Searches for new physics in high-mass fermionic final states and jets with the ATLAS detector at the LHC

Oleksandr Viazlo
on behalf of the ATLAS collaboration

Lund University

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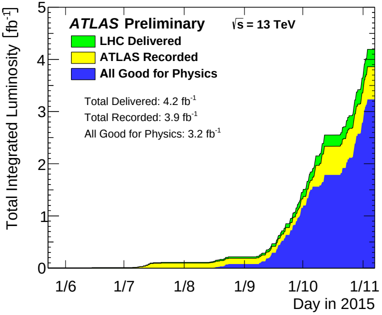
Resonant and non-resonant searches for new physics

Covered analysis

- 13 TeV data only.
  - 3.0 - 3.6 fb^{-1} of luminosity.
- High-mass final states only.



- 8 analysis in total $\rightarrow$ no many details on the slides $\rightarrow$ follow references to find out more!

Fermionic final states

- **lepton + E_T^{miss}** $[W']$
- **di-lepton $\ell^{\pm}\ell^{\mp}$** $[Z'$, Contact Interaction (CI)]
- **di-lepton $e^{\pm}\mu^{\mp}$** $[Z'$, Quantum Black Holes (QBH)]

Hadronic final states (jets)

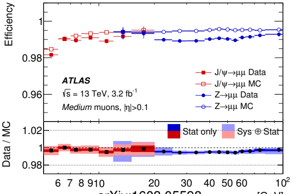
- **di-jet** [QBH, q^*, W', CI]
- **di-jet with b-tagging** $[b^*, Z']$
- **multijet** [QBH, string balls]

Mixed final states

- **lepton and 2 jets/leptons** [QBH]
- **2 leptons and 2+ jets** [leptoquarks]

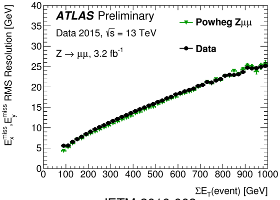
Physics objects performance at 13 TeV

Muon Identification Efficiencies



arXiv:1603.05598

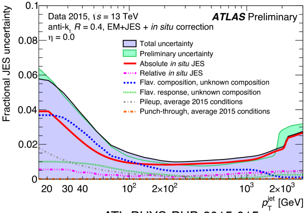
E_T^{miss} uncertainty



JETM-2016-003

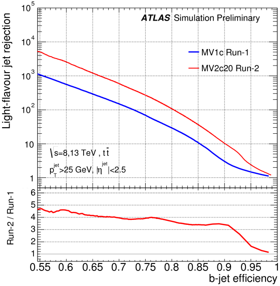
- **Lepton** efficiencies and energy corrections are measured in $J/\psi \to \ell\ell$ and $Z \to \ell\ell$ events.
- E_T^{miss} resolution and scale are evaluated from $Z \to \mu\mu$ events.

Jet Energy Scale uncertainty



ATL-PHYS-PUB-2015-015

Light jet rejection vs. b-jet tag efficiency



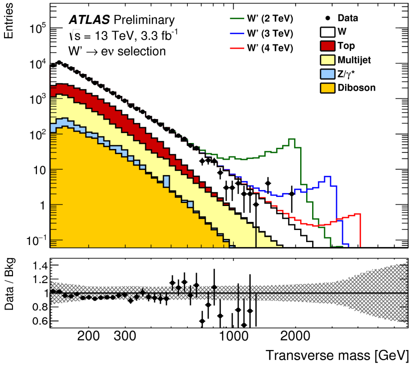
ATL-PHYS-PUB-2015-022

- **Jet** Energy Scale uncertainty is below 3% for TeV jets.
- Significant improvement of **b-tagging** performance:
  - Insertable B-Layer (IBL).
  - better tracking in dense environment.
  - improved b-tagging algorithms.

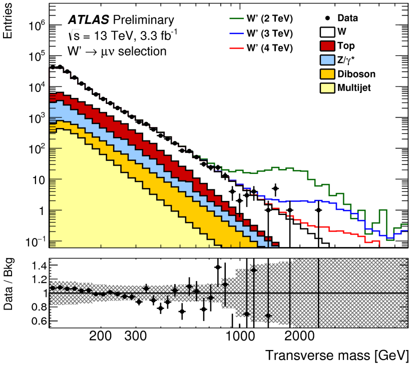
Fermionic final states

- ✷lepton + E_{T}^{miss}
- ✷di-lepton $\ell^{\pm}\ell^{\mp}$
- ✷di-lepton $e^{\pm}\mu^{\mp}$

Electron channel



Muon channel



- Exactly **one isolated electron(muon)** with $p_T > 65(55)$ GeV
- $E_T^{miss} > 65(55)$ GeV
- Search variable:
  $$m_T = \sqrt{2 p_T E_T^{miss} (1 - \cos\varphi_{\ell\nu})}$$

ATLAS-CONF-2015-063

- Dominant background processes:
  - W, Z - from Monte Carlo simulation
    (mass dependent NNLO pQCD and NLO EW corrections)
  - top - from Monte Carlo simulation
    (accurate to NNLO in pQCD)
  - multijet - data-driven matrix method
- No significant deviation from SM is observed.

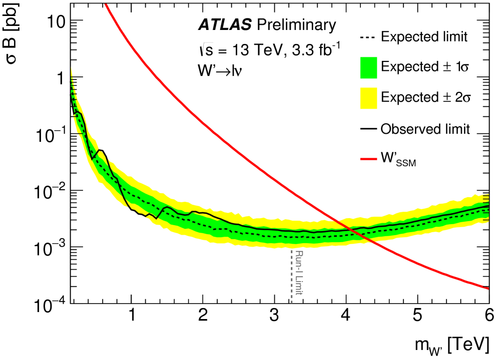
13 TeV results

Decay	$m_{W'}$ limit [TeV] Expected	Observed
$W' \to e\nu$	4.03	3.98
$W' \to \mu\nu$	3.66	3.42
$W' \to \ell\nu$	4.18	4.07

8 TeV results

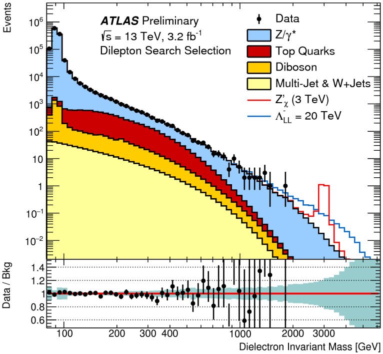
Decay	ATLAS	CMS
$W' \to \ell\nu$	3.24 TeV	3.28 TeV

ATLAS-CONF-2015-063

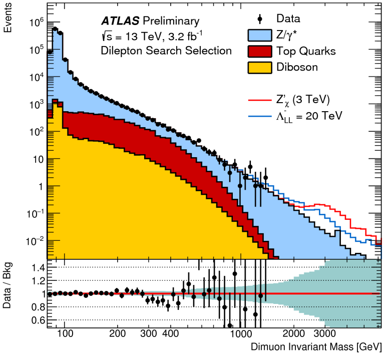


- Benchmark model: W' Sequential Standard Model (SSM)
  - Heavier copy of the SM W, same couplings
  - Branching ratio to WZ set to 0, no interference to W
- **Almost 1 TeV improvement on limits**

Di-electron



Di-muon



- At least **2 isolated leptons** with $p_T > 30$ GeV
- Search variable: di-lepton invariant mass

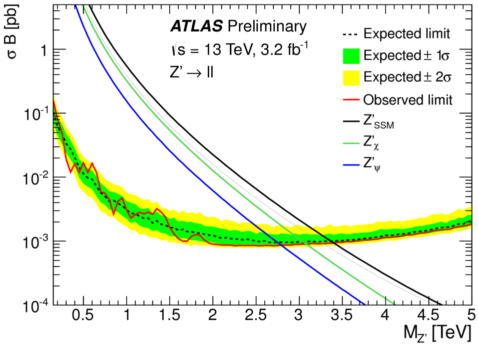
ATLAS-CONF-2015-070

- Dominant background processes:
  - Drell-Yan Z/γ - from Monte Carlo simulation (mass dependent NNLO pQCD and NLO EW corrections)
- Sums of backgrounds are rescaled to match data in the normalisation region 80 GeV $< m_{\ell\ell} <$ 120 GeV.
- No significant excess observed.

Resonant Z' models

- Benchmark SSM (same as for the W'):
  - Z' has the same couplings as SM Z
- E_6 Grand Unified Theory:
  - $E_6 \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$
  - $Z'(\theta_{E_6}) = Z'_\psi \cos\theta_{E_6} + Z'_\chi \sin\theta_{E_6}$
  - 6 commonly motivated states of Z' namely: $Z'_\psi, Z'_N, Z'_\eta, Z'_I, Z'_S, Z'_\chi$
- **400-500 GeV improvements on limits over Run 1 results**

ATLAS-CONF-2015-070

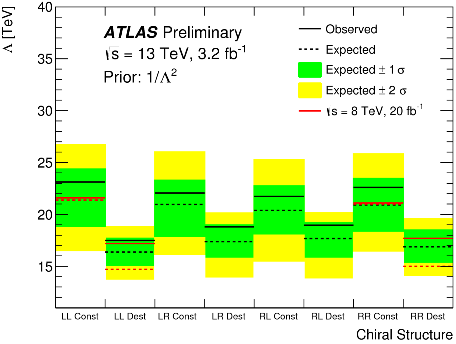


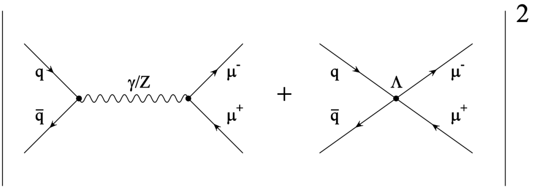
Model	Width [%]	ee [TeV]		$\mu\mu$ [TeV]		$\ell\ell$ [TeV]	
		Exp	Obs	Exp	Obs	Exp	Obs
Z'_{SSM}	3.0	3.17	3.18	2.91	2.98	3.37	3.40
Z'_χ	1.2	2.87	2.88	2.64	2.71	3.05	3.08
Z'_{S}	1.2	2.83	2.84	2.59	2.67	3.00	3.03
Z'_I	1.1	2.78	2.78	2.53	2.62	2.95	2.98
Z'_{N}	0.6	2.64	2.64	2.38	2.48	2.81	2.85
Z'_η	0.6	2.64	2.65	2.38	2.48	2.81	2.85
Z'_ψ	0.5	2.58	2.58	2.32	2.42	2.74	2.79

Non-Resonant Contact Interaction (CI)

- Quark and Lepton Compositeness:
  - Characteristic energy scale Λ corresponds to binding energy between constituents
  - η_{ij} gives chiral structure of the interaction
- Excpect non-resonant deviations in the di-lepton mass spectrum.

ATLAS-CONF-2015-070

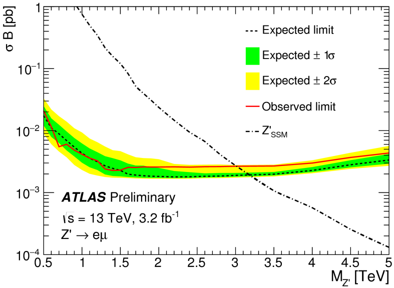


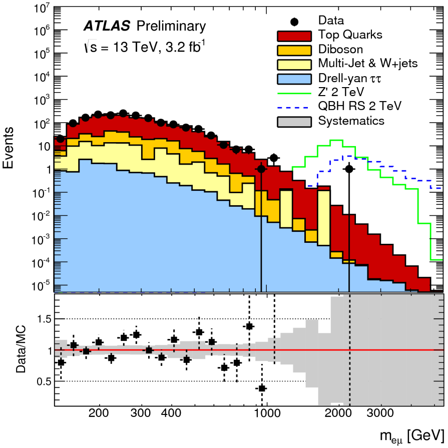


$$\sigma_{tot}(m_{ll}) = \sigma_{DY}(m_{ll}) - \eta_{ij}\frac{F_I}{\Lambda^2} + \frac{F_C}{\Lambda^4}$$

- Direct production of $e^{\pm}\mu^{\mp}$ pair is forbidden by lepton flavour conservation in SM.
- Is allowed in many extensions of the SM (Z', Quantum Black Hole (QBH) models).
- Main backgrounds - from MC simulations. Multi-Jet - data-driven matrix method.
- **0.5 TeV improvement on Z' limit.**

ATLAS-CONF-2015-072



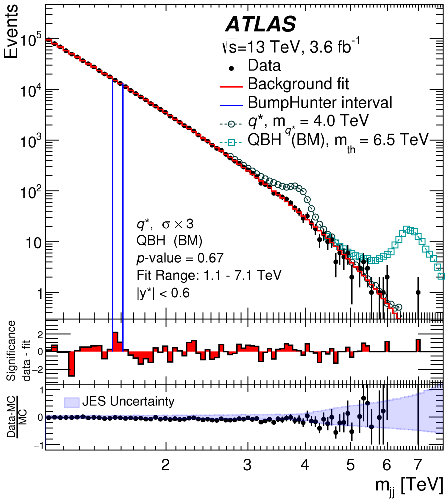


Model	Expected Limit [TeV]	Observed Limit [TeV]
Z' SSM	3.19	3.01
QBH ADD n=6	4.62	4.54
QBH RS n=1	2.56	2.44

Hadronic final states (jets)

- ✴di-jet
- ✴di-jet with b-tagging
- ✴multijet

- At least **two jets** with $p_{\mathrm{T}} > 440$ (50) GeV.
- Search variable: mass m_{jj} of the two leading jets.
- QCD predicts a smoothly falling dijet mass $\rightarrow$ model it with power law function:
  $f(z) = p_1(1-z)^{p_2} z^{p_3}$, where $z \equiv m_{jj}/\sqrt{s}$
- Look for localized excesses wrt. background model.
- Di-jet mass resolution: 2-2.5%
- No significant deviation observed.



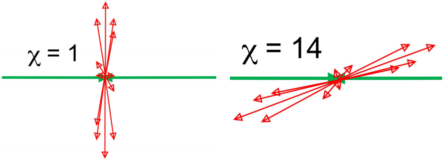
arXiv:1512.01530

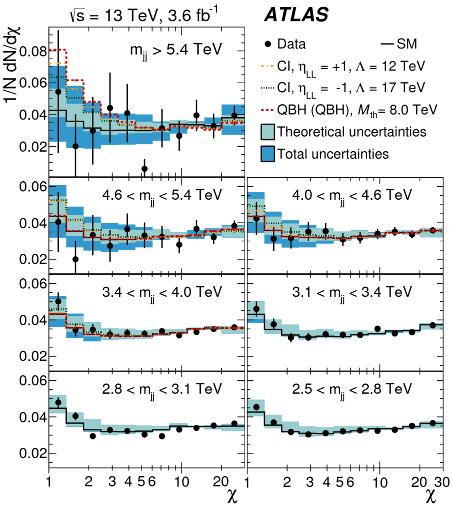
- Complementary to di-jet resonance analysis which does not have sensitivity for wide resonance.
- Search variable: invariant rapidity χ in different m_{jj} ranges.

$$y = ln\left(\frac{E + p_z}{E - p_z}\right) \rightarrow y^* = \frac{y1 - y2}{2}$$

$$\chi = e^{2|y^*|} = e^{|\Delta y|}$$

- Beyond Standard Model (BSM) signal are expected at large angles wrt. the beam $\rightarrow$ at low χ.
- No significant excess observed.
- New mass region explored: $m_{jj} > 5.4$ TeV was not reachable for 8 TeV analysis.





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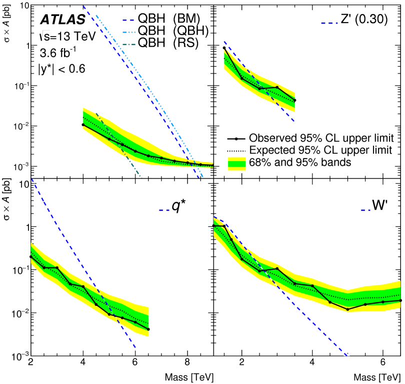
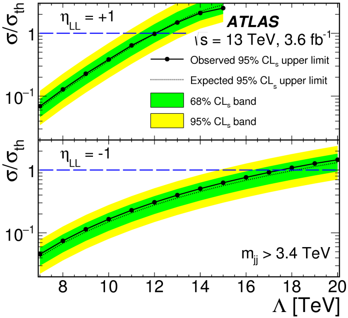
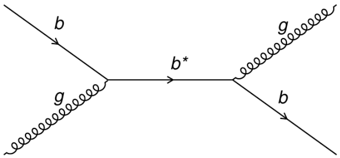


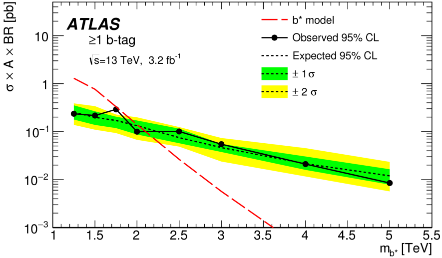


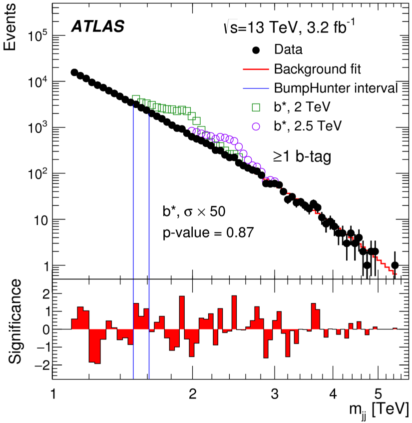
arXiv:1512.01530

Model	95% CL Exclusion limit		
	Run 1 Observed	Observed 13 TeV	Expected 13 TeV
Quantum black holes, ADD (BlackMax generator)	5.6 TeV	8.1 TeV	8.1 TeV
Quantum black holes, ADD (QBH generator)	5.7 TeV	8.3 TeV	8.3 TeV
Quantum black holes, RS (QBH generator)	–	5.3 TeV	5.1 TeV
Excited quark	4.1 TeV	5.2 TeV	4.9 TeV
W'	2.5 TeV	2.6 TeV	2.6 TeV
Contact interactions (η_{LL} =+1)	8.1 TeV	12.0 TeV	12.0 TeV
Contact interactions (η_{LL} =−1)	12.0 TeV	17.5 TeV	18.1 TeV

- Similar selection as for di-jet analysis.
- Signal regions:
  - $\geq$1 b-tagged jets.
  - 2 b-tagged jets.
- Background prediction is compatible with data.
- Excluded mass limits:
  - **b^*: 1.1-2.1 TeV**
  - **leptophobic Z': 1.1-1.5 TeV**
- No such analysis for 8 TeV period.



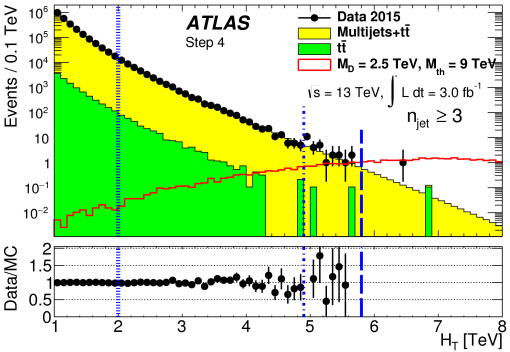


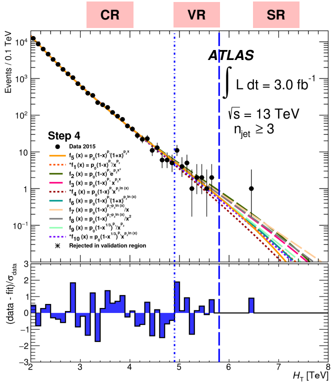


arXiv:1603.08791

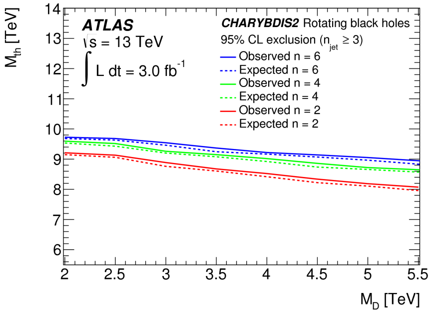
- At least **three jets** with $p_{\mathrm{T}} > 50$ GeV and $|\eta| < 2.8$
- Search variable: Scalar sum of jet transverse momenta (H_{T}) > 1 TeV
- SM background prediction - smooth fit by data (10 functions tested):
  - is done in low-H_{T} Control Region (CR)
  - is cross-checked in medium-H_{T} Validation Region (VR)
  - is used for SM backgound prediction in high-H_{T} Signal Region (SR)
- No significant excess observed.

arXiv:1512.02586

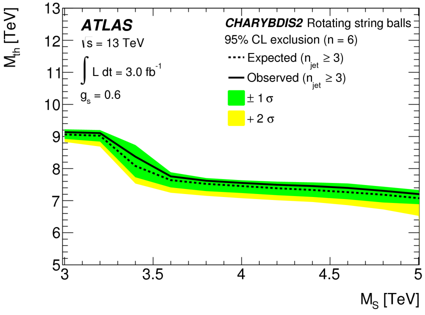




Rotating black holes model



String ball model



- Limits for rotating black holes with 2,4 and 6 extra dimensions are set as a function:
  - fundamental Planck scale (M_D)
  - mass threshold (M_{th})
- Limits for String balls with 6 extra dimensions are set as a function:
  - string scale (M_S)
  - mass threshold (M_{th})
  - string coupling (g_S)

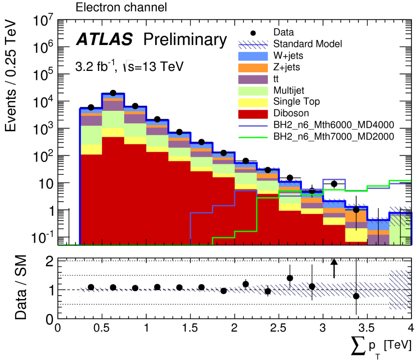
Almost 4 TeV improvement of limit in M_{th}.

arXiv:1512.02586

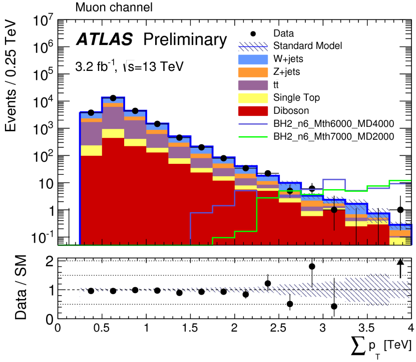
Mixed final states

- ✳ lepton and 2 jets/leptons
- ✳ 2 leptons and 2+ jets

Electron channel



Muon channel

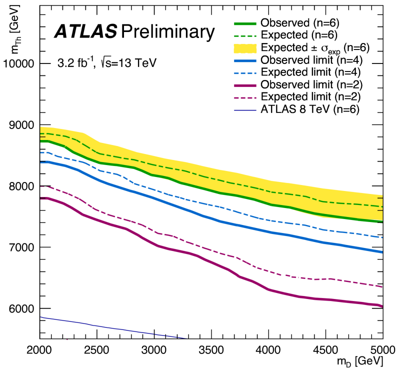


- At least **one lepton** with $p_{\mathrm{T}} > 100$ GeV.
- **Two additional objects** (leptons or jets) with $p_{\mathrm{T}} > 100$ GeV.
- Search variable: $\sum p_{\mathrm{T}}$ of all leptons/jets with $p_{\mathrm{T}} > 60$ GeV ($\sum p_{\mathrm{T}} > 2$ or 3 TeV).

ATLAS-CONF-2016-006

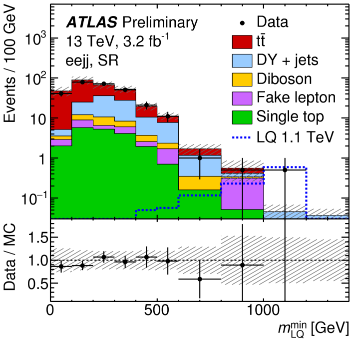
- The $t\bar{t}$, W+jets and Z+jets background normalisation are taken from simultaneous fit in background dedicated CRs.
- Validation Region: $1.5 < \sum p_{\mathrm{T}} < 2.0$ TeV.
- No significant excess observed.

- Limits for rotating black holes with 2,4 and 6 extra dimensions are set as a function:
    - fundamental Planck scale (M_D)
    - mass threshold (M_{th})
- Upper limits on the possible contribution of new physics processes in this class of final states are set at:
    - 12.1 fb for $\sum p_T > 2$ TeV
    - 3.4 fb for $\sum p_T > 3$ TeV
- **Limit in M_{th} is improved by almost 3 TeV.**

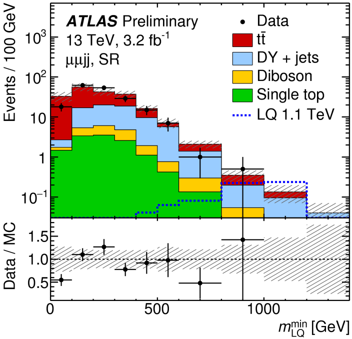


ATLAS-CONF-2016-006

Electron channel

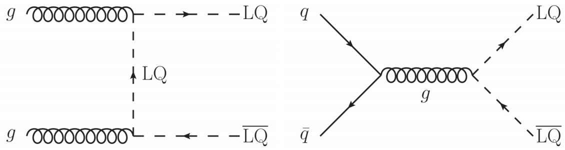


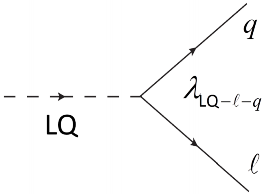
Muon channel

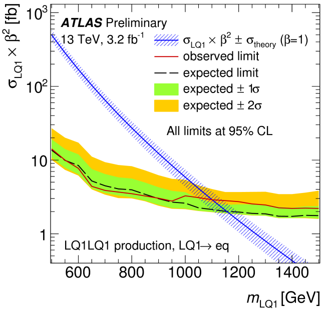


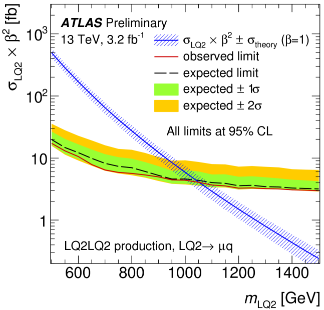
- Inclusive search for a new physics signature of lepton-jet resonances.
- **2 electrons** (**muons**) with $p_T > 30(40)$ GeV and **2+ jets** with $p_T > 50$ GeV.
- 2 lepton-jet pairs: invariant mass difference between them has to be the smallest.
- The $t\bar{t}$ and DY+jets background normalisation are taken from simultaneous fit in background CRs.
- Search variable:
  - m_{LQ}^{min} - minimum invariant mass of 2 lepton-jet pairs ($\sum p_T > 600$ GeV; $m_{\ell\ell} > 130$ GeV).

- Tested model: pair production of first- and second-generation scalar leptoquarks (mBRW model).
- Excluded LQs mass ranges (BR=1):
  - $m_{LQ1} < 1100$ **GeV;** $m_{LQ2} < 1050$ **GeV**
- Observed limit is **stronger by 50 GeV** comparing with ATLAS Run 1 result.
- Limits with different values of BR were set as well.









	Model	Limit 8 / 13 TeV	Limit improvement
Contact Interaction	CI $qqqq$	Λ: 12.0 / 17.5 TeV	5.5 TeV
	CI $qq\ell\ell$	Λ: 21.6 / 23.1 TeV	1.5 TeV
Extra dimentions	ADD QBH	M_{th} : 5.82 / 8.30 TeV	2.48 TeV
	ADD BH high $\sum p_{\mathrm{T}}$	M_{th} : 5.80 / 8.20 TeV	2.40 TeV
	ADD BH multijet	M_{th} : 5.80 / 9.55 TeV	3.75 TeV
Excited fermions	$q^* \rightarrow qg$	m_{q^*}: 4.09 / 5.20 TeV	1.11 TeV
	$b^* \rightarrow bg$	m_{b^*}: - / 2.10 TeV	- TeV
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$M_{Z'}$: 2.90 / 3.40 TeV	0.50 TeV
	SSM $Z' \rightarrow e^{\pm}\mu^{\mp}$	$M_{Z'}$: 2.50 / 3.01 TeV	0.51 TeV
	SSM $W' \rightarrow \ell\nu$	$M_{W'}$: 3.24 / 4.07 TeV	0.83 TeV
	Leptophobic $Z' \rightarrow bb$	$M_{W'}$: - / 1.5 TeV	- TeV
Leptoquarks	Scalar LQ 1st gen	m_{LQ}: 1.05 / 1.10 TeV	0.05 TeV
	Scalar LQ 2nd gen	m_{LQ}: 1.00 / 1.05 TeV	0.05 TeV

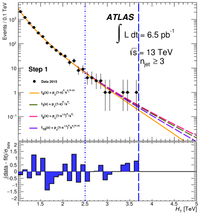
Conclusions

- ✓ Current results on searches for new physics in high-mass fermionic final states and jets have been presented.
- ✓ The sensitivity of all searches already exceeds Run 1 results and new mass regions have been explored.
- ✓ No significant excesses are observed but stronger exclusion limits are set for various models beyond the Standard Model.
- The expected ten times higher luminosity in 2016 will allow a deeper exploration of the 13 TeV regime.

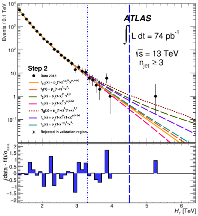
BACKUP

- At least three jets with $p_{\mathrm{T}} > 50$ GeV and $|\eta| < 2.8$
- Search variable: Scalar sum of jet transverse momenta (H_{T}) > 1 TeV
- SM background predicted by data-driven fit-based technique based on 3 regions:
  - Control region (CR) - fit background model to data (10 functions tested)
  - Validation region (VR) - cross-check that the extrapolation procedure is working properly
  - Signal region (SR) - use fit to estimate amount of the SM background
- In order to be sure that CR and VR are not contaminated by possible signal - use bootstrap approach:
  - examine data sets whose size increases by approximately a factor of ten at each step, starting with a sample whose sensitivity is slightly beyond the Run 1 limit.
  - if a search in one step sees no new physics, the possible contributions of signal to the control and validation regions of the next step are small.

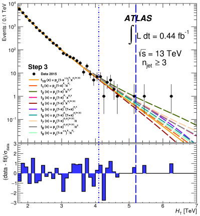
Step 1: 6.5 pb^{-1}



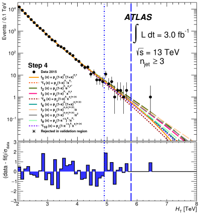
Step 2: 74 pb^{-1}



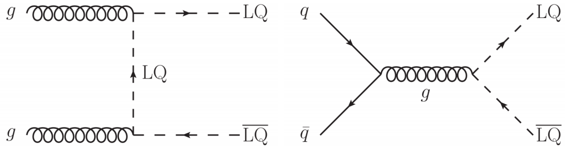
Step 3: 0.44 fb^{-1}

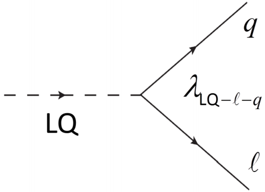


Step 4: 3.0 fb^{-1}

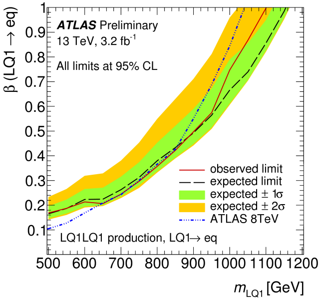


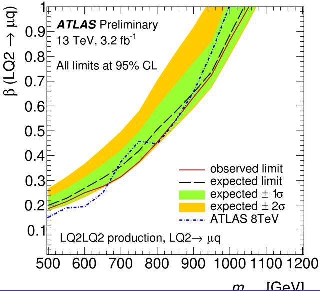
- Tested model: pair production of first- and second-generation scalar leptoquarks (mBRW model).
- Excluded LQs mass ranges (BR=1):
  - $m_{LQ1} < 1100$ GeV
  - $m_{LQ2} < 1050$ GeV
- Observed limit is **stronger by 50 GeV** comparing with ATLAS Run 1 result.





Limits for different assumptions on leptoquark BR

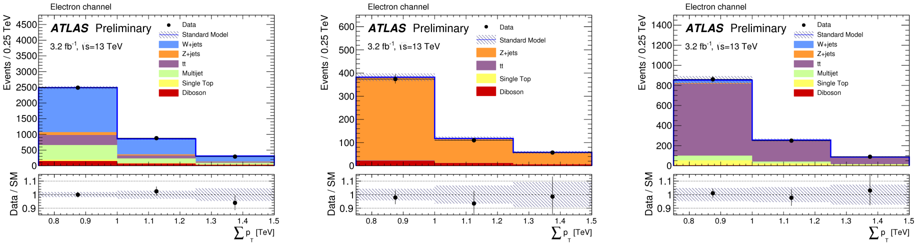




Motivation of analysis selection wrt QBH models

- Gravitational interaction couples to the energy-momentum tensor rather than gauge quantum numbers, final states are expected to be populated ”democratically”.
- It is expected that a significant fraction of final states will contain leptons.
- Lepton + 2 Jets/Leptons selection enhance the signal strength compared to the dominant background at the LHC which arises from quark and gluon scattering processes forming hadronic final states.

Normalization Control Regions

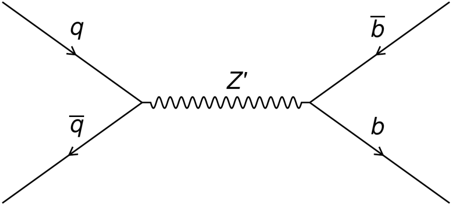


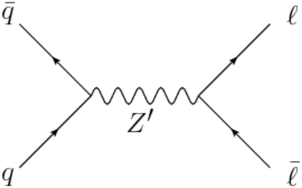
- The backgrounds predictions were adjusted by the likelihood fit.
- Scale factors:
  - W+jets: 0.81 $\pm$ 0.07
  - Z+jets: 1.01 $\pm$ 0.08
  - $t\bar{t}$: 0.95 $\pm$ 0.08

Theoretical BSM models

- ✳ W' and Z' (SSM, E6 GUT)
- ✳ Higher-dimensional QBH
- ✳ String balls
- ✳ Contact Interaction
- ✳ Excited quarks
- ✳ Leptoquarks

- **Sequential Standard Model (SSM)**
  - W' and Z' have the same couplings to fermions as the Standard Model (SM) W and Z bosons.
- **E_6 Grand Unified Theory**
  - $E_6 \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$
  - $Z'(\theta_{E_6}) = Z'_\psi \cos\theta_{E_6} + Z'_\chi \sin\theta_{E_6}$
  - 6 commonly motivated states of Z' namely: $Z'_\psi, Z'_N, Z'_\eta, Z'_I, Z'_S, Z'_\chi$
- **Leptophobic Z′**
  - Z' boson does not couple to the leptons.
  - Derived from different scenarios of the E6 GUT.

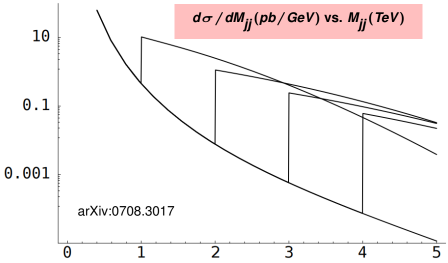




- ADD model - proposed by Arkani-Hamed, Dimopoulos and Dvali.
- RS model - proposed by Randall and Sundrum.
- fundamental Planck scale (M_D) - energy scale at which quantum effects of gravity become strong.
- mass threshold (M_{th}) - threshold where black holes start to form.
- Ideally, black holes would decay isotropically to many energetic particles, in keeping with the prediction of thermal Hawking radiation.
- Expected black hole signature is low multiplicity final states (ADD n = 6):

$$\langle N \rangle \sim \left(\frac{M_{BH}}{M_D} \right)^{8/7} \quad (1)$$

QBH signal on top of SM QCD backgound



String balls

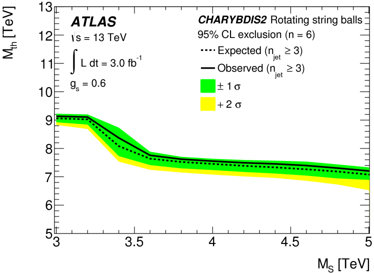
In string theory, black holes have a minimum mass below which they transition into highly excited long and jagged strings — “string balls”.

In summary, the elementary (parton) cross section for string ball/BH production is

arXiv:hep-ph/0108060

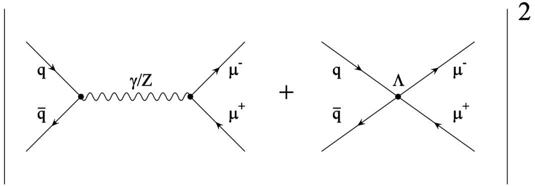
$$\sigma \sim \begin{cases} \dfrac{g_s^2 M_{SB}^2}{M_s^4} & M_s \ll M_{SB} \leq M_s/g_s\,, \\ \dfrac{1}{M_s^2} & M_s/g_s < M_{SB} \leq M_s/g_s^2\,, \\ \dfrac{1}{M_P^2}\left(\dfrac{M_{BH}}{M_P}\right)^{\frac{2}{n+1}} & M_s/g_s^2 < M_{BH}\,. \end{cases} \qquad (2)$$

M_{SB} (M_{BH}) is the mass of the string ball (black hole), and we have used $\alpha' = M_s^{-2}$.
The first two mass ranges lead to string balls, the third to black holes.



Non-Resonant Contact Interaction (CI)

- Quark and Lepton Compositeness:
  - Characteristic energy scale Λ corresponds to binding energy between constituents
  - η_{ij} gives chiral structure of the interaction
- Excpect non-resonant deviations in the di-lepton mass spectrum.

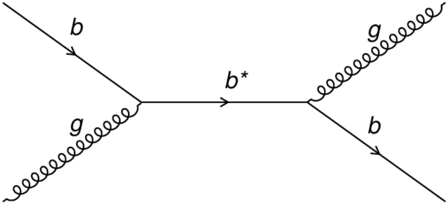


$$\sigma_{tot}(m_{ll}) = \sigma_{DY}(m_{ll}) - \eta_{ij}\frac{F_I}{\Lambda^2} + \frac{F_C}{\Lambda^4}$$

CI Lagrangian is used to describe a new interaction or compositeness in the process $q\overline{q} \to \ell^+\ell^-$:

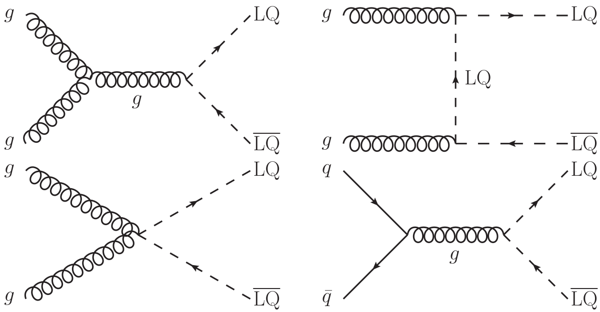
$$\mathcal{L} = \frac{g^2}{\Lambda^2}[\eta_{\rm LL}(\overline{q}_{\rm L}\gamma_\mu q_{\rm L})(\overline{\ell}_{\rm L}\gamma^\mu\ell_{\rm L}) + \eta_{\rm RR}(\overline{q}_{\rm R}\gamma_\mu q_{\rm R})(\overline{\ell}_{\rm R}\gamma^\mu\ell_{\rm R}) \quad (3)$$
$$+ \eta_{\rm LR}(\overline{q}_{\rm L}\gamma_\mu q_{\rm L})(\overline{\ell}_{\rm R}\gamma^\mu\ell_{\rm R}) + \eta_{\rm RL}(\overline{q}_{\rm R}\gamma_\mu q_{\rm R})(\overline{\ell}_{\rm L}\gamma^\mu\ell_{\rm L})]$$

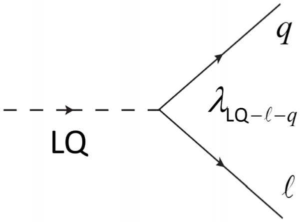
- Excited quarks are a consequence of quark compositeness models that were proposed to explain the generational structure and mass hierarchy of quarks.



Leptoquarks

- LQs possess non-zero baryon and lepton numbers;
  their existence would provide a connection between quarks and leptons.
- LQs carry a colour-triplet charge and a fractional electric charge.
- The signal benchmark model in the analysis is the minimal Buchmüller–Rückl–Wyler model (mBRW).
  - Lepton number and baryon number are separately conserved to prevent fast proton decay.
  - The LQ couplings are also considered to be purely chiral.
  - LQs belong to three generations (first, second and third) which interact only with lepton–quark pairs within the same generation.
  - Lepton-flavour violation is suppressed.





Other materials

- ✶Summary plot of Exotics searches.
- ✶QCD background estimation

ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2016

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	M_D 6.86 TeV	$n = 2$	Preliminary
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\rightarrow \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	3.6	M_{th} 8.3 TeV	$n = 6$	1512.01530
	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	ATLAS-CONF-2016-006
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	1504.05511
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	1 e, μ	1 J	Yes	3.2	G_{KK} mass 1.06 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2015-075
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	–	4 b	–	3.2	G_{KK} mass 475-785 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-017
	Bulk RS $g_{KK} \rightarrow tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \rightarrow tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	3.2	Z' mass 3.4 TeV		ATLAS-CONF-2015-070
	SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \rightarrow bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		Preliminary
	SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	3.2	W' mass 4.07 TeV		ATLAS-CONF-2015-063
	HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A	0 e, μ	1 J	Yes	3.2	W' mass 1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-068
	HVT $W' \rightarrow WZ \rightarrow qqqq$ model A	–	2 J	–	3.2	W' mass 1.38-1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-073
	HVT $W' \rightarrow WH \rightarrow \ell\nu bb$ model B	1 e, μ	1-2 b, 1-0 j	Yes	3.2	W' mass 1.62 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	HVT $Z' \rightarrow ZH \rightarrow \nu\nu bb$ model B	0 e, μ	1-2 b, 1-0 j	Yes	3.2	Z' mass 1.76 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	LRSM $W'_R \rightarrow tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \rightarrow tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	3.6	Λ 17.5 TeV	$\eta_{LL} = -1$	1512.01530
	CI $qq\ell\ell$	2 e, μ	–	–	3.2	Λ 23.1 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2015-070
	CI $uutt$	2 e, μ (SS)	≥ 1 b, 1-4 j	Yes	20.3	Λ 4.3 TeV	$\lvert C_{LL}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	≥ 1 j	Yes	3.2	m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 140$ GeV	Preliminary
	Axial-vector mediator (Dirac DM)	0 e, μ, 1 γ	1 j	Yes	3.2	m_A 650 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 10$ GeV	Preliminary
	$ZZ_{\chi\chi}$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.07 TeV	$\beta = 1$	Preliminary
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.03 TeV	$\beta = 1$	Preliminary
	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 $TT \rightarrow Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \rightarrow Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \rightarrow Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \rightarrow Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \rightarrow WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
	$T_{5/3} \rightarrow Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		1503.05425
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	–	3.2	q^* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \rightarrow qg$	–	2 j	–	3.6	q^* mass 5.2 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.01530
	Excited quark $b^* \rightarrow bg$	–	1 b, 1 j	–	3.2	b^* mass 2.1 TeV		Preliminary
	Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	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	LSTC $a_T \rightarrow W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	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 $H^{\pm\pm} \rightarrow \ell\ell$	2 e, μ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\tau$)=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, $\lvert g\rvert = 1 g_D$, spin 1/2	1509.08059

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

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

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

QCD background estimation

- QCD background is evaluated by using data-driven method (matrix method) since MC is not so reliable.
- Matrix method based on different probabilities of real and fake leptons for passing "tight" and "loose" selection.

Measureable quantities
- T: passes tight selection
- L: passes "loose" selection

Truth quantities
- R: real lepton
- F: fake lepton

$$\begin{pmatrix} N_T \\ N_L \end{pmatrix} = \begin{pmatrix} \epsilon_R & \epsilon_F \\ 1-\epsilon_R & 1-\epsilon_F \end{pmatrix} \begin{pmatrix} N_R \\ N_F \end{pmatrix}$$

- Efficiency of real leptons: $\varepsilon_R = N^{real}(tight)/N^{real}(loose)$
- Efficiency of fake leptons: $\varepsilon_F = N^{fake}(tight)/N^{fake}(loose)$

Number of fake leptons coming from QCD background can be expressed as:

$$\epsilon_F N_F = \frac{\epsilon_F}{\epsilon_R - \epsilon_F} (\epsilon_R (N_L + N_T) - N_T)$$

Tight selection = Signal selection
"Loose" selection:

- Electron: Signal selection wo isolation cut and looser electron ID
- Muon: Signal selection wo isolation cut

Fake Efficiencies are calculated by using jet enriched control region:

- No Z Candidate ($|m_{ll} - m_Z| > 20$ GeV)
- Inverted E_T^{miss} cut
- At least one jet with $p_T > 40$ GeV