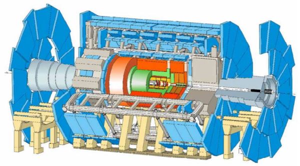


Searches for

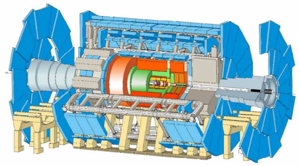
dilepton resonances

with the ATLAS detector

Dr Tracey Berry

Royal Holloway

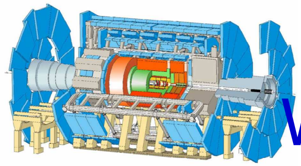
University of London



Overview

- Why are we looking for high-mass dilepton resonances?
- ATLAS & LHC
- 7 TeV search 5 fb^{-1} (full 2011 dataset) http://arxiv.org/pdf/1209.2535v2.pdf
  - Event selection
  - Backgrounds
  - High energy electrons and muons
  - Signal search and limit setting
- 8 TeV search 6 fb^{-1}
- Summary and Outlook

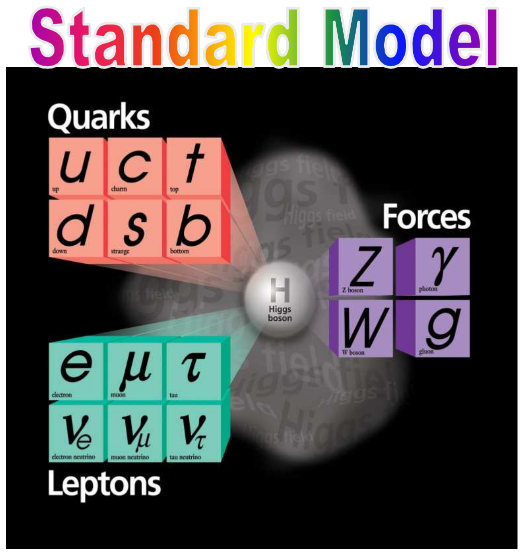
Further information can be found at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults?redirectedfrom=Atlas.ExoticsPublicResults



Why are we looking for Physics beyond the SM?

- The Standard Model of Particle Physics is a very successful theory, but cannot be the end of the story...

- For example, it doesn't
  - have a dark matter candidate
  - explain why gravity is so weak compared to the other fundamental forces

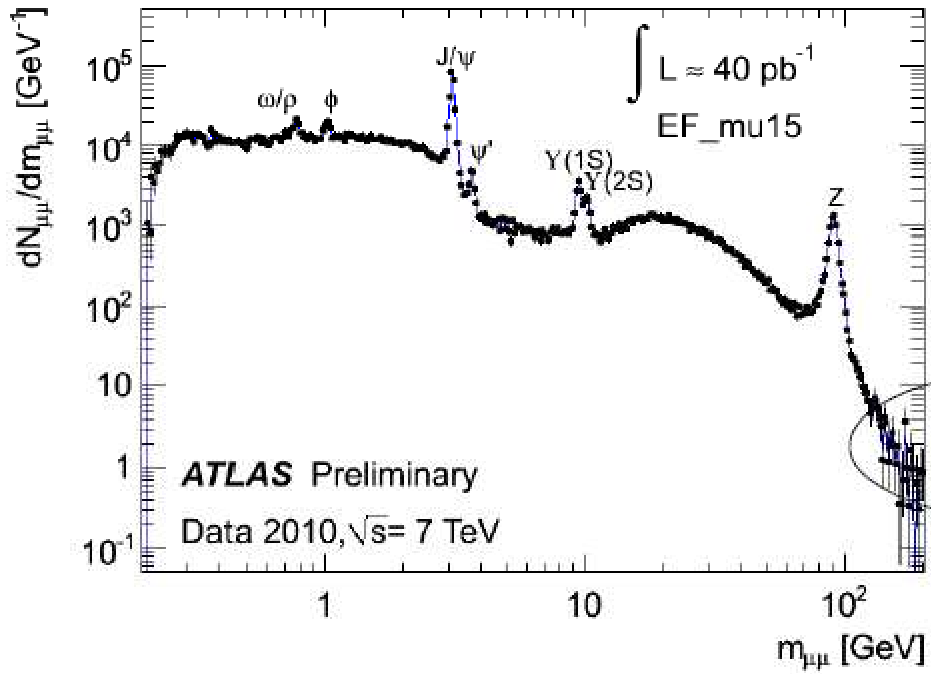


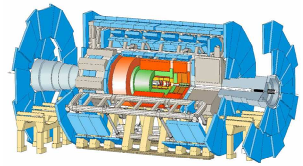
- Questions remain:
  - Are there more symmetries beyond $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$?

  → GUTs with larger symmetry group? Left-right symmetry?

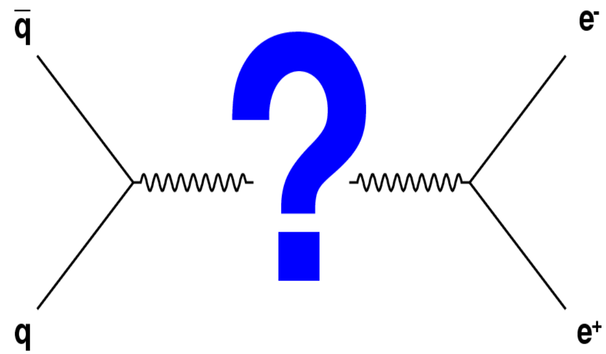
Dilepton Resonances

- Dilepton resonances have been the window to a better understanding of elementary particles and forces before....

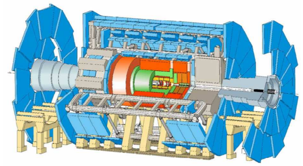




Dilepton Searches



- di-lepton signature (ee + μμ,)
  is a relatively clean final in a hadron collider
  - easily identifiable final state
    with low backgrounds
- has a useful calibration point: Z^0
  - can study selection efficiency, cross-check luminosity and calibrate calorimeter energy and tracker p_T scales
- broad sensitivity to a range of new physics scenarios
  - Z's, Technicolor, Large Extra Dimensions (ADD), Universal Extra Dimensions, Warped Extra Dimensions, Torsion Models, Z*
  - all of the above can show up as an excess in the di-lepton mass spectrum



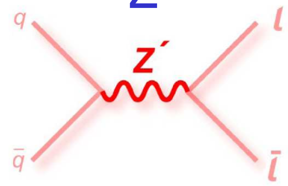
Dilepton Resonances

Dilepton resonances could be a signature of
- new heavy gauge bosons

 (eg. in the E6 model (Grand Unified Theory model))

----> spin-1

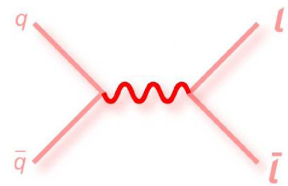
Z′



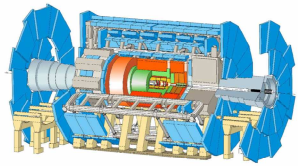
- excited Kaluza-Klein mode of the Randall Sundrum graviton

----> spin-2

G*: RS ED



...and many others (resonance search is fairly model independent)



Additional Symmetries: Z′

New heavy gauge bosons are predicted in several extensions of the SM

Dilepton resonances could be a signature of

- new heavy gauge boson in the E6 model (Grand Unified Theory model)
  (Phys. Rev. D 34 (1986), arXiv:0801.1345v3)

GUT theories

Unification of electroweak and strong forces at high energies

----> 1 overall symmetry, which breaks down at lower energies

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

$$\mathrm{SU}(5) \rightarrow \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

2 additional U(1) groups lead to new neutral gauge fields ψ and χ

The particles associated with the additional fields can mix in a linear combination to form the Z′ candidate:

$$Z'(E_6) = Z'_\psi \cos\theta_{E_6} + Z'_\chi \sin\theta_{E_6}$$

where θ_{E6} is the mixing angle between the two gauge bosons.

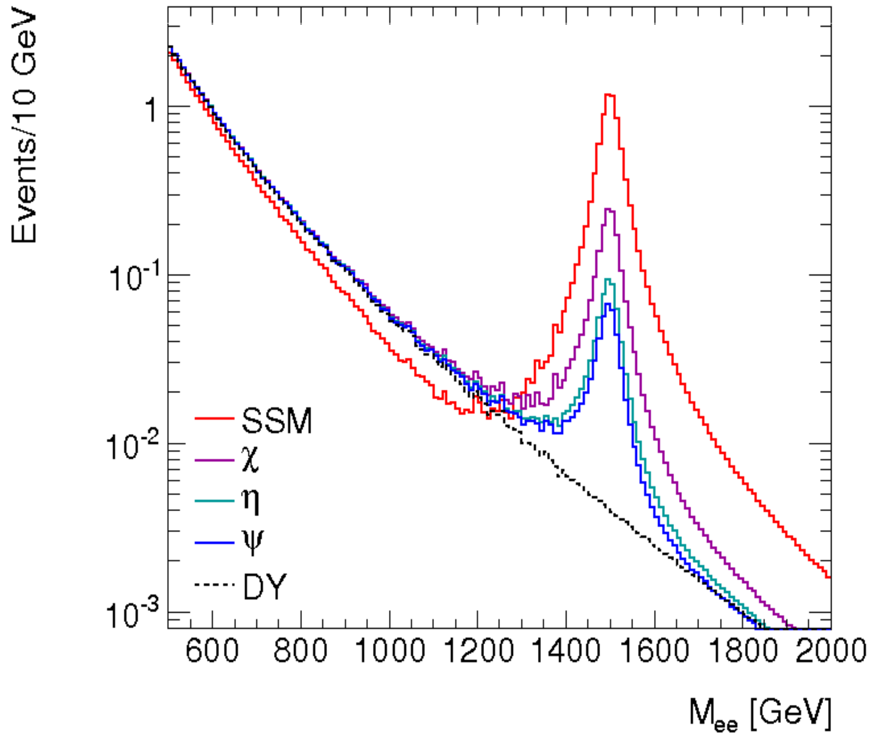
E6 Z′ models

$$Z'(E_6) = Z'_\psi \cos\theta_{E_6} + Z'_\chi \sin\theta_{E_6}$$

- The pattern of spontaneous symmetry breaking and the value of θ_{E6} determine the Z′ couplings to fermions;
- six well motivated choices of θ_{E6} lead to the specific Z′ states named:

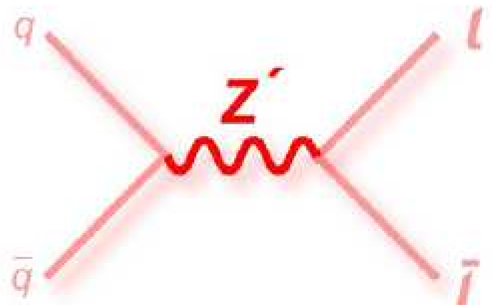
Model	Z'_ψ	Z'_N	Z'_η	Z'_I	Z'_S	Z'_χ
$\sin\theta_{E_6}$	0	$-1/4$	$\sqrt{3/8}$	$\sqrt{5/8}$	$3\sqrt{6}/8$	1
$\cos\theta_{E_6}$	1	$\sqrt{15}/4$	$\sqrt{5/8}$	$-\sqrt{3/8}$	$-\sqrt{10}/8$	0

The expected intrinsic width of the *Z′* for any E6 model is predicted to be between 0.5% and 1.3% $M_{Z'}$

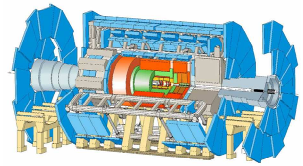


SSM Z′

- Benchmark model for these searches is the Sequential Standard Model (SSM)
  - Z′ has the same couplings to fermions as SM Z
  - The expected intrinsic width of the Z'_{SSM} is 3.1% $M_{Z'}$
  - Z′ width assumed comparable to detector resolution
  - Not theoretically motivated



2010 data: PLB700: 163-180, 2011
2011 data 200 pb-1 update: ATL-CONF-2011-083



Extra Dimensions

In the late 90's Large Extra Dimensions (LED) were proposed as a solution to the hierarchy problem **M_{EW} (1 TeV) << M_{Planck} (10^{19} GeV)?**

ADD

Arkani-Hamed, **D**imopoulos, **D**vali,
Phys Lett B429 (98)

Many (δ) large compactified EDs
In which G can propagate

$$M_{Pl}^2 \sim R^{\delta} M_{Pl(4+\delta)}^{(2+\delta)}$$

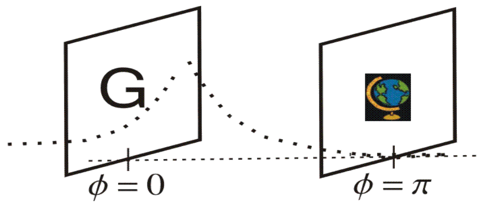
Effective M_{Pl} ~ 1TeV $\rightarrow$ if compact space (R^{δ}) is large

RS

Randall, **S**undrum,
Phys Rev Lett 83 (99)

1 highly curved ED
Gravity localised in the ED

Planck TeV brane



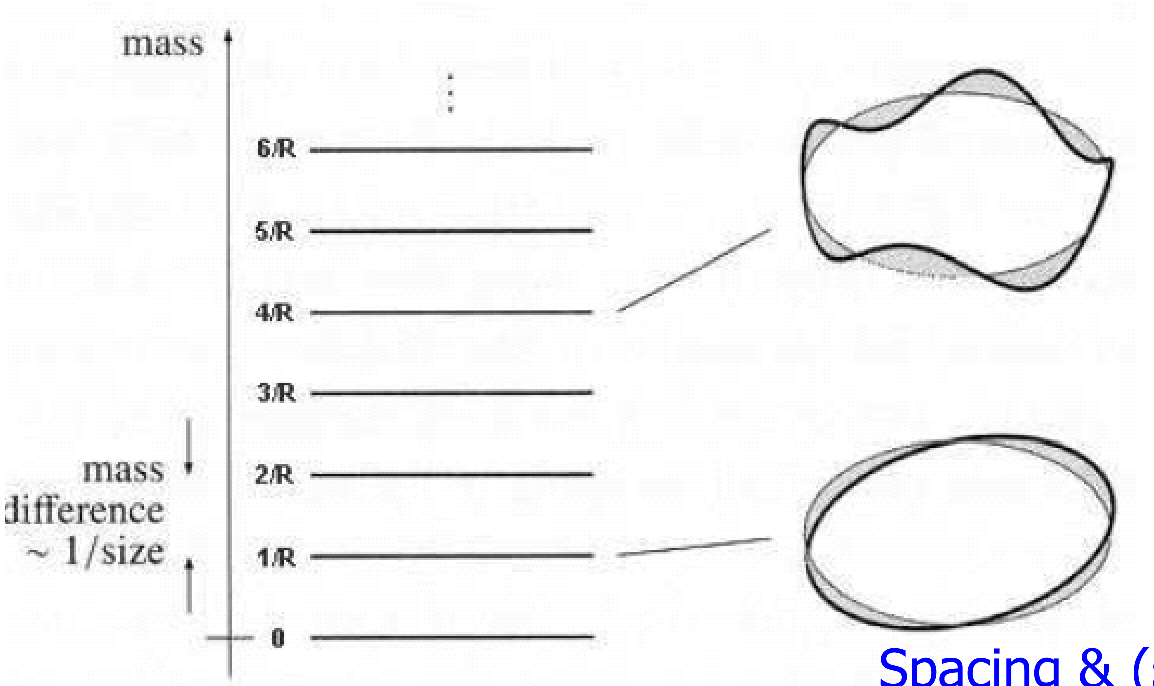
$$\Lambda_{\pi} = \overline{M}_{pl} e^{-kR_c \pi}$$

$\Lambda_{\pi} \sim$ TeV

if warp factor kR_c ~11-12

KK towers/particles

When particles go into the extra dimensions….



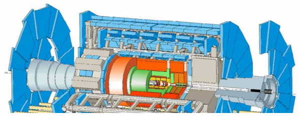
http://universe-review.ca/I15-74-KK.jpg

Like QM particles in a box

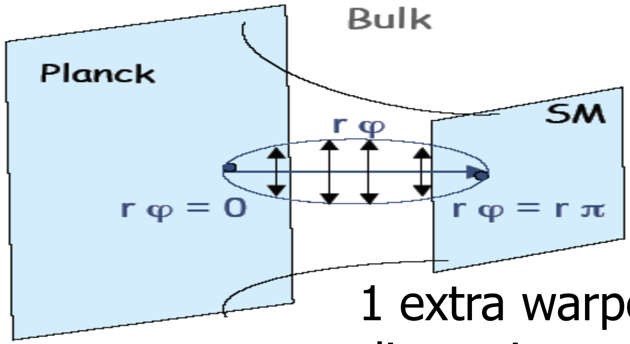
$$M_n = \sqrt{(M_0^2+n^2/R^2)}$$

Spacing & (summation of) KK towers determines the search signature:

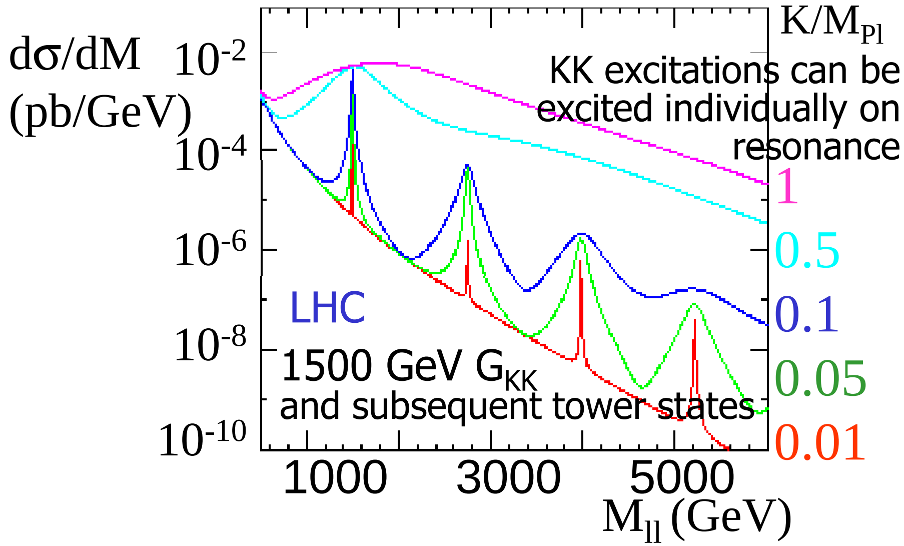
- narrow resonance (RS) or
- broad increase in cross-section (ADD)



Signature for RS Model



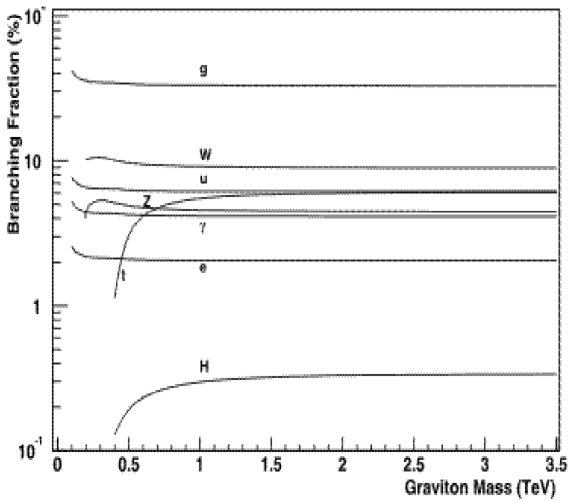
1 extra warped dimension



Signature:

Narrow, high-mass resonance states in dilepton/dijet/diboson channels

$$q\bar{q}, gg \rightarrow G_{KK} \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, jet + jet$$



Model parameters:

- Gravity Scale: $\Lambda_\pi = \overline{M}_{pl} e^{-kR_c\pi}$

  1^{st} graviton excitation mass: $m_1 \rightarrow$ **Resonance** position

  $\Lambda_\pi = m_1 \overline{M}_{pl}/kx_1$, & $m_n = kx_n e^{krc\pi} (J_1(x_n)=0)$
- Coupling constant: $c = k/M_{Pl}$

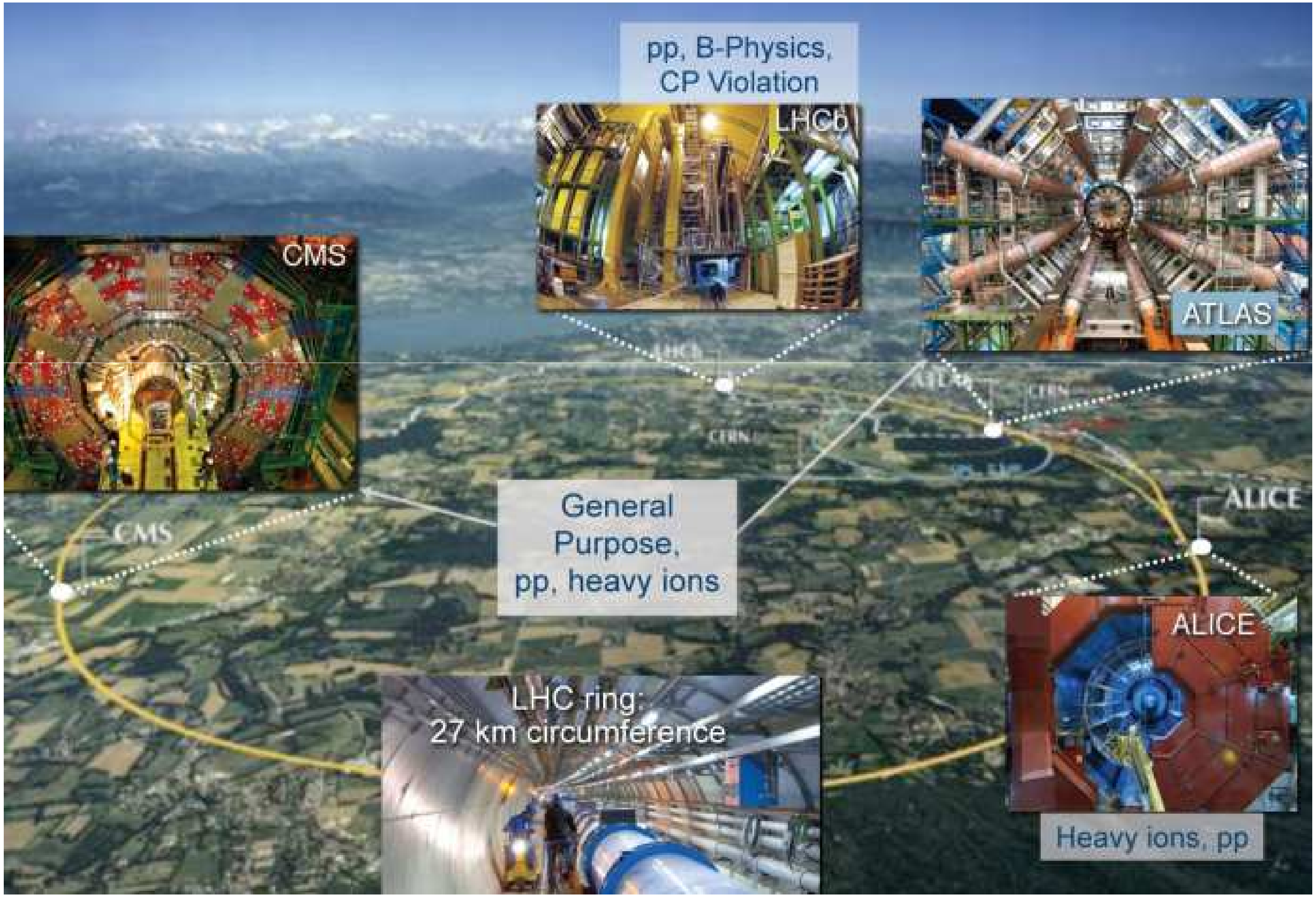
  $\Gamma_1 = \rho m_1 x_1^2 (k/\overline{M}_{pl})^2 \rightarrow$ width

k = curvature, R = compactification radius

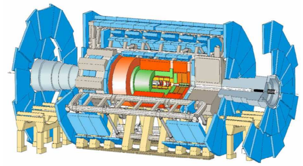
Davoudiasi, Hewett, Rizzo
hep-ph0006041

The LHC &
ATLAS Detector

Large Hadron Collider



A Toroidal LHC AppartuS (ATLAS) DETECTOR



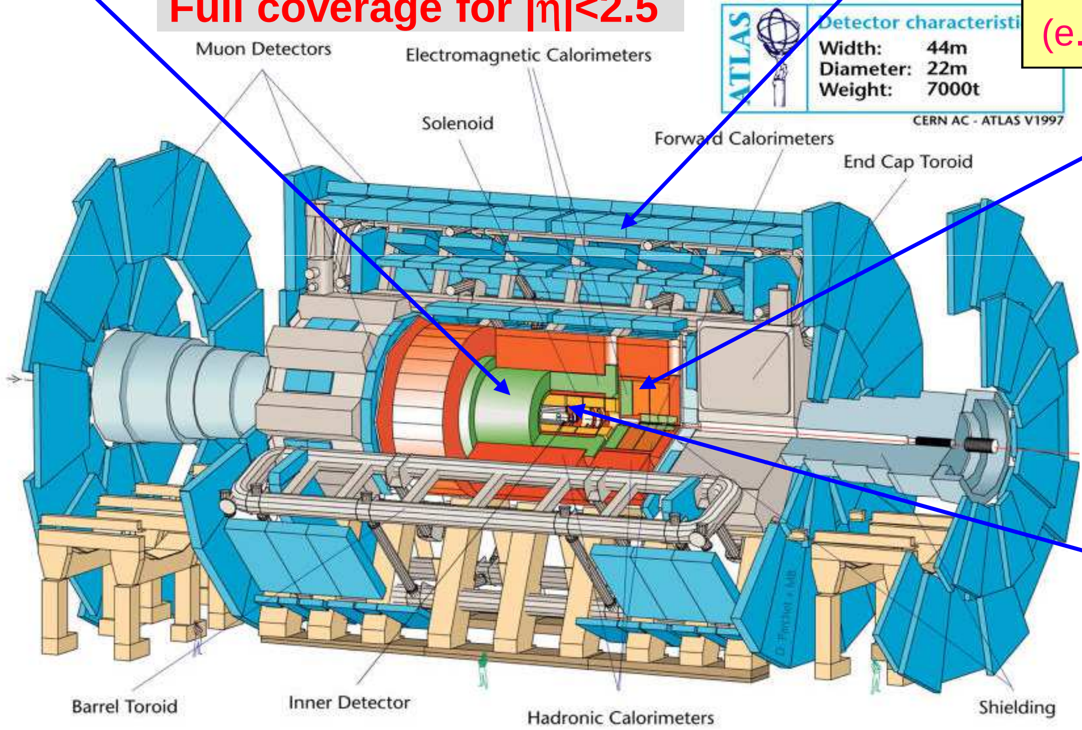
Al large E_T, e resolution dominated by a constant term, which is 1.2 % in the Barrel and 1.8 % endcaps

EM Calorimeters, $\sigma/E \approx 10\%/\sqrt{E(GeV)} \oplus 0.7\%$

excellent electron/photon identification

Good *E* resolution (e.g., $G \rightarrow \gamma\gamma$)

Full coverage for $|\eta|<2.5$



Precision Muon Spectrometer,

$\sigma/p_T \approx 10\%$ at 1 TeV/c

P_T resolution: 10–25 % at 1 TeV/c

Fast response for trigger

Good *p* resolution

(e.g., $Z' \rightarrow \mu\mu$)

Hadron Calorimeters,

$\sigma/E \approx 50\% / \sqrt{E(GeV)} \oplus 3\%$

Good jet and E_T miss performance

Inner Detector:

Si Pixel and strips (SCT) &

Transition radiation tracker (TRT)

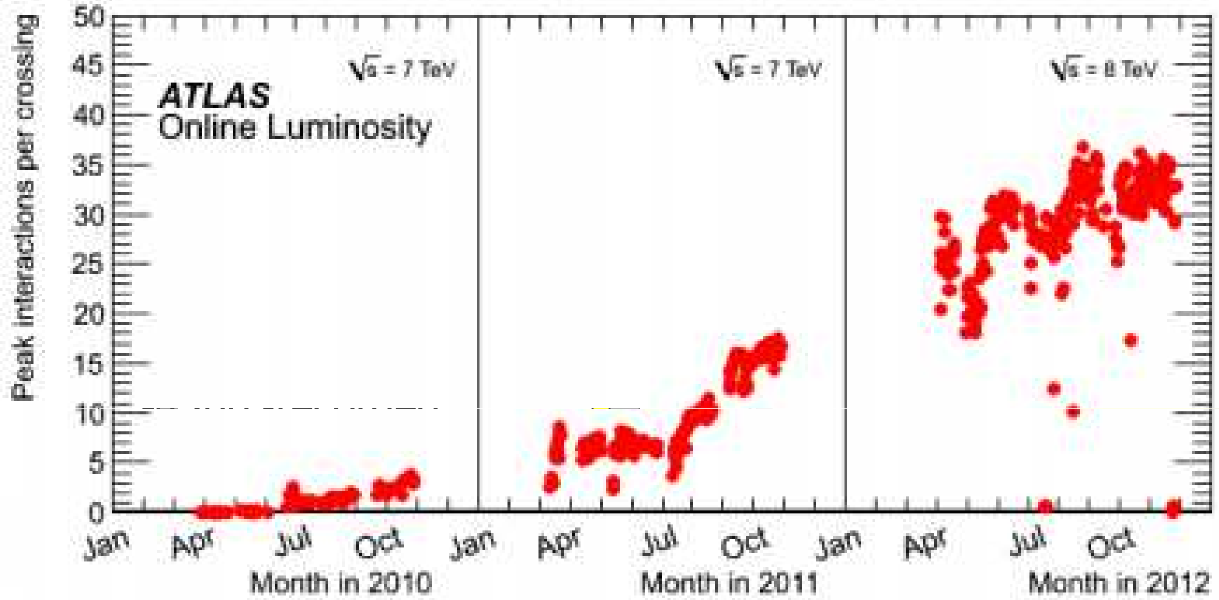
$\sigma/p_T \approx 5 \times 10^{-4}\, p_T \oplus 0.001$

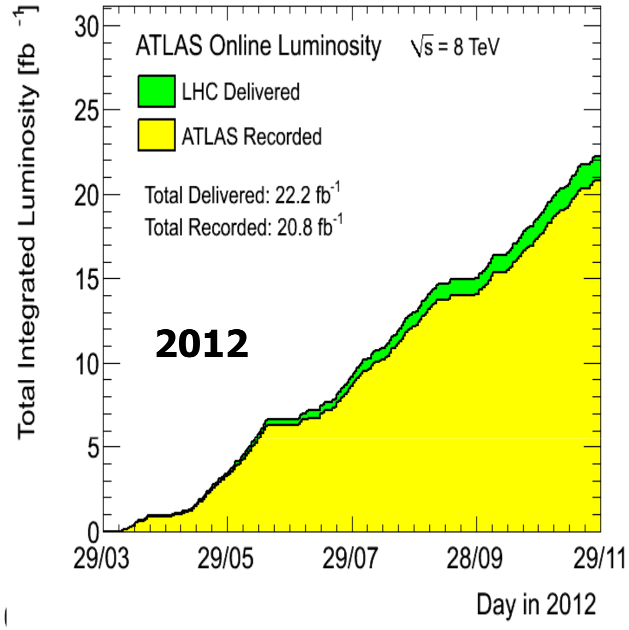
Good impact parameter res.

$\sigma(d_0)$=15μm@20GeV

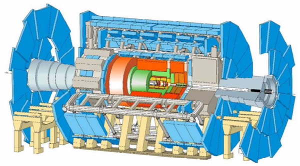
Magnets: solenoid (Inner Detector) 2T, air-core toroids (Muon Spectrometer) ~0.5T

LHC data





- ❑LHC performing extremely well
- ❑Peak luminosity up to 10^{33} cm^{-1} s^{-2}
- ❑Expected luminosity by end of 2012 ~ 25 fb^{-1}
- ❑About 90 % of delivered pp collision are used in the analyses

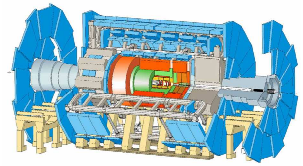


Dilepton Search

5 fb^{-1} @ 7 TeV

Analysis Procedure

- Select events with two leptons of same flavor (ee, $\mu\mu$)
- Search for excess above SM expectations in high invariant mass region



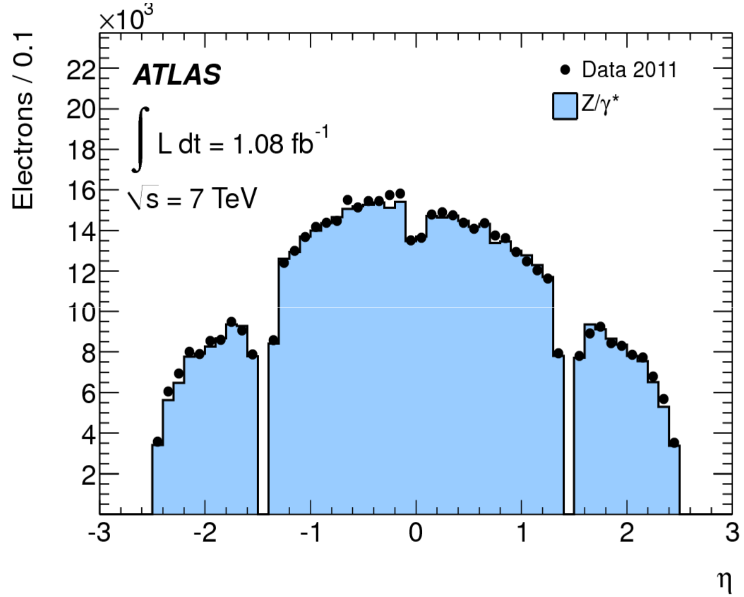
Event Selection

- ATLAS data quality (stable beam, functioning subdetectors etc.)

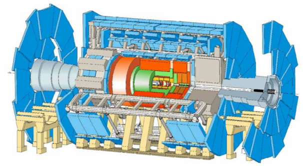
Electron channel

- Trigger on single Medium electron with $E_T > 20$ GeV
- 2 electrons with:
  - $p_T > 25$ GeV
  - Central: $|\eta| < 2.47$ & exclude crack region $1.37 < |\eta| < 1.52$
  - Require track and EM shower shape cuts ("Medium Electron ID")
  - Hit in first pixel layer ("Blayer")
  - Calorimeter Isolation on leading e

    $$\Sigma E_T(\Delta R < 0.2) < 7\text{GeV}$$
  - No opposite charge requirement – to minimize impact of mis-ID



Acceptance
(Z', 1.5 TeV): 67%
(Z', 2.0 TeV): 71 %
(G*, 2.0 TeV): 72%

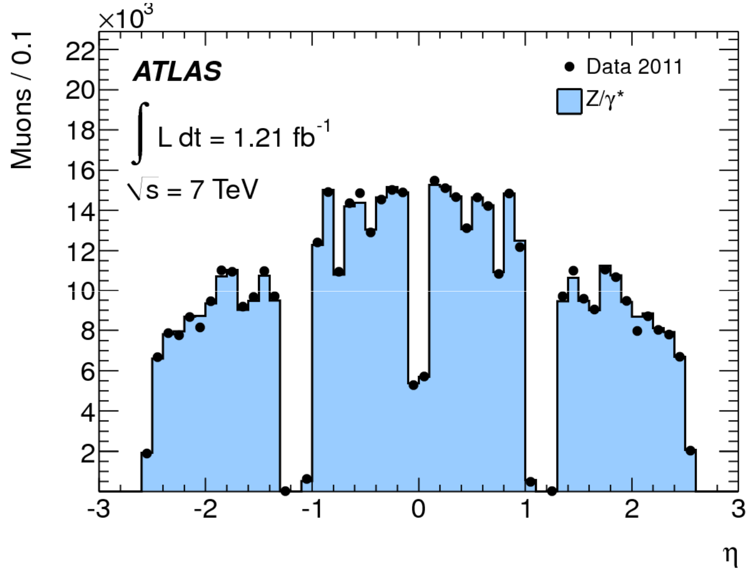


Event Selection

- ATLAS data quality (stable beam, functioning subdetectors etc.)

Muon channel

- Trigger on single Muon with $p_T > 22$ GeV
- Primary vertex with $|z| < 200$ mm
- 2 muons with:
  - $p_T > 25$ GeV
  - Central: $|\eta| < 2.4$
  - Hits in all 3 (+2) muon stations
  - Hit in non-bending plane
  - Veto overlapping hits in barrel and endcaps
  - $|d_0| < 0.2$ mm, $|z_0| < 1$ mm
  - Track Isolation: within $\Sigma p_T^{trk} < 0.05\, p_T$ a cone of $\Delta R < 0.3$
  - Opposite charge
  - Invariant mass > 70 GeV

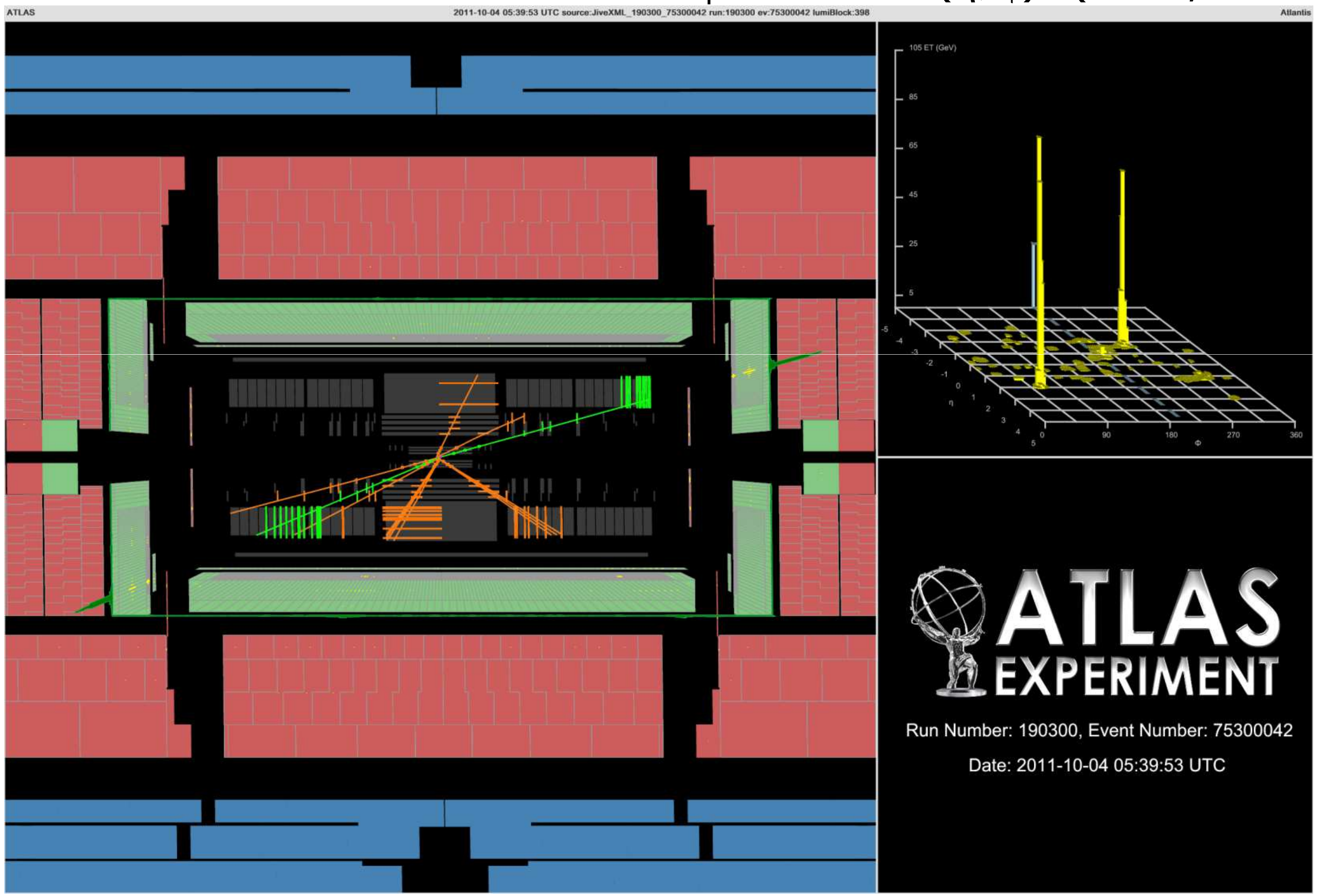


Acceptance
(Z', 1.5 TeV): 42%
(Z', 2.0 TeV): 43 %
(G*, 2.0 TeV): 47%

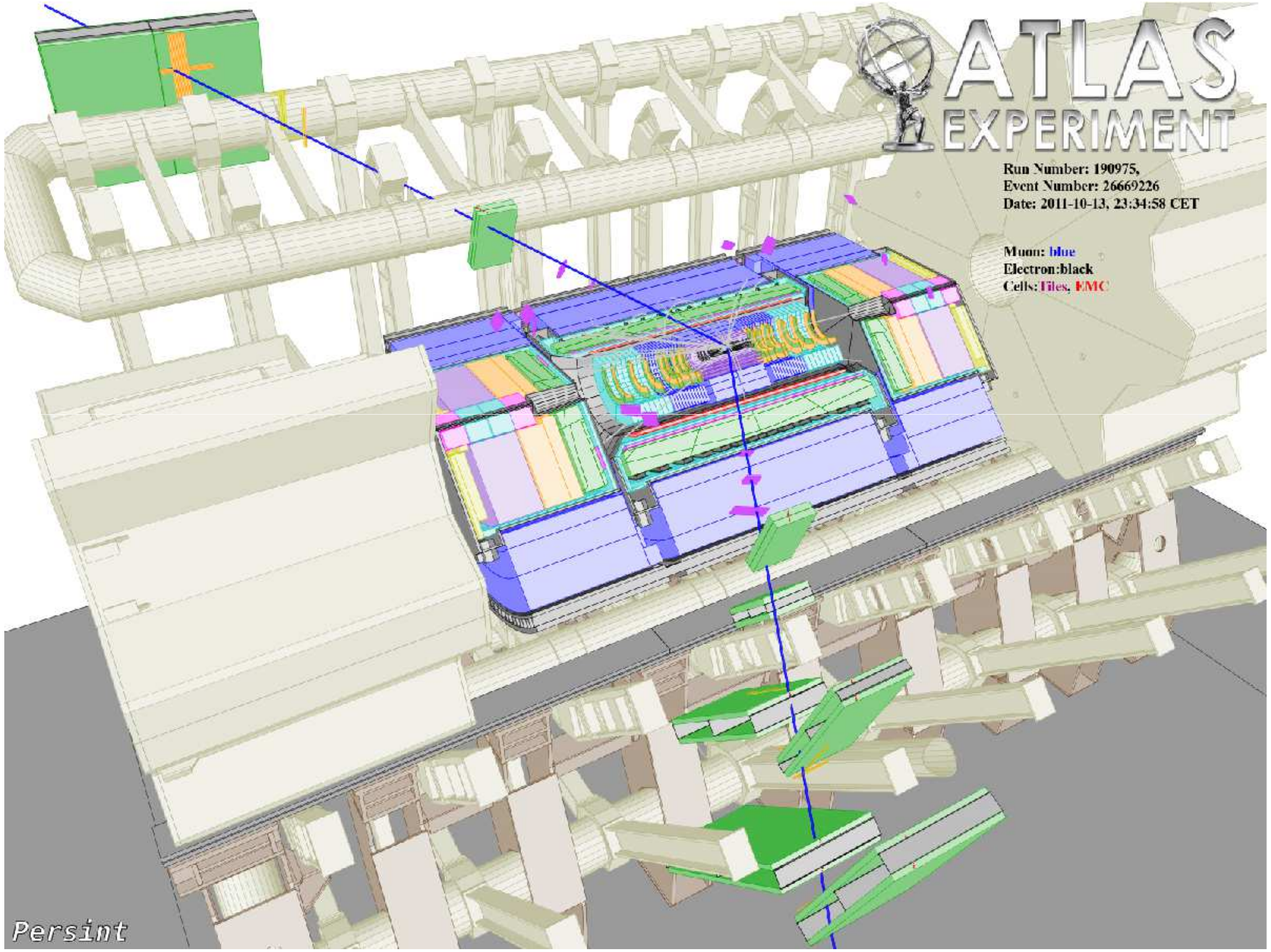
Highest mass ee event

M_{ee}= 1.66 TeV

E_T 329 GeV (η, ϕ)=(2.00, 1.02)
E_T 217 GeV (η, ϕ)=(-1.60, -1.83)



Highest Mass $\mu\mu$ event

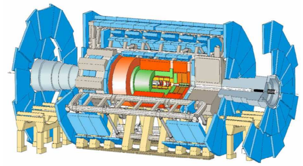


M_{mm}=1.25 TeV

P_T of 648 GeV
(η, ϕ) = (-0.75, 0.49)

P_T of 583 GeV
(η, ϕ) =(-0.36, -2.60)

.



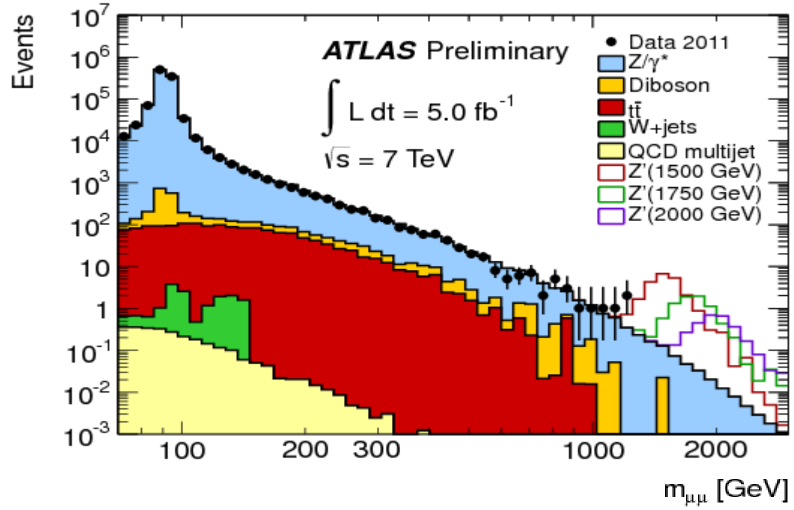
Backgrounds

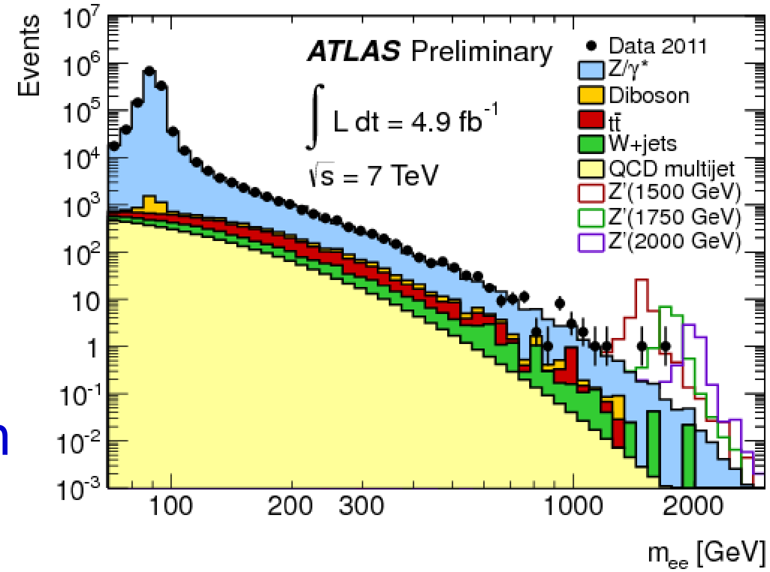
- Backgrounds with two prompt electrons/muons:
  - Drell Yan $\gamma^*/Z \to l^+l^-$

    (irreducible, primary background)
  - Dibosons (WW,WZ,ZZ)
  - ttbar (dileptonic decay)
- Backgrounds with QCD jets, which can fake prompt leptons
  - W+jets
  - QCD multijet production
- Cosmic Rays (negligible contribution to muon channel)

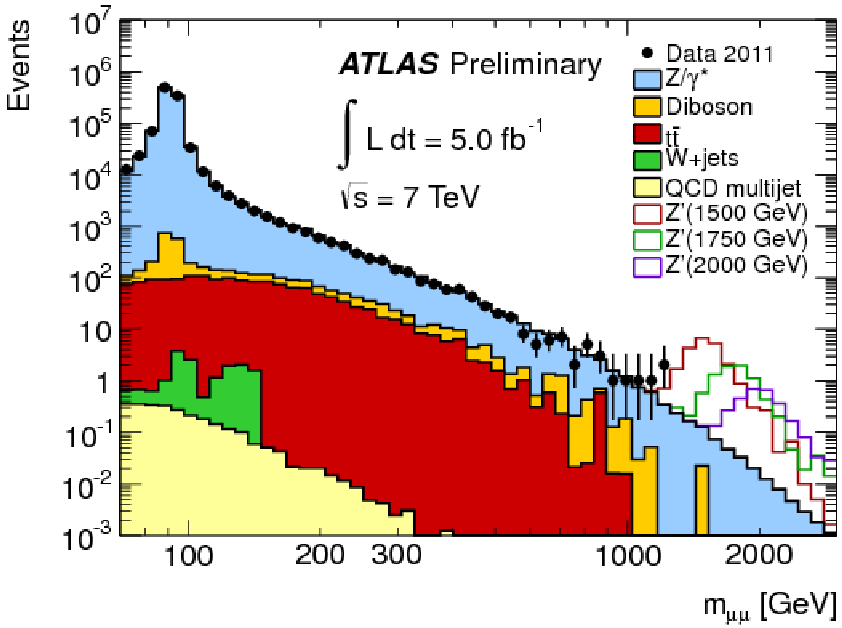
All background except for QCD multijet taken from simulated samples

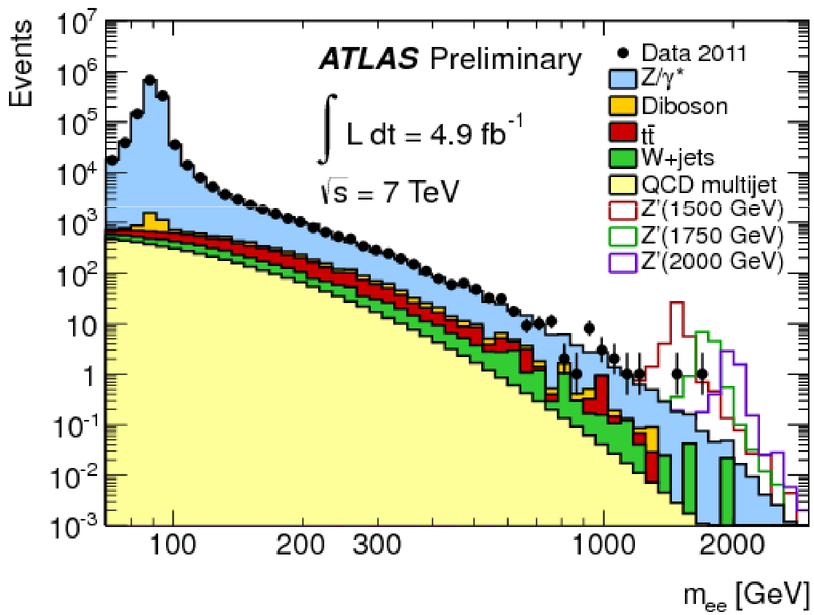
----> What is the fake rate at high energies?

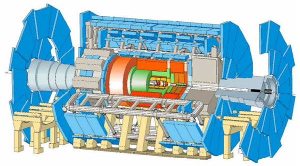




Main Backgrounds

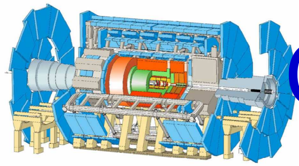






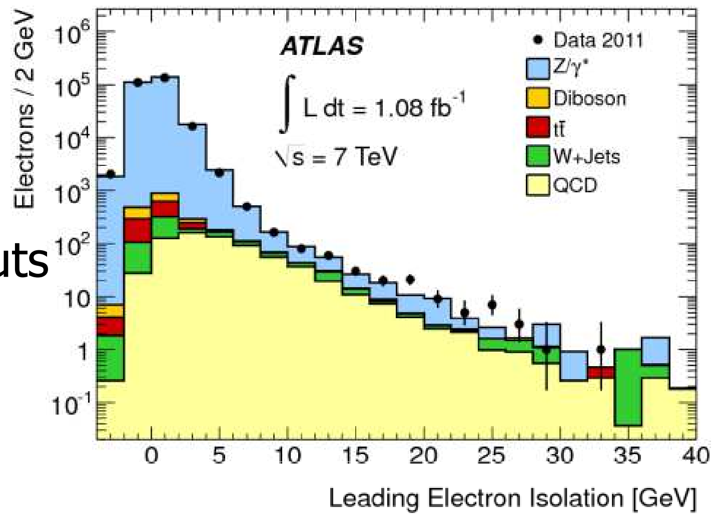
Main Backgrounds

- SM Z/γ Drell-Yan (irreducible, primary background)
  - Produced using Pythia 6.421 with MRST2007 LO*
  - Interference with heavy resonances is small and ignored
  - NNLO K-factors generated using PHOZPR with MSTW2008
- QCD (electron channel only)
  - estimated using "reversed electron identification" and others
- Top quark pair production
  - Produced using MC@NLO 3.41
  - Predicted to approximate-NNLO with 10% uncert.
- SM W+jets (electron channel only)
  - Produced using Alpgen
  - cross-section rescaled to inclusive NNLO calculation of FEWZ
- Dibosons (WW, WZ, ZZ)
  - Produced using Herwig 6.510 with MRST2007 LO*
  - NLO cross-sections calculated using MCFM
- Cosmic Rays (negligible contribution to muon channel)



QCD Multijet Background: electrons

Jets can fake electrons. How large is the fake rate?



1. Baseline Method

►Reverse Identification

- dijet shape from reverted electron identification cuts
- extrapolation to high invariant masses by fitting with empirical function
- normalization by 2-component template fit

2. Cross-check and systematic uncertainties

►Isolation fit method

- use calorimeter isolation distributions
- fit signal/background templates from data for 1st and 2nd electron

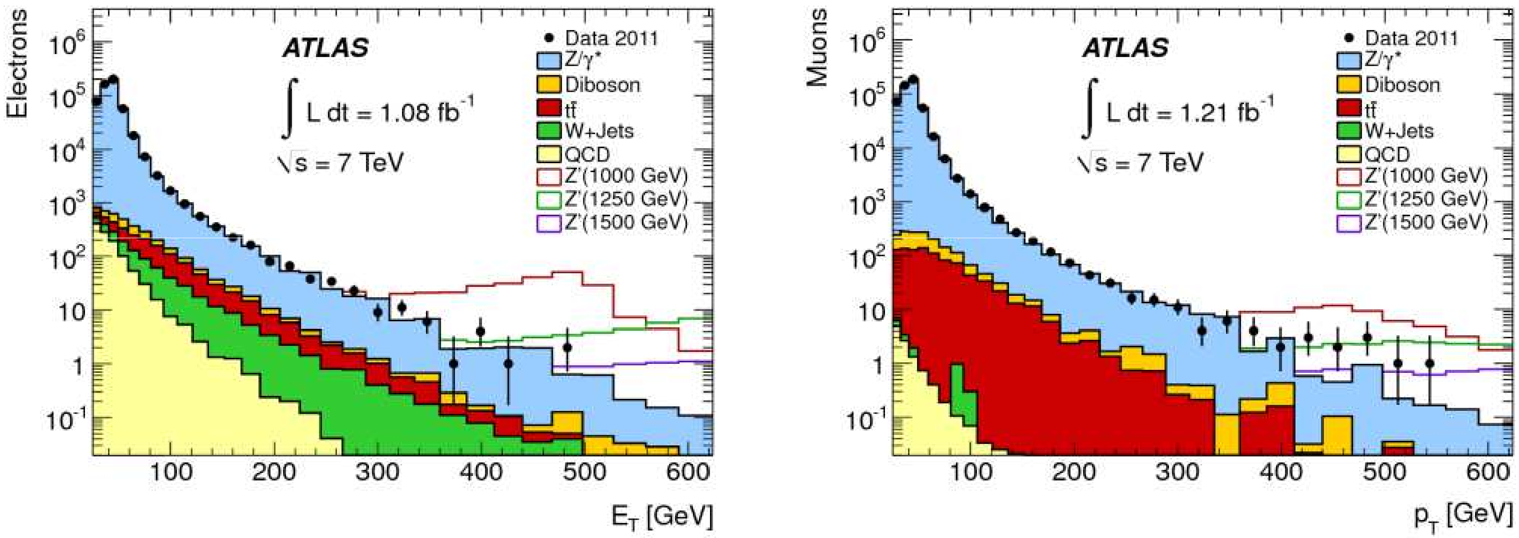
Fake rate estimate

- measure probability for jet-like objects to pass Z' selection (η, E_T)
- apply fake rate on normalization sample (Z' selection on leading, jet selection on second electron)

High p_T Leptons

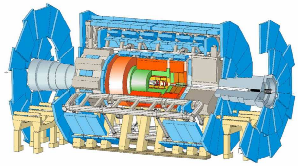
Looking for resonances at high invariant masses

---> need to understand properties of highly energetic objects in ATLAS



Very small control sample, handles:

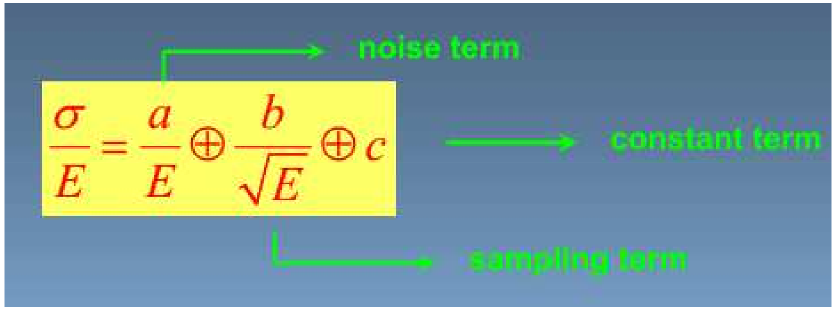
- Muons: calibration runs, cosmics,
- Tag-and-Probe around Z pole ---> extrapolation, simulation

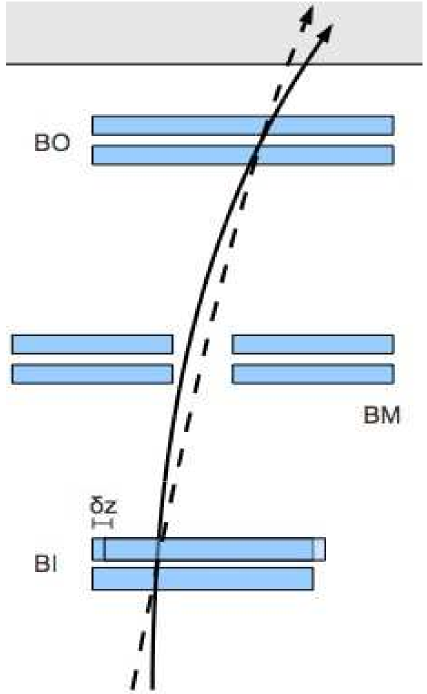


High p_T Leptons – Resolution

Electrons (Resolution 1.2 (barrel)– 1.8% (endcaps) at 1 TeV)

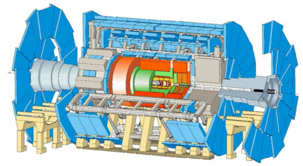
- energy measurement from electromagnetic calorimeter
- resolution at high energies dominated by constant term





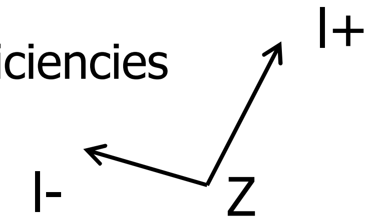
Muons (Resolution > 15% at 1 TeV):

- pt measurement from hits in inner detector and muon spectrometer
- require stringent cuts on number of hits, veto misaligned areas
- measured (as a function of pt) using cosmics, magnet off runs, overlap regions, inner detector vs. muon spectrometer comparisons, Z peak

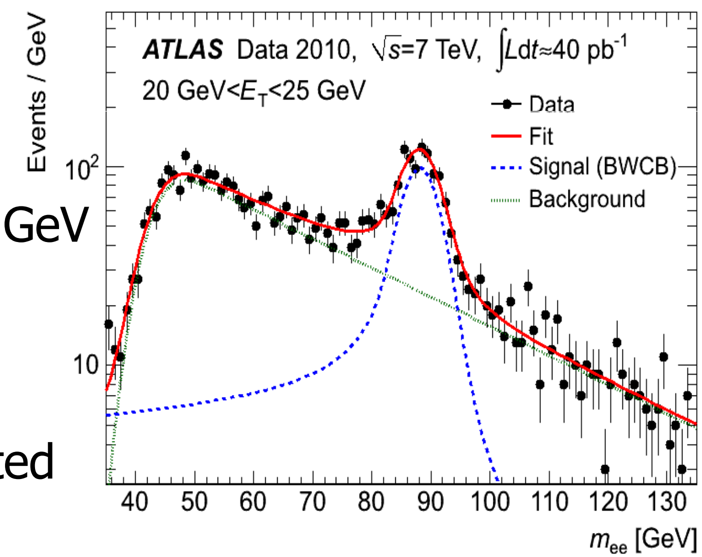


Efficiencies and scale factors

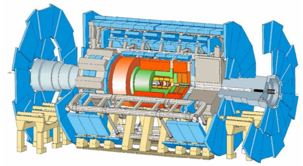
Determine trigger, reconstruction and identification efficiencies in data with Tag-and-Probe



- allows to get relatively unbiased control sample by applying strict cuts on "Tag" and test efficiency on "Probe" (Z ---> l+l-)
- electrons: need to subtract QCD jet background
- leptons from W/Z decay: no estimate above ~200 GeV
- extrapolation by observing of trends, simulation

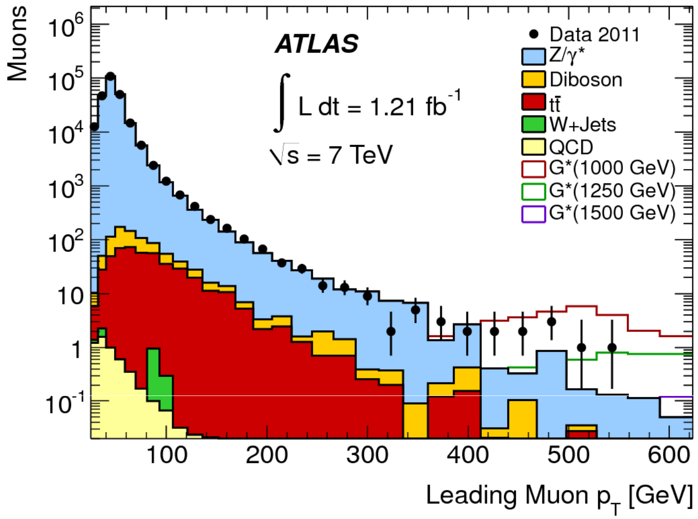


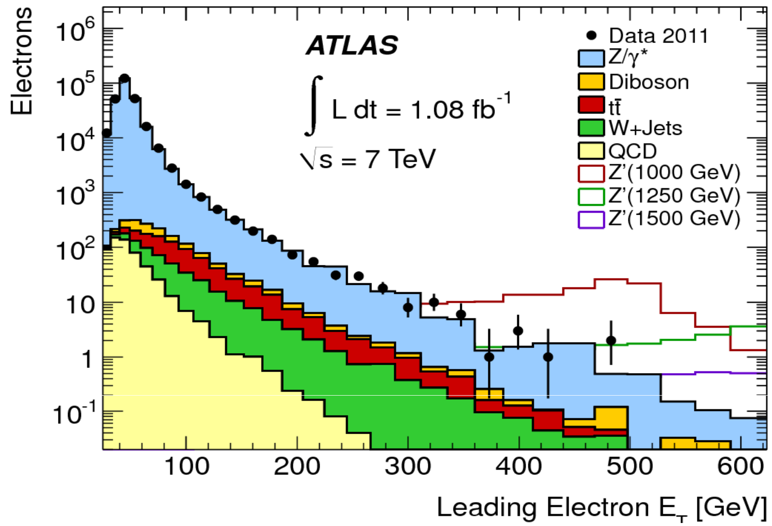
Electrons: No decrease of selection efficiency expected at high energies (careful with isolation cut)

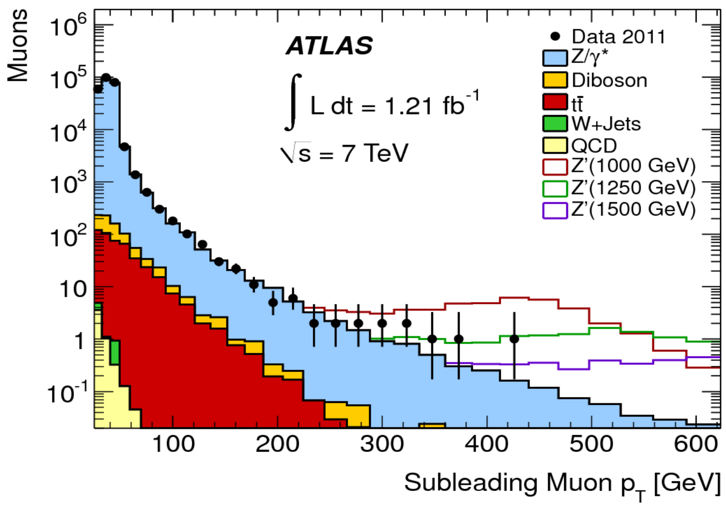


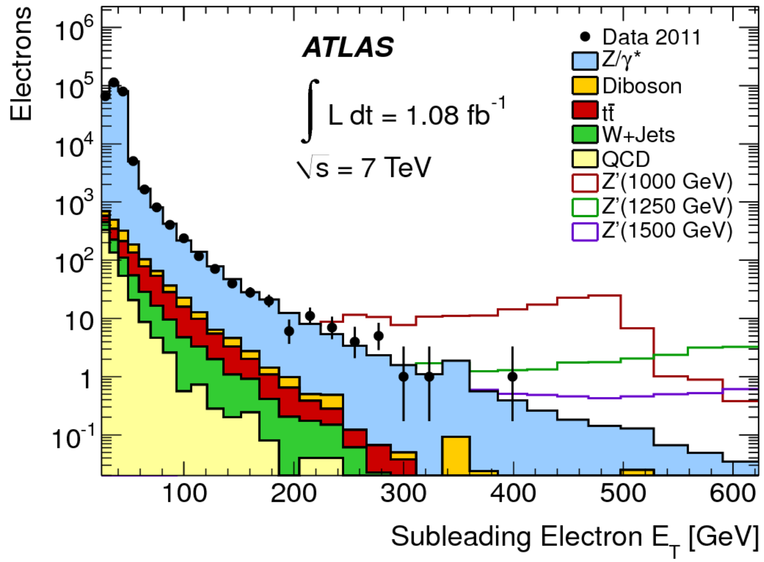
Dilepton Kinematics

Good agreement with background expectations



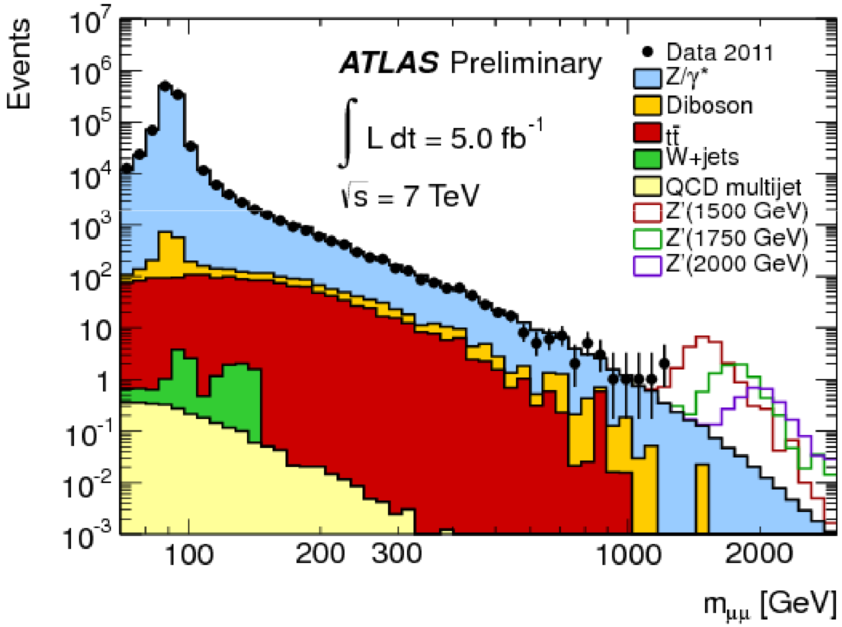


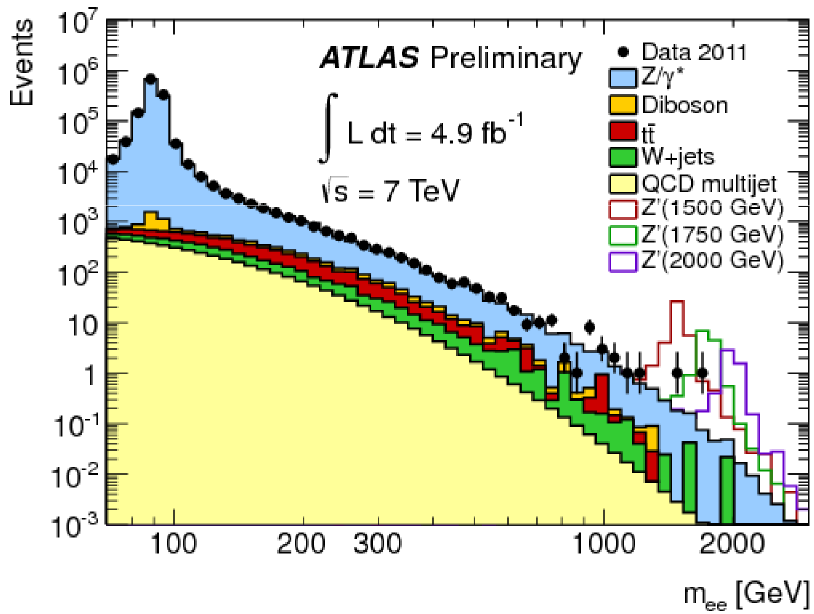




Dilepton Distributions

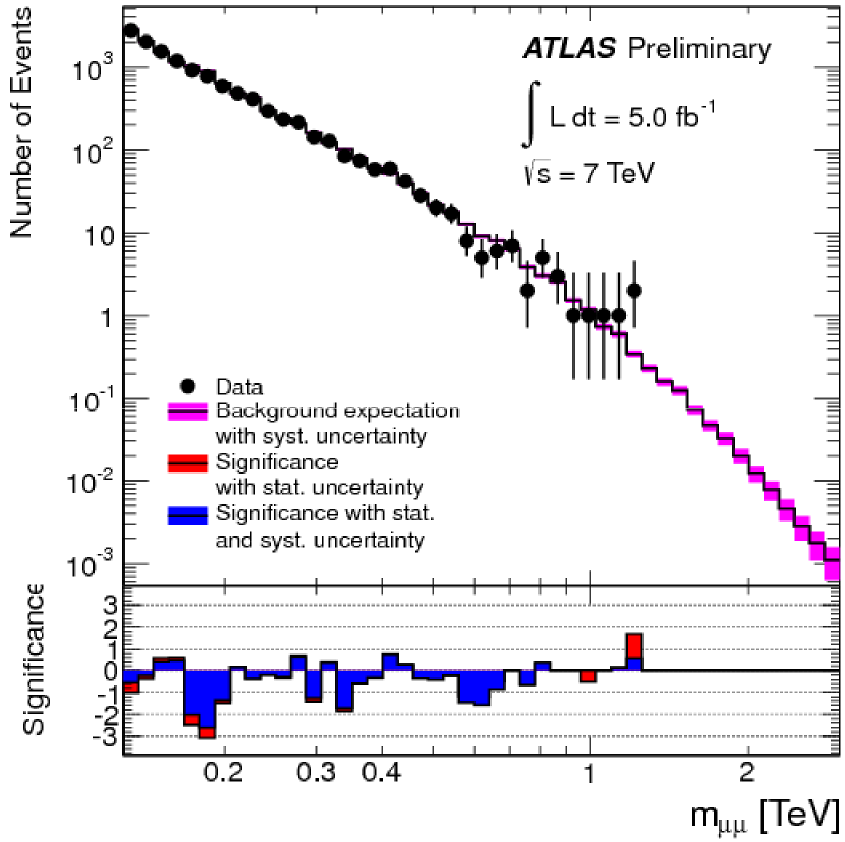
Backgrounds are normalised to data in Z-peak region (70 - 110 GeV)



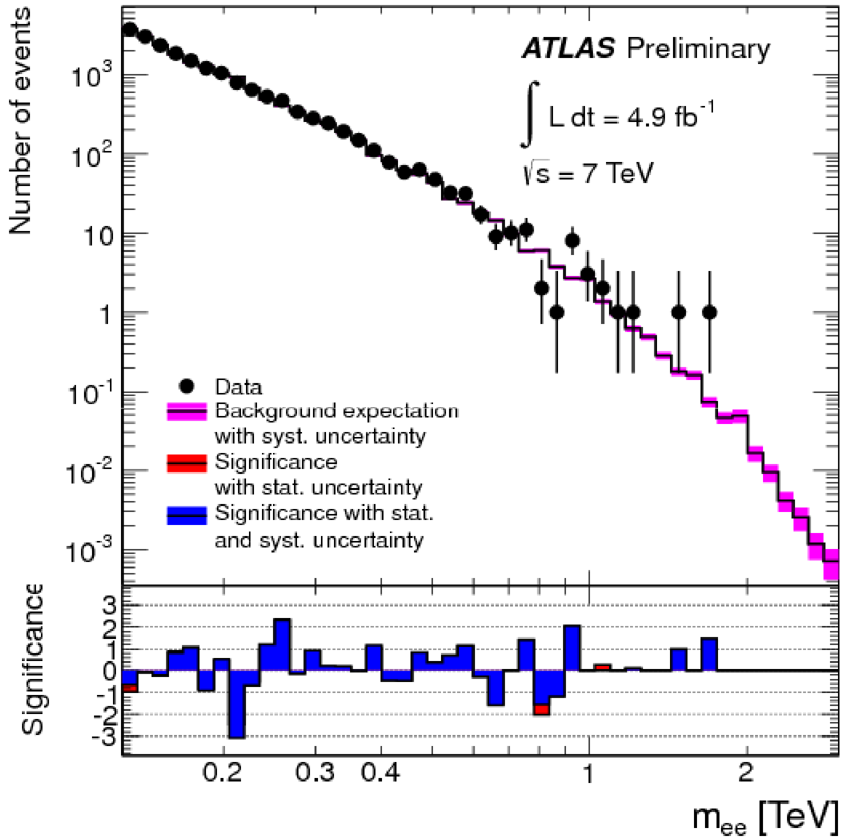


The bin width is constant in log(mll)

New Physics?



p-value = 0.82



p-value = 0.13

No evidence of New Physics... so we set limits!

Limits Setting and Errors

- Because normalize MC to data in Z peak region (70 < $m_{\ell\ell}$ < 110 GeV)

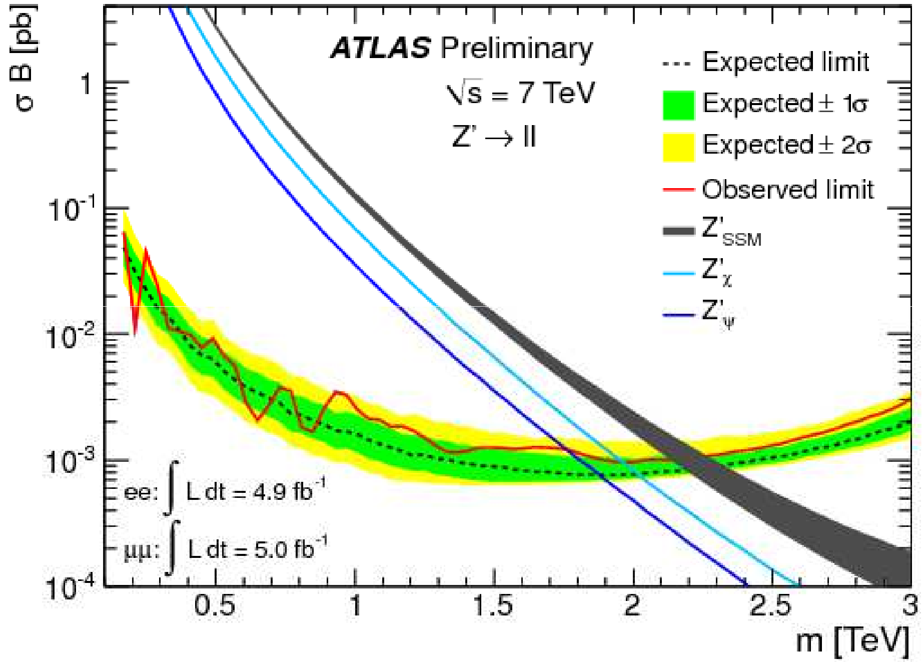
  luminosity and other mass independent systematics cancel between Z and Z′/G
- Uncertainties treated as correlated across all bins

Table 1. Summary of systematic uncertainties on the expected numbers of events at $m_{\ell\ell} = 2$ TeV. NA indicates that the uncertainty is not applicable, and "-" denotes a negligible entry.

Source	Dielectrons		Dimuons	
	Signal	Background	Signal	Background
Normalization	5%	NA	5%	NA
PDF/α_s /scale	NA	20%	NA	20%
Electroweak corrections	NA	4.5%	NA	4.5%
Efficiency	-	-	6%	6%
W + jets and QCD background	NA	26%	NA	-
Total	5%	34%	8%	21%

Z' Limits

- Upper limit on signal cross-section set at 95% C.L.
- Bayesian technique using a template shape fit & a prior assumed to be flat in signal cross-section

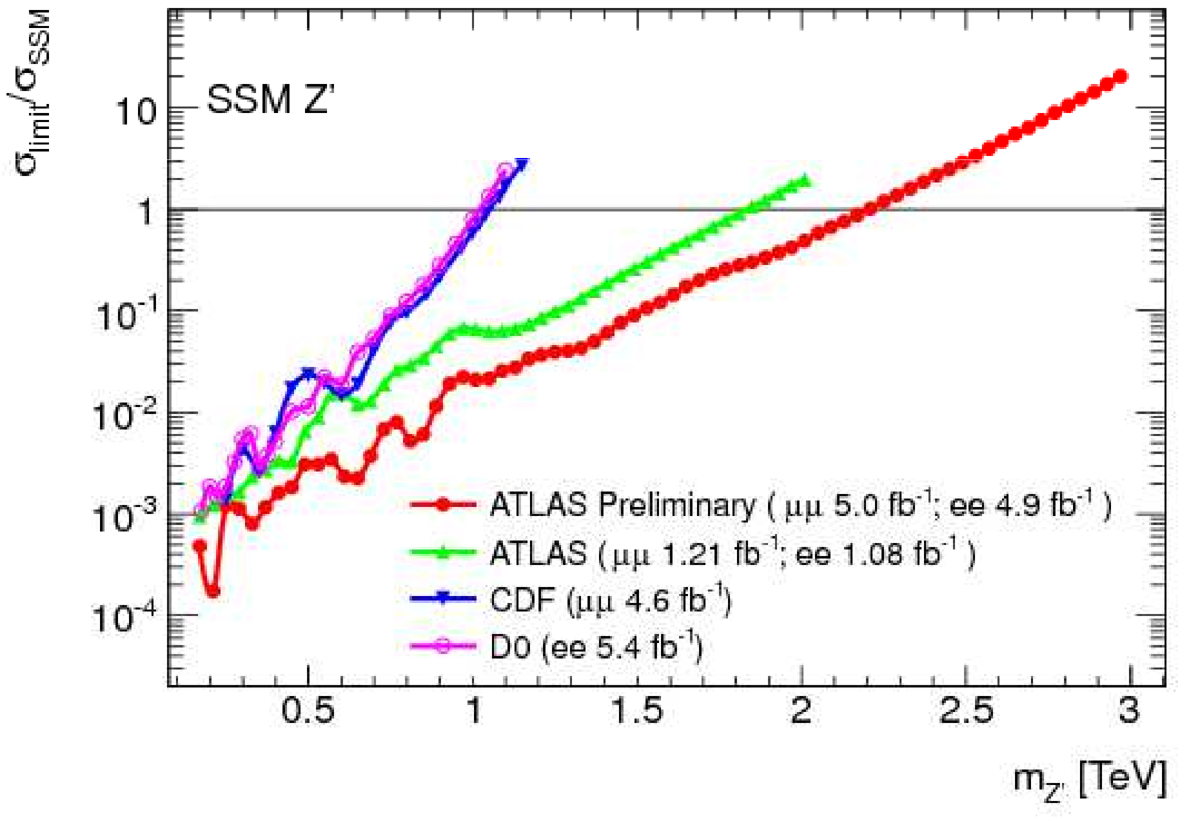


95 % C.L. mass lower limit in TeV on Z'_{SSM} resonance

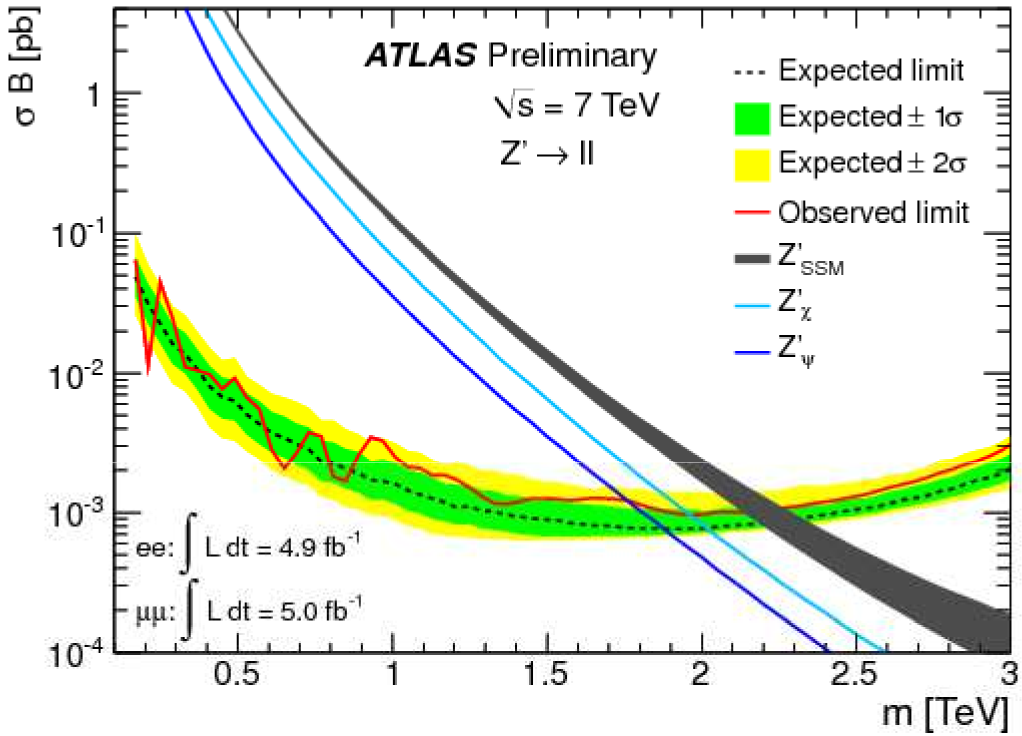
	$Z'_{SSM} \to e^+e^-$	$Z'_{SSM} \to \mu^+\mu^-$	$Z'_{SSM} \to \ell^+\ell^-$
Observed limit [TeV]	2.08	1.99	2.22
Expected limit [TeV]	2.13	2.00	2.25

Comparison of Z'_{SSM} Limits

- Tevatron experiments exclude $M_{(Z'\,SSM)} < 1.071$ TeV
- LHC experiments, using ~40 pb^{-1} 2010 data exclude
  $M_{(Z'\,SSM)} < 1.042$ TeV (ATLAS) & 1.140 TeV (CMS)
- Indirect constraints from LEP extend these limits to 1.787 TeV



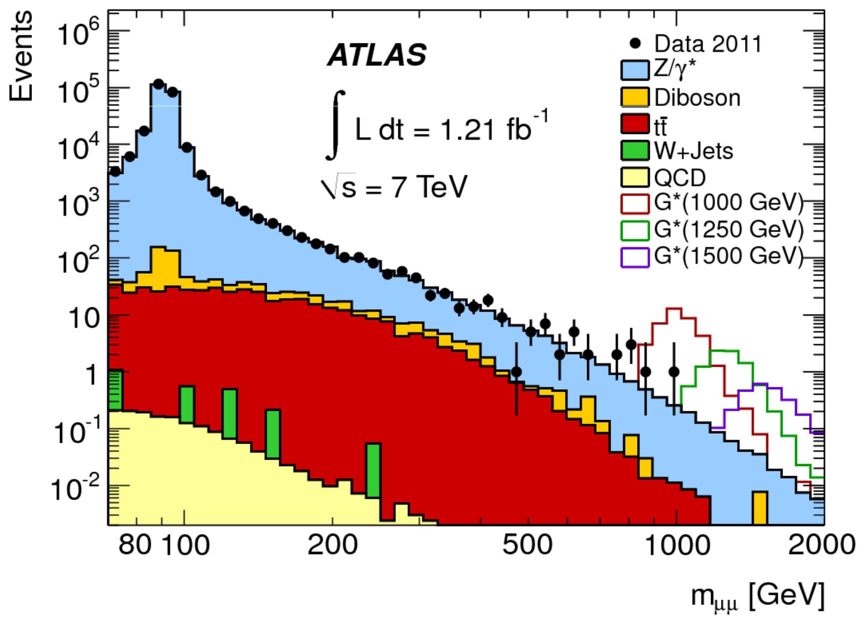
Z′ Combined Limits

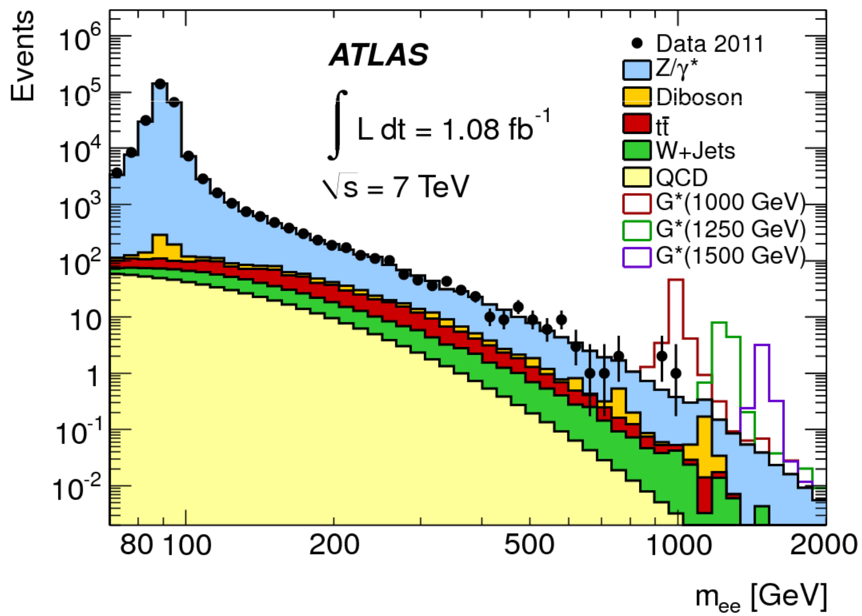


Model	Z'_ψ	Z'_N	Z'_η	Z'_I	Z'_S	Z'_χ
Observed limit [TeV]	1.79	1.79	1.87	1.86	1.91	1.97
Expected limit [TeV]	1.87	1.87	1.92	1.91	1.95	2.00

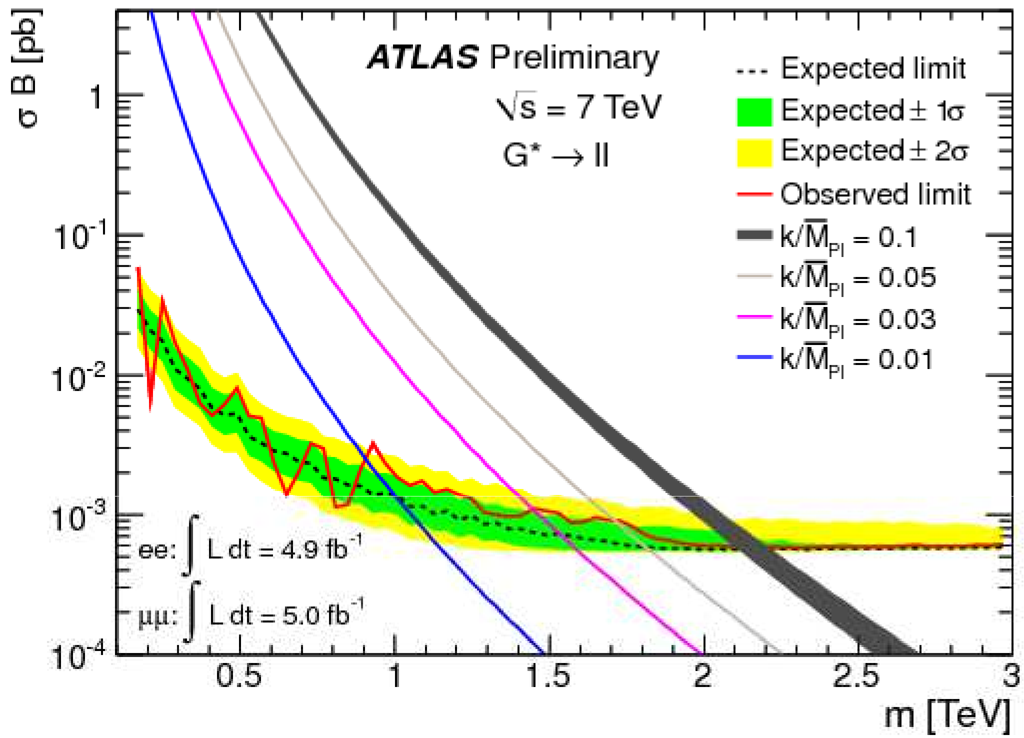
RS Search: Analysis Strategy

- Use same dataset as for Z′ search
- Set limits in a similar bayesian way



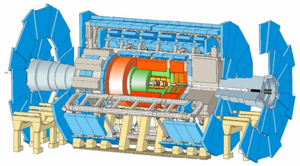


RS G* limits



Model		Mass Limit	(TeV)
k/M_{Pl}=0.1	e^+e^-	$\mu^+\mu^-$	l^+l^-
RS Graviton	2.03 (2.05)	1.90 (1.92)	2.16 (2.17)

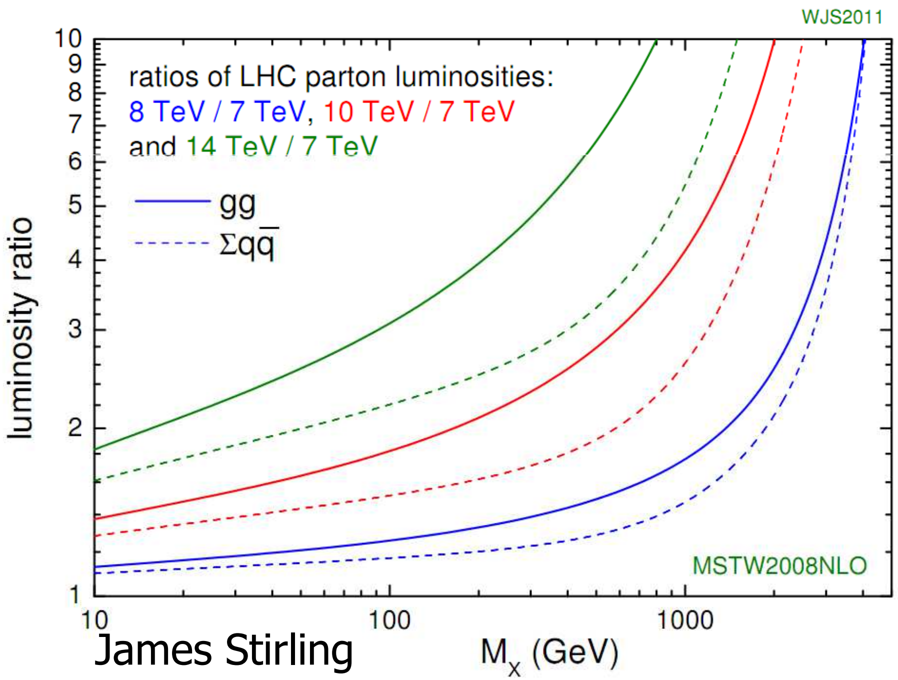
	RS graviton			
Model/Coupling	0.01	0.03	0.05	0.1
Mass limit [TeV]	0.91	1.45	1.71	2.16



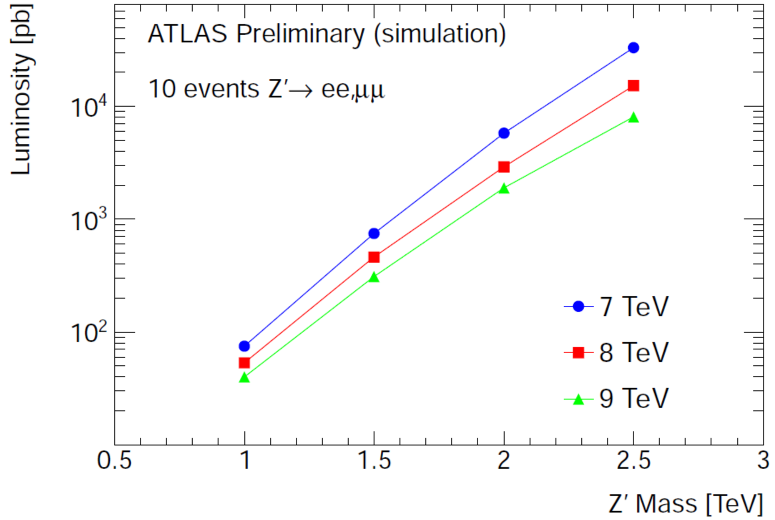
7 → 8 TeV

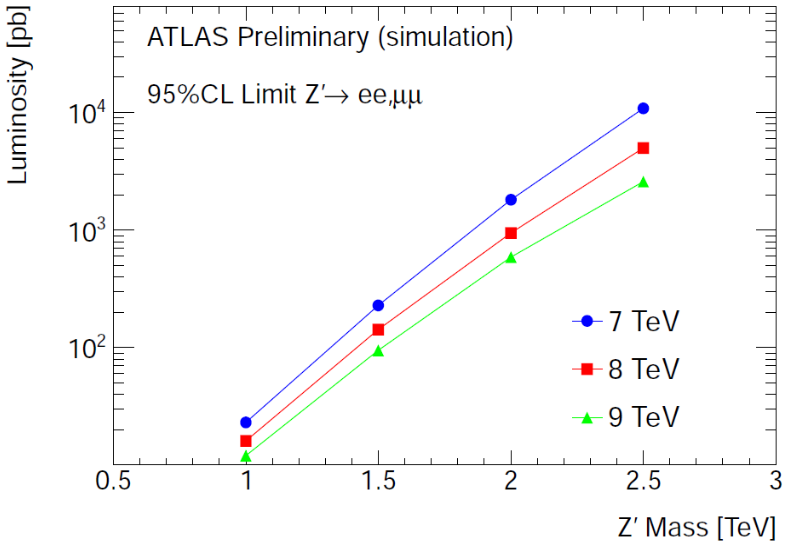
σ(Z′ for $M_{Z'}$=2.5 TeV)~ 2 x higher at 8 TeV than 7 Te V

7->8 gives us extra 10 fb^{-1} at 2 TeV

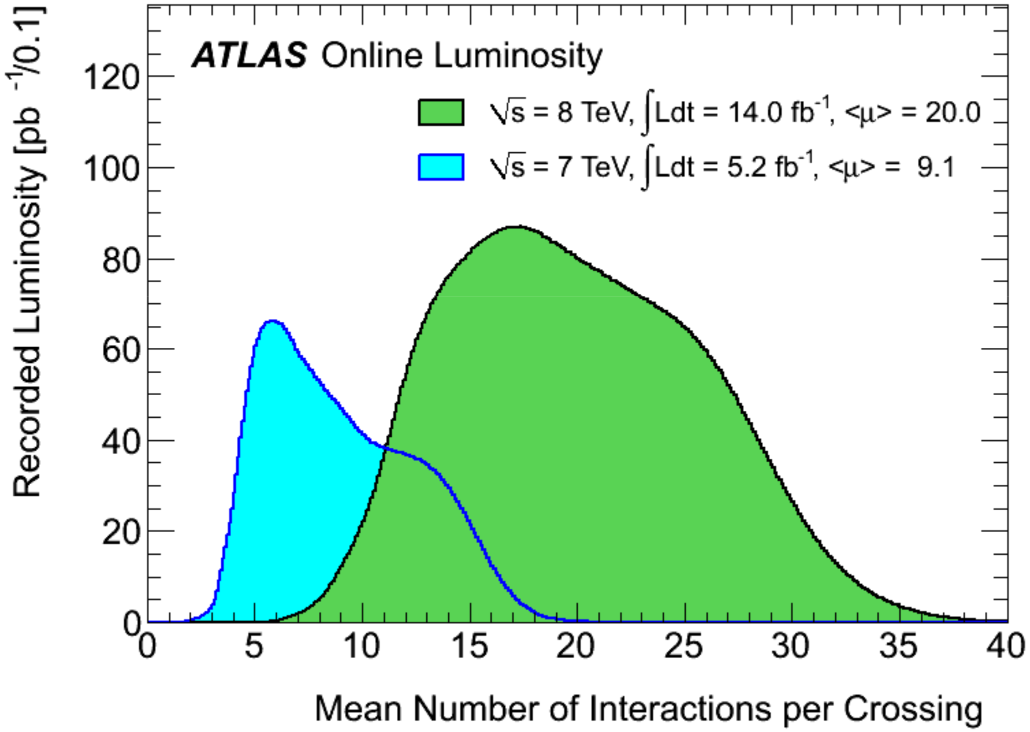


James Stirling

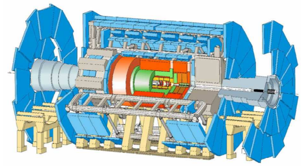




7 → 8 TeV



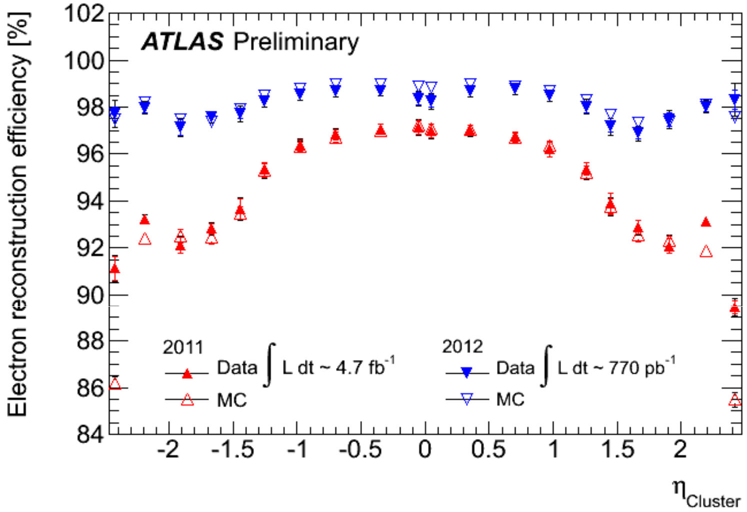
ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 14.0 fb⁻¹, <μ> = 20.0
√s = 7 TeV, ∫Ldt = 5.2 fb⁻¹, <μ> = 9.1
Recorded Luminosity [pb⁻¹/0.1]
Mean Number of Interactions per Crossing
0
20
40
60
80
100
120
0
5
10
15
20
25
30
35
40

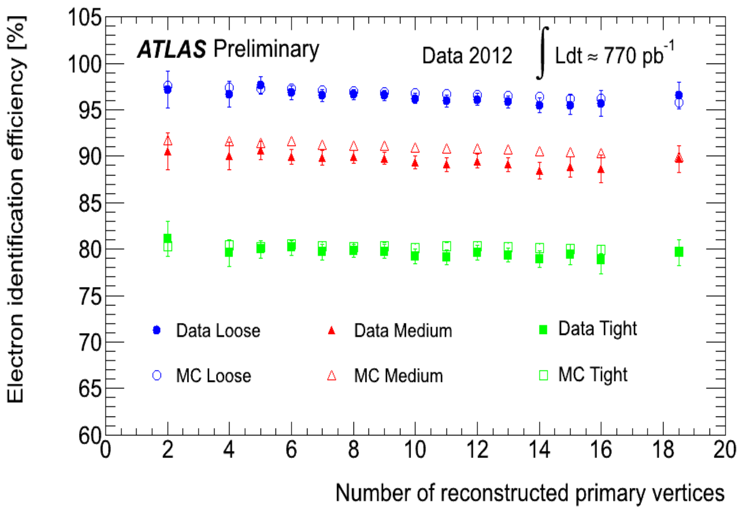


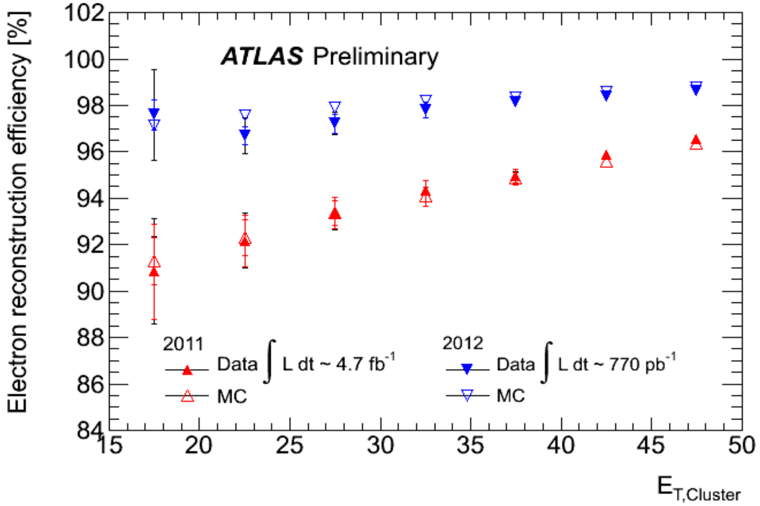
7 → 8 TeV

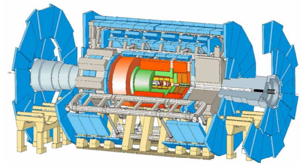
improvements to the electron reconstruction and identification, w.r.t 2011, to maintain good performance in high pile-up conditions.

- ❑The ATLAS track pattern recognition and global χ^2 fit were updated to account for energy losses due to bremsstrahlung,
- ❑and the track-to-cluster matching algorithm was improved to be less sensitive to bremsstrahlung losses.









8 TeV Analysis

Follows the analysis strategy presented for 7 TeV search

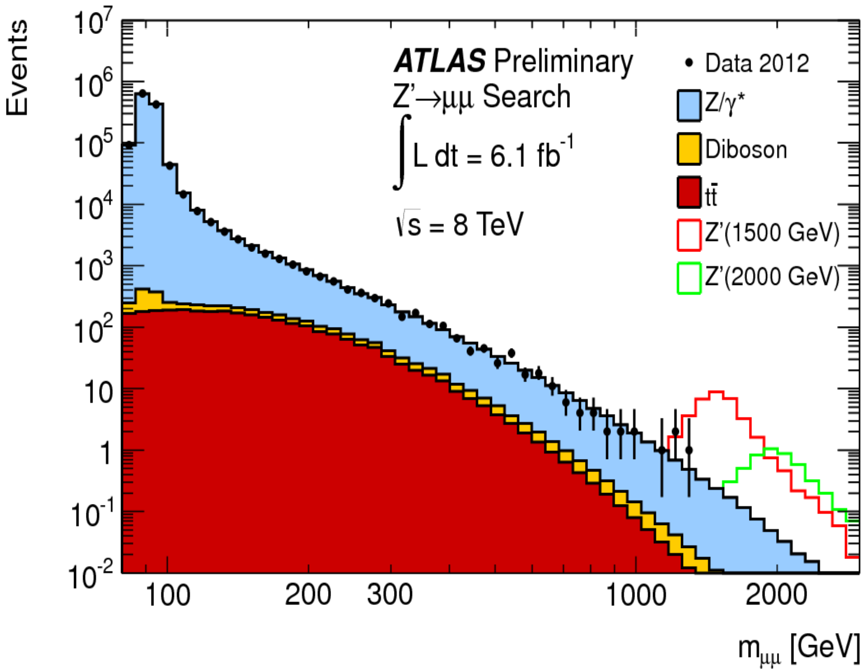
ee changes

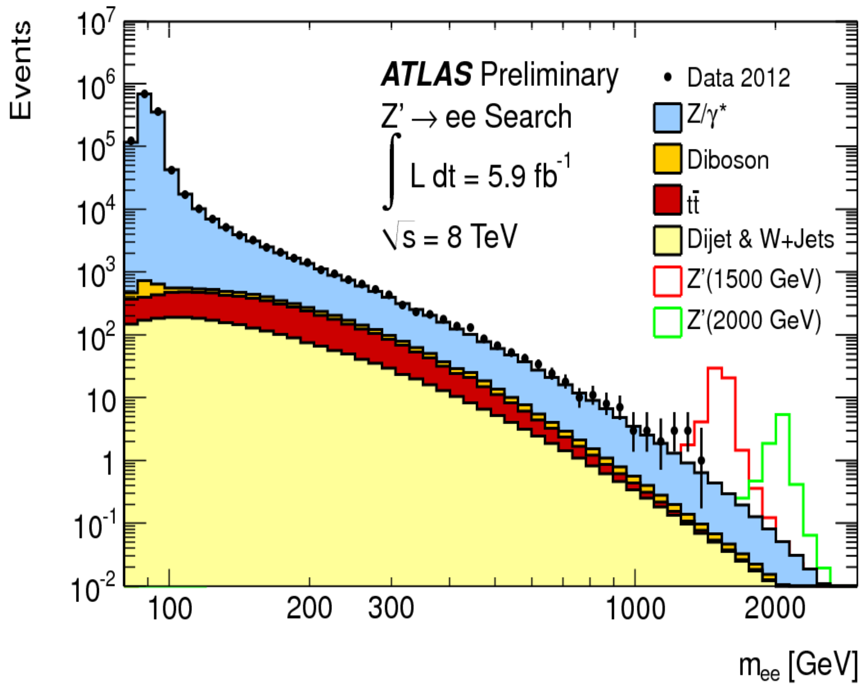
Changed to diphoton trigger with $Et_{leading\ e}$ > 35 GeV & $Et_{subleading\ e}$ >25 GeV

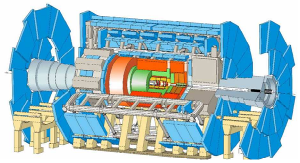
preferred over the dielectron trigger as the lack of requirements on the electron track is advantageous in the background-determination method.

$Pt_{leading\ e}$ > 40 GeV & $Pt_{subleading\ e}$ >30 GeV

Improved e reconstruction algorithm







8 TeV

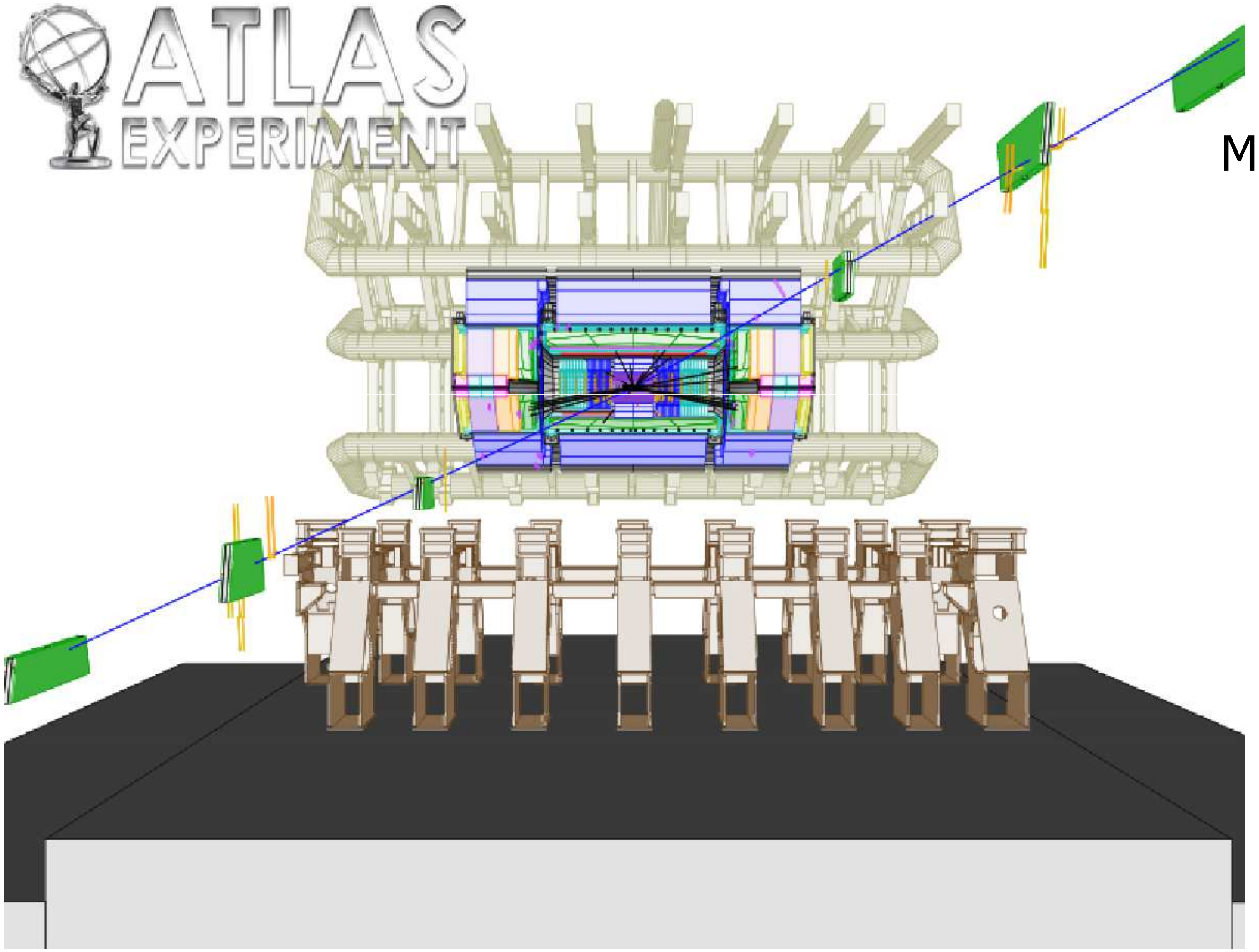
Table 1: The expected and observed number of events in the dielectron channel. The errors quoted include both statistical and systematic uncertainties.

m_{ee} [GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000
Z/γ^*	36200 ± 1500	4330 ± 180	412 ± 20	21.6 ± 1.5	3.03 ± 0.35
$t\bar{t}$	2190 ± 250	750 ± 130	53 ± 19	0.86 ± 0.18	0.041 ± 0.017
W + jets	470 ± 130	130 ± 40	10.6 ± 3.0	0.30 ± 0.09	0.026 ± 0.009
Diboson	482 ± 34	172 ± 22	21 ± 8	0.91 ± 0.05	0.117 ± 0.014
Dijet	720 ± 240	250 ± 120	34 ± 23	2.1 ± 2.0	0.4 ± 0.5
Total	40100 ± 1600	5620 ± 260	530 ± 40	25.8 ± 2.5	3.6 ± 0.6
Data	39875	5760	615	31	5

Table 2: The expected and observed number of events in the dimuon channel. The errors quoted include both statistical and systematic uncertainties.

$m_{\mu\mu}$[GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000
Z/γ^*	27800 ± 1800	2800 ± 250	247 ± 27	12.4 ± 1.6	1.8 ± 0.3
$t\bar{t}$	1390 ± 170	470 ± 100	33 ± 15	0.68 ± 0.30	0.04 ± 0.04
Diboson	306 ± 25	107 ± 17	12 ± 6	0.47 ± 0.09	0.050 ± 0.020
Total	29500 ± 1800	3370 ± 270	293 ± 31	13.6 ± 1.6	1.9 ± 0.3
Data	28516	3341	276	10	3

Highest Mass Event

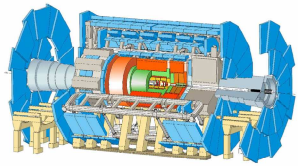


M_{mm}=1.258 TeV

P_T of 289 GeV
(η) = (1.54)

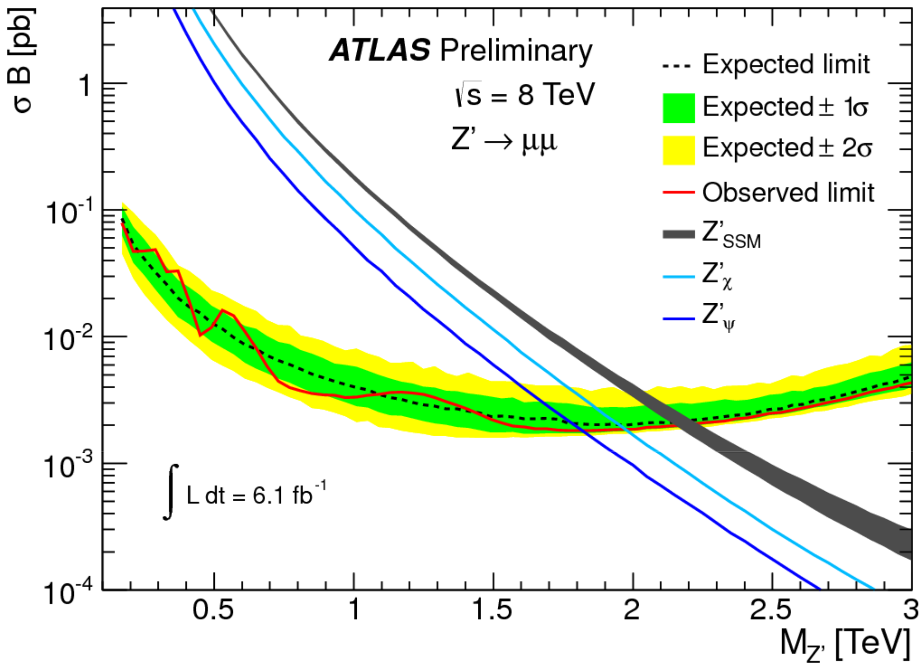
P_T of 274 GeV
(η) =(-1.35)

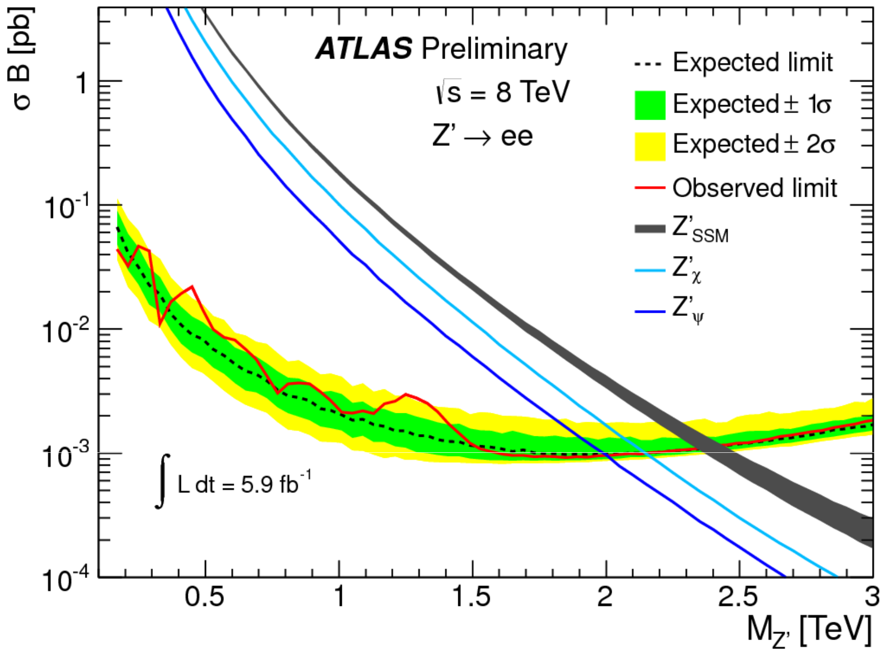
.



8 TeV Analysis

ATLAS-CONF-2012-129





	$Z'_{SSM} \to e^+e^-$	$Z'_{SSM} \to \mu^+\mu^-$	$Z'_{SSM} \to \ell^+\ell^-$
Observed mass limit [TeV]	2.39	2.19	2.49
Expected mass limit [TeV]	2.39	2.17	2.49

Model	Z'_ψ	Z'_N	Z'_η	Z'_I	Z'_S	Z'_χ
Observed mass limit [TeV]	2.09	2.10	2.15	2.14	2.18	2.24
Expected mass limit [TeV]	2.07	2.08	2.14	2.13	2.17	2.23

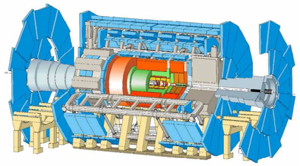
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Summary of Recent LHC SSM Z′ Limits

excluded at at 95% C.L.

7 TeV 2011 data (5 fb^{-1})

	ATLAS	CMS
7 TeV 2011 data (5 fb^{-1})	2.21 TeV	2.33 TeV
7 TeV 2011 + 4 fb^{-1} of 8 TeV 2012 data		2.59 TeV
8 TeV 2012 data (6fb^{-1})	2.49 GeV	

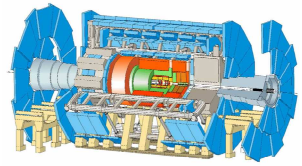


Conclusion

- LHC has been working very well at beam energy 4 TeV
- ATLAS detector has been efficiently collecting data
  - distributions so far consistent with SM expectations

- We have analysed at presented limits using 6 fb^{-1} 2012 data
- ATLAS has recorded over 20 fb^{-1} 2012 data @ 8 TeV
  - We look forward to analysing all of this data
    - Expect updated 8 TeV results in early 2013

- We look forward to searching for New Physics at a higher center of mass energy following the upgrade of the LHC



- Thank You!