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

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On behalf of the ATLAS Collaboration

High-pT lepton final states

- High-pT lepton final states can be created by decays of heavy bosons, quantum black hole, etc. predicted in many models of physics beyond the Standard Model.
  - Extra-dimension, E_6 modules, R-parity violating SUSY, etc..
- These final states have high sensitivity to heavy particle due to high trigger, reconstruction and selection efficiencies.
- Search for high-pT lepton final states is an important program in the ATLAS experiment.

Target final states:

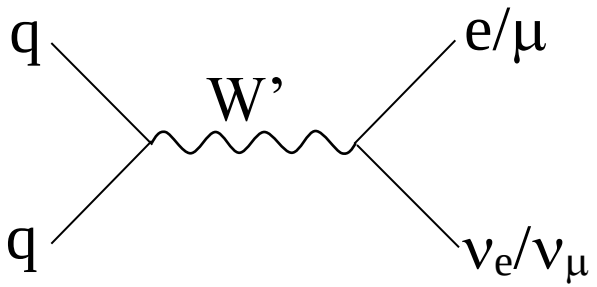
- Single lepton: eν, μν
- Two leptons: ee, μμ, eμ

The analyses were performed by using 2015 data of 3.2 fb^{-1} taken at Sqrt(s)=13 TeV.

Benchmark physics

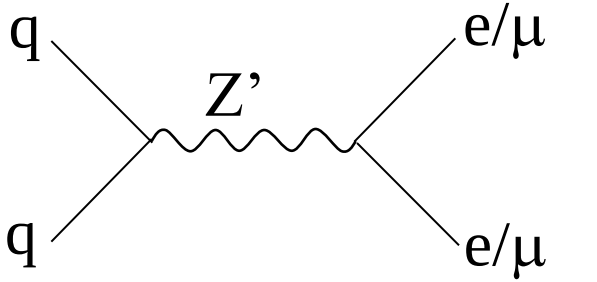
Single lepton final state

- W'→eν/μν: SSM (https://arxiv.org/abs/1606.03977)
- SSM is extended SM with W' and Z'.



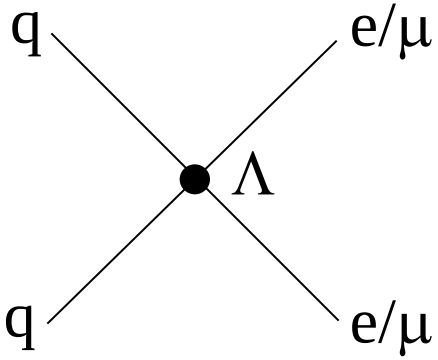
Flavor conserving two lepton final states

- Z'→ee/μμ: SSM, E_6 models
- Non-resonant llqq contact interactions (CI)
- ATLAS-CONF-2015-070 (https://cds.cern.ch/record/2114842)



Flavor violating two lepton final state

- Z'→eμ: SSM
- QBH→eμ: Extra-dimension predicted in n=6 in ADD, n=1 in RS
- ATLAS-CONF-2015-072 (https://cds.cern.ch/record/2114844)



Analysis procedure

1. Event and charged lepton selection

- Cut based selection

2. Background estimation

- Real lepton with MC samples
- Fake lepton with data driven method (Matrix method)

3. Estimation of systematic uncertainties

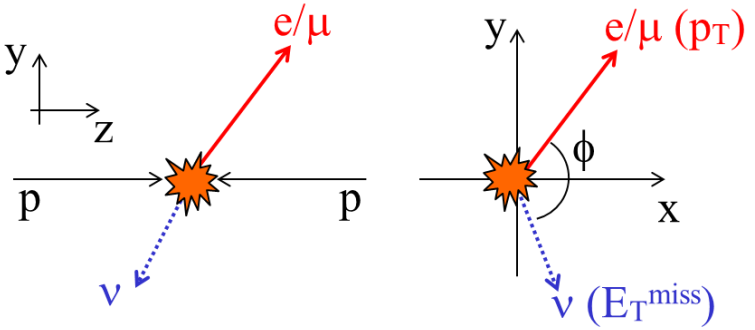
4. Calculation of mass limit

Signal selection

Single lepton selection

- Single electron/muon trigger
- Selecting events with single isolated electron/muon with high-pT.
- The transverse mass is used for the discriminant variable:

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



Two leptons selection

- Single electron/muon trigger (di-electron trigger for Z'→ee)
- Selecting two isolated leptons with high-pT or high-E_T.
- Di-lepton invariant mass (M_{ee}, $M_{\mu\mu}$, $M_{e\mu}$) is reconstructed by using di-lepton pair with the highest scalar pT sum or E_T.

Background estimation

BG from real leptons

- Drell-Yan (DY), ttbar and single top, di-boson
- Estimated with MC.
  - The results of the fitting with smoothly decaying functions is used in case MC statistics is not enough.
- Modeling of DY process with mass-dependent K-factors (NNLO in QCD and NLO in EW)

BG from fake leptons

- Fake leptons from multi-jet or W+jets processes
  - Negligible for di-muon channel.
- Estimated with data-driven method (Matrix method → see next page)

Estimation of multi-jet backgrounds (W')

The matrix method is used to estimate backgrounds from fake leptons.

Measurable quantities

- T: passes "signal" selection
- L: passes "loose" selection

Truth quantities

- R: real leptons
- L: fake leptons

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

(for W' analysis)

- r: fraction of real leptons passing signal selection (evaluated with MC W sample)
- f: fraction of fake leptons passing signal selection (evaluated with jet enriched data sample)

$$N_T^{\text{Multijet}} = f\,N_F = \frac{f}{r-f}\Big(r\,(N_L + N_T) - N_T \Big)$$

Systematic uncertainties

Experimental

- Efficiency (Lepton trigger, reconstruction, identification, isolation)
- Lepton energy scale and resolution
- Missing transverse energy scale, resolution
- Jet scale, resolution
- Luminosity
- Data-driven estimation of instrumental backgrounds (multi-jet)
- Extrapolations to high masses due to low MC statistics
  - top and di-boson in two lepton final states

Theoretical

- PDF choice and variation
- α_s scale, higher-order EW corrections

Example of systematic uncertainties (W')

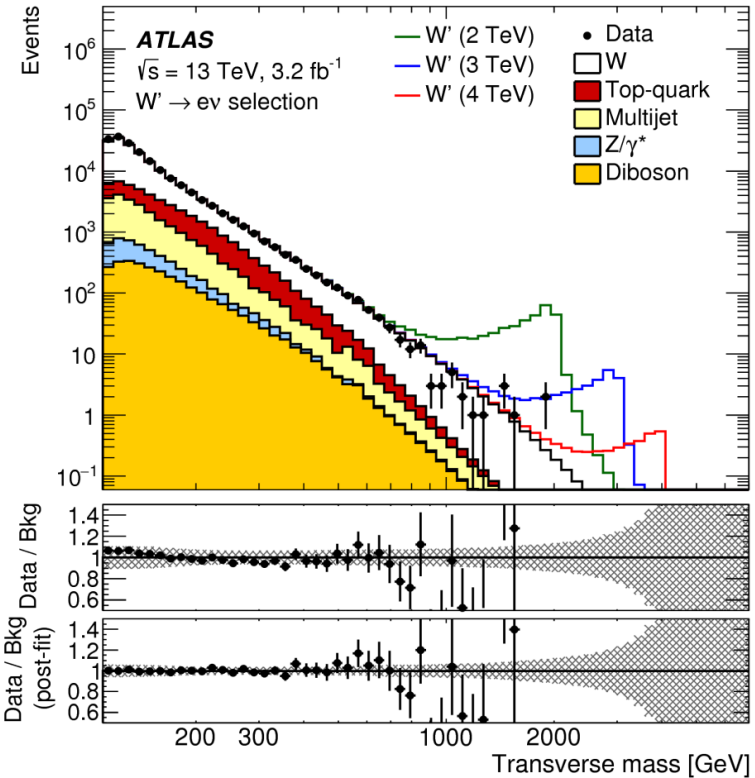
Systematic uncertainties in the expected number of events at mT = 2(4)TeV

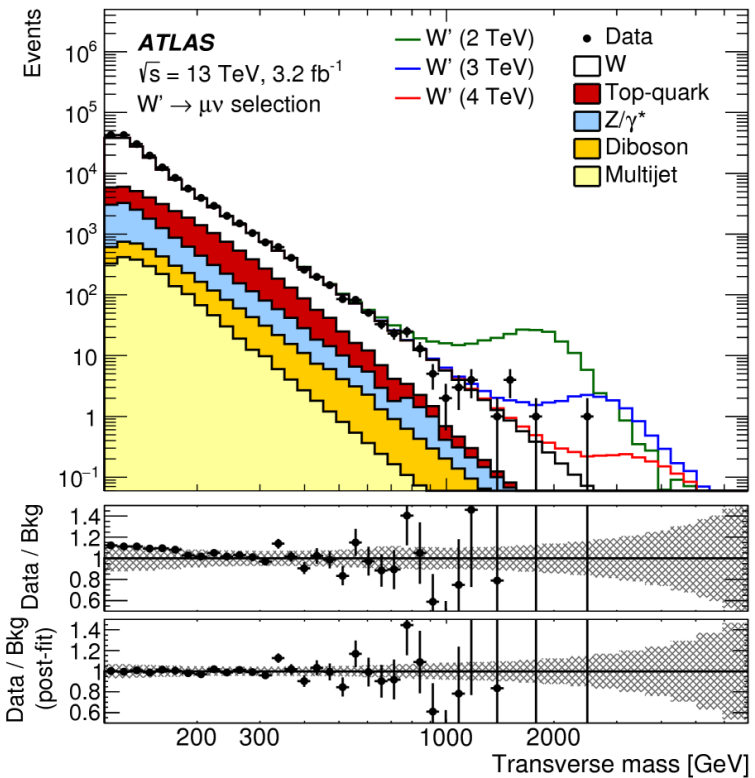
Source	Electron channel		Muon channel	
	Background	Signal	Background	Signal
Trigger	1% (< 0.5%)	1% (< 0.5%)	3% (4%)	4% (4%)
Lepton reconstruction and identification	3% (3%)	3% (3%)	5% (8%)	5% (7%)
Lepton isolation	2% (2%)	2% (2%)	5% (5%)	5% (5%)
Lepton momentum scale and resolution	4% (6%)	10% (7%)	3% (11%)	1% (4%)
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution and scale	< 0.5% (< 0.5%)	< 0.5% (< 0.5%)	< 0.5% (< 0.5%)	< 0.5% (< 0.5%)
Jet energy resolution	< 0.5% (< 0.5%)	< 0.5% (< 0.5%)	1% (2%)	< 0.5% (< 0.5%)
Multijet background	2% (15%)	N/A (N/A)	1% (1%)	N/A (N/A)
Diboson & top-quark bkg.	6% (49%)	N/A (N/A)	5% (15%)	N/A (N/A)
PDF choice for DY	1% (22%)	N/A (N/A)	< 0.5% (1%)	N/A (N/A)
PDF variation for DY	9% (19%)	N/A (N/A)	8% (12%)	N/A (N/A)
Electroweak corrections	5% (9%)	N/A (N/A)	4% (6%)	N/A (N/A)
Luminosity	5% (5%)	5% (5%)	5% (5%)	5% (5%)
Total	14% (60%)	11% (8%)	14% (25%)	9% (12%)

Transverse mass distribution (eν, μν)

- CC-DY dominates over entire mT range. (90% for mT>1TeV)
- The discrepancy of data and MC at low mT (still within 1σ) is within E_T^{miss} related systematic uncertainties.
- The observed events agrees with the background estimate.

Transverse mass distributions for electron and muon channels



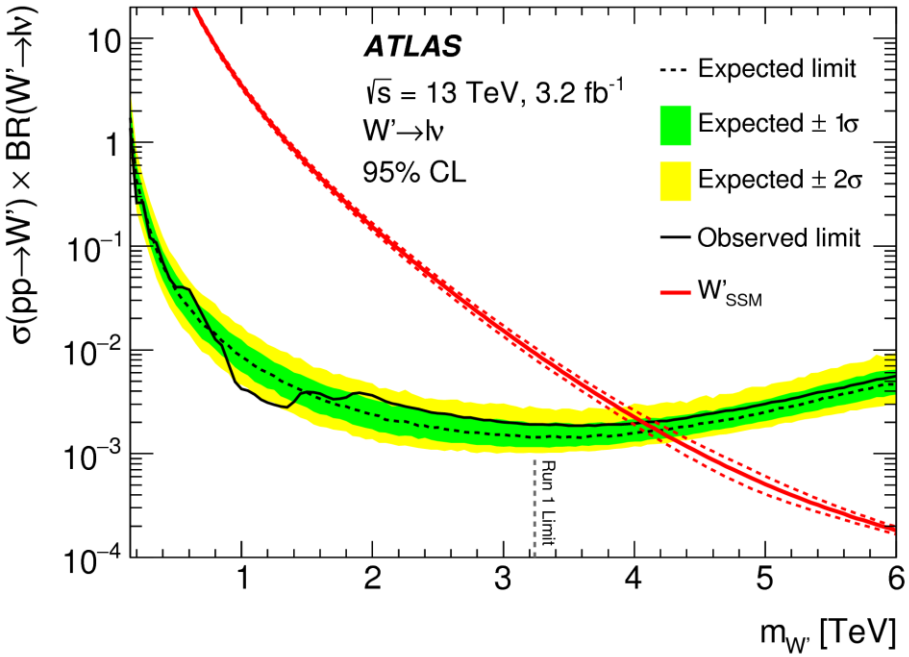


W' mass limit (eν, μν)

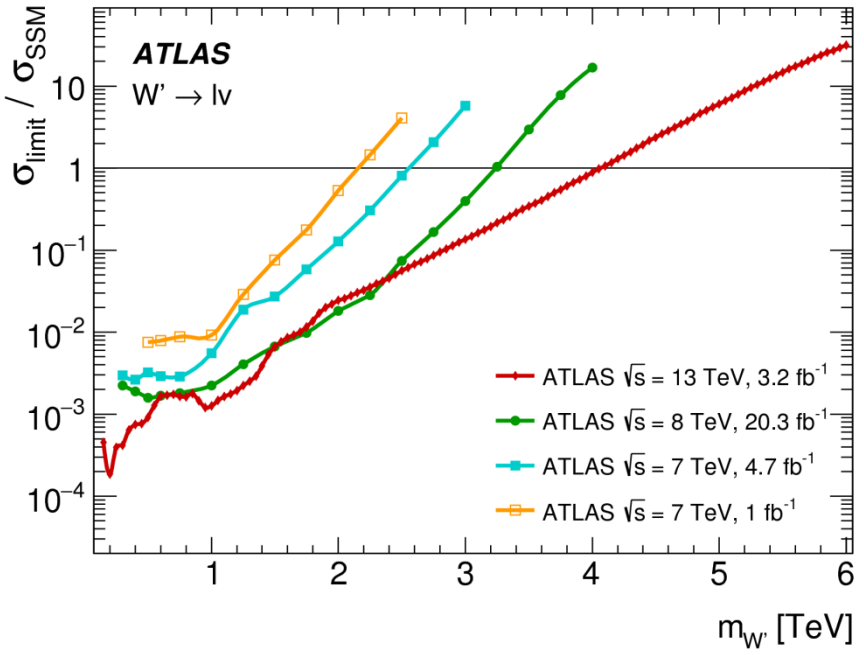
- All observed limits are within 2σ of the expected limit.
- W' mass limit is improved by 800 GeV, compared to ATLAS Run-1 result.

Decay	$m_{W'}$ lower limit [TeV] Expected	Observed
$W' \to e\nu$	3.99	3.96
$W' \to \mu\nu$	3.72	3.56
$W' \to \ell\nu$	4.18	4.07

95% CL upper limits on σ x B



Normalized cross-section limit

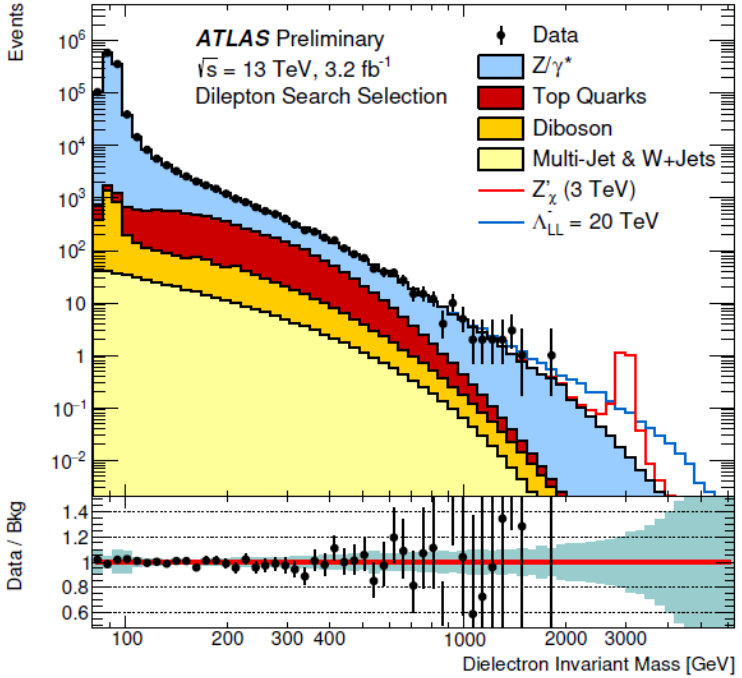


Di-lepton mass limit (ee, μμ)

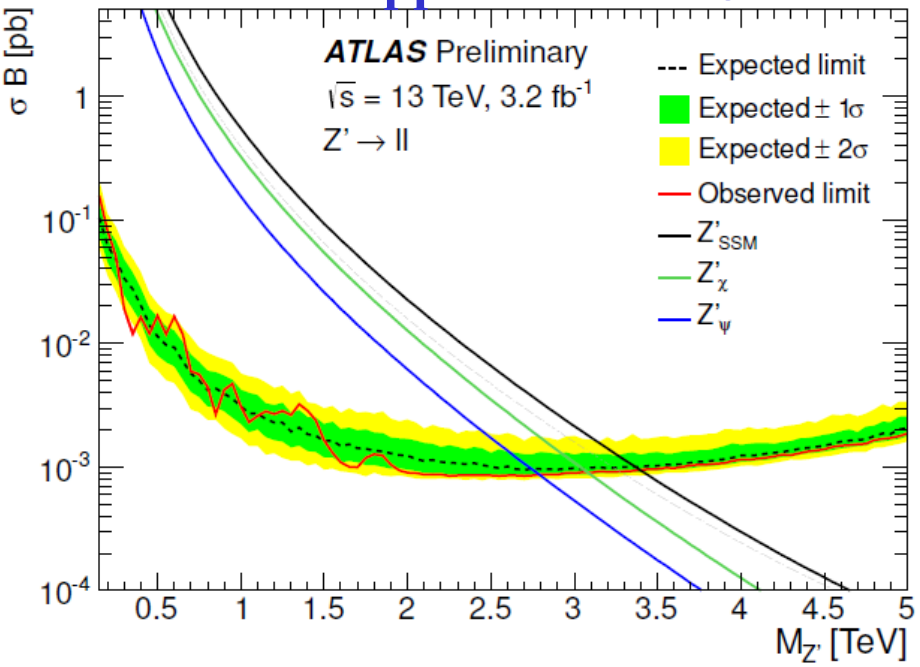
- No significant excess is observed.
- The observed lower mass limits are set in combination with electron and muon channels.
- The mass limit is improved by 500 GeV, compared to ATLAS Run-1 result for Z'SSM

	Mass limit
Z' SSM	3.4 TeV
Z'_χ	3.08 TeV
Z'_Ψ	2.79 TeV

Di-electron mass distribution



95% CL upper limits on σ x B

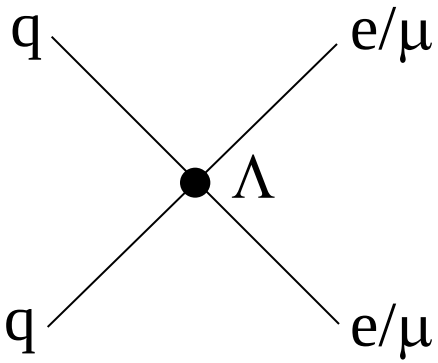


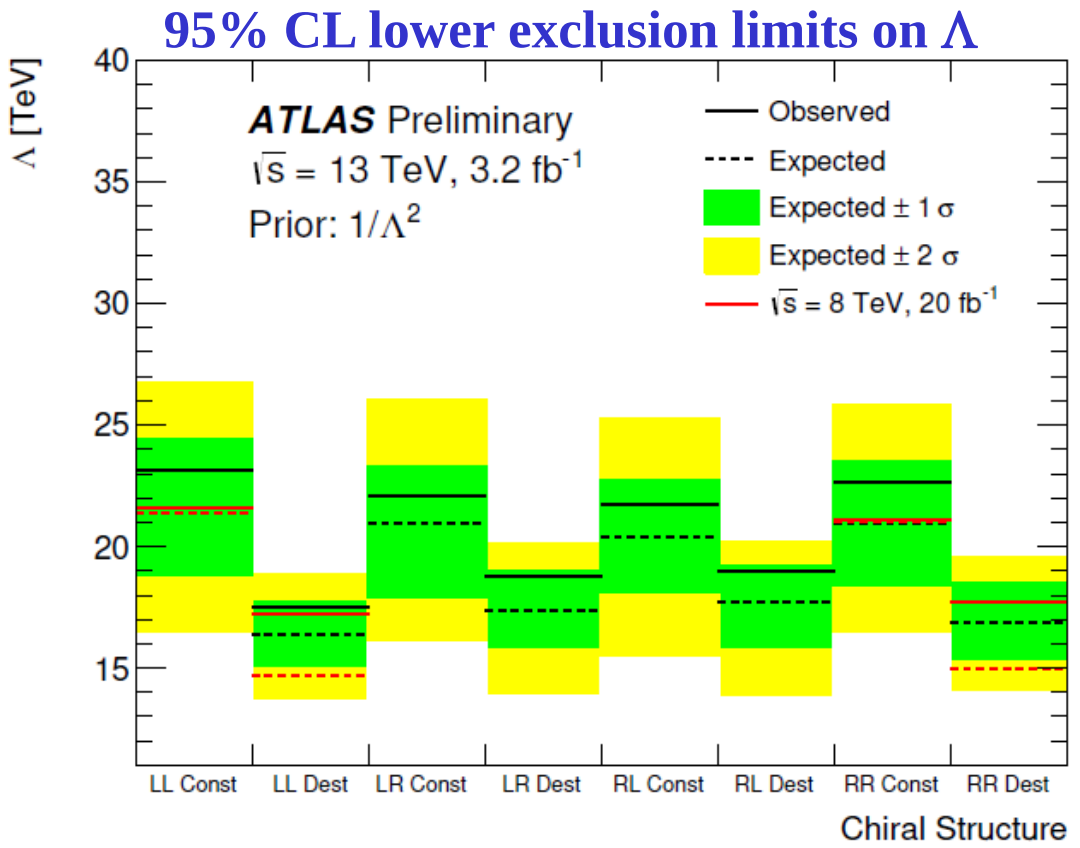
Di-lepton CI scale limit (ee, μμ)

The lower limits on the energy scale Λ for various llqq coupling scenarios are obtained.

$$\mathcal{L} = \frac{g^2}{\Lambda^2}\left[\eta_{LL}(\bar{q}_L\gamma_\mu q_L)(\bar{\ell}_L\gamma^\mu \ell_L) + \eta_{RR}(\bar{q}_R\gamma_\mu q_R)(\bar{\ell}_R\gamma^\mu \ell_R) + \eta_{LR}(\bar{q}_L\gamma_\mu q_L)(\bar{\ell}_R\gamma^\mu \ell_R) + \eta_{RL}(\bar{q}_R\gamma_\mu q_R)(\bar{\ell}_L\gamma^\mu \ell_L)\right]$$

- η_{ij} (i,j = L or R): 1 or -1
- η_{ij} = -1: Constructive
- η_{ij} = +1 : Destructive



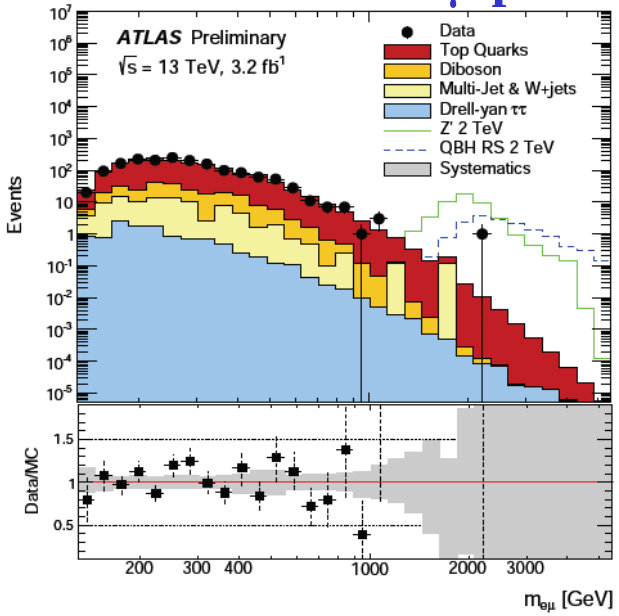


Di-lepton mass limit (eμ)

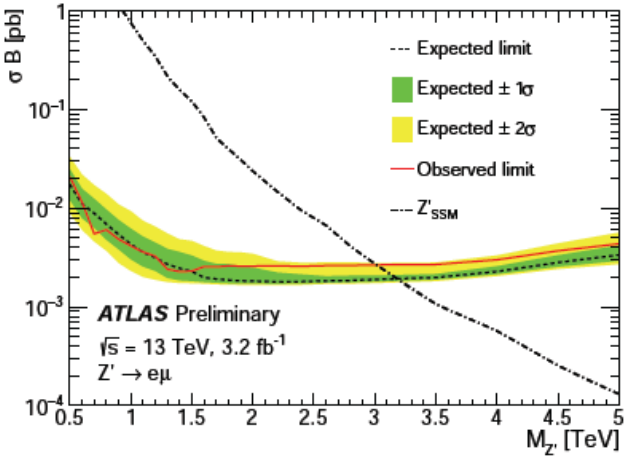
- Good agreement between data and background estimation is observed.
  - The largest local significance: 1.7σ @ $M_{e\mu}$ = 2.1TeV
- The mass limit is improved from Run-1 (2.5 TeV for Z' in Run-1)

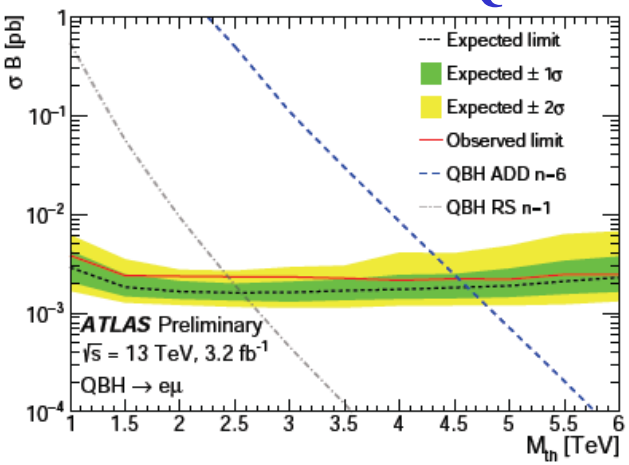
Model	Expected Limit [TeV]	Observed Limit [TeV]
Z′ SSM	3.19	3.01
QBH ADD n=6	4.62	4.54
QBH RS n=1	2.56	2.44

Invariant mass of eμ pairs



95% CL lower mass limits on σ x B of Z' and QBH





Summary and Conclusions

- High-pT lepton final states are powerful probes to search for physics beyond the Standard Model.
- Searches for single and two high-pT lepton final states have been performed in the ATLAS experiment.
- No evidence of the new physics was found by using LHC Run-2 data of 3.2 fb^{-1} taken at Sqrt(s)=13 TeV in 2015.
- The mass limits were improved, compared to the results of Run-1 analyses.
- The improvement of the mass limits is expected with high statistics taken in 2016 (~25fb^{-1}).

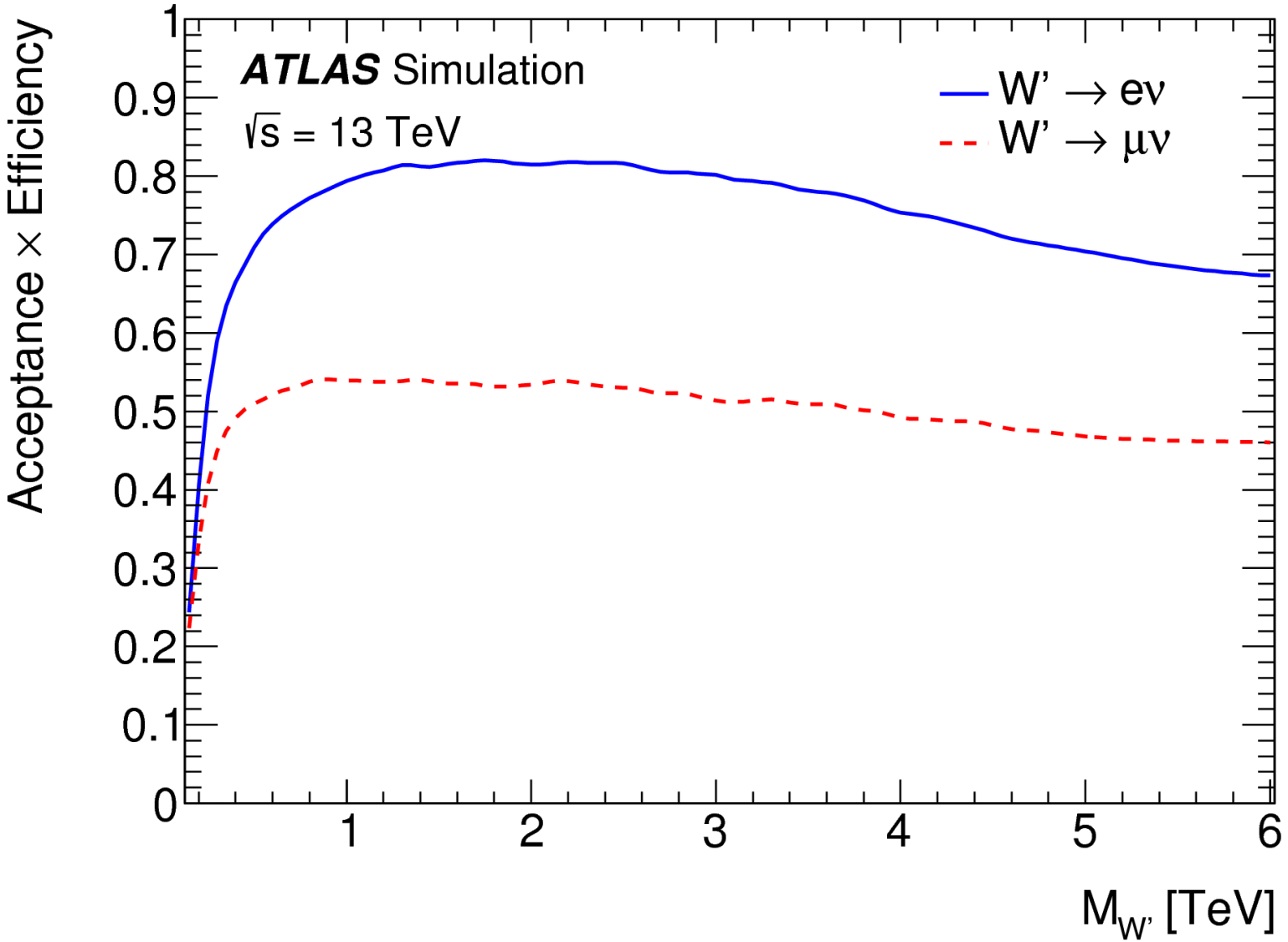
Backup

Efficiency (W')

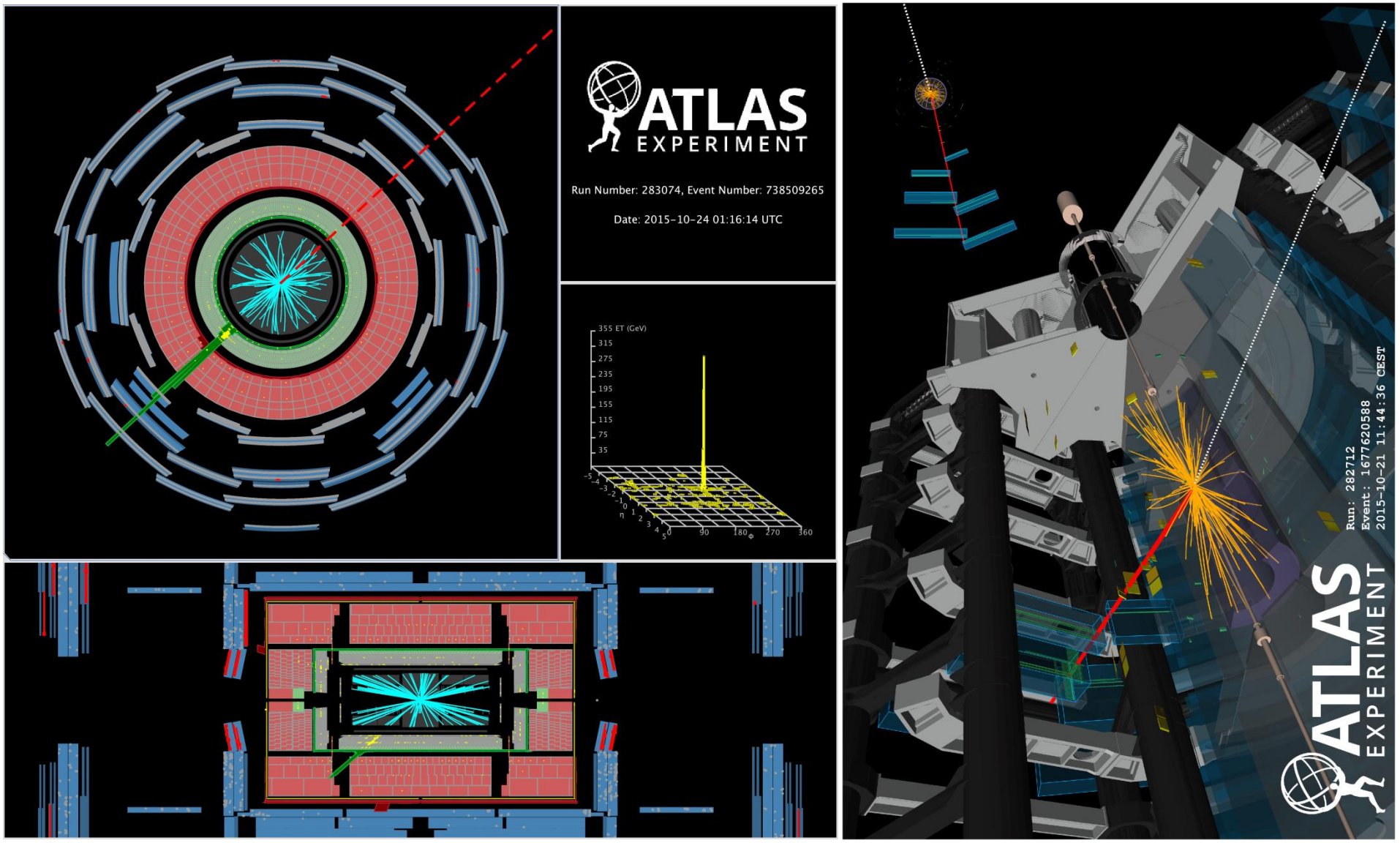
Selection step	SSM W' (2 TeV)	SSM W' (3 TeV)	SSM W' (4 TeV)	SSM W' (5 TeV)
Trigger	92.2%	91.9%	89.8%	86.0%
$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	99.3%	99.2%	99.1%	99.1%
Electron cleaning	99.9%	99.9%	99.9%	100.0%
$p_{\mathrm{T}} > 55\ GeV$	96.6%	96.1%	95.0%	93.6%
d_0 significance	99.8%	99.9%	99.9%	99.8%
Electron identification	95.1%	94.2%	93.4%	93.8%
Isolation	99.1%	99.3%	98.9%	99.2%
Additional electron veto	99.9%	99.9%	99.9%	99.9%
Additional muon veto	100.0%	100.0%	100.0%	100.0%
$E_{\mathrm{T}}^{\mathrm{miss}} > 55\ GeV$	99.9%	99.7%	99.4%	99.0%
$m_{\mathrm{T}} > 110\ GeV$	99.9%	99.9%	99.8%	99.8%
Total efficiency	81.4%	80.2%	75.4%	70.4%

Selection step	SSM W' (2 TeV)	SSM W' (3 TeV)	SSM W' (4 TeV)	SSM W' (5 TeV)
Trigger	75.3%	74.8%	72.6%	69.7%
Combined muon in $\|\eta\| < 2.5$	99.9%	99.8%	99.9%	99.9%
$p_{\mathrm{T}} > 55\ GeV$	99.7%	99.5%	99.1%	98.3%
d_0 significance	99.7%	99.6%	99.6%	99.7%
$\|z_0\| \sin\theta$	99.6%	99.6%	99.5%	99.5%
Muon identification	83.9%	82.8%	83.0%	83.7%
Isolation	99.4%	99.5%	99.5%	99.4%
Additional muon veto	100.0%	100.0%	100.0%	100.0%
Additional electron veto	99.9%	99.8%	99.8%	99.9%
$E_{\mathrm{T}}^{\mathrm{miss}} > 55\ GeV$	99.8%	99.7%	99.4%	98.9%
$m_{\mathrm{T}} > 110\ GeV$	99.9%	99.9%	99.9%	99.8%
Total efficiency	52.9%	51.4%	49.8%	47.9%

Acceptance x efficiency (W’)



Event-display of one high-pT lepton



Systematic errors (ee, μμ)

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%)

Event yield (ee, μμ)

Table 2: Expected and observed event yields in the dielectron (top) and dimuon (bottom) channels in different dilepton mass intervals. The quoted errors correspond to the combined statistical and systematic uncertainties.

m_{ee} [GeV]	500-700	700-900	900-1200	1200-1800	1800-3000	3000-6000
Drell–Yan	145 ± 30	38 ± 6	16 ± 4	5.6 ± 1.6	0.87 ± 0.26	0.026 ± 0.012
Top Quarks	43.8 ± 2.9	5.4 ± 1.2	0.9 ± 0.5	0.09 ± 0.11	0.002 ± 0.006	<0.001
Diboson	7.7 ± 1.1	1.4 ± 0.5	0.39 ± 0.26	0.08 ± 0.12	0.005 ± 0.030	<0.001
Multi-Jet & W+Jets	4 ± 4	1.1 ± 0.8	0.40 ± 0.16	0.089 ± 0.019	0.0042 ± 0.0014	<0.001
Total SM	201 ± 31	46 ± 7	17 ± 4	5.8 ± 1.6	0.88 ± 0.26	0.026 ± 0.012
Data	202	44	17	9	0	0
SM+Z' ($m_{Z'}$ = 3 TeV)	201 ± 31	46 ± 7	17 ± 4	5.9 ± 1.6	2.6 ± 1.1	1.44 ± 0.34
SM+CI ($\Lambda_{\mathrm{LL}}^{-}$ = 25 TeV)	207 ± 31	49 ± 7	20 ± 4	8.0 ± 1.6	2.11 ± 0.27	0.251 ± 0.019
$m_{\mu\mu}$ [GeV]	500-700	700-900	900-1200	1200-1800	1800-3000	3000-6000
Drell–Yan	110 ± 7	27.5 ± 2.2	11.8 ± 1.1	4.5 ± 0.7	0.70 ± 0.08	0.079 ± 0.023
Top Quarks	39.5 ± 0.8	6.7 ± 0.4	0.89 ± 0.15	0.046 ± 0.032	<0.001	<0.001
Diboson	3.98 ± 0.32	0.65 ± 0.11	0.229 ± 0.028	0.022 ± 0.006	0.00104 ± 0.00034	<0.001
Total SM	151 ± 7	35.5 ± 2.3	14.2 ± 1.1	4.6 ± 0.7	0.71 ± 0.08	0.079 ± 0.024
Data	169	28	13	4	0	0
SM+Z' ($m_{Z'}$ = 3 TeV)	151 ± 7	35.5 ± 2.3	14.2 ± 1.1	4.6 ± 0.7	2.13 ± 0.26	0.8 ± 0.4
SM+CI ($\Lambda_{\mathrm{LL}}^{-}$ = 25 TeV)	162 ± 8	38.1 ± 2.4	15.3 ± 1.2	5.5 ± 0.8	0.87 ± 0.09	0.099 ± 0.035

Mass limits (ee, μμ)

Table 3: Observed and expected 95% C.L. lower mass limits for various Z' gauge boson models.

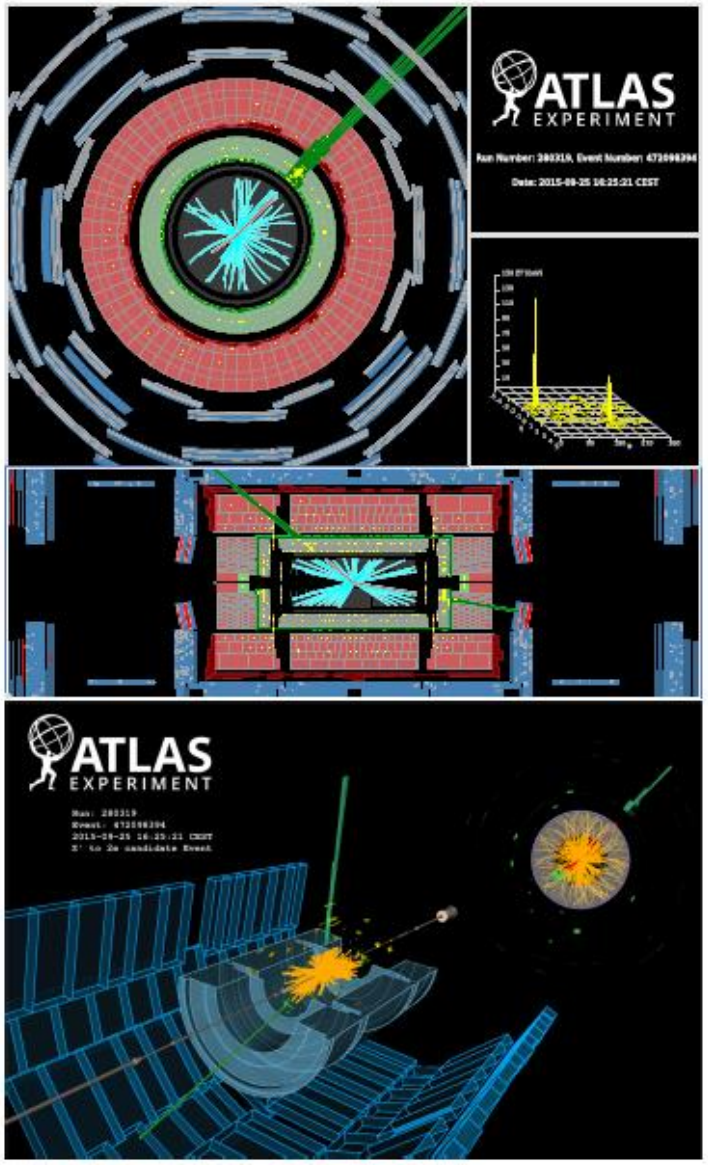
Model	Width [%]	ee [TeV]		$\mu\mu$ [TeV]		$\ell\ell$ [TeV]	
		Exp	Obs	Exp	Obs	Exp	Obs
Z'_{SSM}	3.0	3.17	3.18	2.91	2.98	3.37	3.40
Z'_{χ}	1.2	2.87	2.88	2.64	2.71	3.05	3.08
Z'_{S}	1.2	2.83	2.84	2.59	2.67	3.00	3.03
Z'_{I}	1.1	2.78	2.78	2.53	2.62	2.95	2.98
Z'_{N}	0.6	2.64	2.64	2.38	2.48	2.81	2.85
Z'_{η}	0.6	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

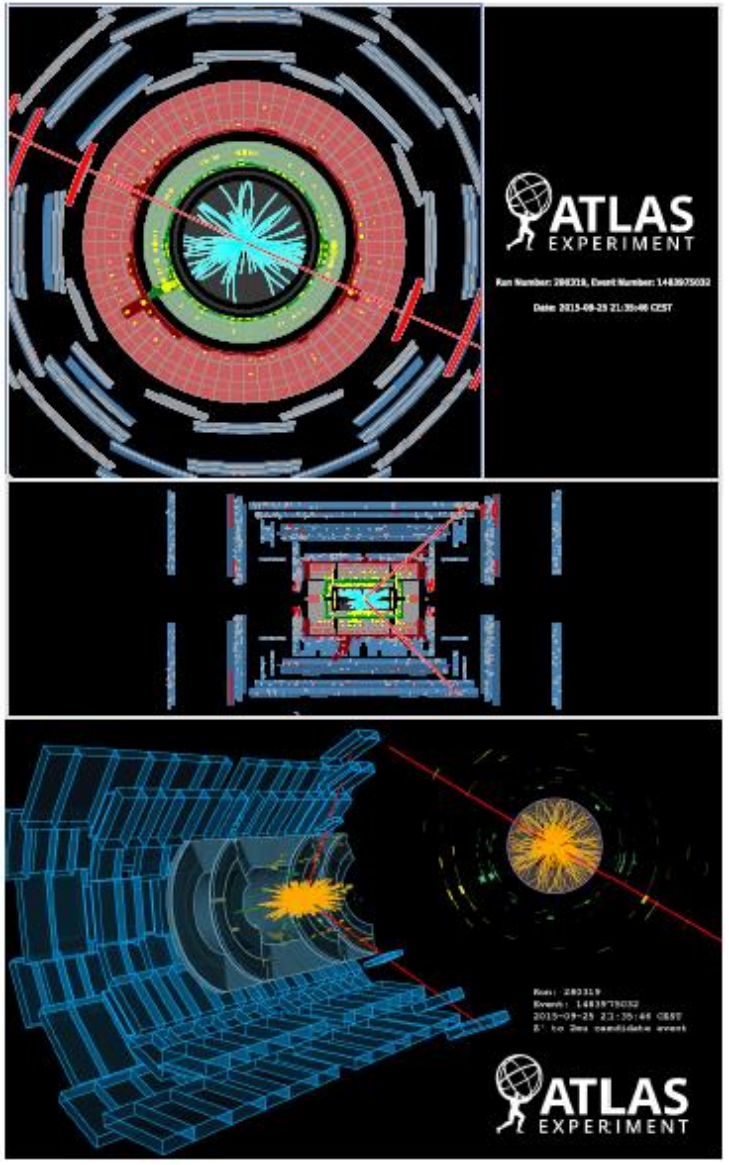
Limits on CI (ee, μμ)

Table 4: Expected and observed 95% C.L. lower exclusion limits on Λ for the LL, LR, RL, and RR chiral coupling scenarios, for both the constructive and destructive interference cases using a uniform positive prior in $1/\Lambda^2$ or $1/\Lambda^4$. The dielectron, dimuon, and combined dilepton channel limits are shown.

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

Event-display (ee, μμ)





Systematic errors (eμ)

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.