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Searches for new phenomena in high-pT lepton final states using the ATLAS detector

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Introduction

- Many Beyond the Standard Model (BSM) theories predict the existence of new vector gauge bosons, generically called W′ and Z′ that can decay to leptons.
    - e.g. Sequential Standard Model and GUT-inspired models.
- **Leptonic signatures** have experimental advantages:
    - Easy to trigger and reconstruct, with high selection efficiencies
    - SM backgrounds are low and/or well-modelled and understood
- Therefore, leptonic signatures also provide a testing ground for other exotic phenomenology such as quantum black holes in theories with extra dimensions and contact interactions in compositeness models.

Overview of the 13 TeV ATLAS results and interpretations

- One lepton:
  - W′ search in the context of the Sequential Standard Model (SSM)
- Two leptons:
  - Lepton flavour conserving:
    - SSM and GUT-models Z′ searches
    - Non-resonant searches for llqq contact interactions
  - Lepton flavour violating:
    - SSM Z′ search
    - Quantum black hole (QBH) searches for the Arkani-Dimopoulos-Dvali (n=6) and Randall-Sundrum (n=1) models

W'→eν,μν

ATLAS-CONF-2015-063

Z′→ee,μμ

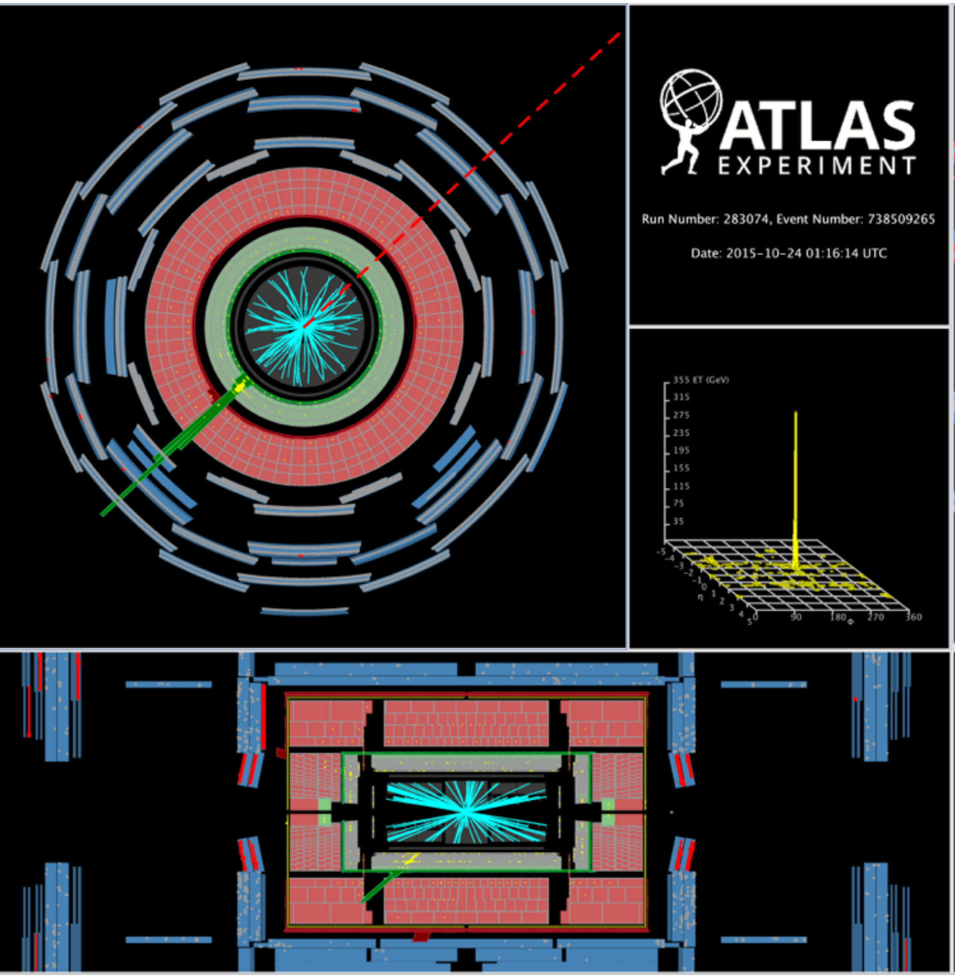
ATLAS-CONF-2015-070

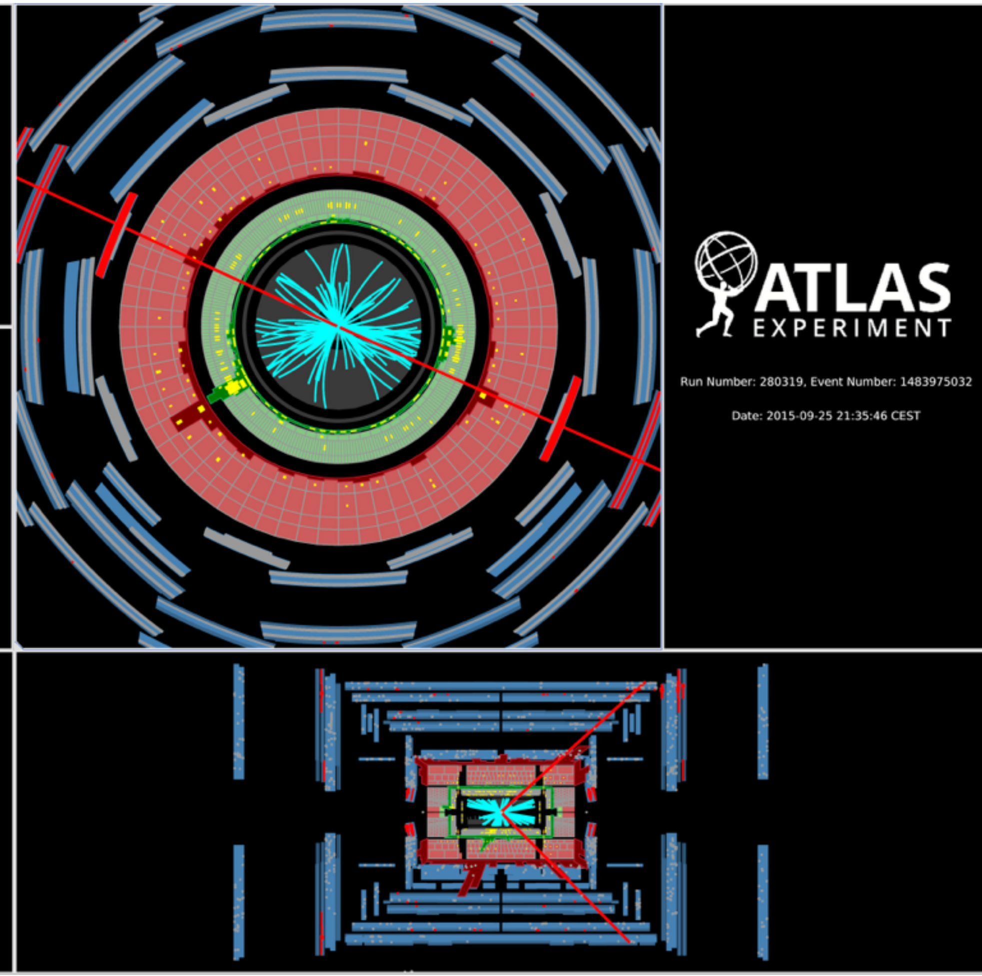
Z′/QBH→eμ

ATLAS-CONF-2015-072

Not covered in this talk, TeV-scale black holes, see: ATLAS-CONF-2016-006

Event displays





p_T^{el} = 1.01 TeV
E_T^{miss} = 0.94 TeV
m_T = 1.95 TeV

p_T^1 = 712 GeV
p_T^2 = 676 GeV
$m_{\mu\mu}$ = 1390 GeV

Event Selection:

- Single electron/muon trigger (dielectron for Z′)
- W′: single lepton plus missing transverse energy (E_T^{miss})
- Z′: ee/μμ or eμ, with veto on additional leptons
    - Opposite charge requirement for μμ

Discriminant variables

- Di-lepton invariant mass is used as discriminant for both narrow resonances and non-resonant searches, in the two lepton case: **M_{ee} / $M_{\mu\mu}$ / $M_{e\mu}$**
- For W′, **transverse mass distribution**:

$$m_T = \sqrt{2p_T^{\ell}p_T^{miss}(1 - \cos\phi_{\ell\nu})}$$

General background estimation approach

- Backgrounds with **real leptons** are estimated with MC simulation: Drell-Yan, single and top-pair, diboson (see more info on backup).
    - Modelling of DY process with mass-dependent K-factors (NNLO in QCD and NLO in EW)
- **Fake leptons** due to hadronic jets in multi-jet or W+jets processes: evaluated with data-driven methods.
- For the two lepton case: background normalizations extracted from Z peak region (80-120 GeV)

Experimental:

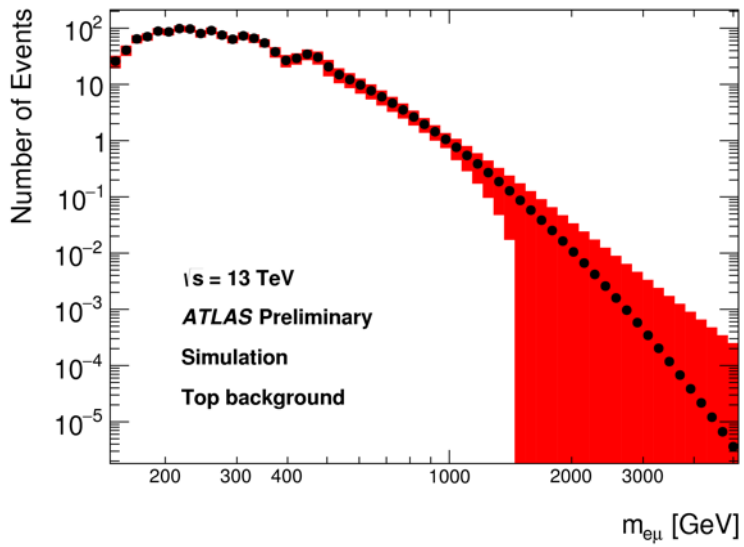
- Lepton trigger efficiency
- Lepton reconstruction / identification / isolation efficiency
- Lepton energy scale and resolution
  - » e.g. muon momentum resolution at TeV scale.
- Missing transverse energy scale / resolution
- Jet scale / resolution
- Luminosity

Theoretical:

Parton distribution functions, α_S scale, higher-order EW corrections.

Background-specific:

- Data-driven estimation of instrumental backgrounds.
- Extrapolations to high masses due to low MC statistics.



W′ searches (eν,μν final states): transverse mass distribution

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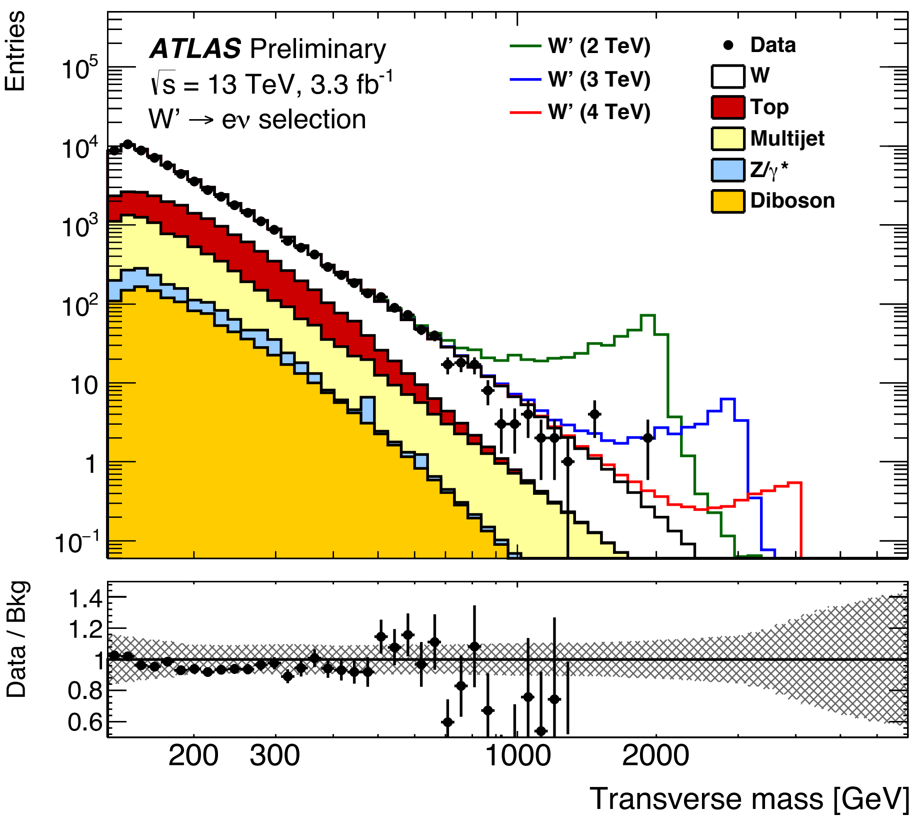
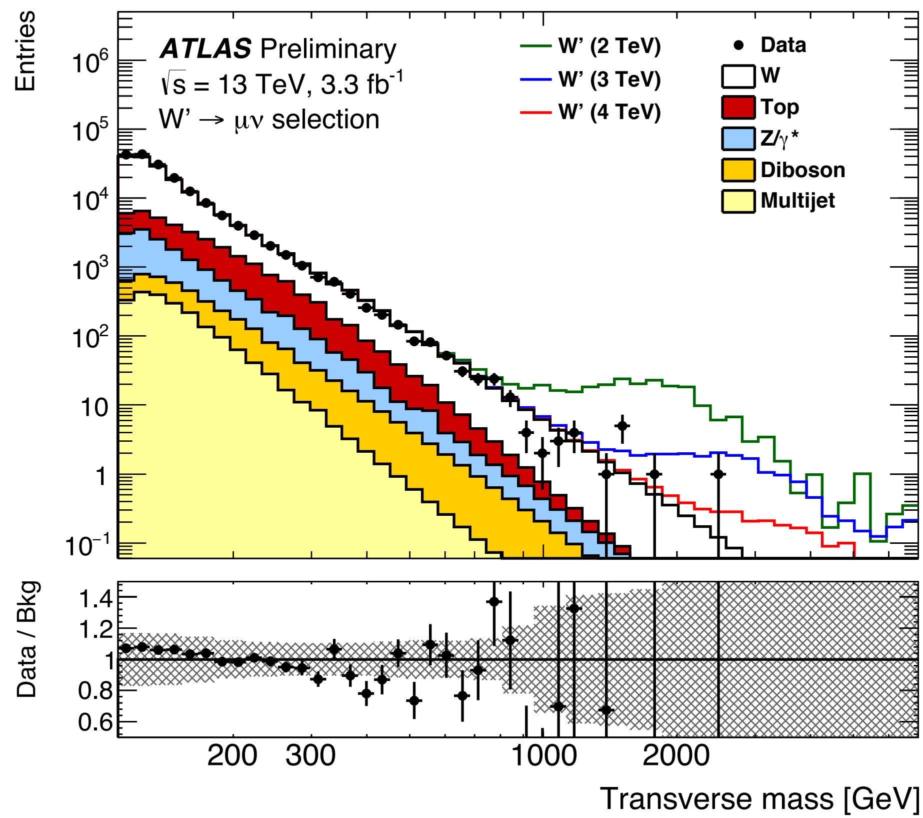
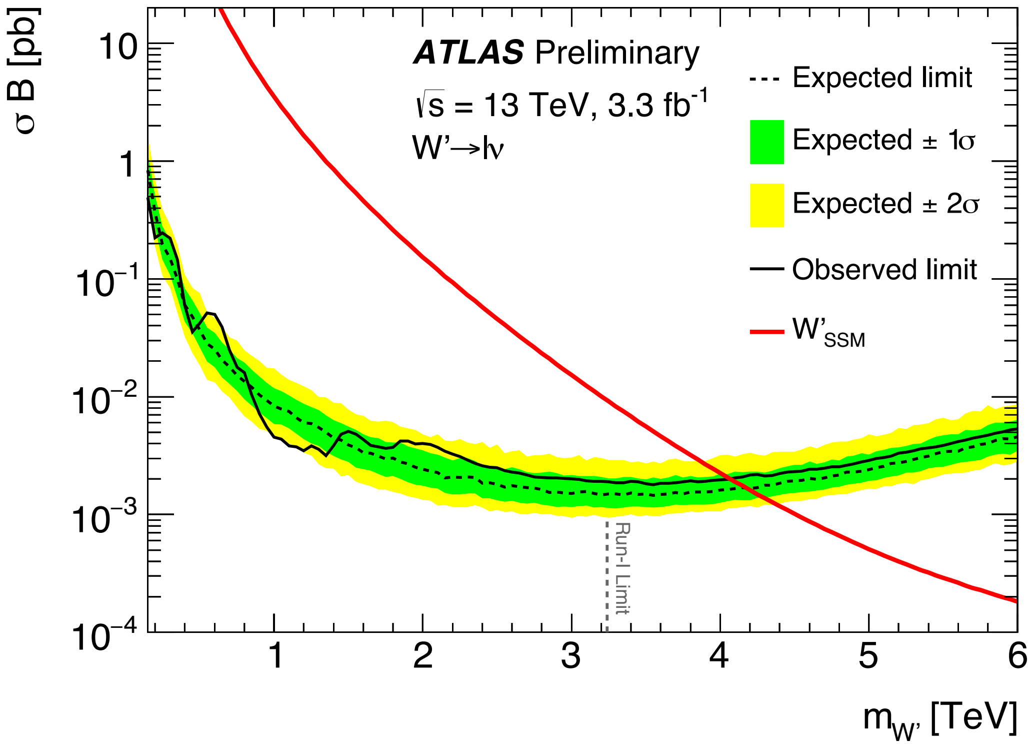
SSM: Additional U(1) gauge symmetry.
W′ and Z′ couplings to fermions are the same as those of the SM W and Z bosons.





- Charged-current DY dominates over entire m_T range (90% for m_T > 1 TeV).
- Multijet production in electron channel, similar (and small) contributions from other processes.

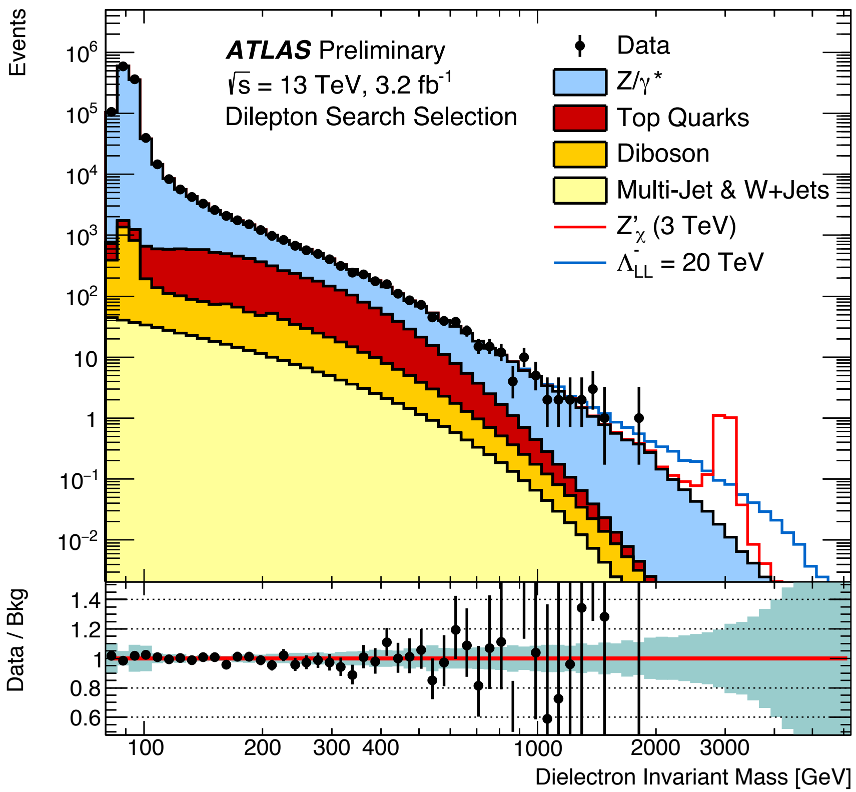


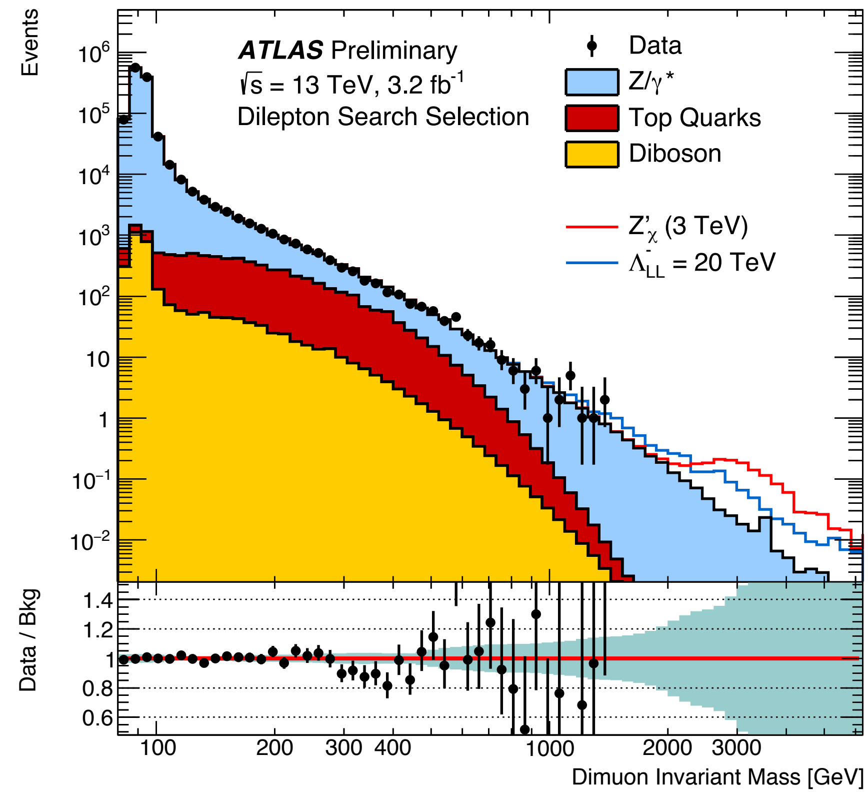
Interpretation with benchmark W'_{SSM} model

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

- Higher sensitivity from the electron channel due to larger A x ε and better energy resolution.
- For both channels, all observed limits are within 2σ of expected limit.
    - Exception: electron channel @ m_T = 600 GeV (local: 2.6σ, global: 1.0σ)
- Improvement of more than 800 GeV compared to ATLAS Run-I result.

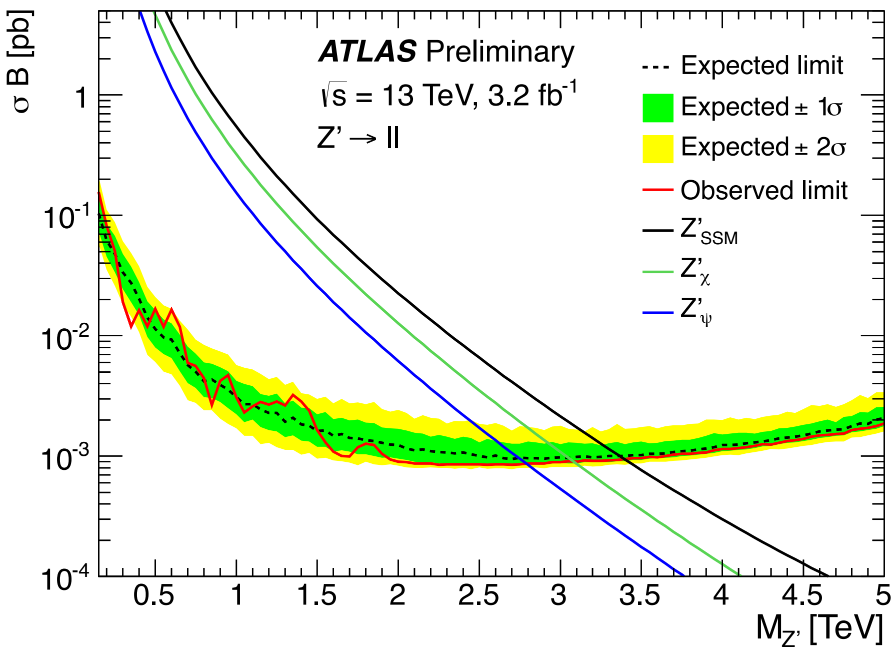
Searches with ee,μμ final states: dilepton mass distribution





- Top and diboson processes are extrapolated to high di-lepton masses ($m_{\ell\ell} > 400$ GeV).
- Background normalizations (for MC-based estimations) are derived from data in the region 80 GeV < $m_{\ell\ell}$ < 120 GeV.

Limits on Z′ production



- Observed lower mass limits (electron and muon channels combined):
  - 3.40 TeV for Z'_{SSM}
  - 3.08 TeV for Z'_{χ}
  - 2.79 TeV for Z'_{ψ}
- Improvement of 500 GeV compared to ATLAS Run-I result for Z'_{SSM}.

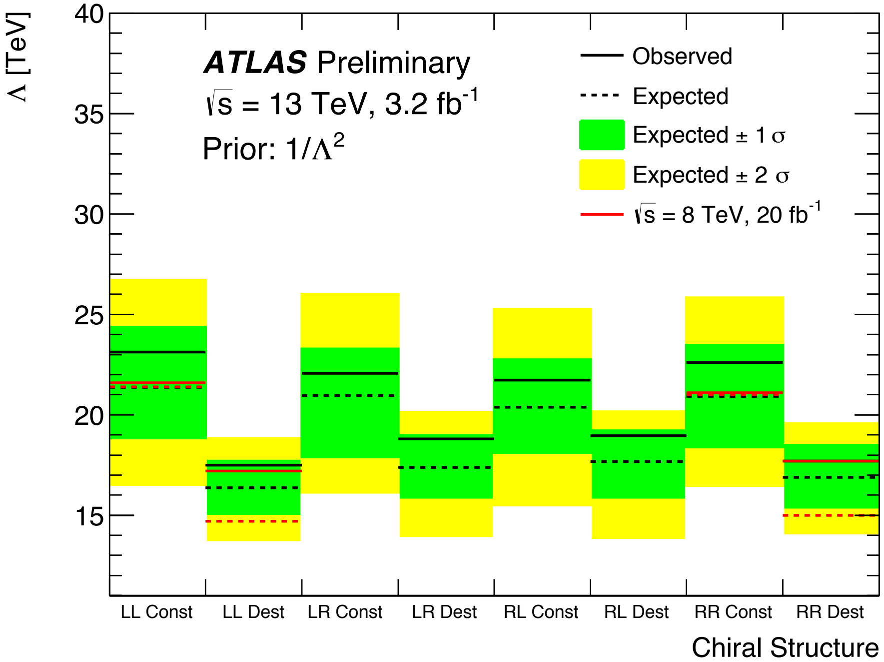
Interpretation with benchmark Z'_{SSM} model and GUT-inspired E_6 models

E_6 gauge group can include two neutral gauge bosons that mix with an angle θ_{E6}:

$$Z'(\theta_{E6}) = Z'_{\psi} \cos\theta_{E6} + Z'_{\chi} \sin\theta_{E6}$$

Six common cases are investigated: Z'_N, Z'_{η}, Z'_{χ}, Z'_{ψ}, Z'_S, Z'_I

Limits on contact interaction Λ scale



- Lower limits on the energy scale Λ range between 16.4 TeV and 23.1 TeV for the various llqq coupling scenarios.

Compositeness models for quarks and leptons predicting contact interactions (CI) with a characteristic scale Λ that produce a non-resonant effect.
Different chiral structures are investigated, with constructive and destructive interference with the SM DY process.

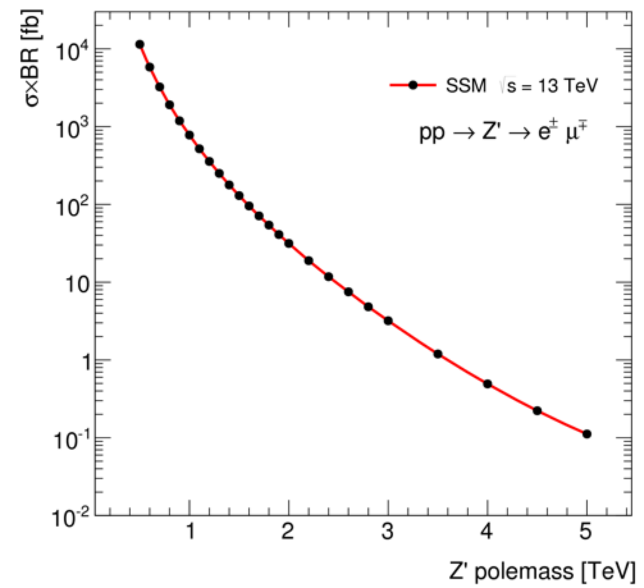
Searches with eμ final states

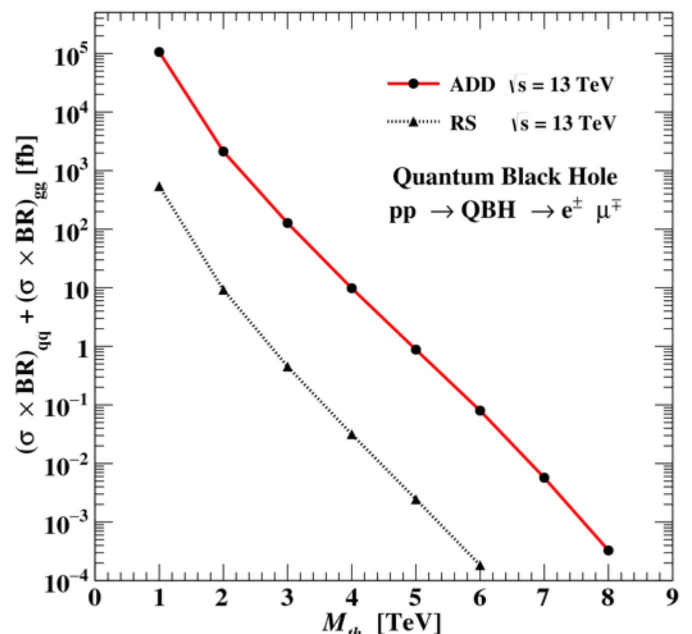
Z′ and quantum black holes

- In the SSM, Z'→ eμ, eτ, μτ decays are predicted and investigated assuming the Z′ does not decay into lepton-flavor conserving modes.

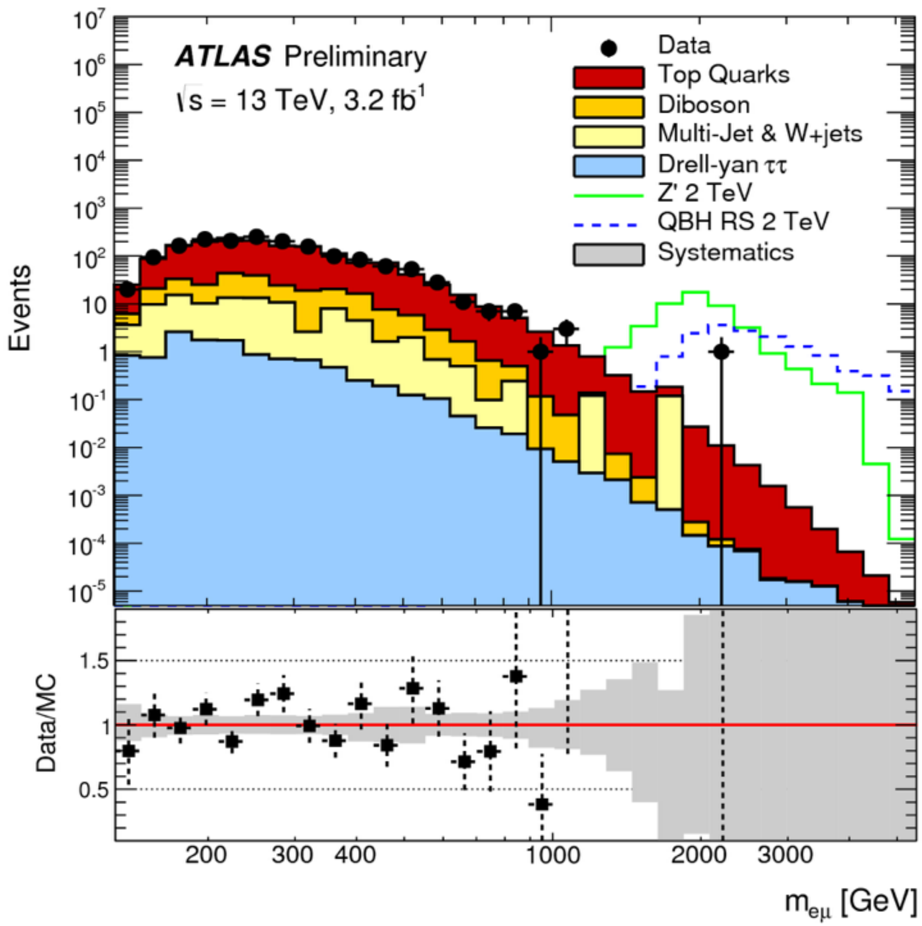
- In the ADD or RS extra dimensions models, a large fraction of quantum black holes will produce two-particle final states.
    - Assumes quantum gravity couples to all particles with equal strength, allowing for eμ decays.

- By requiring different flavor leptons, the DY background is largely suppressed, enhancing the sensitivity of the search.





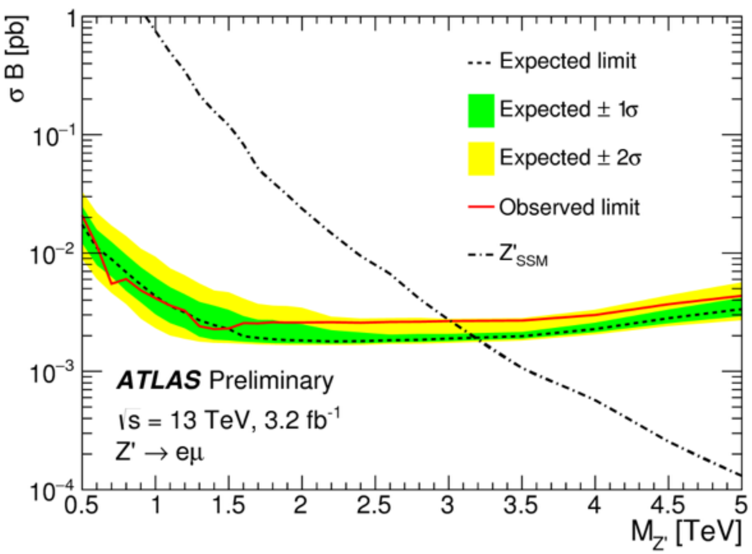
Searches with eμ final states

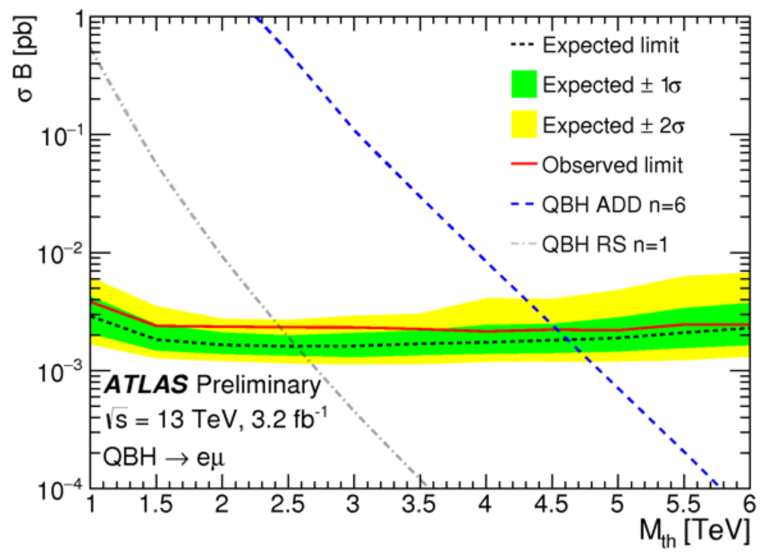


- Top and diboson backgrounds are extrapolated with fits to smoothly decaying functions at high masses (> 1 TeV).
    - Dominant source of uncertainty in the analysis.

- $m_{e\mu}$ < 600 GeV defined as validation region for SM backgrounds
- $m_{e\mu}$ > 600 GeV defined as search region
- Largest local p-value corresponds to a 1.7σ excess at a dilepton mass of 2.1 TeV.

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



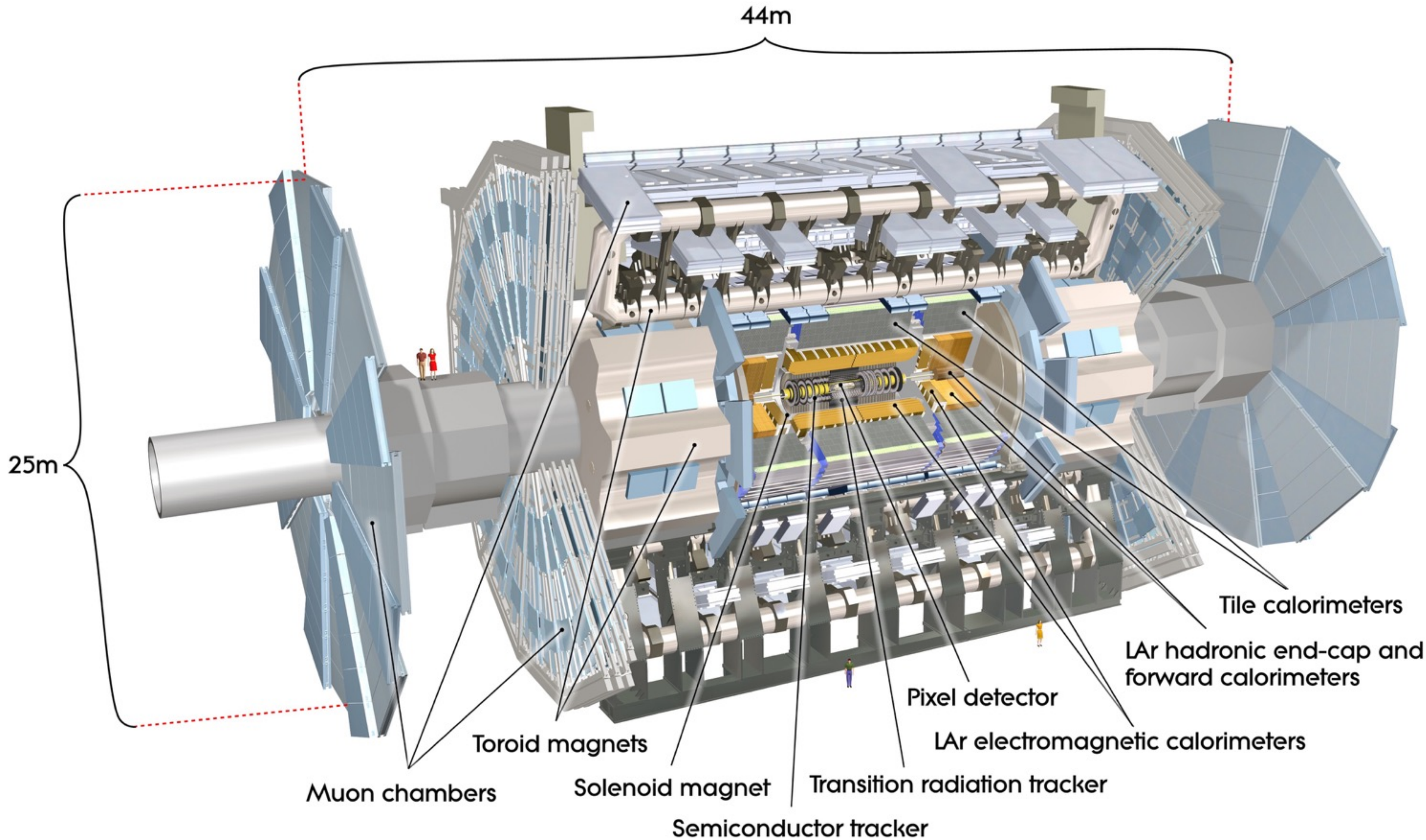


Outlook and Conclusions

- ATLAS has analyses in place to search for W′ and Z′ bosons and other new phenomenology such as quantum black holes and contact interactions.
- The latest ATLAS results use a total of 3.2 fb^{-1} of pp collision data at a centre-of-mass energy of 13 TeV
  - Run 1 limits with full 8 TeV dataset have already been improved.
  - New collisions are now flowing in and we expect ~10 times more data by the end of 2016.
- **Exciting year ahead!!**

Thank you for attention.

Backup slides


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

Matrix element method

- Goal is to estimate the fake lepton background with:
  - real electron efficiency (r), from MC or data
  - electron fake rate (f), from a background enriched sample
- Fake lepton candidates are jets or photons that pass the lepton selection criteria.
- Exclusive samples are defined by loosening the selection criteria on electron candidates.

Measure number of tight and loose leptons.

$$\begin{pmatrix} N_T \\ N_L \end{pmatrix} = \begin{pmatrix} r & f \\ (1-r) & (1-f) \end{pmatrix} \begin{pmatrix} N_R \\ N_F \end{pmatrix}$$

Extract number of real and fake leptons.

Systematic uncertainties on W′ search (ATLAS-CONF-2015-063)

Source	Electron channel		Muon channel	
	Background	Signal	Background	Signal
Trigger	negl. (negl.)	negl. (negl.)	3% (3%)	3% (4%)
Lepton reconstruction and identification	negl. (negl.)	negl. (negl.)	6% (10%)	5% (8%)
Lepton isolation	negl. (negl.)	negl. (negl.)	5% (5%)	5% (5%)
Lepton momentum scale and resolution	3% (3%)	11% (6%)	49% (69%)	5% (21%)
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution and scale	$< 0.5\%$ ($< 0.5\%$)	$< 0.5\%$ ($< 0.5\%$)	1% (1%)	1% (2%)
Jet energy resolution	$< 0.5\%$ ($< 0.5\%$)	$< 0.5\%$ (1%)	1% (1%)	1% (1%)
Multijet background	3% (19%)	N/A (N/A)	negl. (negl.)	N/A (N/A)
PDF choice for DY production	3% (13%)	N/A (N/A)	2% (2%)	N/A (N/A)
PDF variation for DY production	8% (10%)	N/A (N/A)	6% (8%)	N/A (N/A)
Luminosity	8% (4%)	9% (9%)	9% (9%)	9% (9%)
Total	12% (26%)	14% (11%)	51% (71%)	13% (25%)

Table 1: Systematic uncertainties on the expected number of events as evaluated at $m_{\mathrm{T}} = 2$ (4) TeV, both for signal events with a W'_{SSM} mass of 2 (4) TeV and for background. Uncertainties estimated to have an impact $< 3\%$ on the expected number of events for all values of m_{T} are denoted as negligible ("negl"). In case they are negligible in both channels they are not listed. Uncertainties that are not applicable are denoted "N/A".

Systematic uncertainties on Z′ search (ATLAS-CONF-2015-070)

Source	Dielectron		Dimuon	
	Signal	Background	Signal	Background
Normalisation	4.0% (4.0%)	N/A	4.0% (4.0%)	N/A
PDF Choice	N/A	9.1% (17%)	N/A	5.3% (7.4%)
PDF Variation	N/A	5.3% (11%)	N/A	4.4% (6.5%)
PDF Scale	N/A	1.8% (2.3%)	N/A	1.7% (1.9%)
Photon-induced corrections	N/A	3.4% (5.4%)	N/A	3.2% (3.8%)
Efficiency	5.1% (5.0%)	5.1% (5.0%)	13% (19%)	13% (19%)
Scale & Resolution	<1.0% (<1.0%)	7.8% (9.1%)	20% (26%)	20% (46%)
Multi-jet & W+jets	N/A	<1.0% (<1.0%)	N/A	N/A
MC Statistics	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)
Total	6.5% (6.4%)	15% (24%)	25% (32%)	26% (51%)

Table 1: Summary of the systematic uncertainties in the expected number of events at a dilepton mass of 2 TeV (3 TeV). For the background the values quoted represent relative shift in the $m_{\ell\ell}$ histogram bin spanning the given reconstructed $m_{\ell\ell}$ mass of 2 TeV (3 TeV). For the signal uncertainties the values were computed using a Z'_χ signal model with a pole mass of 2 TeV (3 TeV) by comparing yields in the core of the mass peak (within the full width at half maximum) between the distribution varied under a given uncertainty and the nominal distribution. Uncertainties due to high-p_T extrapolation are included in the efficiency uncertainty. N/A represents cases where the uncertainty is not applicable.

Systematic uncertainties on Z′ search (ATLAS-CONF-2015-072)

Source	$m_{e\mu}$=1.0 TeV		$m_{e\mu}$=2.0 TeV		$m_{e\mu}$=3.0 TeV	
	Signal	Background	Signal	Background	Signal	Background
PDF uncertainties	N/A	11.0%	N/A	27%	N/A	41%
Luminosity	5%	5%	5%	5%	5%	5%
Electron Trigger Efficiency	5%	5%	5%	5%	5%	5%
Electron ID	5%	5%	5%	5%	5%	5%
Muon Reconstruction Efficiency	1%	1%	2%	2%	3%	3%
Electron energy scale and resolution	1%	1%	4%	4%	5%	5%
Muon scale and resolution	7%	7%	15%	15%	20%	20%
Muon Trigger Efficiency	2%	2%	2%	2%	2%	2%
Instrumental backgrounds	N/A	1%	N/A	1%	N/A	1%
Background Extrapolation	N/A	25%	N/A	90%	N/A	400%
MC Statistics	2%	N/A	2%	N/A	2%	N/A
Total	12%	32%	17%	100%	23%	400%

Table 1: Quantative summary of the systematic uncertainties taken into account for the expected number of signal and background events. Values are provided for reconstructed electron-muon invariant masses of 1.0, 2.0 and 3.0 TeV. N/A represents cases where the uncertainty is not applicable.

Detailed results on Z′ search (ATLAS-CONF-2015-070)

Model	Width [%]	ee [TeV] Exp	ee [TeV] Obs	$\mu\mu$ [TeV] Exp	$\mu\mu$ [TeV] Obs	$\ell\ell$ [TeV] Exp	$\ell\ell$ [TeV] 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

Channel	Prior	Left-Left [TeV] Const.	Left-Left [TeV] Destr.	Left-Right [TeV] Const.	Left-Right [TeV] Destr.	Right-Left [TeV] Const.	Right-Left [TeV] Destr.	Right-Right [TeV] Const.	Right-Right [TeV] Destr.
Exp: ee	$1/\Lambda^2$	18.5	15.2	18.1	15.8	17.7	16.1	17.9	15.9
Obs: ee	$1/\Lambda^2$	18.3	15.3	17.6	15.8	17.5	15.9	17.5	15.8
Exp: ee	$1/\Lambda^4$	16.9	14.3	16.6	14.8	16.4	14.8	16.5	14.7
Obs: ee	$1/\Lambda^4$	16.7	14.1	16.2	14.5	16.1	14.6	16	14.6
Exp: $\mu\mu$	$1/\Lambda^2$	18.2	14.5	17.5	15.1	17.4	15.4	18.1	14.5
Obs: $\mu\mu$	$1/\Lambda^2$	20.2	15.8	19.7	17.0	19.4	17.1	20.4	15.8
Exp: $\mu\mu$	$1/\Lambda^4$	16.6	13.8	16.3	14.4	16.1	14.5	16.6	13.9
Obs: $\mu\mu$	$1/\Lambda^4$	18.1	15.0	17.7	15.8	17.4	15.9	18.1	15.0
Exp: $\ell\ell$	$1/\Lambda^2$	21.4	16.4	21.0	17.4	20.4	17.7	20.9	16.9
Obs: $\ell\ell$	$1/\Lambda^2$	23.1	17.5	22.1	18.8	21.7	19.0	22.6	17.7
Exp: $\ell\ell$	$1/\Lambda^4$	19.9	15.6	19.0	16.6	18.7	16.6	19.4	16.0
Obs: $\ell\ell$	$1/\Lambda^4$	20.7	16.4	20.0	17.5	19.8	17.6	20.3	16.6

Monte Carlo details

W′	Generator	Normalisation
Charged-current DY	Powheg-Box v2 CT10 PDF Pythia8.186	NNLO pQCD with VRAP CT14NNLO PDF NLO EW with MCSANC
Neutral-current DY	Powheg-Box v2 CT10 PDF Pythia8.186	NNLO pQCD with VRAP CT14NNLO PDF NLO EW with MCSANC
top	Powheg Box v2 CT10 PDF Pythia6	Top++2.0 NNLO+NNLL
single-top	Powheg Box v1 CT10 PDF Pythia6	
Diboson	Sherpa 2.1.1 CT10 PDF	
Signal	Pythia 8.183 NNPDF23 LO PDF	NNLO pQCD with VRAP

Monte Carlo details

LFC Z′ / LFV Z′ / QBH	Generator	Normalisation
Neutral-current DY	Powheg-Box v2 CT10 PDF Pythia8.186 Photos++ 3.52	NNLO pQCD with VRAP CT14NNLO PDF NLO EW with MCSANC (including photon-induced via MRST2004QED)
top	Powheg Box v2 CT10 PDF Pythia6	Top++2.0 NNLO+NNLL
single-top	Powheg Box v1 CT10 PDF Pythia6	
Diboson	Sherpa 2.1.1 CT10 PDF	
Resonant Z'	Pythia 8.183 NNPDF23 LO PDF	NNLO pQCD with VRAP No EW corrections
Non-resonant CI signal	Pythia 8.183 NNPDF23 LO PDF Inteference effects included	NNLO pQCD with VRAP With EW corrections

Monte Carlo details

LFV Z′ / QBH	Generator	Normalisation
Neutral-current DY	Pythia8 NNPDF2.3	NNLO + EW with FEWZ CT14NNLO PDF
top	Powheg Box v2 CT10 PDF Pythia6	Top++2.0 NNLO+NNLL
single-top	Powheg Box v1 CT10 PDF Pythia6	Top++2.0 NNLO+NNLL
Diboson	Sherpa 2.1.1 CT10 PDF ME+PS@NLO prescription	
Resonant Z'	Pythia 8.183 NNPDF23 LO PDF	NNLO pQCD with VRAP No EW corrections
QBH	QBH CTEQ6L1 Pythia8	