KK gravitons at ATLAS

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Work performed with B.C.Allanach, K.Odagiri, M.Palmer, A.Sabetfakrihi and B.R.Webber in the Cambridge SUSY working group. See JHEP 09 (2000) 019, 12(2002) 039.

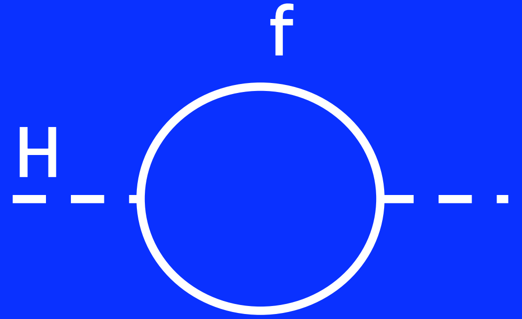
An experimentalists view of the theory

- 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:
Higgs couples to fermions as $-\lambda_f H \bar{f} f$
giving correction to mass of



$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6 m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots\right]$$

Scalars give:

$$\Delta m_H^2 = \frac{\lambda_s}{16\pi^2}\left[\Lambda_{UV}^2 - 2 m_s^2 \ln(\Lambda_{UV}/m_s) + \ldots\right]$$

Λ_{UV} is scale of new physics: Planck Mass?
Need m_H=100 GeV, get m_H=10^{18} GeV

Supersymmetry

Conventional method to fix Higgs mass:

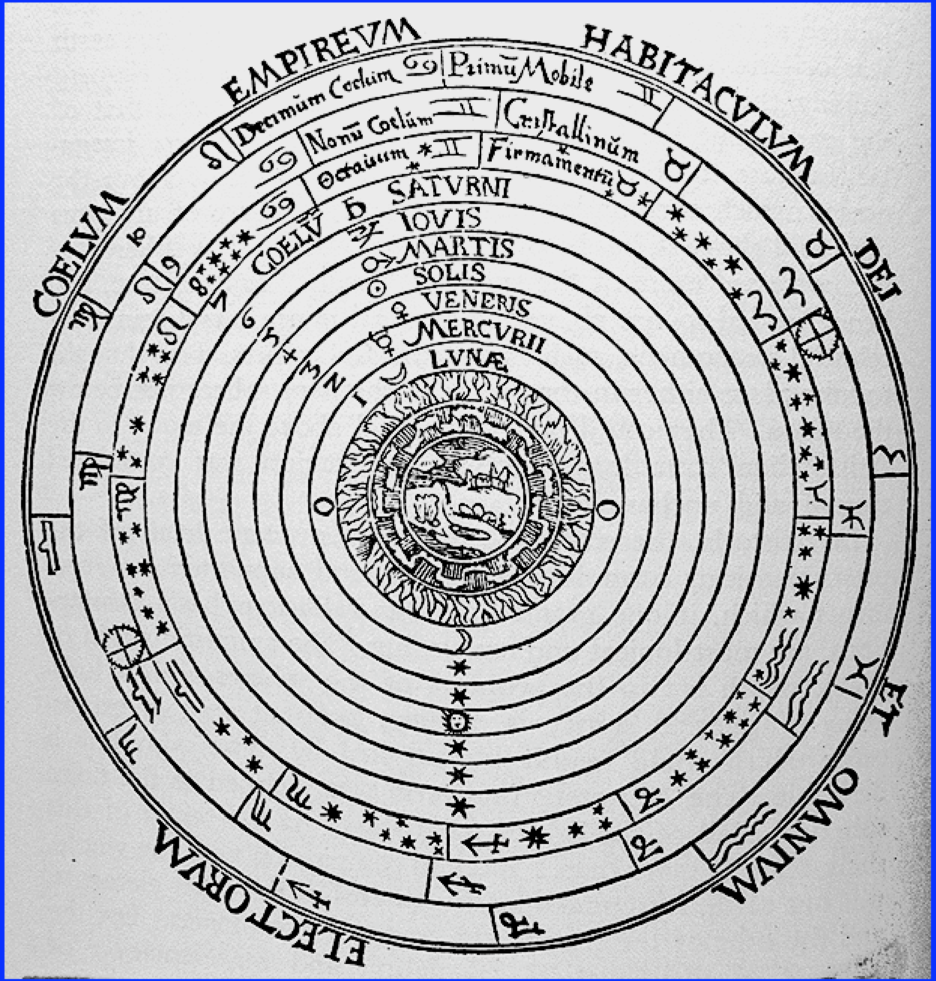
Invoke SUSY
Double the number of states in model
Invoke SUSY breaking
Fermion/boson loops cancel (GIM)

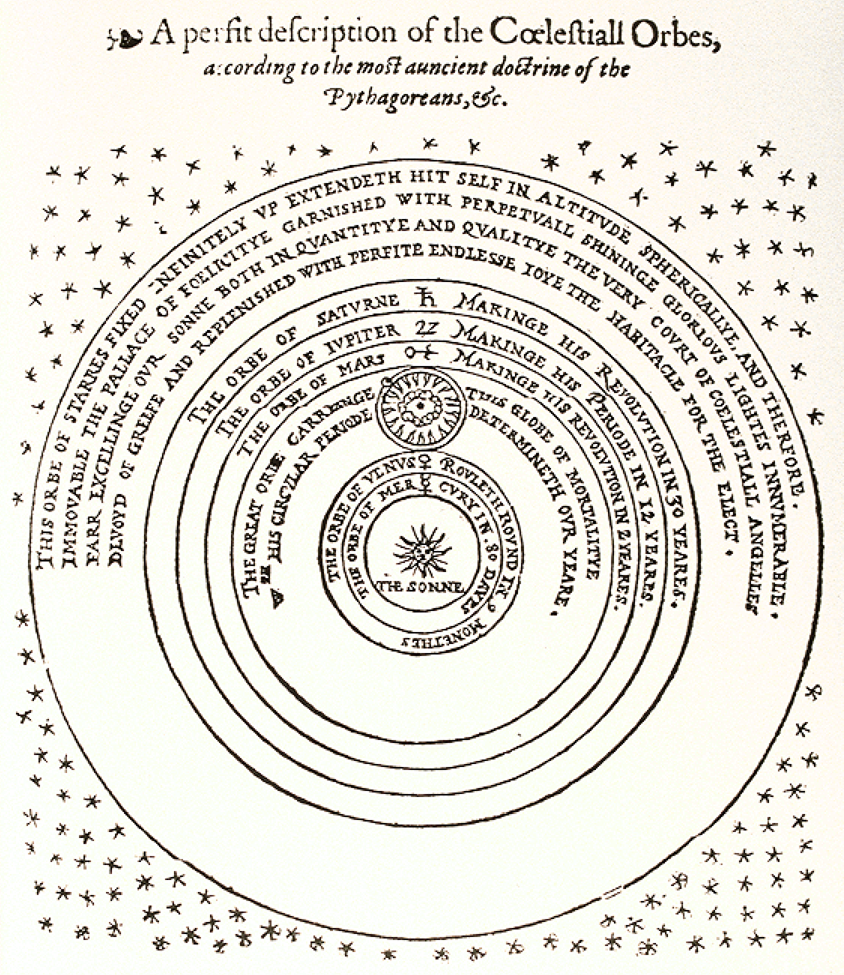
Higgs mass stabilised!

105 new parameters (MSSM)
+48 more free parameters if R_P not conserved

=> SUSY is a good pension plan for experimentalists!

Two views of the world....





A perfit deſcription of the Cœleſtiall Orbes, according to the moſt auncient doctrine of the Pythagoreans, &c.

THIS ORBE OF STARRES FIXED INFINITELY VP EXTENDETH HIT SELF IN ALTITVDE SPHERICALLYE, AND THERFORE IMMOVABLE THE PALLACE OF FOELICITYE GARNISHED WITH PERPETVALL SHININGE GLORIOVS LIGHTES INNVMERABLE, FARR EXCELLINGE OVR SONNE BOTH IN QVANTITYE AND QVALITYE THE VERY COVRT OF COELESTIALL ANGELLES DEVOYD OF GREIFE AND REPLENISHED WITH PERFITE ENDLESSE IOYE THE HABITACLE FOR THE ELECT.

THE ORBE OF SATVRNE ♄ MAKINGE HIS REVOLVTION IN 30 YEARES.

THE ORBE OF IVPITER ♃ MAKINGE HIS PERIODE IN 12 YEARES.

THE ORBE OF MARS ♂ MAKINGE HIS REVOLVTION IN 2 YEARES.

THE GREAT ORBE CARRYINGE THIS GLOBE OF MORTALITYE HIS CIRCULAR PERIODE DETERMINETH OVR YEARE.

THE ORBE OF VENVS ♀ ROVLETH ROVND IN 9 MONETHES.

THE ORBE OF MERCVRY ☿ IN 80 DAYES.

THE SONNE.

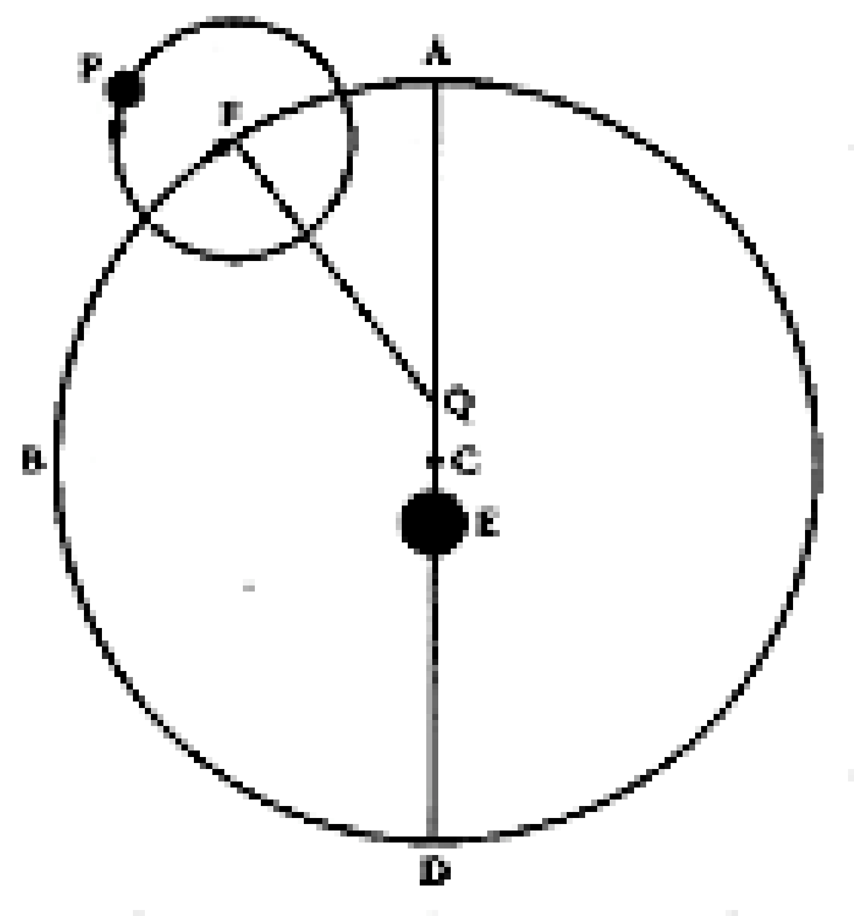
Supersymmetry ....

....hidden perfection

Extra dimensions....

...different scales

Epicycles



From Michael J. Crowe,
Theories of the World from Antiquity
to the Copernican Revolution.

Typical Ptolemaic planetary model

Symmetry is assumed: all orbits are based on circles

But the Earth is not at the centre of the circle (*the eccentric*)

The planet moves on an *epicycle*

The epicycle moves around the *equant*

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

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

Extra dimensions are more of a lottery bet than a pension plan!

Scale of extra dimensions

For 4+n space-time dimensions

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

For $M_{Pl(4+n)} \sim M_W$

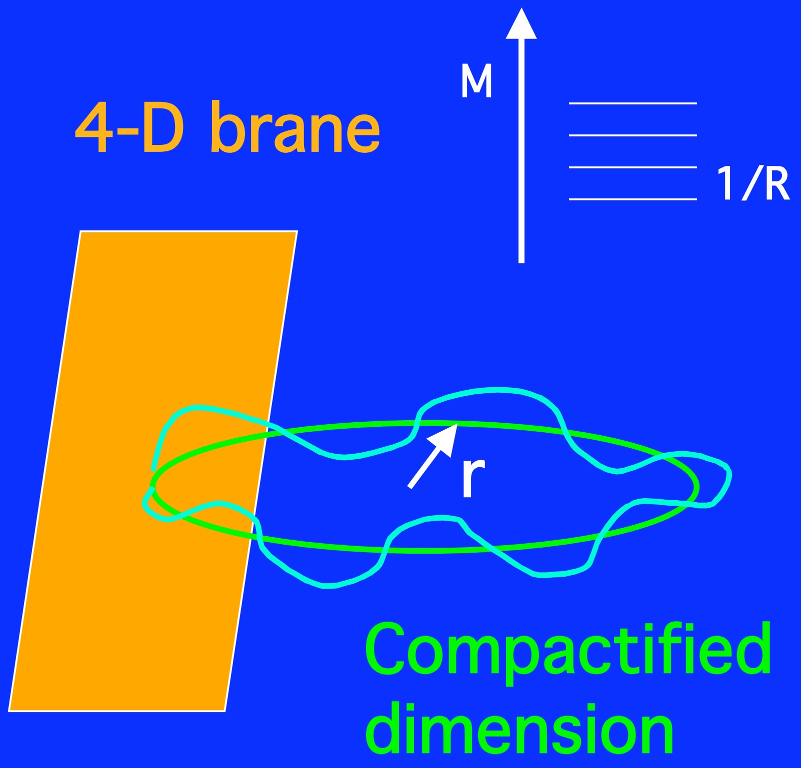
$$\boxed{R \sim 10^{30/n-17}\ cm\ \left(\frac{1TeV}{m_W}\right)^{1+2/n}}$$

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

n=2, R~100 μm-1mm OK (see later)

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

Kaluza Klein modes



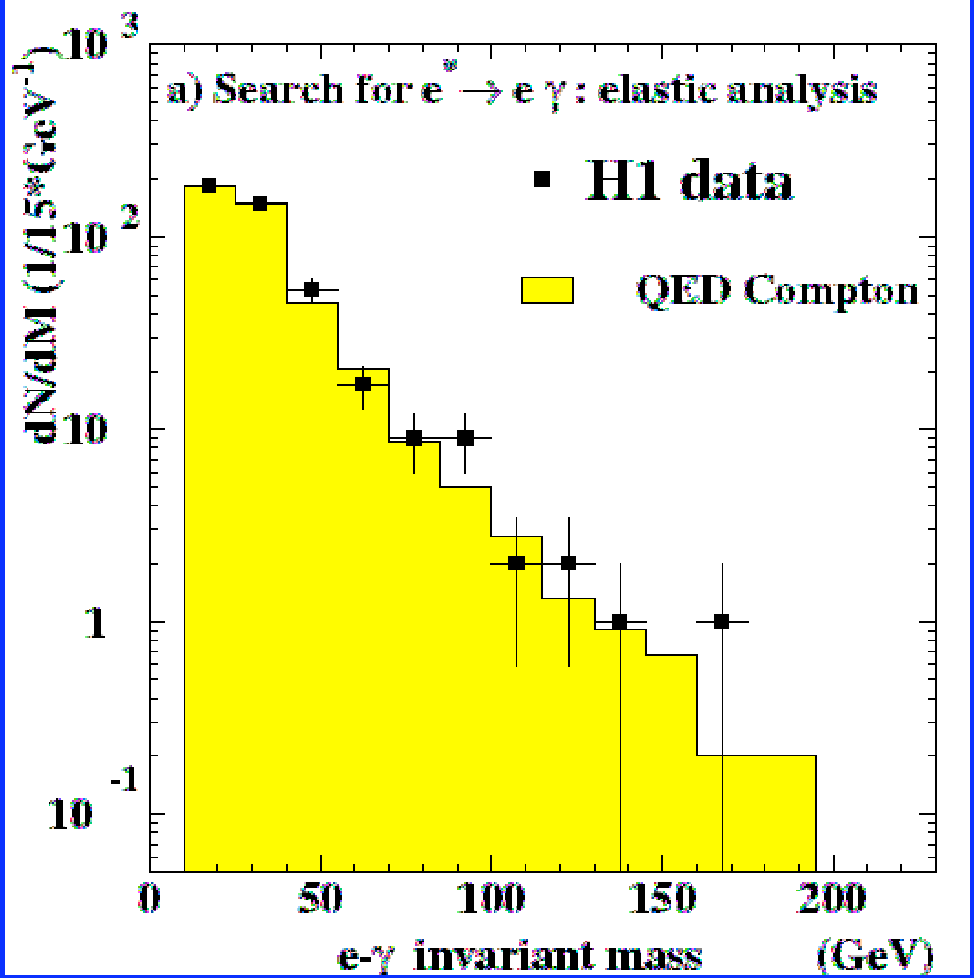
$$p = \hbar/\lambda, \qquad \hbar c = 0.2 GeVfm$$

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

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.

Why are SM fields confined to 3-D space?



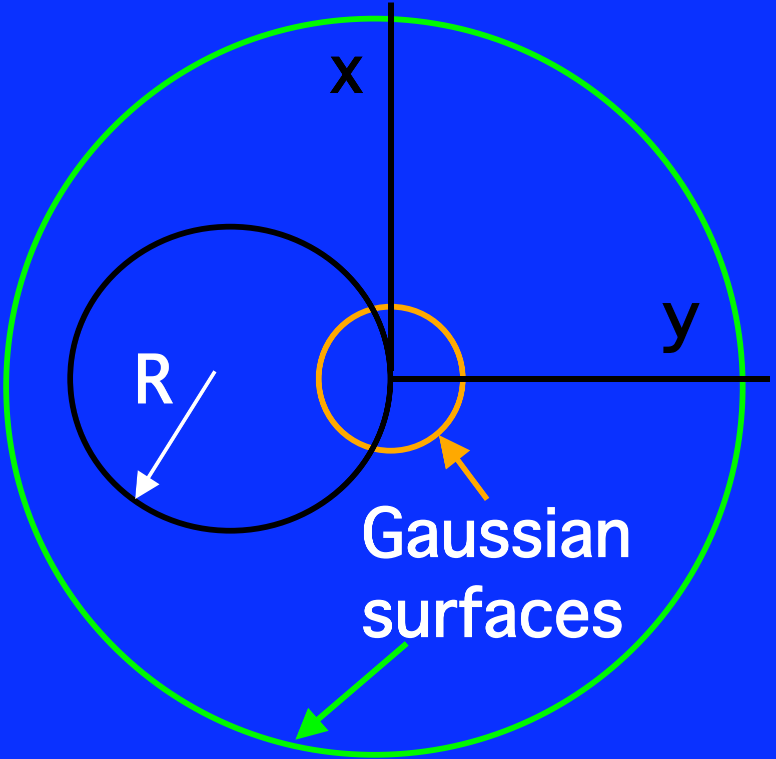
Interactions of SM fields measured to very high precision at scales of 10^{-18} m

If gauge forces acted in bulk, deviations would have been measured

KK modes would exist for SM particles

For large ED, mass splitting would be small.

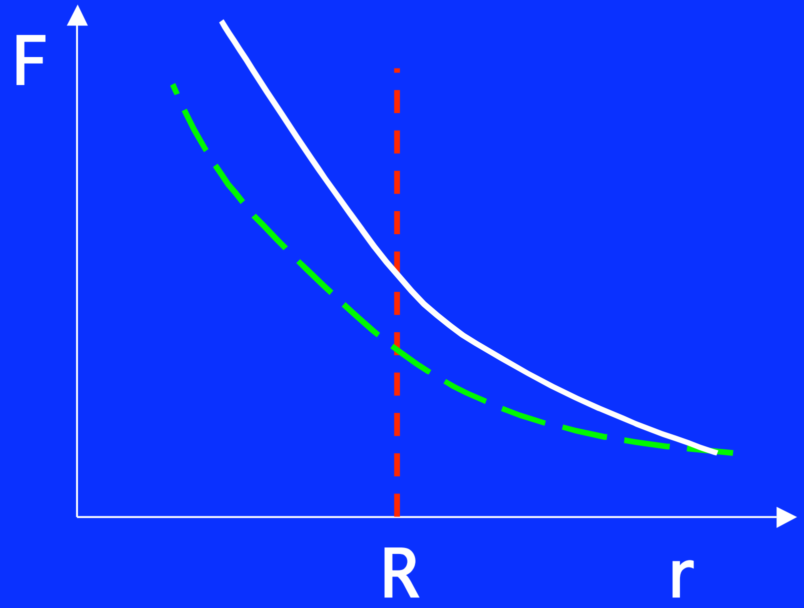
ED signature in Gravity experiments



Gaussian surfaces

r > R Get 3-D result

r < R Get 4-D result



Measuring Gravity in the lab

Torsion balance

Henry Cavendish 1778 (apparatus by Michell)

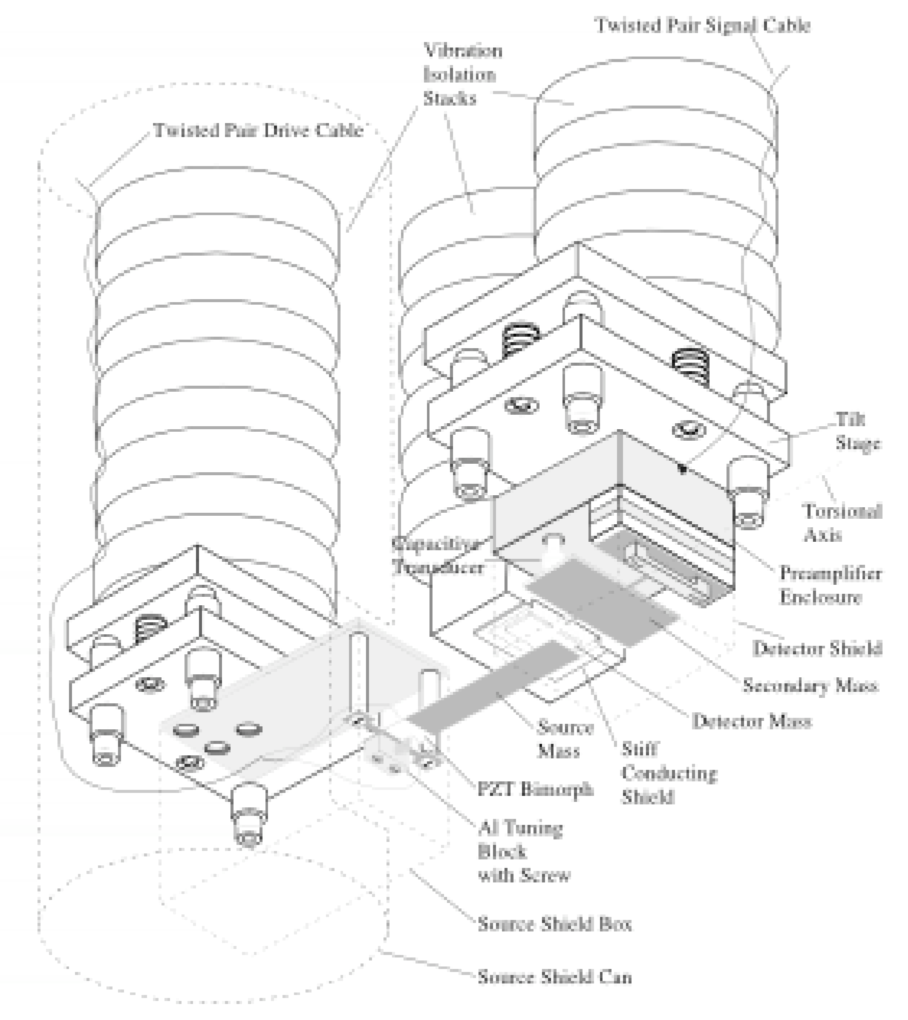
Measured mean density of Earth (no definition of the unit of force).

Sir Charles Boys inferred $G=6.664\times10^{-11}\text{Nm}^2/\text{kg}^2$ from Cavendish's data a century later.

Modern value

$G = (6.6726 \pm 0.0001)\times10^{-11}\ \text{Nm}^2/\text{kg}^2$.

Measuring Gravity in the lab



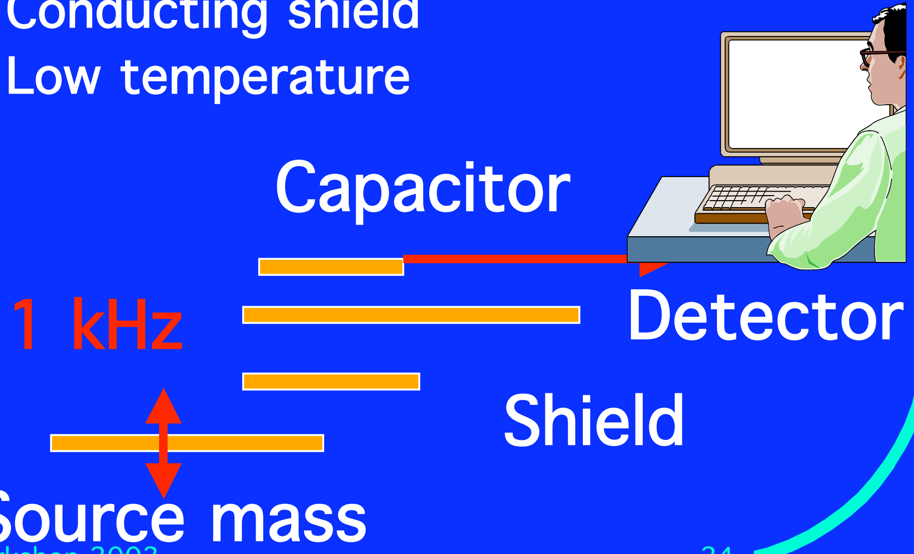
Recent experiment of Long et al hep-ph/0009062

Source mass oscillates at 1kHz

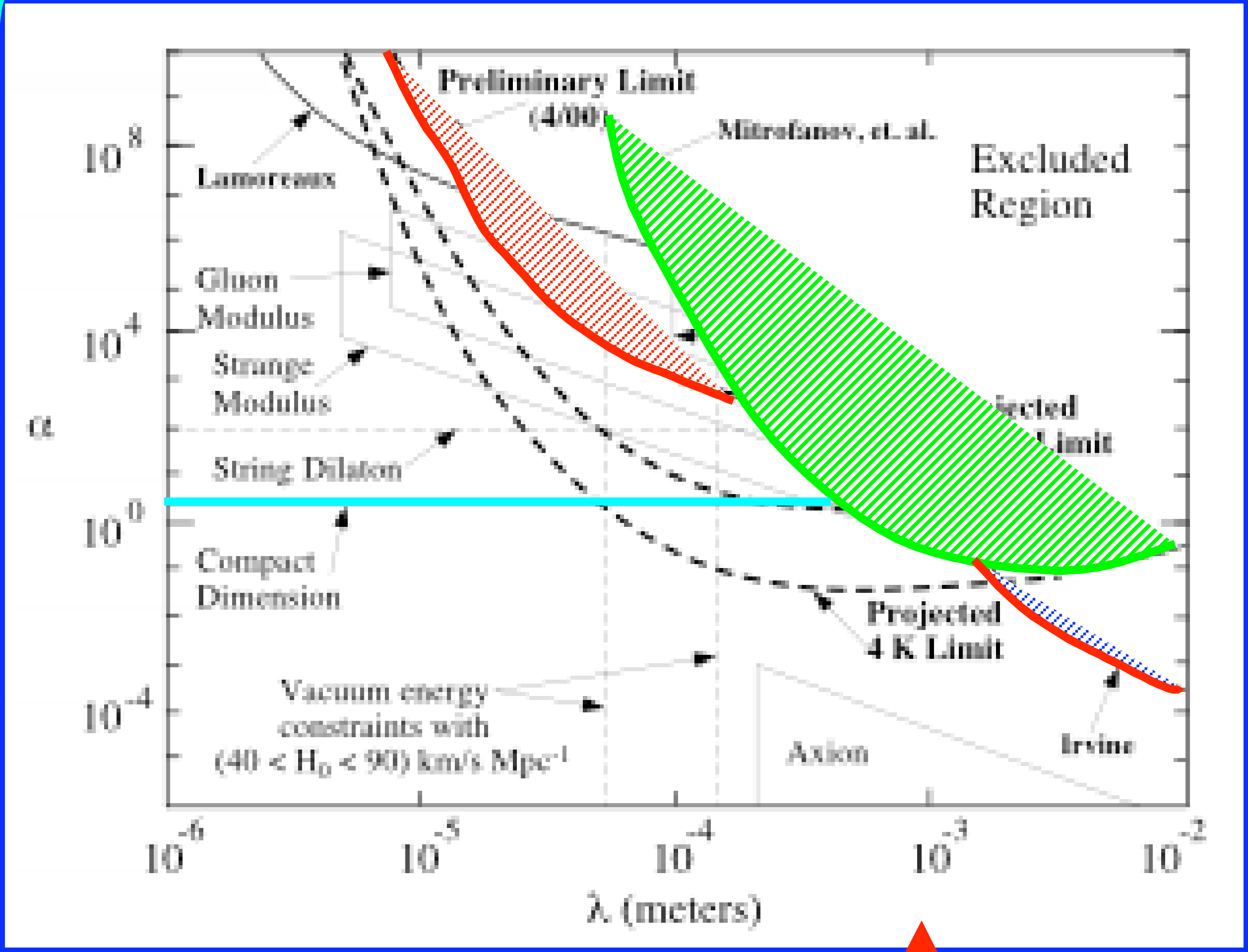
Signal is oscillation of test mass

Must isolate masses from acoustic vibrations, EM coupling

- Run in vacuum
- Isolation stacks
- Conducting shield
- Low temperature



Limits on deviations from Newtonian gravity



1mm

hep-ph/0009062

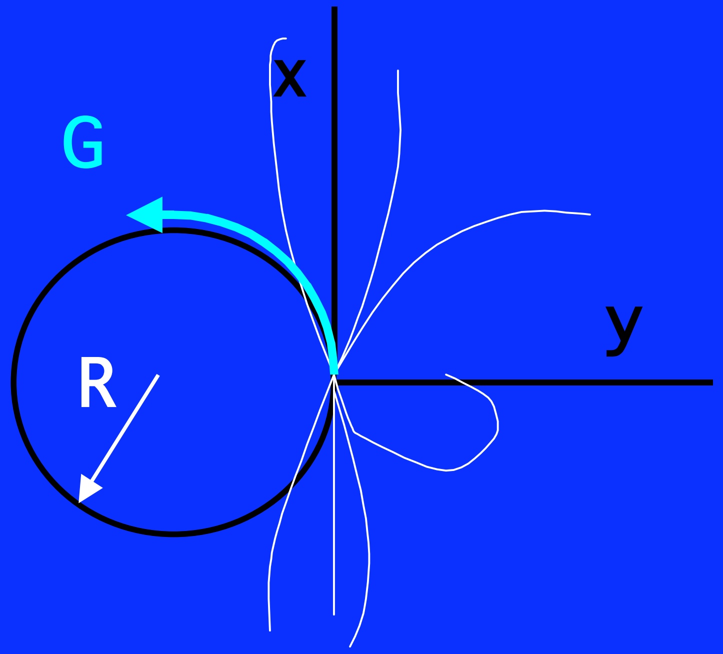
Planetary orbits set very strong limits on gravity at large distances....

...but forces many orders of magnitude stronger than gravity are not excluded at micron scales.

Parameterized as a Yukawa interaction of strength □ relative to gravity and range □

“moduli” = scalars in string theories

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

Searching for graviton resonances at the LHC

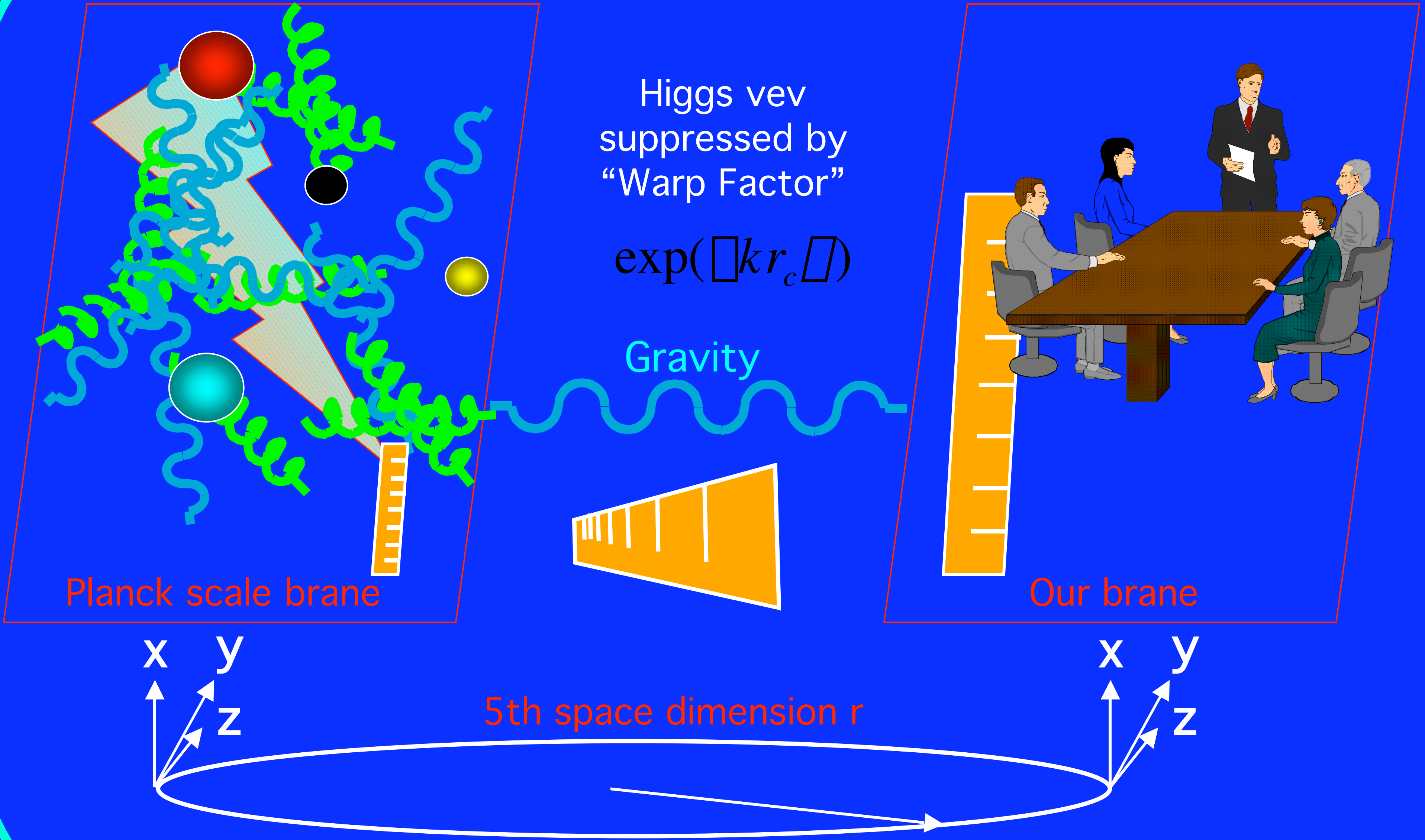
M.A.Parker

Cambridge

- Extra dimension models can contain massive graviton resonances
- In some models, these resonances are well spaced in mass
- With universal couplings, the resonance could be detected in many channels (jet-jet, lepton-lepton, ZZ, WW etc)
- In order to claim a discovery, need to detect resonance and measure spin
- G->e^+e^- gives good signal to noise, small background, and good experimental mass and angular resolution
- Other channels can be used to check universality of couplings.
- Model independent analysis: R-S type model used as test case.

Work performed with B.C.Allanach, K.Odagiri and B.R.Webber in the Cambridge SUSY working group. See JHEP 09 (2000) 019

Warped 5-d spacetime

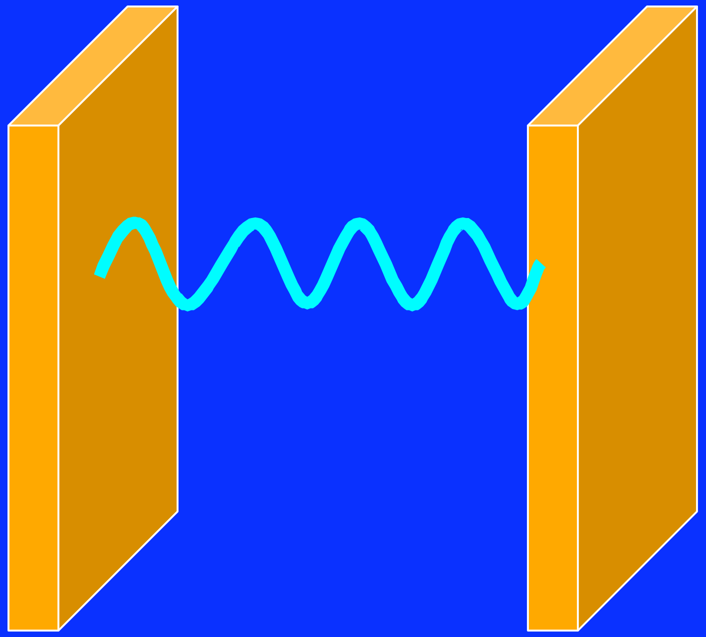


Higgs vev
suppressed by
“Warp Factor”

$$\exp(-k r_c \pi)$$

$$r_c \approx 10^{-32} m$$

Radions and higgs mixing



Radions would mix with Higgs, and so can be detected (in principle)

In the warped ED scenario, two branes are placed at fixed points, □ apart, in the bulk. The brane separation is then a property of the space-time geometry. Can also allow branes to move around in bulk.

One possibility is to use a potential between the branes to keep them separated. Such a scalar potential has a field carrier - the radion.

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 $\boxed{k\,r_c \approx 10}$: no fine tuning

Gravitons have KK excitations with scale

$$\boxed{\Lambda_\pi = \overline{M}_{Pl}\exp(-kr_c\pi)}$$

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

First excitation is at $\boxed{m_1 = kx_1\exp(-kr_c\pi) = 3.83\frac{k}{\overline{M}_{Pl}}\Lambda_\pi}$

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

Analysis is model independent: this model used for illustration

Implementation in Herwig

Model implemented in Herwig to calculate general spin-2 resonance cross sections and decays.

Can handle fermion and boson final states, including the effect of finite W and Z masses.

Interfaced to the ATLAS simulation (ATLFAST) to use realistic model of LHC events and detector resolutions.

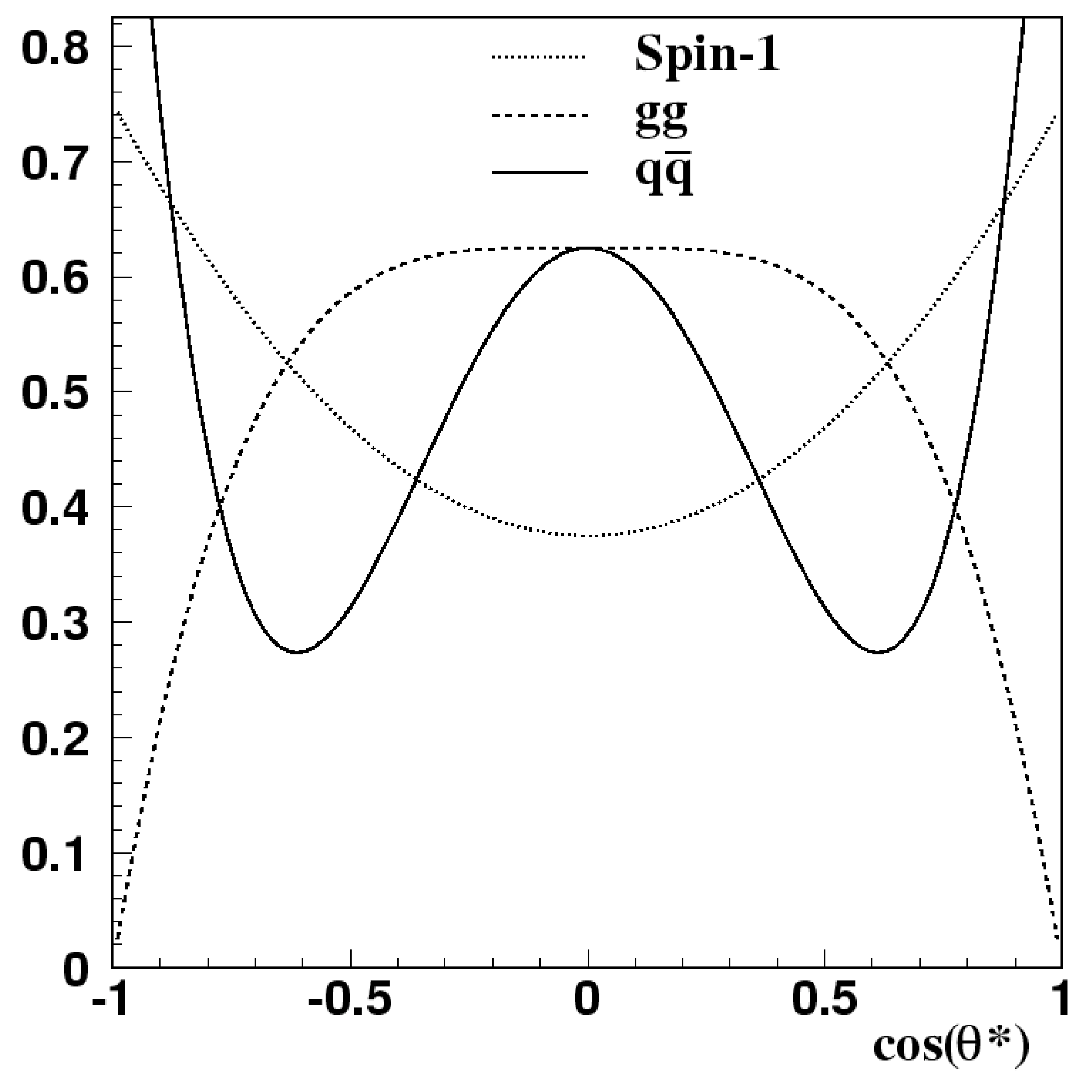
Coupling $= \dfrac{1}{\Lambda_\pi}$

Worst case when $\dfrac{k}{\overline{M}_{Pl}} = 0.01$ giving smallest couplings.

For m_1=500 GeV, Λ_π=13 TeV

Other choices give larger cross-sections and widths

Angular distributions of e^+e^- in graviton frame



Angular distributions are very different depending on the spin of the resonance and the production mechanism.

=>get information on the spin and couplings of the resonance

ATLAS Detector Effects

Best channel G->e^+e^- Good energy and angular resolution

- **Jets: good rate, poor energy/angle resolution, large background**
- **Muons: worse mass resolution at high mass**
- **Z/W: rate and reconstruction problems.**

Main background Drell-Yan

Acceptance for leptons: $|\eta|<2.5$

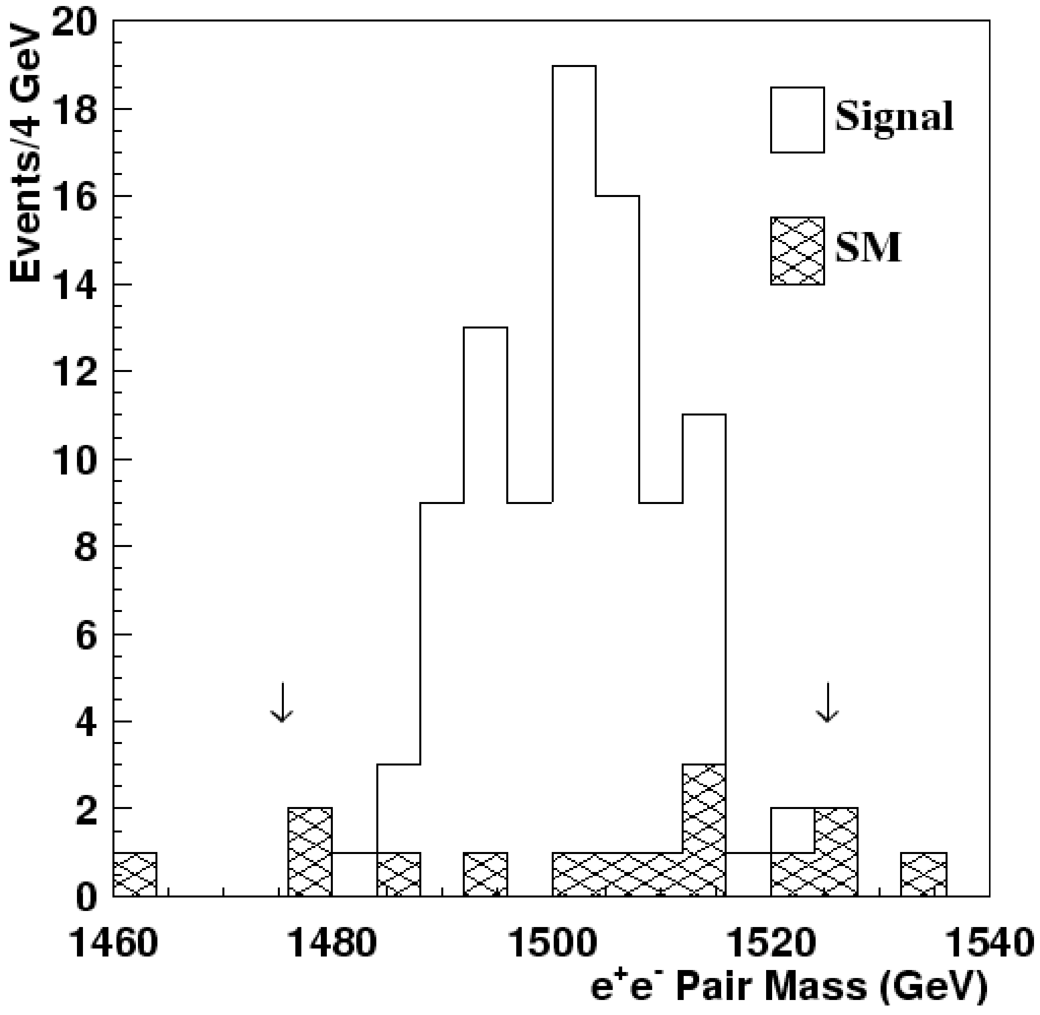
Tracking and identification efficiency included

Energy resolution $$\frac{\Delta E}{E} = \frac{12\%}{\sqrt{E}} \oplus \frac{24.5\%}{E_T} \oplus 0.7\%$$

Mass resolution $$\frac{\sigma_m}{m}(500\,\mathrm{GeV}) = 0.8\%$$

Graviton Resonance

$G \rightarrow e^+e^-$



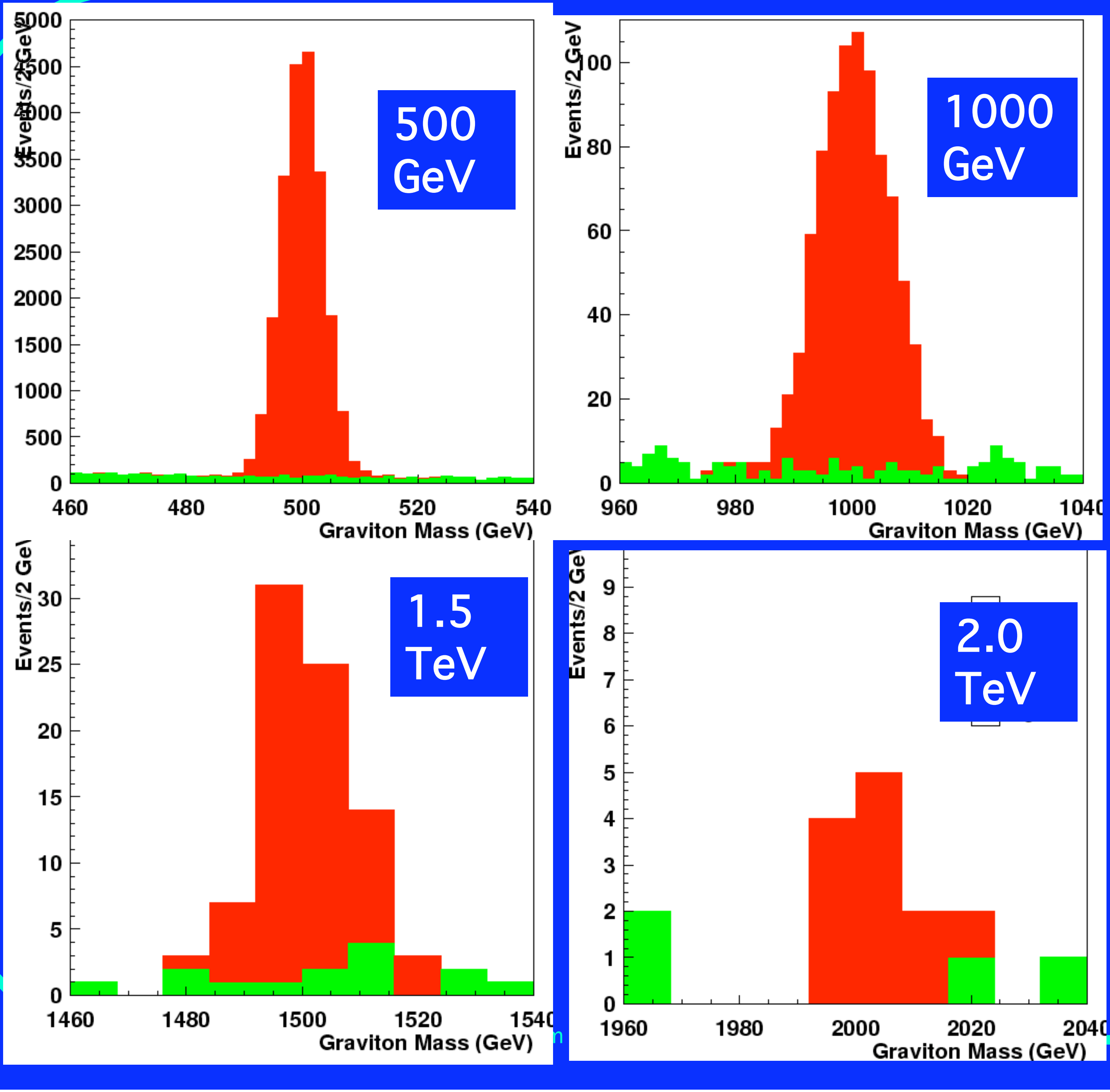
Graviton resonance is very prominent above small SM background, for 100fb^{-1} of integrated luminosity

Plot shows signal for a 1.5 TeV resonance, in the test model.

The Drell-Yan background can be measured and subtracted from the sidebands.

Detector acceptance and efficiency included.

Signal and background for increasing graviton mass



Events expected from Graviton resonance

Signal

Background

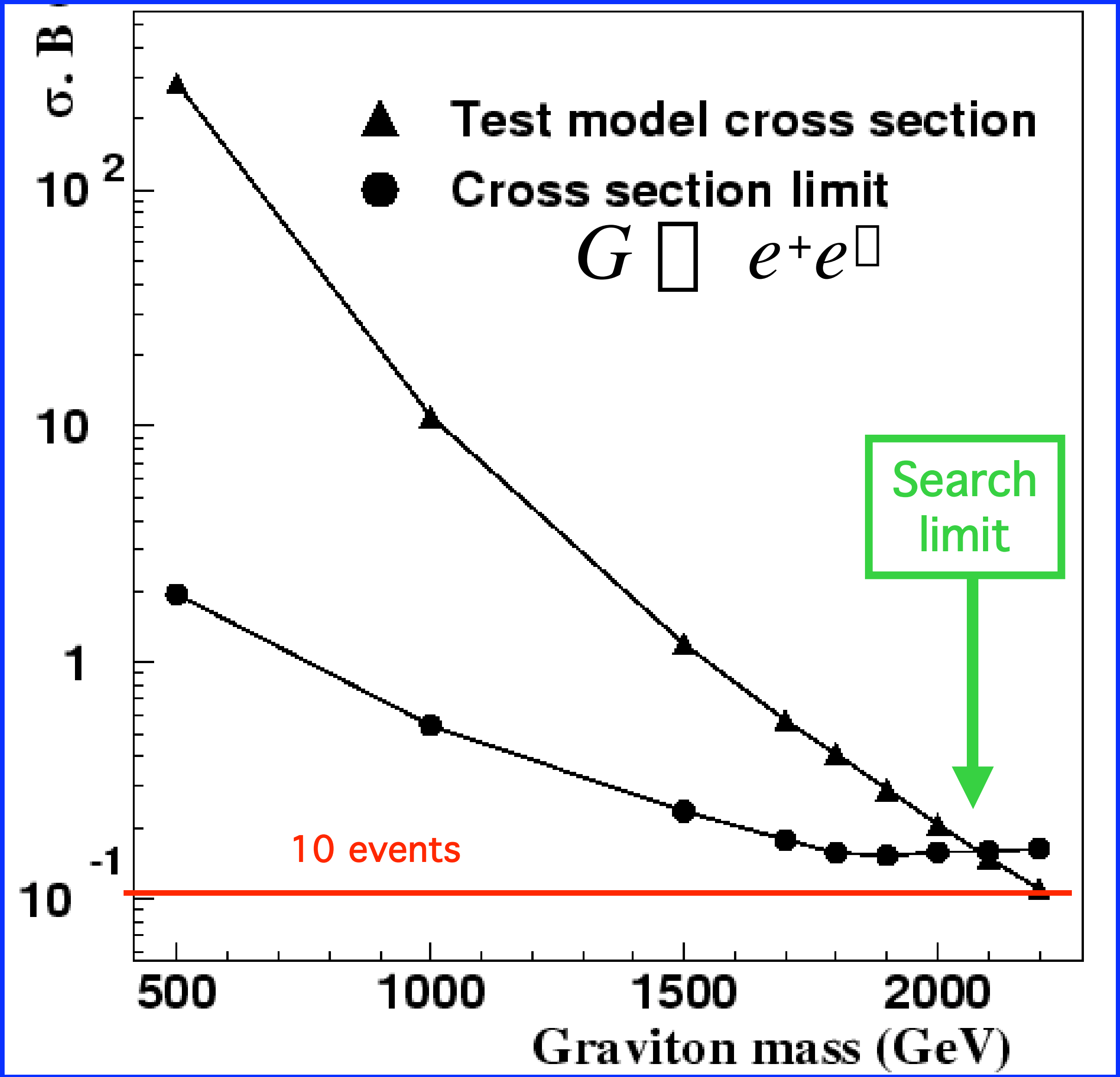
100fb^{-1}

M_G (GeV)	Mass window (GeV)	N_S	N_B	N_S^{MIN}=Max ($5\sqrt{N_B}$,10)	(□.B)^{MIN} fb
500	± 10.46	20750	816	143	1.941
1000	± 18.21	814	65	40	0.542
1500	± 24.37	84	11	16.5	0.235
1700	± 26.53	39	5.8	12.0	0.178
1800	± 27.42	27	4.3	10.4	0.156
1900	± 28.29	19	3.2	10.0	0.152
2000	± 28.76	13	2.3	10.0	0.157
2100	± 30.55	9.4	1.8	10.0	0.159
2200	± 31.46	6.8	1.4	10.0	0.162

Limit

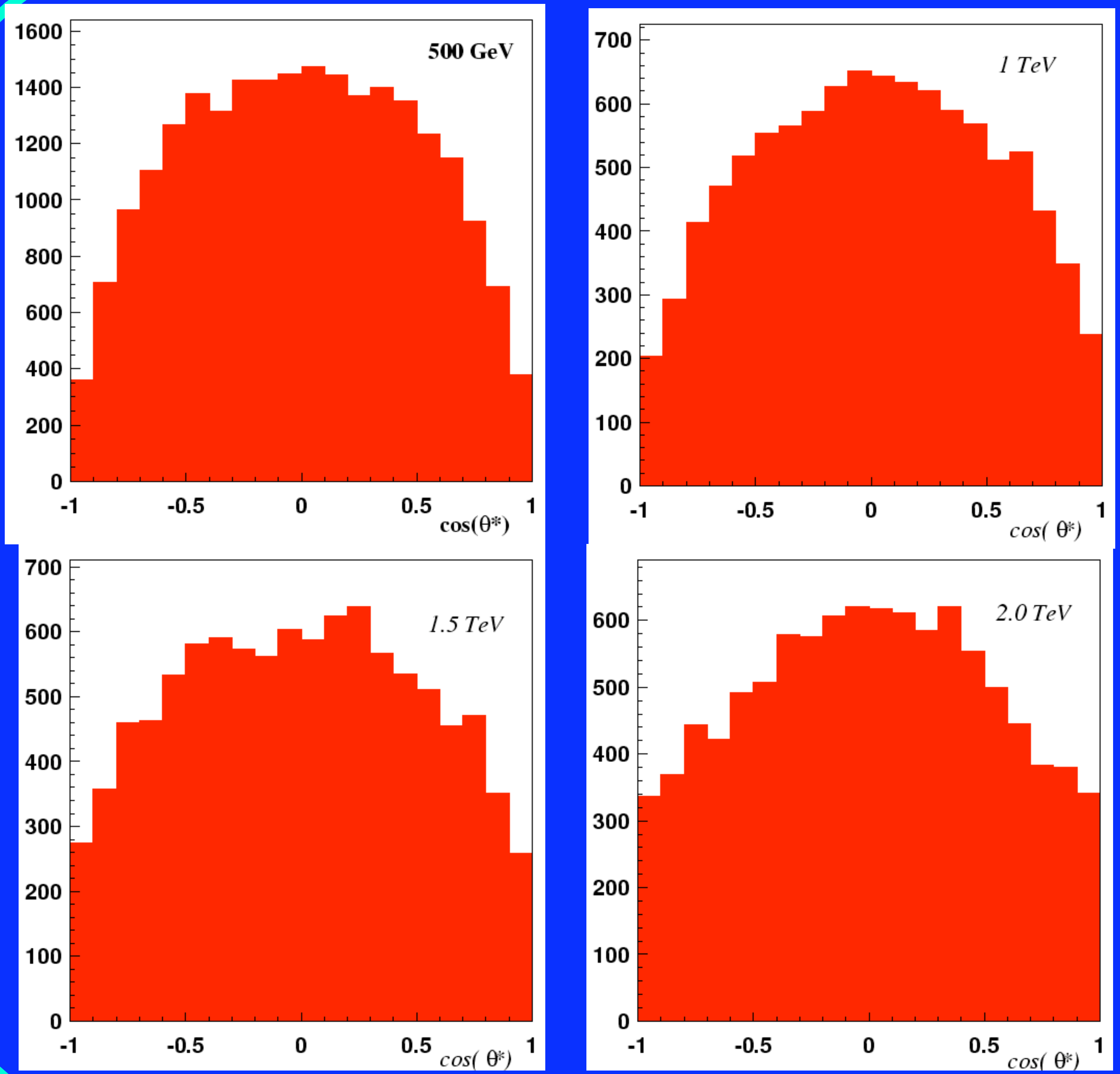
Mass window is ±3x the mass resolution

Production Cross Section



10 events produced for $100 fb^{-1}$ at $m_G = 2.2$ TeV.

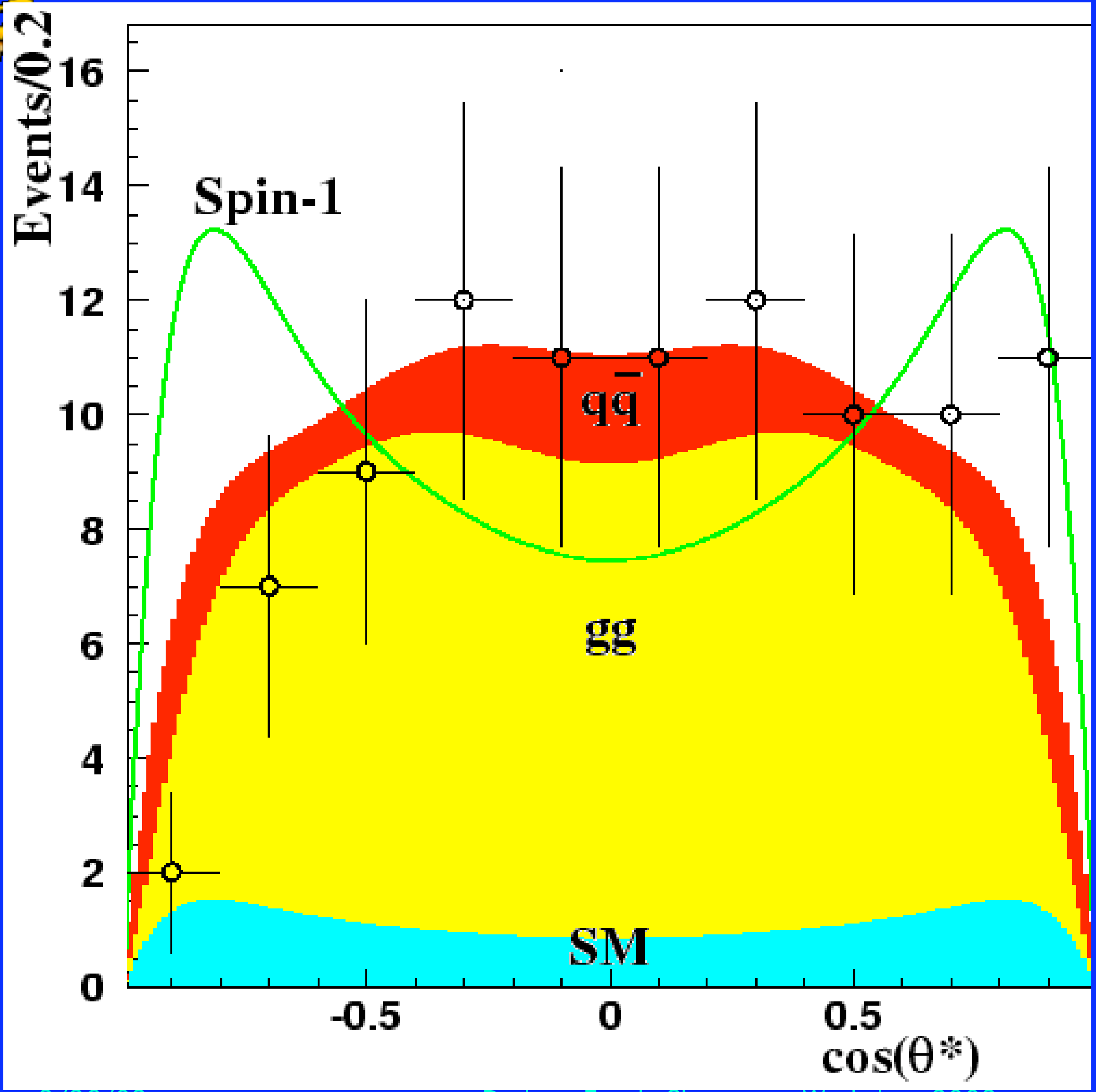
With detector acceptance and efficiency, search limit is at 2080 GeV, for a signal of 10 events and $S/\sqrt{B} > 5$



Angular distribution changes with graviton mass

Production more from qq because of PDFs as graviton mass rises

Angular distribution observed in ATLAS



G 󠀠→ 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 θ*

Determination of the spin of the resonance

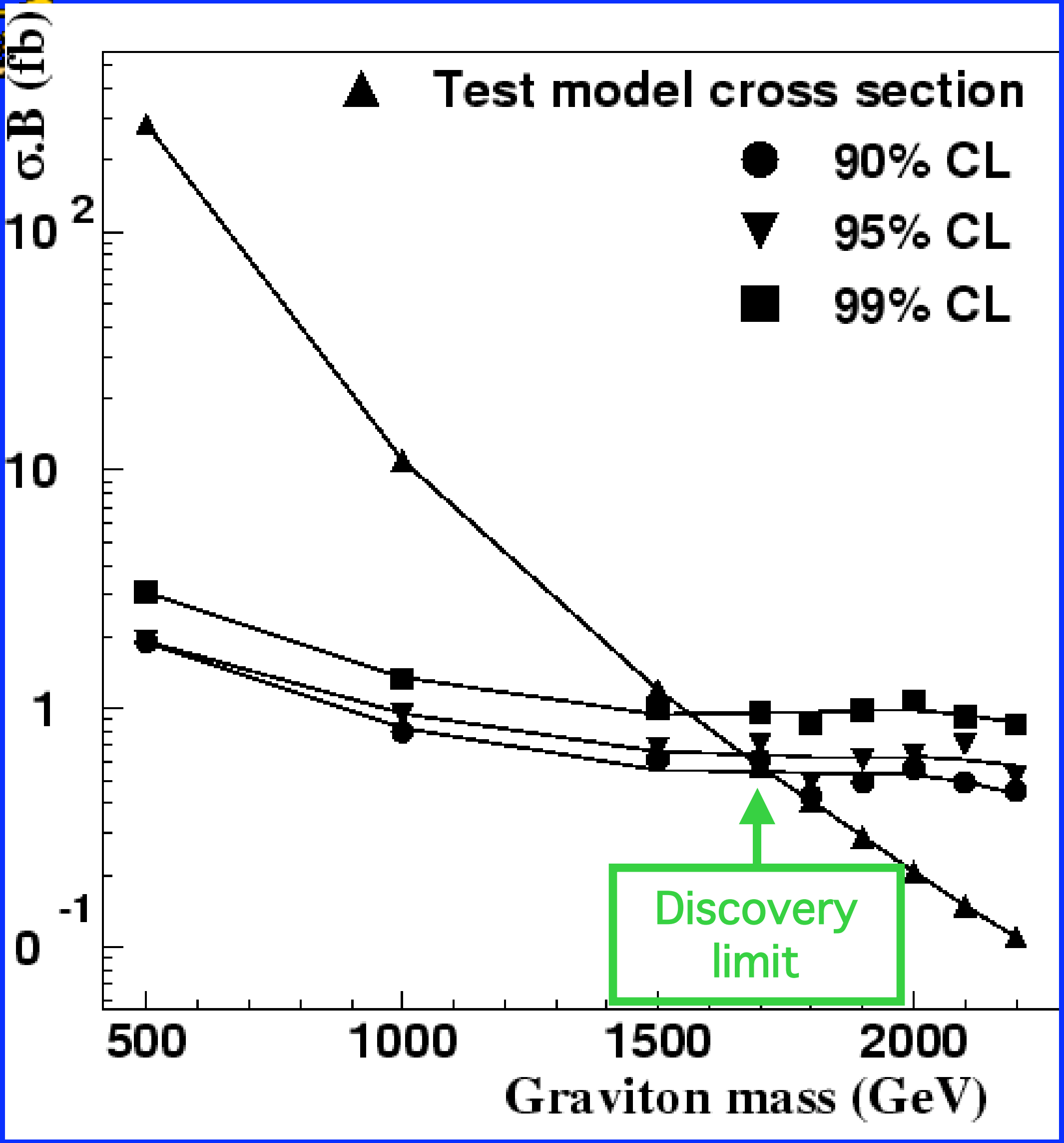
With data, the spin can be determined from a fit to the angular distribution, including background and a mix of qq and gg production mechanisms.

Establish how much data is needed for such a fit to give a significant determination of the spin:

One ATLAS run

1. Generate N_{DY} background events (with statistical fluctuations)
2. Add N_S signal events
3. Take likelihood ratio for a spin-1 prediction and a spin-2 prediction from the test model
4. Increase N_S until the 90% confidence level is reached.
5. Repeat 1-4 many times, to get the average N_S^{MIN} needed for spin-2 to be favoured over spin-1 at 90% confidence
6. Repeat 1-5 for 95 and 99% confidence levels

Angular distribution observed in ATLAS



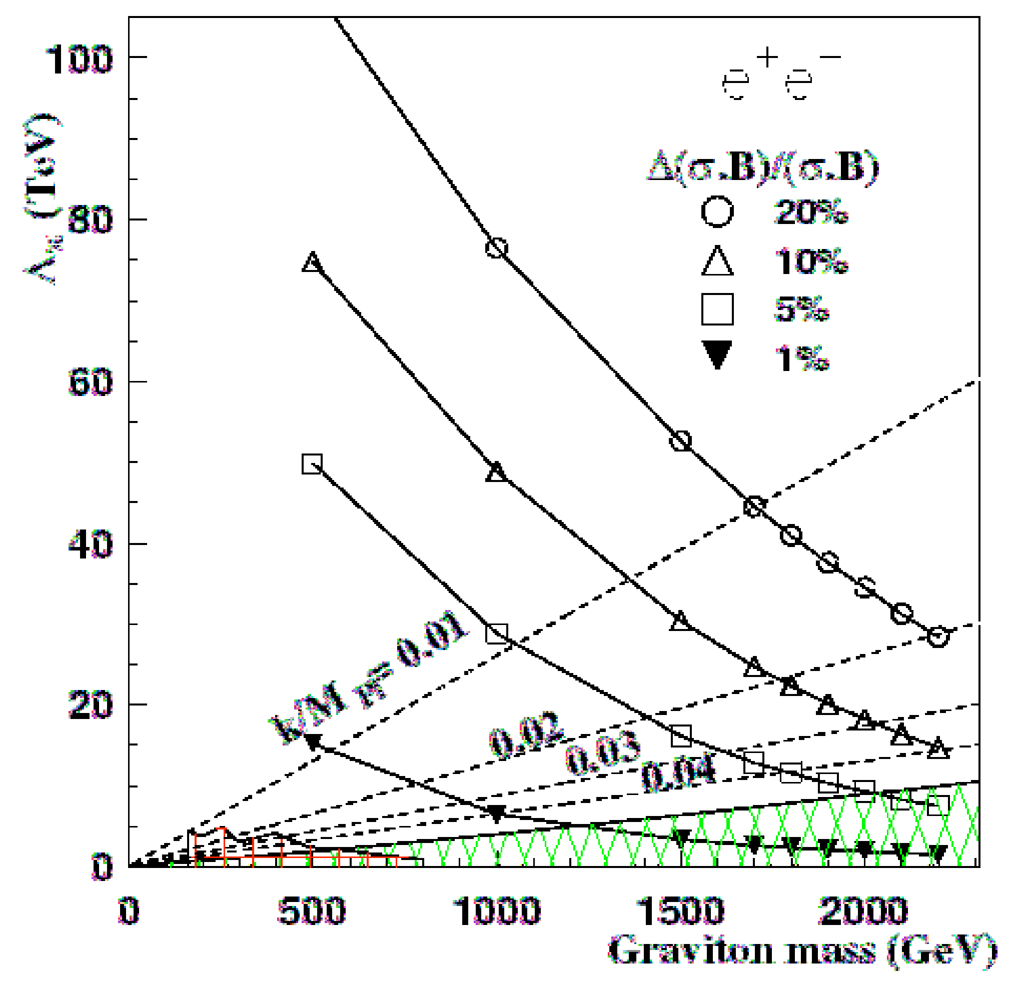
$G \to e^+e^-$

Model independent minimum cross sections needed to distinguish spin-2 from spin-1 at 90,95 and 99% confidence.

Assumes 100fb^{-1} of integrated luminosity

For test model case, can establish spin-2 nature of resonance at 90% confidence up to 1720 GeV resonance mass

Graviton discovery contours



Confidence limits in plane of $\square_{\square}$ vs graviton mass

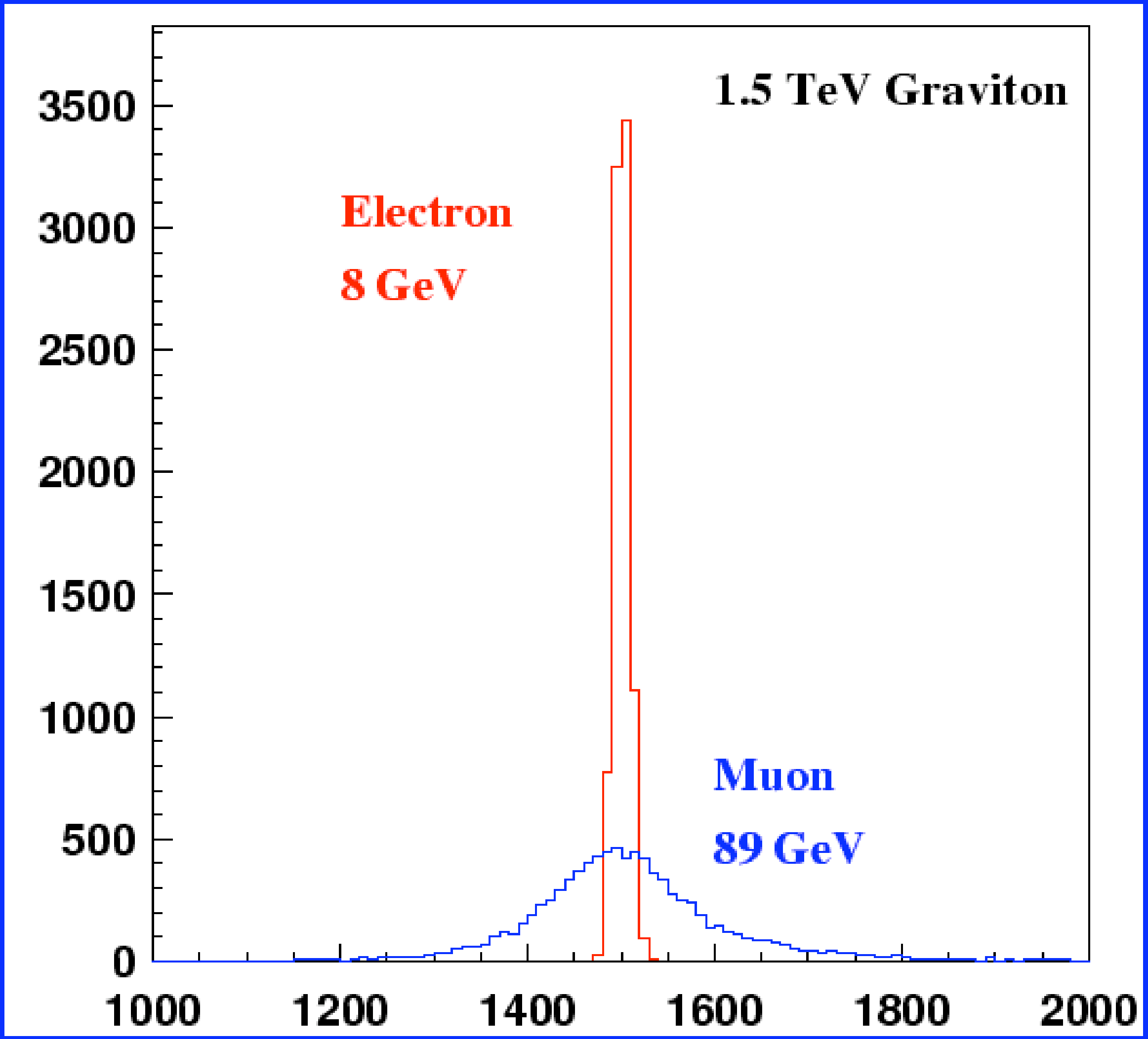
Coupling = 1/ $\square_{\square}$

Test model has k/M_{Pl}=0.01, giving small coupling.

For large k/M_{Pl} coupling is large enough for width to be measured.

(Analysis assumes width<<resolution)

Muon analysis

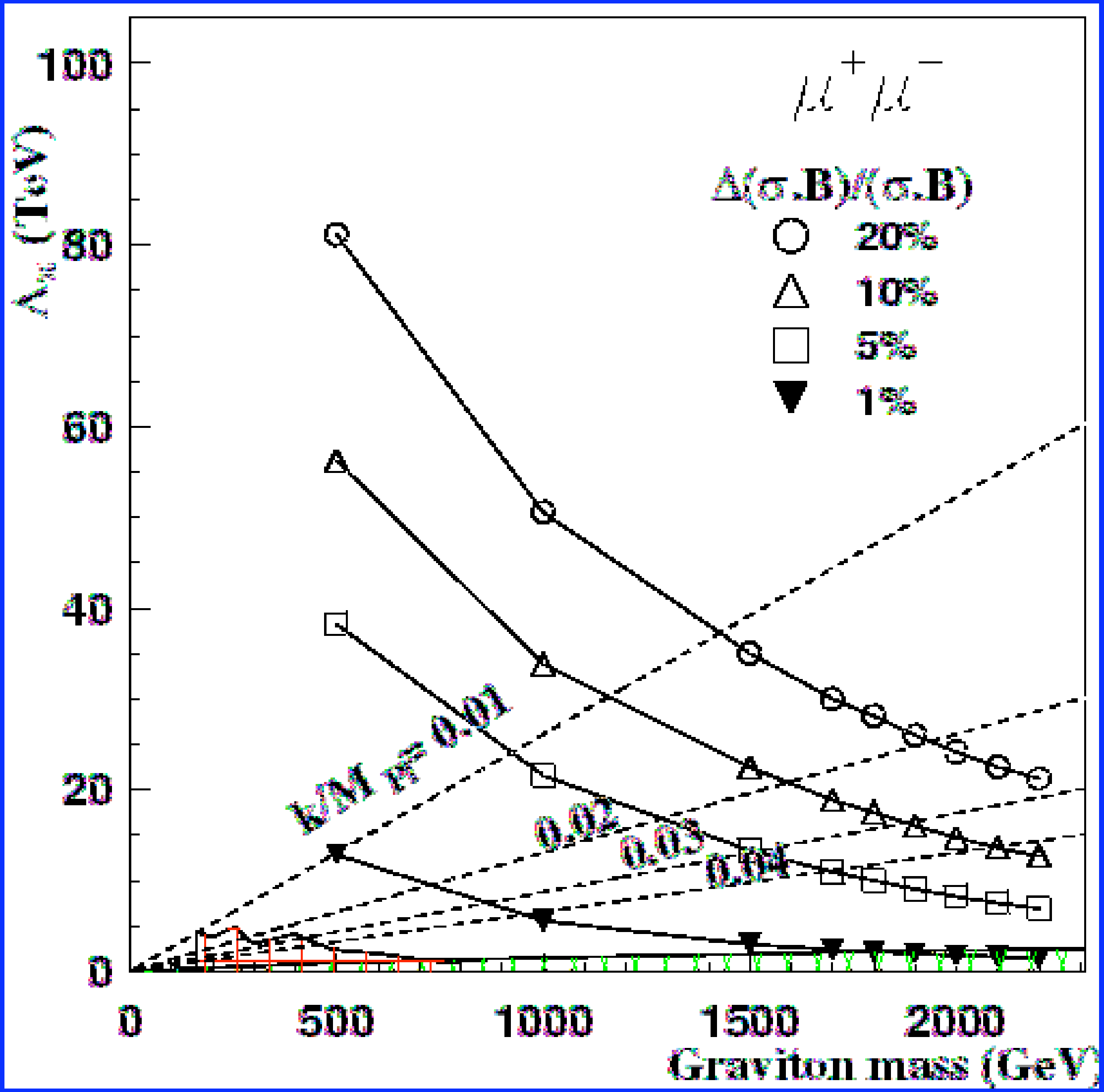


Muon mass resolution much worse than electron at high mass □

Discovery reach in muon channel for M_G<1700 GeV

Muons may be useful to establish universality of graviton coupling

Measurement of the graviton coupling to $\square^{+}\square^{-}$



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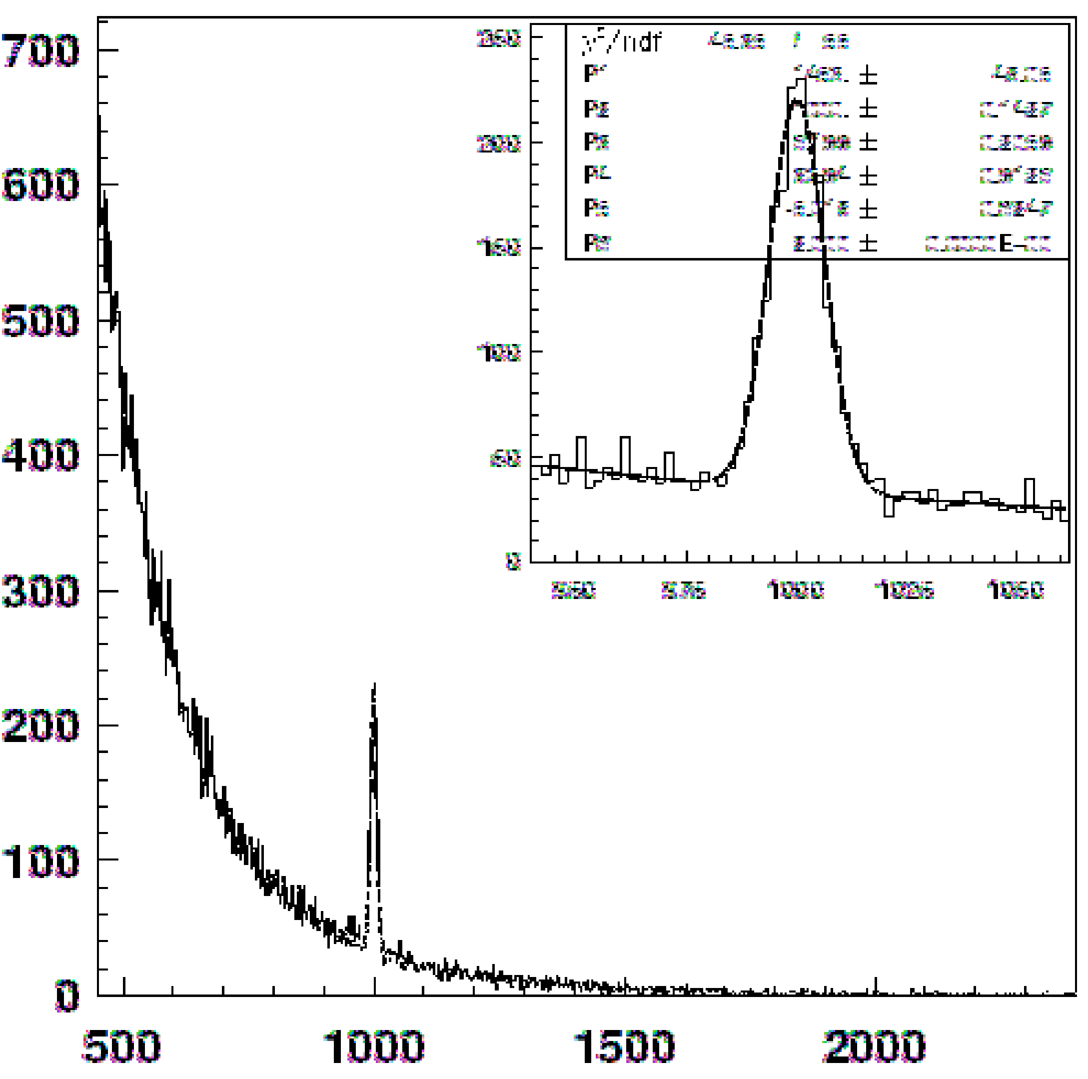
Photon analysis

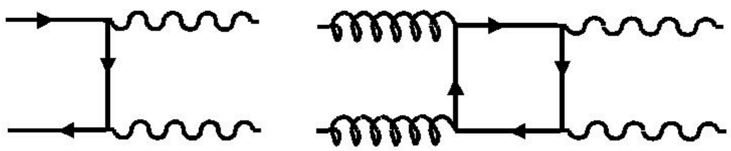


Graviton mass (GeV)

Photon pair mass resolution as good as electrons

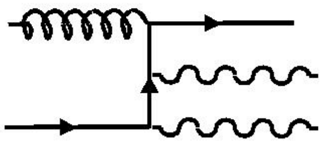
But background uncertain. For standard model (p_t^{min}=150 GeV) □$_{\mathrm{HERWIG}}$=0.36 pb

Included:



Not included:

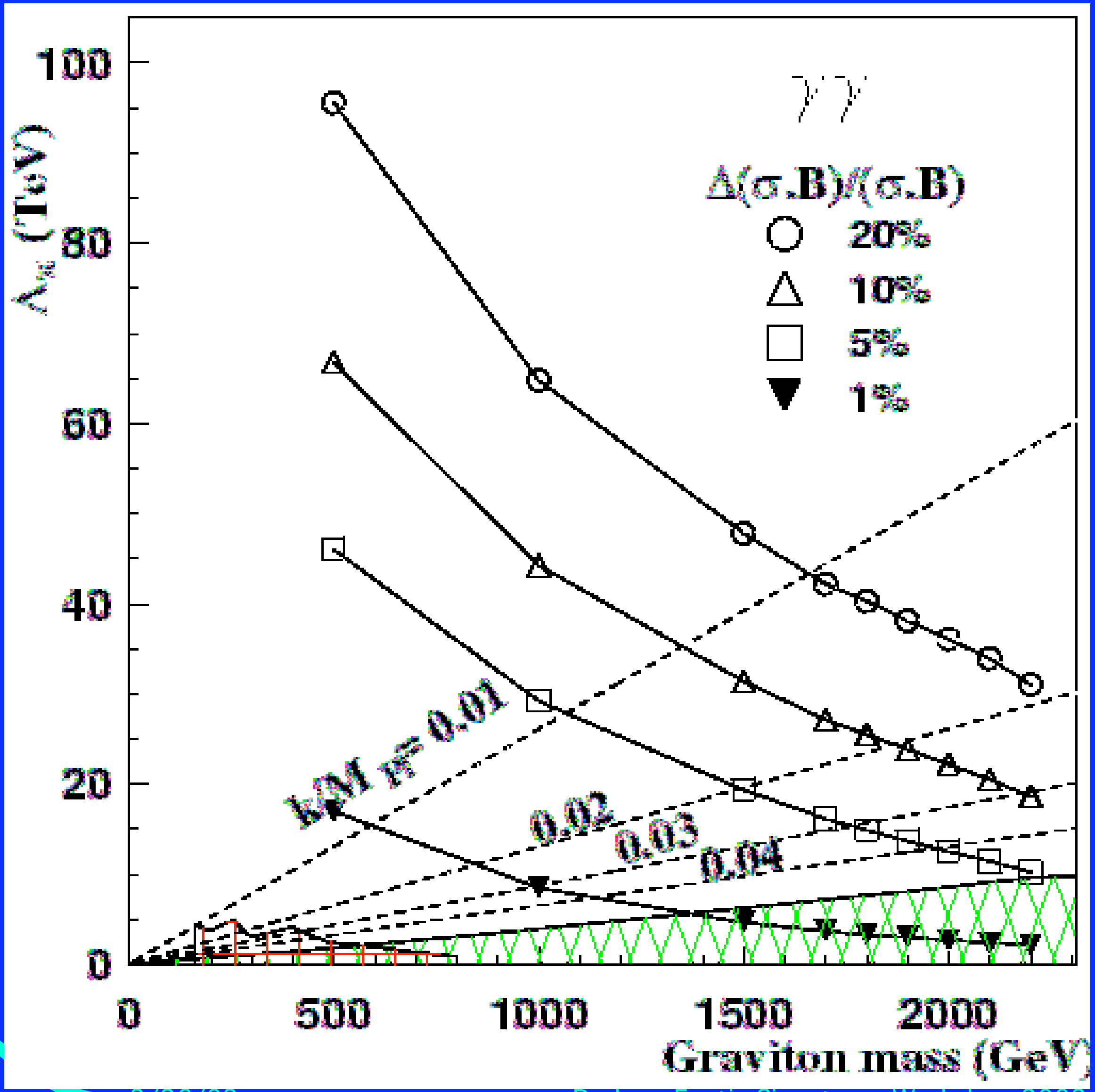
for example



FNAL data indicates □$_{\mathrm{HERWIG}}$ is 5x too small □ use 1.8 pb

Do not trust cos□ distribution for background.

Measurement of the graviton coupling to □□



G □ □□

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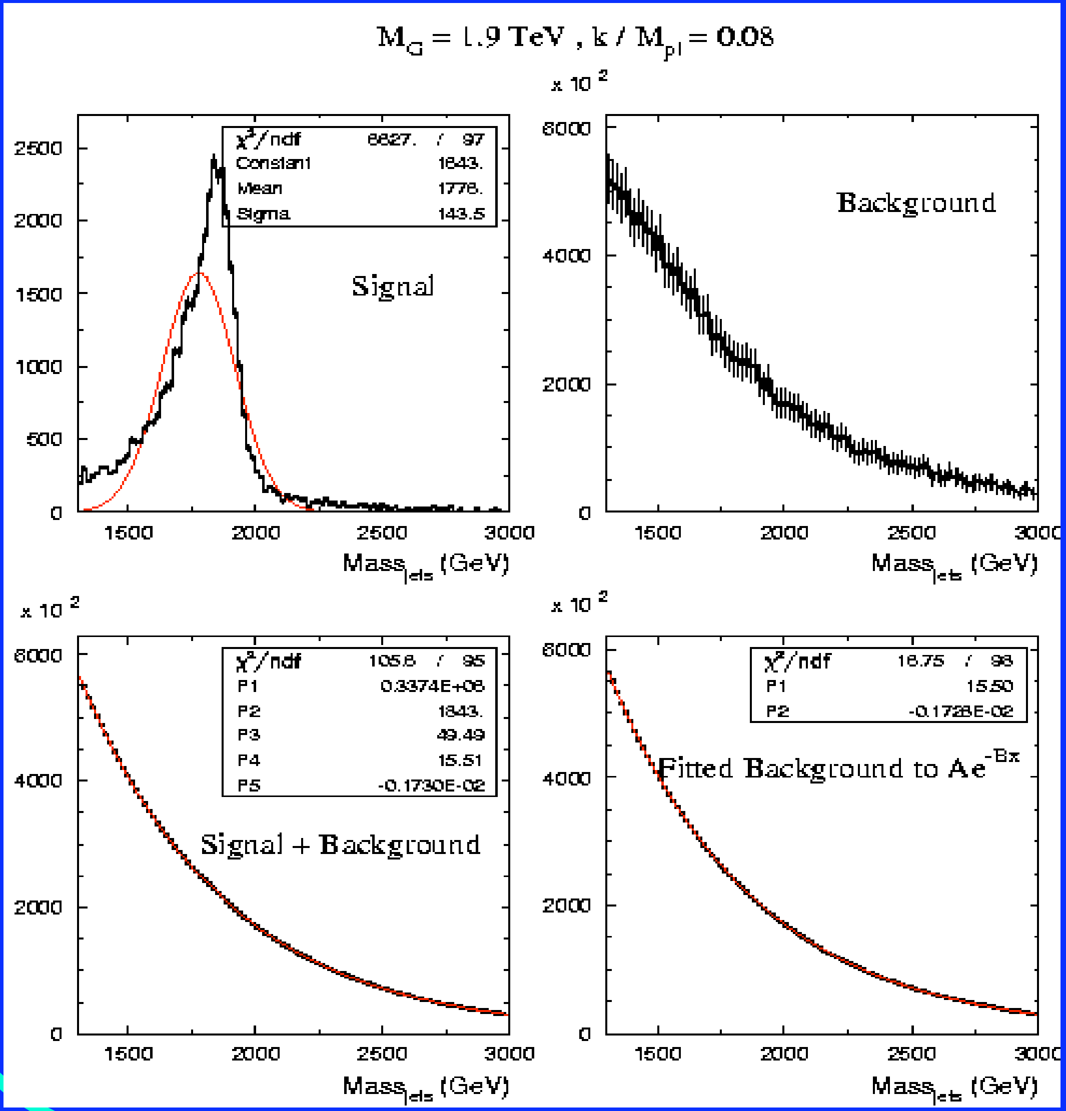
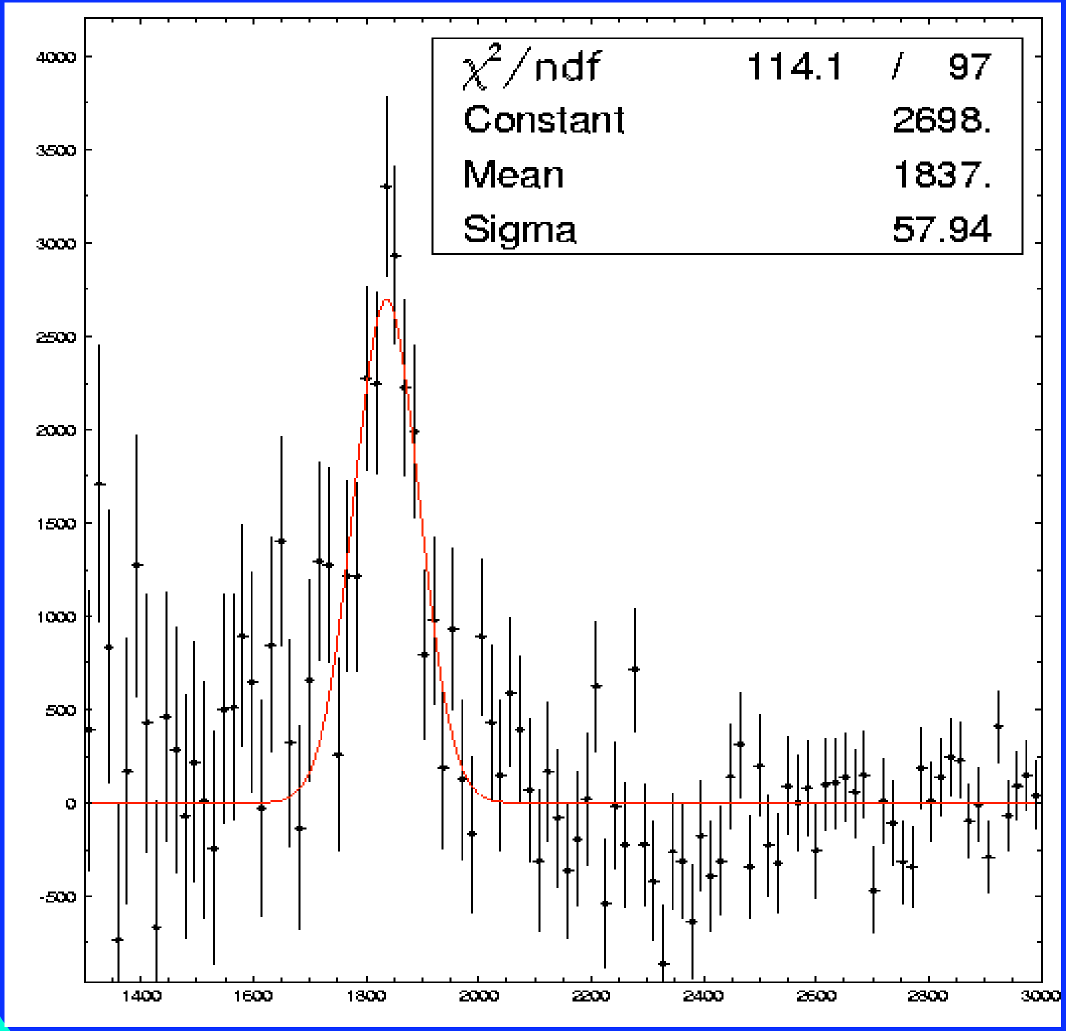
Graviton to jet-jet backgrounds



$k/M_{Pl} = 0.08$

(64x higher cross-section)

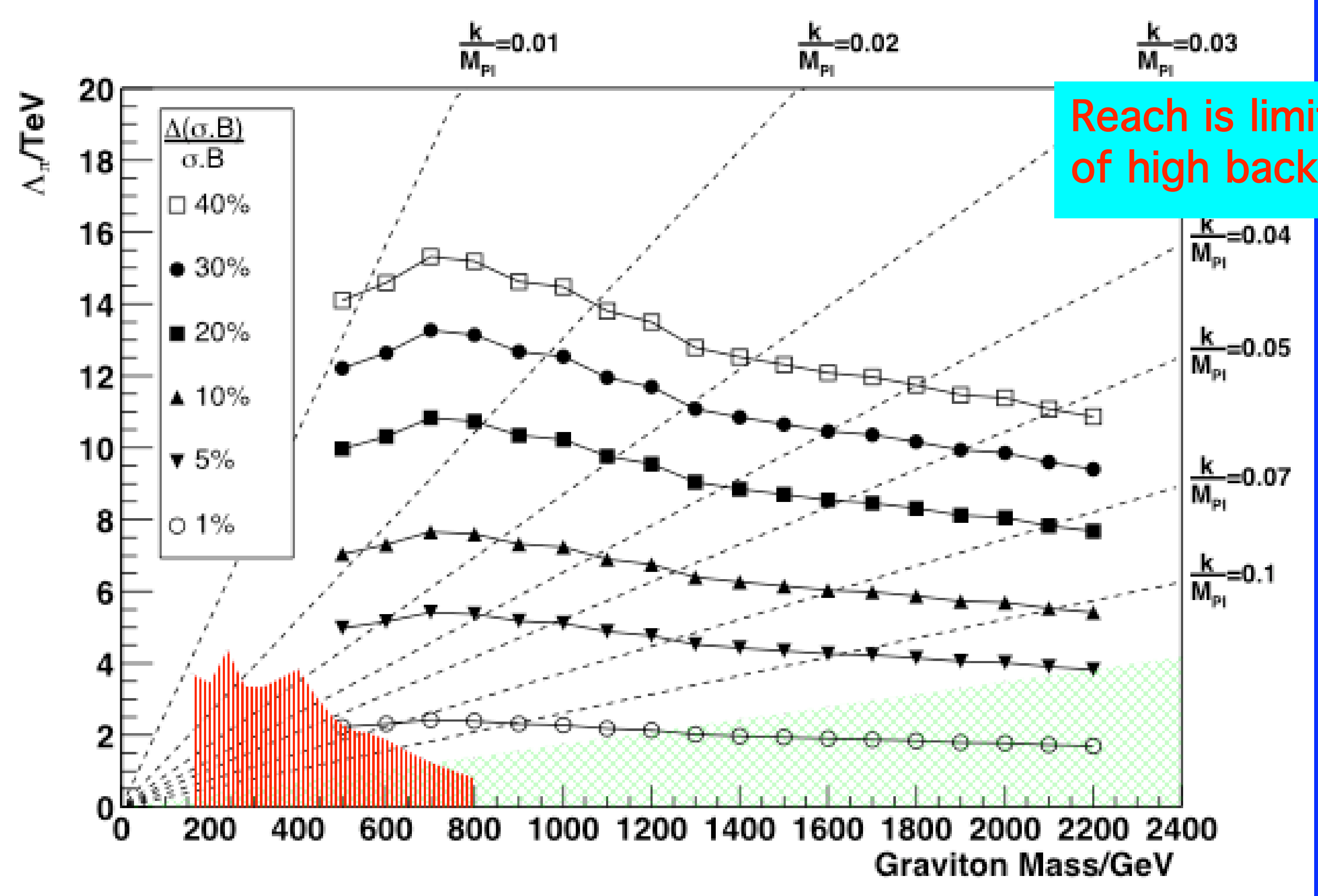
Graviton to jet-jet signal at 1.9 TeV



Significant signal after background subtraction

$k/M_{Pl} = 0.08$
(64x higher cross-section)

Graviton to jet-jet search reach



Reach is limited because of high background

Graviton to WW

Look for $G \to WW \to e\nu jj$

Select 1e, 0 μ, 2 jets, P_T^{miss} from ATLFAST

$\eta_{jet} < 2$

Require Mjj compatible with W mass

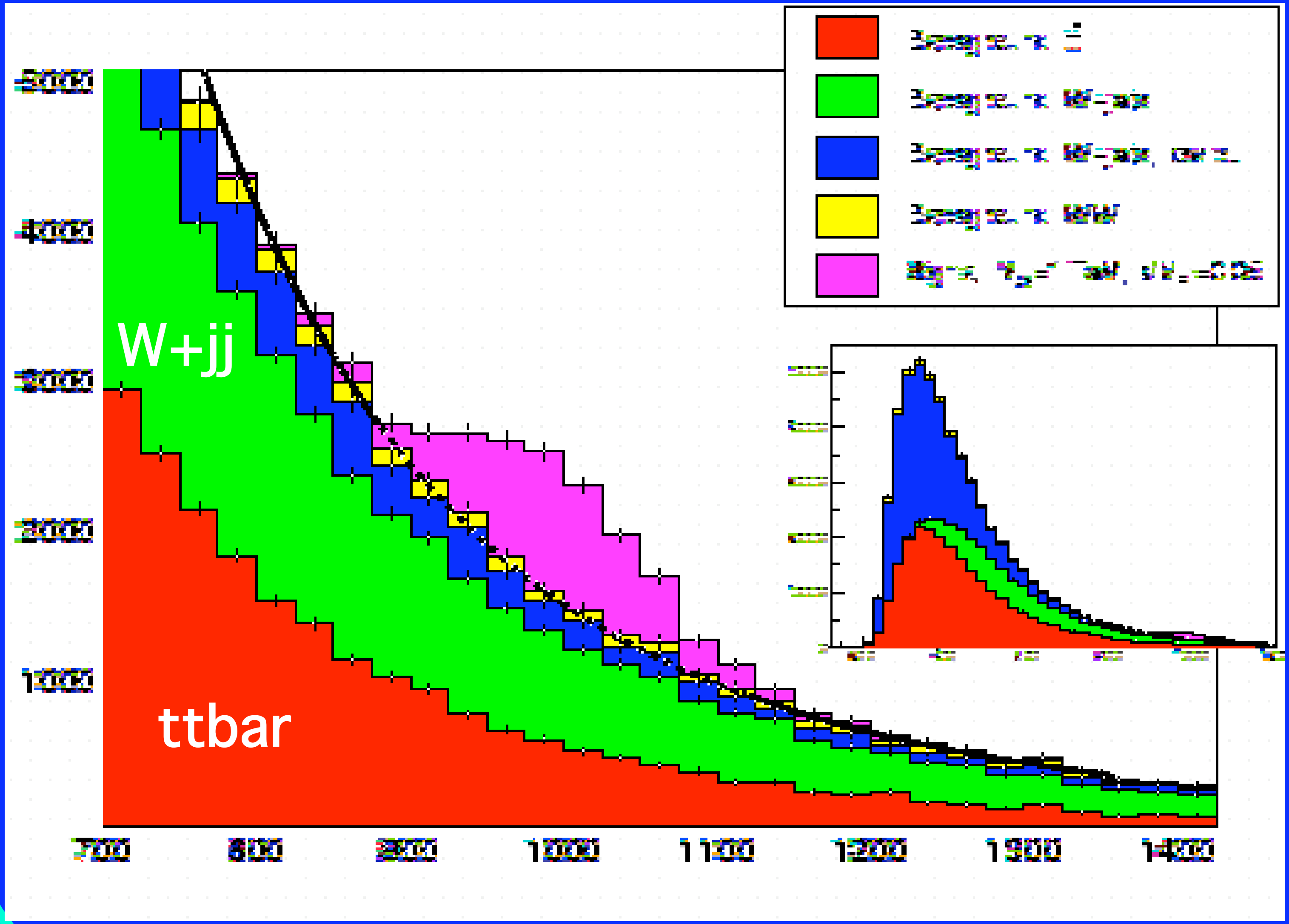
take highest p_T pair in mass window

Solve for $p_z\nu$ using W mass constraint

Plot M_{WW} look for resonance above SM background

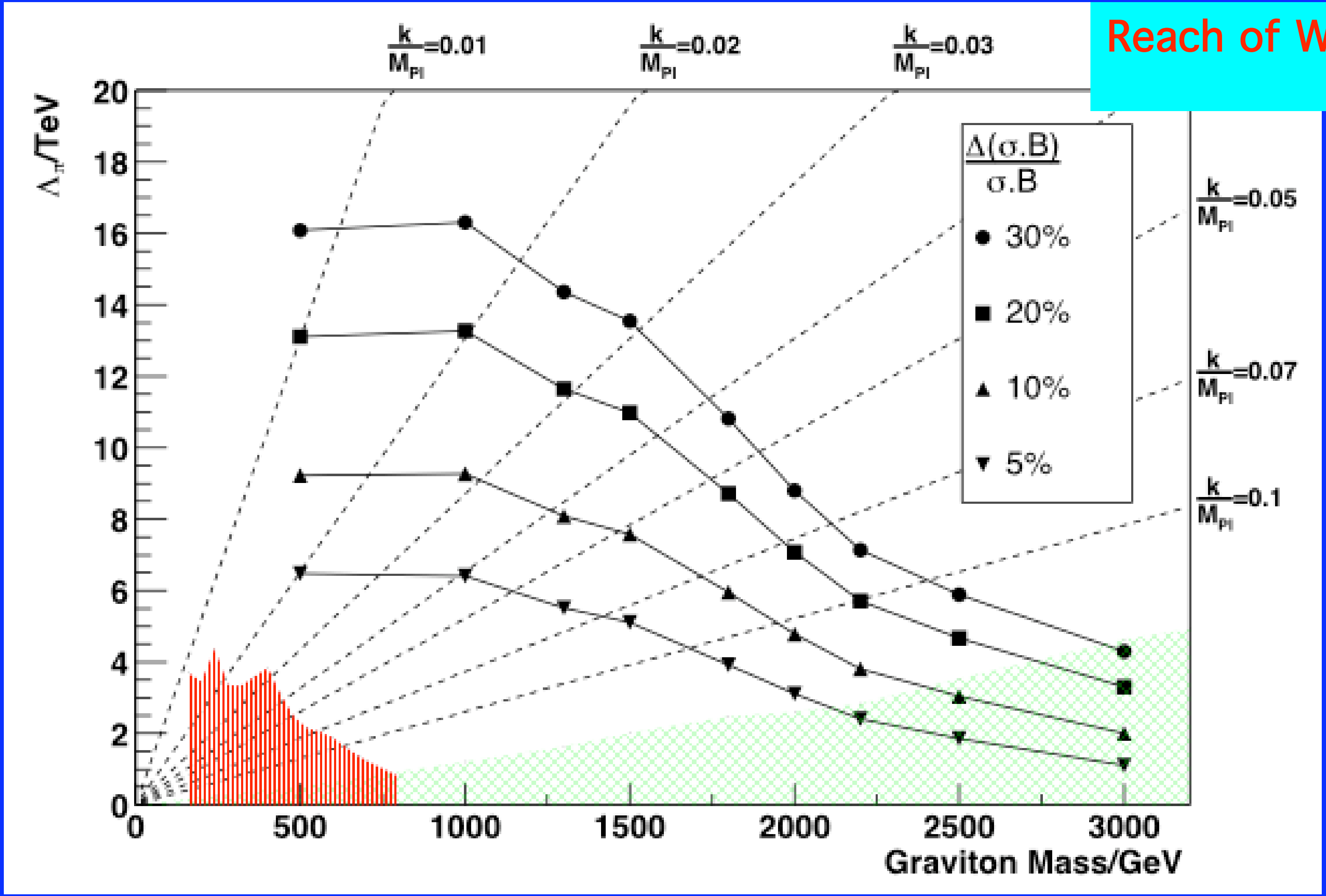
SM background from WW, WZ and ttbar

Graviton to WW: signal and background



WW channel is viable for graviton

Graviton to WW channel



Exploring the extra dimension

Check that the coupling of the resonance is universal: measure rate in as many channels as possible: □□,□□,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 □.B

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

and □.B to 14% from ee channel alone (dominated by statistics).

Then measure

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

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

Conclusions

- Graviton resonances can be detected at the LHC with ATLAS
- For 100fb^{-1} (1 year at full luminosity) expect search to detect graviton masses up to 2080 GeV, using conservative assumptions for e^+e^- channel alone.
- Angular distributions allow graviton to be distinguished from any spin-1 resonance, up to 1720 GeV.
- Angular distribution also gives information on production mechanism.
- Universality of couplings can be checked for leptons and photons, IVBs and quarks over a large part of parameter space.
- Extra dimensions at the Planck length can be explored!