8.882 LHC Physics

Experimental Methods and Measurements

Extra Dimension Searches at the LHC
[Lecture 24, May 05, 2009]

Organization

Project 3

- make sure to hand in very soon

Conference

- Higgs Analysis update is not yet ready
- read the README it contains all relevant info
- e-mail to the course list (Si Xie, sixie@mit.edu, is our local expert!)
- please make sure to ask your questions early!

Physics
Colloquium Series

'09
Spring

The Physics Colloquium Series

Thursday, May 7 at ***4:15 pm*** *in room* ***10-250***

Kip Thorne

California Institute of Technology

"The Warped Side of Our Universe"

For a full listing of this semester's colloquia, please visit our website at **web.mit.edu/physics**

Lecture Outline

Extra dimension searches at the LHC

- theory introduction
- some selected models of extra dimensions
  - large extra dimensions
  - warped extra dimensions
- experimental signatures and searches
- reach of the LHC

Mini Black Holes

- what are they?
- how to detect them at LHC

Kaluza-Klein Theory

Standard Model unifies electromagnetic and weak forces and includes the strong force as well

- uses: SU(3) x SU(2) x U(1) symmetry group
- does not say anything about gravity
- gravitational force much too small, 35 orders of magnitude

Integration of gravity into Standard Model

- 1921 Kaluza GR in 5 spacetime dimensions
- the resulting equations can be split into
  - Einstein's field equations (GR)
  - Maxwell's equations for the EM field
  - and an extra scalar field, radion*
- 1926 Klein proposed extra dimension to be real and just curled up in circle of small radius

* reminds me of the Higgs mechanism solving the mass problem

Kaluza-Klein Theory

Theory: fifth dimension represented

- by U(1) circle group
- can be replaced with general Lie group (many extra dim.)
- generalization called Yang-Mills theory, gauge theories, though here we are in general treating curved spacetime
- for realistic Kaluza-Klein theories the SU(3) x SU(2) x U(1) Standard model has to be generated... but it is theoretically not very appealing (fermions are introduced artificially)
- string theories or *M*-theories deal with this more coherently

Kaluza-Klein Theory

Consequence of the fifth dimension

- particle (graviton) moving along 5^{th} dimension returns to initial position
- explains naturally smallness of gravitational force
  - graviton travels mostly in dimensions we do not observe
  - we notice only small fraction of its force
  - one dimension implies circle size of the universe (very noticeable)
  - several additional dimensions drop circle sizes to atom sizes (unnoticeable)
- motion in all dimensions are overlaid and nothing changes
- as long as the 5^{th} dimension stays small
- standing waves on 5^{th} dimensions can form: $E = n\, h\, c / R$
  - h – Planck constant, c – speed of light
  - R – radius of extra dimension, n – any integer
- energy spectrum called Kaluza-Klein towers (particles?)

Kaluza-Klein Theory

Compact? What does that mean?

- extra dimensions are constrained....
- we cannot see them therefore they have to be compact
- serious constraints on extra dimensions originate from this requirement
- a circle is compact as it allows particles to travel without leaving their position as long as the circle is small enough
- compactification: theory is built using for example 10 dimensions of which 6 have to be compactified to establish our 4 dimensional spacetime

String Theory with Extra Dimensions

Large extra dimensions

(Arkani-Hamed, Dimopoulos and Dvali: PL B426:263 (1998))

- gravity becomes strong at the TeV scale
- compactification on a δ-torus (flat geometry)

boundary conditions cause periodic wave functions

Kaluza Klein modes (towers) of the graviton

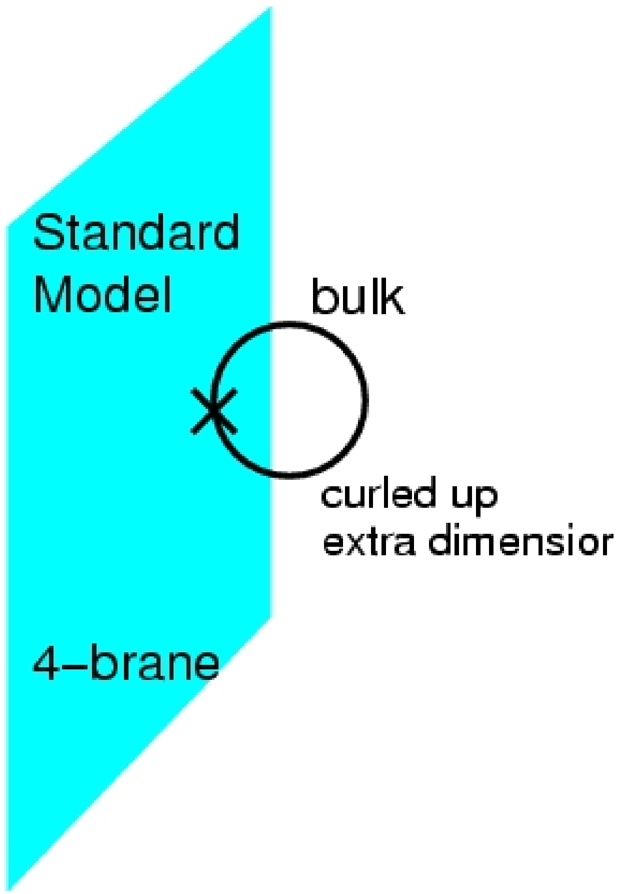
$M_n^2 = M_0^2 + \delta^2/R^2$

real Planck mass: $m_D = M_{Planck,4+\delta}$

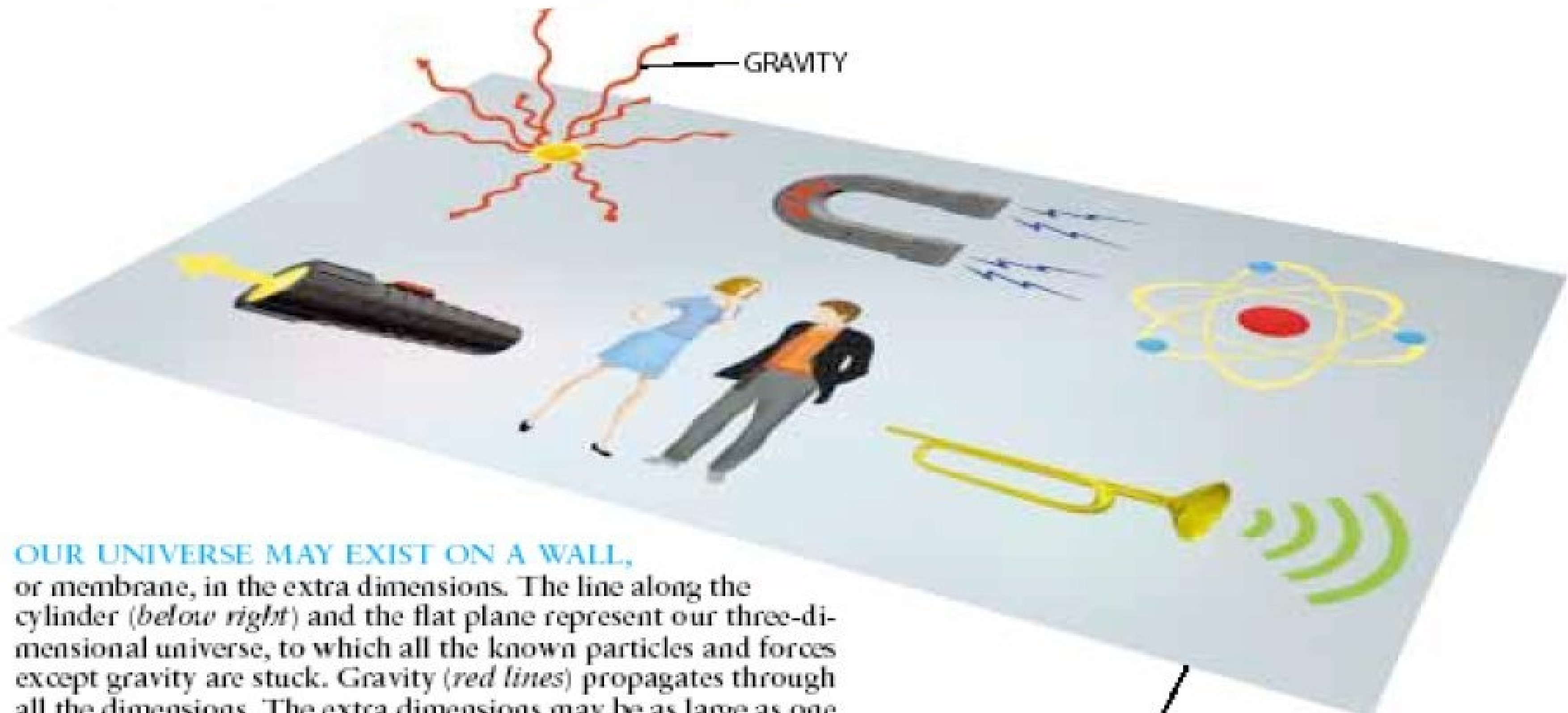
$M_{Planck,4}^2 = (M_{Planck,4+\delta})^{2+\delta} \times R^\delta$

ex. M_D = 1TeV, means R ~1mm (for δ=2)

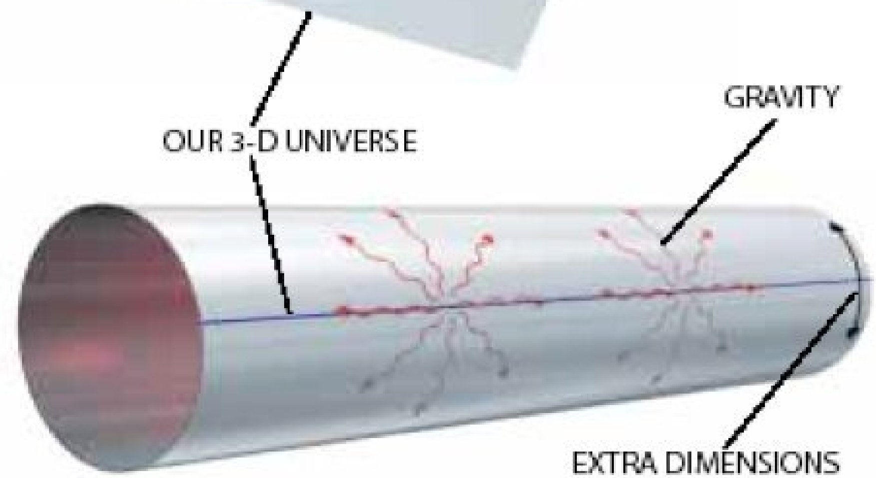
Kaluza Klein modes give an extra contribution to every SM process (should be pretty small) graviton couples to any massive particle



Large Extra Dimensions



OUR UNIVERSE MAY EXIST ON A WALL, or membrane, in the extra dimensions. The line along the cylinder (*below right*) and the flat plane represent our three-dimensional universe, to which all the known particles and forces except gravity are stuck. Gravity (*red lines*) propagates through all the dimensions. The extra dimensions may be as large as one millimeter without violating any existing observations.



Model of Arkani-Hamed, Dvali, Dimopoulos: Standard Model particles are localized on a 3-D brane. Gravity propagates inside the bulk (a more dimensional space)

Figure from Scientific American

Constraints On Large Extra Dimensions

Constraint	n=2		n=3	
	max R_D (mm)	min M_D (TeV)	max R_D (mm)	min M_D (TeV)
Gravity law	0.2	0.6		
Cooling of supernovae by emission of gravitons	7×10^{-4}	10	9×10^{-7}	0.8
Diffused background of cosmic rays ($G_{KK} \rightarrow \gamma\gamma$)	9×10^{-5}	25	2×10^{-7}	1.9
Heating of neutron stars (trapped G_{KK} which decay)	8×10^{-6}	90	3.5×10^{-8}	5
LEP : γG, ZG, virtual exchanges		~ 1 TeV		
Tevatron		~ 1 TeV		

From particle data booklet 2002: G.F.Guidice, J.March-Russel

careful: *n* is what I call δ before

String Theory with Extra Dimensions

Warped metric

(Randall, Sundrum: PRL 83:3370 (1999))

- gravity is strong on the Plank brane
- compactification through warped metric
- warped distance would make our perception of gravity weak while strong at Plank scale (on Plank brane)

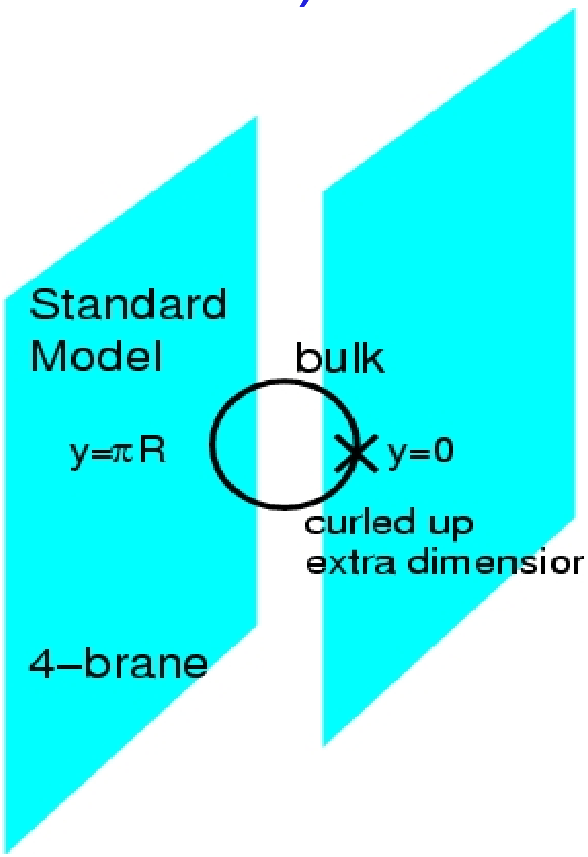
$$ds^2 = \exp(-2kR|y|)\eta_{\mu\nu}dx^\mu dx^\nu - R^2 dy^2$$

distances shrink with *y*

$$\Lambda_\pi = M_{\text{Plank}} \exp(-k\pi R) \approx \text{TeV}$$

graviton resonances in *4D* with:

$$M_n = x_n k \exp(-k\pi R) \quad \text{with} \quad J_1(x_n) = 0$$
$$= x_n (k/M_{\text{Plank}})\Lambda_\pi .$$

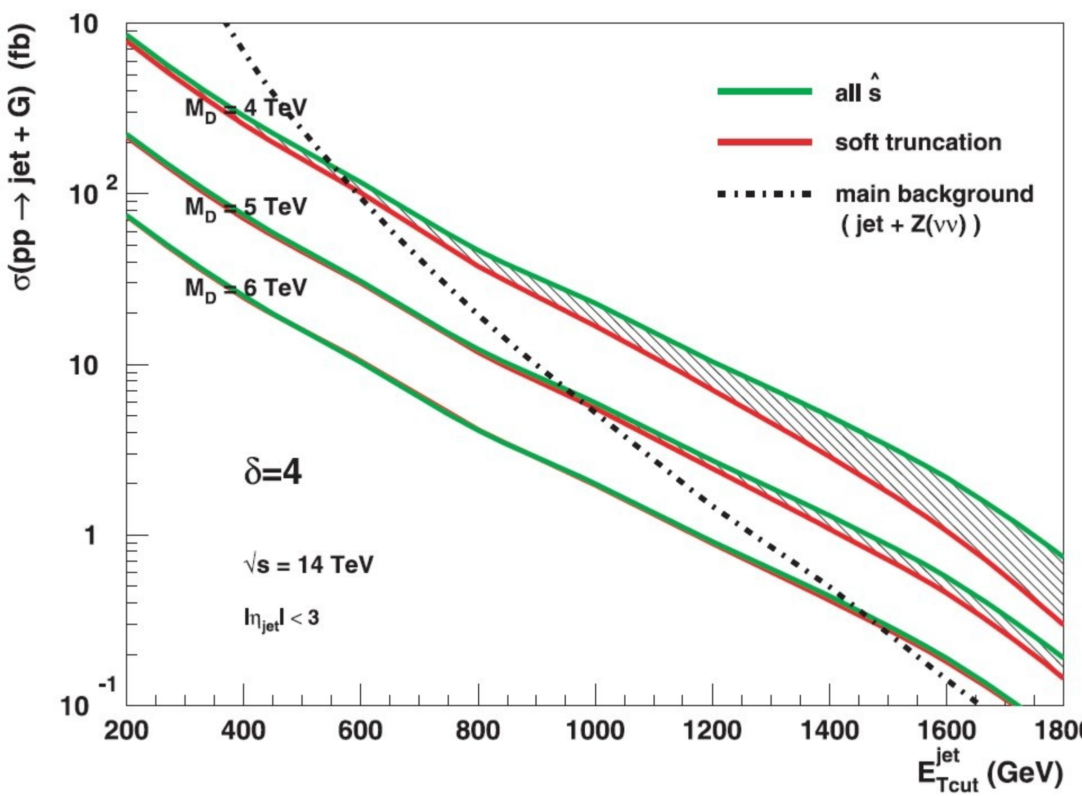


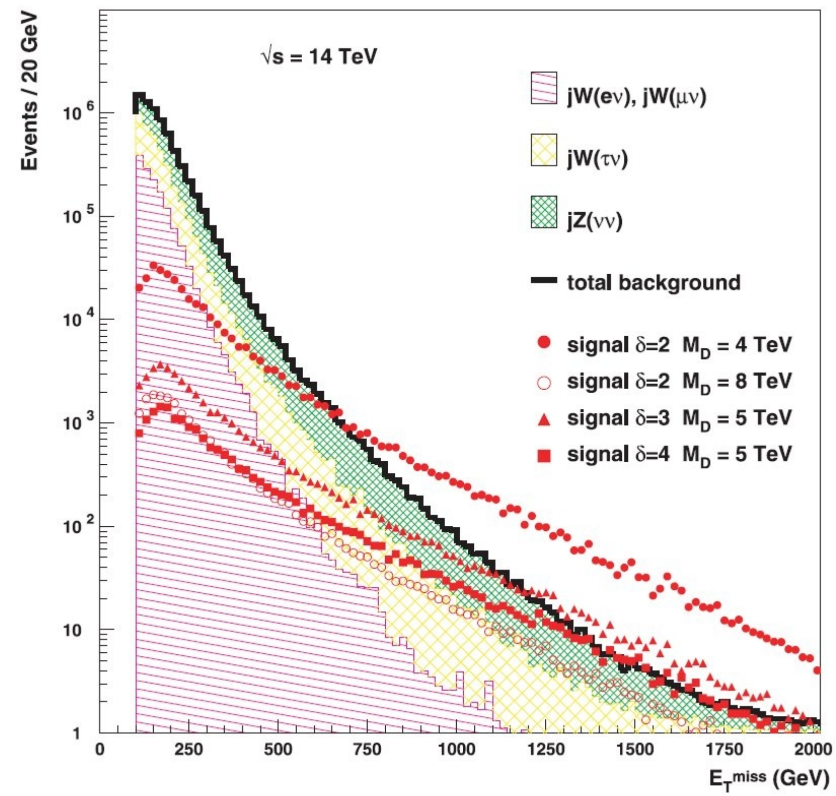
Searches for Extra Dimensions

Large extra dimensions

L.Vacavant, I.Hinchliffe (J. Phys. G: Nucl. Part. Phys. 27 (2001) 1839-1850)
Atlas experiment

- direct graviton production: single jet and missing p_T ($gg \rightarrow gG$, ..)





δ	M_D (TeV)	Low luminosity, 30 fb^{-1} Events	S_{min}	S_{max}	High luminosity, 100 fb^{-1} Events	S_{min}	S_{max}
4	4	448	11.8	31.3	1499	21.4	56.7
	5	117	3.1	8.1	391	5.6	14.8
	6	39	1.0	2.7	134	1.9	5.1
	7	16	0.4	1.1	53	0.8	2.0

Table 1. Number of remaining background events after the selection $\not{E}_T > 1$ TeV.

Type	Low luminosity, 30 fb^{-1}	High luminosity, 100 fb^{-1}
$jZ(\nu\nu)$	153	523
$jW(\tau\nu)$	45	151
$jW(e\nu)$	4	12
$jW(\mu\nu)$	4	14
Total	206	700

Searches for Extra Dimensions

Large extra dimensions: direct graviton search

3 years low lumi : 30 fb^{-1}

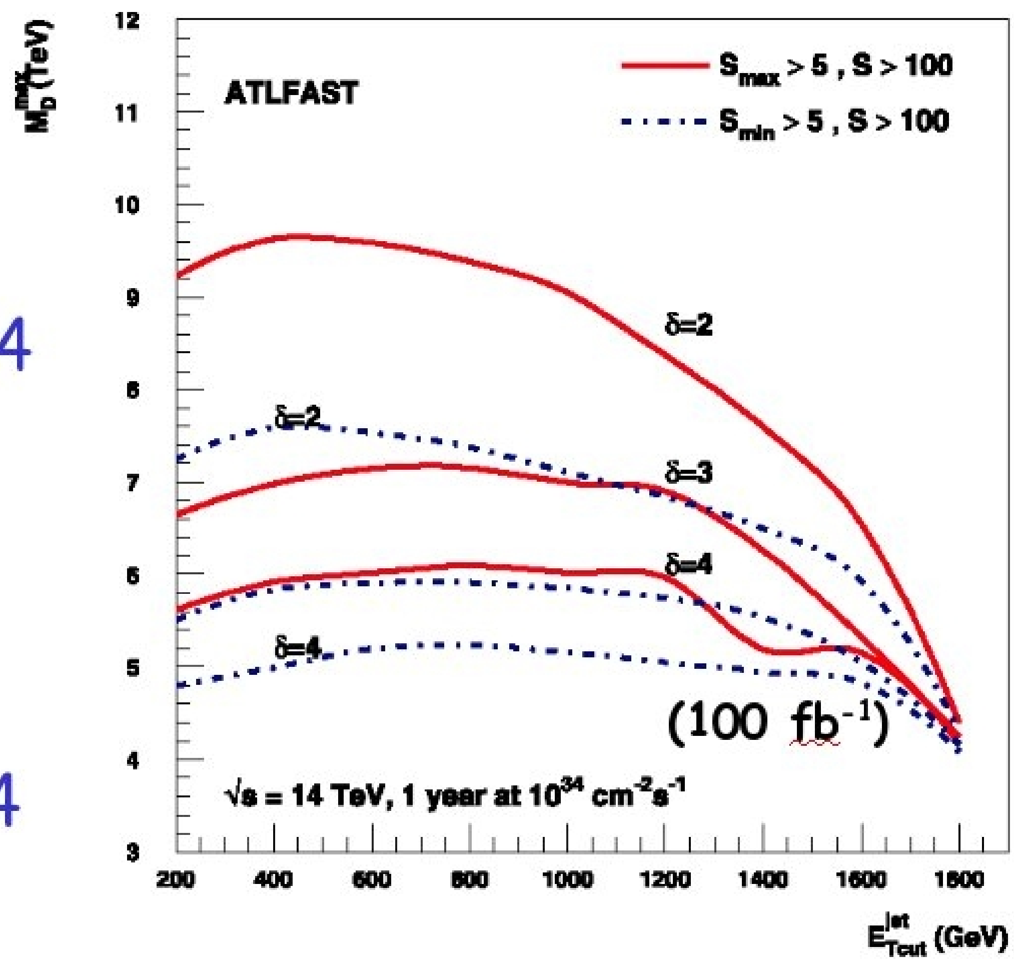
S>50 events, $Signif._{max}$>5

M_D^{max}= 7.7, 6.2, 5.2 for δ=2,3,4

1 year high lumi : 100 fb^{-1}

S>100 events, $Signif._{max}$>5

M_D^{max}= 9.1, 7.0, 6.0 for δ=2,3,4



Stolen from B.Laforge: Moriond QCD 2002 presentation on extra dimension: http://moriond.in2p3.fr/QCD/2002/thursday/pm/laforge.ppt

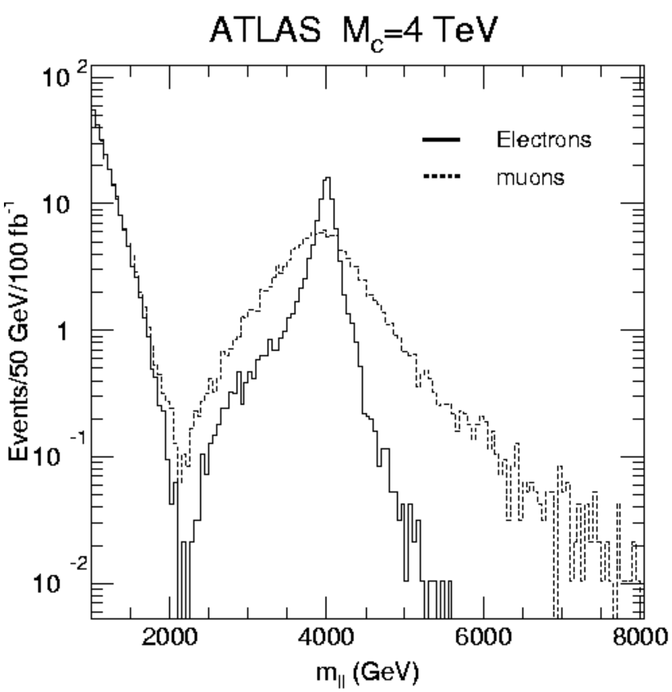
Searches for Extra Dimensions

Extra dimensions at TeV level

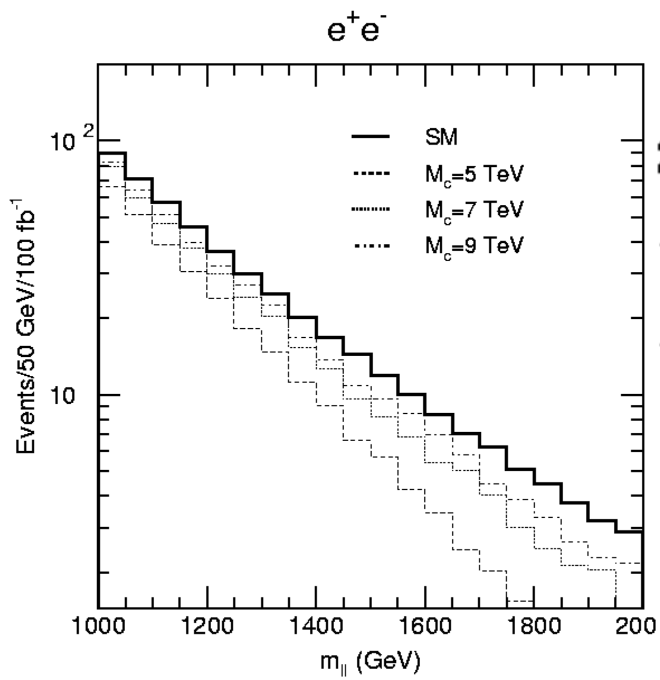
G. Azuelos, G. Polesello (Les Houches 2001 Workshop Proceedings)

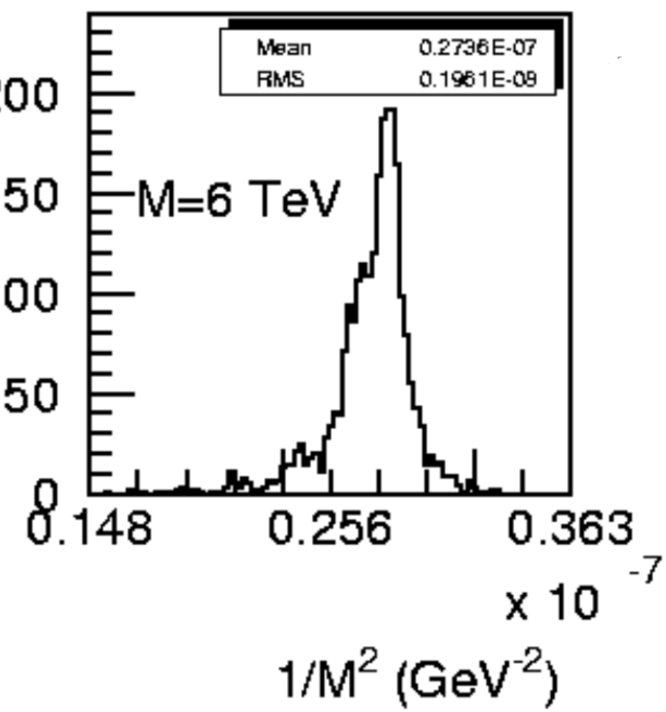
- fermions: open string excitations with ends stuck to brane
- gauge bosons though could also propagate in the bulk
- search for Kaluza-Klein resonances of *Z*, *etc.*

directly



or search for compactification mass in all data with likelihood technique



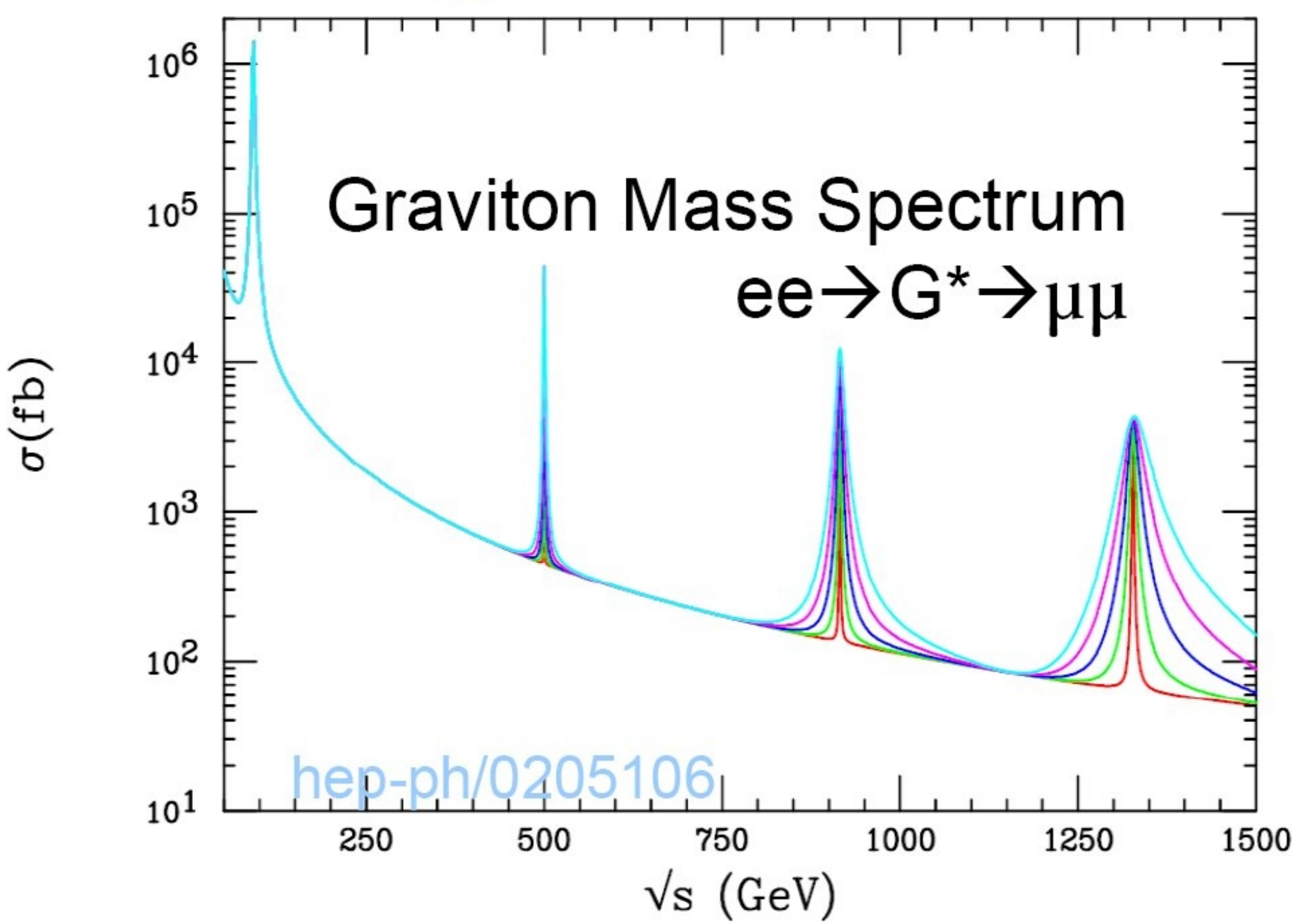


Searches for Extra Dimensions

Direct Search for graviton resonances (warped ED)

- generic search for any model with narrow graviton

$$gg(qq) \to G \to e^+e^-(\mu^+\mu^-)$$



Searches for Extra Dimensions

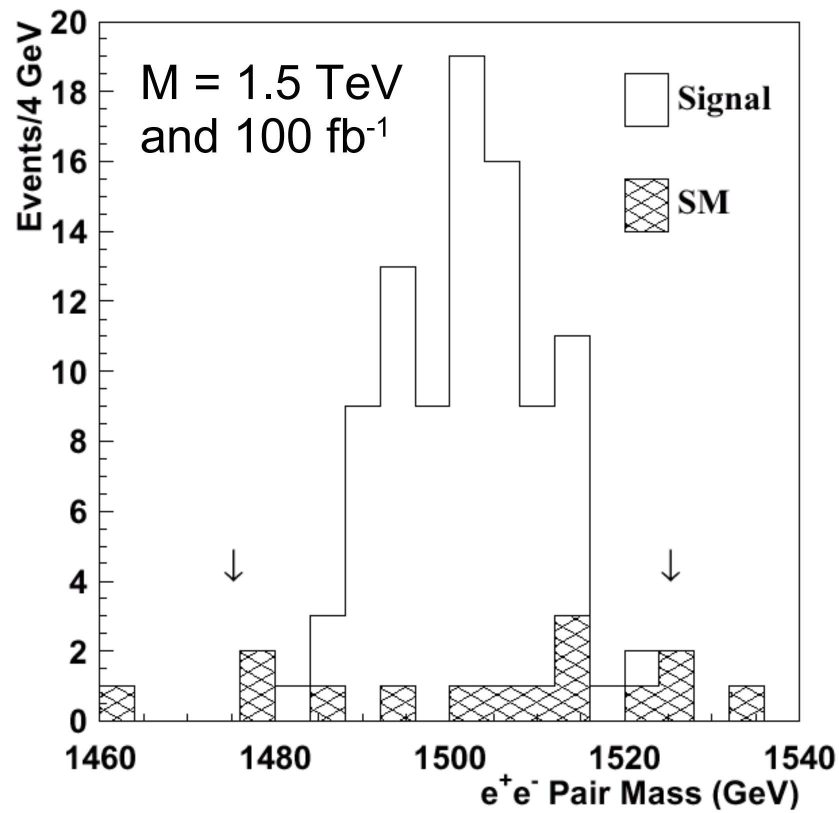
Direct Search for graviton resonances (warped ED)

- generic search for any model with narrow graviton

$$gg(qq) \rightarrow G \rightarrow e^+e^-$$

m_G (GeV)	Mass window (GeV)	N_S	N_B	$N_S^{\rm min}$ (fb)	$(\sigma \cdot B)^{\rm min}$
500	± 10.46	20750	816	142.9	1.941
1000	± 18.21	814	65	40.2	0.542
1500	± 24.37	84.3	11	16.5	0.235
1700	± 26.53	38.6	5.8	12.0	0.178
1800	± 27.42	27.2	4.3	10.4	0.156
1900	± 28.29	19.2	3.2	10.0	0.152
2000	± 28.76	13.2	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

in 100 fb^{-1}(minimum signal/σ for observation)



Sensitivity range: 0.5 – 2 TeV, depending on scenario

B.C. Allanach, K. Odagiri, M.A. Parker, B.R. Weber (JHEP 09 (2000) 019 – ATL-PHYS-2000-029)

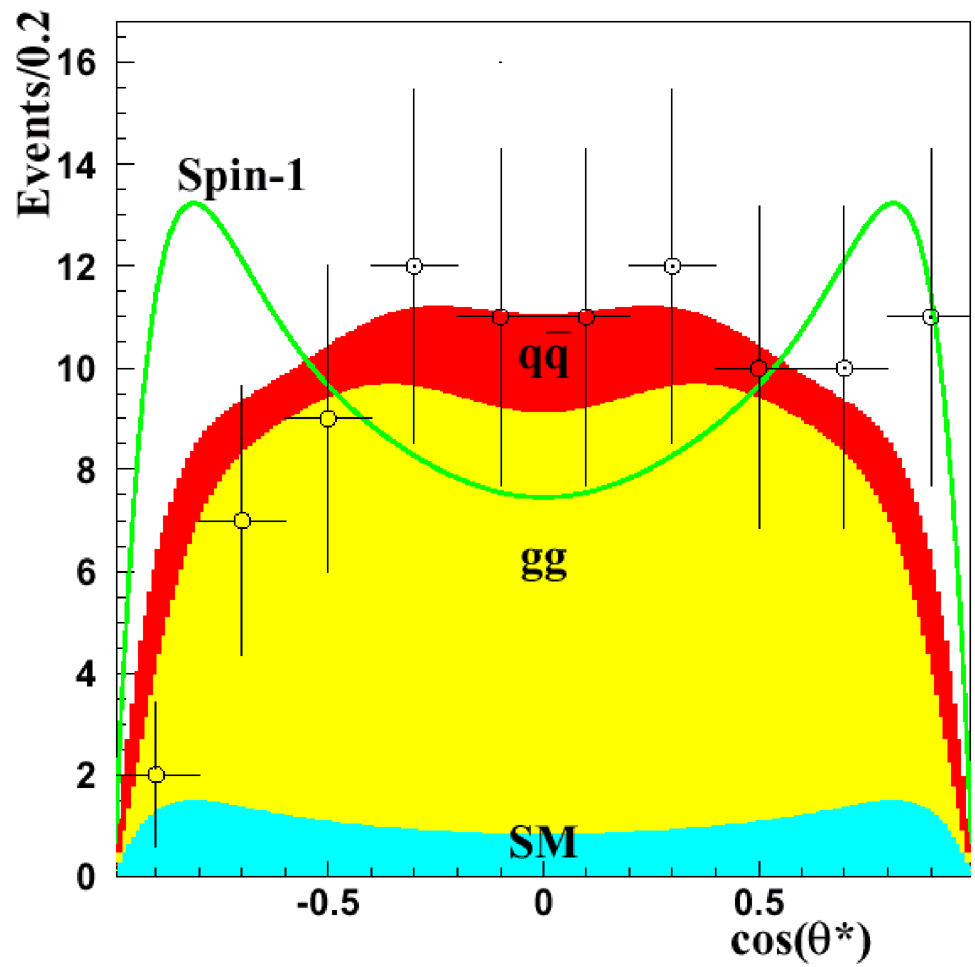
Searches for Extra Dimensions

Direct Search for graviton resonances

- generic search for any model with narrow graviton
- graviton spin = 2

Angular Distributions

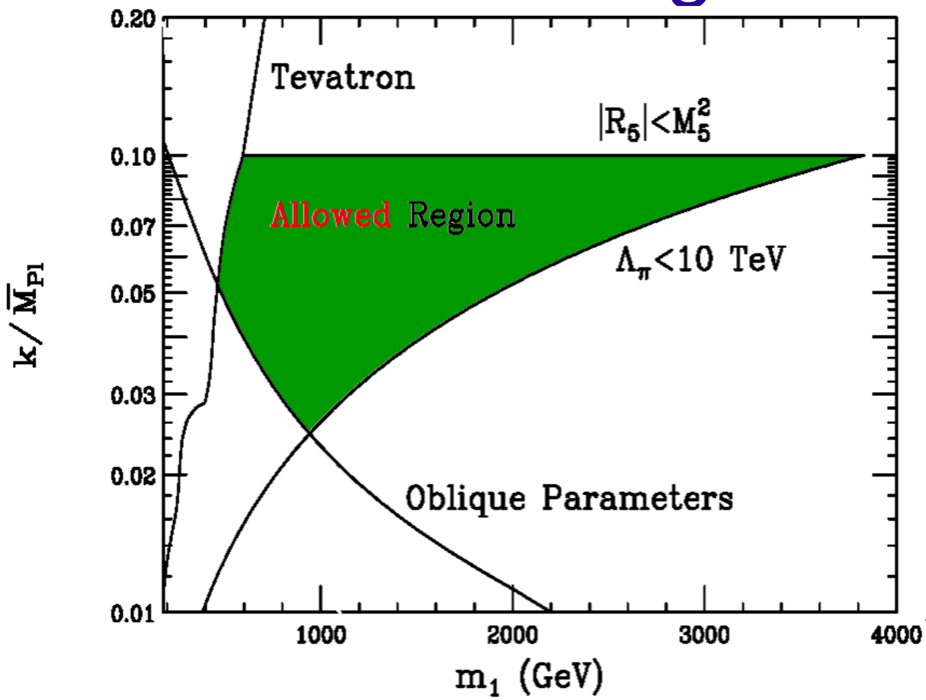
- $qq \to G \to ff: 1 - 3\cos^2\theta + 4\cos^4\theta$
- $gg \to G \to ff: 1 - \cos^4\theta$
- $qq \to G \to VV: 1 - \cos^4\theta$
- $gg \to G \to VV: 1 + 6\cos^2\theta + \cos^4\theta$
- DY background: $1 + \cos^2\theta$



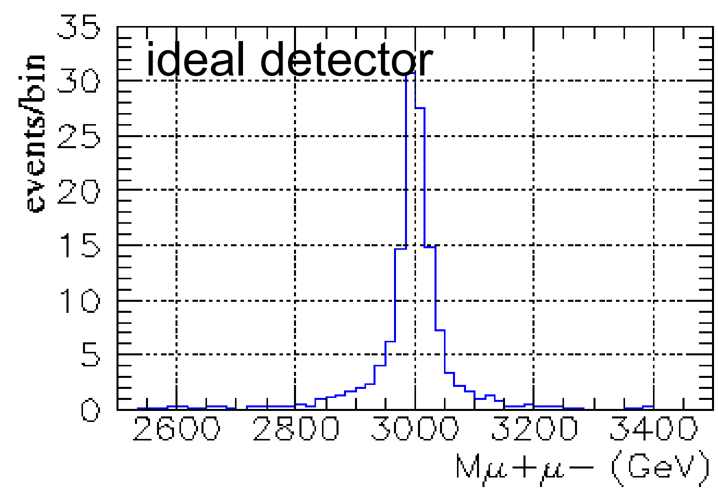
Atlas distinguishes spin 2 from spin 1 up to 1.72 TeV

Searches for Extra Dimensions

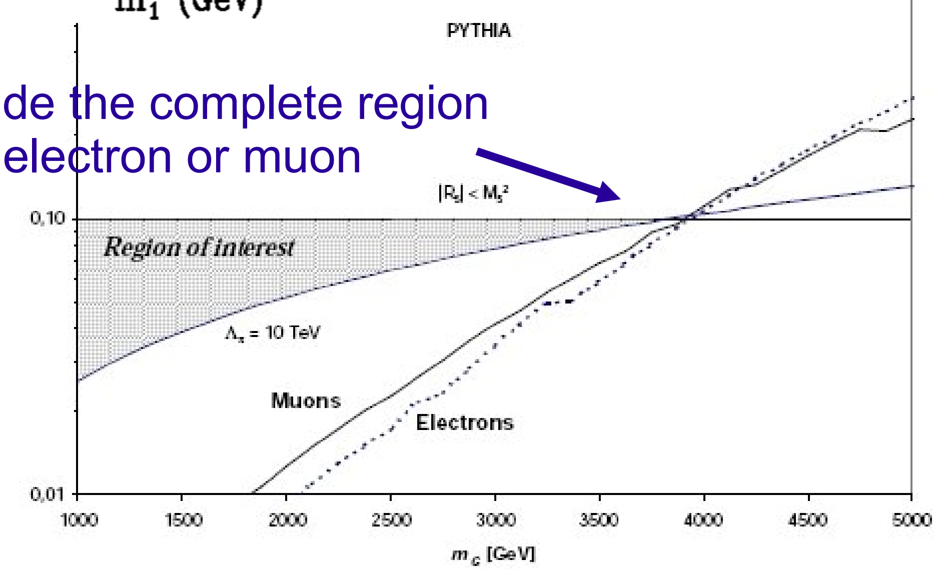
Direct Search for graviton resonances

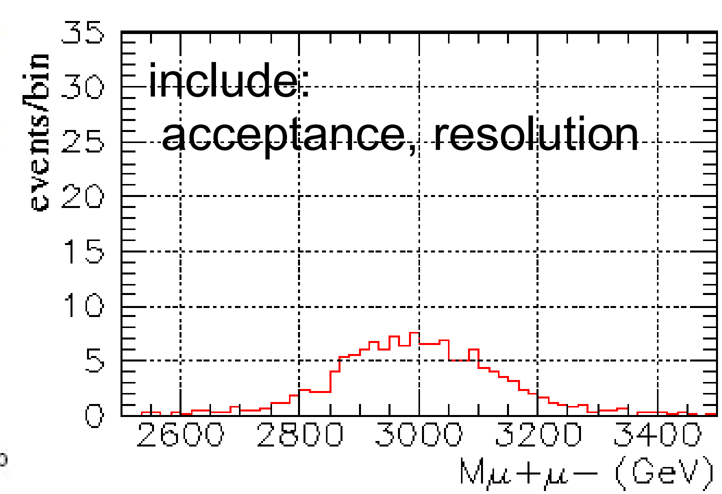


CMS detector performance



CMS can exclude the complete region of interest with electron or muon





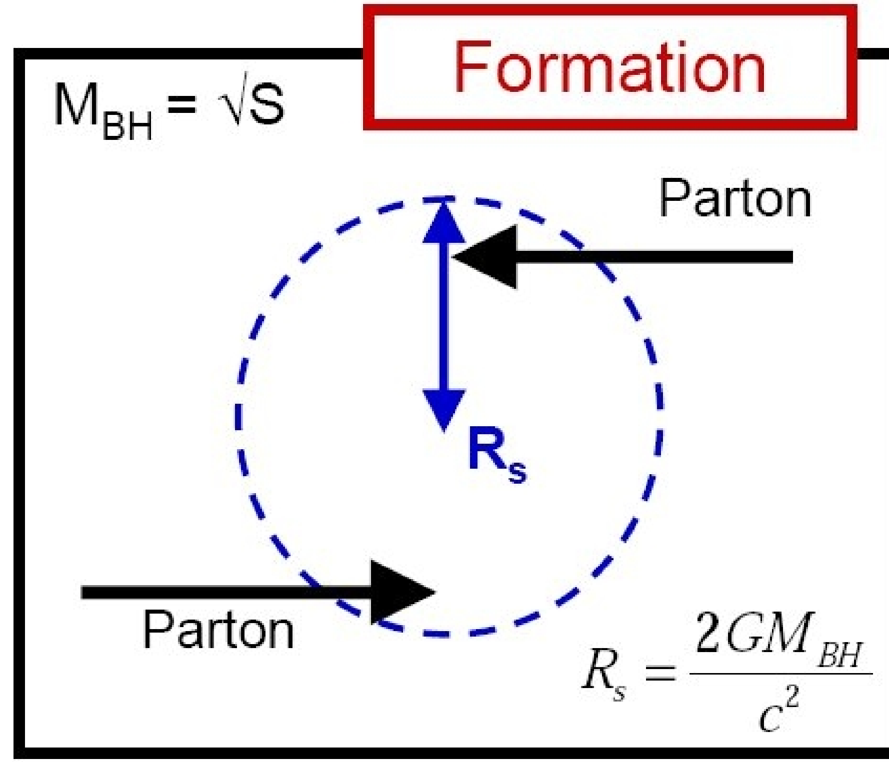
Searches for Micro Black Holes

Black Hole

Harris et al. JHEP (2005) 053

- enough mass at small enough radius to cause photon trapping, cross section:

$$\sigma \approx \pi R_S^2 \approx \mathcal{O}(100\text{ pb})$$



LHC should be a factory of black holes

- lifetime [sec]: $10^{-27} - 10^{-25}$
- decay through Hawking radiation
- equal prob. for all particles

Decay properties: ~ follows black body radiations

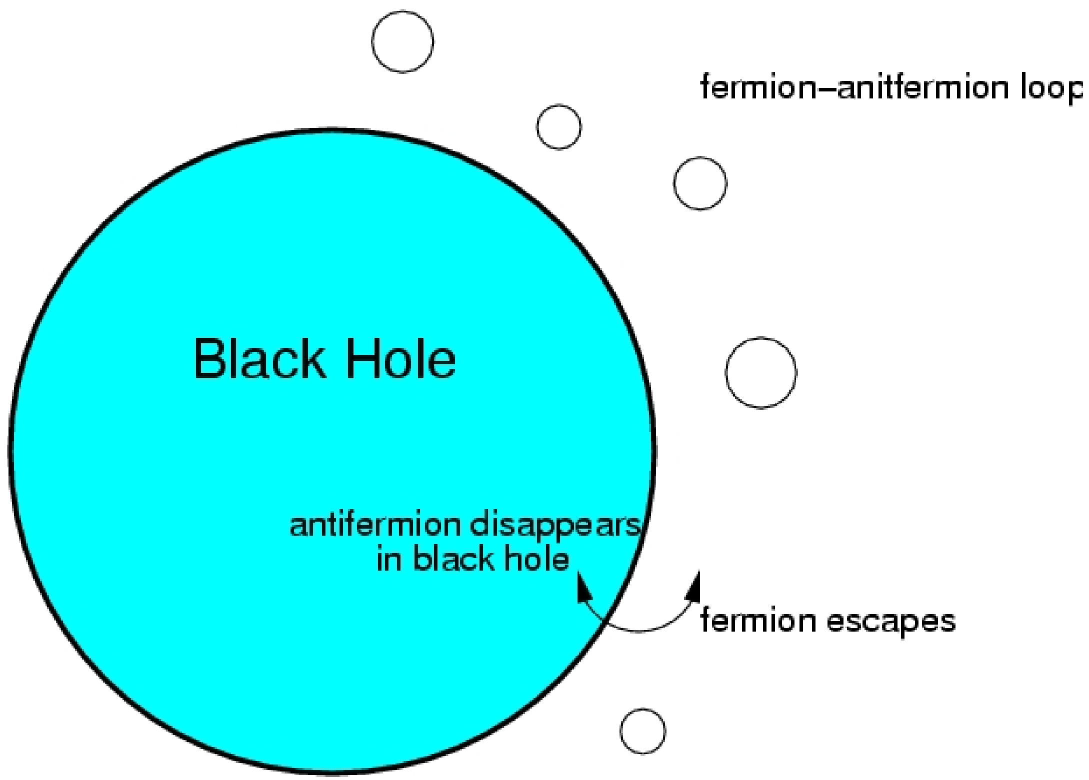
$$T_H = \frac{1+n}{4\pi R_{RB}} \approx \frac{1+n}{M_{BH}^{1/(1+n)}}$$

Hawking Radiation

What is it?

- thermal radiation of a Black Hole
- hmmm.... “Classically, the gravitation is so powerful that nothing, not even radiation or light can escape from the black hole..” so how can this happen?
- it is a quantum effect!

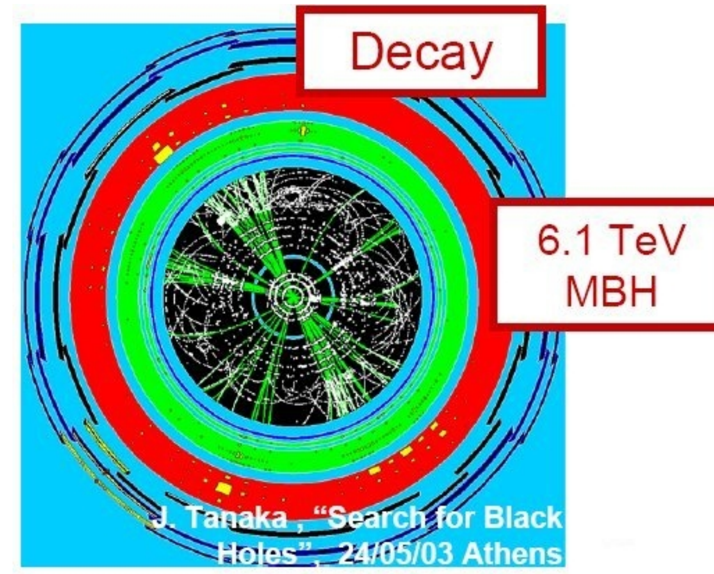
simplified example:
  anti-fermion disappears
  fermion escapes
  anti-fermion must have negative energy to conserve energy overall
  BH looses energy and evaporates

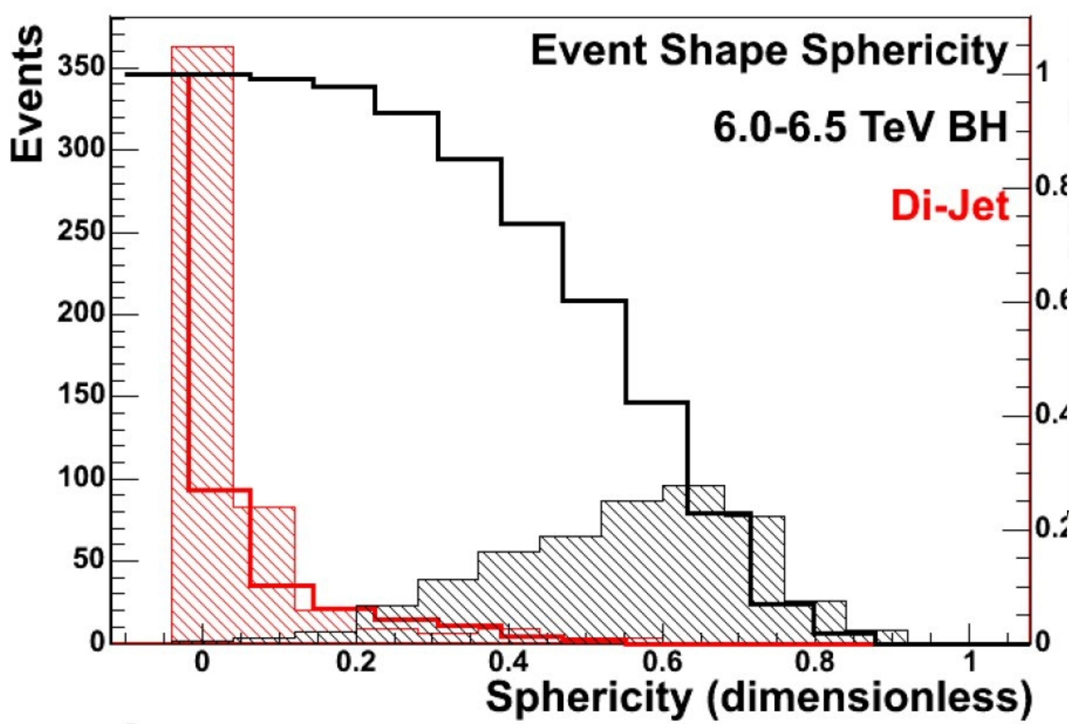


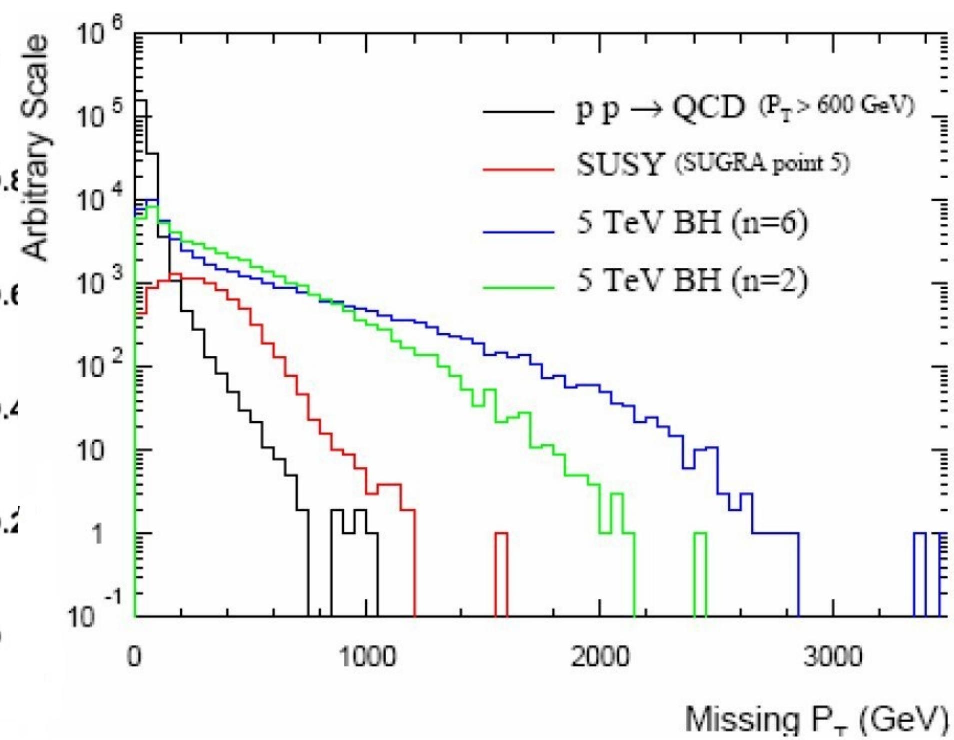
Searches for Micro Black Holes

Micro Black Hole – properties

- democratic decay
- high: multiplicity, sum E_T, sphericity, missing p_T
- LHC reach up to 1 TeV
- theory uncertainties are large







Conclusion

Extra dimensions

- offers a straight forward concept to join electromagnetic and gravitational force: add compact dimension(s)
  - Einstein equations + Maxwell equations + additional scalar field
- same overall coupling strength attained by letting gravitons travel through the compact dimensions
- large extra dimensions (flat geometry) through tubes or extra dimensions with warped metric inflating the length scale between Plank and SM brane
- clear experimental signatures: good potential to find them

Micro black holes

- should exist although observation depends on production mechanism which is not accurately known theoretically

Some utilities for the analysis were explained ....

Next Lecture

Review of

- Higgs Analysis outline and examples