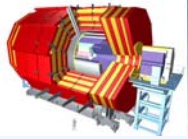
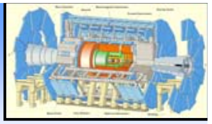
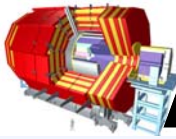




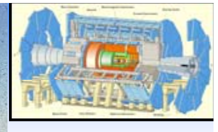
# The Road to Discovery

**Andy Parker**

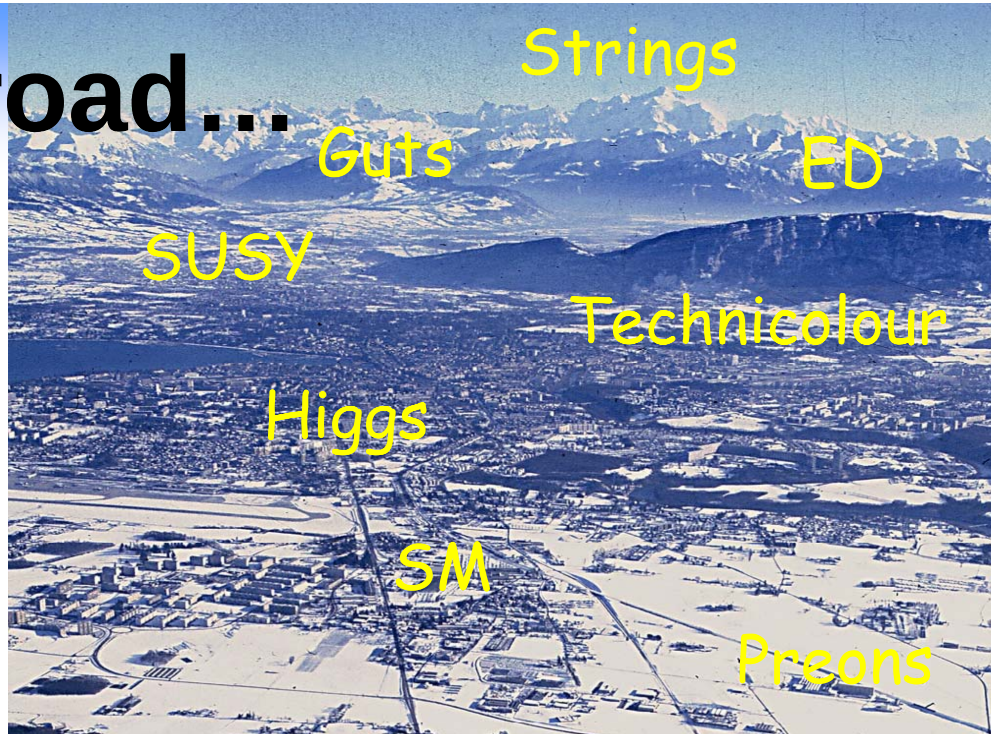
**Cambridge University**



# Along the road…



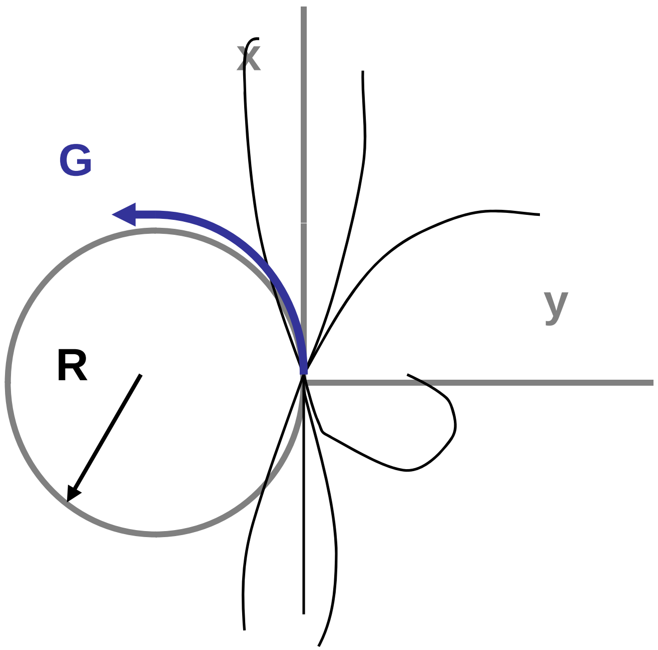
- Preparations - SM Physics, tools, problems
- The local road - hunting the Higgs
- The far horizon - SUSY
- The hidden road - Extra Dimensions



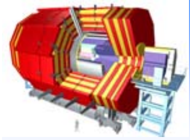

*"The problem is not a want of a theory, but a want of evidence. If scientific advance really came from theorizing, natural scientists would have long ago wrapped up their affairs and gone on to more interesting matters"*
Richard Lewontin NYRB 1995

Thanks to Fabiola Gianotti and many authors of notes etc used in these lectures

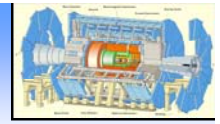
# LED at LHC




- 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 LHC



- Good signatures are — LBNL-45198
- Jet +missing energy channels: — ATL-PHYS-2001-012
  - gg -> gG
  - qg -> qG
  - $q\bar{q}$ -> Gg
- Photon channels
  - $q\bar{q}$ -> G$\gamma$
  - pp -> $\gamma\gamma$X — Virtual graviton exchange
- Lepton channels
  - pp -> l l X — Virtual graviton exchange

# Real graviton production

Cross section:

$$\frac{d^4\sigma}{dm^2 dp_T^2{}_{jet,\gamma} dy_{jet,\gamma} dy_G} = \frac{m_G^{n-2}}{2} \frac{S_{n-1}}{M_D^{n+2}} \frac{d\sigma_m}{dt} \sum_{i,j} \frac{f_i(x_1)}{x_1} \frac{f_j(x_2)}{x_2}$$

Note ED mass scale and n do not separate ->

difficult to extract n

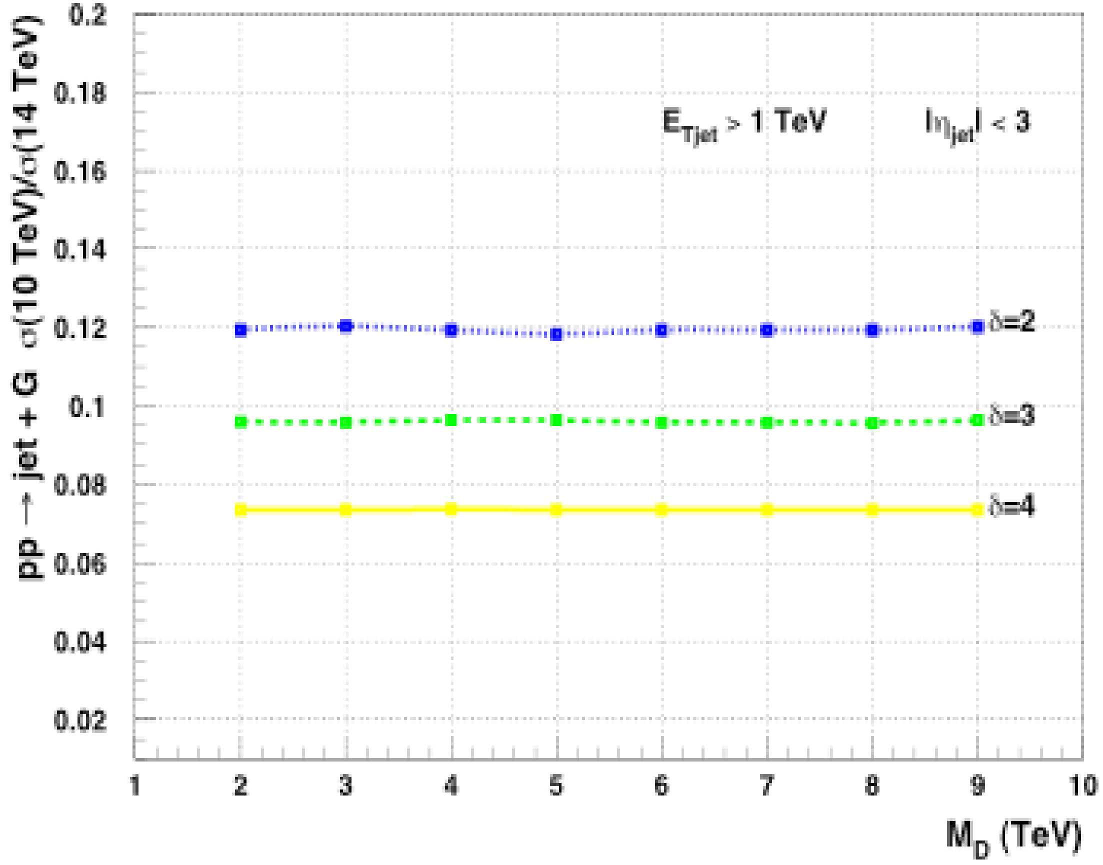
Can use cutoff in $M_D$ from parton distributions

For n>6, cross section unobservable at LHC

Quantum gravity theory unknown ->

Calculation only reliable at energies well away from $M_D$

# Energy variation of cross-section

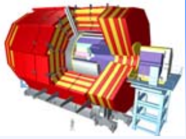



Cross section ratio (10 TeV/14TeV)

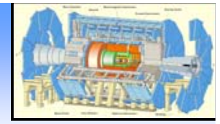
Need to measure to 5% to distinguish n=2,3

Need O(10) more L at 10 TeV

Need luminosity to <5%



# Missing $E_T$ analysis



pp -> jet + $E_T^{Miss}$

Jet energies > 1 TeV

Dominant backgrounds:

Jet + Z -> $\nu\ \nu$

Jet + W-> $\tau\ \nu$

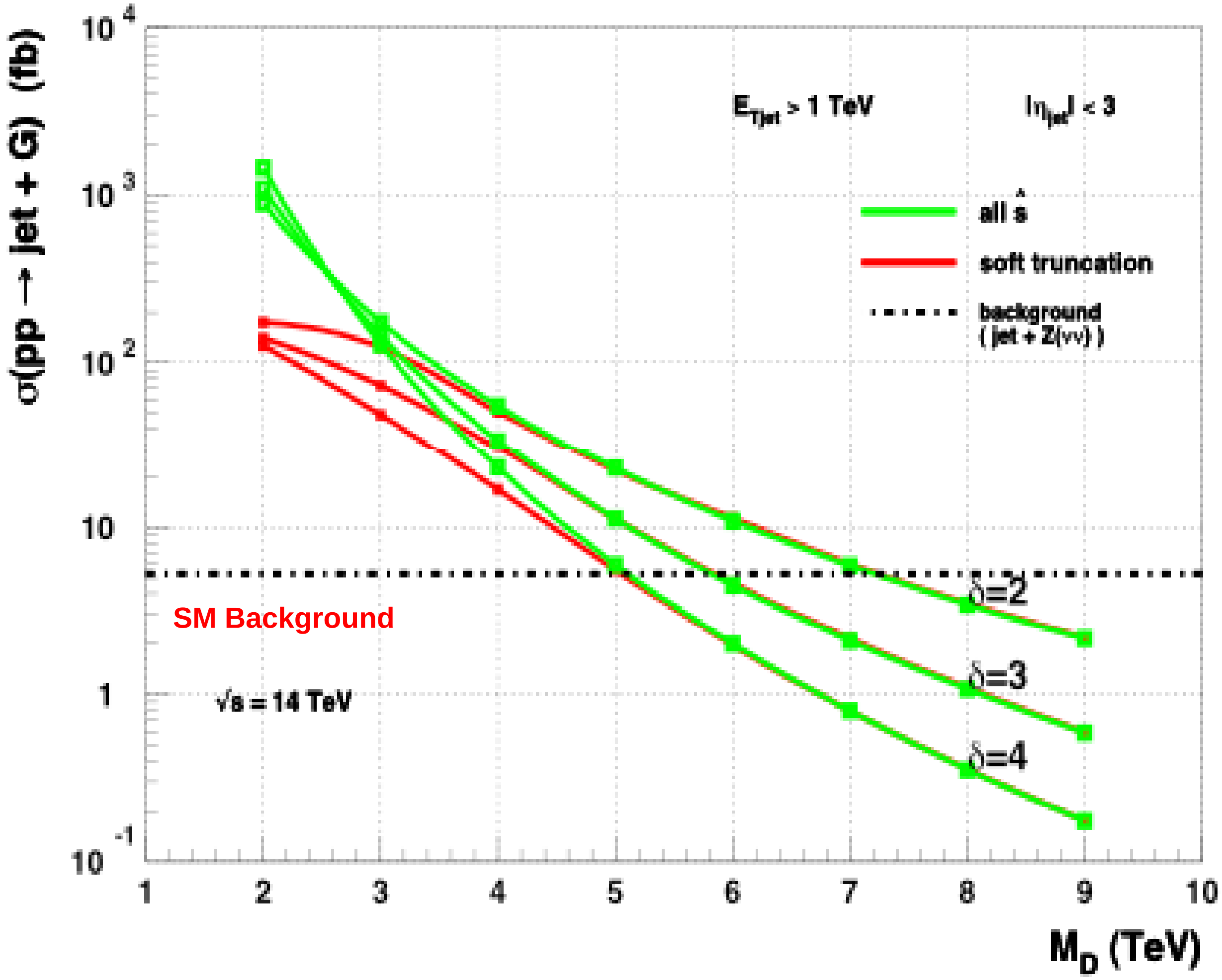
Jet + W-> e $\nu$

} **Use lepton veto**

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
SM Background ~500 events

No prediction for n>4

# Missing $E_T$ signal

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

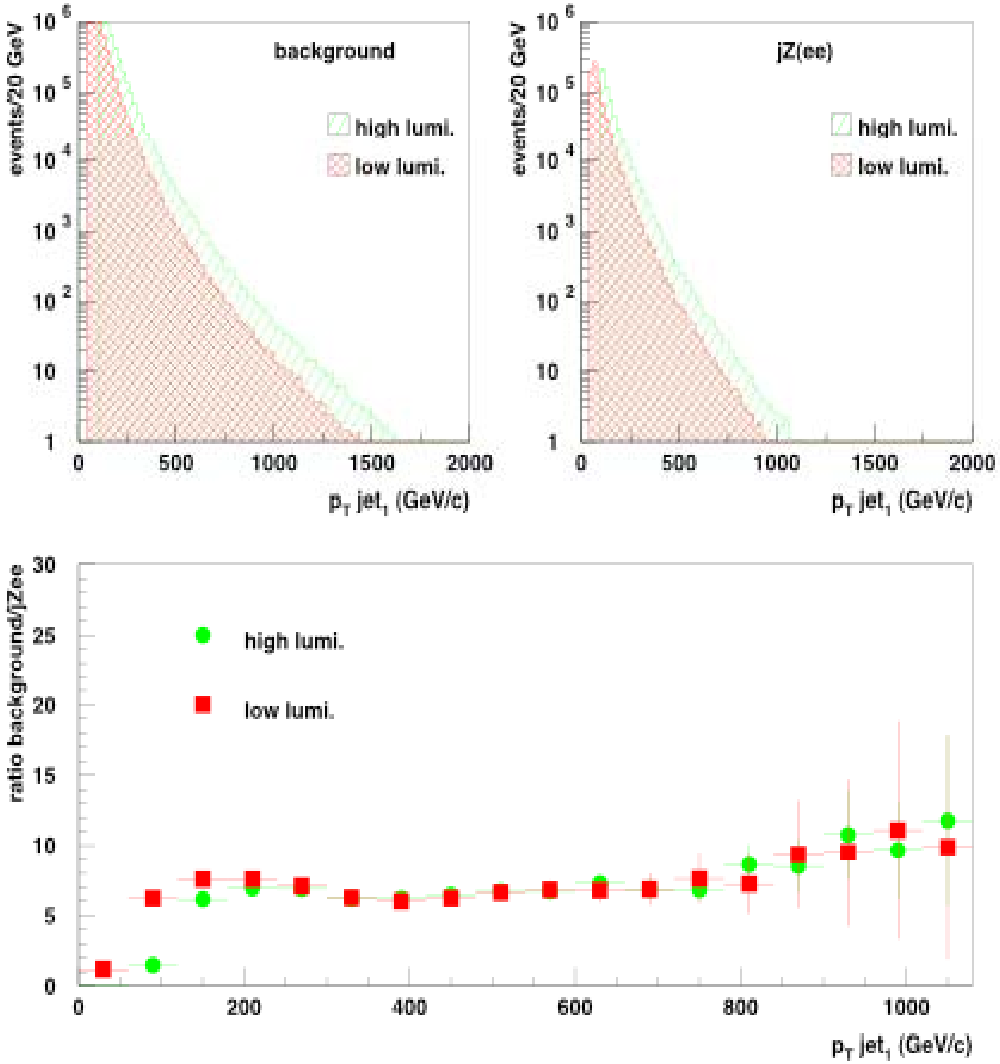
Signal:

Excess of events at high $E_T$

Dominant background

$Z \to \nu\nu$

# Calibration of Z-> νν background




Use Z-> ee

Two isolated electrons, $P_T$>15, $M_{ee}$ within 10 GeV of $M_Z$

Account for acceptance differences e, μ, ν

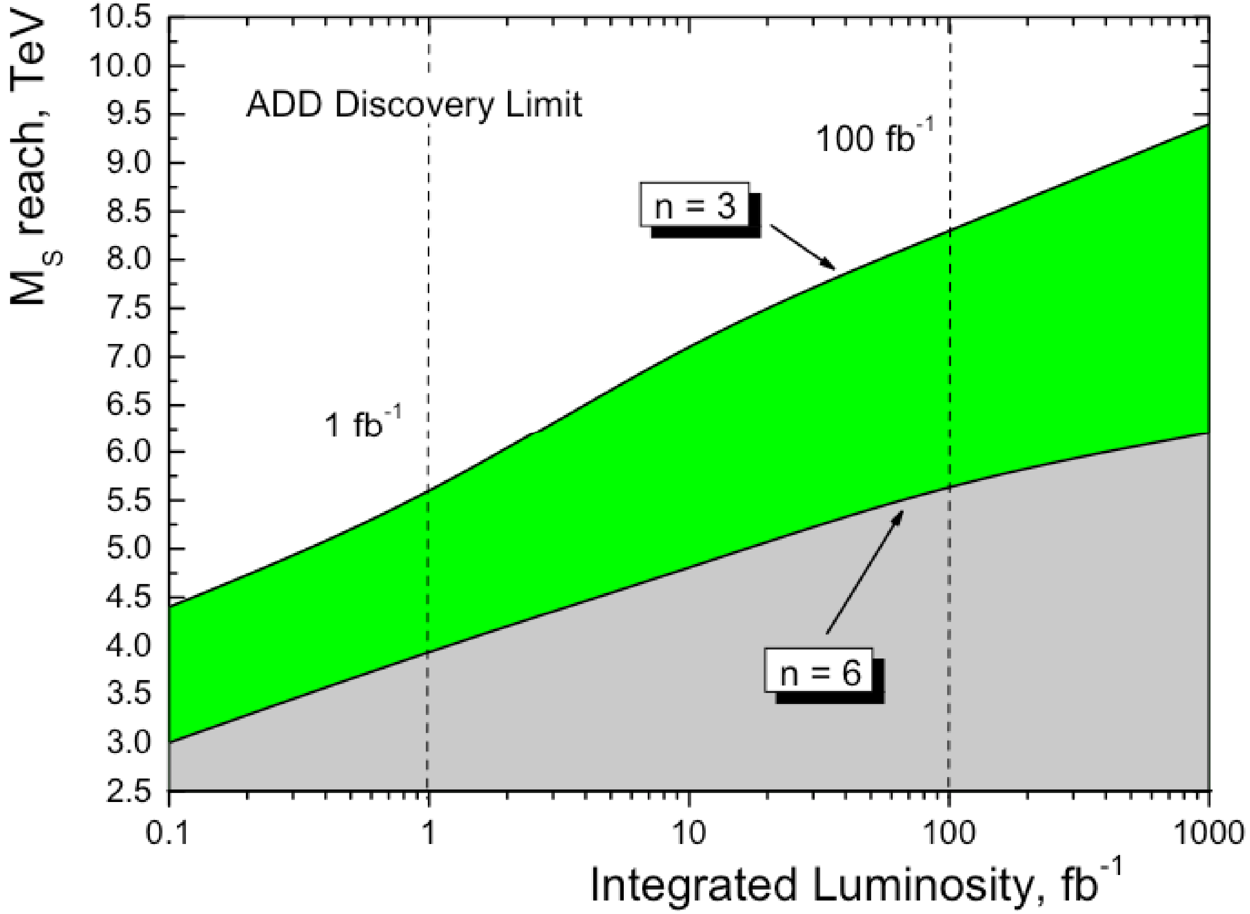
BR's differ by factor 3, so calibration sample has less statistics

# ATLAS Discovery potential

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

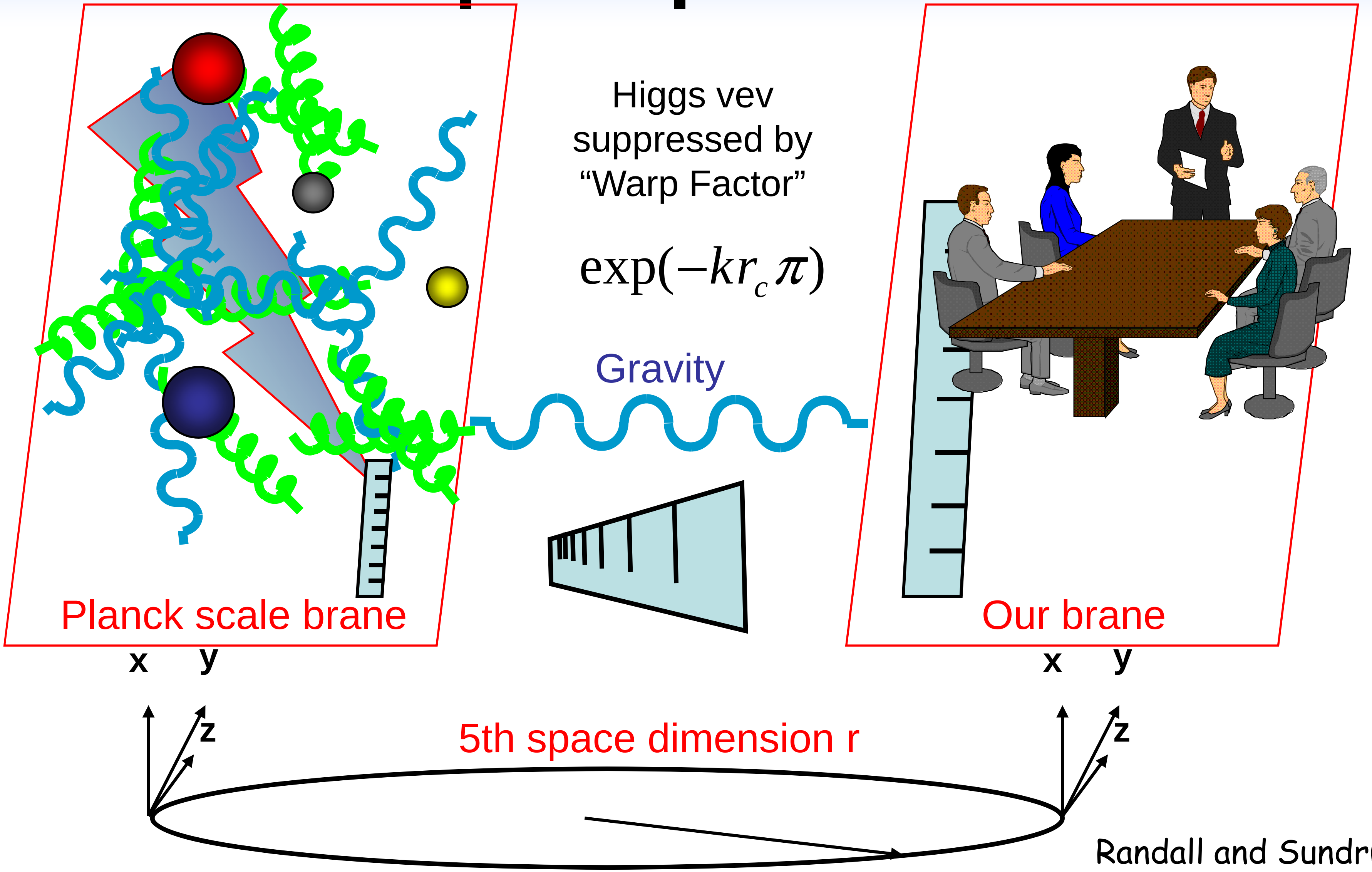
| n | $M_D^{min}$ | $M_D^{Max}$ (TeV) | R |
|---|---|---|---|
| 2 | ~4 | 7.5 | 10 μm |
| 3 | ~4.5 | 5.9 | 300 pm |
| 4 | ~5 | 5.3 | 1 pm |

# CMS discovery reach, ADD




Discovery reach in range 4.5-8.5 TeV for n=3.

# Warped space-times




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

Randall and Sundrum
PRL83,3370(1999)

# R-S models

Consider Randall and Sundrum type models

Gravity propagates in a 5-D non-factorizable geometry

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

Need $kr_c \approx 10$ : no fine tuning

Gravitons have KK excitations with scale

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

Spectrum of graviton excitations seen as resonances which decay to fermion pairs (eg $e^+e^-$)

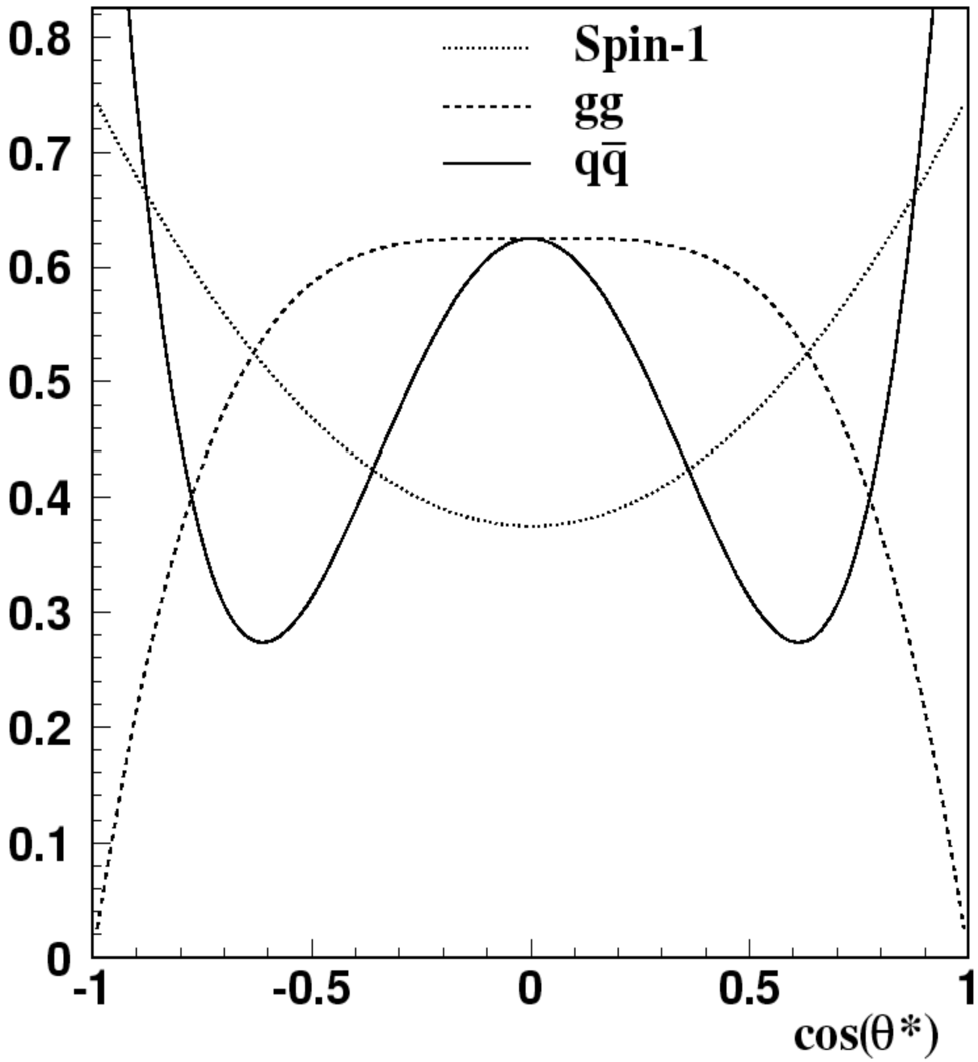
First excitation is at

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

where

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

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

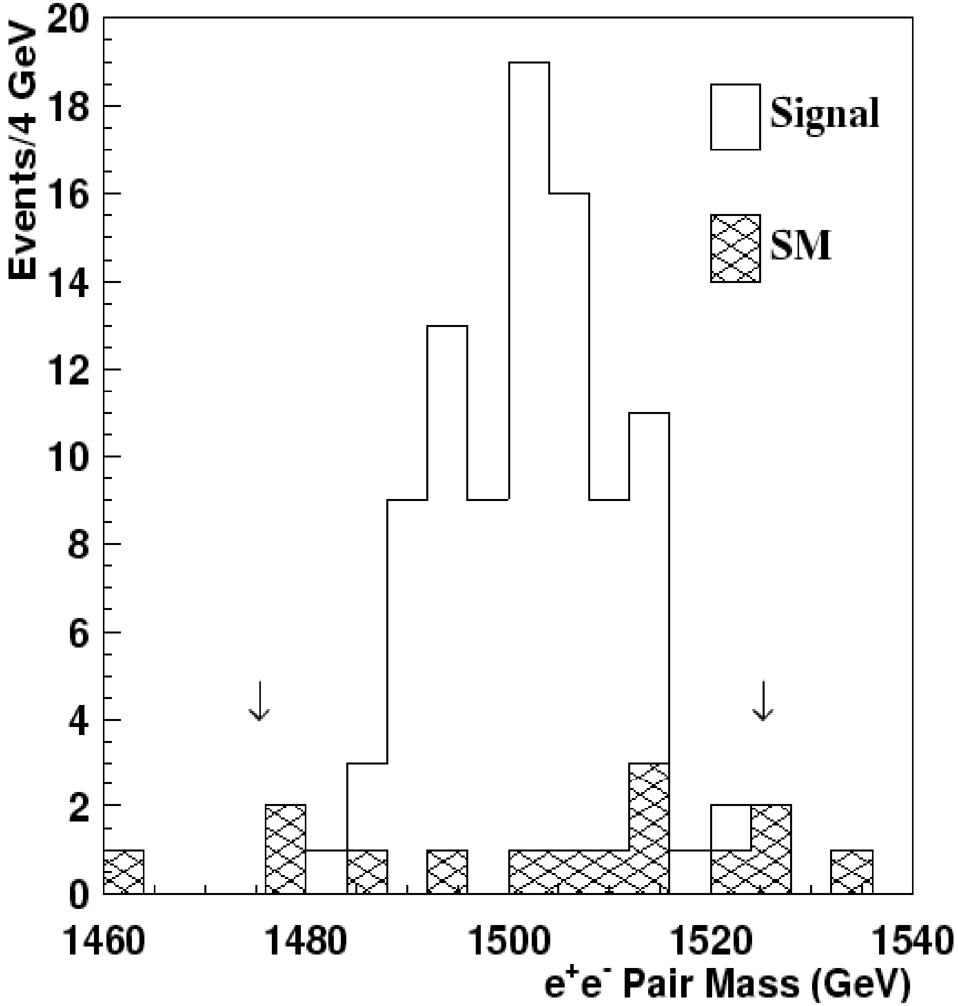



Angular distributions are very different depending on the spin of the resonance and the production mechanism.

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

# 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 RS model.

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

# CMS e+e- resonance search

$e^+e^-$ channel favoured for G resonance as well as Z′ and Z* searches - reach depends on coupling

Z* Z′ G

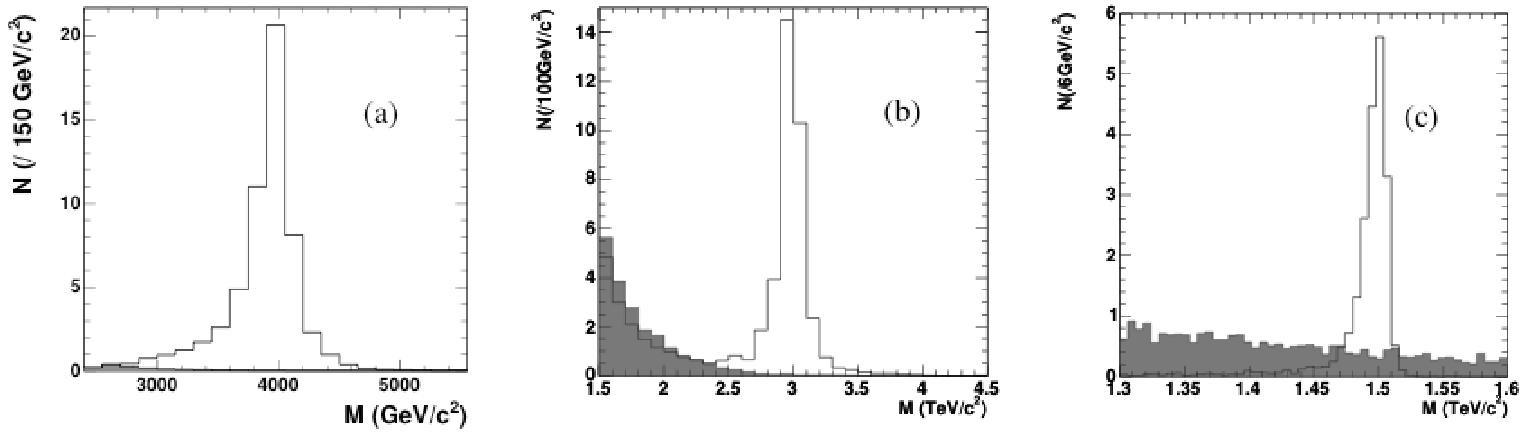
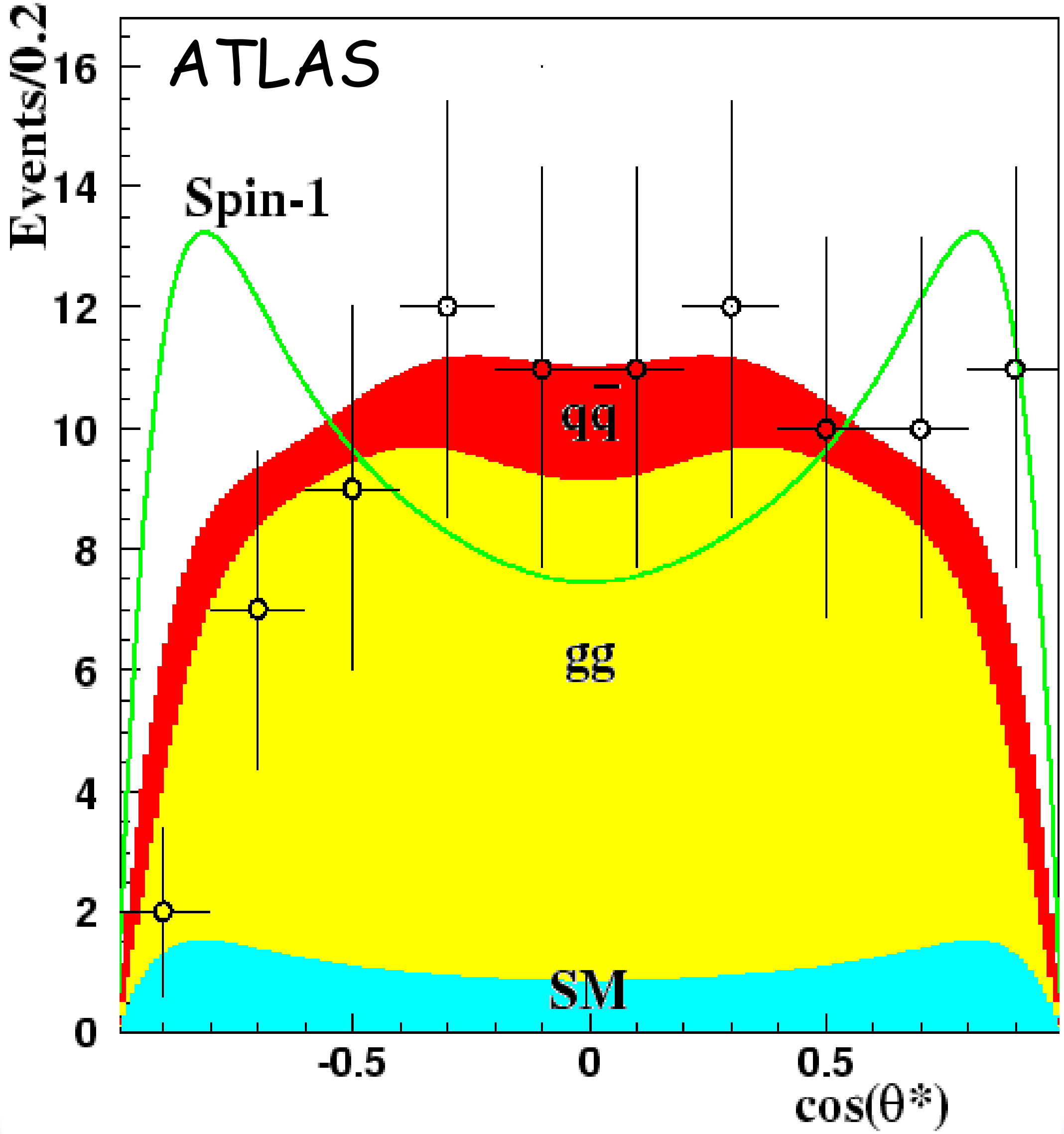



Figure 14.3: Resonance signal (white histograms) and Drell-Yan background (shaded histograms) for KK $Z$ boson production with $M = 4.0\,\text{TeV/c}^2$ (a), SSM $Z'$ boson production with $M = 3.0\,\text{TeV/c}^2$ (b), and graviton production with $M = 1.5\,\text{TeV/c}^2$, coupling parameter $c = 0.01$ (c), for an integrated luminosity of $30\,\text{fb}^{-1}$.

# Angular distribution



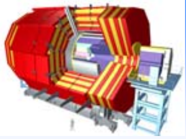

$$G \to e^+e^-$$

1.5 TeV resonance

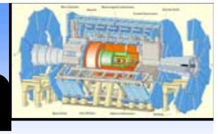
Production dominantly from gluon fusion

Statistics for $100 fb^{-1}$

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



# Exploring the extra dimension



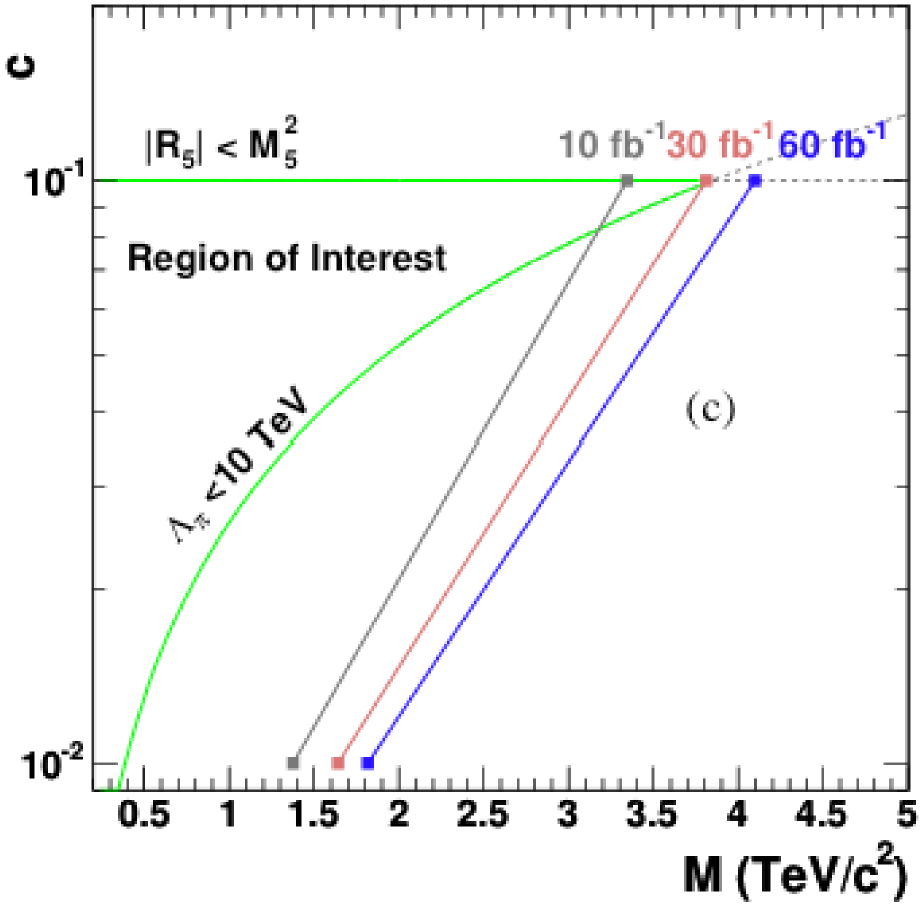
- Check that the coupling of the resonance is universal: measure rate in as many channels as possible: $\mu\mu$,$\gamma\gamma$,jj,bb,tt,WW,ZZ
- Use information from angular distribution to separate gg and qq couplings
- Estimate model parameters k and $r_c$ from resonance mass and $\sigma$.B
- In model with $M_G$=1.5 TeV, measure mass to ±1 GeV and $\sigma$.B to 14% from ee channel alone (dominated by statistics).
- Then measure

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

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

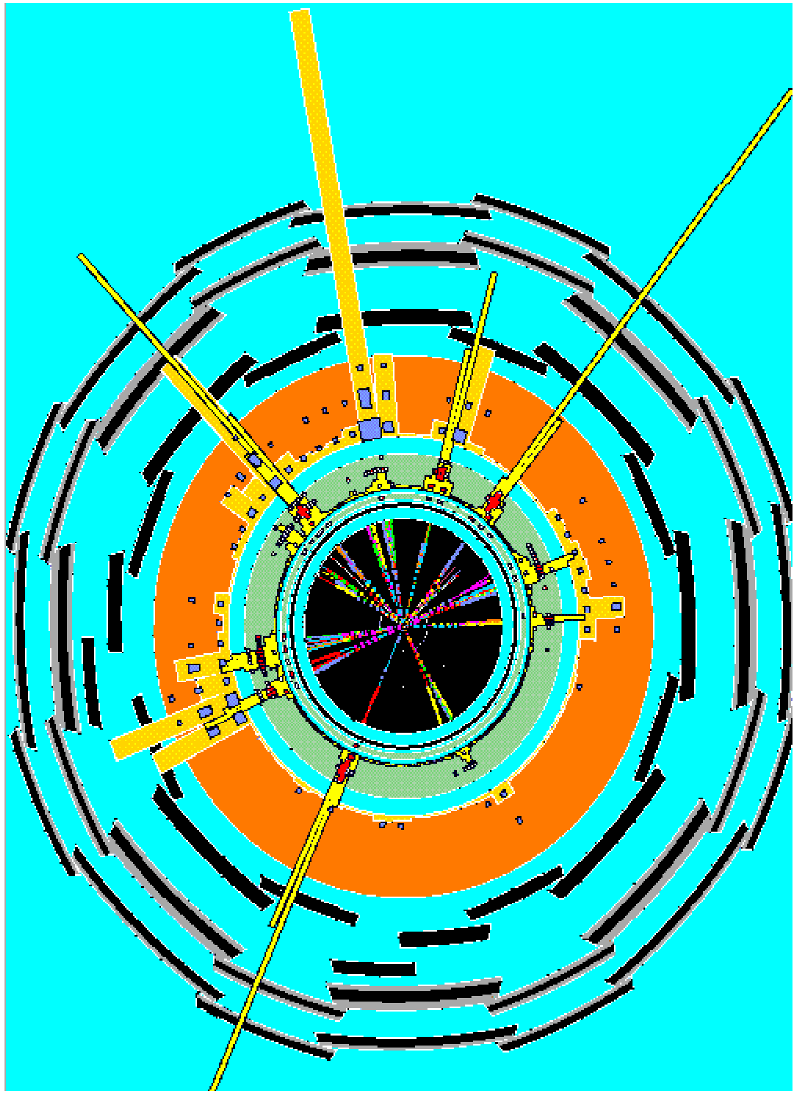
# Graviton search reach

CMS




All of the theoretically interesting parameter space can be excluded with 30 fb$^{-1}$

# 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

Richardson, Harris, Palmer: JHEP 05(2005)053

# Black Hole production cross-section

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

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

- Classical approximation to cross-section
- Controversial…see review by Gingrich hep-ph/0609055
- Very large rates for n=2-6 See hep-ph/0111230
- Almost independent of n

# 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 $r_h$

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

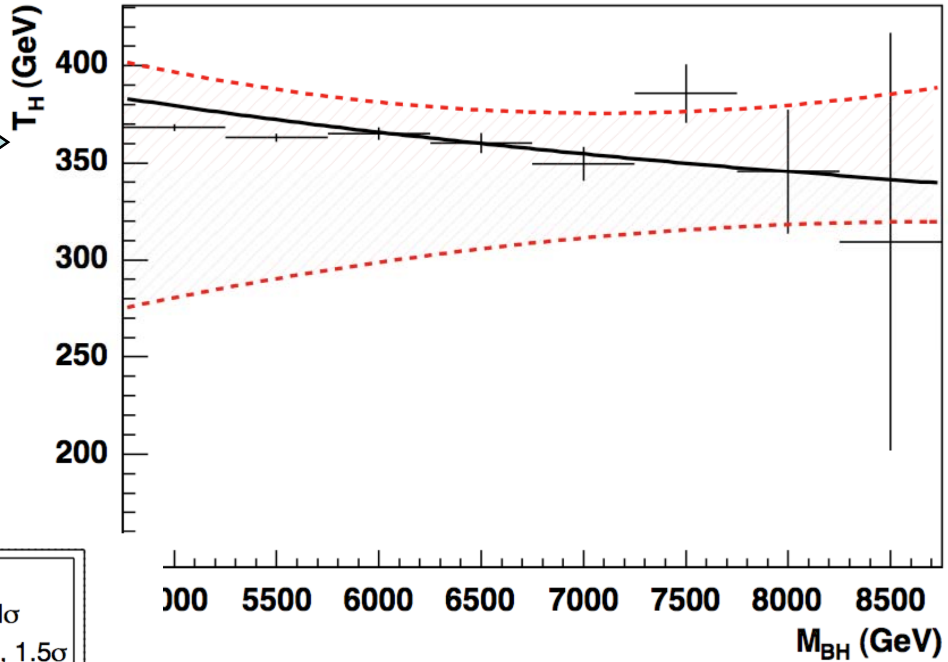
Use observed final state energy spectrum to measure $T_H$ and hence n?

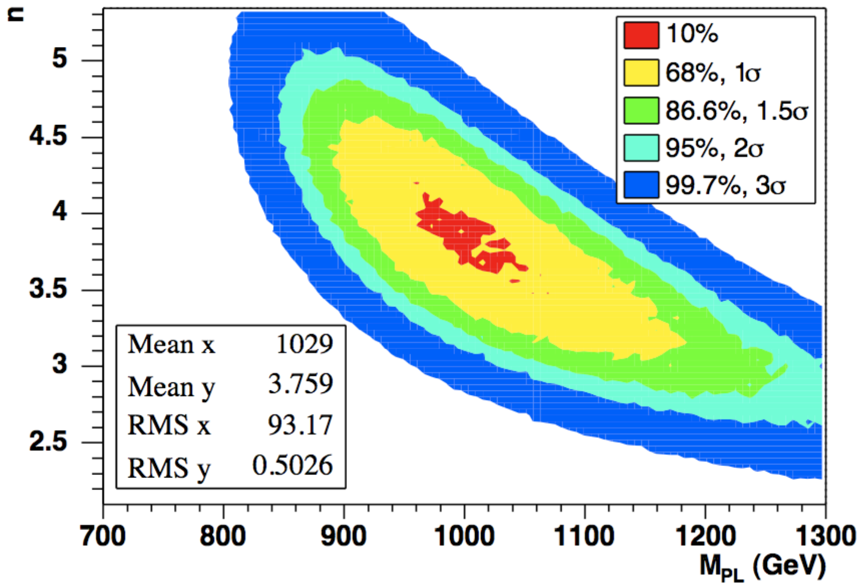
# Black Hole Searches

Can measure characteristic T at average mass

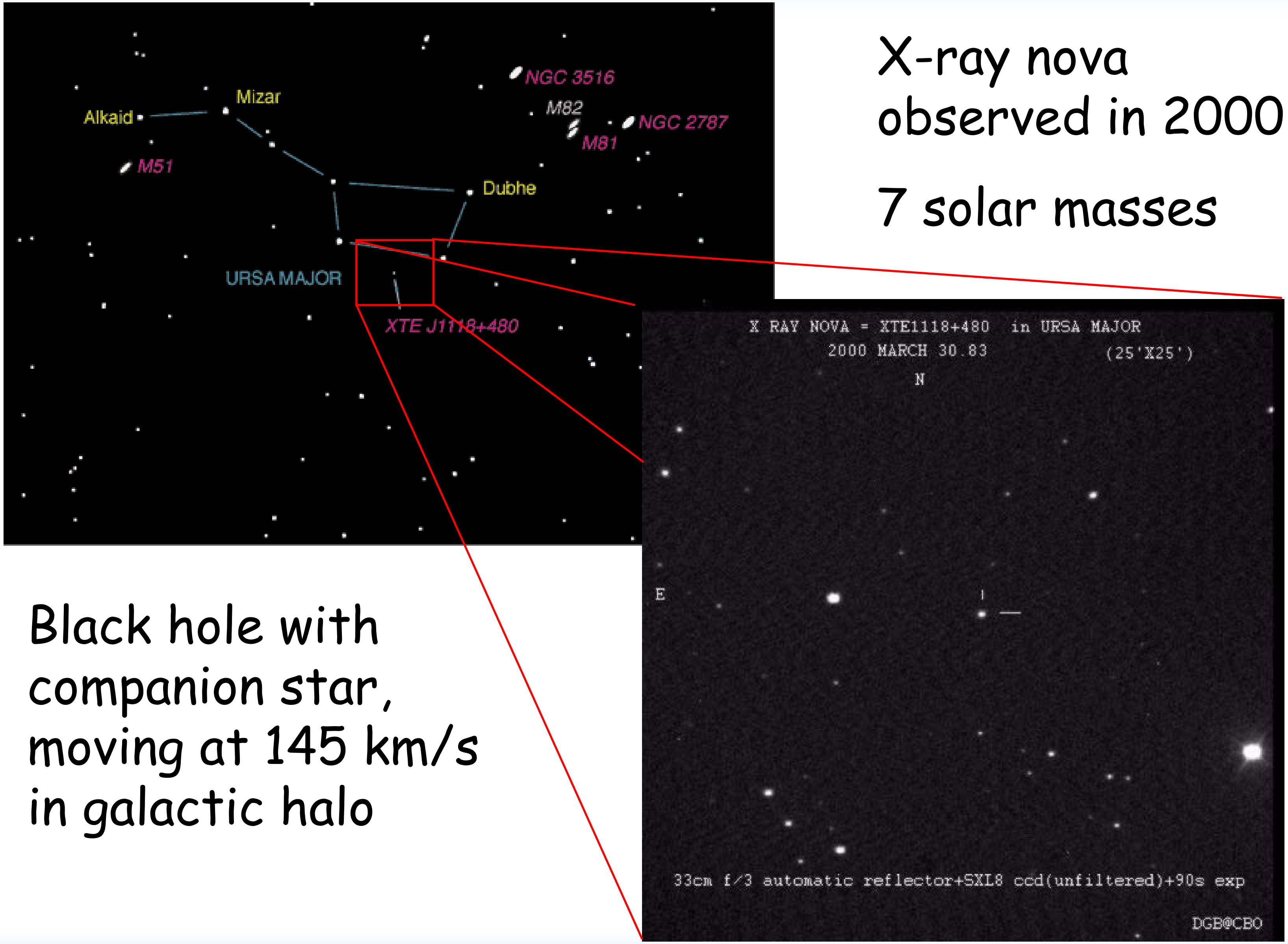
-> combine this with cross section data to extract n.

Assume 20% error on σ



# XTE J1118 +480

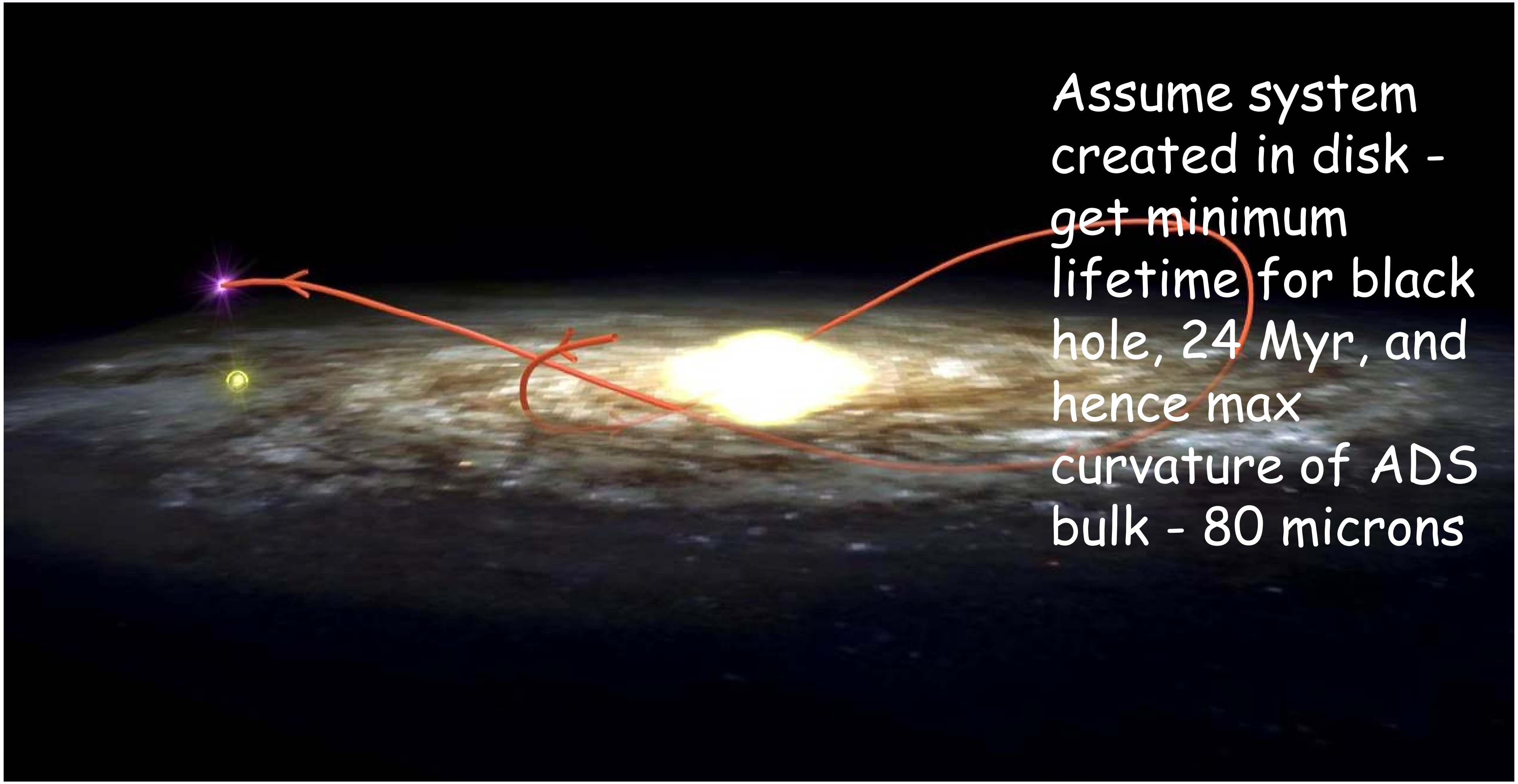



X-ray nova observed in 2000

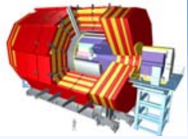
7 solar masses

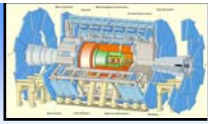
Black hole with companion star, moving at 145 km/s in galactic halo

# XTE J1118 +480




Inferred orbit passes through galactic plane several times.





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…and especially to the Organisers for the kind invitation to speak

# BACK-UP SLIDES