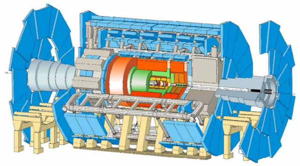
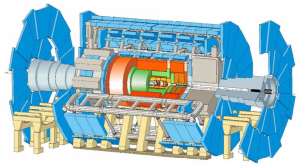


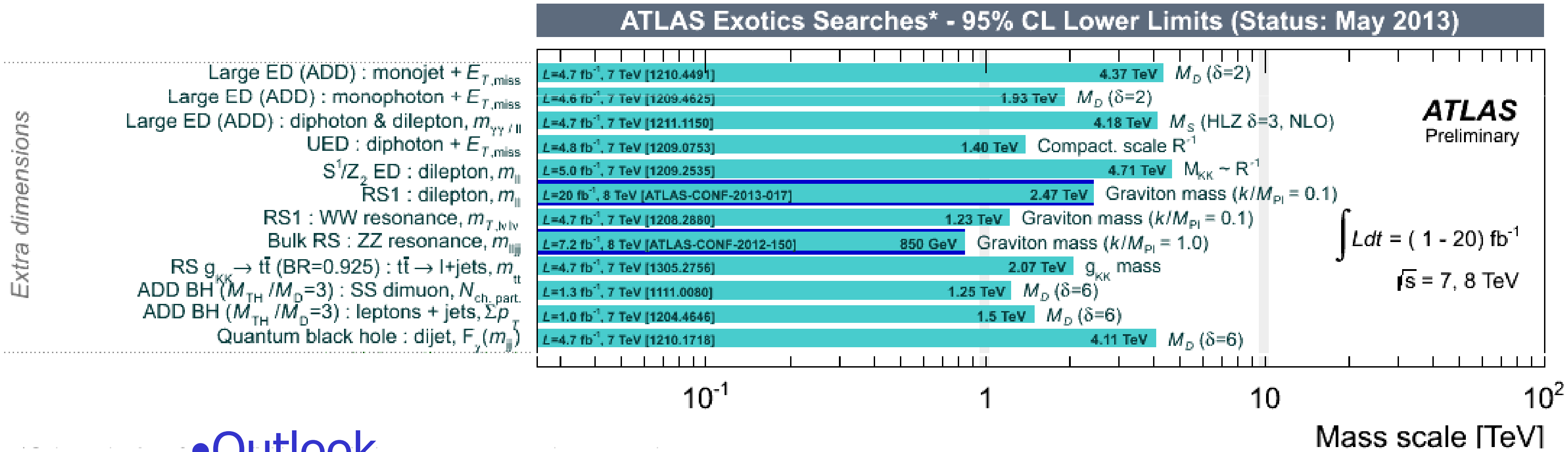
Searches for Gravitational Effects at the TeV scale with the ATLAS detector

Dr Tracey Berry
Royal Holloway
University of London



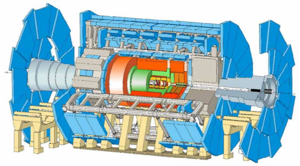
Overview

- Motivation for Gravitational Effects Searches
- Brief Introduction to Extra Dimensional Models
- Selection of ATLAS Gravity Searches

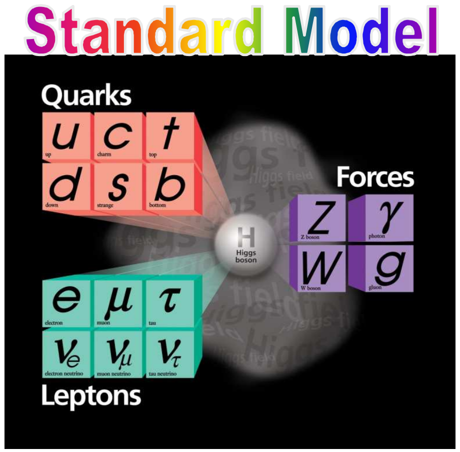


- Outlook

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

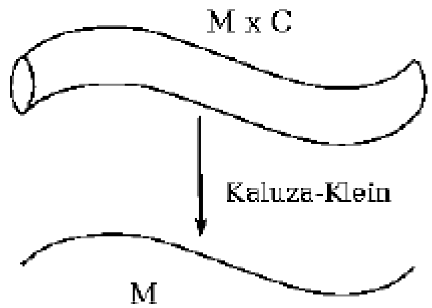
M_{EW} (10^3 GeV) << M_{Planck} (10^{19} GeV)?

→ Extra Dimensional Models

A short History of Extra-Dimensions

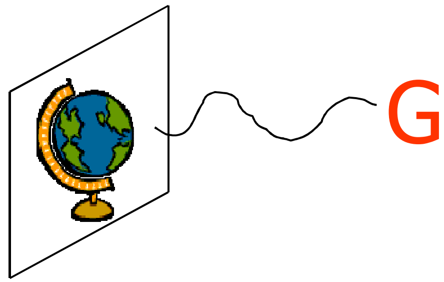
- 1921-26 Kaluza & Klein attempted to unify EM and relativity by adding a dimension to general relativity

  → Compatification → Kaluza-Klein towers

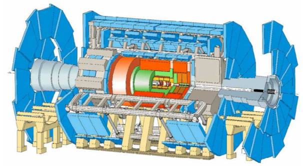


- → E= nhc/R

  (R = ED radius, n = integer)
- 1998: Large ED Arkani-Hamed, Dimopoulis, Dvali)
- 1999: Warped ED: Randall Sundrum



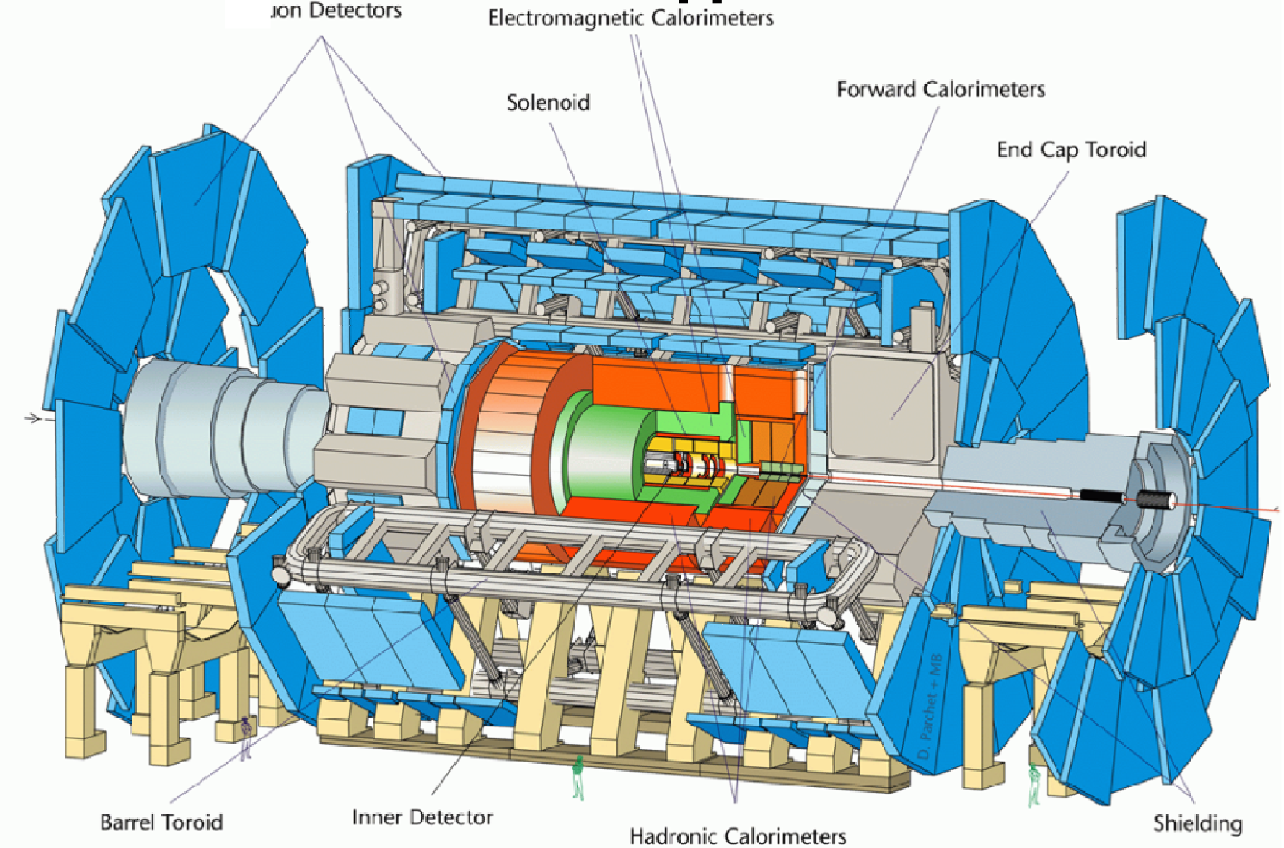
- Since then: many more.....



ATLAS

Large general-purpose particle physics detector

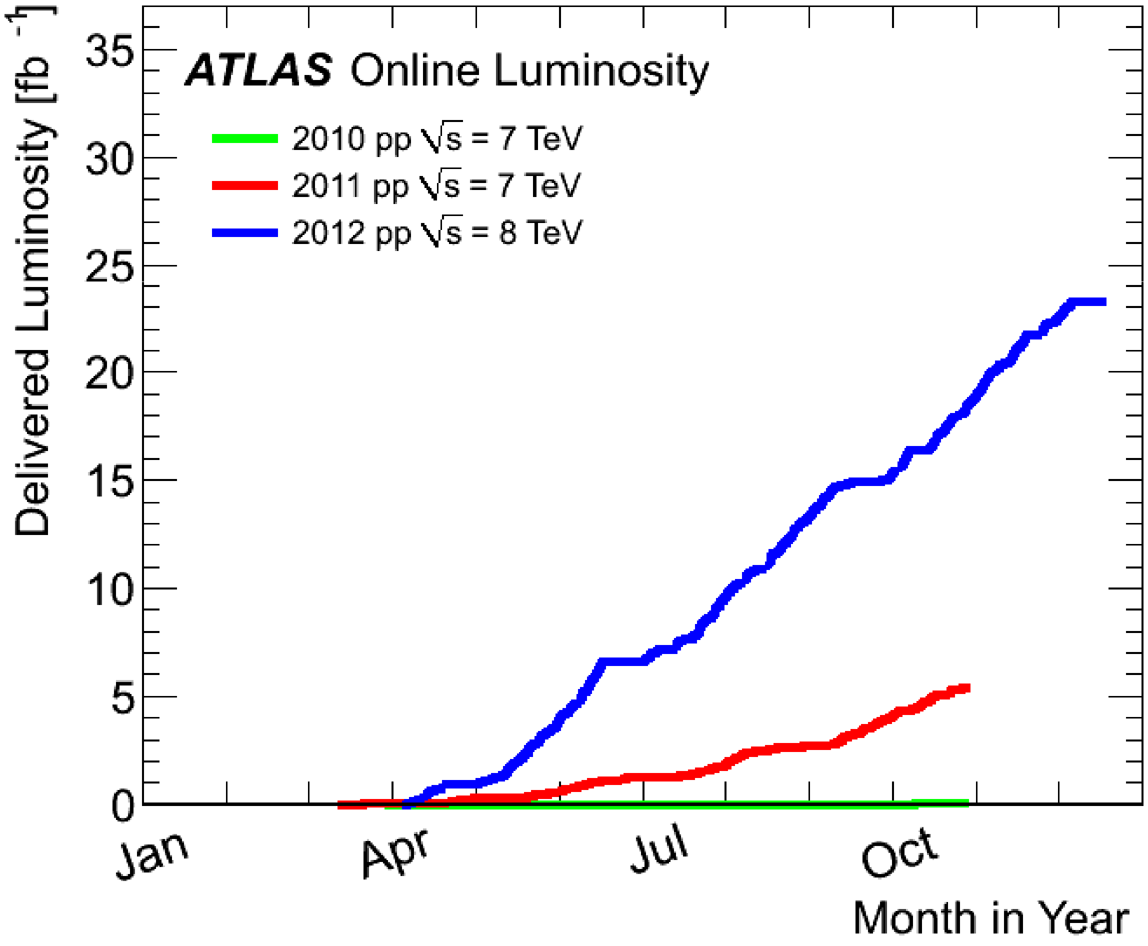
A Toroidal LHC ApparatuS



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

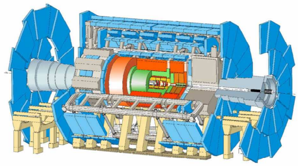
The Large Hadron Collider (LHC)

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



ADD Model

Monojet
Monophoton
Dilepton+Diphoton



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

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

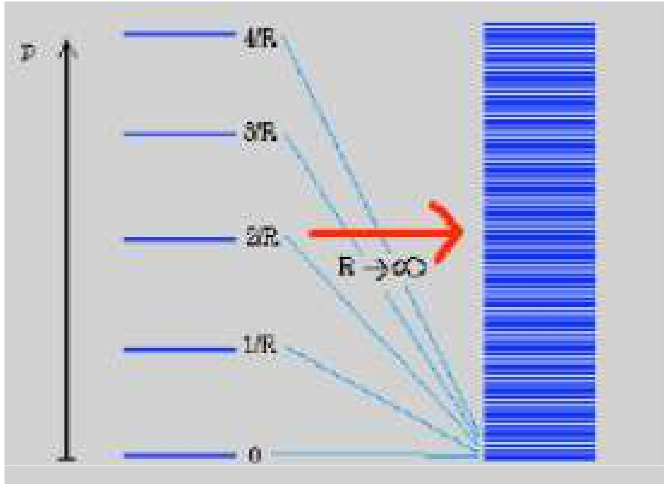
Typical size of ED
For M_D ~ TeV:

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



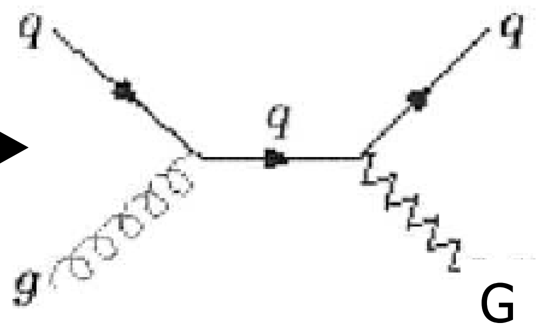
- At ATLAS: 3 ways to look for it:

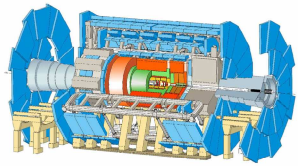
  → Deviation in Dilepton, diphoton or dijet spectrum caused by continuum

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

  → Blackhole

→

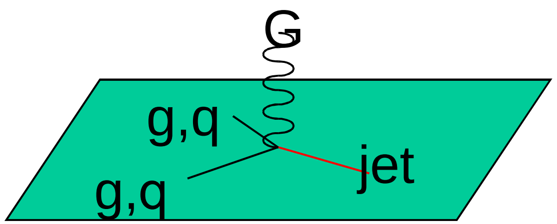




ADD Monojet Search
a single jet plus missing ET

8TeV

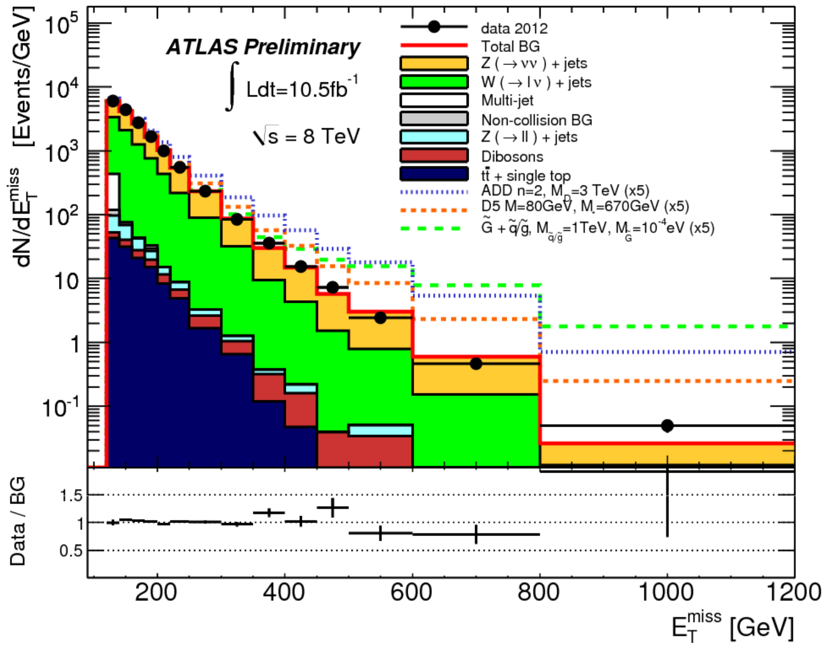
- ADD: Graviton Emission: Produce jet + G
- G disappears into the extra dimension
- Signature:
  single (high pT) jet and missing E_T^{Miss}

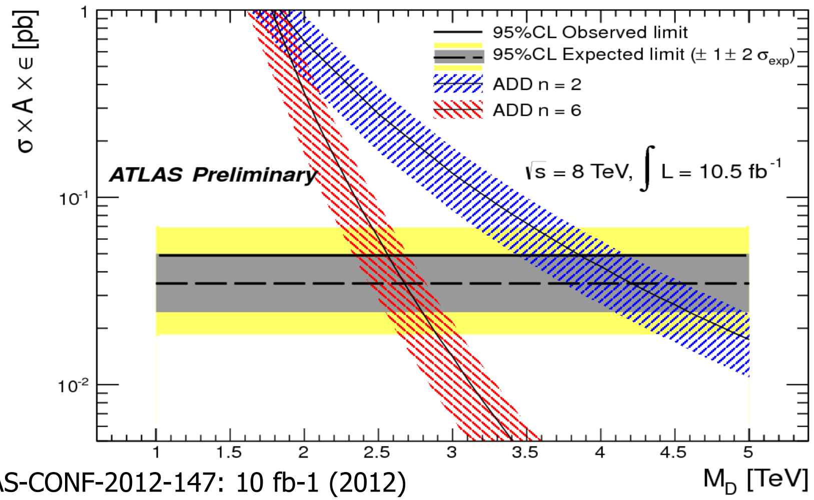


- Challenge:
  →Instrumental background
  → Understanding Z→(νν) + jets

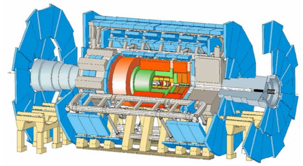
In Search Region
- Total Background 2180
  ±70 (stat. on EWK data bkg estimation)
  ±120 (stat. MC)±100 (syst)
- Data 2353

- Stringent limits on ADD



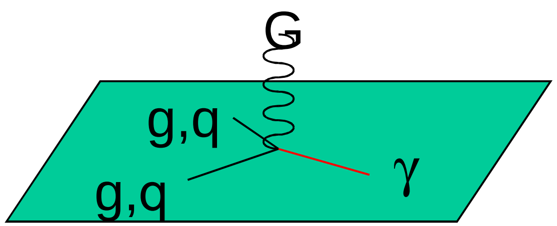


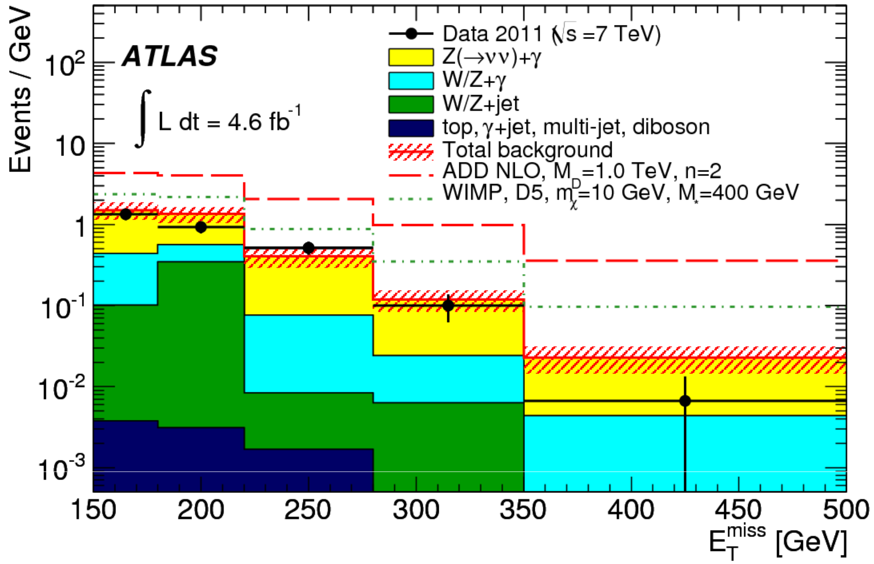
ATLAS-CONF-2012-147: 10 fb-1 (2012)
ATLAS-CONF-2011-096; 1 fb-1of (2011)
2010: arxiv:1106.5327, Phys.Lett.B 705 (2011) 294-312,(33 pb⁻¹)



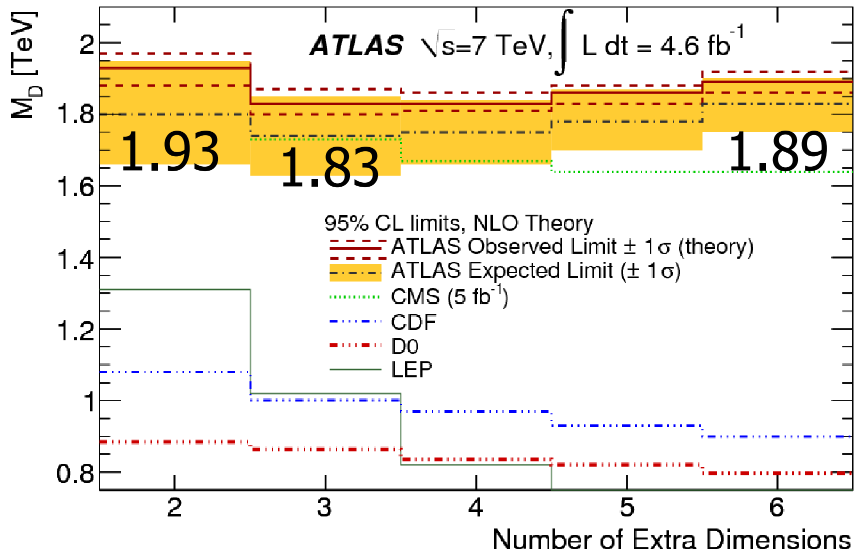
Large ED (ADD): monophoton+Et miss

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



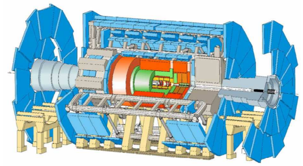


In Search Region
- Total Bkgd: 137±18 (stat) ±9 (syst)
- Data 116



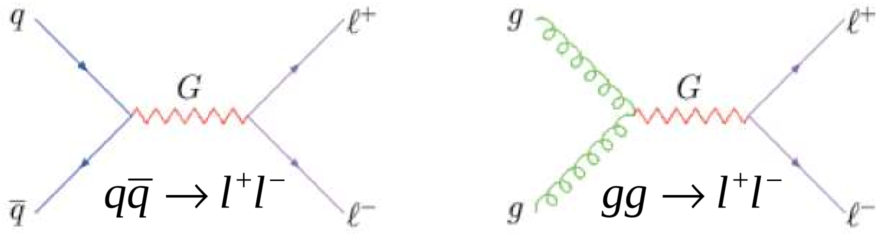
improves previous limits from LEP and Tevatron

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



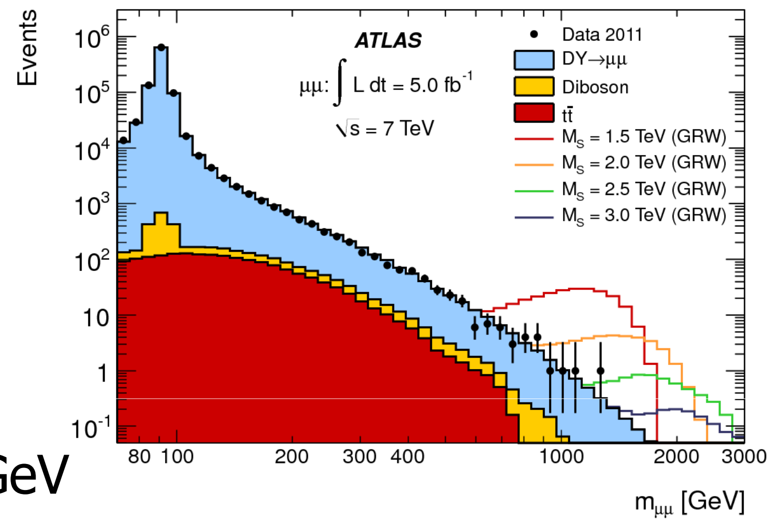
LED (ADD): dilepton

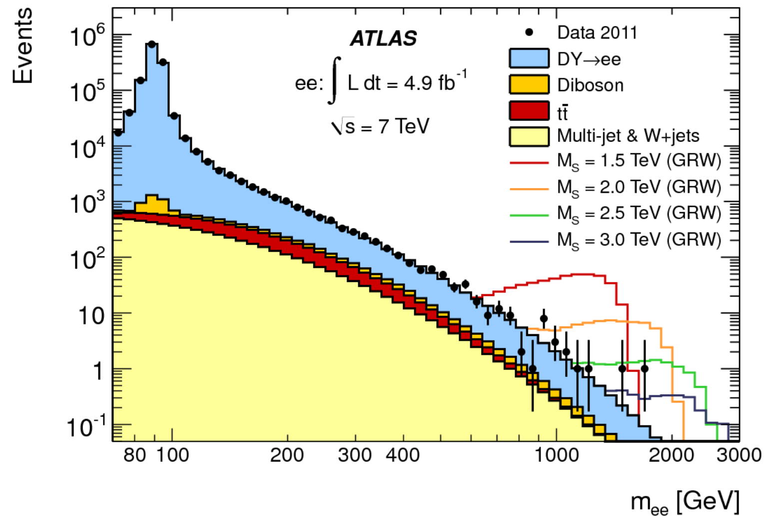
Virtual Graviton Exchange $pp \to G^{KK} \to \mu\mu/ee$



- Final state: 2 opposite sign μ or 2 e
- 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

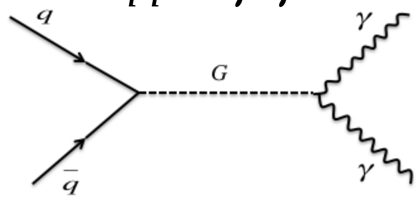




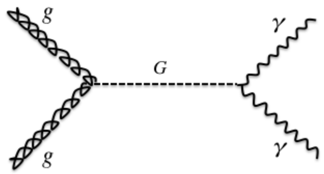
Phys. Rev. D 87, 015010 (2013)

LED (ADD) diphoton

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



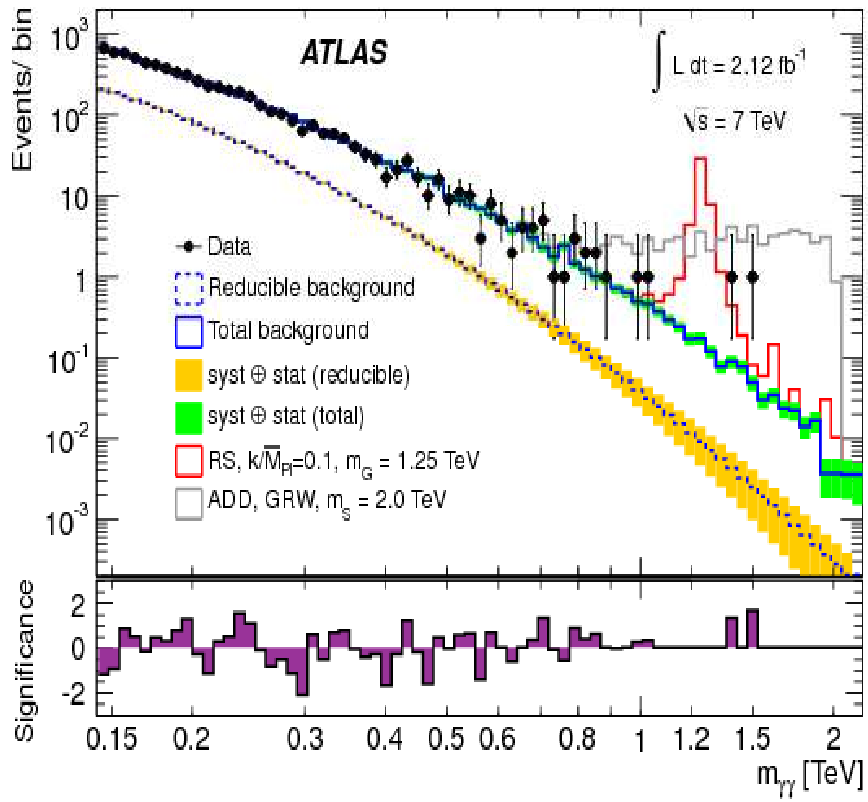
$gg \rightarrow \gamma^{+}\gamma^{-}$

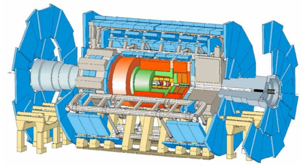


- 2 γ with E_T > 25 GeV
- Energy correction to reduce pile-up & underlying event effects
- ee Overlap removal to combine results with G→ee

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

- Bkgd normalised to data 140 Gev < $m_{\gamma\gamma}$ < 400 GeV





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

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

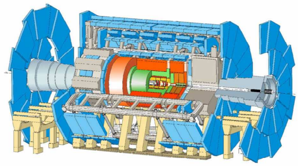
$$\mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{s}\right) & n = 2 \\ \frac{2}{n-2} & n > 2 \end{cases}, \text{ (HLZ)}$$

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

σ independent of the number of ED* in Hewett convention

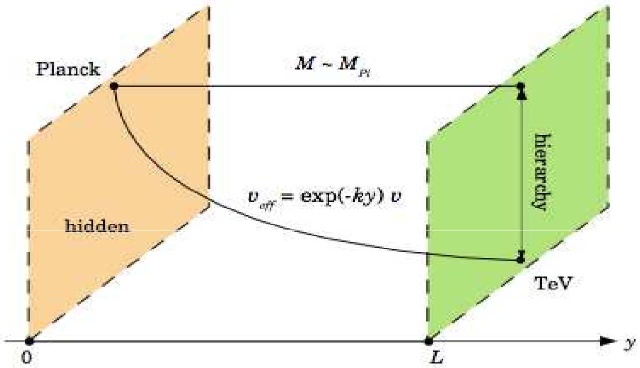
RS Model

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



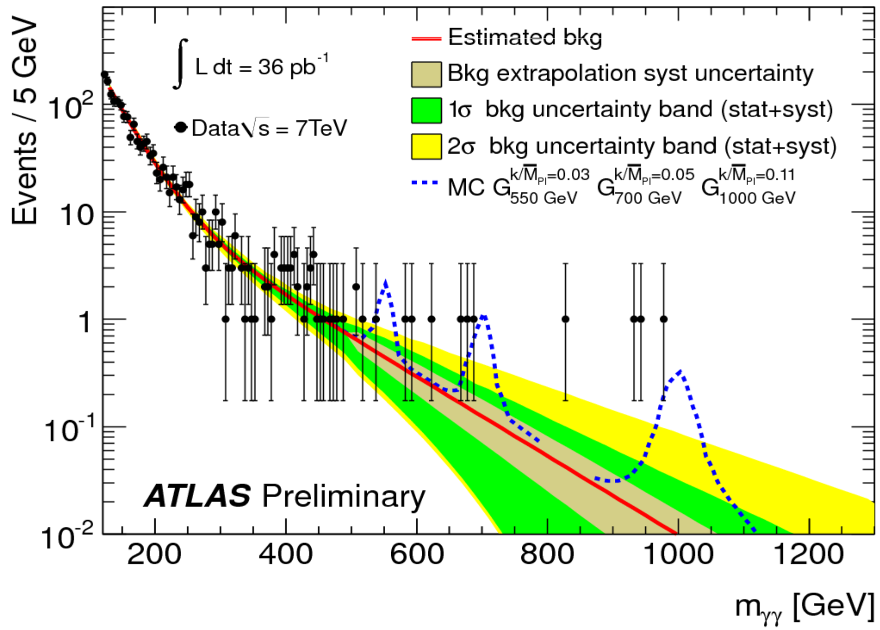
$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

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

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

- 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 $(k/M_{Pl})^2$

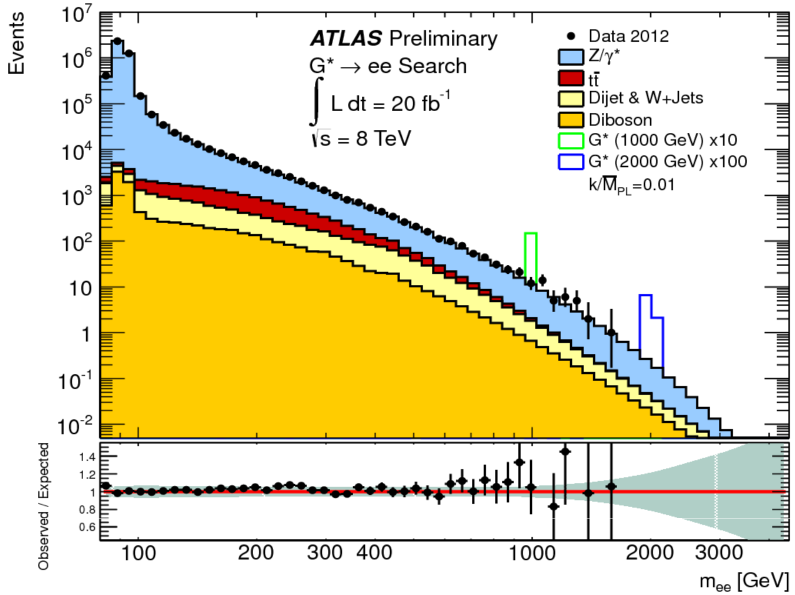


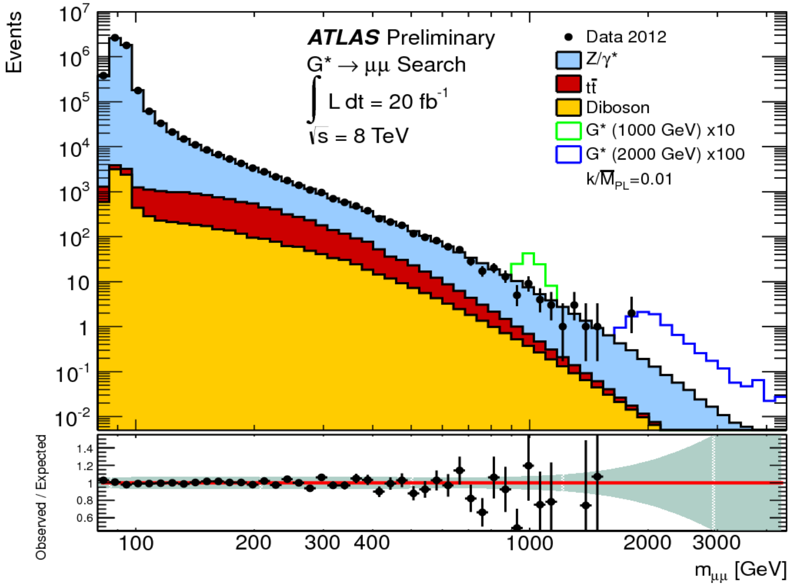
ATL-CONF-2011-044

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

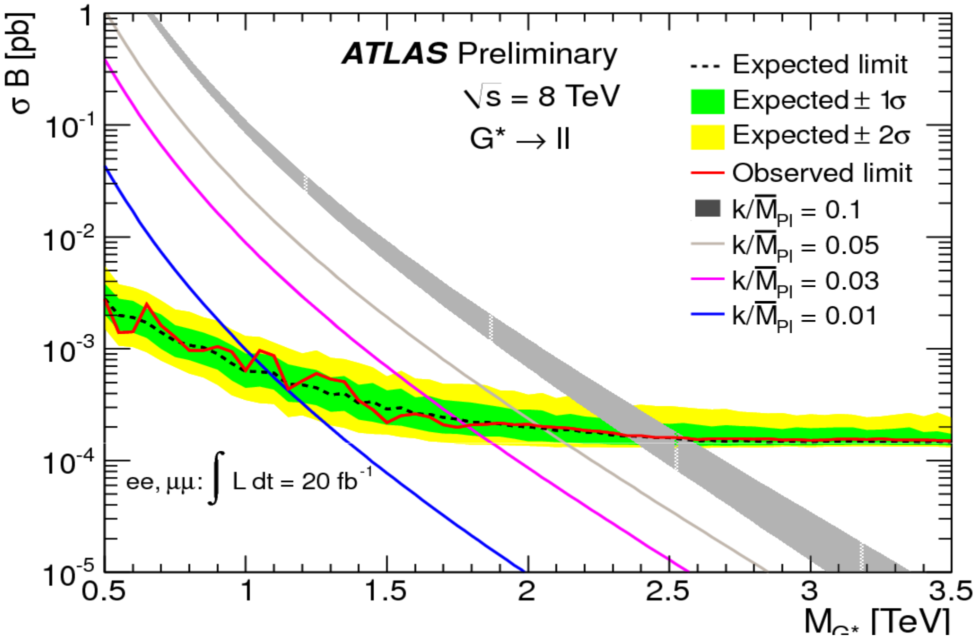




ATLAS-CONF-2013-017, 20 fb-1

RS1: Dilepton

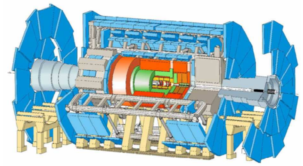
8TeV



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

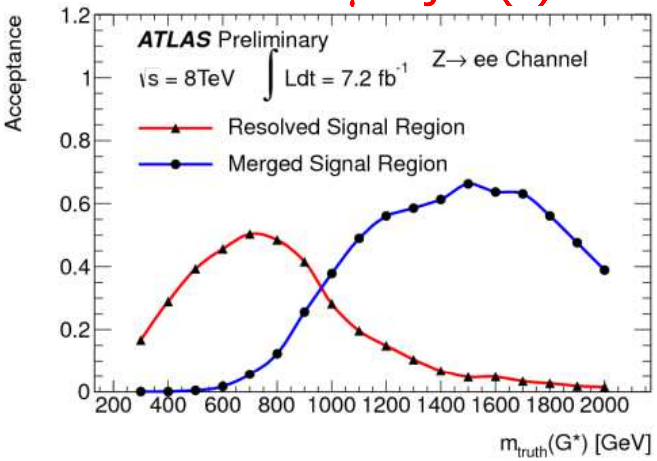
k/M_{Pl}=0.1	$G^* \to e^+e^-$	$G^* \to \mu^+\mu^-$	$G^* \to \ell^+\ell^-$
Observed mass limit [TeV]	2.40	2.10	2.47
Expected mass limit [TeV]	2.40	2.17	2.47

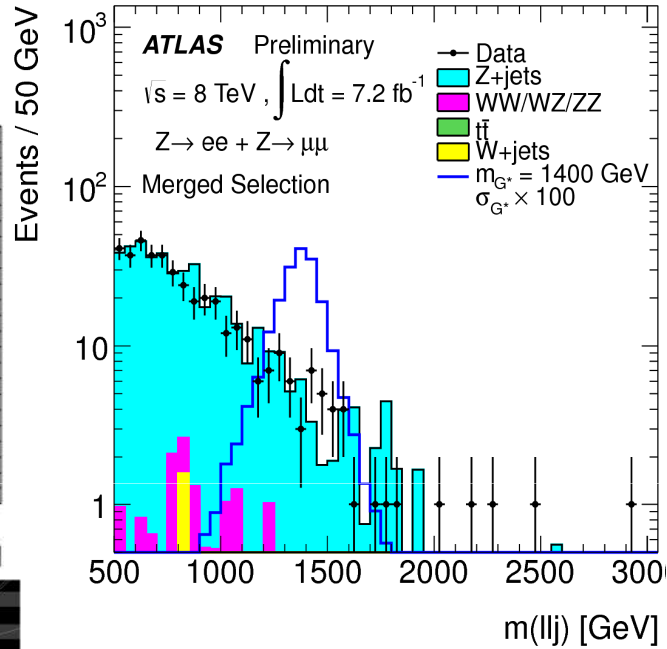
ATLAS sets best limits on this model in this channel!

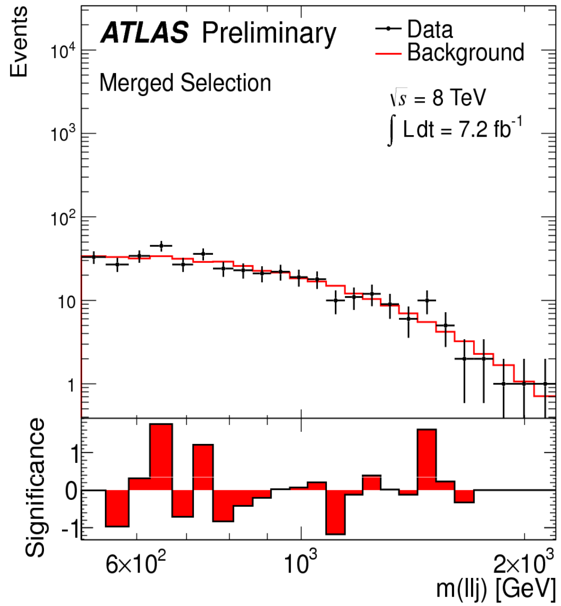


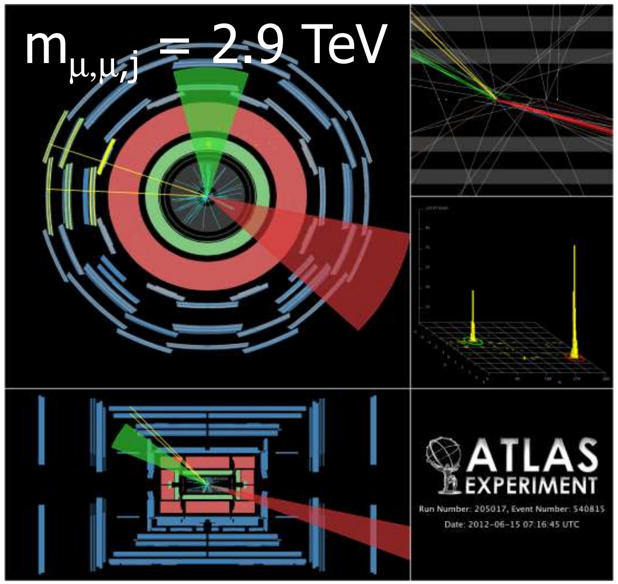
Bulk RS: G*→ZZ → llqq

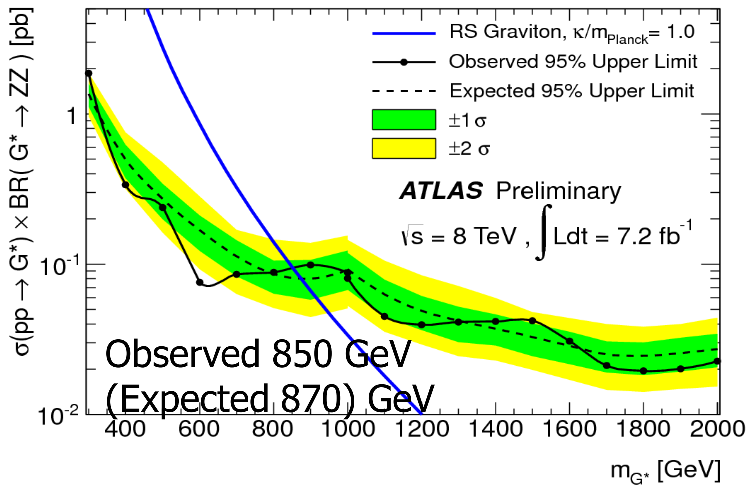
- Signal:
  - 2 e or 2 μ+ jet (s)









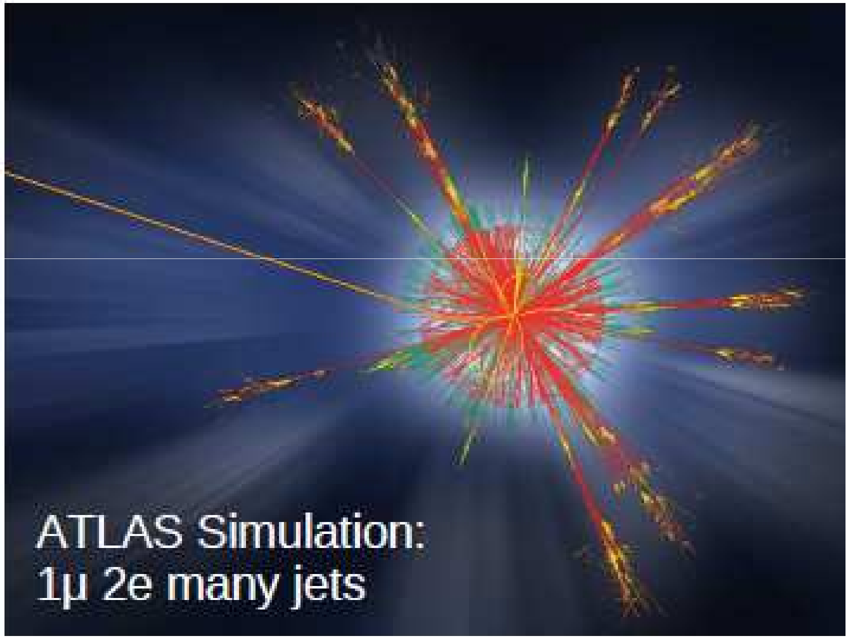


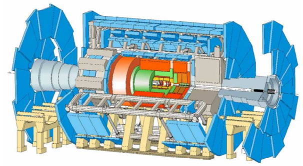
Observed 850 GeV
(Expected 870) GeV

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

Microscopic Black Holes

- If Gravity becomes strong at TeV → strong enough to produce Microscopic black holes decaying through Hawking radiation
- Large uncertainty on models due to our ignorance of quantum gravity
- Semi-classical models only for m(B.H.) >> m(threshold)
- A safe bet: decay is democratic and isotropic → look for (many) jets (and leptons) at high mass

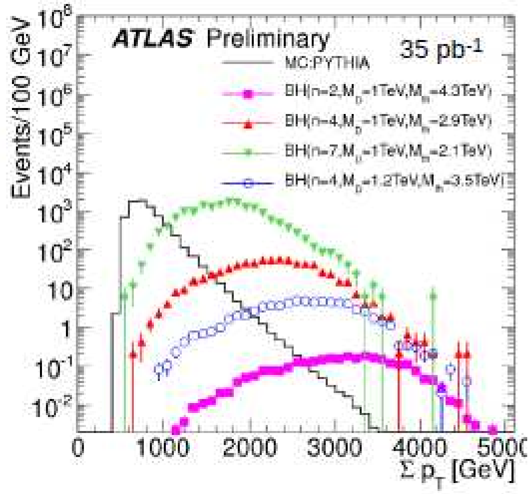


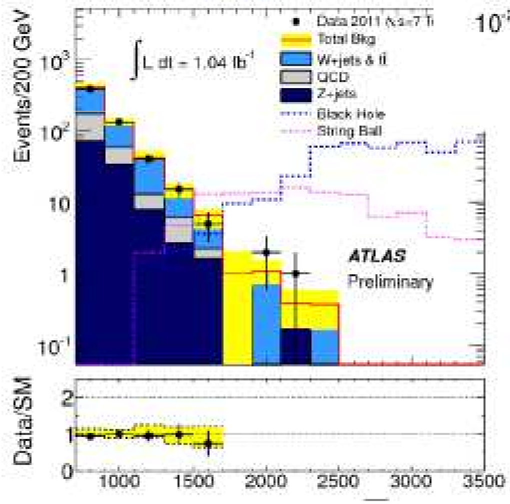


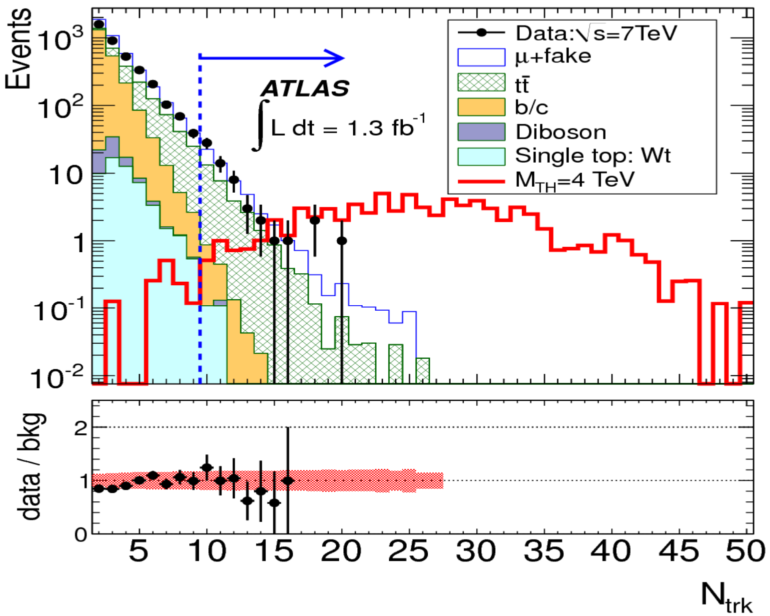
Black Holes

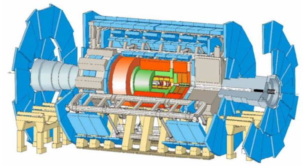
Search Signatures

- Multijet
- Lepton + Jets
- Same-sign Dimuon









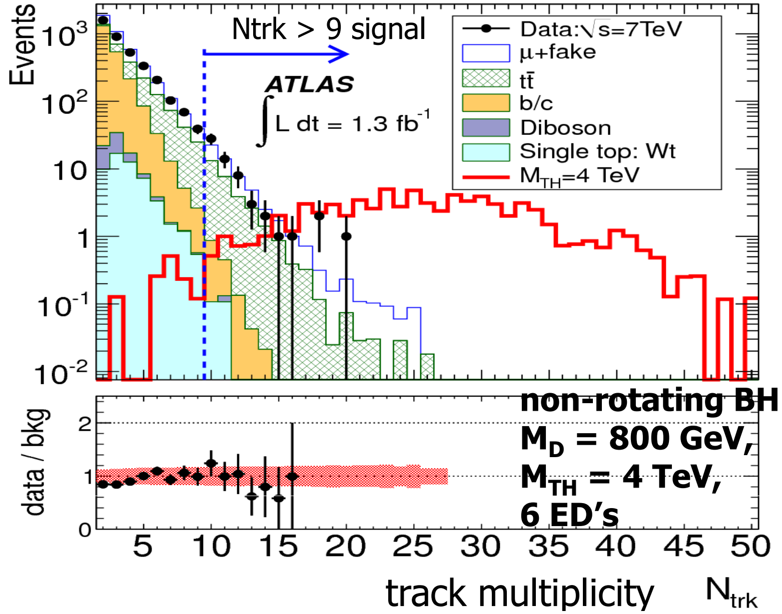
Large ED ADD Model: BH

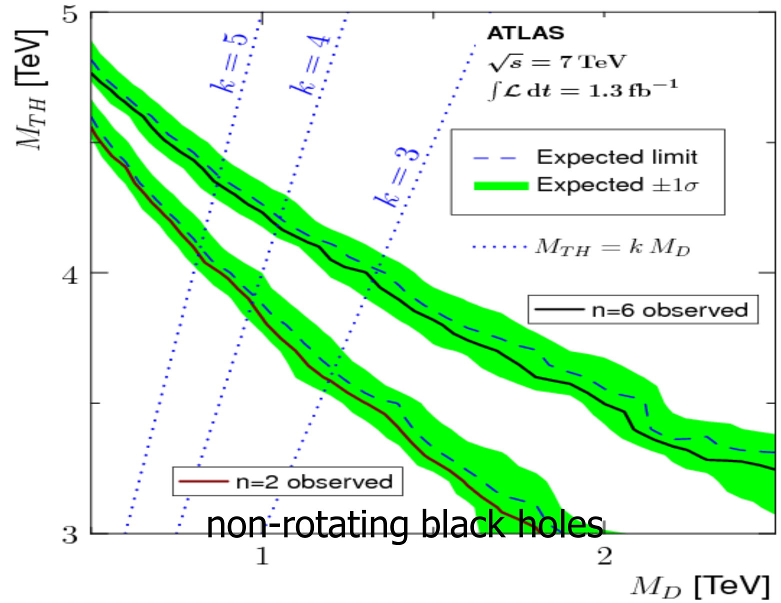
Benchmark Model: Large ED ADD Model

- M_D is the Planck scale in n+4 D ($M_D << M_{Pl}$)
- If there are ED and M_D~1TeV, microscopic black holes (BH) can be produced at LHC

- Assume continuous BH production from M_D to LHC √s=7 TeV, but remove mass region (M_{TH}) close to M_D where classical BH production and semi-classical BH decay approximations are not valid

- Strategy:
- Select events with same sign dimuons,
  - with at least one being isolated, to minimize SM bkgs
- Look at track multiplicity distribution
- No excess over SM expectations seen





2010 data: ATLAS-CONF-2011-065: 31 pb-1
2011: PLB, 1.3 fb-1

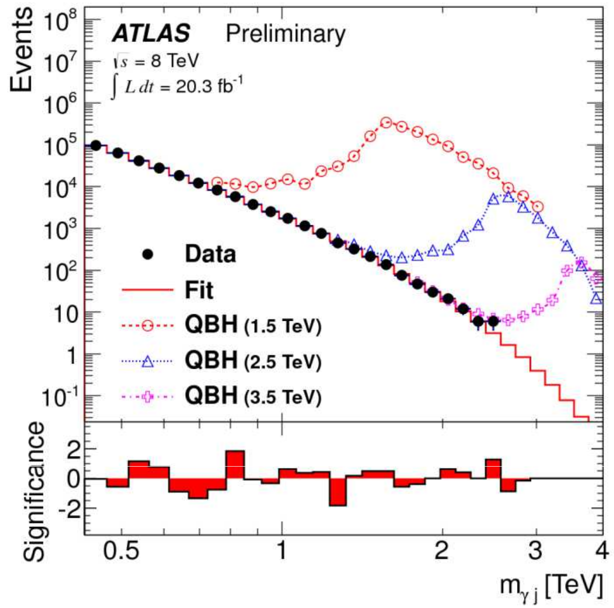
Non-Thermal Quantum Black Holes (QBH)

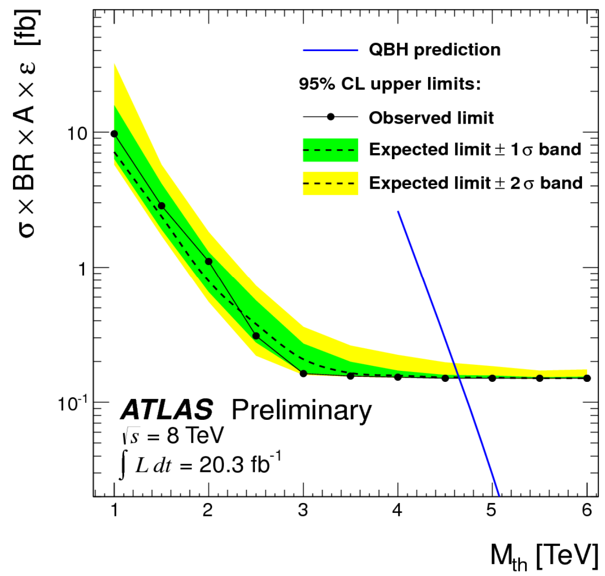
γ + Jet

8TeV

- Model-independent search for resonances in (γ +jet) events

- (γ +jet) mass distribution is compared to a background model fit from data
- No significant deviation from the background-only hypothesis is found
- 95% Confidence limit
  - on generic Gaussian-shaped signals set
  - non-thermal QBH below masses of 4.6 TeV are excluded





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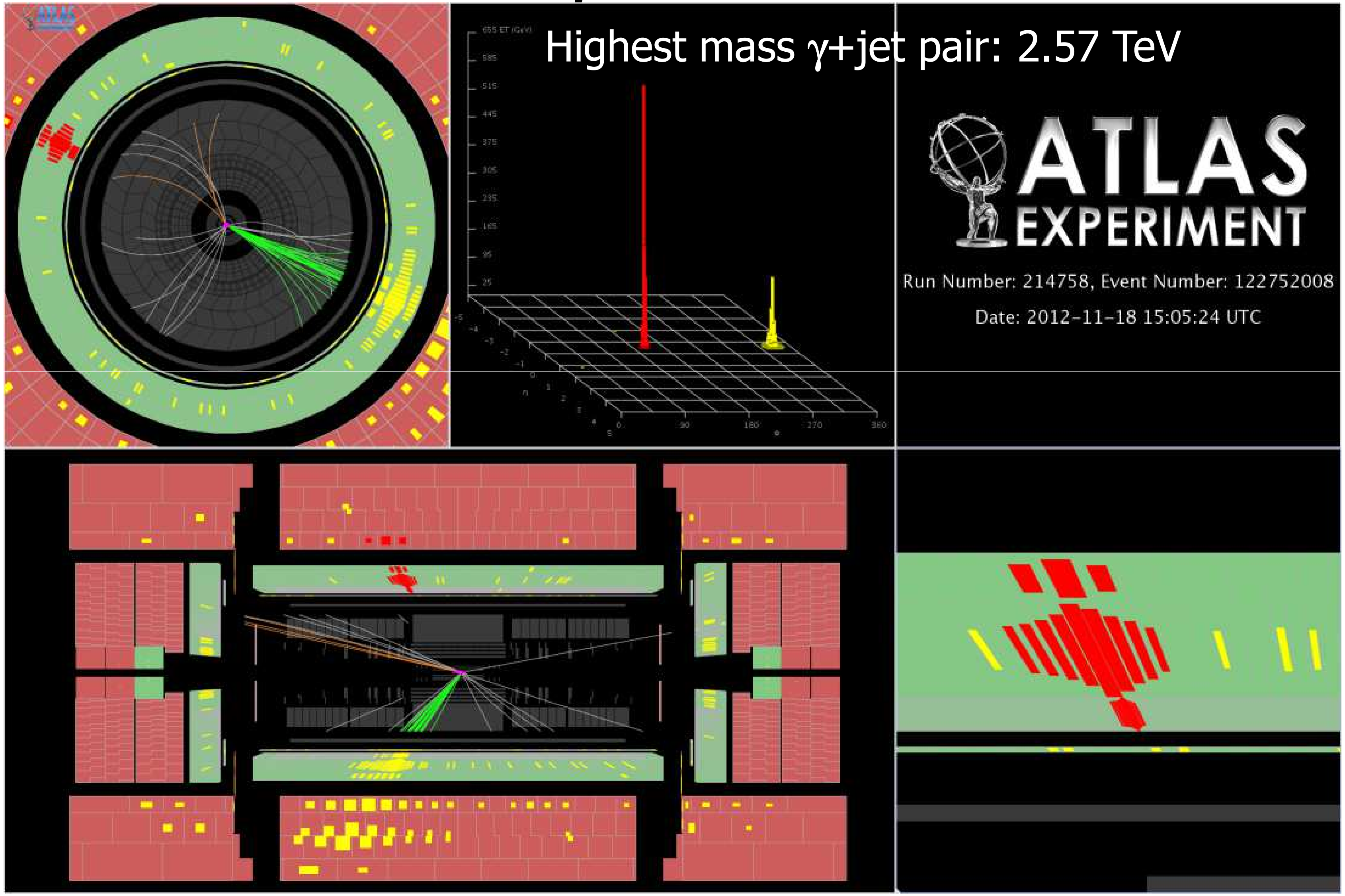
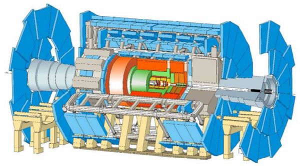




Conclusion

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

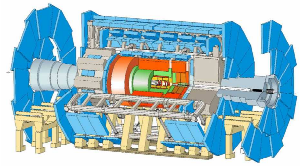
  → TeV leptons

  → Increased pile-up
- Open up new opportunities

  → Boosted objects (W, top)

  → Investigate less obvious signatures

Thanks for inviting me!

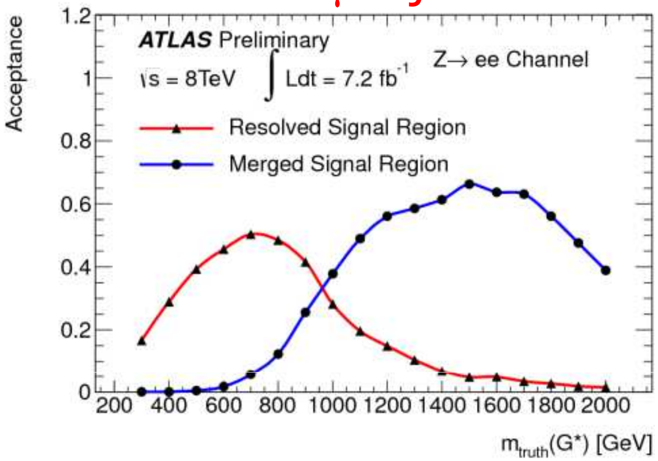


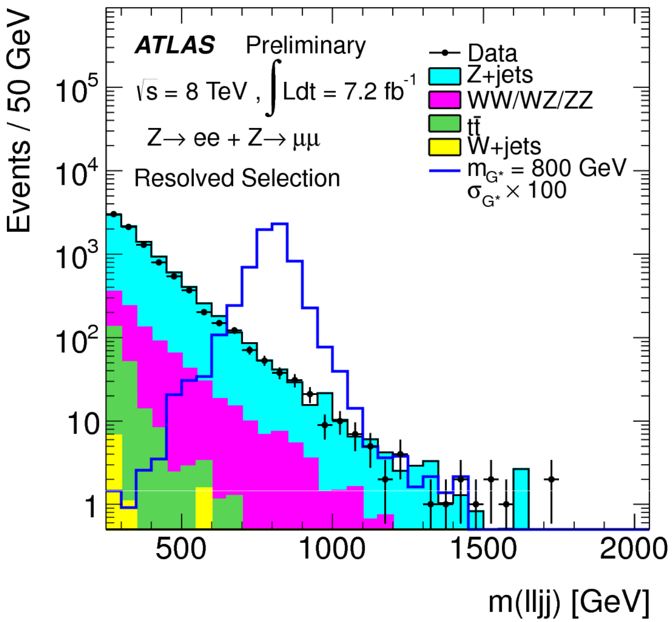
BACK UP SLIDES

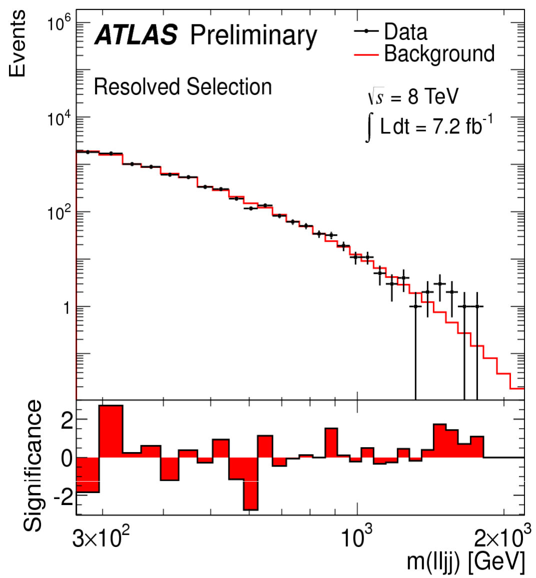
Bulk RS: G*→ZZ → llqq

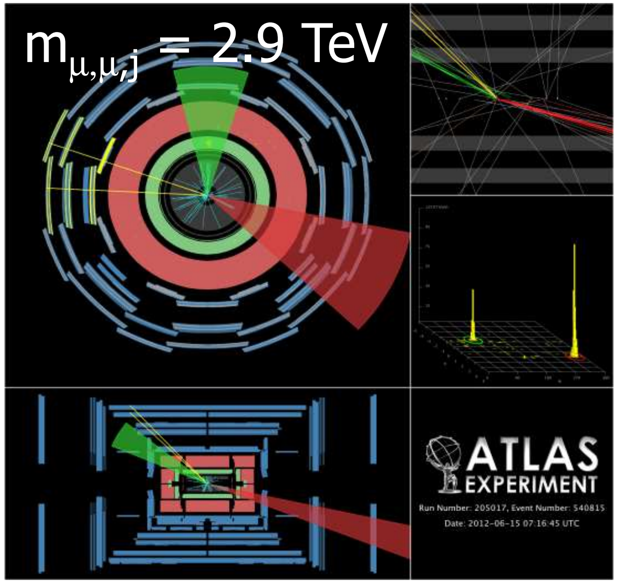
- Signal:

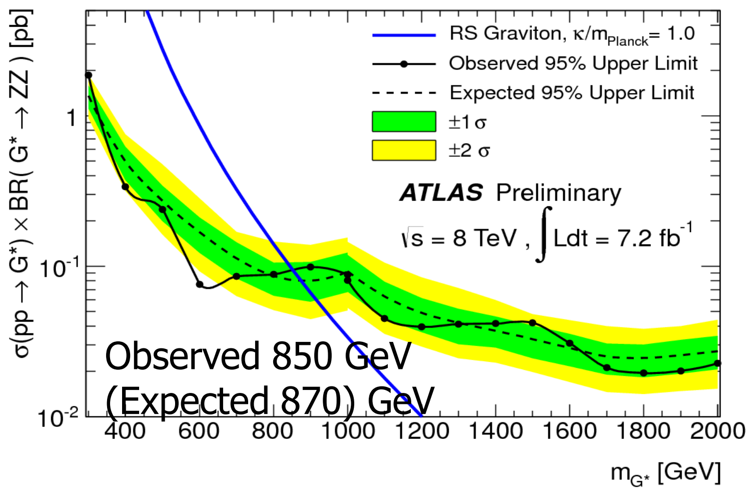
  2 e or 2 μ+ jets











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

QBH Dijet

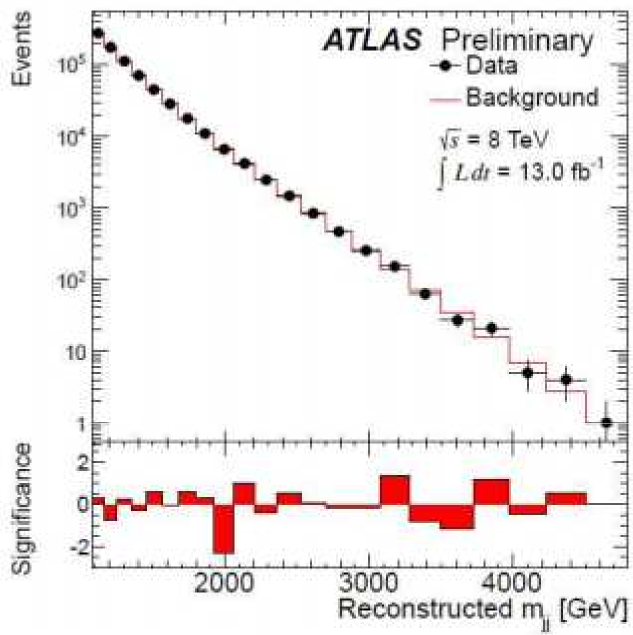
8TeV

- Look for resonance above phenomenological fit of the data:

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

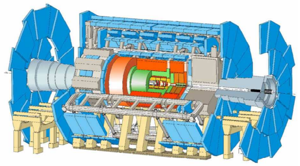
$$x \equiv m_{jj}/\sqrt{s}$$

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



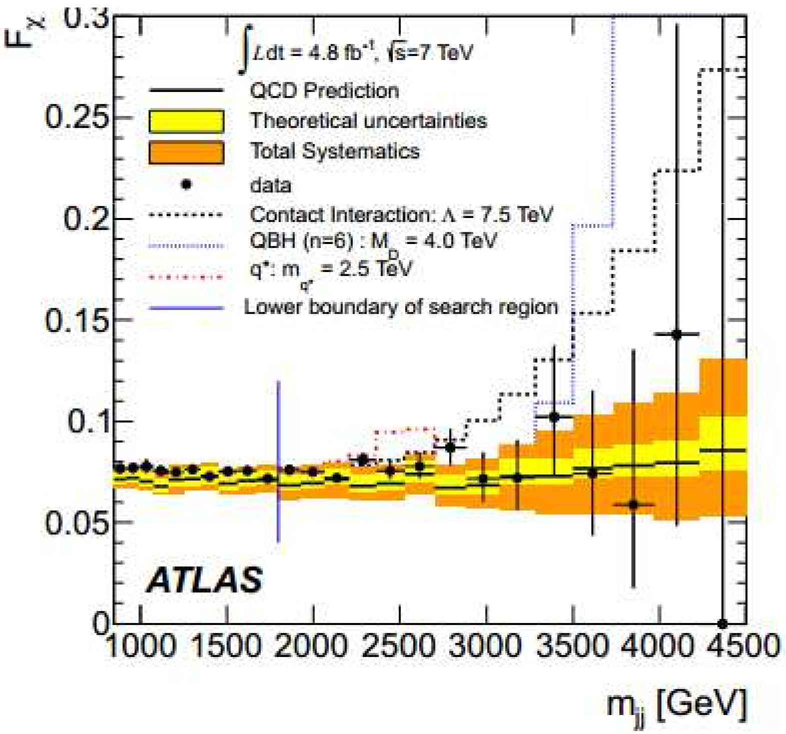
95 % C.L. Limits
Obs Mass Excl [1.20, 1.58]
Exp. Mass Excl: [1.20, 1.43]

Not presently translated into limits on RS or QBH

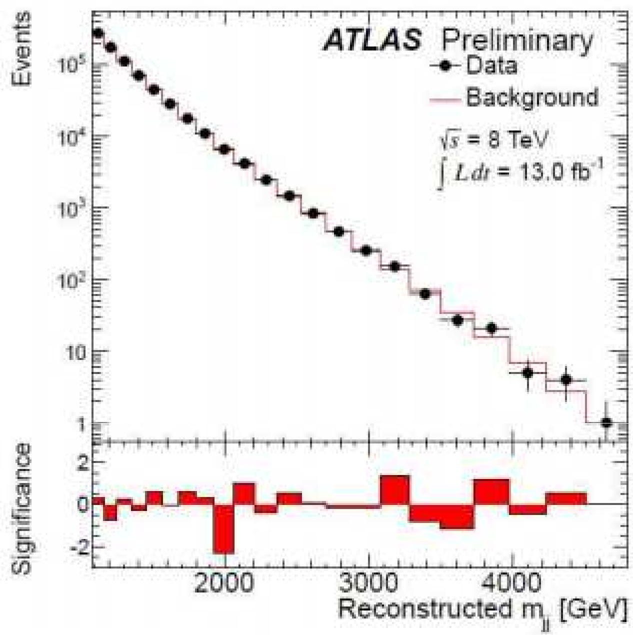


QBH Dijet

$$F_\chi(m_{jj}) \equiv \frac{\mathrm{d}N_{\mathrm{central}}/\mathrm{d}m_{jj}}{\mathrm{d}N_{\mathrm{total}}/\mathrm{d}m_{jj}},$$

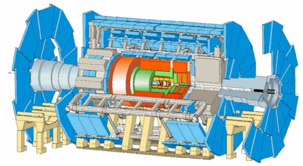


ATLAS 13 fb^{-1} @ 8 TeV [CONF-2012-148]



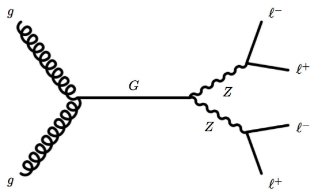
7 TeV

QBH: n= 6 ED exclude quantum gravity scales below 4.11 TeV

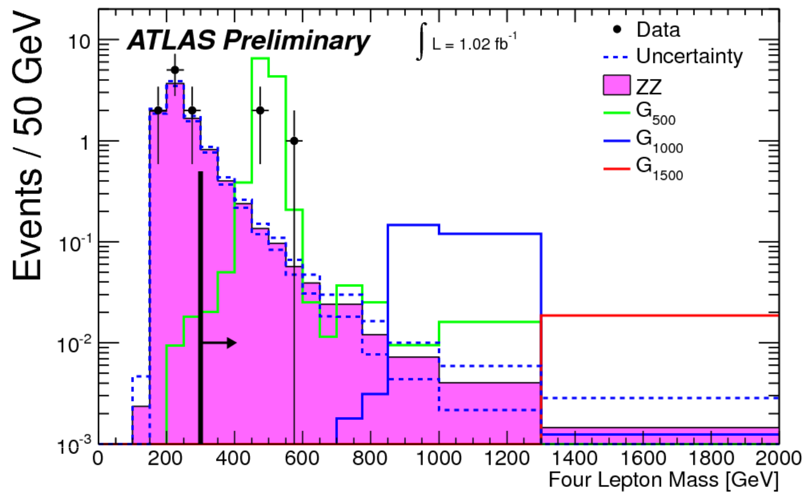


Bulk RS: G*→ZZ → llll with Four Charged Leptons

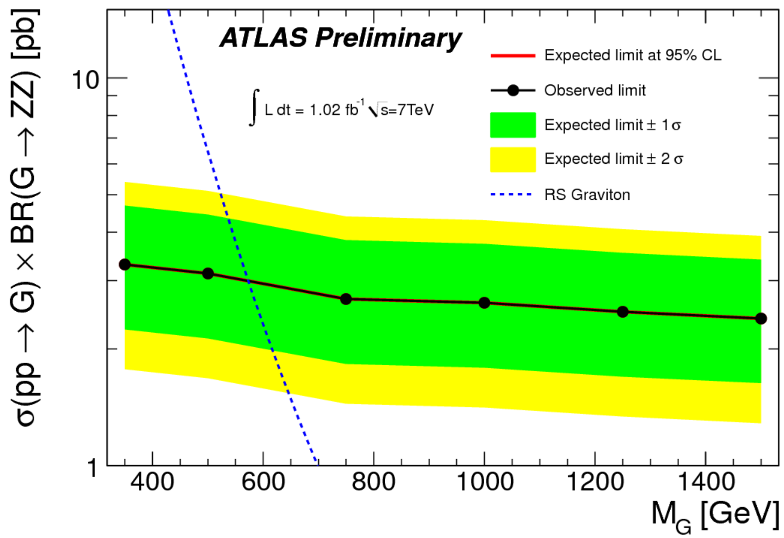
- Signal: Four Charged Leptons
- 2 searches performed in this decay channel ZZ & H^{++} H^{--}



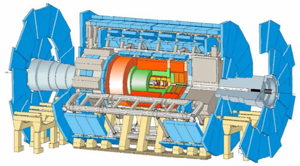
- Events with two identified $Z \rightarrow \ell^+\ell^-$ decays
- For $M_{\ell\ell\ell\ell}$>300 GeV: from SM expect $1.9^{+1.0}_{-0.1}$ (stat) $^{+0.8}_{-0.1}$ (syst) events
- Observe: 3 events



- 95% C.L. Limit σ(production of ZZ from high-mass sources) <0.9 pb in the fiducial region
- For RS model: limits on σ(pp→G)×BF(G→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

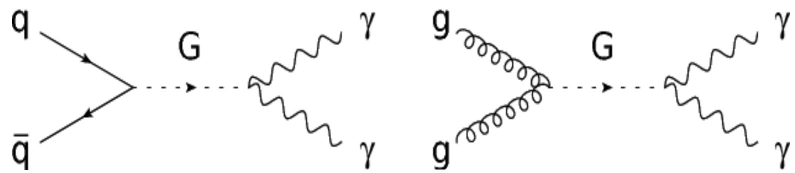


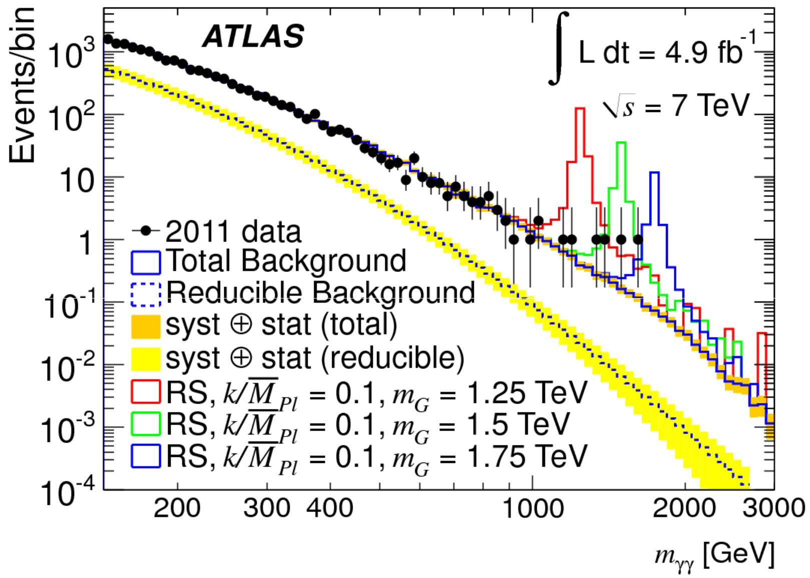
ATLAS-CONF-2011-144

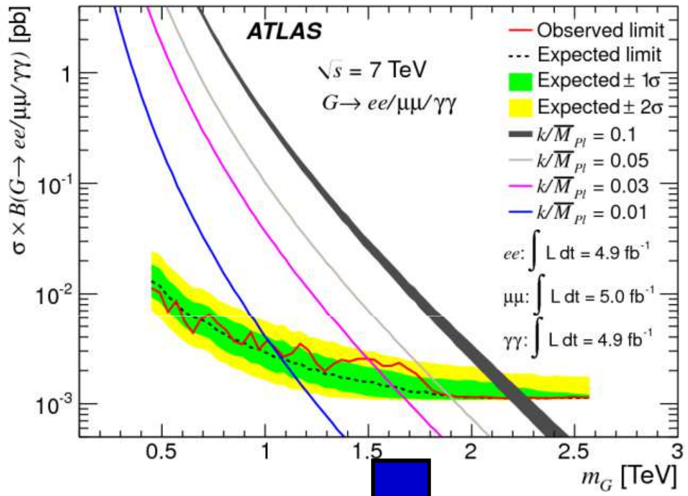


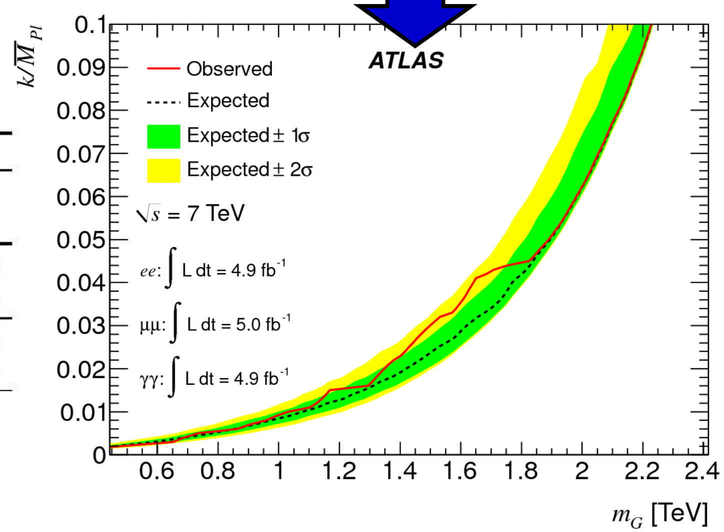
RS Diphotons

- $m_{\gamma\gamma}$ > 500 GeV
- BR (G→gg) = 2 BR(G→μμ /ee)



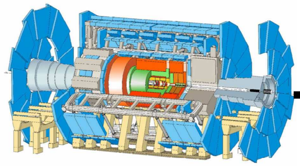






	K-factor value	Channel(s) Used	95 % CL Observed (Expected) Limit [TeV]			
			$k/\overline{M}_{Pl}$ value			
			0.01	0.03	0.05	0.1
LO	1	$G \to \gamma\gamma$	0.87 (0.88)	1.31 (1.36)	1.49 (1.60)	1.91 (1.92)
		$G \to \gamma\gamma/ee/\mu\mu$	0.91 (0.95)	1.39 (1.48)	1.62 (1.75)	2.10 (2.10)
NLO	1.75	$G \to \gamma\gamma$	1.00 (0.98)	1.37 (1.49)	1.63 (1.73)	2.06 (2.05)
		$G \to \gamma\gamma/ee/\mu\mu$	1.03 (1.08)	1.50 (1.63)	1.89 (1.90)	2.23 (2.23)

arXiv:1210.8389; NJP 15, 043007 (2013), 4.9 fb^{-1} , 2012

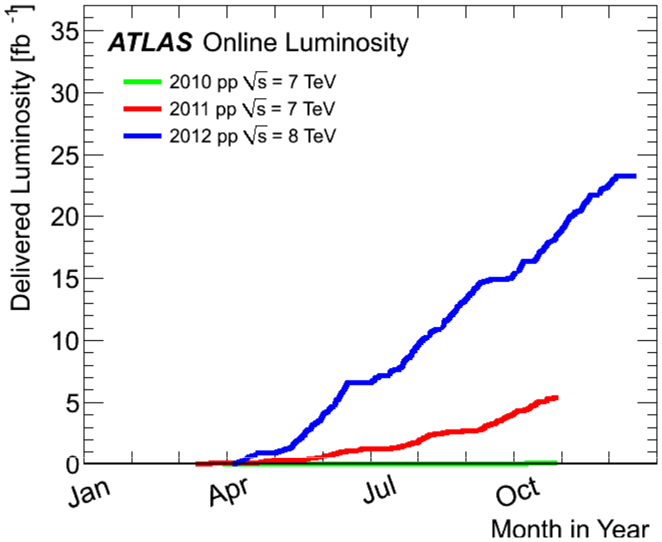
The Large Hadron Collider (LHC)

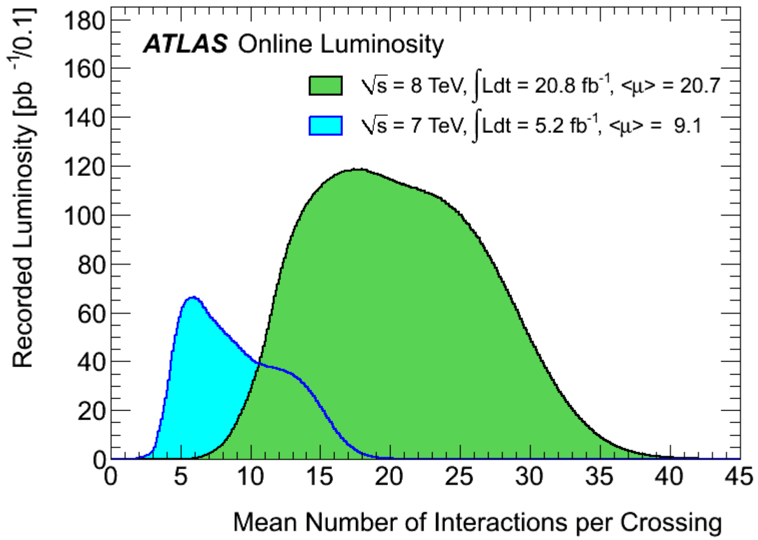
- pp collisions at √s=7 TeV in 2011
  and √s=8 TeV in 2012

- LHC has performed extremely well in 2012
  → 7.7 x10 33 /cm2/s peak luminosity

- 50 ns bunch spacing

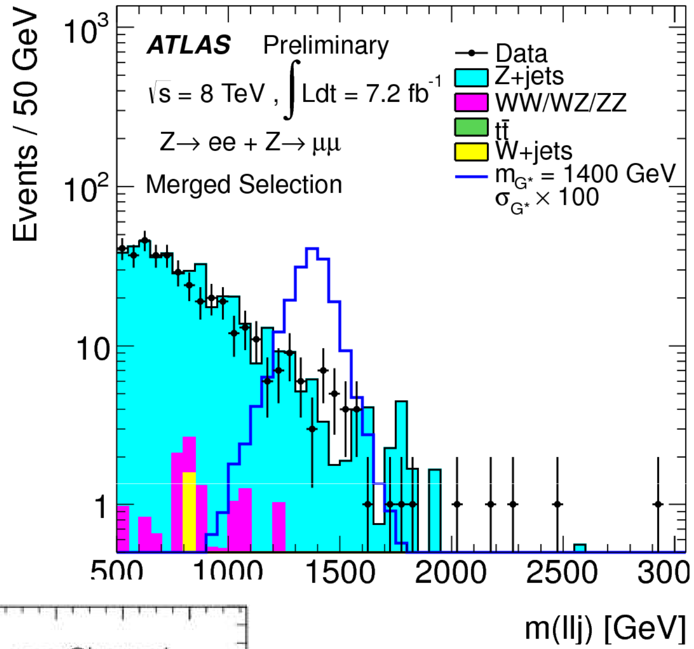
- Pile-up ~ 20 collisions/crossing

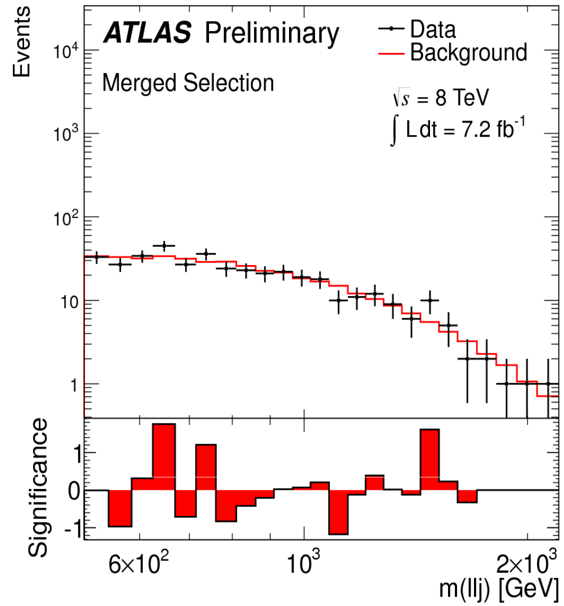


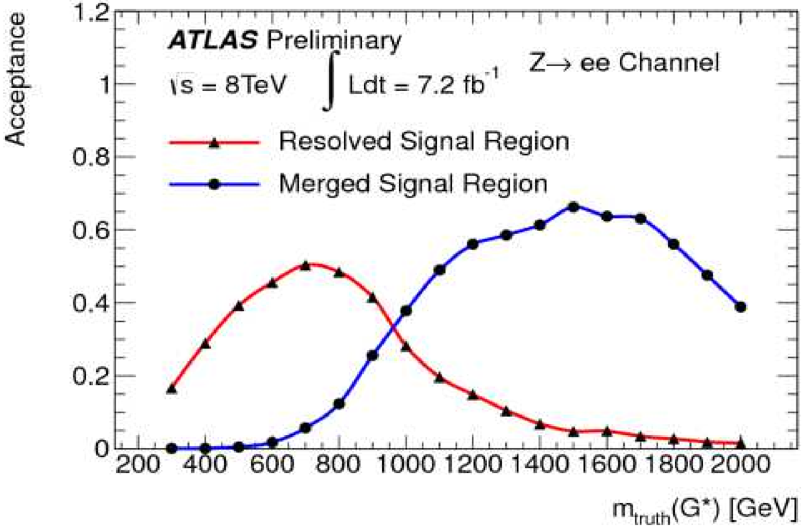


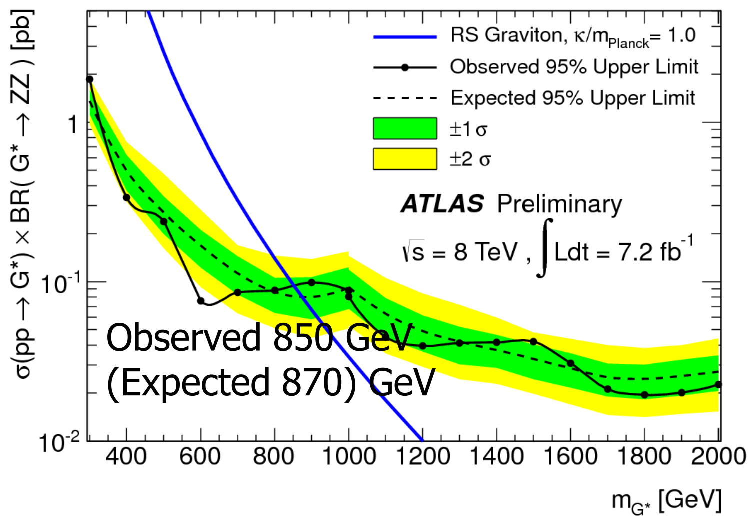
Bulk RS: G*→ZZ → llqq

- Signal:
  - 2 e or 2 μ+ 2 jets









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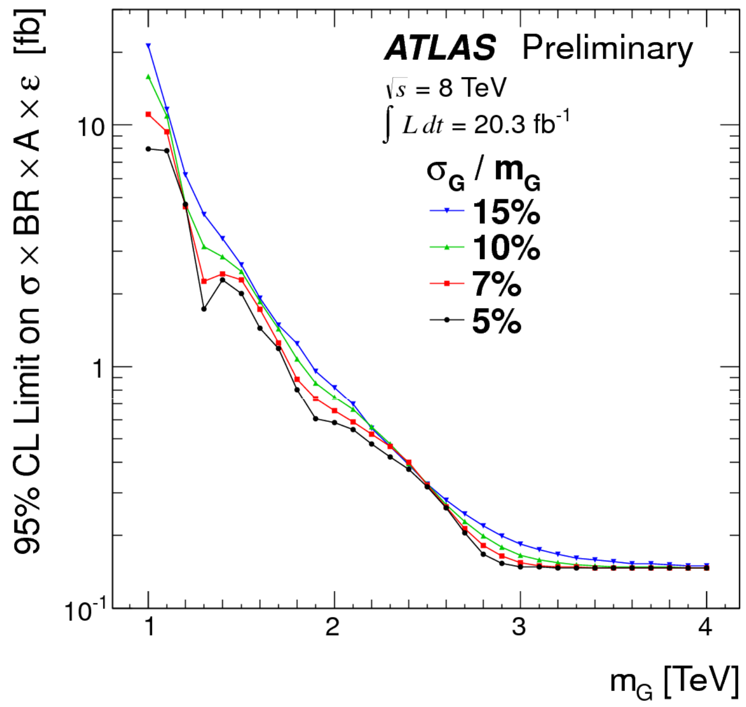
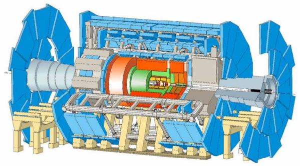


limits on Gaussian resonances exclude 4 TeV resonances with visible cross-section near 0.1 fb



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,

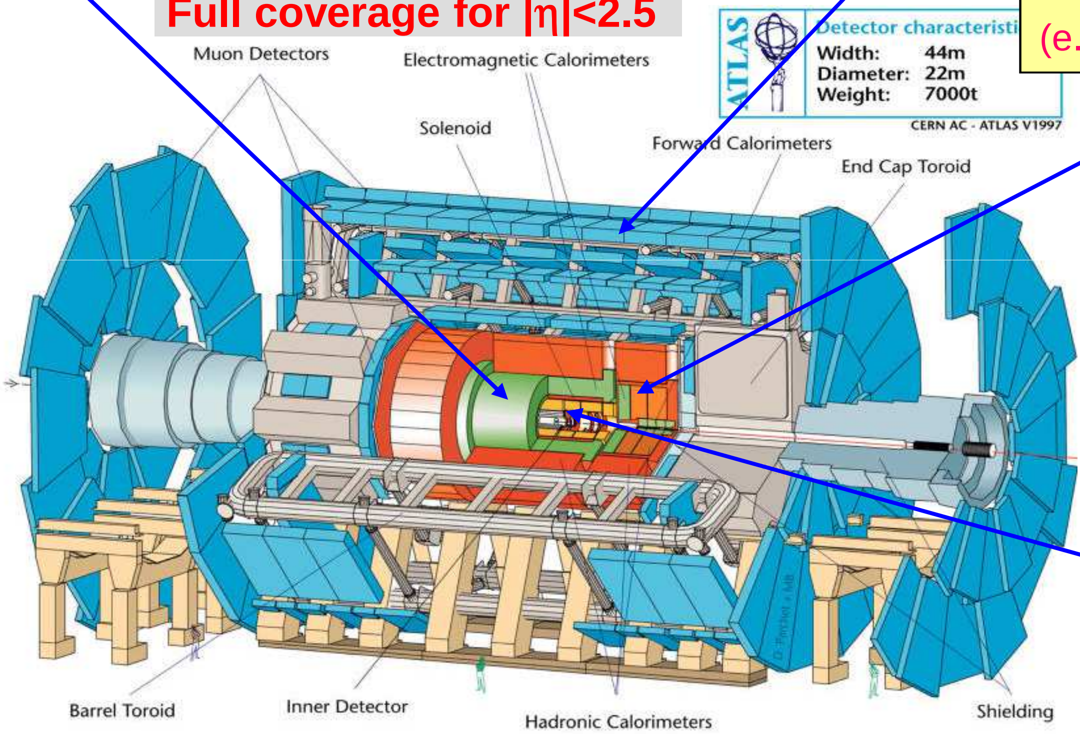
$\sigma/p_T \approx 10\%$ at 1 TeV/c

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