

SEARCHES FOR NEW PHENOMENA IN HIGH-MASS (NON-)RESONANT PRODUCTION WITH THE ATLAS DETECTOR

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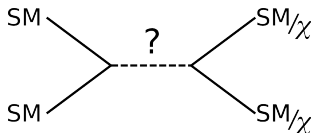
August 25, 2015

ICNFP 2015



- exotics searches at ATLAS
- selected Run I results of exotics searches in various search channels
- first look at analyses status from Run II data taking
- Summary/Outlook

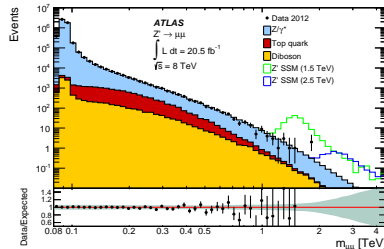
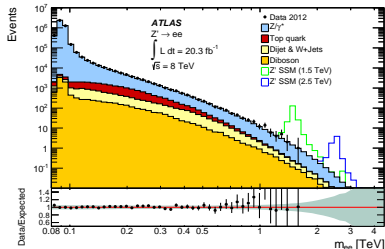
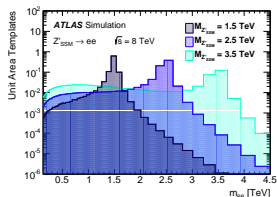
Motivation for Exotics Searches at ATLAS



- short-comings of SM require for new physics to provide solutions
↪ search for new particles, mediators, symmetries
- **hierarchy problem**: not only SUSY models provide solutions but also: models with **extra dimensions**, grand unification theories, sequential SM...
- **dark matter**: many models that predict existence of **WIMPs** (weakly interacting massive particles), generic searches and interpretations in ATLAS analyses
- all published ATLAS exotics results can be found here:
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>
- other analysis results will be presented elsewhere

Run I Analysis Results

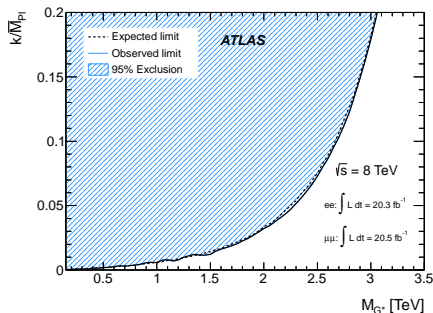
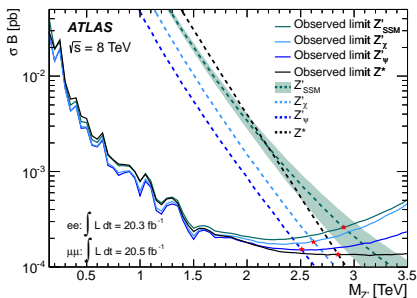
- search for resonances in $m_{\ell\ell}$ distribution ($\ell = e$ or μ)
- resonances predicted in models with Z' -boson, Z^* -boson, gravitons, technimesons, ...
- **analysis strategy:** either two electrons ($E_{T,1} > 40$ GeV, $E_{T,2} > 30$ GeV) or two muons (tight ID) with $p_T > 25$ GeV and opposite charge, background normalized to data in region of Z -boson peak ($80 < m_{\ell\ell} < 110$ GeV), \rightarrow template fit to data (bin width constant in $\log m_{\ell\ell}$) + nuisance parameters (systematic uncertainties)



Results from Dilepton Search

- no data excess above the SM background has been found
- set limits using Bayesian approach

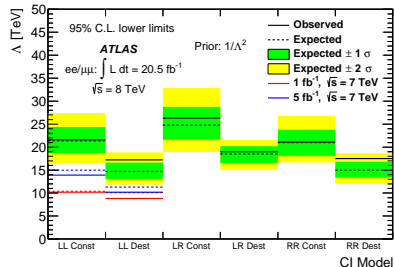
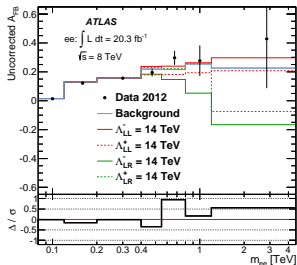
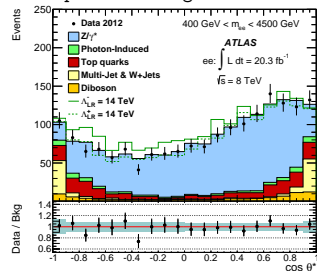
Model	Width [%]	Observed Limit [TeV]	Expected Limit [TeV]
Z'_{SSM}	3.0	2.90	2.87
Z'_χ	1.2	2.62	2.60
Z'_ψ	0.5	2.51	2.46
Z'^*	3.4	2.85	2.82



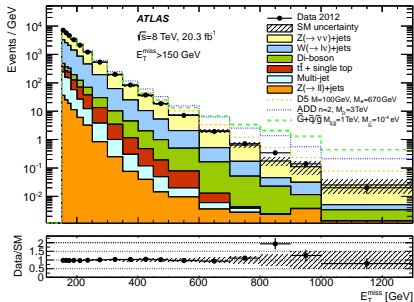
Contact Interaction Search in Dilepton Events

- similar selection as resonance search ($m_{\ell\ell} > 80$ GeV)
- use $m_{\ell\ell}$ and lepton scattering angle θ^* as discriminators
 \hookrightarrow build forward-backward asymmetry from $\cos \theta^*$: $A_{FB} = \frac{N(\cos \theta^* > 0) - N(\cos \theta^* < 0)}{N(\text{all})}$
- backgrounds normalized to data in CR ($80 < m_{\ell\ell} < 120$ GeV)
- Bayesian limit setting on **Contact Interaction scale Λ** :

<http://arxiv.org/abs/1407.2410>



- monojet signature explored when invisible particles are produced: large \cancel{E}_T can be detected if recoiling ISR jet present
 ↪ dark matter, compressed SUSY, extra dimension, invisible Higgs decays...
- $Z \rightarrow \nu\nu + \text{jets}$ dominant background, others: multijet, non-collision, $W/Z + \text{jets}$, diboson and top backgrounds
- **analysis strategy:** define control regions with leptons and fit MC normalization to data for $W/Z + \text{jets}$,
 SR: no leptons, $p_{T,1} > 120$ GeV, different \cancel{E}_T cuts (from 150 to 700 GeV),
 $p_{T,1}/\cancel{E}_T > 0.5$, $\Delta\phi(\cancel{E}_T, \text{jet}) > 1.0$
 compare yields after CR fit → set limits (CL_s , frequentist) on various models



Monojet Search: Dark Matter Interpretation

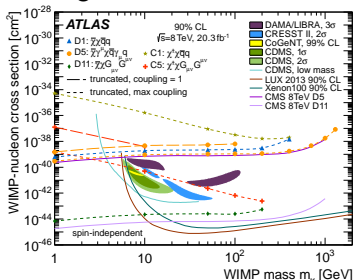
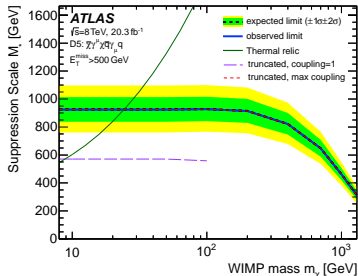
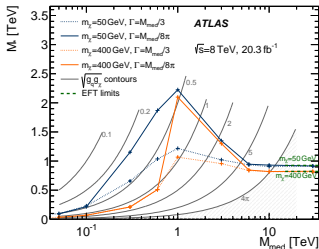
- dark matter model: WIMP production in context of effective field theories (EFT) or simplified models with exchange of heavy mediator

- heavy mediator: set limits on

$$M^* = M_{\text{med}} / \sqrt{g_q g_\chi} \text{ vs. mediator mass } M_{\text{med}}$$

- EFT: limit on suppression scale M^* vs. WIMP mass m_χ for different operators

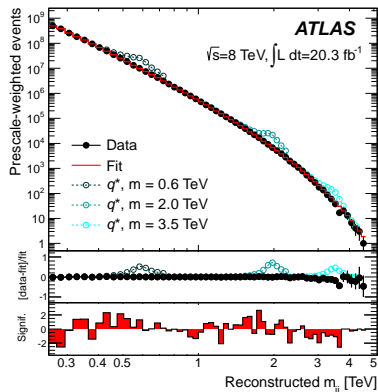
↪ possible to derive WIMP-nucleon scattering cross section limits



- search for resonances in m_{jj} distribution, coverage $250 < m_{jj} < 4500$ GeV
- models: excited quarks, color octet scalars, W' , W^* , quantum black holes
- objects/selection: jets reconstructed with anti- k_T algorithm and $R = 0.6$, at least two jets where leading jets form m_{jj} ($p_T > 50$ GeV, $|y| < 2.8$, $\frac{1}{2}|y_1 - y_2| < 0.6$, $m_{jj} > 250$ GeV)
- background: mostly multijets, calibrated with simulation, smooth function fitted to spectrum in data

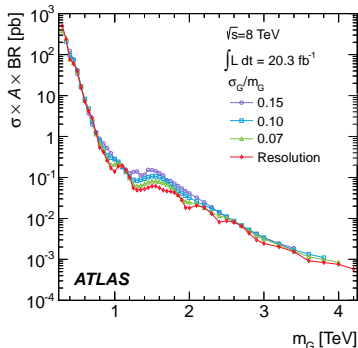
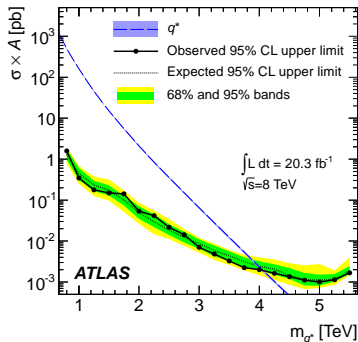
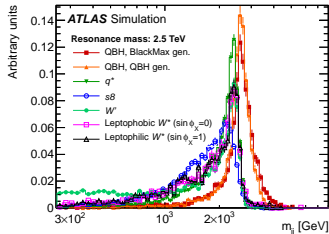
$$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4} \ln x,$$

where $x = m_{jj}/\sqrt{s}$ and p_i free parameters



Results from Dijet Resonance Search

- nuisance parameters for systematic uncertainties in background fit
- \nearrow **BUMPHUNTER** used, Bayesian CL limits are set
- limits on various models and generic resonances with Breit-Wigner/Gauss distributions (Gauss: right plot)



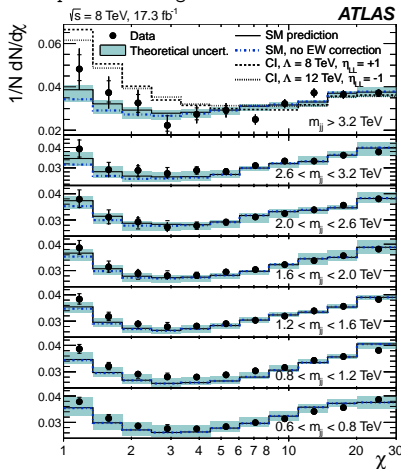
New Physics Searches in Dijet Angular Distributions

- dijet production dominated by t -channel gluon exchange \rightarrow angular distribution peaked at $|\cos\theta^*| = 1$, with θ^* scattering angle in two-jets center-of-mass frame
- new phenomena: more isotropic production
- at least two jets ($p_T > 50$ GeV, $m_{jj} > 600$ GeV, $|y_1 - y_2| < 1.7$, $\frac{1}{2}(y_1 + y_2) < 1.1$)
- angular distribution: $\chi = \exp(2|y_1 - y_2|)$, bins in χ approximated to calorimeter segmentation
- background from PYTHIA8 + higher order QCD and electroweak corrections, χ distribution normalized to unit area

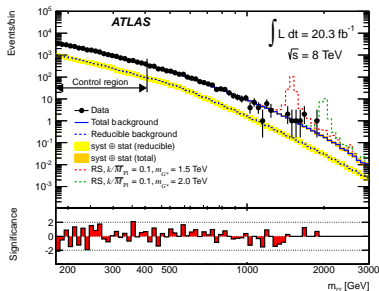
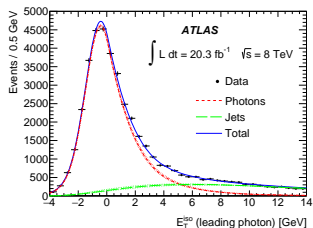
\Rightarrow quark compositeness: limit on **contact interaction scale Λ** :
destructive interference: **8.1 TeV**,
constructive interference: **12.0 TeV**

Phys. Rev. Lett. 114, 221802

<http://arxiv.org/abs/1504.00357>

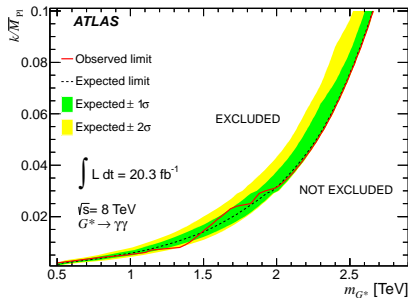
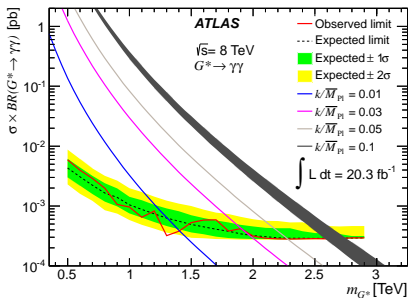


- search for gravitons, Randall-Sundrum extra dimensions via $m_{\gamma\gamma}$ distribution
 - excellent mass resolution, modest background level
 - photons: tight ID, in precision region of EMCal, $E_T > 50$ GeV
 - backgrounds: prompt $\gamma\gamma$ (irreducible): MC shape, normalization from control regions ($m_{\gamma\gamma} < 600$ GeV), misidentified jets (reducible)
- ↪ background composition via template fit to E_T^{iso} in data CR
- ↪ extrapolation to signal region

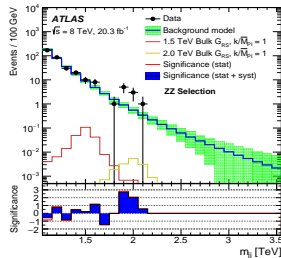
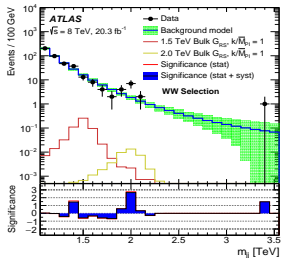
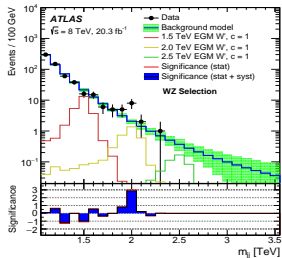
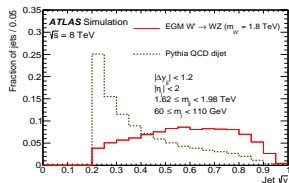


Results from Diphoton Resonance Search

- usage of BUMP HUNTER to find lack of agreement between data and MC for $409 < m_{\gamma\gamma} < 3000$ GeV
- perform likelihood analysis and Bayesian limit setting for RS gravitons

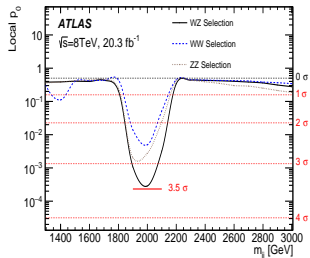
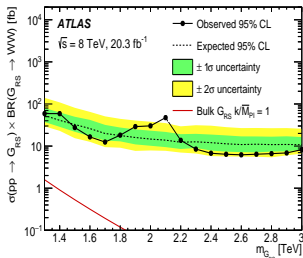
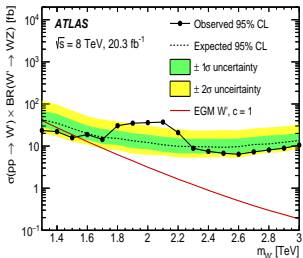


- search for narrow resonances decaying to WW , WZ , ZZ in m_{jj} where jets are tagged as boson jets \leftrightarrow highly boosted bosons decaying to quarks \rightarrow all-hadronic final state
- multijet background dominant: discrimination via boson-tagging variables (jet mass, substructure), background fitted to smoothly falling function
- tagged boson jets in ± 13 GeV window of either W or Z (overlap between channels!) and $p_T > 540$ GeV, no leptons, $\cancel{E}_T < 350$ GeV, $m_{jj} > 1.05$ TeV



Results from Diboson Resonance Search

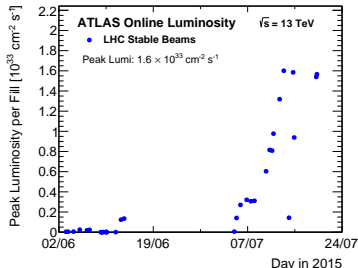
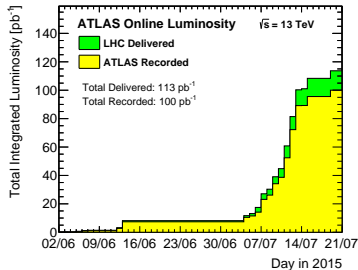
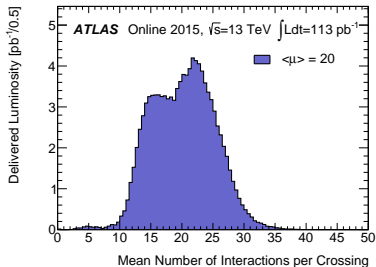
- maximum likelihood fit performed in $1.05 \text{ TeV} < m_{jj} < 3.55 \text{ TeV}$ of background function, systematics treated as nuisance parameters
- **excess** over data found around $m_{jj} = 2 \text{ TeV}$, global significance in WZ channel: 2.5σ (frequentist interpretation)
- benchmark models: $W'_{\text{SSM}} \rightarrow WZ$: exclusion for $1.3 < m_{W'} < 1.5 \text{ TeV}$, $G_{\text{RS}} \rightarrow WW$ or ZZ could not be excluded



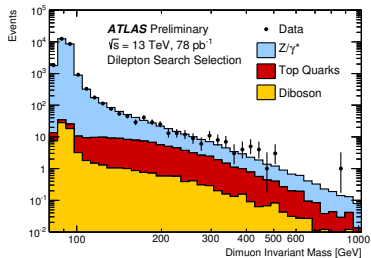
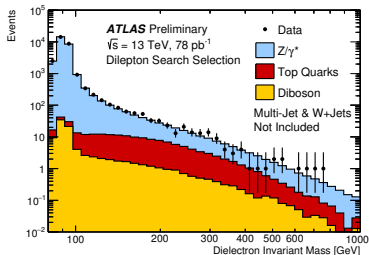
First look at Run II Data

First Look at 13 TeV Data

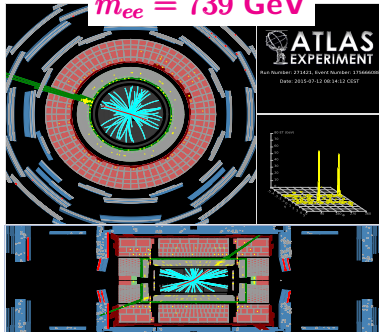
- public luminosity plots:
[LuminosityPublicResultsRun2](#)
- since June: runs with 50 ns bunch spacing
- average number of interactions per bunch crossing: $\langle \mu \rangle = 20$



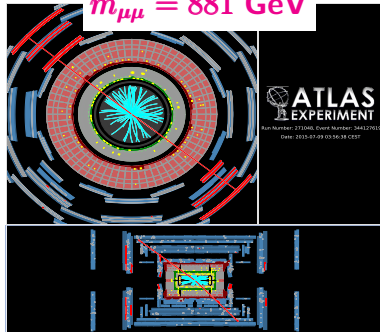
Dilepton Search with 13 TeV Data ([Link](#))



$m_{ee} = 739 \text{ GeV}$

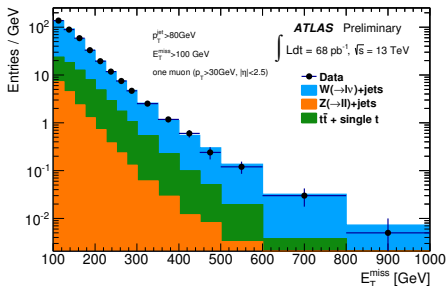


$m_{\mu\mu} = 881 \text{ GeV}$



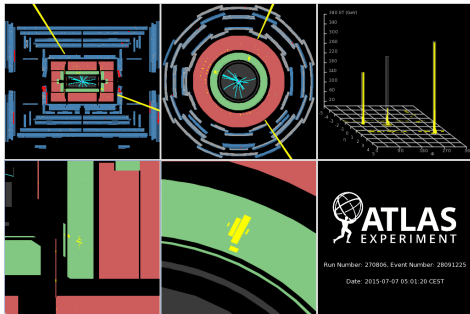
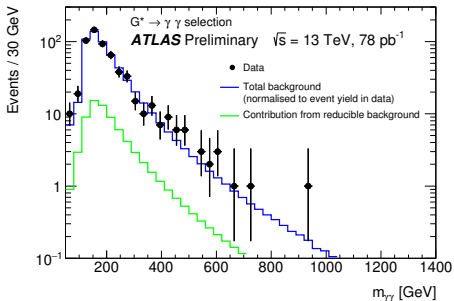
Monojet Search with 13 TeV (Link)

- selection slightly changed w.r.t Run I analysis: upper cut on number of jets (at most 4), no cut on $p_{T,1}/\cancel{E}_T$, $\Delta\phi(\cancel{E}_T, \text{jet}) > 0.4$
- control region plot with 68 pb^{-1} of data: $W \rightarrow \mu\nu$ CR: $\cancel{E}_T > 100 \text{ GeV}$, $p_{T,1} > 80 \text{ GeV}$, exactly one muon
- MC background normalized to data



Diphoton Search with 13 TeV Data ([Link](#))

- diphoton event with highest $m_{\gamma\gamma} = 940$ GeV recorded (see event display)



Summary and Outlook

- selection of recent Run I analysis results have been presented
 - ↔ yet, no significant deviation from SM prediction observed
 - ↔ but some slight excesses observed (e. g. diboson resonance search)
 - ↔ strong limits have been set on many new physics models
- Run II operation has started
 - ↔ recorded 100 pb^{-1} of 13 TeV data with $\langle \mu \rangle = 20$
 - ↔ first check of relevant distributions in MC and data by analysis teams
 - ↔ first results yet to come
 - ↔ hope to exceed Run I sensitivity by end of the year

BACKUP

Summary: Exotics Results Run I

ATLAS Exotics Searches* - 95% CL Exclusion

Status: July 2015

ATLAS Preliminary

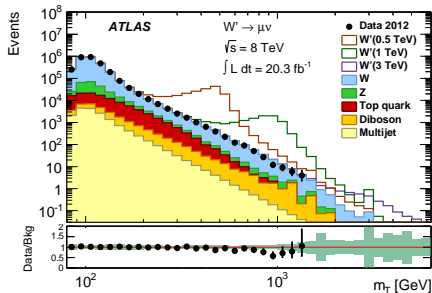
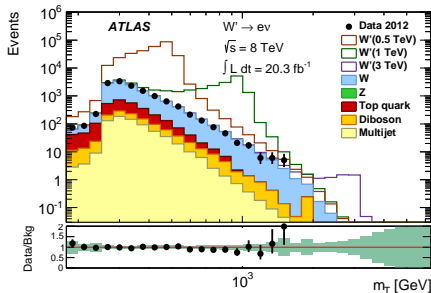
$$\int \mathcal{L} dt = (4.7 - 20.3) \text{ fb}^{-1}$$

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

	Model	ℓ, γ	Jets	E_{miss}^T	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit		Reference	
Extra dimensions	ADD $G_{KK} + g/q$	-	$\geq 1j$	Yes	20.3	M_0	3.25 TeV	$n = 2$	1502.01518
	ADD non-resonant $\ell\ell$	$2e, \mu$	-	-	20.3	M_0	4.7 TeV	$n = 3 \text{ HLZ}$	1407.2410
	ADD OBH $\rightarrow \ell q$	$1e, \mu$	$1j$	-	20.3	M_0	5.2 TeV	$n = 6$	1311.2006
	ADD OBH	-	$\geq 2j$	-	20.3	M_0	5.82 TeV	$n = 6$	1407.1376
	ADD BH high N_{ch}	2μ (SS)	$\geq 2j$	-	20.3	M_0	4.7 TeV	$n = 6, M_0 = 3 \text{ TeV, non-rot BH}$	1308.4075
	ADD BH high Σp_T	$\geq 1e, \mu$	$\geq 2j$	-	20.3	M_0	5.6 TeV	$n = 6, M_0 = 3 \text{ TeV, non-rot BH}$	1405.04254
	ADD BH high multijet	-	$\geq 2j$	-	20.3	M_0	5.8 TeV	$n = 6, M_0 = 3 \text{ TeV, non-rot BH}$	1503.08988
	RS1 $G_{KK} \rightarrow \ell\ell$	$2e, \mu$	-	-	20.3	$G_{KK} \text{ mass}$	2.68 TeV	$k/\bar{M}_0 = 0.1$	1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	20.3	$G_{KK} \text{ mass}$	2.65 TeV	$k/\bar{M}_0 = 0.1$	1504.05511
	Bulk RS $G_{KK} \rightarrow ZZ \rightarrow qq\ell\ell$	$2e, \mu$	$2j/1J$	-	20.3	$G_{KK} \text{ mass}$	740 GeV	$k/\bar{M}_0 = 1.0$	1409.6190
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1e, \mu$	$2j/1J$	Yes	20.3	$W \text{ mass}$	750 GeV	$k/\bar{M}_0 = 1.0$	1503.04677
	Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	-	4b	-	19.5	$G_{KK} \text{ mass}$	500-720 GeV	$k/\bar{M}_0 = 1.0$	1506.00285
	Bulk RS $G_{KK} \rightarrow \ell\ell$	$1e, \mu$	$\geq 1b, \geq 1J/2j$	Yes	20.3	$W \text{ mass}$	2.2 TeV	$BR = 0.925$	1505.07018
	2UED1 RPP	$2e, \mu$ (SS)	$\geq 1b, \geq 1j$	Yes	20.3	$W \text{ mass}$	900 GeV		1504.04605
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2e, \mu$	-	-	20.3	$Z' \text{ mass}$	2.9 TeV	
SSM $Z' \rightarrow \tau\tau$		2τ	-	-	19.5	$Z' \text{ mass}$	2.02 TeV		1502.07177
SSM $W' \rightarrow \ell\nu$		$1e, \mu$	-	Yes	20.3	$W' \text{ mass}$	3.34 TeV		1407.7494
EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$		$3e, \mu$	-	Yes	20.3	$W' \text{ mass}$	1.52 TeV		1406.4456
EGM $W' \rightarrow WZ \rightarrow qq\ell\ell$		$2e, \mu$	$2j/1J$	-	20.3	$W' \text{ mass}$	1.58 TeV		1409.6190
EGM $W' \rightarrow WZ \rightarrow qq\ell\nu$		-	$2J$	-	20.3	$W' \text{ mass}$	1.3-1.5 TeV		1506.00962
HVT $W' \rightarrow WJ \rightarrow \ell\nu bb$		$1e, \mu$	2b	Yes	20.3	$W' \text{ mass}$	1.47 TeV	$g_V = 1$	1505.08089
LRSM $W_R \rightarrow \tau\bar{\nu}$	$1e, \mu$	2b, 0-1j	Yes	20.3	$W' \text{ mass}$	1.52 TeV		1410.4103	
LRSM $W_R \rightarrow \tau\bar{\nu}$	$0e, \mu$	$\geq 1b, 1J$	Yes	20.3	$W' \text{ mass}$	1.76 TeV		1408.0886	
CI	CI $qqqq$	-	$2j$	-	17.3	A	12.0 TeV	$ \zeta_{CI} = 1$	1504.00357
	CI $qq\ell\ell$	$2e, \mu$	-	-	20.3	A	21.6 TeV	$\eta_{CI} = -1$	1407.2410
	CI $uutt$	$2e, \mu$ (SS)	$\geq 1b, \geq 1j$	Yes	20.3	A	4.3 TeV		1504.04605
DM	EFT D9 operator (Dirac)	$0e, \mu$	$\geq 1j$	Yes	20.3	M	974 GeV	at 90% CL for $m(\chi) < 100 \text{ GeV}$	1502.01518
	EFT D9 operator (Dirac)	$0e, \mu$	$1j, \geq 1j$	Yes	20.3	M	2.4 TeV	at 90% CL for $m(\chi) < 100 \text{ GeV}$	1309.4017
LQ	Scalar LQ 1 st gen	$2e$	$\geq 2j$	-	20.3	LQ mass	1.05 TeV	$\beta = 1$	Preliminary
	Scalar LQ 2 nd gen	2μ	$\geq 2j$	-	20.3	LQ mass	1.0 TeV	$\beta = 1$	Preliminary
	Scalar LQ 3 rd gen	$1e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	LQ mass	640 GeV	$\beta = 0$	Preliminary
Heavy quarks	VLQ $TT \rightarrow Ht + X$	$1e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	T mass	855 GeV	T in (TB) doublet	1505.04308
	VLQ $YY \rightarrow Wb + X$	$1e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	Y mass	770 GeV	Y in (BY) doublet	1505.04308
	VLQ $BB \rightarrow Hb + X$	$1e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	B mass	735 GeV	isospin singlet	1505.04308
	VLQ $BB \rightarrow Zb + X$	$2\geq 3e, \mu$	$\geq 2\geq 1b$	-	20.3	B mass	755 GeV	B in (BY) doublet	1400.5500
	$T_{5/3} \rightarrow Wt$	$1e, \mu$	$\geq 1b, \geq 5j$	Yes	20.3	$T_{5/3} \text{ mass}$	840 GeV		1503.05425
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1γ	$1j$	-	20.3	$q^* \text{ mass}$	3.5 TeV	only u^* and d^* , $A = m(q^*)$	1309.3230
	Excited quark $q^* \rightarrow qg$	-	$2j$	-	20.3	$q^* \text{ mass}$	4.09 TeV	only u^* and d^* , $A = m(q^*)$	1407.1376
	Excited quark $b^* \rightarrow Wt$	1 or $2e, \mu$	$1b, 2j$ or $1j$	Yes	4.7	$b^* \text{ mass}$	870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \rightarrow \ell\gamma$	$2e, \mu, 1\gamma$	-	-	13.0	$\ell^* \text{ mass}$	2.3 TeV	$A = 2.2 \text{ TeV}$	1308.1364
Excited lepton $\ell^* \rightarrow \ell W, \nu Z$	$3e, \mu, \tau$	-	-	20.3	$\ell^* \text{ mass}$	1.8 TeV	$A = 1.6 \text{ TeV}$	1411.2021	
Other	LSTC $\Delta_T \rightarrow W\gamma$	$1e, \mu, 1\gamma$	-	Yes	20.3	$\Delta_T \text{ mass}$	960 GeV		1407.8150
	LRSM Majorana ν	$2e, \mu$	$2j$	-	20.3	$\bar{\nu}^M \text{ mass}$	2.0 TeV	$m(W_0) = 2.4 \text{ TeV, no mixing}$	1506.08020
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2e, \mu$ (SS)	-	-	20.3	$H^{\pm\pm} \text{ mass}$	501 GeV	DY production, $BR(H^{\pm\pm} \rightarrow \ell\ell) = 1$	1412.0237
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3e, \mu, \tau$	-	-	20.3	$H^{\pm\pm} \text{ mass}$	400 GeV	DY production, $BR(H^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2021
	Monopole (non-res prod)	$1e, \mu$	1b	Yes	20.3	spin-1 invisible particle mass	637 GeV	$A_{\text{mono}} = 0.2$	1410.5404
	Multi-charged particles	-	-	-	20.3	multi-charged particle mass	783 GeV	DY production, $ \eta = 5e$	1504.04188
	Magnetic monopoles	-	-	-	7.0	monopole mass	1.34 TeV	DY production, $ \eta = 1g_{\text{spin}} \text{ spin } 1/2$	Preliminary

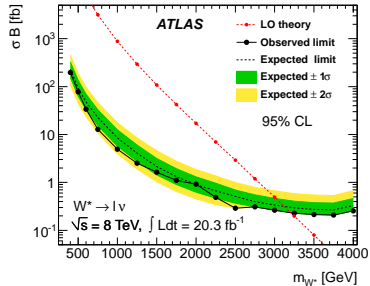
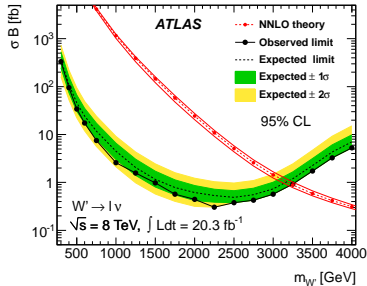
*Only a selection of the available mass limits on new states or phenomena is shown.

- search for W' -like resonance in $m_T \left(= \sqrt{2p_T^\ell \cancel{E}_T (1 - \cos(\angle(\cancel{E}_T, \ell)))} \right)$ spectrum
- also search for $\chi + X$ production, where χ = dark matter particle
- **analysis strategy:** exactly one electron ($E_T > 125$ GeV) or exactly one muon ($p_T > 45$ GeV, tight ID) consistent with primary vertex and $\cancel{E}_T(e) > 125$ GeV and $\cancel{E}_T(\mu) > 45$ GeV,
 multijet background estimated from matrix method around Jacobian peak of m_T
 → extrapolated to high tail by power-law function
 dominant $W \rightarrow \ell\nu$ background estimated from MC



Results from $\ell + \cancel{E}_T$ Search

- Bayesian analysis: optimization of lower cut on m_T for W', W^* , dark matter+ W
 - ↪ likelihood fit with nuisance parameters (systematic uncertainties)
- observed events: deficit in μ -channel (local 2.2σ significance) → limits are set
- $m_{W'_{SSM}} > 3.24$ TeV, chiral W^* with SSM couplings: $m_{W^*} > 3.21$ TeV



Lepton+ \cancel{E}_T Search with 13 TeV Data (Link)

