# BSM searches with top final states

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## Introduction

## LHC as a top factory — able to access BSM searches using a huge sample with the heaviest quark.

Many top-related SM measurements are ongoing.

ttbar

## single-top





ttbar + V





4-tops



Events of same topologies are expected in many BSM.



### **ATL-PHYS-PUB-2021-014**





## Introduction



## Top quark decays to $W^{\pm} + b \ (V_{tb} \sim 1)$

- Several object ID techniques are needed to tag a top quark.
  - High-pT leptons and/or quark-jets from W, neutrinos identified as MET
  - b-jet tagging, top tagging of boosted-top

This talk will not cover SUSY-related and SM-top measurements that shows BSM signs





# $t\bar{t}$ resonance for Z' and $g_{KK}$

## ATLAS full-hadronic channel @ 139 fb<sup>-1</sup>

- used the DNN top-tagging
- Limits set on Z' in topcolor-assisted-technicolor model  $m_{Z'} > 3.9 (4.7)$  TeV for  $\Gamma/m = 1 (3) \%$ 
  - ▶ only 2015-16 data of 36 fb<sup>-1</sup> is available for semi-leptonic channel  $m_{Z'_{TC}} > 3.0 \text{ TeV}$  for  $\Gamma/m = 1\%$ ,  $m_{g_{KK}} > 3.8 \text{ TeV}$  for  $\Gamma/m = 15\%$

## CMS combined all three channels @ 35.9 fb<sup>-1</sup>

Limit set on the Kaluza-Klein gluon in the Randall-Sundrum scenario

$$m_{g_{KK}} > 4.55 \text{ TeV}$$

Limits set on topcolor Z'

 $m_{Z'} > 3.80 \text{ TeV}$  for  $\Gamma/m = 1\%$ 

 $m_{T'} > 5.25 \text{ TeV}$  for  $\Gamma/m = 10\%$ 

 $m_{Z'} > 6.65 \text{ TeV}$  for  $\Gamma/m = 30\%$ 



## ATLAS-EXOT-2015-04, ATLAS-EXOT-2018-48 <u>CMS-B2G-17-017</u>





## tb resonance for W'



## CMS hadronic channel @ 137 fb<sup>-1</sup>

Imits on both right (left)-handed W'

• 
$$m_{W'_{R,L}} > 3.4 \text{ TeV}$$



see <u>T. Novak's</u> and <u>A. O. M. Iorio's</u> resonance search talk for more details

## ATLAS-EXOT-2016-18 <u>CMS-B2G-20-005</u>

## ATLAS @ 36.1 fb<sup>-1</sup>

- searched for only right-handed W'
- combined lepton+jet channel with full-hadronic channel

$$m_{W'_R} > 3.25 \text{ TeV}$$





# BSM searches with $t(\bar{t}) + X$

## Associated production with a boson is very rare process.

- see <u>P. J. Falke's talk</u> for more details
- important topologies to BSM, e.g.
  - Excited fermions, Leptoquarks, Vector-Like Quarks, ...
- No evidence of BSM so far:
  - Excited bottom:  $b^* \rightarrow tW[\underline{CMS-B2G-19-003}, \underline{CMS-PAS-B2G-20-010}]$ 
    - see <u>A.O.M. Iorio's talk for the resonance search</u>
  - Leptoquarks [<u>ATLAS-EXOT-2019-15</u>, <u>ATLAS-EXOT-2019-19</u>, ...]
    - see <u>E. Carquin Lopez's talk</u>
  - Vector-Like Quark (VLQ) searches:
    - $T \rightarrow Zt, T \rightarrow Ht, T \rightarrow Wb, B \rightarrow Wt [ATLAS-EXOT-2017-14, CMS-B2G-19-004, ...]$
    - $W' \rightarrow Tb(tB)[\underline{CMS-PAS-B2G-20-002}]$
    - see next slide and <u>T. R. Andeen's VLQ talk</u>

They are also sensitive to EFT operators (e.g. *tt+Z* related to *tZ* coupling)

see <u>L. Barranco Navarro's</u> and <u>J. Gonzalez's</u> talks in this session [<u>CMS-TOP-19-001</u>, ...]



# VLQ searches and top final states

## Vector-like quarks are expected to decay into final states with third generation quarks.

- Combination of individual searches can cover all possi
- No evidence yet, but the VLQ mass limits are above Te
- Toward more high-mass region with high statistics data a good top tagging may be one of key tool.
- See the latest result of VLQ in <u>T. R. Andeen's talk</u> on Thu





ible sets of VLQ decays.	Analysis	$T\bar{T}$ decay	ΒĒ
eV scale.	$\frac{H(bb)t + X [16]}{W(bb)t + X [16]}$	$HtH\overline{t}$	
ta,	$W(\ell\nu)b + X [30] W(\ell\nu)t + X [32] Z(\mu\nu)t + X [33]$	W b W b - $Z + Z \overline{t}$	И
	$Z(\ell\ell)t/b + X [35]$ $Z(\ell\ell)t/b + X [35]$	ZtZt	Z
ursday.	Tril./s.s. dilepton [36]	$HtH\overline{t}$	W
-	Fully hadronic [37]	HtHt	Ľ.





# 4-top production: $pp \rightarrow t\bar{t}t\bar{t}$

## Very rare process

- $\sigma_{\rm SM}^{t\bar{t}t\bar{t}} \sim 12.0 \pm 2.4$  fb at NLO QCD+EW at  $\sqrt{s} = 13$  TeV
- Sensitive to the top-Higgs Yukawa coupling
- Sensitive to many BSM models, e.g.
  - Gluino pair production in SUSY
  - Heavy scalar/pseudoscalar boson in 2HDM
  - Four-fermion contact interaction within EFT
  - e.g. <u>ATLAS-EXOT-2016-13</u>



## The measured production cross section to be:

## • $\sigma^{t\bar{t}t\bar{t}} = 24^{+7}_{-6}$ fb @ ATLAS

- with a signal significance of  $4.7\sigma$  (2.6 $\sigma$  expected) over background-only hypothesis
- consistent within 2.0 standard deviations with the Standard Model expectation

## • $\sigma^{t\bar{t}t\bar{t}} = 12.6^{+5.8}_{-5.2}$ fb @ CMS

- in good agreement with SM
- set to exclusion limits to several physics models
- see <u>A. Kong's talk</u> for more details



# 4-top production: *pp* → *tttt*

- pseudoscalar boson in Type-II 2HDM and simplified dark matter models. excluded:











# **Interpretation on Dark Matter**

## interpreted $t\bar{t}$ resonance results as dark matter search

## Vector mediator



also different g<sub>q</sub> senearios <u>available</u>

Other dark matter searches with top quarks have been reported.

- Searches for dark matter in  $t\bar{t} + E_T^{miss}$  final states [ATLAS-SUSY-2018-08, CMS-EXO-16-049, and CMS-EXO-18-010]

## Comparison to direct detection experiments

Searches for dark matter produced in association with a single-top [ATLAS-EXOT-2018-43] and CMS-EXO-18-010]



# Dark matter in $t\bar{t} + E_{T}^{miss}$

which couple both to the SM and to the DM.



## ATLAS-SUSY-2018-08 <u>CMS-EXO-16-049</u>, <u>CMS-EXO-18-010</u>















 $\tan\beta$ : ratio of the vaccum expectation values of the two Higgs doublets



## Summary

Top quark may be one of the key tools to search for physics Beyond the Standard Model in LHC.

## Many search results with top final states have been released.

- No direct evidence of new physics, in either model-independent or model-dependent searches
- The EFT interpretation becomes more important.

## The search growing interest towards more rare signal.

- More data will come in LHC Run 3 and HL-LHC.
- We should push to understand our detectors and to develop new techniques of analyses (e.g. top-tagging).

The program to search for BSM with top quarks is far from complete.

More full Run 2 analysis to come. Stay tuned!



# Backup slides

# **Exotics Summary in ATLAS**

### **ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits**

Status: March 2021

	Model	<i>ℓ</i> , γ	Jets†	E <sup>miss</sup> T	∫£ dt[fb	-1]
Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell \nu q q$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP	$\begin{array}{c} 0 \ e, \mu, \tau, \gamma \\ 2 \ \gamma \\ - \\ - \\ 2 \ \gamma \\ multi-channel \\ 1 \ e, \mu \\ 1 \ e, \mu \\ 1 \ e, \mu \end{array} \geq \\ \end{array}$	$ \begin{array}{c} 1 - 4 \\ - \\ 2 \\ j \\ \geq 3 \\ - \\ 2 \\ j / 1 \\ J \\ \geq 2 \\ b, \geq 3 \\ j \end{array} $	Yes – – – Yes Yes Yes	139 36.7 37.0 3.6 139 36.1 139 36.1 36.1	MD           Ms           Mth           Mth           GKK mass           GKK mass           GKK mass           KK mass           KK mass
Gauge bosons	$\begin{array}{l} \text{SSM } Z' \to \ell\ell \\ \text{SSM } Z' \to \tau\tau \\ \text{Leptophobic } Z' \to bb \\ \text{Leptophobic } Z' \to tt \\ \text{SSM } W' \to \ell\nu \\ \text{SSM } W' \to \psi \\ \text{HVT } W' \to WZ \to \ell\nu qq \text{ mode} \\ \text{HVT } W' \to WZ \to \ell\nu qq \text{ mode} \\ \text{HVT } Z' \to ZH \text{ model } B \\ \text{HVT } W' \to WH \text{ model } B \\ \text{LRSM } W_R \to tb \\ \text{LRSM } W_R \to \mu N_R \end{array}$	2 $e, \mu$ 2 $\tau$ 0 $e, \mu$ 1 $e, \mu$ 1 $\tau$ el B 1 $e, \mu$ 0 $-2 e, \mu$ 0 $e, \mu$ multi-channel 2 $\mu$	- 2 b ≥ 1 b, ≥ 2 J - 2 j / 1 J 1-2 b ≥ 1 b, ≥ 2 J 1 J	– Yes Yes Yes Yes Yes	139 36.1 36.1 139 139 36.1 139 139 139 36.1 80	Z' mass Z' mass Z' mass Z' mass W' mass W' mass Z' mass W' mass W <sub>R</sub> mass W <sub>R</sub> mass
CI	CI qqqq CI ℓℓqq CI eebs CI μμbs CI tttt	_ 2 e, μ 2 e 2 μ ≥1 e,μ	2 j - 1 b 1 b ≥1 b, ≥1 j	- - - Yes	37.0 139 139 139 36.1	Λ Λ Λ Λ Λ
DM	Axial-vector med. (Dirac DM) Pseudo-scalar med. (Dirac DM) Vector med. Z'-2HDM (Dirac D Pseudo-scalar med. 2HDM+a Scalar reson. $\phi \rightarrow t\chi$ (Dirac DI	$\begin{array}{c} 0 \ e, \mu, \tau, \gamma \\ 1) \ 0 \ e, \mu, \tau, \gamma \\ OM) \ 0 \ e, \mu \\ 0 \ e, \mu \\ M) \ 0 -1 \ e, \mu \end{array}$	1 - 4 j 1 - 4 j 2 b 2 b 1 b, 0-1 J	Yes Yes Yes Yes Yes	139 139 139 139 36.1	Mmed Mmed Mmed Mmed Mg
ГØ	Scalar LQ 1 <sup>st</sup> gen Scalar LQ 2 <sup>nd</sup> gen Scalar LQ 3 <sup>rd</sup> gen Scalar LQ 3 <sup>rd</sup> gen Scalar LQ 3 <sup>rd</sup> gen Scalar LQ 3 <sup>rd</sup> gen	$2 e \\ 2 \mu \\ 1 \tau \\ 0 e, \mu \\ \ge 2e, \mu, \ge 1\tau \\ 0 e, \mu, \ge 1\tau$	$ \begin{array}{c} \geq 2 \ j \\ \geq 2 \ j \\ 2 \ b \\ \geq 2 \ j, \geq 2 \ b \\ \geq 1 \ j, \geq 1 \ b \\ 0 - 2 \ j, 2 \ b \end{array} $	Yes Yes Yes - Yes	139 139 139 139 139 139 139	LQ mass LQ mass LQ <sup>4</sup> mass LQ <sup>4</sup> mass LQ <sup>4</sup> mass LQ <sup>4</sup> mass
Heavy quarks	$\begin{array}{l} VLQ \ TT \rightarrow Ht/Zt/Wb + X\\ VLQ \ BB \rightarrow Wt/Zb + X\\ VLQ \ T_{5/3} \ T_{5/3}   T_{5/3} \rightarrow Wt + X\\ VLQ \ Y \rightarrow Wb + X\\ VLQ \ B \rightarrow Hb + X\\ VLQ \ QQ \rightarrow WqWq \end{array}$	multi-channel multi-channel ( $2(SS)/\geq 3 e, \mu$ 1 $e, \mu$ 0 $e, \mu$ 1 $e, \mu$	$\geq 1 \text{ b, } \geq 1 \text{ j}$ $\geq 1 \text{ b, } \geq 1 \text{ j}$ $\geq 2 \text{ b, } \geq 1 \text{ j}$ $\geq 4 \text{ j}$	Yes Yes Yes Yes	36.1 36.1 36.1 36.1 79.8 20.3	T mass B mass T <sub>5/3</sub> mass Y mass B mass Q mass
Excited fermions	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton $\ell^*$ Excited lepton $\nu^*$	- 1 γ - 3 e, μ 3 e, μ, τ	2 j 1 j 1 b, 1 j - -	_ _ _ _	139 36.7 36.1 20.3 20.3	q* mass         q* mass         b* mass         ℓ* mass         ν* mass
Other	Type III Seesaw LRSM Majorana $v$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Multi-charged particles Magnetic monopoles $\sqrt{s} = 8 \text{ TeV}$	1 e, μ 2 μ 2,3,4 e, μ (SS 3 e, μ, τ 	≥ 2 j 2 j ) - - - - - - - -	Yes _ _ _ _ _ _ _ <b>TeV</b>	139 36.1 36.1 20.3 36.1 34.4	N <sup>0</sup> mass N <sub>R</sub> mass H <sup>±±</sup> mass H <sup>±±</sup> mass multi-char monopole
	p c l c l c l c l c l c l c l c l c l c	partial data	full da	ta		

\*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).* 



### **ATLAS** Preliminary

 $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$  $\sqrt{s} = 8, 13 \text{ TeV}$ 

Limit Reference **11.2 TeV** *n* = 2 2102.10874 **8.6 TeV** *n* = 3 HLZ NLO 1707.04147 **8.9 TeV** *n* = 6 1703.09127 **9.55 TeV**  $n = 6, M_D = 3$  TeV, rot BH 1512.02586  $k/\overline{M}_{Pl} = 0.1$ 2102.13405 4.5 TeV  $k/\overline{M}_{Pl} = 1.0$ 2.3 TeV 1808.02380  $k/\overline{M}_{Pl} = 1.0$ 2.0 TeV 2004.14636  $\Gamma/m = 15\%$ 3.8 TeV 1804.10823 Tier (1,1),  $\mathcal{B}(A^{(1,1)} \to tt) = 1$ 1.8 TeV 1803.09678 5.1 TeV 1903.06248 2.42 TeV 1709.07242 2.1 TeV 1805.09299  $\Gamma/m = 1.2\%$ 4.1 TeV 2005.05138 6.0 TeV 1906.05609 3.7 TeV 1801.06992 4.3 TeV  $g_V = 3$ 2004.14636  $g_V = 3$ 3.2 TeV ATLAS-CONF-2020-043 3.2 TeV  $g_V = 3$ 2007.05293 3.25 TeV 1807.10473 5.0 TeV  $m(N_R) = 0.5 \text{ TeV}, g_L = g_R$ 1904.12679 **21.8 TeV** η<sub>LL</sub> 1703.09127 **35.8 TeV** η<sub>LL</sub> 2006.12946 ATLAS-CONF-2021-012 **1.8 TeV**  $g_* = 1$  $g_* = 1$ 2.0 TeV ATLAS-CONF-2021-012 2.57 TeV  $|C_{4t}| = 4\pi$ 1811.02305 2.1 TeV  $g_q=0.25, g_{\chi}=1, m(\chi)=1 \text{ GeV}$ 2102.10874 376 GeV  $g_q=1, g_{\chi}=1, m(\chi)=1 \text{ GeV}$ 2102.10874 3.1 TeV  $\tan\beta=1, g_Z=0.8, m(\chi)=100 \text{ GeV}$ ATLAS-CONF-2021-006  $\tan\beta=1, g_{\chi}=1, m(\chi)=10 \text{ GeV}$ 520 GeV ATLAS-CONF-2021-006  $y=0.4, \lambda=0.2, m(\chi)=10 \text{ GeV}$ 3.4 TeV 1812.09743 1.8 TeV  $\beta = 1$ 2006.05872  $\beta = 1$ 1.7 TeV 2006.05872 1.2 TeV  $\mathcal{B}(LQ_3^u \to b\tau) = 1$ ATLAS-CONF-2021-008  $\mathcal{B}(\mathrm{LQ}_3^u \to t\nu) = 1$ 1.24 TeV 2004.14060  $\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1$ 1.43 TeV 2101.11582  $\mathcal{B}(\mathrm{LQ}_{3}^{\tilde{d}} \to b\nu) = 1$ 1.26 TeV 2101.12527 1.37 TeV SU(2) doublet 1808.02343 1.34 TeV SU(2) doublet 1808.02343  $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ 1.64 TeV 1807.11883  $\mathcal{B}(Y \to Wb) = 1, c_R(Wb) = 1$ 1.85 TeV 1812.07343 singlet,  $\kappa_B = 0.5$ **1.21 TeV** ATLAS-CONF-2018-024 690 GeV 1509.04261 6.7 TeV only  $u^*$  and  $d^*$ ,  $\Lambda = m(q^*)$ 1910.08447 5.3 TeV only  $u^*$  and  $d^*$ ,  $\Lambda = m(q^*)$ 1709.10440 2.6 TeV 1805.09299 3.0 TeV  $\Lambda = 3.0 \text{ TeV}$ 1411.2921 1.6 TeV  $\Lambda = 1.6 \text{ TeV}$ 1411.2921 790 GeV 20008.07949  $m(W_R)=4.1~{
m TeV},\,g_L=g_R$ 3.2 TeV 1809.11105 870 GeV DY production 1710.09748 400 Ge\ DY production,  $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ 1411.2921 DY production, |q| = 5e1812.03673 ged particle mass 1.22 TeV 2.37 TeV DY production,  $|g| = 1g_D$ , spin 1/2 1905.10130 mass  $10^{-1}$ 10 Mass scale [TeV]



## **Exotics summary in CMS**

### **Overview of CMS EXO results**

		CMS preliminary	
Other	String resonanceI $Z\gamma$ resonanceIHiggs $\gamma$ resonanceIColor Octect Scalar, $k_s^2 = 1/2$ IScalar DiquarkI $t\bar{t} + \phi$ , pseudoscalar (scalar), $g_{top}^2 \times BR(\phi \rightarrow 2\ell) > = 0.03(0.004)$ I $t\bar{t} + \phi$ , pseudoscalar (scalar), $g_{top}^2 \times BR(\phi \rightarrow 2\ell) > = 0.03(0.04)$	0.015–0.075 1911.04968	<pre>3 (3ℓ, ≥ 4ℓ) 0.108-0.34</pre>
Interactions	quark compositeness $(q\bar{q}), \eta_{LL/RR} = 1$ $\Lambda_{LLR}^{+}$ quark compositeness $(\ell l), \eta_{LL/RR} = 1$ $\Lambda_{LLR}^{+}$ quark compositeness $(q\bar{q}), \eta_{LL/RR} = -1$ $\Lambda_{LLR}^{-}$ quark compositeness $(\ell l), \eta_{LL/RR} = -1$ $\Lambda_{LLR}^{-}$ quark compositeness $(\ell l), \eta_{LL/RR} = -1$ $\Lambda_{LLR}^{-}$ Excited Lepton Contact Interaction $\ell$ Excited Lepton Contact Interaction $\ell$		
Dark Matter	(axial-)vector mediator ( $\chi\chi$ ), $g_q = 0.25$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV (axial-)vector mediator ( $q\bar{q}$ ), $g_q = 0.25$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV scalar mediator ( $+t/t\bar{t}$ ), $g_q = 1$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV pseudoscalar mediator ( $+t/t\bar{t}$ ), $g_q = 1$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV scalar mediator (fermion portal), $\lambda_u = 1$ , $m_\chi = 1$ GeV complex sc. med. (dark QCD), $m_{\pi_{DK}} = 5$ GeV, $c\tau_{X_{DK}} = 25$ mm Baryonic Z', $g_q = 0.25$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV Z' - 2HDM, $g_{Z'} = 0.8$ , $g_{DM} = 1$ , $tan\beta = 1$ , $m_\chi = 100$ GeV vector mediator ( $q\bar{q}$ ), $g_q = 0.25$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV		<0.29 <0.3
RPV	RPV stop to 4 quarksIRPV squark to 4 quarksIRPV gluino to 4 quarksIRPV gluinos to 3 quarksI		
Extra Dimensions	ADD (jj) HLZ, $n_{ED} = 3$ ADD ( $\gamma\gamma$ , $\ell\ell$ ) HLZ, $n_{ED} = 3$ ADD $G_{KK}$ emission, $n = 2$ ADD QBH (jj), $n_{ED} = 6$ ADD QBH ( $e\mu$ ), $n_{ED} = 6$ RS $G_{KK}(\gamma\gamma)$ , $k/\overline{M}_{PI} = 0.1$ RS QBH (jj), $n_{ED} = 1$ RS QBH ( $e\mu$ ), $n_{ED} = 1$ non-rotating BH, $M_D = 4$ TeV, $n_{ED} = 6$ split-UED, $\mu \ge 4$ TeV RS $G_{KK}(q\bar{q}, gg)$ , $k/\overline{M}_{PI} = 0.1$		
Fermions	excited light quark $(q\gamma)$ , $f_S = f = f' = 1$ , $\Lambda = m_q^*$ excited b quark, $f_S = f = f' = 1$ , $\Lambda = m_q^*$ excited light quark $(qg)$ , $\Lambda = m_q^*$ excited electron, $f_S = f = f' = 1$ , $\Lambda = m_e^*$ excited muon, $f_S = f = f' = 1$ , $\Lambda = m_\mu^*$		
Fermions	$v$ MSM, $ V_{eN} ^2 = 1.0$ , $ V_{\mu N} ^2 = 1.0$ $v$ MSM, $ V_{eN}V_{\mu N}^* ^2/( V_{eN} ^2 +  V_{\mu N} ^2) = 1.0$ Type-III seesaw heavy fermions, Flavor-democratic Vector like taus, Doublet		
Leptoquarks	scalar LQ (pair prod.), coupling to 1 <sup>st</sup> gen. fermions, $\beta = 1$ scalar LQ (pair prod.), coupling to 1 <sup>st</sup> gen. fermions, $\beta = 0.5$ scalar LQ (pair prod.), coupling to 2 <sup>nd</sup> gen. fermions, $\beta = 1$ scalar LQ (pair prod.), coupling to 2 <sup>nd</sup> gen. fermions, $\beta = 1$ scalar LQ (pair prod.), coupling to 2 <sup>nd</sup> gen. fermions, $\beta = 0.5$ scalar LQ (pair prod.), coupling to 3 <sup>rd</sup> gen. fermions, $\beta = 1$ scalar LQ (pair prod.), coupling to 3 <sup>rd</sup> gen. fermions, $\beta = 1$		
Heavy Gauge Bosons	$Z_D$ , narrow resonance $I$ $Z_D$ , narrow resonance $I$ $SSM Z'(q\bar{q})$ $I$ $Z'(q\bar{q})$ $I$ $Z'(q\bar{q})$ $I$ Superstring $Z'_{\psi}$ $I$ LFV Z', BR(e $\mu$ ) = 10% $I$ Leptophobic $Z'$ $I$ SSM $W'(\ell v)$ $I$ SSM $W'(\ell v)$ $I$ SSM $W'(\tau v)$ $I$ SSM $W'(q\bar{q})$ $I$ LRSM $W_R(\ell N_R)$ , $M_{N_R} = 0.5M_{W_R}$ $I$ LRSM $W_R(\tau N_R)$ , $M_{N_R} = 0.5M_{W_R}$ $I$ Axigluon, Coloron, $cot\theta = 1$ $I$	0.0115-0.075 1912.04776 0.1 0.01-0.125	( <b>2μ</b> ) [1-0.2 1912.04776 1905.10331 ( <b>1j, 1γ</b> )
		0.1	

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

### **CMS Exotica Summary for 13 TeV**

		36-140 fb <sup>-1</sup> (13 TeV)	
	0.5-8.1       1911.03         0.35-4       1712.03143 (2μ + 1γ; 2e + 1γ; 2j - 172.03143)         0.72-3.25       1808.01257 (1j + 1γ)         0.5-3.7       1911.03947 (2j)         0.5-7.5       1911.03944	i947 ( <b>2j</b> ) + <b>1</b> γ) 7 ( <b>2j</b> )	137 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 137 fb <sup>-1</sup> 137 fb <sup>-1</sup>
108-0.34 1911.04968 ( $3\ell$ , $\geq 4\ell$ )			137 fb <sup>-1</sup> 137 fb <sup>-1</sup>
	0.2–5.6 2001.04521 ( <b>2e + 2j</b> ) 0.2–5.7 2001.04521 ( <b>2µ + 2j</b> )	<12.8 1803.0803 ( <b>2j</b> )	36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 77 fb <sup>-1</sup> 77 fb <sup>-1</sup>
0.29 1901.01553 ( <b>0</b> , $1\ell + \ge 3j + E_T^{miss}$ ) <0.3 1901.01553 ( <b>0</b> , $1\ell + \ge 3j + E_T^{miss}$ ) 0.35-0.7 1911.0376 0.3-0.6 1811.10151 ( <b>1</b> $\mu$	<pre>&lt;1.8 1712.02345 ( <math>\geq</math> 1j + E<sup>miss</sup>) 0.5-2.8 1911.03947 (2j)</pre> <1.4 1712.02345 ( $\geq$ 1j + E <sup>miss</sup> ) <1.54 1810.10069 (4j) <1.9 1908.01713 (h + E <sup>miss</sup> ) 0.5-3.2 1908.01713 (h + E <sup>miss</sup> ) 1 ( $\geq$ 3j) + 1j + E <sup>miss</sup> )		36 fb <sup>-1</sup> 137 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 18 fb <sup>-1</sup> 77 fb <sup>-1</sup>
0.08-0.52 1808.03124 ( <b>2j; 4j</b> ) 0.1-0.72 1806.010	58 ( <b>2j</b> ) 0.1–1.41 1806.01058 ( <b>2j</b> ) <1.5 1810.10092 ( <b>6j</b> )		36 fb <sup>-1</sup> 38 fb <sup>-1</sup> 38 fb <sup>-1</sup> 36 fb <sup>-1</sup>
		<pre>&lt;12 1803.0803 (2j) 12.10443 (2γ, 2ℓ) 1712.02345 (≥ 1j + E<sup>miss</sup>) 303 (2j) 805.06013 (≥ 7j(ℓ, γ))</pre>	36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 37 fb <sup>-1</sup>
	1-5.5       1711.04652 (γ + j)         1-1.8       1711.04652 (γ + j)         0.5-6.3       1911.03947 (2j)         0.25-3.9       1811.03052 (γ + 2e)         0.25-3.8       1811.03052 (γ + 2μ)		36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 137 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup>
<0.88 19 0.12-0.79 1905.1	0.001-1.43       1802.02965; 1806.10905 (3ℓ(μ, e); ≥ 1j + 2ℓ(μ, e))         0.02-1.6       1806.10905 (≥ 1j + μ + e)         11.04968 (3ℓ, ≥ 4ℓ)       1000000000000000000000000000000000000		36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 137 fb <sup>-1</sup> 77 fb <sup>-1</sup>
<1.02 <0.74 1806.034	<pre>&lt;1.44 1811.01197 (2e + 2j) &lt;1.27 1811.01197 (2e + 2j; e + 2j + <math>E_T^{miss}</math>) &lt;1.53 1808.05082 (2µ + 2j) 0.8-1.5 1811.10151 (1µ + 1j + <math>E_T^{miss}</math>) &lt;1.29 1808.05082 (2µ + 2j; µ + 2j + <math>E_T^{miss}</math>) 1811.00806 (2<math>\tau</math> + 2j) 472 (2<math>\tau</math> + b)</pre>		36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 77 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup>
912.04776 ( <b>2</b> μ) <b>, 1γ</b> ) 0.05–0.45 1909.04114 ( <b>2j</b> )	$\begin{array}{c} 0.5-2.9 \\ 1911.03947 \ \textbf{(2j)} \\ \hline 0.2-4.6 \\ 2103.02708 \ \textbf{(2e, 2\mu)} \\ 0.2-4.4 \\ 1802.01122 \ \textbf{(e\mu)} \\ \hline 0.4-5.2 \\ 1803.11133 \ \textbf{(} + \mathbf{E}_{T}^{\text{miss}} ) \\ \hline 0.4-4 \\ 1807.11421 \ (\mathbf{\tau} + \mathbf{E}_{T}^{\text{miss}} ) \\ \hline 0.5-3.6 \\ 1911.03947 \ \textbf{(2j)} \\ \hline <4.4 \\ 1803.11116 \ \textbf{(2\ell + 2j)} \\ \hline <3.5 \\ 1811.00806 \ \textbf{(2\tau + 2j)} \\ \hline 0.5-6.6 \\ 1911.03947 \ \textbf{(2j)} \\ \hline \end{array}$		137 fb <sup>-1</sup> 137 fb <sup>-1</sup> 137 fb <sup>-1</sup> 36 fb <sup>-1</sup> 140 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 36 fb <sup>-1</sup> 137 fb <sup>-1</sup> 36 fb <sup>-1</sup> 137 fb <sup>-1</sup>
	.0 10 mass scale [TeV]		21



# VLQ searches and top final states

Top final state is the most effective signature to search for Vector-Like Quarks.





# Dark matter in $t\bar{t} + E_{T}^{miss}$



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