Search for New Phenomena in the Dilepton Final State Using Proton-Proton Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

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Introduction

- Search for new physics in high mass dielectron and dimuon final states in ATLAS.
- 36.1 fb^{-1} at $\sqrt{s} = 13$ TeV (2015 and 2016).
- *Resonant* and *non-resonant* phenomena.

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Search for new high-mass phenomena in the dilepton final state using 36 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS EXPERIMENT
The ATLAS collaboration
E-mail: atlas.publications@cern.ch

ABSTRACT: A search is conducted for new resonant and non-resonant high-mass phenomena in dielectron and dimuon final states. The search uses 36.1 fb^{-1} of proton-proton collision data, collected at $\sqrt{s} = 13$ TeV by the ATLAS experiment at the LHC in 2015 and 2016. No significant deviation from the Standard Model prediction is observed. Upper limits at 95% credibility level are set on the cross-section times branching ratio for resonances decaying into dileptons, which are converted to lower limits on the resonance mass, up to 4.1 TeV for the E$_6$-motivated Z'_χ. Lower limits on the $qq\ell\ell$ contact interaction scale are set between 2.4 TeV and 40 TeV, depending on the model.

KEYWORDS: Beyond Standard Model, Hadron-Hadron scattering (experiments)

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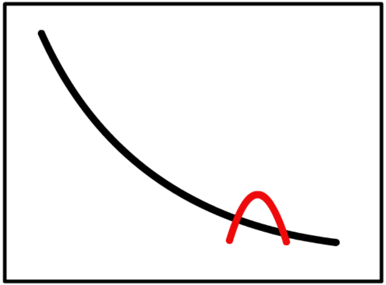
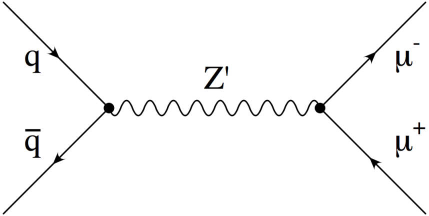
Theoretical Motivation - Resonant

- Additional spin-1 neutral gauge boson, often known as *Z'*.
- Predicted by GUT models based on the E_6 gauge group:

$$E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$$

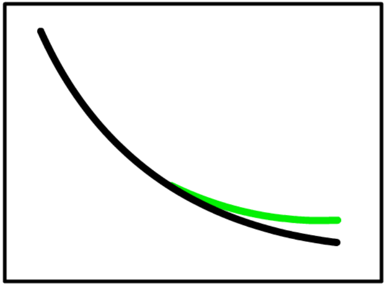
- Gives two new $U(1)$ gauge fields.
- Would be observed as a *narrow resonance* in the dilepton invariant mass spectrum.
- Sequential SM benchmark is an additional heavy boson with the same coupling to fermions as the SM Z.

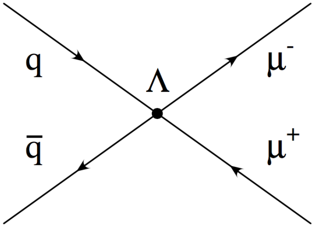




Theoretical Motivation - Non-Resonant

- Contact interactions.
- Probes lepton and quark compositeness.
- Would be observed as a *broad excess* in the dilepton invariant mass spectrum.





General Analysis Strategy

- Look for events with two isolated electrons or muons.
- Reconstruct the dilepton invariant mass m_{ll}.
- Look for divergence from SM predicted m_{ll} spectrum in the form of narrow resonances or broad excesses.
- If no such discrepancy is found, set limits on BSM model parameters.

Selection Criteria

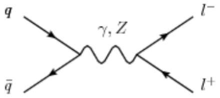
- Event Level Selection:
  - GRL & clean events.
  - At least two muons found.
- Lepton Level Selection:
  - $p_T > 30$ GeV.
  - Isolation and identification criteria.
  - $\eta < 2.5$ and exclude "crack" region between barrel and end-caps.
- High Level Selection:
  - $m_{ll} > 80$ GeV.

Background Estimation

- Background mainly modelled by MC.
- Jets can be misidentified as leptons. Such "fake" leptons are not modelled by MC. They are estimated from data using the so-called *matrix method*.
- Fakes mainly stem from multi-jet and W+jets production.
- Fakes are assumed to be negligible in the muon channel.
- DY Background us smoothed between 120 GeV and 1 TeV. This is done to remove statistical fluctuations.

Background Estimation - MC

Drell-Yan Production



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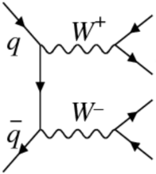
Order	NLO
Shower	Pythia 8.186
PDF	CT10
Samples	Mass-Binned

Diboson Production



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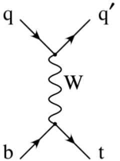
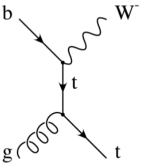
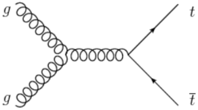
Order	NLO
Shower	Sherpa 2.1.1
PDF	CT10
Samples	Mass-Binned

Top Production



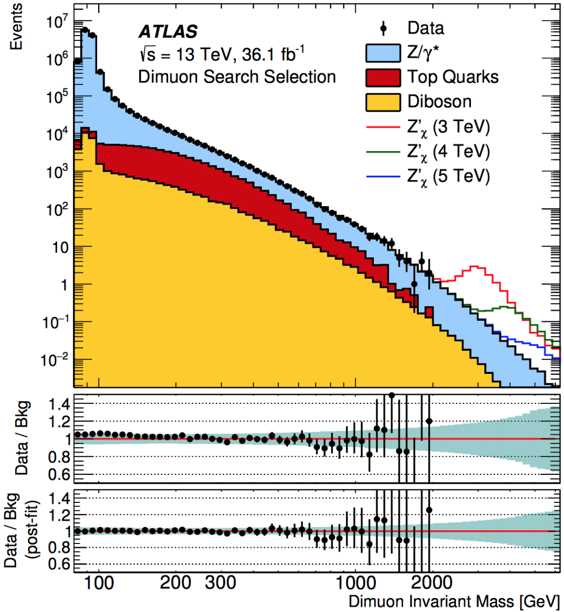
Generator	Powheg v2
Order	NLO
Shower	Pythia 6.428
PDF	CT10
Samples	Unbinned

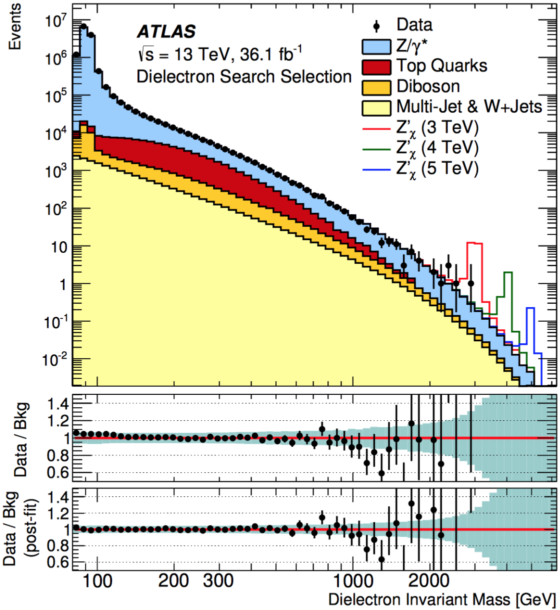




Made by Sebastien Rettie.

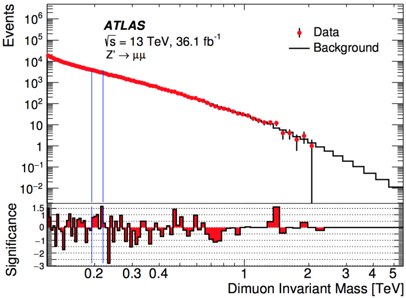
Invariant Mass Distributions

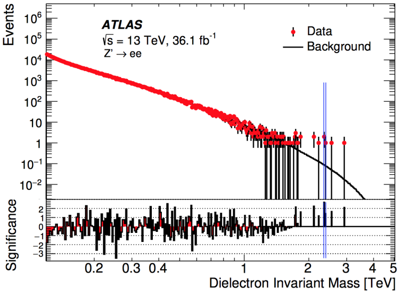




Statistical Analysis - Bumphunter

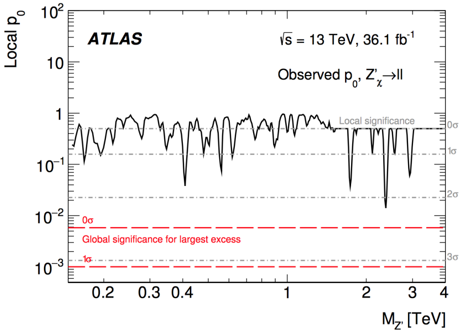
- (Quite) model independent.
- Search consecutive bins for excesses across the whole invariant mass spectrum.
- Window width from 2 bins to half full mass range.
- p-value is calculated for each interval giving the probability of observing as many, or more events, given the SM prediction.
- Background prediction is obtained from marginalisation of nuisance parameters.
- Results: Global p-values 0.71 (ee) and 0.94 ($\mu\mu$). Not significant.





Statistical Analysis - Log Likelihood Test

- Complimentary to the more general bumphunter method.
- Use a signal template based on the Z'_χ model.
- Signal shape is a Breit-Wigner distribution (physics) convoluted with a Crystal Ball distribution (resolution).
- Bin width is chosen to match electron and muon resolution.
- Background prediction is again obtained from marginalisation of nuisance parameters.
- Results: Highest local significance 2.5 σ at 2.37 TeV. Not globally significant.

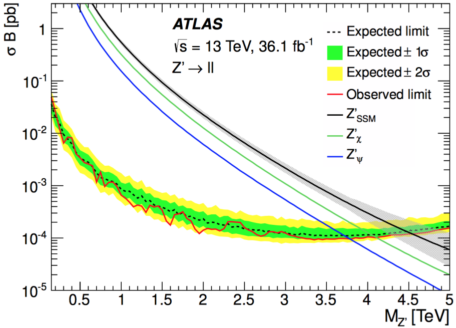


$$q_0 = \begin{cases} 2\ln\left[\frac{\mathcal{L}(\mathrm{data}|0,\hat{\theta}_0)}{\mathcal{L}(\mathrm{data}|\hat{\mu},\hat{\theta})}\right] & \text{for } \hat{\mu} < 0 \\ -2\ln\left[\frac{\mathcal{L}(\mathrm{data}|0,\hat{\theta}_0)}{\mathcal{L}(\mathrm{data}|\hat{\mu},\hat{\theta})}\right] & \text{for } \hat{\mu} \geqslant 0 \end{cases}$$

$$p_0 = P(q_0 > q_0^{obs} | bgr - only)$$
$$Z = \sqrt{q_0}$$

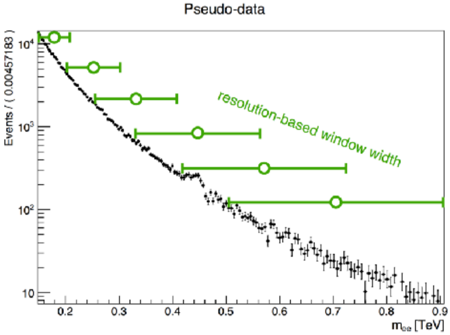
Limits

Model	Width [%]	θ_{E_6} [rad]	Lower limits on $M_{Z'}$ [TeV]					
			ee		$\mu\mu$		$\ell\ell$	
			Obs	Exp	Obs	Exp	Obs	Exp
Z'_{SSM}	3.0	-	4.3	4.3	4.0	3.9	4.5	4.5
Z'_{χ}	1.2	$0.50\,\pi$	3.9	3.9	3.6	3.6	4.1	4.0
Z'_{S}	1.2	$0.63\,\pi$	3.9	3.8	3.6	3.5	4.0	4.0
Z'_{I}	1.1	$0.71\,\pi$	3.8	3.8	3.5	3.4	4.0	3.9
Z'_{η}	0.6	$0.21\,\pi$	3.7	3.7	3.4	3.3	3.9	3.8
Z'_{N}	0.6	$-0.08\,\pi$	3.6	3.6	3.4	3.3	3.8	3.8
Z'_{ψ}	0.5	$0\,\pi$	3.6	3.6	3.3	3.2	3.8	3.7



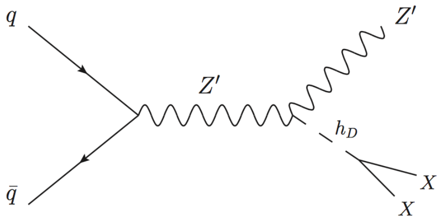
New Plans - Sliding Window Fit

- MC production cannot keep up with data taking. Statistical uncertainty in MC is getting problematically high compared to data.
- We have decided to move away from MC templates to a data driven approach.
- Rather than fitting the whole invariant mass we use a sliding window technique.



New Plans - Exclusive Searches

- Previously only the fully inclusive channel. No selection on missing energy or jets activity.
- We now want to consider some more exclusive channels as well.
- Example: Dilepton + MET
- DM interpretation arXiv:1504.01386



Summary and Conclusion

- Search for new physics in dilepton channel was performed using full 2015 + 2016 ATLAS data.
- No deviation from SM predictions.
- New limits on various Z' and CI models.
- 4.5 TeV for the Z'_{SSM}, 4.1 TeV for the Z'_{χ}.
- Stricter limits than previous $\sqrt{s} = 13$ TeV searches using only 2015 data by as much as 700 GeV.
- New analysis of full run 2 dataset is underway with a new analysis strategy.

Backup

Full Selection Criteria

Electron Selection	Muon Selection
Event Level Selection	
GRL	
Event Cleaning	
At least two electrons found	At least two combined muons found
Trigger: 2e17_lhloose	Trigger: mu26_imedium(2015)/mu26_ivarmedium(2016) OR mu50
Lepton Level Selection	
$p_T > 30$ GeV	
Require opposite charge of the two leptons	
$\lvert z_0 * \sin\theta \rvert < 0.5$ mm	
Good Object Quality	
$\eta < 2.47$ and exclude crack region	$\eta < 2.5$
d_0 significance < 5	d_0 significance < 3
Isolation: Loose	Isolation: LooseTrackOnly
Identification: Medium	Bad Muon Veto
High Level Selection	
$m_{ll} > 80$ GeV	

Background Estimation - Matrix Method

- Measure probabilities that a jet or an electron satisfy both the nominal and loosened electron identification criteria.
- Calculate probabilities r and f of electrons and jets being identified as electrons.
- System of equation can be constructed, giving the contribution from fakes.
- Subscripts L and T stands for loose and nominal identification requirements.
- Subscripts R and F stands for real and fake electrons.

$$\begin{pmatrix} N_{\mathrm{TT}} \\ N_{\mathrm{TL}} \\ N_{\mathrm{LT}} \\ N_{\mathrm{LL}} \end{pmatrix} = \begin{pmatrix} r^2 & rf & fr & f^2 \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)^2 & (1-r)(1-f) & (1-f)(1-r) & (1-f)^2 \end{pmatrix} \begin{pmatrix} N_{\mathrm{RR}} \\ N_{\mathrm{RF}} \\ N_{\mathrm{FR}} \\ N_{\mathrm{FF}} \end{pmatrix}$$

$$N^{\text{Multi-jet \& W+jets}} = rf(N_{\mathrm{RF}} + N_{\mathrm{FR}}) + f^2 N_{\mathrm{FF}}$$

Systematic Uncertainties

Source	Dielectron channel [%]		Dimuon channel [%]	
	Signal	Background	Signal	Background
Luminosity	3.2 (3.2)	3.2 (3.2)	3.2 (3.2)	3.2 (3.2)
MC statistical	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)
Beam energy	2.0 (4.1)	2.0 (4.1)	1.9 (3.1)	1.9 (3.1)
Pile-up effects	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)
DY PDF choice	-	<1.0 (8.4)	-	<1.0 (1.9)
DY PDF variation	-	8.7 (19)	-	7.7 (13)
DY PDF scales	-	1.0 (2.0)	-	<1.0 (1.5)
DY α_S	-	1.6 (2.7)	-	1.4 (2.2)
DY EW corrections	-	2.4 (5.5)	-	2.1 (3.9)
DY γ-induced corrections	-	3.4 (7.6)	-	3.0 (5.4)
Top quarks theoretical	-	<1.0 (<1.0)	-	<1.0 (<1.0)
Dibosons theoretical	-	<1.0 (<1.0)	-	<1.0 (<1.0)
Reconstruction efficiency	<1.0 (<1.0)	<1.0 (<1.0)	10 (17)	10 (17)
Isolation efficiency	9.1 (9.7)	9.1 (9.7)	1.8 (2.0)	1.8 (2.0)
Trigger efficiency	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)
Identification efficiency	2.6 (2.4)	2.6 (2.4)	-	-
Lepton energy scale	<1.0 (<1.0)	4.1 (6.1)	<1.0 (<1.0)	<1.0 (<1.0)
Lepton energy resolution	<1.0 (<1.0)	<1.0 (<1.0)	2.7 (2.7)	<1.0 (6.7)
Multi-jet & W+jets	-	10 (129)	-	-
Total	10 (11)	18 (132)	11 (18)	14 (24)