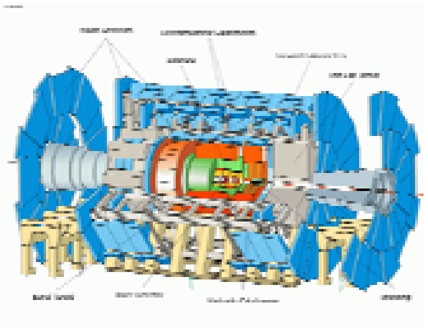
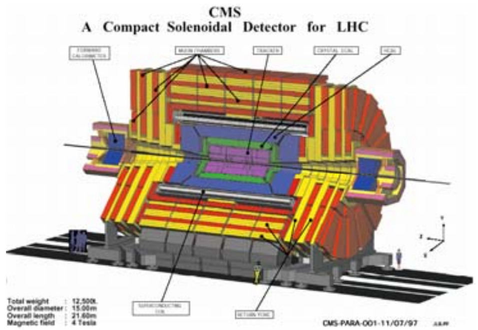
Sensitivity of the LHC Experiments to Extra Dimensions

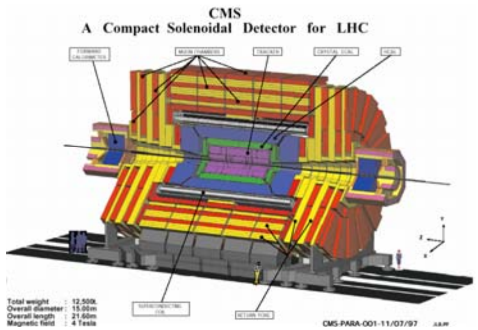


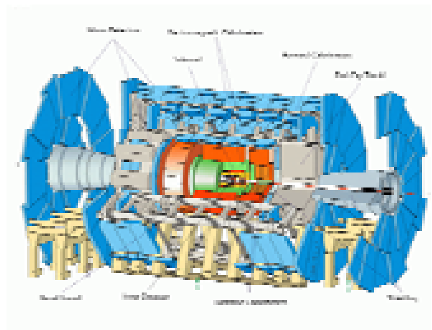
Dr Tracey Berry
Royal Holloway
University of London
On behalf of the ATLAS and CMS collaborations

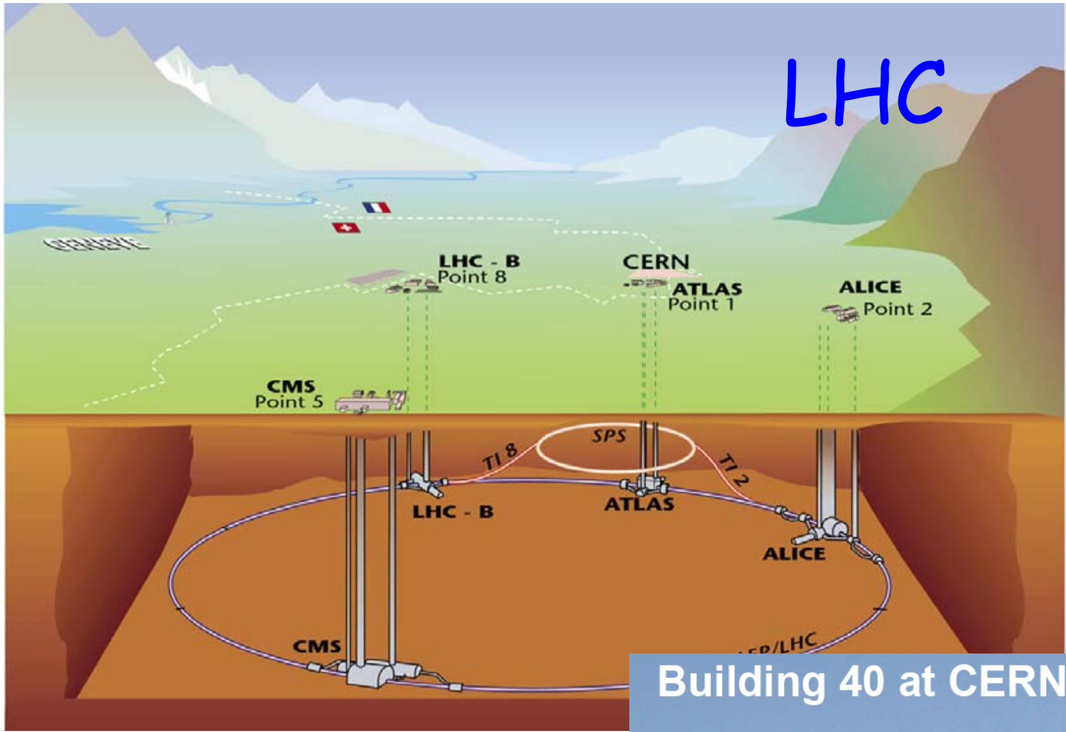


Overview

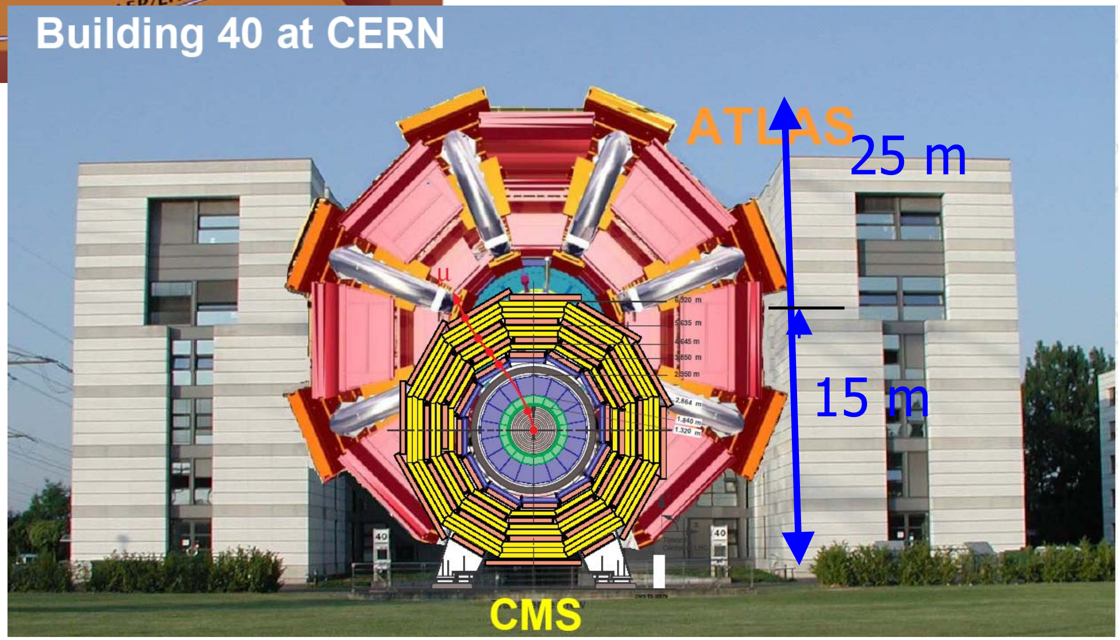
- LHC Experiments: ATLAS & CMS
- Extra Dimensional Models Searches
  - ADD
  - RS
  - TeV^{-1}
- Summary of LHC Start-up Expectations
- Conclusions







Large Hadron Collider
proton–proton collider
@ center of mass energy
$\sqrt{s}$ = 14 TeV

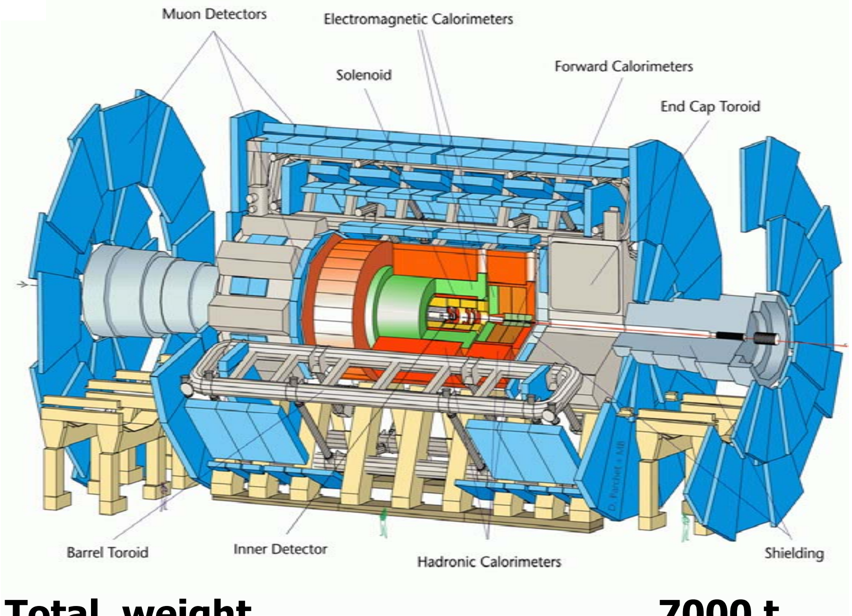


First collisions expected summer 2008

ATLAS and CMS

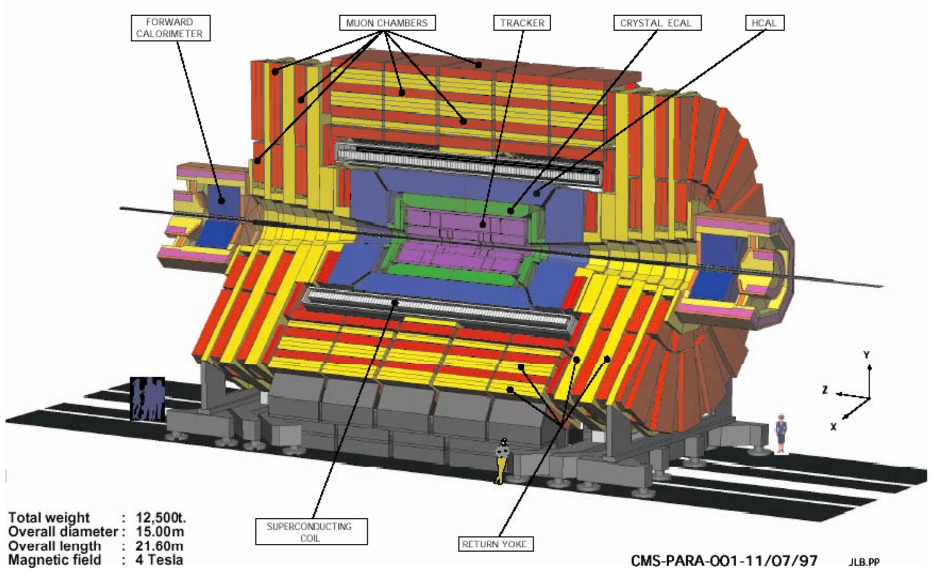
Large general-purpose particle physics detectors

A Large 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



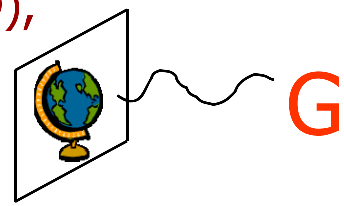
Total weight	**12 500 t**
Overall diameter	**15.00 m**
Overall length	**21.6 m**
Magnetic field	**4 Tesla**

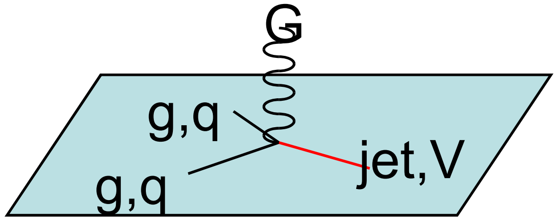
Detector subsystems are designed to measure:
energy and momentum of γ ,e, μ, jets, missing E_T up to a few TeV

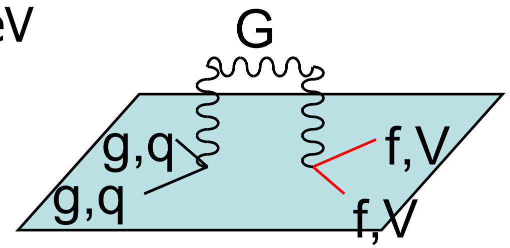
ADD Model

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+δ dimensions

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

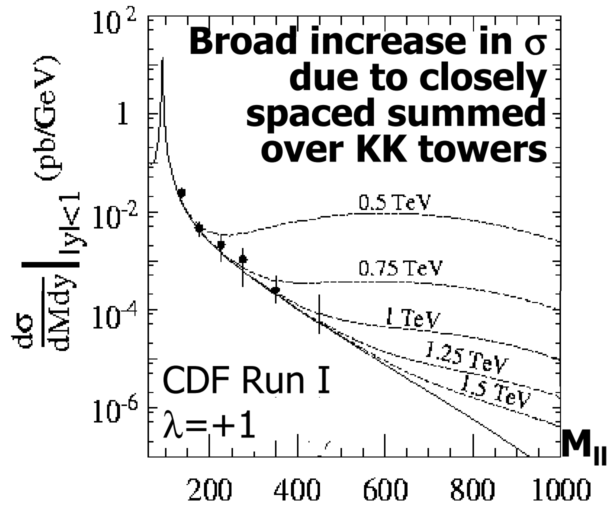
Signature:

❖ Real graviton emission: in association with a vector-boson

jets + missing ET, V+missing ET

❖ Or deviations in virtual graviton exchange

e.g. Excess above di-lepton continuum

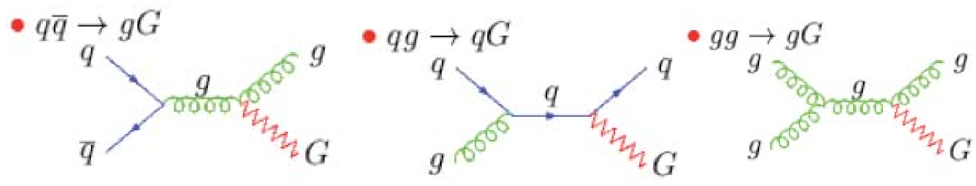


ADD Discovery Limit: Real G Emission

pp→γ+G^KK

Signature: high-p_T photon + high missing E_T

Main Bkgd: irreducible Zγ → ννγ,
Also W→ e(μ,τ)ν, Wγ→ eν, γ+jets,
QCD, di-γ, Z^0+jets



Integrated Lum for a 5s 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				

Rates too low

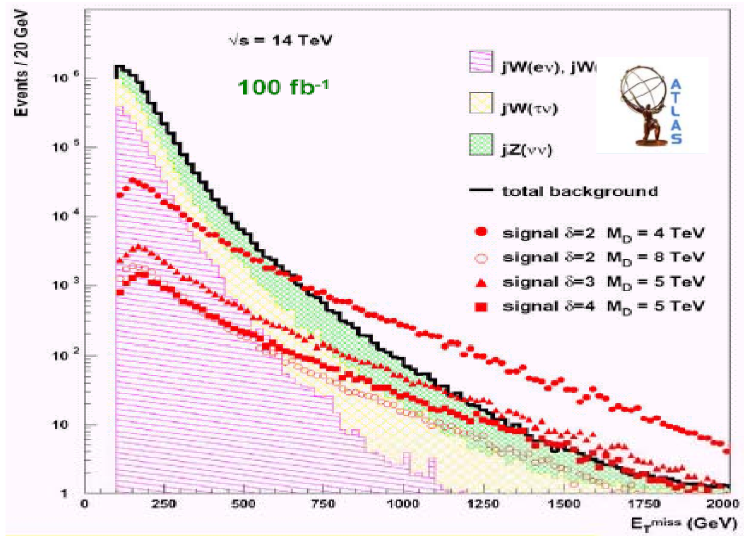
M_D^{MAX} (TeV)	δ=2
HL 100fb^{-1}	4

pp→jet+G^KK

Signature: high E_T jet + large missing E_T
Bkgd: irreducible jet+Z/W →jet+νν /jet+lν
vetos leptons: to reduce jet+W bkdg mainly

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



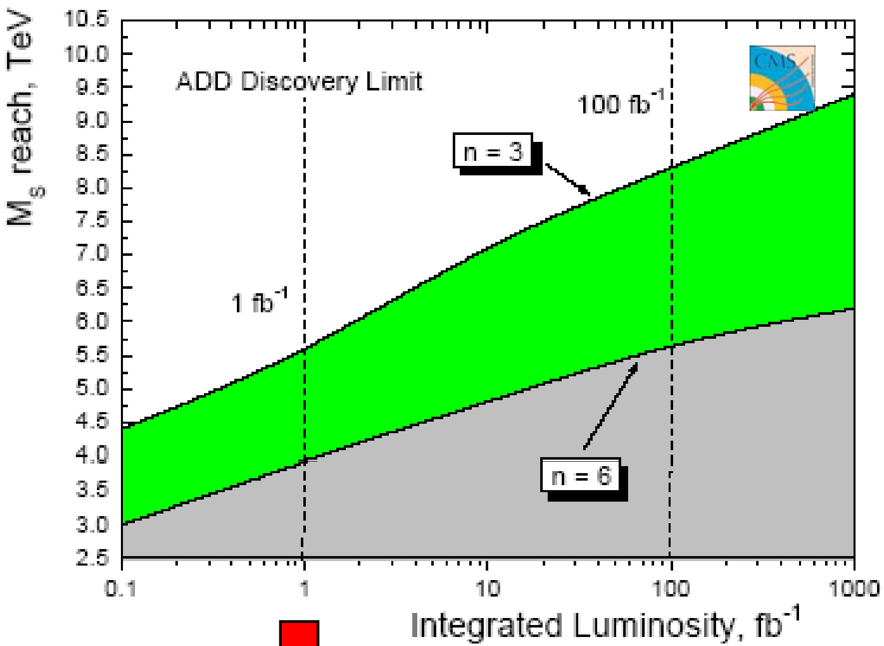
L.Vacavant, I.Hinchcliffe, ATLAS-PHYS 2000-016
J. Phys., G 27 (2001) 1839-50

ADD Discovery Limit: G Exchange

Royal Holloway University of London

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

- Two opposite sign muons & $M_{\mu\mu}$>1 TeV
- Bkg: Irreducible Drell-Yan, also ZZ, WW, WW, tt (suppressed after selection cuts)



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

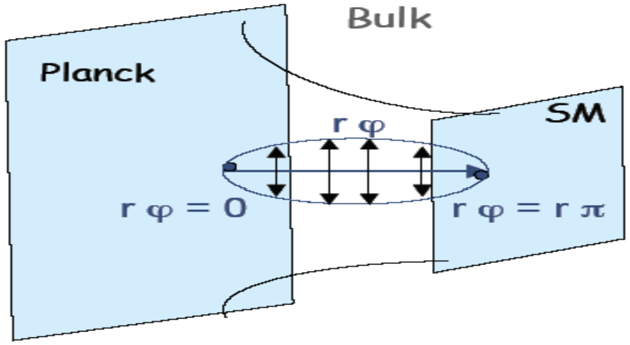
Belotelov et al.,
CMS NOTE 2006/076, CMS PTDR 2006

RS Model

Royal Holloway University of London

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

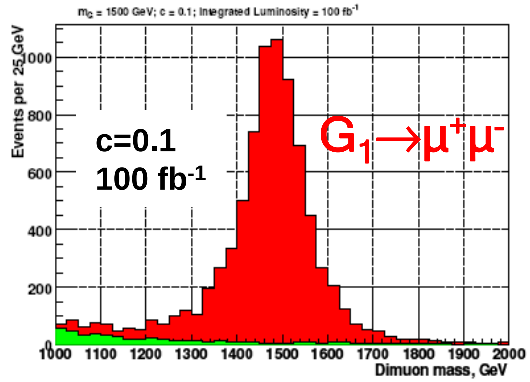
1 extra warped dimension

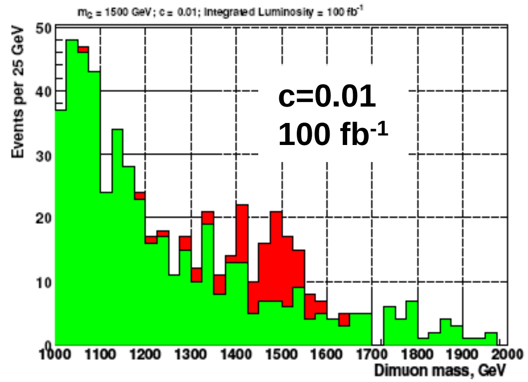


Gravity localised in the ED

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

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





<u>Model parameters</u>:

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

  1st graviton excitation mass: m_1 → **Resonance** position

  $\Lambda_\pi = m_1 \overline{M}_{pl} / k x_1$, & $m_n = k x_n e^{krc\pi} (J_1(x_n)=0)$
- Coupling constant: $c = k/M_{Pl}$

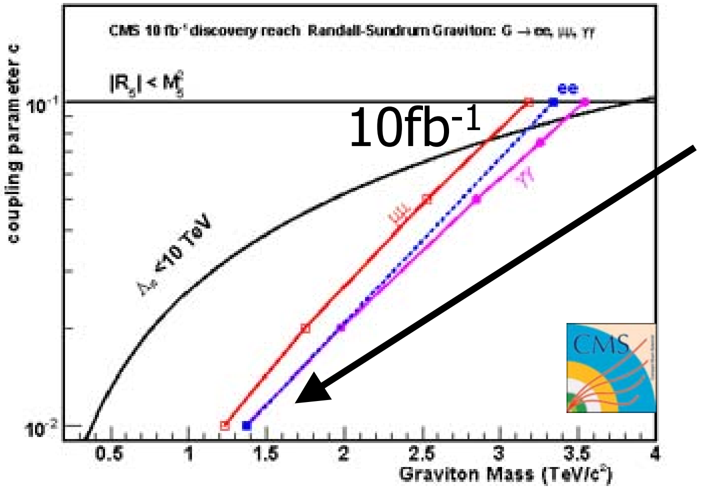
  $\Gamma_1 = \rho m_1 x_1^2 (k/\overline{M}_{pl})^2$ → width

k = curvature, R = compactification radius

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

RS1 Discovery Limit

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



Best channels to search in are G(1)→e$^+$e- and G(1)→γγ due to the energy and angular resolutions of the detectors

Allenach et al, hep-ph0211205

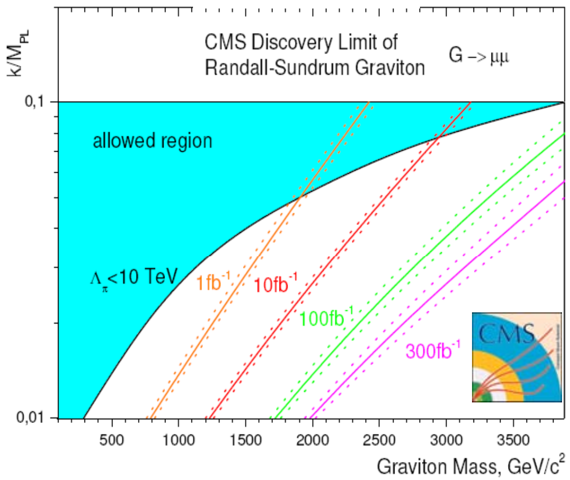
BR(G→γγ) = 2* BR(G→ee/μμ)

Reach for e and γ is comparable for low coupling and M_G: due to the QCD and prompt photon bkgds in the γγ channel which are harder to efficiently suppress

μμ channel trails ee channel due to resolution

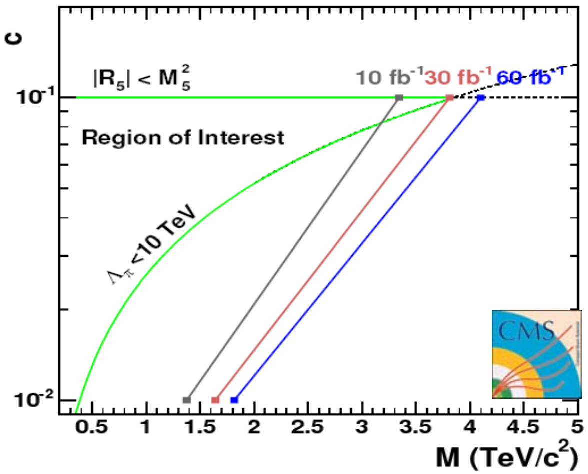
‹ 60 fb^{-1} LHC completely covers the region of interest

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



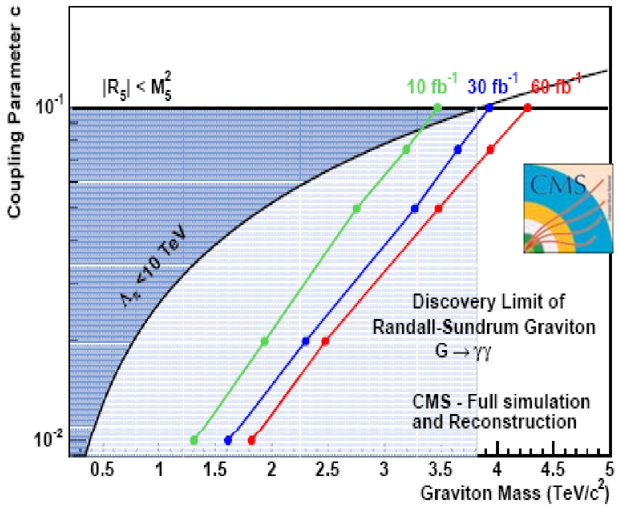
Tracey Berry

$G_1 \to e^+e^-$



SUSY 2007, July, Karlsruhe

$G_1 \to \gamma\gamma$

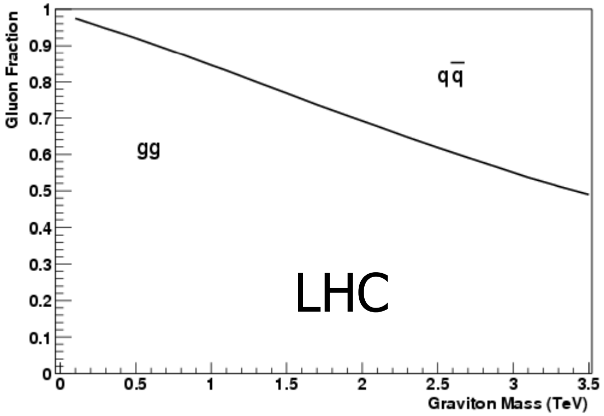


CMS PTDR 2006

RS1 Model Determination

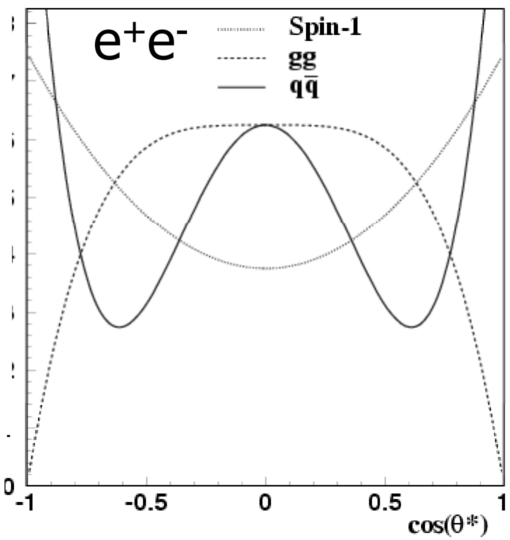
Spin determination of the resonance

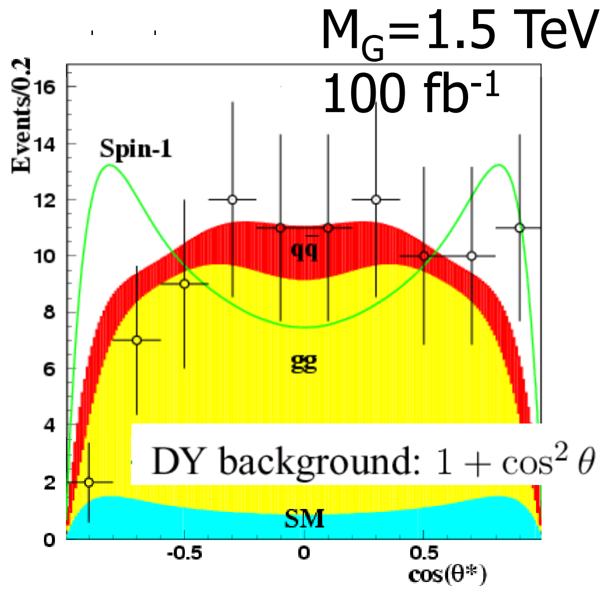
G has spin 2: pp→G→ee has 2 components: gg→G→ee & qq→G→ee each with different angular distributions



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

$gg \rightarrow G \rightarrow ff: 1 - \cos^4\theta$





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)

Allanach et al, hep-ph 0006114

TeV^{-1} Sized Extra Dimensions

I. Antoniadis, PLB246 377 (1990)

- One extra dimension compactified on a S^1/Z^2 orbifold
- Radius of compactification small enough →
  Gauge bosons can travel in the bulk

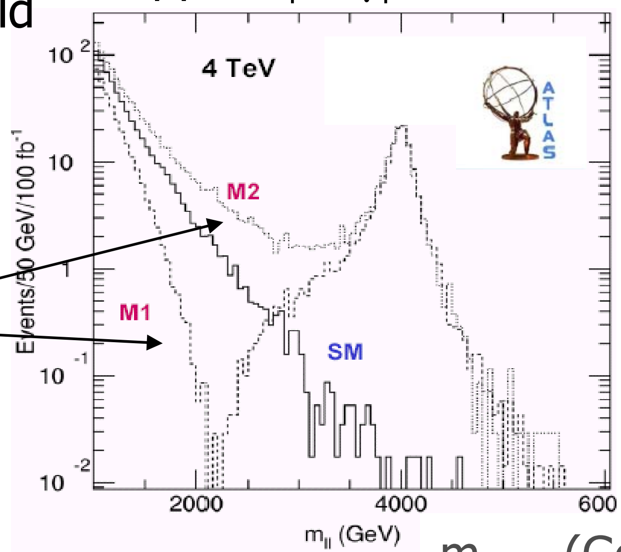
- Fermions (quarks/leptons) localized
  - at a fixed point (M1) or
  - opposite (M2) points

  ⇒ destructive (M1) or constructive (M2) interference of the KK excitations with SM model gauge bosons

Signature:
KK excitations of the gauge bosons ($Z^{(k)}, W^{(k)}$) appear as resonances with masses :
$M_k = \sqrt{(M_0^2+k^2/R^2)}$ where (k=1,2,…) & also interference effects!

- Look for l^+l^- decays of γ and Z^0 KK modes.
  Also in decays (m_T) of $W^{+/-}$ KK modes.
  Or evidence of g* via dijet σ or bb, tt s

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



m_{e+e-} (GeV)

$M_n = M_0$

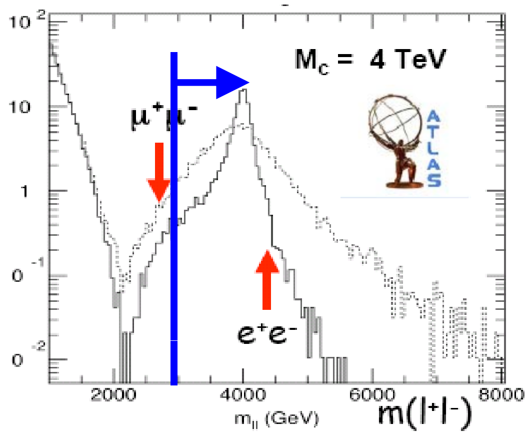
New Parameters
$R=M_C^{-1}$: size of compact dimension
M_C : compactification scale
M_0 : mass of the SM gauge boson

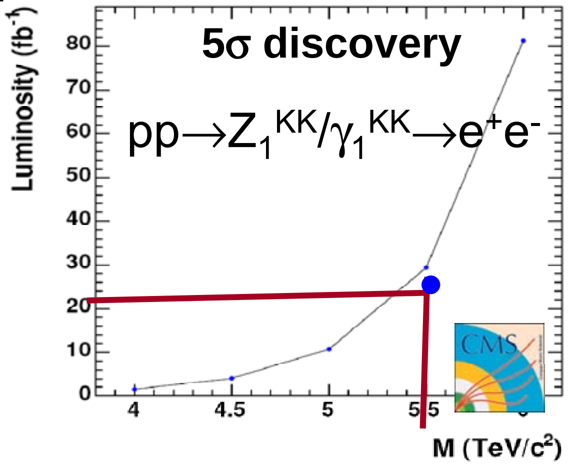
G. Azuelos, G. Polesello
EPJ Direct 10.1140 (2004)

Tev^{-1} Sized Extra Dimensions

Searching for deviations in the dilepton spectrum: 3 methods used

1) Search for the resonance peak

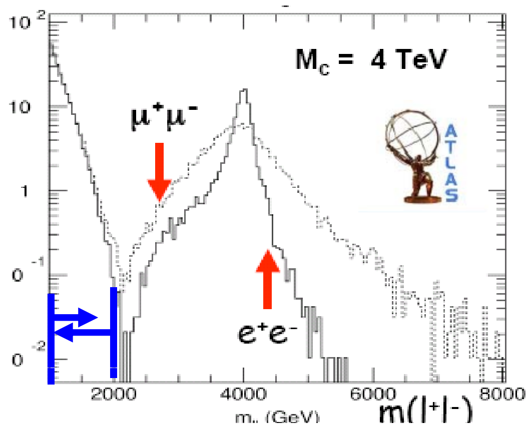


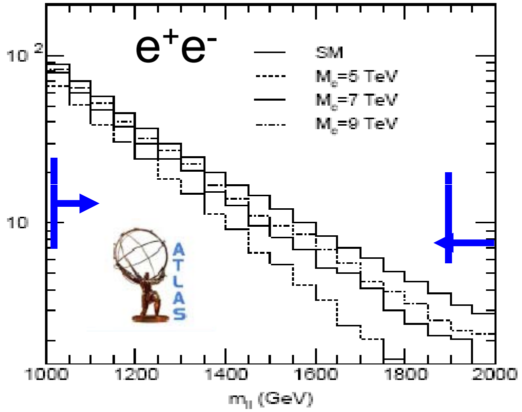


$\mathcal{L}$=30/80 fb^{-1} CMS will be able to detect a peak in the e^+e^- invar. M_{ll} if M_C<5.5/6 TeV.

ATLAS: $\mathcal{L}$=100 fb^{-1}
M_C (R^{-1})<5.8 TeV
(ee+μμ)

2) Search for interference in a mass window





3) Fit to kinematics of signal

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

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

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

ee+μμ: ATLAS 5σ reach is ~8 TeV for $\mathcal{L}$=100 fb^{-1} and ~10.5 TeV for 300 fb^{-1}

Distinguishing $Z^{(1)}/\gamma^{(1)}$ from Z′, RS G

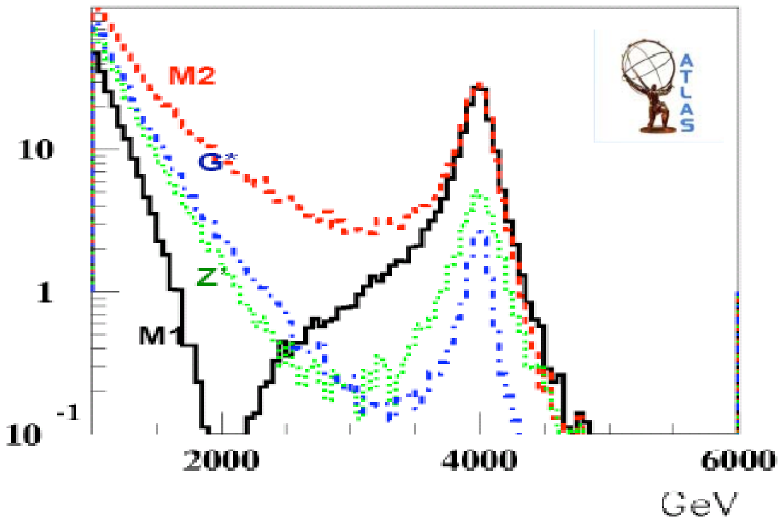
Distinguish

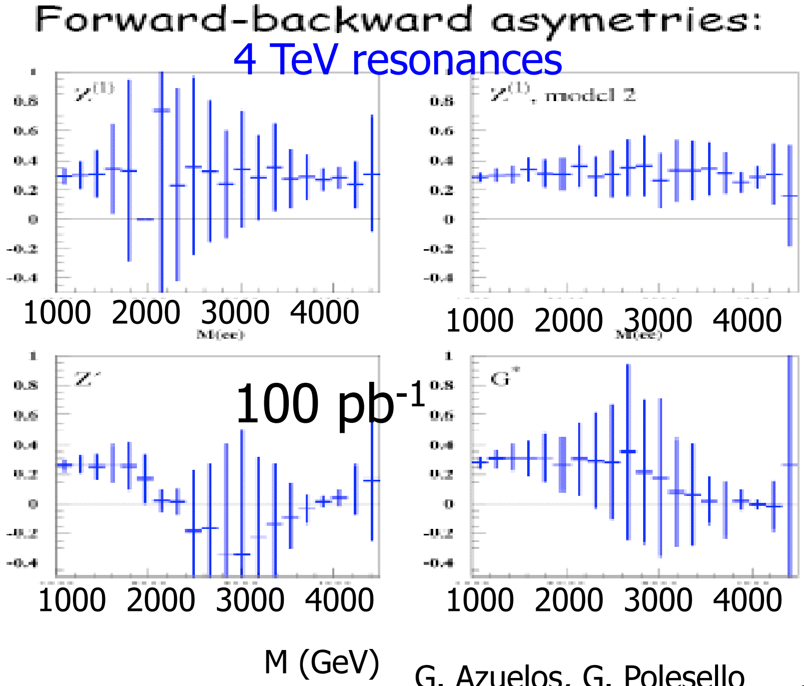
- spin-1 $Z^{(1)}$ from spin-2 G: angular distribution of decay products
- spin-1 $Z^{(1)}$ from spin-1 Z′ with SM-like couplings: forward-backward asymmetry

  due to contributions of the higher lying states, interference terms and additional √2 factor in its coupling to SM fermions.

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

4 TeV $Z^{(1)}/\gamma^{(1)}$ or Z′ or RS Graviton?





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

TeV^{-1} ED Discovery Limits

Royal Holloway University of London

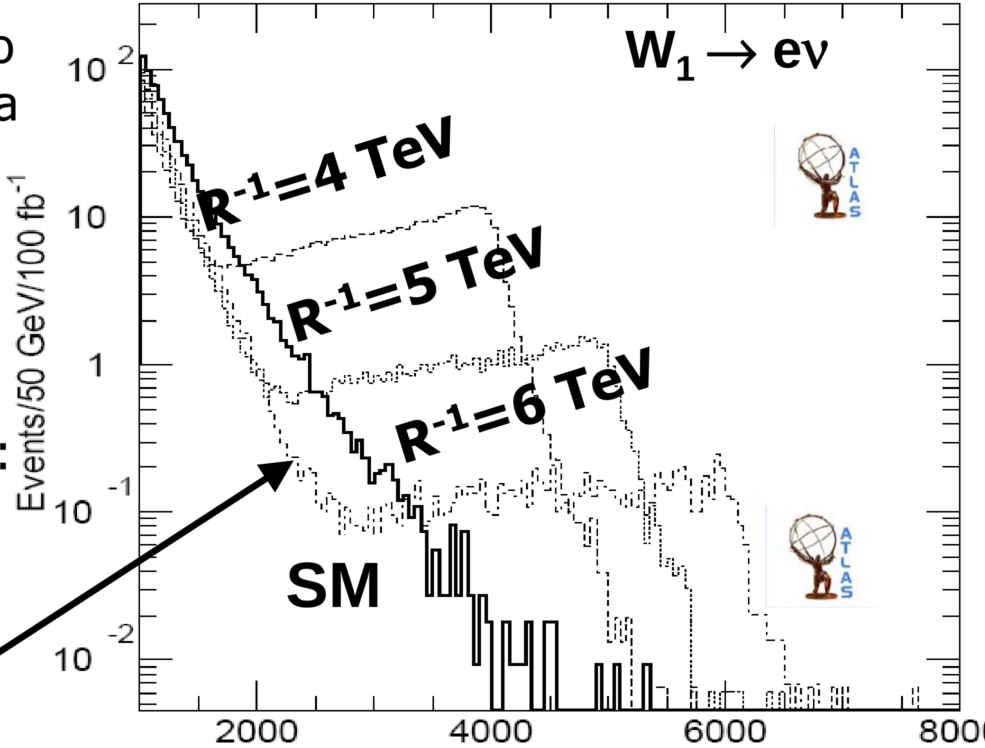
W_{KK} decays

Search for deviations in lepton-neutrino transverse invariant mass ($m_T^{l\nu}$) spectra

1) Search for peak:
L=100 fb^{-1} detect a peak if compactification scale (M_C= R^{-1})<6 TeV
Sum over 2 lepton flavours

2) Studying distribution below the peak: in $m_T^{e\nu}$ spectra
L= 100 fb^{-1} a limit of M_C > 11.7 TeV

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



$m_T^{e\nu}$ (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 g* Discovery Limits

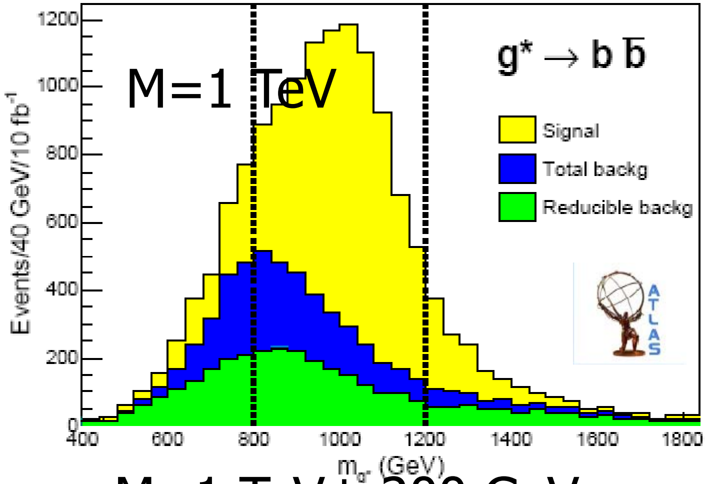
This is more challenging than Z/W which have leptonic decay modes

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

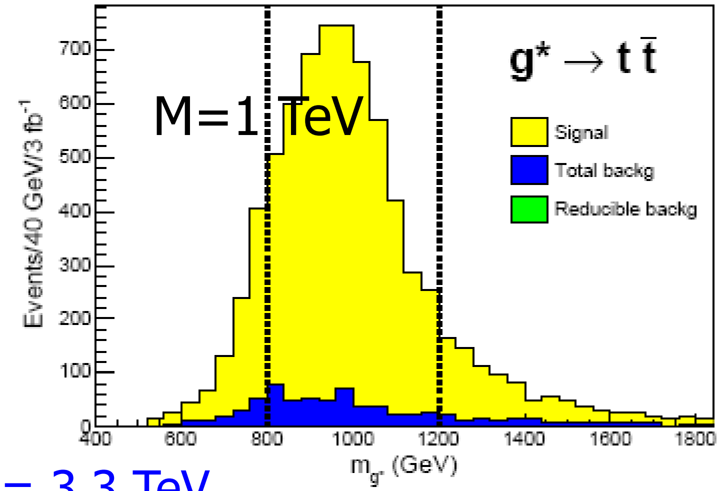
Detect g* by (1) deviation in dijet σ

(2) analysing its decays into heavy quarks

Reconstructed mass peaks



M=1 TeV± 200 GeV



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

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

bbar channel: R^{-1} = 2.7 TeV ttbar channel: R^{-1} = 3.3 TeV

Although bkdg & its uncertainty makes this channel challenging

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

LHC Start-up Expectations

Model	Mass reach	Integrated Luminosity (fb^{-1})
ADD Direct G_{KK}	M_D~ 1.5-1.0 TeV, n = 3-6	1
ADD Virtual G_{KK}	M_D~ 4.3 - 3 TeV, n = 3-6 M_D~ 5 - 4 TeV, n = 3-6	0.1 1
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
TeV^{-1} ($Z_{KK}^{(1)}$)	M_{z1} < 5 TeV	1

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
(Universal Extra Dimensions – not shown here)

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

ATLAS & CMS increasing focus on first year of data taking

- Understand/optimize detector performance (calibration, alignment, …)
- Understand/measure Standard Model processes (bkg sources)

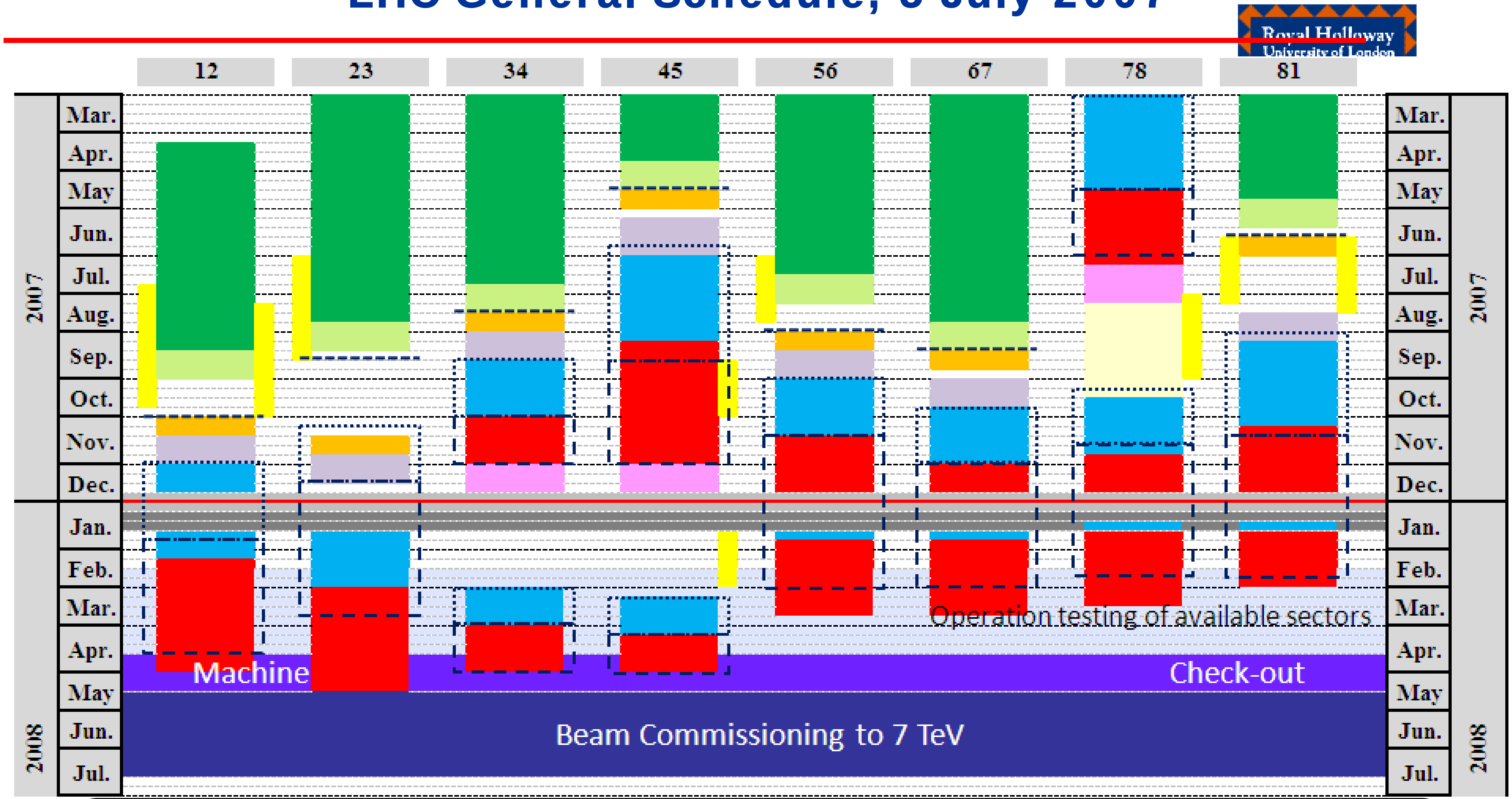
Once these are achieved ATLAS & CMS could potentially have new physics results within months!

BACKUP SLIDES!

General schedule

- Engineering run originally foreseen at end 2007 now precluded by delays in installation and equipment commissioning.
- 450 GeV operation now part of normal setting up procedure for beam commissioning to high-energy
- General schedule has been revised, accounting for inner triplet repairs and their impact on sector commissioning
  - All technical systems commissioned to 7 TeV operation, and machine closed April 2008
  - Beam commissioning starts May 2008
  - First collisions at 14 TeV c.m. July 2008
  - Luminosity evolution will be dominated by our confidence in the machine protection system and by the ability of the detectors to absorb the rates.
- No provision in success-oriented schedule for major mishaps, e.g. additional warm-up/cooldown of sector

LHC General Schedule, 5 July 2007



General schedule Baseline rev. 4.0

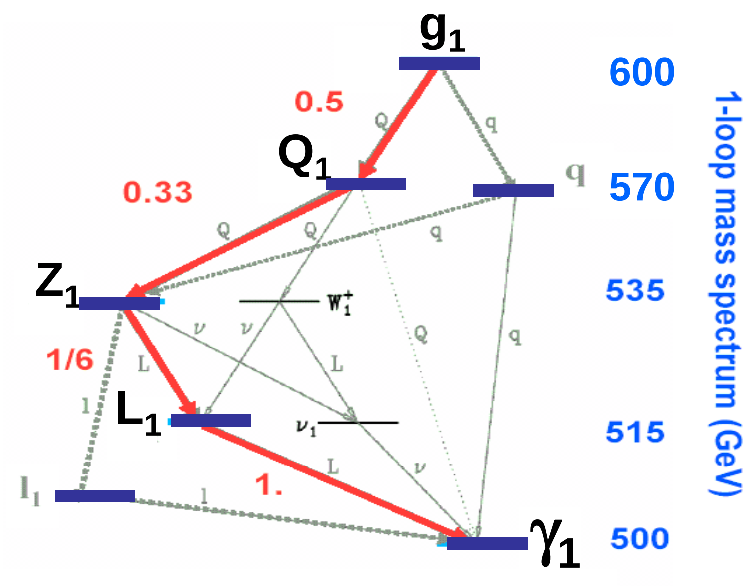
- Global pressure test &Consolidation
- Cool-down
- Powering Tests
- Interconnection of the continuous cryostat
- Leak tests of the last sub-sectors
- Inner Triplets repairs & interconnections
- Global pressure test &Consolidation
- Flushing
- Cool-down
- Warm up
- Powering Tests

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

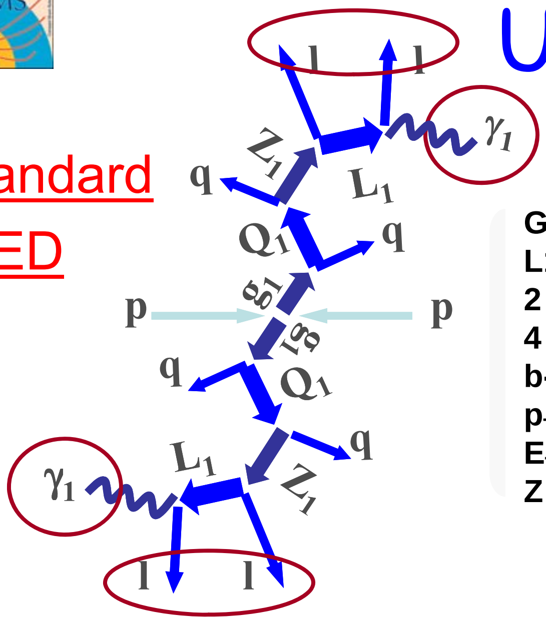


Thick/Fat brane

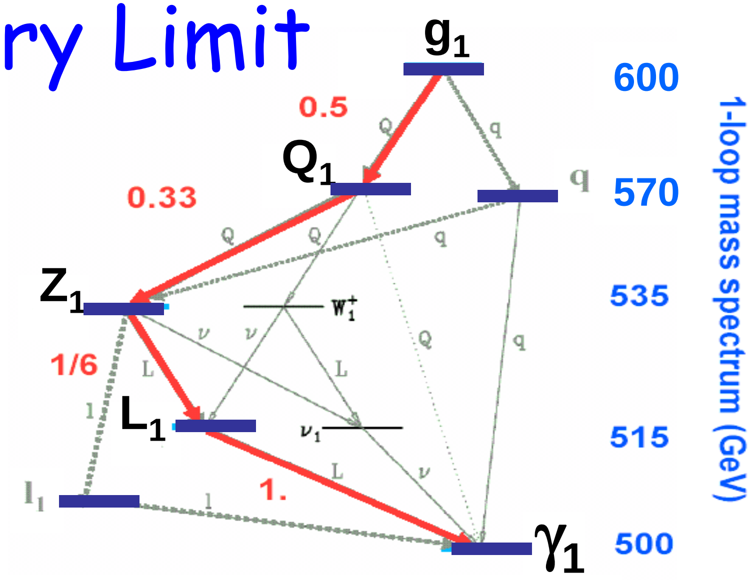
- ❑ SM brane is endowed with a finite thickness in the ED
- ❑ Gravity-matter interactions break KK number conservation:
  - 1st level KK states decay to G+SM.
  - If radiative corrections → mass degeneracy is broken and γ and leptons are produced.

UED Discovery Limit

Standard UED



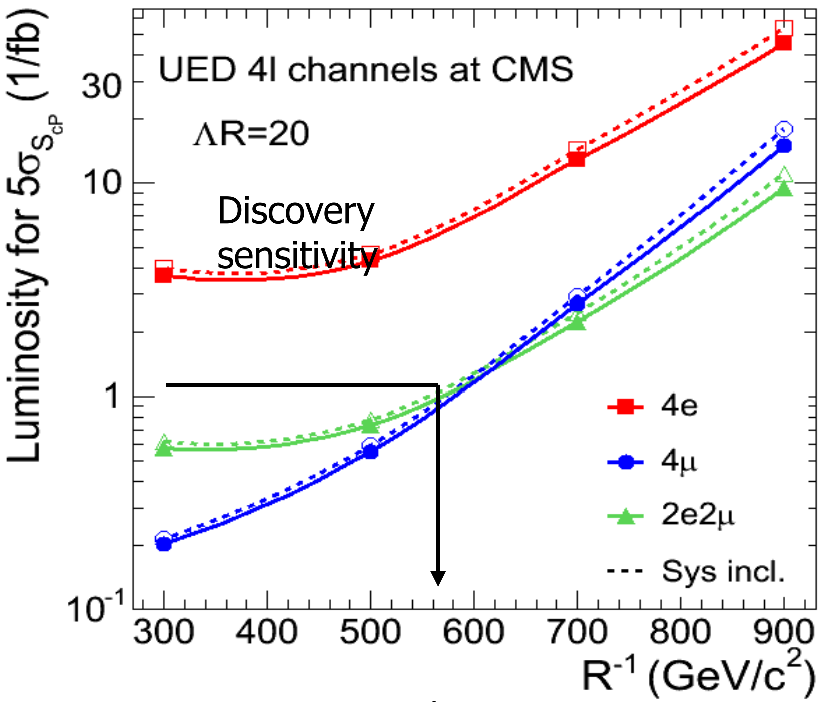
Geo accep
L1,HLT
2 OSSF
4 ISO
b-tag veto
$p_T^l<$
E_T^{miss}
Z veto



$$pp \rightarrow g_1 g_1 \rightarrow 4l + 4q + 2LKP \rightarrow 4l + 4\ jets + \not{P}_T$$
$$pp \rightarrow g_1 Q_1 \rightarrow 4l + 3q + 2LKP \rightarrow 4l + 3\ jets + \not{P}_T$$
$$pp \rightarrow Q_1 Q_1 \rightarrow 4l + 2q + 2LKP \rightarrow 4l + 2\ jets + \not{P}_T$$

Signature: 4 low-p_T isolated leptons (2 pairs of opposite sign, same flavour leptons) + n jets + missing E_T (from 2 undetected γ_1)
Irreducible Bckg: ttbar + n jets(n = 0,1,2),
4 b-quarks, ZZ, Zbbar

Studied for low lum run ~$2\times10^{33}cm^{-2}s^{-1}$

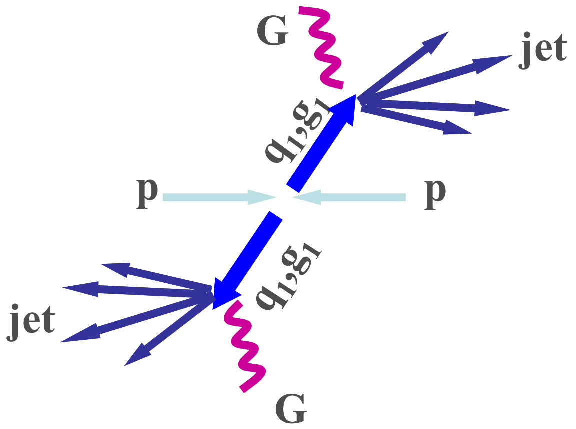


CMS CR 2006/057

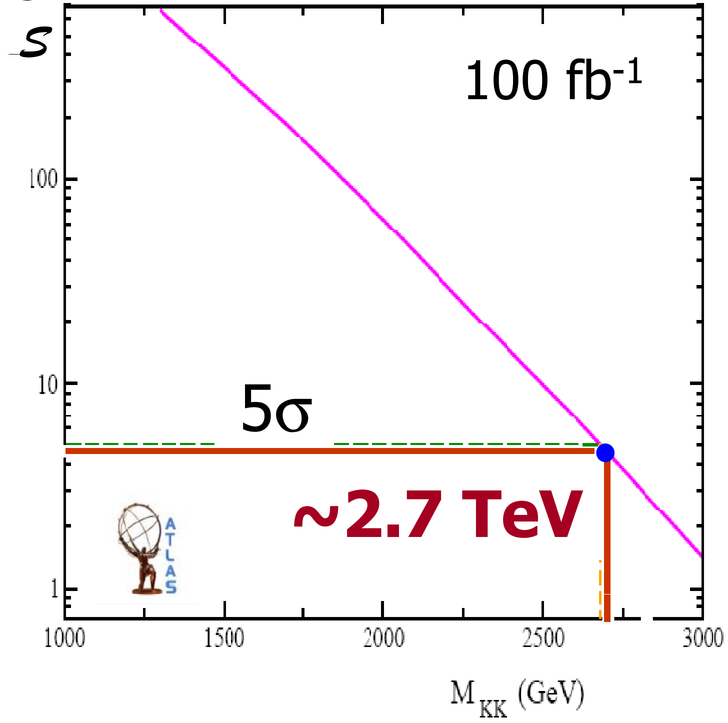
UED Discovery Limit

Thick brane in UED with TeV^{-1} size

$$pp \rightarrow g_1 g_1 / q_1 g_1 / q_1 q_1 \rightarrow 2\,jets + \not{E}_T$$



Significance vs Mass of 1st KK excitation



Signature:
2 back-to back jets + missing E_T (>775 GeV)

Irreducible Bckg: $Z(\rightarrow \nu\nu)$ jj, $W(\rightarrow l\nu)$ jj

5σ discovery possible at ATLAS with 100 fb^{-1} if first KK excitation mass < 2.7 TeV

P. H. Beauchemin, G. Azuelos
ATL-PHYS-PUB-2005-003

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.
UED 4 leptons	R^{-1} ~ 600 GeV	1.0	Theor.+Exp.
Thick brane	R^{-1} = 1.3 TeV	6 pb^{-1}	

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

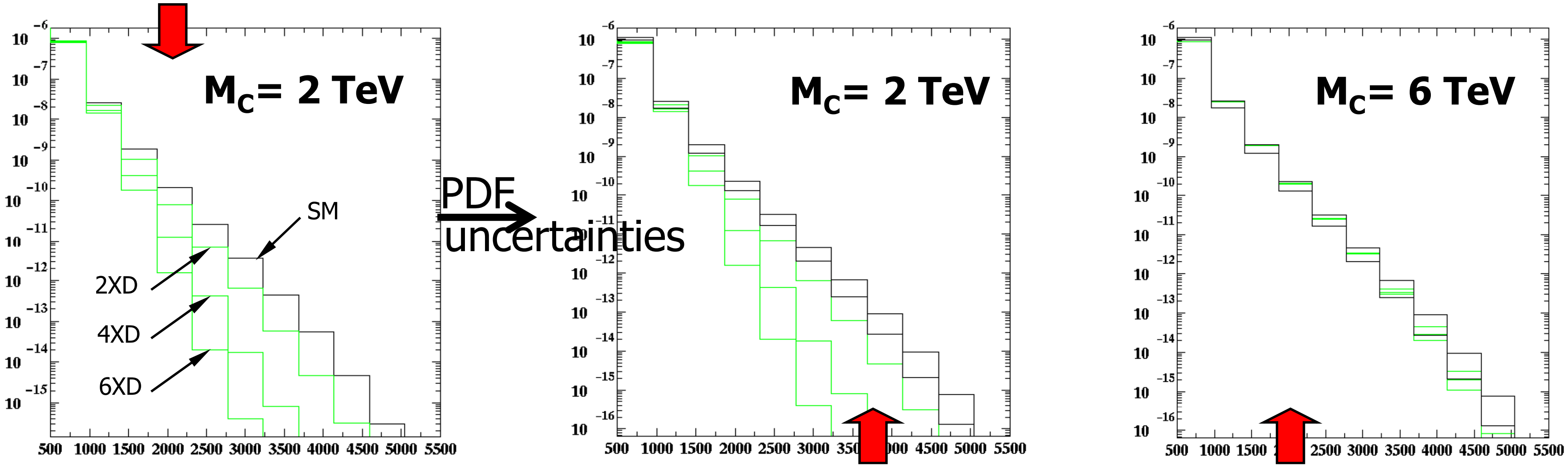
Theoretical Uncertainties

- 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)

Ferrag, hep-ph/0407303

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

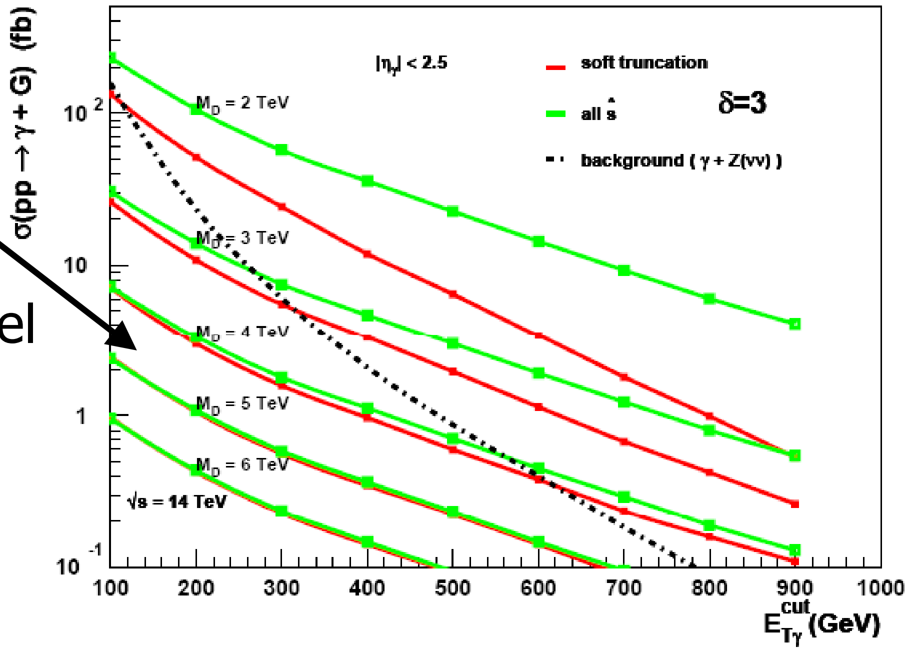
$pp \rightarrow \gamma + G^{KK}$: $qq \rightarrow \gamma G^{KK}$

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

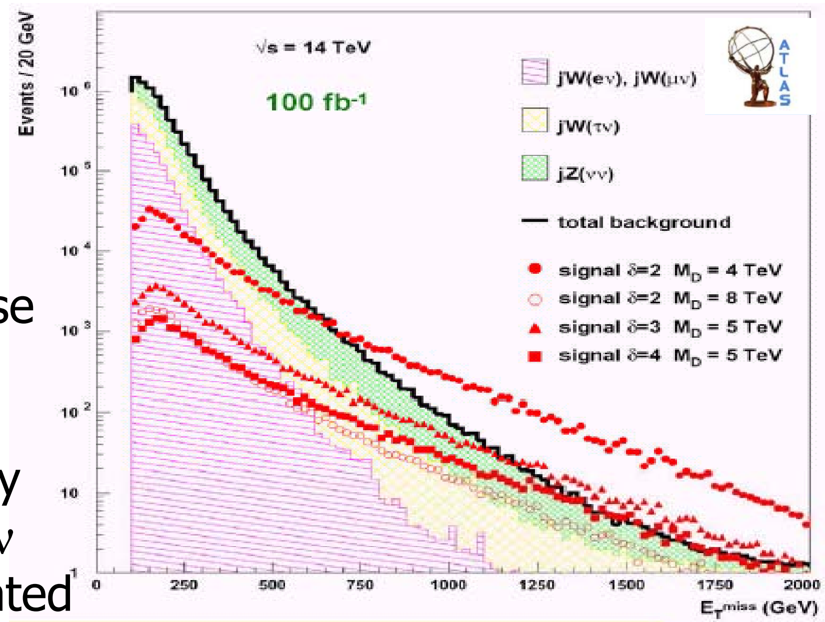
This signature could be used as confirmation after the discovery in the jet channels

ADD Discovery Limit: jet+G Emission

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

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

↖ 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.
- ❑ ISAJET with CTEQ3L
- ❑ Fast simulation/reco

Discovery limits

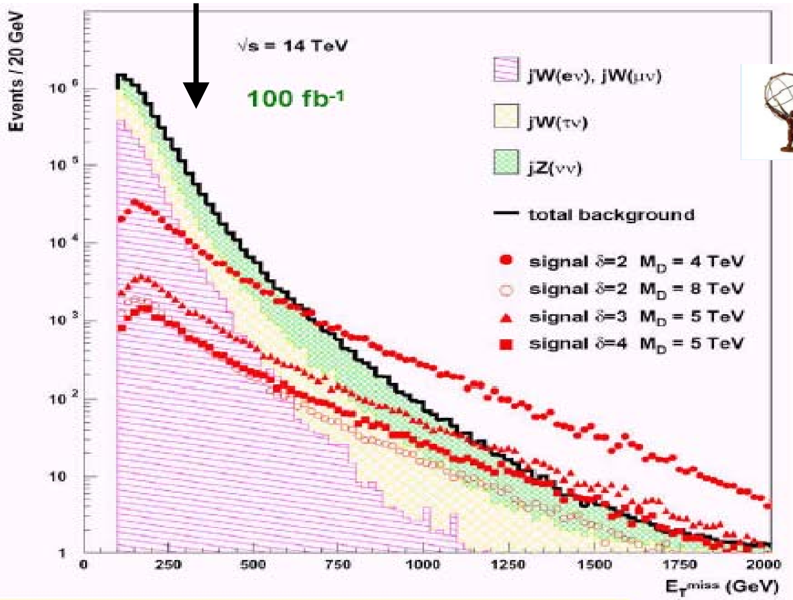
$M_{Pl(4+d)}^{MAX}$(TeV)	δ=2	δ=3	δ=4
LL 30fb^{-1}	7.7	6.2	5.2
HL 100fb^{-1}	9.1	7.0	6.0

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

ADD Parameters: jet+G Emission

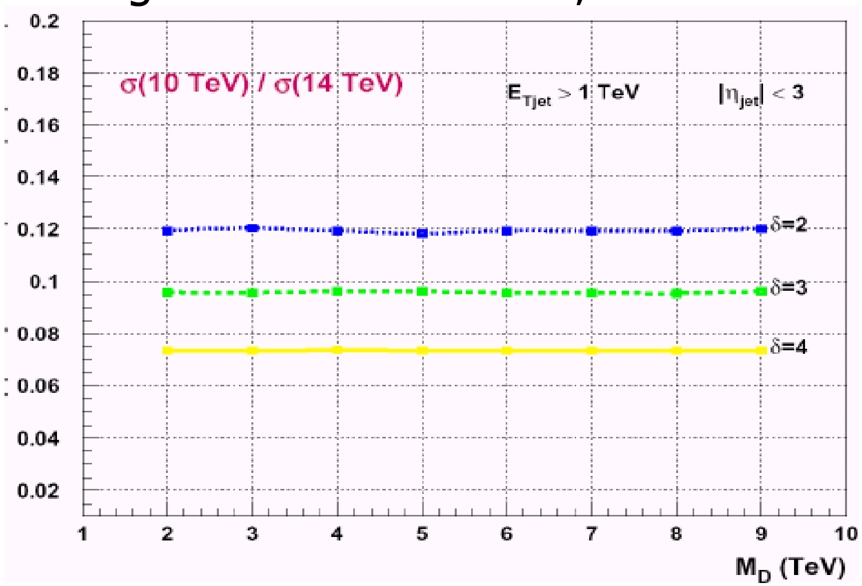
To characterise the model need to measure M_D and δ

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



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

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



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

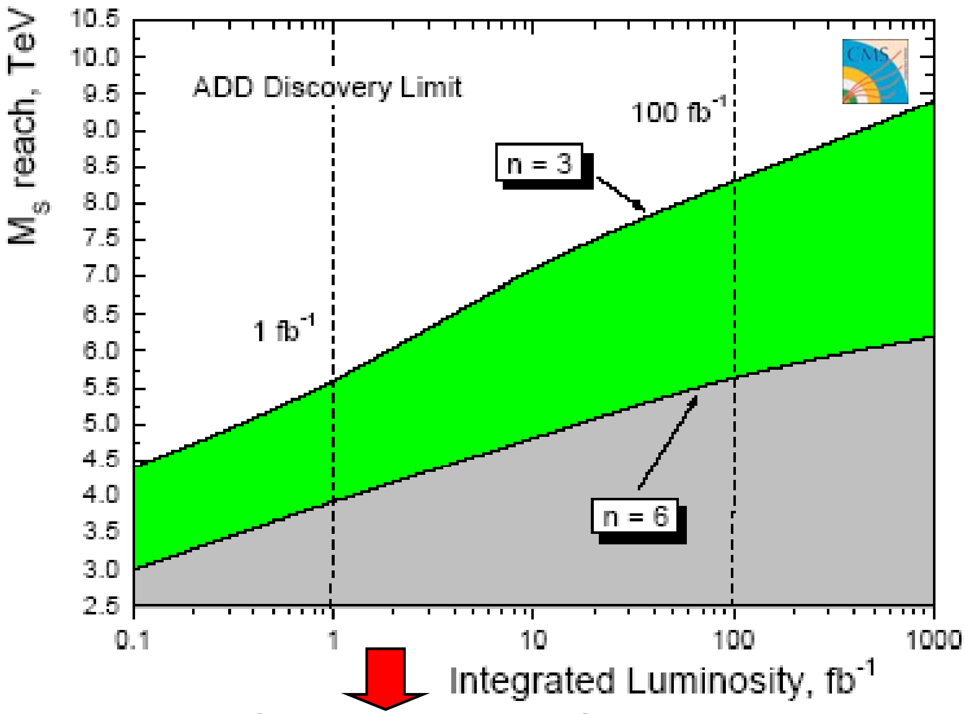
L.Vacavant, I.Hinchcliffe, ATLAS-PHYS 2000-016
J. Phys., G 27 (2001) 1839-50

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 Limits Summary

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

$\delta<=2$ ruled out

$M_D>1$TeV 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}

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

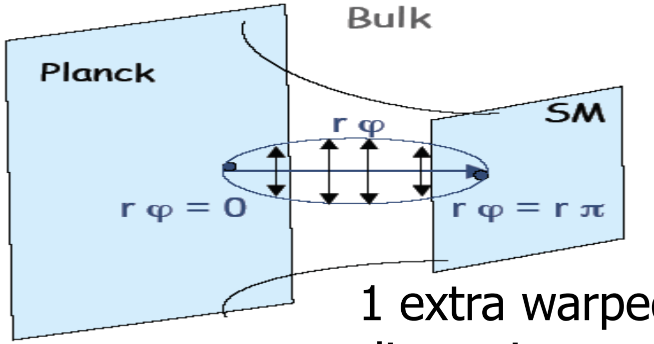
Jet+Met ATLAS

$M_{Pl(4+d)}^{MAX}$(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

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

  1st graviton excitation mass: m_1 → **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: $c = k/M_{Pl}$

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

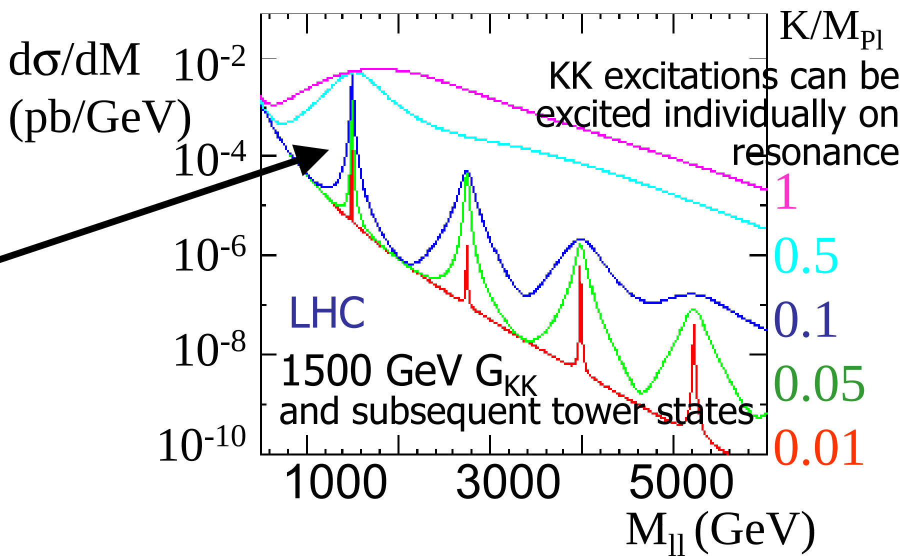
k = curvature, R = compactification radius

Signature:

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

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.

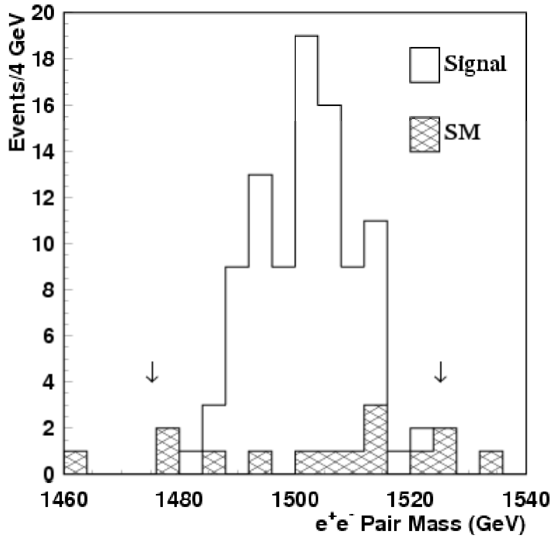
Allenach et al, JHEP 9 19 (2000), JHEP 0212 39 (2002)



Davoudiasl, Hewett, Rizzo
hep-ph0006041

RS1 Discovery Limit

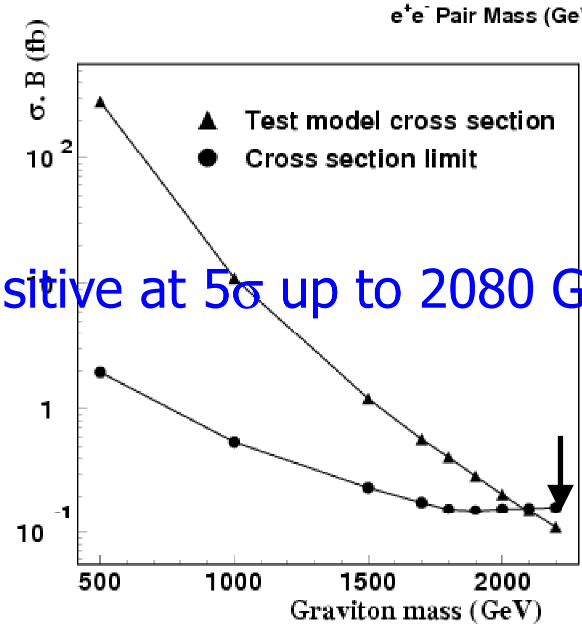
- Best channels to search in are G(1)→e+e- and G(1)→γγ due to the energy and angular resolutions of the LHC detectors
- G(1)→e+e- best chance of discovery due to relatively small bkdg, from Drell-Yan*



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

Tracey Berry

SUSY 2007, July, Karlsru

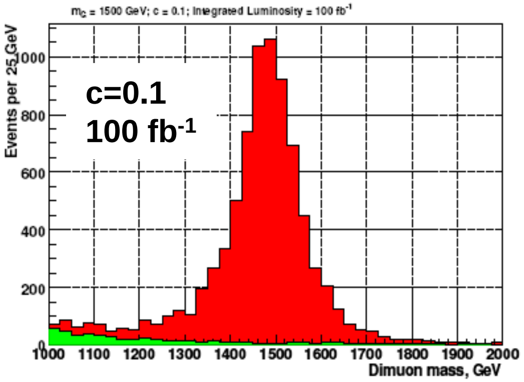
Allenach et al, hep-ph0006114

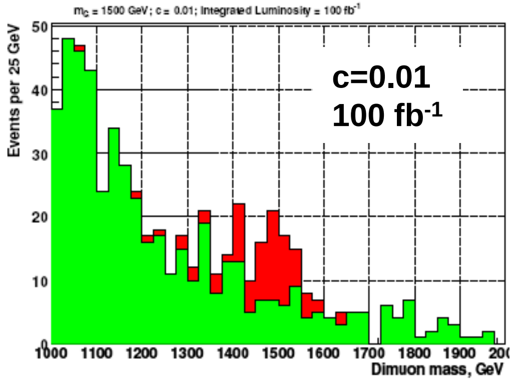
*Allenach et al, hep-ph0211205

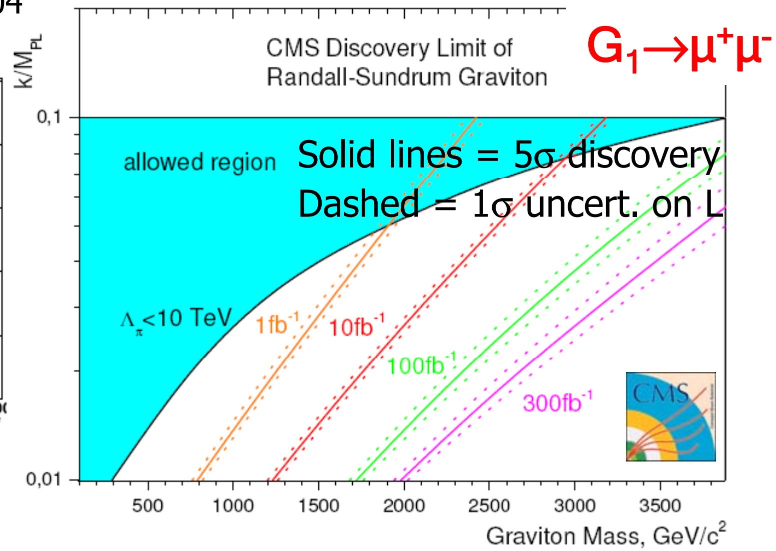
RS1 Discovery Limit

Di-lepton states

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

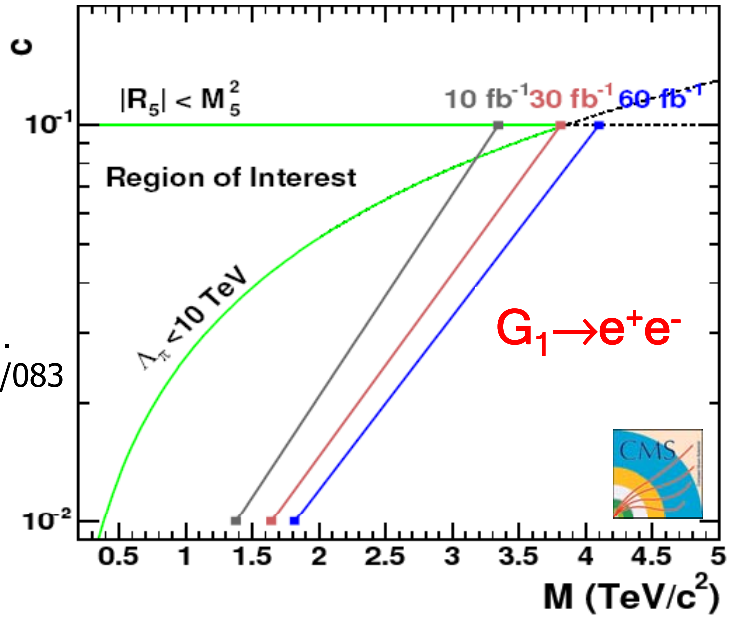






- Two muons/electrons in the final state
- Bckg: Drell-Yan/ZZ/WW/ZW/ttbar
- PYTHIA/CTEQ6L
- LO + K=1.30 both for signal and DY
- Full (GEANT-4) and fast simulation/reco
- Viable L1 + HLT(rigger) cuts
- Theoretical uncert.
- Misalignment, trigger and off-line reco inefficiency, pile-up

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

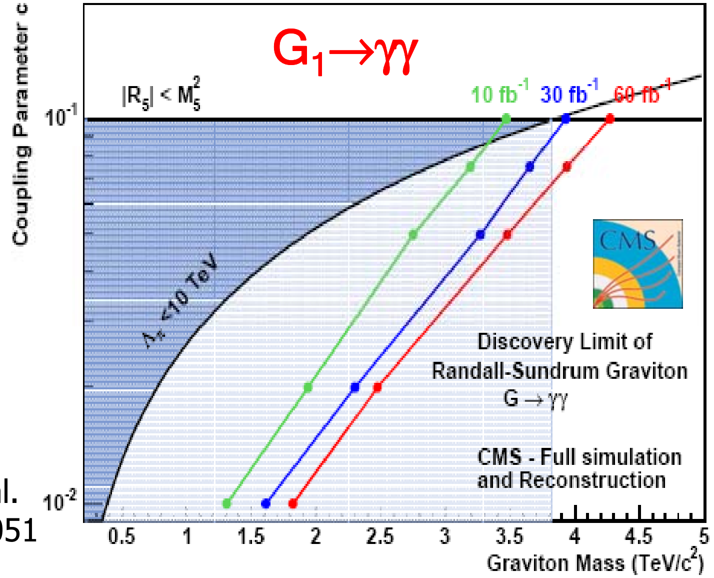


RS1 Discovery Limit

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

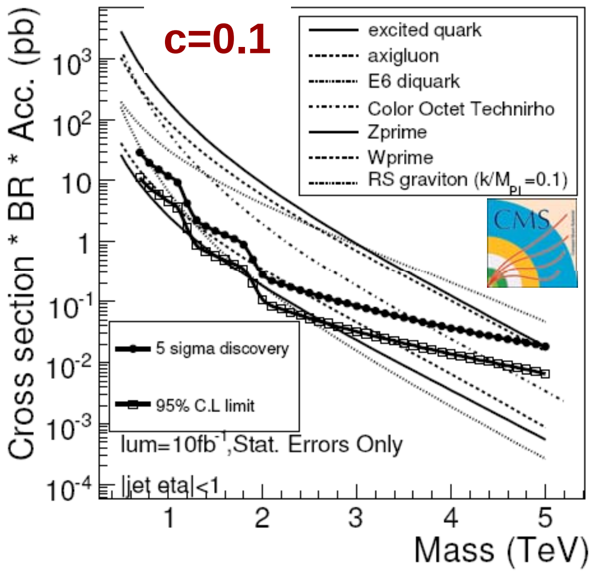
M.-C. Lemaire et al.
CMS NOTE 2006/051
CMS PTDR 2006



Di-jet states

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

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

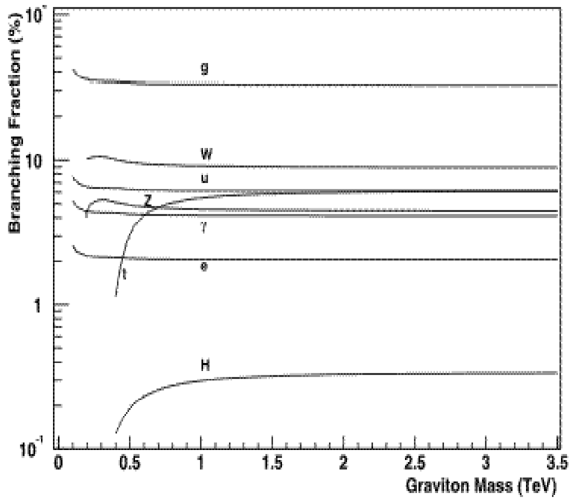


5σ Discovered Mass: 0.7-0.8 TeV/c^2

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.

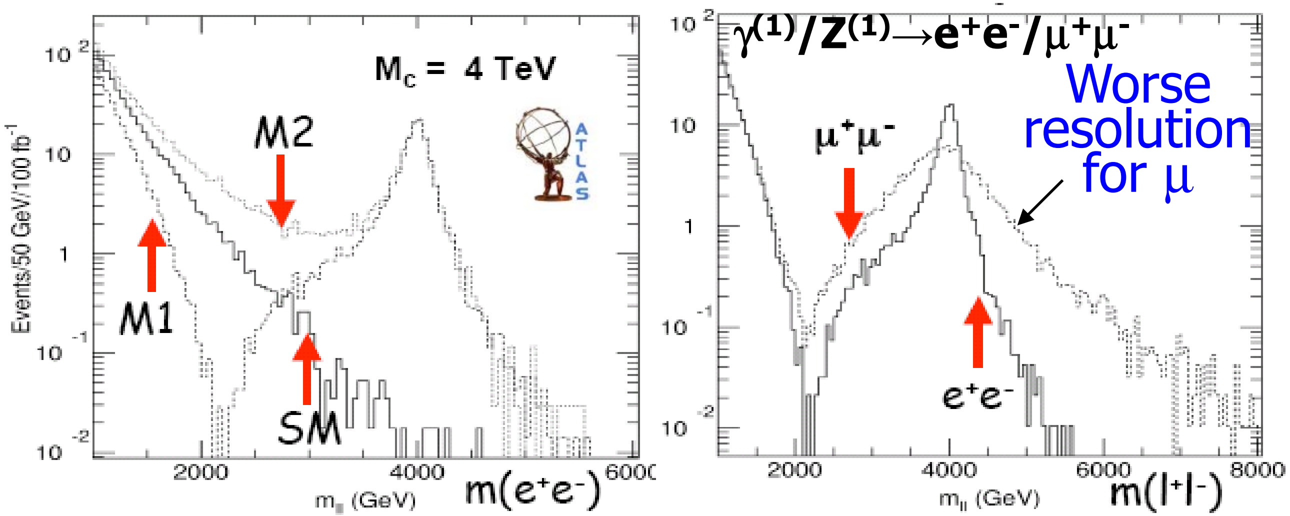
Also the size (R) of the ED could also be estimated from mass and cross-section measurements.

Allenach et al, hep-ph0211205

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

TeV^{-1} ED Discovery Limits

ATLAS expectations for e and μ:
2 leptons with Pt>20GeV in |η|<2.5, m_{ll}>1TeV
Reducible backgrounds from tt, 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)

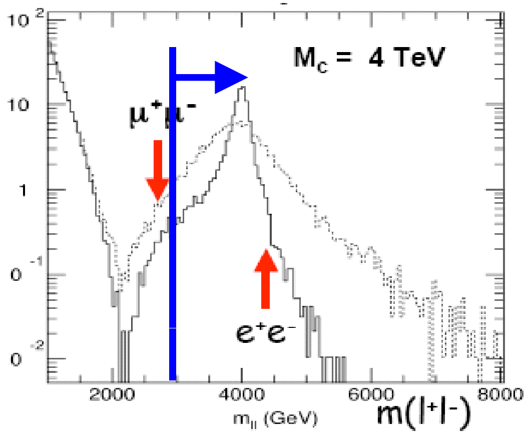
G. Azuelos, G. Polesello (Les Houches 2001 Workshop Proceedings), Physics at TeV Colliders, 210-228 (2001)

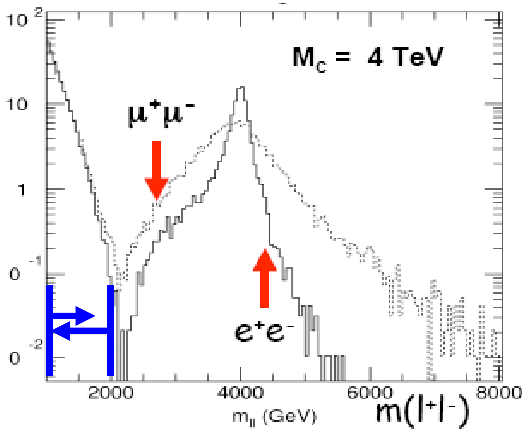
TeV^{-1} ED Discovery Limits

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

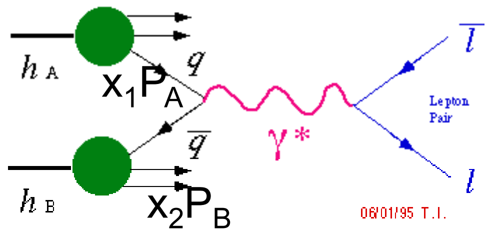
Several Methods have been used to determine the discovery limits for this signature: model independent & dependent

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





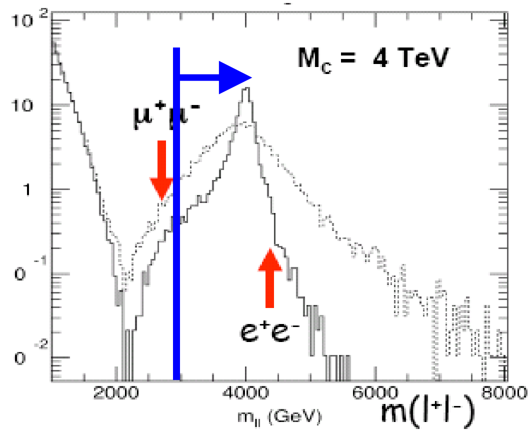
Event kinematics* can be fully defined by the 3 variables



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

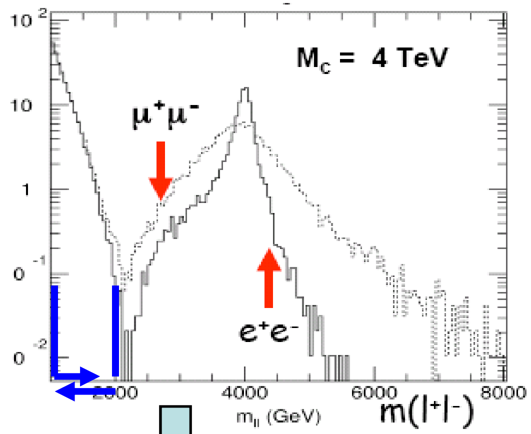
$$S = (N-N_B)/\sqrt{N_B} > 5$$

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

Method 2: Mass Window

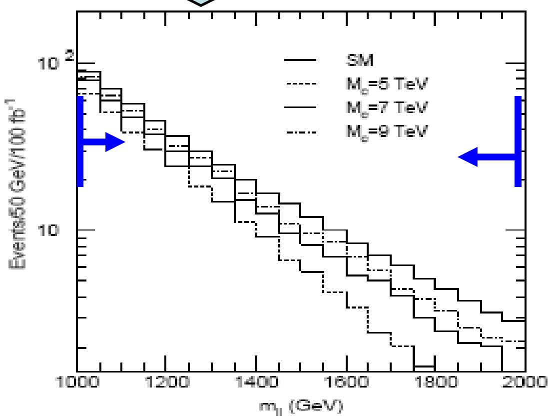
1st approach to study the **off-peak** region:

- 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

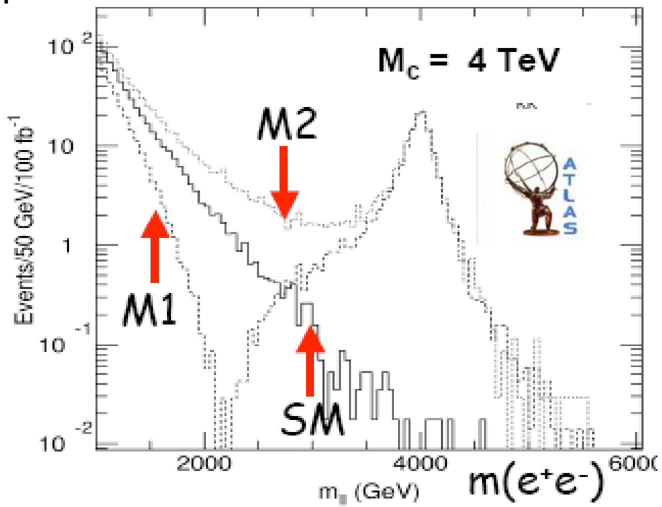
- Model Dependent

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.

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

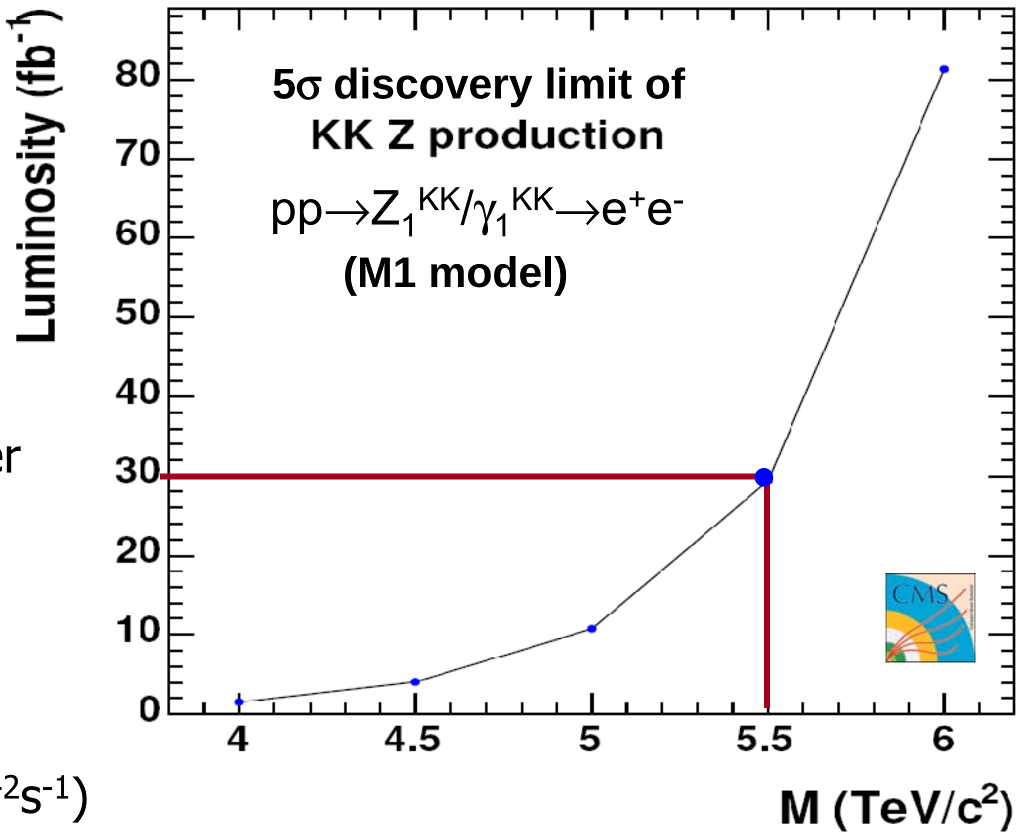


With 300 fb^{-1} can reach 13.5 TeV (ee+μμ)

TeV^{-1} ED Discovery Limits

Di-electron states (Z_{KK} decays)

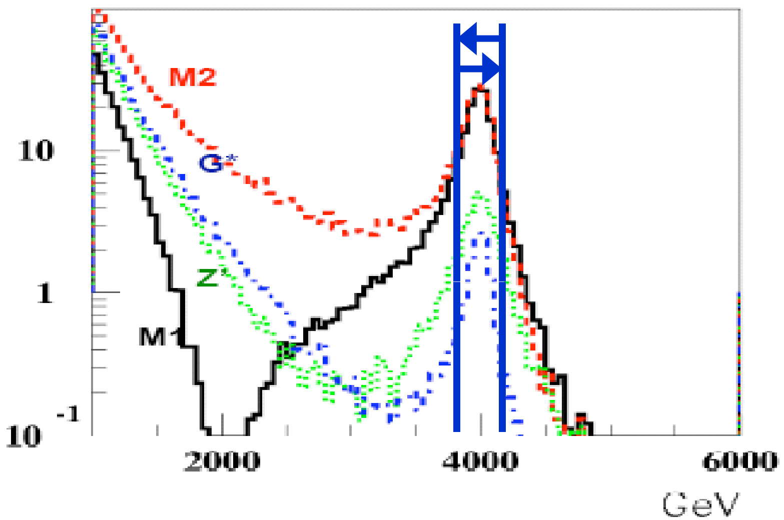
- Two high p_T isolated electrons in the final state
- Bckg: irreducible: Drell-Yan Also ZZ/WW/ZW/ttabr
- Signal and Bkgd: PYTHIA, CTEQ61M, PHOTOS used for inner bremsstrahlung production
- LO + K=1.30 for signals, LO + K-factors for bckg.
- Full (GEANT-4) simulation/reco with pile-up at low lum. ($\sim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

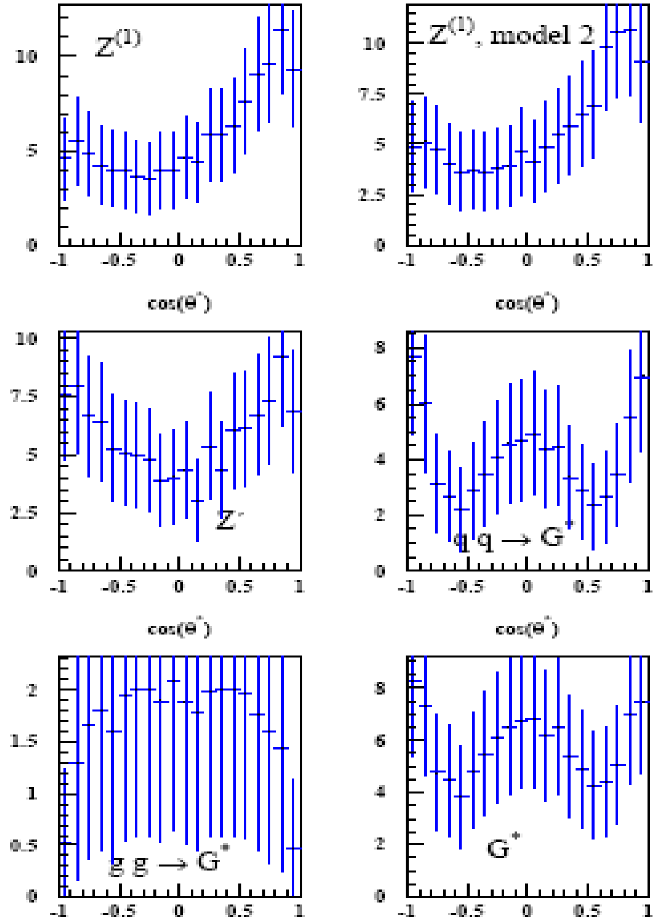
Distinguishing $Z^{(1)}$ from Z', RS G



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

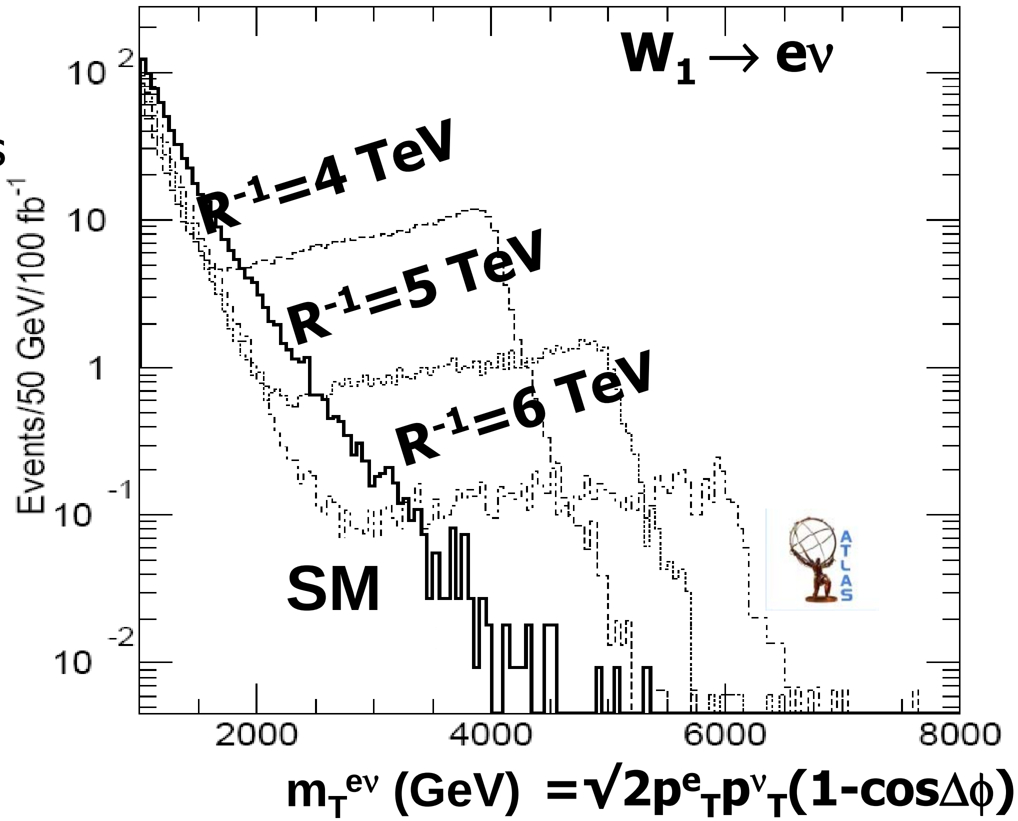
G. Azuelos, G. Polesello EPJ Direct 10.1140 (2004)

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: $W \to e\nu$, 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



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

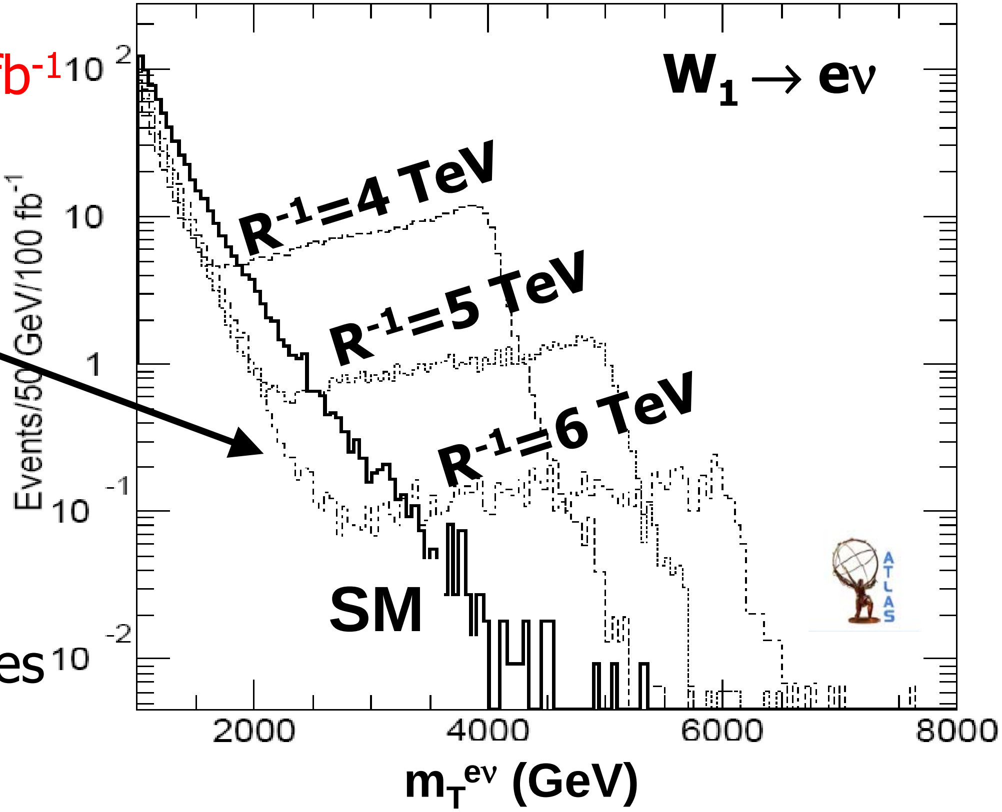
W_{KK} decays

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 $W \to \mu\nu$ since momentum spread - can't do optimised fit which uses peak edge

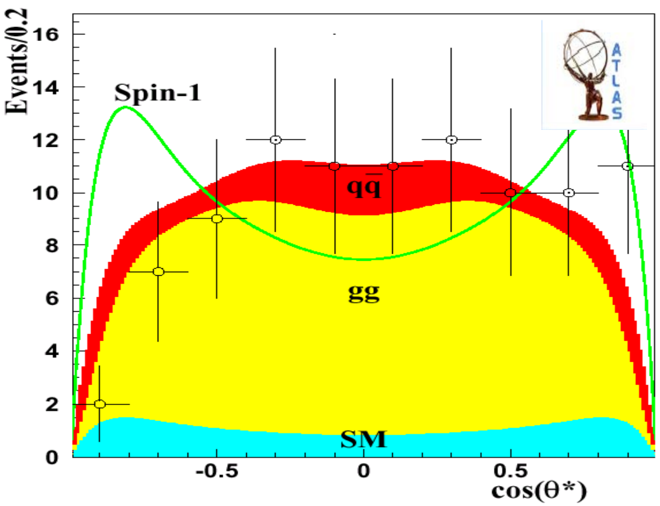
G. Polesello, M. Patra
EPJ Direct, ATLAS 2003-023
G. Polesello, M. Patra
EPJ Direct C 32 Sup.2 (2004) pp.55-67

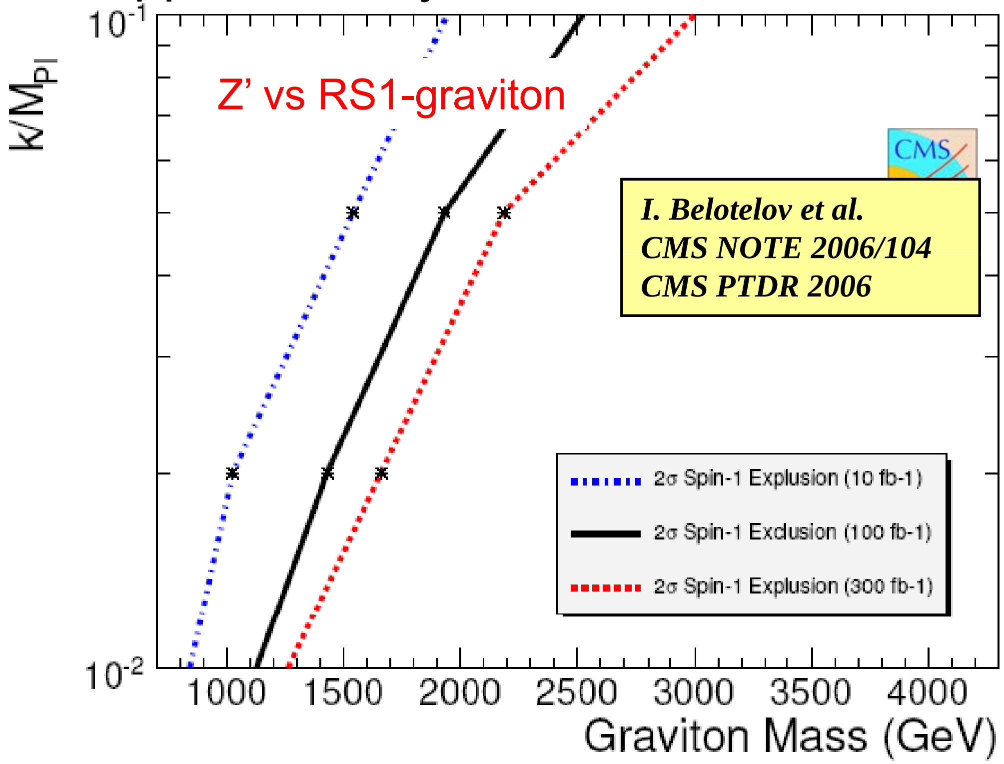
Spin-1/Spin-2 Discrimination

Spin-1 States: Z′ from extended gauge models, Z_{KK}
Spin-2 States: RS1-graviton
Method: unbinned likelihood ratio statistics incorporating the angles in of the decay products the Collins-Soper farme (R.Cousins et al. JHEP11 (2005) 046).
The statististical technique has been applied to fully simu/reco events.

Angular distributions

- $qq \to G \to ff$: $1 - 3\cos^2\theta + 4\cos^4\theta$
- $gg \to G \to ff$: $1 - \cos^4\theta$
- $qq \to G \to VV$: $1 - \cos^4\theta$
- $gg \to G \to VV$: $1 + 6\cos^2\theta + \cos^4\theta$
- DY background: $1 + \cos^2\theta$





Older results on spin discrimination from
ATLA SUSY

B.C. Allanach et al, JHEP 09 (2000) 019; ATL-PHYS-2000-029

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)

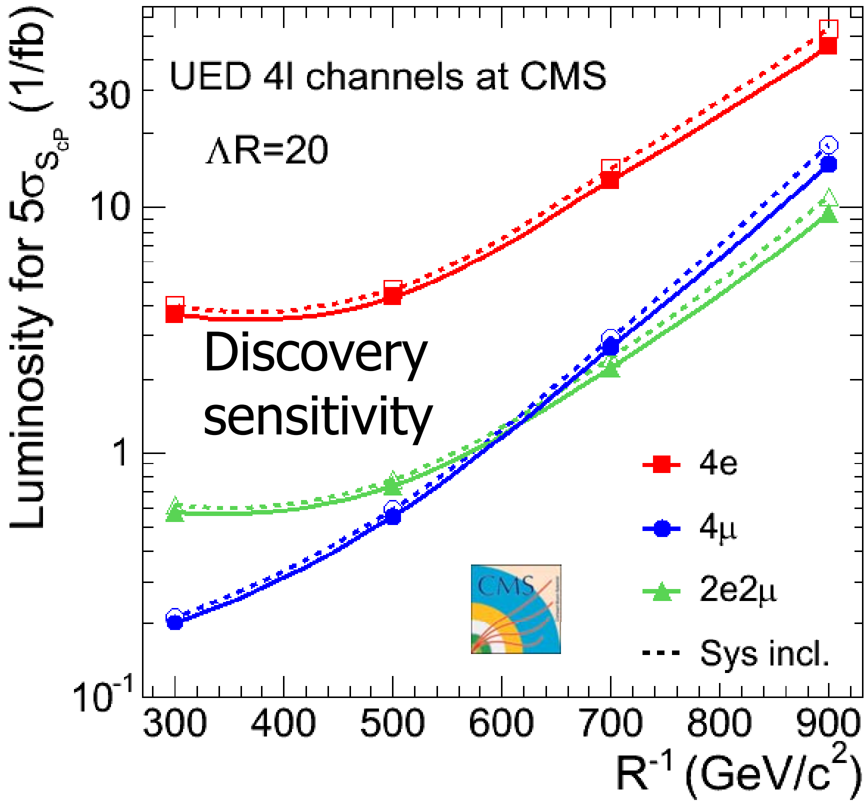
UED Discovery Limit

Standard UED

$$pp \to g_1 g_1 \to 4l + 4q + 2LKP \to 4l + 4\,jets + \not{P}_T$$
$$pp \to g_1 Q_1 \to 4l + 3q + 2LKP \to 4l + 3\,jets + \not{P}_T$$
$$pp \to Q_1 Q_1 \to 4l + 2q + 2LKP \to 4l + 2\,jets + \not{P}_T$$

- ❑ 4 leptons in the final state + missing p_T
- ❑ Irreducible Bckg: ttbar + n jets (n = 0,1,2), 4 b-quarks, ZZ, Zbbar
- ❑ To improve bkdg rejection over signal: apply b-tagging and Z-tagging vetoes
- ❑ CompHEP for signal and CompHEP, PYTHIA, Alpgen for bckg. with CTEQ5L
- ❑ Full simulation/reco + L1 + HLT(rigger) cuts
- ❑ Theoretical and experimental uncert.

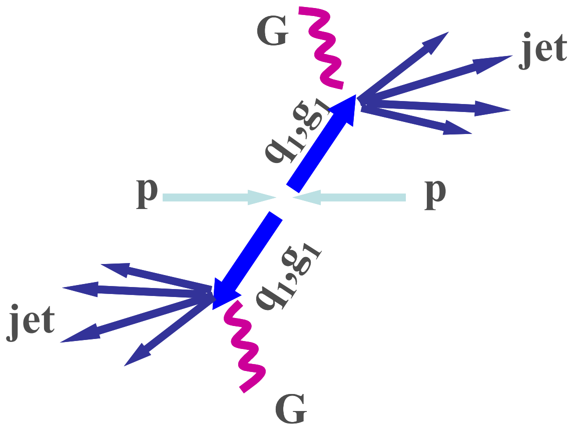
Studied for low lum run ~$2\times10^{33}cm^{-2}s^{-1}$



UED Discovery Limit

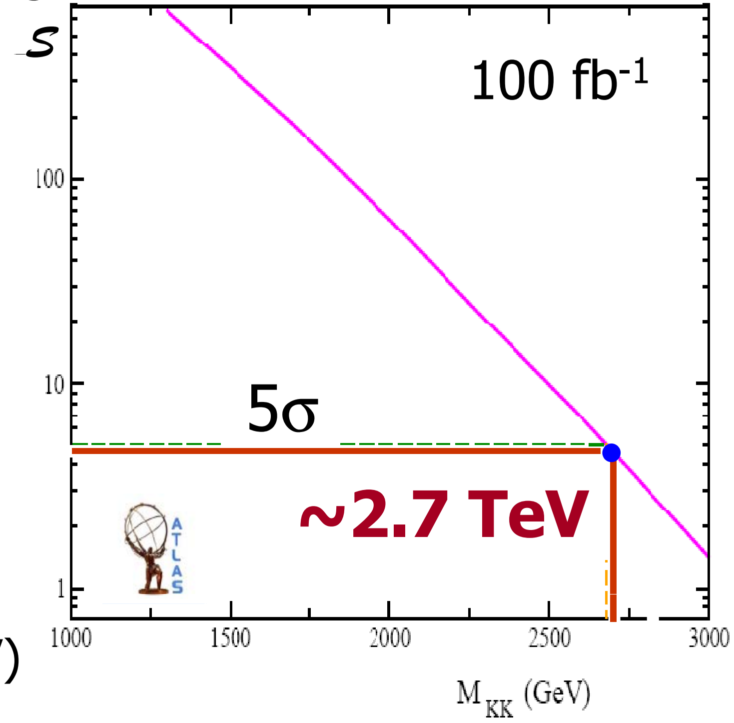
Thick brane in UED with TeV^{-1} size

$$pp \to g_1 g_1 / q_1 g_1 / q_1 q_1 \to 2\,jets + \not{E}_T$$



- 2 back-to back jets + missing E_T (>775 GeV)
- Irreducible Bckg: Z(→νν) jj, W(→lν) jj
- PYTHIA/CTEQ5L + SHERPA for bckgr.
- Fast simulation/reco

Significance vs Mass of 1st KK excitation

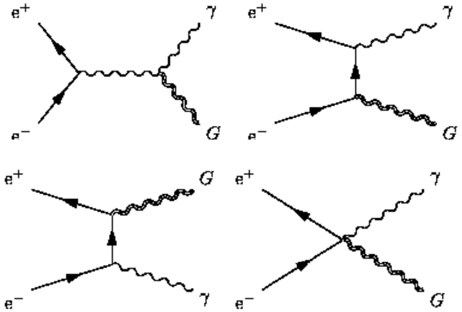


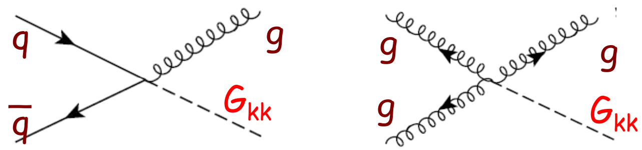
5σ discovery possible at ATLAS with 100 fb^{-1} if first KK excitation mass < 2.7 TeV

Present ADD Emission Limits

Royal Holloway University of London

LEP and Tevatron results are complementary





For n>4: CDF limits best

jet+ME$_T$

Tevatron better at large values of n, because of the higher energy, which is a bigger effect at larger values of n.

$\sigma\ \alpha$ total number of possible modes in the KK tower N_{KK}

$\sigma\ \alpha\ N_{KK}\ \alpha\ \sqrt{}$(s-hat)

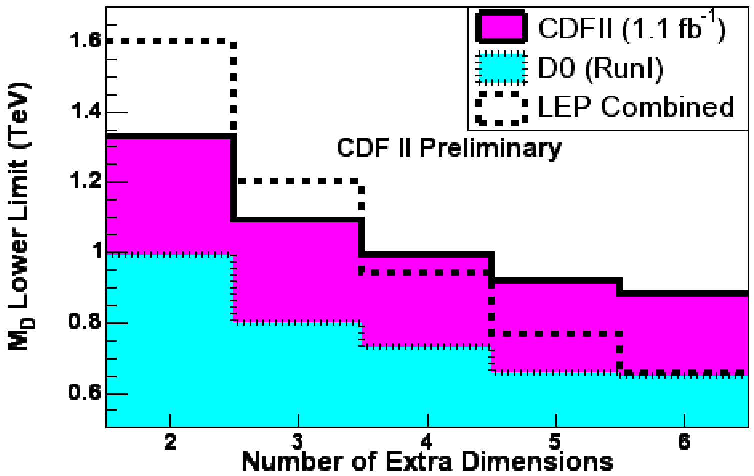
But this is true for each ED, so $\sigma\ \alpha\ (\sqrt{}(\text{s-hat}))^n$

$\Rightarrow$the difference in energy is a bigger effect for n=6 than n=2

For n<4: LEP limits best

γ+ME$_T$

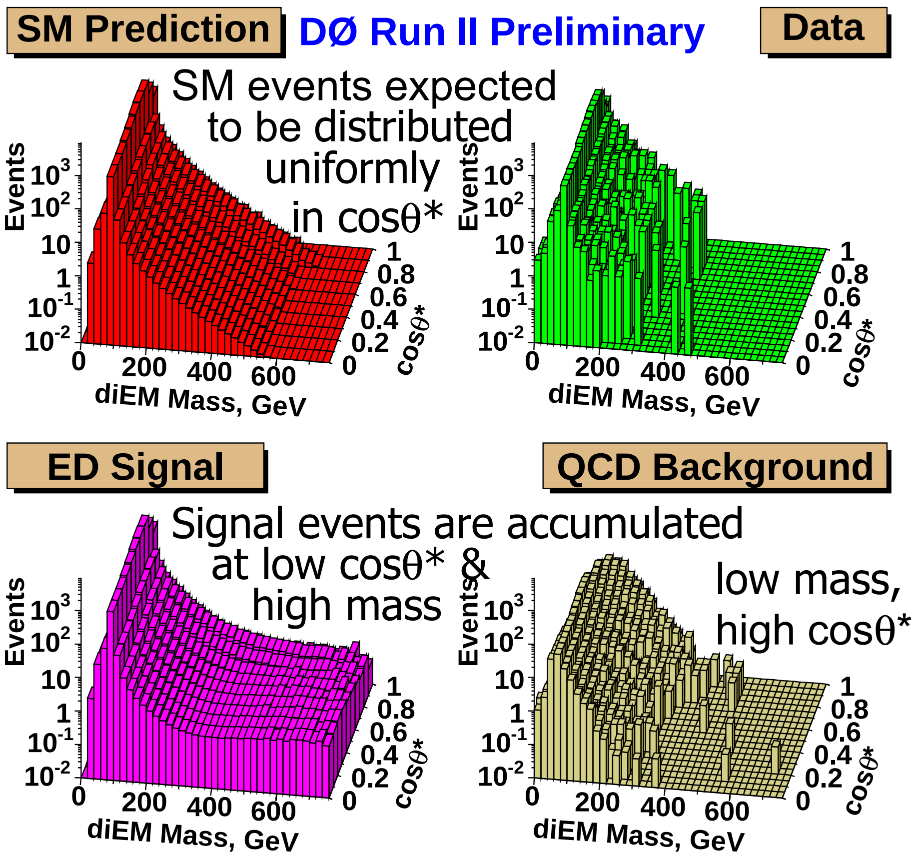
γ+ME$_T$ at LEP is cleaner & has lower backgrounds than jet+ME$_T$ (Tevatron), so the precision of their experiments wins out for lower values of n



D0 ee+γγ ADD LED

Use all the information of the event – can gain in sensitivity

D0 perform a combined fit of the invariant mass and angular information (cosθ*) spectrum to extract limits



- Parameterise σ in terms of

$$\eta = \lambda / M_s^4$$

$$\sigma = \underbrace{\sigma_{SM}}_{\text{SM}} + \underbrace{\eta\sigma_{INT}}_{\text{Interference}} + \underbrace{\eta^2\sigma_{KK}}_{\text{ED term}} + \underbrace{\sigma_{BG}}_{\text{Background}}$$

- 3D templates used to set limits

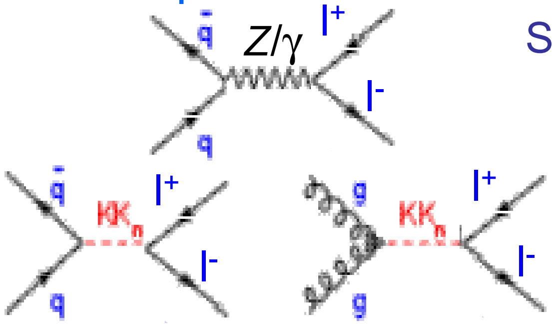
Whereas CDF did general 200 pb^{-1} search looking at invariant mass only and used same data for RS and ADD model search (as well as RPV υ and Z')

ADD: G Exchange

Search for spin-2 broad σ change

⇒ study deviations in invariant mass & angular distribution from SM processes

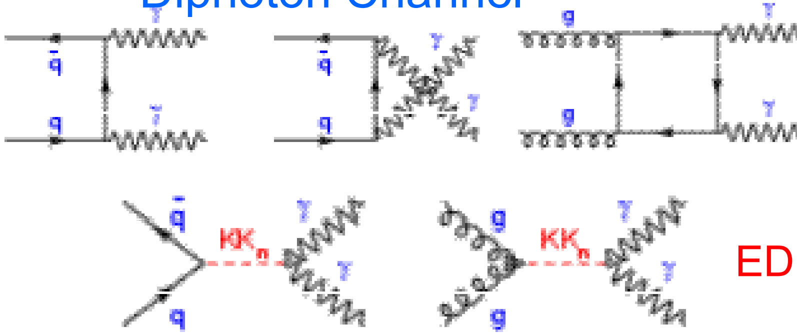
Dilepton Channel



SM

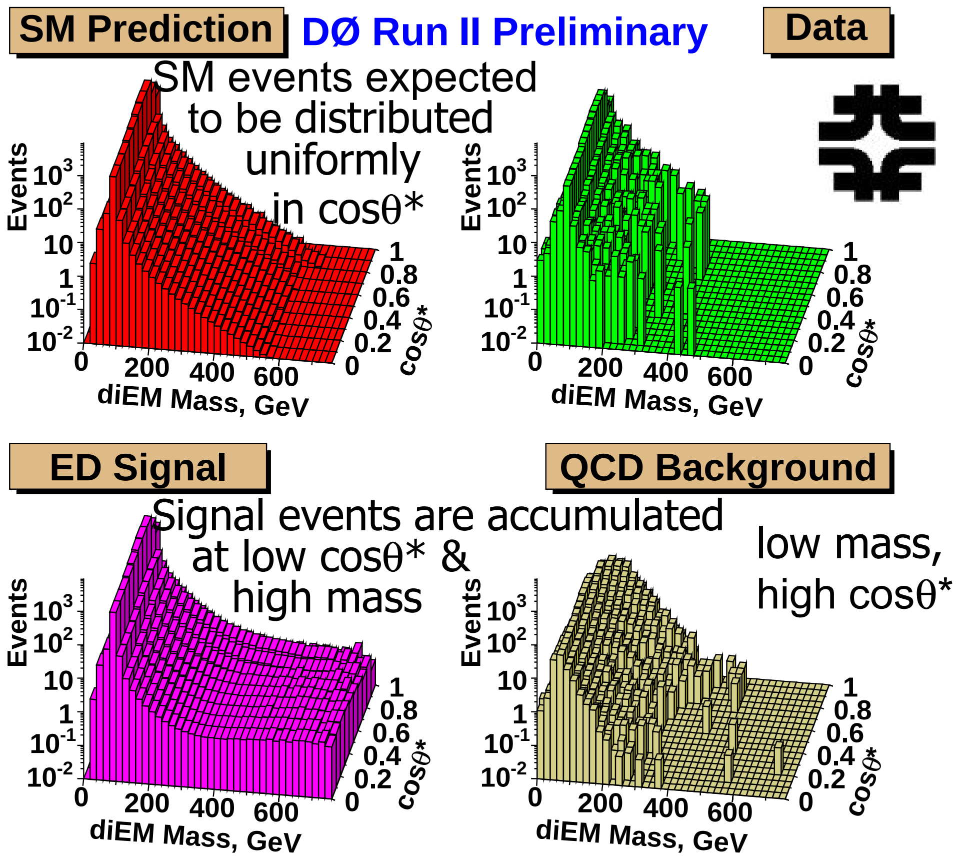
ED

Diphoton Channel



SM

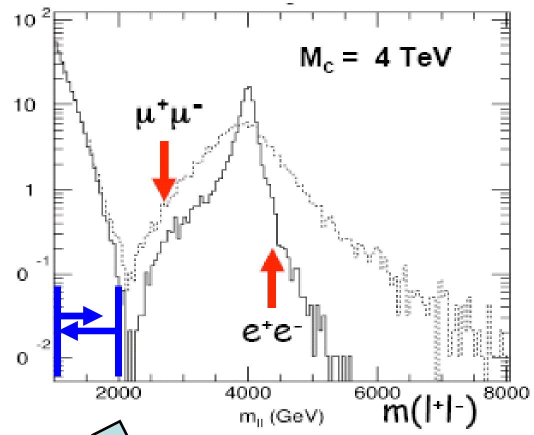
ED



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

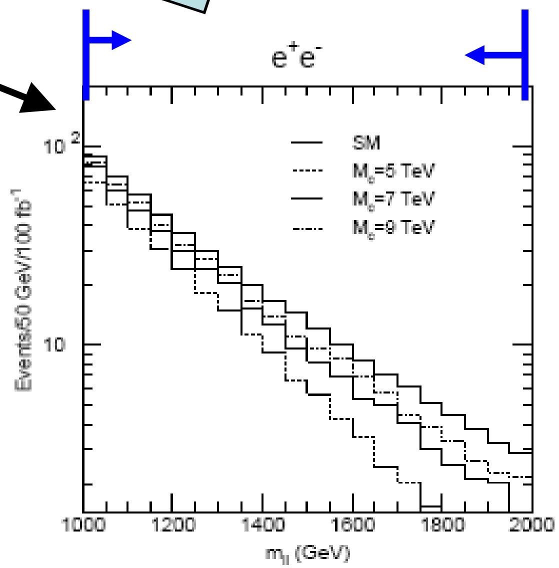


Consideration of the mass interval

- The statistical significance somewhat increases by lowering the lower limit of the considered mass window, at the price of a worse N/N_B.
- Systematic uncertainty in knowledge of the m_{ll} shape sets a limit on the detectable ratio: N/N_B

Deviation from the SM is 15 % for 8 TeV reach and ~ 10 % for 10.5 TeV:

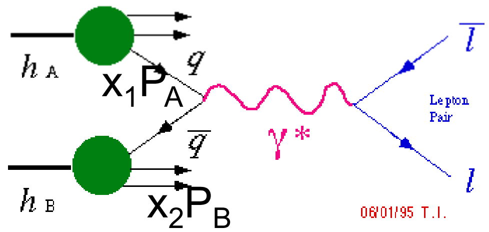
This defines the level of systematic control on the relevant region of SM m_{ll} needed to exploit the statistical power of the data.



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: x_1, x_2, cos theta

Where x_i is the fraction of the proton momentum carried by parton i and theta is the scattering angle in the partonic centre of mass system.

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

$2P_L^{ll}/\sqrt{s} = x_1 - x_2$, $m_{ll}^2 = x_1 x_2 s$ P_L =4-momentum of the detected lepton

In the Collins-Soper convention: in which there is equal sharing of the l^+l^- system transverse momentum between the quarks

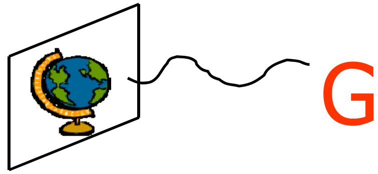
*Ignoring the transverse momentum of the l^+l^- system

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

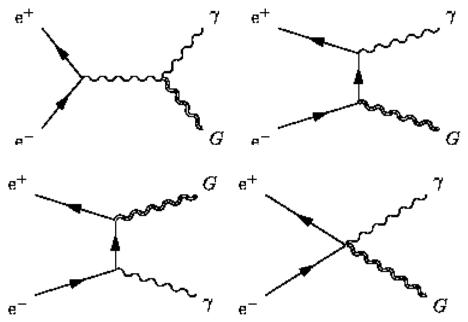
Can detect at collider detectors via:

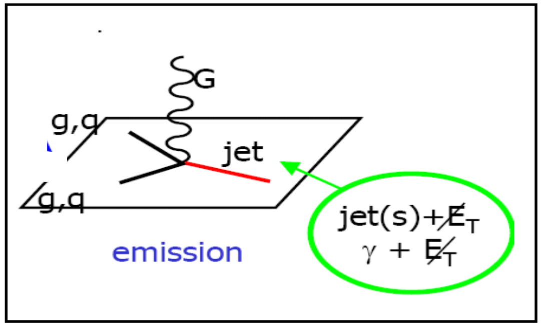
- graviton emission
- Or graviton exchange

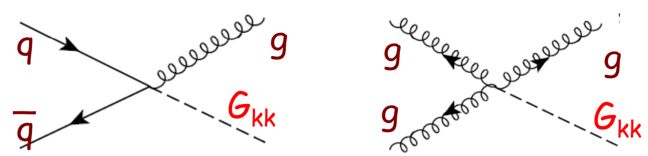
*Cullen, Perelstein
Phys. Rev. Lett 83,268 (1999)

Present ADD Emission Limits

LEP and Tevatron results are complementary

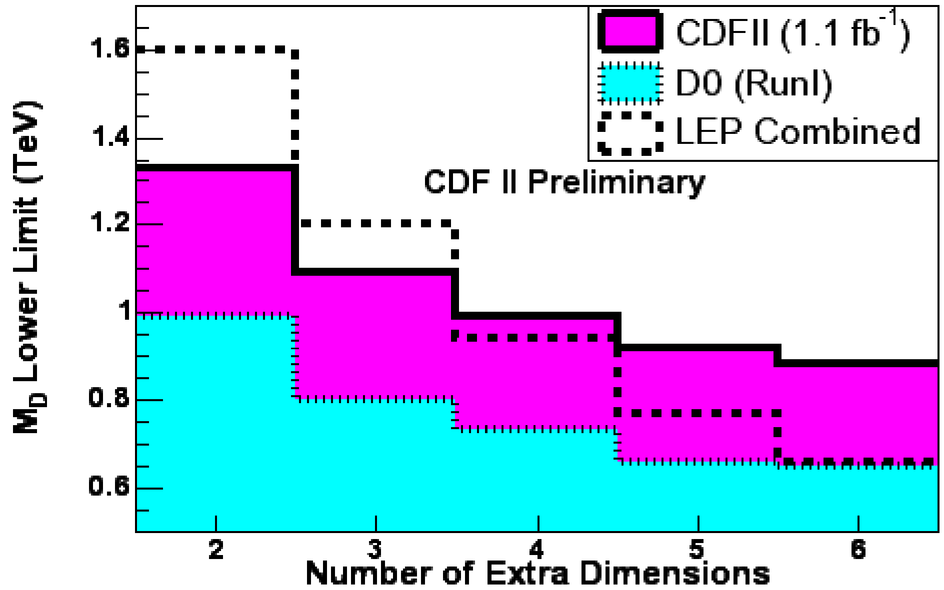






For n>4: CDF limits best jet+ME_T

For n<4: LEP limits best γ+ME_T



n	M_D (TeV/c^2) K=1.3	R (mm)
2	> 1.33	<0.27
3	> 1.09	< 3.1×10^{-6}
4	> 0.99	< 9.9×10^{-9}
5	> 0.92	< 3.2×10^{-10}
6	> 0.88	< 3.1×10^{-11}

Tevatron ADD Exchange Limits

Both D0 and CDF have observed no significant excess

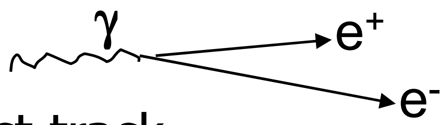
95% CL lower limits on fundamental Planck scale (M_s) in TeV, using different formalisms:

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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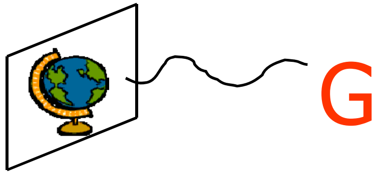


- $\delta=1 \rightarrow R \sim 10^{13}$ cm, ruled out because deviations from Newtonian gravity over solar distances have not been observed
- $\delta=2 \rightarrow R \sim 1$ mm, not likely because of cosmological arguments:

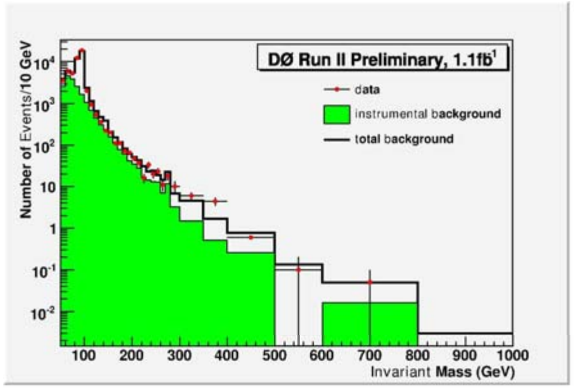
In particular graviton emission from Supernova 1987a* implies $M_D > 50$ TeV
Closest allowed $M_{Pl(4+n)}$ value for $\delta=2$ is ~30 TeV, out of reach at LHC

- LEP & Tevatron limits is $M_{Pl(4+\delta)} \sim> 1$TeV

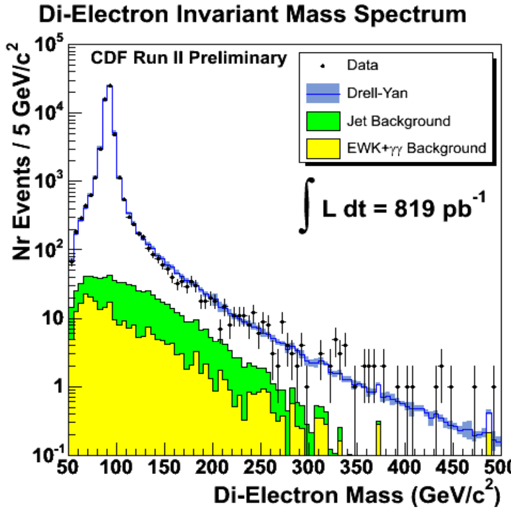
- $\delta>6$ difficult to probe at LHC since cross-sections are very low

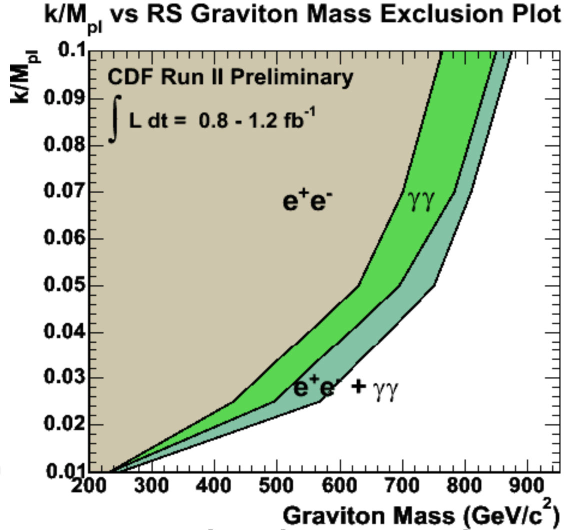
*Cullen, Perelstein
Phys. Rev. Lett 83,268 (1999)

Present RS Constraints

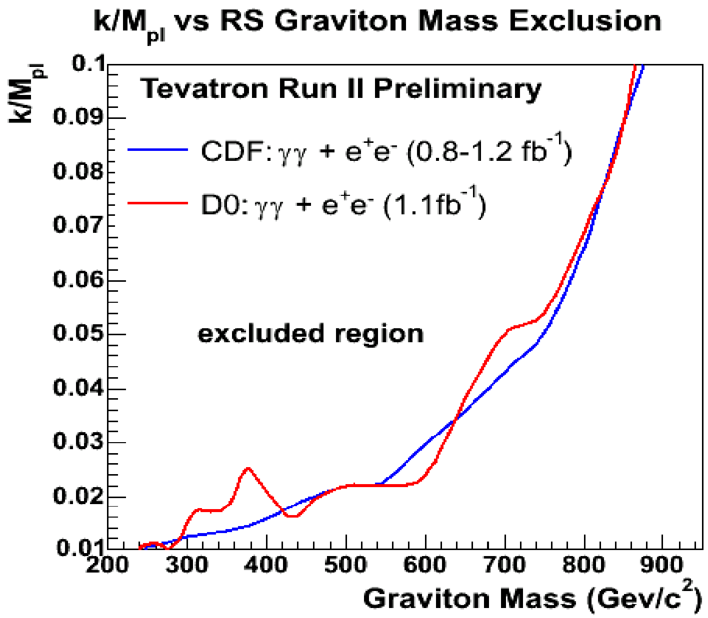


D0 performed combined ee+γγ (diem search)





CDF performed ee & γγ search, then combine



Present Experimental Limits

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

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

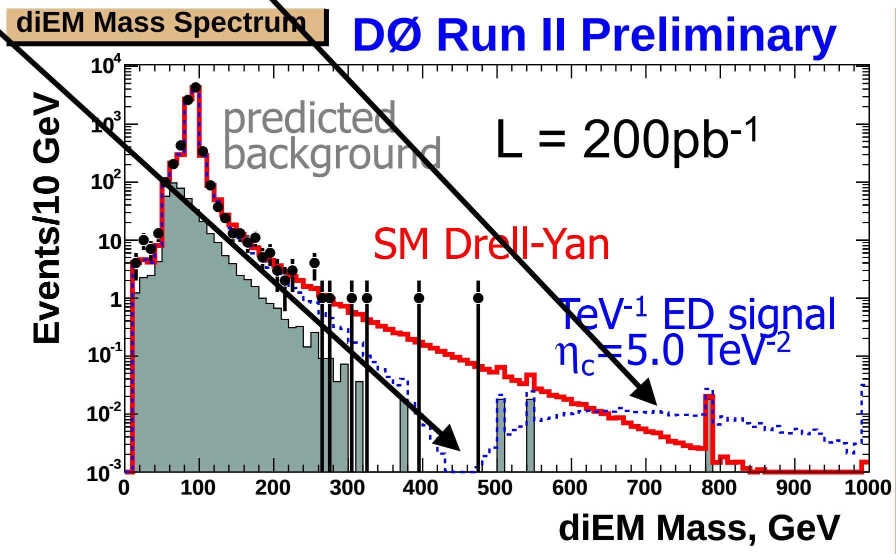
Search Signature: Signal has 2 distinct features:

- 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 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

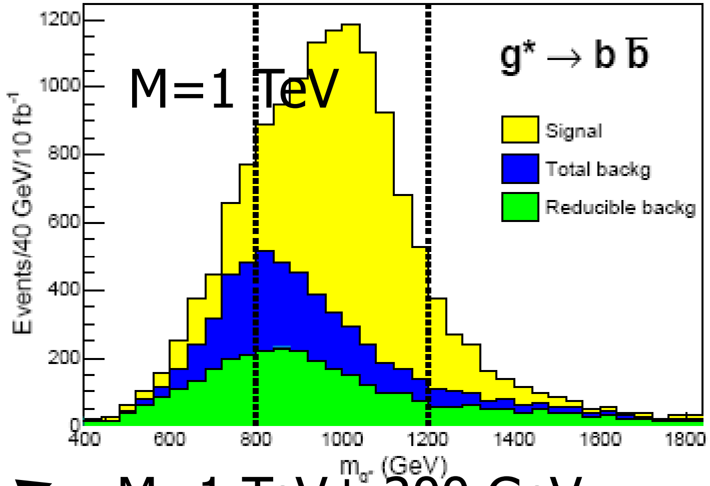
$$q\bar{q} \rightarrow g^* \rightarrow b\bar{b}, q\bar{q} \rightarrow g^* \rightarrow t\bar{t}$$

- 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

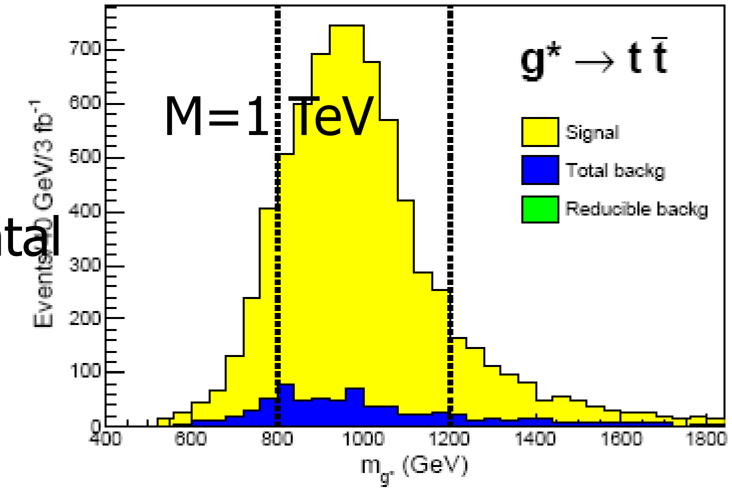
Width expected to be
$\Gamma(g^*) = 2\ \alpha_s M$ where M=g* mass
$\Rightarrow \Gamma(g^*) \sim 200$ GeV for M=1 TeV

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

Reconstructed mass peaks



M=1 TeV± 200 GeV



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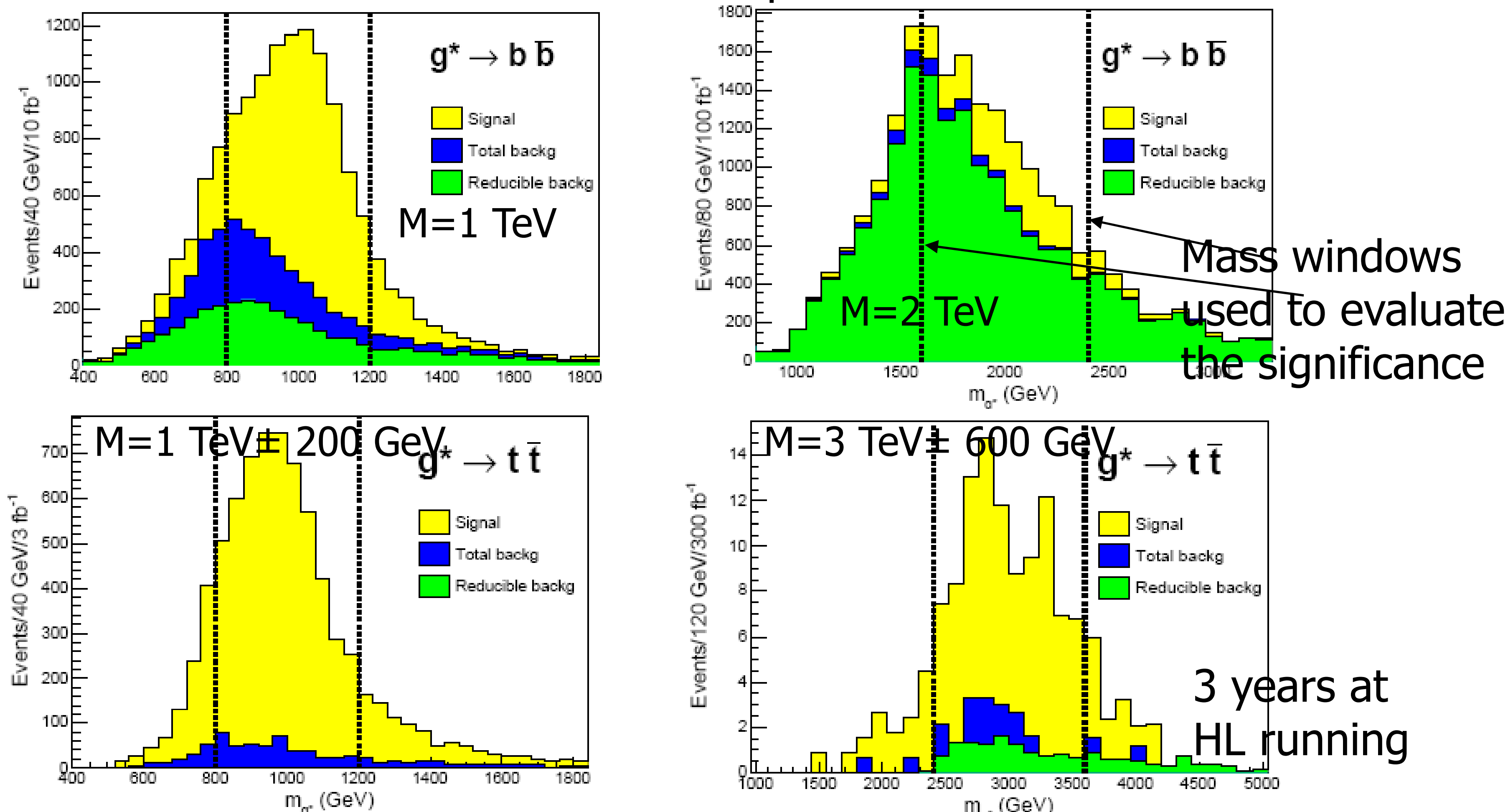
TeV^{-1} ED g* Discovery Limits

Reconstructed mass peaks



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

bbar channel: R^{-1} = 2.7 TeV ttbar channel: R^{-1} = 3.3 TeV

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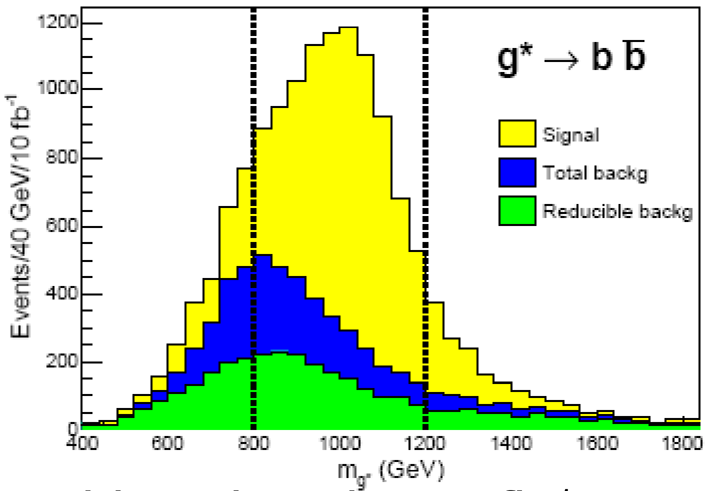
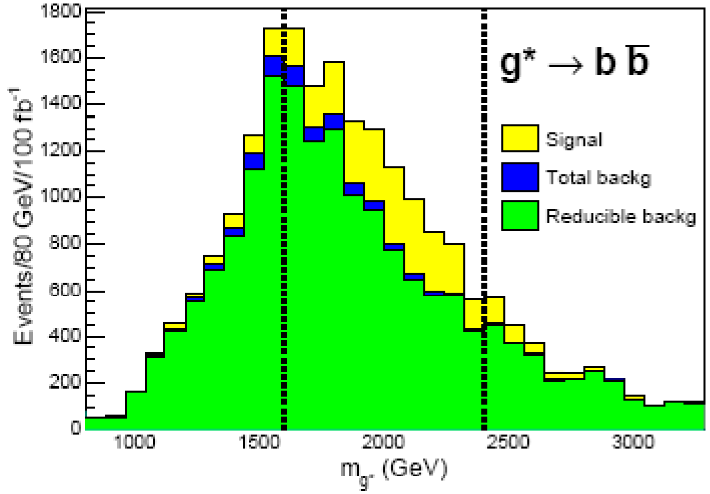
TeV^{-1} ED g* Discovery Limits

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.

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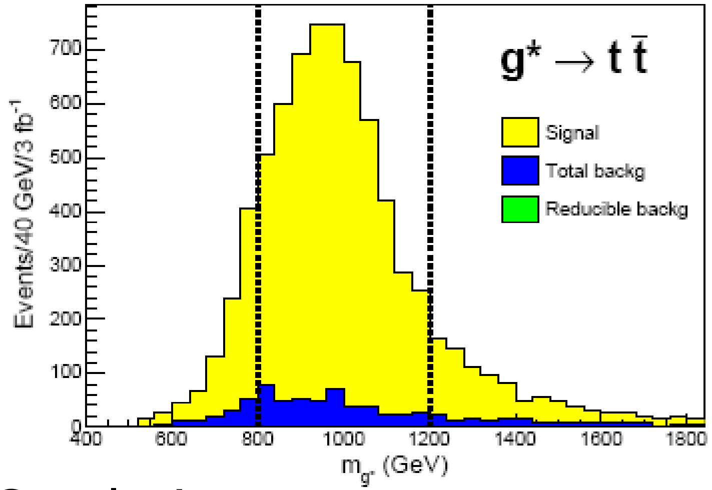
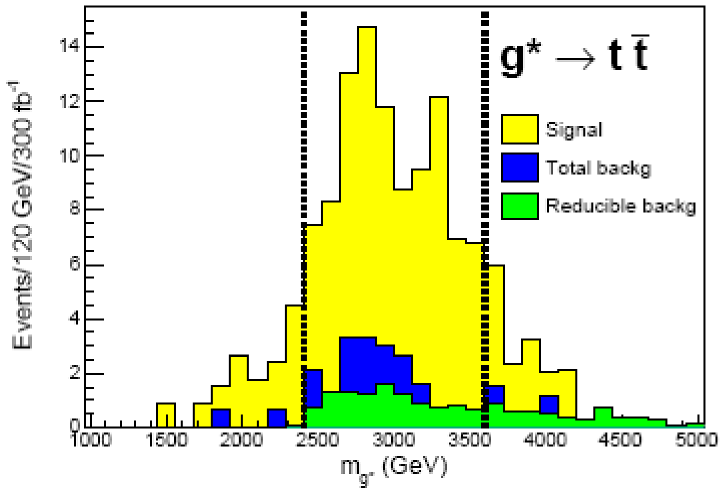
TeV^{-1} ED g* Discovery Limits

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.

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A Toroidal LHC AppartuS (ATLAS) DETECTOR

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

excellent electron/photon identification

Good E resolution (e.g., $H \to \gamma\gamma$)

Precision Muon Spectrometer,

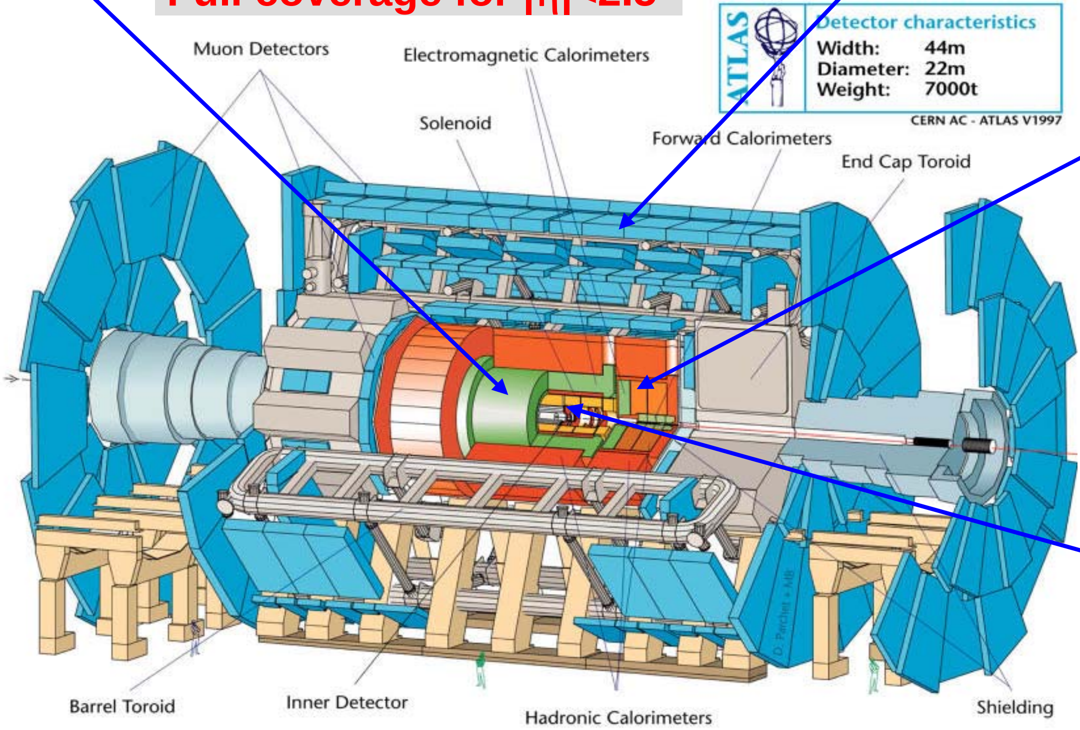
$\sigma/p_T \approx 10\%$ at 1 TeV/c

Fast response for trigger

Good p resolution

(e.g., $A/Z' \to \mu\mu$, $H \to 4\mu$)

Full coverage for $|\eta|<2.5$



Hadron Calorimeters,

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

Good jet and E_T miss performance

(e.g., $H \to \tau\tau$)

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.

$\sigma(d_0)=15\mu m@20GeV$ (e.g. $H \to bb$)

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

Compact Muon Solenoid (CMS) DETECTOR

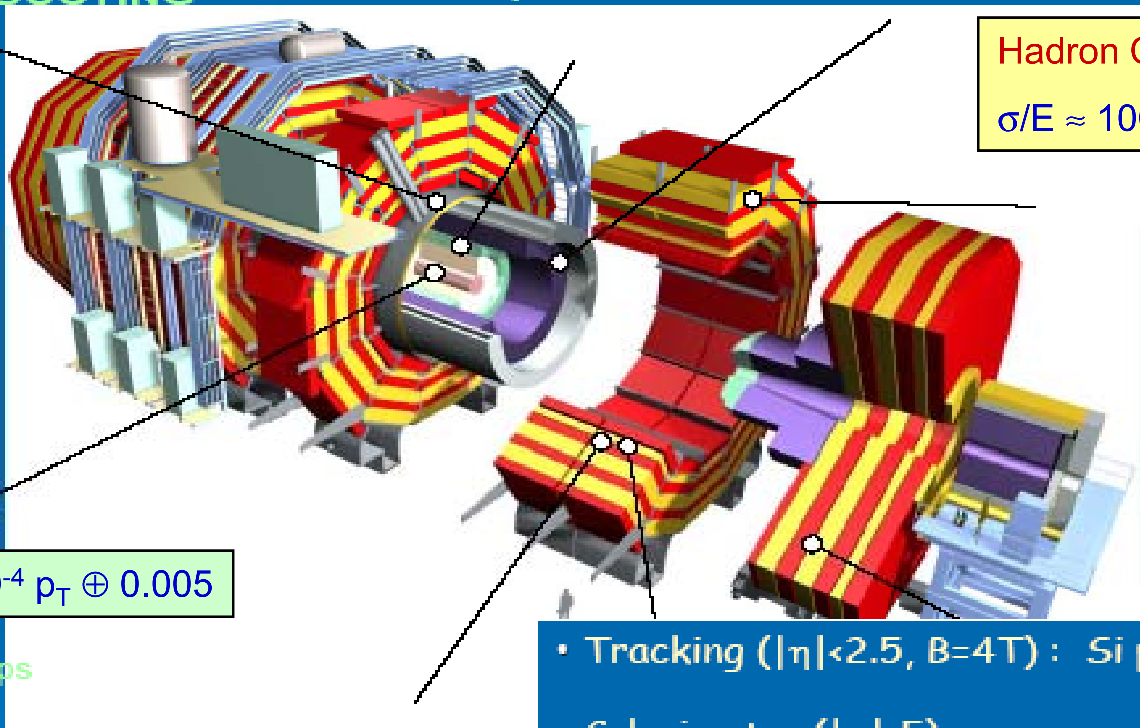
EM Calorimeter,

$\sigma/E \approx 3\%/\sqrt{E(GeV)} \oplus 0.5\%$

CALORIMETERS

Scintillating PbWO4 crystals | ECAL | HCAL | Plastic scintillator/brass sandwich

SUPERCONDUCTING COIL



Hadron Calorimeter,

$\sigma/E \approx 100\% / \sqrt{E(GeV)} \oplus 5\%$

IRON YOKE

TRACKER

$\sigma/p_T \approx 1.5 \times 10^{-4}\, p_T \oplus 0.005$

Silicon Microstrips
Pixels

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

MUON E

Drift Tube Chambers

- Tracking ($|\eta|$<2.5, B=4T) : Si pixels and strips
- Calorimetry ($|\eta|$<5) :
  -- EM : $PbWO_4$ crystals
  -- HAD: brass-scintillator (central+ end-cap), Fe-Quartz (fwd)
- Muon Spectrometer ($|\eta|$<2.5) : return yoke of solenoid instrumented with muon chambers

Muon Spectrometer,

$\sigma/p_T \approx 5\%$ at 1 TeV/c (from Tracker)

ATLAS detector

- High energy electrons are detected by LAr calorimeter.
- Muons are detected by the Muon System.
- Expected electron energy resolution is:
  - ~0.6% for E=500GeV,
  - ~0.5% for E=1000GeV.
- Muon transverse momentum (p_T) resolution is:
  - ~6% for p_T=500GeV,
  - ~11% for p_T=1000GeV.

Electron energy resolution

$$\frac{\sigma(E)}{E} = \frac{9.5\%}{\sqrt{E}} \oplus 0.45\%$$