The Search for Maximal Weirdness

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Outline:

1. String theory, branes, and extra dimensions
2. Collider signals of extra dimensions
3. Randall-Sundrum theory
4. Gravity-in-a-box
5. Holography and the braneworld

String Theory Unbound

To what extent can we use string theory as a guide/prognosticator of Beyond-the-SM phenomenology?

- Problem: string theory has a huge number of stable consistent vacuum states, giving wildly different low energy physics.

- Some day string theory will indeed correlate in deep ways the parameters of the effective theory that we have measured in experiments.

- This requires understanding string theory at a more fundamental level, as well as mapping out the moduli space of its possible vacuum states.

- Meanwhile, string theory is already affecting our thinking about Beyond the Standard Model physics. This influence is of two types:

  - Suggesting new physics possibilities or scenarios which would seem unmotivated (i.e. wacko) otherwise.
  - Making connections between new physics ideas which seem unrelated from a conventional field theory perspective.

- In the bottom up approach, we isolate certain aspects, ideas, and degrees of freedom of string theory and ignore the rest.

- This is certainly much easier than doing real string theory, although this game can also be played in string theory by taking advantage of special decoupling and/or simplifying limits.

- At any rate this is a productive and probably not too misguided strategy.

- Of course a prime example of this strategy are the braneworld extra dimensions scenarios.

- These scenarios involve at least two new kinds of Beyond-the-SM degrees of freedom:

  - Kaluza-Klein (KK) modes for particles in the bulk, and

  - Brane fluctuation modes.

- Experiments measure an effective KK mode spectral density $\rho(m^2)$, where the KK mass m^2 is just the total of the squared momentum components transverse to the brane. This density $\rho(m^2)$ depends both on the geometry of the extra dimensions, and on wave function suppression of the couplings.

• Branes have gauge theories "trapped" on their worldvolumes. E.g. :

$$S_{\text{brane}} = -f^4 \int d^4x \, \sqrt{\det\left[\gamma^\mu_\nu + 2\pi\alpha' F^\mu_\nu\right]}$$

where f^4 is the brane tension, and $\gamma_{\mu\nu}$ is the induced metric, which can be expressed as:

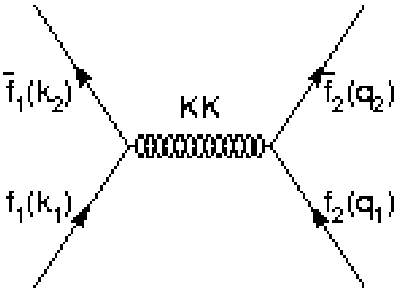
$$\gamma_{\mu\nu} = \partial_\mu Y^M \partial_\nu Y^N \, g_{MN}$$

We can parametrize the worldvolume such that

$$Y^\mu = x^\mu \; ; \qquad Y^m = \phi^m$$

where the scalar fields are the branons, the brane fluctuation modes.

• Note when we turn off brane fluctuations ($f \to \infty$)the couplings to KK modes do not conserve KK momentum. E.g. suppose two SM particles on the brane exchange a $d = 4 + n$ bulk graviton:



Let $p_i \equiv (k_1 - k_2)$, $p_f \equiv (q_1 - q_2)$. So:

$$i\mathcal{M} = \int d^4x\, d^4y\, \left[-iT_i^{\mu\nu} \mathrm{e}^{ip_i\cdot x}\right] \int d^{4+n}p\, \frac{iP_{\mu\nu\rho\lambda}}{p^2 + i\epsilon} \mathrm{e}^{ip\cdot(x-y)} \times \left[-iT_f^{\rho\lambda} \mathrm{e}^{ip_f\cdot y}\right]$$

where, in harmonic gauge:

$$P_{MNPQ} = \frac{1}{2}\left(\eta_{MP}\eta_{NQ} + \eta_{MQ}\eta_{NP}\right) - \frac{1}{2+n}\eta_{MN}\eta_{PQ}$$

Since $\int d^4x\, d^4y$ only enforces 4d momentum conservation we get:

$$i\mathcal{M} = \left[-iT_i^{\mu\nu}\right] \sum_n \frac{iP_{\mu\nu\rho\lambda}}{(p_i)^2 + (p_n)^2 + i\epsilon} \left[-iT_f^{\rho\lambda}\right] \delta^4(p_i - p_f)$$

For finite brane tension KK monentum conservation is restored via the branon dynamics.

M. Bando, T. Kugo, T. Noguchi, K. Yoshioka

- More precisely, the KK mode expansions of the bulk fields coupling to brane fields contain factors

$$\mathrm{e}^{i\frac{n}{R}\phi(x)} = :\mathrm{e}^{i\frac{n}{R}\phi(x)}:\mathrm{e}^{-\frac{1}{2}(\frac{n}{R})^2\frac{1}{f^4 l_s^2}}$$

where l_s is the UV regulator of the ϕ propagator.

- There are two ways at interpreting this Gaussian factor:
  - It is a delta sequence which (with the appropriate factors out front) becomes the delta function enforcing KK monentum conservation as $f \to 0$.
  - The Gaussian factor represents the UV softening of the effective KK spectral density for the bulk modes, due to their coupling to an extended object (the brane).

Wittgenstein was right

• So in this picture, it appears we live in a world consisting of the elementary particles of the SM, plus KK modes, branes, and strings.

• But, one thing string theory is teaching us is that it is difficult to formulate unambigious definitions of simple concepts, like "table", or "elementary particle".

• Some of this has to with the deep principles of duality and of holography...

Holography

(G. 't Hooft; L. Susskind)

- The existence of black holes suggests that somehow, at the most basic level, quantum information is encoded holographically.
- The first concrete realization of quantum holography is Maldacena's AdS/CFT correspondence. At low energies, this relates 5d AdS bulk gravity (weakly coupled) to a strongly coupled 4d conformally invariant gauge theory on the AdS boundary.
- The Randall-Sundrum warped gravity scenario is a generalization of this holographic duality.
- In the basic Randall-Sundrum set-up with a single brane, physics as observed on the brane has a purely 4d holographic description:

(Maldacena; Witten; Gubser; Giddings, Katz, Randall; Hawking, Hertog, Reall; Giddings, Katz; Arkani-Hamed)

$$S_{\rm holo} = \int d^4x\,\sqrt{-\gamma}\,\left[-\tau + \mathcal{L}_{\rm brane}(\gamma,\psi) + \mathcal{L}_{\rm CFT}(\gamma,\chi) + \mathcal{L}_{\rm grav}(\gamma)\right]$$

- This describes 4d brane matter coupled to a "hidden sector" 4d CFT via 4d gravity.

- The 4d CFT has a UV cutoff, reflecting the fact that the brane is not at the AdS boundary. Thus it is an effective 4d CFT, nonlocal due to the coarse-graining.
- We can compute the stress tensor of the effective 4d CFT:
  - Use the 5d Einstein eqns to compute the gravitational disturbance on the Planck brane of some particular 5d bulk physics.
  - Reverse engineer the 4d Einstein eqns on the Planck brane, to compute what effective 4d stress tensor would give an equivalent gravitational disturbance.
- This leads to weird dual descriptions: e.g. a particle which detaches itself from the brane and falls off into the bulk, is dual to a an expanding smooth shell of CFT matter on the brane.

Compositeness and nonlocality

- Indeed this network of ideas seems to be telling us something important about the role of compositeness and of nonlocality:

- Interesting new versions of compositeness are popping up in various new strong coupling regimes (B. Dobrescu; A. Nelson and M. Strassler, N. Arkani-Hamed,...).

- Nonlocal effects on potentially observable scales are also popping up all over (see e.g. J. Hewett's talk).

- I will discuss one unusually weird manifestation of both these concepts...

Elementary particles as black holes

- Our understanding of black hole physics has greatly advanced by considering branes as microscopic (extremal, extra-dimensional) limits of black holes. So black holes $\Leftrightarrow$ branes.

- D-branes appear as special BPS solitons in certain limits of string theory. They include DØ branes, particle-like objects. Because they are BPS, the spectrum of n bound DØ branes looks like a tower of evenly spaced massive modes - in fact they are the KK modes of the 11th dimension of M-theory. So particles $\Leftrightarrow$ solitons $\Leftrightarrow$ KK modes.

- Are all elementary particles in some sense black holes?

L. Susskind, ...

- Suppose we consider particle collisions at superPlanckian energies. Here "Planck" is the effective Planck scale M_*, which could be just a few TeV.
- Roughly speaking, if the impact parameter b is smaller than or of the order of

$$b \sim \sqrt{s}/M_*^2$$

then a black hole will form. Thus a high energy point particle becomes an object with finite transverse "size" b.

- The Compton wavelength *decreases* with increasing energy, while the transverse "size" *increases* with increasing energy.
- Energy growing with size sounds like strings or branes.

Maximal Weirdness

- It now appears in string theory that there are examples where "particles" acquire a transverse size at high energies:
- E.g. "Attack of the giant gravitons from Anti de Sitter space" (J. McGreevy, L. Susskind, N. Toumbas).
- E.g. Wrapped branes in warped compactifications of M theory or string theory (E. Silverstein).

In the second case, we compactify 11 dim Horava-Witten theory on a K3 surface, and wrap a 2-brane on a cycle of the K3 with some area A_0. The geometry is warped along the 11th dimension (call this coordinate y).

• The wrapped brane should look almost like a point particle to us, with some fuzziness in its size of order the UV cutoff l_{11}. Taking into account the warping, it has energy

$$E = y^{1/2}\,\frac{A_0}{l_{11}^3}$$

Taking into account the warping, its transverse size is

$$R = y^{1/6}\,l_{11}$$

So this object has a brane-like energy/size relation:

$$E \propto R^3$$

• In fact, this object is neither a point particle nor a brane, rather it is something in between.

• You can see this by counting states. Compute the KK modes (with respect to the warped direction y) of the wrapped 2-brane. The scalar KK modes are the solutions of a 1 dim Schrodinger eqn with a potential which is approximately quadratic. The KK modes are discrete with

$$E^4 \propto (n + 1/2)$$

• The number of these KK states increases like E^4, compared to $n \propto E$ for a point particle! On the other hand, for a brane (or any extended object), the number of states increase exponentially with energy.

• These new objects are called elastic states (nylons).

Phenomenology

- Could there be accessible regimes where what you thought were point particles turn into nylons?
- Linear colliders are a good way to look for this!
- Note this is not like the usual quark/lepton compositeness, since there (presumably) aren't any bound pointlike constituents. You don't necessarily generate the 4-fermion terms of Eichten-Lane-Peskin, just form factors:

$$\frac{d\sigma}{dQ^2} = \left(\frac{d\sigma}{dQ^2}\right)_{SM} \cdot F_e^2(Q^2) \cdot F_f^2(Q^2),$$

where

$$F(Q^2) = 1 + \frac{1}{6}Q^2 R^2$$

The current best limits on this "electron radius" appear to be from LEP (D. Bourilkov):

$$R_e < 2.8 \cdot 10^{-17}\text{cm}$$