ATLAS searches for heavy resonances

Large Hadron Collider Physics

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On behalf of the ATLAS collaboration
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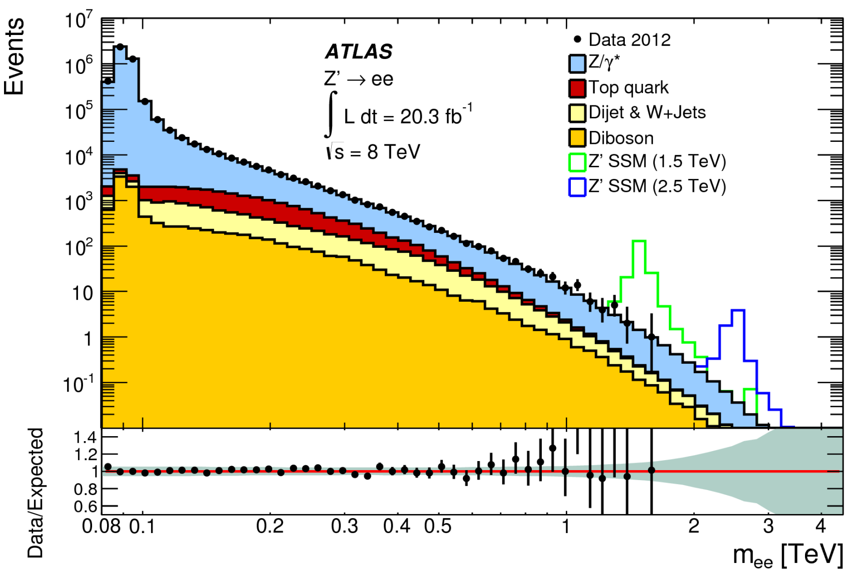
Introduction

ATLAS is carrying out many BSM searches

- Great to have found the Higgs, but is there more?
- Many ideas and models

Resonances are an obvious place to look

- Appear in many models
- Often dramatic signal on a mundane background
- Sidebands confirm understanding of Standard Model and detector
- Figure shows example
  - SSM $Z' \longrightarrow ee$
  - Details later

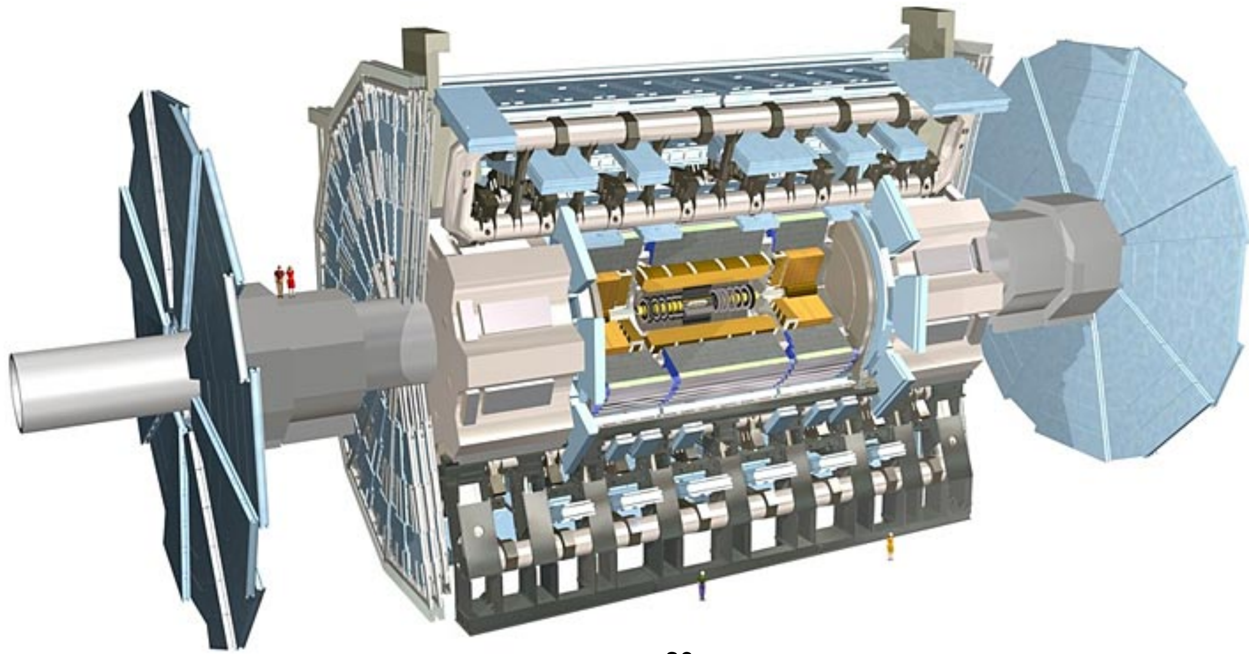


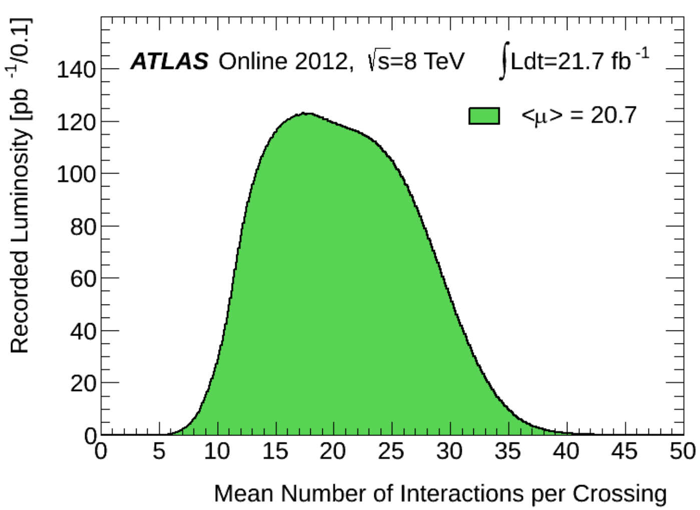
ATLAS detector

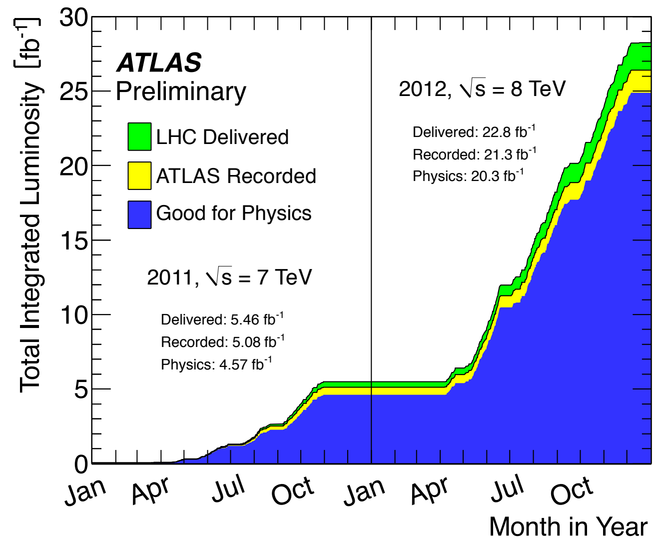
ATLAS 2012

8 TeV *pp*

L_{int} = 20 fb^{-1}







Searches

The following resonance searches are described here

- Dilepton: $Z' \longrightarrow ll$ and other interpretations
- $W' \longrightarrow l\nu$
- $W' \longrightarrow WZ \longrightarrow lll\nu$
- $G^* \longrightarrow HH \longrightarrow bbbb$
- QBH$\longrightarrow lj$ (QBH = quantum black hole)

For more, see the ATLAS public results page

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

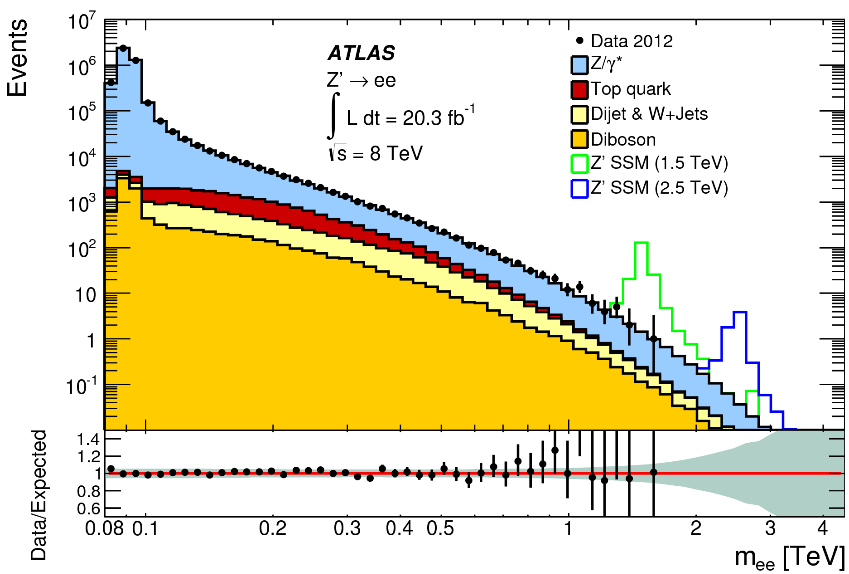
Dilepton search

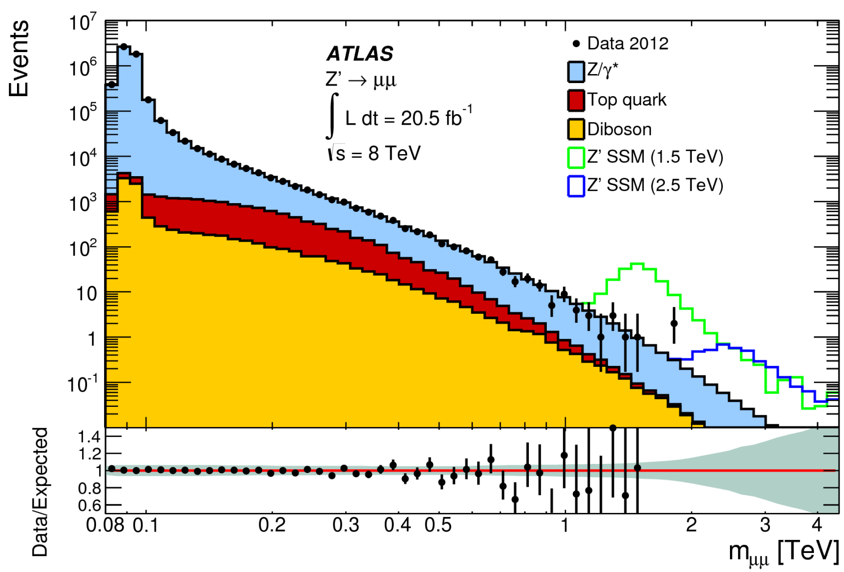
Dilepton search results were recently submitted for publication

- Submitted to Phys. Rev. D (arXiv:1405.4123)
- Preliminary $Z' \to ll$ results were released in March 2013
- New results include many models

Search spectra below

- Left is *ee,* right is μμ
- Search variable is the dilepton mass





Dilepton limits

Statistical analysis

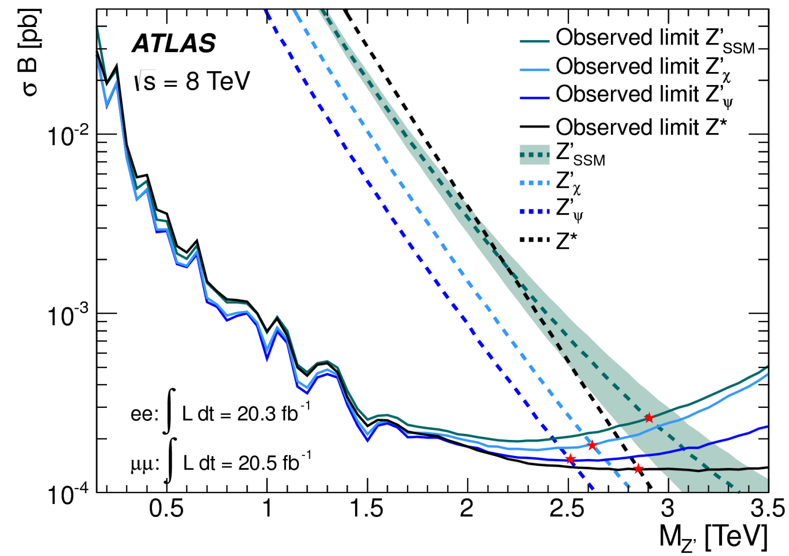
- Spectra show no evidence for BSM resonance
- Bayesian analysis done for a fine-grained scan over m_{ll}
- For a variety of signals

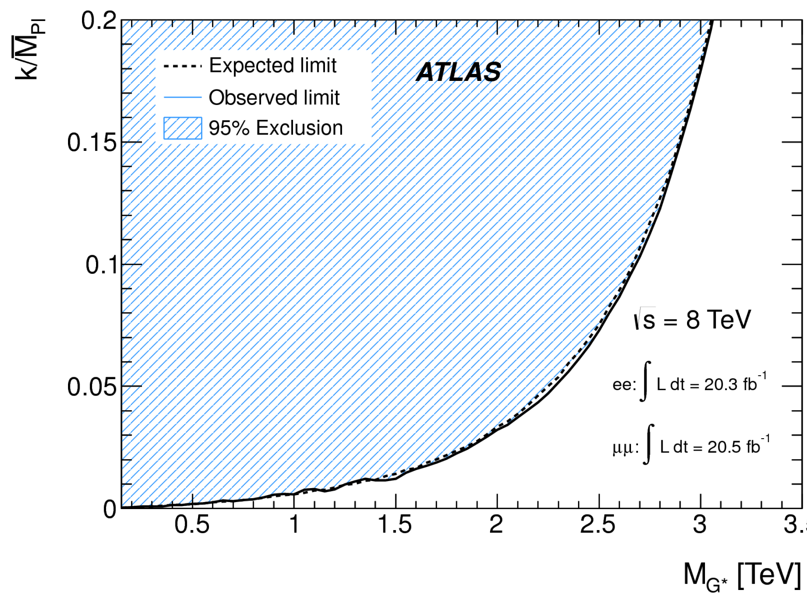
Z′ and *Z**

- Classic SSM *Z′*
- E_6 models Z_χ and Z_ψ
  - Weaker and narrower than *Z′*
- *Z** - tensor coupling
- SSM $m_{Z'} > 2.9$ TeV

*G** (first KK graviton excitation)

- Limit on coupling vs. mass
- $M_{G*} > 2.7$ TeV for $\frac{k}{\overline{M}_{Pl}} > 0.1$





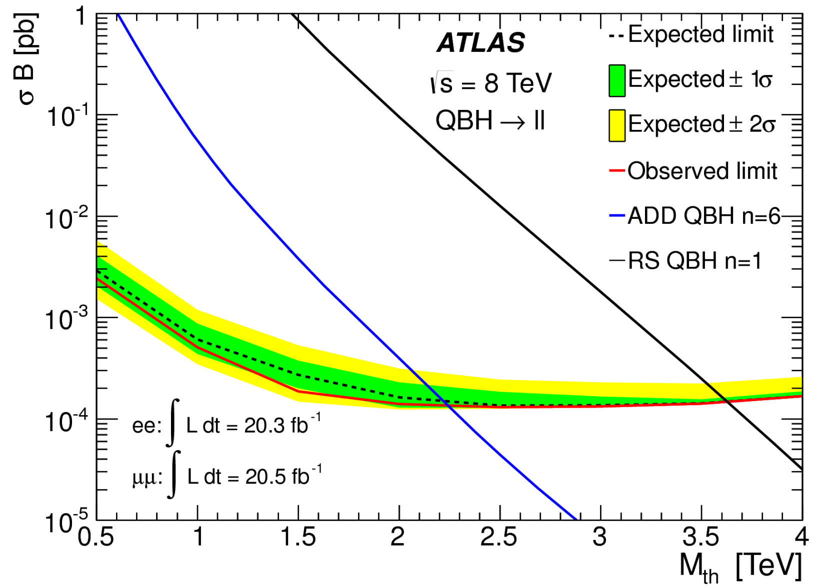
Dilepton limits (2)

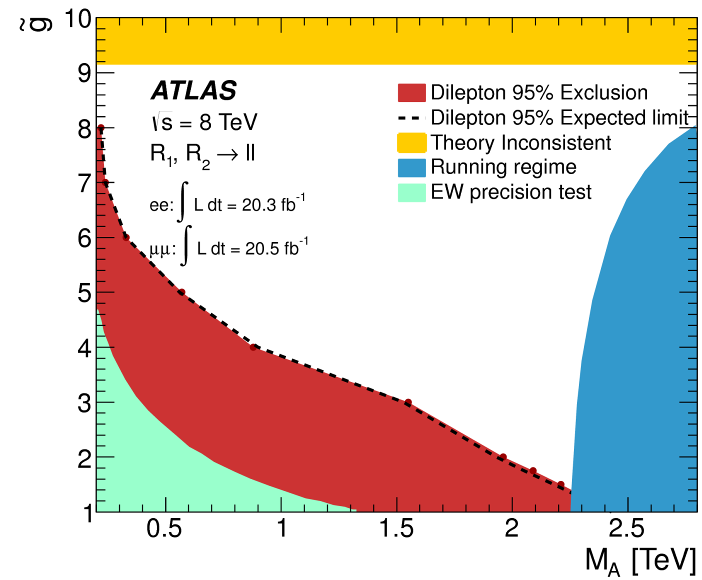
QBH (quantum black hole)

- Low-scale quantum gravity BH can decay to two objects
- See later discussion
- Limits shown as function of threshold mass
  - For both RS and ADD (n = 6)

Minimal Walking Technicolor

- Model is a composite Higgs consistent with present LHC observations
- Techni-meson decay to *ll*
- Limits shown as function of coupling and axial-vector mass

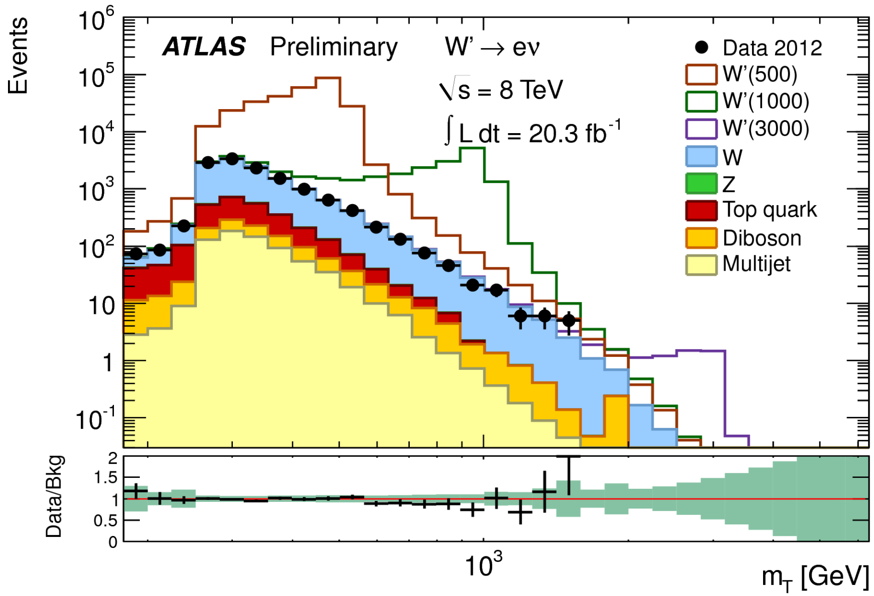


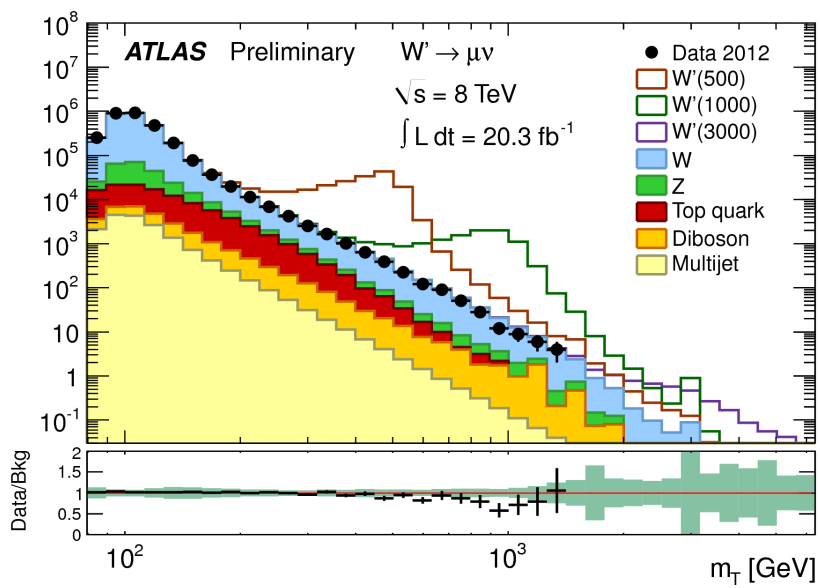


$W' \rightarrow l\nu$ search

Lepton + MET resonance search

- [ATLAS-CONF-2014-017]
- Signal is a single high-pT lepton (*e* or *μ*)
  - Separate search for each channel
  - Large missing transverse momentum (MET)
- Search performed in transverse mass
  - $m_T = \sqrt{2 p_T E_T^{miss} (1 - \cos\varphi_{l\nu})}$

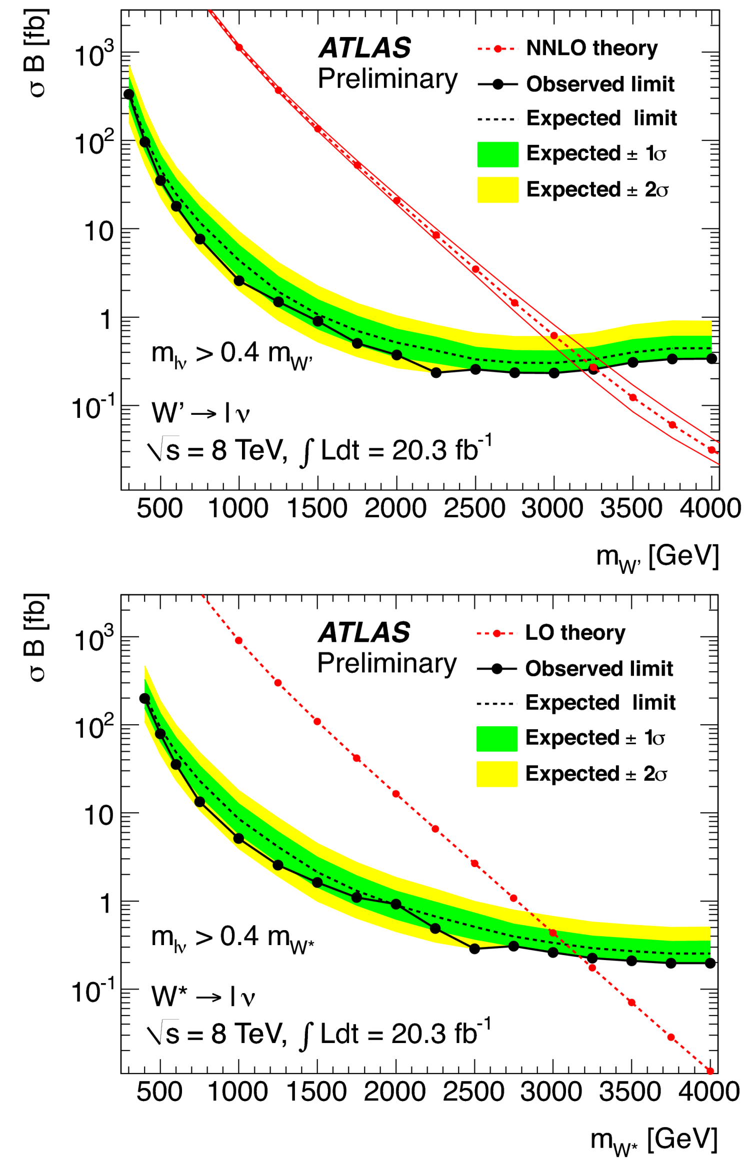




$W' \longrightarrow l\nu$ limits

Statistical analysis

- BG estimated from Monte Carlo
- Signal from MC and measurements of electron and muon efficiencies
  - Signal efficiency: 20-40%
  - SSM W′
  - Excited chiral boson
- Single-bin Bayesian analysis
  - Variable threshold on m_T
- No evidence of signal
- Limits shown in plots
  - Combination of electron and muon channels
  - $m_{W'} > 3.3$ TeV



Diboson resonances

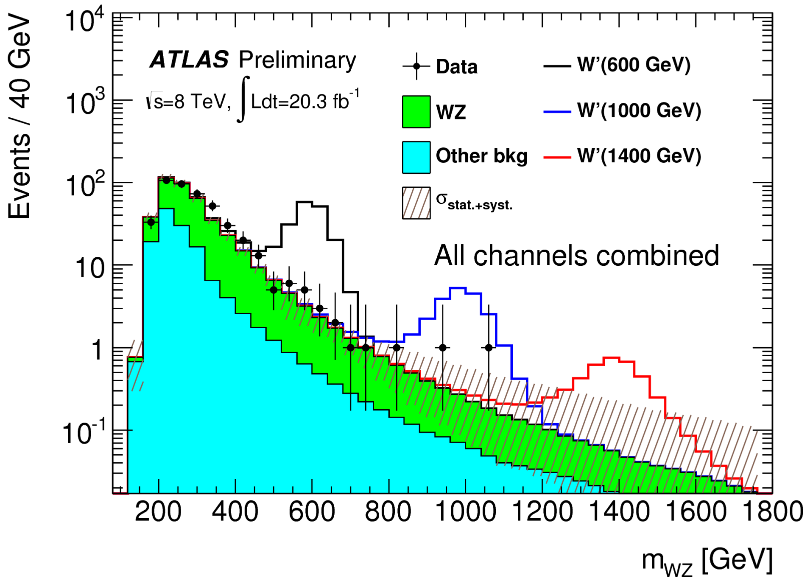
Many models predict diboson resonances

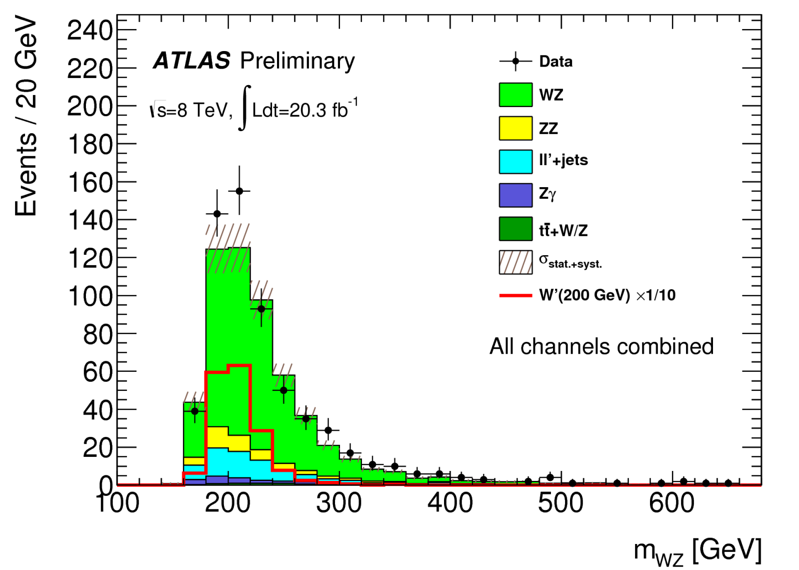
- GUTs, Little Higgs, Technicolor, composite Higgs, extra dimensions, …
- SSM Z′ and *W′* are often used as benchmarks
  - Also graviton
- ATLAS is carrying out searches in many channels
  - *WZ, WW, ZZ, HH, …*
- And there are many decay modes for the bosons
  - $W \longrightarrow l\nu$, $Z \longrightarrow ll$, $H \longrightarrow bb$, …
- Report here on two recent results
  - $W' \longrightarrow WZ \longrightarrow lll\nu$
  - $X \longrightarrow HH \longrightarrow bbbb$

$W' \longrightarrow WZ \longrightarrow lll\nu$ search

Fully-leptonic search for W'

- ATLAS-CONF-2014-015
- Lepton = electron or muon
- Z from opposite-sign, same-flavor leptons
  - $|m_{ll} - m_Z| < 20$ GeV
- W from lepton and MET (assumed from neutrino)
  - Neutrino p_z determined from $m_{l\nu} = m_W$
  - Smallest real or real part of imaginary solution retained
- Search in m_{WZ} in two distinct signal regions
  - $\Delta\varphi(l, \text{MET}) < 1.5$ for high mass
    - Inverse for low mass
  - Search boundary at 250 GeV

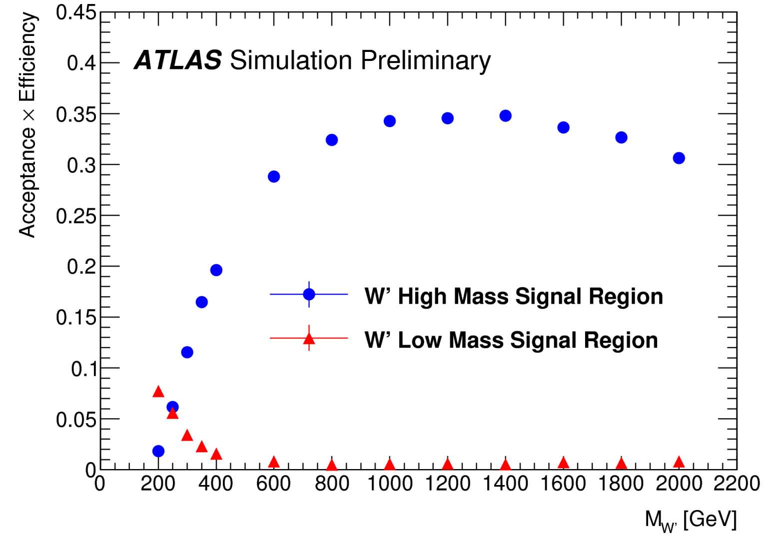


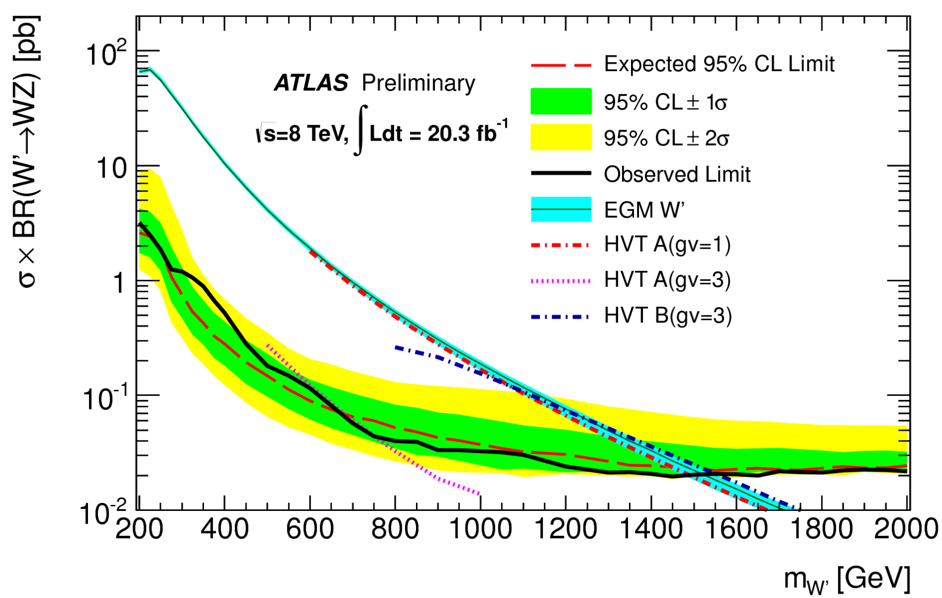


$W' \longrightarrow WZ \longrightarrow lll\nu$ limits

Statistical analysis

- BG taken from Monte Carlo
- Signal from MC and data-driven estimates of lepton efficiencies and fake rates
  - Signal efficiency shown in plot (6-35%)
- No evidence for signal
- CL_S evaluation of limits
  - See figure
  - $m_{W'} > 1.5$ TeV
- Limits also set for HVT (heavy vector triplets) with different strength parameters

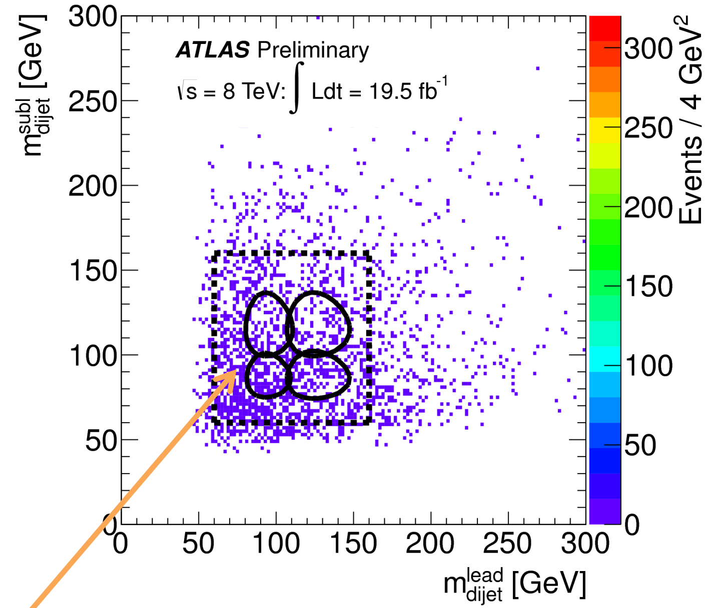


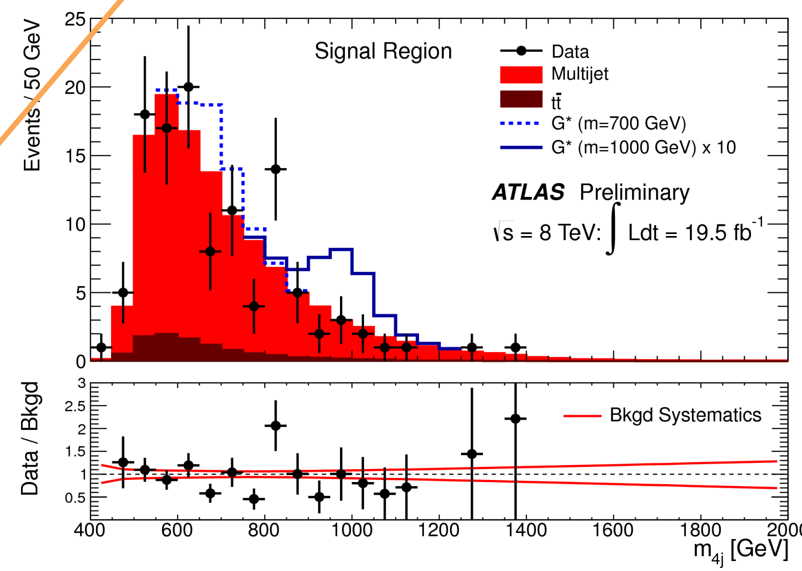


$G^* \longrightarrow HH \longrightarrow bbbb$ search

Di-Higgs search

- With Higgs boson observation, we can now search for decays to Higgs
- Here search for G^* decay to a narrow HH resonance
- Both Higgs decay to bb
- Signal is four b-jets where each of two distinct bb pairs has mass close to 125 GeV
  - Plus veto of events where extra jets look like top
- Remaining BG is 90% multijet
  - Normalized using control region (i.e. not HH or ZH) and comparing with same for 2-tag
- Lower plots shows the search spectrum after selection

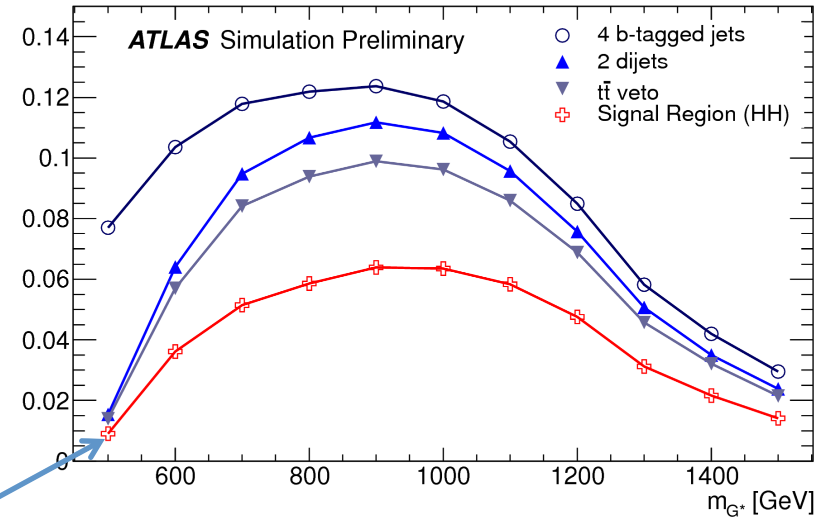


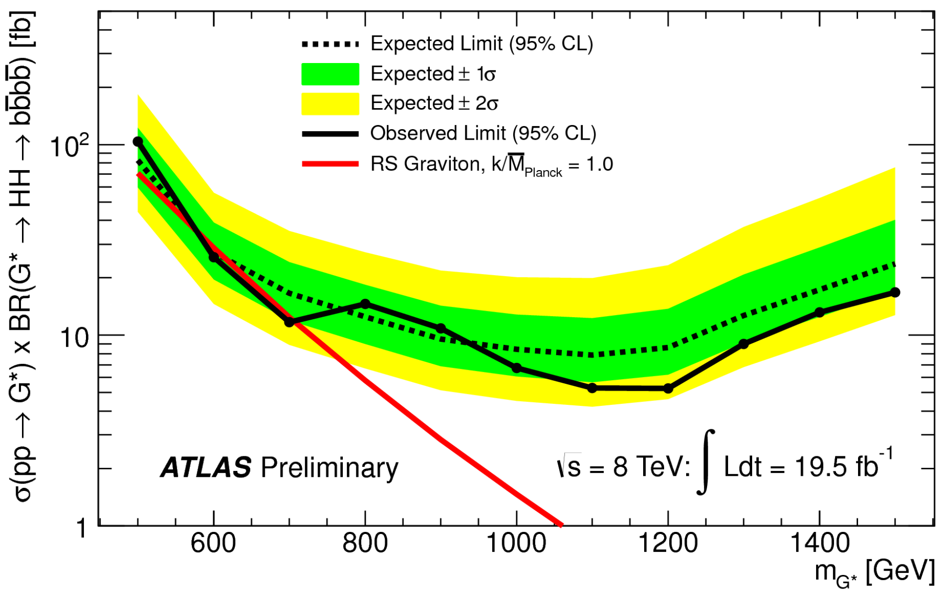


$G^* \longrightarrow HH \longrightarrow bbbb$ limits

Statistical analysis

- Search range 0.5 - 1.5 TeV
- No evidence for signal
- Limits obtained with CL_s
- Signal (first KK excitation of gravition) shape and normalization taken from simulation
- Signal efficiency: 2-6%
- Plot at right shows cross section limits
- Benchmark excluded for $590 < m_{G*} < 710$ GeV
- [ATLAS-CONF-2014-005]





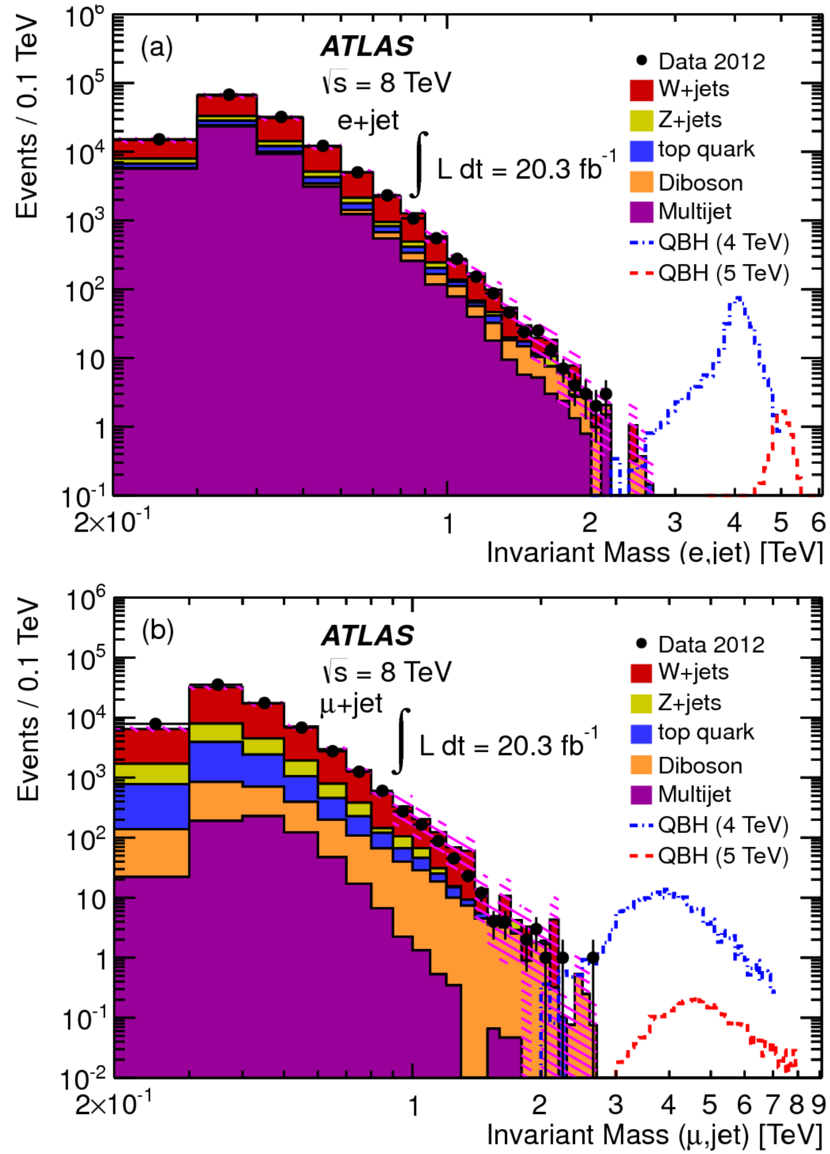
QBH⟶*lj* search

Quantum black holes (QBHs)

- Predicted in low-scale quantum gravity theories
- With mass near m_D, QBH may decay to two particles
  - Unlike semiclassical BHs which decay to may particles
  - m_D = scale of quantum gravity

QBH search

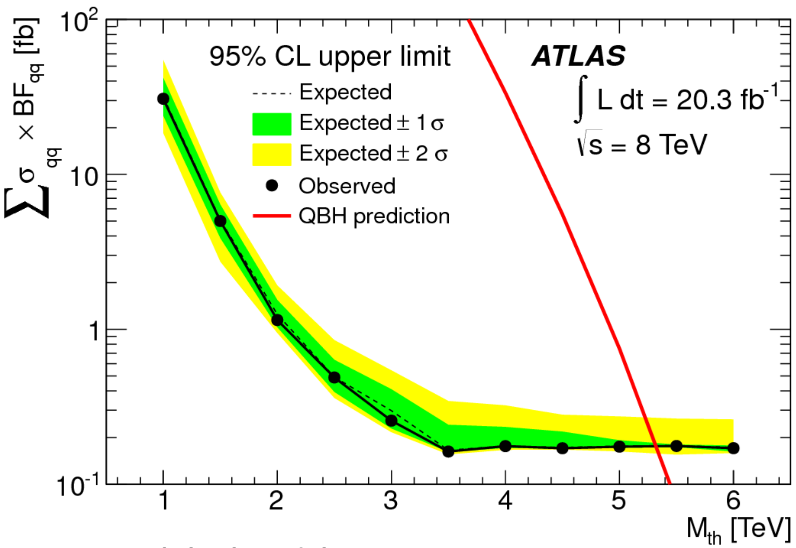
- Search in the lepton-jet (*lj*) channel where BG is small
  - lepton = electron or muon
- Figures show m_{lj}
  - Lepton + highest-p_T jet
  - Top is electron channel
  - Bottom is muon channel



QBH⟶lj limits

Statistical analysis

- BG shapes taken from simulation with normalization obtained from control regions and MET spectra
- Signal depends on assumed threshold mass M_{th}
  - Modeling approximations are valid above this value
  - Taken to be equivalent to the inverse gravitational radius
  - The number of signal events is obtained by counting those with m_{lj} above a threshold close to M_{th}
    - Difference accounts for detector resolution
- No evidence for signal
- Limits evaluated using CL_S
  - Figure at right
    - For n= 6 ADD extra dimensions
    - M_{th} > 5.3 TeV



- PRL 112, 091804 (2014)
- Similar search for gamma+jet final state published last year
  - PLB 728, 562 (2013)

Summary and conclusions

ATLAS searches for heavy resonances

- Part of a wide-ranging search for physics beyond the Standard Model
- A few recent searches are reported here
  - These and many earlier searches and other ATLAS results available from ATLAS public results page
  - Expect more results on 2012 data in the coming months
- So far the standard model looks pretty good
  - No BSM observations yet
  - But many limits on BSM signals
  - Chart on following page summarizes these using benchmark signals
    - See papers and public notes for full kinematic limits

Future

- These and other resonance searches will be extended significantly in the upcoming and future runs at the LHC
- ATLAS-PHYS-PUB-2013-003 concludes, in the absence of a signal, the limit for the SSM Z' increases to $m > 7.8$ TeV for 3000 fb^{-1} at 14 TeV

ATLAS Exotics Searches* - 95% CL Exclusion

Status: April 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell/\gamma\gamma$	2γ or $2e, \mu$	–	–	4.7	M_S 4.18 TeV	$n = 3$ HLZ NLO	1211.1150
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	ATLAS-CONF-2014-016
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	G_{KK} mass 2.47 TeV	$k/\overline{M}_{Pl} = 0.1$	ATLAS-CONF-2013-017
	RS1 $G_{KK} \to ZZ \to \ell\ell qq/\ell\ell\ell\ell$	2 or $4\ e, \mu$	2 j or –	–	1.0	G_{KK} mass 845 GeV	$k/\overline{M}_{Pl} = 0.1$	1203.0718
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\ e, \mu$	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 0.5-2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	20.3	Z' mass 2.86 TeV		ATLAS-CONF-2013-017
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\,\ell'\ell'$	$3\ e, \mu$	–	Yes	20.3	W' mass 1.52 TeV		ATLAS-CONF-2014-015
	LRSM $W'_R \to t\bar{b}$	$1\ e, \mu$	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\ e, \mu$	–	–	5.0	Λ 13.9 TeV	$\eta_{LL} = -1$	1211.1150
	CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator	–	1-2 j	Yes	10.5	M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator	–	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	$1\ e, \mu, 1\ \tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	$1\ e, \mu$	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $BB \to Zb + X$	$2\ e, \mu$	≥ 2 b	–	14.3	B mass 725 GeV	B in (B,Y) doublet	ATLAS-CONF-2013-056
	Vector-like quark $BB \to Wt + X$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	13.0	q^* mass 3.84 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2012-148
	Excited quark $b^* \to Wt$	1 or $2\ e, \mu$	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\ e, \mu, 1\ \gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LRSM Majorana ν	$2\ e, \mu$	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\ e, \mu$	–	–	5.8	$N^{\pm}$ mass 245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e, \mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g \rvert = 1 g_D$	1207.6411

$\sqrt{s}$ = 7 TeV $\sqrt{s}$ = 8 TeV

10^{-1} 1 10 **Mass scale [TeV]**

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