Quantum gravity and unification

Einstein on unification

It is well-known that Albert Einstein spent much of the latter part of his life vainly searching for unification, although designing the nuclear forces and certainly with no intention of reconciling quantum mechanics and GR. Already in 1929, he published a paper on the unified theory (pictured below). In this paper, he states with wonderful and characteristic lucidity what the criteria should be of a ‘unified theory’ to describe as far as possible all phenomena and their inherent links, and to do so on the basis of a minimal number of assumptions and logically independent basic concepts. The second of these goals (also known as the principle of Occam’s razor) refers to ‘logical unity’, and goes on to say: ‘Roughly but truthfully, one might say: we not only want to understand how nature works, but we are also after the perhaps utopian and presumptuous goal of understanding why nature is the way it is and not otherwise.’

An extract from Einstein’s 1929 paper in which he set out his approach to unification. (From a commorative publication for Aurel Stodola, Zurich, 1929.)

initial excitement about supersymmetry in the 1970s had nothing to do with the hierarchy problem, but rather it brought about a breakthrough in trying to obtain the so-called Coleman–Mandula no-go theorem – a beautiful possibility that is precisely not realised by the models currently being tested at the LHC.

In fact, the reduplication of internal quantum numbers predicted by N = 1 supersymmetry is avoided in theories with extended (N>1) supergravities, where the maximum N = 8 supersymmetry stands out as the most symmetric. Its status with regard to perturbative finiteness is still unclear, although recent work has revealed amazing and unexpected cancellations. However, there is one very strange agreement between this theory and observation, first emphasised by Gell-Mann: the number of spin-1/2 fermions remaining after complete breaking of supersymmetry is 48 = 3 × 16, equal to the number of quarks and leptons (including right-handed neutrinos) in three generations (see p41).

To go beyond the partial matching of quantum numbers achieved so far will, however, require some completely new insights, especially concerning the emergence of chiral gauge interactions.

Then again, perhaps supersymmetry is not the end of the story. There is plenty of evidence that another type of symmetry may be equally important, namely duality symmetry. The first example of such a symmetry, electromagnetic duality, was discovered by Dirac in 1931. He realised that Maxwell’s equations in vacuum are invariant under rotations of the electric and magnetic fields into one another – an insight that led him to predict the existence of magnetic monopoles. While magnetic monopoles have not been seen, duality symmetries have turned out to be ubiquitous in supergravity and string theory, and they also reveal a fascinating and unexpected link with the so-called exceptional Lie groups.

More recently, hints of an enormous symmetry enhancement have also appeared in a completely different place, namely the study of cosmological solutions of Einstein’s equations near a space-like singularity. This mathematical analysis has revealed tantalising evidence of a truly exceptional infinite-dimensional duality symmetry, which is so large that it is referred to as ‘E10’ for short.

Outstanding questions

Our summary, then, is very simple: all of the important questions in QG remain wide open, despite a great deal of effort and numerous promising ideas. In the light of this conclusion, the LHC will play an important role in unveiling the secret of how everything fits together, no matter what the final outcome of the experiments will be. This is especially true if nature chooses not to abide by current theoretical preferences and expectations.

Over the past decades, we have learnt that the SM is a most economical and neatly tight knot structure, and there is now mounting evidence that minor modifications may suffice for it to survive to the highest energies. To look for such subtle deviations will therefore be a main task for the LHC in the years ahead. If our view of the Planck scale remains unobstructed by intermediate scales, the popular model-builders’ strategy of adding ever more unseen particles and couplings may come to an end. In that case, the challenge of explaining the structure of the low-energy world from a Planck-scale theory of quantum gravity looks larger than ever.

Résumé

La face quantique de la gravité

La physique théorétique est à la croisée des chemins, et nul ne sait pour l’instant ce qui se trouve au-delà de la relativité générale ou du Modèle standard. Il est admis que nous ne pourrons progresser qu’avec une théorie plus complète de la gravité quantique, qui unifierait peut-être la gravité avec les autres interactions fondamentales de la nature. Or, après plus de 40 ans d’un effort intellectuel collectif sans précédent, les approches de la gravité quantique sont toujours plus diversifiées et aucune convergence n’est en vue. Si nous voulons sortir un jour de cette impasse, nous devons nous inspirer des progrès historiques d’Einstein.

Hermann Niccolai, Max Planck Institute for Gravitational Physics, Potsdam, Germany.

The LHC’s extra dimension

The discovery of additional space–time dimensions would revolutionise physics, but after 20 years of dedicated searches at particle colliders, we have turned up empty handed.

At 10.00 a.m. on 9 August 2016, physicists gathered at the Sheraton hotel in Chicago for the “Beyond the Standard Model” session at the ICHEP conference. The mood was one of slight disappointment. An excess of ‘diphoton’ events at a mass of 750 GeV reported by the LHC’s ATLAS and CMS experiments in 2015 had not shown up in the 2016 data, ending a burst of activity that saw some 540 phenomenology papers uploaded to the arXiv preprint server in a period of just eight months. Among the proposed explanations for the putative new high-mass resonance were extra space–time dimensions, an idea that has been around since Theodor Kaluza and Oscar Klein attempted to unify the electromagnetic and gravitational forces a century ago.

In the modern language of string theory, extra dimensions are required to ensure the mathematical consistency of the theory. They are typically thought to be very small, close to the Planck length (10−35 m). In the 1990s, however, theorists trying to solve problems with supersymmetry suggested that some of these extra dimensions could be as large as 10−3 m, corresponding to an energy scale in the TeV range. In 1998, as proposed by Arkani-Hamed and co-workers, theories emerged with even larger extra dimensions, which predicted detectable effects in contemporary collider experiments. In such large extra-dimension (LED) scenarios, gravity can become stronger than we perceive in 3D due to the increased space available. In addition to showing us an entirely different view of the universe, extra dimensions offer an elegant solution to the so-called hierarchy problem, which arises because the Planck scale (where gravity becomes as strong as the other three forces) is 17 orders of magnitude larger than the electroweak scale.

Particle physicists normally ignore gravity because it is feeble compared with the other three forces. In theories where gravity gets stronger at small distances due to the opening of extra dimensions, however, it can catch up and lead to phenomena at colliders with high enough rates that they can be measured in experiments. The possibility of having extra space dimensions at the TeV scale was a game-changer. Scientists from experiments at the LEP, Tevatron and HERA colliders quickly produced tailored searches for signals for this new beyond-the-Standard Model (SM) physics scenario. No evidence was found in their accumulated data, setting lower limits on the scale of extra dimensions of around 1 TeV.

By the turn of the century, a number of possible new experimental signatures had been identified for extra-dimension searches, many of which were studied in detail while assessing the physics performance of the LHC experiments. For the case of LEDS, where gravity is the only force that can expand in these dimensions, high-energy collider experiments were just one approach. Smaller “tabletop” scale experiments aiming to measure the strength of gravity at sub-millimetre distances were also in pursuit of extra dimensions, but no deviation from the Newtonian law has been observed to date. In addition, there were also significant constraints from astrophysics processes on the possible number and size of these dimensions.

Enter the LHC. Analysis strategies to search for extra dimensions have been deployed from the beginning of high-energy LHC operations in 2010, and the recent increase in the LHC’s collision energy to
The initial high enthusiasm for extra-dimension theories has waned.

13 TeV has extended the search window considerably. Although no positive signal of the presence of extra dimensions has been observed so far, a big leap forward has been taken in excluding large portions of the TeV scale phase-space where extra dimensions could live. A particular feature of LED-type searches is the production of a single very energetic “mono-object” that does not balance the transverse momentum carried by anything else emerging from the collision (as would be required by momentum and energy conservation). Examples of such objects are particle jets, very energetic photons or heavy W and Z vector bosons. Such collisions only occur if either the emerging jet or boson is balanced by a graviton that escapes detection. However, the production of a jet plus a Z boson that decays into neutrinos can mimic a graviton production signal. The absence of any excess in the mono-jet or mono-photon event channels at the LHC has put stringent limits on LEDs (figure 1), with 100 fb−1 of data already bypassing previous collider search limits. LEDs can also manifest themselves as a new contribution to the continuum in the invariant mass spectrum of two energetic photons (figure 2) or fermions (dileptons or dijets). Here too, though, no signals have been observed, and the LHC has now excluded such contributions for extra-dimension scales up to several TeV.

In 1999, another extra-dimension scenario was proposed by Randall and Sundrum (RS), which led to a quite different phenomenology compared with that expected from LEDs. In its simplest form, the RS idea contains two fundamental 3D branes, one of which most of all SM particles live, and one on which gravity lives. Gravity is assumed to be intrinsically strong, but the warped space between the two branes makes it appear weak on the brane where we live. The experimental signature of such scenarios is the production of so-called Kaluza–Klein (spiral-2 graviton) resonances that can be observed in the invariant mass spectra of dimuons or dibosons. The most accessible spectra to the LHC experiments include the diphoton and dilepton spectra, in which no new resonance signal has been found, and at present the limits on putative Kaluza–Klein gravitons are about 4 TeV, depending on RS-model parameters. Analyses of dijet final states provide even more stringent limits of up to 7 TeV. Further extensions of the RS model, in particular the production of top quark–antiquark resonances, offer a more sensitive signature, but despite intense searches, no signal has been detected.

Searching in the dark

At the start of 2000, it was realised that large or warped extra dimensions could lead to a new type of signature at the LHC: microscopic black holes. These can form when two colliding particles come close enough to each other, namely to within the Schwarzschild radius or black-hole event horizon, and can be as large as a femtometre in the presence of TeV-scale extra dimensions at the LHC. Such microscopic black holes would evaporate via Hawking radiation on time scales of around 10−3 s, way before they could suck up any matter, and provide an ideal opportunity to study quantum gravity in the laboratory. Black holes that are produced with a mass significantly above the formation threshold are expected to evaporate in high-energy multi-particle final states leading to plenty of particle jets, leptons, photons and even Higgs particles. Searches for such energetic multi-object final states in excess of the SM expectation have been performed since the first collisions at the LHC at 7 TeV, but none have been found. If black holes are produced closer to the formation threshold, these would be expected to decay in a much smaller final-state topology, for instance into dijets. The CMS and ATLAS experiments have been looking for all of these final states up until the latest 13 TeV data (figure 3), but no signal has been observed so far for black-hole masses up to about 9 TeV.

Several other possible incarnations of extra-dimension theories have been proposed and searched for at the LHC. So-called TeV-type extra dimensions allow for more SM particles, for example partners of the heavy W and Z bosons, to enter in the bulk, and these would show up as high-mass resonances in diphoton and other invariant mass spectra. These new resonances have a spin equal to one, and hence such signatures could be more tedious to detect because they can interfere with the SM Drell–Yan production background. Nevertheless, no such resonances have been discovered so far.

In so-called universal extra-dimension (UED) scenarios, all particles have states that can go into the bulk. If this scenario is correct, a completely new particle spectrum of partners of the SM particles should show up at the LHC at high masses. Although this looks very much like what would be expected from supersymmetry, where all known SM particles have partners, the Kaluza–Klein partners would have exactly the same spin as their SM partners, whereas supersymmetry transforms bosons into fermions and vice versa. Alas, no new particles either for Kaluza–Klein partners or supersymmetry candidates have been observed, pushing the lower mass limits beyond 1 TeV for certain particle types.

Final hope

Collider data so far have not yet given us any sign of the existence of extra dimensions, or for that matter a sign that gravity is becoming strong at the TeV scale. It is possible that, even if they exist, the extra dimensions could be as small as predicted by string theory, in which case they would not be able to solve the hierarchy problem. The idea is still very much alive, however, and searches will continue as more data are recorded at the LHC.

Even excellent and attractive ideas need confirmation from data, and inevitably the initial high enthusiasm for extra-dimension theories may have waned somewhat in recent years. Although such confirmation could come from the next generation of colliders, such as possible higher-energy machines, there is unfortunately no guarantee. It could be that we have to turn to even more outlandish ideas to progress further.

● Further reading

ATLAS results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
CMS results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

Résumento

A busca de dimensões extras em escala sub-teV pode continuar, já que não há sinais confirmados de partículas exóticas.

Albert De Roeck, CERN, and Greg Landsberg, Brown University.

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13 TeV has extended the search window considerably. Although no positive signal of the presence of extra dimensions has been observed so far, a big leap forward has been taken in excluding large portions of the TeV scale phase-space where extra dimensions could live. A particular feature of LED-type searches is the production of a single very energetic “mono-object” that does not balance the transverse momentum carried by anything else emerging from the collision (as would be required by momentum and energy conservation). Examples of such objects are particle jets, very energetic photons or heavy W and Z vector bosons. Such collisions only appear to be imbalanced, however, because the emerging jet or boson is balanced by a graviton that escapes detection. Hence SM processes such as the production of a jet plus a Z boson that decays into neutrinos can mimic a graviton production signal. The absence of any excess in the mono-jet or mono-photon event channels at the LHC has put stringent limits on LEDs (figure 1), with 2010 collision data at 7 TeV setting all limits at 95% CL. 

The experimental signature of such scenarios is the production of so-called Kaluza–Klein (spin-2 graviton) resonances that can be observed in the invariant mass spectra of dileptons or dijets. The most accessible scenarios to the LHC experiments include the diphoton and dilepton spectra, in which no new resonance signal has been found, and at present the limits on putative Kaluza–Klein gravitons are about 4 TeV, depending on RS-model parameters. Analyses of dijet final states provide even more stringent limits of up to 7 TeV. Further extensions of the RS model, in particular the production of top quark–antiquark resonances, offer a more sensitive signature, but despite intense searches, no signal has been detected. 

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**Further reading** 

**Collider results** 

ATLAS results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults. CMS results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO. 

**Résumé** 

La dimension supplémentaire du LHC

La physique des particules ignore généralement la gravité, car elle est trop faible en comparaison des trois autres forces. Toutefois, les théories mettant en jeu des dimensions supplémentaires de l’espace, développées à la fin des années 1990, prédissent que la gravité n’est pas du tout ce qu’elle semble être, et qu’elle pourrait causer des phénomènes exotiques dans les collisions, comme des trous noirs microscopiques. La recherche de dimensions supplémentaires a été menée dès le début de l’exploitation du LHC, en 2010. Aucun signal positif n’a été observé jusqu’ici, mais les expériences ATLAS et CMS ont déjà éliminé de grandes parties de l’espace de phase à l’échelle du TeV, et les recherches se poursuivront à mesure que davantage de données seront enregistrées au LHC et dans les futures machines.

Albert De Roeck, CERN, and Greg Landsberg, Brown University.