SEARCH FOR (EVIDENCE FOR) EXTRA DIMENSIONS @ LHC

HEP Mad-07, Antananarivo

September 2007

Erez Etzion, Tel Aviv University, Israel

OUTLINE

- History of dimensions/extra dimensions
- Introduction and Motivations.
- Standard Model Particles in Extra Dimensions.
- Living on a Brane : Gravity in the Extra Dimensions.
- Warped Extra Dimensions.
- Previous measurements (well … limits..)
- **Preparations and expectations from LHC**

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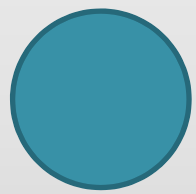
DIMENSIONS - THE POWER OF ANALYTIC GEOMETRY

$$x^2 + y^2 = 1$$

Circle

$$x^2 + y^2 + z^2 = 1$$



Sphere

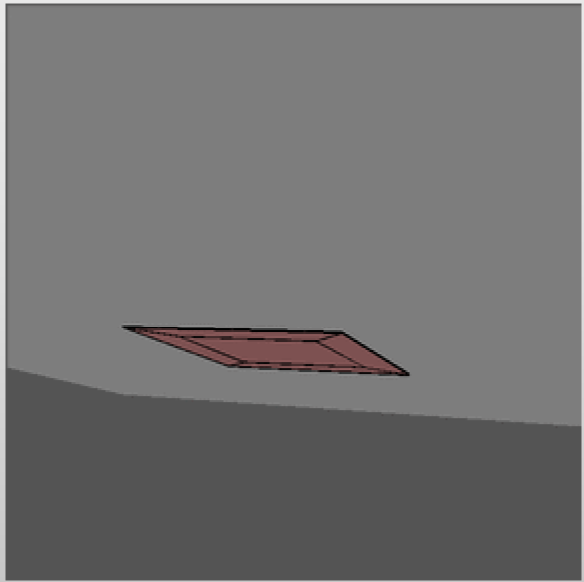
$$x^2 + y^2 + z^2 + w^2 = 1$$

Hypersphere

PROJECTION OF DIMENSIONS

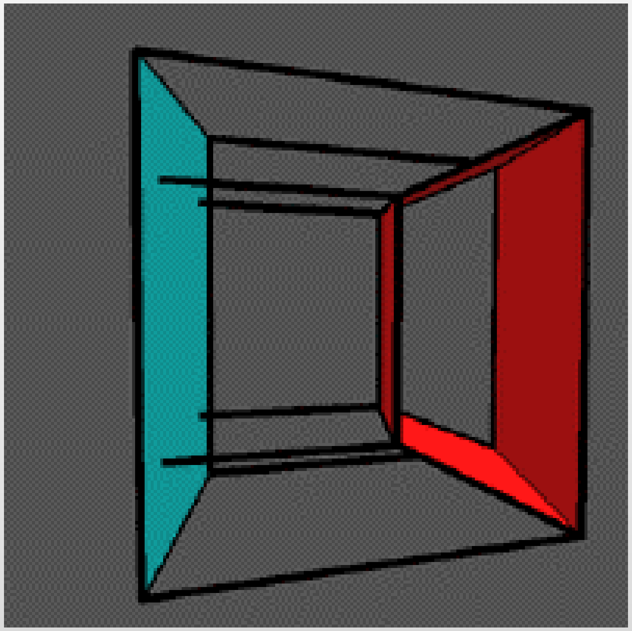
- We can make a picture of the 3-dimensional shadows of 4-dimensional objects
- This is like the more familiar case of 2-dim shadows of 3-dim objects

- The shadow of a rotating cube looks like 6 distorted squares moving through each other



PROJECTION OF 4-DIMENSIONAL OBJECT

- The 3-dimensional shadow of a rotating hypercube looks like 8 distorted cubes moving through each other



EXTRA DIMENSIONS AND PHYSICS ? !

- OK, extra dimensions could make sense in mathematics..
- Do they also make sense in Physics ?
- Could there be more physical dimensions than the three we see?
- If so, why are the extra dimensions hidden?
- What are they good for?

"TIME IS THE FOURTH DIMENSION"

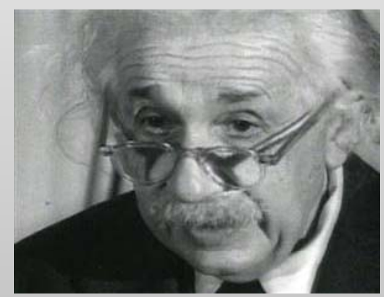
-A Einstein 1 9 0 5

- Four dimensional space-time: x,y,z and t
- There is a universal constant "c" which converts measurements of time into measurements of space

THE FIFTH DIMENSION

- In 1914, Finnish physicist – Gunnar Nordstorm showed that gravity and EM could be unified as a single force, in a theory with an extra spatial dimension.

- Einstein ignored Nordstorm's idea, (probably because it used Nordstorm's own interpretation for gravity, which was then in competition with his own).

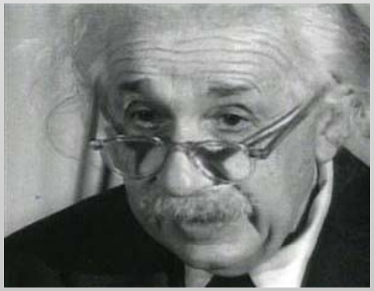


THE FIFTH DIMENSION

- In 1919, Polish Mathematician Theodor Kaluza brought back the idea of a fifth dimension, this time using Einstein's theory of gravity

This made all the difference:

- "The idea of achieving [unified theory] by means of a five-dimensional cylinder world never dawned on me… At first glance I like your idea enormously"

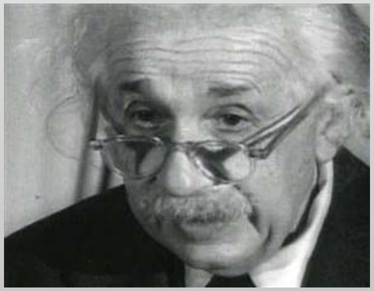


THE FIFTH DIMENSION IS A CIRCLE

- Nordstrom, Kaluza and Einstein all assumed that the fifth dimension wasn't real, since other wise why don't they see it?

In 1926, Swedish physicist Oscar Klein proposed that the fifth dimension is real, but too small to be seen

- "Klein's paper is Beautiful and impressive."



IS THE EXTRA DIMENSION A CIRCLE?

A simple example:

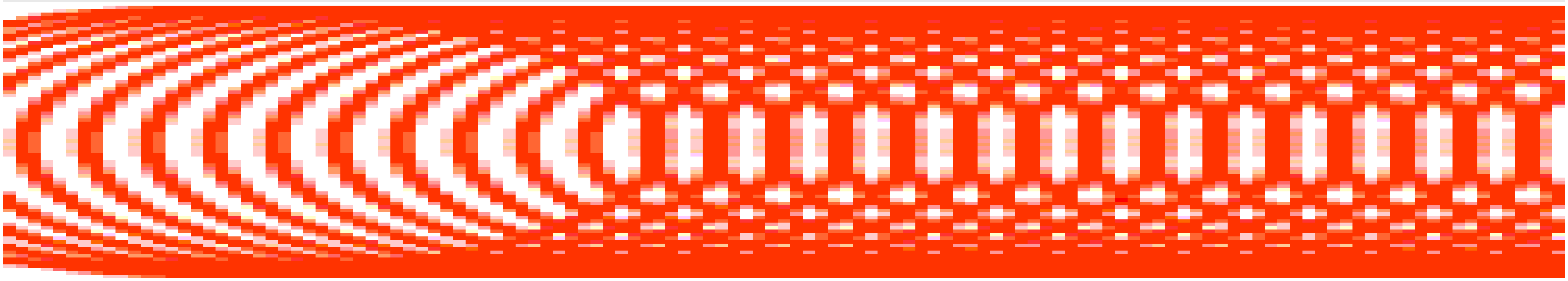
The tightrope walker view

The ant view:

The ant sees an extra dimension an extra tiny circle at every point along the tightrope

THE FIFTH DIMENSION IS A CIRCLE

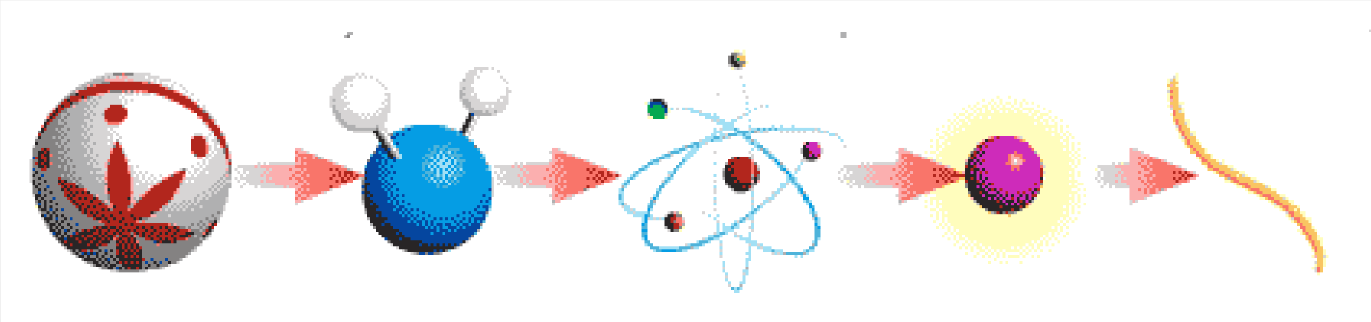
- Klein computed how small the circle of the 5th dimension should be in order to give a unified theory of gravity and EM



- He ended up with : 10^{-32} meter

AND.. THIS WAS THE END OF THE STORY FOR THE NEXT 50 YEARS – BASIC OF STRING THEORY

In the 70s several physicists started to construct a revolutionary new theory. In this theory all the elementary particles are just different vibrations of microscopic strings



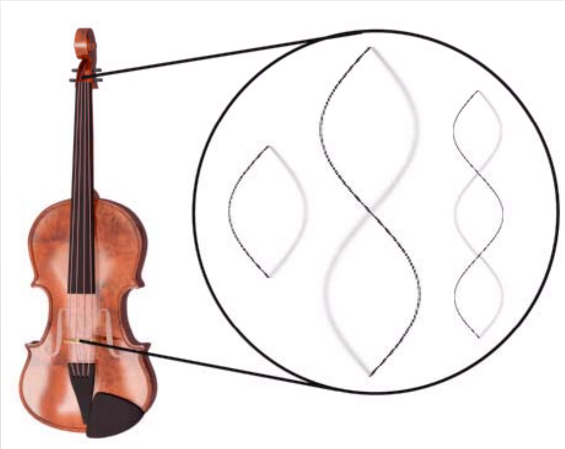
" All particles and forces are manifestation of different resonances of tiny one dimensional strings (or possibly membranes) vibrating in ten dimensions.

They are so small , our most precise machinery is too crude to detect them "

(Microsoft Encarta Encyclopedia)

WHAT ARE SUPERSTRINGS

- Like guitar strings, they are elastic,
  and they have tension.



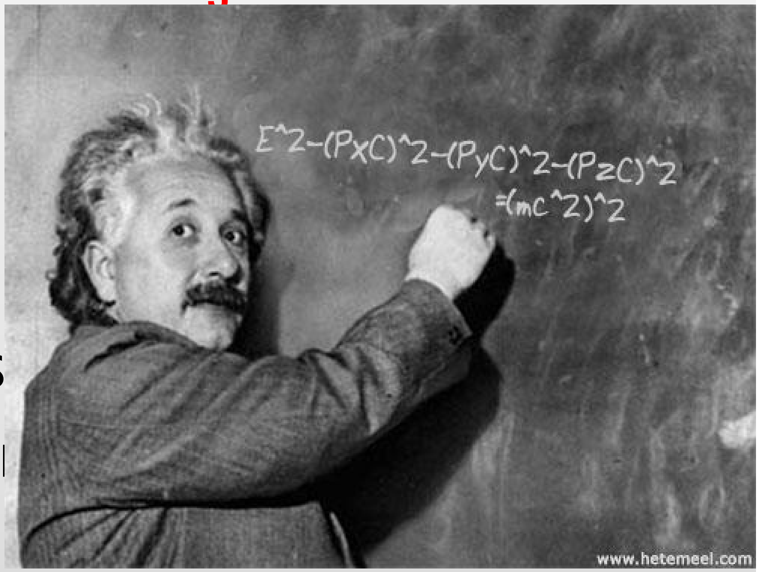
- Like the pitch and overtones of guitar string, they have their own special vibrations, called the string modes.

Unlike guitar strings, superstrings are made out of nothing, and they have one dimension.

Unlike guitar strings, which are stretched by tuning pegs, superstrings have to stretch themselves..

SPECIAL RELATIVITY

- Which means it give us the mass of the "particles" in term of the energy and momentum of the vibrating superstring



Massless particles?

- For photons, or neutrinos this concept of s delicate cancellation between the vibratio stretching energy.

- In the original superstring theory the cancellation did not work

$$E^2 - (P_x c)^2 - (P_y c)^2 - (P_z c)^2 \neq 0$$

MASSLESS PARTICLES?

Two solutions

- Supersymmetry which reduces the quantum wiggles.
- Increase the number of spatial dimensions that the string can wiggle in.

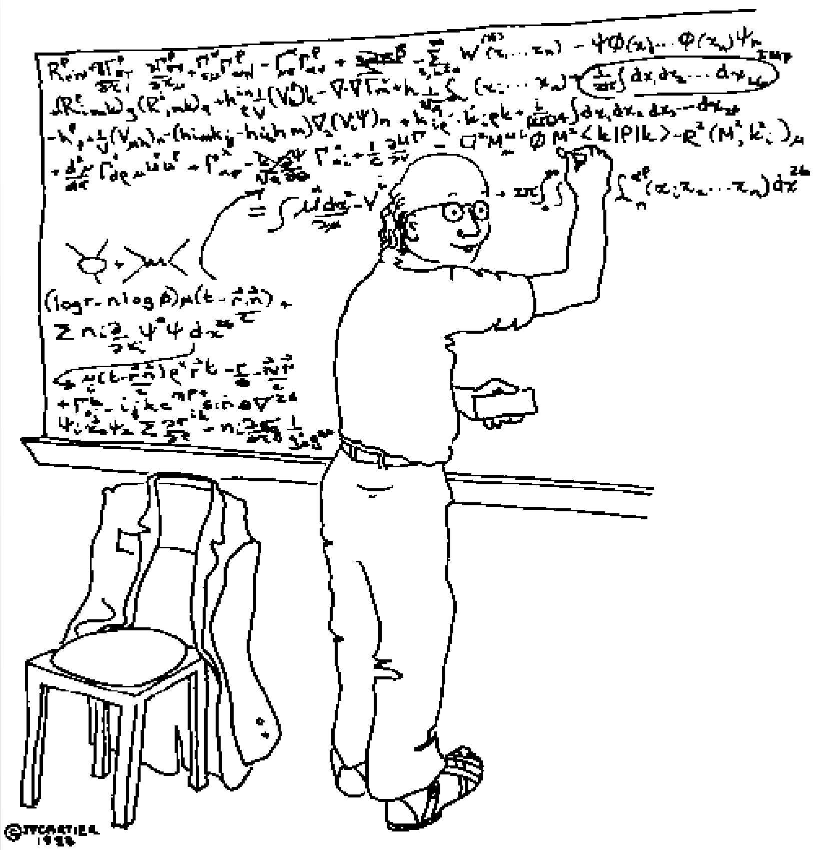
With 9 spatial dimensions can superstrings produced particles that satisfy

$$E^2 - \vec{P}^2 = 0$$

It took 10 years of neglect, finally at 1984 anomaly cancellation was calculated and superstring became a hot idea

HOW DO WE DETECT THESE TINY DIMENSIONS

- Even if extra dimensions make sense in theory to be considered as physics we need to find a way to detect them in experiments
- The detection obviously depends on the physical mechanism they are using in order to hide.
- A starting point – Klein suggestion they are not detected because of their size:



"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."

DERIVATION

$$\begin{cases} \partial_A \partial^A \phi = \left(\partial_\mu \partial^\mu - \partial_5{}^2\right)\phi = 0 \\ \phi = \sum_n \chi_n(y)\Psi_n(x) \end{cases}$$

Klein Gordon in 5 dim

Leads to

$$\sum_n \left(\chi_n \partial_\mu \partial^\mu \Psi_n - \Psi_n \partial_5{}^2 \chi_n\right) = 0$$

$$\partial_5{}^2 \chi_n = -m_n{}^2 \chi_n$$

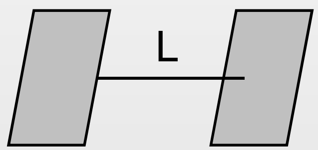
And if we define

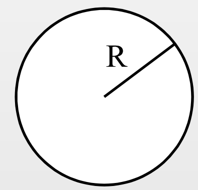
$$\sum_n \chi_n \left(\partial_\mu \partial^\mu + m_n{}^2\right)\Psi_n = 0$$

DERIVATION- KK MODES

$$\chi_n = A_n e^{i m_n y} + B_n e^{-i m_n y}$$

The general solution is given by harmonic functions with two options of boundary conditions





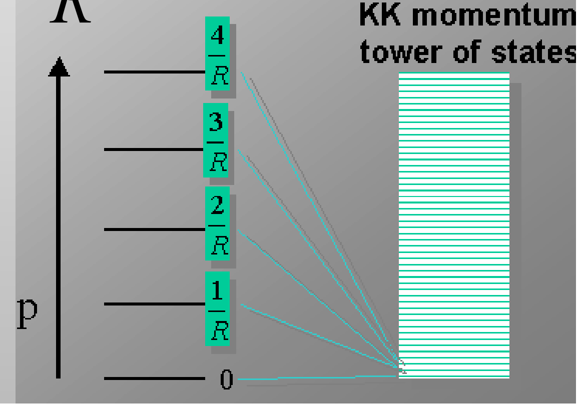
$$\chi_n \propto \sin\left(\frac{ny}{L}\right)$$

$$\chi_n \propto A_n \cos\left(\frac{ny}{R}\right) + B_n \sin\left(\frac{ny}{R}\right)$$

$$m_n = \frac{n}{L}$$

$$m_n = \frac{n}{R}$$

$$M_{Z^n}{}^2 = M_{Z_0}{}^2 + \left(\frac{n}{R}\right)^2$$

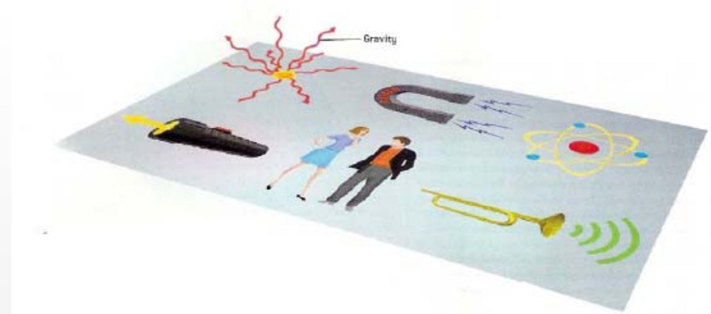


WHO TRAVEL TO ED?

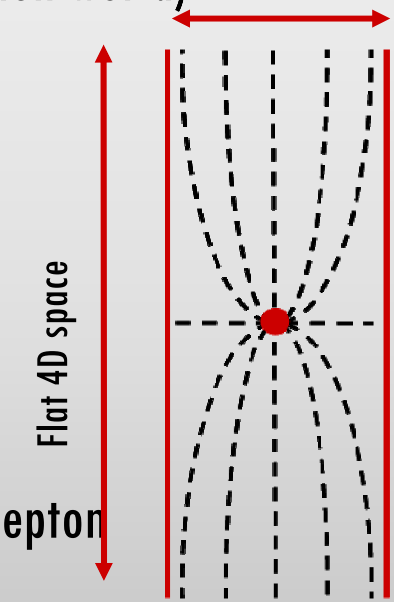
- What we don’t know is which of the elementary particles can move into the ED
- Therefore we don’t know to which KK mode we should look for.
- In string theory it is acceptable that none of the standard material particle can move into ED..

LARGE EXTRA DIMENSIONS-ADD (1998)

Arkani-Hamed et al. PLB429(1998)263
Antoniadis et al. PLB436(1998)257



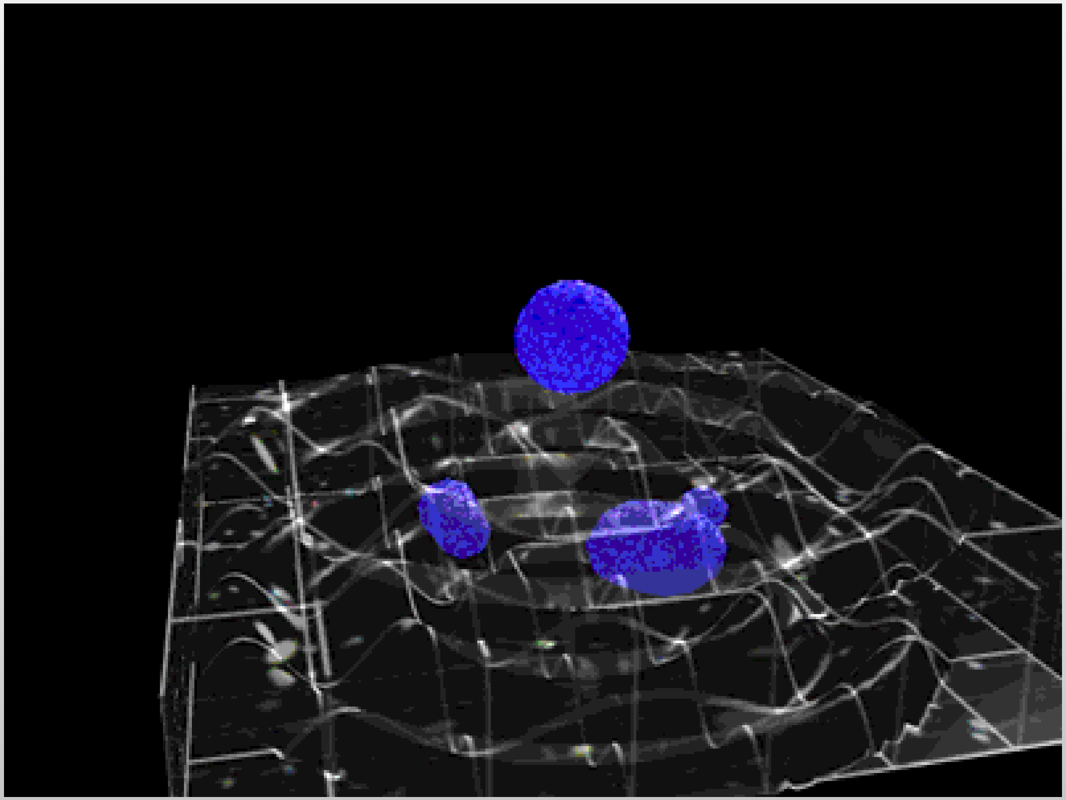
- The real world is multidimensional: n flat Euclidian – extra spatial dimensions, the maximal total number of dimensions is 3+1 (our) +6 (extra)=9+1.
- The fundamental scale is not Planck scale but $M_D \sim$ TeV ➔ $R_C \sim$ mm (for $\delta=2$)
- SM particles and interactions live on a 3D brane (another "parallel" hidden world)
- Gravity becomes strong at TeV ➔ size of ED $\leq$ 1 mm
- SM confined in 4D, only gravity in the ED (bulk)
- two parameters:
  - number of extra (compactified) dimensions: δ
  - new fundamental mass scale M_D:
- Search channels
  - (Virtual) Gravitons contribution to SM processes – excess above di-lepton continuum
  - Real Gravitons production - Jets + missing Et, photon + missing Et.



ADD- DETECTION IN ACCELERATORS

•The KK graviton that is produced in “our “ brnae

Will disappear into ED …



PROBING THE EXTRA DIMENSIONS

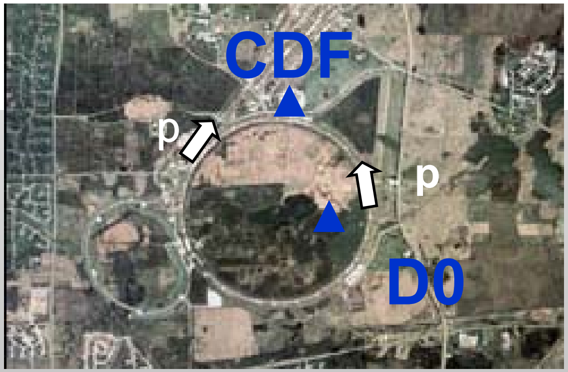
PROBING THE EXTRA DIMENSIONS

ACCELERATORS EXPERIMENTAL EFFORT

- Accelerators are the powerful tool for exploring the ED
- If it is the Klein's tiny ED the accelerators can go down to 10^{-19} meter!
- On the other hand if the brane-world is correct we can produce KK
- gravitons at the LHC.
- Past: LEP experiments (LEP1 @91 GeV, LEP2 @ 136-208 GeV –set some limits
- Present: Tevatron (CDF, D0) – continue with searches and limits.

Tevatron: Highest energy collider operating in the world!

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



- (near) Future LHC – (discovery?)

LHC DETECTORS

• Large Hadron Collider (LHC) is a 14 TeV proton-proton collider at CERN

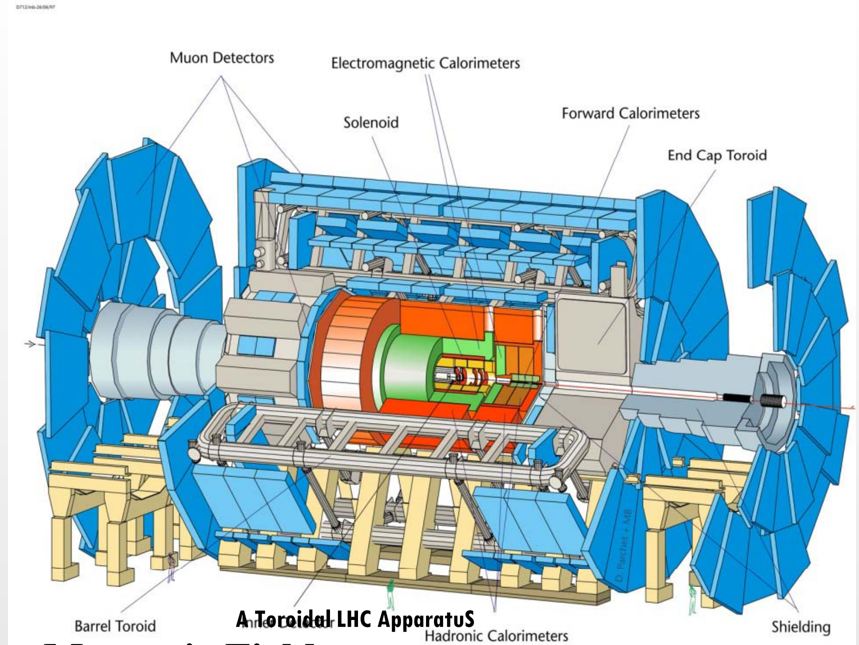
• LHC will start taking data in mid-2008

• Luminosity goals: 1->10 fb^{-1}/year (first 3 years)

100 fb^{-1}/year (subsequently)

•Two multi-purpose detectors ATLAS and CMS experiments

•Detectors designed to measure momentum of photons, electrons, muons, jets, missing E_T up to a few TeV.



Magnetic Field

ATLAS

2T solenoid plus air core toroid

Inner Detector

$\sigma/p_T \sim 0.05\%\ p_T(GeV)\ (+)\ 0.1\%$

Tracking in range $|\eta| < 2.5$

EM Calorimetry

$\sigma/E \sim 10\% / \sqrt{E(GeV)}\ (+)\ 1\%$

Fine granularity up to $|\eta| < 2.5$

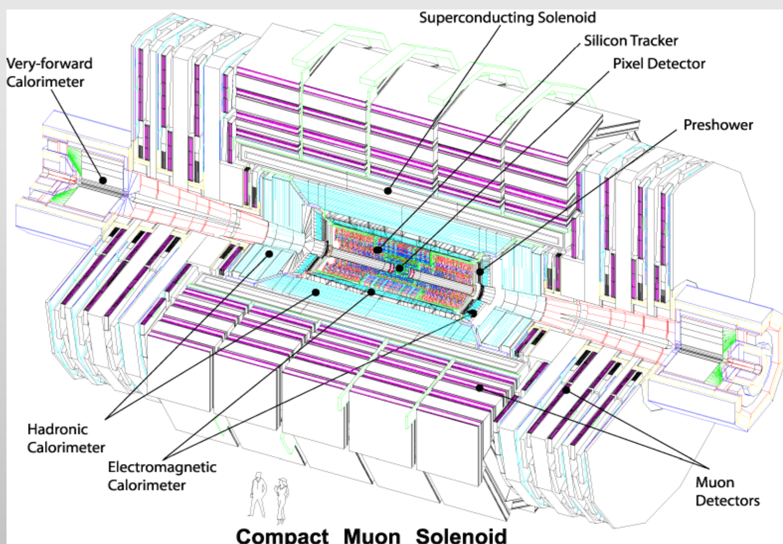
Hadronic Calorimetry

$\sigma/E \sim 50\% / \sqrt{E(GeV)}\ (+)\ 3\%$

Muon Spectrometer

$\sigma/p_T \sim 2\text{-}7\ \%$

Covers $|\eta| < 2.7$

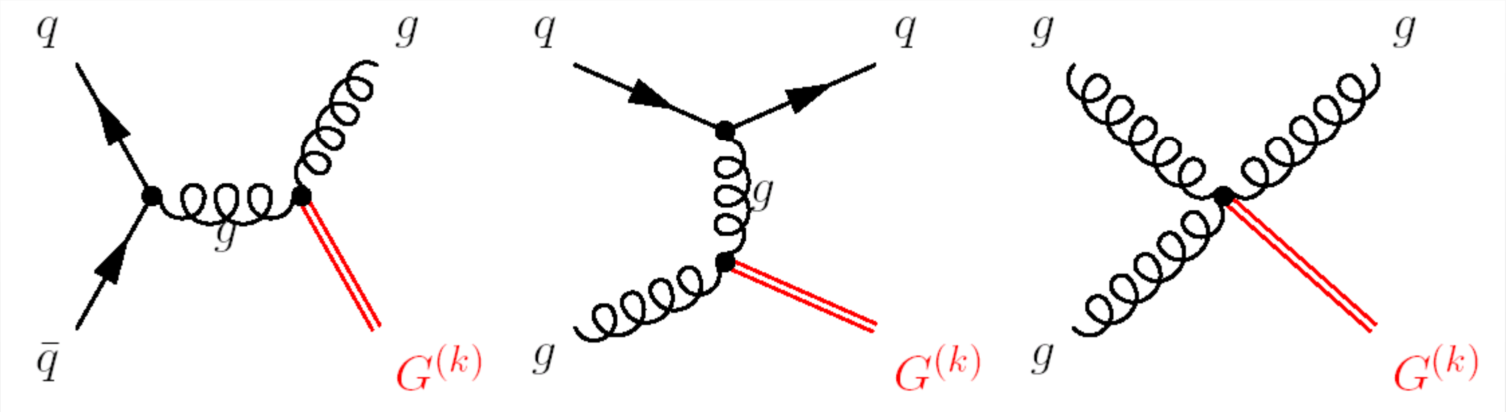


CMS

LARGE EXTRA DIMENSIONS - ADD

DIRECT PRODUCTION OF KK GRAVITONS

$G^{(k)}$ as an external leg=> missing energy in 4D



Signatures: mono Jet+ ~~Et~~, γ + ~~Et~~

Selection:

- trigger: jet (|η|<5) + E_t^{miss} diff @ low L vs high L
- lepton veto (|η|<2.5) – ε~98%
- central jet (|η|<2.5)
- large E_T^{miss}

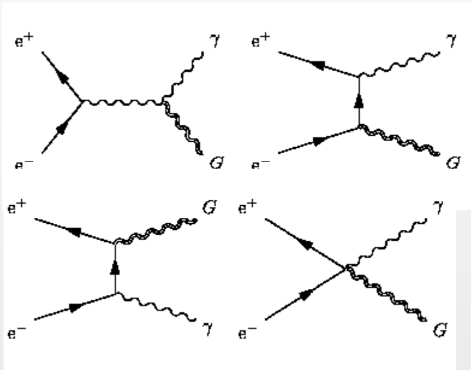
Background for jet signal:

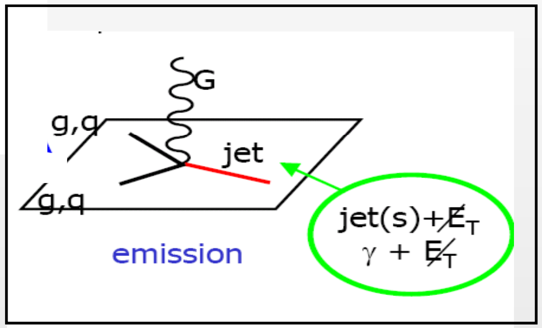
- jZ(νν), jW(τν), jW(eν), jW(μν)

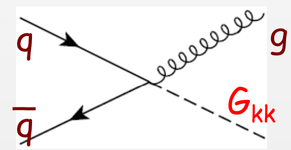
ATLAS: Lvacavant I. Hinchliffe J.Phys. G: Nucl. Part. Phys. 27 1839 (2001)

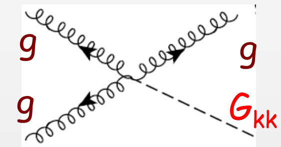
PRESENT ADD LIMITS

LEP and Tevatron results are complementary







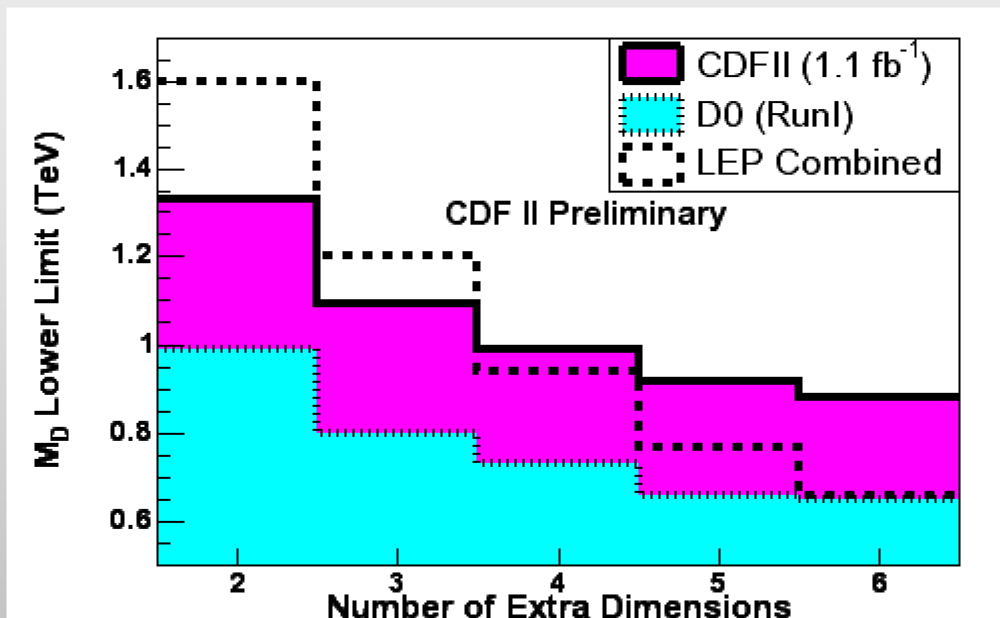


For n>4: CDF limits best

jet+ME_T

For n<4: LEP limits best

γ+ME_T

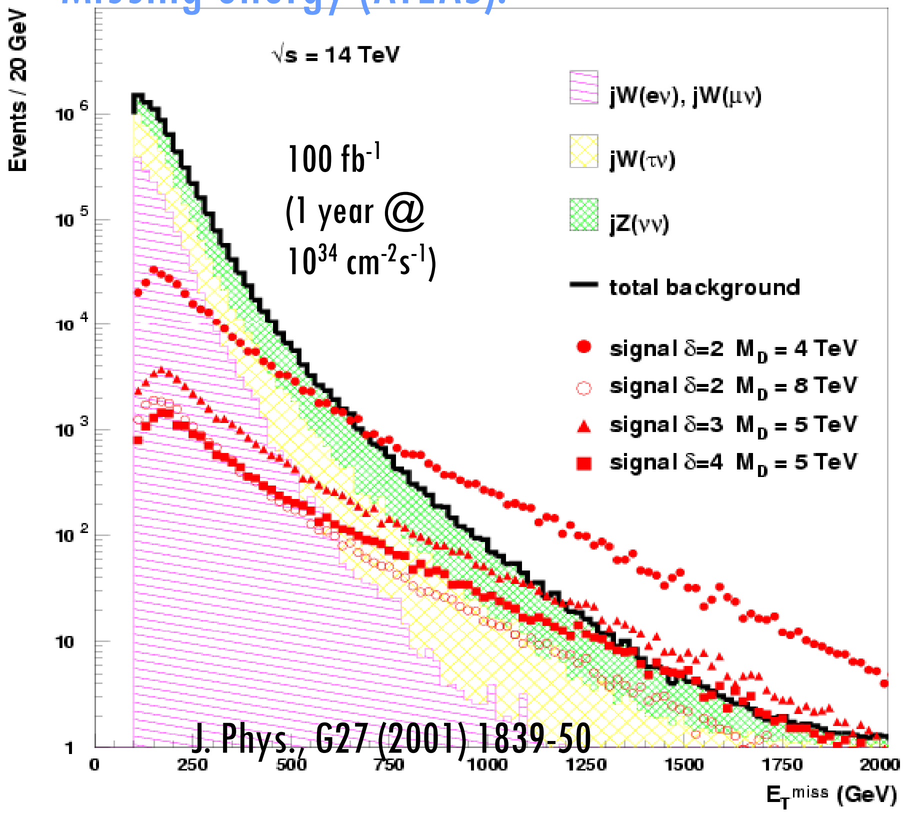


n	M_D (TeV/c^2) K=1.3	R (mm)
2	> 1.33	<0.27
3	> 1.09	< 3.1×10^{-6}
4	> 0.99	< 9.9×10^{-9}
5	> 0.92	< 3.2×10^{-10}
6	> 0.88	< 3.1×10^{-11}

LARGE EXTRA DIMENSIONS

DIRECT PRODUCTION OF KK GRAVITONS @ LHC

Missing energy (ATLAS):



CMS Note 2006 (J. Weng et al.,)

M_D=1-1.5 TeV for 1 fb^{-1}

M_D=2-2.5 TeV for 10 fb^{-1}

M_D=3-3.5 TeV for 60 fb^{-1}

Sensitivity for 100 fb^{-1}:

- $S/\sqrt{B} > 5$
- > 100 signal events
- E_T(jet) > 1 TeV

➔ jet + $G^{(k)}$ signature: **discovery**

	$\delta = 2$	$\delta = 3$	$\delta = 4$
M_D^{max}	9.1 TeV	7.0 TeV	6.0 TeV
$R_{compact}$	8 μm	2 Å	1 pm
M_D^{min}	~ 4 TeV	~ 4.5 TeV	~ 5 TeV

➔ photon + $G^{(k)}$ signature: **confirm.**

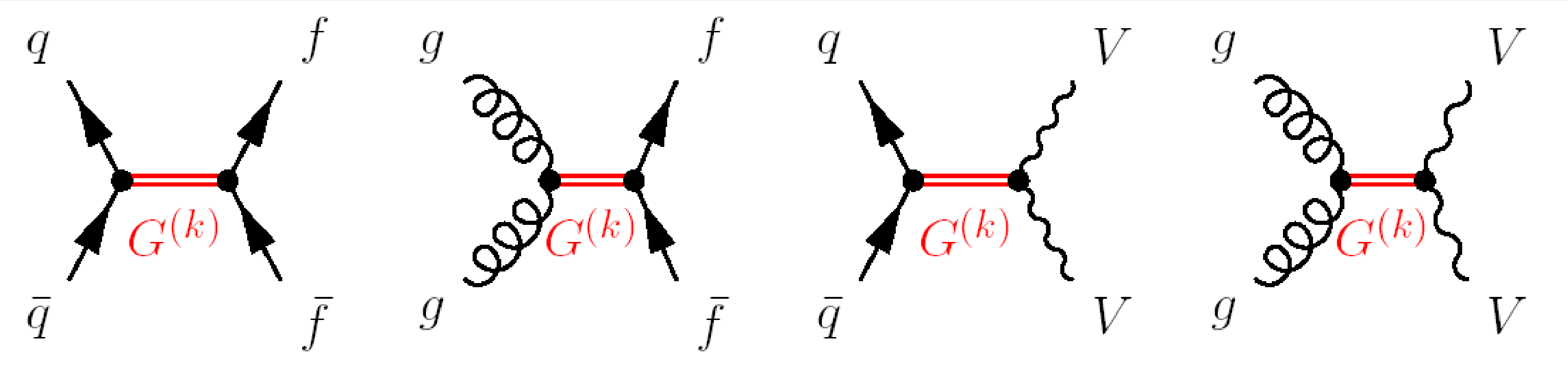
	$\delta = 2$
M_D^{max}	4.5 TeV
$R_{compact}$	32 μm
M_D^{min}	~3.5 TeV

LARGE EXTRA DIMENSIONS

VIRTUAL EXCHANGE OF KK GRAVITONS

Virtual exchange of gravitons at LHC:

$G^{(k)}$ as an internal line leg=> new contributions to amplitudes



Signatures: deviations from SM in Drell-Yan X-sections, asymmetries w.r.t. SM (sensitivity mostly from interference terms, KK exchange $\propto M_s^{-8}$)

ATLAS study:

- partonic cross-sections
- amplitude divergent for $\delta > 1$:

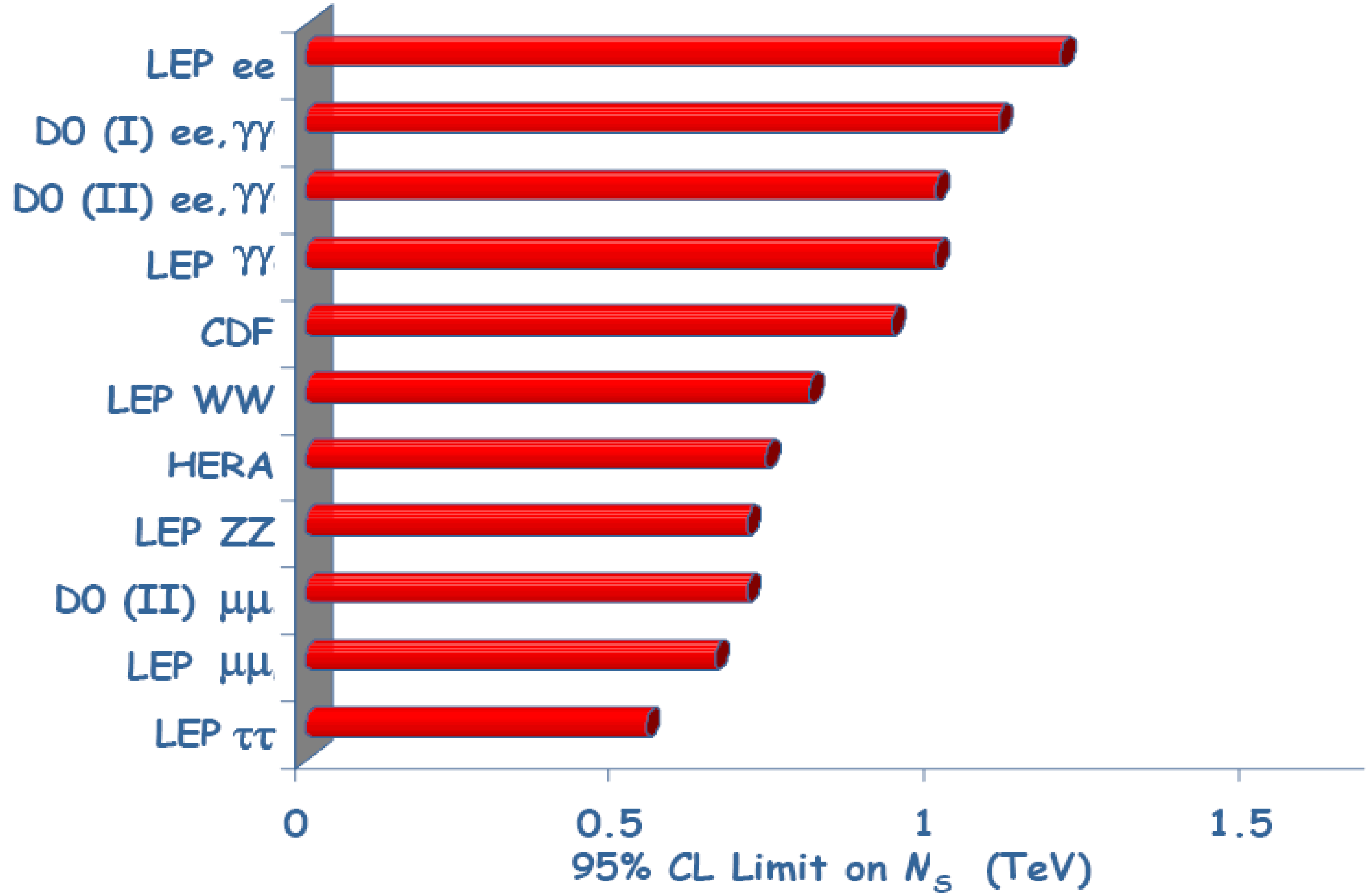
naive cut-off at $M_{ll,\gamma\gamma} < 0.9\ M_S$ (not to violate unitarity)

K.Cheung hep-ph/0003306, J.L.Hewett hep-ph/9811356

ATLAS: V. Kabachenko, A. Miagkov, A. Zenin, ATL-PHYS-2001-012

LARGE EXTRA DIMENSIONS

Summary of limits from virtual effects



BRANE-WORLD SCENARIOS - (RS)

Randall & Sundrum PRL83(1999)3370

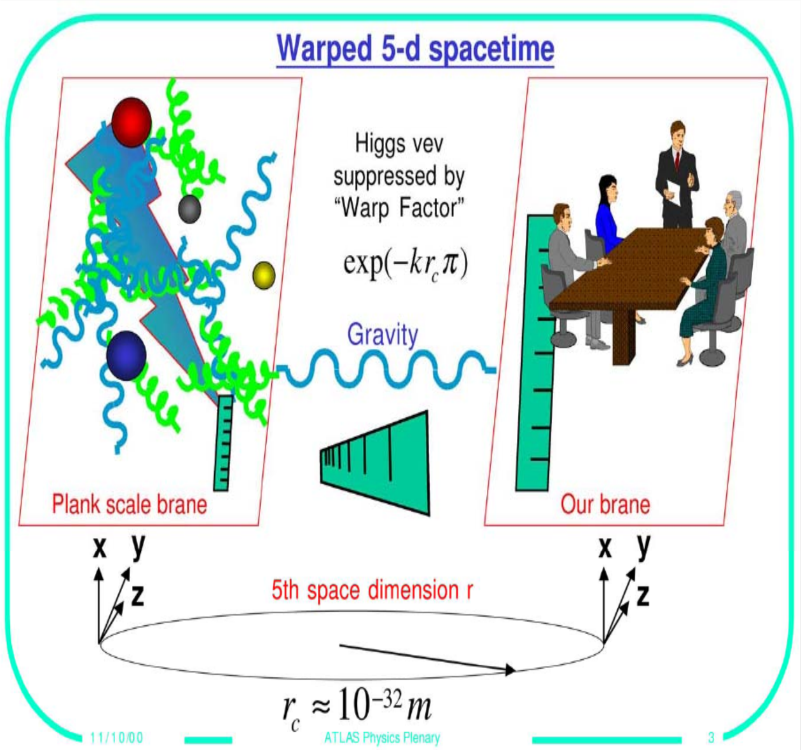


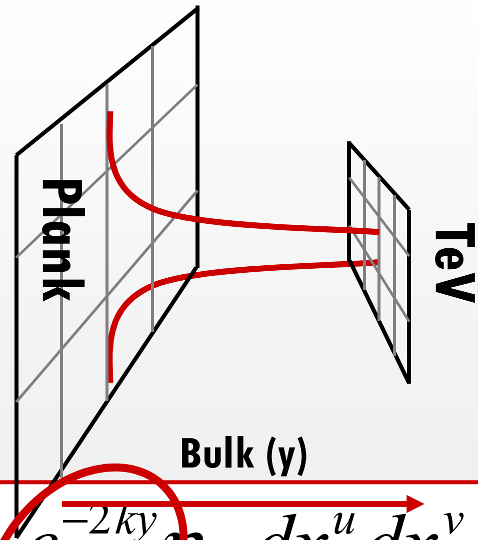
Figure de A. Parker

In this scenario only graviton and exotic particles can move in the "bulk" of the ED universe.

Ordinary particles are trapped on a brane and can't move in the ED

If this idea is correct the ED may be large!! only experiments with gravity or gravitons will detect the presence of extra dimensions

WARPED EXTRA DIMENSIONS



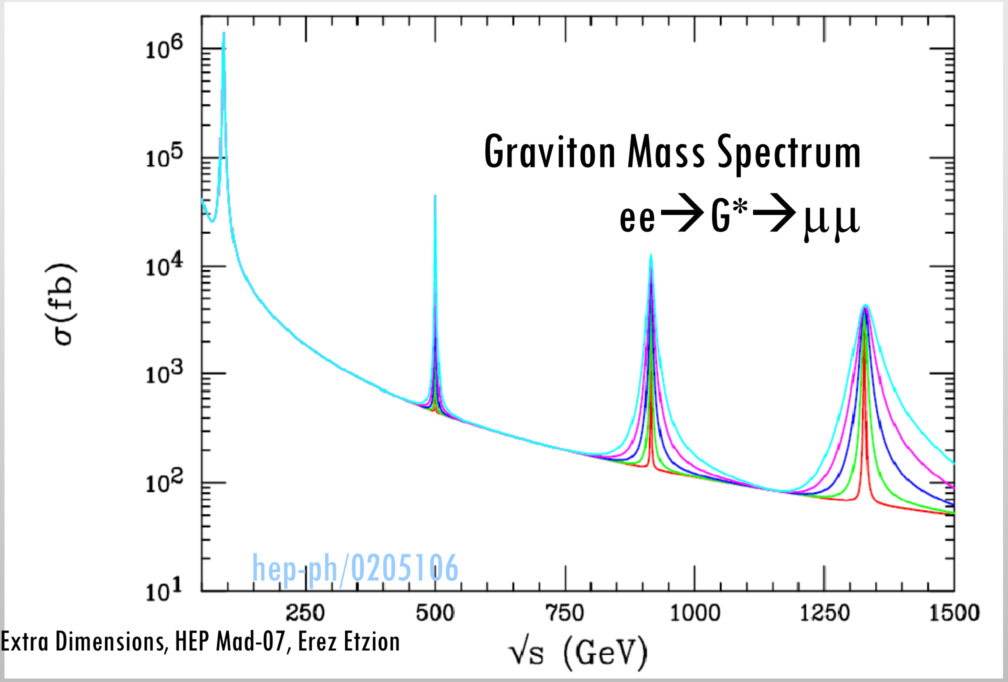
$$ds^2 = e^{-2ky}\eta_{uv}dx^u dx^v - dy^2$$

Randall Sundrum (type I)

- Brane metric scales as function of bulk position
- Solves Hierarchy problem using warp factor
- Small extra space dimensions
- Well separated graviton mass spectrum

Characterized by

$$k/\overline{M}_{pl}$$



LOTS OF RESEARCH DIRECTION ..

- RS: Narrow resonances
- RS: Radion
- Mini black holes
- You name it….

TEV^{-1}-SIZED EXTRA DIMENSIONS

KALUZA-KLEIN GAUGE BOSONS

Basics: I. Antoniadis, PLB246 377 (1990)

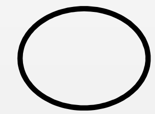
- one extra dimension
- compactified on a S^1/Z^2 orbifold
- radius of compactification small enough ➔ gauge bosons in the bulk
- fermions localized on:
  - a fixed point (M1 model): invariance under $y \rightarrow -y$
  - opposite fixed points (M2 model): under $y \rightarrow y + 2\pi R$
- Kaluza-Klein spectra for $Z^{(k)}, W^{(k)}$: $m_k^2 = m_0^2 + k^2 M_C^2$
  - for $M_C = 4$ TeV: $m_1 = 4$ TeV, $m_2 = 8$ TeV (out of reach .. ☹)

➔look for $pp \rightarrow \gamma^{(1)}/Z^{(1)} \rightarrow l^+l^-$ on top of SM Drell-Yan

➔D0 limit $M_C > 1.12$ TeV at 95% C.L

➔LEP Bound for this process (precision EW corrections): $M_c > 4TeV$

S^1



$\frac{S^1}{Z_2}$

ATLAS study:

- matrix elements from T.Rizzo — T. Rizzo, PRD **61** 055005 (2000)
-
- ATLAS fast simulation — **ATLAS:** G.Azuelos, G.Polesello, Proc. Les Houches 2001

MC SIMULATION OF KK PARTICLES

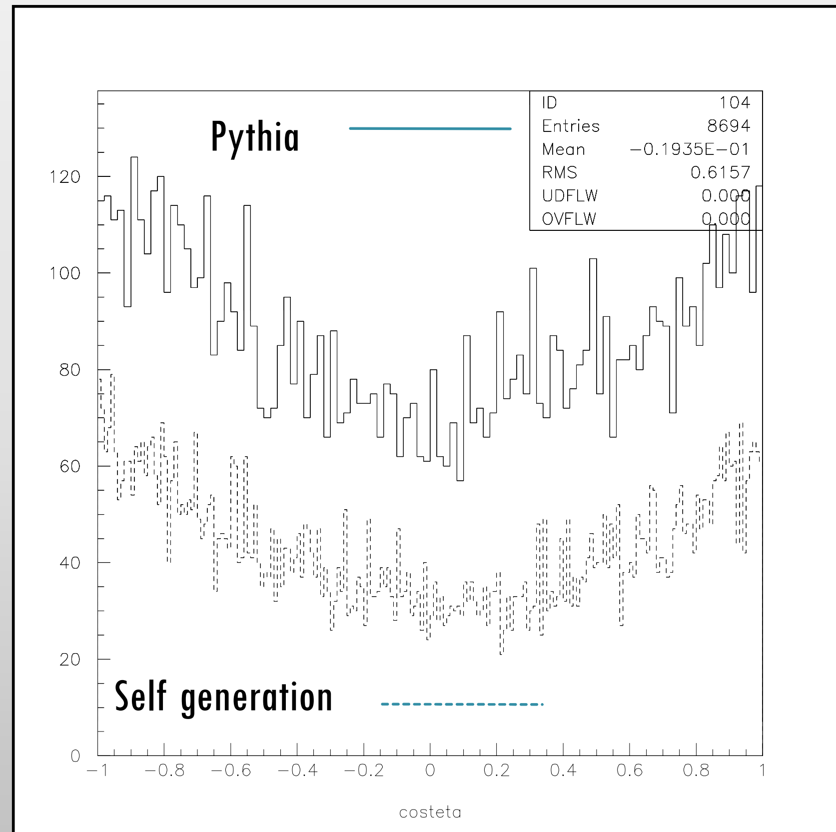
- We choose to simulate events with PYTHIA which simulates hard and soft interactions, parton distributions, initial and final state parton showers, multiple interactions, fragmentation and decay. A small problem as other standard MC programs– it doesn't contain the KK required for our study.
- In order to add processes to the detailed well tested simulation of programs like PYTHIA / HERWIG etc once can start with a "private" Matrix Element Generator and allow standard simulation code to continue with the decay, the radiation, the harmonization etc..
- A possible interface is the Les Houches Accord which enables transfer of the generated events to HERWIG or PYTHIA to continue with the simulation of the process.

$$pp \to Z_0 \to \mu^+ \mu^-$$

Angular distribution

$$\sigma \propto s\left[\sum_{\substack{+,+\\-,-}}\left|\frac{g_l{}^a g_f{}^b}{\left(s-M^2\right)^2+\left(i\Gamma M\right)^2}+\frac{Q_l Q_f}{s}\right|^2\right]\left(1+\cos\theta\right)^2+s\left[\sum_{\substack{+,-\\-,+}}\left|\frac{g_l{}^a g_f{}^b}{\left(s-M^2\right)^2+\left(i\Gamma M\right)^2}+\frac{Q_l Q_f}{s}\right|^2\right]\left(1-\cos\theta\right)^2$$

$$f(\theta)=1+\cos^2\theta+\frac{2B}{A}\cos\theta$$

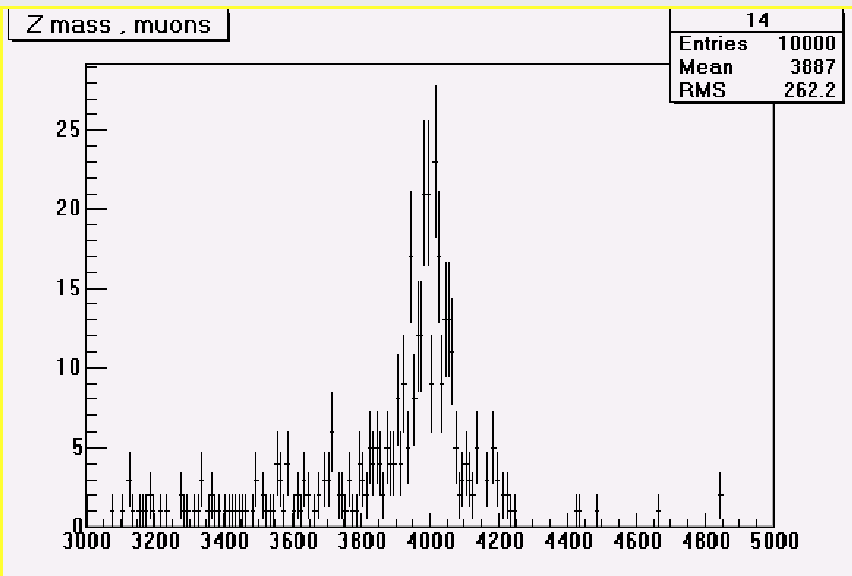


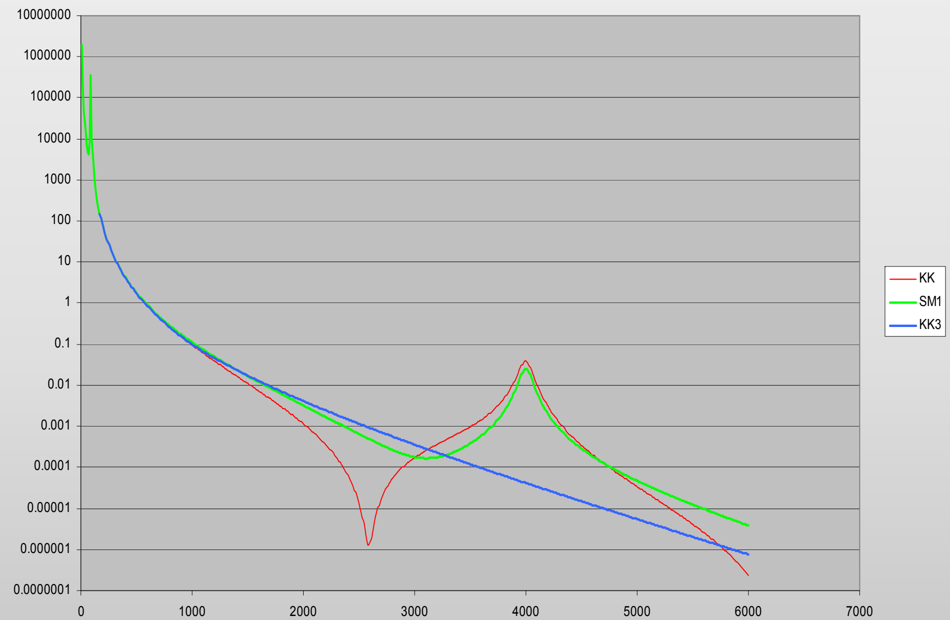
$$pp \to Z_0, Z', \gamma' \to \mu^+ \mu^-$$

Cross section: $$\sigma \propto s^2 \sum_{a,b} \left| \frac{g_l^{\,a} g_f^{\,b}}{\left(s - M_{z^0}^{\,2}\right)^2 + \left(i\Gamma_{z^0} M_{z^0}\right)^2} + \frac{g_l^{\,a} g_f^{\,b}}{\left(s - M_{z'}^{\,2}\right)^2 + \left(i\Gamma_{z'} M_{z'}\right)^2} + + \frac{Q_l Q_f}{s^2} \right|^2$$

Di-muon invariant mass,
generated with Pythia Z'

Analytical calculation



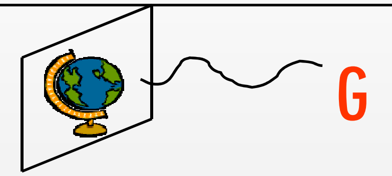


Ecm[GeV]

Ecm[GeV]

WE TALKED ABOUT

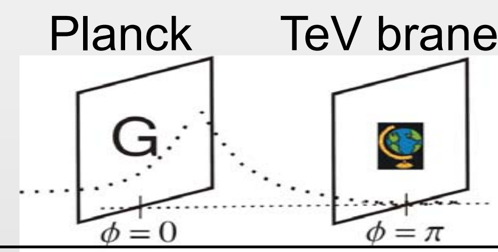
ADD **A**rkani-Hamed, **D**imopoulos, **D**vali, Phys Lett B429 (98)



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

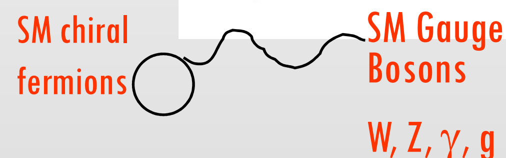
In which G can propagate, SM particles restricted to 3D brane

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)



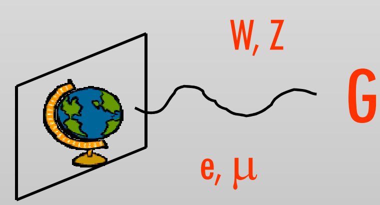
Bosons could also propagate in the bulk

Fermions are localized at the same (opposite) orbifold point: destructive (constructive) interference between SM gauge bosons and KK excitations

UED

All SM particles propagate in "Universal" ED

often embedded in large ED



LHC START-UP EXPECTATIONS

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

Sergi Shmatov , ICHEP2006, Moscow, July 2006

CONCLUSIONS

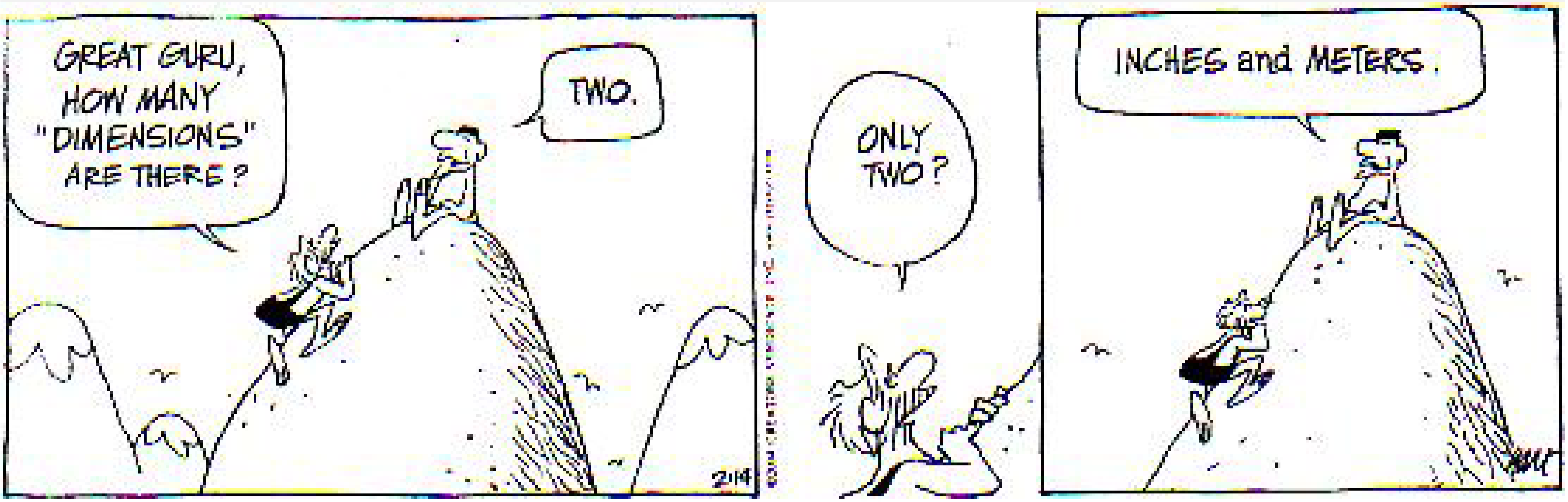
The discovery potential of ATLAS (and CMS) makes it possible to investigate if extra dimensions really exist within various ED scenarios at a few TeV scale.

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

New results have been predicted with data collected in the start-up LHC weeks (integrated luminosity<1 fb^{-1})

ARE THERE EXTRA DIMENSIONS?

Ask the Gurus



LIKELIHOOD IN LHC

- Likelihood:

$$\textit{Higgs} \geq \textit{Supersymmetry} \geq \textit{Extra Dimensions}$$

- Impact:

$$\textit{Higgs} \leq \textit{Supersymmetry} \leq \textit{Extra Dimensions}$$

EXPERIMENTAL UNCERTAINTIES

- Energy Miscalibration => performance of e/gamma/hadron energy reconstruction
- Misalignment effect => increase of mass residuals by around 30%
- Drift time and drift velocities
- Magnetic and gravitational field effects => can shift the mass resolution by 5-10%
- Pile-up => mass residuals increase by 0.2%
- Background uncertainties (variation of BG shape) => reduce the significance of measurement by 10-15%
- Trigger and reconstruction acceptance uncertainties

THEORETICAL UNCERTAINTIES

- QCD and EW high order corrections
- Parton Distribution Functions (PDF)
- Hard process scale (Q^2)
- Cuts performance, estimation of measurements significance

- And on top of all- is there any certainty on what are we looking for?

TEV^{-1}-SIZED EXTRA DIMENSIONS

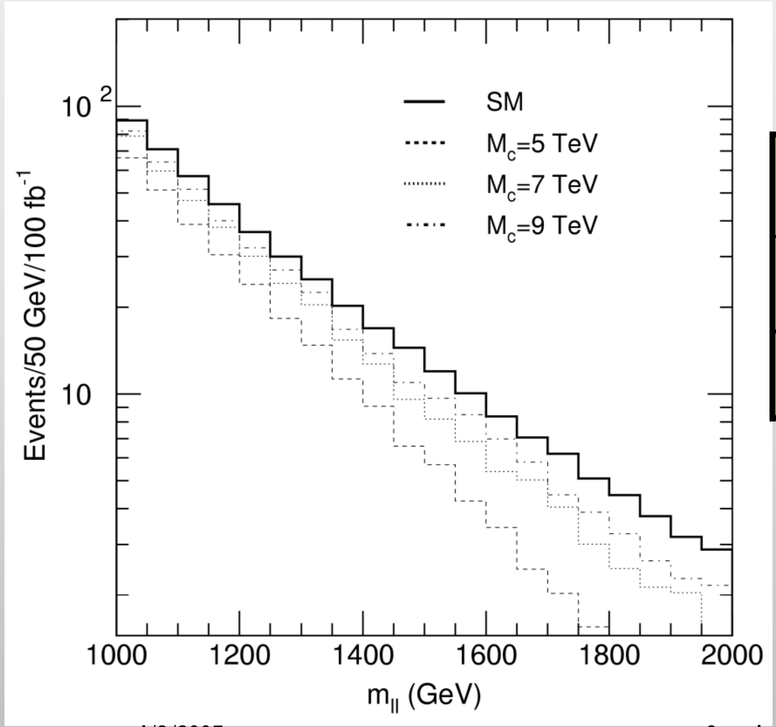
$\gamma^{(1)}/Z^{(1)}$ KALUZA-KLEIN GAUGE BOSONS

Sensitivity from peak region:

for 100 fb^{-1}, $S/\sqrt{B} > 5$, $S > 10$:

$M_C^{max} = 5.8$ TeV

Optimal reach (using interferences in tail region):



➔ likelihood fit analysis w/ MC experiments

electrons			e+μ
100 fb^{-1}	200 fb^{-1}	300 fb^{-1}	300 fb^{-1}
9.5 TeV	11 TeV	12 TeV	13.5 TeV

detailed study of systematics:

- energy scale, calibration
- higher order QCD & EW corrections
- PDFs