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!
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\textsuperscript{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\textsuperscript{th} dimension stays small
- standing waves on 5\textsuperscript{th} dimensions can form: \( E = n \frac{h c}{R} \)
  - \( h \) – 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 $\delta$-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. $M_D = 1\text{TeV}$, means $R \sim 1\text{mm}$ (for $\delta=2$)

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

<table>
<thead>
<tr>
<th>Constraint</th>
<th>n=2</th>
<th>n=3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>max $R_D$ (mm)</td>
<td>min $M_D$ (TeV)</td>
</tr>
<tr>
<td>Gravity law</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Cooling of supernovae by emission of gravitons</td>
<td>$7 \times 10^{-4}$</td>
<td>10</td>
</tr>
<tr>
<td>Diffused background of cosmic rays ($G_{KK} \to \gamma\gamma$)</td>
<td>$9 \times 10^{-5}$</td>
<td>25</td>
</tr>
<tr>
<td>Heating of neutron stars (trapped $G_{KK}$ which decay)</td>
<td>$8 \times 10^{-6}$</td>
<td>90</td>
</tr>
<tr>
<td>LEP : $\gamma G$, $ZG$, virtual exchanges</td>
<td>$\sim 1$ TeV</td>
<td></td>
</tr>
<tr>
<td>Tevatron</td>
<td>$\sim 1$ TeV</td>
<td></td>
</tr>
</tbody>
</table>

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

careful: $n$ is what I call $\delta$ before
String Theory with Extra Dimensions

Warped metric

- 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:

\[ M_n = x_n k \exp(-k\pi R) \] with \( J_1(x_n) = 0 \)

\[ = x_n (k/M_{\text{Plank}}) \Lambda_\pi. \]
Searches for Extra Dimensions

Large extra dimensions

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

Atlas experiment

<table>
<thead>
<tr>
<th>$\delta$ (TeV)</th>
<th>$M_D$ (TeV)</th>
<th>Low luminosity, 30 fb$^{-1}$</th>
<th>High luminosity, 100 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Events</td>
<td>$S_{min}$</td>
<td>$S_{max}$</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>448</td>
<td>11.8</td>
</tr>
<tr>
<td>5</td>
<td>117</td>
<td>5.6</td>
<td>8.1</td>
</tr>
<tr>
<td>6</td>
<td>39</td>
<td>1.0</td>
<td>2.7</td>
</tr>
<tr>
<td>7</td>
<td>16</td>
<td>0.4</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 1. Number of remaining background events after the selection $E_T > 1$ TeV.
Searches for Extra Dimensions

Large extra dimensions: direct graviton search

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

\( S > 50 \) events, Signif.\(_{\text{max}}\) > 5
\( M_D^{\text{max}} = 7.7, 6.2, 5.2 \) for \( \delta = 2, 3, 4 \)

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

\( S > 100 \) events, Signif.\(_{\text{max}}\) > 5
\( M_D^{\text{max}} = 9.1, 7.0, 6.0 \) for \( \delta = 2, 3, 4 \)

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

C. Paus, LHC Physics: Extra Dimension Searches at the LHC
Searches for Extra Dimensions

Extra dimensions at TeV level

- 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

G. Azuelos, G. Polesello (Les Houches 2001 Workshop Proceedings)
Searches for Extra Dimensions

Direct Search for graviton resonances (warped ED)

- generic search for any model with narrow graviton

\[ gg(qq) \rightarrow G \rightarrow e^+ e^- (\mu^+ \mu^-) \]
Searches for Extra Dimensions

Direct Search for graviton resonances (warped ED)

- generic search for any model with narrow graviton

\[ gg(qq) \rightarrow G \rightarrow e^+ e^- \]

<table>
<thead>
<tr>
<th>( m_G ) (GeV)</th>
<th>Mass window (GeV)</th>
<th>( N_S )</th>
<th>( N_B )</th>
<th>( N_S^{\text{min}} ) (fb)</th>
<th>( (\sigma \cdot B)^{\text{min}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>±10.46</td>
<td>20750</td>
<td>816</td>
<td>142.9</td>
<td>1.941</td>
</tr>
<tr>
<td>1000</td>
<td>±18.21</td>
<td>814</td>
<td>65</td>
<td>40.2</td>
<td>0.542</td>
</tr>
<tr>
<td>1500</td>
<td>±24.37</td>
<td>84.3</td>
<td>11</td>
<td>16.5</td>
<td>0.235</td>
</tr>
<tr>
<td>1700</td>
<td>±26.53</td>
<td>38.6</td>
<td>5.8</td>
<td>12.0</td>
<td>0.178</td>
</tr>
<tr>
<td>1800</td>
<td>±27.42</td>
<td>27.2</td>
<td>4.3</td>
<td>10.4</td>
<td>0.156</td>
</tr>
<tr>
<td>1900</td>
<td>±28.29</td>
<td>19.2</td>
<td>3.2</td>
<td>10.0</td>
<td>0.152</td>
</tr>
<tr>
<td>2000</td>
<td>±28.76</td>
<td>13.2</td>
<td>2.3</td>
<td>10.0</td>
<td>0.157</td>
</tr>
<tr>
<td>2100</td>
<td>±30.55</td>
<td>9.4</td>
<td>1.8</td>
<td>10.0</td>
<td>0.159</td>
</tr>
<tr>
<td>2200</td>
<td>±31.46</td>
<td>6.8</td>
<td>1.4</td>
<td>10.0</td>
<td>0.162</td>
</tr>
</tbody>
</table>

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

Sensitivity range: 0.5 – 2 TeV, depending on scenario


C.Paus, LHC Physics: Extra Dimension Searches at the LHC
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 can exclude the complete region of interest with electron or muon

CMS detector performance
Searches for Micro Black Holes

Black Hole

- 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
- hmmmm.... “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

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**Event Shape Sphericity**

- **6.0-6.5 TeV BH**
- **Di-Jet**

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**Missing $P_T$ (GeV)**

- $p p \rightarrow$ QCD ($P_T > 600$ GeV)
- SUSY (SUGRA point 5)
- 5 TeV BH (n=6)
- 5 TeV BH (n=2)
Conclusion

Extra dimensions

- offers a straightforward 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 Planck 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