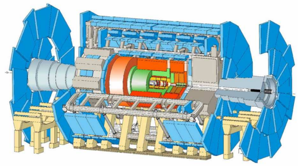
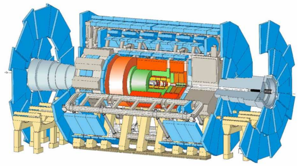


Searches for Extra Dimensions using the ATLAS detector

Dr Tracey Berry

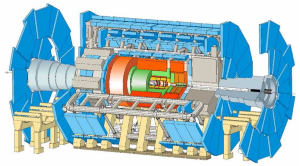
Royal Holloway
University of London



Overview

- Introduction:
  - Motivation for Extra Dimensional Model Searches
  - Extra Dimensional Models
- ATLAS & LHC
- Search Signatures/Channels used at ATLAS:
  - Overview of ATLAS Searches & Results
- Summary and Outlook

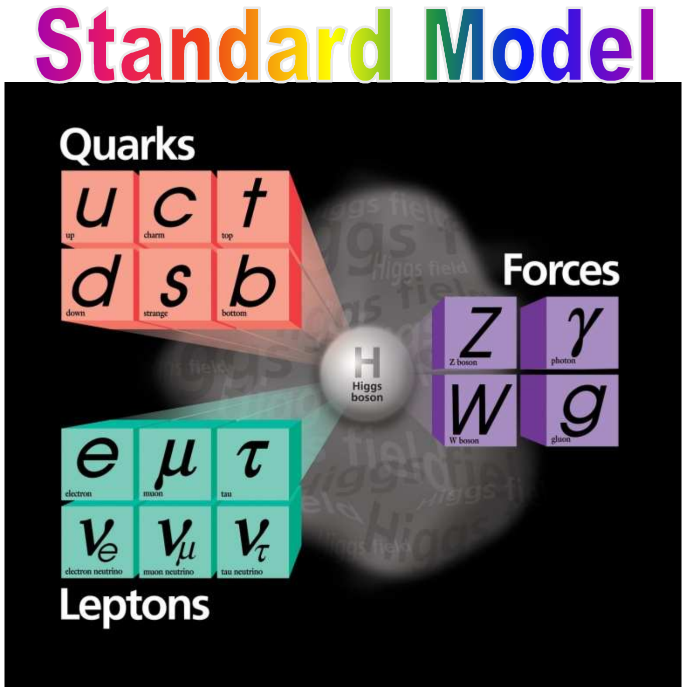
Further information can be found at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults?redirectedfrom=Atlas.ExoticsPublicResults



The Standard Model

The SM : particles + forces

Gravity is not included!



Motivation for searching for something beyond the SM….

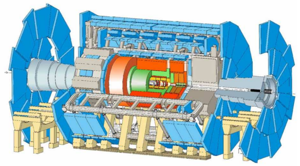
Forces in Nature

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)?

Table from Cigdem Issever, Oxford



ED Model Motivations

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

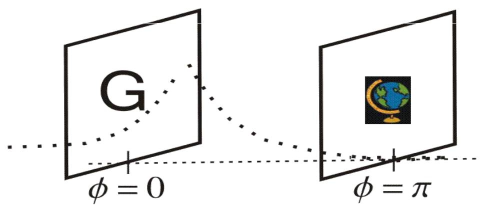
$$M_{Pl}^2 \sim R^{\delta} M_{Pl(4+\delta)}^{(2+\delta)}$$

Effective $M_{Pl} \sim$ 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



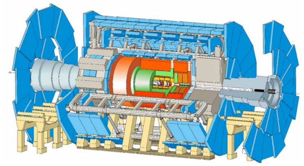
$$\Lambda_{\pi} = M_{pl} e^{-kR_c\pi}$$

$\Lambda_{\pi} \sim$ TeV

if warp factor $kR_c \sim$11-12

Since then, new Extra Dimensional models have been developed and been used to solve/address other problems:
Dark Matter, Dark Energy, SUSY Breaking, etc

These models can be/have been experimentally tested at high energy colliders



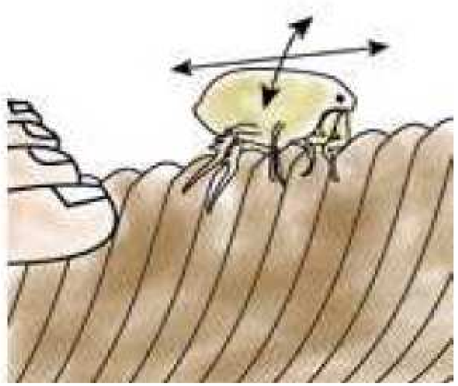
Extra Dimensions?

If ED exist, why haven't we observed them?

The "extra" dimensions could be hidden to us:

- E.g. To a tightrope walker, the tightrope is one-dimensional: he/she can only move forward or backward

• But an ant can go around the tightrope as well …



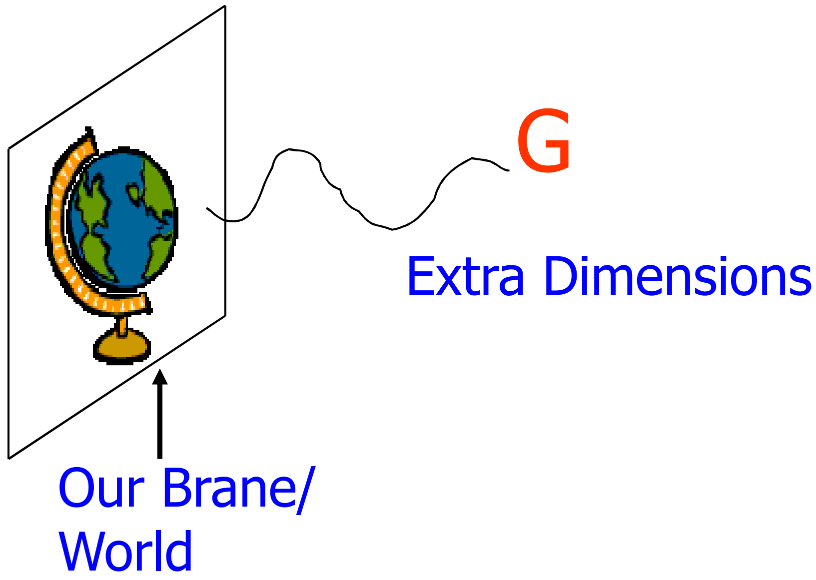
tp://www.particleadventure.org/frameless/extra_dim.html

- The "extra" dimensions may be too small to be detectable at energies less than ~ 10^{19} GeV (E.g. they are small that only extremely energetic particles could fit into them (so we need high energies to probe them))

Extra Dimensions?

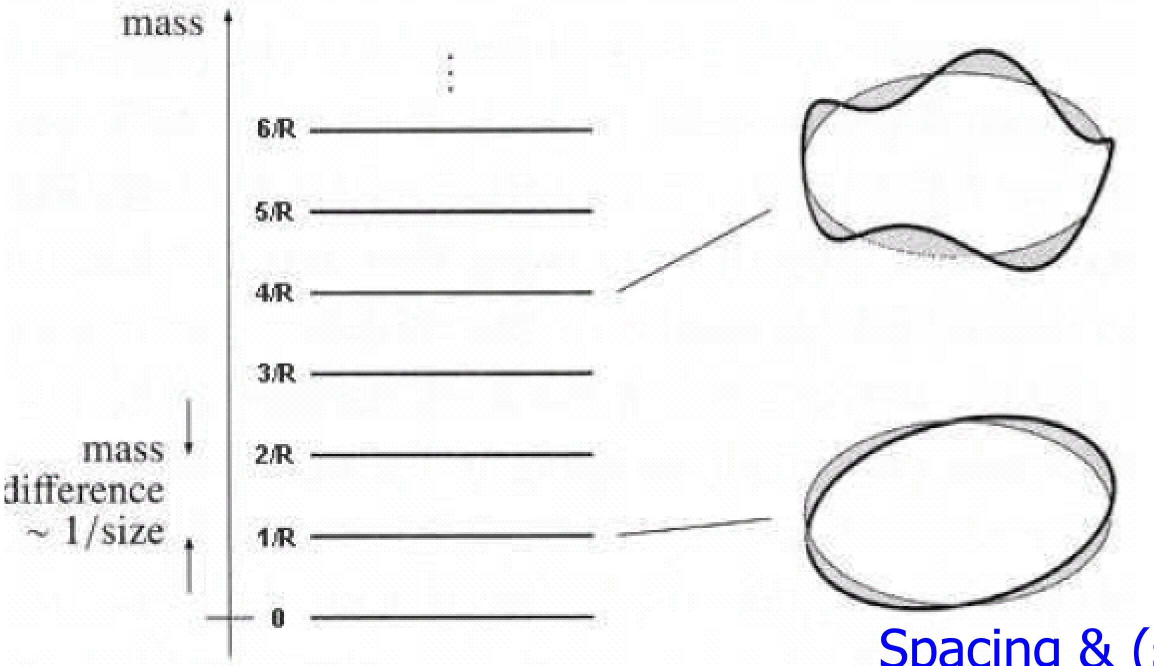
Or only some kinds of matter are able to move in the extra dimensions, and we are confined to our world.

like something that was forced to reside on the surface of a tabletop, being unaware of any such thing as up or down.



KK towers/particles

When particles go into the extra dimensions….



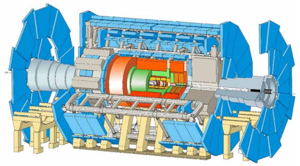
http://universe-review.ca/I15-74-KK.jpg

Like QM particles in a box

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

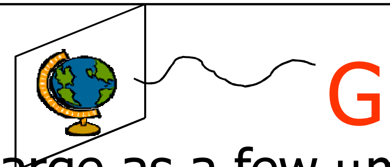
Spacing & (summation of) KK towers determines the search signature:

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



Extra Dimensional Models

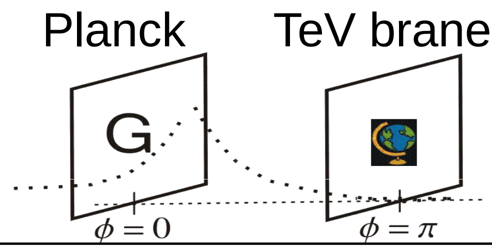
ADD — **A**rkani-Hamed, **D**imopoulos, **D**vali,
Phys Lett B429 (98)



(Many) Large flat Extra-Dimensions (LED) could be as large as a few μm
In which G can propagate, SM particles restricted to 3D brane

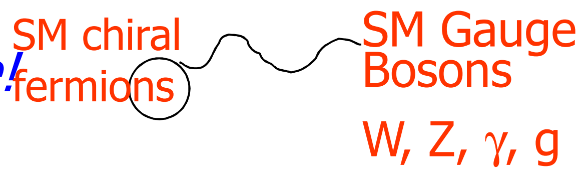
RS — **R**andall, **S**undrum,
Phys Rev Lett 83 (99)b

Small highly curved extra spatial dimension
(RS1 – two branes) Gravity localised in the ED



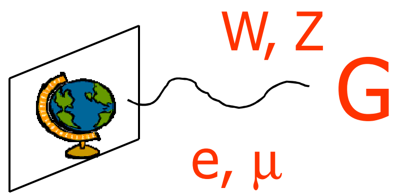
TeV^{-1} sized EDs — Dienes, Dudas, Gherghetta, Nucl Phys B537 (99) *Not covered here!*

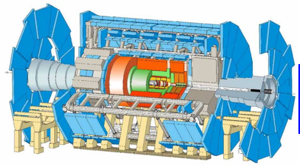
Bosons could also propagate in the bulk



UED

All SM particles propagate in "Universal" ED
often embedded in large ED

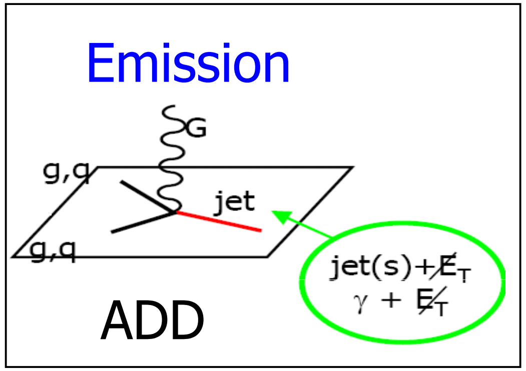


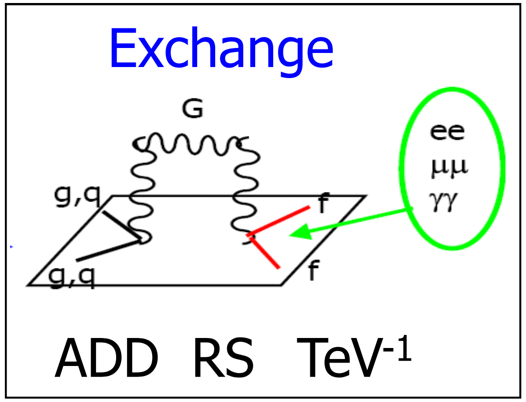


Experimental Signatures of ED

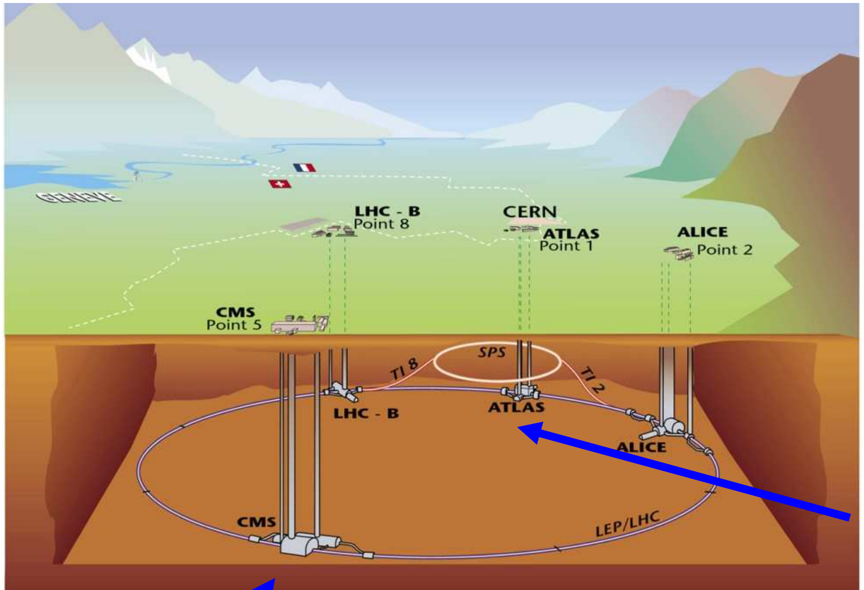
Covered in this talk

- Large Extra Dimensions (ADD)
  - KK Graviton Direct Production → Missing E_T signature
    Single jets/Single photons + missing ET
  - KK Graviton Exchange → Drell-Yan
    Di-lepton continuum modifications
- Randall-Sundrum Model
  - KK Graviton →TeV resonances
    Di-lepton and di-photon resonances
    tt-bar resonances
- UED Model
  - Di-photon + Met





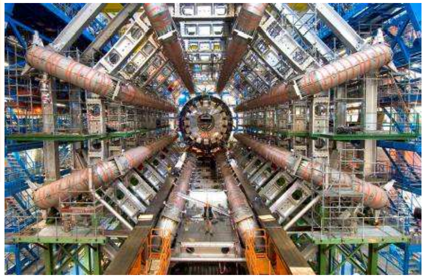
ED Search Facilities!

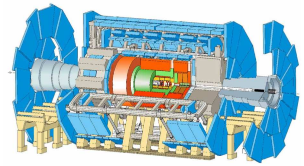


LHC: proton – proton collisions

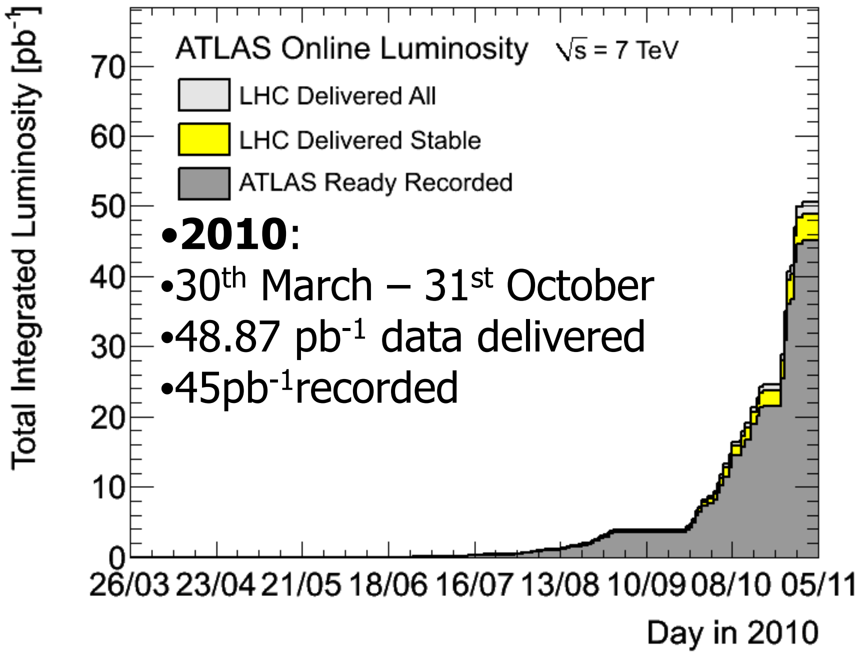
High center of mass energy

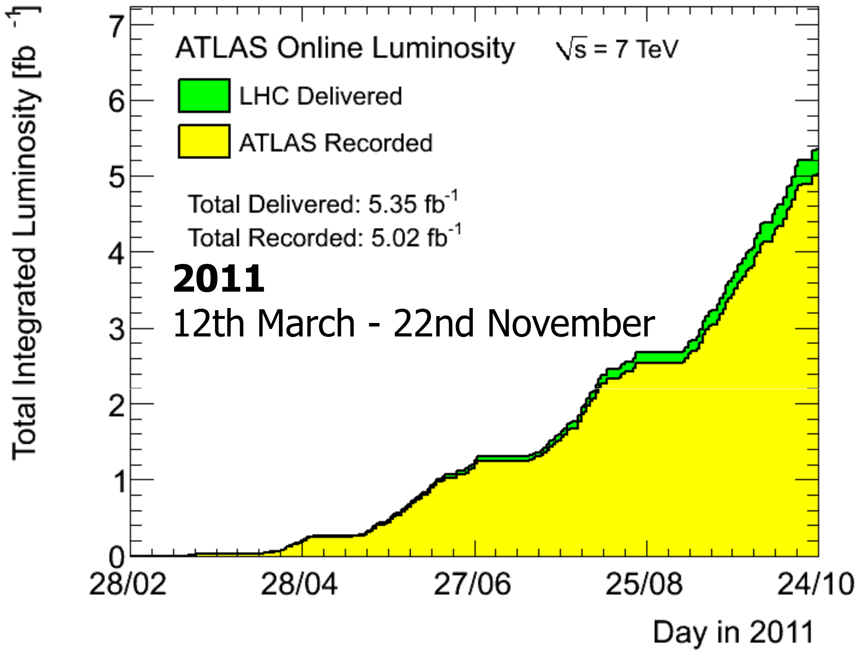
$\sqrt{s}$ = 7 TeV -> 8 -> 14 TeV





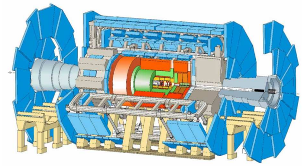
LHC data





Of 48.87 pb^{-1} delivered:
40% in the last week
over 60% in the last month

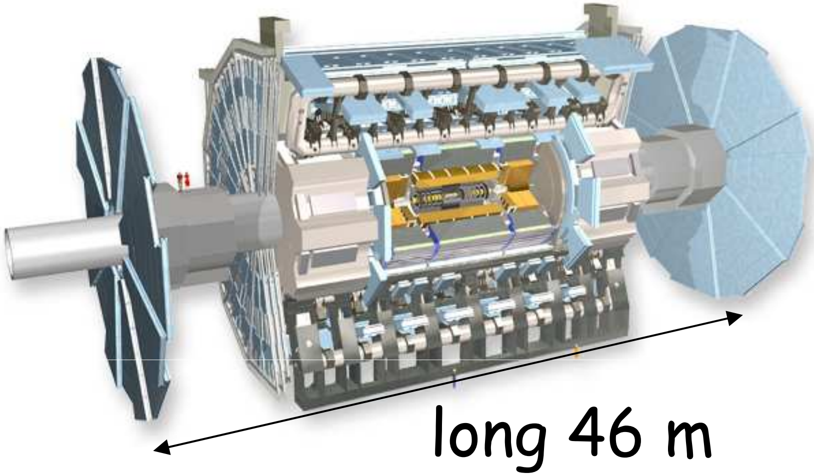
equivalent of 2010 dataset:
collected in one day in 2011 running

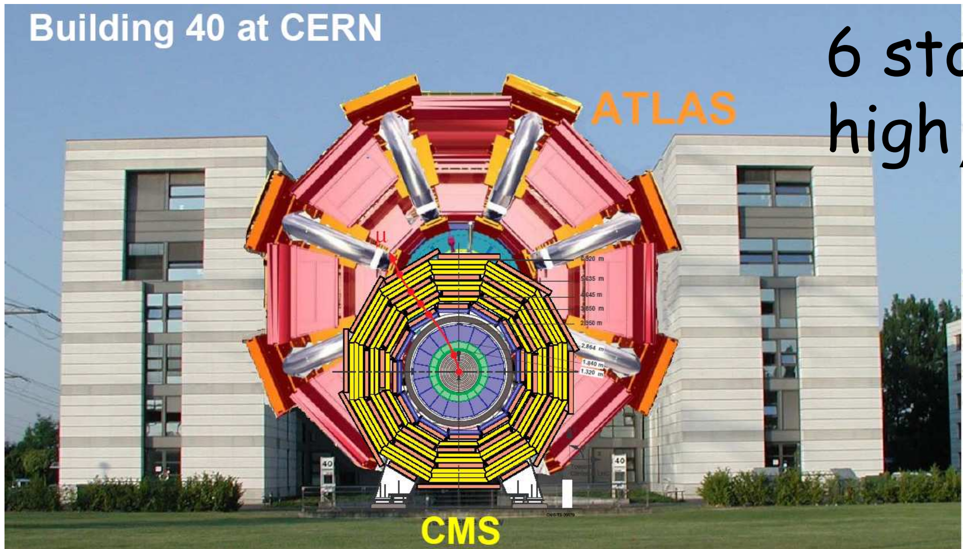


ATLAS

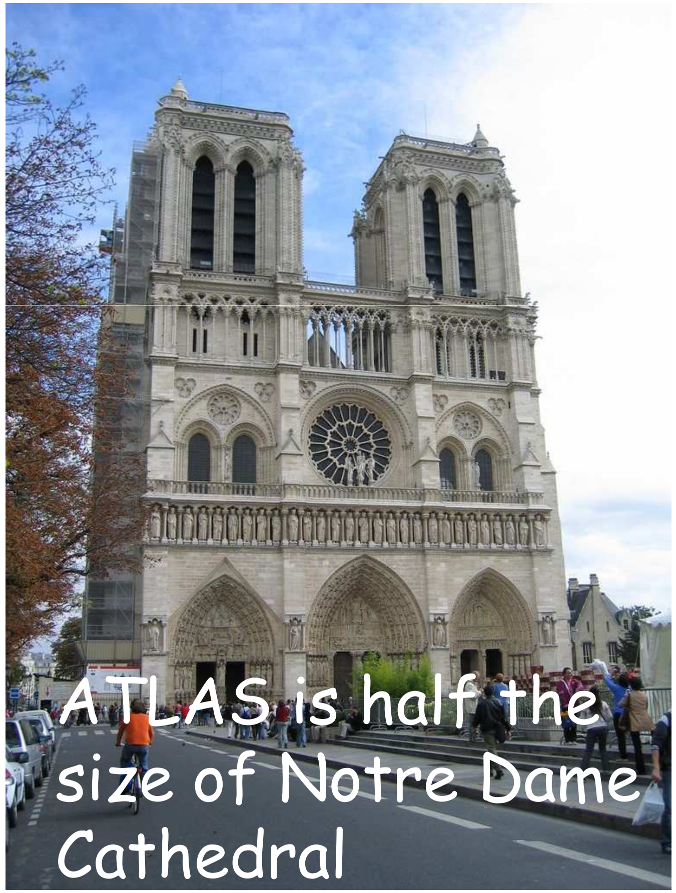
Largest volume particle detector ever constructed!

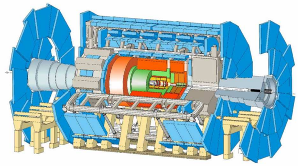
Overall diameter 25 m





6 storeys high

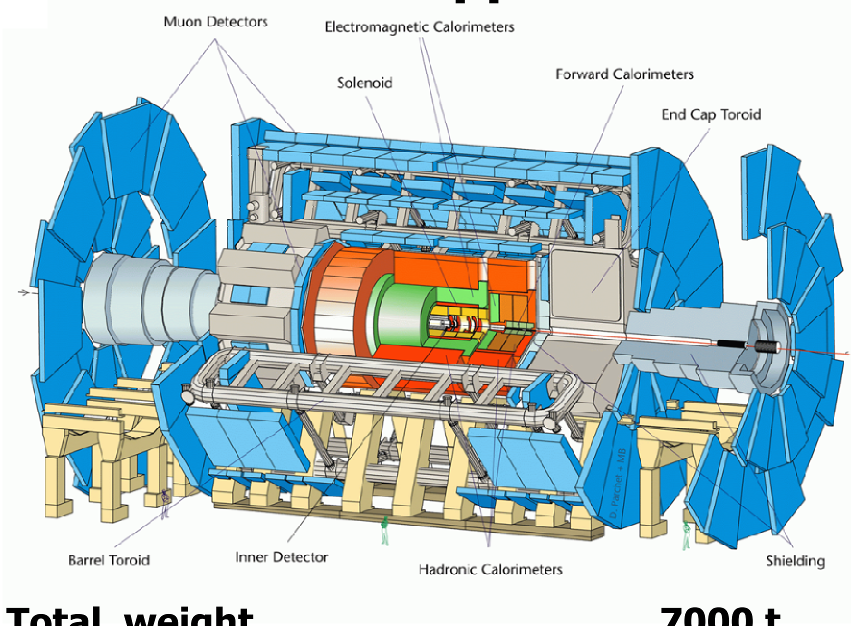




ATLAS

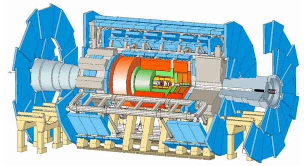
Large general-purpose particle physics detector

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**

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



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., $G \rightarrow \gamma\gamma$)

Full coverage for $|\eta|<2.5$

Precision Muon Spectrometer,

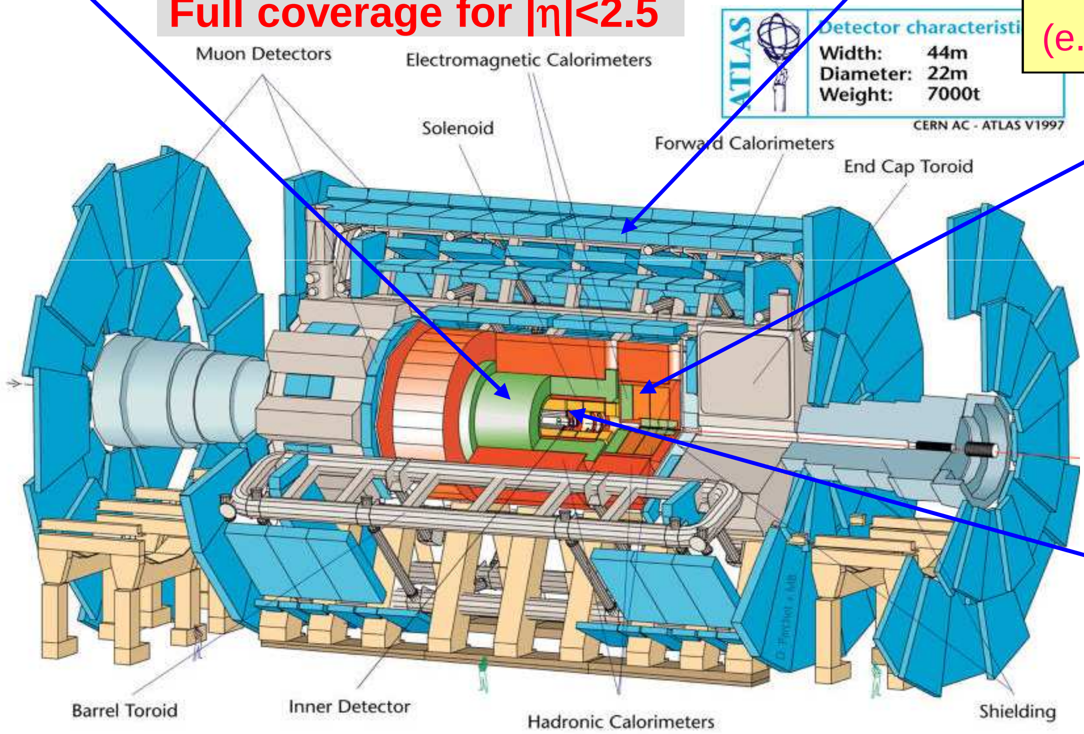
$\sigma/p_T \approx 10\%$ at 1 TeV/c

P_T resolution: 10–25 % at 1 TeV/c

Fast response for trigger

Good *p* resolution

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



Hadron Calorimeters,

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

Good jet and E_T miss performance

Inner Detector:

Si Pixel and strips (SCT) &

Transition radiation tracker (TRT)

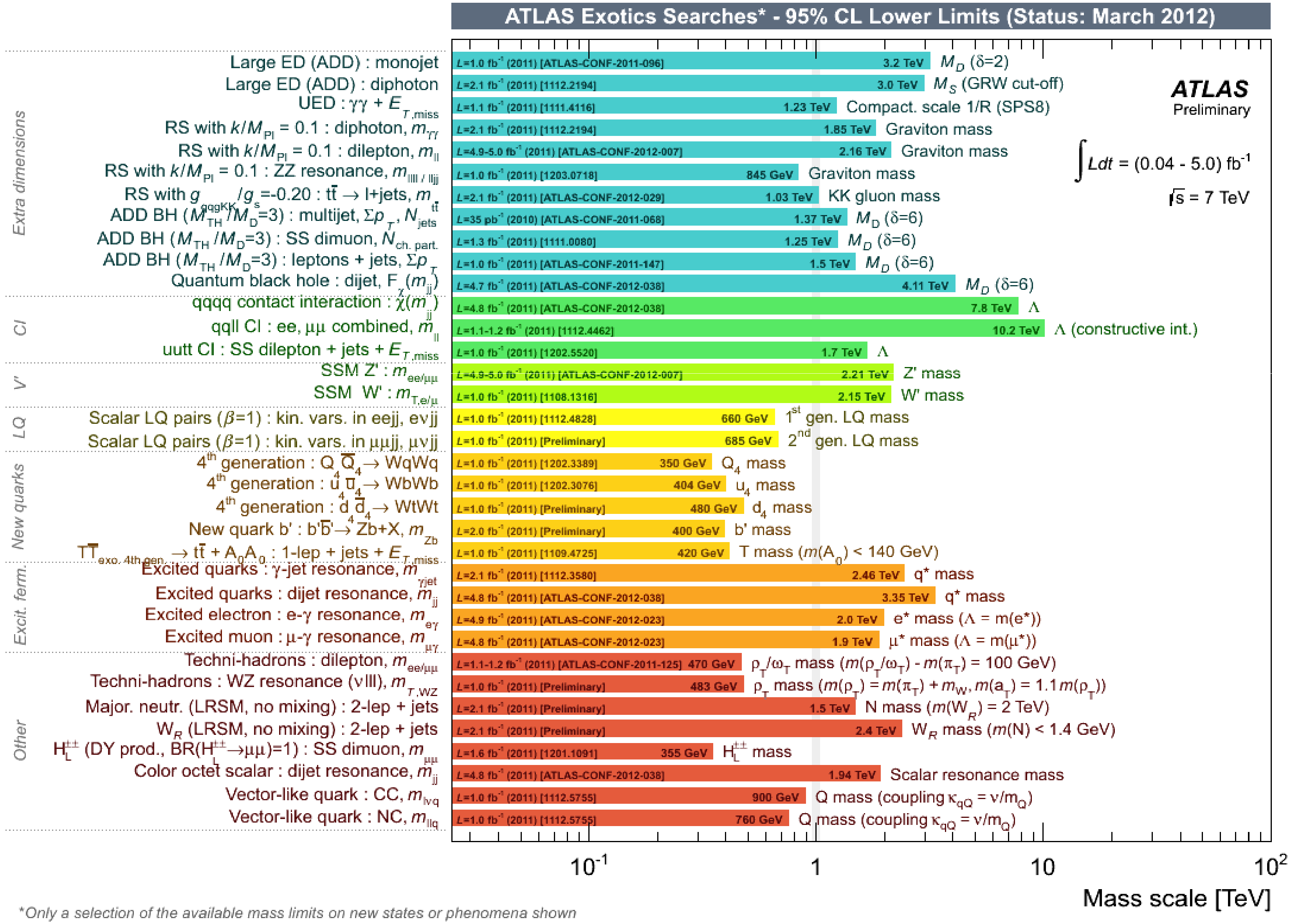
$\sigma/p_T \approx 5 \times 10^{-4}\, p_T \oplus 0.001$

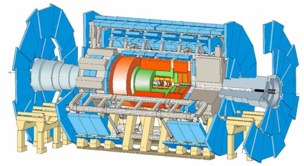
Good impact parameter res.

$\sigma(d_0)=15\mu m@20GeV$

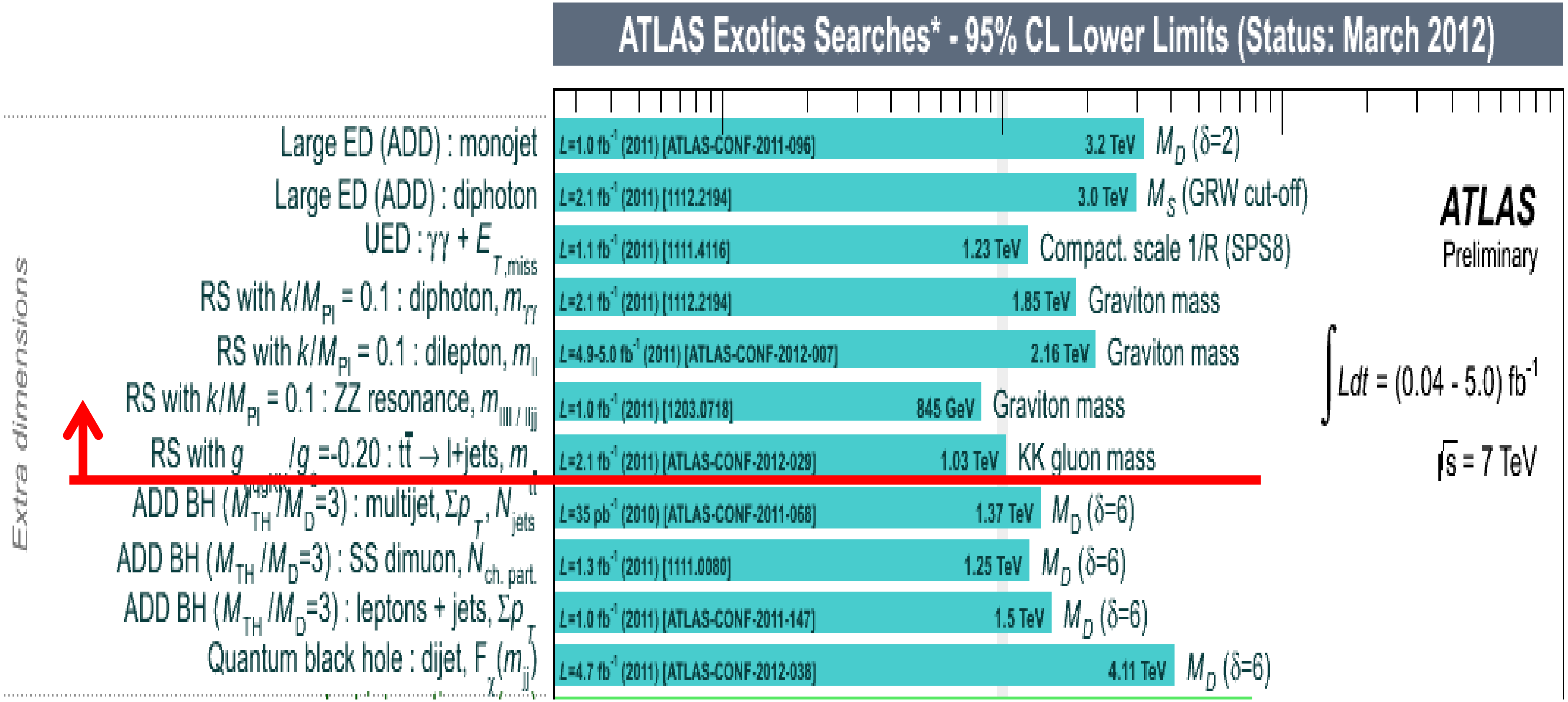
Magnets: solenoid (Inner Detector) 2T, air-core toroids (Muon Spectrometer) ~0.5T

ATLAS Exotics Searches





ATLAS Exotics Searches

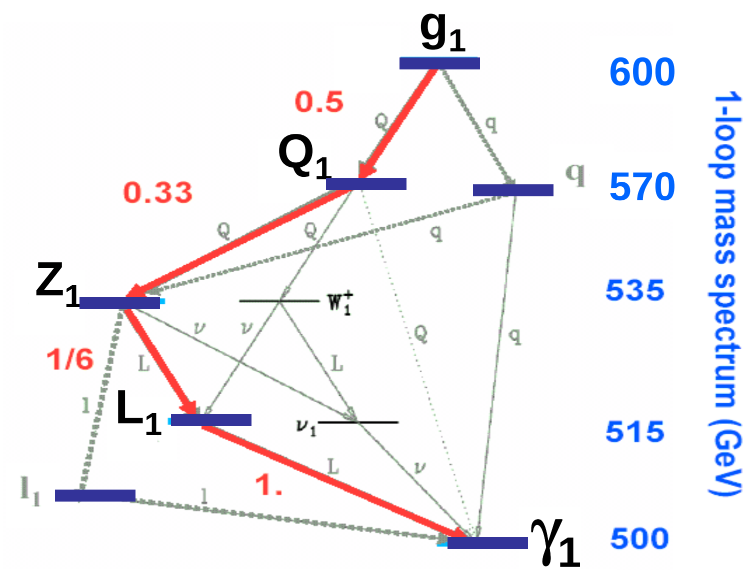


UED

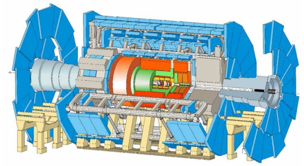
Universal Extra Dimensions

Standard/Minimal UED

- ❑ All particles can travel into the bulk, so each SM particle has an infinite tower of KK partners
- ❑ Spin of the KK particles is the same as their SM partners
- ❑ In minimal UED: 1 ED compactified in an orbifold (S1/Z2) of size R
  - ❑ KK parity conservation → the lightest massive KK particle (LKP) is stable (dark matter candidate).
  - ❑ Level one KK states must be pair produced
- ❑ Mass degeneration except if radiative corrections included



The model parameters: compactificaton radius R, cut-off scale Λ, m_h



Present Constraints on UED

Bounds to the compactification scale:

- Precision **EWK** data measurements set a lower bound of

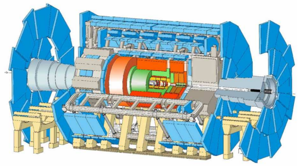
  $R^{-1} > 300$ GeV

  Phys. Rev. D64, 035002 (2001) Appelquist, Cheung, Dobrescu

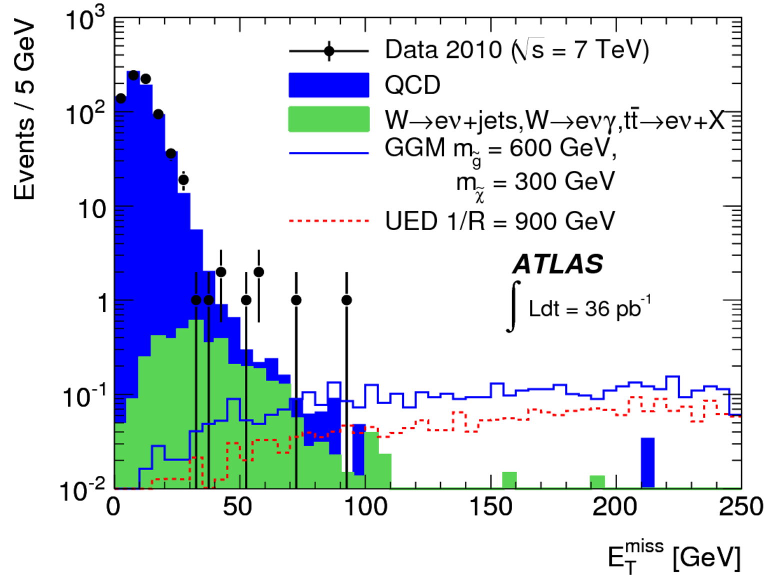
- **DARK MATTER** constraints imply that

  $600 < R^{-1} < 1050$ GeV

  Servant , Tait, Nucl. Phys. B650,391 (2003)

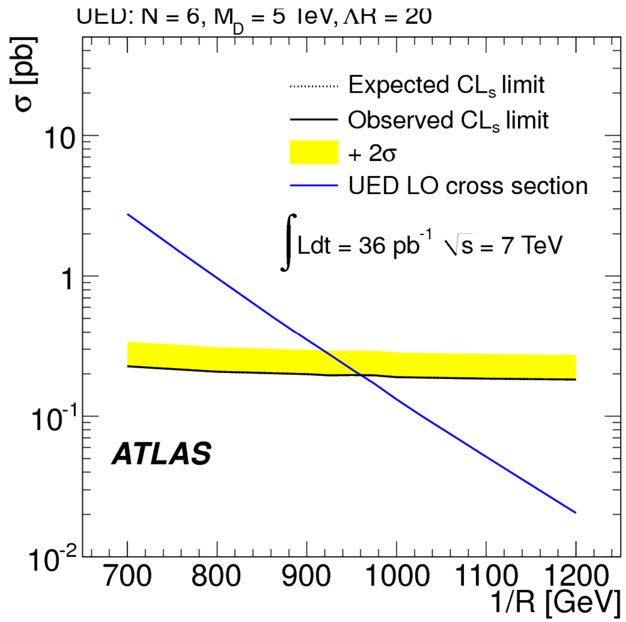


Universal Extra Dimensions
Diphoton + E_T^{Miss}



- Effective theory of one TeV^{-1} size UED valid at >1/R (R = ED size)
  - –SM particles in bulk→KK excitations
  - –Mass degeneracy of KK excitations broken by radiative corrections
  - -Lowest KK particle γ* decays to γ +G

- Expect excess of UED events at high E_T^{Miss}:
  - –No events observed in E_T^{Miss}>125GeV
  - –Background events expected 0.10±0.04(stat) ±0.05(syst)

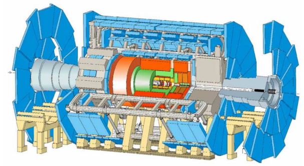


- UL @ 95% CL on σ<0.18-0.23pb for 1/R=700-1200 GeV in UED model
- Exclude @95% C.L. 1/R<961 GeV

arXiv:1107.05661, submitted to EPJC

ADD Model

Monojet: (ADD)
Diphotons (RS+ ADD)

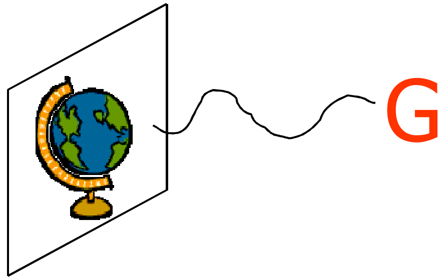


ADD Model

Arkani-Hamed, Dimopoulos, Dvali, Phys Lett B429 (98), Nuc.Phys.B544(1999)

(Many) Large flat Extra-Dimensions (LED),
could be as large as a few μm
the maximum total number of dimensions is 3(our) + 6(extra)=9

G can propagate in ED



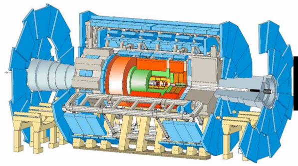
SM particles restricted to 3D brane

The fundamental scale is not planckian: $M_D = M_{Pl(4+\delta)} \sim$ TeV

Model parameters are:
- δ = number of ED
- $M_{Pl}(4+\delta)$ = Planck mass in the $4+\delta$ dimensions

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

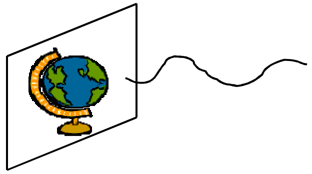
For $M_{Pl} \sim 10^{19}$ GeV and $M_{Pl(4+\delta)} \sim M_{EW} \rightarrow$ $R \sim 10^{32/\delta} \times 10^{-17}$ cm



Present Constraints on the ADD Model

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

For $M_{Pl} \sim 10^{19}$ GeV and $M_{Pl(4+\delta)} \sim M_{EW} \rightarrow$ $R \sim 10^{32/\delta} \times 10^{-17}$ cm



G

- $\delta=1 \rightarrow R \sim 10^{13}$ cm, ruled out because deviations from Newtonian gravity over solar distances have not been observed
- $\delta=2 \rightarrow R \sim 1$ mm, not likely because of cosmological arguments:

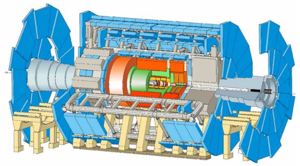
In particular graviton emission from Supernova 1987a* implies $M_D > 50$ TeV
Closest allowed $M_{Pl(4+n)}$ value for $\delta=2$ is ~30 TeV, out of reach at LHC

Can detect at collider detectors via:

- graviton emission
- Or graviton exchange

- LEP & Tevatron limits is $M_{Pl(4+\delta)} \sim> 1$TeV
- $\delta>6$ difficult to probe at LHC since cross-sections are very low

*Cullen, Perelstein
Phys. Rev. Lett 83,268 (1999)

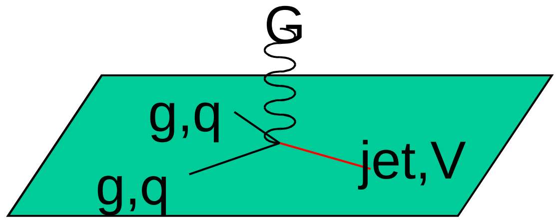


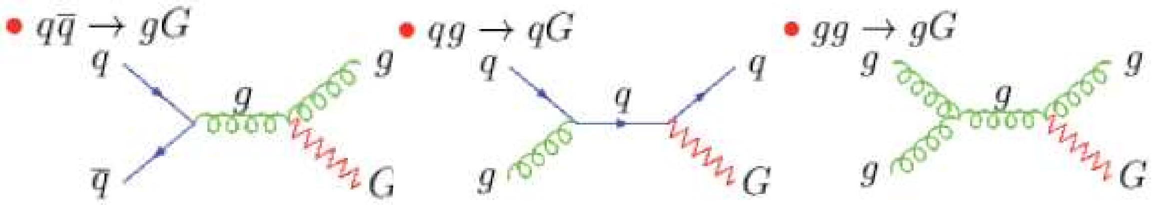
ADD Collider Signatures

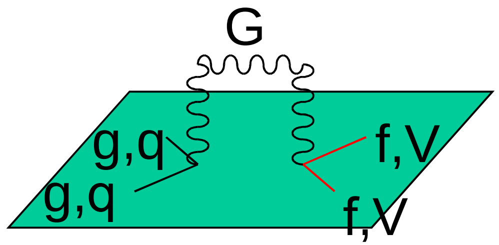
➢**Real Graviton emission** in association with a vector-boson

Signature: jets + missing E_T, V+missing E_T

σ depends on the number of ED





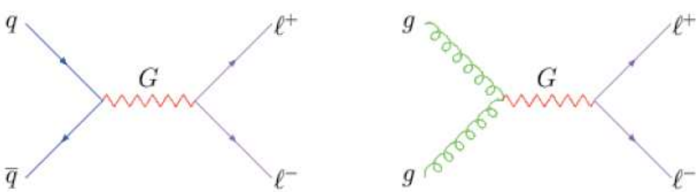


➢**Virtual Graviton exchange**

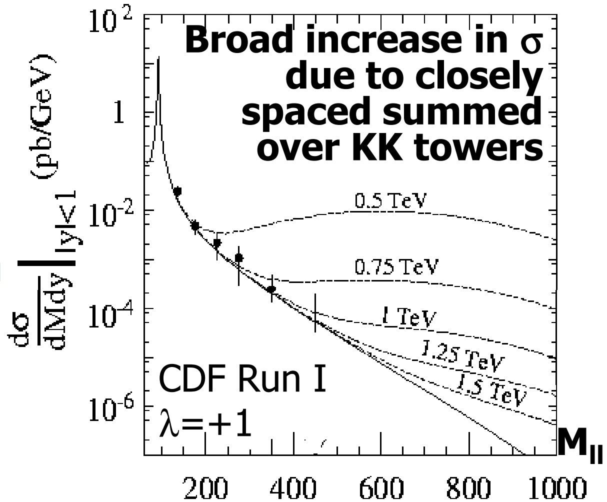
Signature:

deviations in σ and asymmetries of SM processes e.g. qq $\rightarrow$ l^+l^-, $\gamma\,\gamma$ & new processes e.g. gg $\rightarrow$ l^+l^-

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

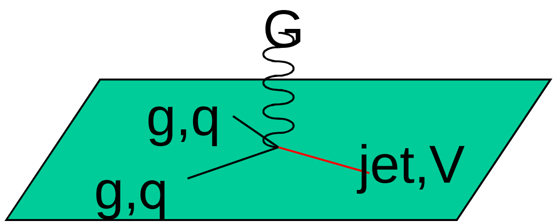


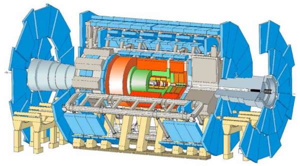
Excess above di-lepton continuum



ADD Model

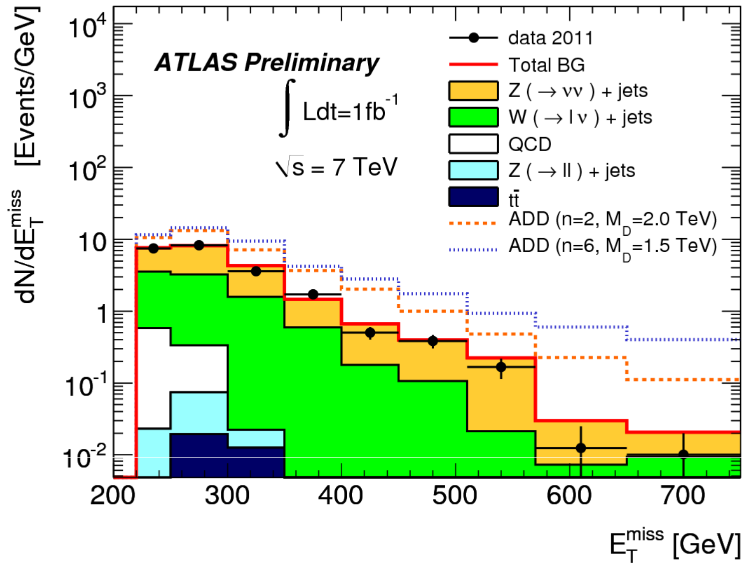
Real Graviton emission





ADD: Monojet Search
a single jet plus missing ET

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



Missing ETtrigger

•Signal region ("HighPt")

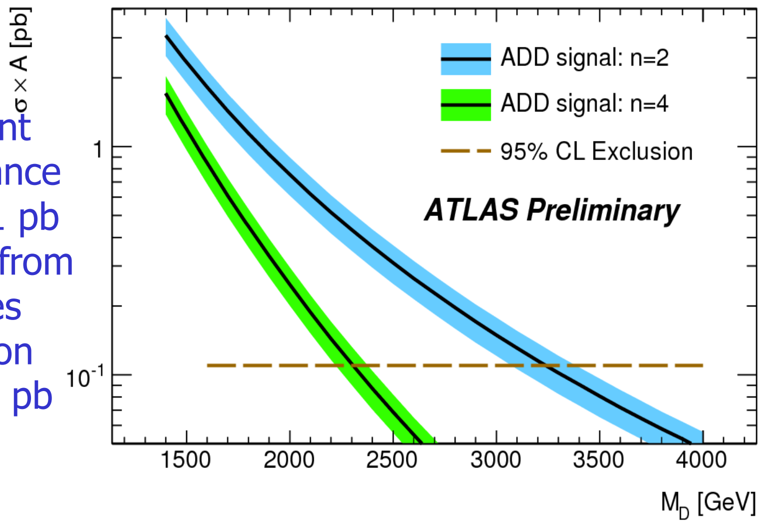
–p_T^{j1}> 250 GeV, missing E_T> 220 GeV

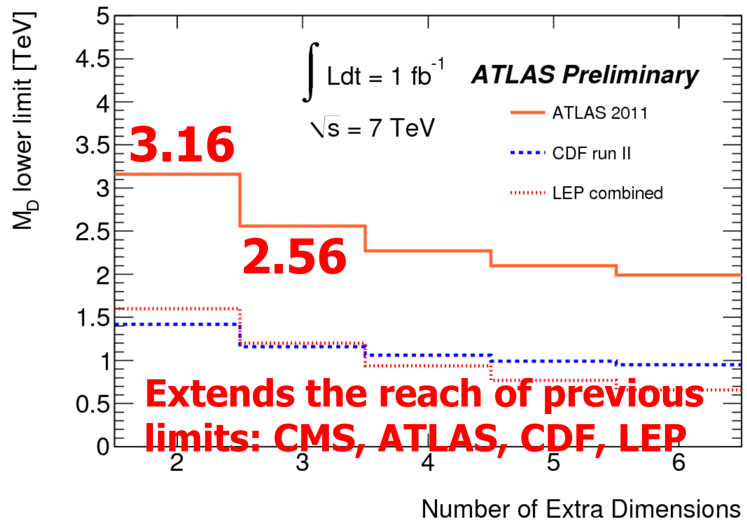
–p_T^{j2}< 60 GeV, Δφ(j2, missing E_T) > 0.5

–No reasonable e's, μ's

Good Agreement between data and background prediction: 965 events: 1010 ± 37 (stat) ± 65 (syst)

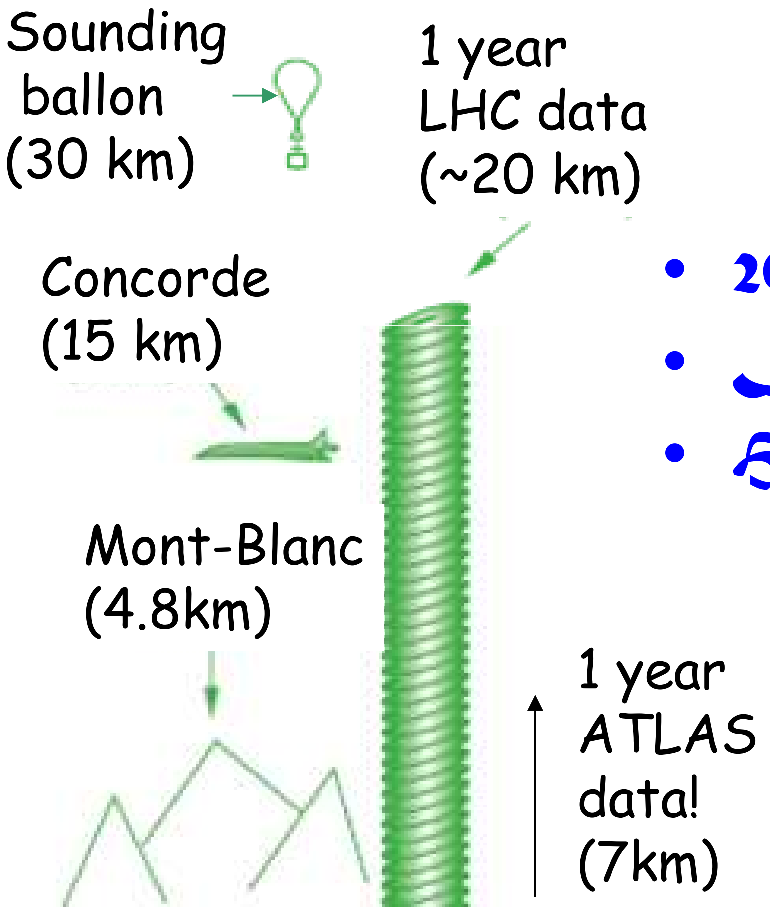
•Model-independent limit on σ*Acceptance @ 95% CL = 0.11 pb Using Acceptance from ADD signal samples (Pythia): 95% CL on fiducial σ = 0.13 pb





ATLAS-CONF-2011-096; 1 fb-1of 2011
2010: arxiv:1106.5327, submitted to PLB (33 pb^{-1})

Original LHC Data / Prospects



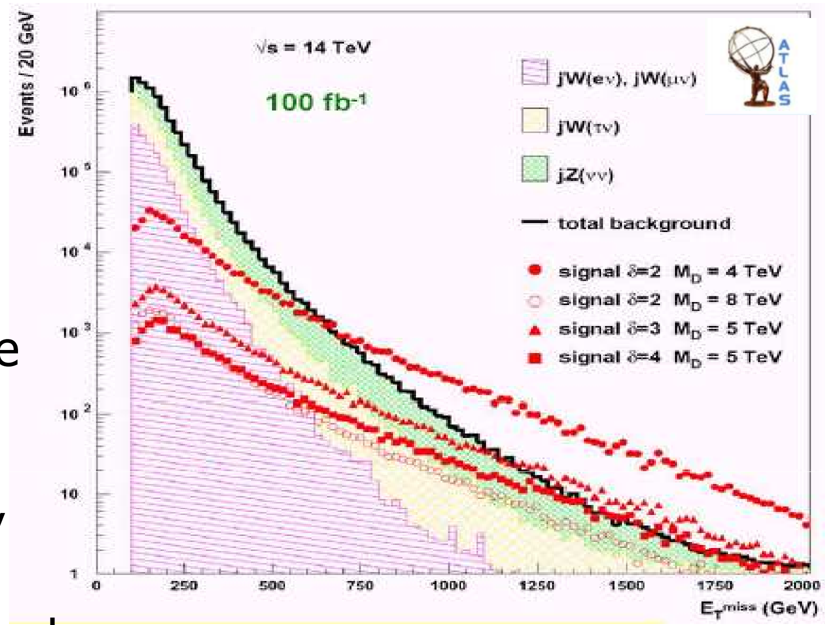
- 2009: 10 TeV 100 pb^{-1}
- Low Lum: $2x10^{33}$ cm^2s^{-1} $O(10fb^{-1}/yr)$
- High Lum: 10^{34} cm^2s^{-1} 100 fb^{-1}/yr

ADD Discovery Limit:jet+G Emission

Real graviton production $pp \to jet + G^{KK}$

$gg \to gG$, $qg \to qG$ & $qq \to Gg$

Dominant subprocess

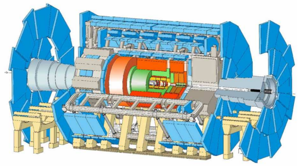


- ❑Signature: jet + G ⇒ jet with high transverse energy (E_T>500 GeV)+ high missing E_T (E_T^{miss}>500 GeV),
- ❑ vetos leptons: to reduce jet+W bkdg mainly
- ❑ Bkgd.: irreducible jet+Z/W →jet+νν /jet+lν
  jZ(νν) dominant bkgd, can be calibrated using ee and μμ decays of Z.

Discovery limits

$M_{Pl(4+d)}^{MAX}$(TeV)	δ=2	δ=3	δ=4
LL $30fb^{-1}$	7.7	6.2	5.2
HL $100fb^{-1}$	9.1	7.0	6.0

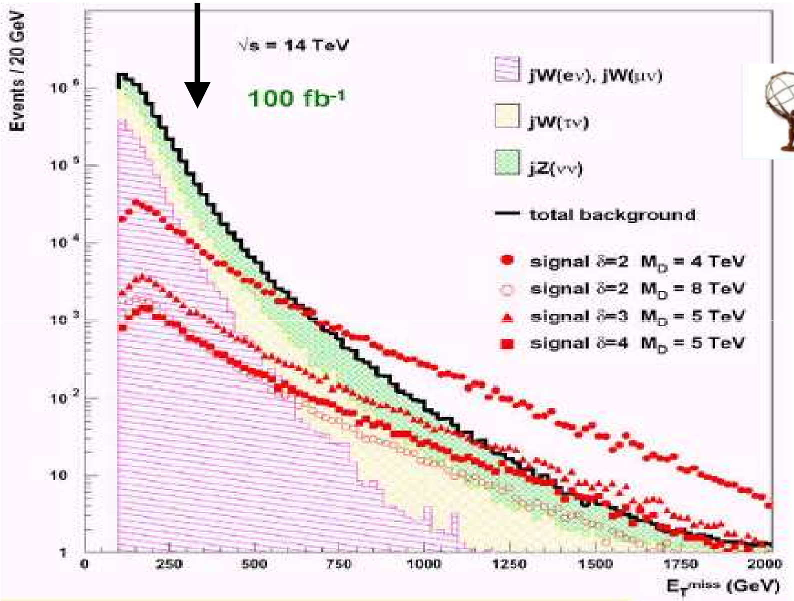
L.Vacavant, I.Hinchcliffe, ATLAS-PHYS 2000-016
J. Phys., G 27 (2001) 1839-50



ADD Parameters: jet+G Emission

To characterise the model need to measure M_D and δ

Measuring $\sigma(pp \rightarrow jet+G^{KK})$ gives ambiguous results



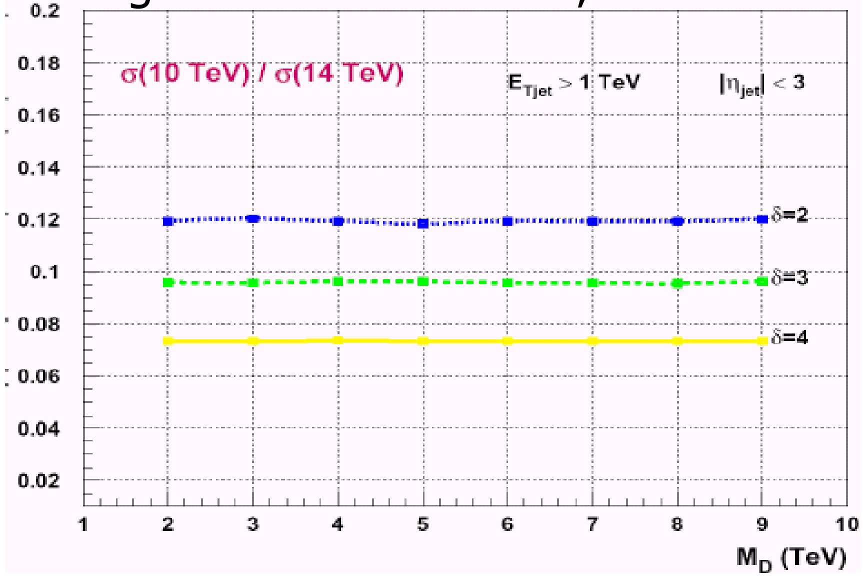
Rates at 14 TeV of $\delta=2$ $M_D=6$ TeV very similar to $\delta=3$ $M_D=5$ TeV whereas
Rates at 10 TeV of ($\delta=2$ $M_D=6$ TeV) and ($\delta=3$ $M_D=5$ TeV) differ by ~ factor of 2

Use variation of σ on $\sqrt{s}$

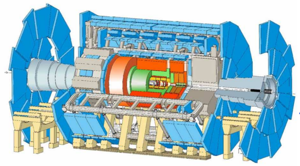
σ at different $\sqrt{s}$ almost independent of M_D, varies with δ

Run at two different $\sqrt{s}$

e.g. 10 TeV and 14 TeV, need 50 fb^{-1}



L.Vacavant, I.Hinchcliffe, ATLAS-PHYS 2000-016
J. Phys., G 27 (2001) 1839-50



ADD Discovery Limit: γ+G Emission

J. Weng et al. CMS NOTE 2006/129

Real graviton production $pp \to \gamma + G^{KK}$

- $\gamma G \Rightarrow$ high-p_T photon + high missing E_T

  At low p_T the bkgd, particularly irreducible $Z\gamma \to \nu\nu\gamma$ is too large$\Rightarrow$ require p_T>400 GeV

- Main Bkgd: $Z\gamma \to \nu\nu\gamma$,

  Also $W \to e(\mu,\tau)\nu$, $W\gamma \to e\nu$, γ+jets, QCD, di-γ, Z^0+jets

Integrated Lum for a 5σ significance discovery

Significance: $\mathcal{S}=2(\sqrt{(S+B)}-\sqrt{B})>5$

M_D/n	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$
$M_D = 1.0$ TeV	0.21 fb^{-1}	0.16 fb^{-1}	0.14 fb^{-1}	0.15 fb^{-1}	0.15 fb^{-1}
$M_D = 1.5$ TeV	0.83 fb^{-1}	0.59 fb^{-1}	0.56 fb^{-1}	0.61 fb^{-1}	0.59 fb^{-1}
$M_D = 2.0$ TeV	2.8 fb^{-1}	2.1 fb^{-1}	1.9 fb^{-1}	2.1 fb^{-1}	2.3 fb^{-1}
$M_D = 2.5$ TeV	9.9 fb^{-1}	8.2 fb^{-1}	8.7 fb^{-1}	9.4 fb^{-1}	10.9 fb^{-1}
$M_D = 3.0$ TeV	47.8 fb^{-1}	46.4 fb^{-1}	64.4 fb^{-1}	100.8 fb^{-1}	261.2 fb^{-1}
$M_D = 3.5$ TeV	5 σ discovery not possible anymore				

M_D= 1– 1.5 TeV for 1 fb^{-1}
2 - 2.5 TeV for 10 fb^{-1}
3 - 3.5 TeV for 60 fb^{-1}

ADD Discovery Limit: γ+G Emission

ATLAS

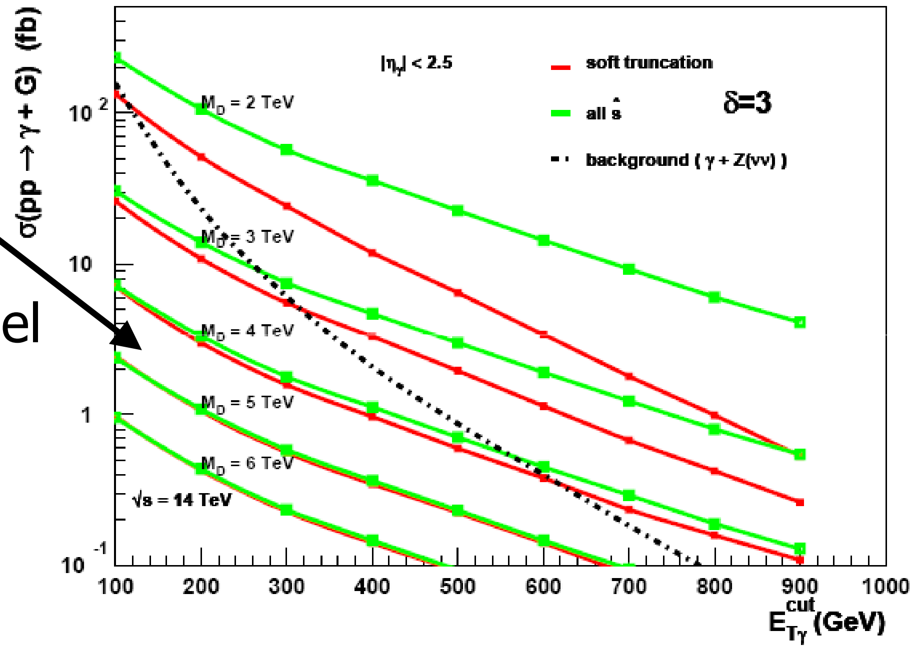
$pp \to \gamma + G^{KK}$: $qq \to \gamma G^{KK}$

Rates for $M_D \geq$ 4TeV are very low

M_D^{MAX} (TeV)	δ=2
HL 100fb^{-1}	4

For δ>2: No region where the model independent predictions can be made and where the rate is high enough to observe signal events over the background.

This gets worse as δ increases



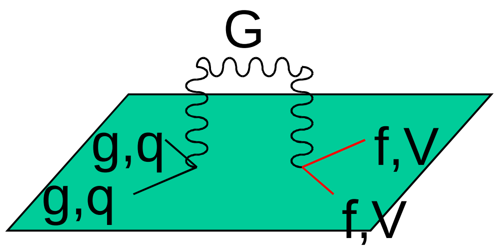
- Better limits from the jet+G emission which has a higher production rate

This signature could be used as confirmation after the discovery in the jet channels

L.Vacavant, I.Hinchcliffe
ATLAS-PHYS 2000-016
J. Phys., G 27 (2001) 1839-50

ADD Model

Graviton Exchange



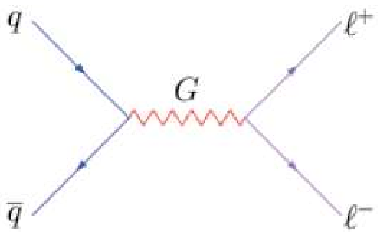
ADD Collider Signatures

➢ **Virtual Graviton Emission**

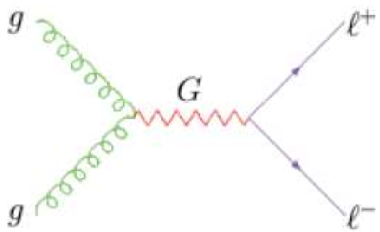
➢ **Virtual Graviton exchange**

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

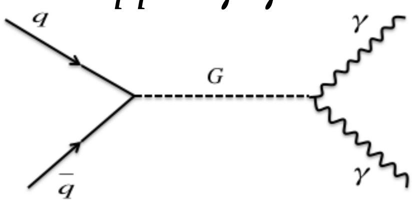
$q\bar{q} \rightarrow l^+l^-$



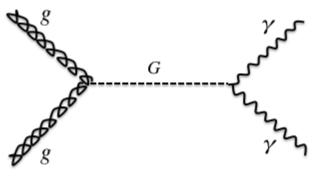
$gg \rightarrow l^+l^-$

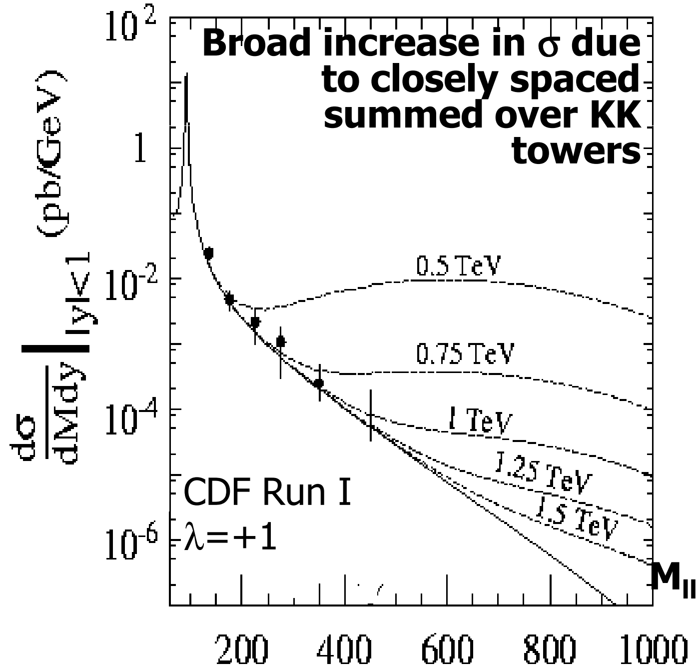


$q\bar{q} \rightarrow \gamma^+\gamma^-$



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





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

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

RS G*->$\gamma\gamma$
Analysis Procedure & Event Selection

Select events with two diphotons

Search for excess above SM expectations in high invariant mass region

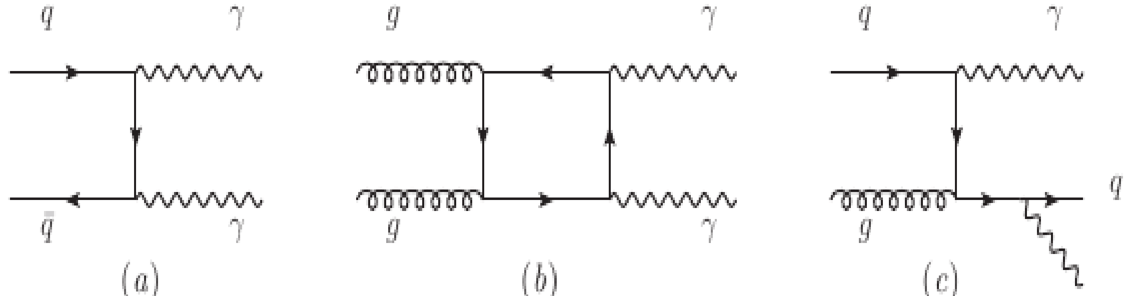
Diphoton channel

- Trigger on 2 γ (or e) with E_T > 20 GeV
- Good Runs
- >= 1 primary vertex with >=3 tracks
- 2 γ with
  - E_T > 25 GeV
  - Passing Tight γ ID criteria
  - $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$
  - $E_T\gamma$ Isolation (0.4)< 5 GeV
  - Energy correction to reduce pile-up & underlying event effects
- ee Overlap removal

(so can combine results with G->ee result)

Main Backgrounds

- **Irreducible Background SM γγ production**



Born process box process bremsstrahlung process

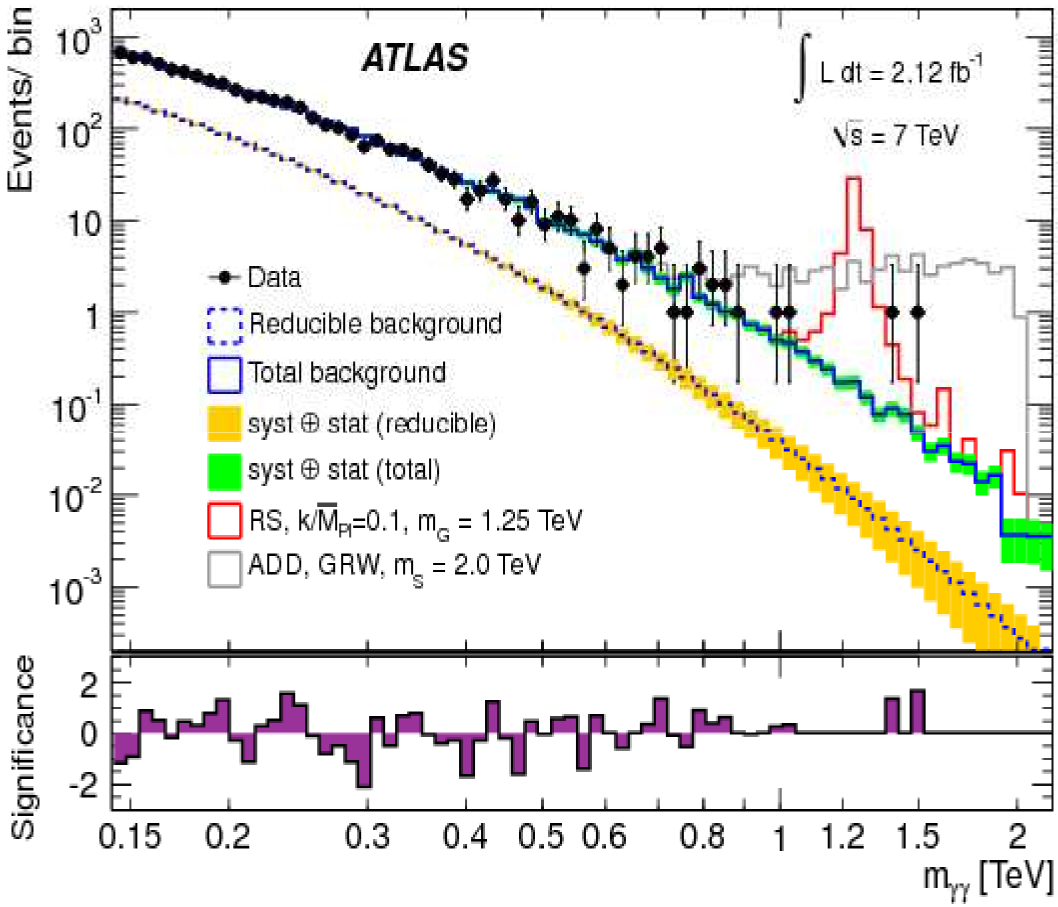
•simulated with pythia (v6.424) and MRST2007LOMOD PDFs
•pythia events reweighted as a function of $m_{\gamma\gamma}$ to the differential cross section predicted by the NLO calculation of diphox (v 1.3.2).

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

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

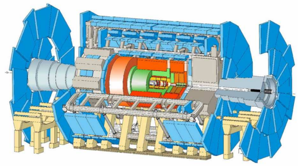
- **Total Background**: normalised to data 140 Gev < $m_{\gamma\gamma}$ < 400 GeV

Diphoton Distributions



Good agreement with data and expected background

P=0.28



ADD Limits

- Counting experiment (BAT):
- Set limit on number of signal events above a given mass threshold
- Translate into a limit on Acc*eff*xsec $\sigma'_{tot} = \sigma'_{SM} + \eta_G \sigma'_{int} + \eta_G^2 \sigma'_G.$
- Use theoretical dependence between Acc*eff*xsec and η_G
- Optimized 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: $\eta = \frac{\lambda}{M_S{}^4}$

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

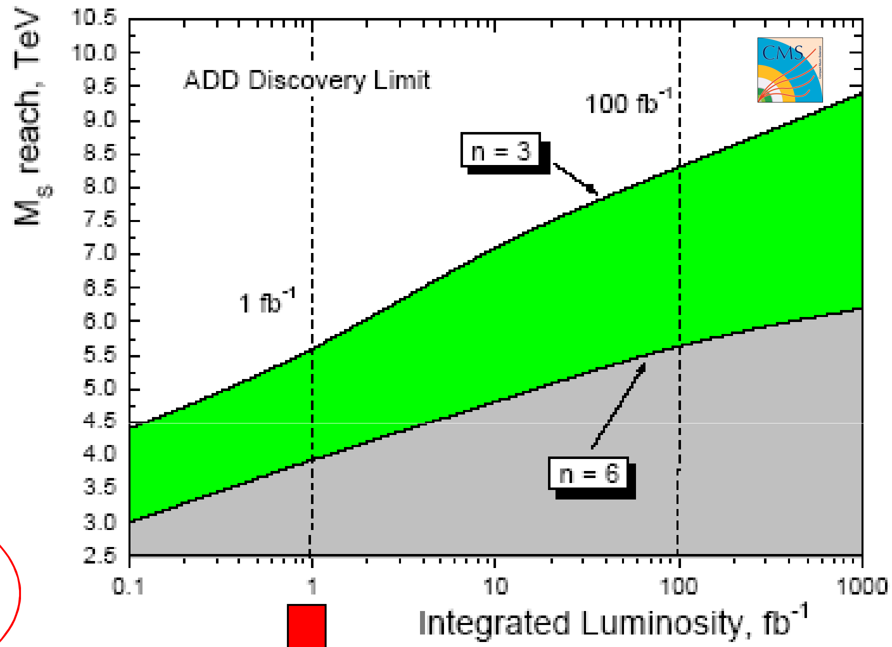
LHC ADD Discovery Limit: G Exchange

$pp \to G^{KK} \to \mu\mu$

<u>Virtual graviton production</u>

- Two opposite sign muons in the final state with $M_{\mu\mu}$>1 TeV
- Irreducible background from Drell-Yan, also ZZ, WW, WW, tt (suppressed after selection cuts)
- PYTHIA with ISR/FSR + CTEQ6L, LO + K=1.38

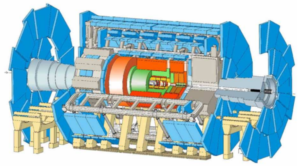
channel	n / luminosiy		2	3	4	5
$\gamma\gamma$	10 fb^{-1}	M_S^{max} (TeV)	6.3	5.6	5.1	4.9
		S/B	36/18	36/18	39/25	34/13
	100 fb^{-1}	M_S^{max} (TeV)	7.9	7.3	6.7	6.3
		S/B	50/53	62/96	55/72	51/53
l^+l^-	10 fb^{-1}	M_S^{max} (TeV)	6.6	5.9	5.4	5.1
		S/B	33/11	31/8	30/6	30/6
	100 fb^{-1}	M_S^{max} (TeV)	7.9	7.5	7.0	6.6
		S/B	49/48	38/21	36/16	29/6
Fast MC $\gamma\gamma + l^+l^-$	10 fb^{-1}	M_S^{max} (TeV)	7.0	6.3	5.7	5.4
	100 fb^{-1}	M_S^{max} (TeV)	8.1	7.9	7.4	7.0



1 fb^{-1}: 3.9-5.5 TeV for n=6..3
10 fb^{-1}: 4.8-7.2 TeV for n=6..3
100 fb^{-1}: 5.7-8.3 TeV for n=6..3
300 fb^{-1}: 5.9-8.8 TeV for n=6..3

V. Kabachenko et al.
ATL-PHYS-2001-012

Belotelov et al.,
CMS NOTE 2006/076, CMS PTDR 20(



ADD Discovery Limits Summary

Can use LHC to search for ADD ED with $\delta<6$

$\delta<=2$ ruled out

$M_D>2.1 – 1.3$TeV (n=2, 7) from Tevatron

Photon+Met CMS

Discovery above 3.5 TeV not possible in this channel

M_D= 1– 1.5 TeV for 1 fb^{-1}
2 - 2.5 TeV for 10 fb^{-1}
3 - 3.5 TeV for 60 fb^{-1}

Jet+Met ATLAS

$M_{Pl(4+d)}^{MAX}$(TeV)	$\delta=2$	$\delta=3$	$\delta=4$
LL 30fb^{-1}	7.7	6.2	5.2
HL 100fb^{-1}	9.1	7.0	6.0

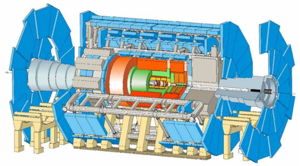
CMS Exchange limits:

1 fb^{-1}: 3.9-5.5 TeV for n=6..3
10 fb^{-1}: 4.8-7.2 TeV for n=6..3
100 fb^{-1}: 5.7-8.3 TeV for n=6..3
300 fb^{-1}: 5.9-8.8 TeV for n=6..3

ATLAS Exchange Limits

$\gamma\gamma + l^+l^-$	10 fb^{-1}	M_S^{max} (TeV)	7.0	6.3	5.7	5.4
	100 fb^{-1}	M_S^{max} (TeV)	8.1	7.9	7.4	7.0

RS Model



Randall Sundrum ED

RS Gravitons (G)

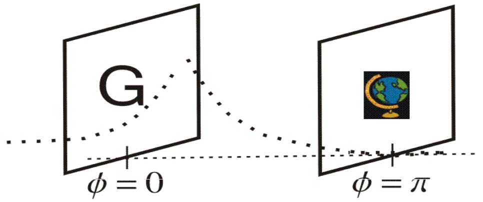
•5-D space-time bound by two 3+1D branes with SM particles localized on one and gravity on the other

•Only G propagate in bulk resulting in massive spin-2 Kaluza-Klein (KK) excitations

• k is space-time curvature in ED

RS — **R**andall, **S**undrum, Phys Rev Lett 83 (99)

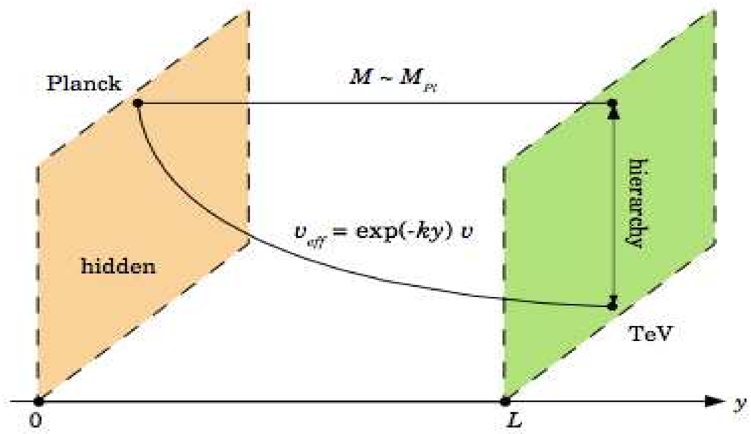
1 highly curved ED
Gravity localised in the ED



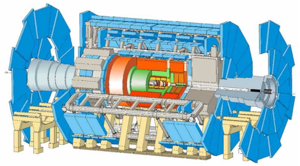
$\Lambda_\pi = \overline{M}_{pl} e^{-kR_c\pi}$

$\Lambda_\pi \sim$ TeV

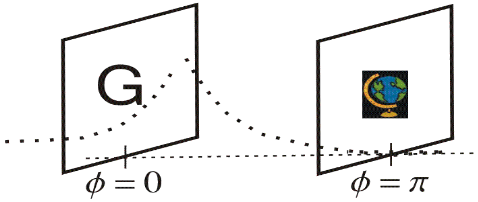
if warp factor kR_c ~11-12



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

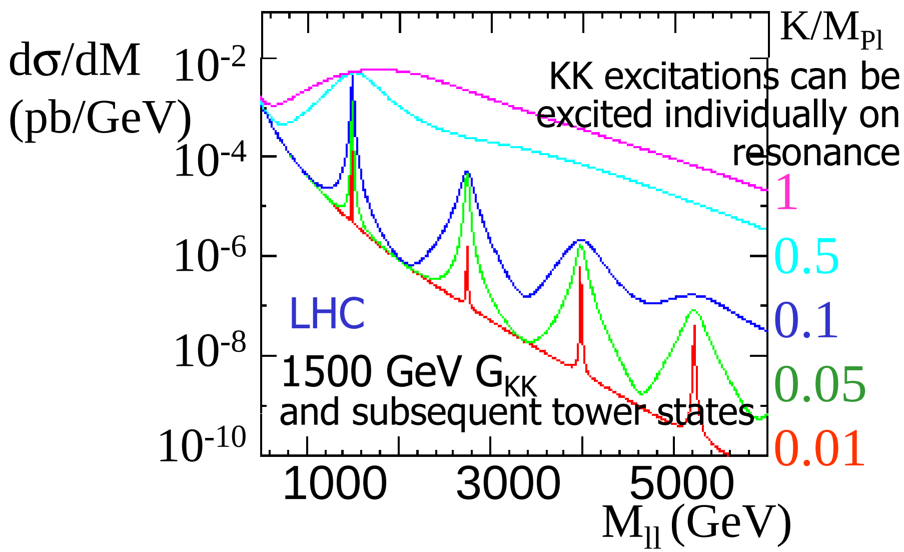


Signature for RS Model



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

The model can be parameterised in terms of the mass of the lightest excitation (m_G) and the coupling k/M_{Pl}



Model parameters:

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

  1st 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: $c = k/M_{Pl}$

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

k = curvature, R = compactification radius

Width of resonance is proportional to m_G and to $(k/M_{Pl})^2$

Narrow intrinsic width if $k/M_{Pl} < 0.1$ (k is space-time curvature in ED)

Davoudiasi, Hewett, Rizzo

Signature for RS Model

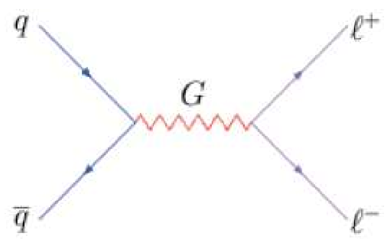
Signature:

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

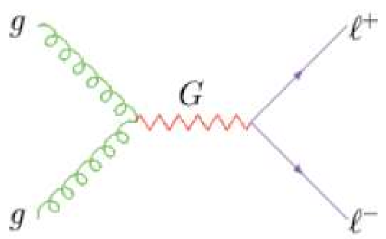
$$q\bar{q}, gg \rightarrow G_{KK} \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, jet + jet$$

BR to gg twice that to ee or mm

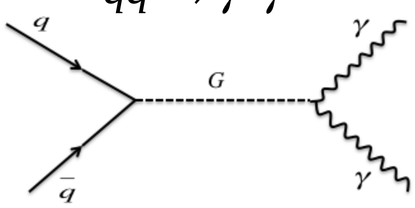
$q\bar{q} \rightarrow l^+l^-$



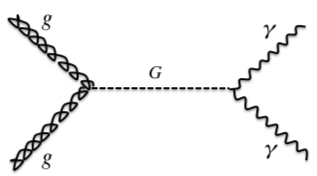
$gg \rightarrow l^+l^-$

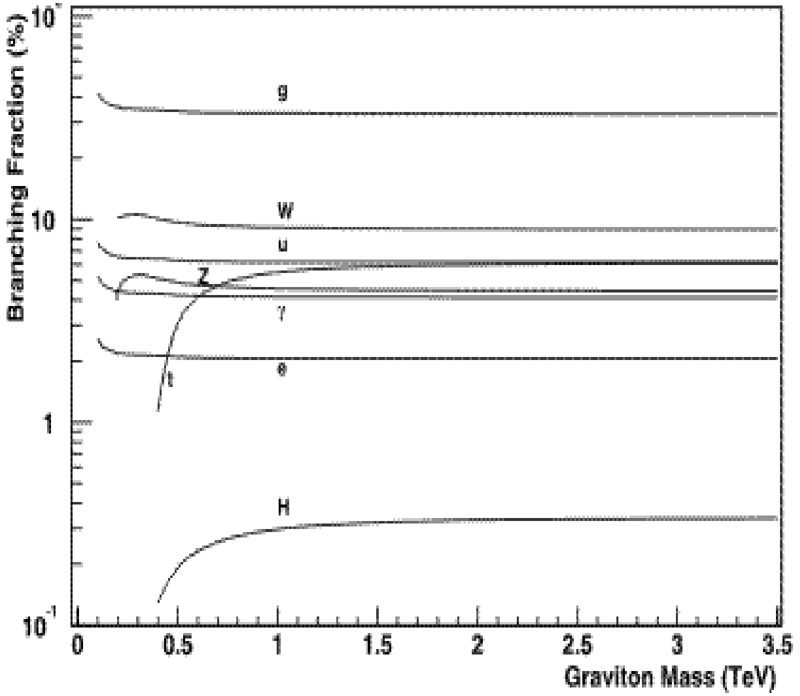


$q\bar{q} \rightarrow \gamma^+\gamma^-$



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





Davoudiasl, Hewett, Rizzo
hep-ph0006041

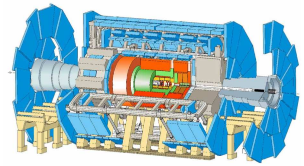
RS Searches for Extra Dimensions

Dileptons (RS)

Diphotons (RS+ ADD)

g_{qqgKK}/g_s: tt-bar->l+jets($H_T+E_T^{miss}$)(RS)

ZZ resonance (RS)



RS ED G*: Dileptons
Analysis Procedure & Event Selection

Select events with two leptons of same flavor (ee, μμ)

Search for excess above SM expectations in high invariant mass region

Muon channel

- Trigger on single Muon with $p_T > 22$ GeV
- Primary vertex with $|z| < 200$ mm
- 2 muons with:
  - $p_T > 25$ GeV
  - $|\eta| < 2.4$
  - 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
  - Isolation: $\Sigma p_T^{trk} < 0.05\, p_T$ within a cone of $\Delta R < 0.3$
  - Opposite charge

Electron channel

- Trigger on single Medium electron with $E_T > 20$ GeV
- 2 electrons with:
  - $p_T > 25$ GeV
  - $|\eta| < 2.47$, exclude crack region
  - $1.37 < |\eta| < 1.52$
  - Medium Electron ID
  - Hit in first pixel layer ("Blayer")
  - Isolation: $\Sigma E_T(\Delta R < 0.2) < 7$GeV
  - No opposite charge requirement – to minimize impact of mis-ID

Analysis Procedure & Event Selection

Total signal acceptance for Z′ (G*) ->ee   71 % (72%) for a mass of 2 TeV

Z′ (G*) ->μμ   43 % (47 %)

Muon channel

- Trigger on single Muon with p_T > 22 GeV
- Primary vertex with |z| < 200 mm
- 2 muons with:
  - p_T > 25 GeV
  - $|\eta| < 2.4$
  - 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
  - Isolation: $\Sigma p_T^{trk} < 0.05\, p_T$ within a cone of $\Delta R < 0.3$
  - Opposite charge

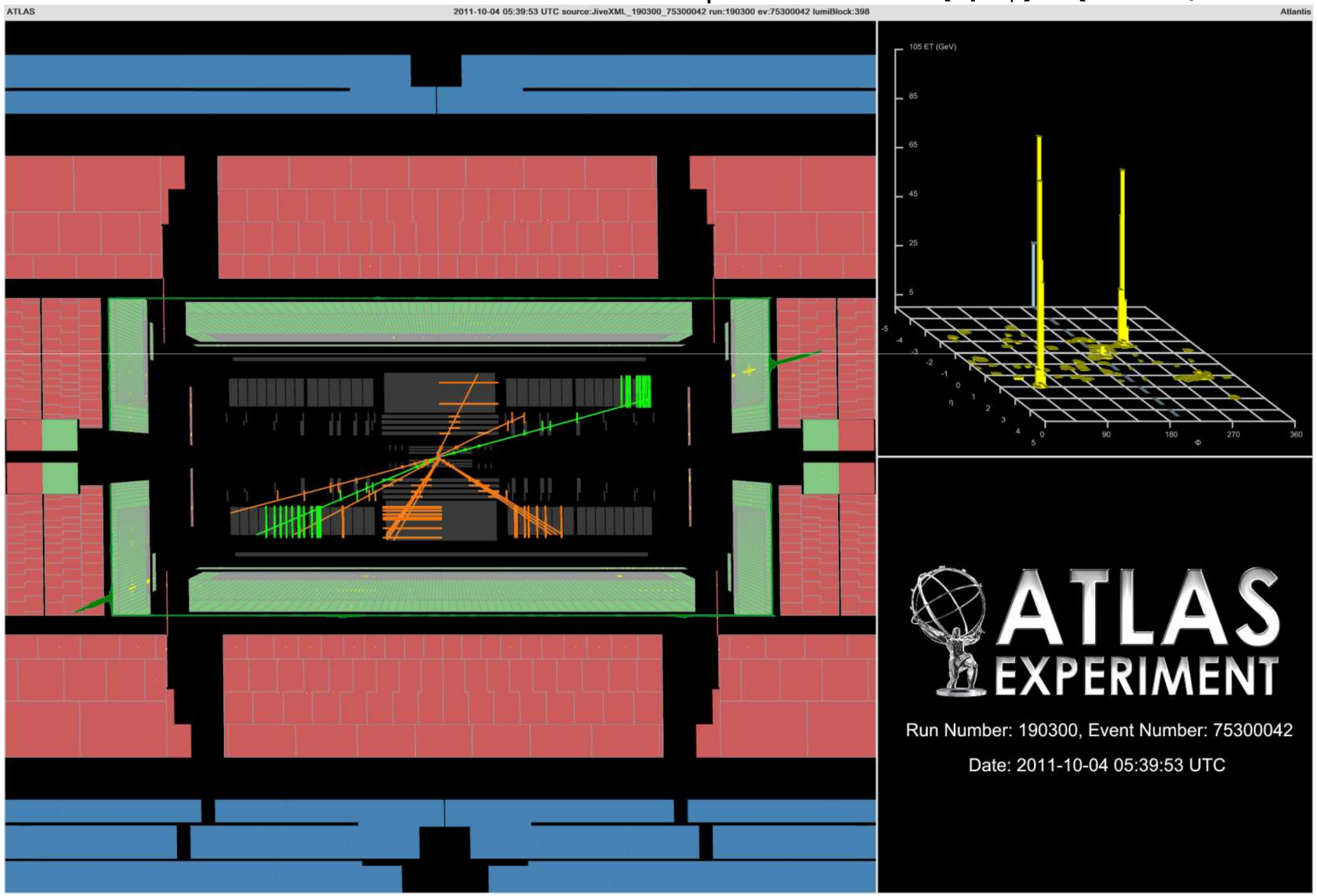
Electron channel

- Trigger on single Medium electron with E_T > 20 GeV
- 2 electrons with:
  - p_T > 25 GeV
  - $|\eta| < 2.47$, exclude crack region
  - $1.37 < |\eta| < 1.52$
  - Medium Electron ID
  - Hit in first pixel layer ("Blayer")
  - isolation: $\Sigma E_T(\Delta R < 0.2) < 7$GeV
  - No opposite charge requirement – to minimize impact of mis-ID

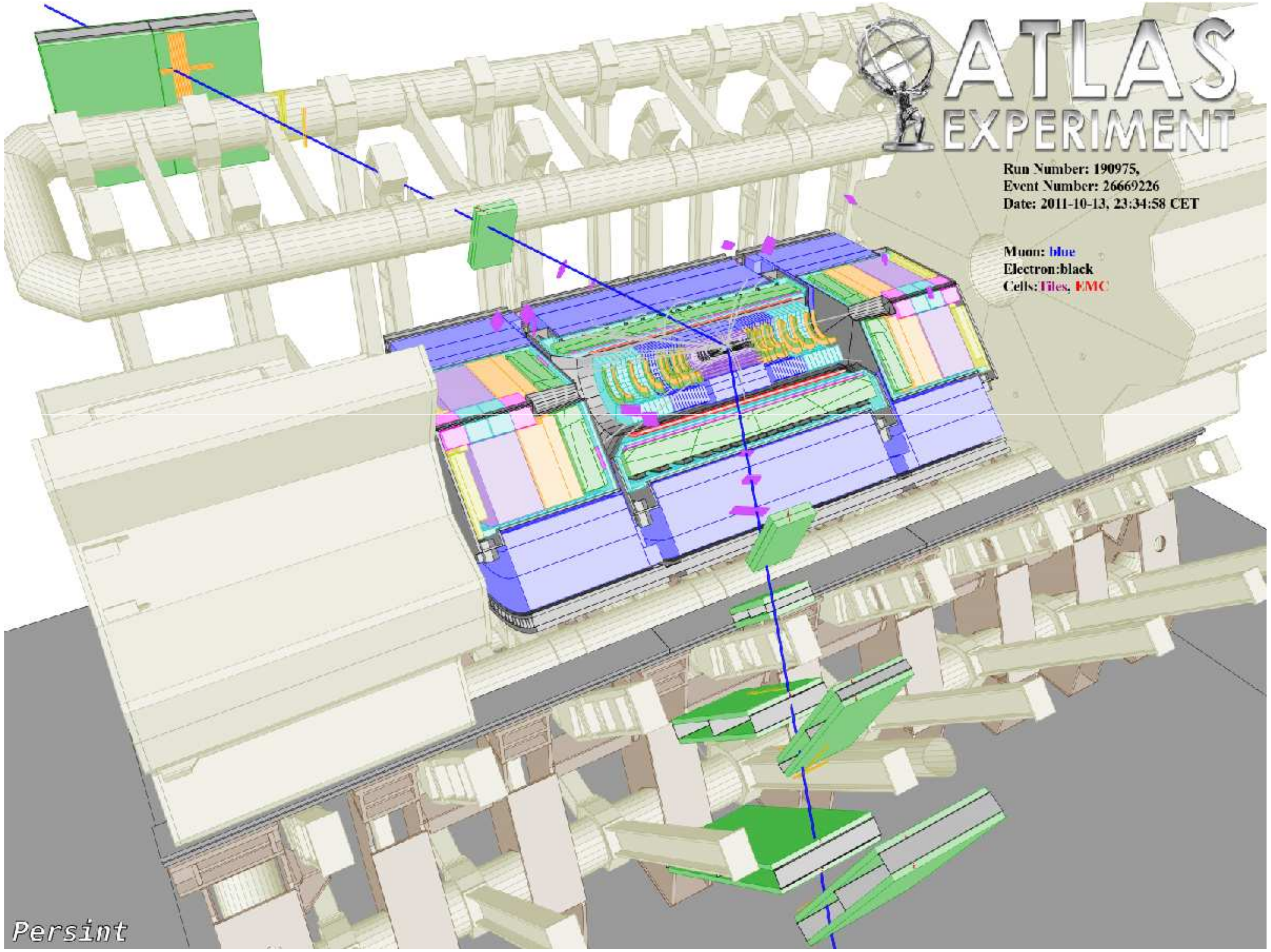
Highest mass ee event

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

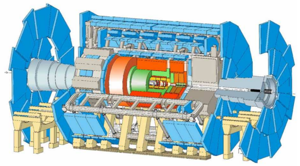


M_{mm}=1.25 TeV

P_T of 648 GeV
(η, ϕ) = (-0.75, 0.49)

P_T of 583 GeV
(η, ϕ) =(-0.36, -2.60)

.



Main Backgrounds

- SM Z/γ Drell-Yan (irreducible, primary background)

  $\gamma^*/Z \to l^+l^-$

- QCD (electron channel only)

- Top quark pair production

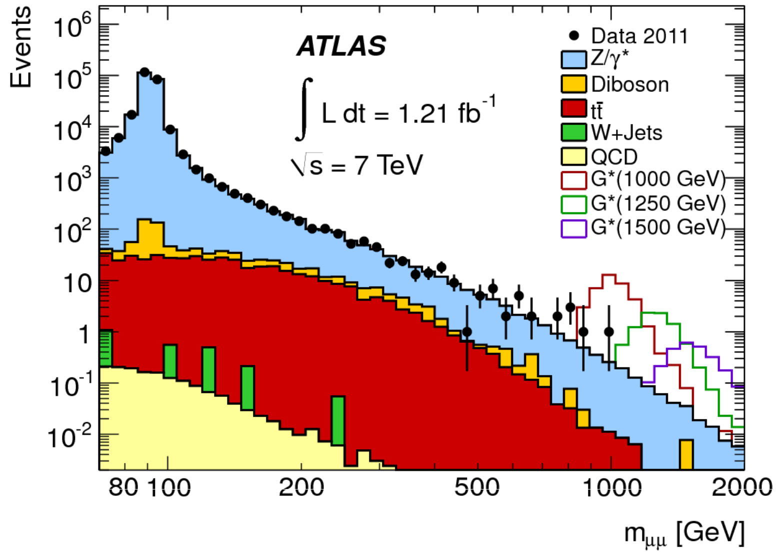
  where tt goes to e+e-, mu+mu-

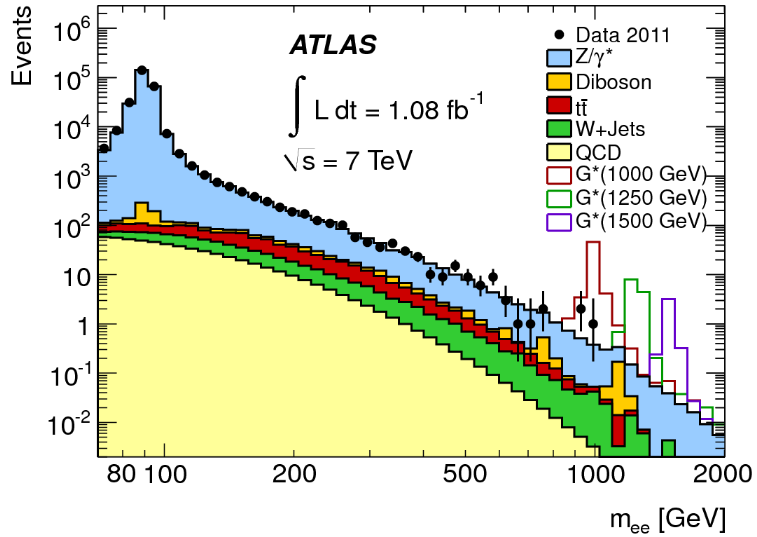
- SM W+jets (electron channel only)

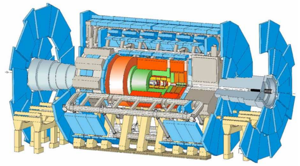
  where the jets are misidentified as electrons

- Dibosons (WW, WZ, ZZ)

- Cosmic Rays (negligible contribution to muon channel)





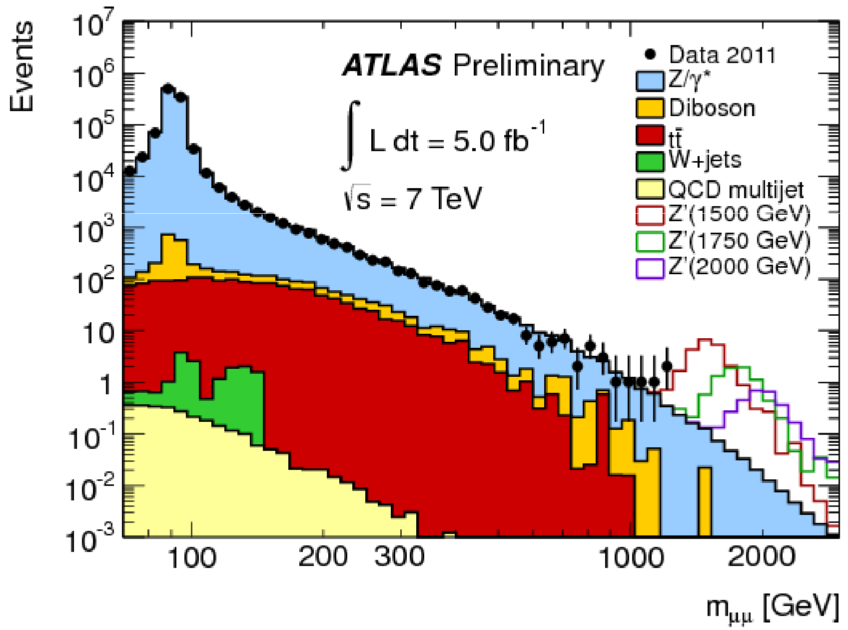


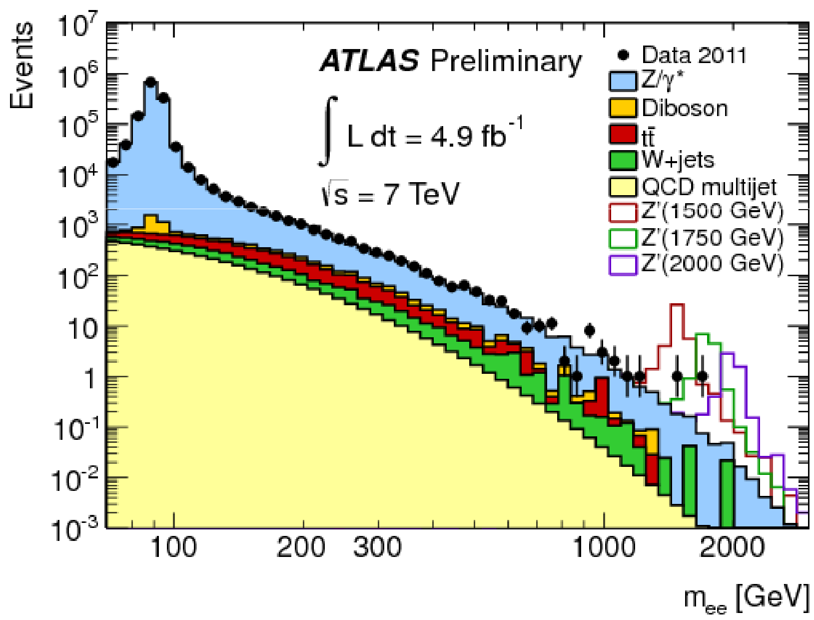
Main Backgrounds

- 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)

Dilepton Distributions

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

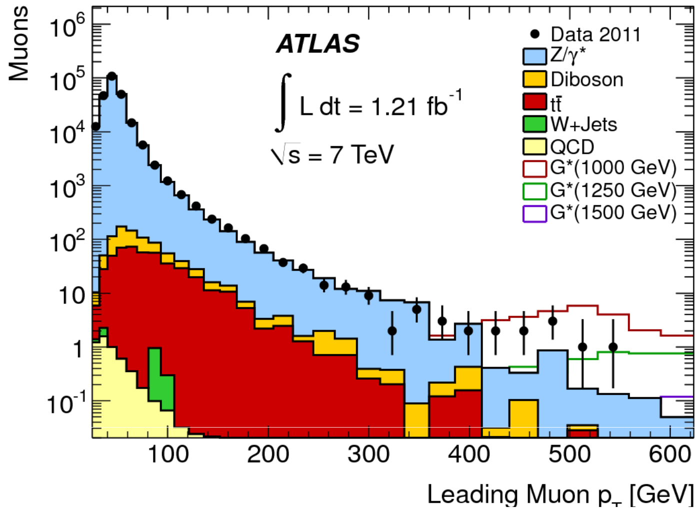


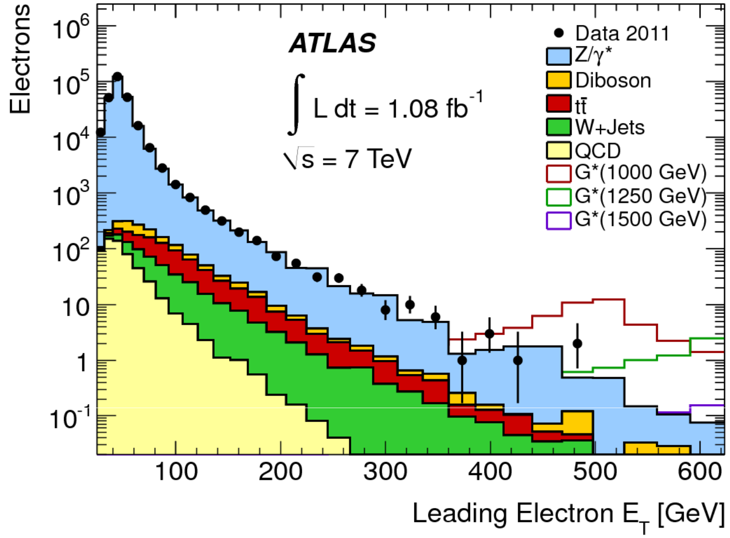


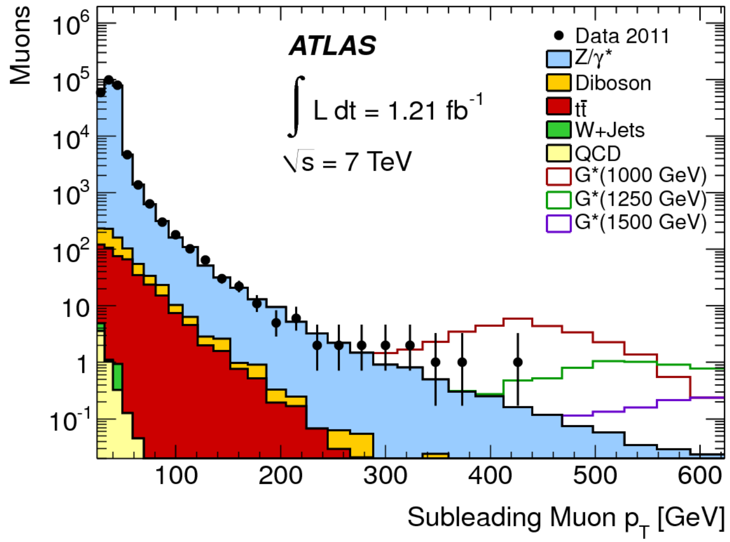
The bin width is constant in log(mll)

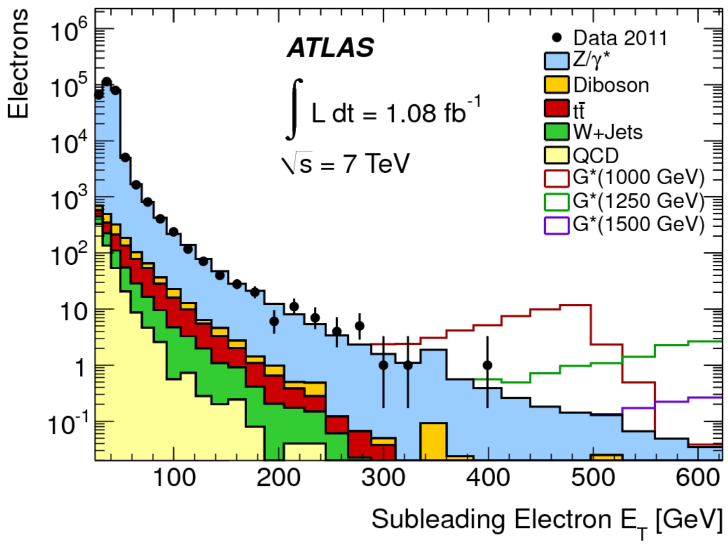
Dilepton Kinematics

Good agreement with background expectations

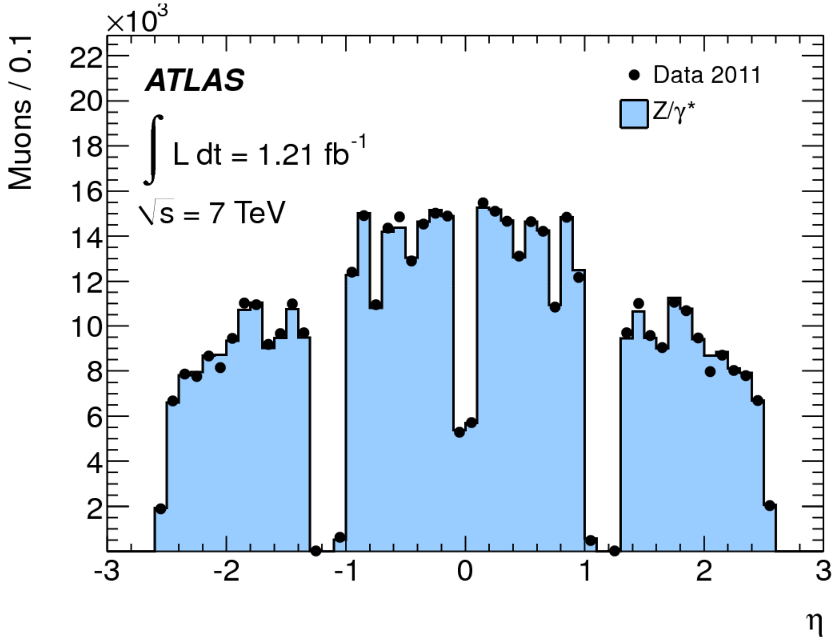


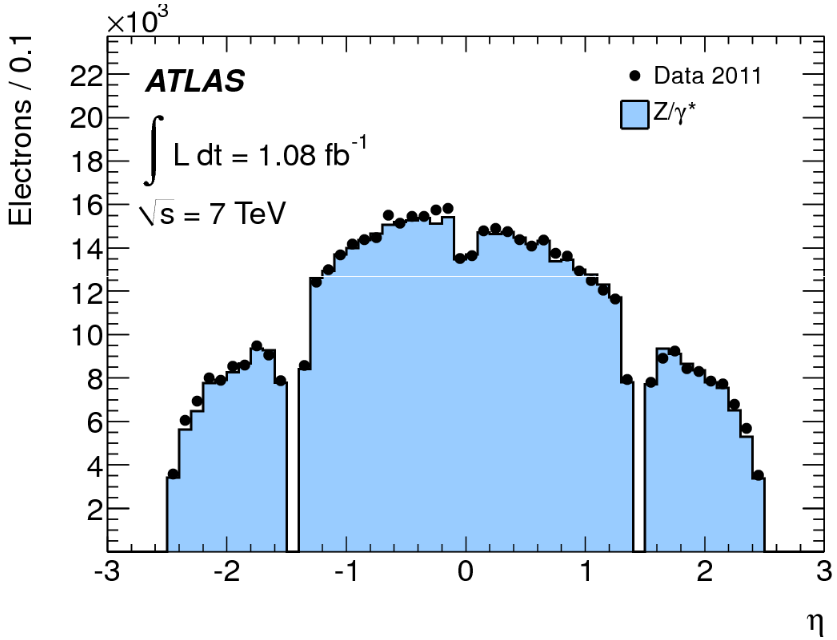




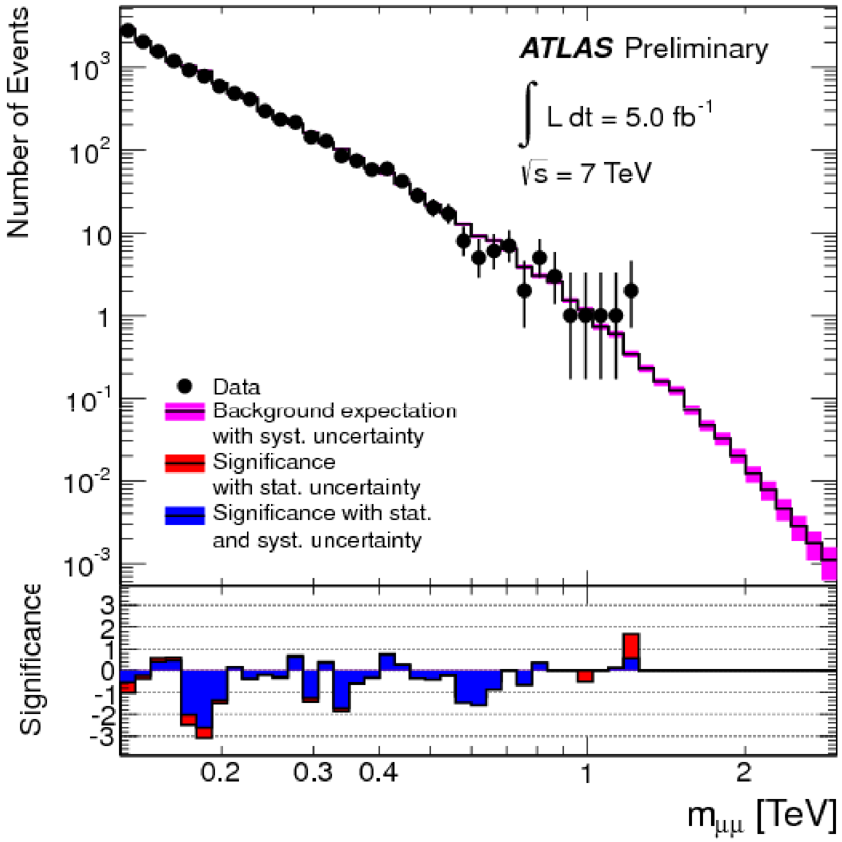


Dilepton Kinematics

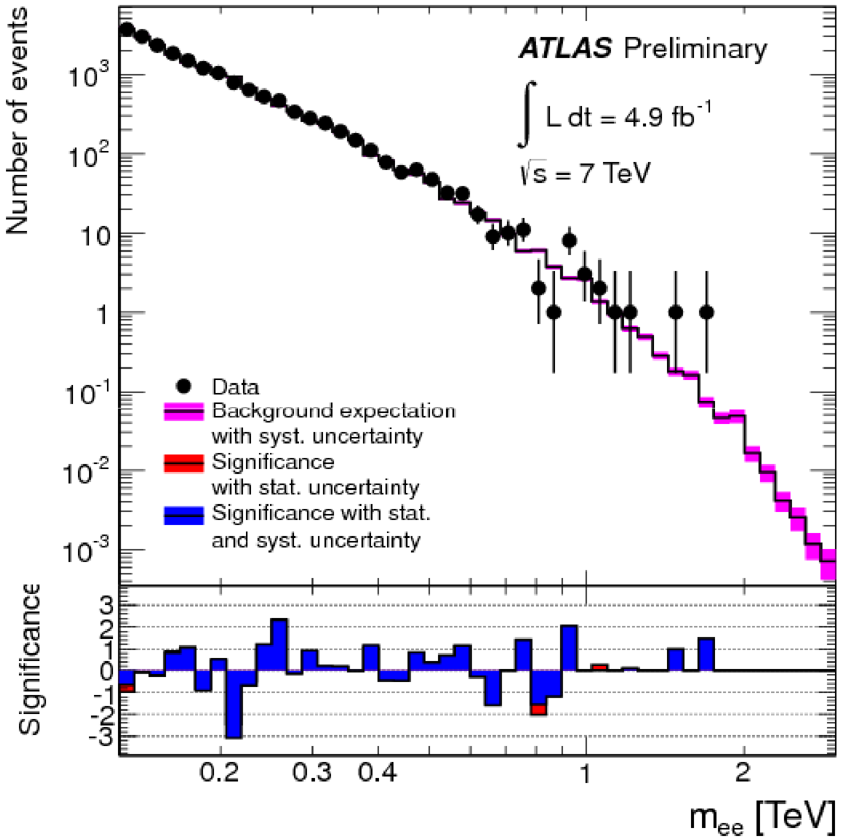




New Physics?



p-value = 0.82



p-value = 0.13

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

Limits Setting and Errors

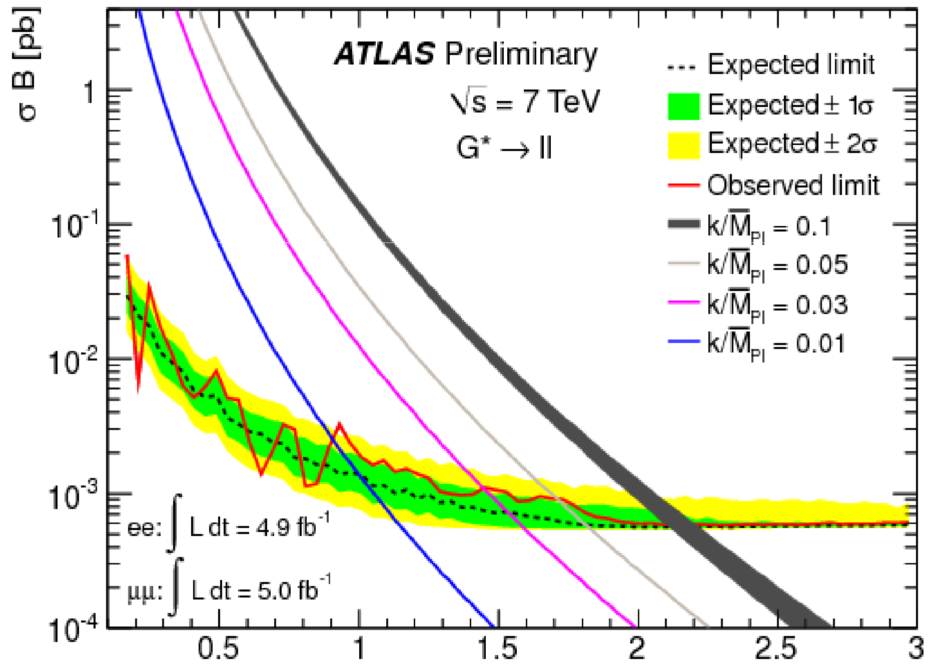
- Because normalize MC to data in Z peak region (70 < $m_{\ell\ell}$ < 110 GeV) luminosity and other mass independent systematics cancel between Z and Z'/G
- Uncertainties treated as correlated across all bins

Table 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.

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	3.5%	NA	-
Total	5%	21%	8%	21%

RS G*->Dilepton limits

- Set an 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



See later for 1 fb^{-1} combination with $\gamma\gamma$ channel!

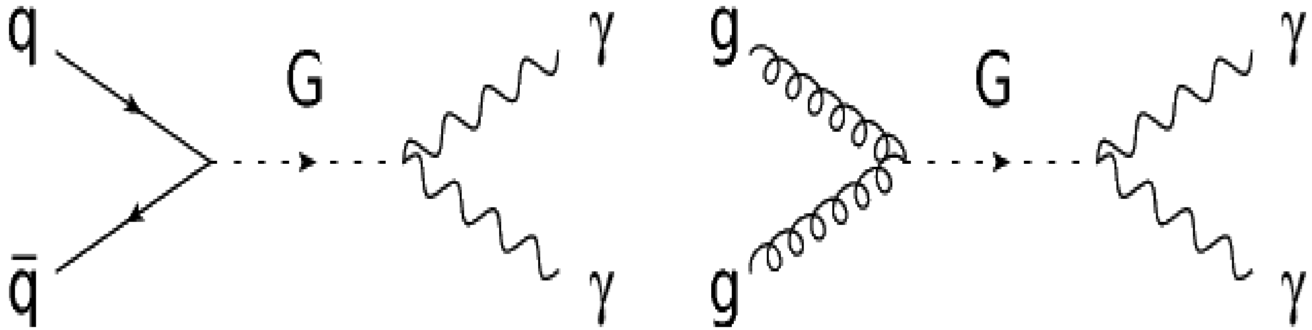
Model		Mass Limit	(TeV)
k/M_{Pl}=0.1	e^+e^-	$\mu^+\mu^-$	l^+l^-
RS Graviton	2.03 (2.05)	1.90 (1.92)	2.16 (2.17)

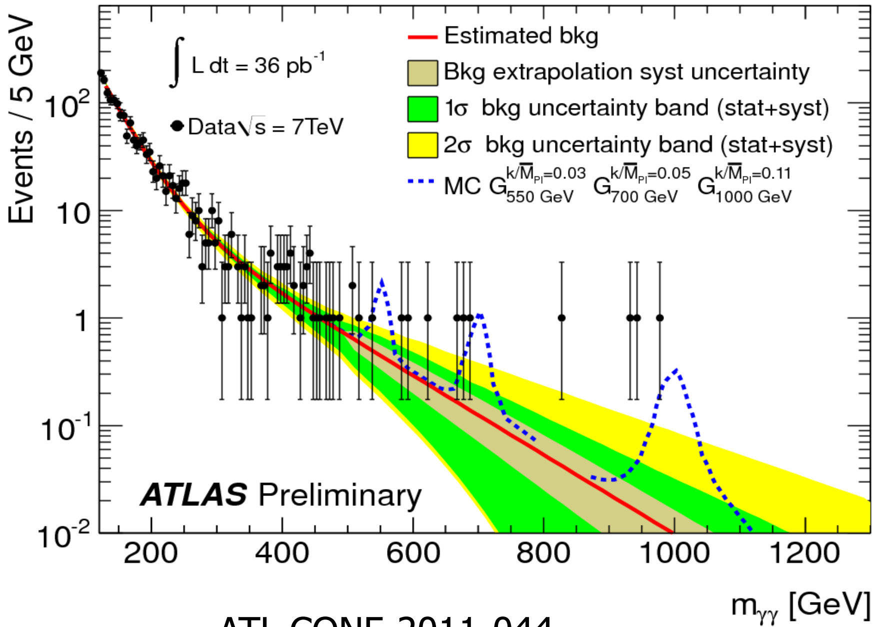
Observed (Expected) 95 % C.L. mass lower limit

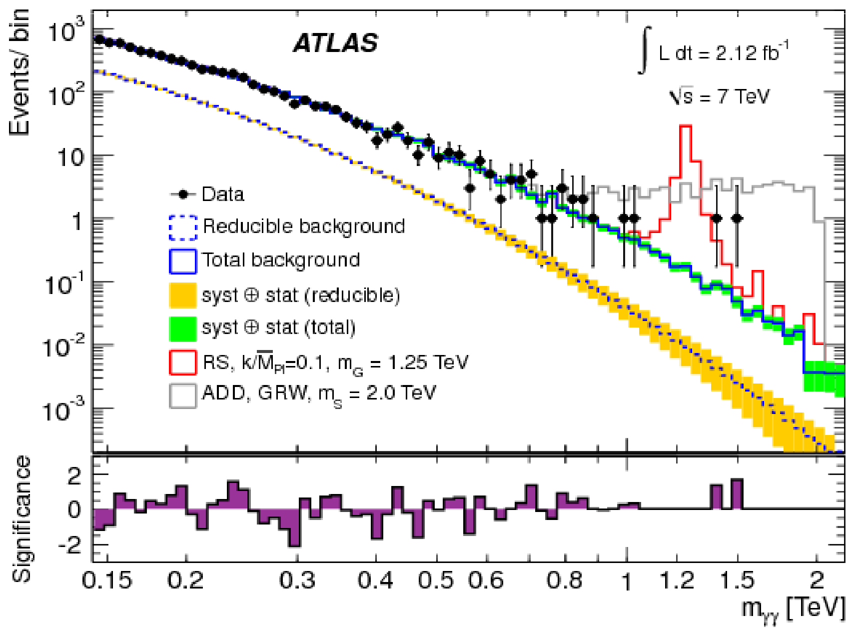
	RS graviton			
Model/Coupling	0.01	0.03	0.05	0.1
Mass limit [TeV]	0.91	1.45	1.71	2.16

RS ED: Diphotons

RS Gravitons (G)







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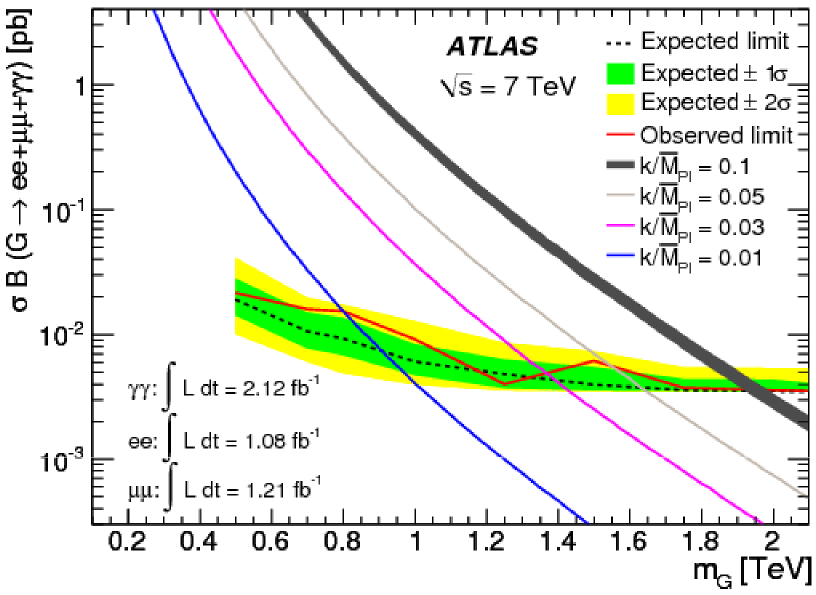
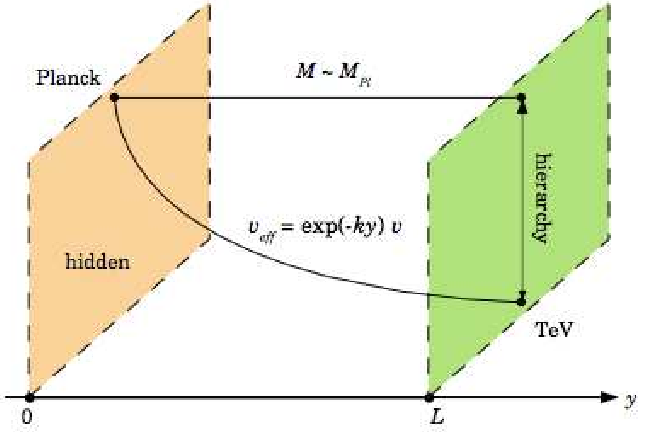
RS Limits

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

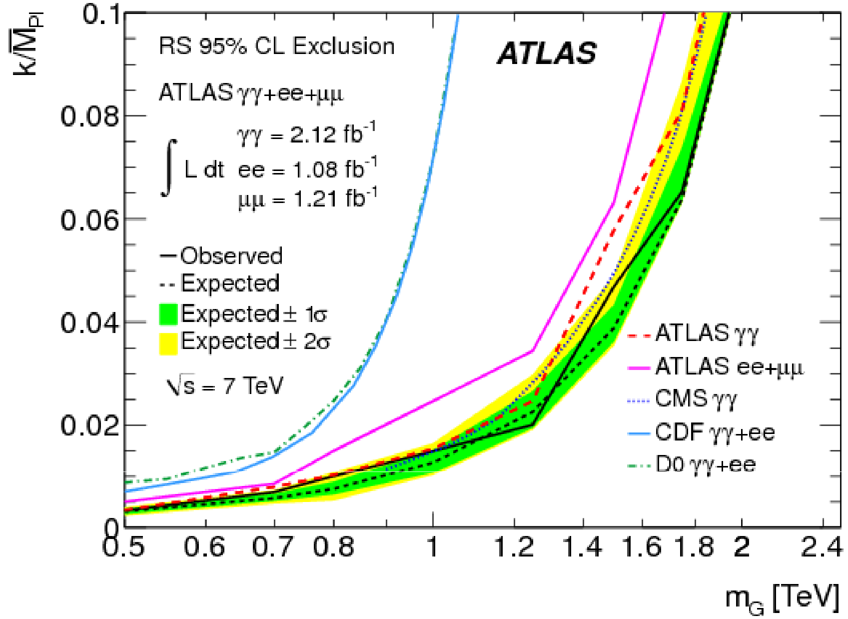


	k-Factor Value	Channel(s) Used	95% CL Observed (Expected) Limit [TeV] $k/\overline{M}_{Pl}$ Value 0.01	0.03	0.05	0.1
LO	1	$G \to \gamma\gamma$	0.78 (0.82)	1.26 (1.27)	1.38 (1.49)	1.80 (1.81)
		$G \to \gamma\gamma/ee/\mu\mu$	0.76(0.85)	1.32 (1.31)	1.47 (1.55)	1.90 (1.90)
NLO	1.75	$G \to \gamma\gamma$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

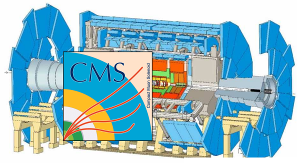
RS G*->gg Present Limits



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

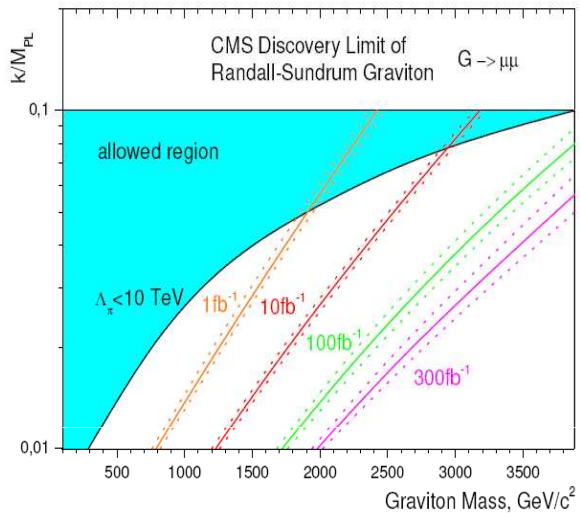


k/M_{Pl}	95% CL mass limit (TeV)			
	D0	CDF	CMS ($2.2fb^{-1}$)	ATLAS ($2.1fb^{-1}$)
0.01	0.56	0.47	0.86	0.80
0.1	1.05	0.98	1.84	1.85



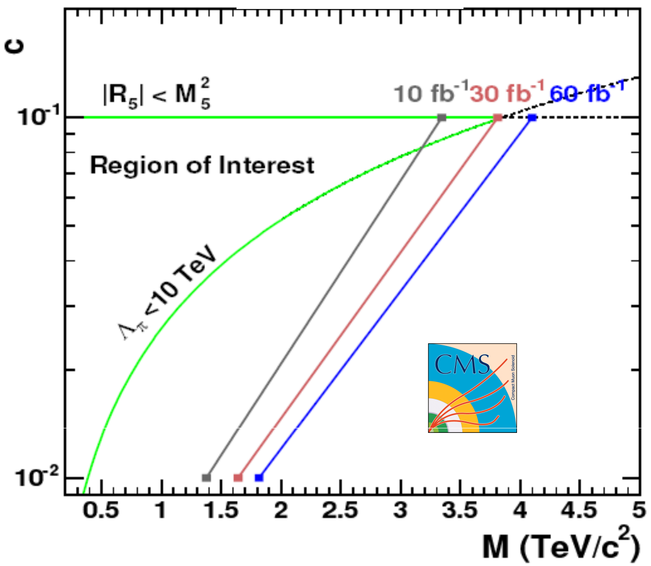
LHC RS Discovery Limits

$G_1 \to \mu^+\mu^-$

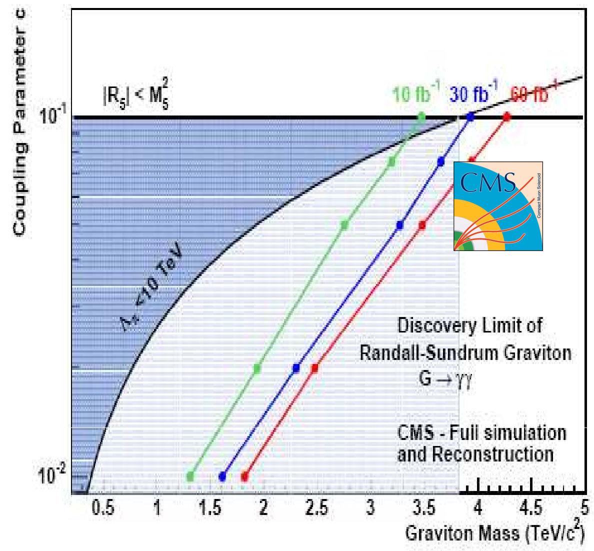


Solid lines = 5σ discovery
Dashed = 1σ uncert. on L

$G_1 \to ee$



$G_1 \to \gamma\gamma$



Theoretical Constraints

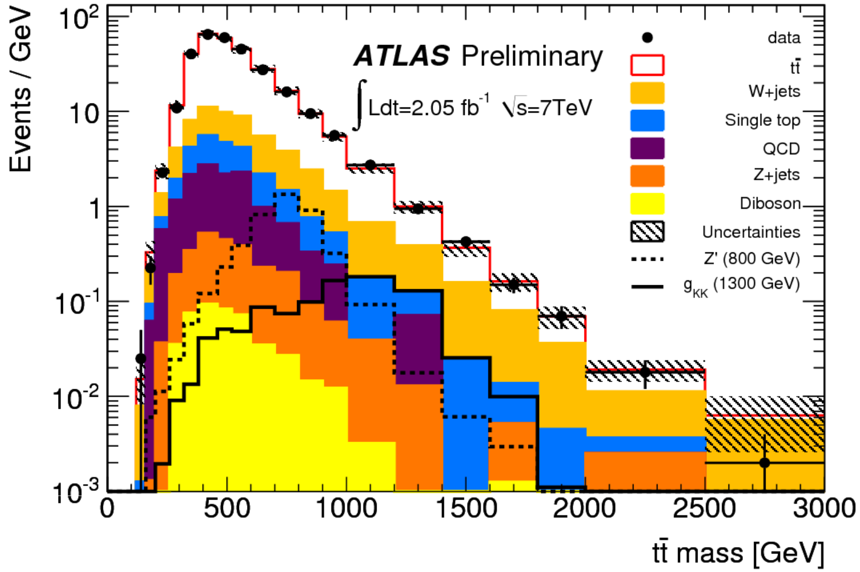
- c>0.1 disfavoured as bulk curvature becomes to large (larger than the 5-dim Planck scale)
- Theoretically preferred Λ_π<10TeV assures no new hierarchy appears between m_{EW} and Λ_π

LHC completely covers the region of interest

tt Resonances in the Dilepton Channel

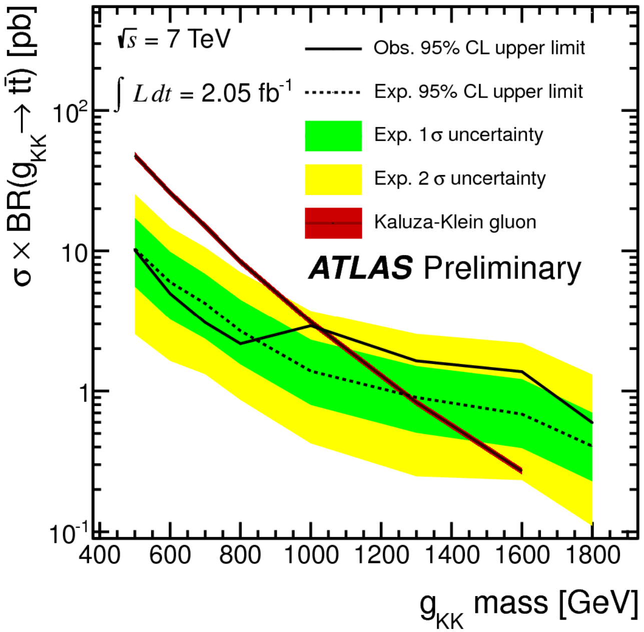
- Signal RS $g_{KK} \rightarrow$ tt-bar :
- tt-bar→bW+$\bar{b}$W-→bb-bar lνlν

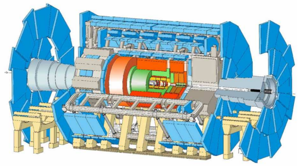
No statistically significant excess above the SM expectation observed



UL @ 95% C.L. on σ.BR(resonance→tt-bar) pairs as a function of the resonance pole mass

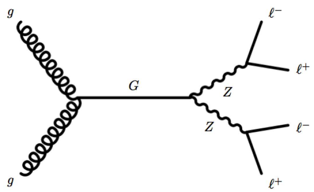
Lower mass limit of 1.025 TeV for a Kaluza Klein gluon resonance in the RS Model



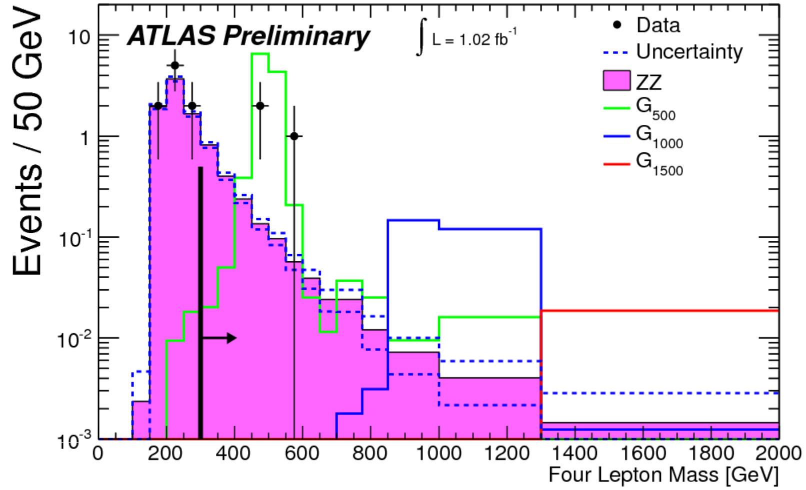


RS G*→ZZ → llll with Four Charged Leptons

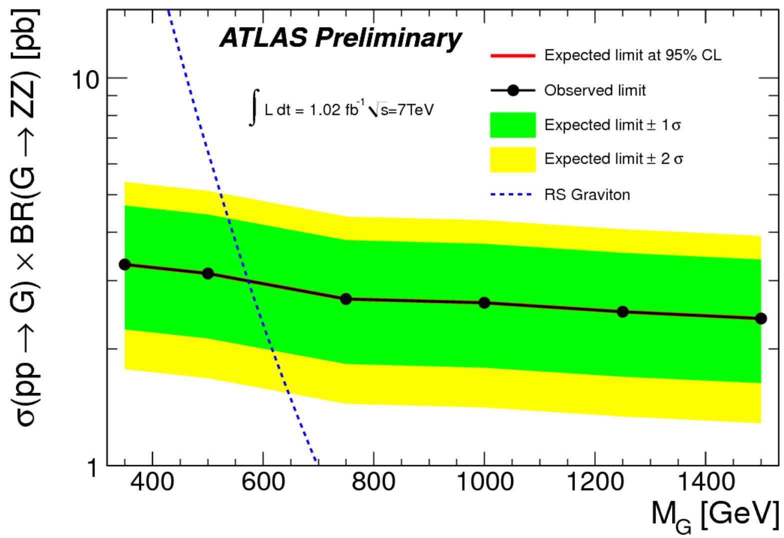
- Signal: Four Charged Leptons
- 2 searches performed in this decay channel ZZ & H++H--



- Events with two identified Z→ℓ+ℓ− 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



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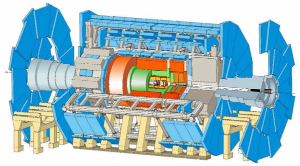


Conclusion/Outlook

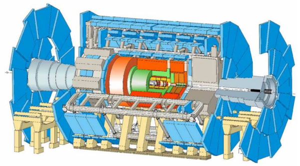
- LHC was working very well at beam energy 3.5 TeV
  - Now taking data at beam energy 4 TeV

- ATLAS detector is efficiently collecting data
  - No significant excesses yet observed
  - Distributions so far consistent with SM expectations

- We look forward to searching for New Physics

  …. more exciting results from ATLAS to come:

  aiming for new results with full $5pb^{-1}$ for ICHEP and also first analyses with 8 TeV data



The End!

- Thanks for listening!