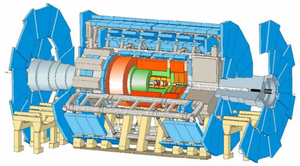


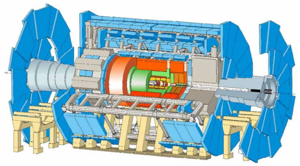
Graviton

searches using the ATLAS detector

Dr Tracey Berry

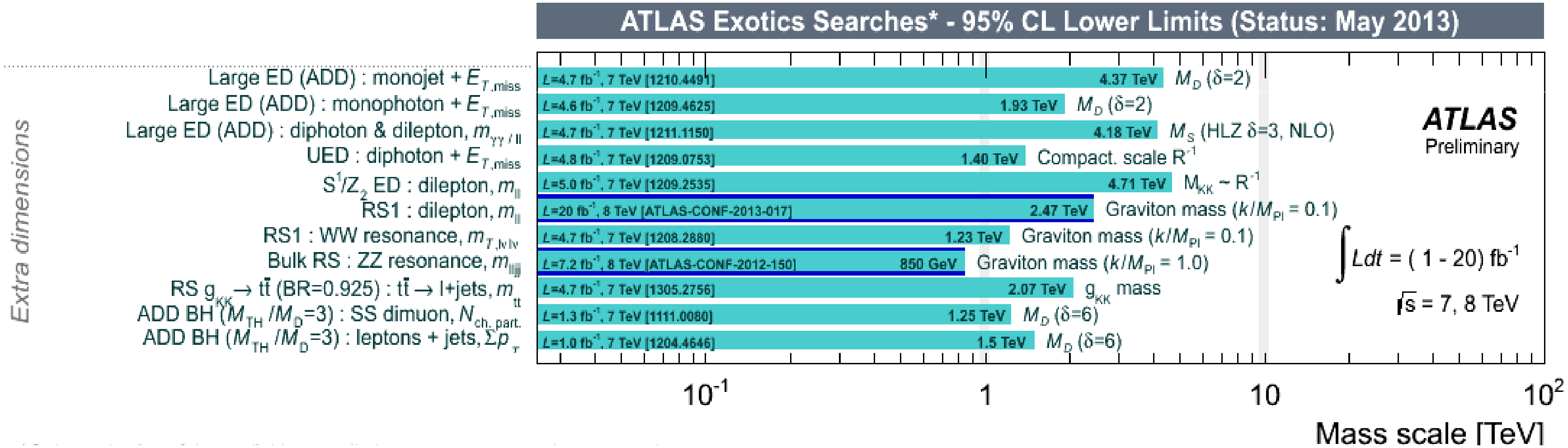
Royal Holloway

University of London



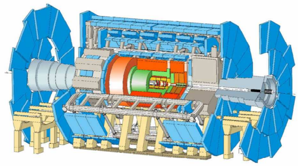
Overview

- Motivation for Gravitational Effects Searches
- Brief Introduction to Extra Dimensional Models
- LHC & ATLAS
- An overview of ATLAS Graviton Searches

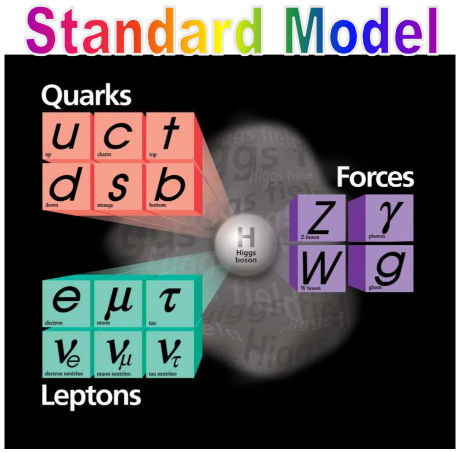


- Conclusions/Outlook

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



The Standard Model



Motivation for searching for something beyond the SM….

Gravity	Weak	Electromagnetic	Strong
Graviton (not observed)	W^+, W^-, Z	Photon	Gluon
All	Quarks & Leptons	Quarks, charged leptons, W^+, W^-	Quarks & gluons
10^{-41}	0.8	1	25

Gravity is very weak! → Hierarchy Problem

M_{EW} (10^3 GeV) << M_{Planck} (10^{19} GeV)?

→ Extra Dimensional Models

A short History of Extra-Dimensions

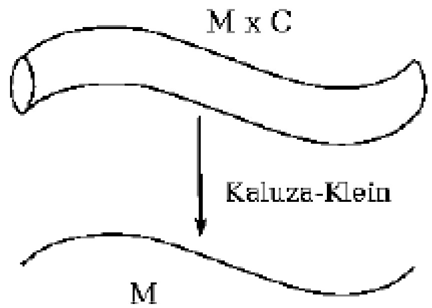
- 1921-26 Kaluza & Klein attempted to unify EM and relativity by adding a dimension to general relativity

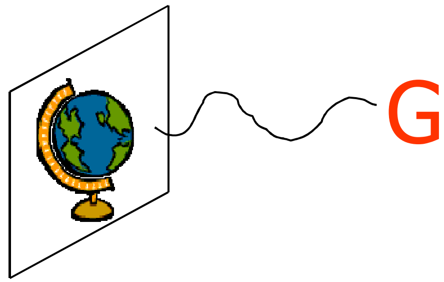
  → Compatification → Kaluza-Klein towers

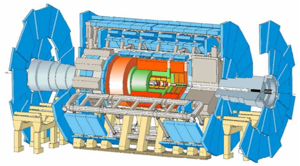
- → E= nhc/R

  (R = ED radius, n = integer)

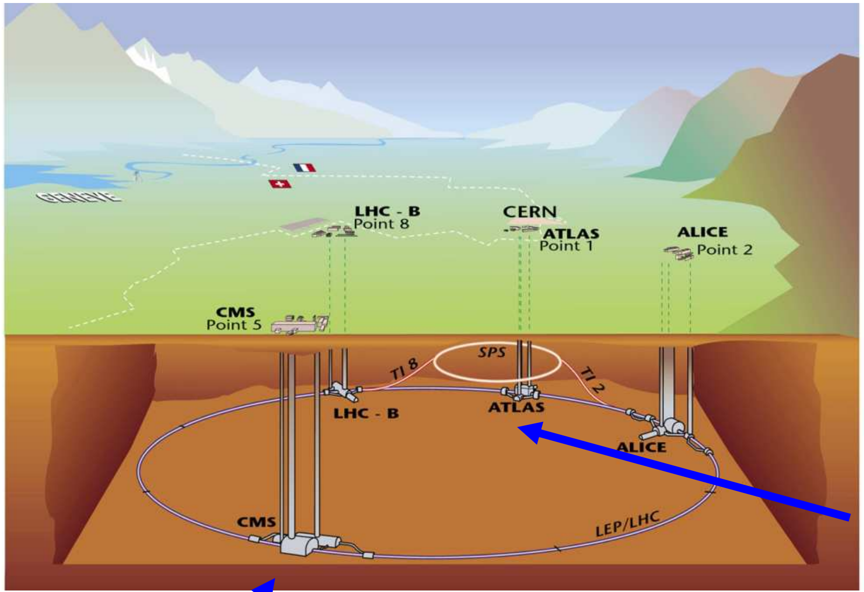
- 1998: Large ED Arkani-Hamed, Dimopoulis, Dvali)
- 1999: Warped ED: Randall Sundrum
- Since then: many more.....







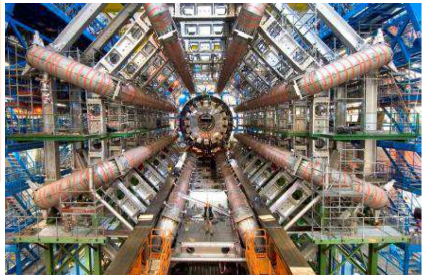
Large Hadron Collider (LHC)

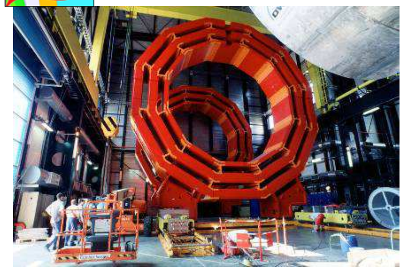


proton – proton collisions

@ $\sqrt{s}$ = 7, 8

Future: 13-14 TeV



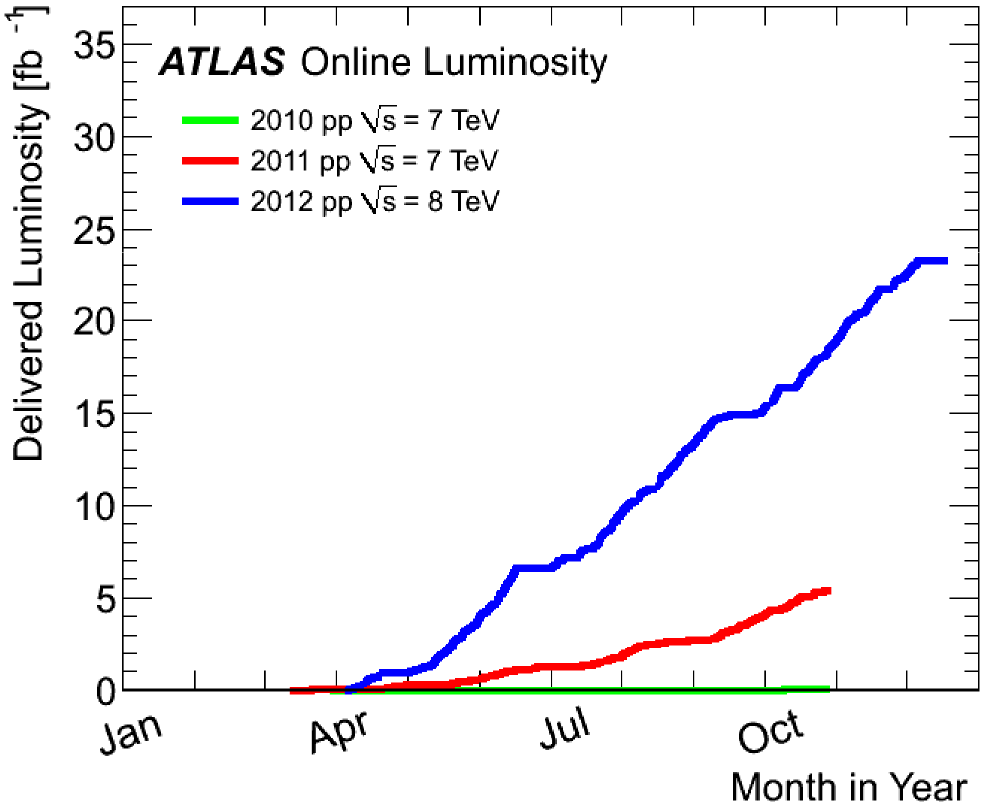


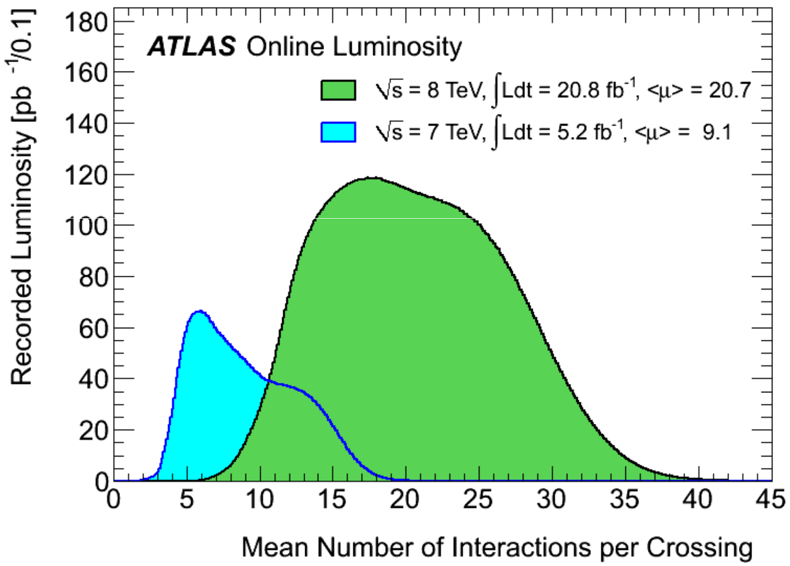
6

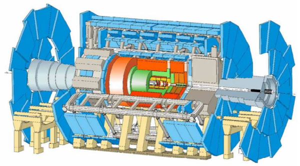
6

The Large Hadron Collider (LHC)

pp collisions at √s=7 TeV in 2011
and √s=8 TeV in 2012



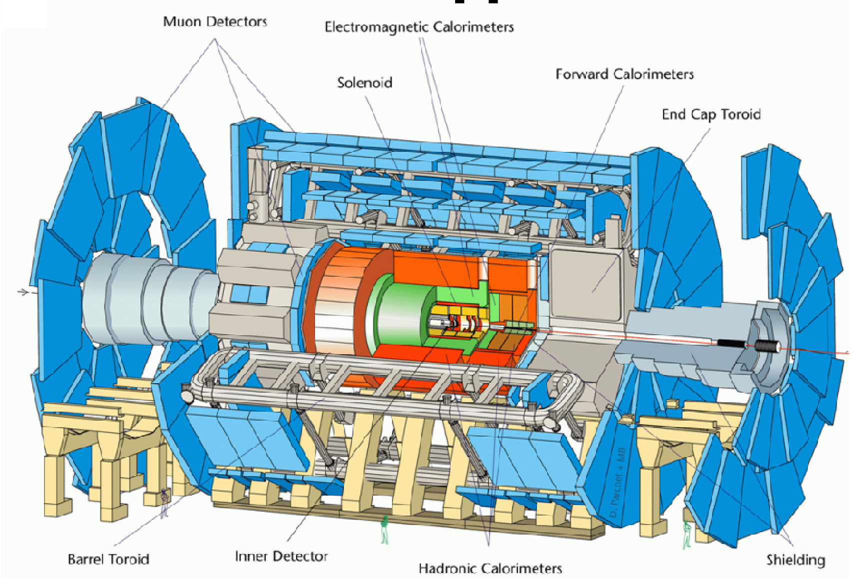




ATLAS and CMS Experiments

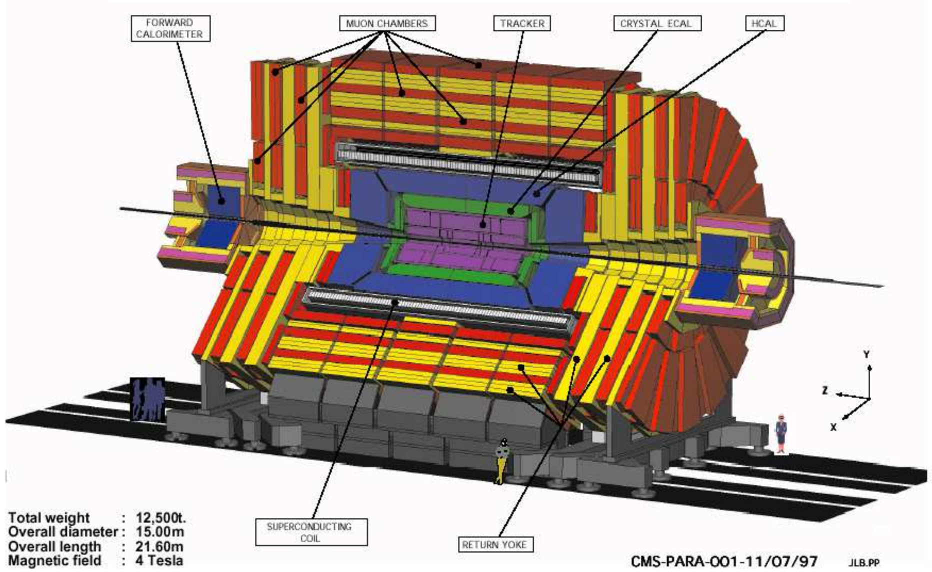
Large general-purpose particle physics detectors

A Toroidal LHC ApparatuS



Total weight	**7000 t**
Overall diameter	**25 m**
Barrel toroid length	**26 m**
End-cap end-wall chamber span	**46 m**
Magnetic field	**2 Tesla**

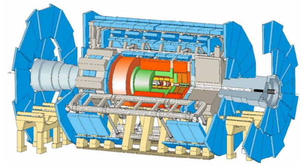
Compact Muon Solenoid



Total weight	**12 500 t**
Overall diameter	**15.00 m**
Overall length	**21.6 m**
Magnetic field	**4 Tesla**

Detector subsystems are designed to measure:
energy and momentum of γ ,e, μ, jets, missing E_T up to a few TeV

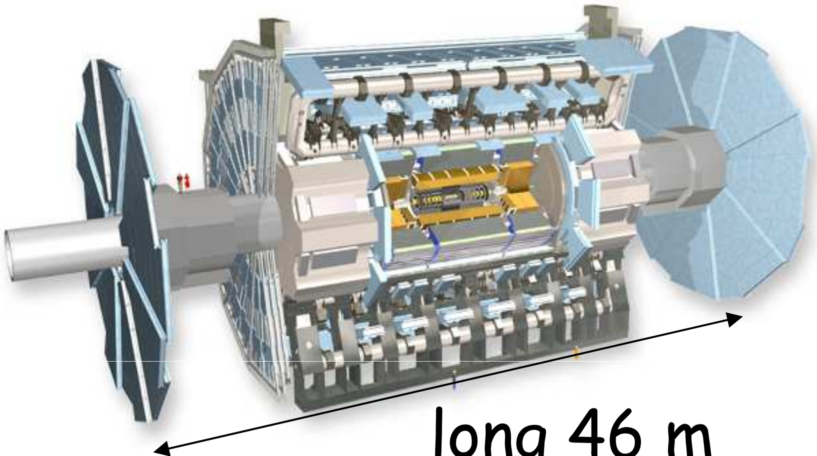
8



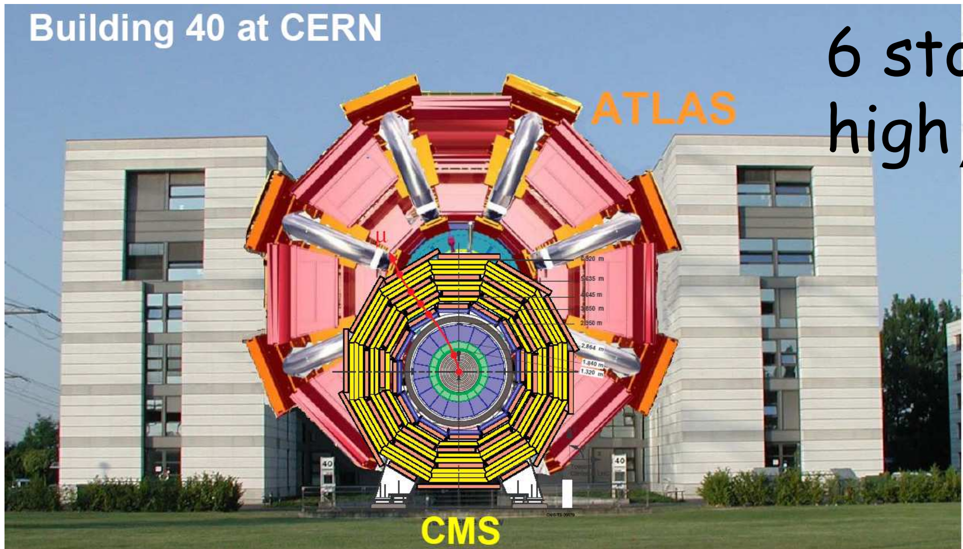
ATLAS

Largest volume particle detector ever constructed!

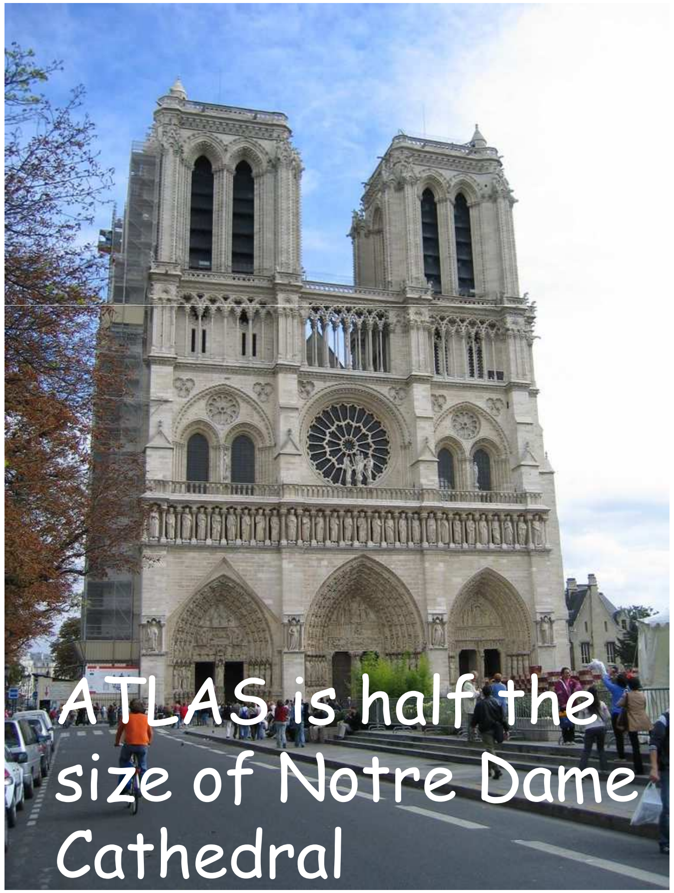
Overall
diameter
25 m



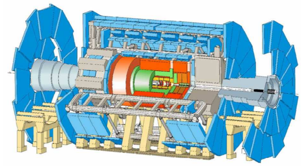
long 46 m



6 storeys
high



9



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

excellent electron/photon identification

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

Precision Muon Spectrometer,

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

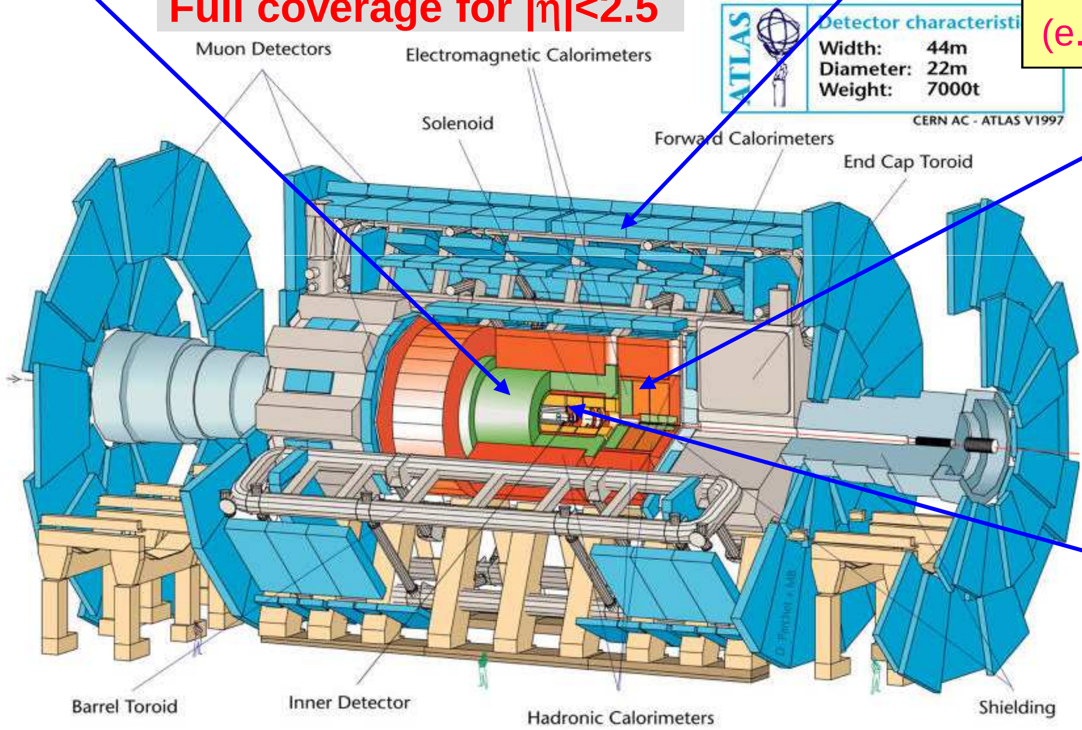
P_T resolution: 10–25 % at 1 TeV/c

Fast response for trigger

Good *p* resolution

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

Full coverage for |η|<2.5



Hadron Calorimeters,

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

Good jet and E_T miss performance

Inner Detector:

Si Pixel and strips (SCT) &

Transition radiation tracker (TRT)

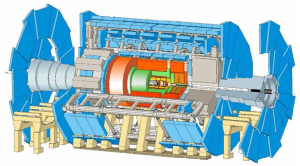
$\sigma/p_T \approx 5 \times 10^{-4}\, p_T \oplus 0.001$

Good impact parameter res.

$\sigma(d_0)$=15μm@20GeV

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

ADD Model



Large Extra Dimensions (ADD)

- Basic Idea: Gravity becomes strong at the TeV-scale

  → solves the hierarchy Problem

- Apply Gauss's Law in 3+n dimensions:
  - For r<< R: V(r) ~ 1/ r^(n+1)

  Gravity gets stronger at small distances!
  - For r>> R: V(r) = 1/r

  (ED not visible at large distances)

- n=1 and 2: excluded from macroscopic gravity

$M_{Pl}^2 \sim M_D^{(2+n)}\, R^n$

Model parameters are:

- n = number of ED
- M_D = Planck mass in the 4+n dimensions

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2}} \frac{1}{r^{n+1}}, \; (r \ll R)$$

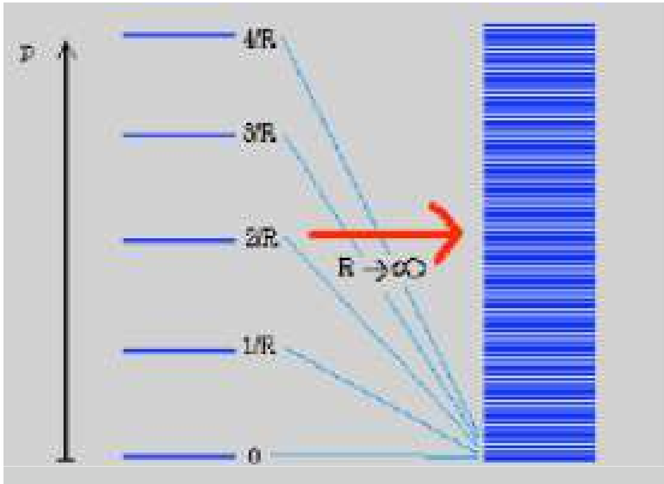
Typical size of ED
For M_D ~ TeV:

n	R
1	~ 1 mpc
2	~ 1 mm
4	~ 1 pm
6	~ 1 fm

Large Extra-Dimensions (ADD)

- KK tower of excited gravitons:
  - Large ED means small ΔE between state: ΔE ~ 1/R

  → Experimentally : continuum

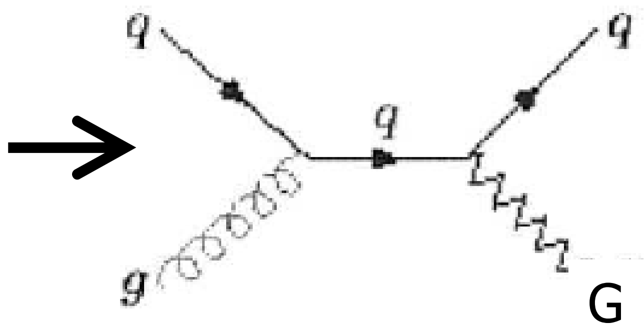


- At ATLAS: 3 ways to look for it:

  → Deviation in Dilepton, diphoton or dijet spectrum caused by continuum

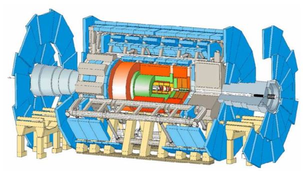
  → Monojet/monophoton: graviton production recoiling against quark or photon

  → Blackholes (not covered here)



ADD Model

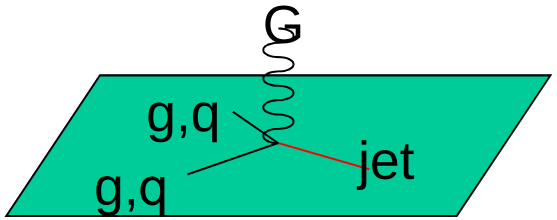
Monojet
Monophoton
Dilepton+Diphoton

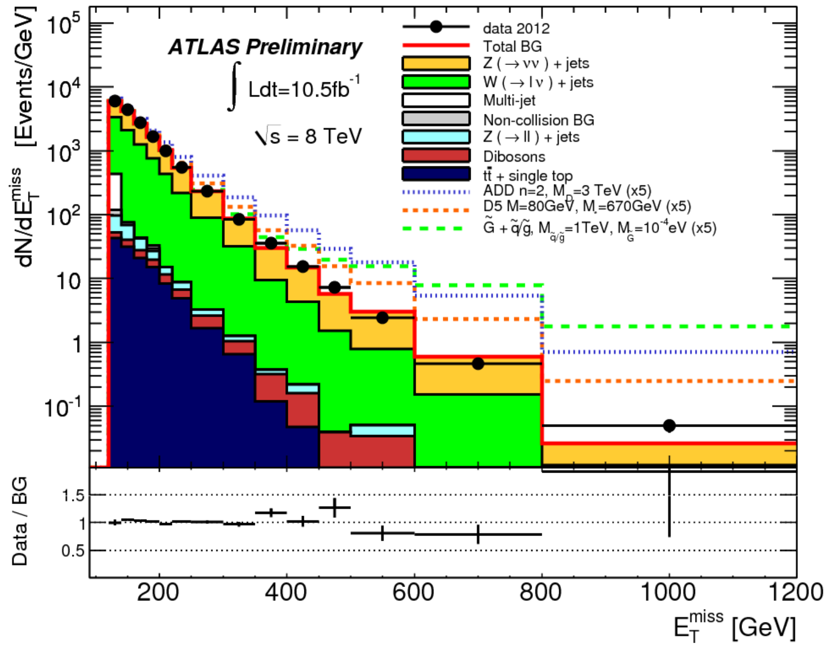


ADD Monojet Search
a single jet plus missing ET

8TeV

- ADD: Graviton Emission: Produce jet + G
- G disappears into the extra dimension
- Signature:
  single (high pT) jet and missing E_T^{Miss}

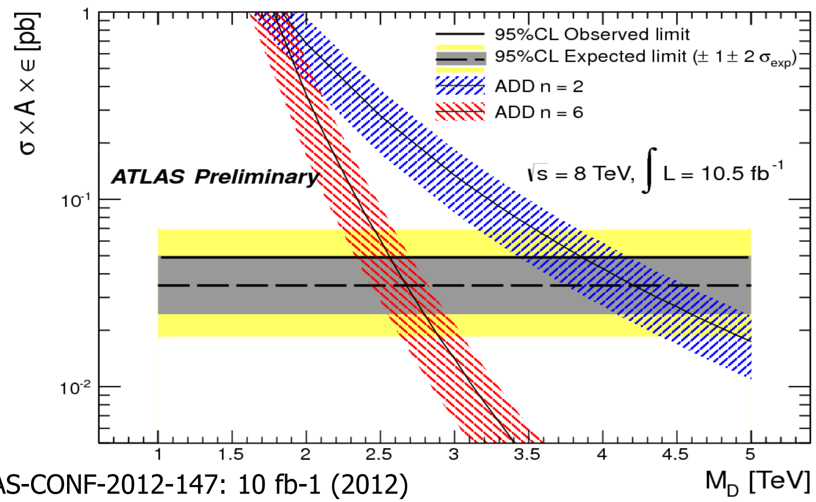




- Challenge:
  →Instrumental background
  → Understanding Z→(νν) + jets

In Search Region

- Total Background 2180
  ±70 (stat. on EWK data bkg estimation)
  ±120 (stat. MC)±100 (syst)
- Data 2353



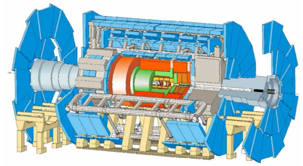
ATLAS-CONF-2012-147: 10 fb-1 (2012)
ATLAS-CONF-2011-096; 1 fb-1of (2011)
2010: arxiv:1106.5327, Phys.Lett.B 705 (2011) 294-312,(33 pb-1)

ADD Model

Monojet

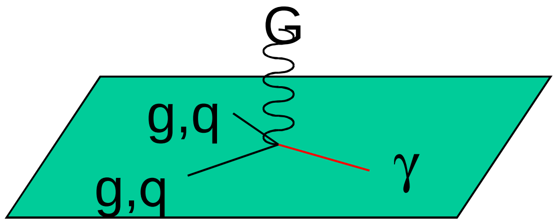
Monophoton

Dilepton+Diphoton



Large ED (ADD): monophoton+Et miss

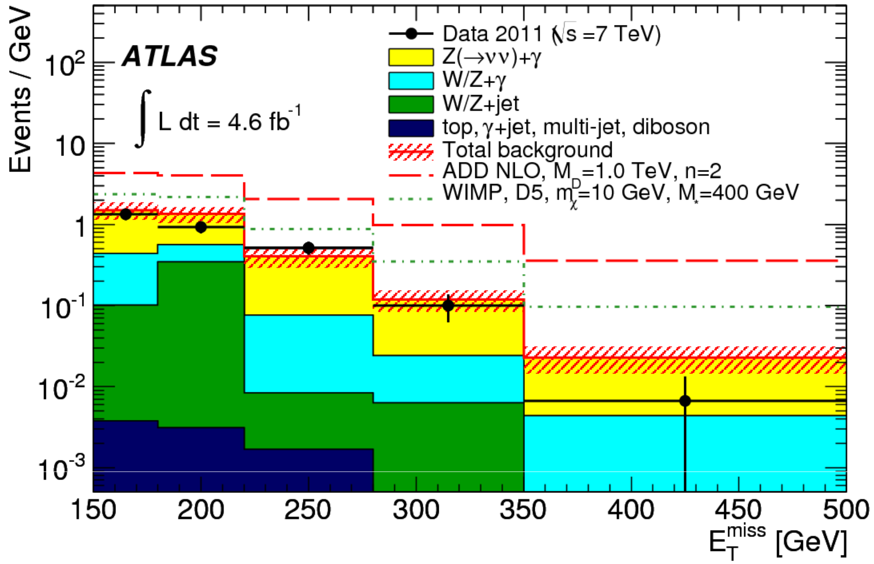
- ADD: Graviton Emission:
  Produce photon + G
- G disappears into the extra dimension
- Signature:
  single (high pT) photon and missing E_T^{Miss}

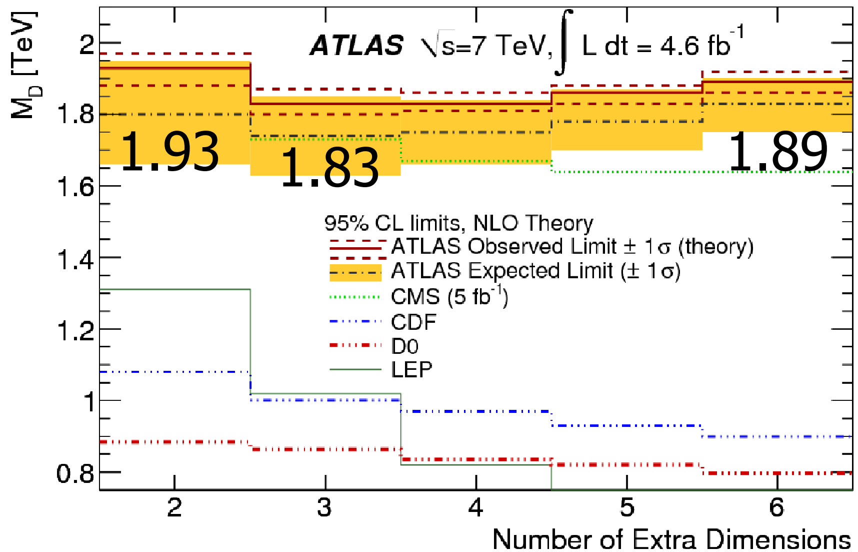


In Search Region
- Total Bkgd: 137±18 (stat) ±9 (syst)
- Data 116

improves previous limits
from LEP and Tevatron

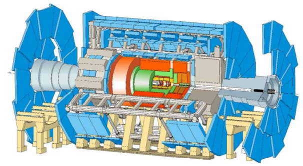
arXiv: 1209.4625,PRL 110, 011802 (2013), 4.6 pb-1 (2011)





ADD Model

Monojet
Monophoton
Dilepton+Diphoton

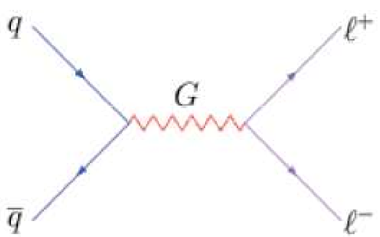


ADD Collider Signatures

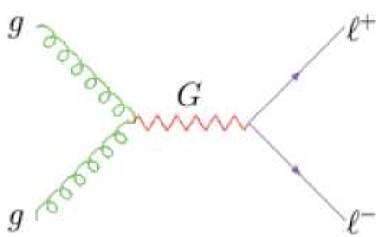
- **Virtual Graviton Emission**
- **Virtual Graviton exchange**

Signature: deviations in σ and asymmetries of SM processes
e.g. qq → l^+l^-, γ γ & new processes e.g. gg → l^+l^-

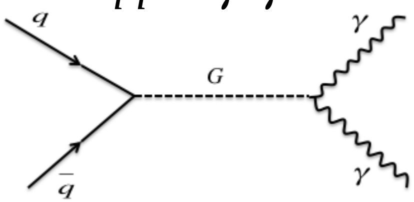
$q\bar{q} \to l^+l^-$



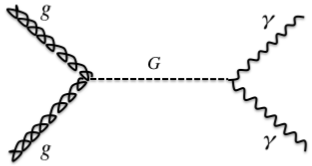
$gg \to l^+l^-$

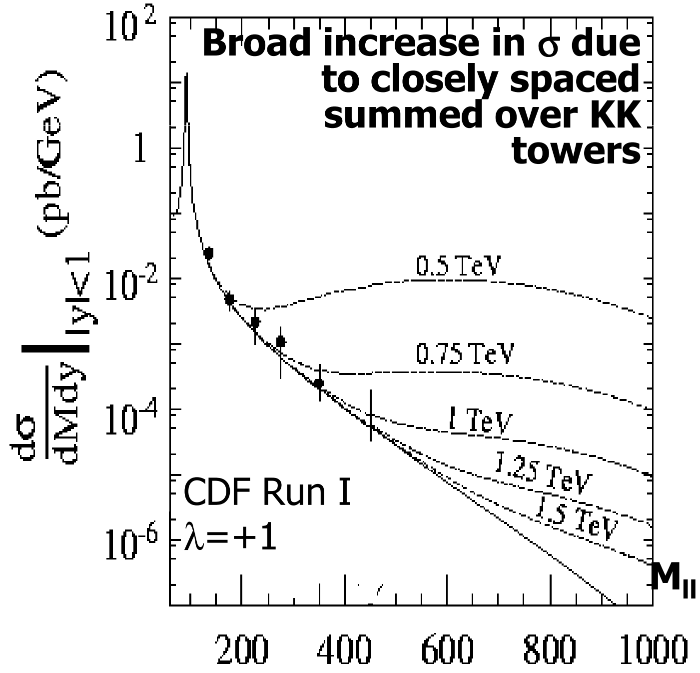


$q\bar{q} \to \gamma^+\gamma^-$



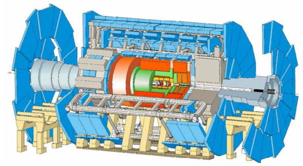
$gg \to \gamma^+\gamma^-$





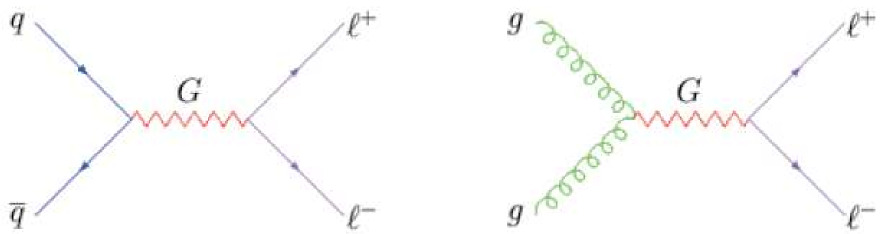
- Parameterise σ in terms of $\eta = \frac{\lambda}{M_S{}^4}$

$$\sigma'_{tot} = \sigma'_{SM} + \eta G \sigma'_{int} + \eta_G^2 \sigma'_G .$$

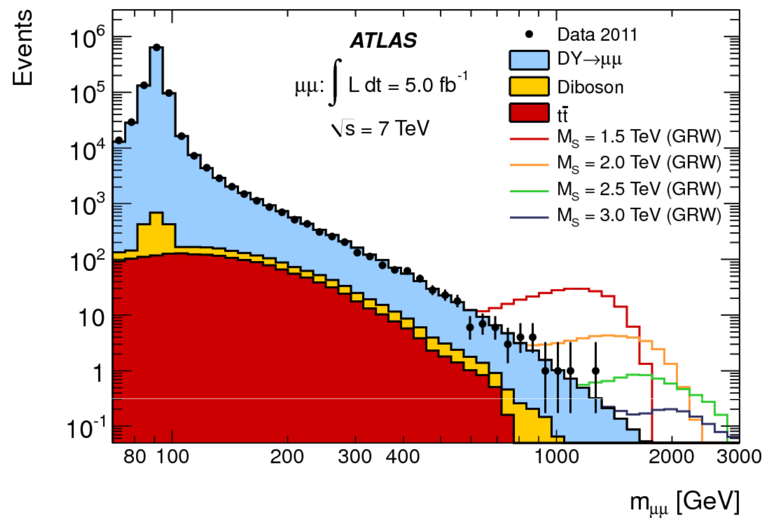


LED (ADD): dilepton

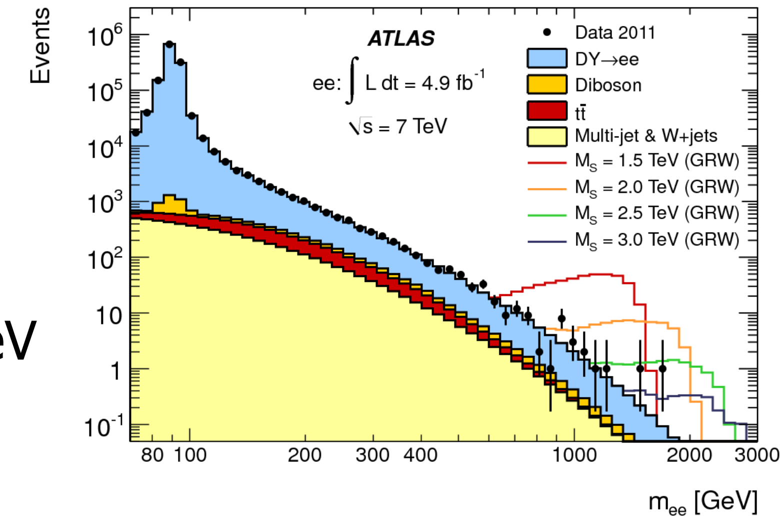
Virtual Graviton Exchange pp→G^{KK}→μμ/ee



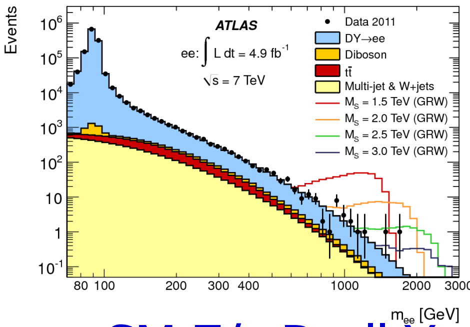
$q\bar{q} \to l^+l^-$ $gg \to l^+l^-$



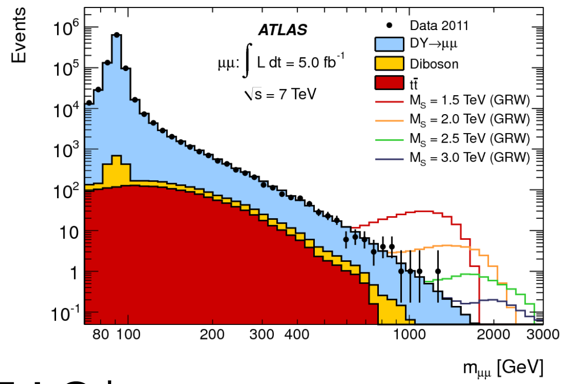
- Final state: 2 opposite sign μ or 2 e
- Search for excess above SM expectations in high invariant mass region
- Optimized Search Region m_{ll} > 1300 GeV



Phys. Rev. D 87, 015010 (2013)



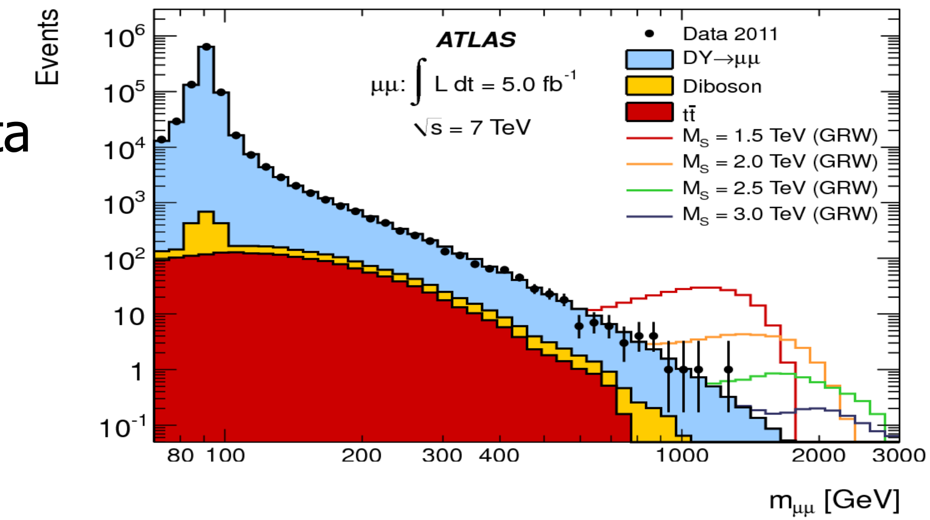
Main Backgrounds



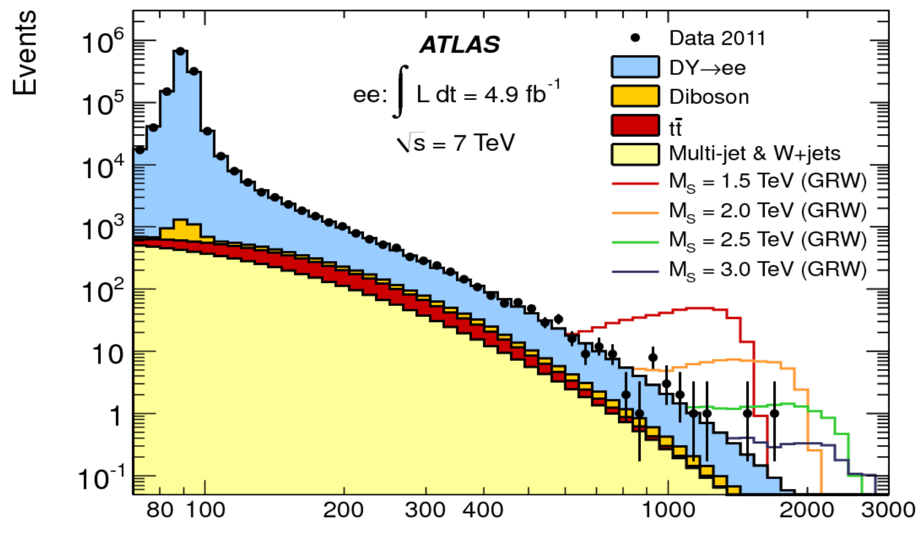
- SM Z/γ Drell-Yan (irreducible, primary background)
  - Produced using Pythia 6.421 with MRST2007 LO*
  - Interference with heavy resonances is small and ignored
  - NNLO K-factors generated using PHOZPR with MSTW2008
- QCD (electron channel only)
  - estimated using “reversed electron identification" 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)

LED (ADD): dilepton

- Backgrounds are normalised to data in Z-peak region (70 - 110 GeV)
- Optimized Search Region $m_{\gamma\gamma}$ > 1300 GeV



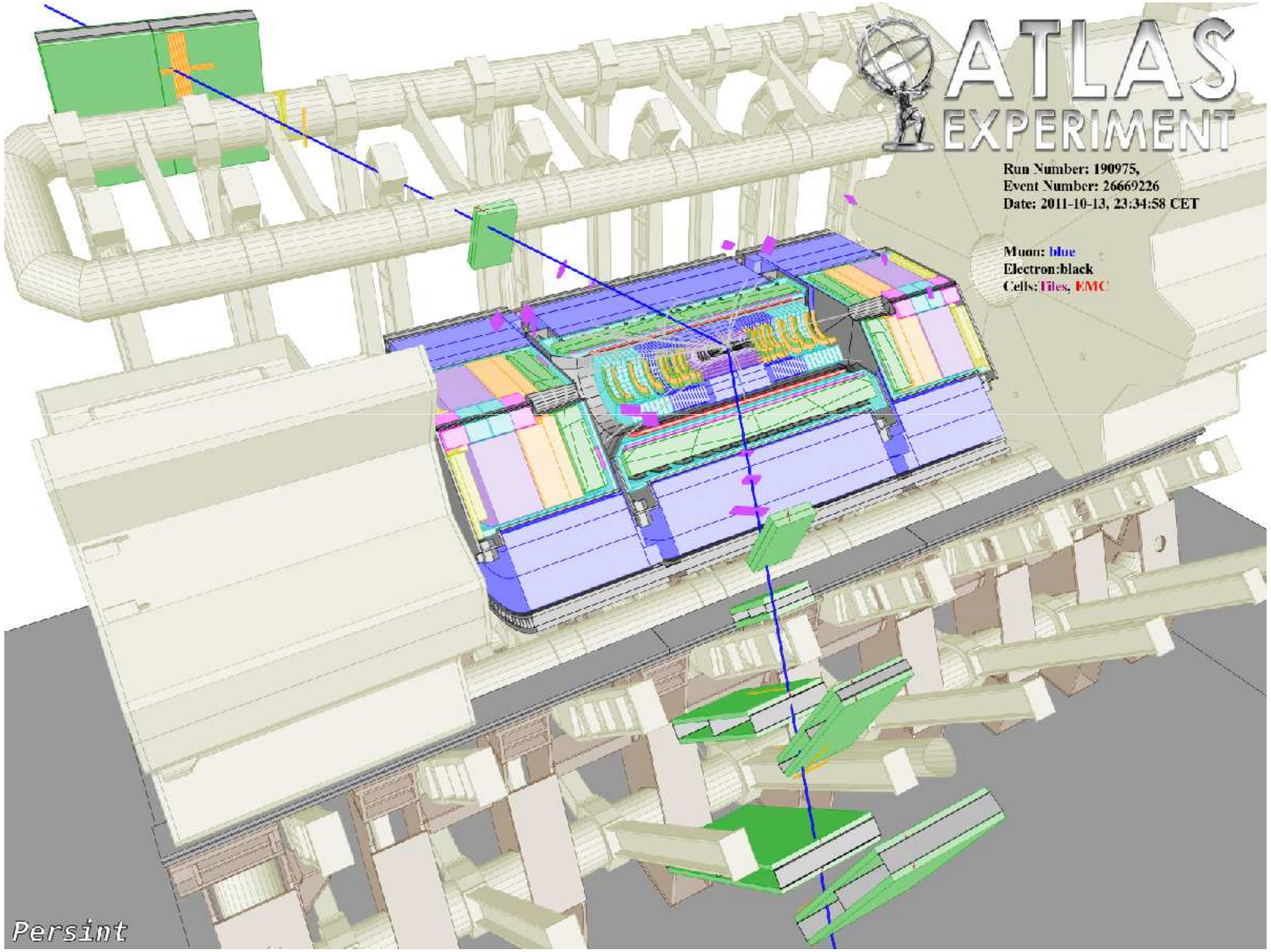
Process	ee	$\mu\mu$
DY	0.89 ± 0.21	0.54 ± 0.16
$t\bar{t}$	< 0.01	< 0.01
Diboson	0.075 ± 0.005	0.059 ± 0.010
Multijet/W+jets	0.16 ± 0.20	–
Total background	1.13 ± 0.29	0.60 ± 0.16
$M_S = 1.5$ TeV	72 ± 5	47 ± 9
$M_S = 2.0$ TeV	40.2 ± 2.6	22 ± 4
$M_S = 2.5$ TeV	11.7 ± 0.9	6.3 ± 1.1
$M_S = 3.0$ TeV	4.2 ± 0.4	2.3 ± 0.4
Data	2	0



The bin width is constant in log(mll)

Phys. Rev. D 87, 015010 (2013)

Highest Mass μμ event



$M_{\mu\mu}$=1.25 TeV

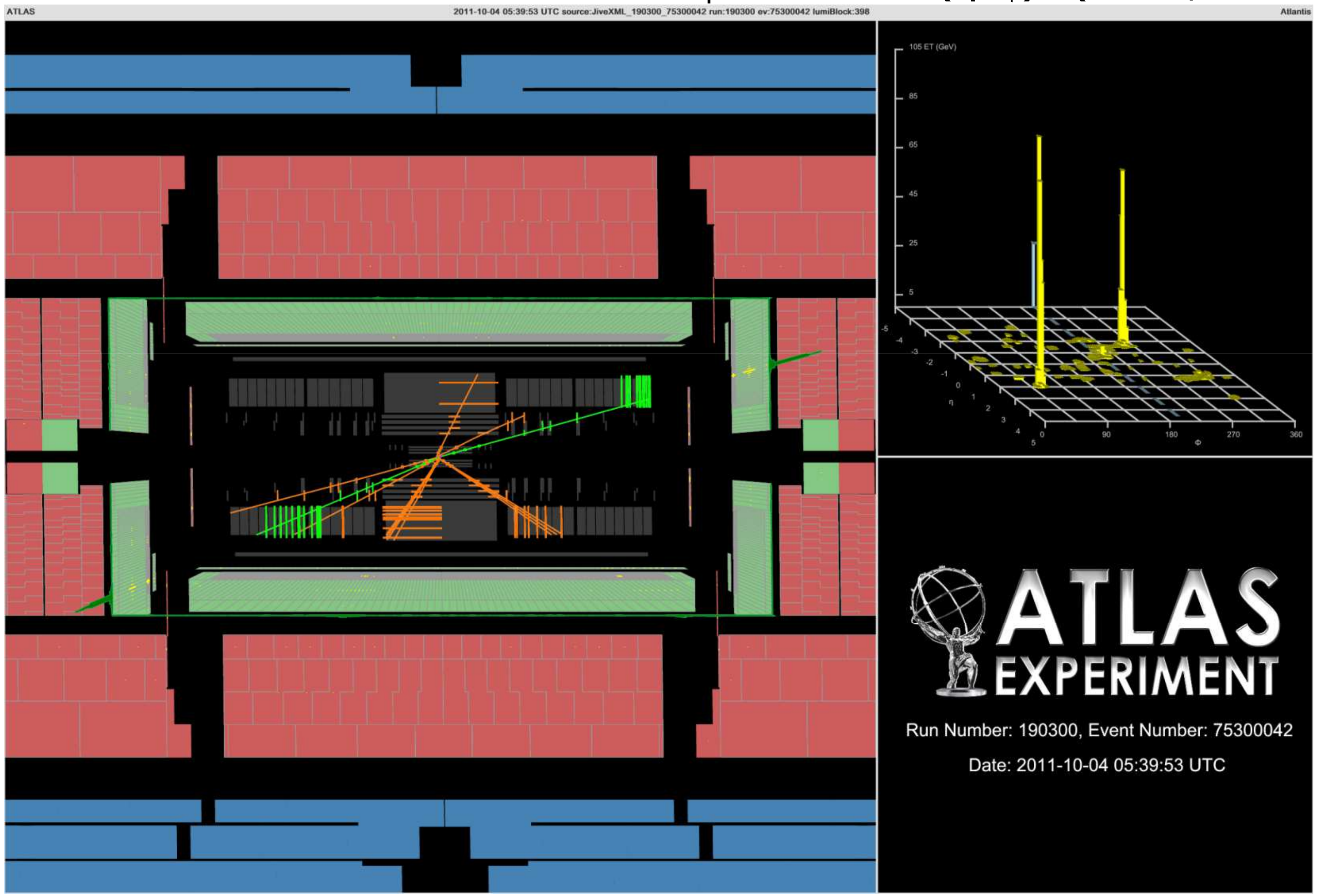
P_T of 648 GeV
$(\eta, \phi) = (-0.75, 0.49)$

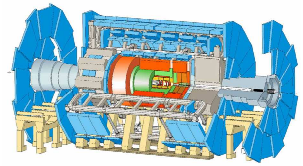
P_T of 583 GeV
$(\eta, \phi) = (-0.36, -2.60)$

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)





Limits Setting and Errors

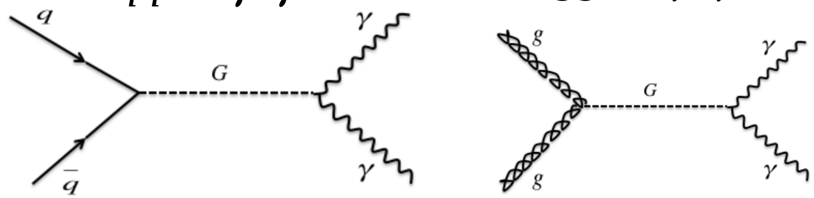
- Because normalize MC to data in Z peak region (70 < $m_{\ell\ell}$ < 110 GeV) luminosity and other mass independent systematics cancel between Z and Z′/G

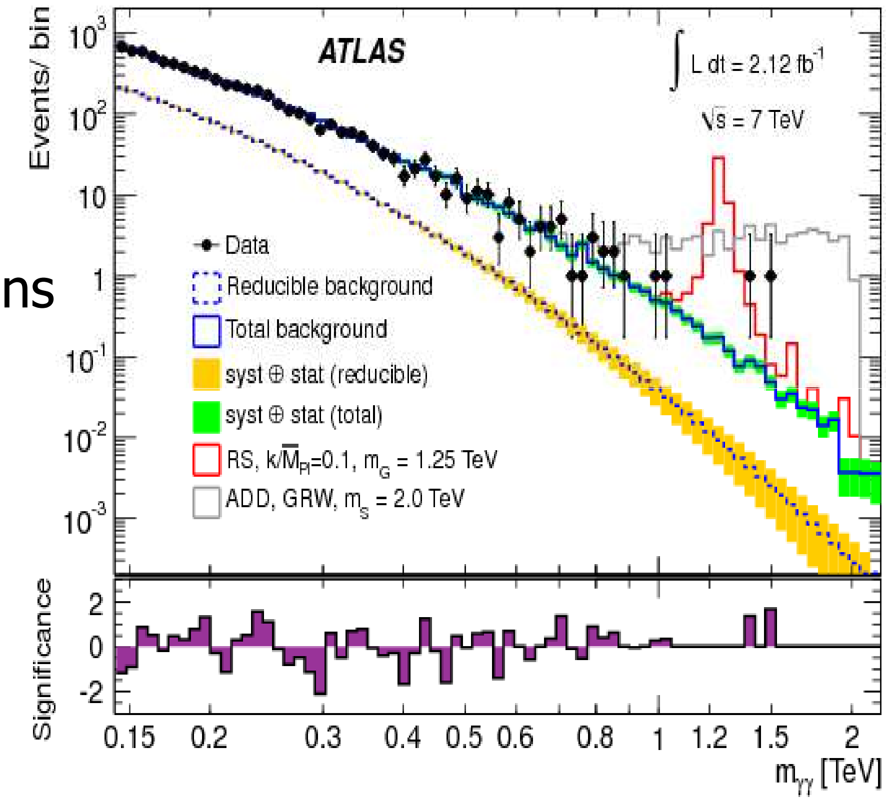
TABLE III. Summary of systematic uncertainties in the expected numbers of events for a dilepton mass of 1 TeV (2 TeV). NA indicates that the uncertainty is not applicable.

Source	ee Signal	ee Background	$\mu\mu$ Signal	$\mu\mu$ Background
Normalization	5% (5%)	NA	5% (5%)	NA
PDFs/α_S/scale	NA	7% (20%)	NA	7% (20%)
Electroweak k-factor	NA	2.3% (4.5%)	NA	2.3% (4.5%)
Efficiency	1.0% (2.0%)	1.0% (2.0%)	3.0% (6.0%)	3.0% (6.0%)
Scale/Resolution	1.2% (2.4%)	1.2% (2.4%)	1.2% (12%)	1.2% (12%)
Multi-jets/W+jets background	NA	12% (26%)	NA	$< 0.1\%$
Total	5% (6%)	14% (33%)	6% (14%)	8% (25%)

LED (ADD) diphoton

$q\bar{q} \to \gamma^+\gamma^-$ $gg \to \gamma^+\gamma^-$

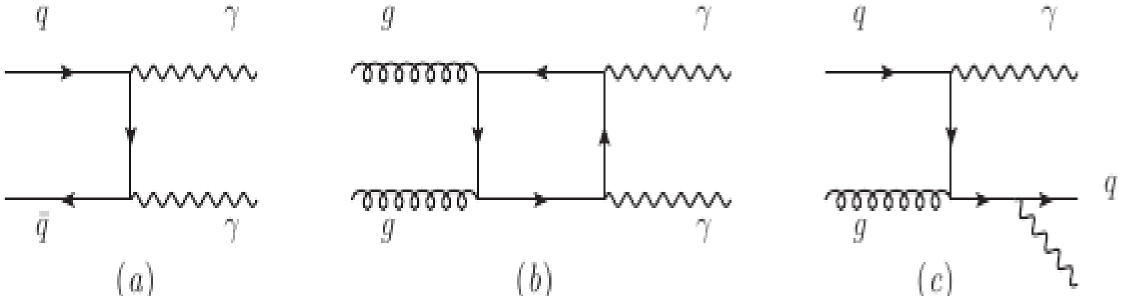




- 2 γ with E_T > 25 GeV
- Search for excess above SM expectations in high invariant mass region
- ee Overlap removal to combine results with G→ee
- Energy correction to reduce pile-up & underlying event effects
- Optimized Search Region $m_{\gamma\gamma}$ > 1100 GeV

Main Backgrounds

- **Irreducible Background SM γγ production**



Born process box process bremsstrahlung process

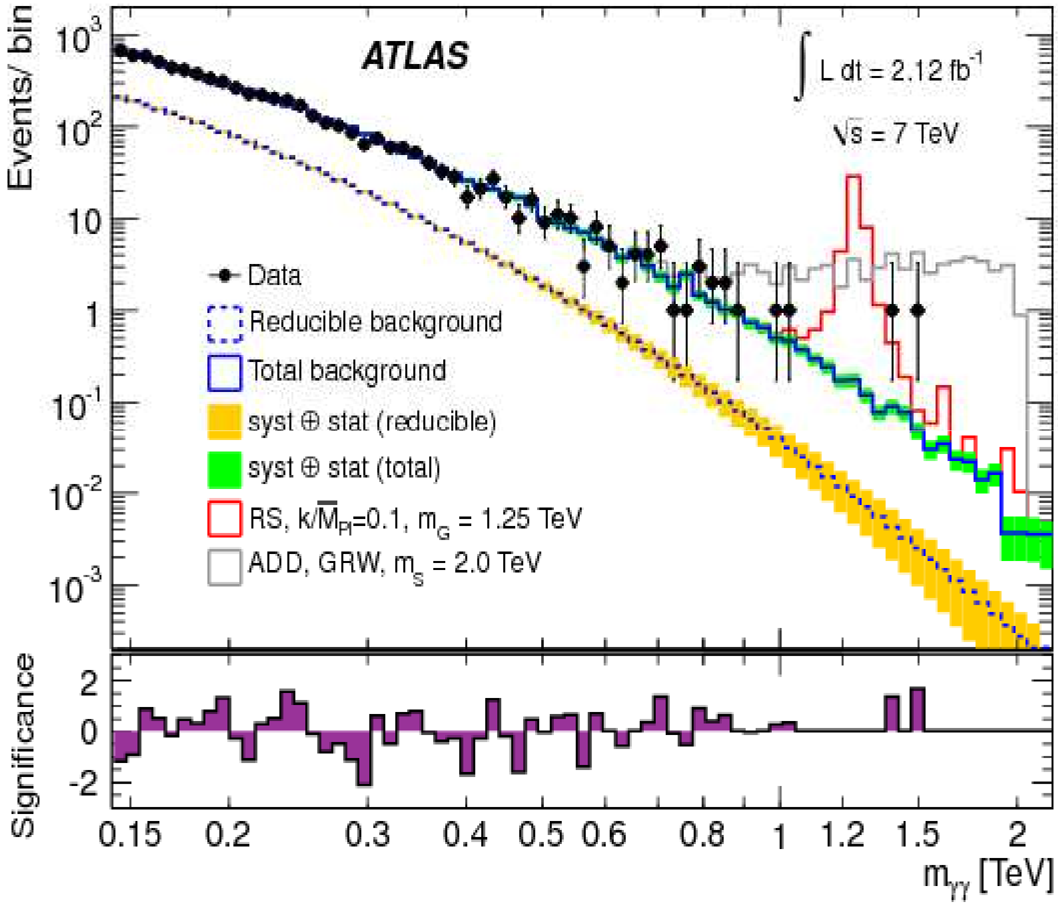
•simulated with pythia (v6.424) and MRST2007LOMOD PDFs
•pythia events reweighted as a function of $m_{\gamma\gamma}$ to the differential cross section predicted by the NLO calculation of diphox (v 1.3.2).

- **Reducible Background**
  - γ + (misidentified) jet
  - jet + jet

  Shape determined using data-driven background enriched control samples & extrapolated to high mass

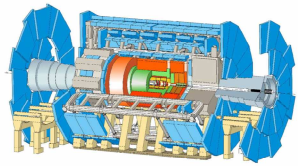
- **Total Background**: normalised to data 140 Gev < $m_{\gamma\gamma}$ < 400 GeV

Diphoton Distributions



Good agreement with data and expected background

P=0.28

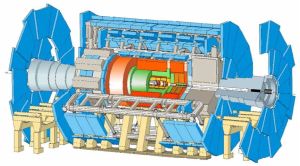


Uncertainties

- Limits obtained using a Bayesian approach, with a flat prior on the signal cross-section.
- Systematic uncertainties incorporated as Gaussian nuisance parameters and integrated over

Source of Uncertainty	Signal Uncertainty (%)
Integrated Luminosity	3.7
MC Statistics	1.0
Bunch Crossing Identification	1.0
Photon Trigger	2.0
Pileup	2.5
Photon Efficiency and ID	4.3
Total Signal Uncertainty	6.7

arXiv:1112.2194,CERN-PH-EP-2011-189, submitted to PRL



ADD Limits

- Search Region $m_{\gamma\gamma}$ > 1100 GeV

Parameter	Central value	Relative Uncertainty
Integrated Luminosity	$2.12\,fb^{-1}$	3.7%
Number of data events	2	
Number of predicted bkgnd events	1.18±0.24	20%

Limits

- Observed (expected) 95 % CL upper limit on σ = 2.53 (1.95) fb
- Translated into 95 % CL limits on the parameter on η and M_S:

$$\sigma'_{tot} = \sigma'_{SM} + \eta_G \sigma'_{int} + \eta_G^2 \sigma'_G. \qquad \eta = \frac{\lambda}{M_S{}^4}$$

k-factor Value	GRW	Hewett		HLZ				
		Pos	Neg	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
1	2.67	2.39	2.13	3.18	2.67	2.42	2.25	2.13
1.7	2.95	2.64	2.26	3.51	2.95	2.67	2.48	2.35

Dilepton+Diphoton

$$\sigma'_{tot} = \sigma'_{SM} + \eta_G \sigma'_{int} + \eta_G^2 \sigma'_G.$$

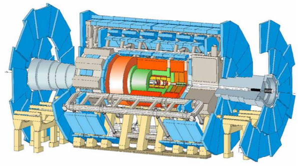
$$\eta = \frac{F}{M_S{}^4}$$

Channel	Prior	GRW	Hewett	HLZ				
				$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
ee	$1/M_S^4$	2.95	2.63	3.51	2.95	2.66	2.48	2.34
	$1/M_S^8$	2.82	2.67	3.08	2.82	2.68	2.59	2.52
$\mu\mu$	$1/M_S^4$	3.07	2.74	3.65	3.07	2.77	2.58	2.44
	$1/M_S^8$	2.82	2.67	3.08	2.82	2.68	2.59	2.52
$ee + \mu\mu$	$1/M_S^4$	3.27	2.92	3.88	3.27	2.95	2.75	2.60
	$1/M_S^8$	3.09	2.92	3.37	3.09	2.94	2.84	2.76
$ee + \mu\mu$	$1/M_S^4$	3.51	3.14	4.18	3.51	3.17	2.95	2.79
$+ \gamma\gamma$	$1/M_S^8$	3.39	3.20	3.69	3.39	3.22	3.11	3.02

$$\mathcal{F} = 1, \text{ (GRW)}$$

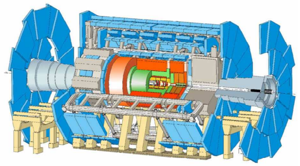
$$\mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{\hat{s}}\right) & n = 2 \\ \frac{2}{n-2} & n > 2 \end{cases}, \text{ (HLZ)}$$

$$\mathcal{F} = \pm\frac{2}{\pi}, \text{ (Hewett)}$$



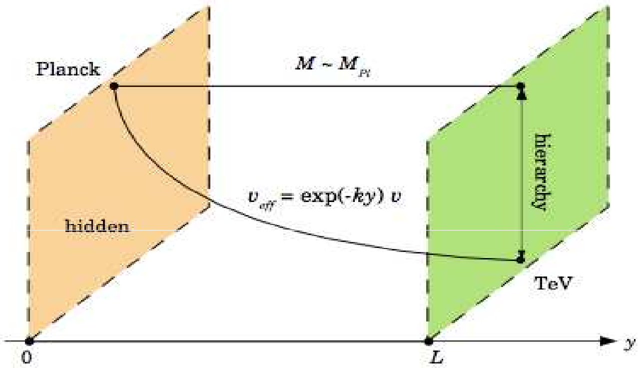
RS Model

Dileptons
Diphotons
(Dijets)
ZZ



Randall-Sundrum (RS1)

- 5-D space-time bound by two 3+1D branes with SM particles localized on one and gravity on the other

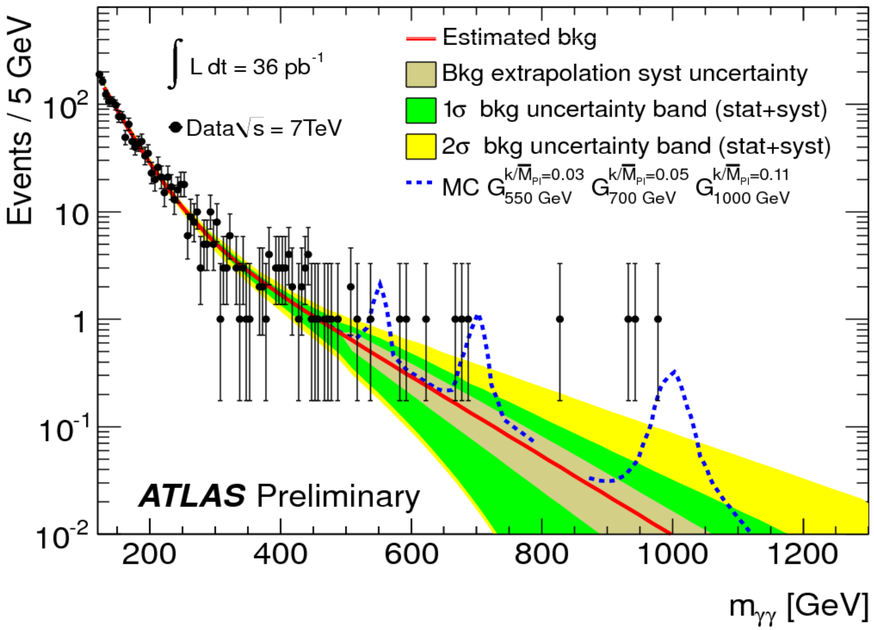


$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

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

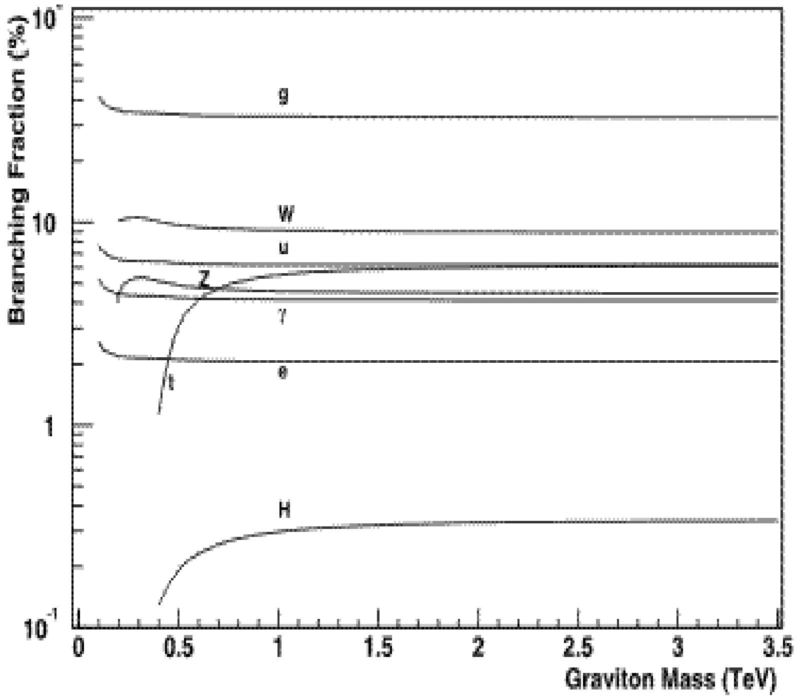
$$\Lambda_\pi \sim \text{TeV}$$

- k is space-time curvature in ED
- Only G propagate in bulk resulting ir massive spin-2 Kaluza-Klein (KK) excitations
- The model can be parameterised in terms of the mass of the lightest excitation (m_G) and the coupling k/M_{Pl}
- Width of resonance is proportional to m_G and to $(k/M_{Pl})^2$

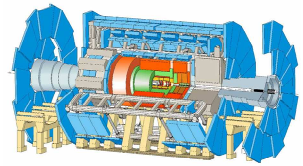


ATL-CONF-2011-044

RS Model



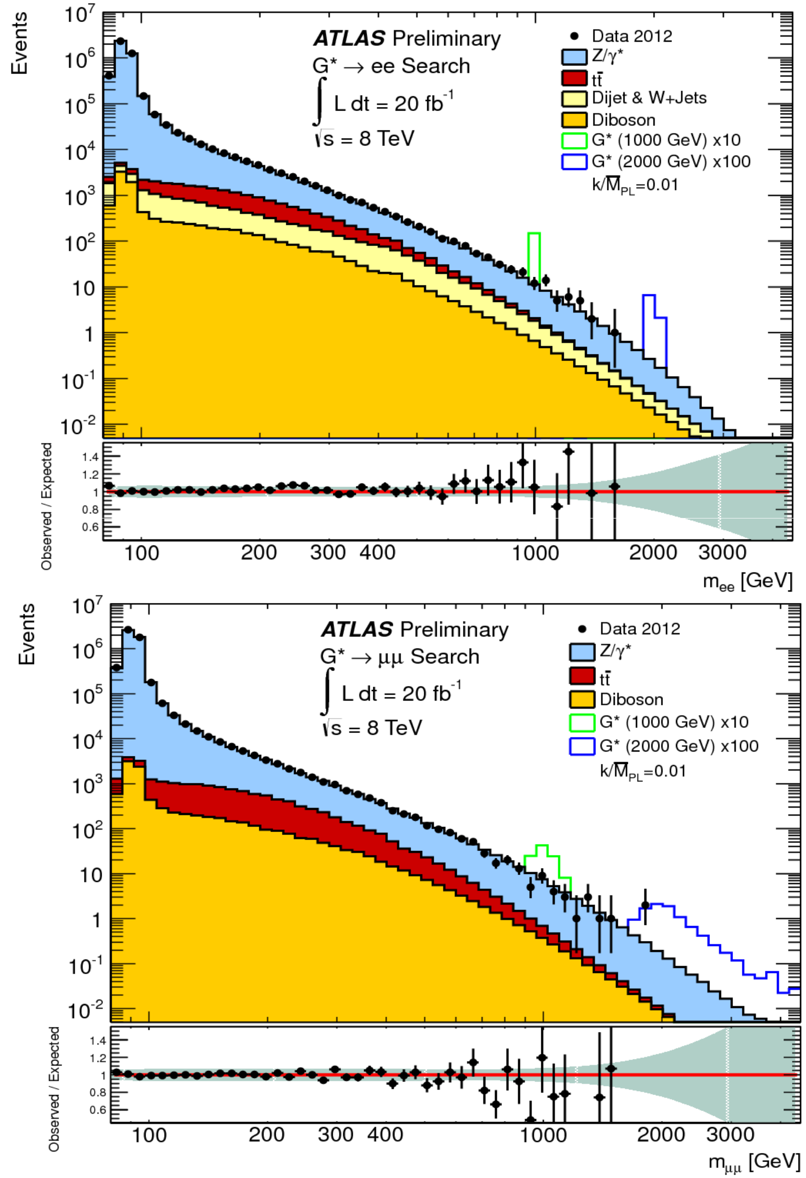
Dileptons
Diphotons
(Dijets)
ZZ



RS1: Dilepton

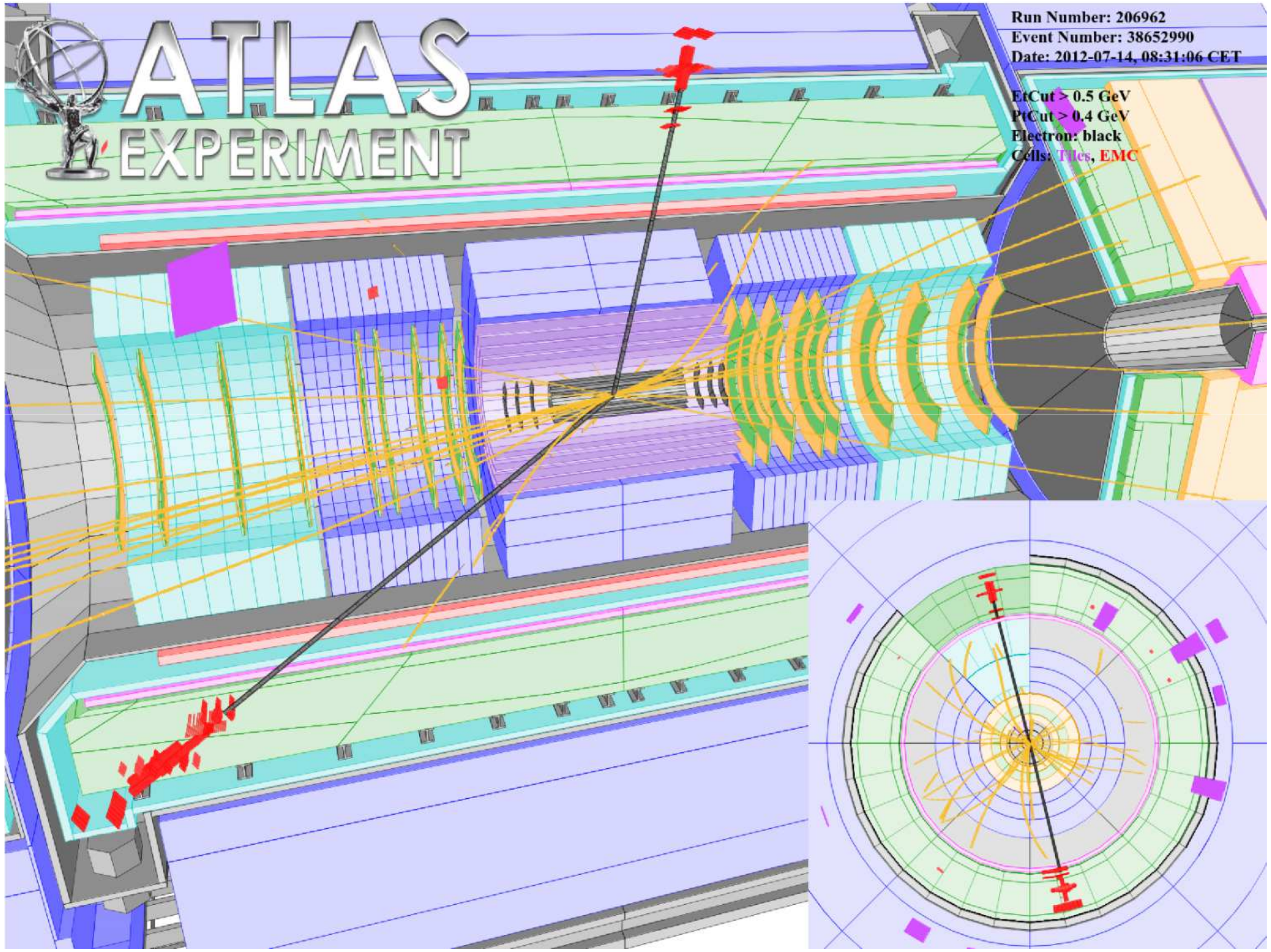
8TeV

- Select events with two leptons of same flavor (ee, $\mu\mu$)
- Opposite sign for $\mu\mu$
- No opposite charge requirement for ee – to minimize impact of mis-ID
- Signature: search for resonance at high invariant mass region
- Backgrounds are normalised to data in Z-peak region (70 - 110 GeV)
- Fit templates to obtain limits



ATLAS-CONF-2013-017, 20 fb-1

Highest mass ee Event



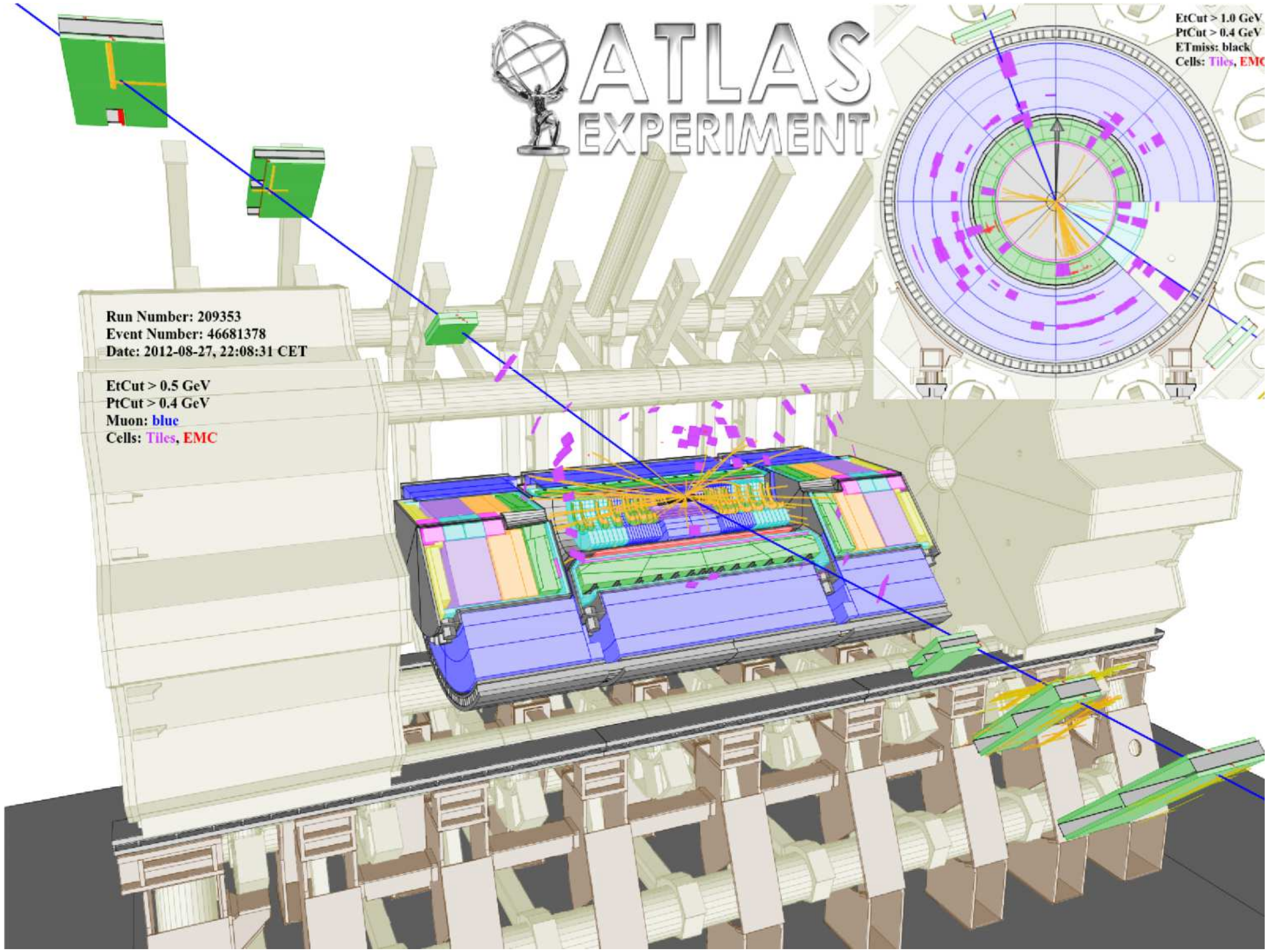
M_{ee}=1.541 TeV

P_T of 588 GeV
(η) = (1.25)

P_T of 584 GeV
(η) =(-0.29)

.

Highest mass μμ Event



$M_{\mu\mu}$=1.844 TeV

P_T of 653 GeV
(η) = (0.99)

P_T of 646 GeV
(η, ϕ) =(-0.85)

.

Systematic Uncertainties

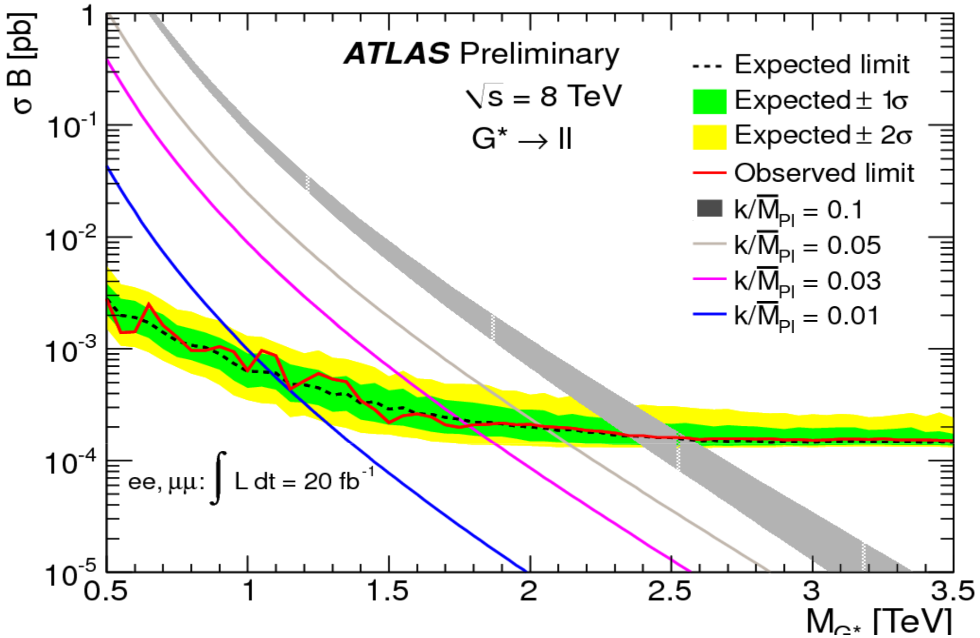
Table 3: Summary of systematic uncertainties on the expected numbers of events at $m_{\ell\ell} = 2$ TeV. NA indicates that the uncertainty is not applicable, and "-" denotes a negligible entry (i.e. $< 3\%$). Numbers in parentheses on the resolution and total uncertainty lines correspond to the loose dimuon selection.

Source	Dielectrons		Dimuons	
	Signal	Background	Signal	Background
Normalization	5%	NA	5%	NA
PDF variation	NA	15%	NA	15%
PDF choice	NA	17%	NA	17%
Scale	NA	-	NA	-
α_s	NA	4%	NA	4%
Electroweak corrections	NA	3%	NA	3%
Photon-induced corrections	NA	4%	NA	4%
Efficiency	-	-	6%	6%
Resolution	-	-	-	3% (7%)
W + jet and multi-jet background	NA	9%	NA	-
Diboson and ttbar extrapolation	NA	5%	NA	4%
Total	5%	26%	8%	25% (26%)

ATLAS-CONF-2013-017

RS1: Dilepton

8TeV

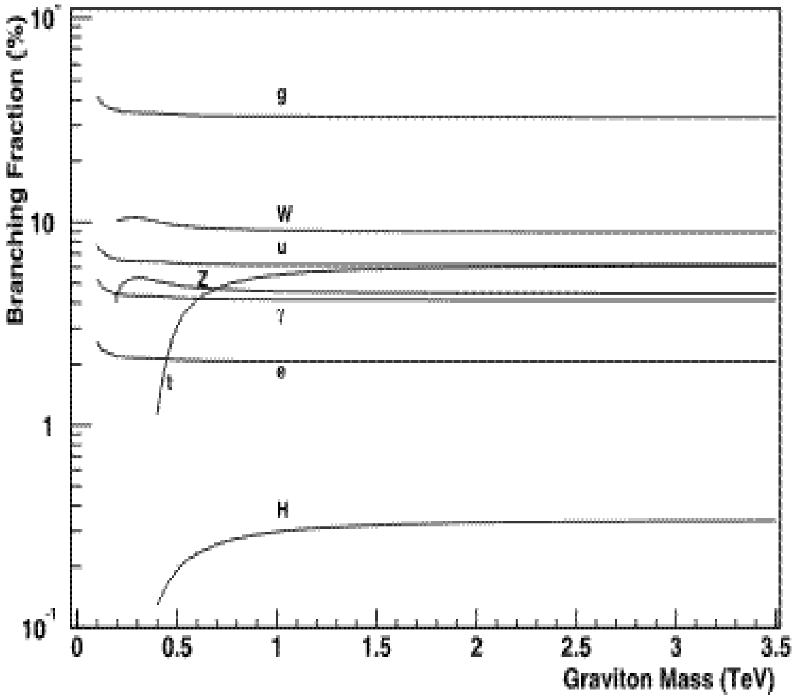


e^+e^-, $\mu^+\mu^-$ and combined 95% C.L. mass limits on graviton (G^*).

k/M_{Pl}=0.1	$G^* \to e^+e^-$	$G^* \to \mu^+\mu^-$	$G^* \to \ell^+\ell^-$
Observed mass limit [TeV]	2.40	2.10	2.47
Expected mass limit [TeV]	2.40	2.17	2.47

ATLAS sets best limits on this model in this channel!

RS Model

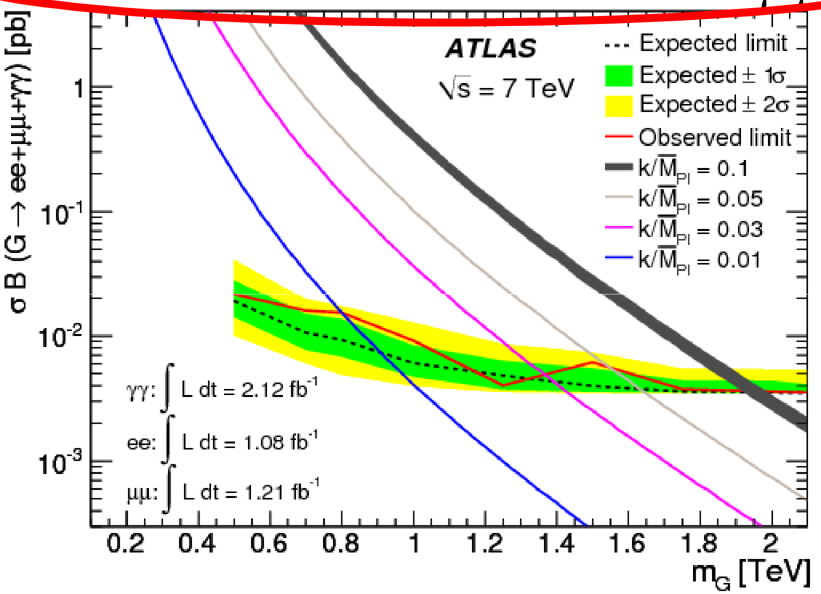


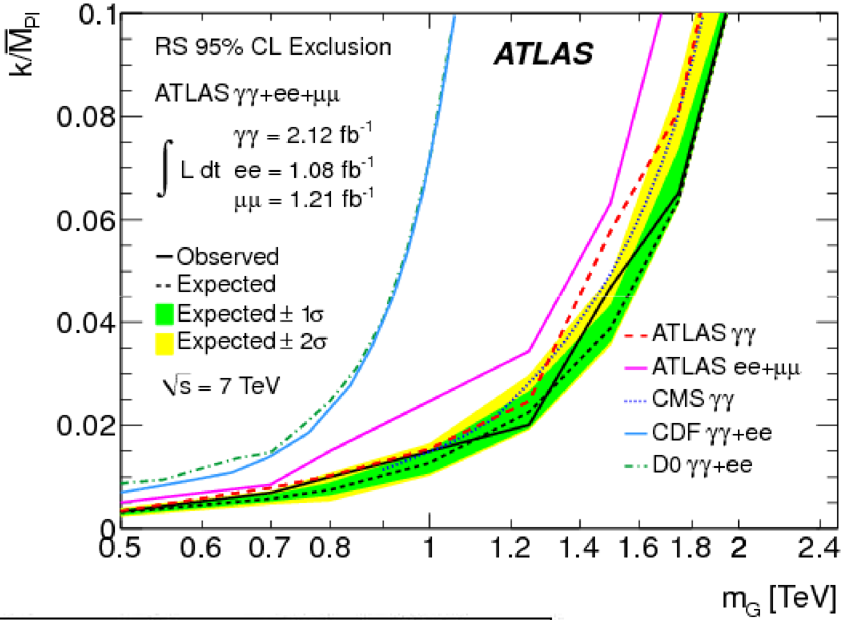
Dileptons
Diphotons
(Dijets)
ZZ

ATLAS Older combined limits

RS Limits

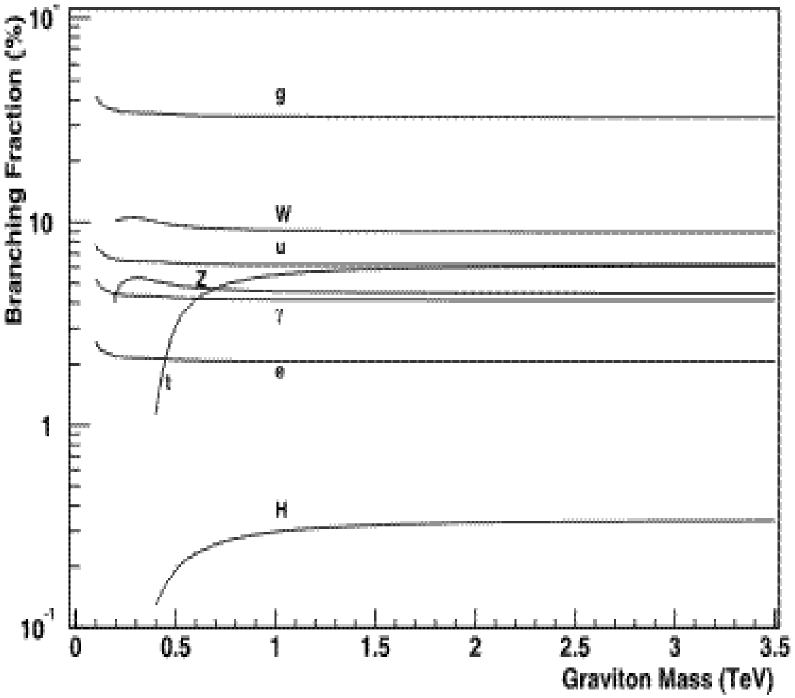
- $m_{\gamma\gamma}$ > 500 GeV
- Limits obtained using same method, as for dilepton search
- BR for G is twice that of $G \to \gamma\gamma$





	k-Factor Value	Channel(s) Used	95% CL Observed (Expected) Limit [TeV] $k/\overline{M}_{Pl}$ Value 0.01	0.03	0.05	0.1
LO	1	$G \to \gamma\gamma$	0.78 (0.82)	1.26 (1.27)	1.38 (1.49)	1.80 (1.81)
		$G \to \gamma\gamma/ee/\mu\mu$	0.76(0.85)	1.32 (1.31)	1.47 (1.55)	1.90 (1.90)
NLO	1.75	$G \to \gamma\gamma$	0.80 (0.87)	1.30 (1.33)	1.43 (1.56)	1.85 (1.86)
		$G \to \gamma\gamma/ee/\mu\mu$	0.80 (0.90)	1.37 (1.38)	1.55 (1.62)	1.95 (1.96)

RS Model



Dileptons
Diphotons
(Dijets)
ZZ

QBH Dijet

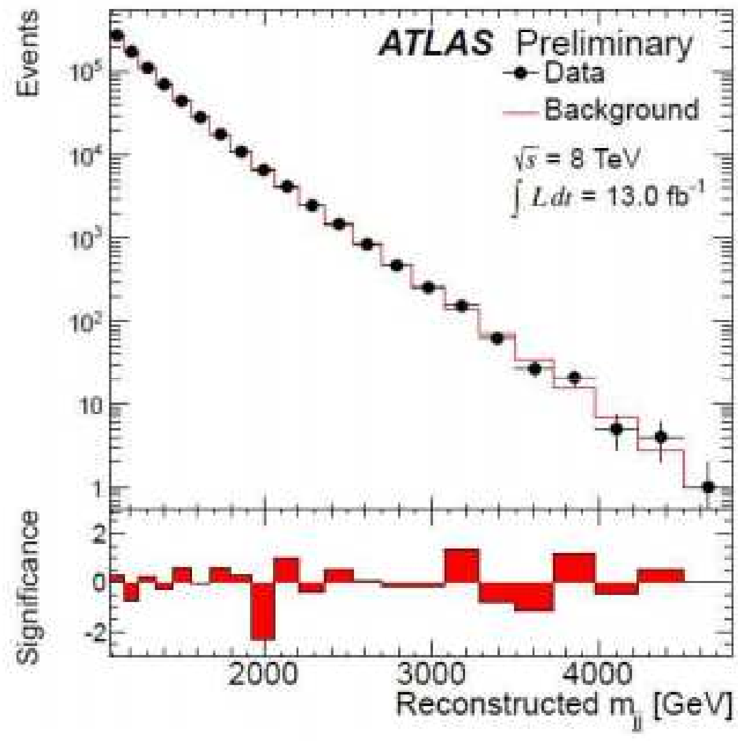
8TeV

ATLAS 13 fb^{-1} @ 8 TeV [CONF-2012-148]

- Look for resonance above phenomenological fit of the data:

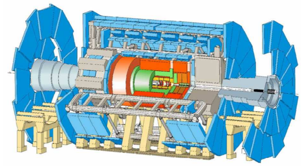
$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x}$$

$$x \equiv m_{jj}/\sqrt{s}$$



Not presently translated into limits on RS or QBH

95 % C.L. Limits
Obs Mass Excl [1.20, 1.58]
Exp. Mass Excl: [1.20, 1.43]



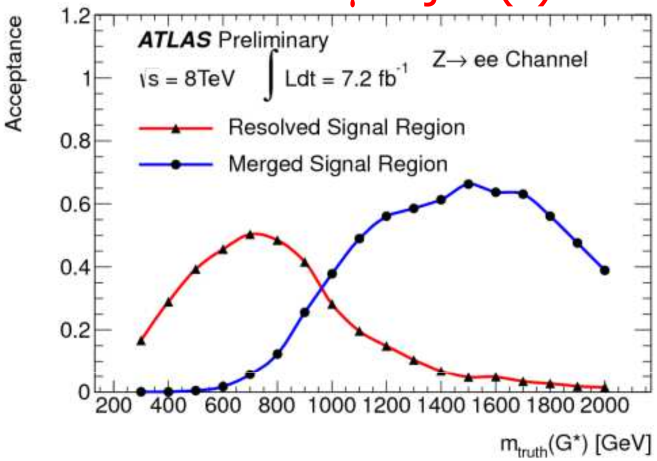
Bulk RS Model

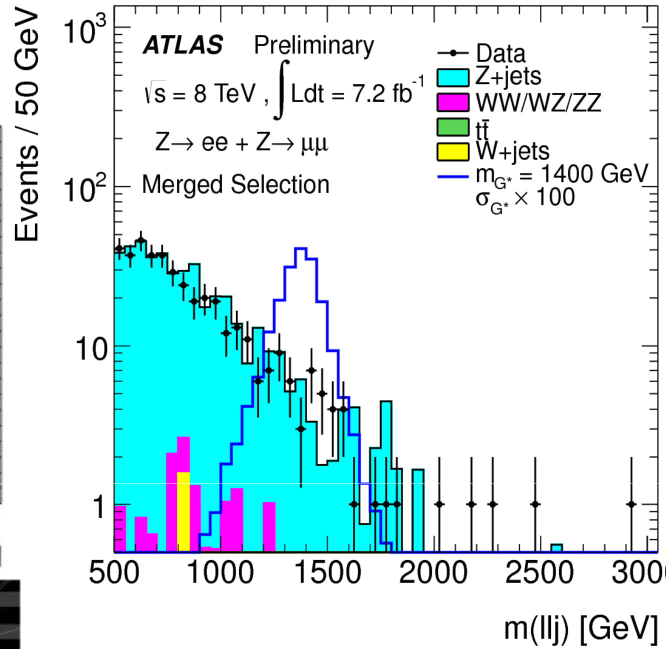
Dileptons
Diphotons
(Dijets)
ZZ

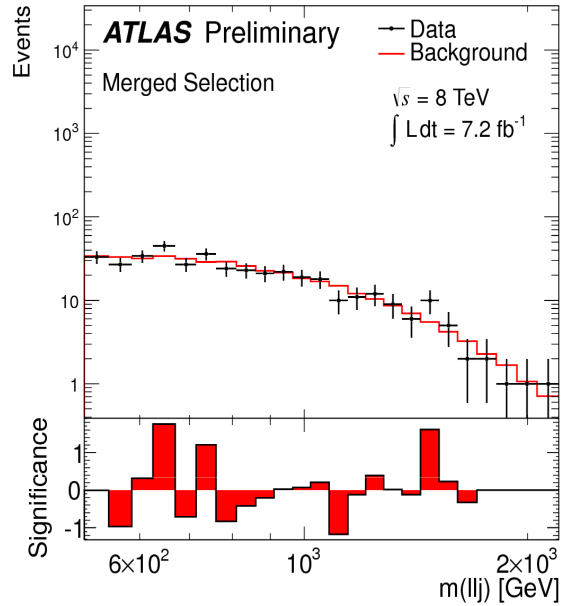
Bulk RS: G*→ZZ → llqq

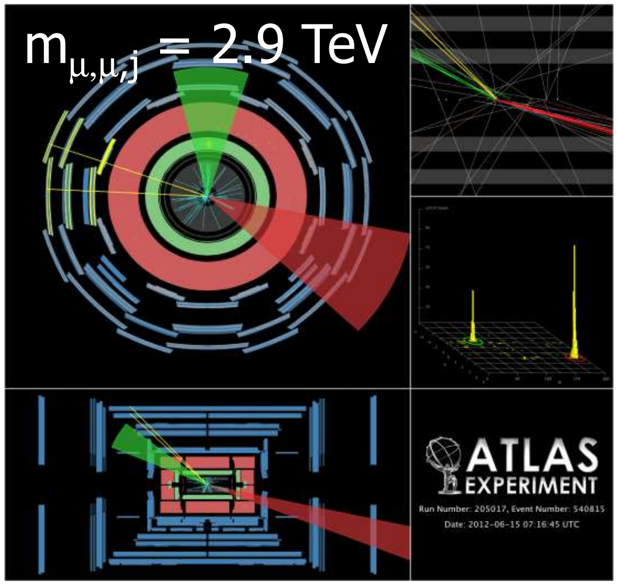
- Signal:

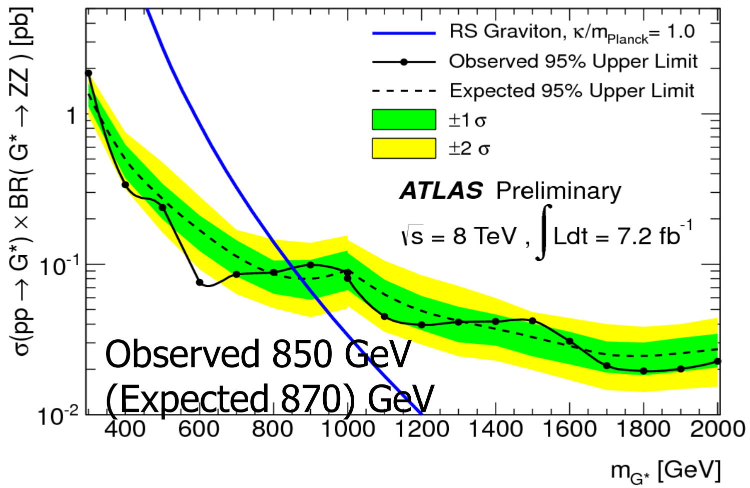
  2 e or 2 μ+ jet (s)



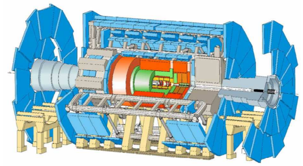






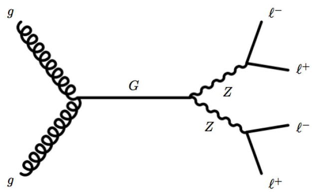


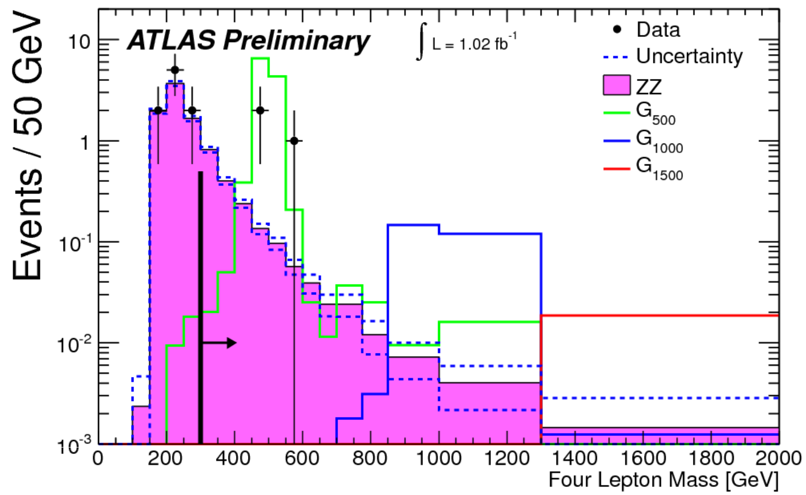
 ATLAS-CONF-2012-150, 7.2 pb-1 at 8 TeV



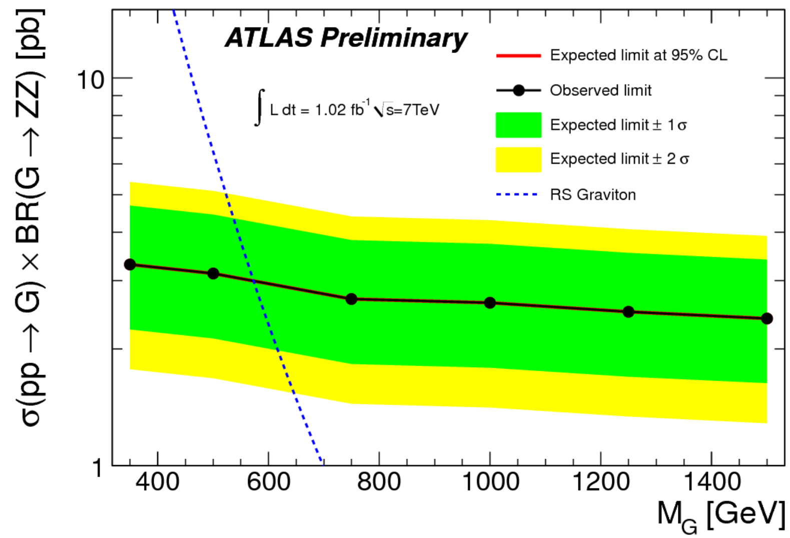
Bulk RS: $G^* \rightarrow ZZ \rightarrow llll$ with Four Charged Leptons

- Signal: Four Charged Leptons
- 2 searches performed in this decay channel ZZ & $H^{++}H^{--}$
- Events with two identified $Z \rightarrow \ell^+\ell^-$ decays
- For $M_{\ell\ell\ell\ell}$>300 GeV: from SM expect $1.9^{+1.0}_{-0.1}$ (stat) $^{+0.8}_{-0.1}$ (syst) events
- Observe: 3 events

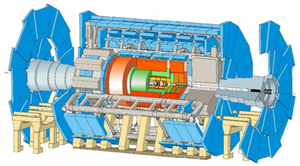




- 95% C.L. Limit σ(production of ZZ from high-mass sources) <0.9 pb in the fiducial region
- For RS model: limits on $\sigma(pp\rightarrow G)\times BF(G\rightarrow ZZ)$ of 2.6-3.3 pb depending on the resonance mass
- For a coupling of k/M_{pl}=0.1 , the median expected 95% C.L. lower limit M_G>575 GeV equal to the observed limit



ATLAS-CONF-2011-144



Conclusion

- Unfortunately, evidence for Gravitons have not yet been observed
- However, the 13/14 TeV run will open another window of opportunity for discovering BSM physics!
- Experimental challenges as we enter further the Multi-TeV world:

  → TeV leptons

  → Increased pile-up

- Open up new opportunities to explore un-resolved questions ...... gravity, dark matter....

Thanks for inviting me!