How to Find the Fifth Dimension

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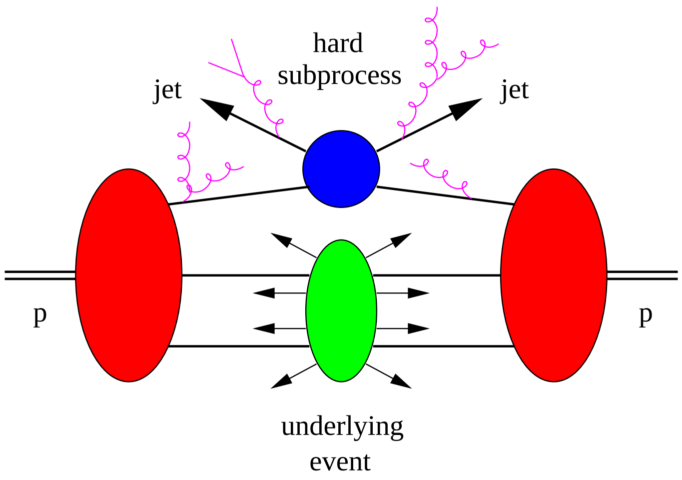
In 2006 the Large Hadron Collider (LHC) will start operating at CERN in Geneva. The LHC is arguably the largest machine ever built. Amongst many other components, it has a 27-kilometre ring of superconducting magnets cooled by 700,000 litres of liquid helium. It will produce head-on collisions between beams of protons with energies of 7 TeV (tera-electron-volts), almost eight thousand times their rest energy mc^2. The kinetic energy of each beam will be equal to that of a 200 ton train travelling at 200 km/hour, squeezed into a beam-spot 30 μm in diameter.

What is the purpose of such a huge machine? The so-called Standard Model of particle physics, which accounts for all known phenomena in terms of three "generations" of quarks and leptons interacting via four fundamental forces, has now been verified with impressive precision. However, the Standard Model has a plethora of parameters that have to be fed in from experiment: particle masses, interaction strengths, etc. Many competing theoretical ideas seek to explain these parameters in terms of more fundamental concepts. Such theoretical speculations are highly constrained by data from precision experiments at lower energies, especially those at the CERN Large Electron Positron (LEP) collider, the previous inhabitant of the LHC tunnel. The theories that can satisfy these constraints generally predict that phenomena outside the framework of the Standard Model will start to appear in the new range of energies accessible at the LHC.

The question my colleagues and I have been addressing over the past few years is this: Given any particular theory of physics beyond the Standard Model, what precisely is expected to happen at the LHC? And how could one most effectively test such a theory and measure its parameters? We have developed computer programs for this purpose, which can simulate all aspects of high-energy particle collisions, not only according to the Standard Model but also in a wide range of more fundamental theories. The aim of these simulations is to help us to refine the theories, the design of the LHC experiments, and the strategies for analysing the data.

The simulation of high-energy particle collisions is complicated by the fact that each collision event has several components:

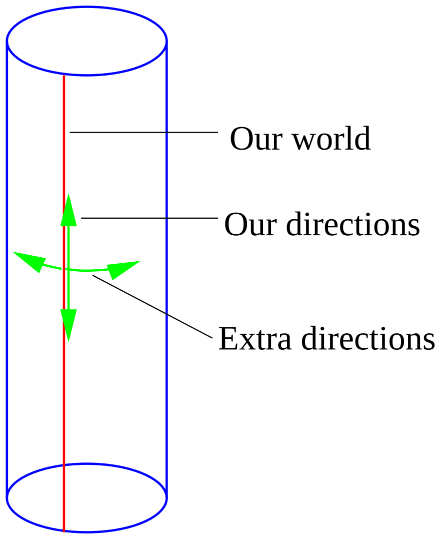


- The distributions of the constituent quarks, antiquarks and gluons inside the incoming protons;
- The "hard subprocess", a collision between constituents in which there is a large transfer of momentum – this is where new physics beyond the Standard Model should appear;
- Quark/gluon showering on incoming and outgoing constituents – this gives rise to the observed pattern of "jets" of produced particles;
- The "underlying event" – yet more particles are produced as the clouds of remaining proton constituents pass through each other;
- Hadronization – the process in which the outgoing quarks, antiquarks and gluons recombine to form the observed particles.

To illustrate our work I will choose one of the more exotic scenarios for physics beyond the Standard Model, in which space has an extra dimension that only becomes manifest at short distances and high energies. Since time is already regarded as a kind of fourth dimension, we are talking here about a fifth dimension of space-time.

The purpose of the extra dimension is to explain why gravity is so much weaker than the Standard Model forces. For example, the electrical force between an atomic nucleus and its orbiting electrons is 10^{39} times stronger than the gravitational force between them. The basic idea is that gravity may in fact have an intrinsic strength similar to that of the other forces, but appears weaker because it operates in a higher-dimensional space.

In the type of model I shall discuss here (a Randall-Sundrum model), the extra dimension is "curled up", as illustrated by the lower-dimensional analogy below.



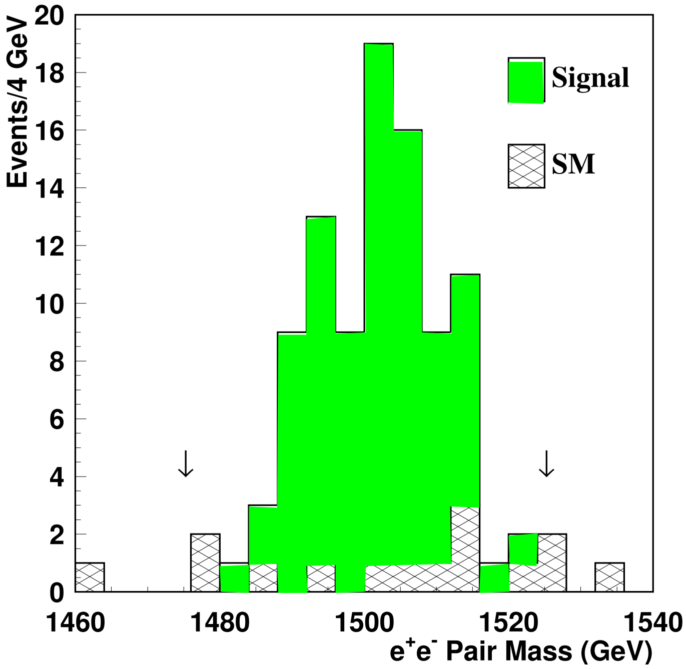
The line on the tube is the one-dimensional analogue of our three-spatial-dimensional world. All the particles and forces except gravity are trapped in this lower-dimensional subspace of a higher-dimensional world. Gravity, however, controls the structure of space itself and necessarily spreads out in all directions. On a distance scale small compared to the size of the curled-up dimension, this means that it should depart from Newton's inverse-square force law. On larger scales, Newton's law is obeyed but the strength of gravity is low due to its dissipation in other unseen directions.

In many models, the size of the extra dimension is exceedingly small and hence is not detectable in classical gravitational experiments. However, in particle collisions one can excite resonances of the gravitational field in the new directions, with frequencies characteristic of the size of the extra dimension. The quanta of these excitations would be new particles, partners of the graviton (the massless quantum of the gravitational field), but they would have interactions and masses on the typical Standard Model scale, up to a few TeV.

What would be the characteristic signatures of such a "graviton resonance" particle in the LHC experiments? Once the minimum energy needed to create its rest-mass has been exceeded, it should be produced at a rate comparable with Standard Model particles. However, it will also decay readily into those particles, and so its lifetime will be very short and its brief existence will have to be inferred from the characteristic pattern of its decay products. This pattern depend on two types of features of the decaying particle: its intrinsic properties (mass and spin) and the way it interacts with other particles.

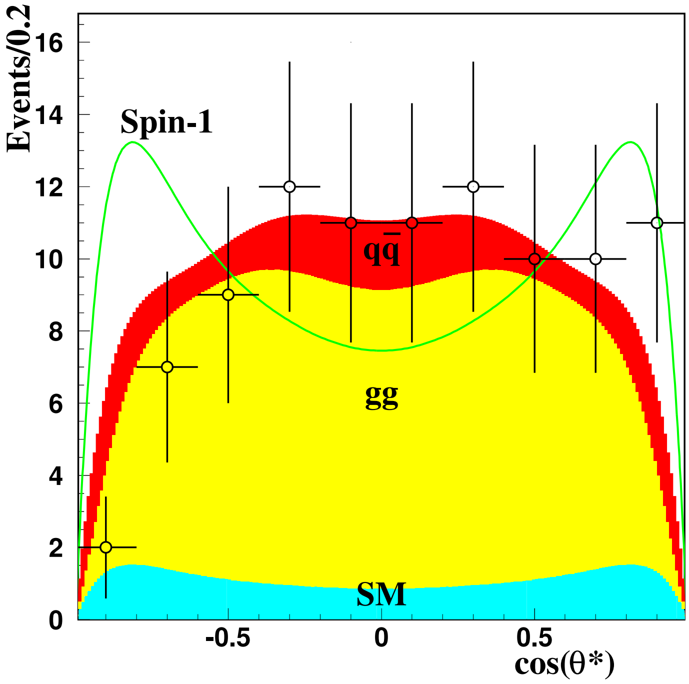
Taking the second point first, a graviton resonance should interact directly with the energy-momentum of other particles, like the graviton, rather than with any specific property such as charge. This would make it an unusually "democratic" particle, decaying equally freely into a wide range of familiar particles such as electrons, photons, neutrinos and quarks. Of these, the decay products that the LHC experiments will detect and identify most easily are electrons. Thus the preferred process to study is decay into electron-positron pairs.

Turning to the intrinsic properties of the graviton resonance, we need to measure its mass and spin from the decay products. The mass can be reconstructed directly from the momenta of the electron and positron using momentum conservation. The result of our simulation for a graviton resonance with a mass of 1.5 TeV is shown below:



The number of entries in the histogram corresponds to one year of LHC running at high intensity. The hatched boxes show the background from conventional Standard Model processes. The observed width of the peak in the signal is due to errors in the reconstruction of the electron and positron momenta from the experimental data – a simulation of one of the LHC detectors (the one called ATLAS) is included – the intrinsic width of the resonance peak being negligible (about 0.2 GeV).

Like the graviton, but unlike all other fundamental particles, a graviton resonance should carry two units of spin angular momentum. This should show up in the angular distribution of the decay products. The relevant angle θ^* is the one between the incoming proton beams and the momentum of the outgoing electron, in the rest-frame of the graviton resonance. As shown below, the LHC experiments should be able to distinguish clearly between the expected distribution and the alternative hypothesis of one unit of spin.



The different coloured regions here correspond to two different ways in which the graviton resonance could be produced in the proton-proton collisions that will take place at the LHC. A proton contains three types of fundamental constituents: quarks, antiquarks and gluons. The graviton resonance could be created only in a quark-antiquark or gluon-gluon collision. These are expected to contribute with the different proportions and distributions shown.

From our simulations we conclude that the LHC experiments can indeed discover a graviton resonance if one exists with a mass below about 2 TeV. That would be indirect but (to particle physicists) rather convincing evidence of at least one extra dimension.

I should emphasise that extra dimensions are by no means the only, or even the most credible, option for physics beyond the Standard Model. Most of the others involve supersymmetry, which our simulations show could also be discovered at the LHC, but that is a whole other story.

I should like to end by paying tribute to my collaborators in the simulation business over the past twenty years, especially Gennaro Corcella, Ian Knowles, Pino Marchesini, Stefano Moretti, Peter Richardson and Mike Seymour. My work on physics beyond the Standard Model has been within the framework of the Cambridge Supersymmetry Working Group, a very effective collaboration between theorists and ATLAS experimenters led by Andy Parker. The work on graviton resonances described here was done with Ben Allanach, Kosuke Odagiri and Andy Parker.