UNIVERSITÀ DEGLI STUDI DI MILANO

INFN

Searches for low and high mass resonances in $p - p$ collisions with ATLAS and CMS

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CMS

Aug. 30, 2018

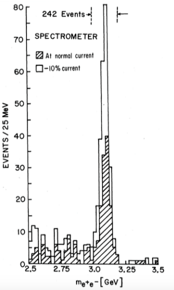
ATLAS EXPERIMENT

TeVPa conference, Berlin, Germany

Outline

Outline of this talk:

- Summary: no new resonance in *pp* collisions so far
- Introduction
- Overview of search methods
- Some selected (null) results
- Conclusions and outlook

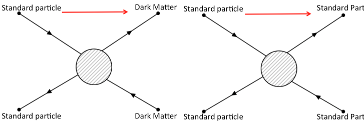


"Experimental observation of a heavy particle J"

Aubert et al., P.R.L. 12 Nov. 1974

Resonances:
paradigm for new physics, direct discovery of a new particle

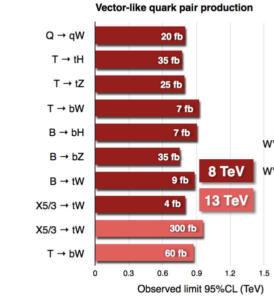
Relevance for dark matter: any mediator should show as a resonance in SM particles. May be only reachable final state at LHC if DM fermion mass is too large

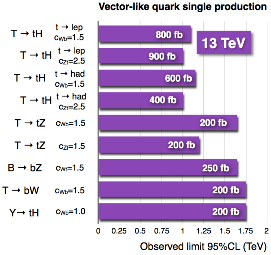


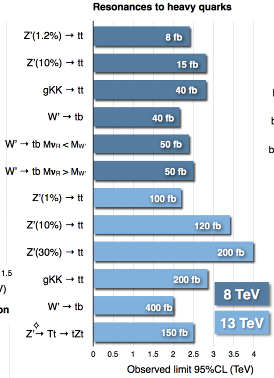
- model independent analysis,
- limits on specific models (including DM mediators)

Hadron collider: leptonic decay modes cleaner, hadronic decays larger *BR*

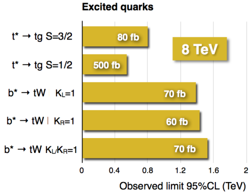
Summary of CMS searches

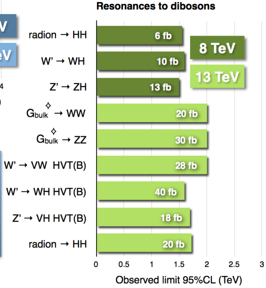






B2G
new physics searches with heavy SM particles





◊model-independent

Summary of ATLAS searches

Extra Dimensions (KK)

Z', W'

Heavy quarks (VLQ)

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 79.8)\ \text{fb}^{-1}$ $\sqrt{s}$ = 8, 13 TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e,μ	1 − 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e,μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e,μ	–	–	36.1	Z' mass 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e,μ	–	Yes	79.8	W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e,μ	2 J	–	79.8	V' mass 4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass 3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η^-_{LL}		1703.09127
	CI $\ell\ell qq$	2 e,μ	–	–	36.1	Λ 40.0 TeV η^-_{LL}		1707.02424
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	0 e,μ	1 − 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e,μ	1 − 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e,μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e,μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3} T_{5/3} \lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	1 e,μ	≥ 1 b, ≥ 1j	Yes	3.2	Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c(YWb)$= 1/$\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e,μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e,μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e,μ,τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e,μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 e,μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e,μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e,μ,τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e,μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1509.08059

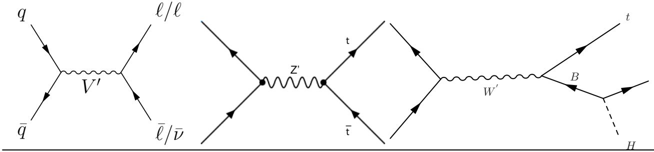
$\sqrt{s}$ = 8 TeV | $\sqrt{s}$ = 13 TeV

Mass scale [TeV]: 10^{-1}, 1, 10

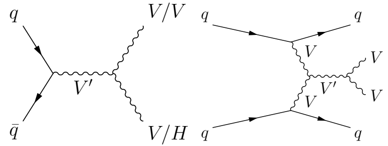
*Only a selection of the available mass limits on new states or phenomena is shown.

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

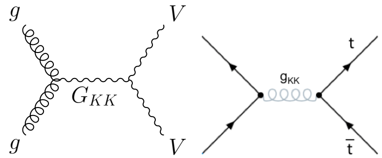
Production and decay models



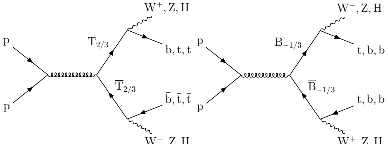
Extra vector bosons $V' \Rightarrow W'$ or Z' decaying to fermions



Extra vector bosons decaying to SM vector bosons or H



Extra dimension KK graviton or gluon decaying to vector bosons or fermions



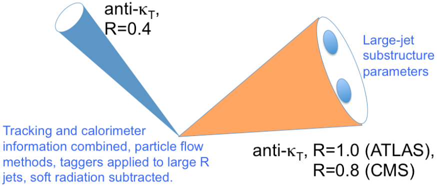
Vector-like quarks (VLQ), spin 1/2 singlets not coupled with Higgs decaying to SM bosons and quarks

Experimentally

- Select the final state of the resonance and the mass range
- Select/propose the appropriate trigger
- Select the physical *"objects"* (e.g. type and number of jets, leptons) appropriate to the search range. *Jets:* clustering of energy and/or tracks from partons
- Select candidate events in the most unbiased way
- Estimate background and systematics variations (jet energy scale, lepton scale...) to be used as nuisance parameters in fit
- Run favourite peak searching algorithm on invariant masses and angular variables; run a fit to set limits on $\sigma \times \mathcal{BR}$
- Compare with MC simulated signal and put limits on specific models. One-dimensional limits (vs. mass) bidimensional limits (coupling-mass plane).
- Same analysis and final state can be reinterpreted to put limits to various resonance models
- Combine limits from analyses of different final states of the same resonance type
- Low-mass: $50 \leq 300$ GeV, but analysis dependent

Most used analysis techniques

A physics object: jet from q or g, or boosted $(q\,q)$

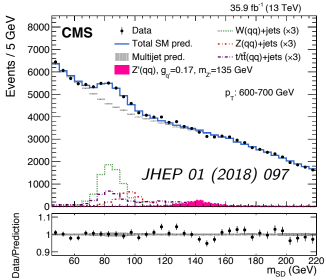


Background determination methods:

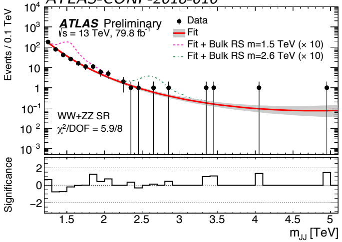
- Monte Carlo samples
- Data-driven background estimation (e.g. sidebands)
- Direct input to fit, or parametrization with smooth function

Systematic uncertainties: jet energy scale, jet p_T scale, background shape; anything that may introduce a bump; integrated luminosity; systematic variations accounted for in the fit

Large R jet Invariant mass distribution



ATLAS-CONF-2018-016



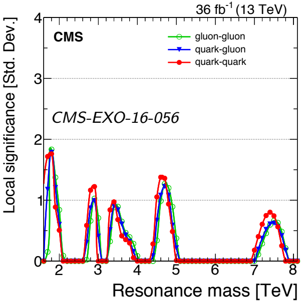
Peak search and limits

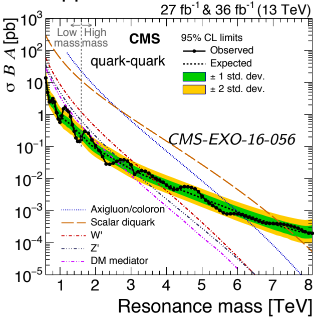
Peak search algorithms: narrow or wide resonances, sliding window methods; local significance of a peak

If no peak is found with sufficient significance, limit is set:

Fit: frequentist Confidence Level used to set 95%CL limits on $\sigma \times \mathcal{BR}$ vs. invariant mass.

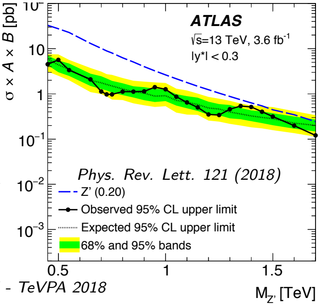
Model of resonance production and coupling is overlapped to obtain mass limits





Search for dijet resonances using narrow and wide jets

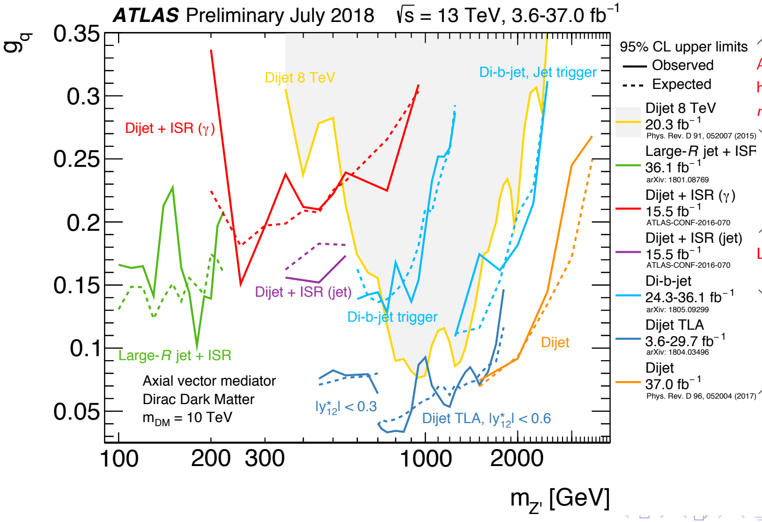
Dijet resonances at low mass using trigger-level jets

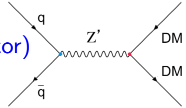


Combining channels: Z' DM mediator

Combining different channels for the same resonance model:

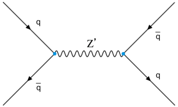
Limits to mass and couplings of a *leptophobic* Z' (Dark matter mediator)



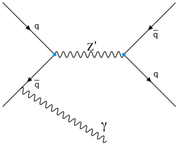


Assume dark fermion too heavy to be produced

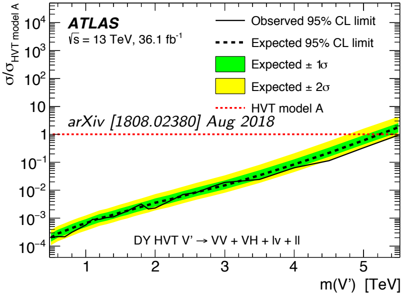
$m_{df} > 10$ TeV

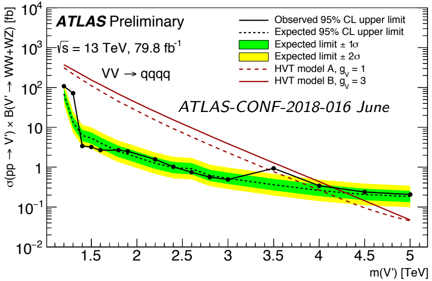


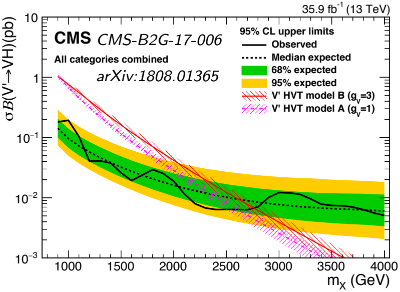
Low-mass expmt. strategy



Recent results: V' searches





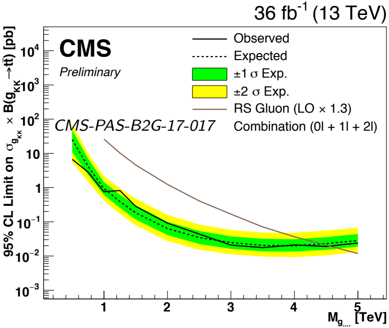


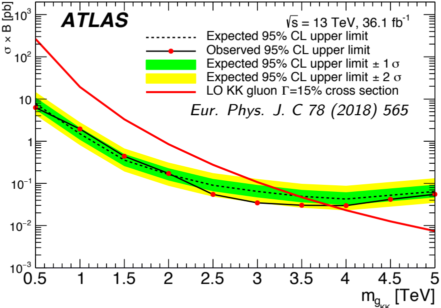
(a) combination of searches for V' to VV, or VH, or $\ell^+\ell^-$ or $\ell\nu$
(b) All hadronic decay to $qqqq$ with 79.8 fb^{-1}
(c) CMS result for $V' \to VH \to q\bar{q}\tau^+\tau^-$
All results for a Heavy Vector Triplet model

DeBlas et al.,Papadopulos et al.

CMS also $W' \to tbH$ mediated by VLQ, limit on $\sigma Br \leq 0.18$ to 0.01 pb *CMS-PAS-B2G-18-001*

Recent results: extra dimensions

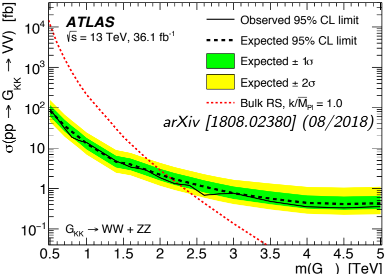




Searching a KK-gluon (RS model) in $t\bar{t}$
(a) CMS search combines $0, 1, 2,$-lepton decay mode of top pair; large R jets for 0ℓ.
(b) ATLAS only 1ℓ+jets decay
(c) ATLAS result for RS-KK graviton $G_{KK} \to ZZ$ or WW

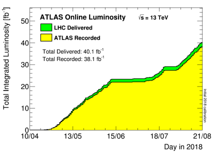
All results for a Randall-Sundrum model

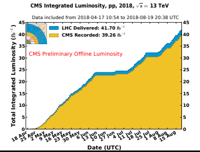
Randall Sundrum PRL 83 (1999)



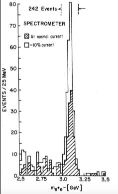
Conclusions

- Search for new resonances is a key mission for LHC experiments.
- So far $\mathcal{O}(100)$ analyses have looked for resonances in various final states
- No hint of new resonances so far
- Limits are set in the order of ≈ 2 to 4 TeV for V' and ≈ 1 TeV for VLQ's
- New analyses to cover all possible final states and parameter space
- Better understanding of detectors and improvements on trigger and systematics make progress faster than statistics only
- More luminosity is being collected: target 150 fb^{-1} achieved and being surpassed to extend the search range
- Unexpected findings can be around the corner





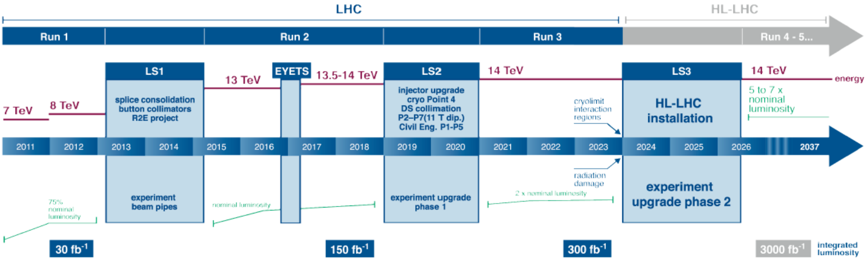
$\approx 41\ \text{fb}^{-1}$ per experiment delivered in 2018



Backup

EXTRAS

LHC Plans


LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
13.5-14 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
injector upgrade
cryo Point 4
DS collimation
P2–P7(11 T dip.)
Civil Eng. P1-P5
cryolimit
interaction
regions
HL-LHC
installation
5 to 7 x
nominal
luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2037
radiation
damage
75%
nominal
luminosity
experiment
beam pipes
nominal luminosity
experiment upgrade
phase 1
2 x nominal luminosity
experiment
upgrade phase 2
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated
luminosity

Summary Table

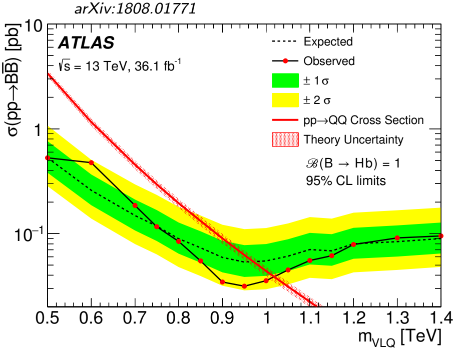
V := Z^0 or $W^{\pm}$, DMM := dark matter mediator; ℓ := $e^{\pm}$ or $\mu^{\pm}$ G_{KK} := Kaluza-Klein graviton; g_{KK} := Kaluza-Klein gluon;

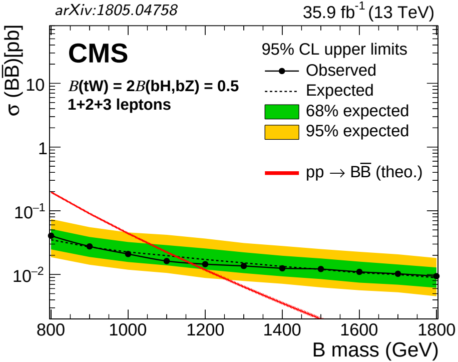
TLj := Trigger Level jets

Resonance	Decay Channel	Exp.	Limit (95%)CL	Reference
Z' (DM)	Di-jet	CMS	$m_{DMM} > 2.7$ TeV	CMS-EXO-16-056
Z' (DM)	Di-jet (TLj)	ATLAS	$m_{Z'} > 1.65$ TeV	PRL 121 (2018)
V'(HVT)	$VV, VH, \ell\ell, \ell\nu$	ATLAS	$m_{Z'} > 5.5$ TeV	arXiv [1808.02380]
V' (HVT)	jets (qqqq)	ATLAS	$m_{Z'} \notin [1.20, 3.40]$	ATLAS-CONF-2018-016
V'(HVT)	$V' \rightarrow (q\bar{q})(\tau^+\tau^-)$	CMS	$m_{V'} > 2.8$ TeV	arXiv [1808.01365]
W' (VLQ)	$W' \rightarrow tbH$	CMS	$m_{W'} > 1.6$ TeV	CMS-PAS-B2G-18-001
g_{KK} (RS)	$t\bar{t}; 0, 1, 2\ell$	CMS	$m_g \notin [0.5, 4.55]$	CMS-PAS-B2G-17-017
g_{KK} (RS)	$t\bar{t}; t\bar{t} \rightarrow 1\ell$	ATLAS	$m_G > 3.7$ TeV	Eur. Phys. J. C78 (2018)
G_{KK} (RS)	VV	ATLAS	$m_G > 2.3$ TeV	arXiv[1808.02380]
VLQ	Hadrons	ATLAS	$m_T > 1.01$ TeV	arXiv [1808.01771]
VLQ	$1, 2, 3\ell$	CMS	$m_T > 1.14$ TeV	arXiv [1805.04758]

Disclaimer: Limits need to be taken with care: different hypothesis are used.

Recent results: Vector-like Quarks

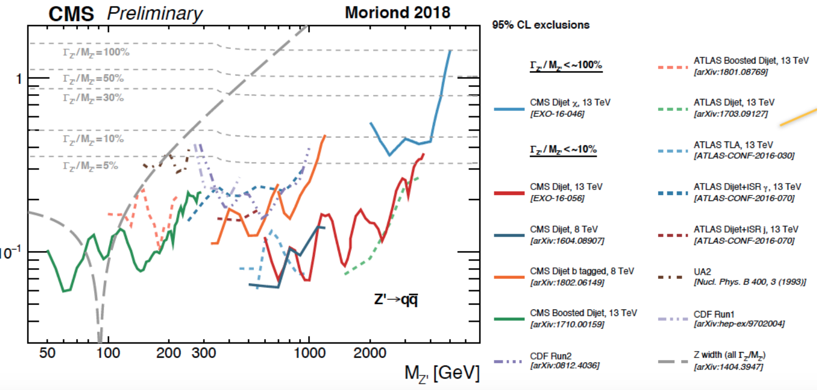




Spin 1/2 coloured particles. Singlet, doublets, triplets. $T(q = +2/3)$, $B(q = -1/3)$
Decay $T \to W^- b$, $T \to Ht$, $T \to Zt$
Single production and pair production:
CMS: Final state containing 1, 2 (same sign) and 3 leptons

ATLAS: all hadronic final states

Combining channels (CMS) Z' DM mediator



Leptonic decays of Z' DM mediator