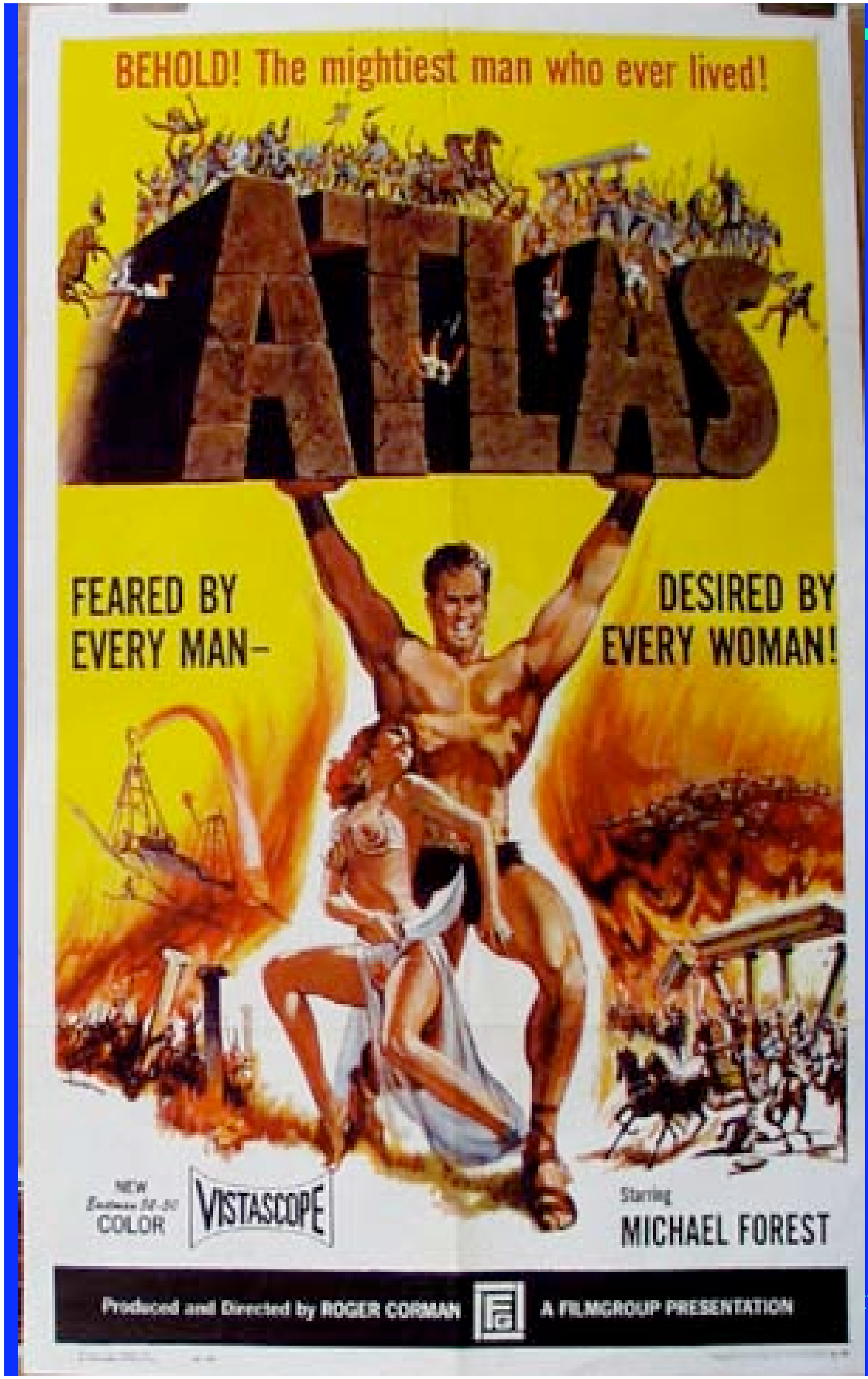
# Searching for Extra Space Dimensions at the LHC

M.A.Parker

Cavendish Laboratory

Cambridge




I shall use ATLAS to illustrate LHC physics, because it is the experiment I know best.

Both general purpose detectors - ATLAS and CMS - have very similar physics performance.

# An experimentalists view of the theory

- SM is wonderful!
  - All experimental data is explained to high precision
  - Theory checked at distance scales of $1/M_W = 2.5 \times 10^{-18}$ m
  - Only one state is unaccounted for - the Higgs
  - There is only one free parameter which is unknown - $M_H$
  - No contradiction between the best fit Higgs mass and search limit.

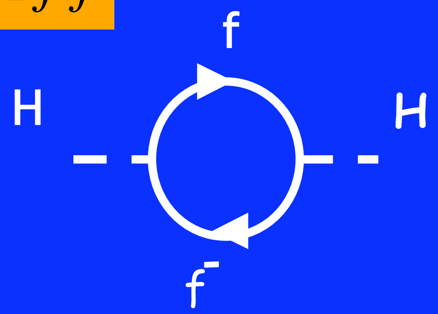
- But theorists don't agree!
  - Higgs mass is unstable against quantum corrections
  - Hierarchy problem - $M_W$=80 GeV, $M_H$<1 TeV, $M_{Pl}=10^{19}$ GeV

# The Hierarchy Problem

Try to calculate $m_H$:

First order prediction is $m_H = \sqrt{2}\mu\hbar / c$

But Higgs couples to fermions as $-\lambda_f H \bar{f} f$




Need to compute contribution of every fermion loop diagram.

Integral over all possible momemtum states is divergent, since there is no limit to the momemtum k which can circulate in the loop - Higgs mass is infinite!

If we cut off at $\Lambda_{UV}$, $M_H \approx \Lambda_{UV}$

Planck Mass? Need $m_H$<780 GeV, get $m_H=10^{18}$ GeV!!

# SUSY vs Extra Dimensions

Traditional solution: impose SUSY, double number of states in model.

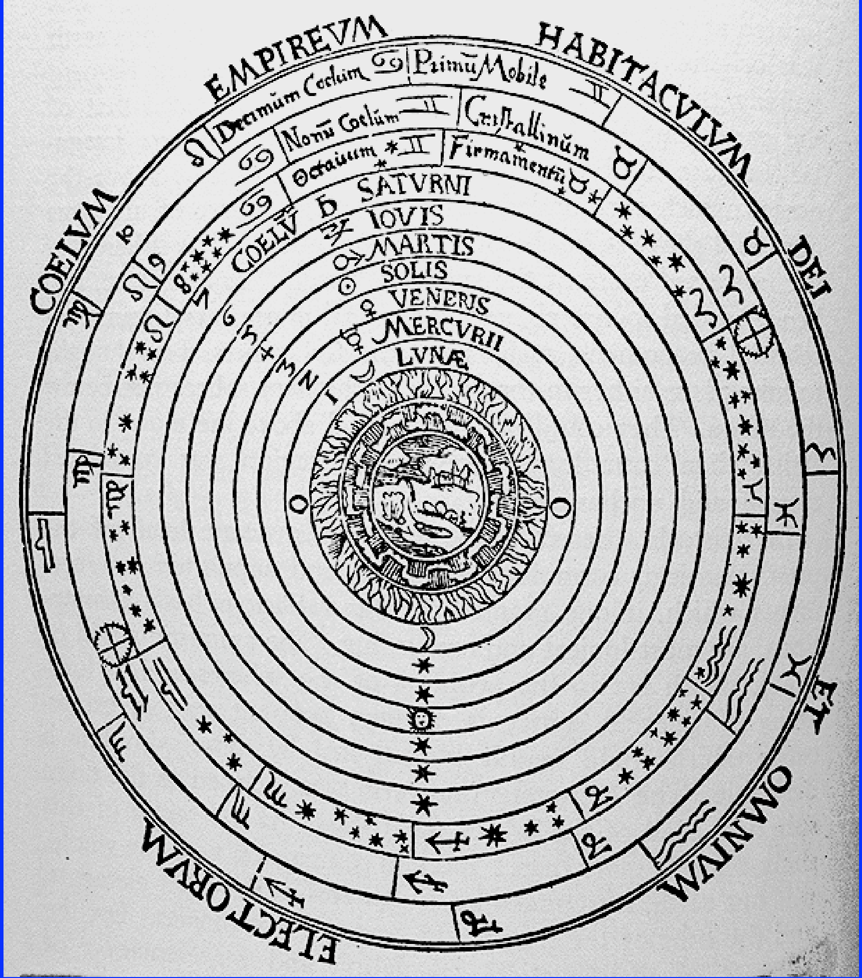
Break SUSY at high scale in "hidden sector"

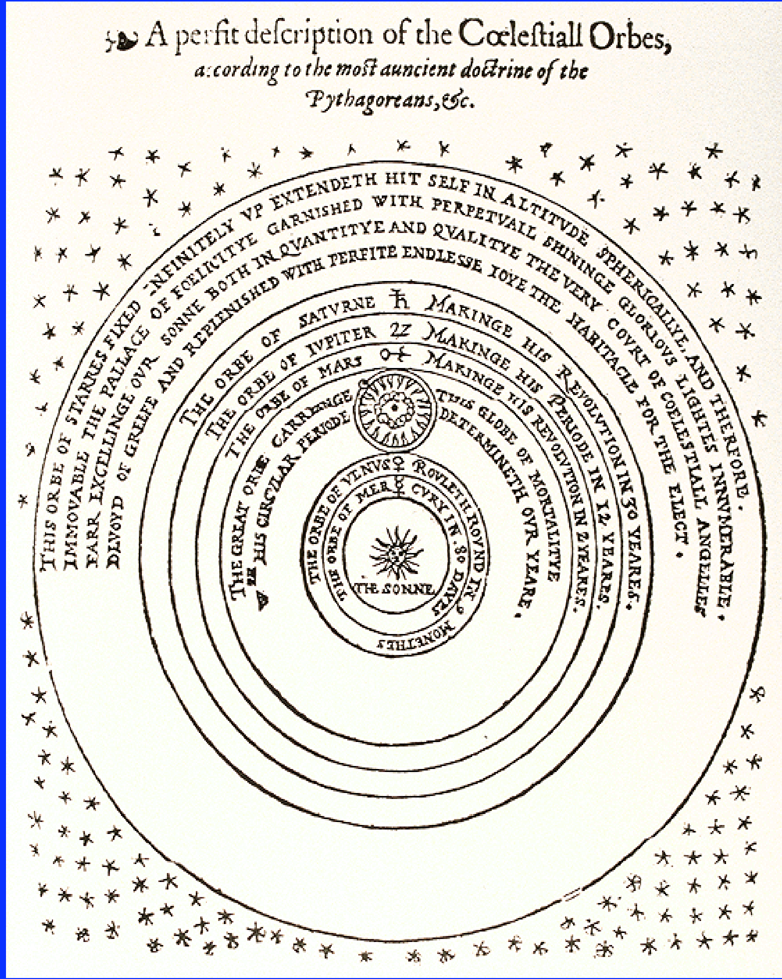
- ✔ Raises SUSY masses, and generates EW symmetry breaking
- ✔ Cancels divergences to all orders
- ✘ Introduces many new parameters (105 in MSSM)
- ✘ Requires "hidden sector" with particular interactions to SM

Extra dimensions: provide new physics which lowers Planck scale to EW scale.

- ✔ Eliminates hierarchy problem in mass
- ✘ Introduces new length hierarchy to explain

# Two views of the world....




Supersymmetry ....

....hidden perfection

Extra dimensions....

...different scales

# Extra Dimensions

Hypothesize that there are extra space dimensions

Volume of bulk space >> volume of 3-D space

Hypothesize that gravity operates throughout the bulk

SM fields confined to 3-D

ADD model (hep-ph/9803315)

Then unified field will have "diluted" gravity, as seen in 3-D

If we choose n-D gravity scale=weak scale then…

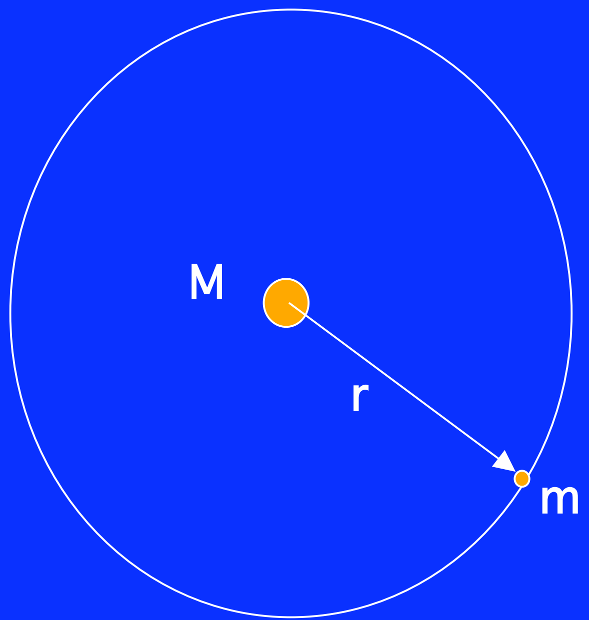
Only one scale -> no hierarchy problem!

Can experimentally access quantum gravity!

But extra dimension is different scale from "normal" ones

-> new scale to explain

# Gravity in 3-D space




Gauss's theorem:

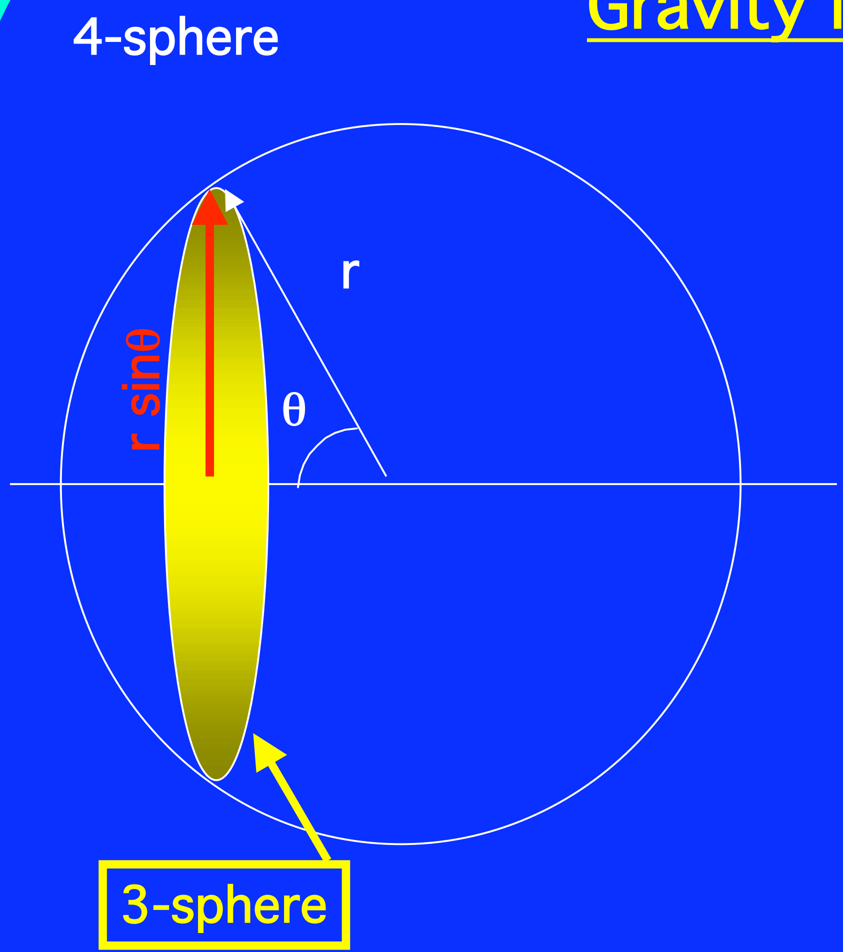
Field at r given by

$$\oint \vec{F}/m \, d\vec{S} = 4\pi GM$$

$$F/m \, 4\pi r^2 = 4\pi GM$$

$$F = GMm/r^2$$

# Gravity in 4-D space




Compute volume of 4-sphere

$$V_4(r) = \int_0^{\pi} V_3(r\sin\theta)\, r\sin\theta\, d\theta$$

$$= \int_0^{\pi} \tfrac{4\pi}{3} r^4 \sin^4\theta\, d\theta$$

$$= \tfrac{1}{2}\pi^2 r^4$$

$$S_4 = \frac{d}{dr} V_4 = 2\pi^2 r^3$$

$$F / m\, S_4 = 4\pi G M$$

$$F = \frac{2GMm}{\pi r^3}$$

$$G = 8\pi R^n M_D^{-(2+n)}$$

Relate the gravitational coupling in 3D to that in 4D:

$$\overline{M}_{PL} = \sqrt{\frac{\hbar c}{8\pi G}}$$

Separation can't exceed R in ED

Generalise to n extra dimensions

$$\overline{M}_{Pl}^{2} = R^{n} M_{*}^{(2+n)}$$

where $M_*$ is the bulk Planck mass in n+4 dimensions, and R is the radius of the extra dimensions.

# Scale of extra dimensions

For 4+n space-time dimensions

$$M_{Pl}^2 \approx M_{Pl(4+n)}^{2+n} R^n$$

For $M_{Pl(4+n)}$ ~ O(TeV)

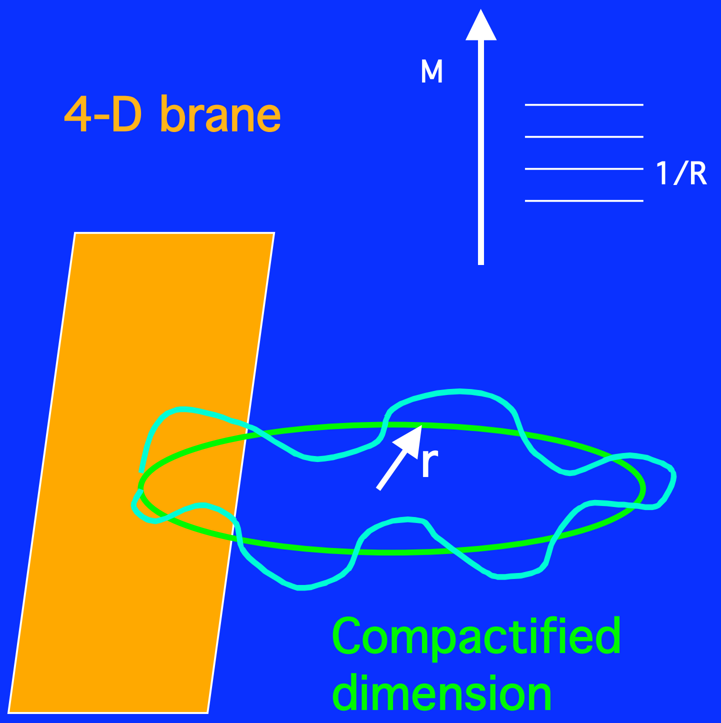
$$R \approx 10^{30/n-17}\ cm \left( \frac{1TeV}{M_{Pl(4+n)}} \right)^{1+2/n}$$

n=1, R=$10^{13}$ cm ruled out by planetary orbits

n=2, R~100 $\mu$m-1mm OK (see later)

-> Conclude extra dimensions must be compactified at <1mm

# Kaluza Klein modes




Particles in compact extra dimension:

- Wavelength set by periodic boundary condition
- States will be evenly spaced in mass
  - "tower of Kaluza-Klein modes"
- Spacing depends on scale of ED
  - For large ED (order of mm) spacing is very small - use density of states
  - For small ED, spacing can be very large.

$$p = \hbar / \lambda, \qquad \hbar c = 0.2 GeV fm$$

$$\lambda = 1mm, \qquad p = 0.2/10^{12} = 2.10^{-13} GeV$$

# Variations on the ED theme...

Universal Extra Dimensions hep-ph/0012100

- All SM Fields can propagate in bulk -> 1/R > 300 GeV
- KK number conservation evades electroweak constraints

Non-universal Extra Dimensions

- Some SM fields can propagate in bulk (eg gauge bosons)

Warped Extra Dimensions

- Effect of Planck-scale EDs amplified by warp factor (See Randall-Sundrum models) hep-th/9905221

Supersymmetric Large Extra Dimensions

- Attempt to solve both hierarchy problem and cosmological constant problem in one go. hep-th/0304256, 0402200

ED models can provide new ways to generate symmetry breaking in SM and SUSY, fermion masses etc…

# The Cosmological Constant

Even harder problem than hierarchy/Higgs mass!

Observed value of vacuum energy density $\rho$ is very small

$$\rho = v^4 = 8 \times 10^{-47} \text{ GeV}^4$$
$$\rightarrow v \approx 3 \times 10^{-12} \text{ GeV}$$

Any particle mass should generate a contribution to $\rho$ so electron alone gives $(5\times10^{-4})^4 = 6\times10^{-14}$ GeV$^4$

$$\delta\rho \approx m^4$$

SM requires cancellations to 60 order of magnitude!

SUSY gives large contribution from SUSY breaking

$$\delta\rho \approx m_{SB}^4$$

In SLED models $\rho$ is brane tension, cancelled by curvature term: problem may be soluble if n=2 and M=O(TeV).

# Identifying ED vs SUSY states

If SM fields propagate in the bulk EDs get spectrum of massive states with same quantum numbers as known SM particles.

This looks like SUSY, except for spin - KK excitations are fermions

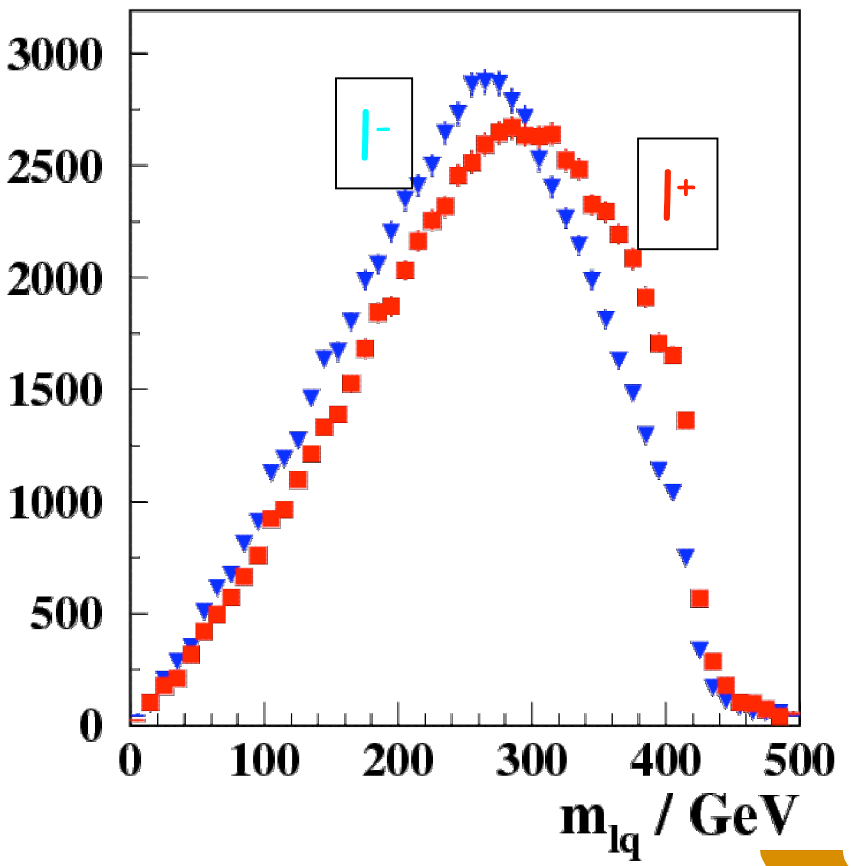
Becomes vital to measure spin of any new massive state.

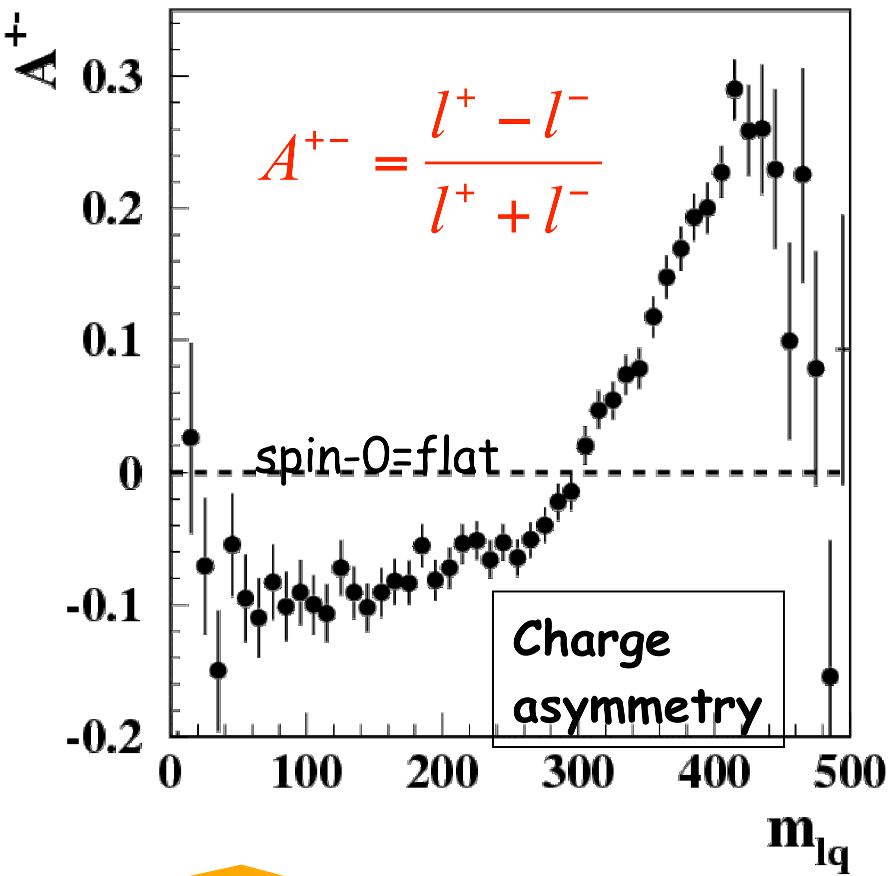
New work shows that it may be possible to extract spin information at LHC, exploiting rapidity difference in quark-antiquark annihilation in pp collisions.

Alan Barr Phys Lett B. 596 205-212, 2004

From Alan Barr

# Parton Level

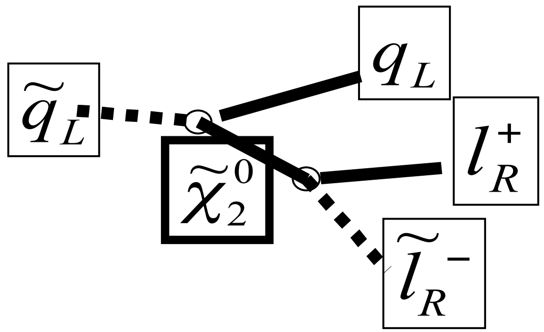


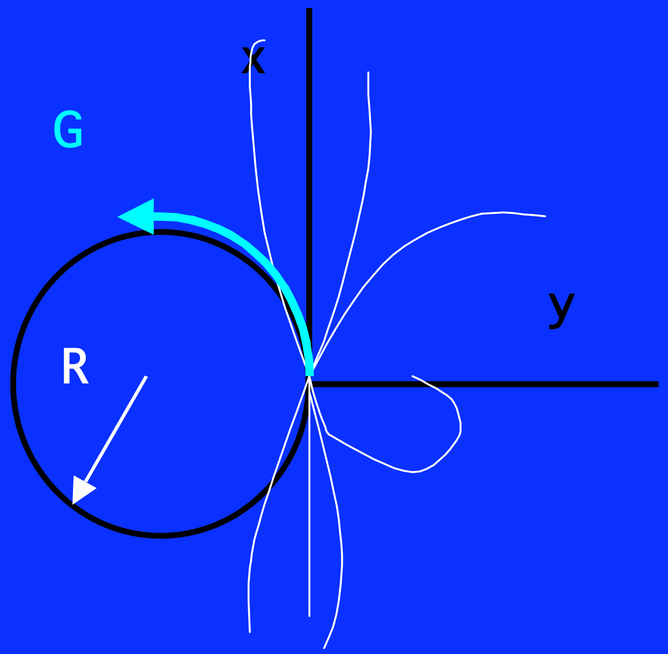

Experimentally measurable
-> q and q-bar
-> near and far leptons

difference/sum

Shape indicates that $\chi_2^0$ is spin-half



# Signatures for Large Extra Dimensions at Colliders




ADD model (hep-ph/9803315)

Each excited graviton state has normal gravitational couplings

-> negligible effect

LED: very large number of KK states in tower

Sum over states is large.

=> Missing energy signature with massless gravitons escaping into the extra dimensions

# Signatures at the LHC

Good signatures are LBNL-45198

- Jet +missing energy channels: ATL-PHYS-2001-012
  - $gg \to gG$
  - $qg \to qG$
  - $q\bar{q} \to Gg$
- Photon channels
  - $q\bar{q} \to G\gamma$
  - $pp \to \gamma\gamma X$ Virtual graviton exchange
- Lepton channels
  - $pp \to \lambda\lambda\ X$ Virtual graviton exchange

# Missing $E_T$ analysis

pp -> jet + $E_T^{Miss}$ Jet energies > 1 TeV

Dominant backgrounds:

Jet + Z -> $\nu\ \nu$ use ee mode to calibrate

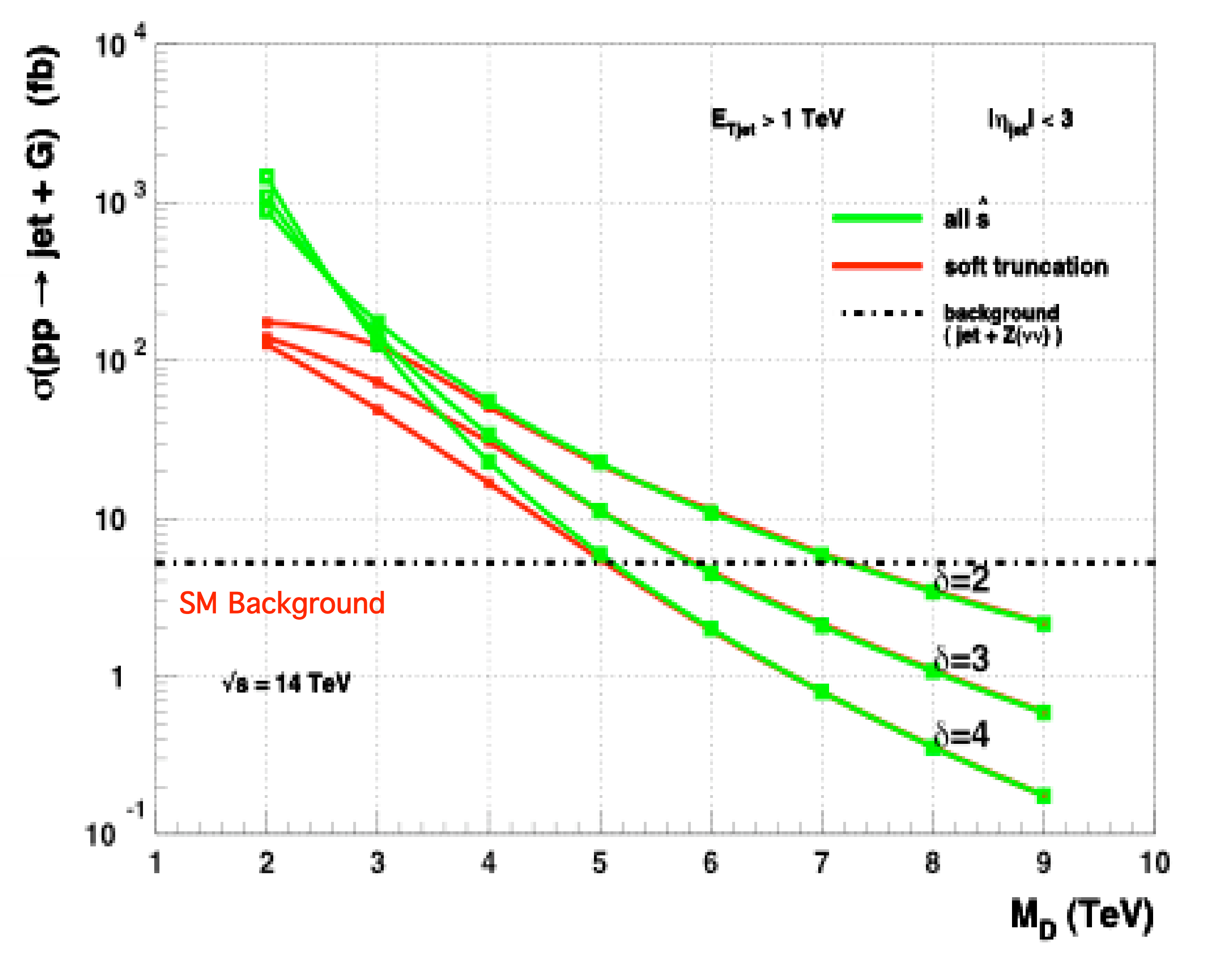
Jet + W-> $\tau\ \nu$ } Use lepton veto

Jet + W-> e $\nu$

Veto isolated leptons (<10 GeV within $\Delta$R=0.2)

Instrumental background to $E_T^{Miss}$ is small

# High $P_T$ jet cross section




$E_T^{Jet} > 1$ TeV

$|\eta_{Jet}| < 3$

$100 fb^{-1}$ of data expected

SM Background ~500 events

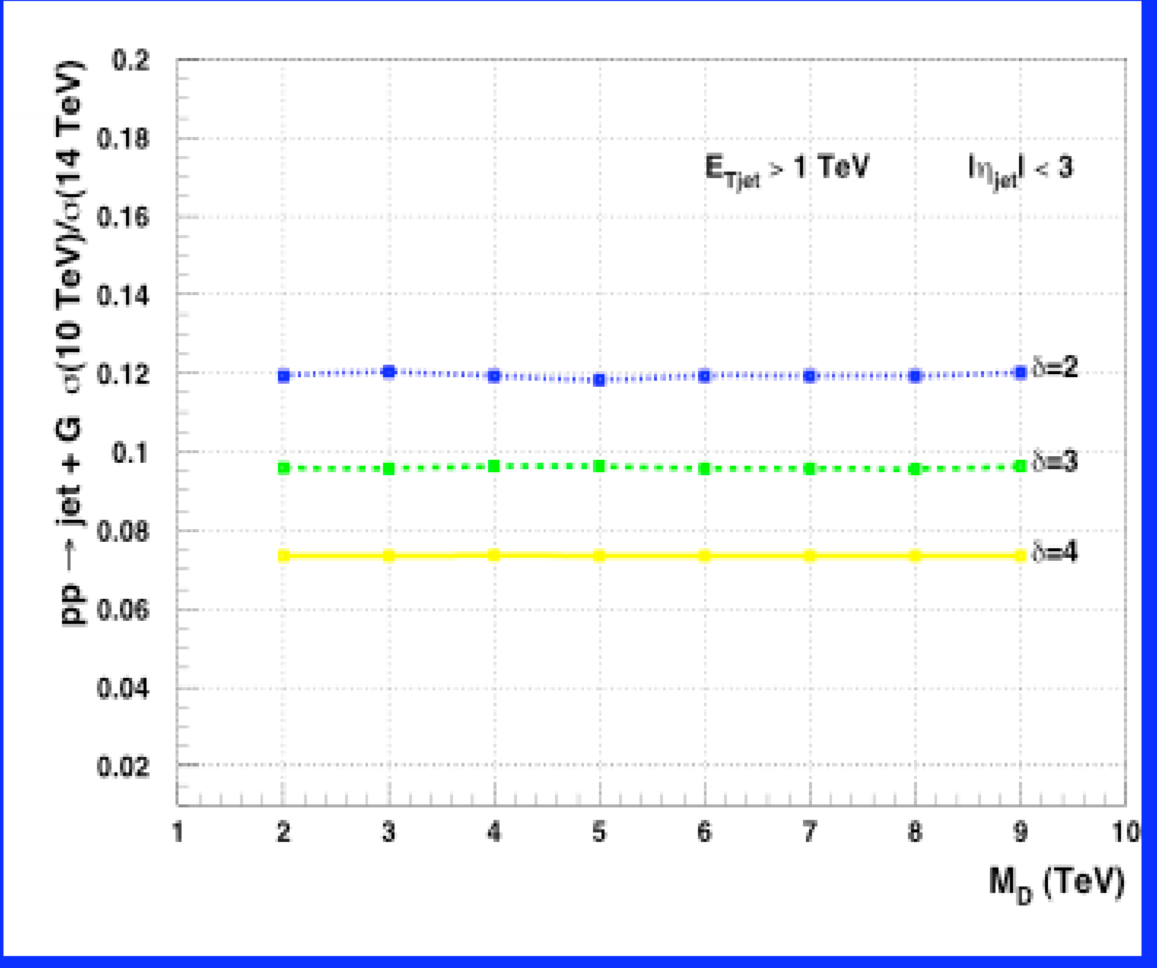
No prediction for n>4

# Discovery potential

$5\sigma$ discovery limits, $E_T$>1 TeV, $100 fb^{-1}$

| n | $M_D^{min}$ | $M_D^{Max}$ (TeV) | R |
|---|---|---|---|
| 2 | ~4 | 7.5 | 10 μm |
| 3 | ~4.5 | 5.9 | 300 pm |
| 4 | ~5 | 5.3 | 1 pm |

# Variation with $E_{CM}$ at LHC



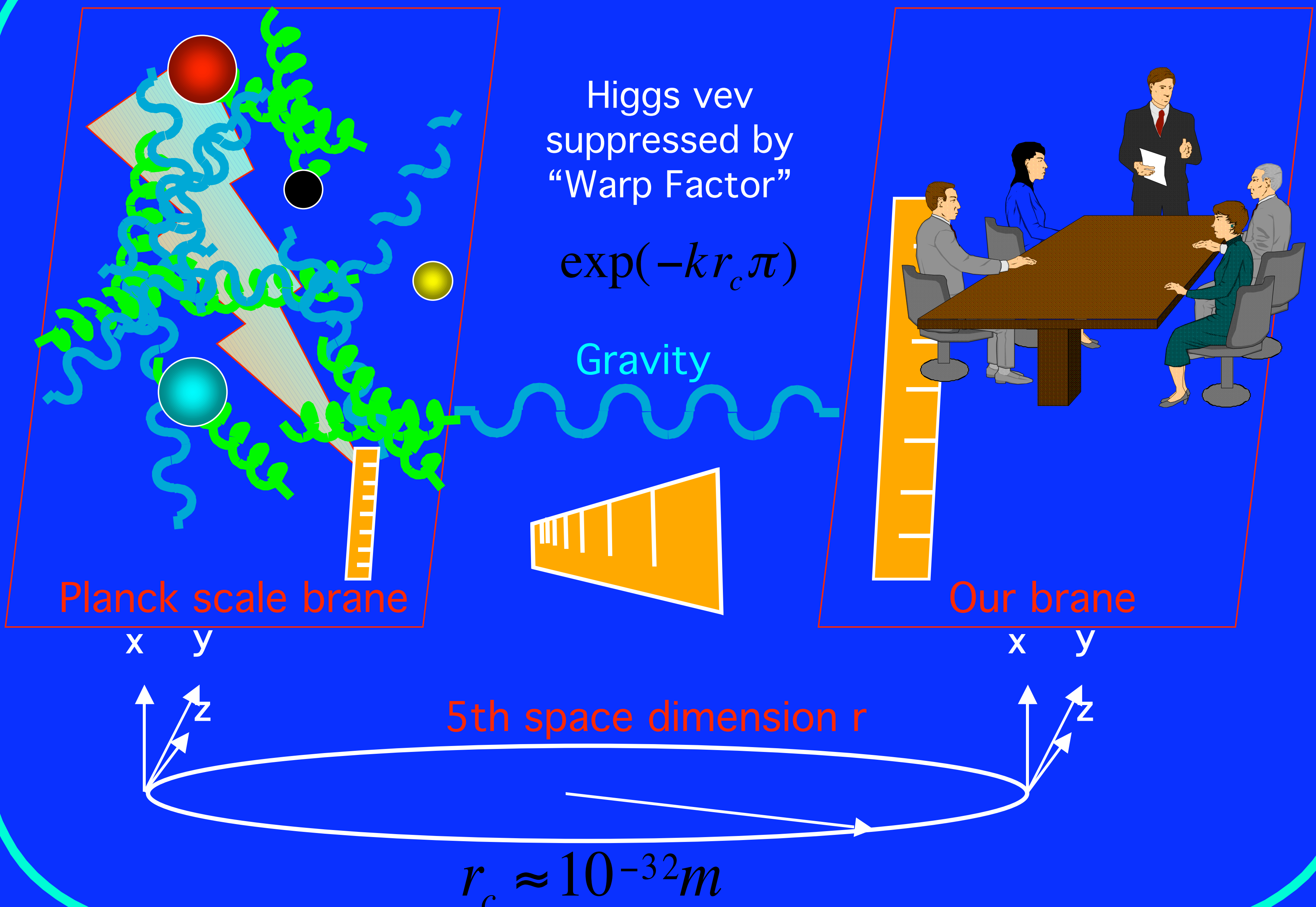

Cross section ratio (10 TeV/14TeV)

Need to measure to 5% to distinguish n=2,3

Need O(10) more L at 10 TeV

Need luminosity to <5%

# Warped 5-d spacetime



# Warped Extra dimensions

Consider Randall and Sundrum type models as test case

Gravity propagates in a 5-D non-factorizable geometry

Hierarchy between $M_{Planck}$ and $M_{Weak}$ generated by "warp factor"

Need $k r_c \approx 10$ no fine tuning

Gravitons have KK excitations with scale

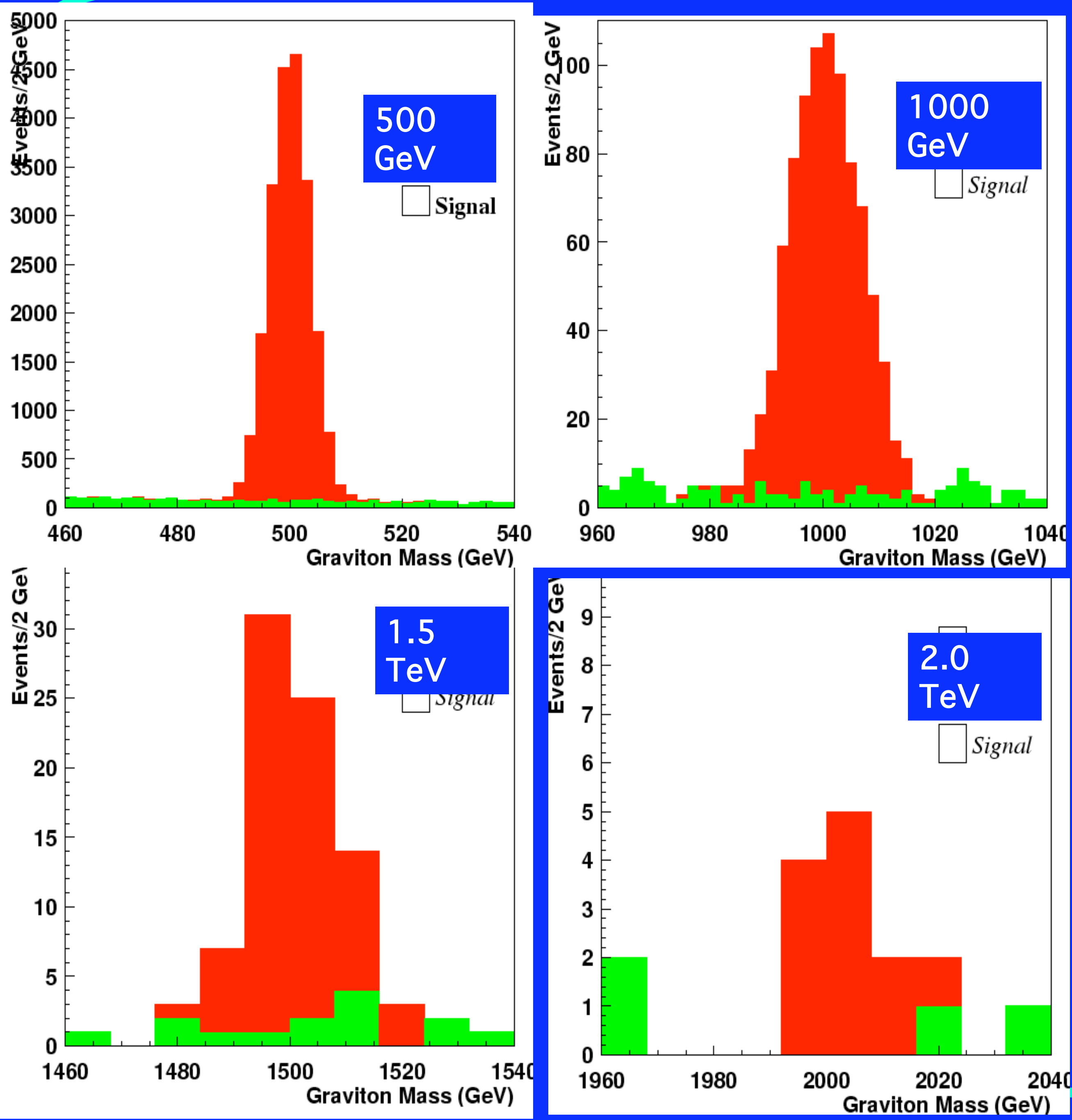
$$\Lambda_\pi = \overline{M}_{Pl} \exp(-k r_c \pi)$$

This gives a spectrum of graviton excitations which can be detected as resonances at colliders.

First excitation is at $m_1 = k x_1 \exp(-k r_c \pi) = 3.83 \frac{k}{\overline{M}_{Pl}} \Lambda_\pi$

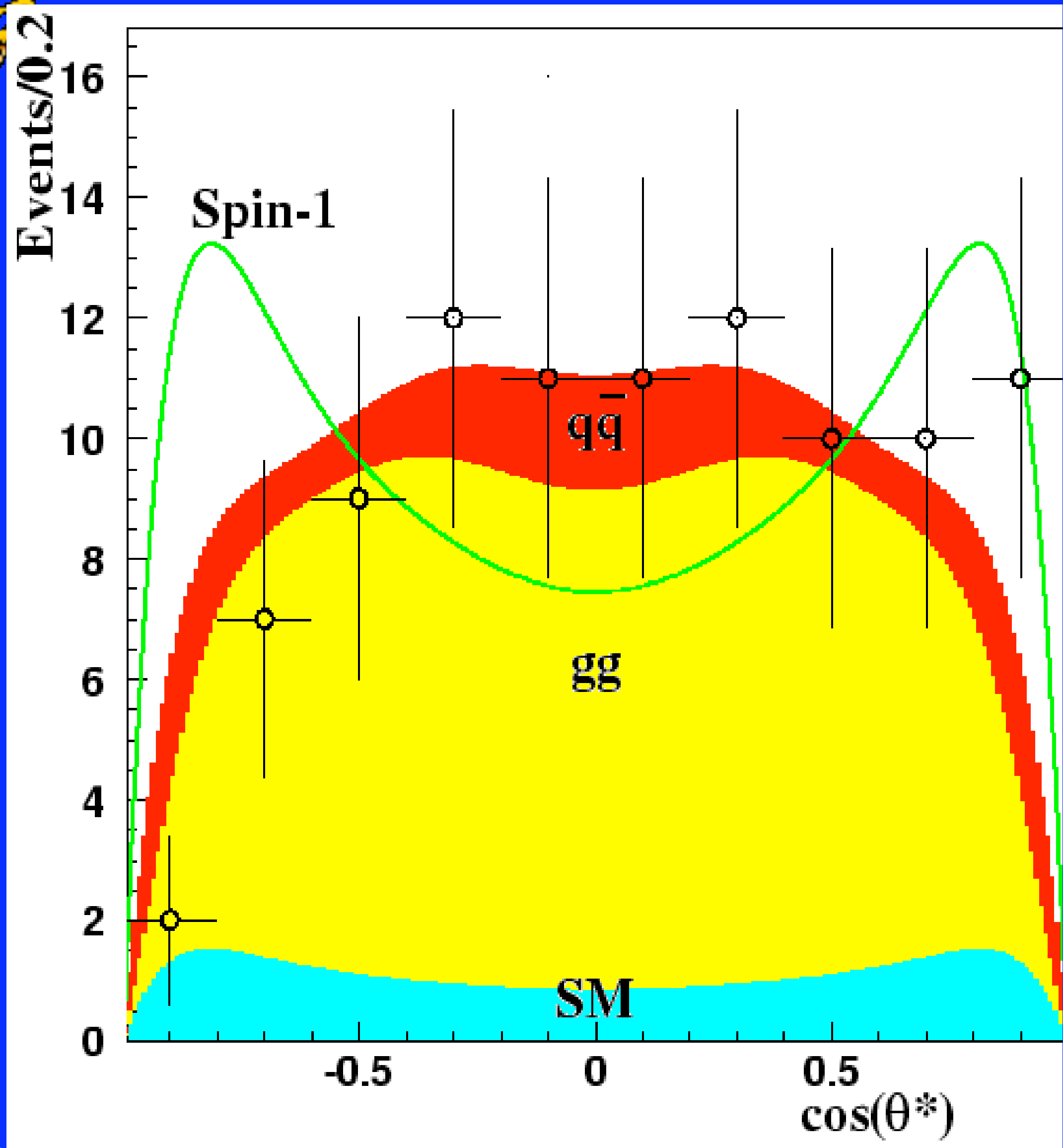
where $0.01 \le \frac{k}{\overline{M}_{Pl}} \le 1$

*Analysis is model independent: this model used for illustration*




Signal and background for increasing graviton mass

# Angular distribution observed in ATLAS




$G \to e^+e^-$

1.5 TeV resonance mass

Production dominantly from gluon fusion

Statistics for 100fb$^{-1}$ of integrated luminosity (1 year at high luminosity)

Acceptance removes events at high cos $\theta^*$

# Exploring the extra dimension

Check that the coupling of the resonance is universal: measure rate in as many channels as possible: $\mu\mu,\gamma\gamma$,jj,bb,tt,WW,ZZ

Use information from angular distribution to separate gg and qq couplings

Estimate model parameters k and $r_c$ from resonance mass and $\sigma$.B

For example, in test model with $M_G$=1.5 TeV, get mass to ±1 GeV

and $\sigma$.B to 14% from ee channel alone (dominated by statistics).

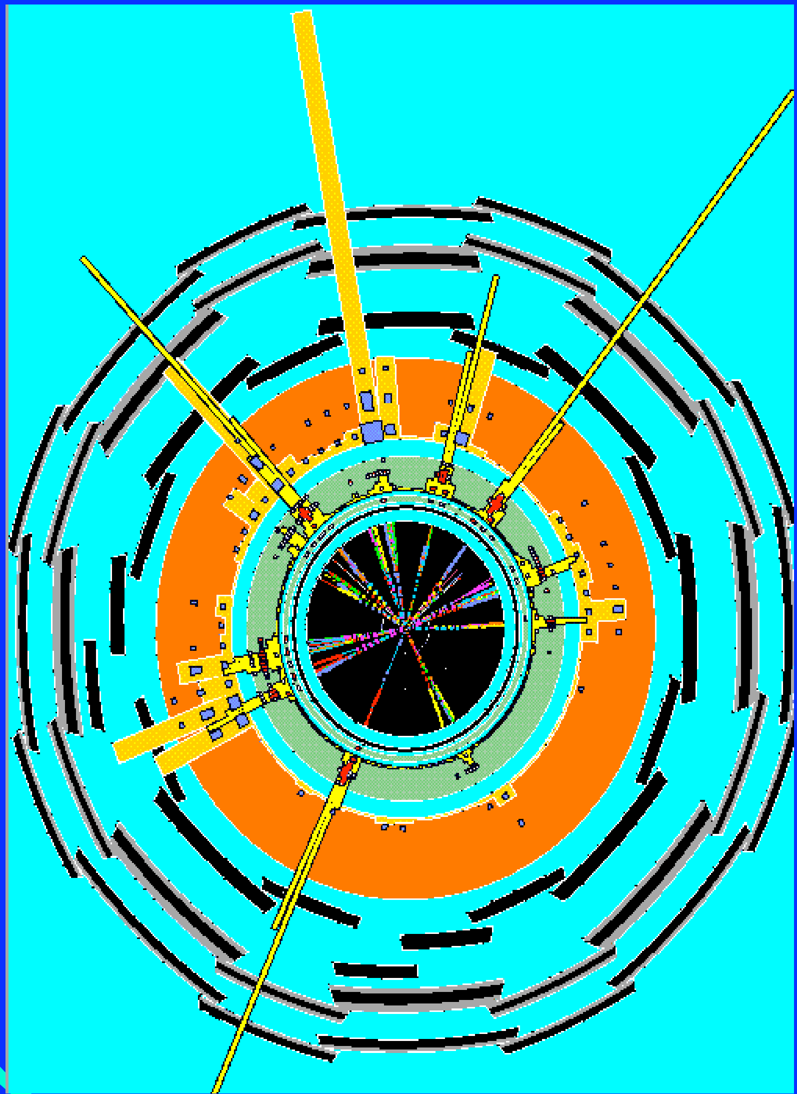
Then measure

$$k = (2.43 \pm 0.17) \times 10^{16}\ GeV$$

$$r_c = (8.2 \pm 0.6) \times 10^{-32} m$$

Allanach et al JHEP 0009:019,2000, JHEP 0212:039,2002.

# Black hole production



Low scale gravity in extra dimensions allows black hole production at colliders.

Decay by Hawking radiation (without eating the planet)

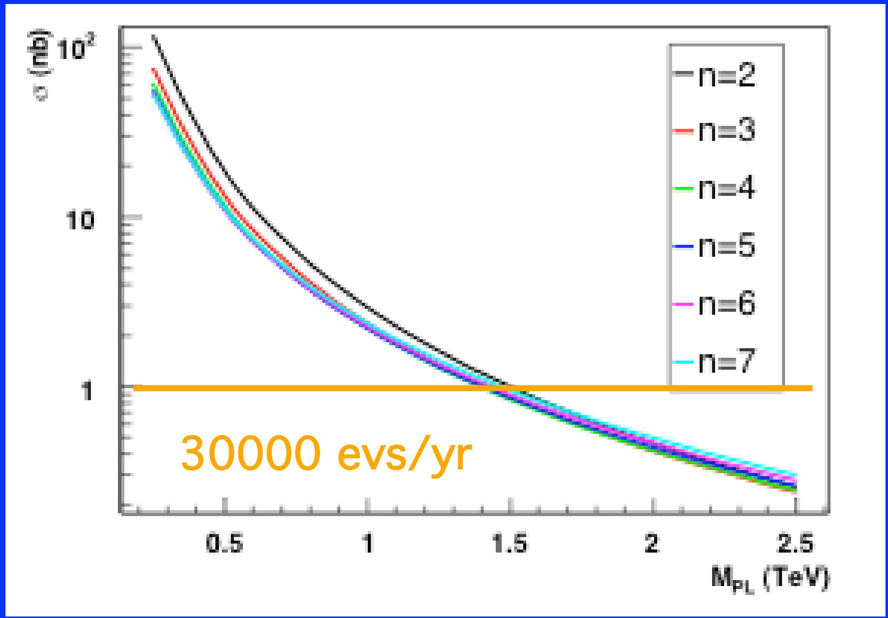
8 TeV mass black hole decaying to leptons and jets in ATLAS

8 partons produced with

$p_T$>500 GeV

Charybdis Event generator: Richardson, Harris, Palmer. hep-ph/0411022

# Black hole production cross-sections at LHC




Classical approximation to cross-section
(Controversial…)

$$\sigma_{BH} \sim \pi r_h^2$$

Very large rates for n=2-6
Almost independent of n

See hep-ph/0111230

# Black hole decay

Decay occurs by Hawking radiation, modified by "grey body" factors

Hawking Temperature $T_H$

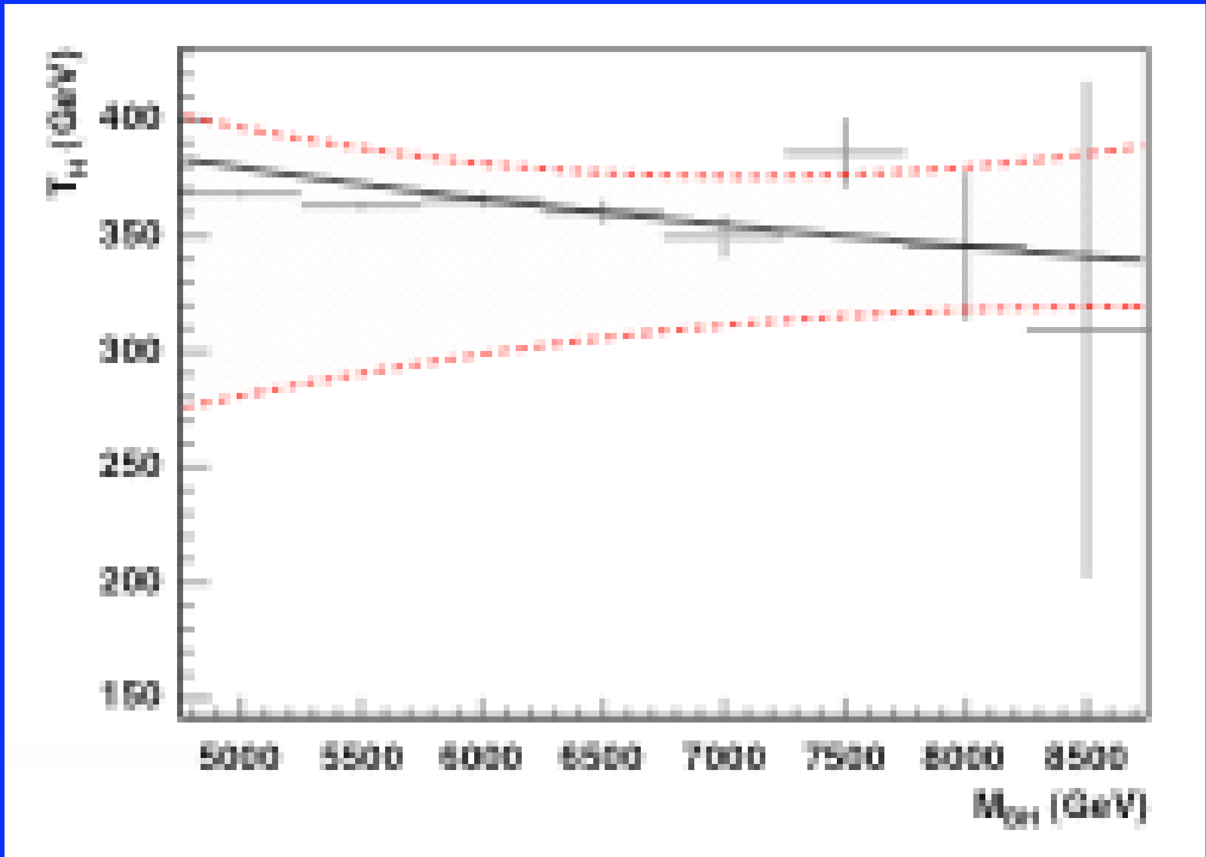
$$T_H = (n+1)/4\pi r_h$$

Black Hole radius $r_h$

$$r_h \sim \frac{\hbar}{M_{Pl}c}\left(\frac{m_{BH}}{M_{Pl}}\right)^{1/(n+1)}$$

Use observed final state energy spectrum to measure $T_H$ and hence n?

# Measurement of Black Hole Temperature variation with $M_{BH}$

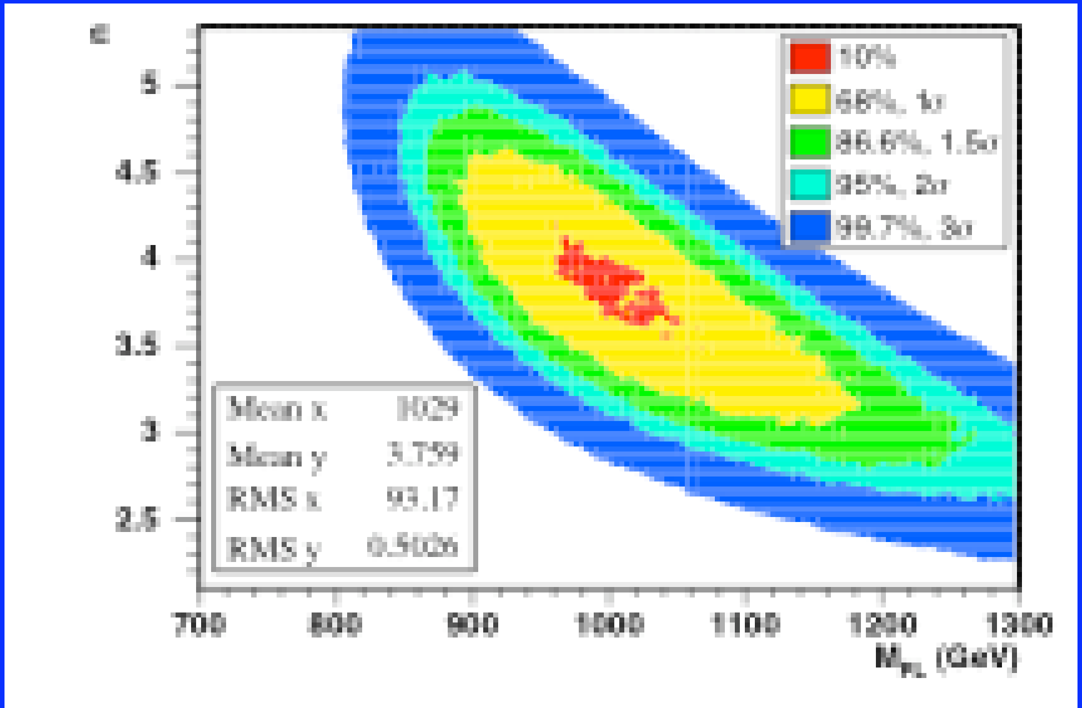



T against $M_{BH}$ for n=4, with sys error band.

Impossible to extract variation in T

Can measure characteristic T at average mass -> combine this with cross section data to extract n.

# Extraction of n and $M_{PL}$




Number of dimensions and Planck mass can be obtained in a correlated way.

n=4.0 + 0.6 - 1.0

$M_{PL}$ = 1029 +200 - 100 GeV

# Conclusions

Extra dimensional theories provide an exciting alternative to the normal picture of physics beyond the standard model

A wide variety of new phenomena are predicted within reach of experiments.

Exciting times (and spaces?) ahead!