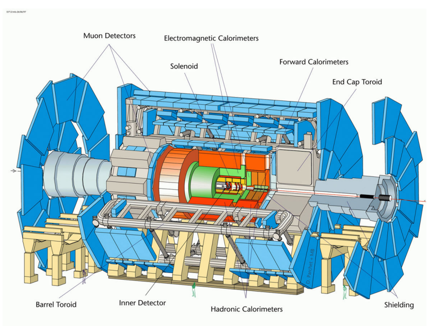
LHC &

Extra Dimensions



Dr Tracey Berry

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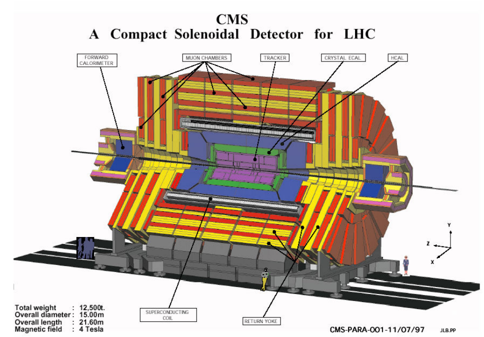
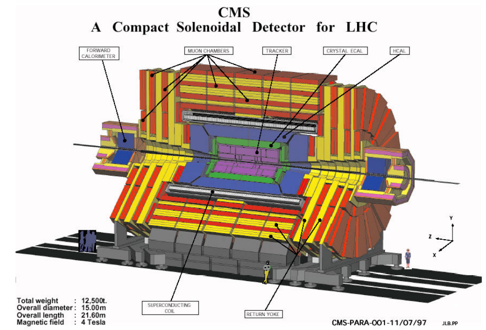
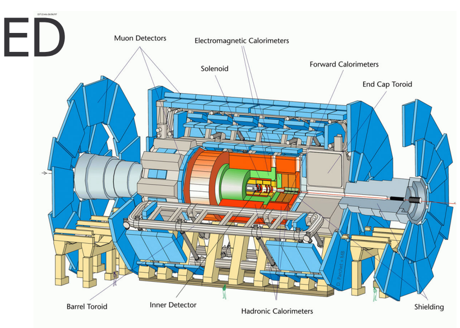


IFT

LHC & Extra Dimensions

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

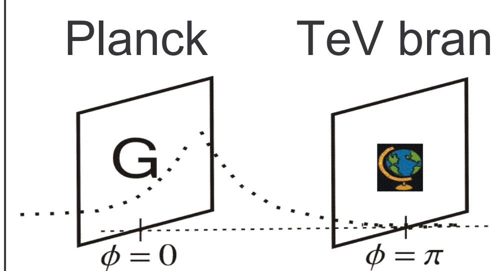
$$M_{Pl}^2 \sim R^{\delta} M_{Pl(4+\delta)}^{(2+\delta)}$$

Effective $M_{Pl} \sim$ 1TeV $\rightarrow$ if compact space (R^{δ}) is large

RS

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

1 highly curved ED
Gravity localised in the ED



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

$\Lambda_{\pi} \sim$ TeV

if warp factor kR_c ~11-12

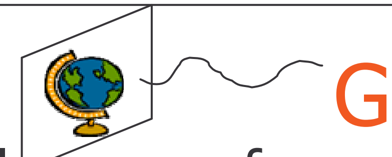
Since then, new Extra Dimensional models have been developed and been used to solved other problems:
Dark Matter, Dark Energy, SUSY Breaking, etc

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

Extra Dimensional Models

ADD

Arkani-Hamed, Dimopoulos, Dvali,
Phys Lett B429 (98)

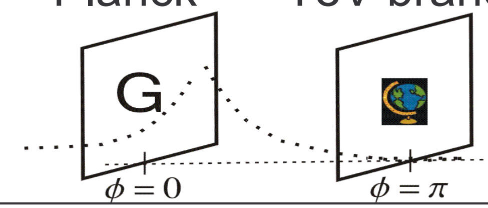


(Many) Large flat Extra-Dimensions (LED) could be as large as a few μm
In which G can propagate, SM particles restricted to 3D brane

RS

Randall, Sundrum,
Phys Rev Lett 83 (99)b

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



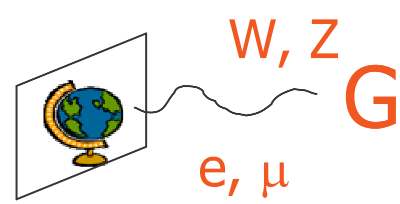
TeV^{-1} sized EDs

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

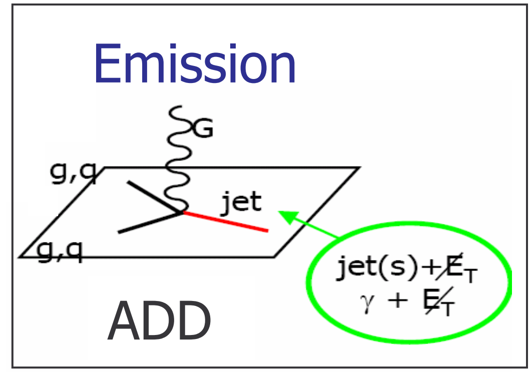
All SM particles propagate in "Universal" ED
often embedded in large ED

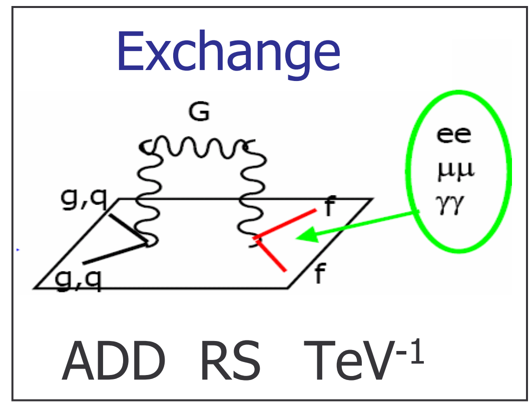


Experimental Signatures of ED

Covered in this talk

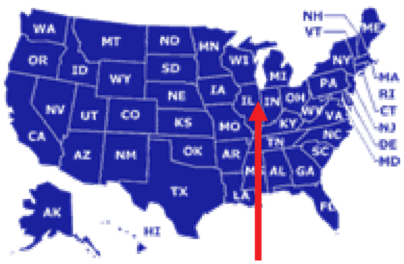
- Single jets/Single photons + missing E_T
(direct graviton production in ADD)
- Di-lepton, di-jet continuum modifications
(virtual graviton production in ADD)
- Di-lepton, di-jet and di-photon resonances
(new particles) in RS1-model (RS1-graviton) and TeV^{-1} ED model (Z^{KK})
- Single leptons + missing E_T
in TeV^{-1} ED model (W^{KK})
- Back-to-back energetic jets + missing E_T (UED)
- 4 jets + 4 leptons + missing E_T (mUED)

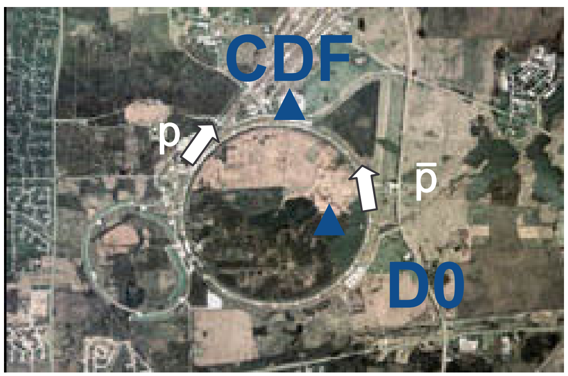




Present/Past ED Search Facilities

Tevatron, Fermilab, USA



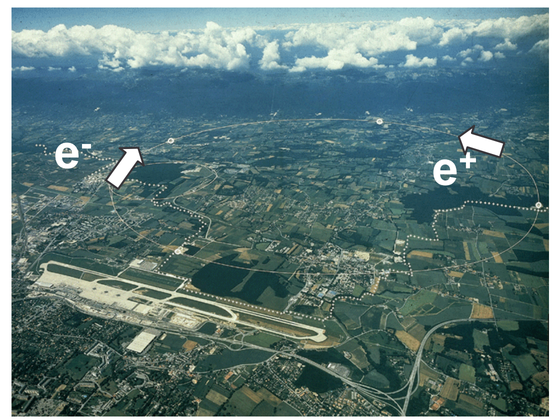


Tevatron: Highest energy collider operating in the world!

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

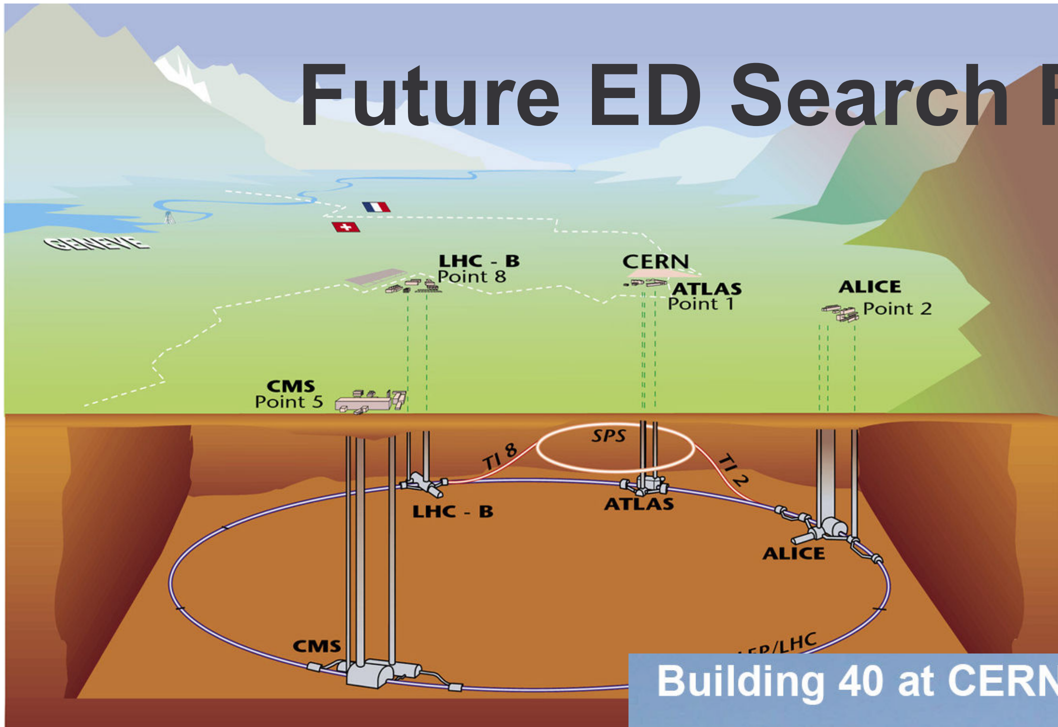
LEP, CERN, Geneva

CERN: world's largest particle physics laboratory



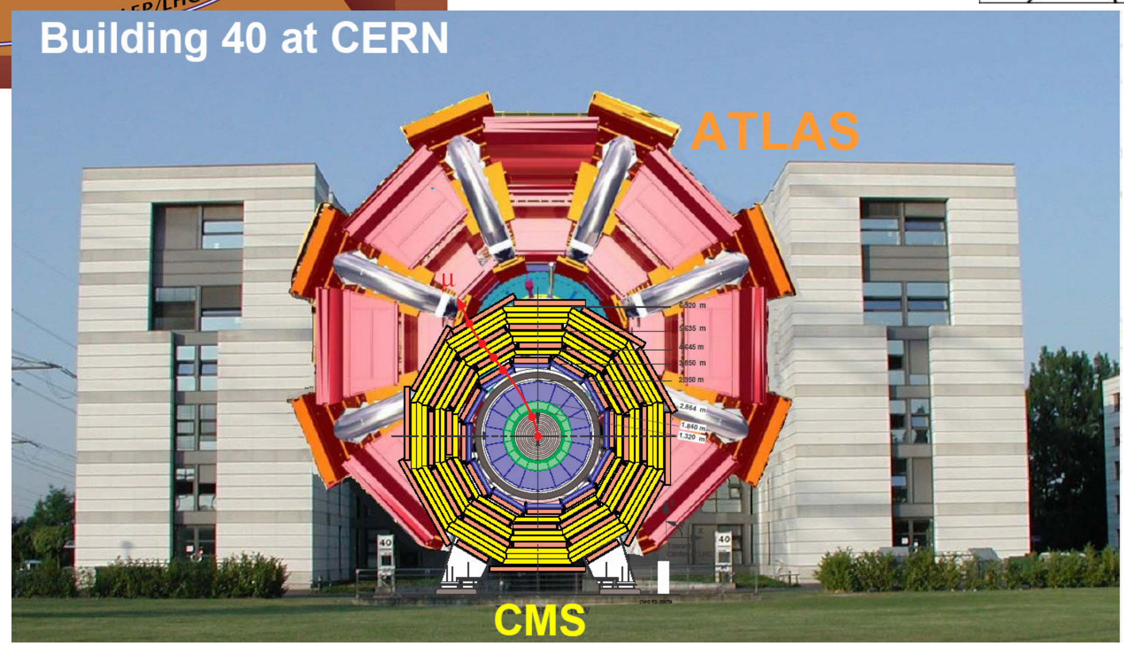
LEP I $\sqrt{s}$ = 91 GeV
LEP II $\sqrt{s}$ = 136-208 GeV

Future ED Search Facilities!



Bigger & Better (?!)
Collider & Detectors!!

Higher CM of mass energy
LHC: $\sqrt{s}$ = 14 TeV

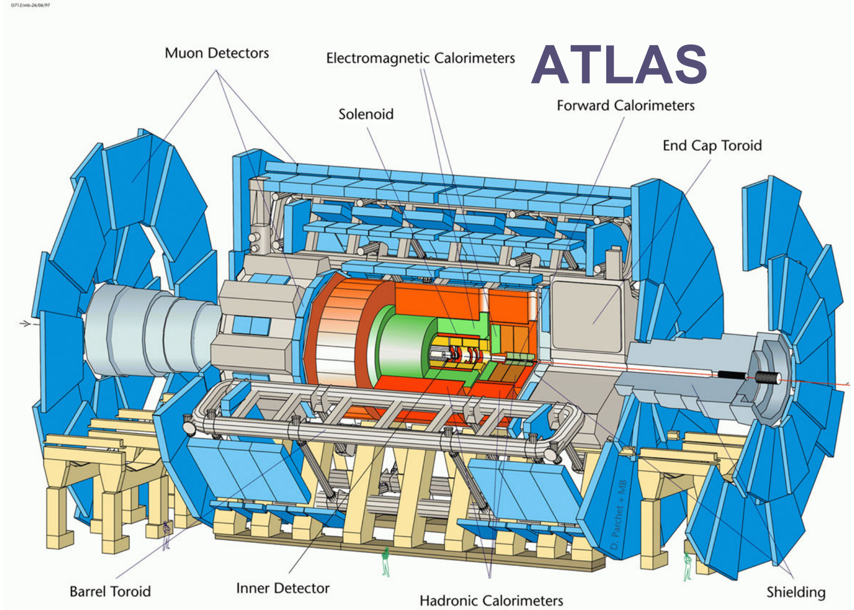


Aim of Tev4LHC
use what has been
learnt at the Tevatron
to fully exploit LHC's
physics potential

ATLAS and CMS Experiments

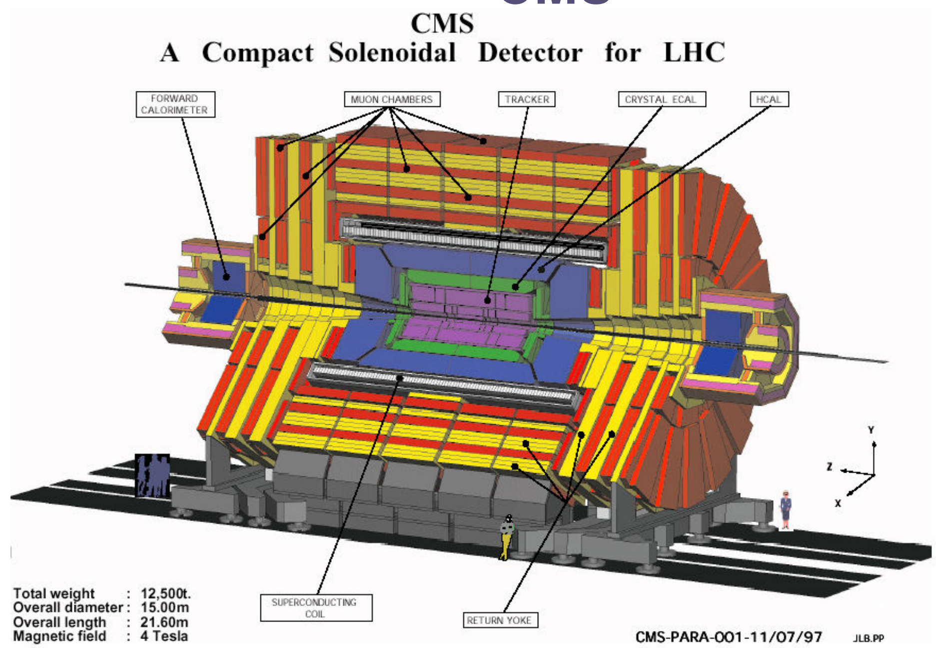
Large general-purpose particle physics detectors

ATLAS



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**

CMS



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

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 and gravitational 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

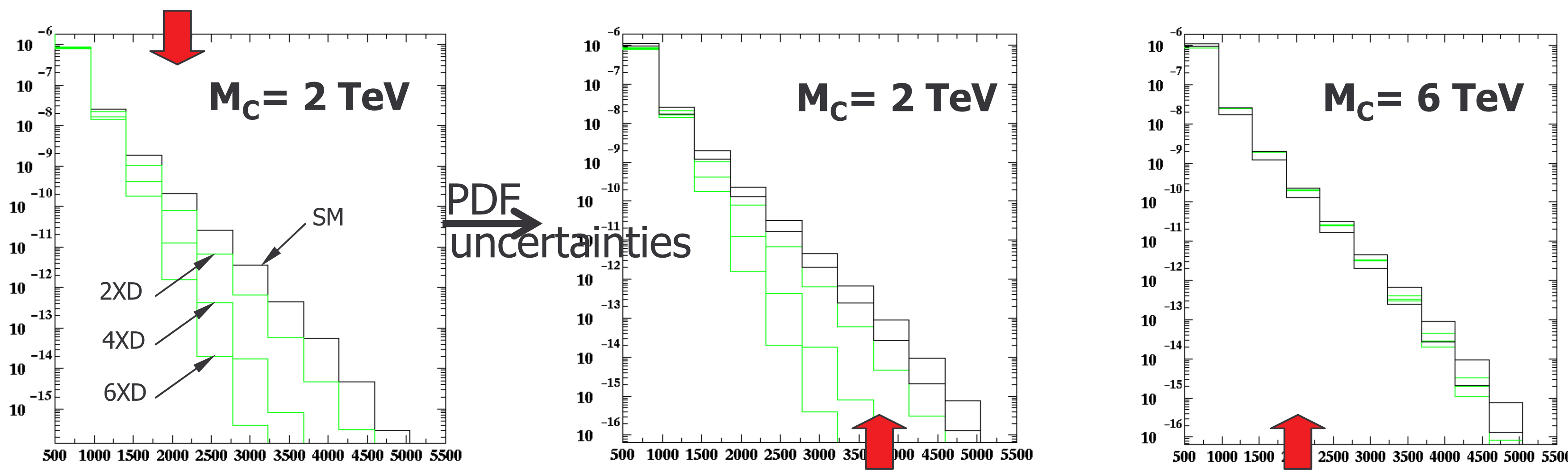
Theoretical Uncertainties

- 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.



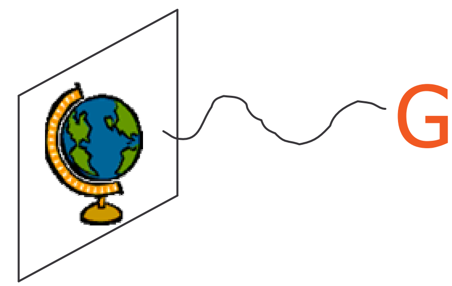
- PDF uncertainties (mainly due to high-x gluon) give an uncertainty "zone" on the SM cross sections
- This reduces sensitivity to M_C from 5 TeV to 2 (3) TeV for δ= 4, 6 and for δ=2 sensitivity is lost (M_C<2 TeV)

ADD Model

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

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

G can propagate in ED



SM particles restricted to 3D brane

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

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

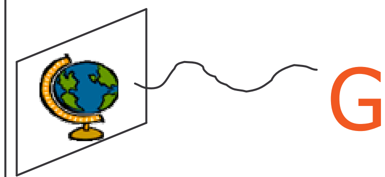
$M_{Pl}^2 \sim R^\delta M_{Pl(4+\delta)}^{(2+\delta)}$

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

Present Constraints on the ADD Model

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

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



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

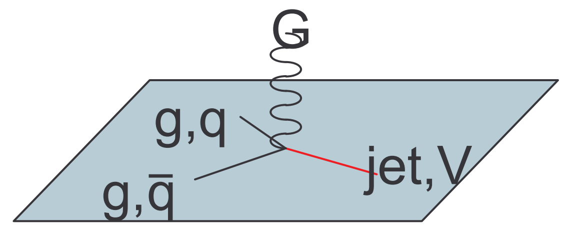
*Cullen, Perelstein
Phys. Rev. Lett 83,268 (1999)

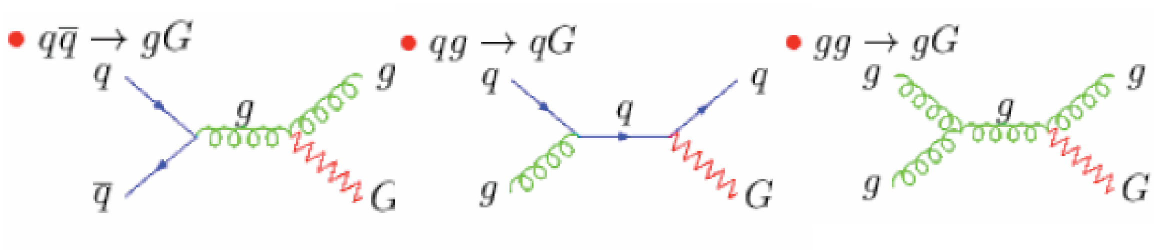
ADD Collider Signatures

➢ **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

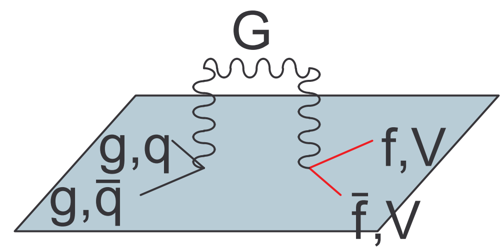


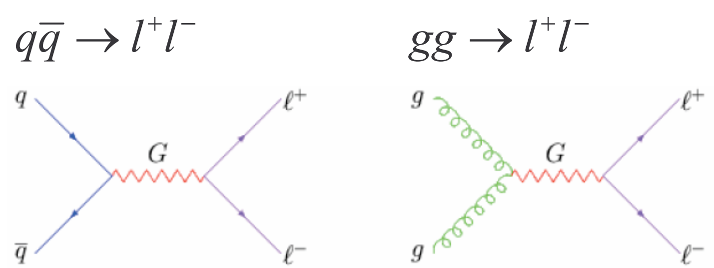


➢ **Virtual Graviton exchange**

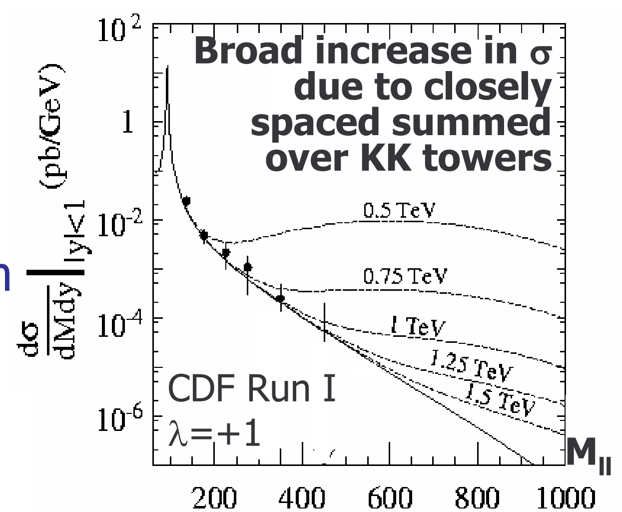
Signature:

deviations in σ and asymmetries of SM processes e.g. $q\bar{q} \to l^+l^-$, γ γ & new processes e.g. $gg \to l^+l^-$





Excess above di-lepton continuum



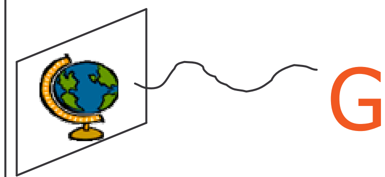
Tracey Berry

Getting ready for the LHC, Madrid
Oct 23-27, 2006

Present Constraints on the ADD Model

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

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



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- $\delta=2 \rightarrow R \sim 1$ 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

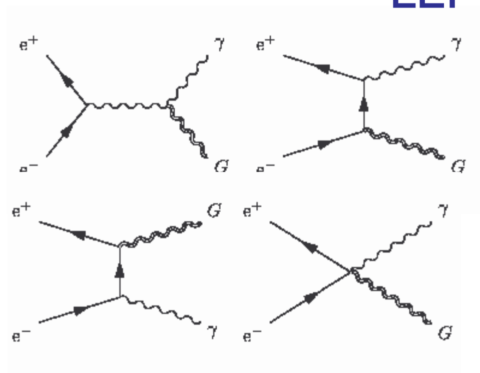
- LEP & Tevatron limits is $M_{Pl(4+\delta)} \sim> 1$TeV

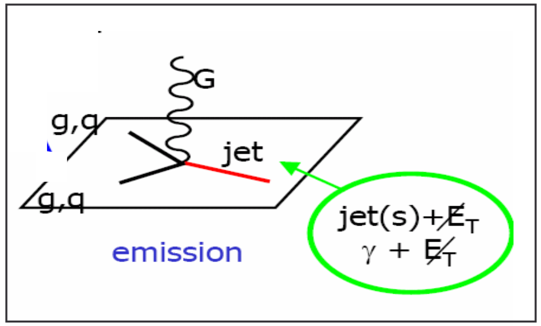
- $\delta>6$ difficult to probe at LHC since cross-sections are very low

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

Present ADD Emission Limits

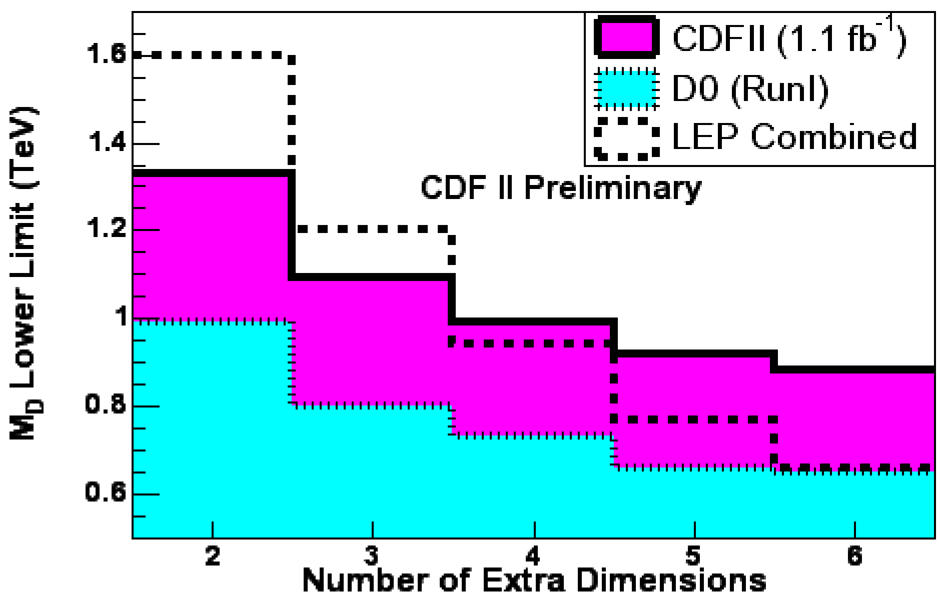
LEP and Tevatron results are complementary





For n<4: LEP limits best γ+ME_T

For n>4: CDF limits best jet+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}

ADD Discovery Limit: γ+G Emission

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

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 $Z\gamma \rightarrow \nu\nu\gamma$ is too large$\Rightarrow$ require p_T>400 GeV
- Main Bkgd: $Z\gamma \rightarrow \nu\nu\gamma$,

  Also $W \rightarrow e(\mu,\tau)\nu$, $W\gamma \rightarrow e\nu$, 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	5σ 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

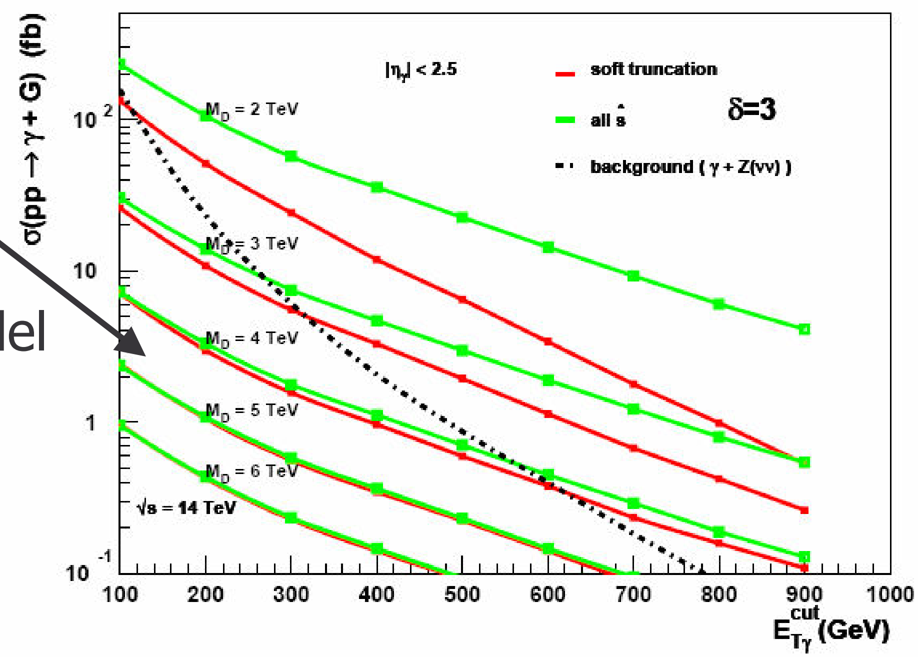
$pp \rightarrow \gamma + G^{KK}$: $q\bar{q} \rightarrow \gamma G^{KK}$

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

M_D^{MAX} (TeV)	$\delta=2$
HL 100fb^{-1}	4

For $\delta>2$: 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

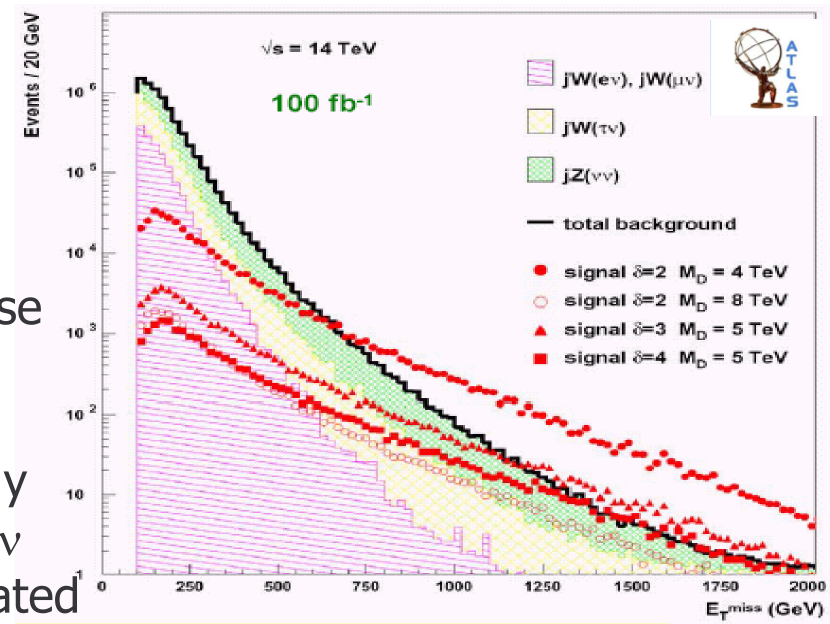
This signature could be used as confirmation after the discovery in the jet channels

ADD Discovery Limit: jet+G Emission

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

$gg \to gG$, $qg \to qG$ & $q\bar{q} \to Gg$

Dominant subprocess ($qg \to qG$)



- 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

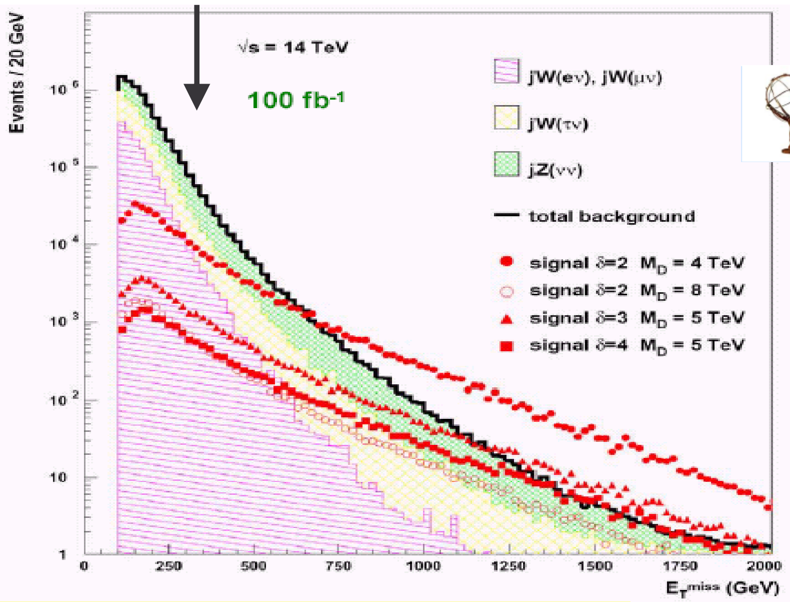
$M_{Pl(4+d)}^{MAX}$(TeV)	δ=2	δ=3	δ=4
LL 30fb^{-1}	7.7	6.2	5.2
HL 100fb^{-1}	9.1	7.0	6.0

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

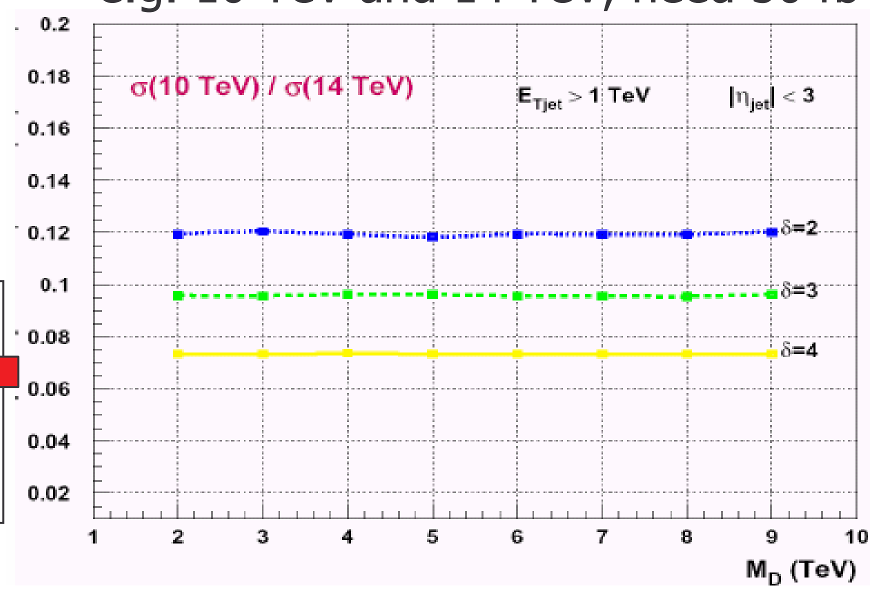
Measuring $\sigma(pp \to jet+G^{KK})$ gives ambiguous results



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

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

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



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

Tevatron ADD Exchange Limits

Both D0 and CDF have observed no significant excess

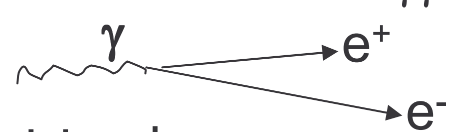
95% CL lower limits on fundamental Planck scale (M_s) in TeV, using different formalisms:

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



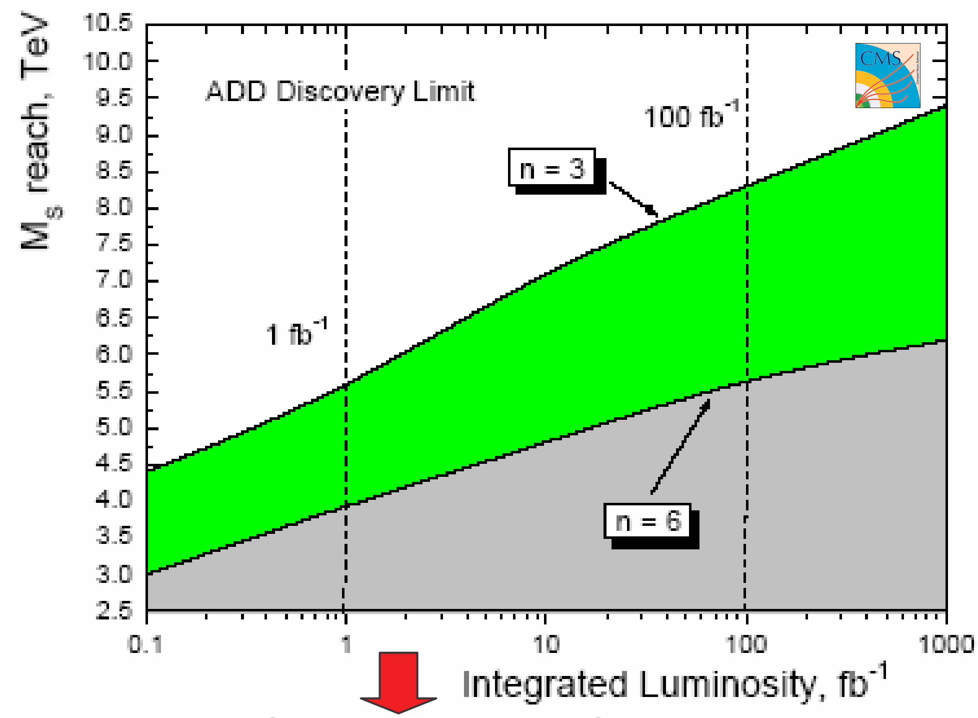
- γ ID requires no track, but γ converts ($\rightarrow$ee)
- e ID requires a track, but loose track due to imperfect track reconstruction/crack

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

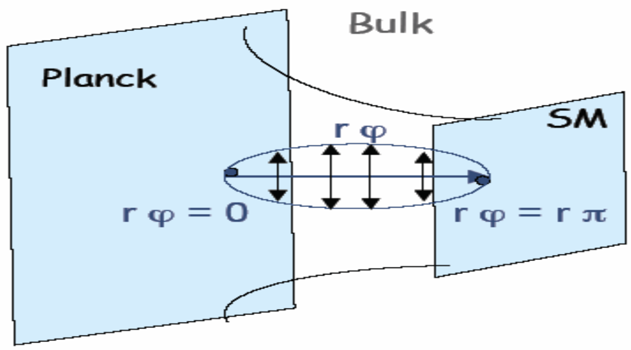
Fast MC

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

Experimental Signature for RS Model



Model parameters:

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

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

  $\Lambda_\pi = m_1 M_{pl}/kx_1$, & $m_n = kx_n e^{krc\pi} (J_1(x_n)=0)$
- 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

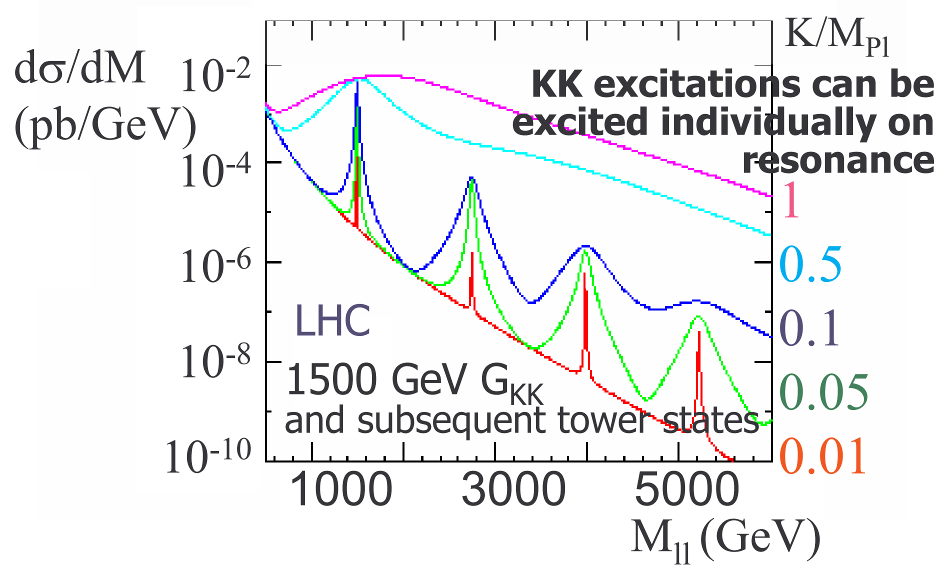
Signature:

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

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

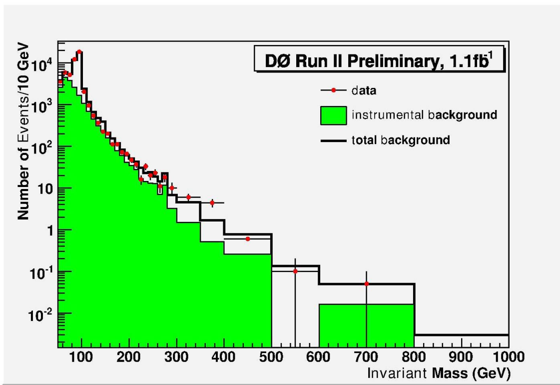
At the LHC only the 1st excitations are likely to be seen at the LHC, since the other modes are suppressed by the falling parton distribution functions.

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

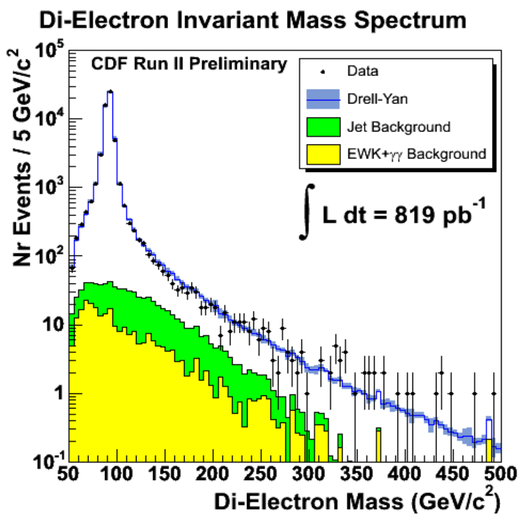


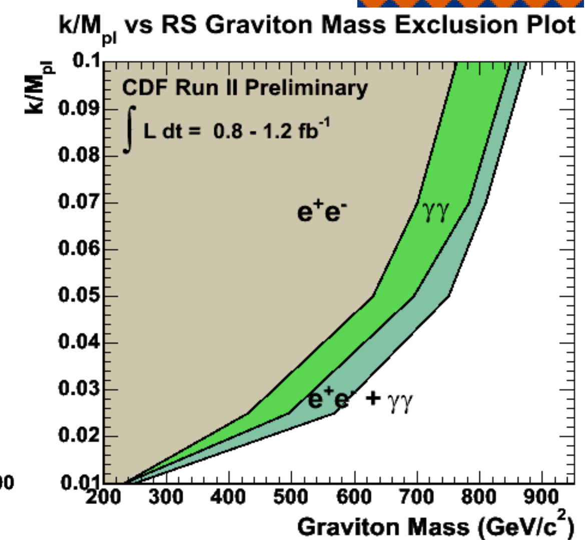
Davoudiasl, Hewett, Rizzo
hep-ph0006041

Present RS Constraints

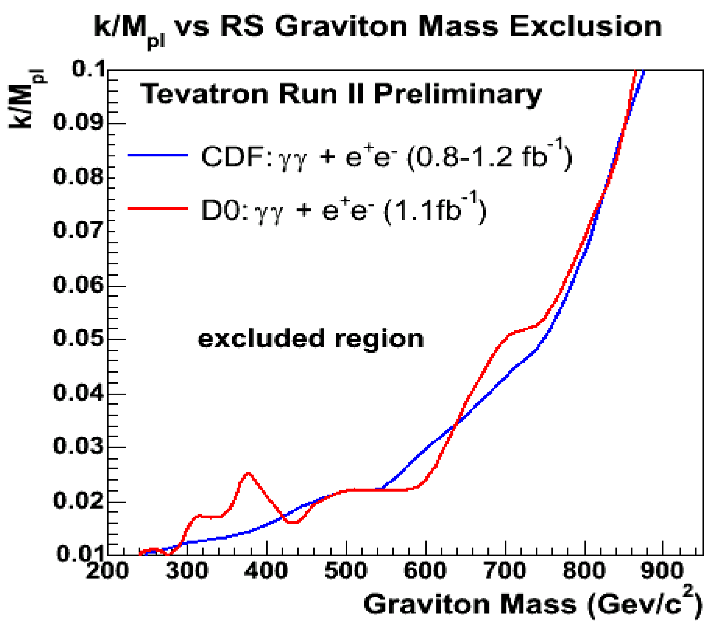


D0 performed combined ee+$\gamma\gamma$ (diem search)





CDF performed ee & $\gamma\gamma$ search, then combine



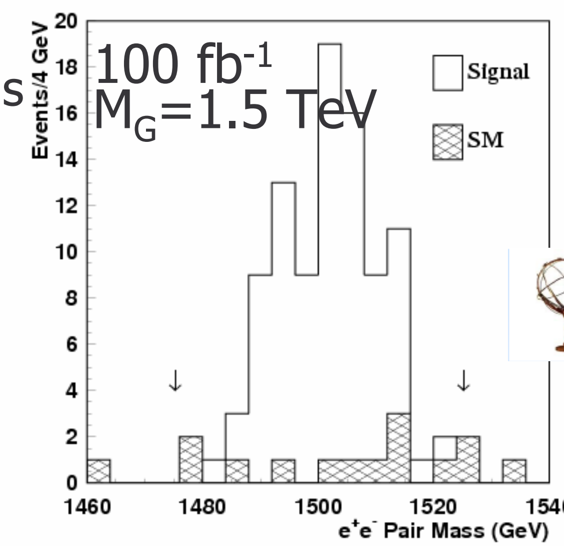
Present Experimental Limits

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

RS1 Discovery Limit

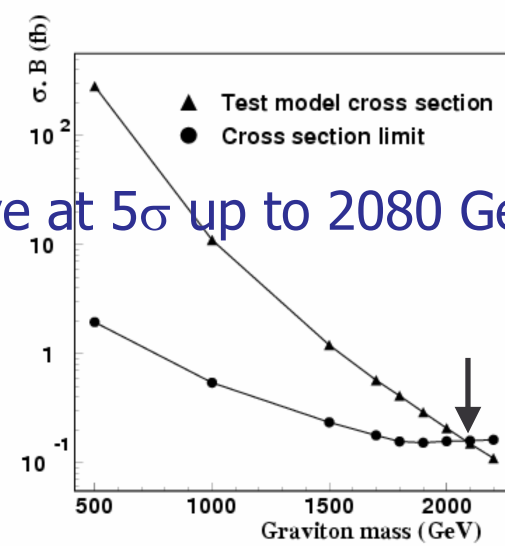
- Best channels to search in are G(1)→e+e- and G(1)→γγ due to the energy and angular resolutions of the LHC detectors
- G(1)→e+e- best chance of discovery due to relatively small bkdg, from Drell-Yan*



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

Allenach et al, hep-ph0006114

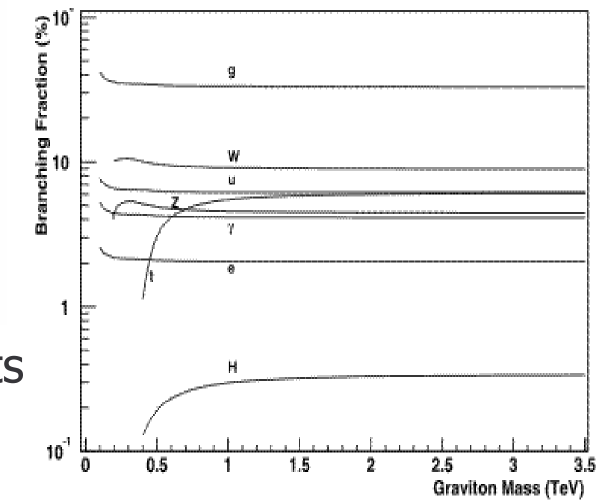
*Allenach et al, hep-ph0211205

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.



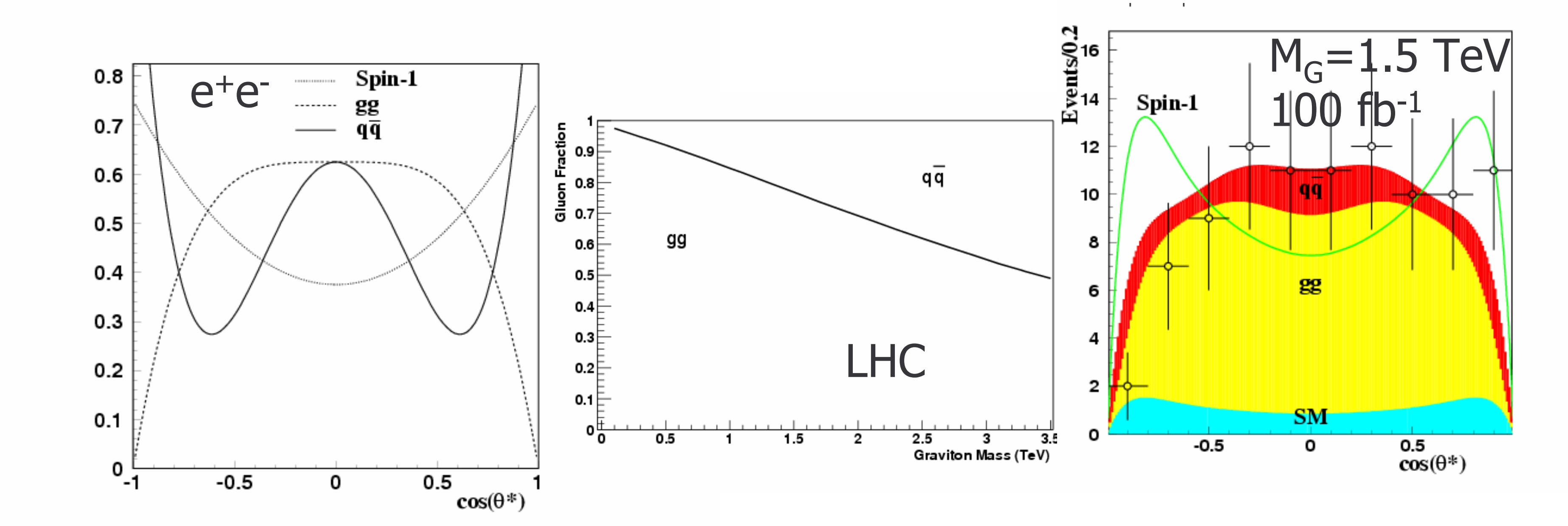
Also the size (R) of the ED could also be estimated from mass and cross-section measurements.

Allenach et al, hep-ph0211205

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

RS1 Model Determination

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



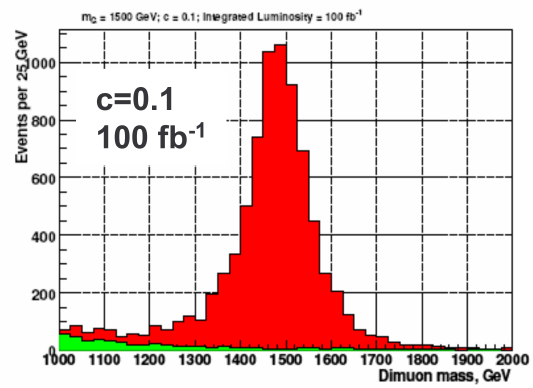
Note: acceptance at large pseudo-rapidities is essential for spin discrimination (1.5<|eta|<2.5)

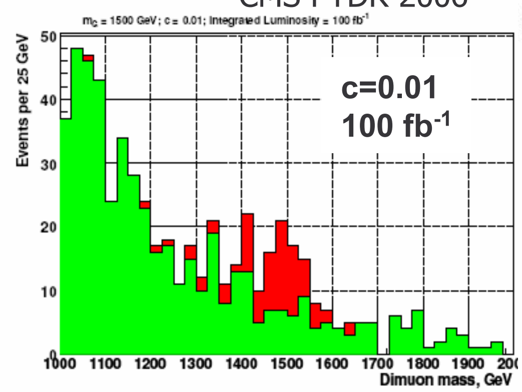
Allanach et al, hep-ph 0006114

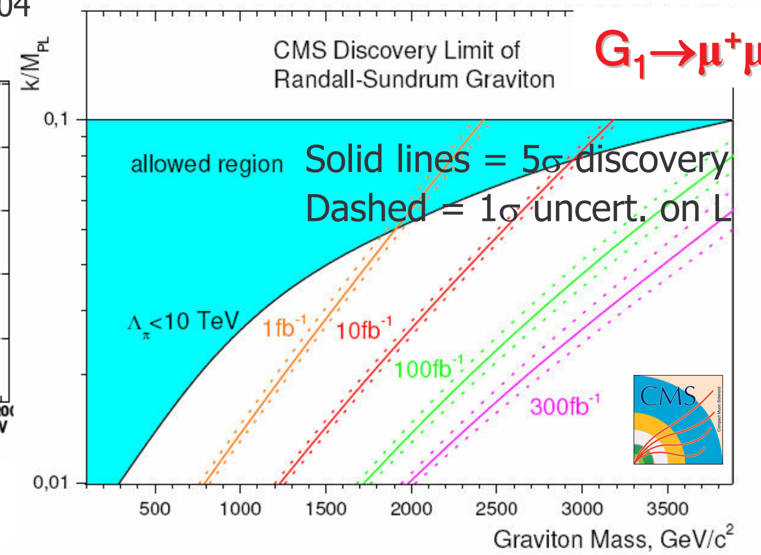
RS1 Discovery Limit

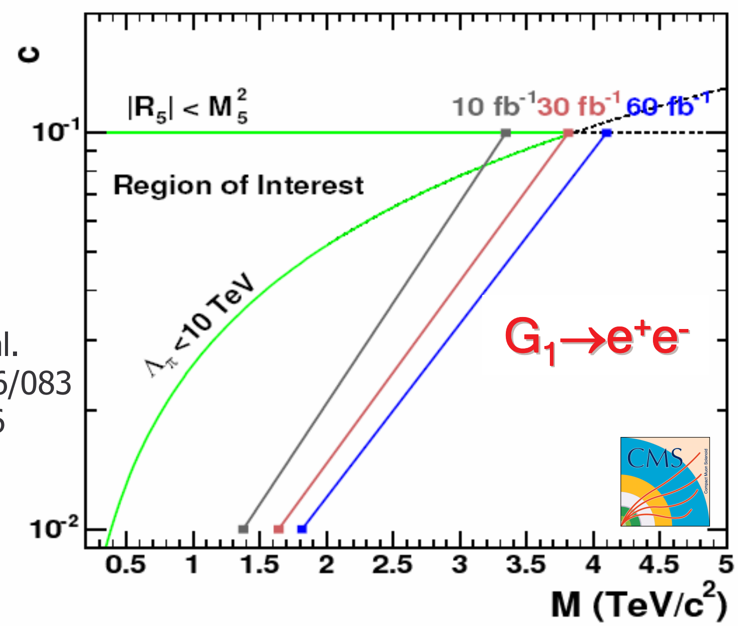
Di-lepton states

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

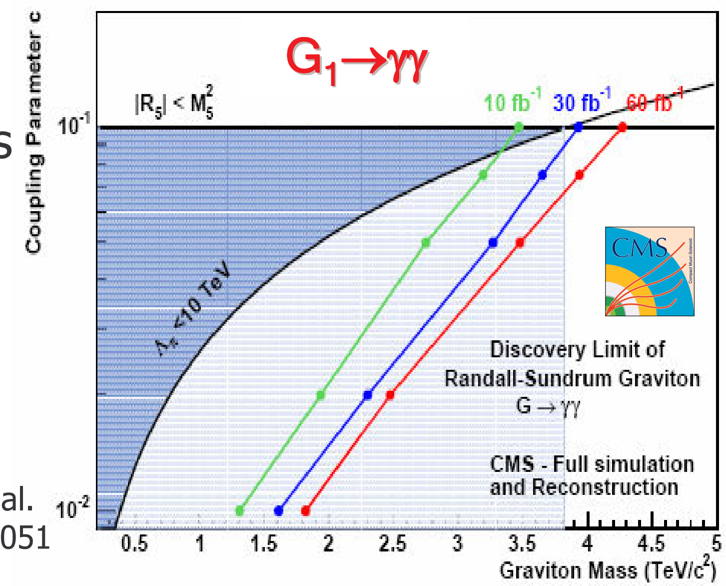
B. Clerbaux et al.
CMS NOTE 2006/083
CMS PTDR 2006

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

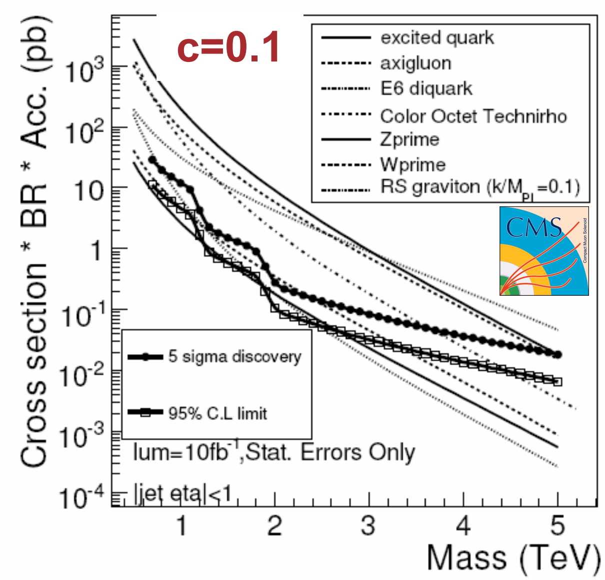
M.-C. Lemaire et al.
CMS NOTE 2006/051
CMS PTDR 2006



Di-jet states

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

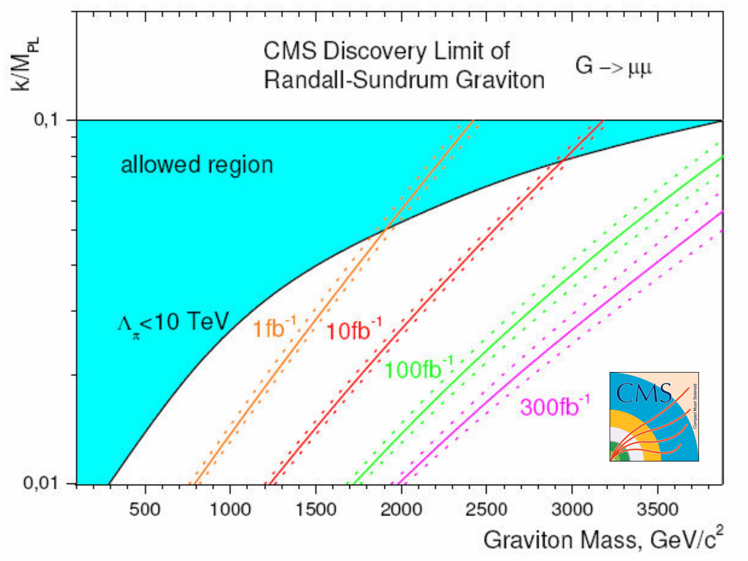
K. Gumus et al.
CMS NOTE 2006/070
CMS PTDR 2006



5σ Discovered Mass: 0.7-0.8 TeV/c^2

CMS RS Discovery Limits

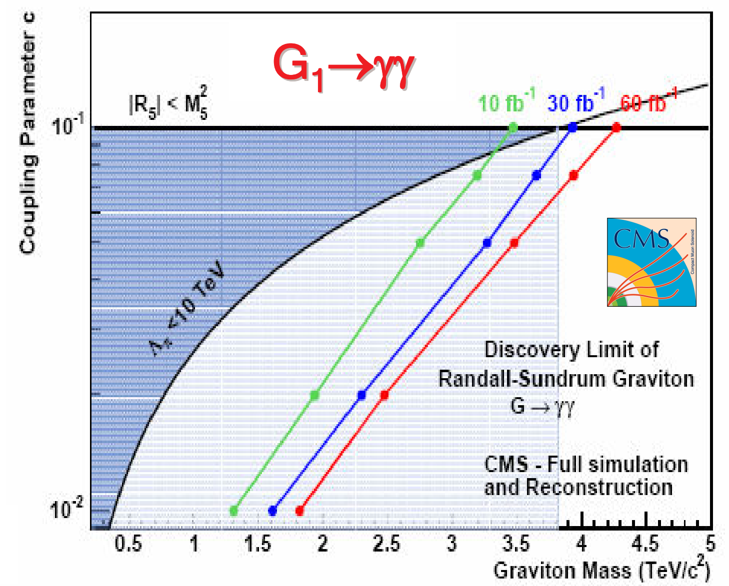
$G_1 \rightarrow \mu^+\mu^-$



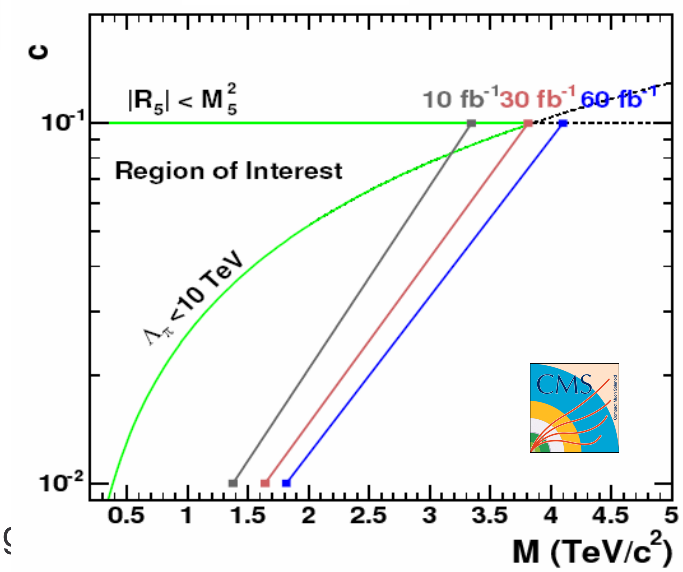
c>0.1 disfavoured as bulk curvature becomes to large (larger than the 5-dim Planck scale)

Theoretically preferred Λ_π<10TeV

$G_1 \rightarrow \gamma\gamma$



$G_1 \rightarrow e^+e^-$



LHC completely covers the region of interest

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
  ⇒ Search for KK excitations of Z,γ..

<u>New Parameters</u>

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

M_C : corresponding compactification scale

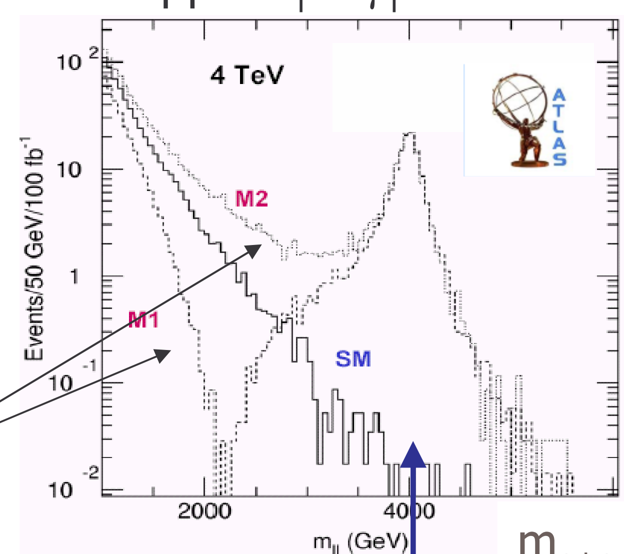
M_0 : mass of the SM gauge boson

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!

- Fermion-gauge boson couplings can be exponentially suppressed for higher KK-modes
- Fundamental fermions (quarks/leptons) can be localized at the same (M1) or opposite (M2) points of orbifold
  ⇒ destructive (M1) or constructive (M2) interference of the KK excitations with SM model gauge bosons

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

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



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:

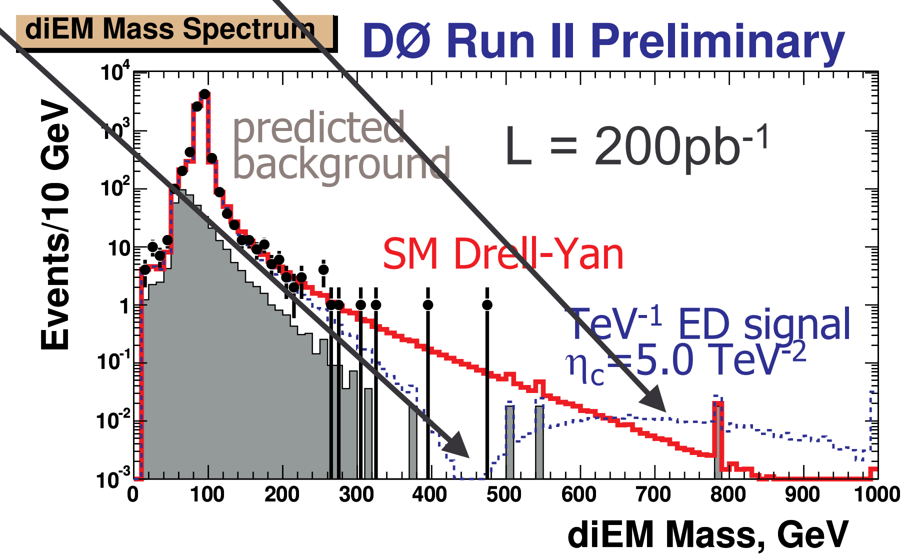
- enhancement at large masses (like LED)
- negative interference between the 1st KK state of the Z/γ and the SM Drell-Yan in between the Z mass and M_C

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

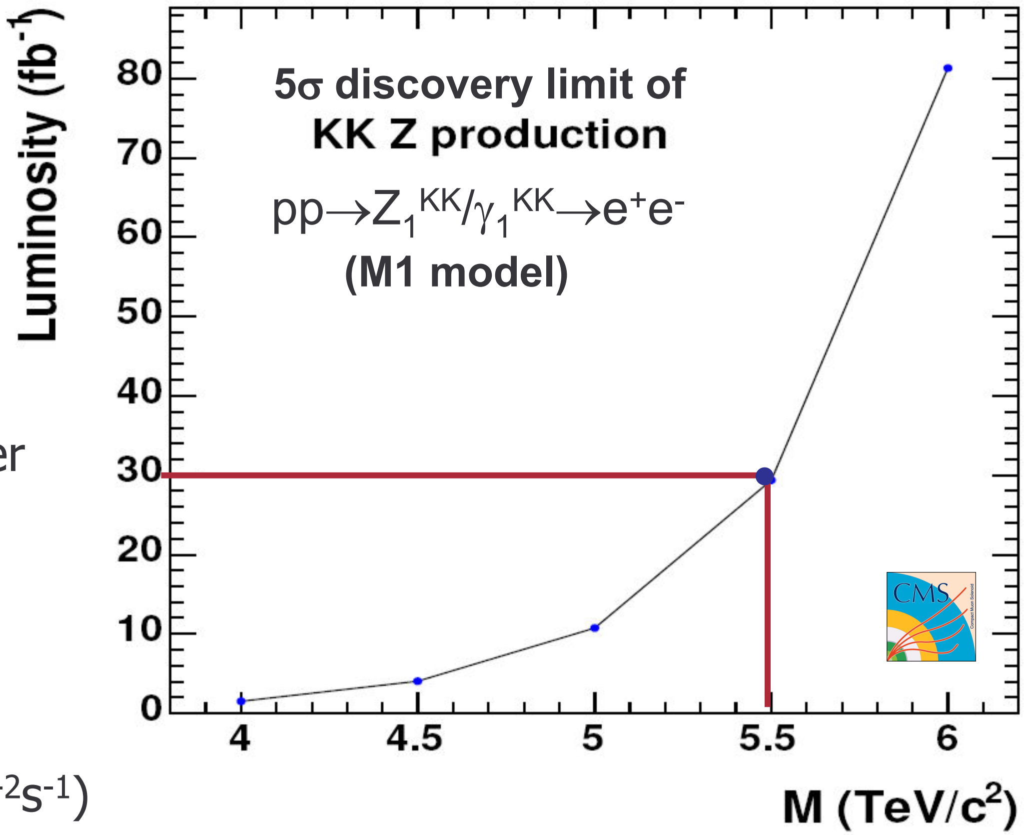
World Combined Limit $M_C > 6.8$ TeV at 95% C.L, dominated by LEP2 measurements



TeV^{-1} ED Discovery Limits

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.



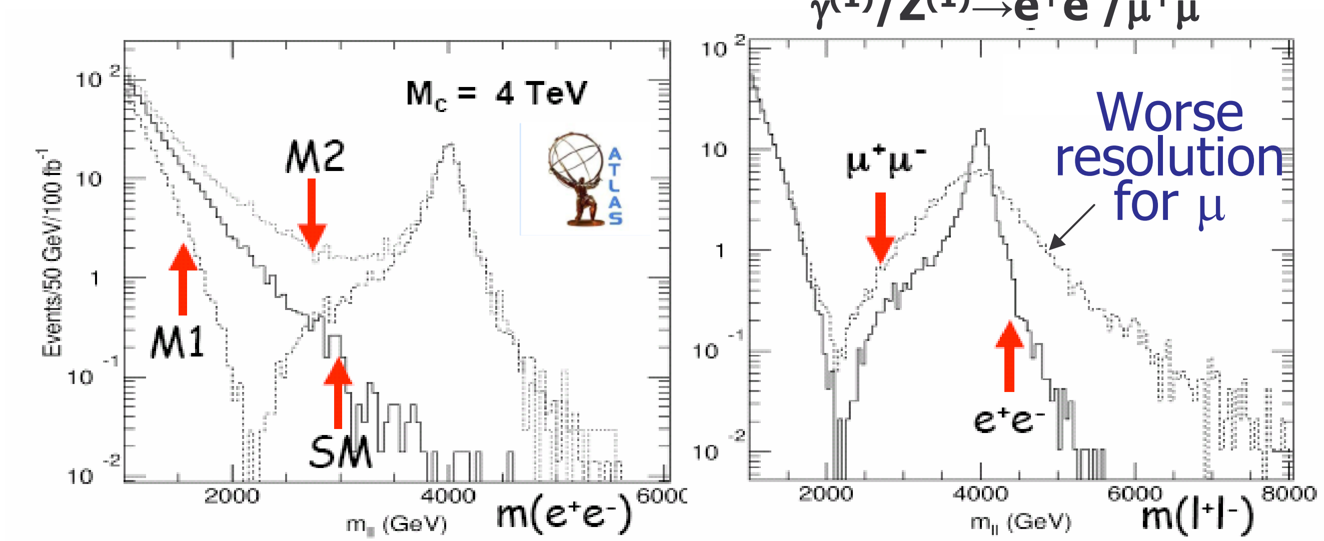
With $\mathcal{L}$=30/80 fb^{-1} CMS will be able to detect a peak in the e^+e^- invar. mass distribution if M_C<5.5/6 TeV.

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

TeV^{-1} ED Discovery Limits

ATLAS expectations for e and μ:
PYTHIA + Fast simu/parameterized reco + Theor. uncert.

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



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

- Requiring >10 events above a given m_{ll} and $S = (N-N_B)/\sqrt{N_B} > 5$
  With 100 fb^{-1} ATLAS will be able to detect resonance if M_C (R^{-1})<5.8 TeV (ee+μμ)

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.

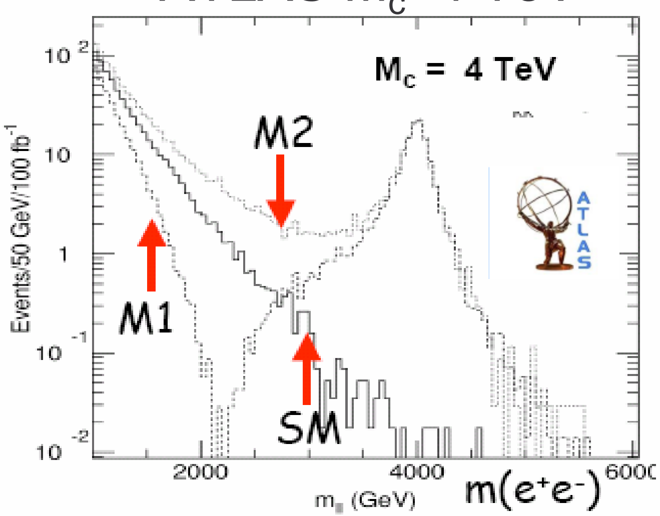
G. Azuelos, G. Polesello
EPJ Direct 10.1140 (2004)

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

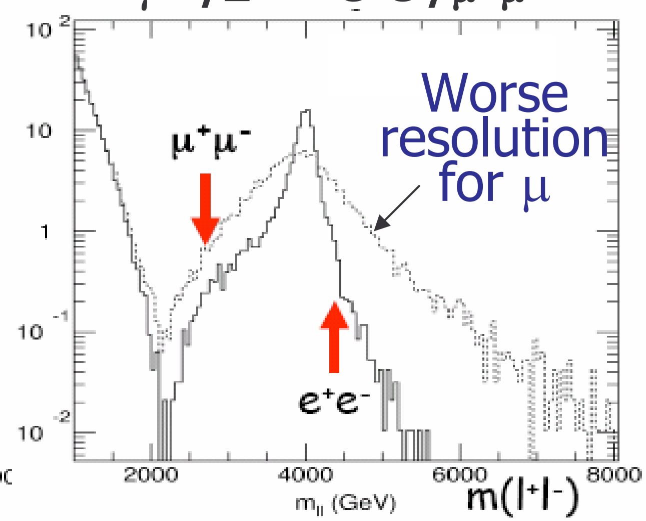
TeV^{-1} ED Discovery Limits

ATLAS expectations for e and μ:
PYTHIA + Fast simu/paramaterized reco + Theor. uncert.

ATLAS M_c=4 TeV



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



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

2 TeV e in ATLFAST:

$\Delta E/E \sim 0.7$ %

~20% for μ

- Requiring >10 events above a given m_{ll} and and $S= (N-N_B)/\sqrt{N_B} > 5$
  With 100 fb^{-1} ATLAS will be able to detect resonance if $M_C(R^{-1})$<5.8 TeV (ee+μμ)
- Using a maximum likelihood method to fit the reconstructed distributions describing the kinematics of the event:
  With 300 fb^{-1} can reach 13.5 TeV (ee+μμ)

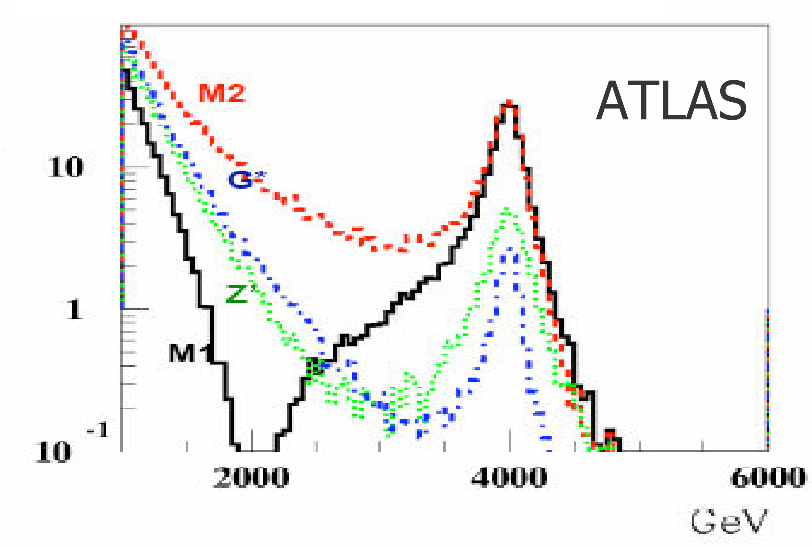
G. Azuelos, G. Polesello
EPJ Direct 10.1140 (2004)

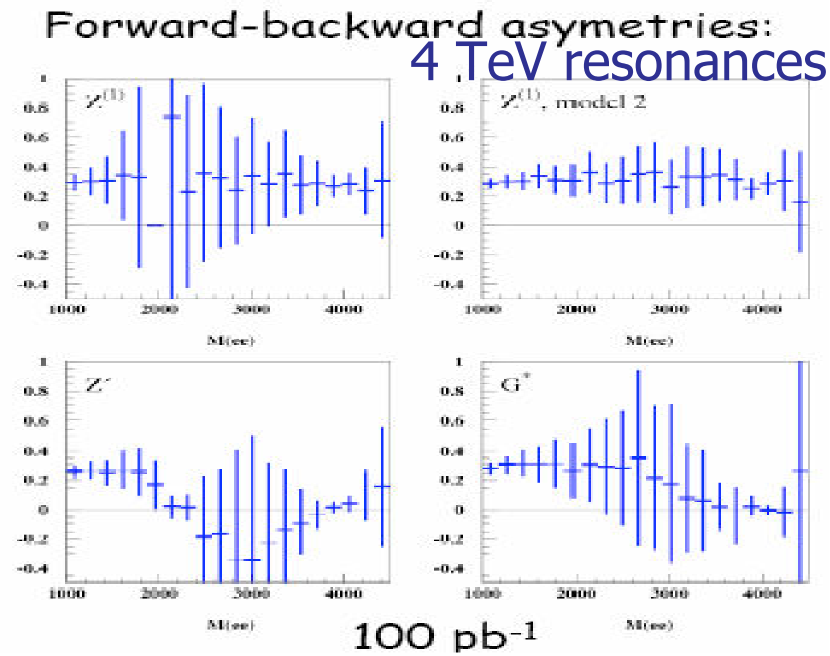
G. Azuelos, G. Polesello (Les Houches 2001 Workshop Proceedings), Physics at TeV Colliders, 210-228 (2001)

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 $L=300fb^{-1}$.





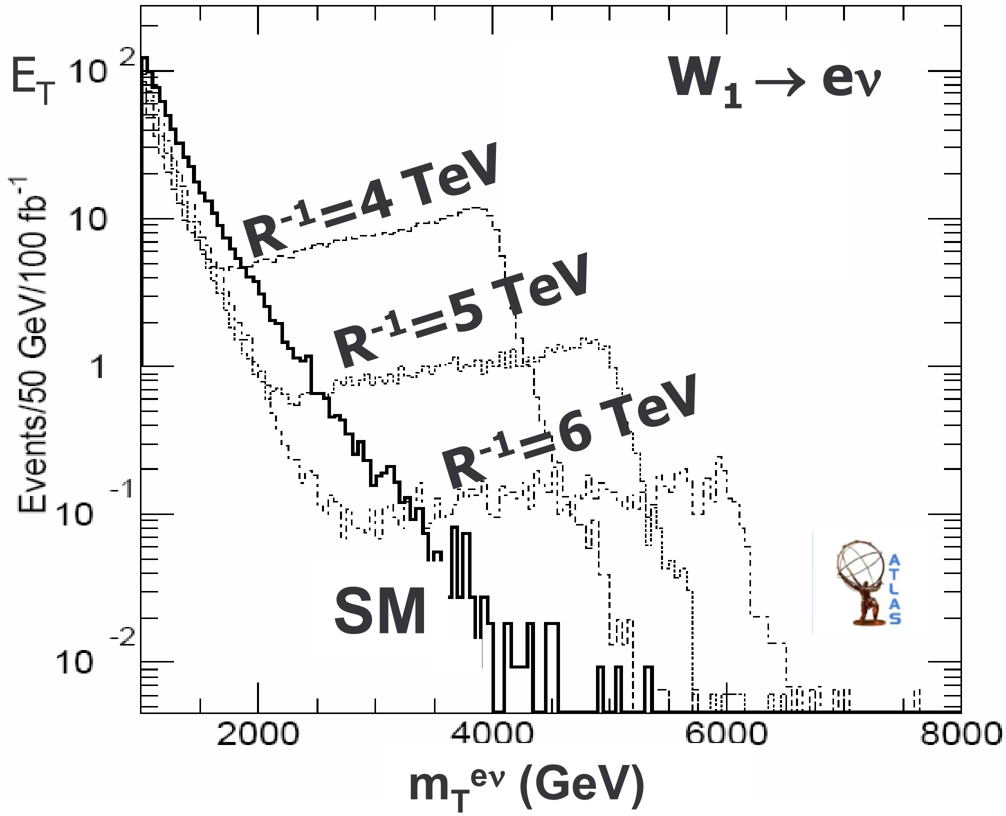
TeV^{-1} ED Discovery Limits

W_{KK} decays

- Isolated high-p_T lepton + missing E_T
- Invmass (l,ν) > 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

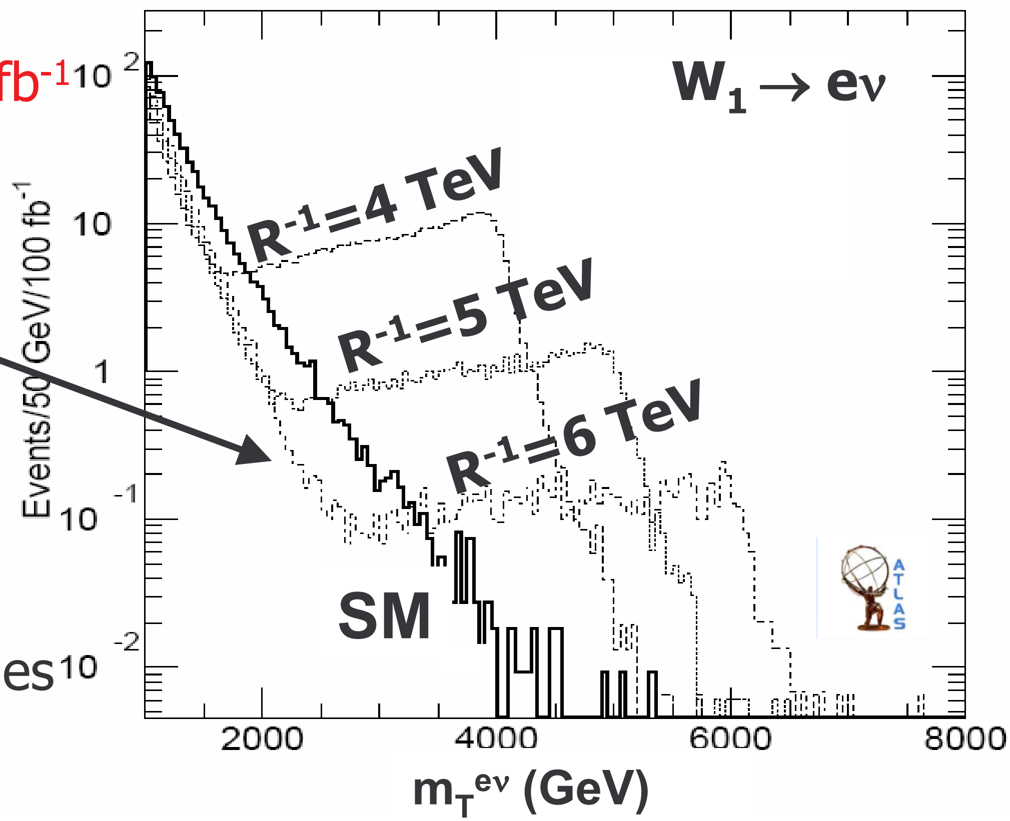
W_{KK} decays

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

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 = $\sqrt{2}$ * SM couplings

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

TeV^{-1} ED g* Discovery Limits

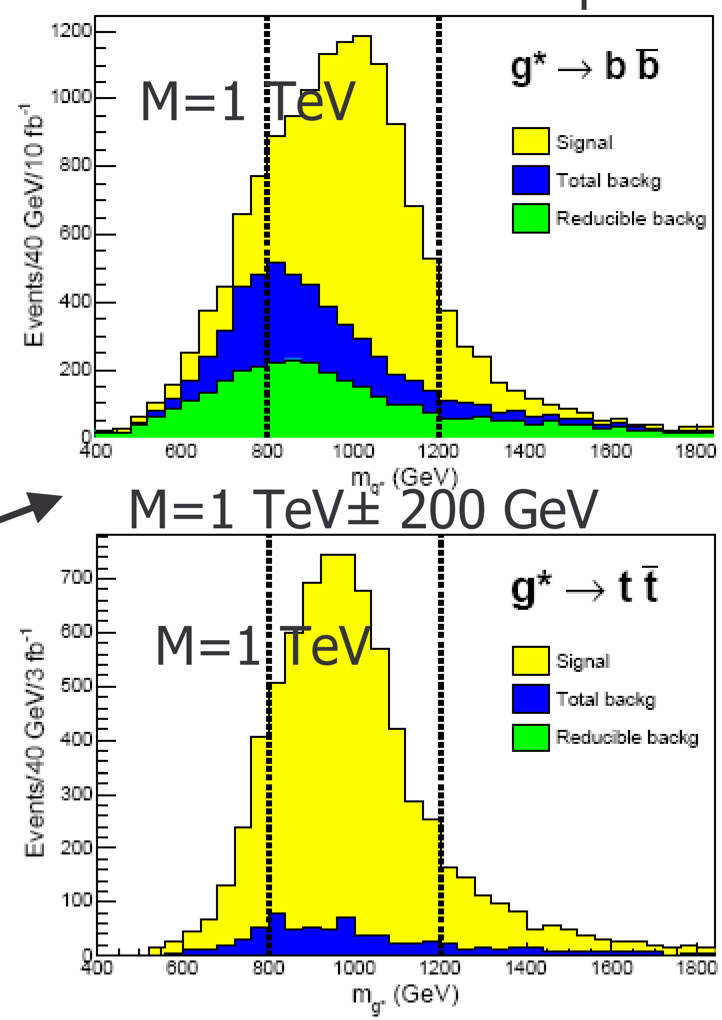
Gluon excitation decays

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

- ❑ 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)

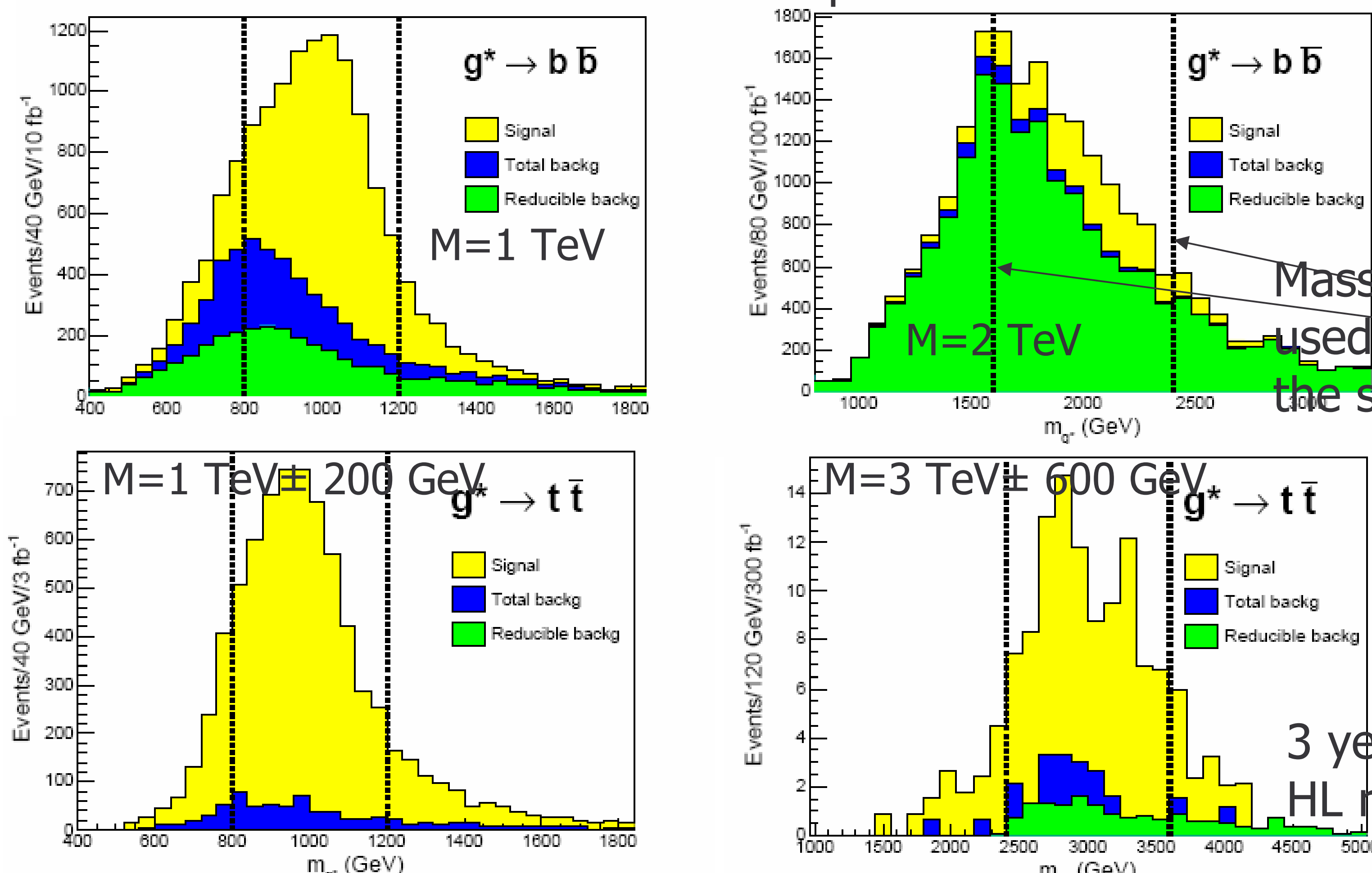
Reconstructed mass peaks



M=1 TeV± 200 GeV

TeV^{-1} ED g* Discovery Limits

Reconstructed mass peaks

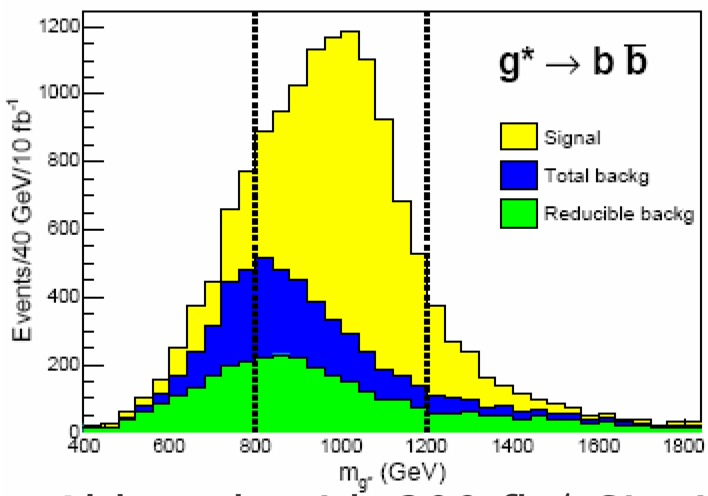


With 300 fb^{-1} Significance of 5 achieved for:

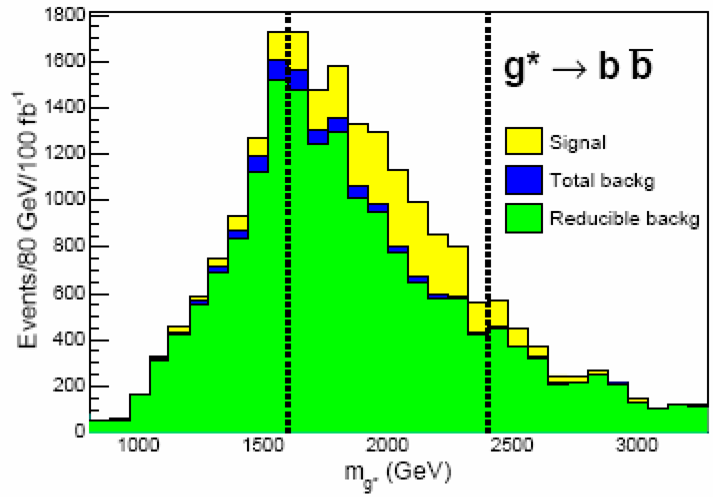
bbar channel: R^{-1} = 2.7 TeV   ttbar channel: R^{-1} = 3.3 TeV

TeV^{-1} ED g* Discovery Limits

M=1 TeV



M=2 TeV



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

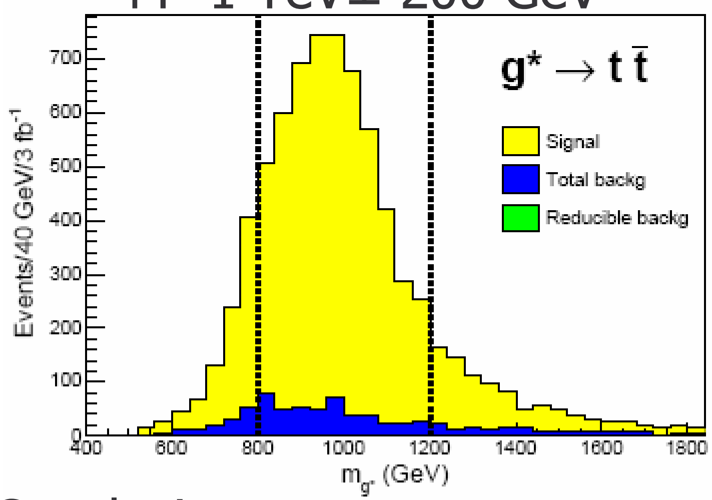
bbar channel: R^{-1} = 2.7 TeV

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.

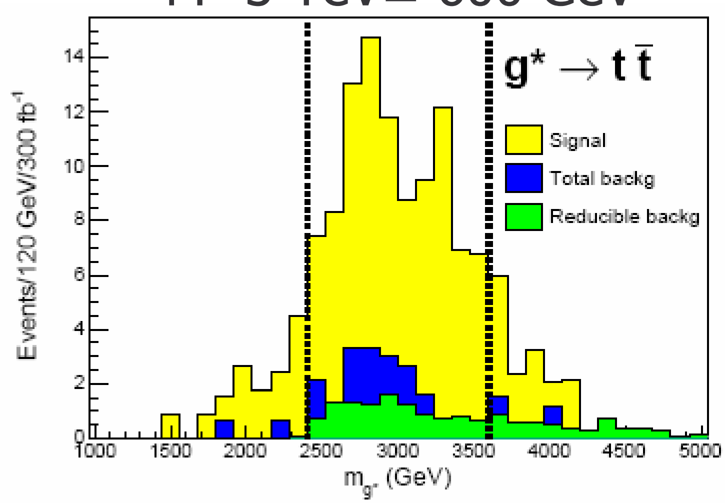
TeV^{-1} ED g* Discovery Limits

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



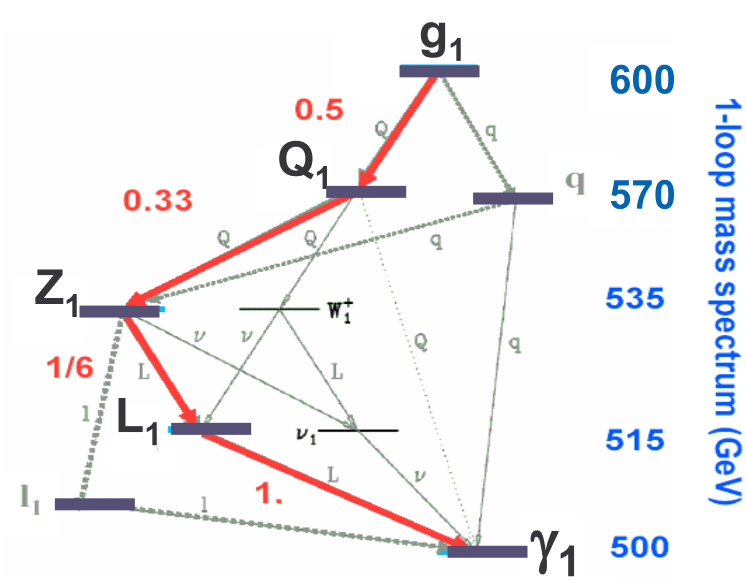
Conclusion:
g* decays into b-quarks are difficult to detect, decays into t-quarks might yield a significant signal for g* mass below 3.3 TeV.
This could be used to confirm the presence of g* in the case that an excess in the dijet σ is observed.

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.

Present Constraints on UED

Bounds to the compactification scale:

- Precision EWK data measurements set a lower bound of

  $R^{-1} > 300$ GeV

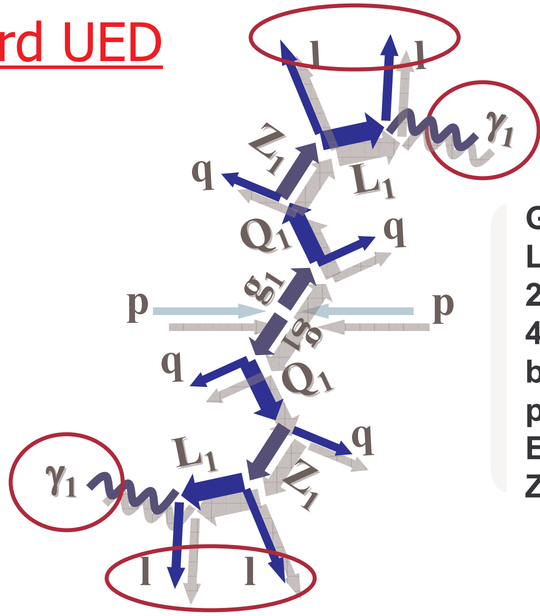
  Phys. Rev. D64, 035002 (2001) Appelquist, Cheung, Dobrescu

- Dark matter constraints imply that $600 < R^{-1} < 1050$ GeV

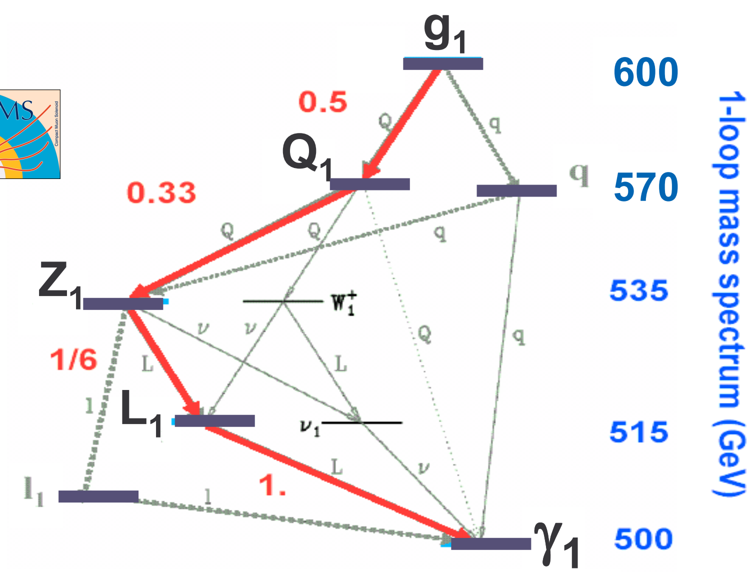
  Servant , Tait, Nucl. Phys. B650,391 (2003)

UED Discovery Limit

Standard UED



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



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

Final State:
4 low-p_T isolated leptons (2 pairs of opposite sign, same flavour leptons) + n jets + missing E_T (from 2 undetected γ_1)

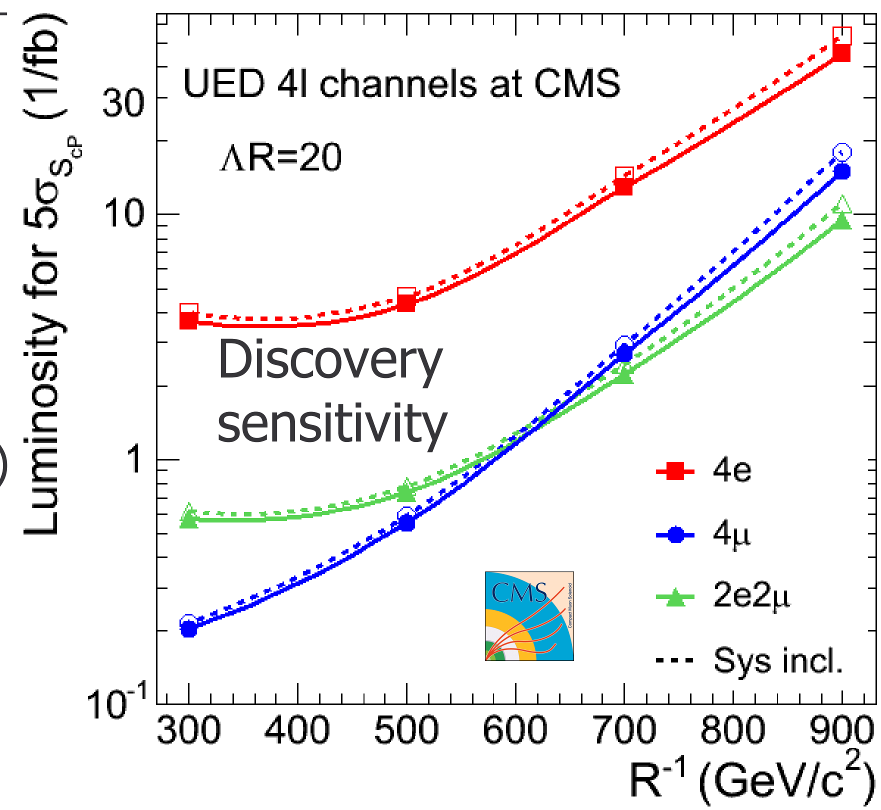
Standard UED

UED Discovery Limit

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

- ❑ 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.

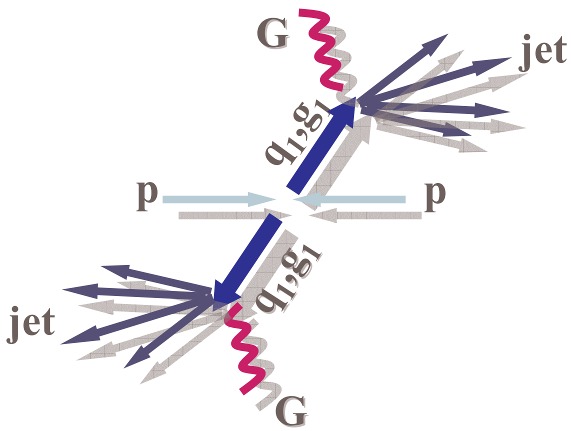
Studied for low lum run ~$2\times10^{33}cm^{-2}s^{-1}$



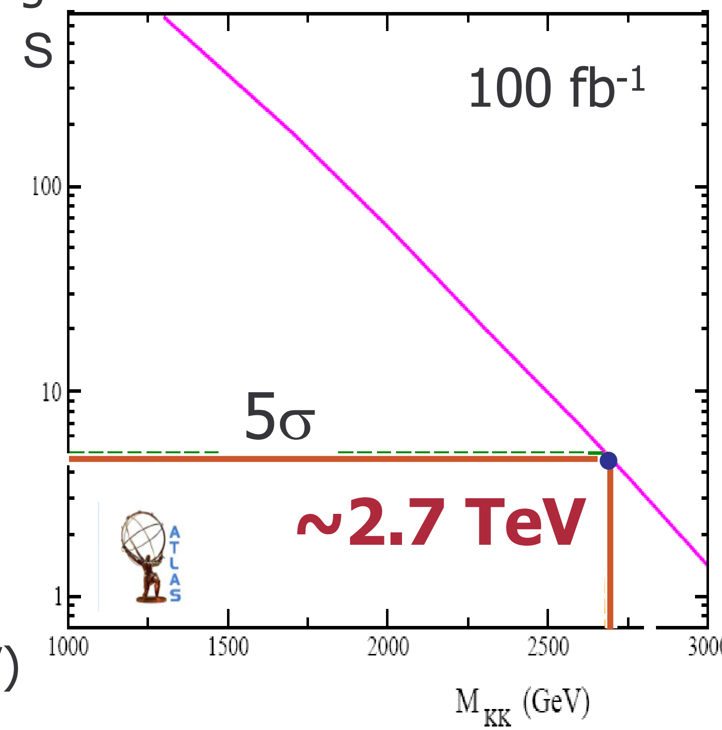
UED Discovery Limit

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

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



Significance vs Mass of 1st KK excitation



- 2 back-to back jets + missing E_T (>775 GeV)
- Irreducible Bckg: $Z(\rightarrow \nu\nu)$ jj, $W(\rightarrow l\nu)$ jj
- PYTHIA/CTEQ5L + SHERPA for bckgr.
- Fast simulation/reco

5σ discovery possible at ATLAS with 100 fb^{-1} if first KK excitation mass < 2.7 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.
UED 4 leptons	R^{-1} ~ 600 GeV	1.0	Theor.+Exp.
Thick brane	R^{-1} = 1.3 TeV	6 pb^{-1}	

Conclusions

Royal Holloway University of London

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

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 collected in the start-up LHC weeks (integrated luminosity$<1\ fb^{-1}$)

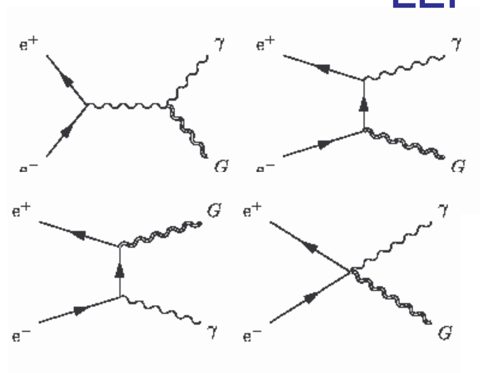
For methods to disentangle new physics from SM physics, see lectures by M. Mangano.
For Gravitaton/Black Holes see talk by: B. Webber.

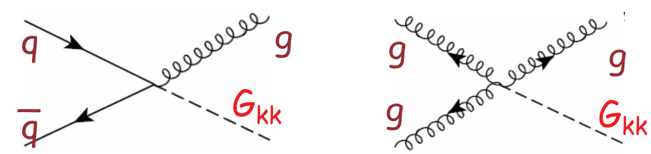
The End!

Backup slides...

Present ADD Emission Limits

LEP and Tevatron results are complementary

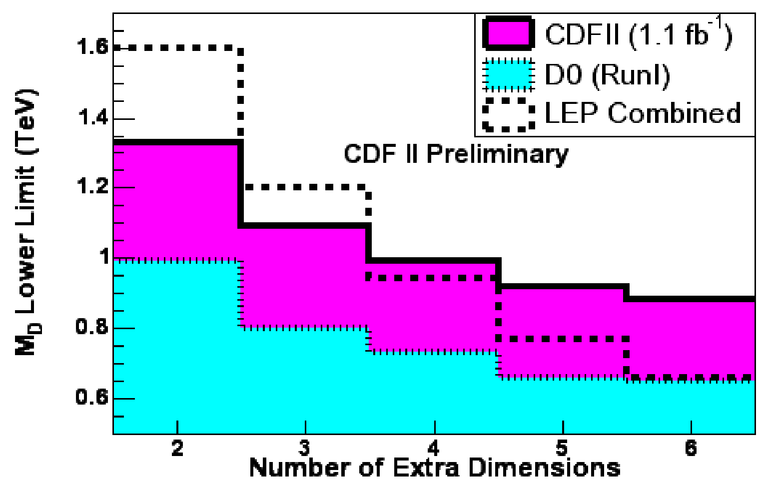




For n<4: LEP limits best

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



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.

$\sigma \propto$ total number of possible modes in the KK tower N_{KK}
$\sigma \propto N_{KK} \propto \sqrt{(s\text{-hat})}$
But this is true for each ED,
so $\sigma \propto (\sqrt{(s\text{-hat})})^n$

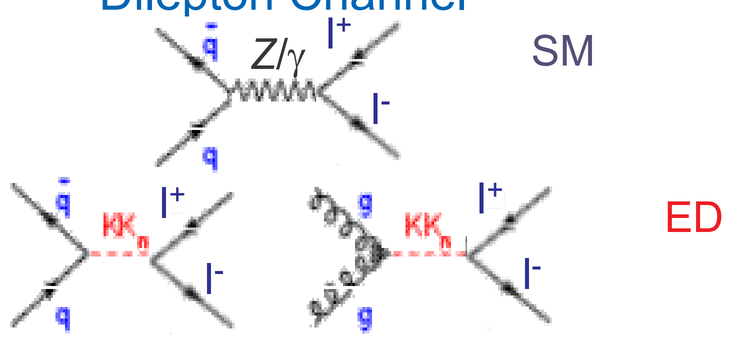
$\Rightarrow$the difference in energy is a bigger effect for n=6 than n=2

ADD: G Exchange?

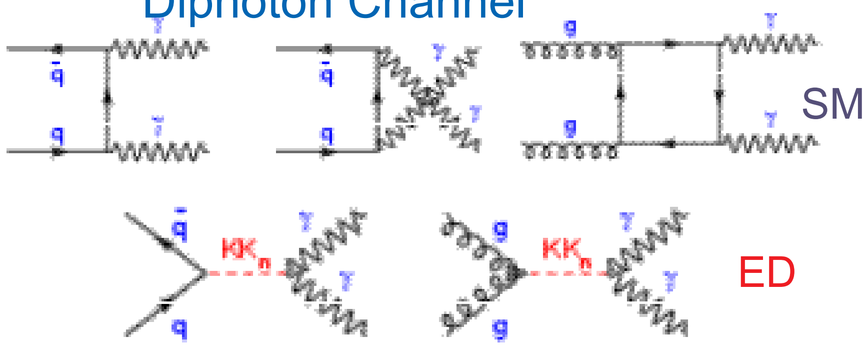
Search for spin-2 broad σ change

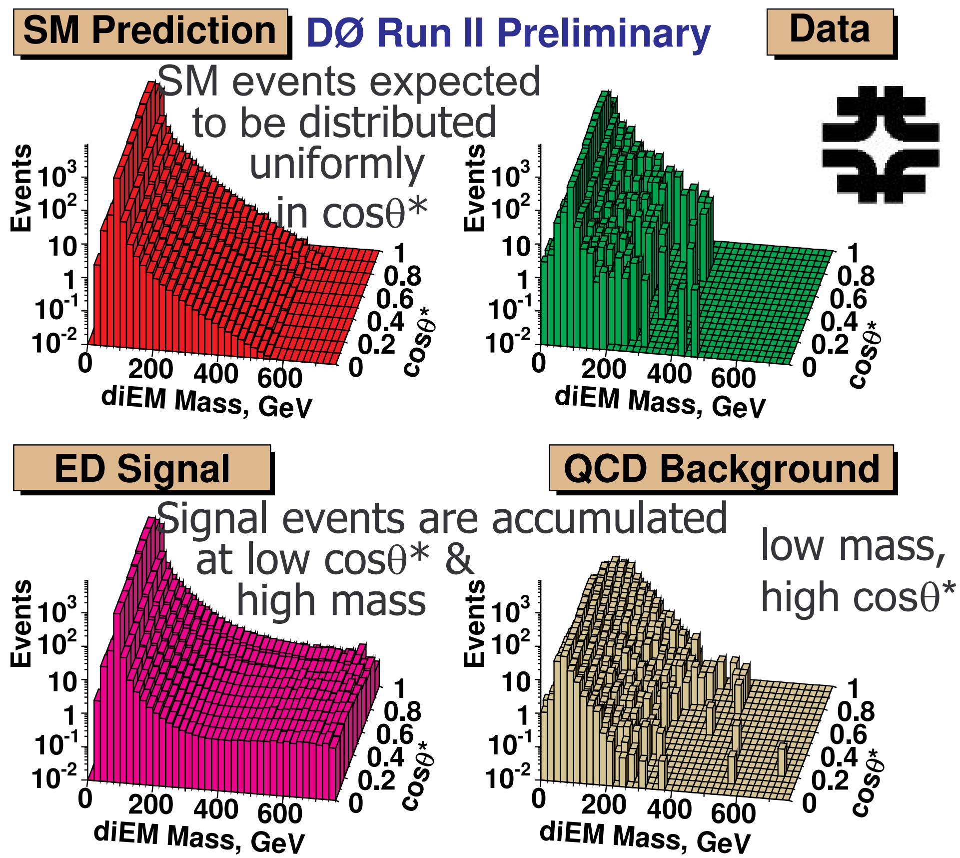
⇒ study deviations in invariant mass & angular distribution from SM processes

Dilepton Channel



Diphoton Channel



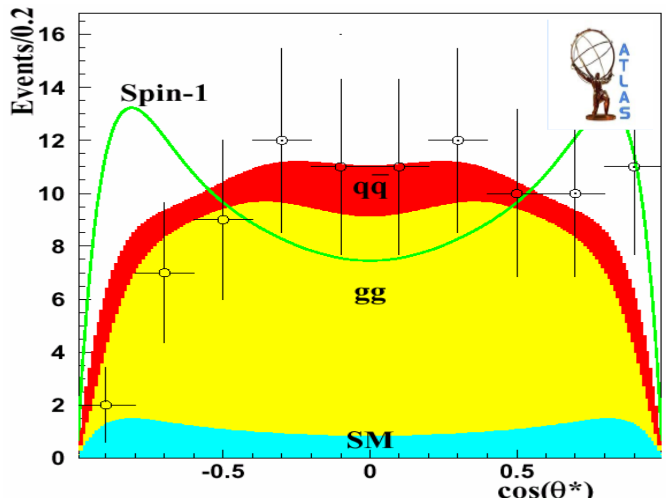


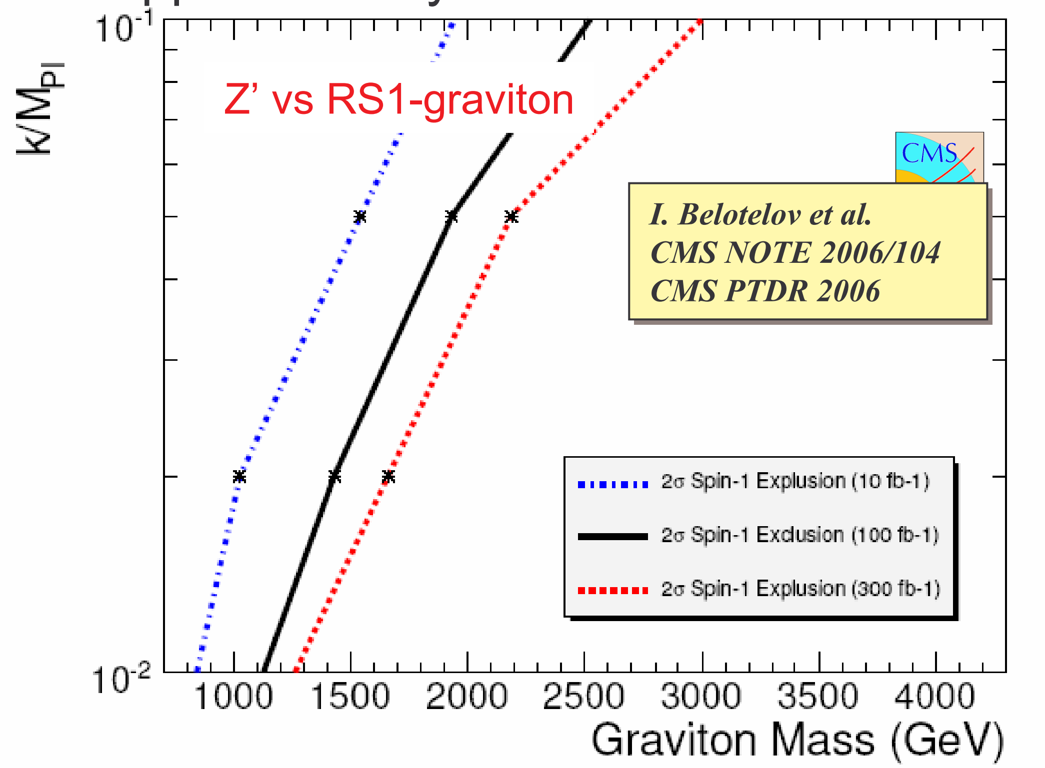
Spin-1/Spin-2 Discrimination

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 ATLAS can be found

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