Extra-dimensional Physics

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Why Consider Extra D?

- String theory: at least six unseen dims
- General Relativity: why 4?
- New ways of approaching old problems
  - Cosmology: still many unanswered questions
  - Hierarchy, flavor, GUTs
Key New Features

- Particles can be separated in extra dimensions—e.g.: protects against FCNC’s
- New length scales: size and curvature
- New scenarios for strongly interacting theories
What do extra dimensions look like?
How many?
What shape?
How big are they?
Are they all the same?
We don’t know how many

Up to six (seven?) in string theory

But for particle physics, we’re only interested in ones that are bigger than the Planck scale

You might have thought only very big ones have observable consequences but not true...

Even small dimensions can constrain interactions and therefore predictions
Extra dimension can be curled up
Can be simple (circle, torus)
Complicated (Calabi-Yau)
They can be bounded between branes
They can be flat or they can be warped
Depends on energy—Einstein’s Eqns
Size Limit?

- Depends on set-up
- Bounds come from Kaluza-Klein (KK) modes
- Fingerprints of extra dimensions
- From a 4D perspective, they are particles with extra-dimensional momentum
- KK masses depend on quantized values of momenta
KK Modes

- Particles with extra-dimensional momentum

- For compactification on a circle

\[ p = \frac{n}{R} \]

\[ m^2 = m_0^2 + \frac{n^2}{R^2} \]
What to Look For

- If extra dimension near experimental bound
- And particles are in the bulk
- You will see heavy partners of all particles
- Partners of the electron will be fermions
- Not bosons as in SUSY
- Partners should all have similar masses
- If very lucky, would see more than one
- Would then be easier to test extra dim hypothesis
Bound on Extra dimension

- If flat extra dimension of size $r$
- $m \sim 1/r, 2/r, 3/r, \ldots$
- If all particles are in the bulk
- All particles would have KK partners
- We haven’t seen additional charged particles up to $m \sim TeV$
- Extra dimensions have to be smaller than $10^{-17}$
With Branes?

- Space can be bounded between branes; not rolled-up
- More importantly for expt
- Particles can be confined to branes
- Arkani-Hamed, Dimopoulos, Dvali (ADD) looked at extreme situation
- Everything but gravity on a brane
Gravity different

Gravity has to be in the bulk:

- Gravity-geometry connection
- GR: all sources of energy influence gravity
- String theory: open strings vs. closed-strings
SM Particles on Branes

- All bounds come from gravity
- Adelberger-Heckel Eot-Wash experiment puts bound at about 0.2 mm
- Current bound on size
Branes that Distort Space

- Bound on extra dimension’s size changes when branes and the bulk carry energy
- They can distort space
- In fact, so much that an infinite extra dimension is possible
- Gravitational field (and graviton) get localized near a brane
DIFFERENT brane scenario: Warped Geometry

- \( ds^2 = e^{-kr}(-dt^2 + dx^2) + dr^2 \)
Warped Geometry and Size Bound

- With warped geometry, extra dimension can be infinite
- Gravity and graviton localized in region depending on curvature

**SUMMARY:**

- No branes: $10^{-17}$ cm
- With branes, 0.2 cm
- With branes and curvature: infinite!
Extra Dimensions and PP

- Hierarchy Problem
  - Question of why gravity is so weak
  - With extra dimensions, new explanations
- ADD: gravity is diluted in an extra dimension
- RS1: space is warped so gravity is weak in some places but not in others
- $M_{pl}^2 = M_*^{n+2} R^n$
- To address hierarchy, $M_* \sim \text{TeV}$
- $R$ large to get big Planck mass
- How large depends on number of $d$
  - $n=1$: billion km (nope)
  - $n=2$: mm (marginal)
  - $n=3$: nm (OK)
  - $n=6$: 10 fm (fine)
  - ...
How to Find Them?

- Look for KK modes
- But KK modes only couple with gravitational strength
- Gravity, astrophysical tests
- Also colliders: there are a lot of them!
- \( \sigma \sim \frac{1}{M_{Pl}^2} (ER)^n \)
- \( \sim \frac{1}{M_*^2} (E/M_*)^n \)
- When \( E \sim \text{TeV} \), substantial KK production
quantum gravity at colliders

because we are on a brane, 2 SM particles can collide to produce a single massive graviton

\[ G_{\mu\nu} f_i f_j \]

\[ g^{\alpha}(n) a \]

\[ g^{\beta}(k_1) b \]

\[ g^{\gamma}(k_2) c \]

the graviton “escapes” into the extra dimensions

Searches for monojet and missing energy signature: present and future
RS1

- Add another brane to warped scenario

Planck brane: Gravitybrane

TeV brane: Weak brane:
RS1

- No large dimension necessary to explain weakness of gravity
- Graviton’s interaction is \textit{exponentially} suppressed away from “Gravitybrane”
- Gravity is weak everywhere except Gravitybrane
- Mass hierarchy \textit{natural} on Weakbrane!
Another way to see that hierarchy is natural is to rescale.

Since only a single graviton with only a single interaction strength.

Can reproduce suppressed graviton amplitude by rescaling all masses.

In other words, TeV mass natural on Weakbrane.

In fact, all masses should be TeV.

KK modes, 5D black holes, strong gauge interactions.
RS1 Signatures

- Experimental consequences very distinctive
- KK modes interact not with Planck-suppressed interactions
- TeV-suppressed interactions!
- Means resonances produced and decay in detector
- Will look like true resonances—
- If we’re lucky, we can even see they are spin-2.
- Very dramatic signals if RS1 correct
collider signals would be dramatically different

Figure 4: The cross section for $e^+e^- \rightarrow \mu^+\mu^-$ including the exchange of a KK tower of gravitons in the Randall-Sundrum model with $m_1 = 500$ GeV. The curves correspond to $k/M_{Pl}$ in the range $0.01 - 0.05$. 

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Angular distributions

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

- Unlike ADD, RS1 dimension is not very big.
- That means gauge interactions, particles can be in the bulk.
- If that’s true, there will be KK resonances of charged particles too (not just graviton).
- Furthermore, can get unification in this picture.
- TeV max energy on Weakbrane but energies up to Planck energy explored in bulk.
**New Topic: Sequestering**

- Extra dimensions have potential to address other problems as well.
- So far, we’ve exploited new distance scales and geometry.
- But simple fact that particles can be separated can also have important consequences.
- For supersymmetry, for example.
Two branes: SUSY broken on 2nd
Gaugino Masses: Different!

\[ M_i = -b_i g_i^2 M_{SUSY} \, . \]

Gluino

WEIRD SPECTRUM

Photino

150 GeV

Charged Wino
Neutral wino

WINO

LSP
FIG. 1. The mass splitting $\Delta M \equiv m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ and decay lengths $\sigma\tau$ in the $(\mu, M_2)$ plane. (a) The anomaly-mediated relation $M_1 \approx 3.3 M_2$ is assumed, and $\tan \beta = 10$. Similar results are obtained for $\mu > 0$. The discovery region for trigger II is shown. (See text.) (b) The same for a more general Wino LSP model, with $\tan \beta = 3$ and $M_1 = -1.5 M_2$, along with the discovery reach for triggers I – III. (See text.)
Can search for winos now! Signature of extra dimension—even though very small

Very hard to get this spectrum without extra dimensions.
Search

- Look for short stopped tracks
- Evidence of Wino LSP
- With near degeneracy of charged, neutral states
- Also new ways to look for dark matter
- Winos interact more strongly
  - Extra dim even give new ideas for SUSY-
  - And new ways to search!
Conclusions

- Just a sample of new ideas
- Lots of possibilities with extra dimensions
- More to come (next talk...)
- Distinctive experimental signatures
- Pays off to think about how to find them
- Will be useful, no matter what turns out to be there