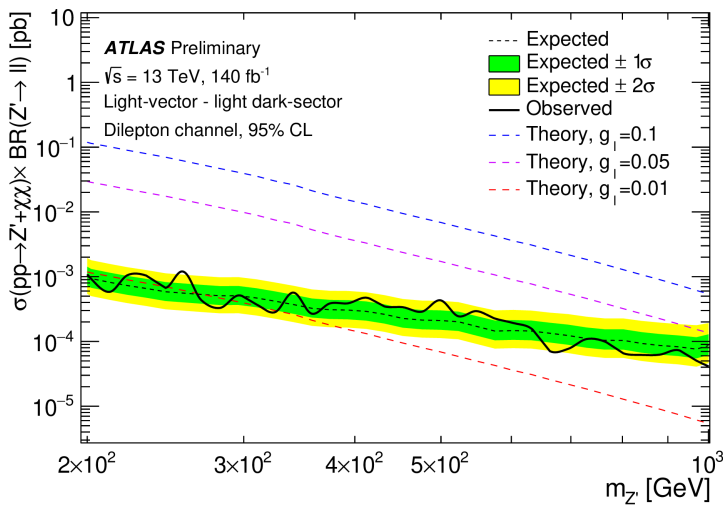


ATLAS-CONF-2023-045

- No significant deviations from the SM are observed
 - ➔ Derive limits as a function of the Z' mass as well as limits on the Z' coupling to leptons



	Dark Higgs	Light Vector
Light dark-sector	$m_\chi = 5 \text{ GeV}$ $m_{h_D} = 125 \text{ GeV}$	$m_{\chi_1} = 5 \text{ GeV}$ $m_{\chi_2} = m_{\chi_1} + m_{Z'} + 25 \text{ GeV}$
Heavy dark-sector	$m_\chi = 5 \text{ GeV}$ $m_{h_D} = m_{Z'}$	$m_{\chi_1} = m_{Z'}/2$ $m_{\chi_2} = 2m_{Z'}$



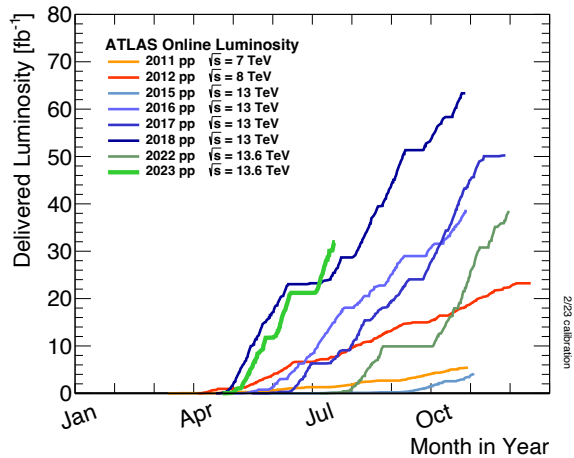
- Three coupling parameters considered in each model:
 - Coupling of the Z' to quarks (g_q)
 - Coupling of the Z' to leptons (g_l)
 - Coupling of the Z' to the dark-sector particles (g_{DM})
- In the dark-Higgs model the coupling g_{DM} is the coupling between the Z' and h_D
- In the light-vector model g_{DM} is the coupling between Z' and the dark-sector particles χ_1 and χ_2
- Couplings to quarks and leptons are assumed to be constant across generations
- Couplings considered for this search are $g_{DM} = 1$, $g_q = 0.1$, and $g_l = 0.01$
- Non-zero g_l introduced to allow the leptonic decay of the Z' boson



Conclusion and Outlook



- ATLAS performed many searches for heavy resonances
- Many more to come with $\sqrt{s} = 13.6$ TeV



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	M0	11.2 TeV, $n=2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M5	8.6 TeV, $n=3$ HLZ NLO	1707.04147
	ADD QBH	-	$2 j$	-	139	M6	9.4 TeV, $n=6$	1910.08447
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M7	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, $k/M_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass	2.3 TeV, $k/M_{Pl} = 1.0$	1808.02380
Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2$	Yes	36.1	g_{KK} mass	3.8 TeV, $\Gamma/m = 15\%$	1804.10823	
2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	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, $\Gamma/m = 1.2\%$	1903.06248
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass	2.42 TeV	1709.07242
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	36.1	Z' mass	2.1 TeV	1805.09599
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass	4.1 TeV	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 $W' \rightarrow tb$	-	$\geq 1 b, \geq 1 J$	-	139	W' mass	4.4 TeV	ATLAS-CONF-2021-043	
HVT $W' \rightarrow WZ$ model B	$0-2 e, \mu$	$2 j / 1 J$	Yes	139	W' mass	4.3 TeV	2004.14636	
HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell' \ell'$ model C	$3 e, \mu$	$2 j$ (VBF)	Yes	139	W' mass	340 GeV	2207.03925	
HVT $Z' \rightarrow WW$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	Z' mass	3.9 TeV, $g_V = 3$	2004.14636	
LRSM $W_R \rightarrow \mu N_R$	2μ	$1 J$	-	80	W_R mass	5.0 TeV, $m(N_R) = 0.5 \text{ TeV, } g_S = g_R$	1904.12679	
CI	CI $qqqq$	-	$2 j$	-	37.0	A	21.8 TeV, η_{LL}	1703.09127
	CI $\ell\ell qq$	$2 e, \mu$	-	-	139	A	35.8 TeV, η_{LL}	2006.12946
	CI $e\ell b\bar{b}$	$2 e, \mu$	$1 b$	-	139	A	1.8 TeV, $g_s = 1$	2105.13847
	CI $\mu\mu b\bar{b}$	2μ	$1 b$	-	139	A	2.0 TeV, $ C_{4j} = 4\tau$	2105.13847
	CI $t\bar{t} t\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	A	2.57 TeV	1811.02305
DM	Axial-vector med. (Dirac DM)	-	$2 j$	-	139	m_{med}	376 GeV, $g_a = 0.25, g_s = 1, m(\chi) = 10 \text{ TeV}$	ATL-PHYS-PUB-2022-036
	Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	$m_{Z'}$	3.0 TeV, $g_s = 1, g_2 = 0.8, m(\chi) = 100 \text{ GeV}$	2102.10874
	Vector med. Z' -2HDM (Dirac DM)	$0 e, \mu, \tau$	$2 b$	Yes	139	m_h	800 GeV, $\tan\beta = 1, g_s = 1, m(\chi) = 10 \text{ GeV}$	2108.13391
Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139			ATLAS-CONF-2021-036	
LQ	Scalar LQ 1 st gen	$2 e$	$\geq 2 j$	Yes	139	LQ mass	1.8 TeV, $\beta = 1$	2006.05872
	Scalar LQ 2 nd gen	2μ	$\geq 2 j$	Yes	139	LQ mass	1.7 TeV, $\beta = 1$	2006.05872
	Scalar LQ 3 rd gen	1τ	$2 b$	Yes	139	LQ^{\pm} mass	1.49 TeV, $\mathcal{B}(LQ^{\pm} \rightarrow b\tau) = 1$	2303.01294
	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	LQ^0 mass	1.24 TeV, $\mathcal{B}(LQ^0 \rightarrow \tau\nu) = 1$	2004.14060
	Scalar LQ 3 rd gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 j, \geq 1 b$	-	-	139	LQ^{\pm} mass	1.43 TeV, $\mathcal{B}(LQ^{\pm} \rightarrow \tau\nu) = 1$	2101.11582
	Scalar LQ 3 rd gen	$0 e, \mu, \geq 1 \tau, \geq 0-2 j, 2 b$	Yes	139	LQ^0 mass	1.26 TeV, $\mathcal{B}(LQ^0 \rightarrow b\nu) = 1$	2101.12527	
Vector LQ mix gen	multi-channel	$\geq 1 j, \geq 1 b$	Yes	139	LQ^{\pm} mass	2.0 TeV, $\mathcal{B}(U_1 \rightarrow t\mu) = 1, \text{YM coupl.}$	ATLAS-CONF-2022-052	
Vector LQ 3 rd gen	$2 e, \mu, \tau$	$\geq 1 b$	Yes	139	LQ^0 mass	1.96 TeV, $\mathcal{B}(LQ^0 \rightarrow b\nu) = 1, \text{YM coupl.}$	2303.01294	
Vector-like fermions	VLO $TT \rightarrow Zt + X$	$2e/2\mu/\geq 3e, \mu$	$\geq 1 b, \geq 1 j$	-	139	T mass	1.46 TeV	SU(2) doublet
	VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass	1.34 TeV	SU(2) doublet
	VLO $T_{3/2} T_{3/2} \rightarrow Wt/Zb + X$	$2(SS) \geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{3/2}$ mass	1.64 TeV, $\mathcal{B}(T_{3/2} \rightarrow Wt) = 1, c(T_{3/2} Wt) = 1$	1807.11863
	VLO $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	139	T mass	1.8 TeV, $\kappa_T = 0.5$	ATLAS-CONF-2021-040
	VLO $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass	1.85 TeV, $\mathcal{B}(Y \rightarrow Wb) = 1, c_Y(Wb) = 1$	1812.07343
	VLO $B \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1j, \geq 1J$	-	139	B mass	2.0 TeV, SU(2) doublet, $\kappa_B = 0.3$	ATLAS-CONF-2021-018
VLL $\tau' \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	τ' mass	898 GeV	SU(2) doublet	
Exact ferm.	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	139	q^* mass	6.7 TeV, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \rightarrow q\gamma$	1γ	$1 j$	-	36.7	q^* mass	5.3 TeV, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	139	b^* mass	3.2 TeV	1910.08447
	Excited lepton τ^*	2τ	$\geq 2 j$	-	139	τ^* mass	4.6 TeV, $\Lambda = 4.6 \text{ TeV}$	2303.09444
Other	Type III Seesaw	$2, 3, 4 e, \mu$	$\geq 2 j$	Yes	139	N^0 mass	910 GeV	2202.02039
	LRSM Majorana ν	2μ	$2 j$	-	36.1	N_R mass	3.2 TeV, $m(W_R) = 4.1 \text{ TeV, } g_L = g_R$	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	DY production	1.59 TeV, $ q = 5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	-	-	-	34.4	monopole mass	2.37 TeV, $ g = 1g_D, \text{spin } 1/2$	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).



Back-up

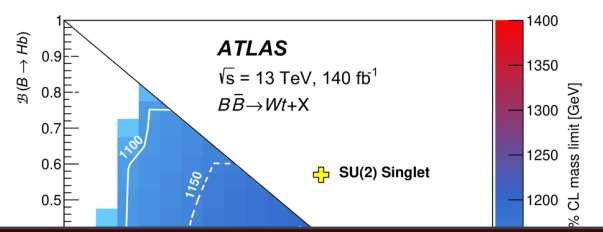
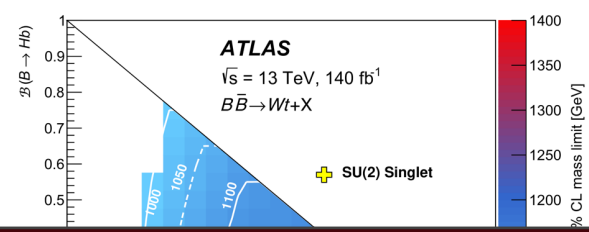
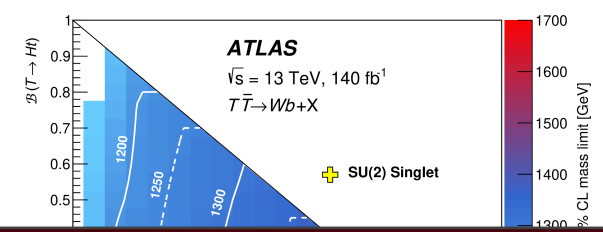
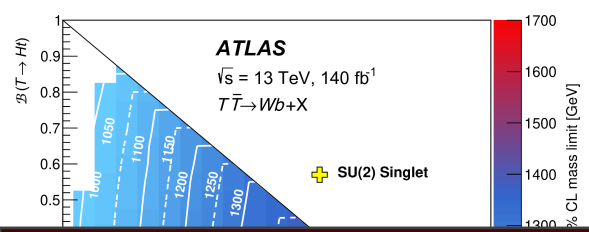
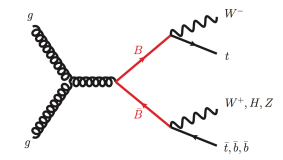
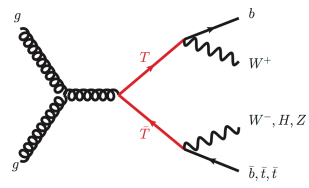






VLQ pair production search in the $Wb+X$ final state

- VLQs can decay via a flavor-changing neutral current or a charged current
 → T and B to each have three possible decays: $T \rightarrow Wb/Zt/Ht$ and $B \rightarrow Wt/Zb/Hb$
- Expected and observed 95% CL lower limits on the mass of the T -quark in the branching-ratio plane of $B(T \rightarrow Wb)$ versus $B(T \rightarrow Ht)$





[arxiv:2311.03944](https://arxiv.org/abs/2311.03944)

Search for dark jets

- New Z' resonance
 - Decays into a pair of dark quarks which hadronise into dark hadrons before promptly decaying back as SM particles
- Selecting events containing large-R jets with high track multiplicity

