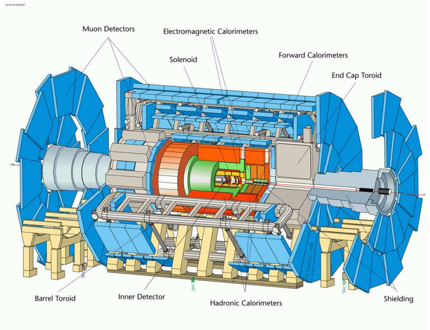
Review of Present Searches for
Extra Dimensions
And Prospects for the LHC



Dr Tracey Berry
Royal Holloway
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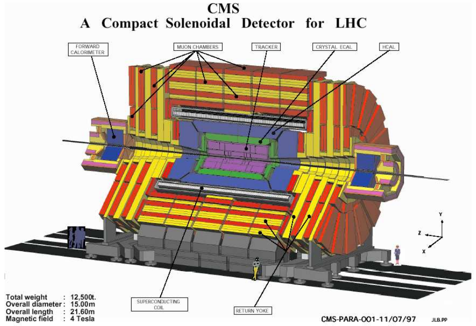


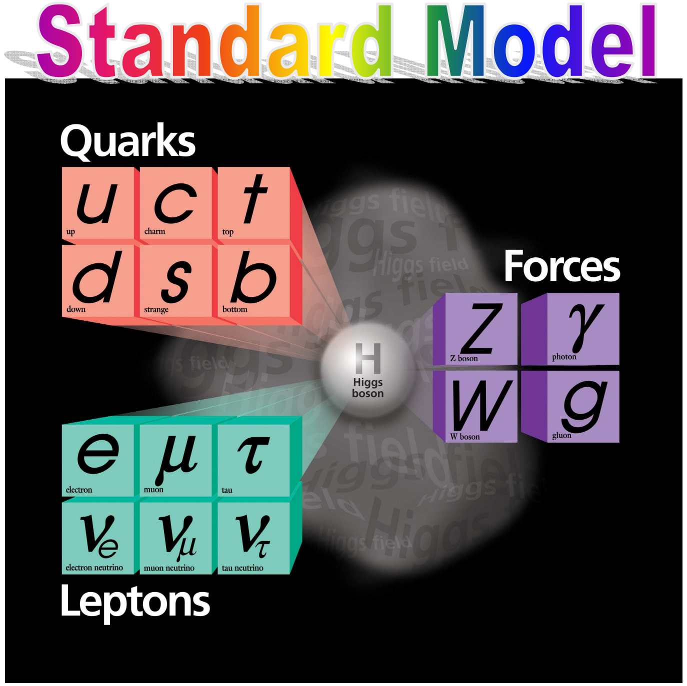
Overview

- Extra Dimension Models
- Search Facilities
  - **ADD**
    - LEP
    - Tevatron: CDF & D0
    - LHC: ATLAS & CMS
  - **RS**
    - CDF Searches
    - LHC: ATLAS & CMS
  - **TeV-1**
    - D0
    - LHC: ATLAS & CMS
  - **(UED)**
- Summary

The Standard Model

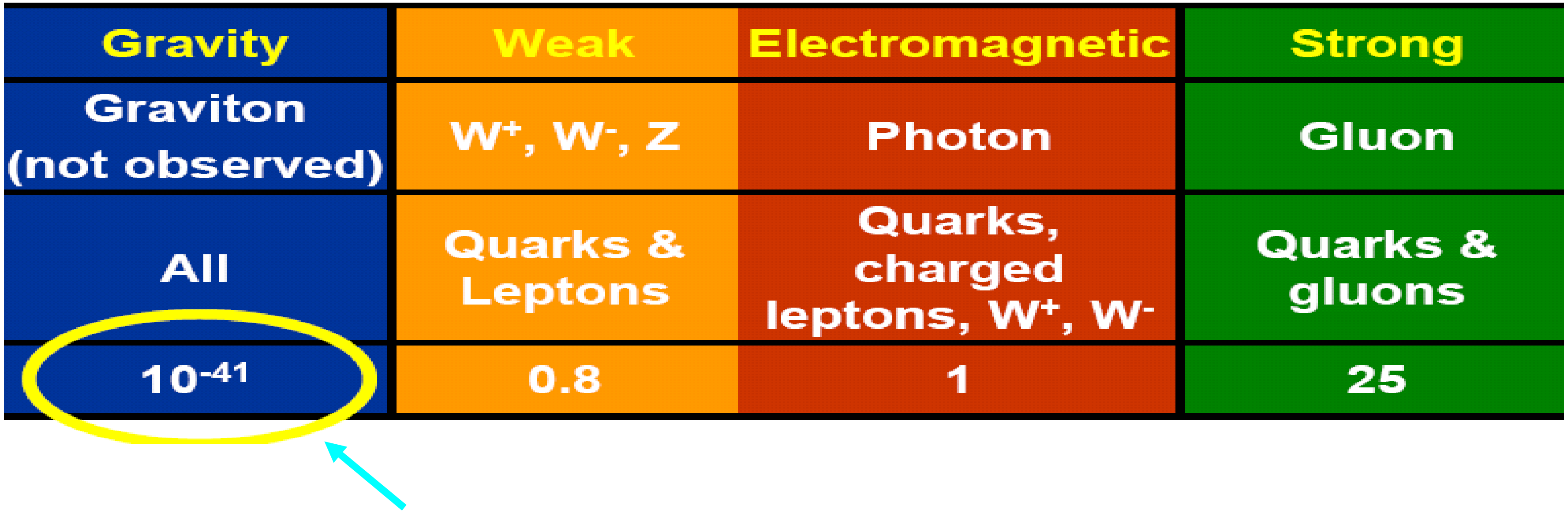
The SM : particles + forces

Gravity is not included!



Motivation for searching for something beyond the SM….

Forces in Nature



Gravity	Weak	Electromagnetic	Strong
Graviton (not observed)	W^+, W^-, Z	Photon	Gluon
All	Quarks & Leptons	Quarks, charged leptons, W^+, W^-	Quarks & gluons
10^{-41}	0.8	1	25

Gravity is very weak! → Hierarchy Problem

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

Table from
Cigdem Issever,
Oxford

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

Many (δ) large compactified EDs
In which G can propagate

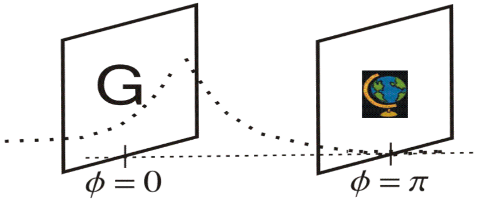
$$\boxed{M_{Pl}^2 \sim R^{\delta} M_{Pl(4+\delta)}^{(2+\delta)}}$$

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

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

1 highly curved ED
Gravity localised in the ED

Planck TeV brane



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

$\Lambda_{\pi} \sim$ 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

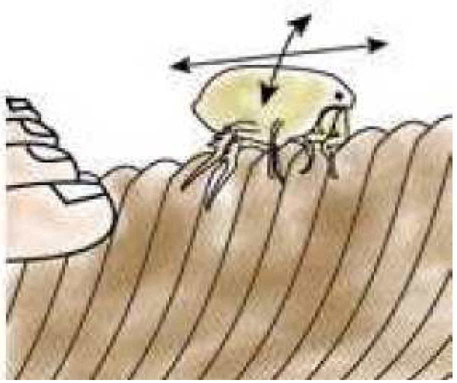
Extra Dimensions?

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

The "extra" dimensions could be hidden to us:

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

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



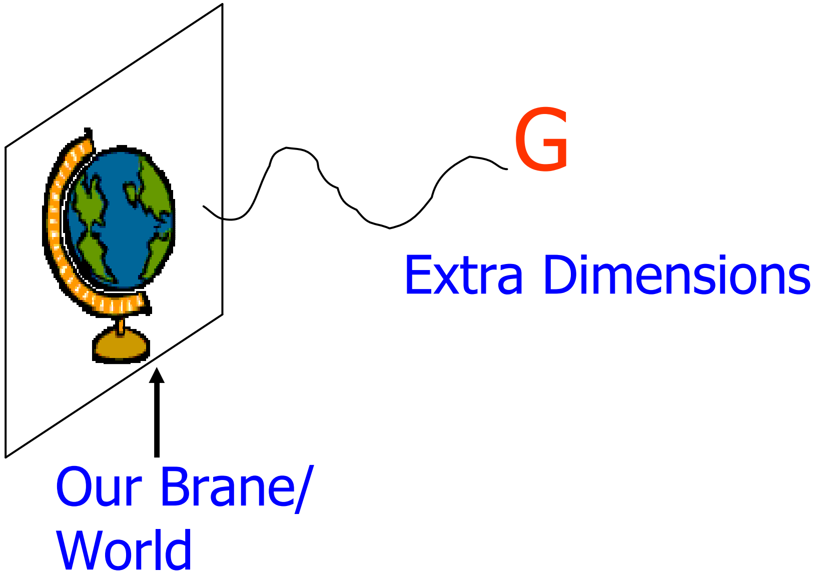
p://www.particleadventure.org/frameless/extra_dim.html

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

Extra Dimensions?

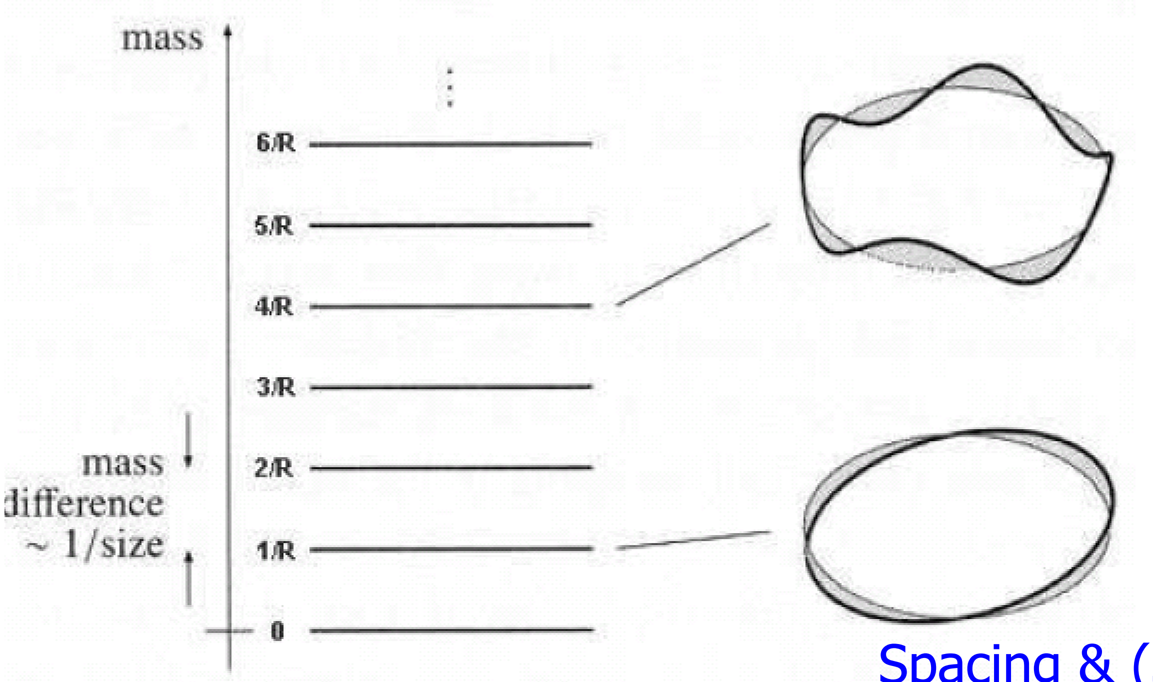
Or only some kinds of matter are able to move in the extra dimensions, and we are confined to our world.

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



KK towers/particles

When particles go into the extra dimensions….



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

Like QM particles in a box

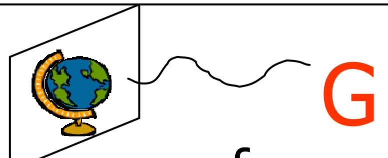
$M_n = \sqrt{(M_0^2+n^2/R^2)}$

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

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

Extra Dimensional Models

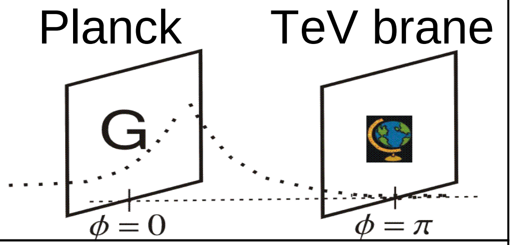
ADD **A**rkani-Hamed, **D**imopoulos, **D**vali,
Phys Lett B429 (98)



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

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

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



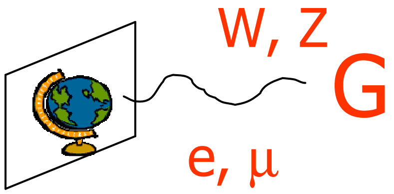
TeV^{-1} sized EDs Dienes, Dudas, Gherghetta,
Nucl Phys B537 (99)

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

UED

Not covered here!

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



Experimental Signatures of ED

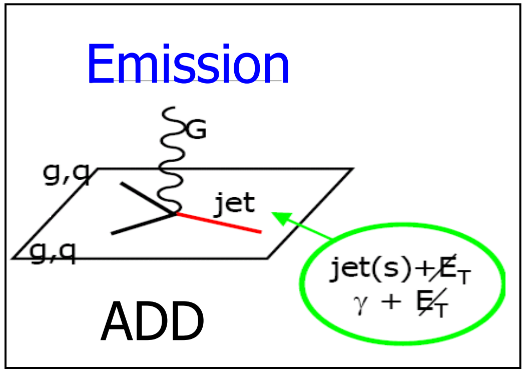
Covered in this talk

- Large Extra Dimensions (ADD)
    - KK Graviton Direct Production → Missing E_T signature

      Single jets/Single photons + missing ET

    - KK Graviton Exchange → Drell-Yan

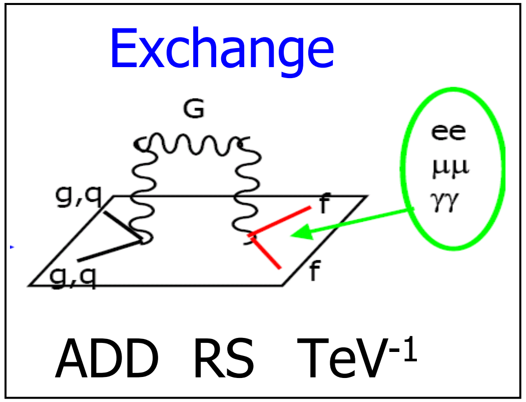
      Di-lepton, di-jet continuum modifications



- Randall-Sundrum Model
    - KK Graviton →TeV resonances

      Di-lepton, di-jet and di-photon resonances

      Diboson resonances



- TeV^{-1} Model
    - KK Gauge Bosons (Z_{KK}) (also W_{KK})

      Di-lepton resonances

Past ED Search Facilities

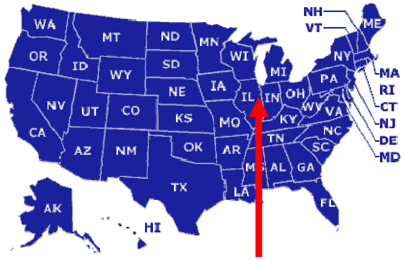
LEP, CERN, Geneva

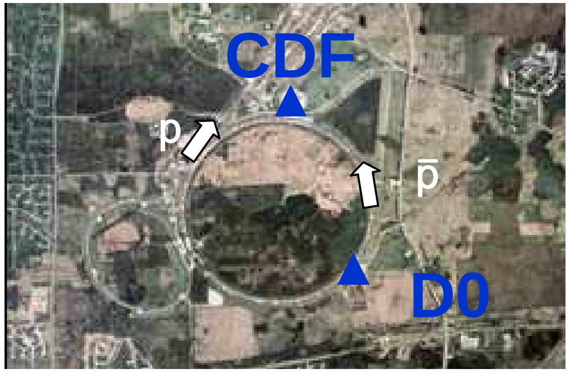
CERN: world's largest particle physics laboratory

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

Present ED Search Facilities

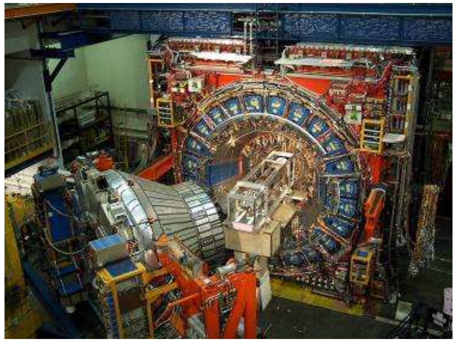
Tevatron, Fermilab, USA



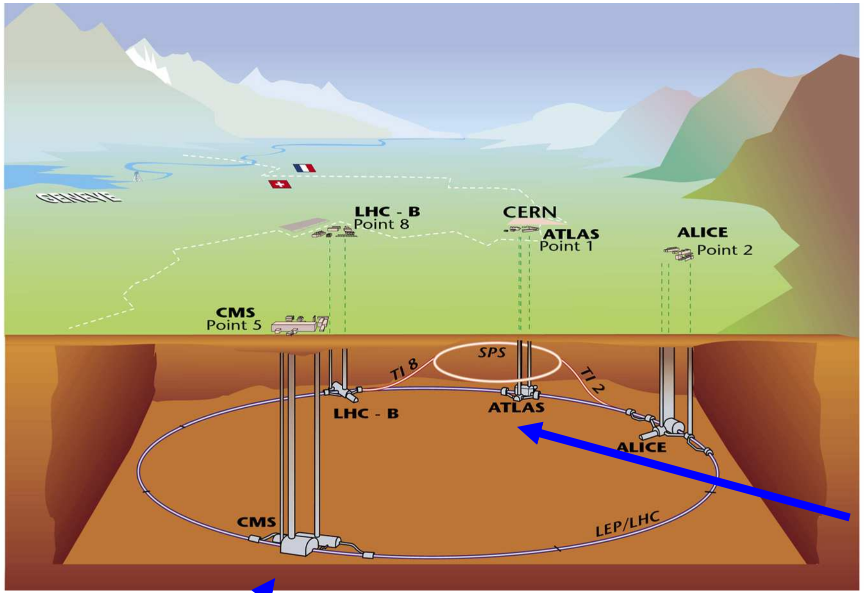


Tevatron: Highest energy collider operating in the world!

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

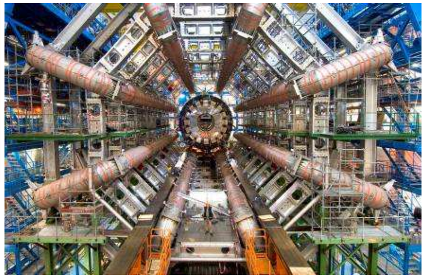


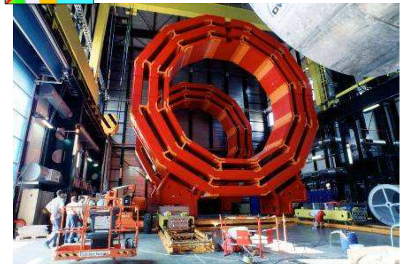
Future ED Search Facilities!



Bigger Collider & Detectors!!

LHC: proton – proton collisions
Higher center of mass energy
$\sqrt{s}$ = 14 TeV

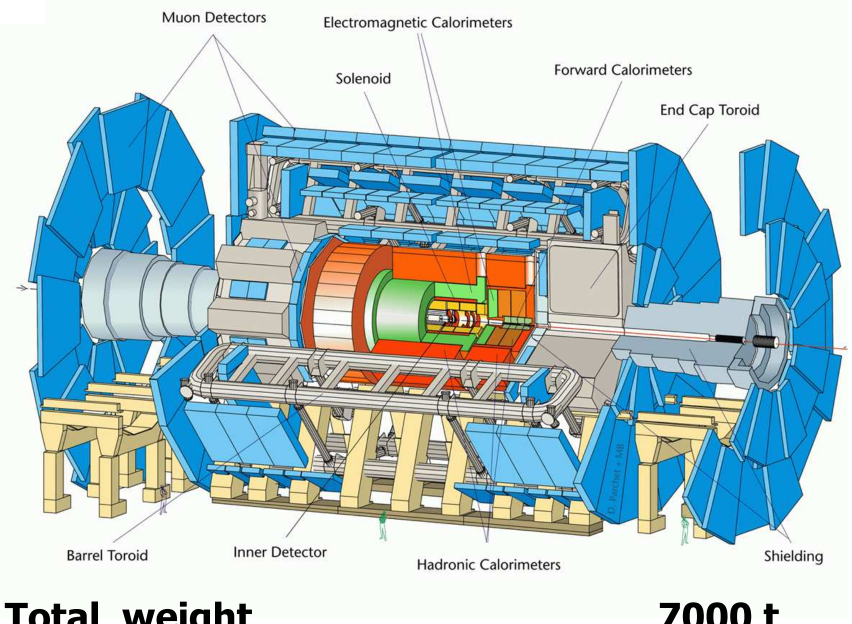




ATLAS and CMS Experiments

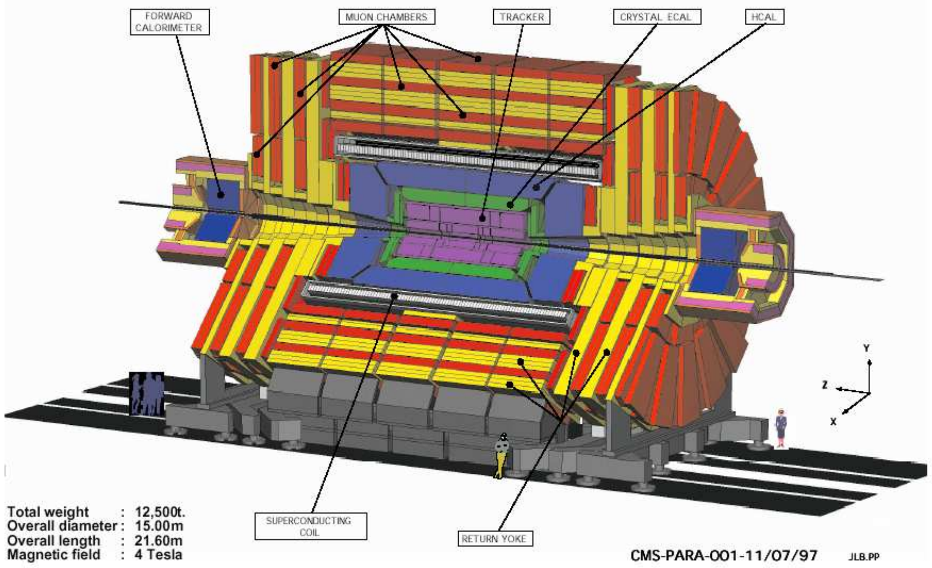
Large general-purpose particle physics detectors

A Toroidal LHC ApparatuS



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

Compact Muon Solenoid



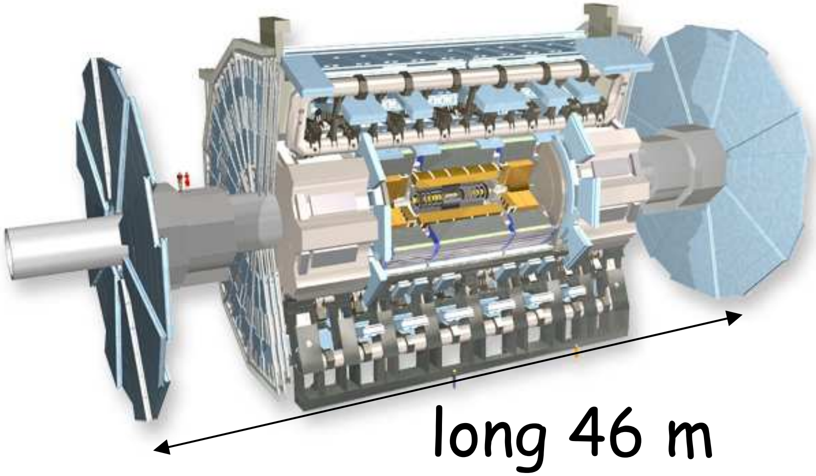
Total weight	**12 500 t**
Overall diameter	**15.00 m**
Overall length	**21.6 m**
Magnetic field	**4 Tesla**

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

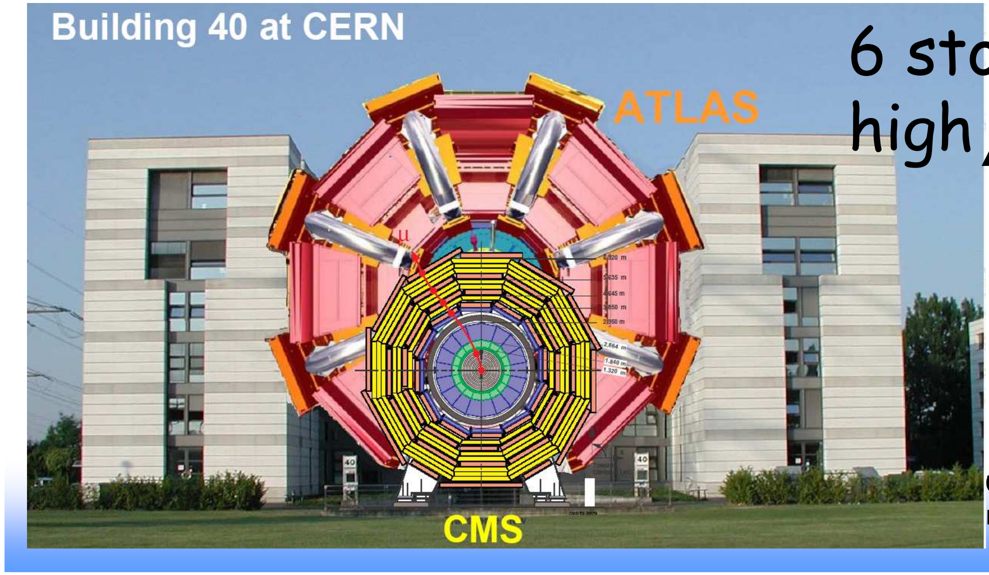
ATLAS

Largest volume particle detector ever constructed!

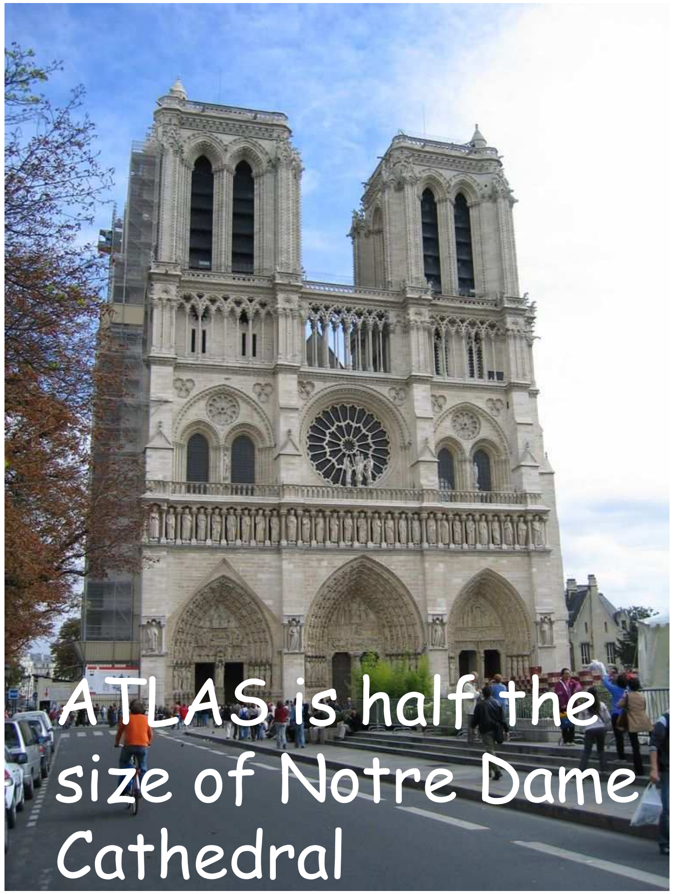
Overall
diameter
25 m



long 46 m



6 storeys
high



ATLAS is half the size of Notre Dame Cathedral

LHC best 'working schedule‘ 2009

- **Moving out of magnets affected by the incident** has started. It is foreseen to **remove 39 dipoles**, including 6 (3 at each side) in a buffer zone. These magnets should not be affected but will be re-tested just to confirm that the limits of the affected region are understood. **14 SSS quadrupoles** will also be moved out.
- **All magnets to be brought to the surface should be out before the Christmas shutdown.** By then 20 dipoles should already be back in the machine. The plan is to install the first dipole (from the set of spares) already this week.
- The test bench (for cold testing) is a limiting factor. Capacity to be ramped up after connection of 18 kW plant (now 6 kW) in February 2009.
- **Last magnet should be back in end of March 2009;**

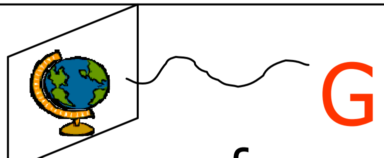
  whole machine cold again beginning of July.

  This means optimistically: first beam in the machine end of July.

ADD Model

Non-Search Constraints on the ADD Model

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



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

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

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

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

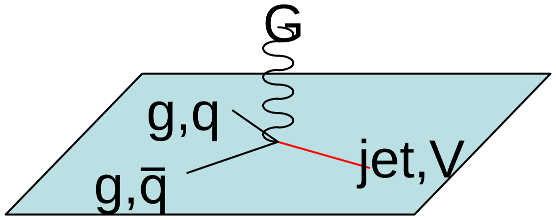
*Cullen, Perelstein
Phys. Rev. Lett 83,268 (1999)

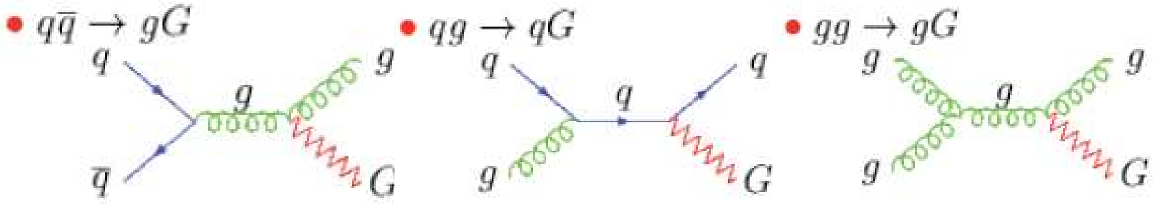
ADD Collider Signatures

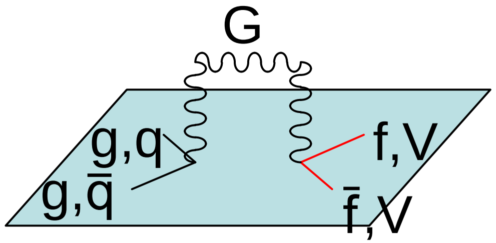
- **Real Graviton emission** in association with a vector-boson

Signature: jets + missing E_T, V+missing E_T

σ depends on the number of ED





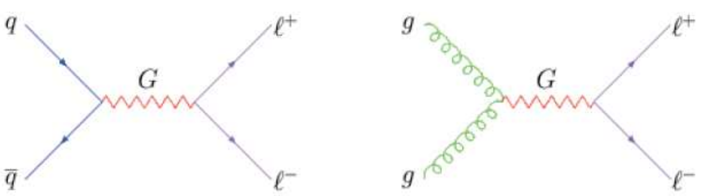


- **Virtual Graviton exchange**

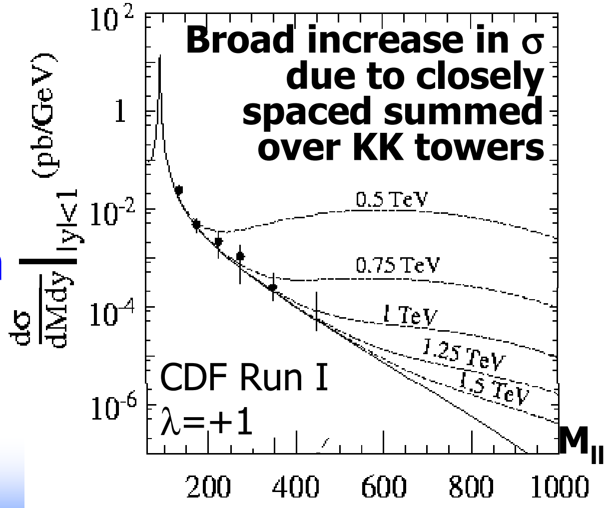
Signature:

deviations in σ and asymmetries of SM processes e.g. qq̄ → l⁺l⁻, γ γ & new processes e.g. gg → l⁺l⁻

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

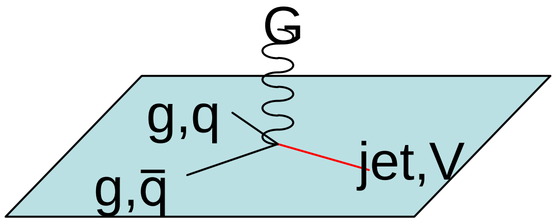


Excess above di-lepton continuum


Broad increase in σ due to closely spaced summed over KK towers

ADD Model

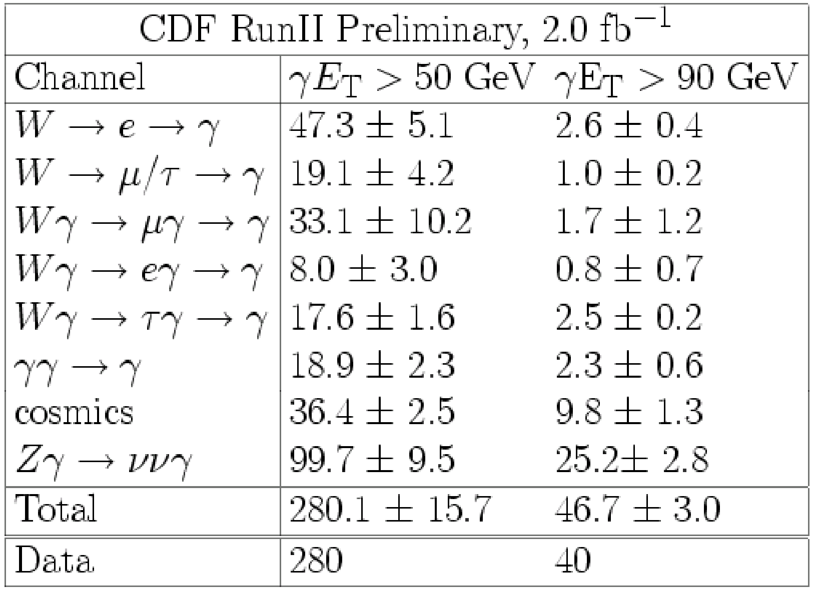
Real Graviton emission



CDF ADD G emission Search: Photon+MET channel in RunII

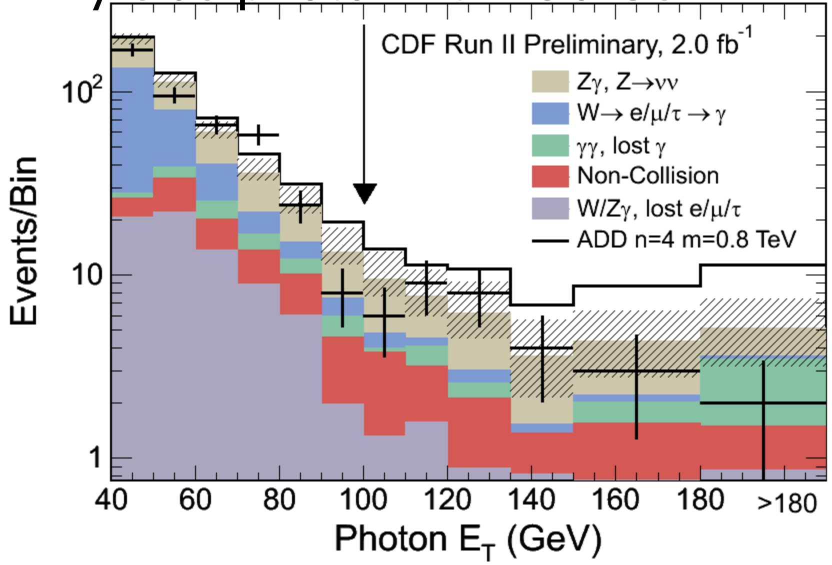
<u>Data Selection</u>
Central Photon Et > 50 GeV
Missing Et > 50 GeV
No jets with Et > 15 GeV
No tracks with Pt > 10 GeV
At least 3 low Pt COT tracks

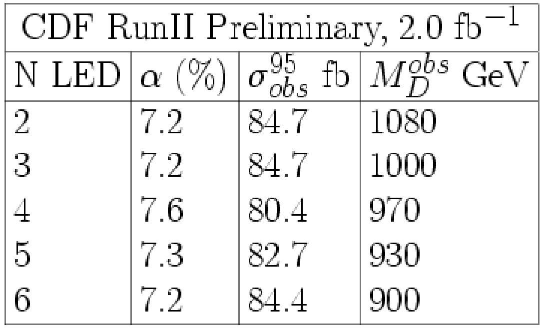
<u>Background Predictions</u>



CDF RunII Preliminary, 2.0 fb^{-1}		
Channel	$\gamma E_T > 50$ GeV	$\gamma E_T > 90$ GeV
$W \to e \to \gamma$	47.3 ± 5.1	2.6 ± 0.4
$W \to \mu/\tau \to \gamma$	19.1 ± 4.2	1.0 ± 0.2
$W\gamma \to \mu\gamma \to \gamma$	33.1 ± 10.2	1.7 ± 1.2
$W\gamma \to e\gamma \to \gamma$	8.0 ± 3.0	0.8 ± 0.7
$W\gamma \to \tau\gamma \to \gamma$	17.6 ± 1.6	2.5 ± 0.2
$\gamma\gamma \to \gamma$	18.9 ± 2.3	2.3 ± 0.6
cosmics	36.4 ± 2.5	9.8 ± 1.3
$Z\gamma \to \nu\nu\gamma$	99.7 ± 9.5	25.2 ± 2.8
Total	280.1 ± 15.7	46.7 ± 3.0
Data	280	40

optimization for the ADD model yields photon Et > 90 GeV





CDF RunII Preliminary, 2.0 fb^{-1}			
N LED	α (%)	σ^{95}_{obs} fb	M_D^{obs} GeV
2	7.2	84.7	1080
3	7.2	84.7	1000
4	7.6	80.4	970
5	7.3	82.7	930
6	7.2	84.4	900

M Goncharov, V Krutelyov, R Culbertson, A Pronko

CDF ADD G emission Search: Jets+MET channel in RunII

Data Selection

Optimized Search for LED

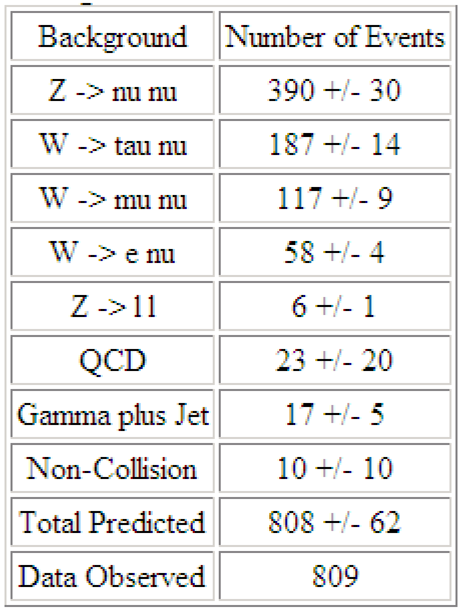
Leading Jet Et > 150 GeV

Event Missing Et > 120 GeV

Allow 2nd Jet with Et < 60 GeV

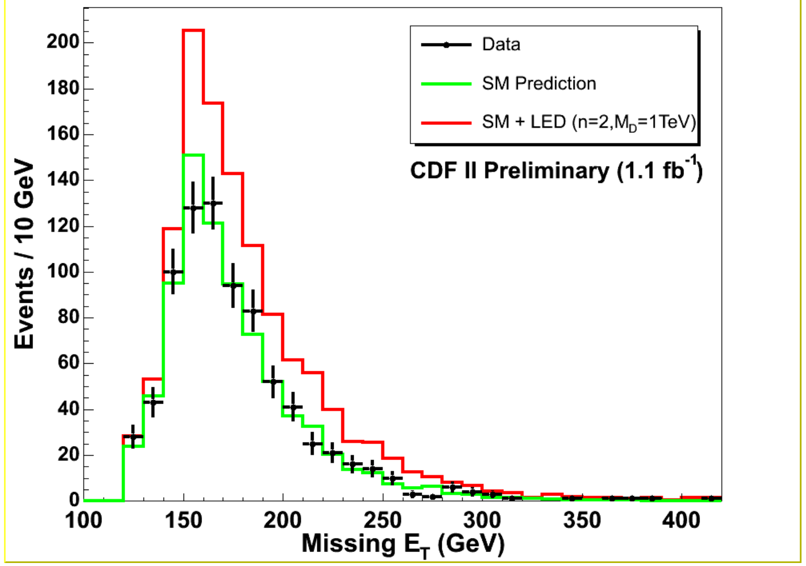
No 3rd Jet with Et > 20 GeV

Background Predictions

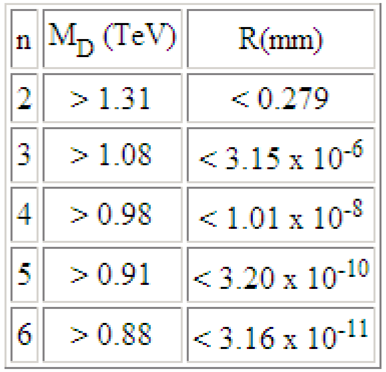


Background	Number of Events
Z -> nu nu	390 +/- 30
W -> tau nu	187 +/- 14
W -> mu nu	117 +/- 9
W -> e nu	58 +/- 4
Z ->ll	6 +/- 1
QCD	23 +/- 20
Gamma plus Jet	17 +/- 5
Non-Collision	10 +/- 10
Total Predicted	808 +/- 62
Data Observed	809

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



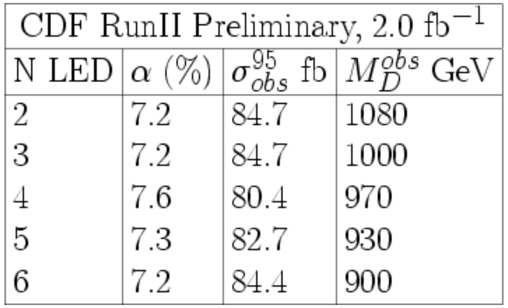
- LED Limits:



n	M_D (TeV)	R(mm)
2	> 1.31	< 0.279
3	> 1.08	< 3.15 x 10^{-6}
4	> 0.98	< 1.01 x 10^{-8}
5	> 0.91	< 3.20 x 10^{-10}
6	> 0.88	< 3.16 x 10^{-11}

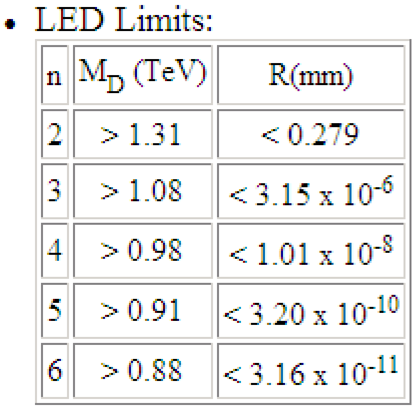
ADD G Emission Searches: in RunII

Photon+MET



CDF RunII Preliminary, 2.0 fb^{-1}			
N LED	α (%)	σ^{95}_{obs} fb	M^{obs}_{D} GeV
2	7.2	84.7	1080
3	7.2	84.7	1000
4	7.6	80.4	970
5	7.3	82.7	930
6	7.2	84.4	900

Jets+MET



- LED Limits:

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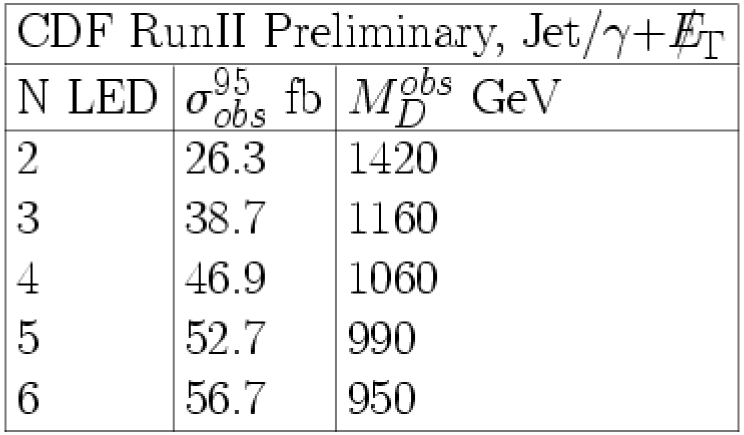
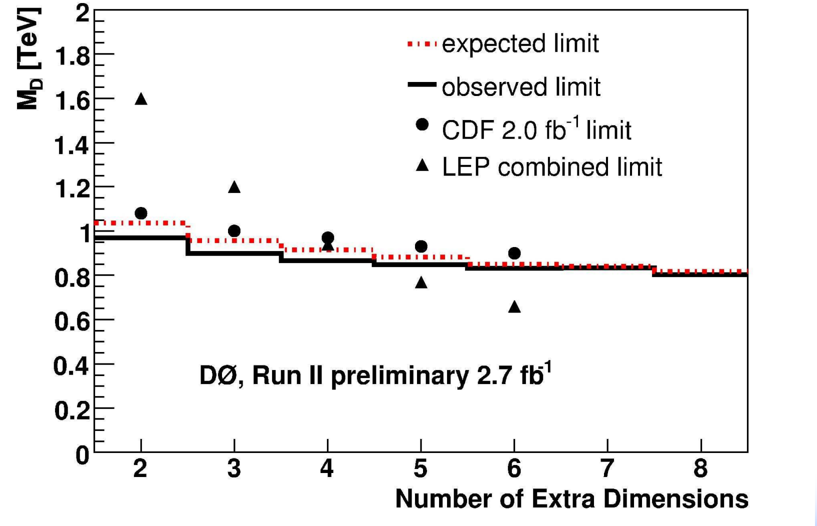
Combined



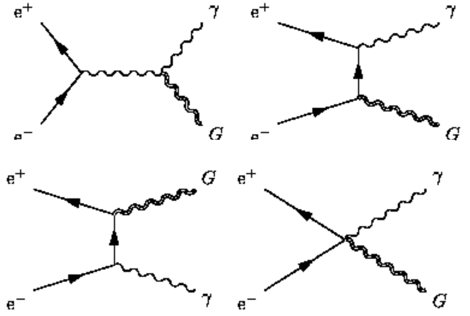
CDF RunII Preliminary, Jet/γ+$\not\!\!E_T$		
N LED	σ^{95}_{obs} fb	M^{obs}_{D} GeV
2	26.3	1420
3	38.7	1160
4	46.9	1060
5	52.7	990
6	56.7	950

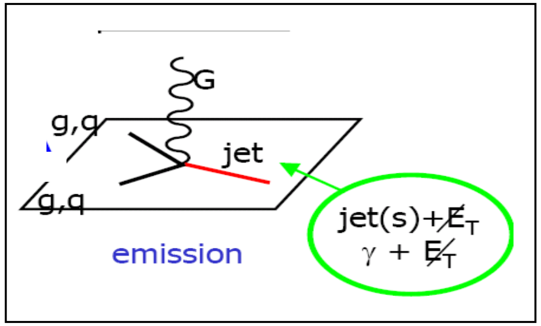
D0's Jet+MEt 2.7fb^{-1} search limit not so exclusive as CDF's combined limit

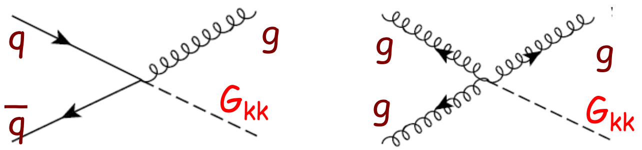


Present ADD Emission Limits

LEP and Tevatron results are complementary

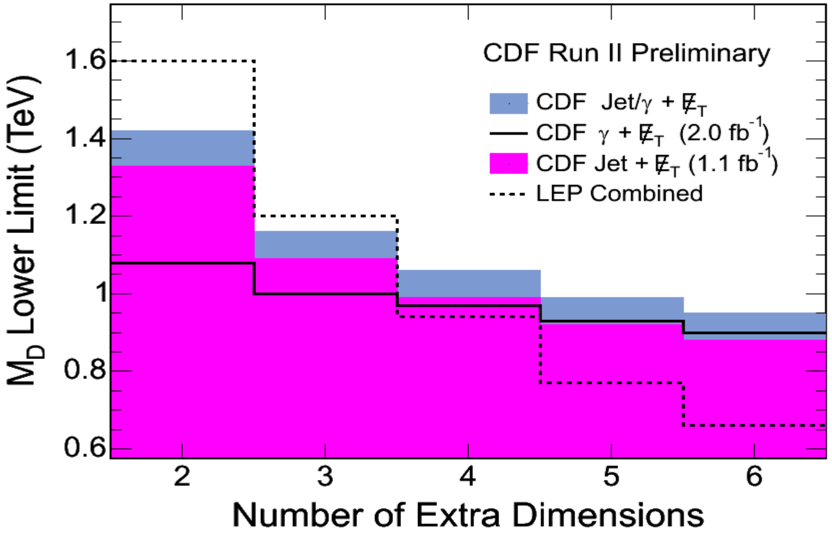


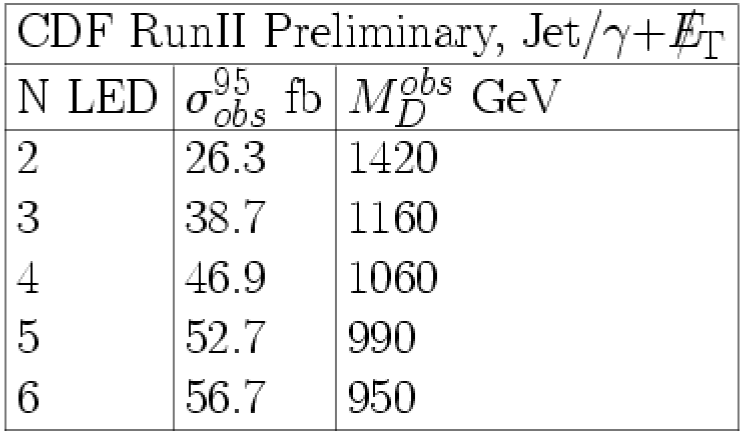




For n>=4: CDF combined limits best

For n<4: LEP limits best γ+ME$_T$



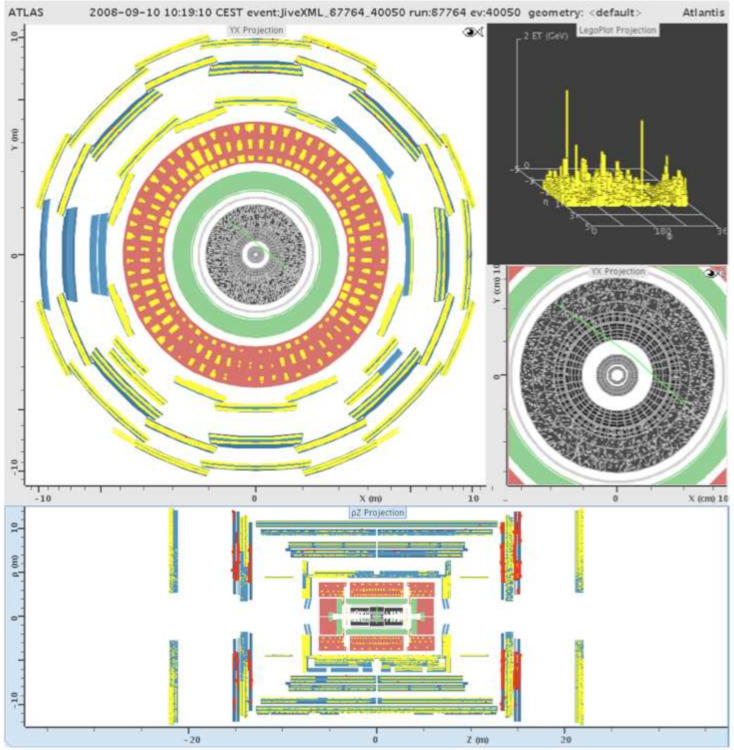


CDF RunII Preliminary, Jet/γ+$\not E_T$

N LED	σ^{95}_{obs} fb	M_D^{obs} GeV
2	26.3	1420
3	38.7	1160
4	46.9	1060
5	52.7	990
6	56.7	950

The Future…LHC…

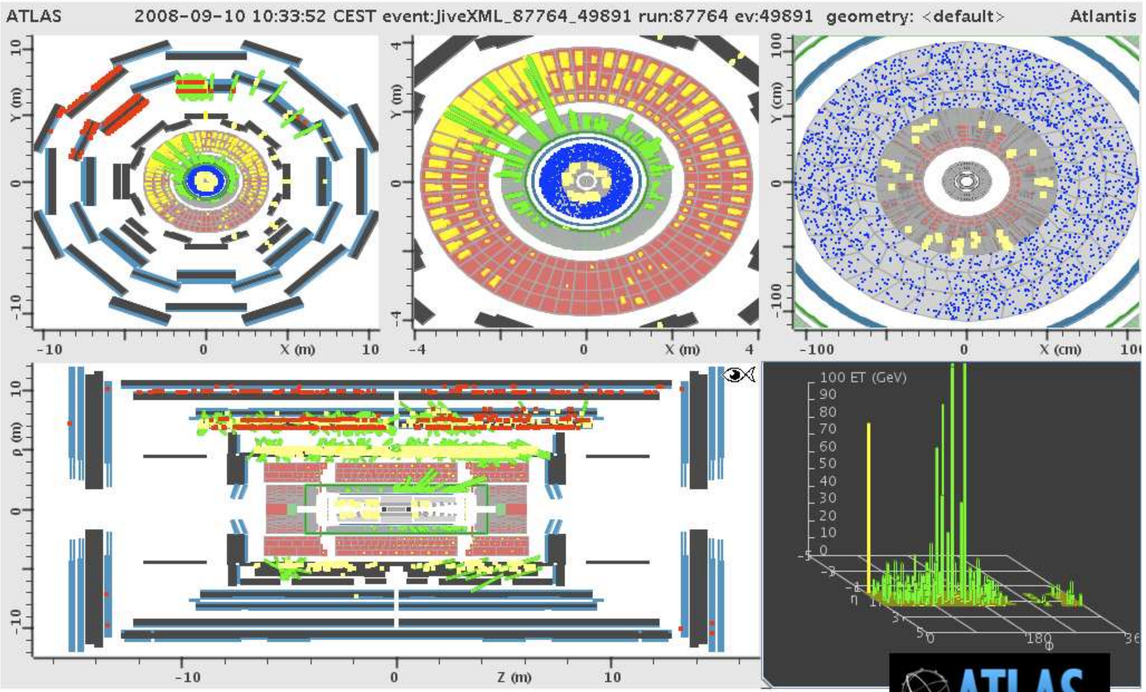
- What we can do when we have collisions and more data…



ATLAS EXPERIMENT
http://atlas.ch

first beam event seen in ATLAS

- ...more data…

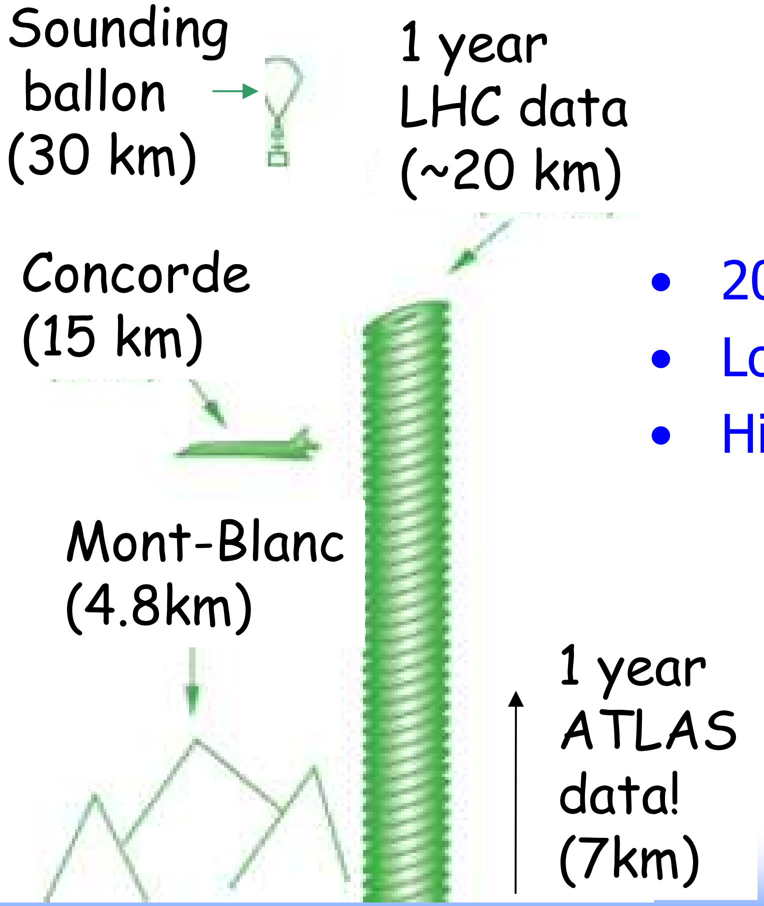


2nd beam event seen in ATLAS

- And a bit more…….

LHC Data / Prospects

In 1 year ATLAS will record 3200 Terabytes of data equivalent to: 7 km of stacked up CDROMs !



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

ADD Discovery Limit: γ+G Emission

J. Weng et al. CMS NOTE 2006/129

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

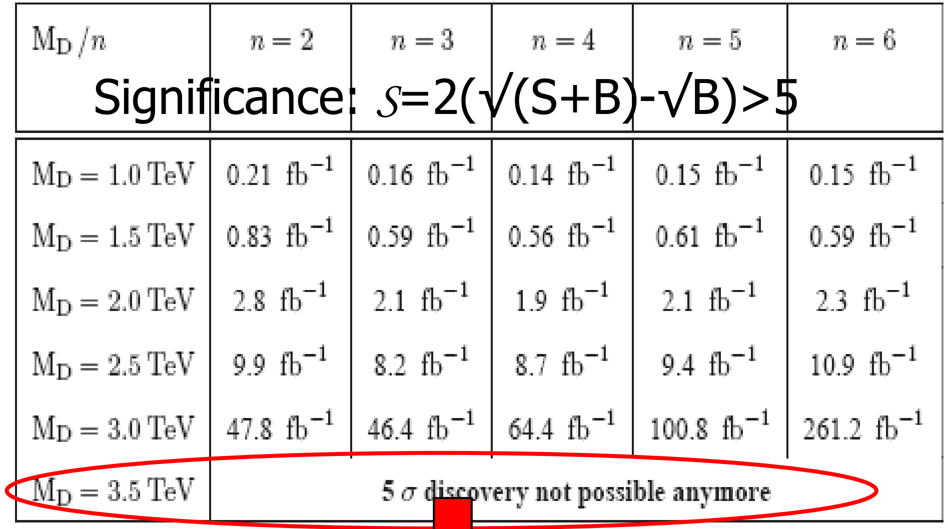
- ☐ $\gamma G \Rightarrow$ high-p_T photon + high missing E_T

  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

Integrated Lum for a 5σ significance discovery



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				

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

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

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

ADD Discovery Limit: γ+G Emission

ATLAS

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

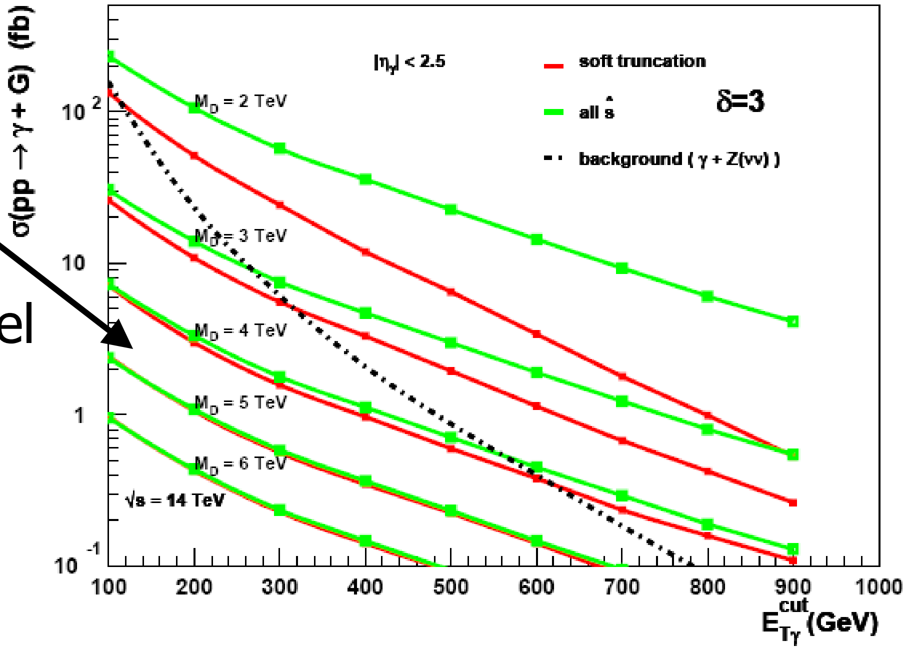
$pp \rightarrow \gamma + G^{KK}$: $q\bar{q} \rightarrow \gamma G^{KK}$

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

M_D^{MAX} (TeV)	δ=2
HL 100fb^{-1}	4

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

This gets worse as δ increases



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

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

ADD Discovery Limit: jet+G Emission

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

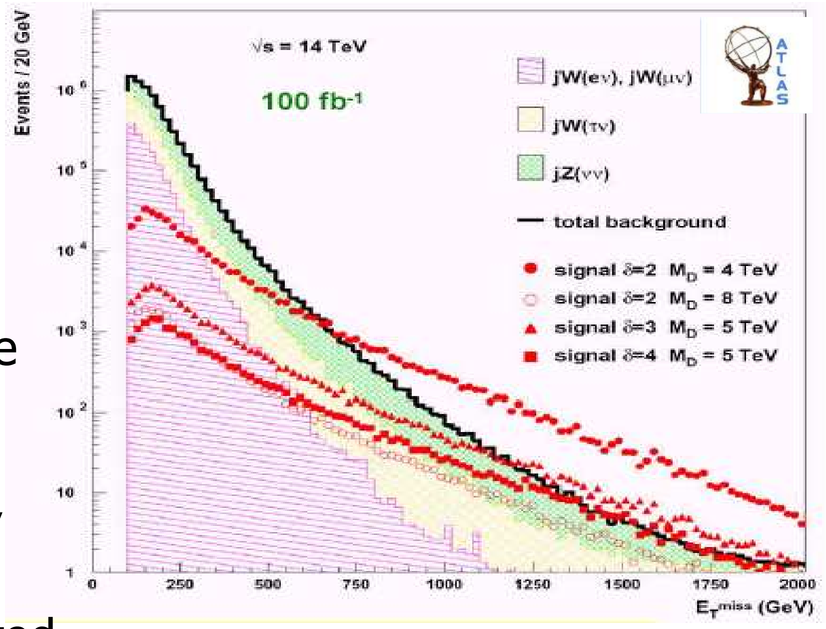
gg→gG, qg→qG & q$\bar{q}$→Gg

Dominant subprocess

❑Signature: jet + G ⇒ jet with high transverse energy (E_T>500 GeV)+ high missing E_T (E_T^{miss}>500 GeV),

❑ vetos leptons: to reduce jet+W bkdg mainly

❑ Bkgd.: irreducible jet+Z/W →jet+νν /jet+lν
jZ(νν) dominant bkgd, can be calibrated using ee and μμ decays of Z.



Discovery limits

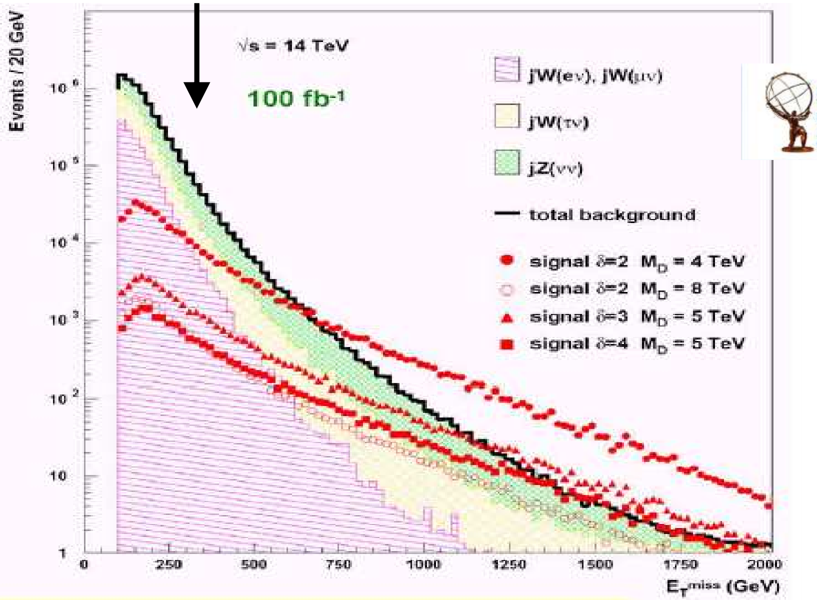
$M_{Pl(4+d)}^{MAX}$(TeV)	δ=2	δ=3	δ=4
LL $30fb^{-1}$	7.7	6.2	5.2
HL $100fb^{-1}$	9.1	7.0	6.0

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

ADD Parameters: jet+G Emission

To characterise the model need to measure M_D and δ

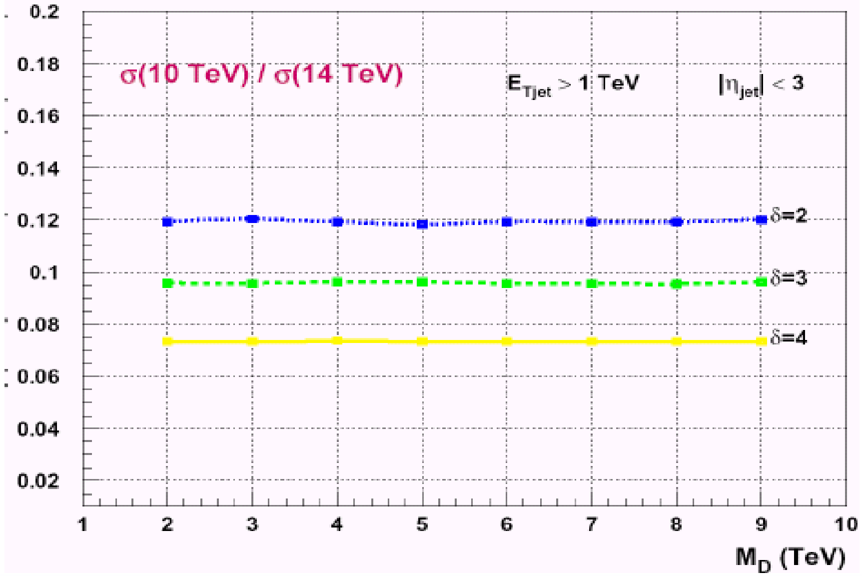
Measuring $\sigma(pp \to jet+G^{KK})$ gives ambiguous results



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

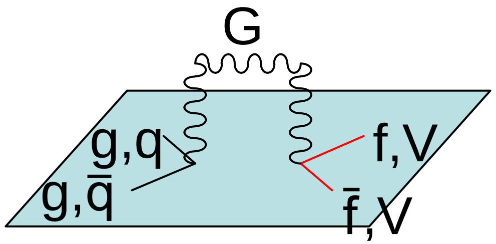
Run at two different $\sqrt{s}$
e.g. 10 TeV and 14 TeV, need 50 fb^{-1}



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

ADD Model

Graviton Exchange

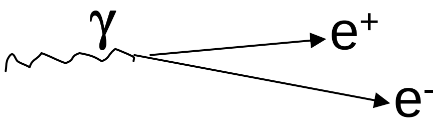


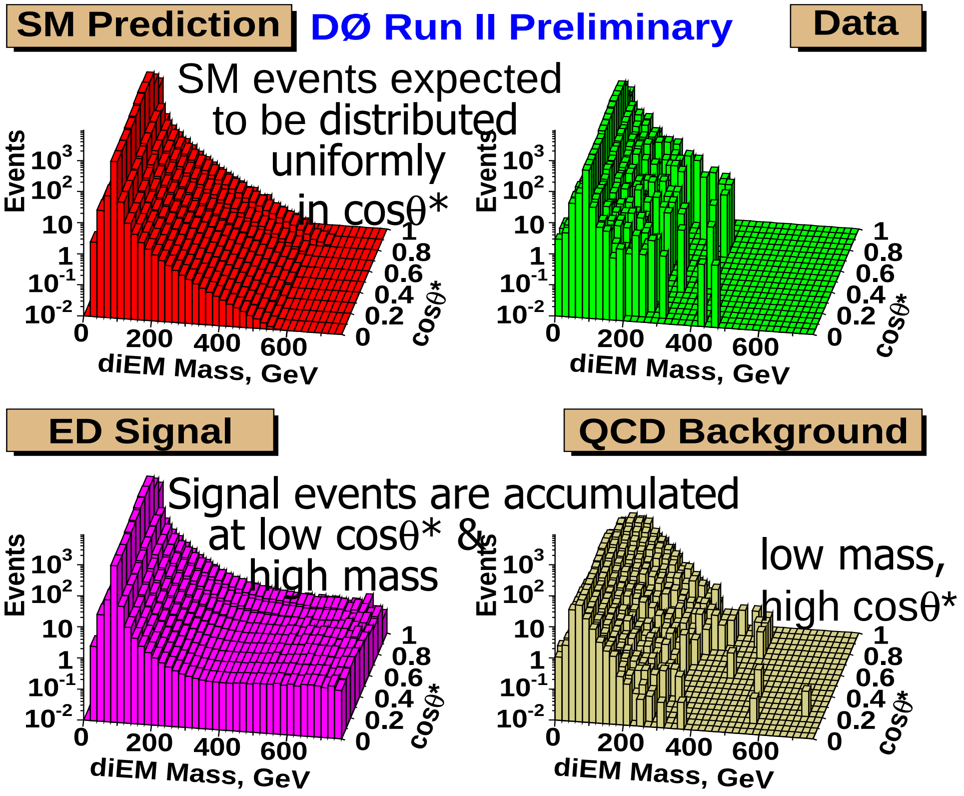
D0 ee+γγ ADD: G Exchange

D0 perform a combined 2D fit of the invariant mass and angular information (cosθ*) spectrum to extract limits

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

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





SM events expected to be distributed uniformly in cosθ*

Signal events are accumulated at low cosθ* & high mass

low mass, high cosθ*

Tevatron ADD Exchange Limits

Both D0 and CDF have observed no significant excess

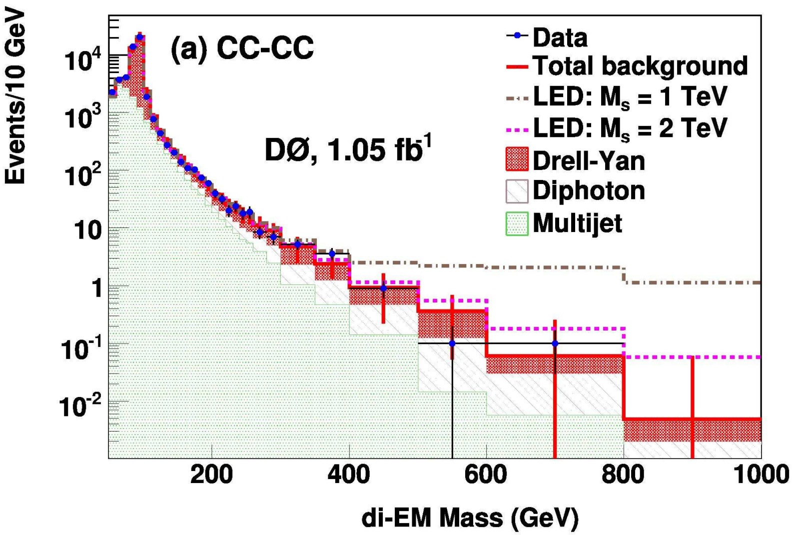
95% CL lower limits on fundamental Planck scale (M_s) in TeV, using different formalisms:

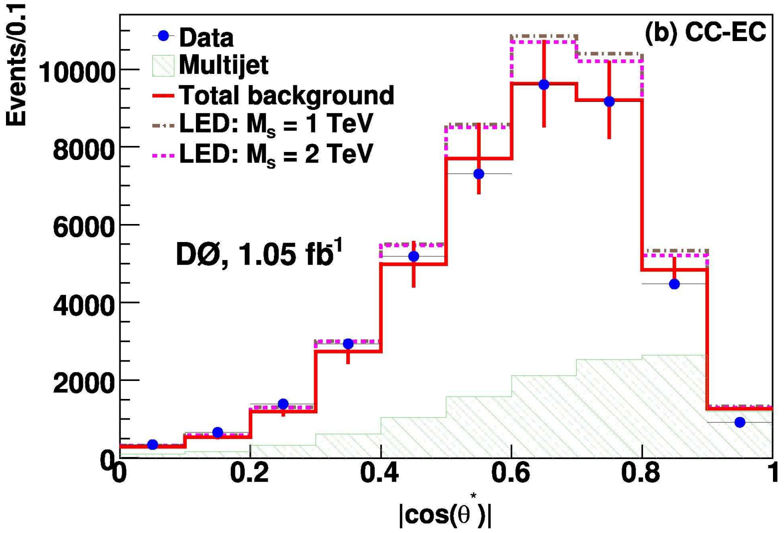
Historical Interest!

	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

These results surpassed by D0's 1.05 fb-1 diEM search…..

D0 LED Search for LED: ee+γγ





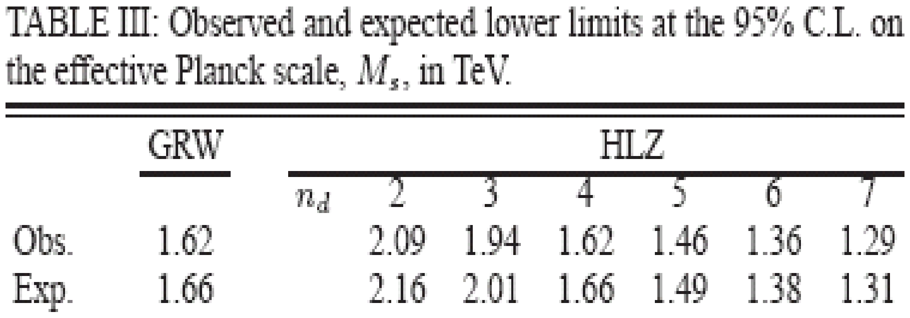
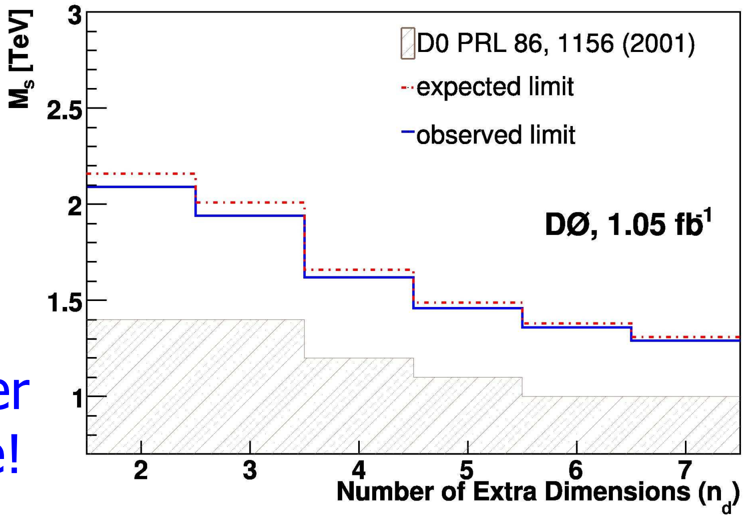


TABLE III: Observed and expected lower limits at the 95% C.L. on the effective Planck scale, M_s, in TeV.

	GRW	HLZ					
		n_d 2	3	4	5	6	7
Obs.	1.62	2.09	1.94	1.62	1.46	1.36	1.29
Exp.	1.66	2.16	2.01	1.66	1.49	1.38	1.31



most stringent collider limits on LED to date!

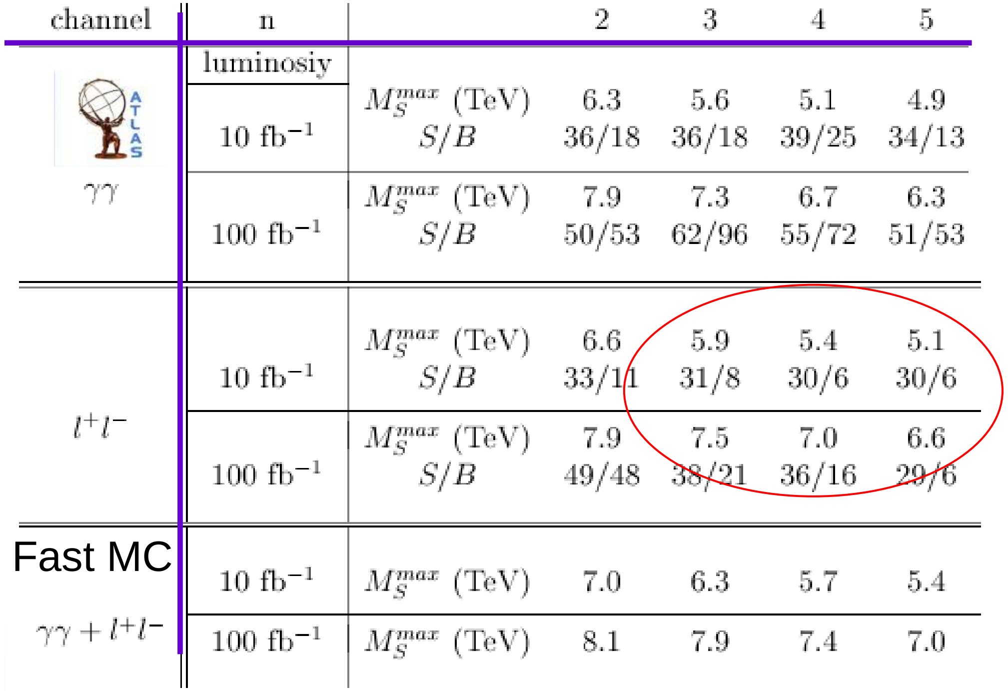
arXiv:0809.2813v1 hep-ex

LHC ADD Discovery Limit: G Exchange

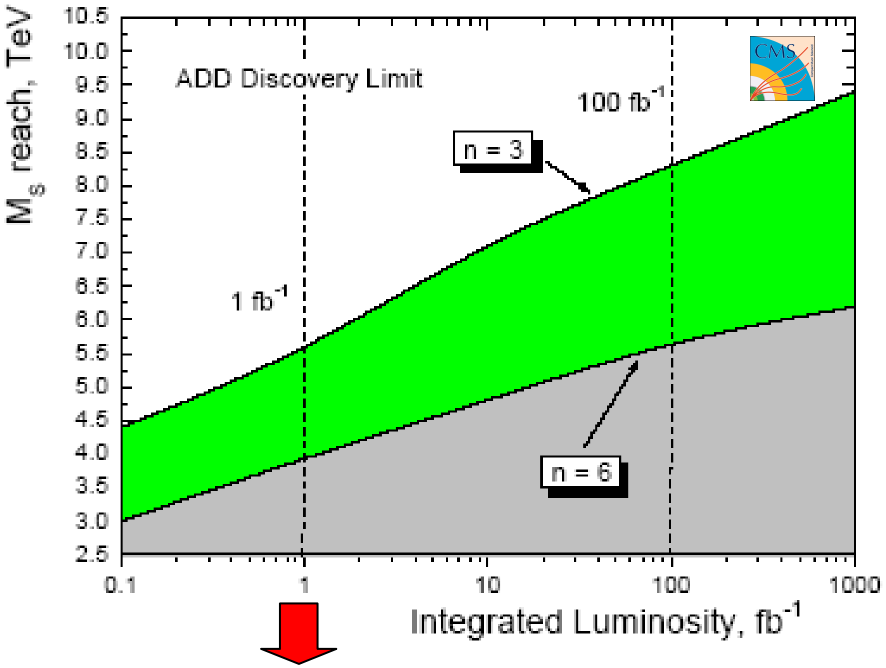
$pp \rightarrow G^{KK} \rightarrow \mu\mu$

Virtual graviton production

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



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



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

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

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

ADD Discovery Limits Summary

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

δ<=2 ruled out

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

Photon+Met CMS

Discovery above 3.5 TeV not possible in this channel

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

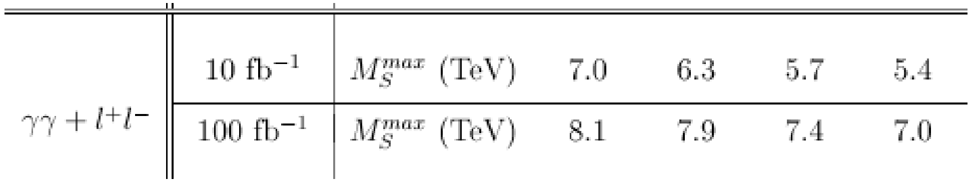
Jet+Met ATLAS

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

CMS Exchange limits:

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

ATLAS Exchange Limits



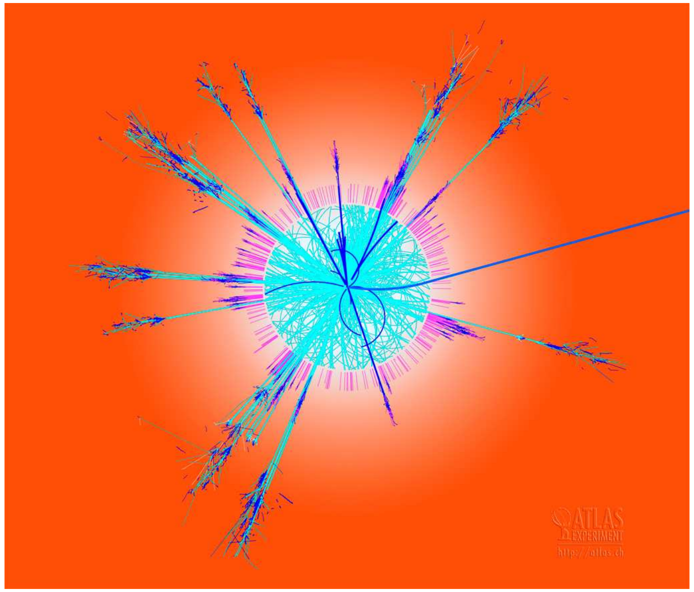
$\gamma\gamma + l^+l^-$	10 fb^{-1}	M_S^{max} (TeV)	7.0	6.3	5.7	5.4
	100 fb^{-1}	M_S^{max} (TeV)	8.1	7.9	7.4	7.0

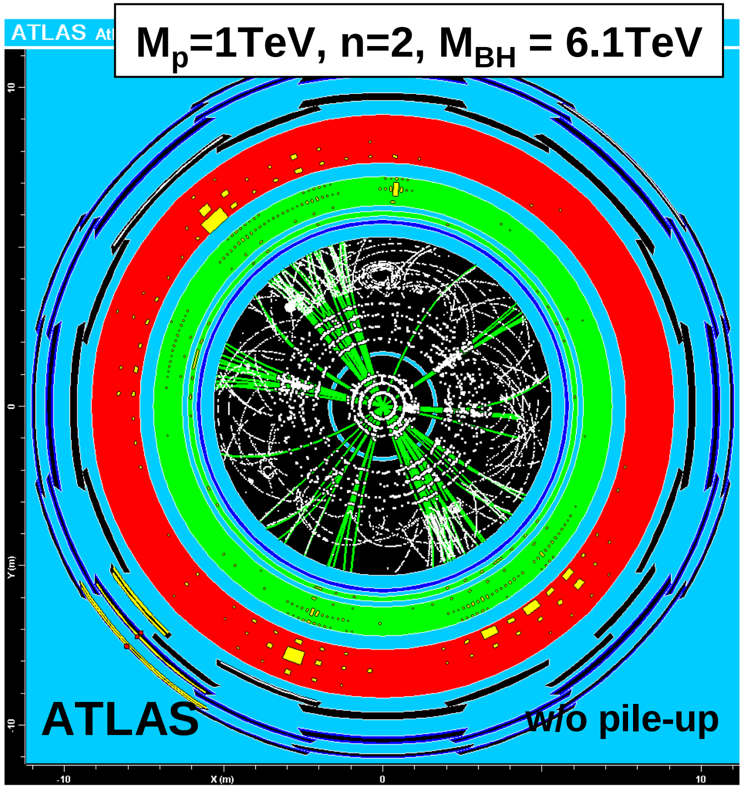
[redacted]

LHC: Black Hole Signatures

Dimopoulos and Landsberg PRL87 (2001) 161602

- In large ED (ADD) scenario, when impact parameter smaller than Schwartzschild radius Black Hole produced with potentially large x-sec (~100 pb).
- Decays democratically through Black Body radiation of SM states – Boltzmann energy distribution.

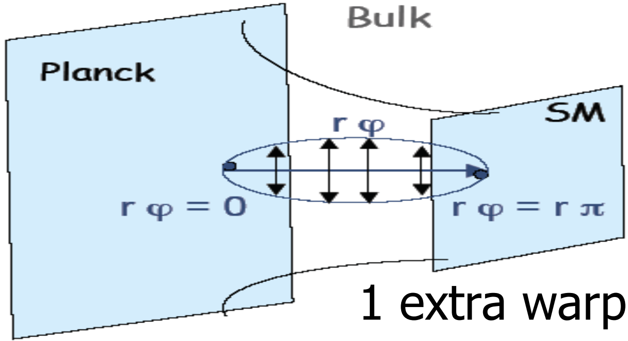




- Discovery potential (preliminary)
  - M_p < ~4 TeV → < ~ 1 day
  - M_p < ~6 TeV → < ~ 1 year
- Studies continue …

RS Model

Experimental Signature for RS Model

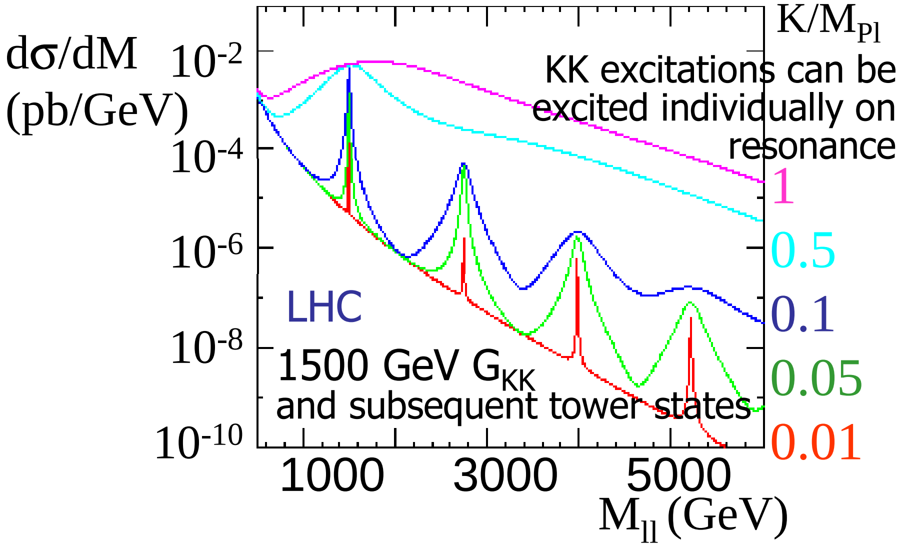


1 extra warped dimension

Signature:

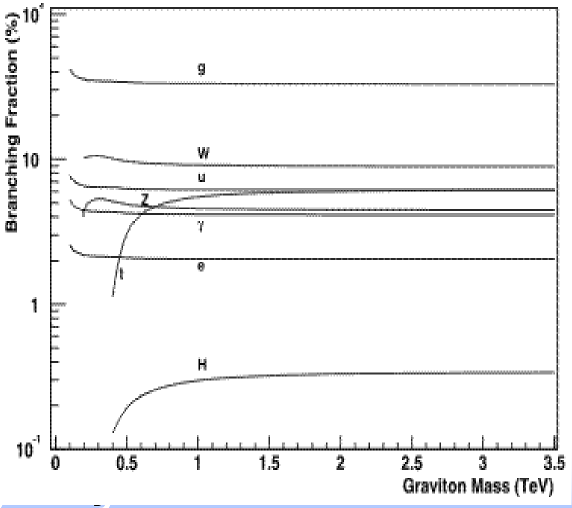
Narrow, high-mass resonance states in dilepton/dijet/diboson channels

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



KK excitations can be excited individually on resonance

1500 GeV G_{KK} and subsequent tower states



Model parameters:

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

  Resonance

  1st graviton excitation mass: $m_1 \rightarrow$ 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

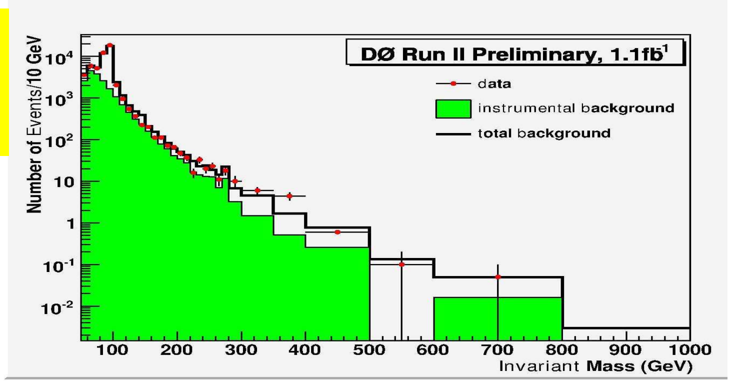
k = curvature, R = compactification radius

Davoudiasl, Hewett, Rizzo
hep-ph0006041

Tevatron RS Searches

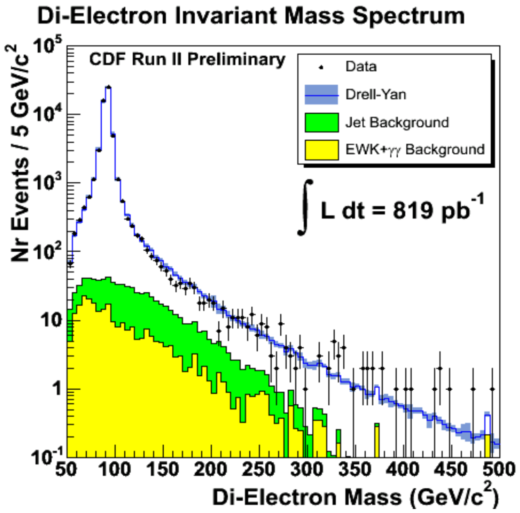
- Graviton decaying to ee or $\gamma\gamma$ ($\mu\mu$)
- Backgrounds:
  - Drell-Yan ee, direct $\gamma\gamma$ production
  - Jets: fake e, $\pi^0 \to \gamma\gamma$,
- Data consistent with background
- Limits on coupling (k/M_{Pl}) vs m(1st KK- mode)

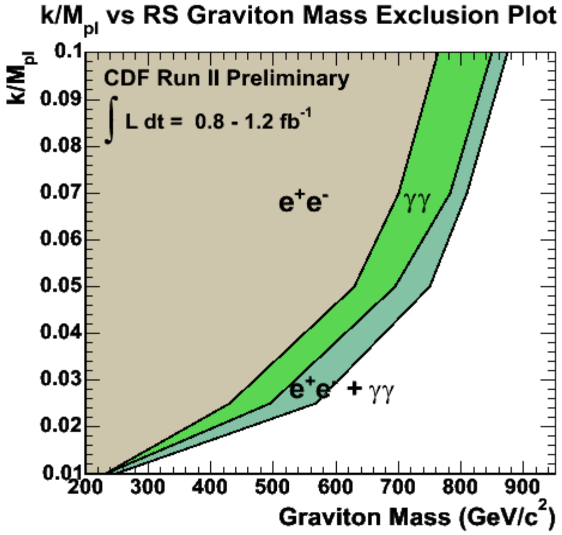
Old Searches

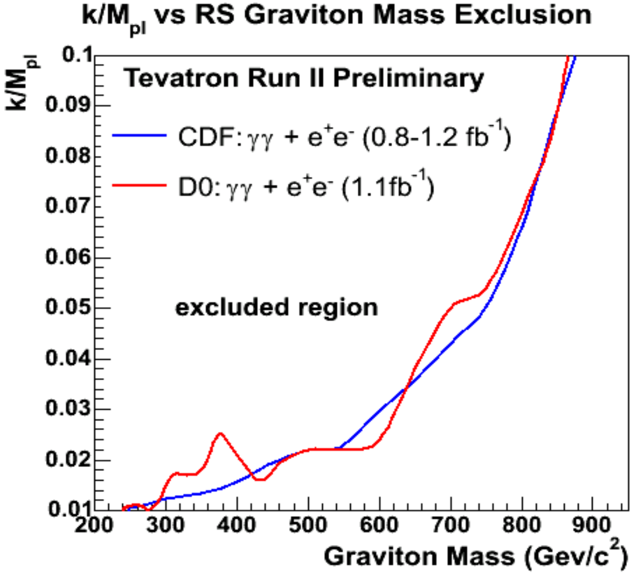


D0 performed combined ee+$\gamma\gamma$ (diem search)

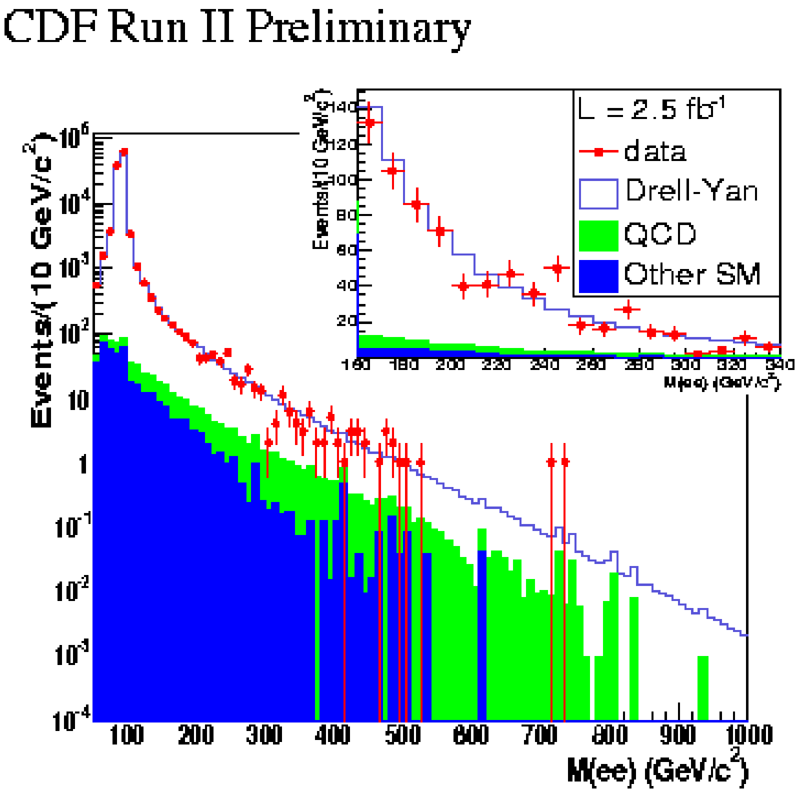
CDF performed ee & $\gamma\gamma$ search, then combine



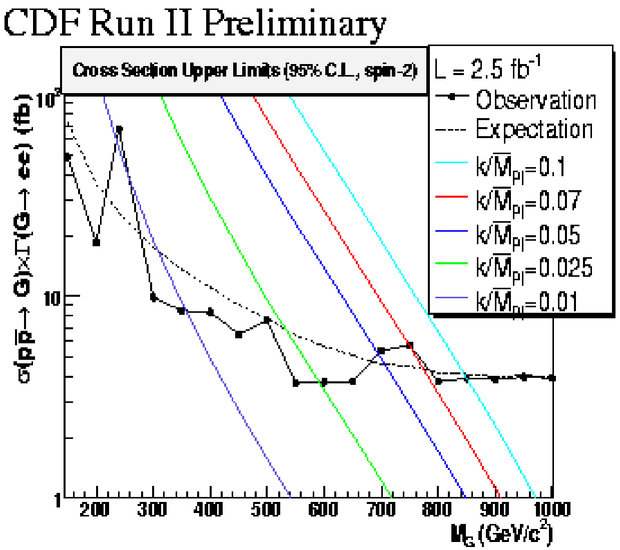


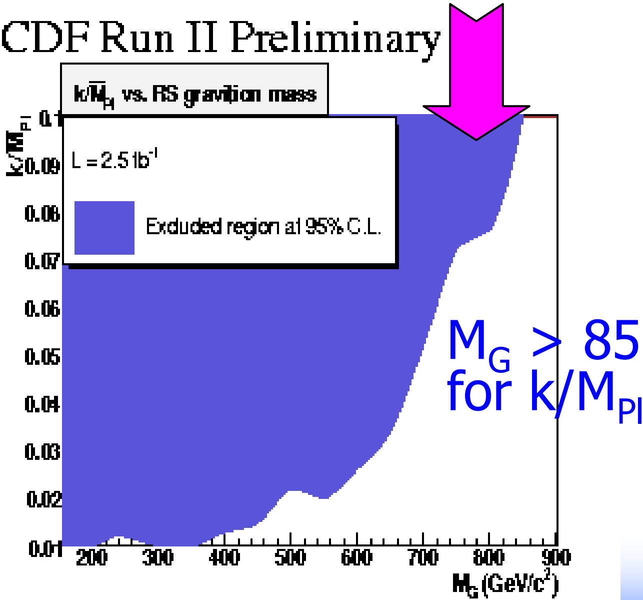


RS: CDF ee 2.5 fb^{-1}



- Most significant excess at m_{ee} ~ 240 GeV (3.8 sigma)





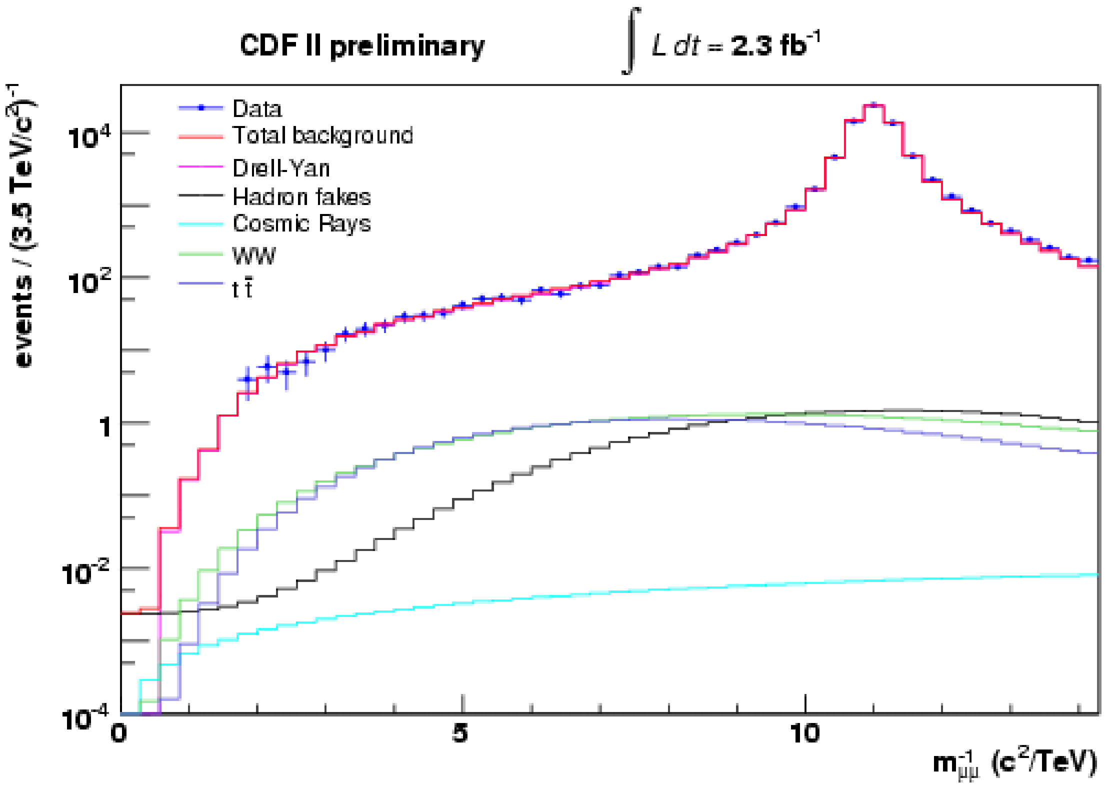
M_G > 850 GeV/c^2 for k/M_{Pl}=0.1

RS: CDF μμ 2.3 fb^{-1}

At high mass, the observed width of the dimuon invariant mass distribution is dominated by the track curvature resolution:

Resulting in an approximately constant resolution in.

$\delta m^{-1}{}_{\mu^{-}\mu} \approx 0.17\ \text{TeV}^{-1}$.

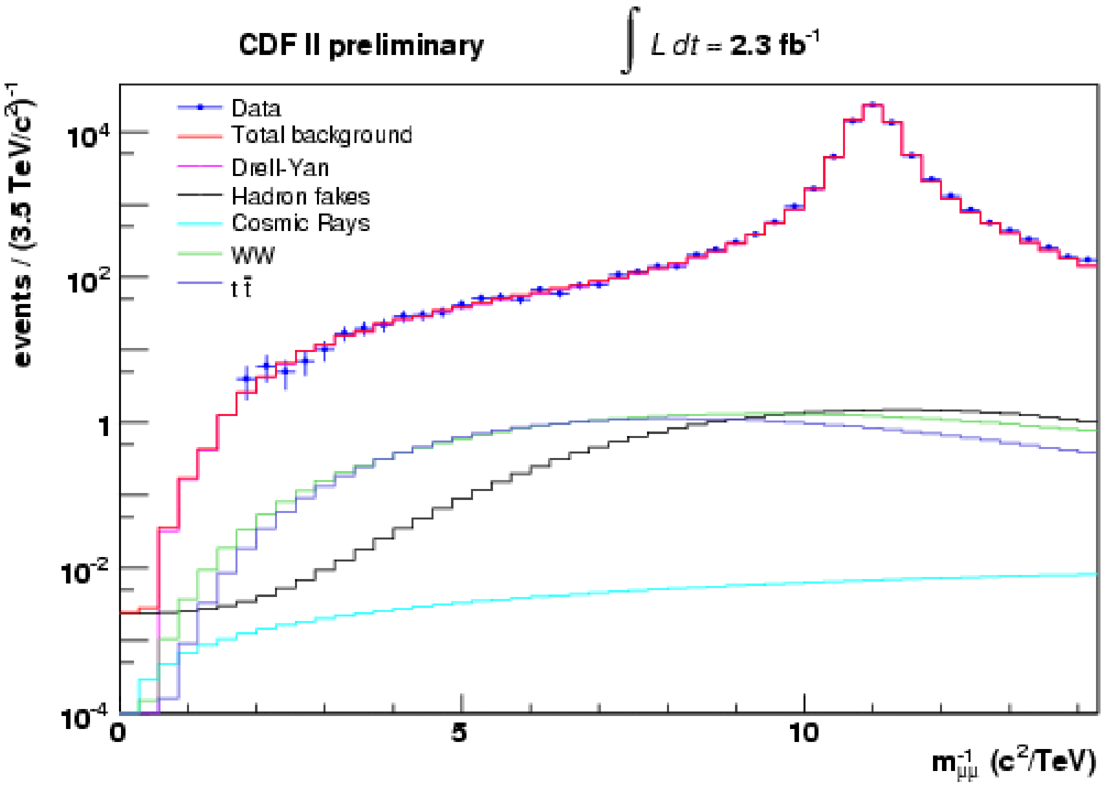


Hep-ex:
arZXiv:0811.0053v1

RS: CDF $\mu\mu$ 2.3 fb^{-1}

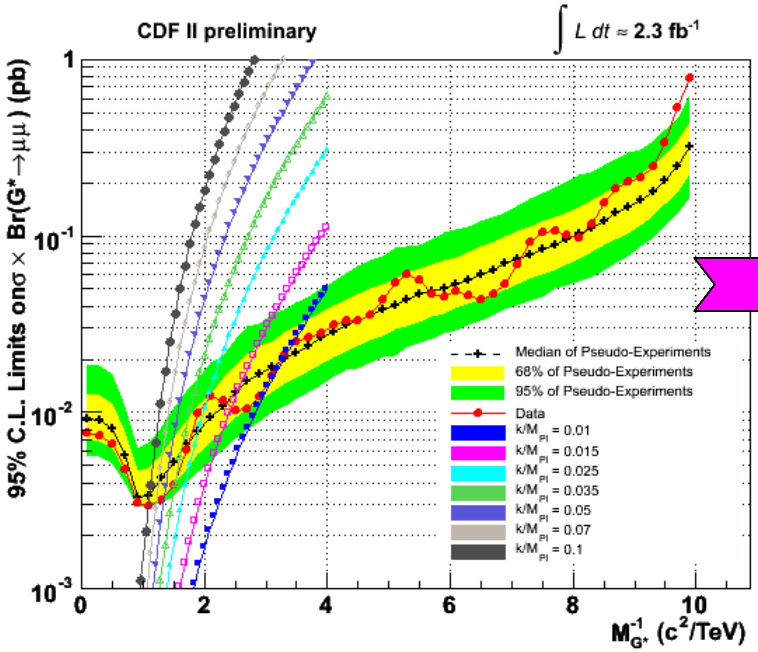
Search strategy

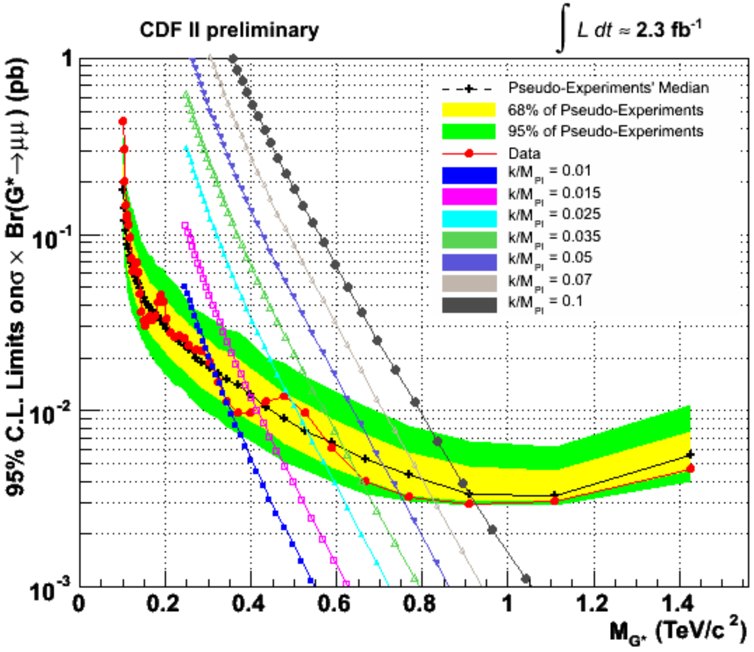
- To construct templates of the inverse invariant mass distribution for a range of Z' boson pole masses,
- add the background distributions to the templates,
- and compare the templates to the $m^{-1}_{\mu\mu}$ distribution from data in the search region $m_{\mu\mu} > 100$ GeV ($m^{-1}_{\mu\mu} < 10$ TeV^{-1}.)



- The simulated templates (including backgrounds) are normalized to the data in the 70 GeV < m^{-1}_{mm} < 100 GeV normalization region.

RS: CDF $\mu\mu$ 2.3 fb^{-1}

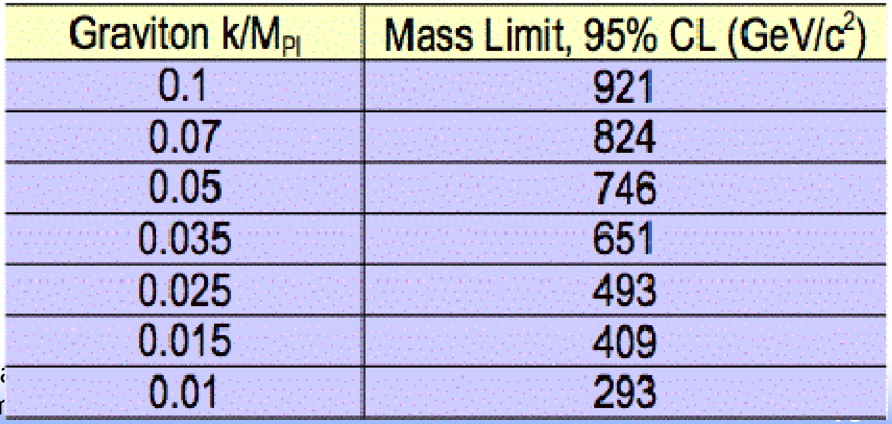




These results exceed the CDF ee channel

Best present limits – almost at 1 TeV

CDF II preliminary L = 2.3 fb^{-1}



Graviton k/M$_{Pl}$	Mass Limit, 95% CL (GeV/c^2)
0.1	921
0.07	824
0.05	746
0.035	651
0.025	493
0.015	409
0.01	293

CDF: $G \rightarrow ZZ \rightarrow eeee$

$\sigma.BR(G \rightarrow ZZ)=292fb$ (RS model)

→ expect of 0.66 $G \rightarrow ZZ \rightarrow eeee$ events produced in 2 fb^{-1} of data.

In Search region:

M_{eeee} 500 - 1000 GeV/c^2

Estimated background:

0.028 +/- 0.009 (stat) +/- 0.011 (syst)

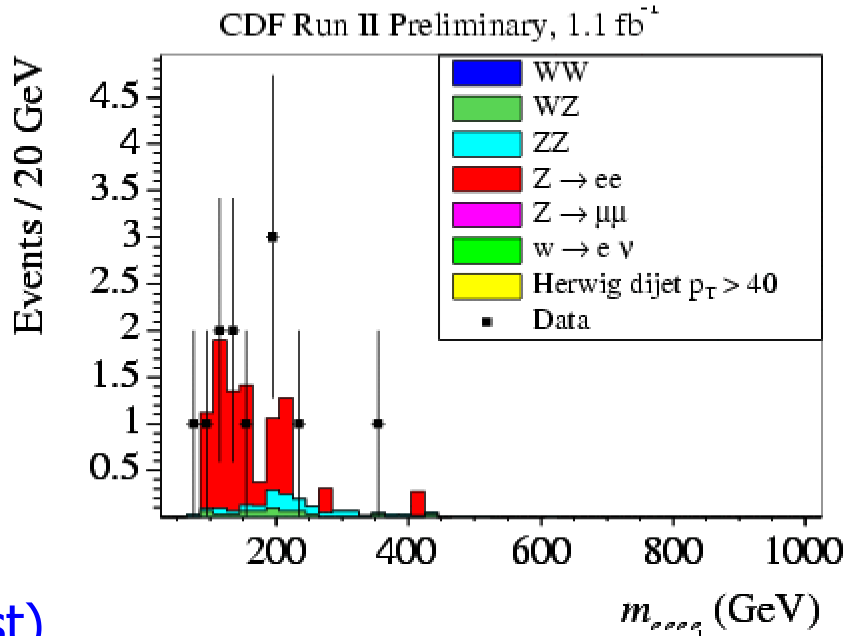
Observe

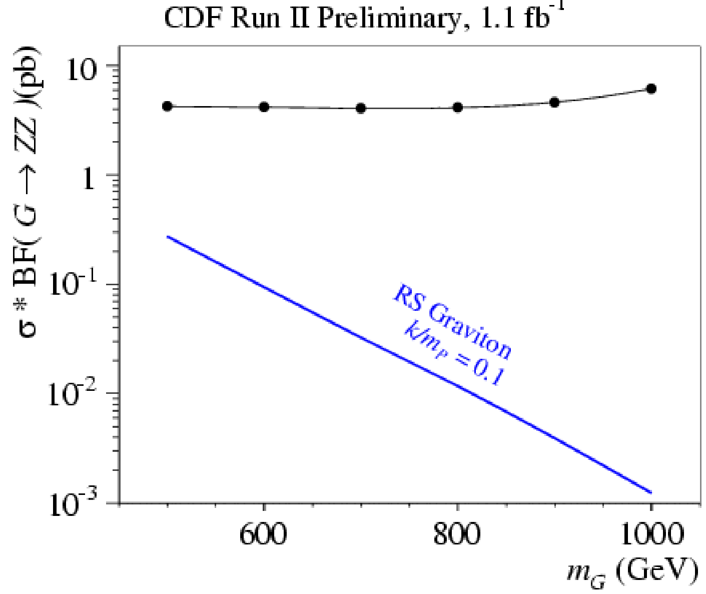
zero events

Limit:

$\sigma \times BF(G \rightarrow ZZ) <\sim 4$ pb for

$m_{graviton}$ = 500-800 GeV



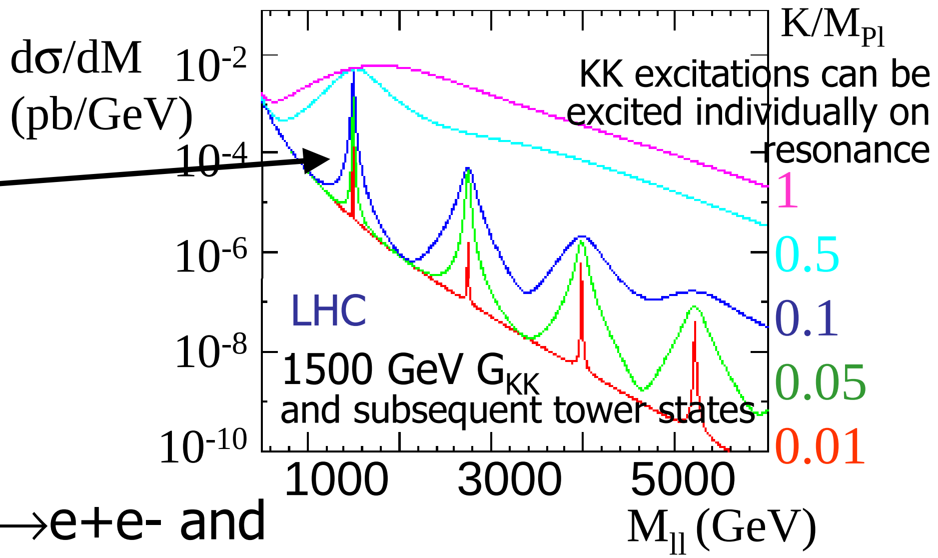


LHC RS1 Discovery Limit

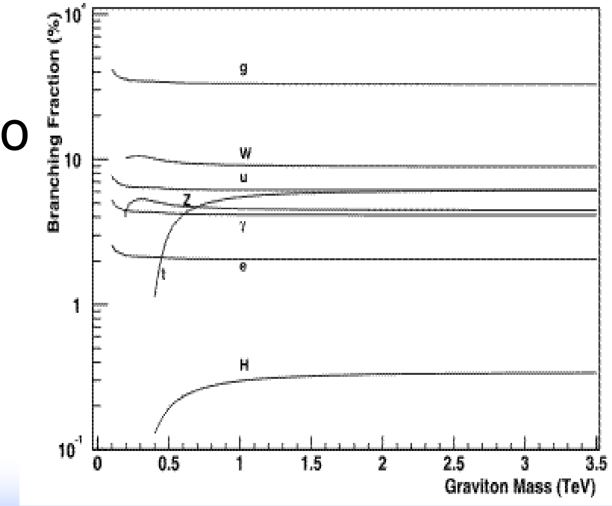
Davoudiasl, Hewett, Rizzo
hep-ph0006041

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

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



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



Allenach et al, hep-ph0006114

*Allenach et al, hep-ph0211205

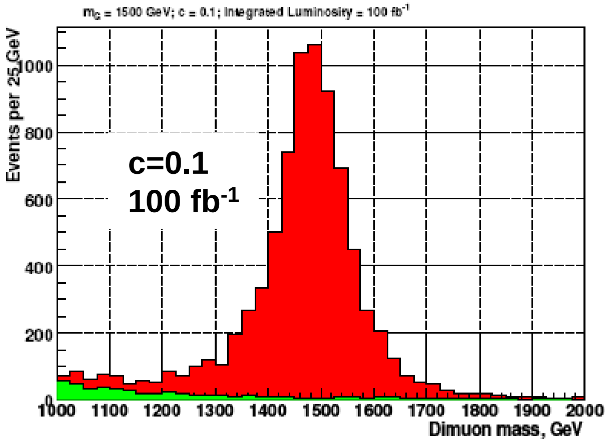
RS1 Discovery Limit

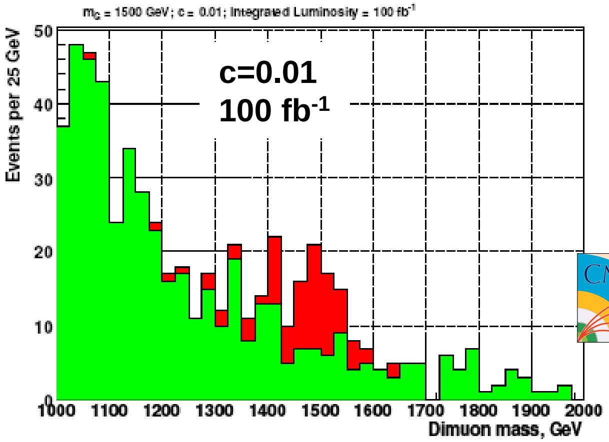
- Searches perfomed in ee/mm/gg and dijet channels

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

Di-electron/Di-muon states

- Bckg:
- Drell Yan /ZZ/WW/ZW/ttbar





Di-photon states

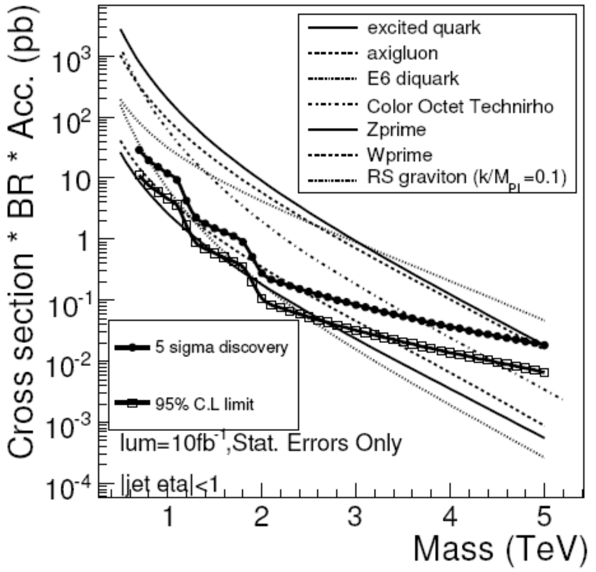
M.-C. Lemaire et al.
CMS NOTE 2006/051
CMS PTDR 2006

- Two photons in the final state
- Bckg: prompt di-photons, QCD hadronic jets and gamma+jet events, Drell-Yan e^+e^-

Di-jet states

- Bckg: QCD hadronic jets

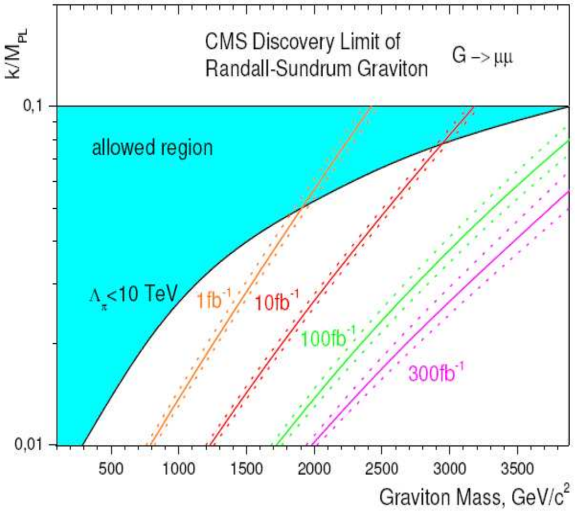
5σ Discovered Mass: 0.7-0.8 TeV/c^2



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

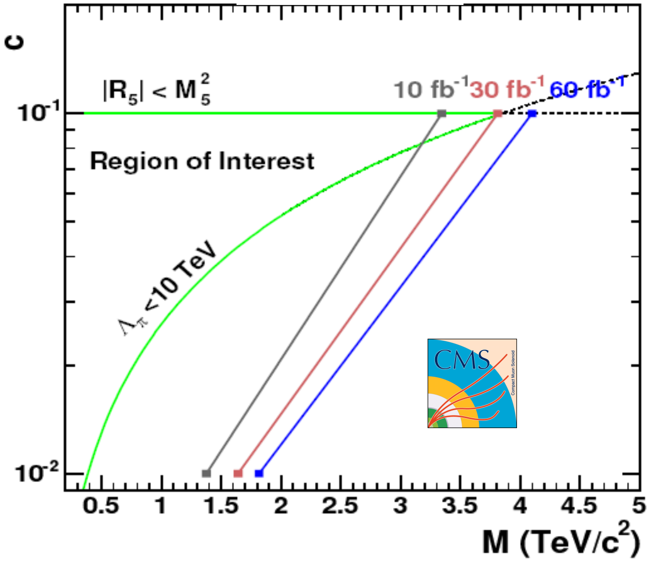
CMS RS Discovery Limits

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

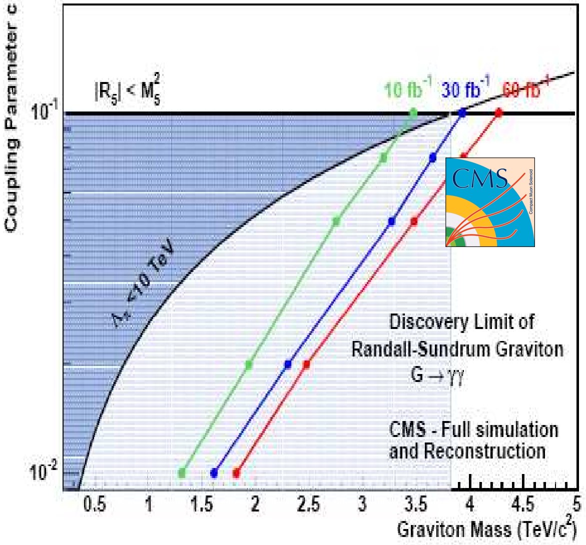


Solid lines = 5σ discovery
Dashed = 1σ uncert. on L

$G_1 \to ee$



$G_1 \to \gamma\gamma$



Theoretical Constraints

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

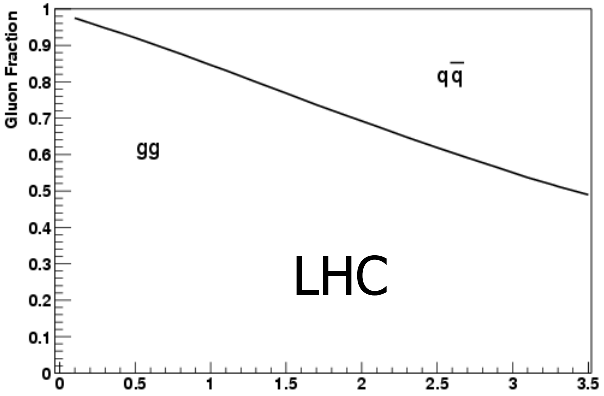
LHC completely covers the region of interest

RS1 Model Determination

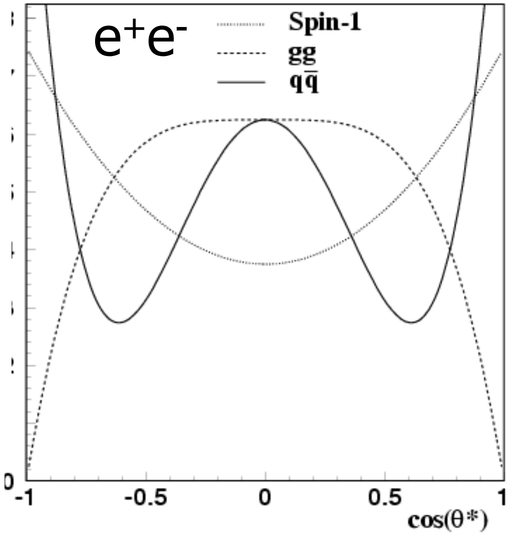
How could a RS G resonance be distinguished from a Z′ resonance?

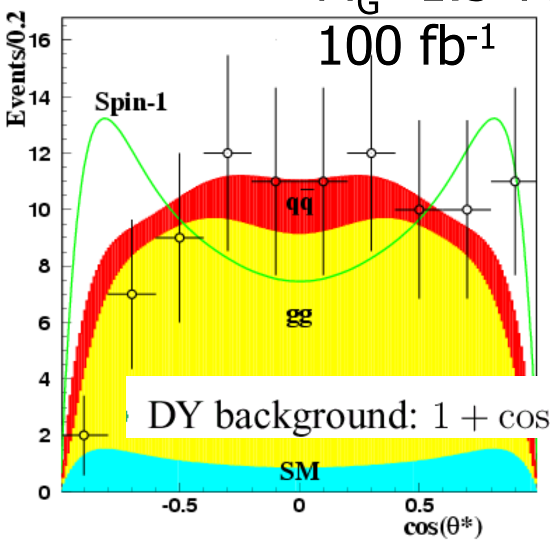
Potentially using Spin information:

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



- $qq \to G \to f\bar{f}: 1 - 3\cos^2\theta + 4\cos^4\theta$
- $gg \to G \to f\bar{f}: 1 - \cos^4\theta$





M_G=1.5 TeV

100 fb^{-1}

DY background: $1 + \cos^2\theta$

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

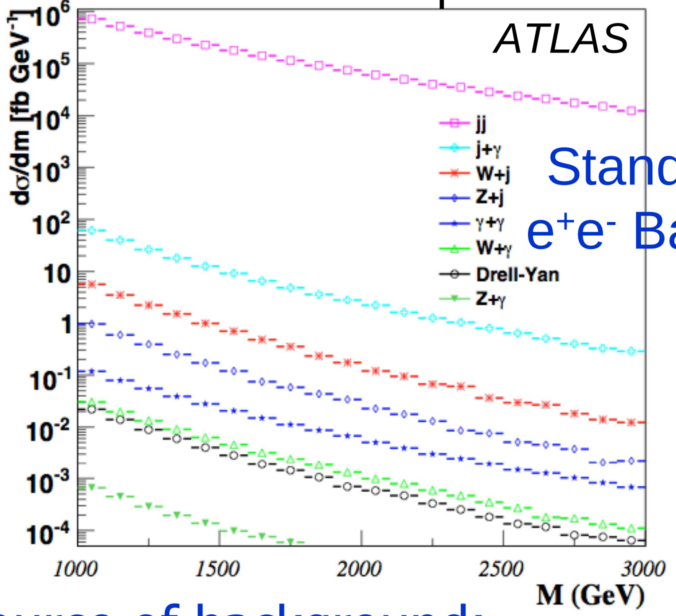
ATLAS CSC Note:RS G→ee Searches

Reaches/Search limits for new physics being investigated (CSC)…

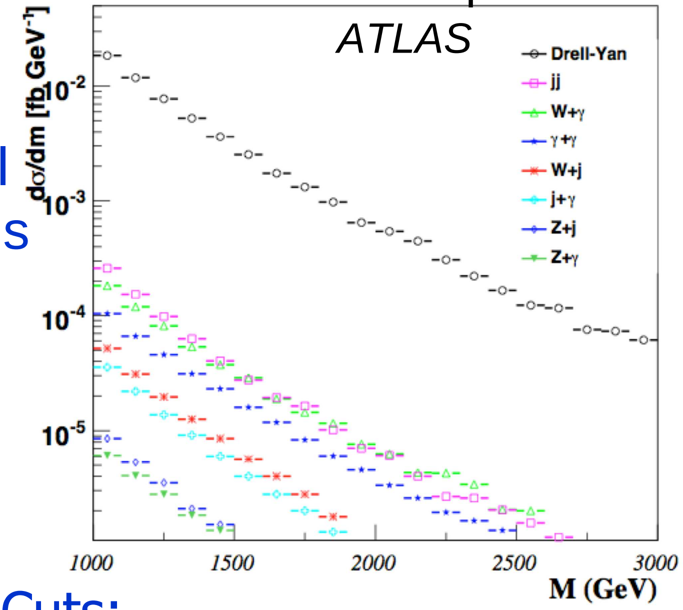
Backgrounds for X→ee /μμ/ ττ studied & cuts developed

before selection requirements

after selection requirements



Standard Model e^+e^- Backgrounds



Source of background:

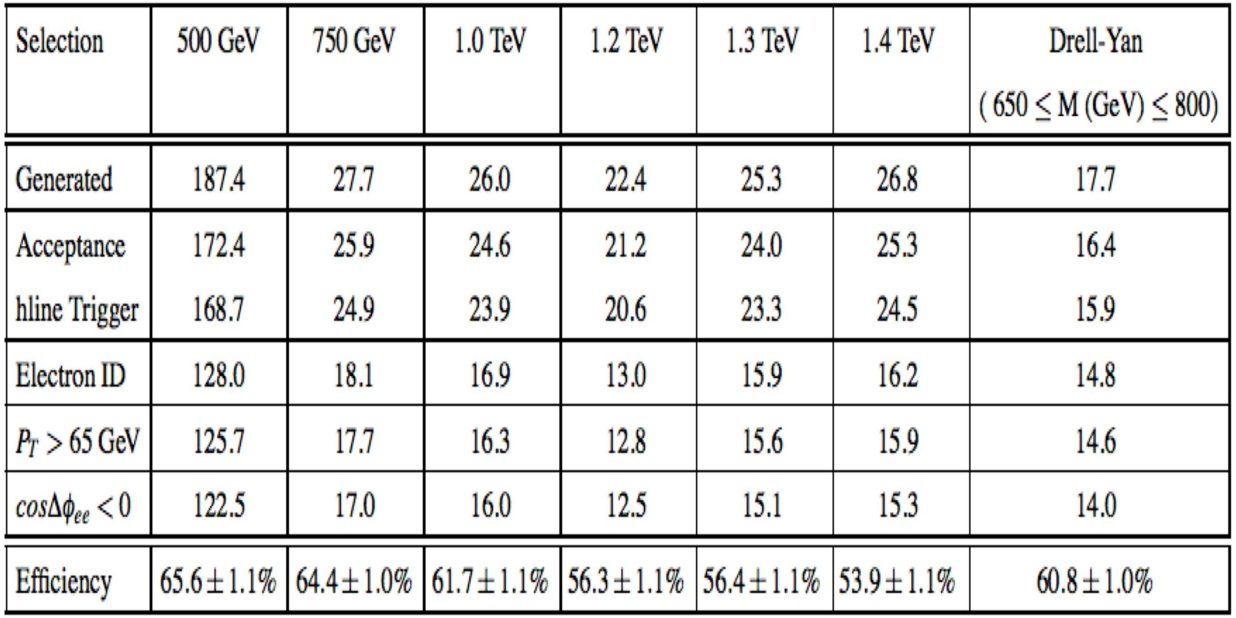
- (irreducible) Drell-Yan
- Jet→e, γ→e contamination
- e and μ production from Z and W decay

Cuts:

- $R_{e\text{-}jet}=10^4$, $R_{e\text{-}gamma}=10$, Pt and pseudorapidity ($R_{e\text{-}jet}$ & $R_{e\text{-}gamma}$ varied by a factor 2)
- The Drell-Yan is the dominant background

CERN-OPEN-2008-020

RS Model G→ee



Selection	500 GeV	750 GeV	1.0 TeV	1.2 TeV	1.3 TeV	1.4 TeV	Drell-Yan ($650 \le M\,(\mathrm{GeV}) \le 800$)
Generated	187.4	27.7	26.0	22.4	25.3	26.8	17.7
Acceptance	172.4	25.9	24.6	21.2	24.0	25.3	16.4
hline Trigger	168.7	24.9	23.9	20.6	23.3	24.5	15.9
Electron ID	128.0	18.1	16.9	13.0	15.9	16.2	14.8
$P_T > 65$ GeV	125.7	17.7	16.3	12.8	15.6	15.9	14.6
$cos\Delta\phi_{ee} < 0$	122.5	17.0	16.0	12.5	15.1	15.3	14.0
Efficiency	$65.6 \pm 1.1\%$	$64.4 \pm 1.0\%$	$61.7 \pm 1.1\%$	$56.3 \pm 1.1\%$	$56.4 \pm 1.1\%$	$53.9 \pm 1.1\%$	$60.8 \pm 1.0\%$

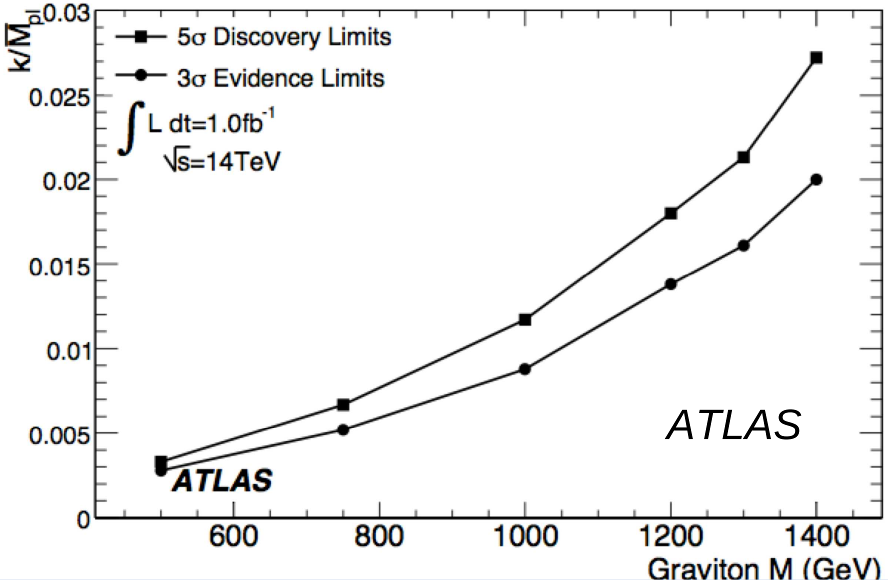
2 loose electrons

DY extrapolated using:

$$exp^{2.2M^{0.3}}$$

5σ discovery with 1 fb^{-1}:

up to m_{G*}=1.5 TeV



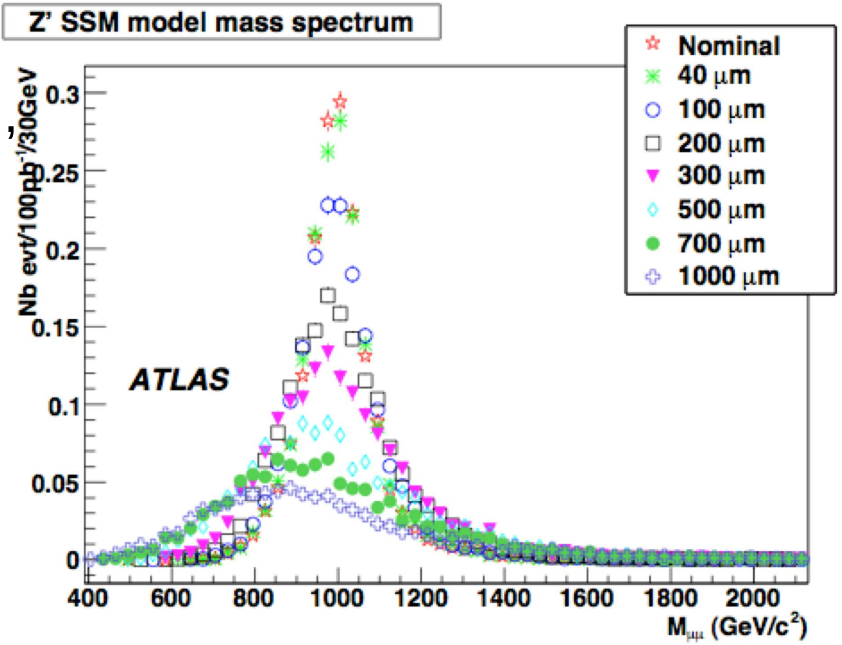
CERN-OPEN-2008-020

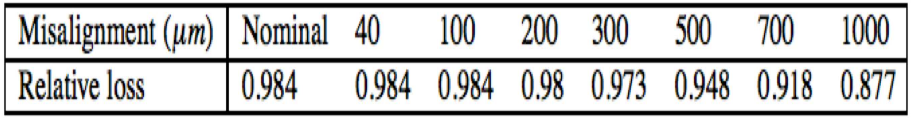
What if the detector is not perfect immediately!/Experimental Issues!

ATLAS has been investigating…

E.g. Spectrometer and tracker not aligned, Calorimeter calibration not optimal …

Mis-alignment of muon spectrometer downgrades the mass resolution
- for Z'→μμ most important systematic.
- Affects the reconstruction efficiencies and sensitivities





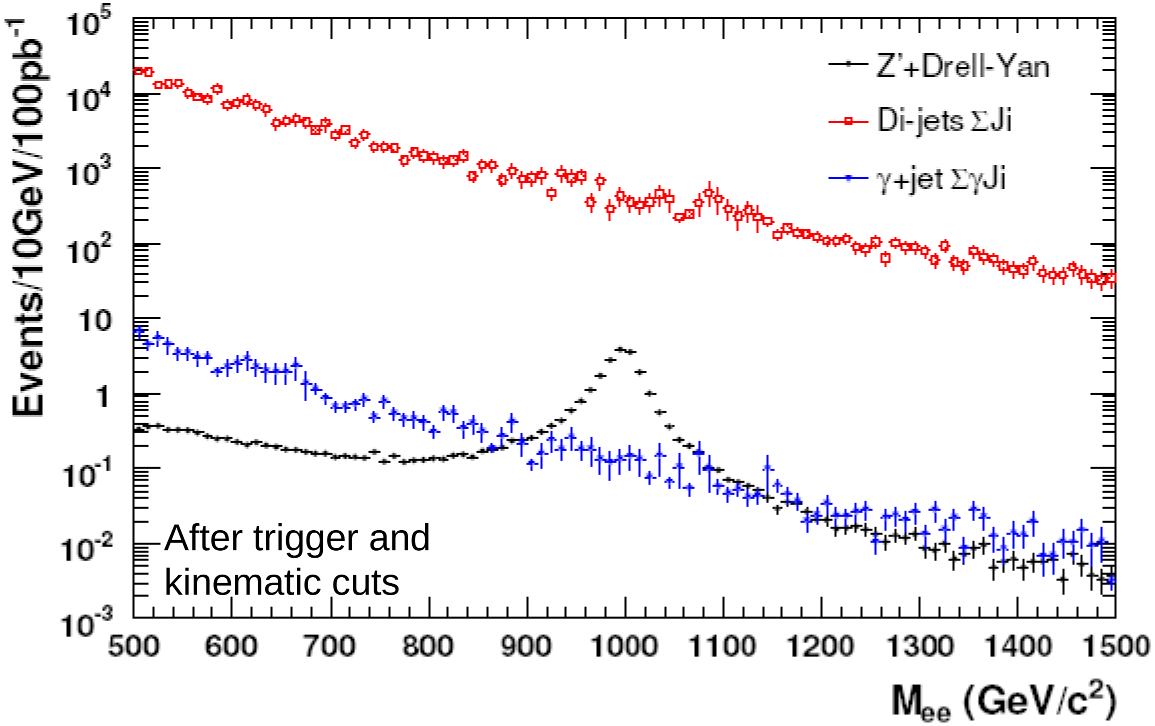
Misalignment (μm)	Nominal	40	100	200	300	500	700	1000
Relative loss	0.984	0.984	0.984	0.98	0.973	0.948	0.918	0.877

CERN-OPEN-2008-020

Can the EM calorimeter be used in a stand-alone way to find a Z'→ee or G→ee/γγ?

- i.e. not include the tracker or the HAD calorimeter?

Challenge!



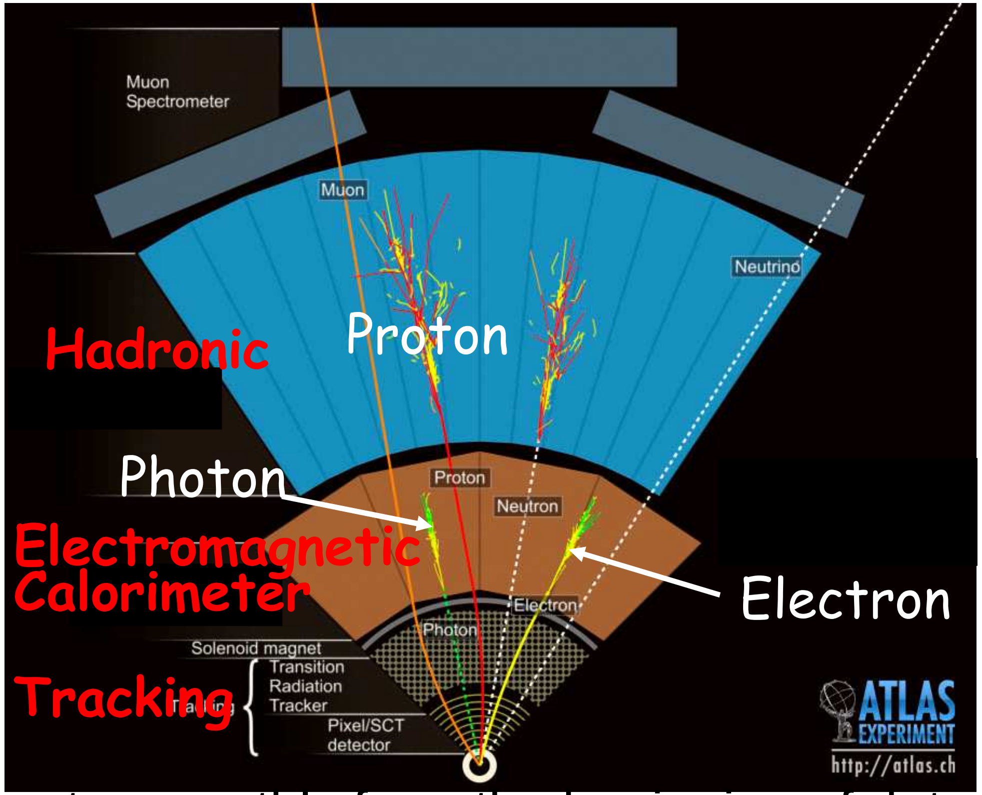
ATL-PHYS-INT-2008-020

Electron Identification/ Background Rejection

- Usually involved matching a EM cluster with a track to distinguish from γ
- What if the tracker is misaligned?

- To reject background from jets
- Electron ID usually includes a Had/EM cut

- Can the EM calorimeter be used in a stand-alone way?
- i.e. not include the tracker or the HAD calorimeter?



The EM calorimeter is expected to operate smoothly from the beginning of data taking, even if the rest of the ATLAS detector is not operating smoothly – tested for 10 years and in situ

RS G→γγ

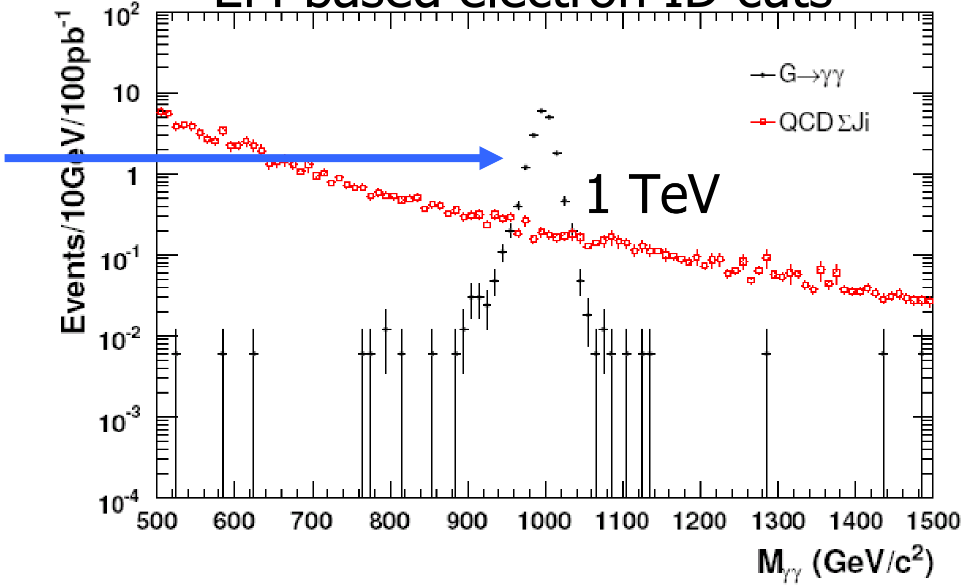
Interesting study for Z'→ee with EM calorimeter only: also applied a 1 TeV G →γγ.

Developed 3 simple and robust cuts :

- Based on EM calorimeter only
- η-independant cuts

Resonance appears clearly above the dominant QCD background with 100 pb^{-1} of LHC data

EM-based electron ID cuts



assumes a production cross-section of 0.3 pb

a large coupling between graviton excitations and SM particles (c = 0:05)

ATL-PHYS-INT-2008-020

TeV-1 Model

TeV^{-1} Extra Dimension Model

I. Antoniadis, PLB246 377 (1990)

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

New Parameters

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

M_C : corresponding compactification scale

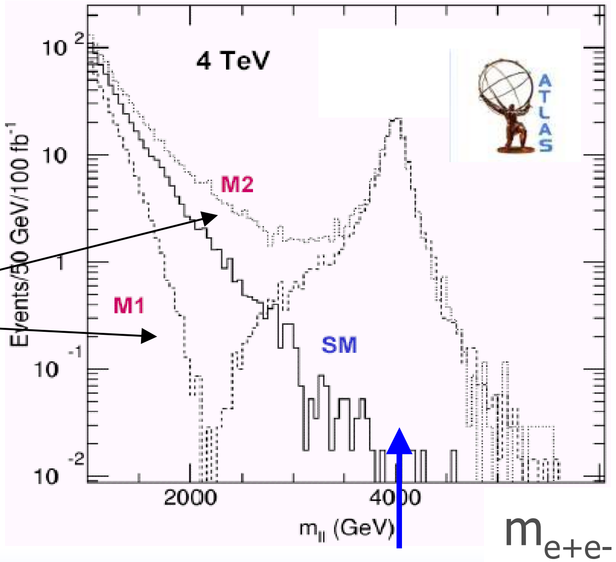
M_0 : mass of the SM gauge boson

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

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

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

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



m_{e+e-} (GeV)

$M_n = M_0$

Present Constraints on TeV^{-1} ED

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

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

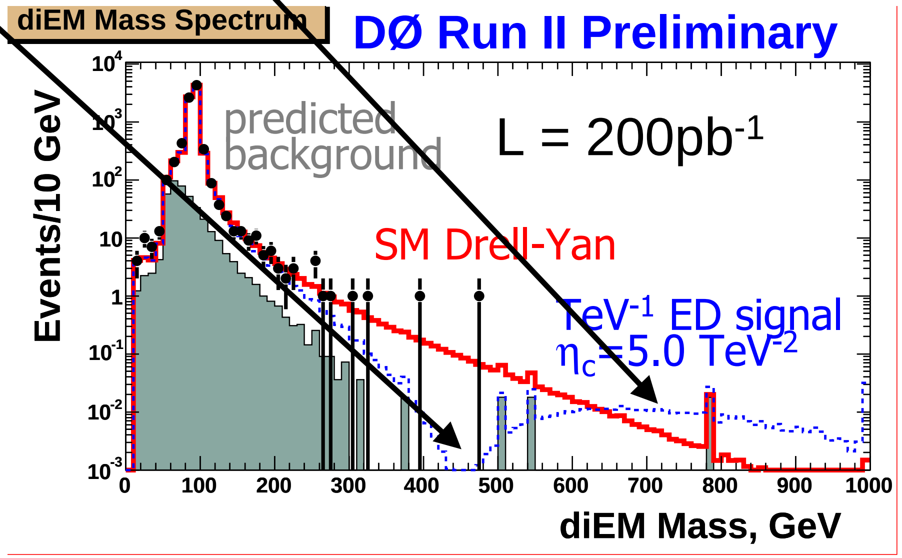
Search Signature: Signal has 2 distinct features:

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

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

- 2 high p_T isolated diEM objects
- Bckg: irreducible: Drell-Yan

Also ZZ/WW/ZW/ttbar



Lower limit on the compactification scale of the longitudinal ED:

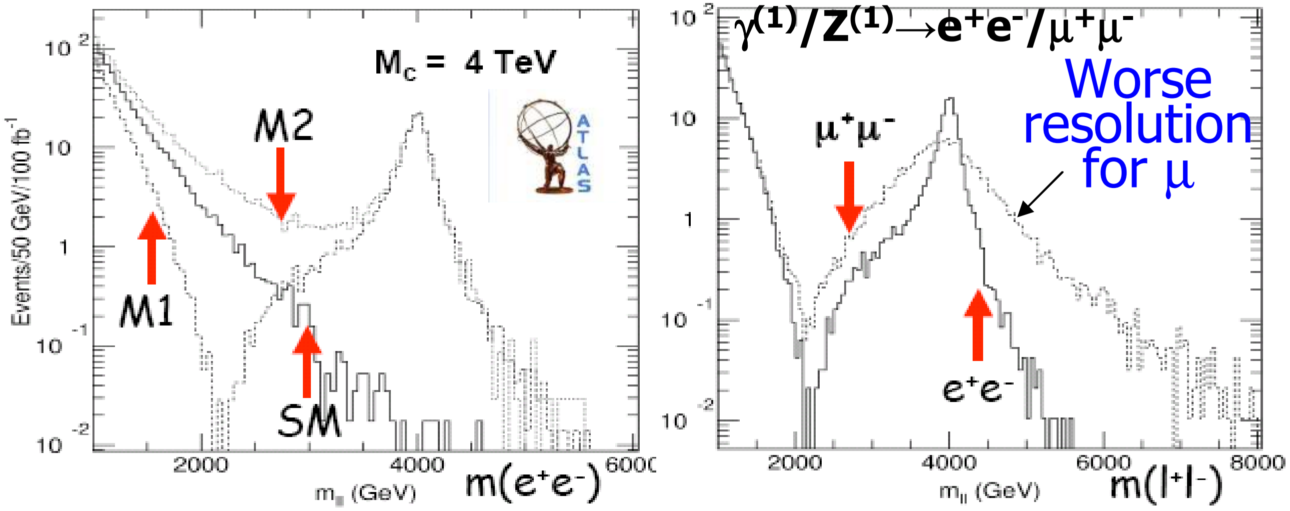
M_C>1.12 TeV at 95% C.L.

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

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



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

Worse resolution for μ

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:

ΔE/E~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)

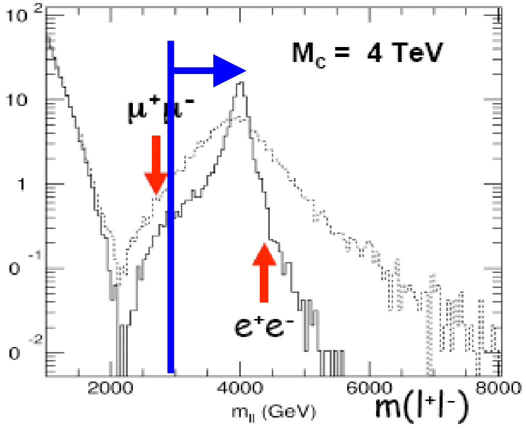
TeV^{-1} ED Discovery Limits

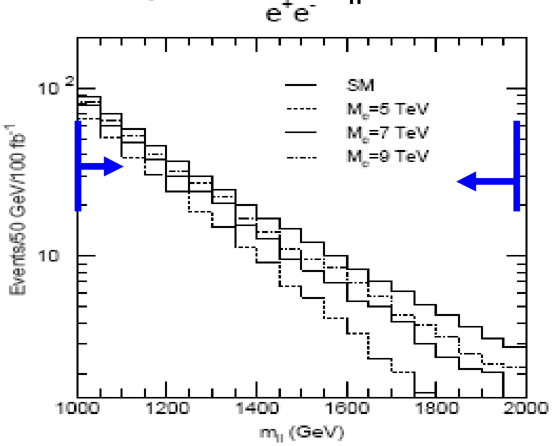
$\gamma^{(1)}/Z^{(1)} \rightarrow e^+e^-/\mu^+\mu^-$

ATLAS have studied 3 methods 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

2 leptons with Pt>20GeV in $|\eta|<2.5$, m_{ll}>1TeV



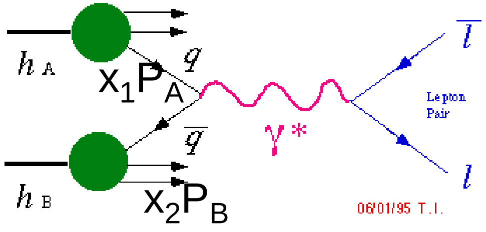


For (ee+μμ) using this method, the reach is

$M_C\,(R^{-1})$<5.8 TeV :100 fb^{-1}

~8 TeV for L=100 fb^{-1}
~10.5 TeV for 300 fb^{-1}

Event kinematics* can be fully defined by the 3 variables



13.5 TeV with 300 fb^{-1}

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

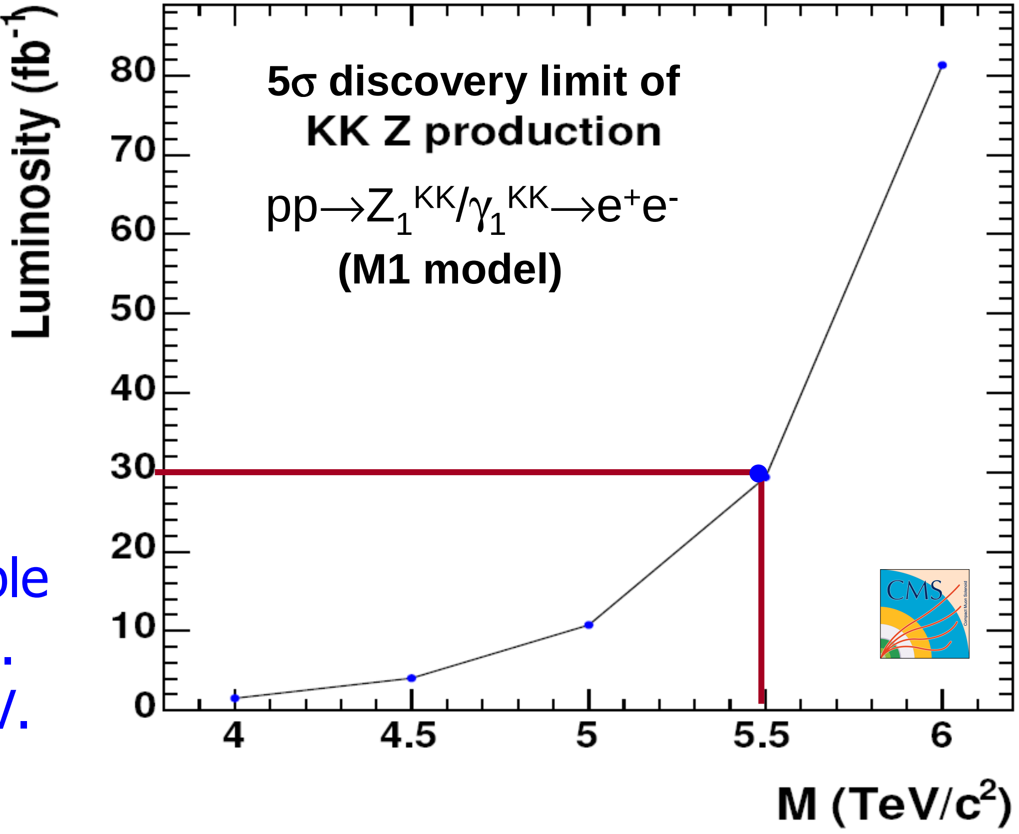
TeV^{-1} ED Discovery Limits

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

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

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	M_{G1}~1.35- 3.3 TeV, c=0.01-0.1	10
di-photons	M_{G1}~1.31- 3.47 TeV, c=0.01-0.1	10
di-muons	M_{G1}~0.8- 2.3 TeV, c=0.01-0.1	1
di-jets	M_{G1}~0.7- 0.8 TeV, c=0.1	0.1
TeV^{-1} ($Z_{KK}^{(1)}$)	M_{z1} < 5 TeV	1

Conclusions

Lots of different searches & channels being used to search for Extra Dimensions!

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

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

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

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

The End!