PARTICLE PHYSICS

Do the space-warp

There is good reason to suppose that the Universe has more than three spatial dimensions. The first dedicated search for warped extra dimensions has drawn a blank, but hopes are high for the future.

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With a couple of notable and distinguished exceptions, fundamental science has usually progressed through experimental discoveries, followed later by theoretical enlightenment. Einstein's general theory of relativity is often cited as one of the exceptions to the rule. In the past couple of decades, however, the standard model of particle physics has also overtaken experiment by successfully predicting what is later observed. Theories with extra dimensions of space could follow suit, but results[1] from the D0 experiment at Fermilab, Chicago — presented in *Physical Review Letters* — show that any additional gravitational force tied to the existence of such dimensions must be weak.

The standard model's diverse predictions have been verified to a high level of accuracy. But there is a problem. The mechanism for the generation of mass in the standard model has an ugly feature: through quantum fluctuations into the heaviest particles that exist, matter could become much heavier than it is. Back-of-the-envelope calculations worryingly suggest that it could become 10^{14} times too heavy.

To fix the mass problem, Randall and Sundrum[2] invented a scenario in which all of our matter is stuck on a three-dimensional surface in a four-dimensional space. The region we are stuck in is called a 'brane'. Gravity is not stuck to the brane, it feels the effects of the extra dimension, which is actually very small (about 10^{-35} m). At the other end of the extra dimension is another brane where everything is much heavier than on our brane: about 10^{14} times heavier, in fact. The extra dimension is warped: its length scale gets exponentially larger the nearer one gets to our brane.

It is this warping effect that purports to solve the mass problem. On the brane at the other side of the extra dimension to us (known as the Planck brane), any particle masses are ultra-heavy. But if you work out what happens to their masses along the extra dimension, it turns out that they are warped down to much smaller masses on our brane. It's easy to demand in such a model that the warping is about the right amount to produce the masses we observe.

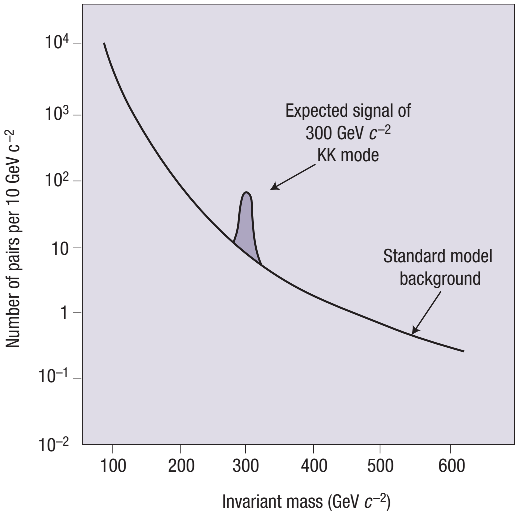

Figure 1 The signature of a graviton. The number of electron–antielectron and photon–photon pairs detected by the D0 experiment[1] as a function of the invariant mass of the pair is a smooth distribution, following the expectation from the standard model. As an example, the superimposed peak shows the signal expected if a graviton (Kaluza–Klein mode) exists with mass 300 GeV c^{-2}. There is as yet no evidence of a graviton in the D0 data. (Figure derived from ref. 1.)

This idea has now been tested at the Tevatron, Fermilab's 2-TeV proton–antiproton collider. The D0 detector, positioned at a collision point, is a large and sophisticated machine that effectively takes an electronic snapshot of the particles that emerge. Every collision is a quantum event, implying that many different final states occur on a probabilistic basis: the statistical properties of the events must be measured to deduce facts about the underlying physical processes.

If nature is like the Randall–Sundrum model, the high-energy collisions could produce a heavy mode of the graviton, called a Kaluza–Klein (or KK) mode, which couples to matter more strongly than ordinary gravity does. However, the additional gravitational force that arises from the KK mode is so short-range that it would not affect any observations of macroscopic gravity. The KK mode created in high-energy collisions would immediately decay into a particle and an antiparticle. Although the existence of the KK mode is too fleeting to be seen directly, the D0 team hoped to be able to infer its presence by measuring the particle–antiparticle pair.

The team searched their data for electron–antielectron, muon–antimuon and photon–photon pairs. Such pairs can, however, be produced by decays of ordinary particles — a *Z* boson, for instance. When the number of pairs seen is plotted as a function of the invariant mass of the pair (related to their energy and momenta), the distribution falls off steadily above an invariant mass of 100 GeV c^{-2}. But if some pairs are produced by the KK mode, the invariant mass of those pairs is close to the mass of the heavy graviton, creating a tell-tale bump in the spectrum (Fig. 1).

No bump was seen in the D0 data[1], meaning that gravitons lighter than 600 GeV c^{-2} do not exist. It is possible, however, that gravitons have masses of up to several TeV c^{-2} and that the experiment has not collected enough data yet to see them. The Tevatron collider is still running, so the sensitivity of this search will increase when more data are added to the analysis. Even if no KK modes are observed by the Tevatron experiments (D0 and its sister detector CDF), CERN's Large Hadron Collider will be able effectively to cover all of the interesting mass range for these particles. The LHC, due to begin operation in mid-2007, will collide protons with protons at an energy seven times that of the Tevatron, and thus could produce KK modes several times heavier.

What would happen if a bump were discovered in the invariant-mass distribution? After the champagne had been drunk, there would be a lot of work to do. A bump in the distribution is not conclusive proof of a KK mode of a graviton — it might be caused by some other new heavy particle. But there are some properties of graviton KK modes that distinguish them from other possibilities, the most important being that they have two units of spin (double the spin of the *Z* boson). This is manifest in the probability distribution for the angles at which particles are produced in the decay, which can be measured to confirm that the decaying object is spin-2.

Such a discovery would revolutionize particle physics: not only would the reason for light matter be found, but for the first time experiments could study a quantum gravitational force.

REFERENCES

1. Abazov, V. M. *et al.* (D0 collaboration) *Phys. Rev. Lett.* **95,** 091801 (2005).
2. Randall, L. & Sundrum, R . *Phys. Rev. Lett.* **83,** 3370–3373 (1999).