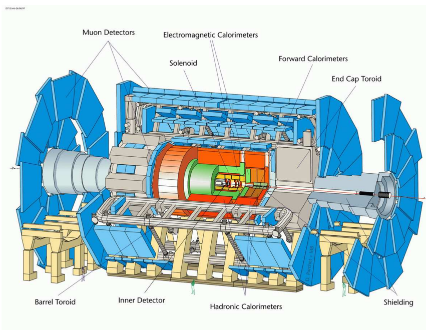
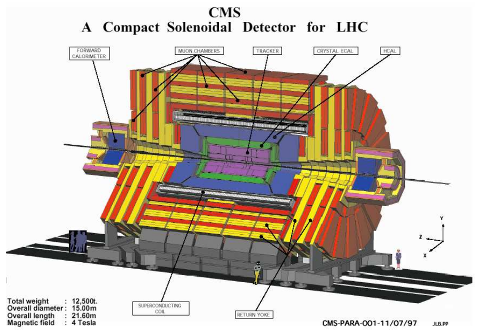
Searches for Extra Dimensions at the LHC



Dr Tracey Berry
Royal Holloway
University of London



Overview

- Theoretical Motivations
- Extra Dimensional Models Considered
- Signatures Covered
- Search Facilities: ATLAS & CMS
- Present Constraints and Discovery Limits for ED (ADD, RS, TeV^{-1})
- Uncertainties
- Summary of LHC Start-up Expectations
- Conclusions

Extra Dimensions: 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

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

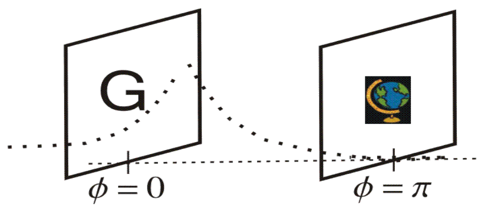
Effective M_{Pl} ~ 1TeV → if compact space (R^{δ}) is large

RS

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

1 highly curved ED
Gravity localised in the ED

Planck TeV brane



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

Λ_{π} ~ TeV

if warp factor kR_c ~11-12

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

Some of these models can be/have been experimentally tested at high energy colliders

Extra dimensions?

- "String theories" predict that there are actually 10 or 11 dimensions of space-time
- The "extra" dimensions may be too small to be detectable at energies less than ~ 10^{19} GeV
  - To a tightrope walker, the tightrope is one-dimensional: he can only move forward or backward

Extra Dimensions

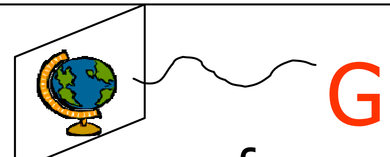
- More than the 3 space + 1 time dimensions we experience
- The "extra" dimensions could be hidden to us:
  - E.g. they are small that only extremely energetic particles could fit into them

    (so we need high energies to probe them)
  - 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.

Extra Dimensional Models

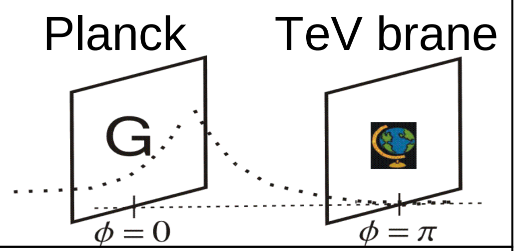
ADD **A**rkani-Hamed, **D**imopoulos, **D**vali,
Phys Lett B429 (98)



(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



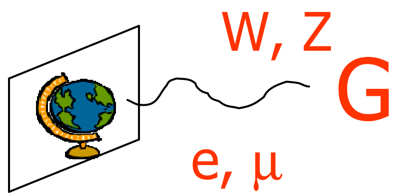
TeV^{-1} sized EDs Dienes, Dudas, Gherghetta,
Nucl Phys B537 (99)

Bosons could also propagate in the bulk
Fermions are localized at the same (opposite) orbifold point: destructive (constructive) interference between SM gauge bosons and KK excitations

UED

Not covered here!

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



Main phenomenologies under study at the LHC

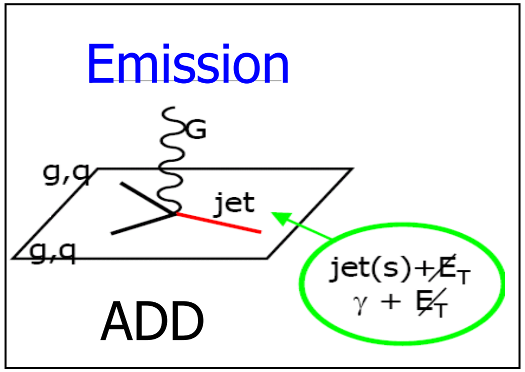
- Large Extra Dimensions (ADD): only gravity in the bulk
  - KK Graviton Direct Production → Missing E_T signature
  - KK Graviton Exchange → Drell-Yan

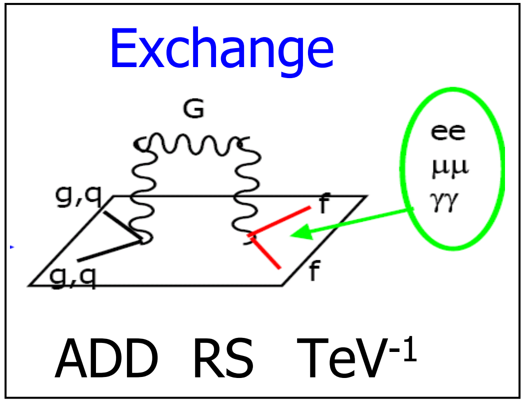
- Randall-Sundrum Model
  - KK Graviton →TeV resonances
  - Radion → Higgs-like signature
- TeV^{-1} Extra Dimensions: also gauge fields in the bulk
  - KK gauge bosons → multi-TeV resonances
  - Different α_s running
- Universal Extra Dimensions: all SM fields in the bulk
  - Through radiative corrections, spectrum of KK resonance: SUSY-like phenomenology
  - Semi-stable KK resonances of quarks
- Black-Hole production

Experimental Signatures of ED

Covered in this talk

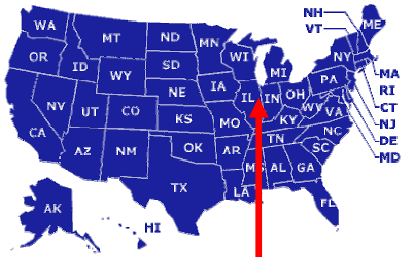
- Single jets/Single photons + missing E_T
(direct graviton production in ADD)
- Di-lepton, di-jet continuum modifications
(virtual graviton production in ADD)
- Di-lepton, di-jet and di-photon resonances
(new particles) in RS1-model (RS1-graviton) and TeV^{-1} ED model (Z^{KK})
- (Single leptons + missing E_T
in TeV^{-1} ED model (W^{KK})
- $b\bar{b}$ $t\bar{t}$ resonances
in TeV^{-1} ED model)

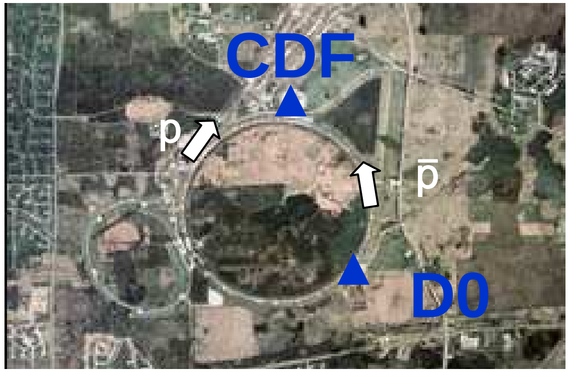




Present/Past ED Search Facilities

Tevatron, Fermilab, USA





Tevatron: Highest energy collider operating in the world!

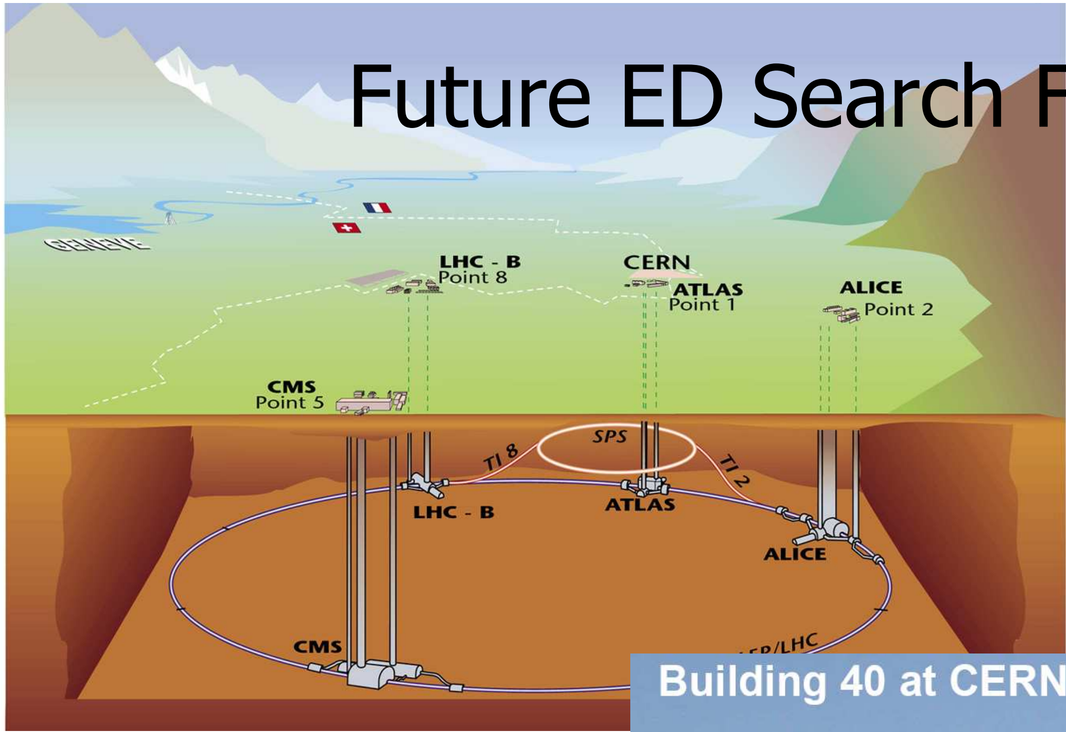
Run I $\sqrt{s}$ = 1.8 TeV
Run II $\sqrt{s}$ = 1.96 TeV

LEP, CERN, Geneva

CERN: world's largest particle physics laboratory

LEP I $\sqrt{s}$ = 91 GeV
LEP II $\sqrt{s}$ = 136-208 GeV

Future ED Search Facilities!

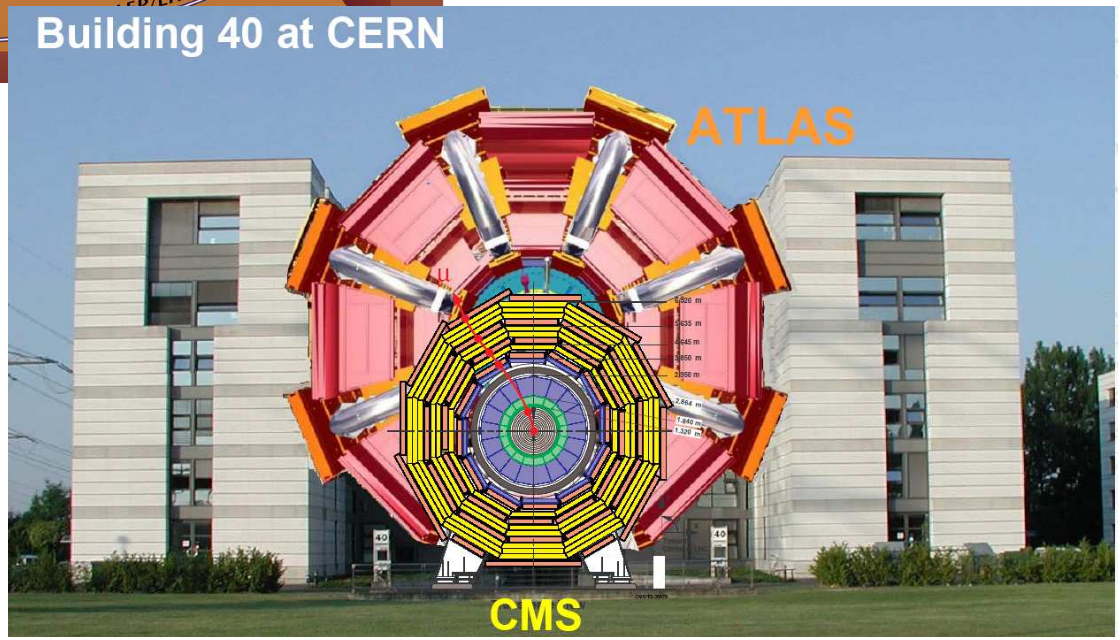


Bigger Collider & Detectors!!

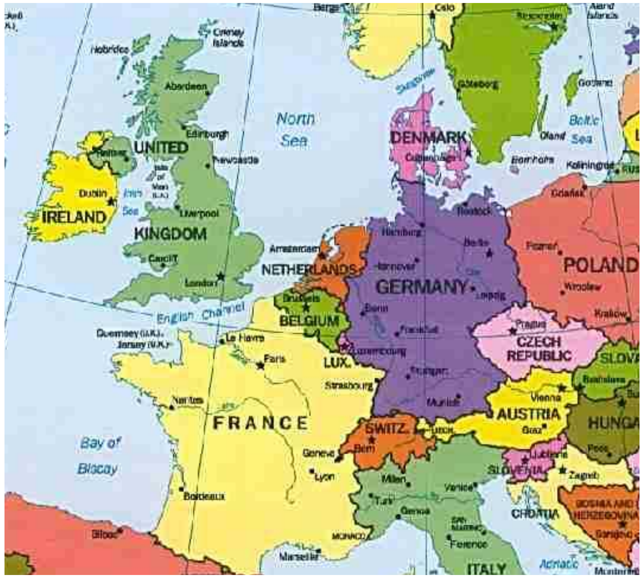
LHC: proton – proton collisions

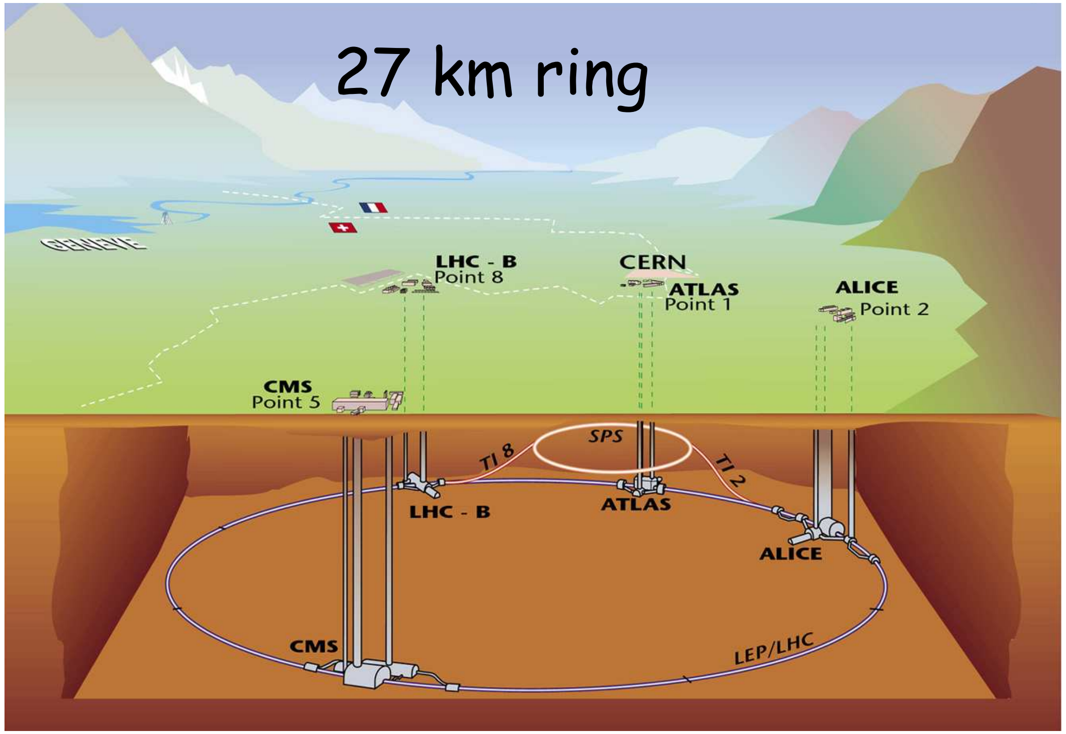
Higher center of mass energy

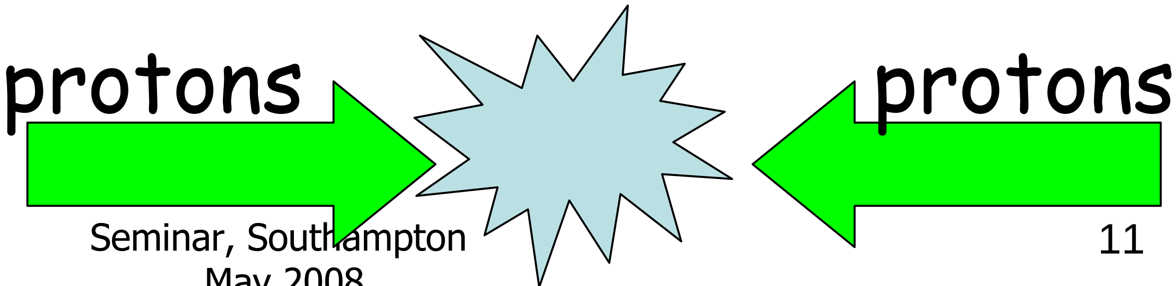
$\sqrt{s}$ = 14 TeV



Large Hadron Collider



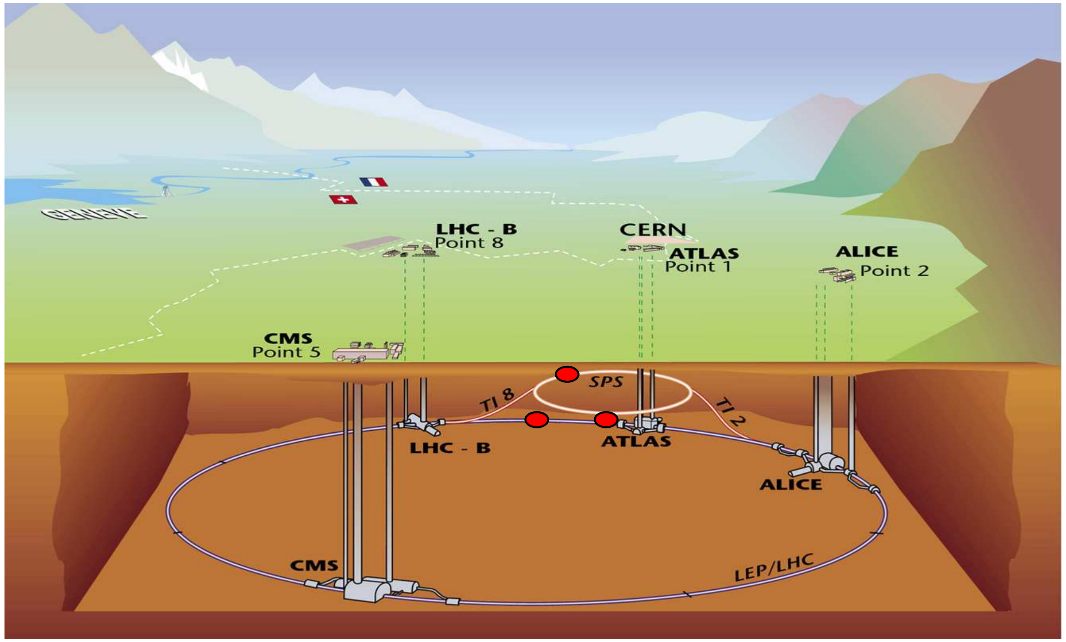




Large Hadron Collider

The is LHC the world's largest particle accelerator

It accelerates protons to 99.9999991 % of the speed of light!

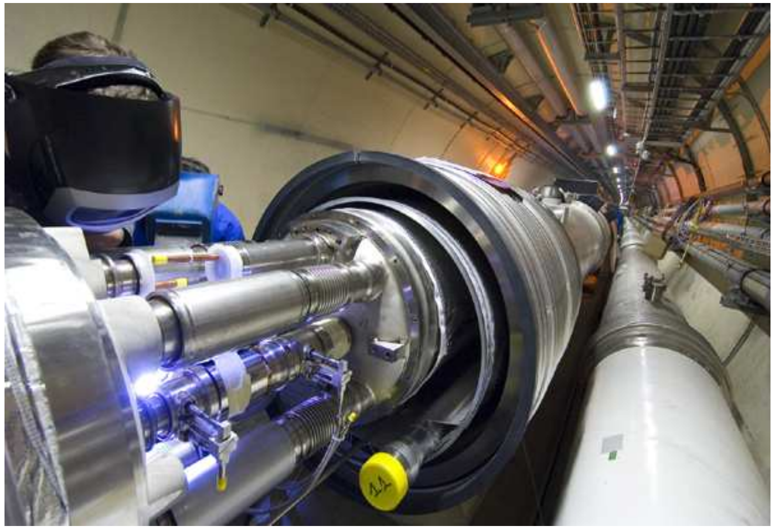


A chain of accelerators to reach the required energy
Protons circle the 27km ring 11000 times per second!

Inside the tunnel at the Large Hadron Collider

LHC Magnets

9300 magnets inside the ring

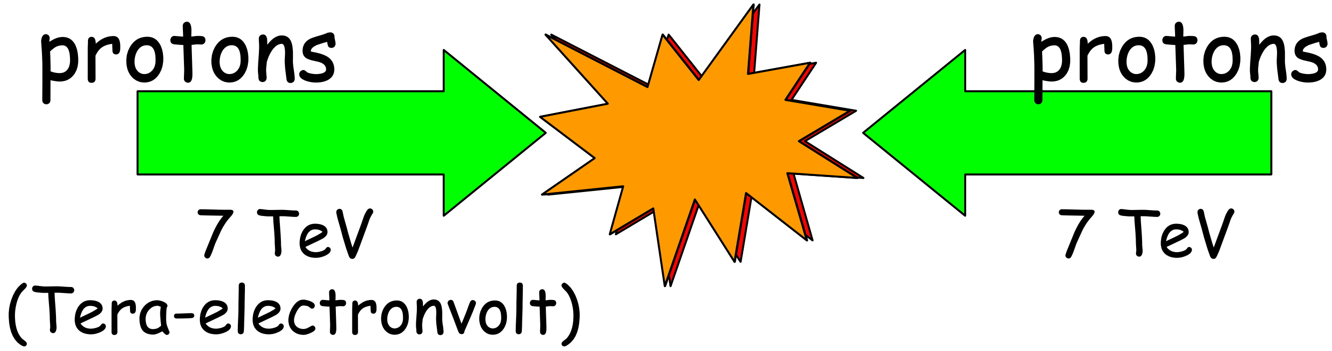


The LHC is kept at a super cool by the 'cryogenic distribution system', which circulates superfluid helium around the accelerator ring.

It is at temperature of -271.3°C (1.9 K) – even colder than outer space!

Just one-eighth of its cryogenic distribution system would qualify as the world's largest fridge!

Collisions



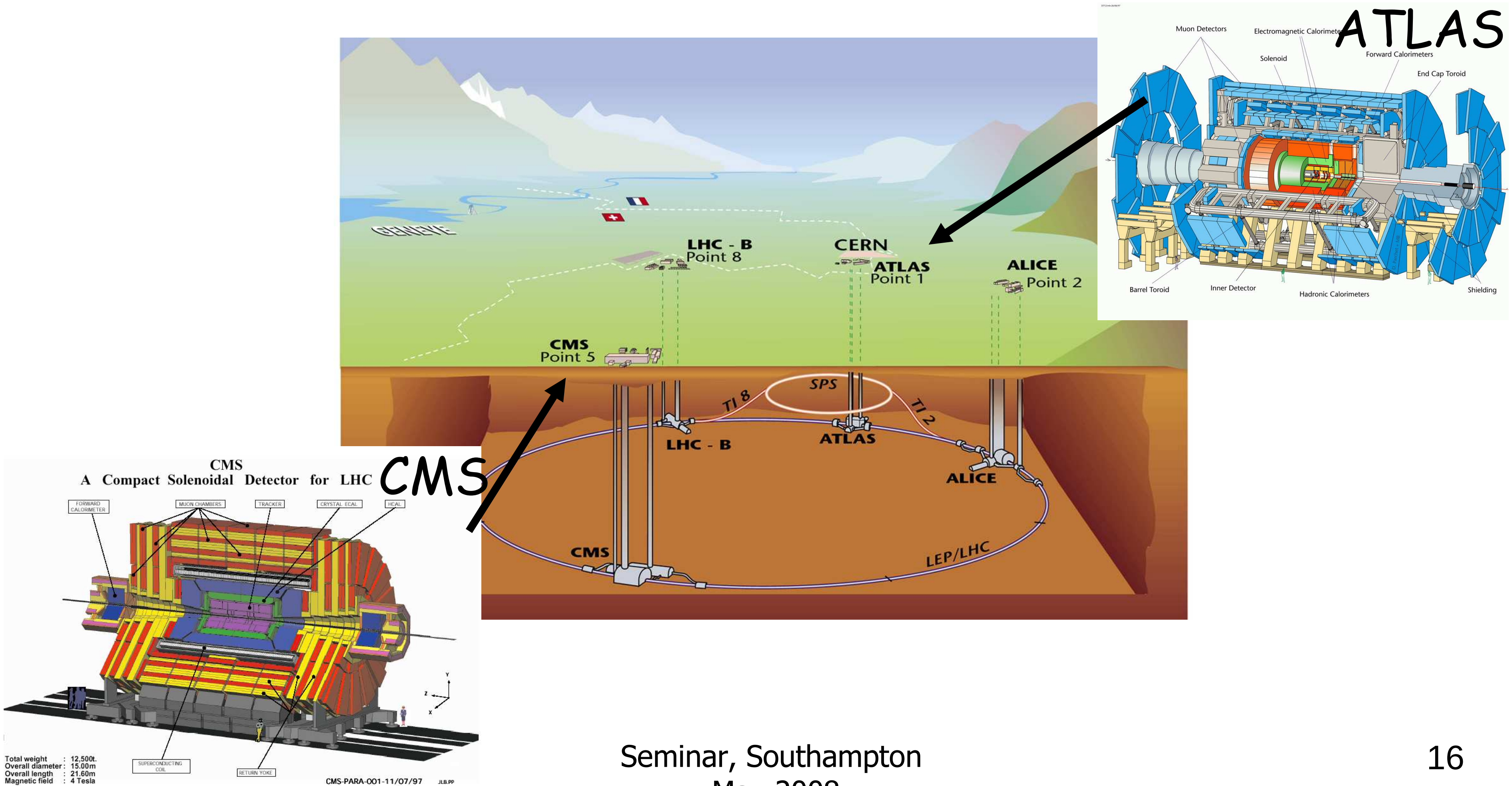
head-to-head collisions energy = 14 TeV

7 times the energy of any previous accelerator

The collision generate temperatures more than 100 000 times hotter than the heart of the Sun!

600 million collisions per second

Detectors

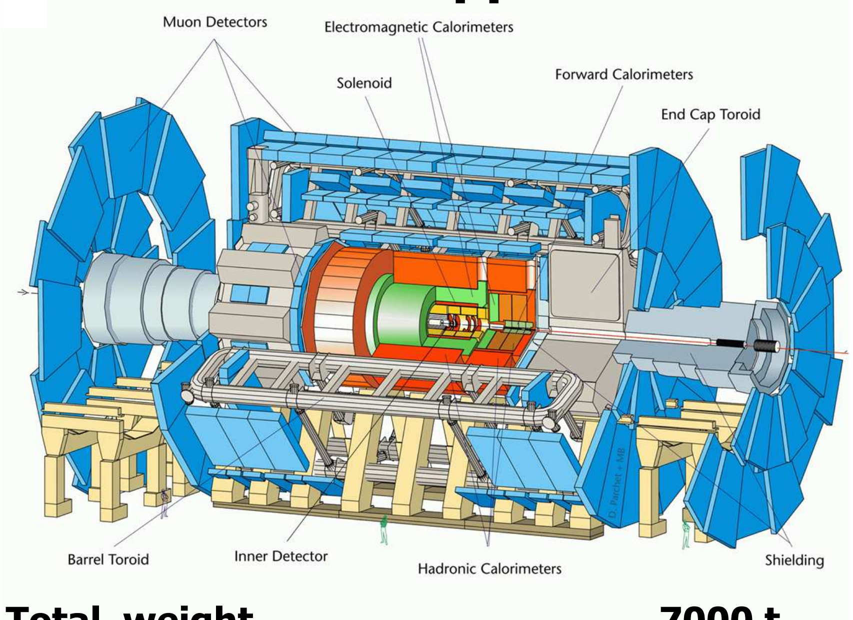


ATLAS
Muon Detectors
Electromagnetic Calorimete
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
CMS
CMS
A Compact Solenoidal Detector for LHC
FORWARD CALORIMETER
MUON CHAMBERS
TRACKER
CRYSTAL ECAL
HCAL
SUPERCONDUCTING COIL
RETURN YOKE
Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla
CMS-PARA-001-11/07/97

ATLAS and CMS Experiments

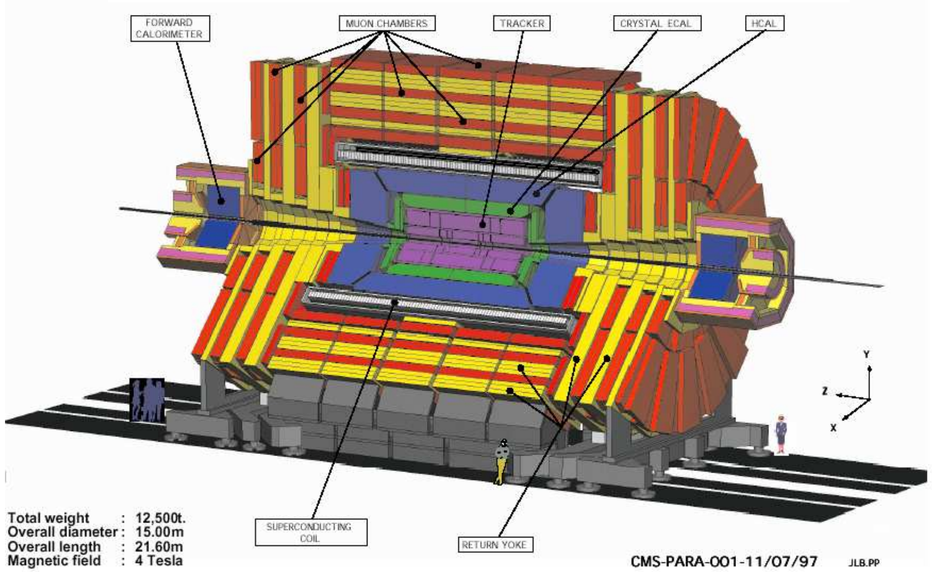
Large general-purpose particle physics detectors

A Toroidal LHC ApparatuS



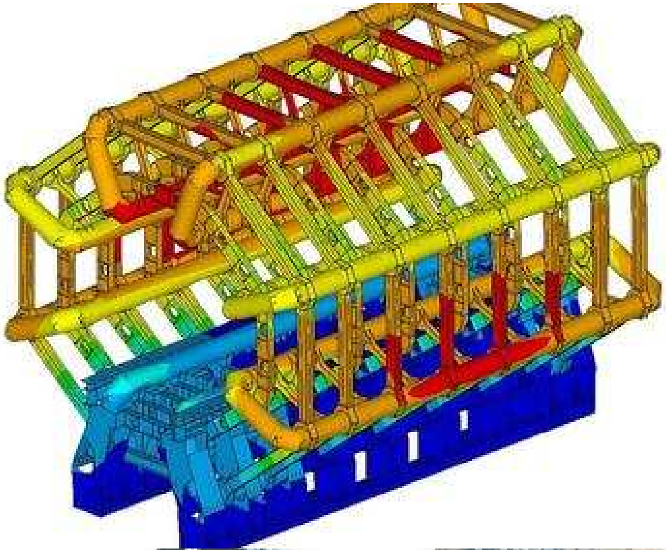
Total weight	**7000 t**
Overall diameter	**25 m**
Barrel toroid length	**26 m**
End-cap end-wall chamber span	**46 m**
Magnetic field	**2 Tesla**

Compact Muon Solenoid

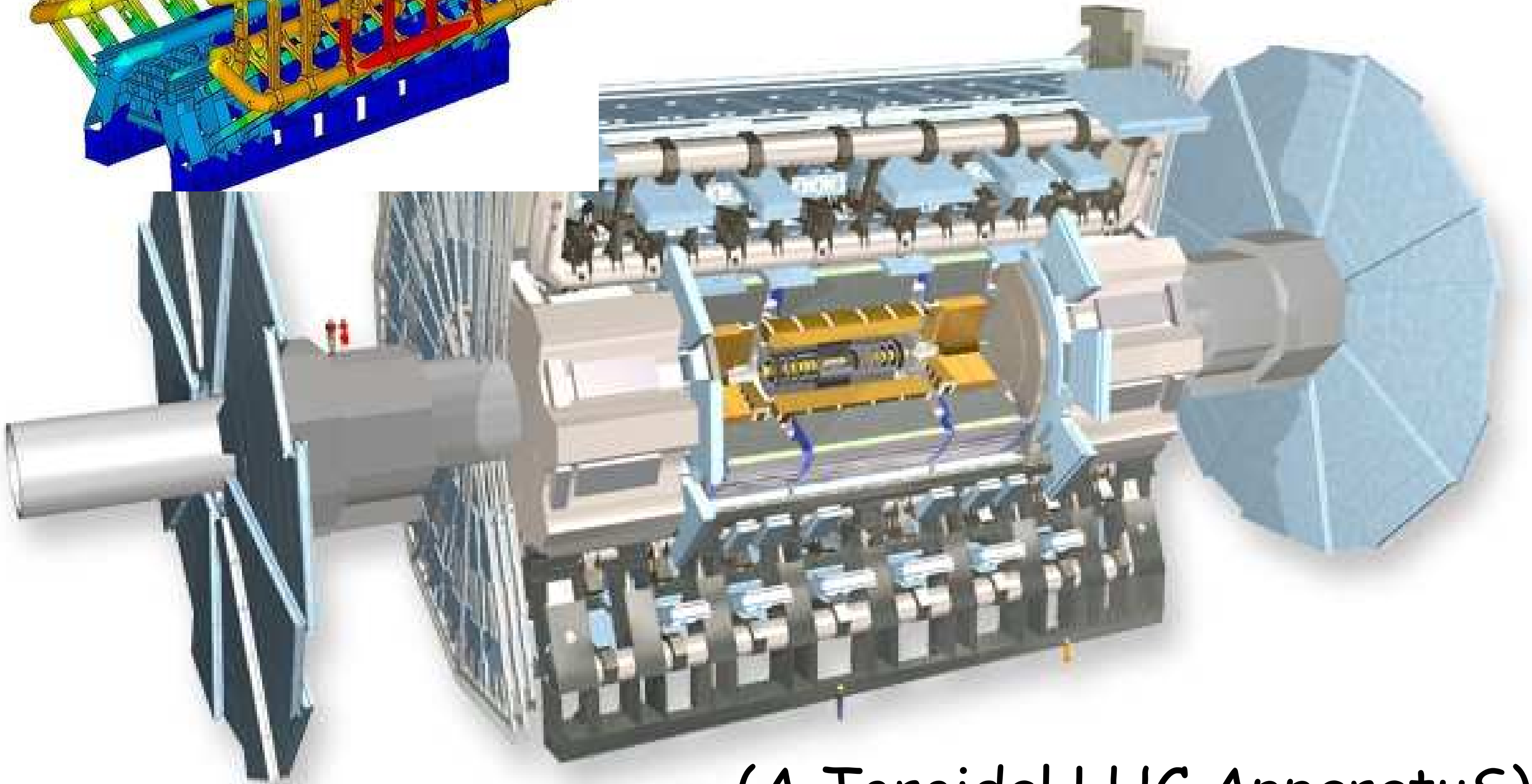


Total weight	**12 500 t**
Overall diameter	**15.00 m**
Overall length	**21.6 m**
Magnetic field	**4 Tesla**

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



ATLAS



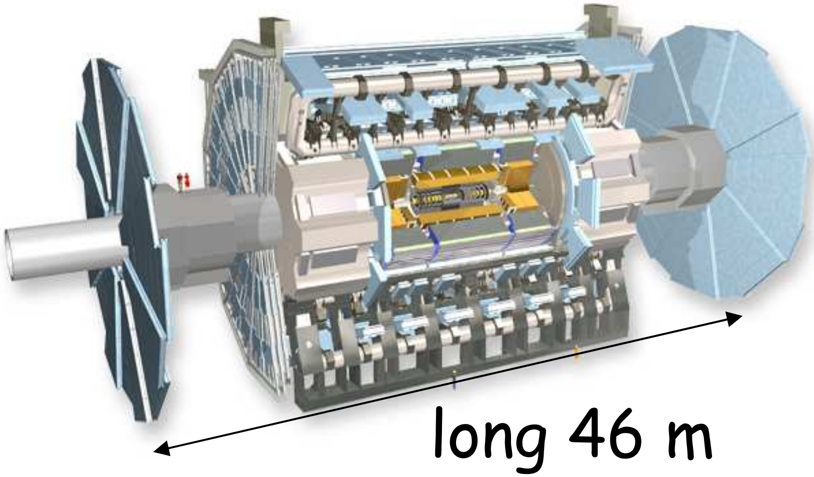
(A Toroidal LHC ApparatuS)

May 2008

ATLAS

Largest volume particle detector ever constructed!

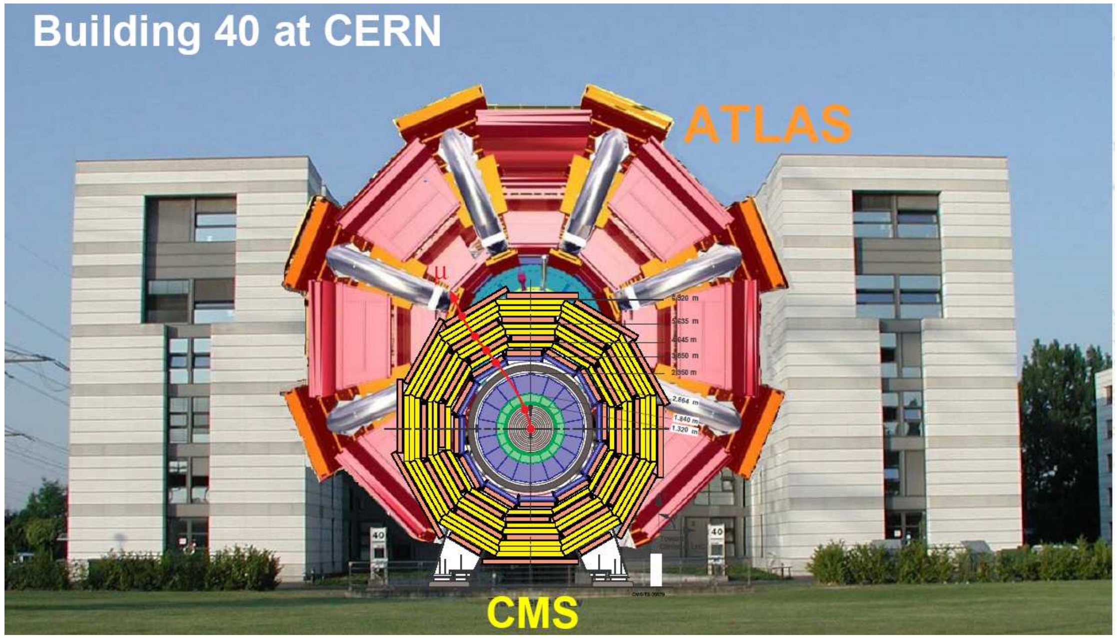
Overall diameter 25 m



ATLAS is half the size of Notre Dame Cathedral

Detectors

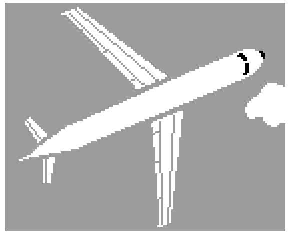
6 storeys high

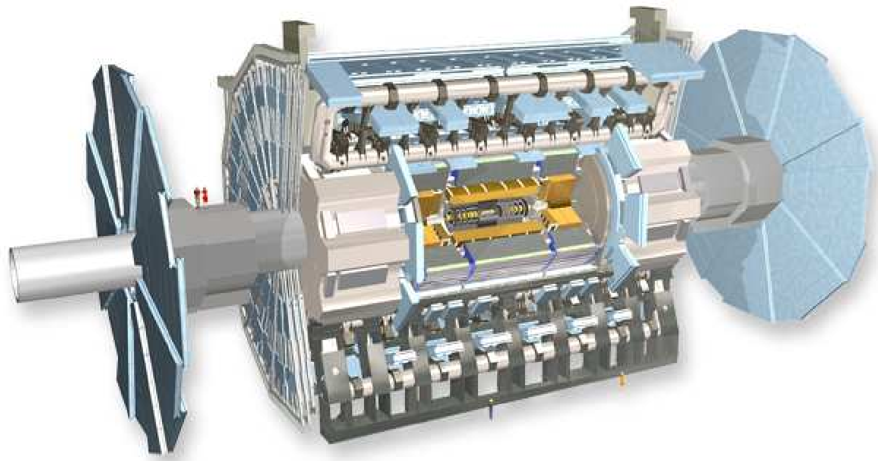


ATLAS

Total weight: 7000 tonnes

= 100 jets (empty)

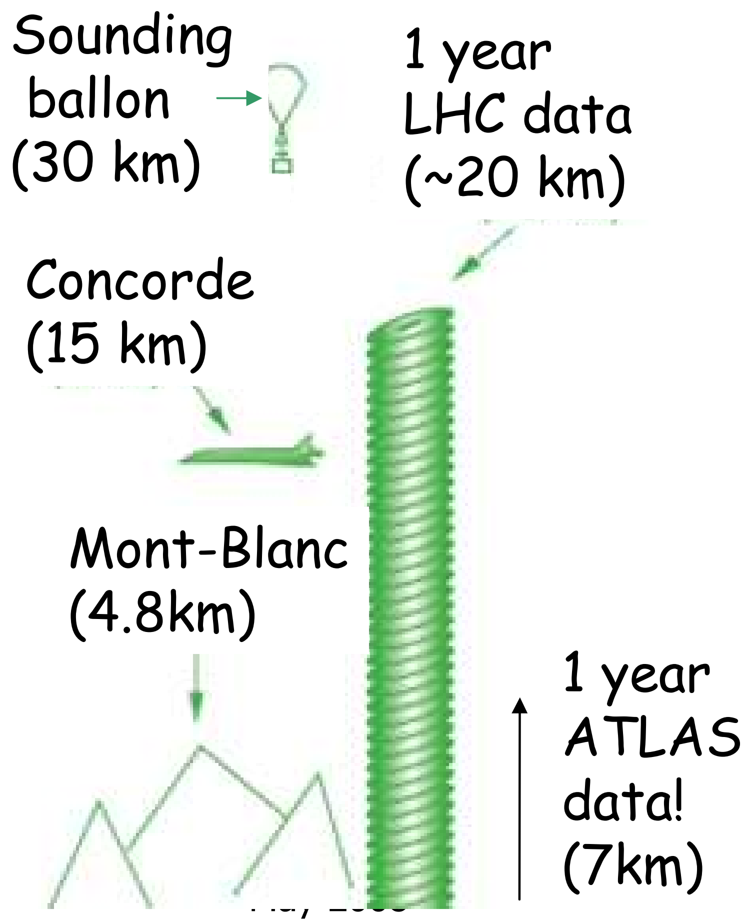




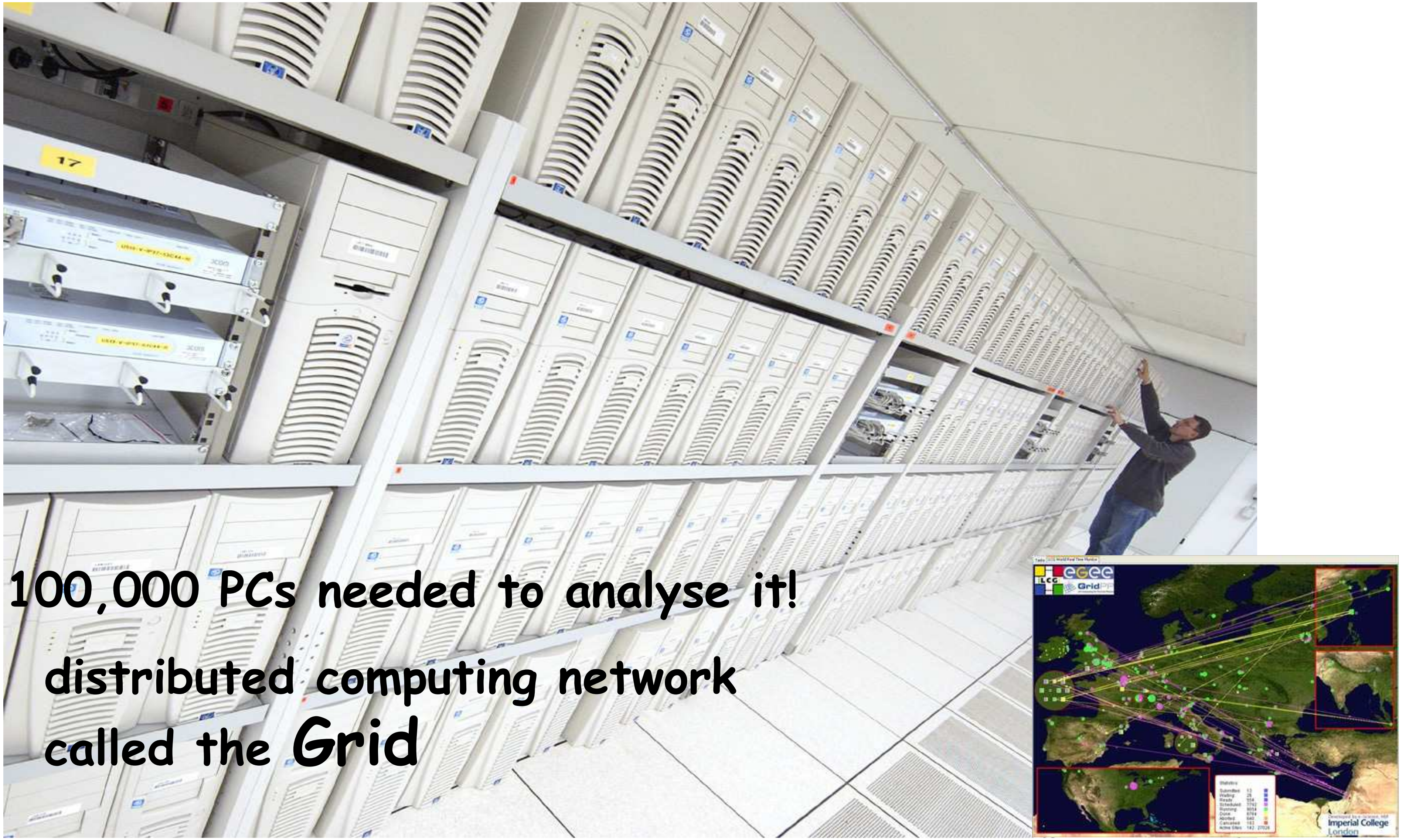
Data

In 1 year ATLAS will record 3200 Terabytes of data

equivalent to: 7 km of stacked up CDROMs !



The Computing Challenge



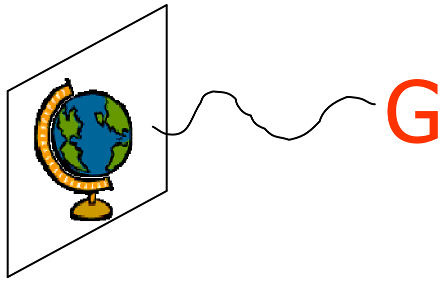
100,000 PCs needed to analyse it!

distributed computing network
called the **Grid**

ADD Model

Arkani-Hamed, **D**imopoulos, **D**vali, Phys Lett B429 (98), Nuc.Phys.B544(1999)

(Many) Large flat Extra-Dimensions (LED),
could be as large as a few μm



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

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

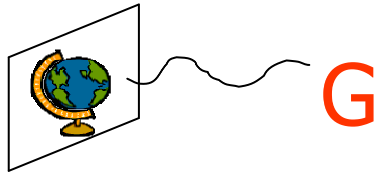
For $M_{Pl} \sim 10^{19}$ GeV and $M_{Pl(4+\delta)} \sim M_{EW} \rightarrow$ $R \sim 10^{32/\delta} \times 10^{-17}$ cm

Present Constraints on the ADD Model

Royal Holloway University of London

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

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



- $\delta=1 \rightarrow R \sim 10^{13}$ 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

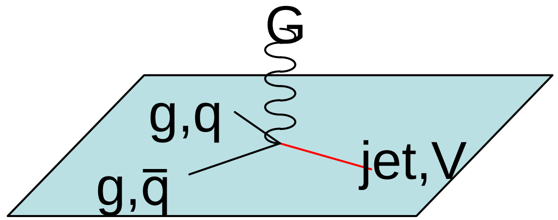
*Cullen, Perelstein
Phys. Rev. Lett 83,268 (1999)

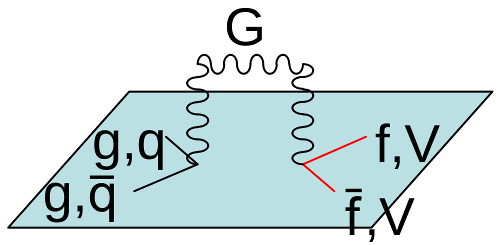
ADD Collider Signatures

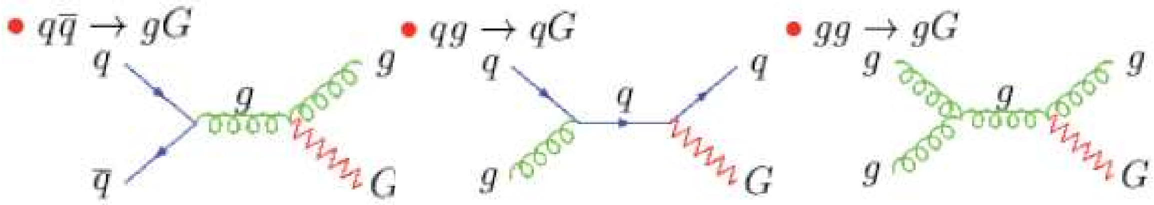
➢**Real Graviton emission** in association with a vector-boson

Signature: jets + missing E_T, V+missing E_T

σ depends on the number of ED







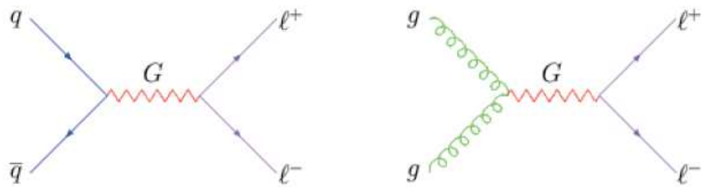
➢**Virtual Graviton exchange**

Signature:

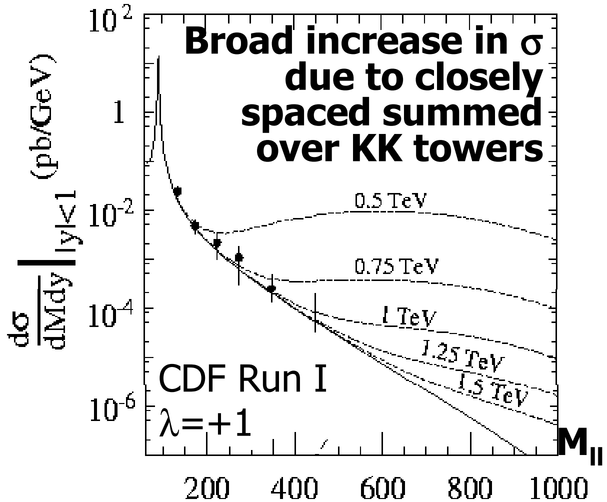
deviations in σ and asymmetries of SM processes

e.g. $q\bar{q} \to l^+l^-$, $\gamma\gamma$ & new processes e.g. $gg \to l^+l^-$

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

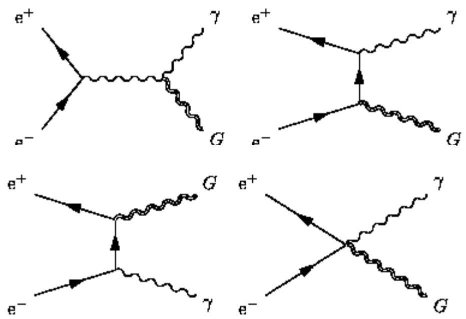


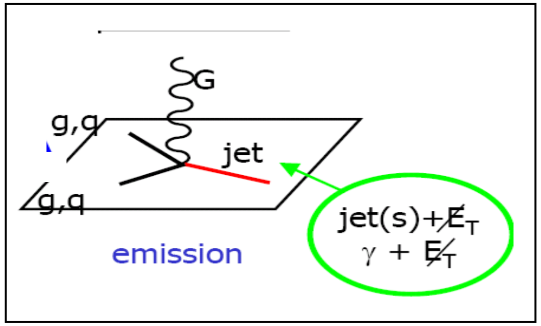
Excess above di-lepton continuum

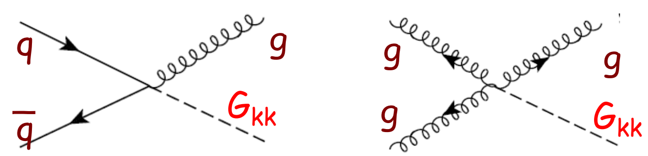


Present ADD Emission Limits

LEP and Tevatron results are complementary

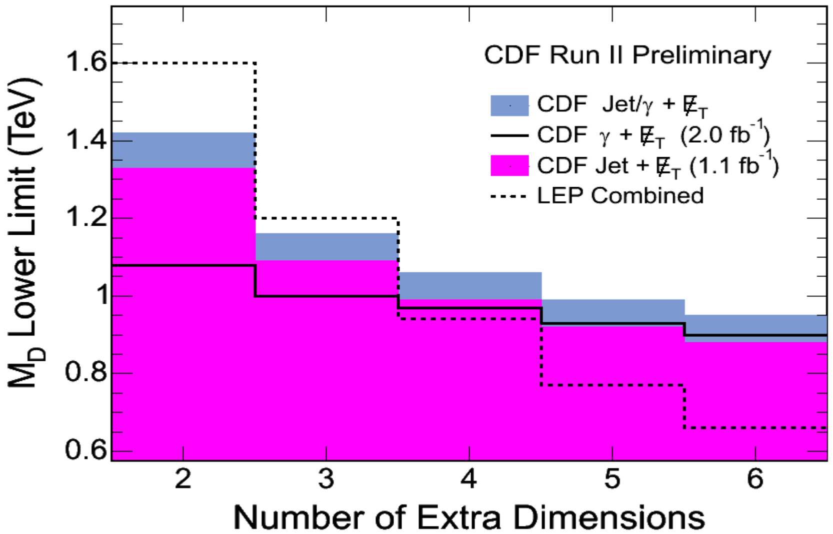






For n>4: CDF combined limits best

For n<4: LEP limits best γ+ME_T



CDF RunII Preliminary, Jet/γ+$\not{E}_T$		
N LED	σ^{95}_{obs} fb	M_D^{obs} GeV
2	26.3	1420
3	38.7	1160
4	46.9	1060
5	52.7	990
6	56.7	950

Tevatron ADD Exchange Limits

Both D0 and CDF have observed no significant excess

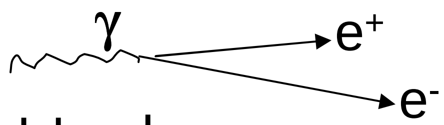
95% CL lower limits on fundamental Planck scale (M_s) in TeV, using different formalisms:

most stringent collider limits on LED to date!

	GRW	HLZ for n=						Hewett
		2	3	4	5	6	7	λ=+1/-1
D0 Run II: $\mu\mu$	1.09	1.00	1.29	1.09	0.98	0.91	0.86	0.97/0.95
D0 Run II: ee+$\gamma\gamma$	1.36	1.56	1.61	1.36	1.23	1.14	1.08	1.22/1.10
D0 Run I+II: ee+$\gamma\gamma$	1.43	1.61	1.70	1.43	1.29	1.20	1.14	1.28/NA
CDF Run II: ee 200pb^{-1}	1.11		1.32	1.11	1.00	0.93	0.88	0.96/0.99

D0 perform a 2D search in invariant mass & angular distribution

And to maximise reconstruction efficiency they perform combined ee+$\gamma\gamma$ (diEM) search: reduces inefficiencies from



- γ ID requires no track, but γ converts ($\rightarrow$ee)
- e ID requires a track, but loose track due to imperfect track reconstruction/crack

Present Constraints on the ADD Model

Royal Holloway University of London

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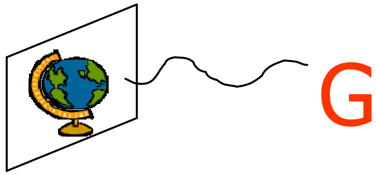

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In particular graviton emission from Supernova 1987a* implies M_D>50 TeV
Closest allowed $M_{Pl(4+n)}$ value for $\delta=2$ is ~30 TeV, out of reach at LHC

- 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 Discovery Limit: γ+G Emission

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

J. Weng et al. CMS NOTE 2006/129

- $\gamma G \Rightarrow$ 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
- Signals generated with PYTHIA (compared to SHERPA)
  Bkgds: PYTHIA and compared to SHERPA/CompHEP/Madgraph (B)
  Using CTEQ6L
- Full simulation & reconstruction
- Theoretical uncert.

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}

Not considered by CMS analysis: Cosmic Rays at rate of 11 HZ: main background at CDF, also beam halo muons for p_T> 400 GeV rate 1 HZ

ADD Discovery Limit: γ+G Emission

ATLAS

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

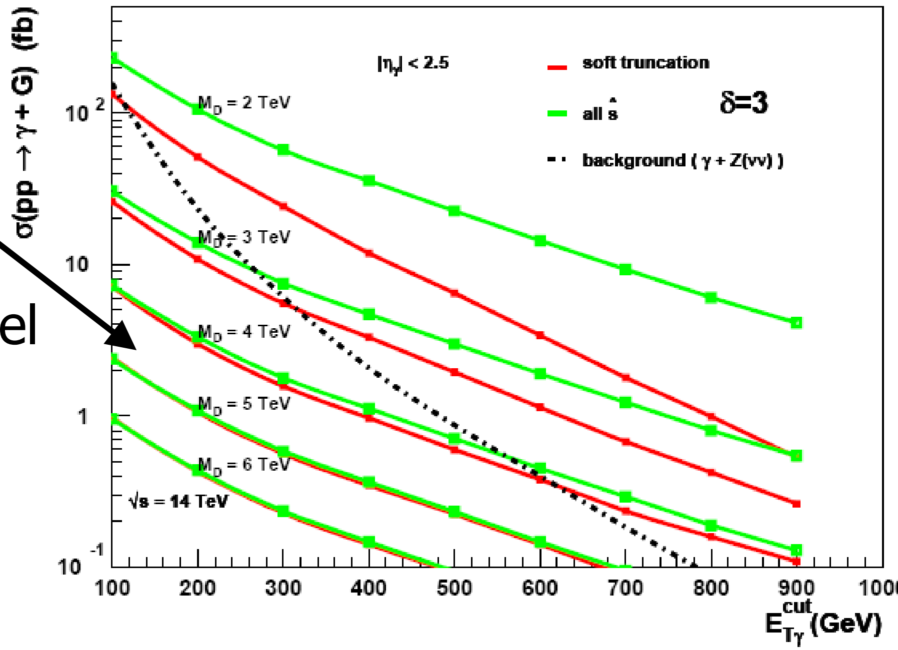
$pp \rightarrow \gamma + G^{KK}$: $q\bar{q} \rightarrow \gamma G^{KK}$

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

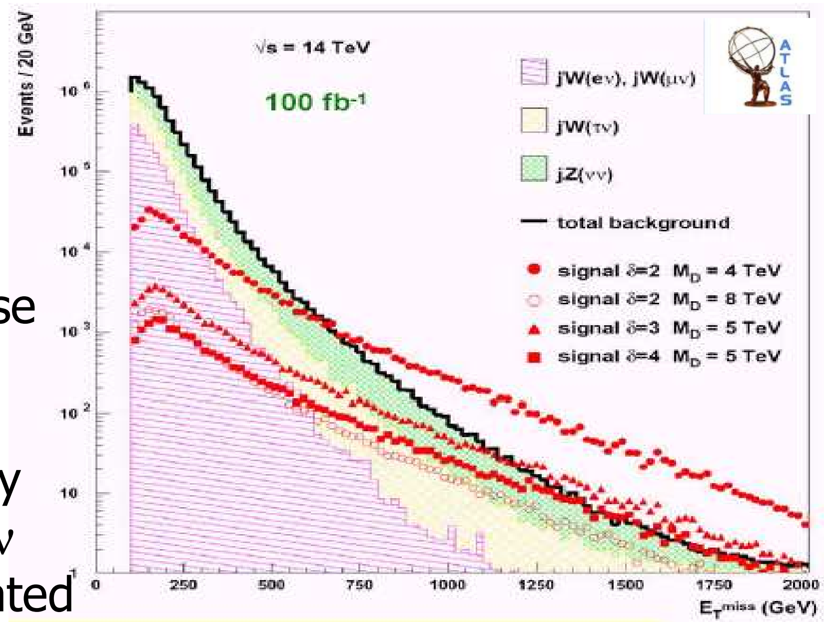
This signature could be used as confirmation after the discovery in the jet channels

ADD Discovery Limit: jet+G Emission

Real graviton production   pp→jet+G^{KK}

gg→gG, qg→qG & qq̄→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.
- ❑ ISAJET with CTEQ3L
- ❑ Fast simulation/reco

Discovery limits

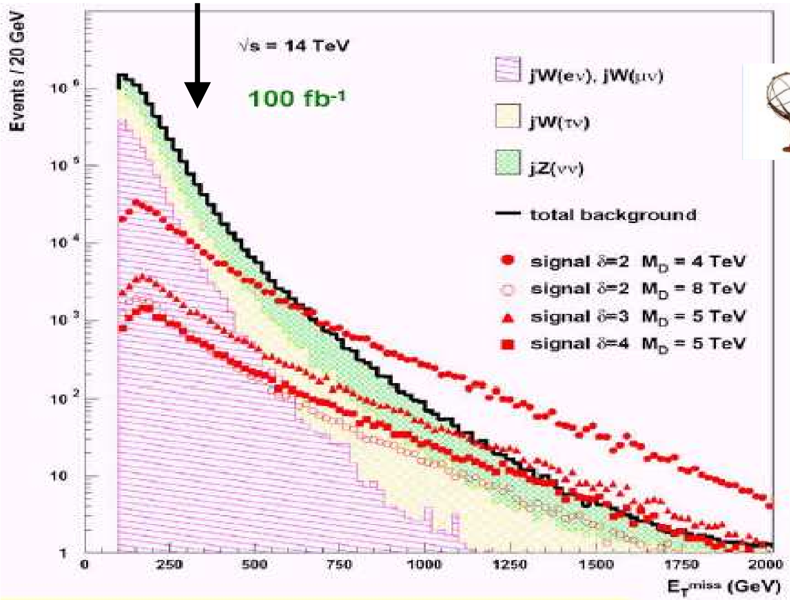
$M_{Pl(4+d)}^{MAX}$(TeV)	δ=2	δ=3	δ=4
LL 30fb^{-1}	7.7	6.2	5.2
HL 100fb^{-1}	9.1	7.0	6.0

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

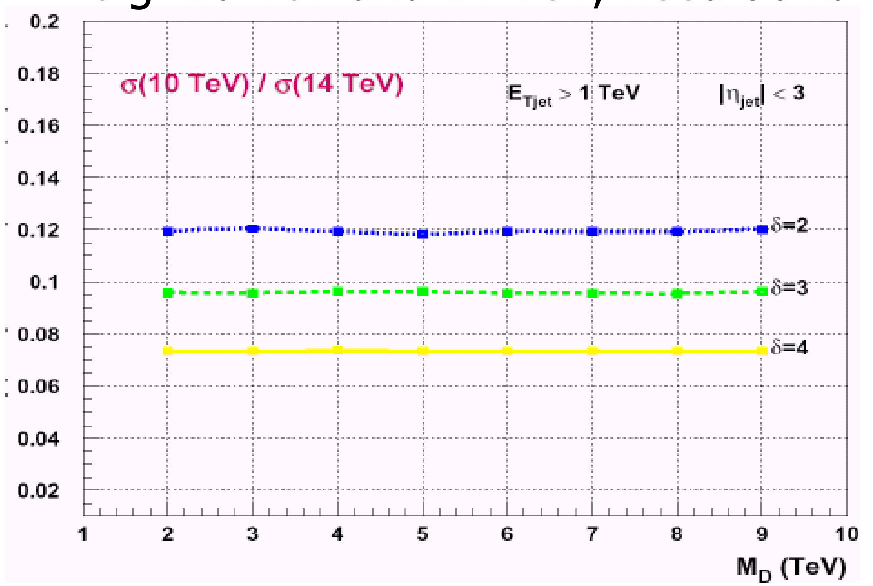
Measuring $\sigma(pp \to jet+G^{KK})$ gives ambiguous results



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

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

Run at two different $\sqrt{s}$
e.g. 10 TeV and 14 TeV, need 50 fb^{-1}



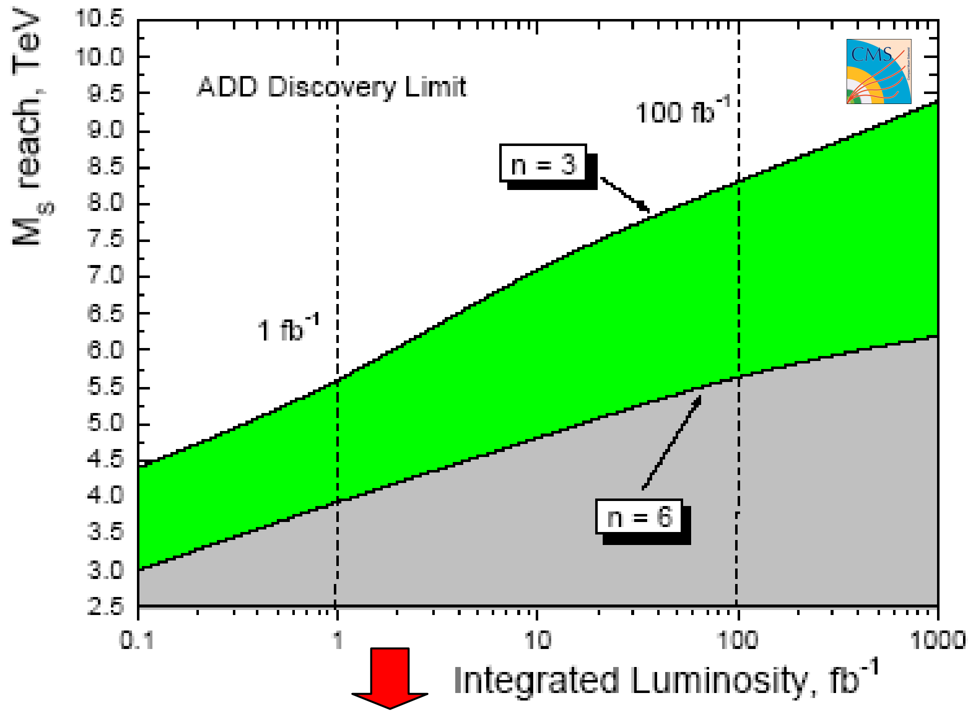
L.Vacavant, I.Hinchcliffe, ATLAS-PHYS 2000-016
J. Phys., G 27 (2001) 1839-50

ADD Discovery Limit: G Exchange

Virtual graviton production

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

- ❑ 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
- ❑ Full (GEANT-4) simulation/reco + L1 + HLT(riger)
- ❑ Theoretical uncert.
- ❑ μ and tracker misalignment, trigger and off-line recon. inefficiency, acceptance due to PDF



Confidence limits for

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

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

ADD Discovery Limit: G Exchange

Virtual graviton production

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
$\gamma\gamma + l^+l^-$	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

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

Fast MC

CMS Confidence 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

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

ADD Discovery Limits Summary

Can use LHC to search for ADD ED with δ<6

δ<=2 ruled out

M_D>1TeV 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)	δ=2	δ=3	δ=4
LL 30fb^{-1}	7.7	6.2	5.2
HL 100fb^{-1}	9.1	7.0	6.0

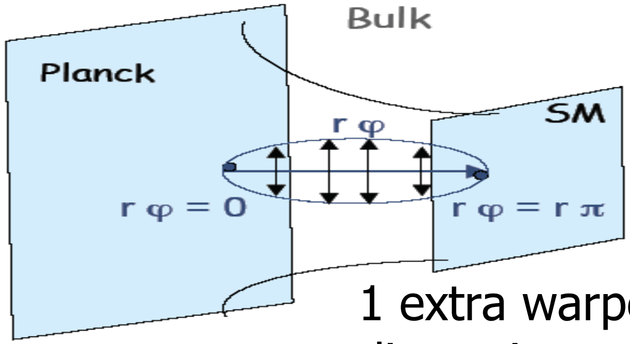
CMS Exchange limits:

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

Experimental Signature for RS Model



1 extra warped dimension

Model parameters:

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

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

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

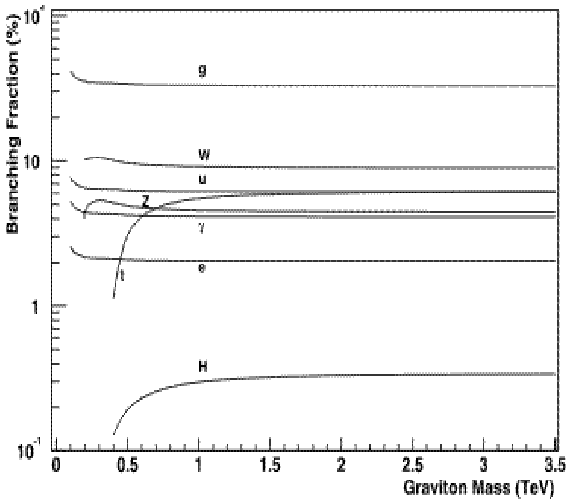
  $\Gamma_1 = \rho m_1 x_1^2 (k/\overline{M}_{pl})^2 \rightarrow$ width

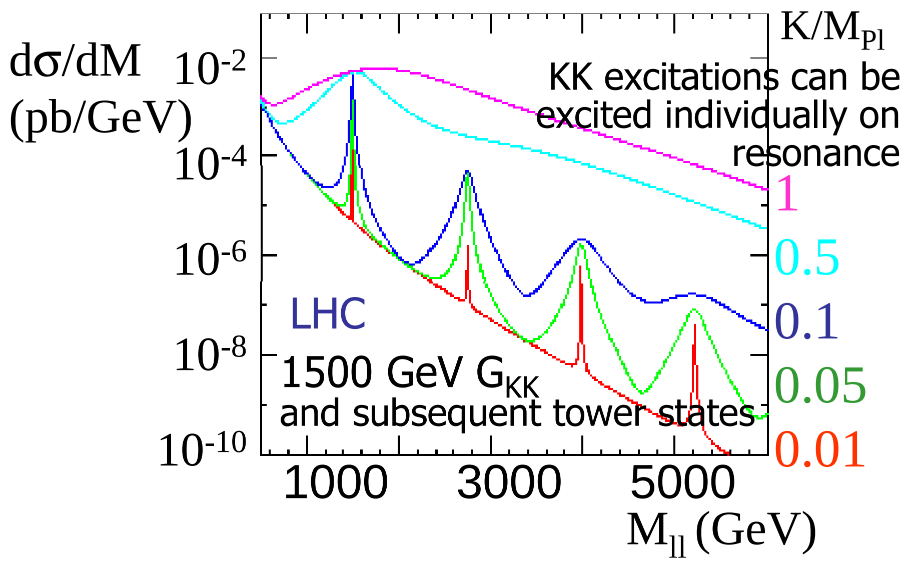
k = curvature, R = compactification radius

Signature:

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

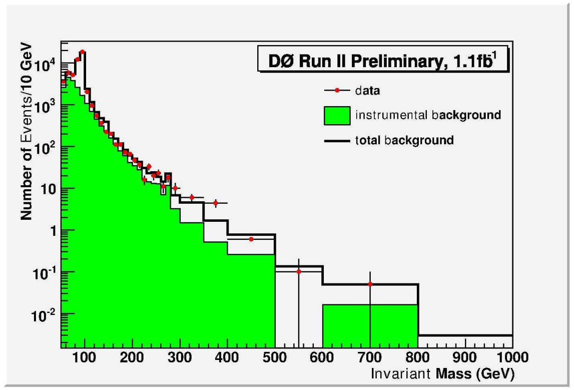
$q\bar{q}, gg \rightarrow G_{KK} \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, jet + jet$



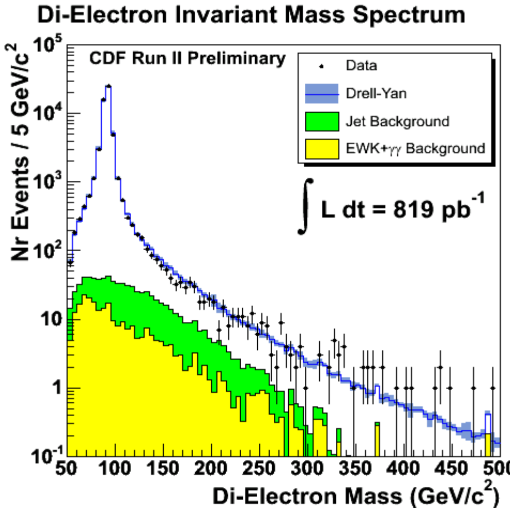


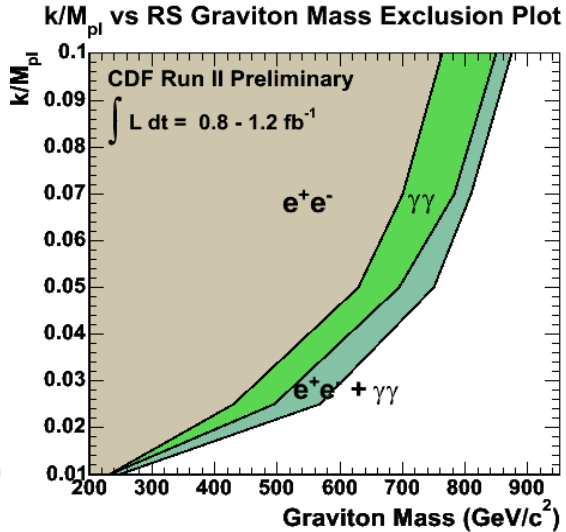
Davoudiasl, Hewett, Rizzo
hep-ph0006041

Present RS Constraints

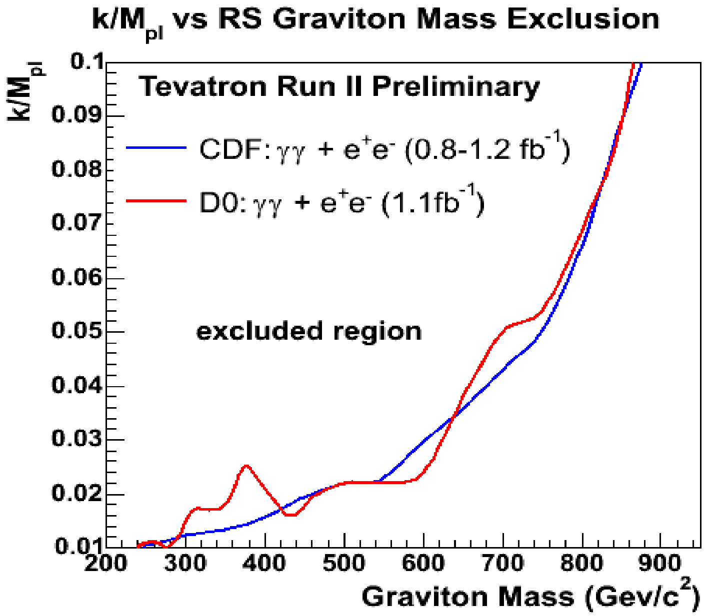


D0 performed combined ee+γγ (diem search)





CDF performed ee & γγ search, then combine



<u>Present Experimental Limits</u>

<u>Theoretical Constraints</u>

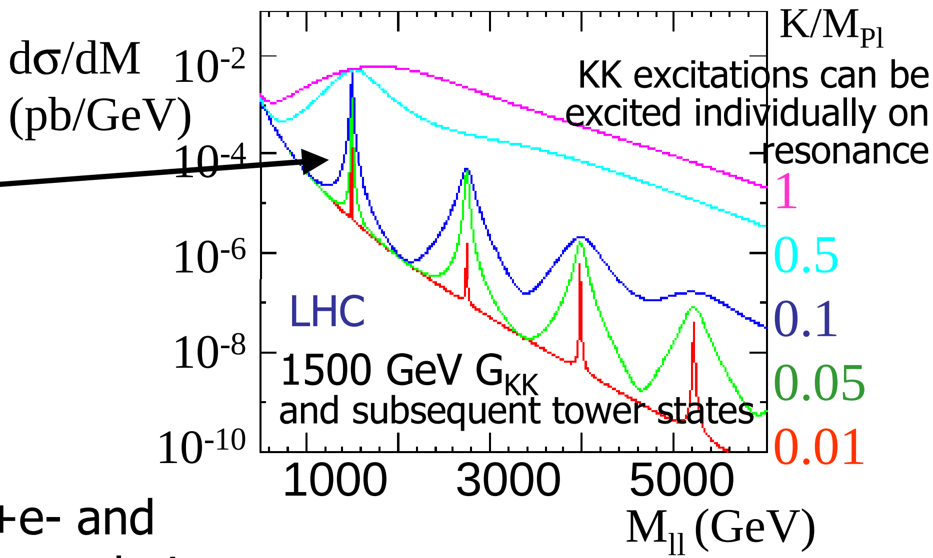
- c>0.1 disfavoured as bulk curvature becomes to large (larger than the 5-dim Planck scale)
- Theoretically preferred Λ_π<10TeV assures no new hierarchy appears between m_{EW} and Λ_π

RS1 Discovery Limit

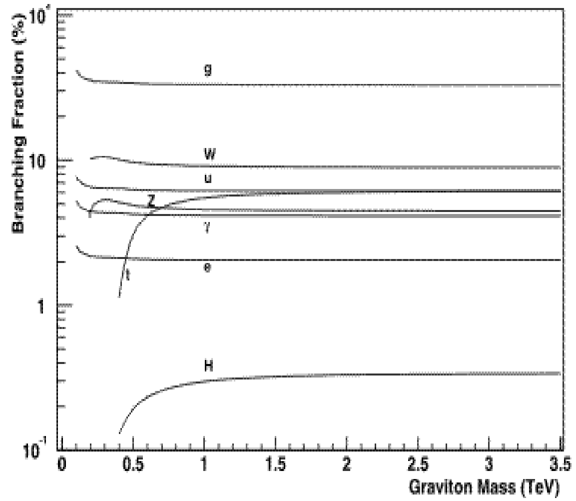
Davoudiasl, Hewett, Rizzo
hep-ph0006041

At the LHC only the 1st excitations are likely to be seen at the LHC, since the other modes are suppressed by the falling parton distribution functions.

Allenach et al, JHEP 9 19 (2000), JHEP 0212 39 (2002)



- Best channels to search in are G(1)→e+e- and G(1)→γγ due to the energy and angular resolutions of the LHC detectors
- G(1)→e+e- best chance of discovery due to relatively small bkdg, from Drell-Yan*



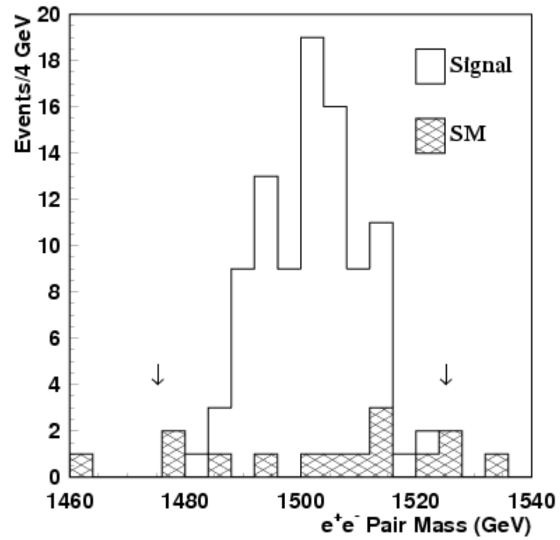
Allenach et al, hep-ph0006114

*Allenach et al, hep-ph0211205

RS1 Discovery Limit

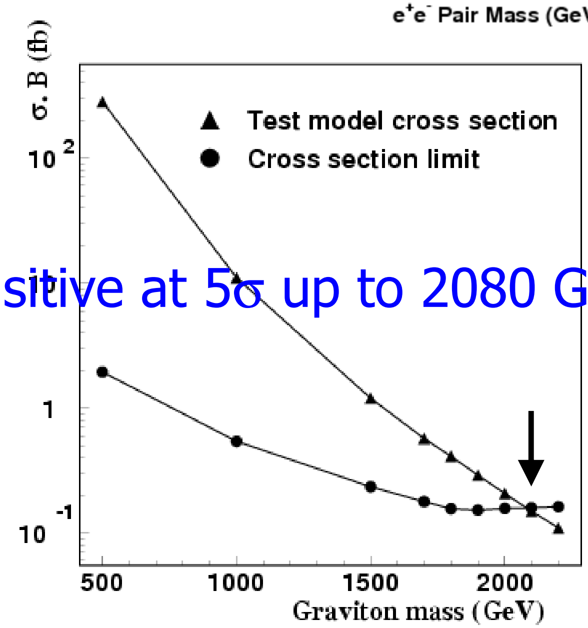
Di-electron

- HERWIG
- Main Bkdg: Drell-Yan
- Model-independent analysis
- RS model with k/M_{Pl}=0.01 as a reference (pessimisitc scenario)
- Fast Simulation



*Reach goes up to 3.5 TeV for c=0.1 for a 20% measurement of the coupling.

Sensitive at 5σ up to 2080 GeV



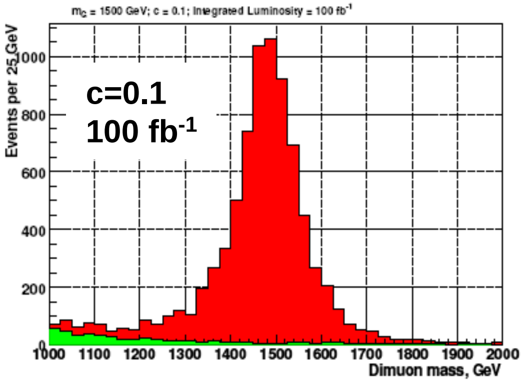
Allenach et al, hep-ph0006114

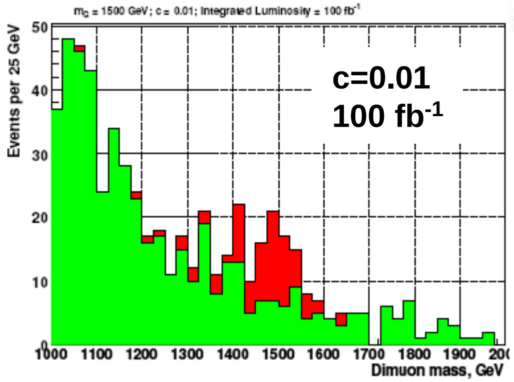
*Allenach et al, hep-ph0211205

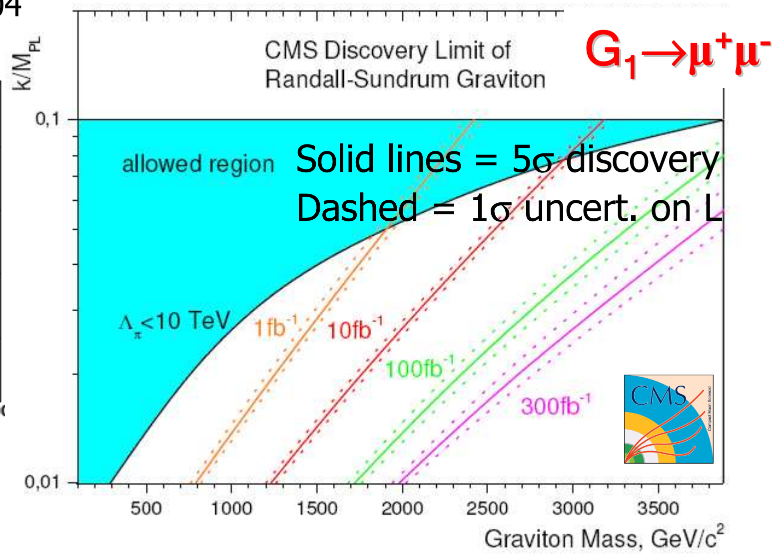
RS1 Discovery Limit

Di-lepton states

I. Belotelov et al.
CMS NOTE 2006/104
CMS PTDR 2006

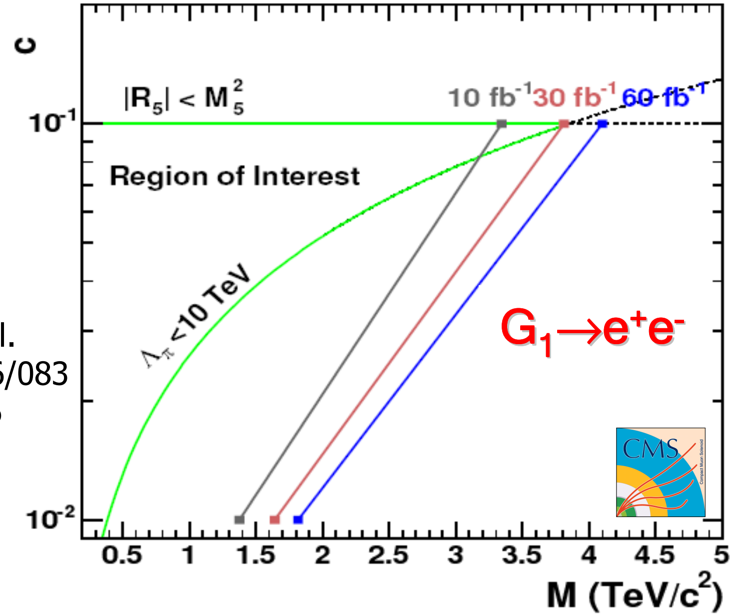






- Two muons/electrons in the final state
- Bckg: Drell-Yan/ZZ/WW/ZW/ttbar
- PYTHIA/CTEQ6L
- LO + K=1.30 both for signal and DY
- Full (GEANT-4) and fast simulation/reco
- Viable L1 + HLT(rigger) cuts
- Theoretical uncert.
- Misalignment, trigger and off-line reco inefficiency, pile-up

B. Clerbaux et al.
CMS NOTE 2006/083
CMS PTDR 2006

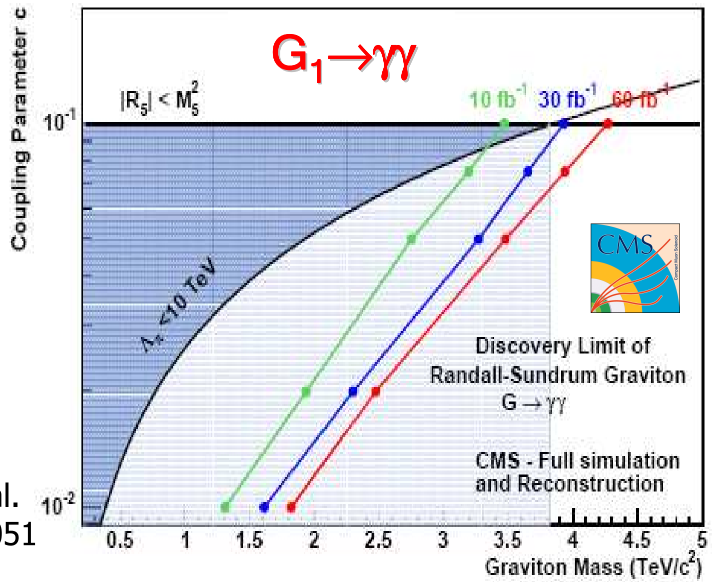


RS1 Discovery Limit

Di-photon states

- Two photons in the final state
- Bckg: prompt di-photons, QCD hadronic jets and gamma+jet events, Drell-Yan e^+e^-
- PYTHIA/CTEQ5L
- LO for signal, LO + K-factors for bckg.
- Fast simulation/reco + a few points with full GEANT-4 MC
- Viable L1 + HLT(rigger) cuts
- Theoretical uncert.
- Preselection inefficiency

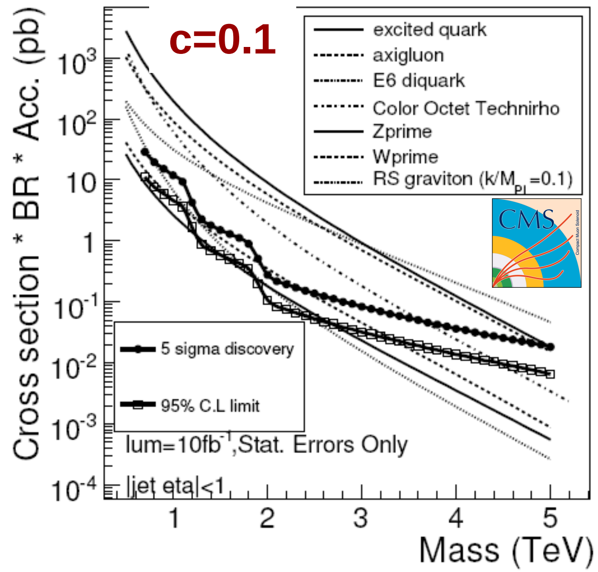
M.-C. Lemaire et al.
CMS NOTE 2006/051
CMS PTDR 2006



Di-jet states

- Bckg: QCD hadronic jets
- L1 + HLT(rigger) cuts

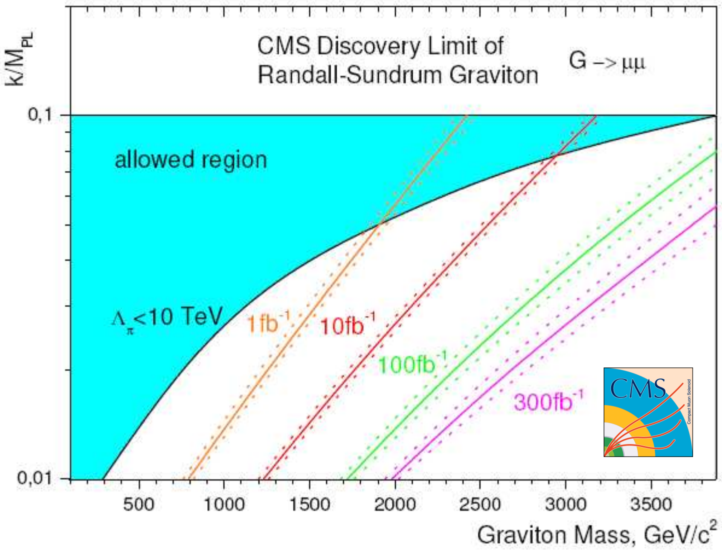
K. Gumus et al.
CMS NOTE 2006/070
CMS PTDR 2006



5σ Discovered Mass: 0.7-0.8 TeV/c^2

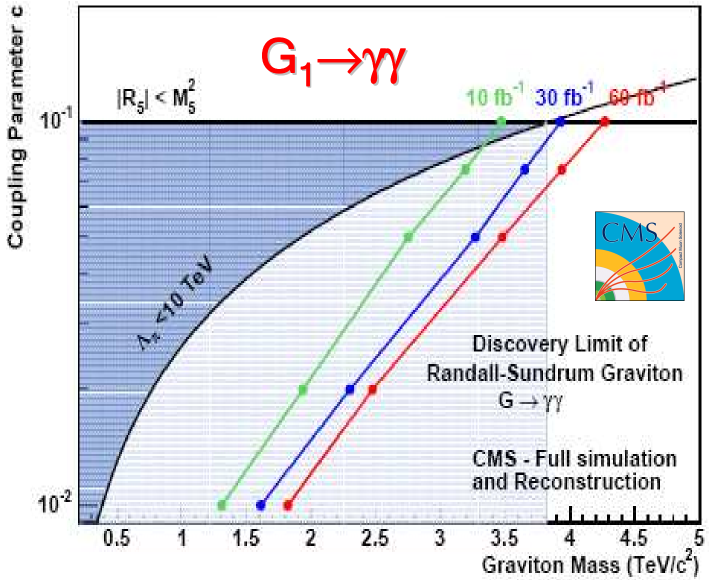
CMS RS Discovery Limits

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

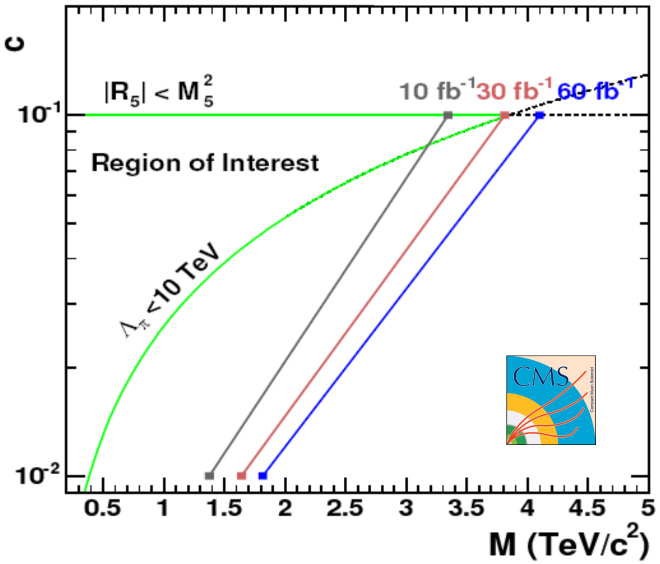


c>0.1 disfavoured as bulk curvature becomes to large (larger than the 5-dim Planck scale)

Theoretically preferred Λ_π<10TeV



$G_1 \to e^+e^-$



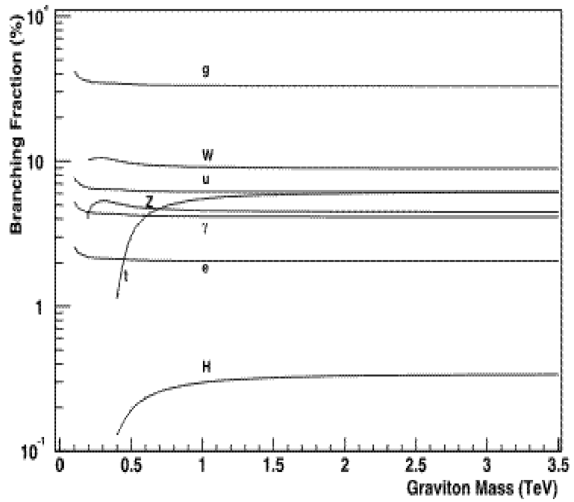
LHC completely covers the region of interest

RS1 Model Parameters

A resonance could be seen in many other channels: $\mu\mu$, $\gamma\gamma$, jj, bbbar, ttbar, WW, ZZ, hence allowing to check universality of its couplings:

Channel	Point m_G, Λ_π (TeV)							
	1,10	1,20	1,30	2,10	2,20	2,30	3,10	3,20
e^+e^-	1.6	3.3	5.3	5.4	11.0	17.1	15.1	30.7
$\mu^+\mu^-$	1.9	4.5	8.2	6.2	15.2	28.2	15.1	32.7
$\gamma\gamma$	1.2	2.9	5.2	3.9	8.8	15.2	10.5	23.0
WW	11.6	44.9	-	38.2	-	-	-	-
ZZ	13.7	50.1	-	52.7	-	-	-	-
jj	19.0	77.0	-	31.0	-	-	59.0	-

Relative precision achievable (in %) for measurements of σ.B in each channel for fixed points in the M_G,Λ_π plane. Points with errors above 100% are not shown.



Also the size (R) of the ED could also be estimated from mass and cross-section measurements.

Allenach et al, hep-ph0211205

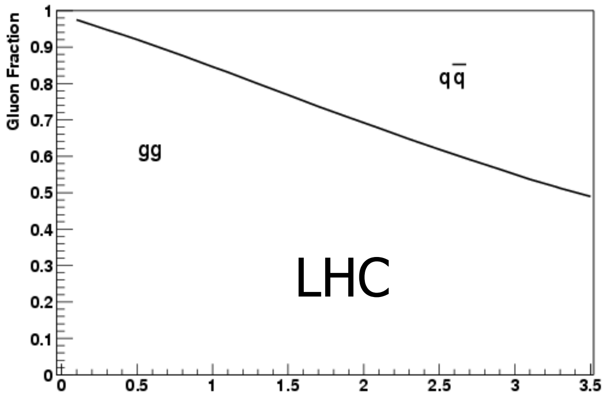
Allenach et al, JHEP 9 19 (2000), JHEP 0212 39 (2002)

RS1 Model Determination

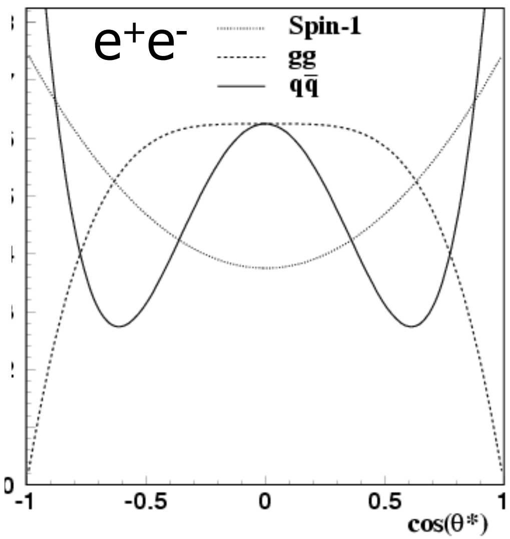
How could a RS G resonance be distinguished from a Z′ resonance?

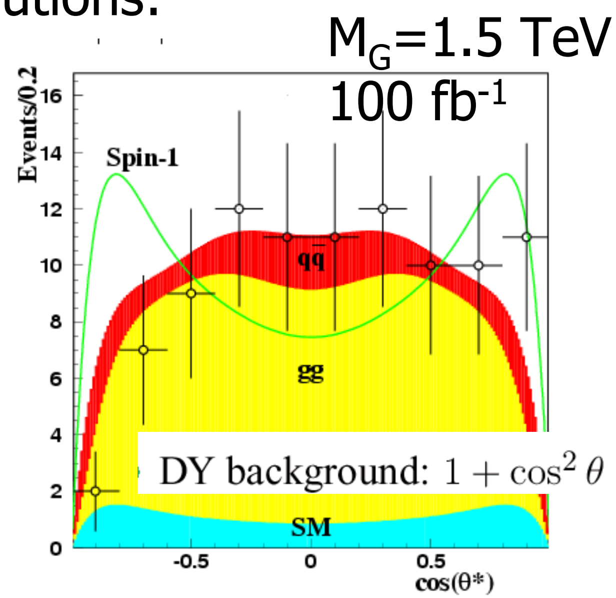
Potentially using Spin information:

G has spin 2: $pp \to G \to ee$ has 2 components: $gg \to G \to ee$ & $q\bar{q} \to G \to ee$: each with different angular distributions:



- $qq \to G \to ff$: $1 - 3\cos^2\theta + 4\cos^4\theta$
- $gg \to G \to ff$: $1 - \cos^4\theta$





Spin-2 could be determined (spin-1 ruled out) with 90% C.L. up to M_G = 1720 GeV with 100 fb^{-1}

Note: acceptance at large pseudo-rapidities is essential for spin discrimination (1.5<|eta|<2.5)

TeV^{-1} Extra Dimension Model

I. Antoniadis, PLB246 377 (1990)

- Multi-dimensional space with orbifolding (5D in the simplest case, n=1)
- The fundamental scale is not planckian: $M_D \sim$ TeV
- Gauge bosons can travel in the bulk
  $\Rightarrow$ Search for KK excitations of Z,γ..

New Parameters

$R=M_C^{-1}$: size of the compact dimension

M_C : corresponding compactification scale

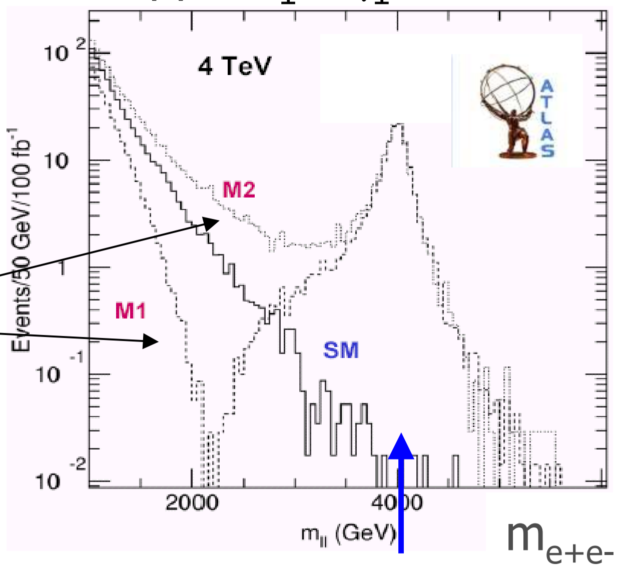
M_0 : mass of the SM gauge boson

Characteristic Signature: KK excitations of the gauge bosons appearing as resonances with masses : $M_n = \sqrt{(M_0^2+n^2/R^2)}$ where (n=1,2,…) & also interference effects!

- Fundamental fermions (quarks/leptons) can be localized at the same (M1) or opposite (M2) points of orbifold
  $\Rightarrow$ destructive (M1) or constructive (M2) interference of the KK excitations with SM model gauge bosons

G. Azuelos, G. Polesello
EPJ Direct 10.1140 (2004)

$pp \rightarrow Z_1^{KK}/\gamma_1^{KK} \rightarrow e^+e^-$



m_{e+e-} (GeV)

$M_n = M_0$

Present Constraints on TeV^{-1} ED

D0 performed the first dedicated experimental search for TeV^{-1} ED at a collider

Search for effects of virtual exchanges of the KK states of the Z and γ

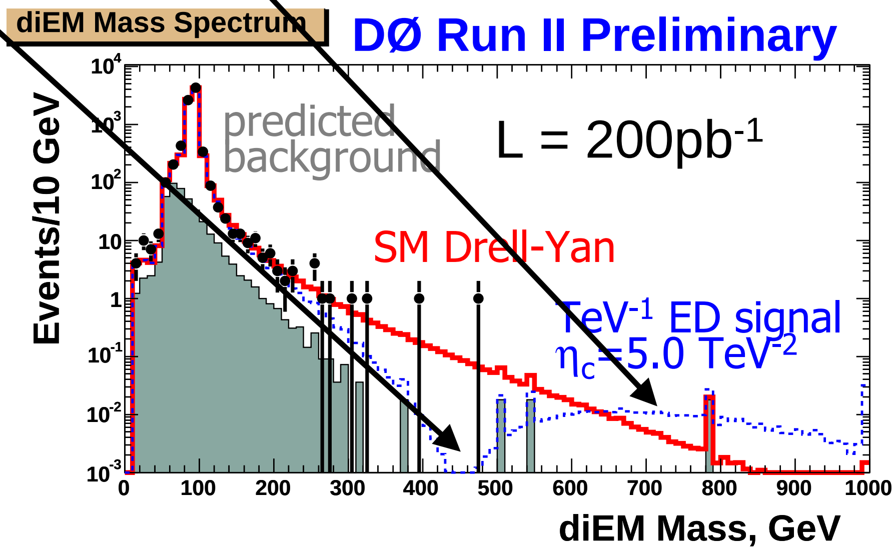
Search Signature: Signal has 2 distinct features:

- enhancement at large masses (like LED)
- negative interference between the 1st KK state of the Z/γ and the SM Drell-Yan in between the Z mass and M_C

diEM search 200 pb^{-1}
Lower limit on the compactification scale of the longitudinal ED:
$M_C > 1.12$ TeV at 95% C.L.

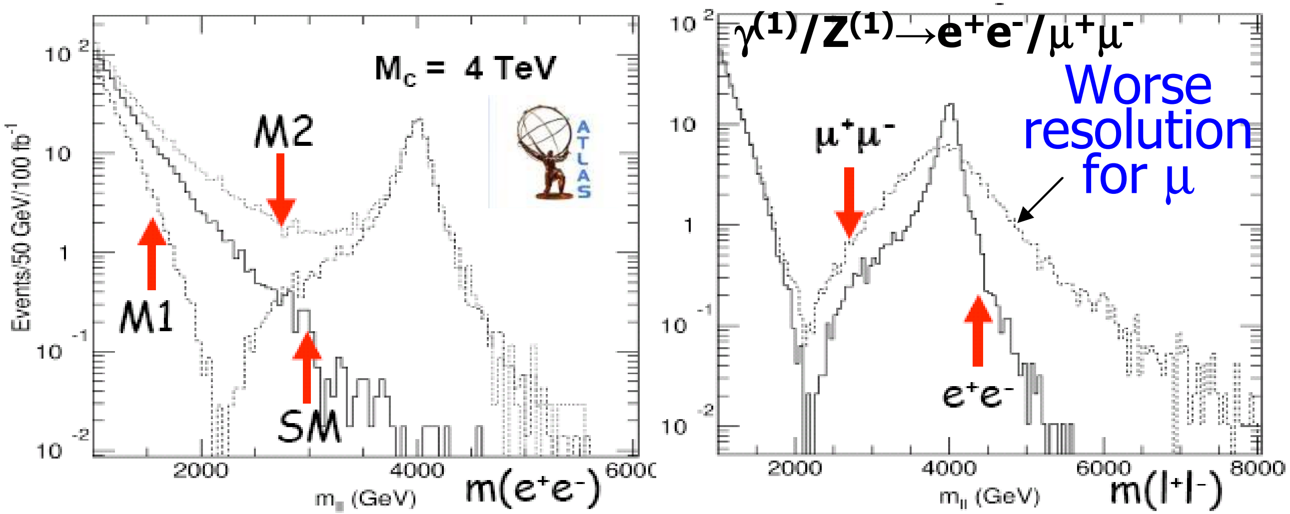
Better Limit: from precision electroweak data $M_C \geq 4$ GeV

World Combined Limit $M_C > 6.8$ TeV at 95% C.L, dominated by LEP2 measurements



TeV^{-1} ED Discovery Limits

<u>ATLAS expectations for e and μ</u>:
2 leptons with Pt>20GeV in $|\eta|<2.5$, $m_{ll}>1$TeV
Reducible backgrounds from $t\bar{t}$, WW, WZ, ZZ
PYTHIA + Fast simu/paramaterized reco + Theor. uncert.



In ee channel experimental resolution is smaller than the natural width of the $Z^{(1)}$, in μμ channel exp. momentum resol. dominates the width

2 TeV e in ATLFAST:

$\Delta E/E \sim 0.7$ %

~20% for μ

Even for lowest resonances of M_C (4 TeV), no events would be observed for the n=2 resonances of Z and γ at 8 TeV ($M_n = \sqrt{(M_0^2+n^2/R^2)}$), which would have been the most striking signature for this kind of model.

G. Azuelos, G. Polesello EPJ Direct 10.1140 (2004)

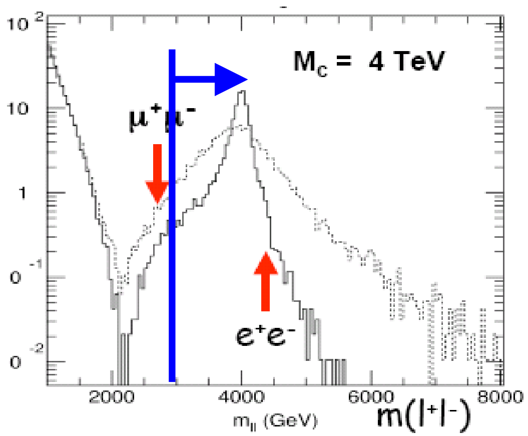
G. Azuelos, G. Polesello (Les Houches 2001 Workshop Proceedings), Physics at TeV Colliders, 210-228 (2001)

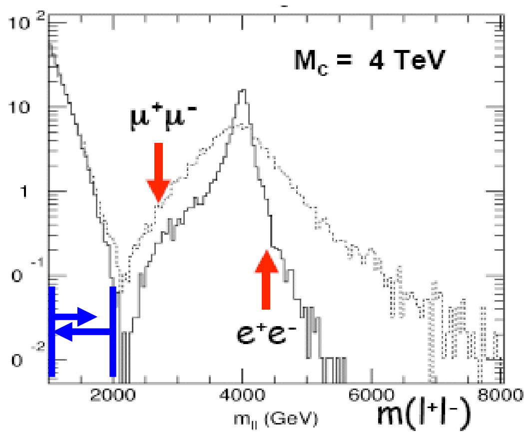
TeV^{-1} ED Discovery Limits

$\gamma^{(1)}/Z^{(1)} \rightarrow e^+e^-/\mu^+\mu^-$

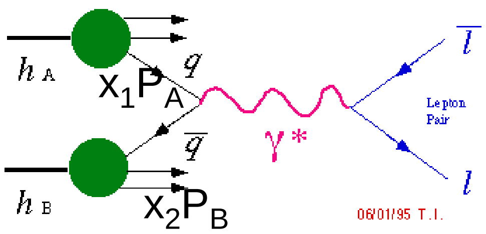
Several Methods have been used to determine the discovery limits for this signature: model independent & dependent

1) Model independent search for the resonance peak– lower mass limit
2) 2 sided search window – search for the interference
3) Model dependent – fit to kinematics of signal





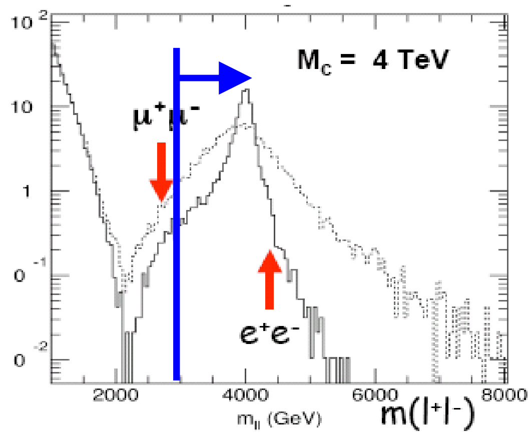
Event kinematics* can be fully defined by the 3 variables



Method 1: Lower Mass Limit

- Model Independent

Simple number counting technique.
Naïve reach estimate for the observation of an increase in the m_{ll} distribution



Choice of lower bound
For each different M_C value:
lower bound on m_{ll} is different:
chosen such to keep as much as possible of the resonance width

M_C mass of lowest lying KK excitation

Number of events expected in **the peak** for L = 100 fb^{-1}

M_{ll}^{lower} Signal Bkdg

M_c(GeV)	Cut (GeV)	$N(e)$	$N(\mu)$	$N_B(e)$	$N_B(\mu)$
4000	3000	172	157	1.85	2.6
5000	4000	23	20	0.15	0.62
5500	4000	9	8	0.15	0.62
6000	4500	3.3	2.8	0.05	0.1
7000	5000	0.45	0.38	0.015	0.05
8000	6000	0.042	0.052	0.0015	0.012

Arbitrary requirement for discovery:
require 10 events to be detected above m_{ll} summed over the lepton flavours, and a statistical significance

$$S = (N-N_B)/\sqrt{N_B} > 5$$

For 100 fb^{-1} using this method, the reach is M_C (R^{-1})<5.8 TeV (ee+μμ)

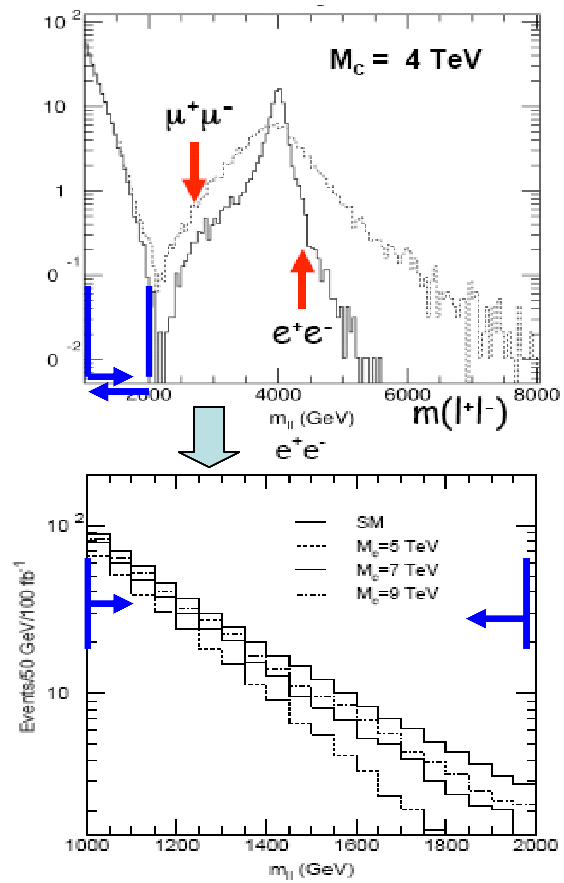
Method 2: Mass Window

1st approach to study the **off-peak** region:

- Evaluate N_S and N_B within a mass range – compare to w.r.t SM

e^+e^- 100 fb^{-1} in mass window
$1000 < m_{ee} < 2000$ GeV

M_c(GeV)	$N(e)$	M_c(GeV)	$N(e)$
SM	498	8000	420
4000	225	8500	428
5000	310	9000	434
5500	339	10000	447
6000	364	11000	458
7000	396	12000	465



- For ee+μμ channels, the ATLAS 5σ reach is ~8 TeV for L=100 fb^{-1} and ~10.5 TeV for 300 fb^{-1}

Better limit than the M_C (R^{-1})<5.8 TeV (ee+μμ) for 100 fb^{-1} using lower bound method 1 to search for the resonance

Method 3: Optimal Reach and Mass Measurement

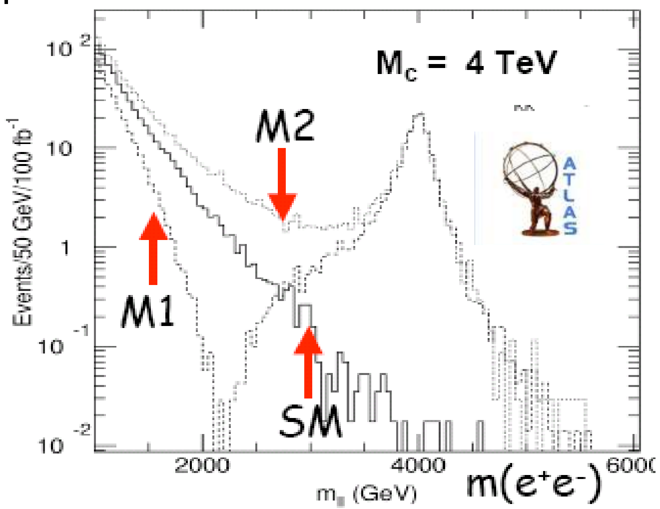
- Model Dependent

Use the full information in the events, not just m_{ll}

Event kinematics* are fully defined by the 3 variables

An optimal measurement of M_C can be obtained by a likelihood fit to the reconstructed distributions for these 3 variables.

$\gamma^{(1)}/Z^{(1)} \rightarrow e^+e^-/\mu^+\mu^-$

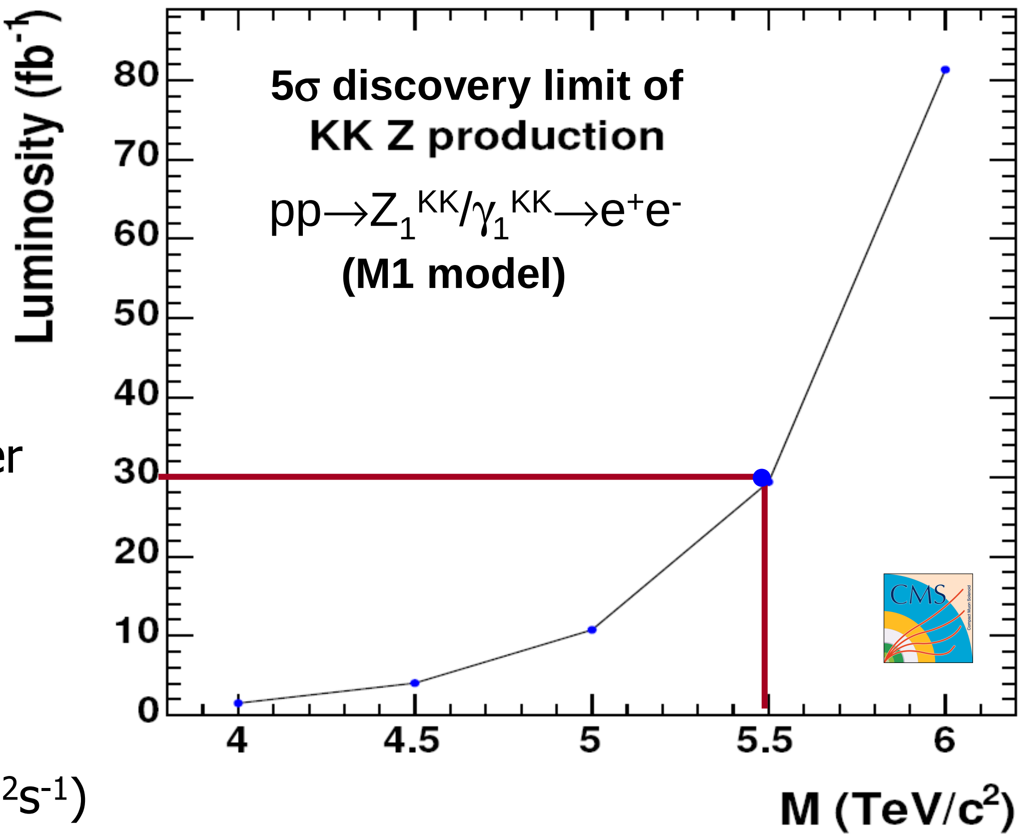


With 300 fb^{-1} can reach 13.5 TeV (ee+$\mu\mu$)

TeV^{-1} ED Discovery Limits

Di-electron states (Z_{KK} decays)

- Two high p_T isolated electrons in the final state
- Bckg: irreducible: Drell-Yan Also ZZ/WW/ZW/ttabr
- Signal and Bkgd: PYTHIA, CTEQ61M, PHOTOS used for inner bremsstrahlung production
- LO + K=1.30 for signals, LO + K-factors for bckg.
- Full (GEANT-4) simulation/reco with pile-up at low lum. ($\sim 10^{33}cm^{-2}s^{-1}$)
- L1 + HLTrigger cuts
- Theoretical uncert.



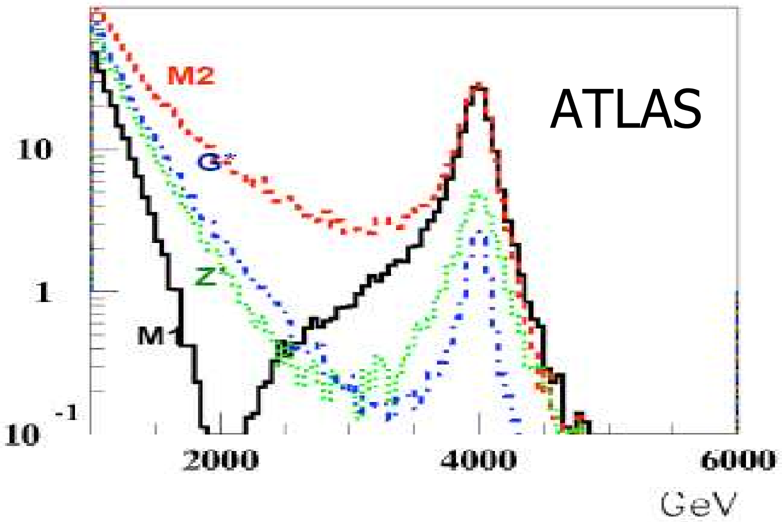
With $\mathcal{L}$=30/80 fb^{-1} CMS will be able to detect a peak in the e^+e^- invar. mass distribution if M_C<5.5/6 TeV.

B. Clerbaux et al.
CMS NOTE 2006/083
CMS PTDR 2006b

Model Discrimination

How could a 4 TeV $Z^{(1)}/\gamma^{(1)}$ resonance be distinguished from a 4 TeV Z′ or Randall-Sundrum Model Graviton ?

4 TeV resonances
$Z^{(1)}$ or Z′ or RS Graviton?



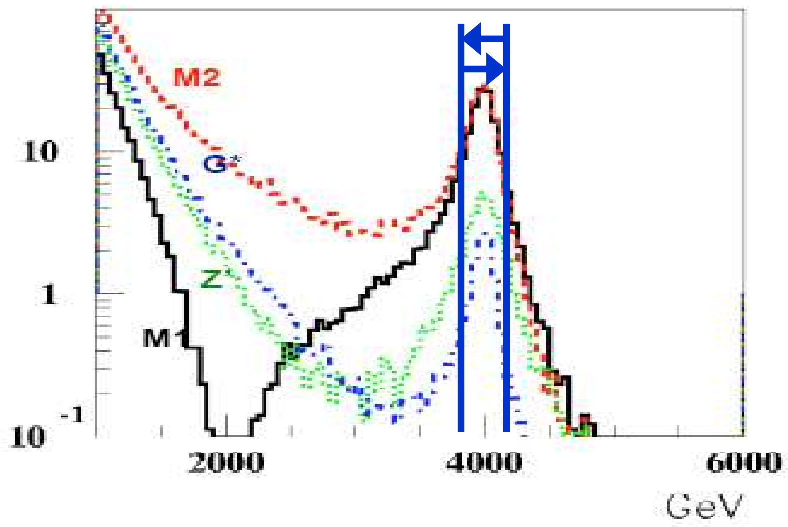
Mass distributions are normalized to a luminosity of 100 fb^{-1}

Look at the angular distributions of the decay products

Note: Z and $Z^{(1)}$: spin-1
G : spin-2

G. Azuelos, G. Polesello
EPJ Direct 10.1140 (2004)

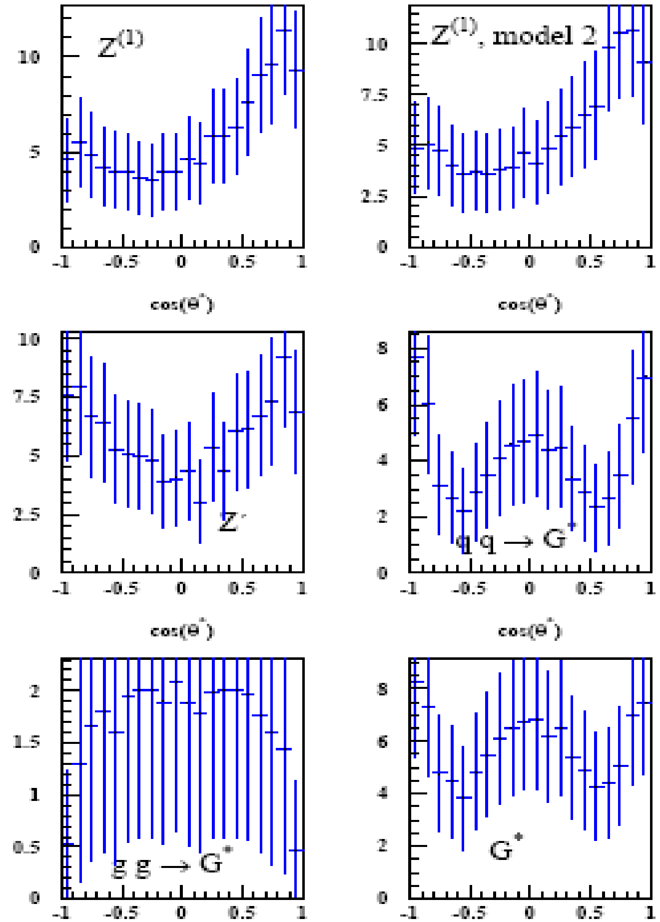
Distinguishing $Z^{(1)}$ from Z', RS G



Select events around the peak of the resonance 3750 GeV < M_{ee} < 4250 GeV

Plot cosine of the angle of the lepton, w.r.t the beam direction, the frame of the decaying resonance.

(+ve direction was defined by the sign of reconstructed momentum in the dilepton system.)



Angular distributions are normalized to 116 events, the number predicted with a luminosity of 100 fb^{-1} for the $Z^{(1)}/\gamma^{(1)}$ case

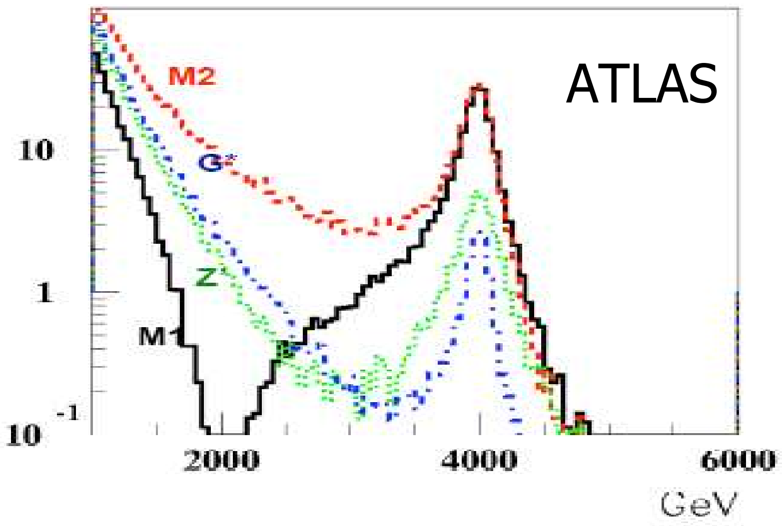
G. Azuelos, G. Polesello EPJ Direct 10.1140 (2004)

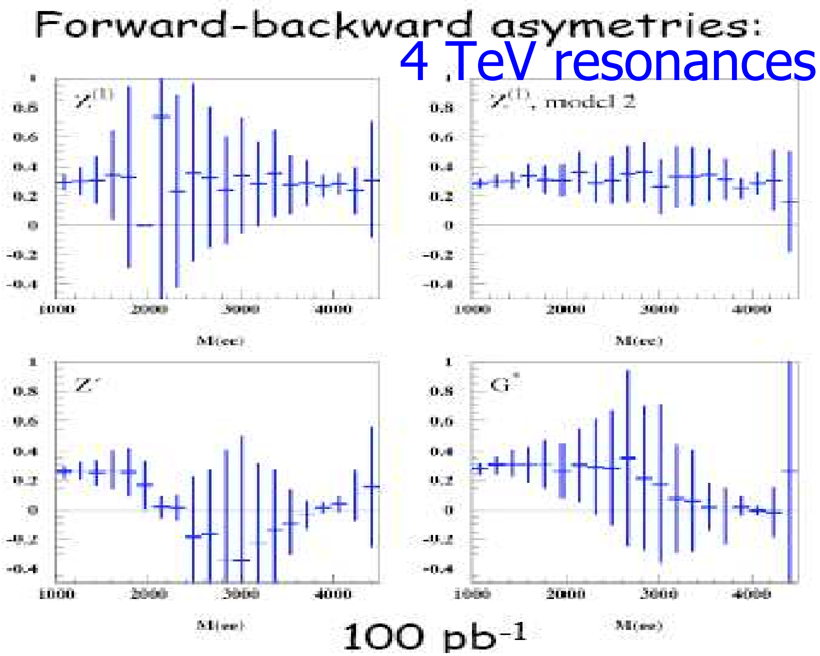
Distinguishing $Z^{(1)}$ from Z', RS G

- Spin 1 $Z^{(1)}$ signal can be distinguished from a spin-2 narrow graviton resonance using the angular distribution of its decay products.
- $Z^{(1)}$ can also be distinguished from a Z' with SM-like couplings using the distribution of the forward-backward asymmetry: due to contributions of the higher lying states, the interference terms and the additional √2 factor in its coupling to SM fermions.

The $Z^{(1)}$ can be discriminated for masses up to about 5 TeV with $L=300fb^{-1}$.

$Z^{(1)}$ or Z' or RS Graviton?





G. Azuelos, G. Polesello
EPJ Direct 10.1140 (2004)

Experimental Uncertainties

Systematic uncertainties associated with the detector measurements

- Luminosity
- Energy miscalibration which affects the performance of e/γ/hadron energy reconstruction
- Drift time and drift velocities uncertainties
- Misalignment affects track and vertex reconstruction efficiency $\rightarrow$ increase of the mass residuals by around 30%
- Magnetic field effects $\rightarrow$ can cause a scale shift in a mass resolution by 5-10%
- Pile-up $\rightarrow$ mass residuals increase by around 0.1-0.2%
- Trigger and reconstruction acceptance uncertainties

$\rightarrow$ Affect the background and signal

- Background uncertainties: variations of the bkgd shape $\rightarrow$ a drop of about 10-15% in the significance values

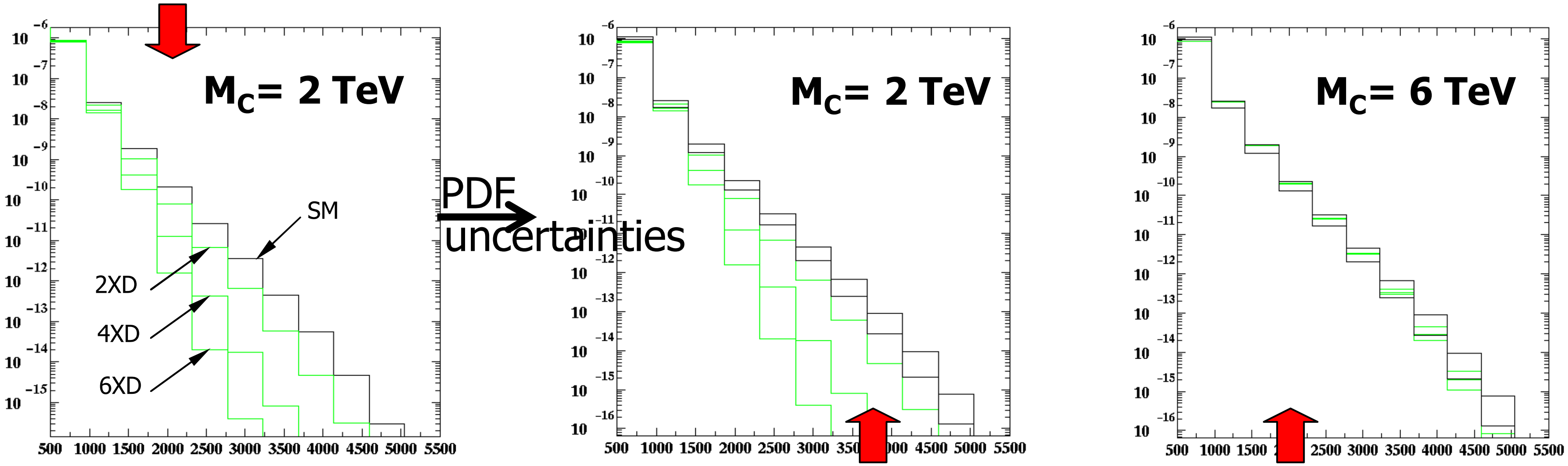
Theoretical Uncertainties

- QCD and EW higher-order corrections (K-factors)
- Parton Distribution Functions (PDF)
- Hard process scale (Q^2)
- Differences between Next-to-Next-to-Leading Order (NNLO), NLO and LO calcalations

$\rightarrow$ affect signal and background magnitudes,
efficiency of the selection cuts,
significance computation…

PDF Impact on Sensitivity to ED

- Extra dimensions affect the di-jet cross section through the running of α_s.
  $\rightarrow$ So could potentially use σ deviation to detect ED
  Parameterised by number of extra dimensions δ and compactification scale M_c.



- PDF uncertainties (mainly due to high-x gluon) give an uncertainty "zone" on the SM cross sections
- This reduces sensitivity to M_C from 5 TeV to 2 (3) TeV for δ= 4, 6 and
  for δ=2 sensitivity is lost (M_C<2 TeV)

LHC Start-up Expectations

Model	Mass reach	Integrated Luminosity (fb^{-1})	Systematic uncertainties
ADD Direct G_{KK}	M_D~ 1.5-1.0 TeV, n = 3-6	1	Theor.
ADD Virtual G_{KK}	M_D~ 4.3 - 3 TeV, n = 3-6 M_D~ 5 - 4 TeV, n = 3-6	0.1 1	Theor.+Exp.
RS1 di-electrons di-photons di-muons di-jets	M_{G1}~1.35- 3.3 TeV, c=0.01-0.1 M_{G1}~1.31- 3.47 TeV, c=0.01-0.1 M_{G1}~0.8- 2.3 TeV, c=0.01-0.1 M_{G1}~0.7- 0.8 TeV, c=0.1	10 10 1 0.1	Theor.+Exp. (only stat. for di-jets)
TeV^{-1} ($Z_{KK}^{(1)}$)	M_{z1} < 5 TeV	1	Theor.

Conclusions

The discovery potential of both experiments makes it possible to investigate if extra dimensions really exist within various ED scenarios at a few TeV scale:

Large Extra-Dimensions (ADD model)
Randall-Sundrum (RS1)
TeV^{-1} Extra dimension Model

Reaches in different channels depend on the performance of detector systems: proper energy, momentum, angular reconstruction for high-energy leptons and jets, Et measurement, b-tagging and identification of prompt photons

New results have been predicted with data of an integrated luminosity$<1\ fb^{-1}$

The End!

Backup slides…

Run Coordination

MANCHESTER 1824

T. Wengler

Atlas Week 07-Apr-08

Operations: recent tests and planning

- Running schedule
- Recent highlights
- Shifts and training
- Control Room layout
- Running efficiency
  - Messages
  - Transition timing

Schedule: March – April

Month	Date	System	Requirements, remarks	Parallel	Shifts
	Week 13 24/3 - 30/3	L1Calo + CTP 3 days	Starting work with Calos when ready		
April	Week 14 31/3 - 6/4	Calos+L1Cal+HLT 1 week		start testing tdaq-01-09	
	Week 15 7/4 - 13/4	Muons 11/4 (WE?)	Available for systems + CTP tests	Decide/install new offline release by 7/4 April 7-10 Tile laser testing → unavailable	
	Week 16 14/4 - 20/4	Muons 14-16/4 Tile 17/18	Available for systems + CTP tests	ID standalone tests w/o CTP No Tile LB for 10 days, EB available	
	Week 17 21/4 - 27/4	TDAQ/HLT week	ID ROSs in use	ID standalone tests w/o CTP; BCM integration?	

Schedule: May

Month	Date	System	Requirements, remarks	Parallel	Shifts
April	Week 18 28/ - 29/4	L1Calo+Calo run?			
May	Week 18 30/4 - 4/5	3 days TRT + 3 Days SCT	Sub-systems: Transition to tdaq-01-09		
	Week 19 5/5 – 11/5	2 days ID combined running including Pixel DAQ	Towards end of week after transition to 01-09	Start of magnet test ~HLT algos available	
May Week 20	12/5-18/5	Calo+L1calo+HLT	-Timing, calo DQ, debugging, high rate, algo tests - Finish with a stable week end run?	Week days: morning expert work; evening calo + central desks WE: 24/7 calos + central desks	
Week 21	19/5-25/5	Muon+L1Mu+HLT	-Same as above - Finish with a stable week end run? with calos?	Week days: morning expert work; evening muon (calo?)+ central desks WE: 24/7 muon (calos?) + central desks	
Week 22	26/5-1/6	ID+DAQ+HLT Beam pipe closure	-Same as above -Dedicated DAQ test after detector testing and before HLT testing	Week days: morning expert work; evening ID (Muon/calo?) + central desks WE: 24/7 ID (muon/calos?) +	

Schedule: June

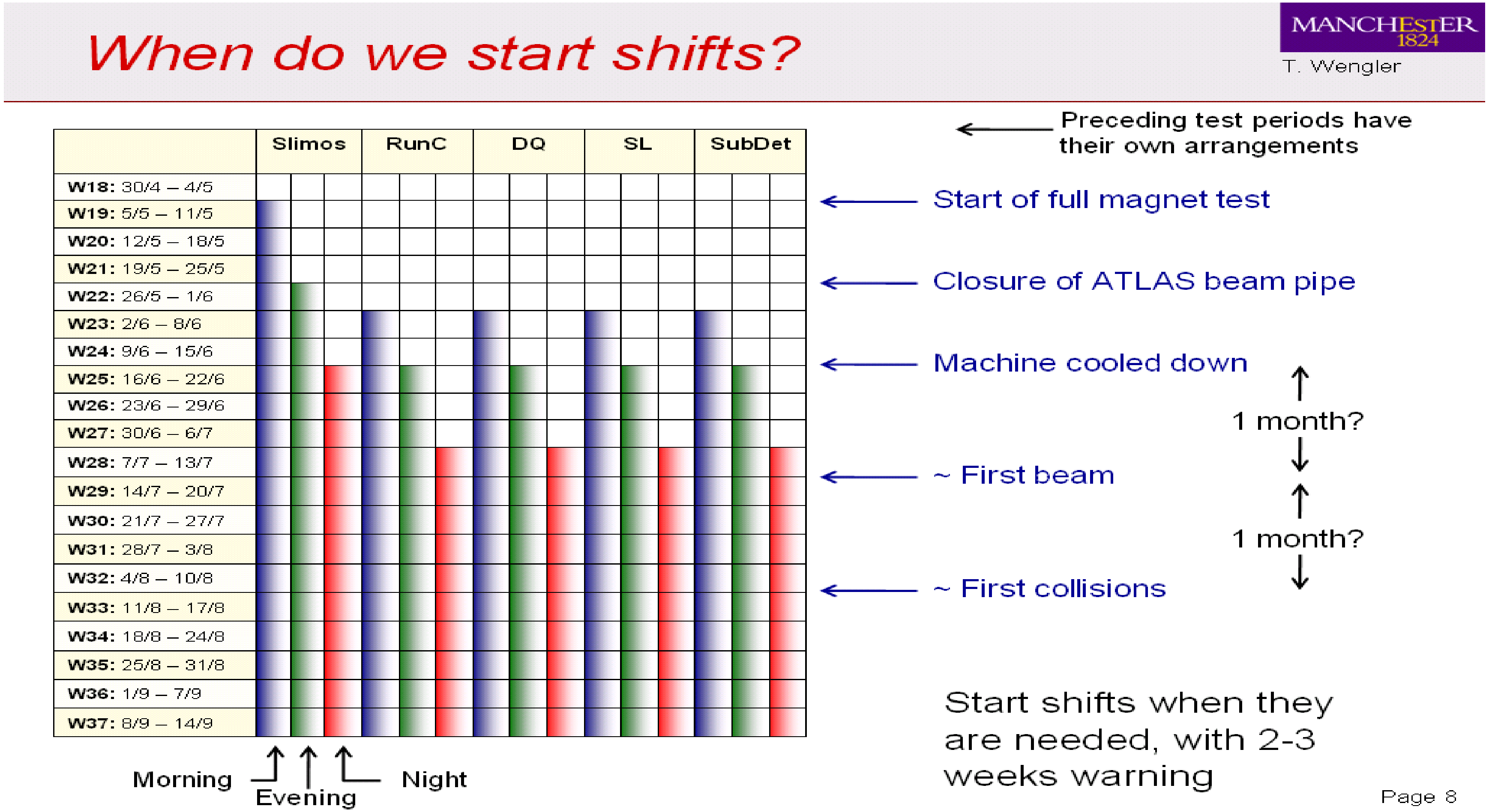
Month	Date	System	Requirements, remarks	Parallel	Shifts
June	Week 23 2/6 – 8/6		No Tier-0 !	Magnet test FDR-2	
	Week 24 9/6 – 15/6			Magnet test	
	Week 25 16/6 – 22/6		LHC cold?	Magnet test	
	Week 26 23/6 – 29/6			Magnet test	
July	Week 27	ATLAS running ?			

→Slides are used for discussion in run meeting

→Master schedule (including interventions) is at: http://cern.ch/atlas-run-schedule

Linked from Operations page, to read: Membership in atlas-gen@cern.ch and NICE username/password

First Collisions?



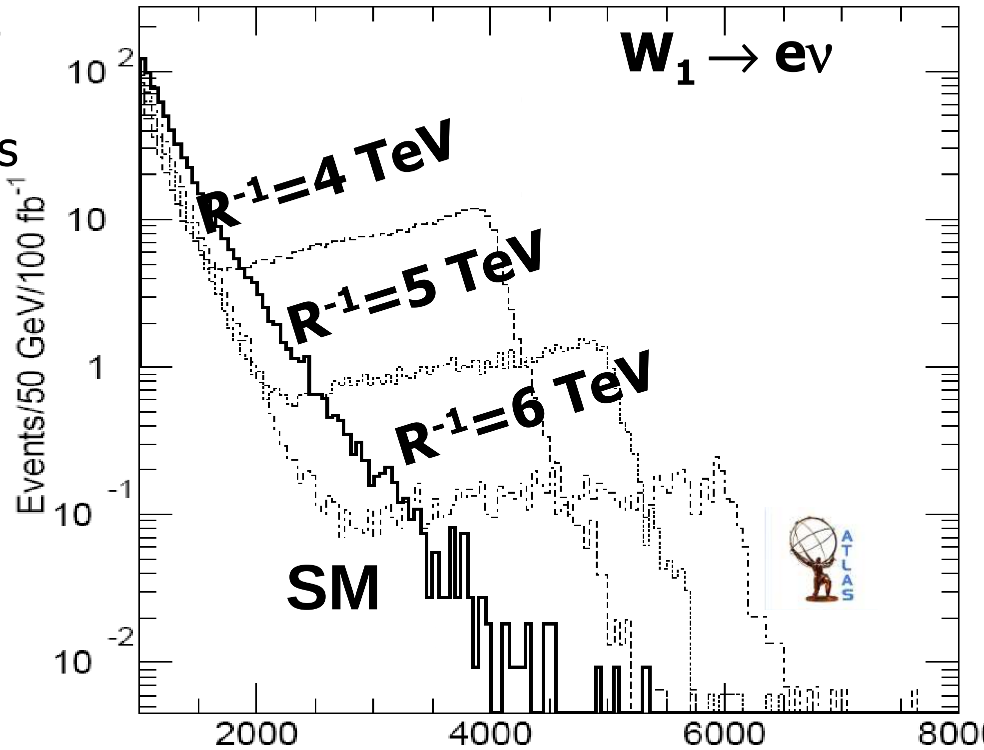
TeV^{-1} ED Discovery Limits

W_{KK} decays

- Isolated high-p_T lepton >200 GeV + missing E_T > 200 GeV
- Invmass (l,ν) ($m_{l\nu}$)> 1 TeV, veto jets
- Bckg: irreducible bkdg: W→eν,
  Also pairs: WW, WZ, ZZ, ttbar
- Fast simulation/reco

Sum over 2 lepton flavours

For L=100 fb^{-1} a peak in the lepton-neutrino transverse invariant mass ($m_T^{l\nu}$) will be detected if the compactification scale (M_C= R^{-1}) is < 6 TeV



$m_T^{e\nu}$ (GeV) $=\sqrt{2p^e_T p^\nu_T(1-\cos\Delta\phi)}$

If a peak is detected, a measurement of the couplings of the boson to the leptons and quarks can be performed for M_C up to ~ 5 TeV.

G. Polesello, M. Patra
EPJ Direct, ATLAS 2003-023
G. Polesello, M. Patra
EPJ Direct C 32 Sup.2 (2004) pp.55-67

TeV^{-1} ED Discovery Limits

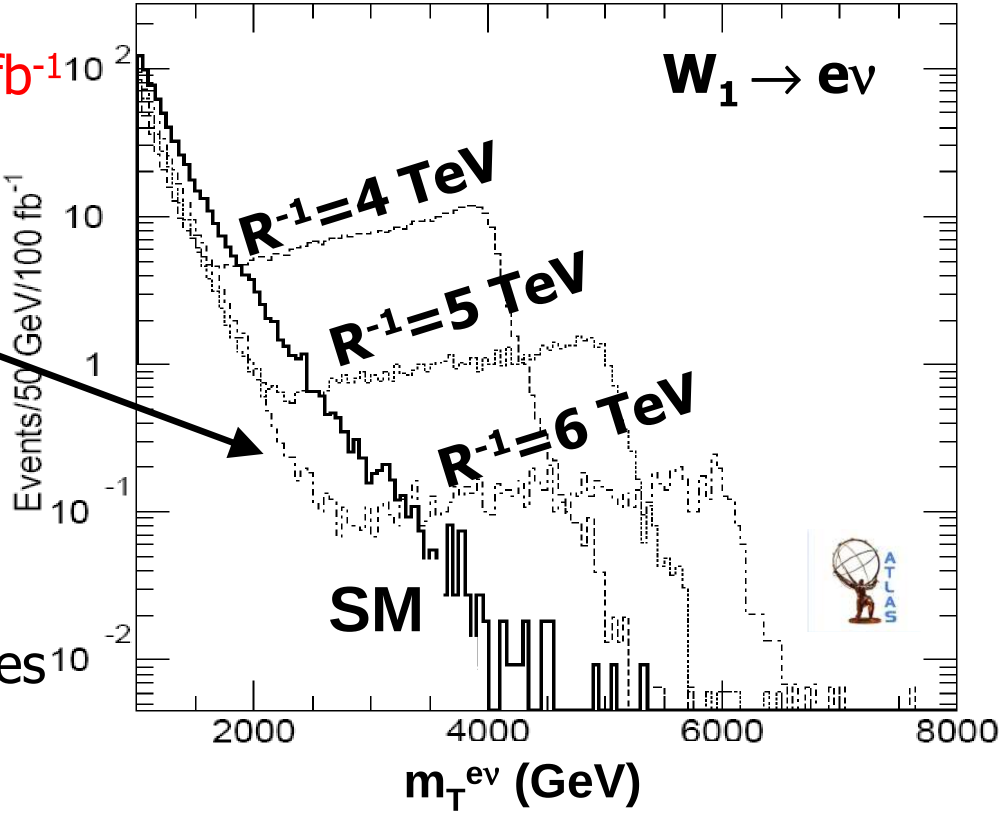
W_{KK} decays

If no signal is observed with 100 fb^{-1} a limit of M_C > 11.7 TeV can be obtained from studying the $m_T^{e\nu}$ distribution below the peak:

Here: suppression in σ

- due to –ve interference (M1) between SM gauge bosons and the whole tower of KK excitations

- sizable even for M_C above the ones accessible to a direct detection of the mass peak.



- Can't get such a limit with $W \rightarrow \mu\nu$ since momentum spread - can't do optimised fit which uses peak edge

G. Polesello, M. Patra
EPJ Direct, ATLAS 2003-023

G. Polesello, M. Patra
EPJ Direct C 32 Sup.2 (2004) pp.55-67

TeV^{-1} ED g* Discovery Limits

This is more challenging than Z/W which have leptonic decay modes

Detect KK gluon excitations (g*) by reconstructing their hadronic decays (no leptonic decays).

Detect g* by (1) deviation in dijet σ

(2) analysing its decays into heavy quarks

Coupling of g* to quarks = √2 * SM couplings

$\Rightarrow$ g* $\rightarrow$ wide resonances decaying into pairs of quarks

TeV^{-1} ED g* Discovery Limits

Gluon excitation decays

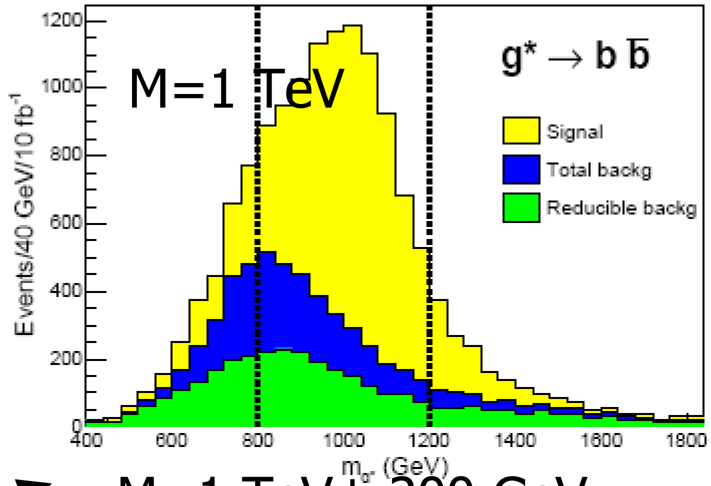
$$q\bar{q} \to g^* \to b\bar{b}, q\bar{q} \to g^* \to t\bar{t}$$

- ❑ bbar or ttbar jets
- ❑For ttbar one t is forced to decay leptonically
- ❑ Bckg: SM continuum bbar, ttbar, 2 jets, W +jets
- ❑ PYTHIA
- ❑ Fast simulation/reco

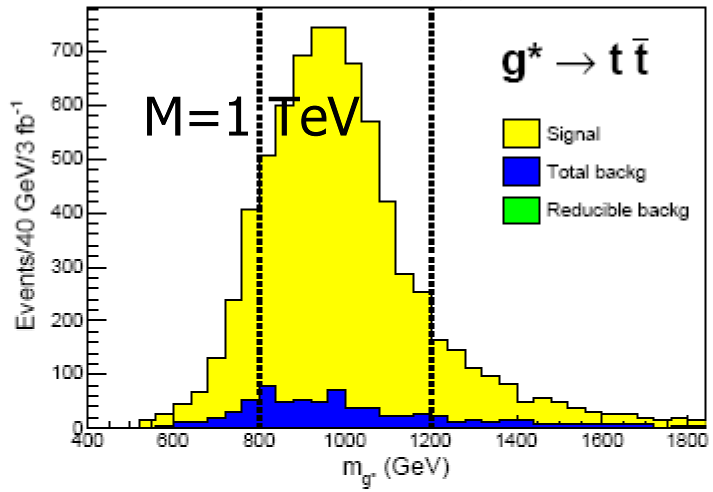
Width expected to be
$\Gamma(g^*) = 2\,\alpha_s M$ where M=g* mass
$\Rightarrow \Gamma(g^*) \sim 200$ GeV for M=1 TeV

For M=1 TeV natural width ~= experimental effects (fragmentation and detector resolution)

Reconstructed mass peaks

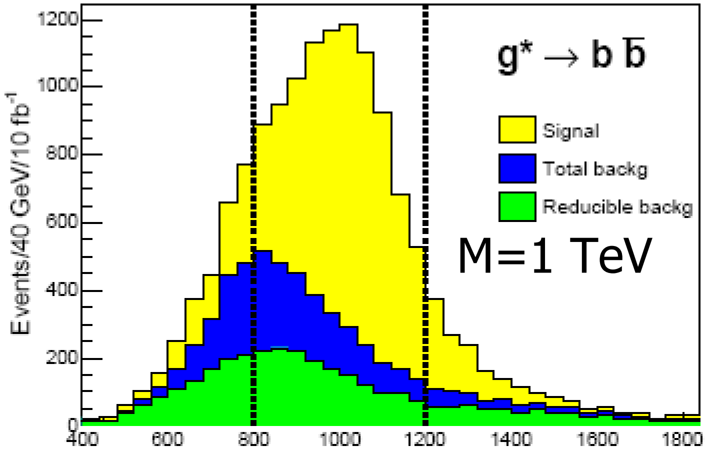


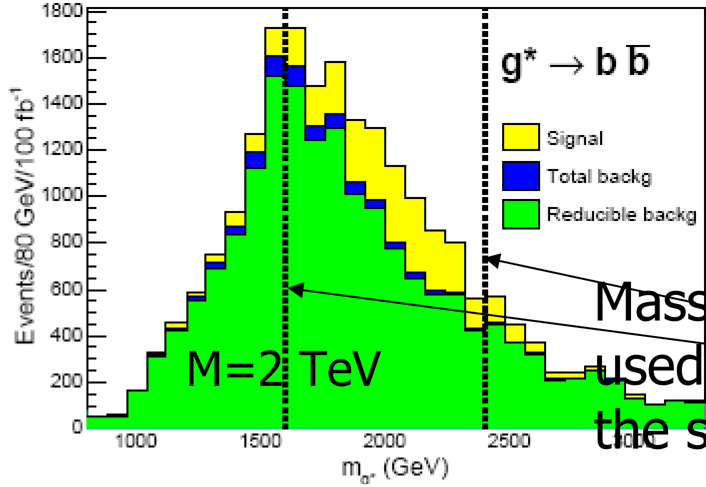
M=1 TeV± 200 GeV



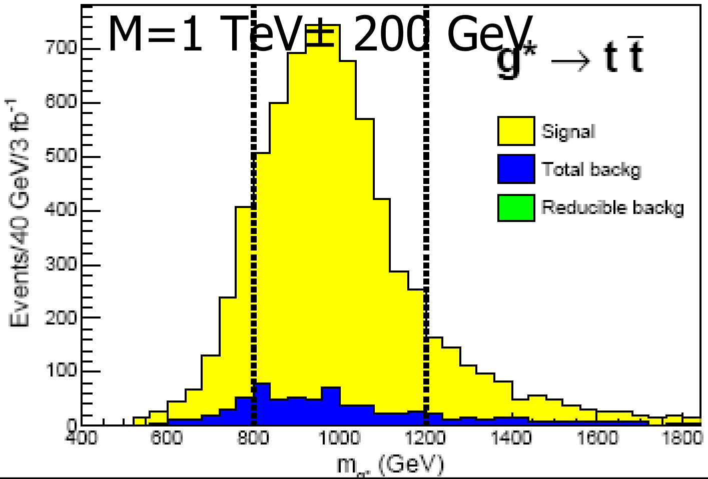
TeV^{-1} ED g* Discovery Limits

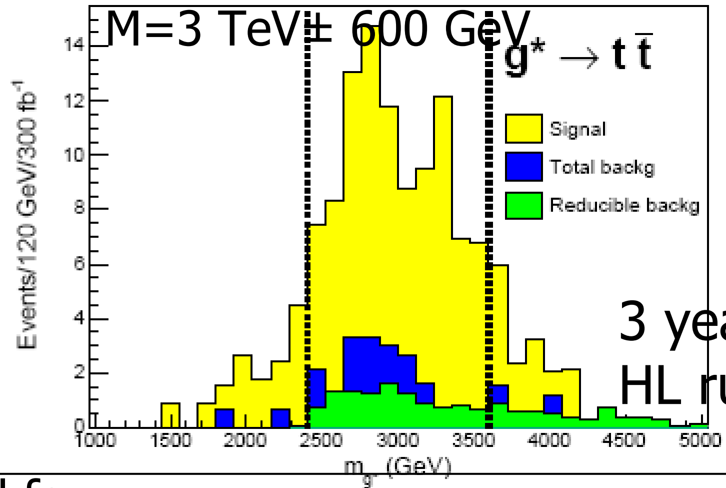
Reconstructed mass peaks





Mass windows used to evaluate the significance





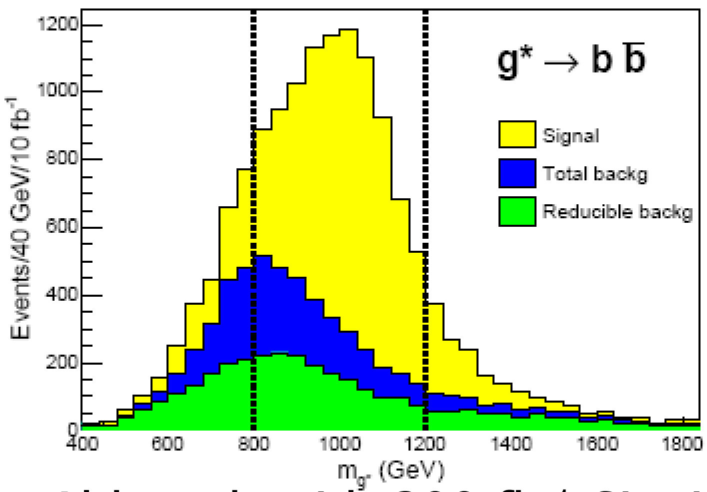
3 years at HL running

With 300 fb^{-1} Significance of 5 achieved for:
bbar channel: R^{-1} = 2.7 TeV ttbar channel: R^{-1} = 3.3 TeV

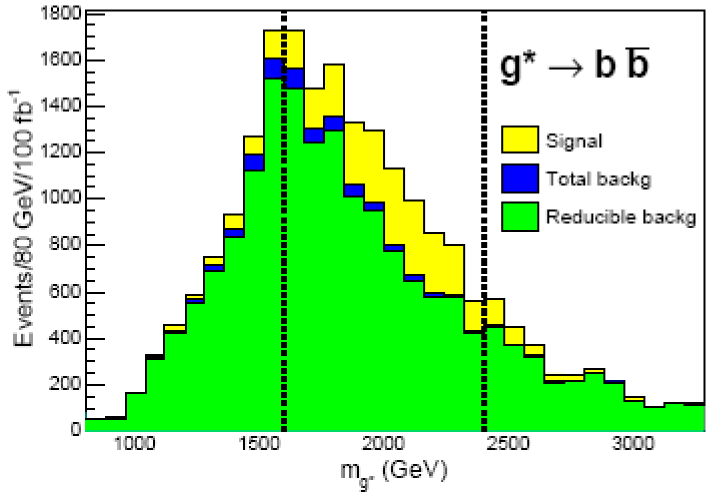
L. March, E. Ros, B. Salvachua, ATL-PHYS-PUB-2006-002

TeV^{-1} ED g* Discovery Limits

M=1 TeV



M=2 TeV



Although with 300 fb^{-1} Significance of 5 achieved for:

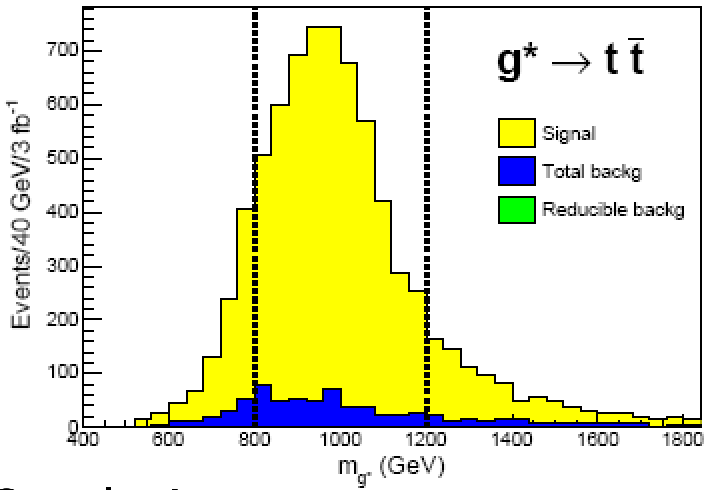
bbar channel: R^{-1} = 2.7 TeV

However, it is not in general possible to obtain a mass peak well separated from the bkdg. ⇒ it is unlikely that an excess of events in the g*→bbar channel could be used as evidence of the g* resonance, since there are large uncertainties in the calculations of the bkdgs. For M=1TeV the peak displacements could be used as evidence for new physics if the b-jet energy scale can be accurately computed.

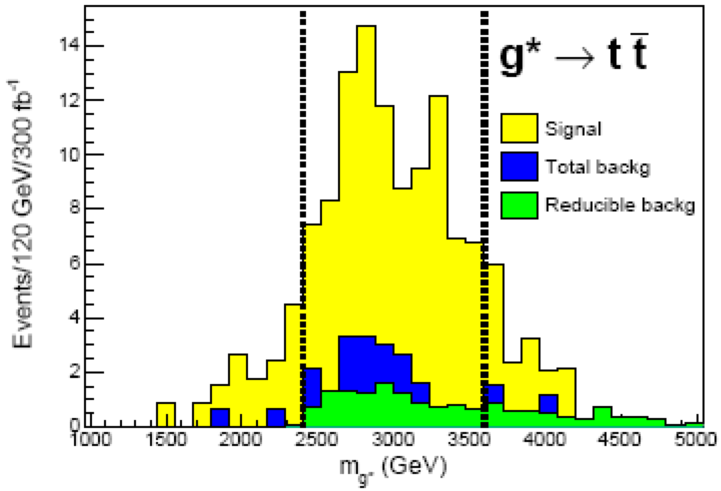
TeV^{-1} ED g* Discovery Limits

But in g*→ttbar, the bkdg is mainly irreducible and not so large.
⇒ g* resonance can be detected in this decay channel if the tt-bar σ can be computed in a reliable way.

M=1 TeV± 200 GeV



M=3 TeV± 600 GeV



Conclusion:
g* decays into b-quarks are difficult to detect, decays into t-quarks might yield a significant signal for g* mass below 3.3 TeV.
This could be used to confirm the presence of g* in the case that an excess in the dijet σ is observed.