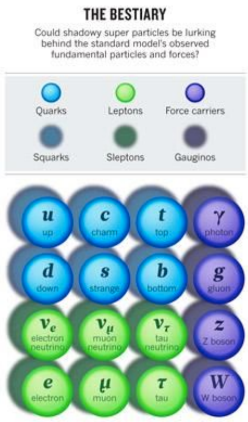
Beautiful theory collides with smashing particle data
Latest results from the LHC are casting doubt on the theory of supersymmetry.

Geoff Brumfiel


"Any squarks in here?" The ATLAS detector (above) at the Large Hadron Collider has failed to find predicted 'super partners' of fundamental particles.C. MARCELLONI/CERN

"Wonderful, beautiful and unique" is how Gordon Kane describes supersymmetry theory. Kane, a theoretical physicist at the University of Michigan in Ann Arbor, has spent about 30 years working on supersymmetry, a theory that he and many others believe solves a host of problems with our understanding of the subatomic world.

Yet there is growing anxiety that the theory, however elegant it might be, is wrong. Data from the Large Hadron Collider (LHC), a 27-kilometre proton smasher that straddles the French–Swiss border near Geneva, Switzerland, have shown no sign of the 'super particles' that the theory predicts[1–3]. "We're painting supersymmetry into a corner," says Chris Lester, a particle physicist at the University of Cambridge, UK, who works with the LHC's ATLAS detector. Along with the LHC's Compact Muon Solenoid experiment, ATLAS has spent the past year hunting for super particles, and is now set to gather more data when the LHC begins a high-power run in the next few weeks. If the detectors fail to find any super particles by the end of the year, the theory could be in serious trouble.



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Supersymmetry (known as SUSY and pronounced 'Susie') emerged in the 1970s as a way to solve a major shortcoming of the standard model of particle physics, which describes the behaviour of the fundamental particles that make up normal matter (see 'The bestiary'). Researchers have now found every particle predicted by the model, save one: the Higgs boson, theorized to help endow other particles with mass.

The Higgs is crucial to the theory, but its predicted mass is subject to wild fluctuations caused by quantum effects from other fundamental particles. Those fluctuations can increase the Higgs' expected mass to a point at which other fundamental particles should be much more massive than they actually are, effectively breaking the standard model. Theorists can eliminate the fluctuations from their equations, but only by setting the Higgs mass to a very precise value — a fraction heavier or lighter and the whole theoretical edifice collapses. Many physicists are uncomfortable with any theory that requires such delicate fine-tuning to work.

SUSY offers an alternative to this 'fine-tuning' problem. The theory postulates that each regular particle has a heavier supersymmetrical partner, many of which are unstable and rarely interact with normal matter. The quantum fluctuations of the supersymmetrical particles perfectly cancel out those of the regular particles, returning the Higgs boson to an acceptable mass range.

Theorists have also discovered that SUSY can solve other problems. Some of the lightest supersymmetrical particles could be the elusive dark matter that cosmologists have been hunting for since the 1930s. Although it has never been seen, dark matter makes up about 83% of the matter in the Universe, according to observations of how galaxies move. SUSY can also be used to bring together all the forces except gravity into a single force at high energies, a big step towards a 'theory of everything' that unifies and explains all known physics — one of the ultimate goals of science. Perhaps most important for some theorists, "SUSY is very beautiful mathematically", says Ben Allanach, a theorist at the University of Cambridge.

SUSY's utility and mathematical grace have instilled a "religious devotion" among its followers, says Adam Falkowski, a theorist at the University of Paris-South in France. But colliders have failed to turn up direct evidence of the super particles predicted by the theory. The Tevatron at the Fermi National Accelerator Laboratory in Batavia, Illinois, for example, has found no evidence of supersymmetrical quarks ('squarks') at masses of up to 379 gigaelectronvolts (energy and mass are used interchangeably in the world of particle physics).

The LHC is now rapidly accumulating data at higher energies, ruling out heavier territory for the super particles. This creates a serious problem for SUSY (see 'SUSY's mid-life crisis'). As the super particles increase in mass, they no longer perfectly cancel out the troubling quantum fluctuations that they were meant to correct. Theorists can still make SUSY work, but only by assuming very specific masses for the super particles — the kind of fine-tuning exercise that the theory was invented to avoid. As the LHC collects more data, SUSY will require increasingly intrusive tweaks to the masses of the particles.

So far the LHC has doubled the mass limit set by the Tevatron, showing no evidence of squarks at energies up to about 700 gigaelectronvolts. By the end of the year, it will reach 1,000 gigaelectronvolts — potentially ruling out some of the most favoured variations of supersymmetry theory.

"I wouldn't say I'm concerned," says John Ellis, a theorist at CERN, Europe's particle-physics lab near Geneva, who has worked on supersymmetry for decades. He says that he will wait until the end of 2012 — once more runs at high energy have been completed — before abandoning SUSY. Falkowski, a long-time critic of the theory, thinks that the lack of detections already suggest that SUSY is dead.

"Privately, a lot of people think that the situation is not good for SUSY," says Alessandro Strumia, a theorist at the University of Pisa in Italy, who recently produced a paper about the impact of the LHC's latest results on the fine-tuning problem4. "This is a big political issue in our field," he adds. "For some great physicists, it is the difference between getting a Nobel prize and admitting they spent their lives on the wrong track." Ellis agrees: "I've been working on it for almost 30 years now, and I can imagine that some people might get a little bit nervous."

"Plenty of things will change if we fail to discover SUSY," says Lester. Theoretical physicists will have to go back to the drawing board and find an alternative way to solve the problems with the standard model. That's not necessarily a bad thing, he adds: "For particle physics as a whole it will be really exciting."

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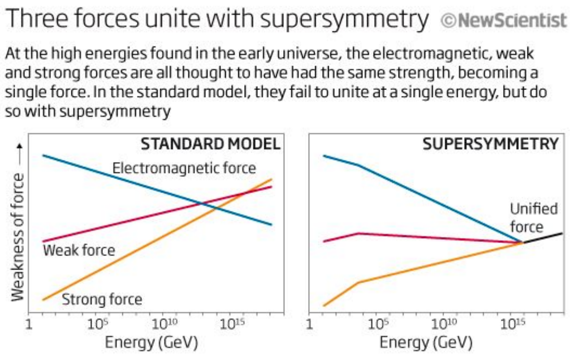

What if supersymmetry is wrong?

- 17:27 15 March 2011 by **Amanda Gefter**
- Magazine issue 2804. **Subscribe and save**
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Three decades of theorising and calculating. Entire careers spent constructing ideas. Nine billion dollars invested in an underground ring that spans two nations. Ten thousand dedicated scientists and engineers looking for the particle physics equivalent of a needle in a haystack. It's all been leading to this moment. Small wonder that amid bated breath, you can hear a lot of nervous laughter.

"It's got to be there, damn it!" Nobel prizewinning physicist Frank Wilczek chuckles in his office at the Massachusetts Institute of Technology in Cambridge. He's talking about supersymmetry, endearingly known as SUSY, a theory that most physicists believe will lead them beyond the standard model of particle physics, the tried-and-true model of how particles and forces interact, and one big step closer to understanding how reality works.

Physicists are doggedly searching for it in the debris of particle collisions from ATLAS and CMS, two experiments at CERN's Large Hadron Collider near Geneva, Switzerland. A year into their runs, neither have glimpsed so much as a hint of SUSY particles at masses up to 700 gigaelectronvolts – well within the range theorists expect it to lurk (arxiv.org/abs/1103.1984, arxiv.org/abs/1102.2357, arxiv.org/abs/1102.5290, arxiv.org/abs/1101.1628).

Rumours are spreading of SUSY's demise, and alternative theories are already waiting in the wings (see box below). But for many physicists like Wilczek, SUSY is just too beautiful to be wrong. "It would be really cruel of nature to get us this far, and have the next step in sight, and then it's all just a joke on us."

Supersymmetry suggests that the two basic types of particles that make up our world – fermions, the matter particles such as electrons and quarks, and bosons, the force-carrying particles such as photons and gluons – are merely two aspects of a single particle.

Perplexing problems

It's an elegant idea and if correct, could solve some of the most perplexing problems in physics. It endows the elusive Higgs particle, which is believed to be responsible for giving every other known particle its mass, with just the right mass of its own to keep the whole edifice of particle physics from crumbling around us. Without SUSY, the Higgs mass is heavily influenced by the quantum behaviour of the vacuum.

As it interacts with the vacuum's virtual particles, its mass skyrockets, growing so large that the standard model breaks down. SUSY saves the day – for every virtual interaction that drives up the Higgs mass, there is a *svirtual* interaction that drives it back down.

Just as importantly, SUSY unifies the three fundamental forces of the standard model, suggesting that electromagnetism and the strong and weak nuclear forces merge into a single superforce at high energies (see diagram).

Dark matter

What's more, it provides an ideal candidate for the mysterious dark matter that seems to be holding galaxies together, accounting for approximately 80 per cent of all the matter in the universe. It even appears to be an essential ingredient in string theory, physicists' leading contender for a theory of everything that will finally unite gravity with the other three forces.

No competing theory is able to solve all four problems in one fell swoop. That's what makes SUSY so compelling and explains why many physicists are on tenterhooks.

Not everyone, though. "I never really believed in SUSY anyway," says physicist Jonathan Butterworth of University College London, who works on the LHC's ATLAS experiment. Butterworth admits, though, that the LHC's search has only just begun. "It would have been something of a surprise if it had shown up by now," he says, explaining that the LHC will gather 20 times as much data by the end of the year, and another factor of 10 by the end of 2012. "There's plenty of room for SUSY to show up."

Kenneth Lane of Boston University in Massachusetts agrees. "The suspicions of the death of supersymmetry are premature," he says. "But that's the only nice thing I'll say about it."

Fifth force

Lane prefers an alternative theory. With physicist Estia Eichten of Batavia, Illinois, Lane showed that particles could come by their masses without a Higgs boson if there is a fifth force in addition to the four we know about: technicolour. It is similar to the strong force, which binds quarks together, but operates at much higher energies. "There's already a precedent for it in nature," Lane says, adding that it could also provide a new candidate for dark matter.

The LHC will be able to put the theory to the test. Just as quarks pair up to form mesons, techniquarks pair up to form technimesons with masses ranging from 250 GeV to 700 GeV – well within the LHC's reach. If technimesons exist, the LHC should find them within the next few years.

Lane has already made a bet that this underdog theory will prevail. At a 1994 conference, Lane was out to dinner with Nobel laureates Gerard 't Hooft and David Gross. "We drank a lot of wine and David and I made a bet about whether SUSY would be found at the LHC after they had a certain amount of data," Lane says. "The loser has to take everyone to dinner at a three-star restaurant."

Ultimate theory

For his part, Butterworth is betting on something totally unforeseen. "I think maybe there's a whole new set of forces," he says. "I just think nature is more likely to surprise us than to fit in with our guesses."

But Wilczek is putting his money behind SUSY. "I'll happily give even money, and probably better odds than that if pressed, that we'll see some form of SUSY within 10 years."

That could help shed light on another mystery of supersymmetry – why it's not perfectly symmetric. If it were, "sparticles" would weigh as much as their normal cousins – and would have been seen by now. Instead, physicists believe supersymmetry is broken, with sparticles weighing more than their standard-model partners.

"There's no consensus on how SUSY is broken," says Wilczek. Many models implicate gravity in the process, so if the LHC does find signs of SUSY, it could usher in a way to merge gravity with the other fundamental forces, providing an ultimate theory of everything.

If supersymmetry isn't real

SUSY solves four puzzles at once, but other theories can attack them too

Makes the Higgs work

Technicolour This is a fifth force, similar to the strong force that binds quarks but at higher energies, endowing particles with mass without the need for a Higgs

Holographic technicolour If the technicolour force has the same strength across a range of energy scales, it is mathematically equivalent to a warped space-time geometry in five dimensions, simplifying the technicolour equations

Little Higgs This new kind of symmetry gives the standard model's Higgs the right mass. Fermions are partnered with new, heavier fermions and bosons with new, heavier bosons

Unifies electromagnetic, weak and strong forces

Randall-Sundrum model Our universe exists on a 4D membrane surrounded by five warped dimensions. Inside the warped 5D world, the forces all have the same strength; they seem different to us because of our limited perspective

Multiverse If there are an infinite number of universes, we might just happen to live in one with forces at the strengths we observe – possibly because it's one of the few universes that could support life. If so, the forces might not be unified at all

Candidates for dark matter

Technicolour Dark matter would be made of a neutron-like particle made of "technifermions"

Axions Hypothetical particles 500 million times lighter than an electron

Modified Newtonian Dynamics (MOND) In this theory, there is no dark matter at all. Instead, Newton's law of gravity is tweaked to explain the observed motions of galaxies

Key ingredient in string theory

Loop quantum gravity It's not clear that SUSY is required for string theory, but lack of SUSY would bolster alternatives like LQG, which suggests that space is built of discrete units of geometry

The word: Technicolour

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- Magazine issue 2521. **Subscribe and save**

NOTHING to do with a Hollywood film-making process, technicolour takes us back to the beginning of the universe, when two of the fundamental forces of nature, electromagnetism and the weak force (which governs particle decay within the atomic nucleus), were united in a single force - the electroweak force. When the universe cooled, the forces split apart. The two seem very different today: photons, carriers of electromagnetism, are massless, while W and Z particles, carriers of the weak force, have mass. But why?

To explain how the Ws and Zs got mass, physicists proposed something called the Higgs - a quantum field that permeates all space. The particle associated with the Higgs field, the Higgs boson, is so revered it is dubbed "the God particle". But some physicists are putting their faith in another theory: technicolour.

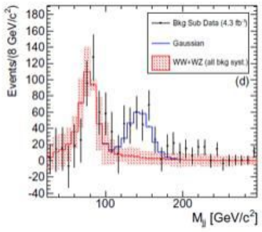
First, a bit on Higgs. Many physicists believe the Higgs field formed as the universe cooled, giving empty space an ordered structure, like an ice crystal freezing out of water. The W and Z particles, which started off massless like the photon, suddenly found it difficult to move through the Higgs field: they became sluggish, as if they'd put on mass.

But the Higgs theory offers no explanation as to why space should have this ordered structure. Enter technicolour. Technicolour is a fifth force, an addition to the known four, which acts on particles named techniquarks. The force is so strong that a techniquark pair cannot be separated except at very high energies, as at the big bang. As the universe cooled after the big bang, the techniquarks paired off and have remained glued together ever since. This sea of techniquark pairs explains the ordered structure of empty space.

But how does technicolour give Ws and Zs mass? Like ordinary particles, techniquarks have a property called spin, which can be left or right-handed. At high energies, when techniquarks are unpaired, the laws of physics dictate that a left-handed techniquark cannot transform into a right-handed one, and vice versa. These rules would be broken even if a techniquark was observed as having the opposite spin. However, something moving faster than a left-handed techniquark would see it spinning the other way (the way a car in the next lane appears to move backward as you pass it). To prevent that from happening, techniquarks have to move at the speed of light so nothing can outrun them - and the only particles that can do that are massless ones. Therefore, in the searing energies of the early universe, photons, and the constituents of Ws and Zs, were all massless.

But as the universe cooled, left and right-handed techniquarks paired up. Techniquarks now appear only as combinations of each other. Right-handed can look like left-handed, and vice versa, which means that techniquarks must be moving slower than the speed of light and have therefore acquired mass. The massive techniquark pairs form massive W and Z particles.

So which theory is correct? Only experiment can decide. The Large Hadron Collider at CERN in Switzerland, due to begin particle-smashing in 2007, should find the Higgs boson if it exists. If it doesn't, the hunt for techniquarks is on.



Mystery signal at Fermilab hints at 'technicolour' force

- 19:46 07 April 2011 by **Amanda Gefter**
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The physics world is buzzing with news of an unexpected sighting at Fermilab's Tevatron collider in Illinois – a glimpse of an unidentified particle that, should it prove to be real, will radically alter physicists' prevailing ideas about how nature works and how particles get their mass.

The candidate particle may not belong to the standard model of particle physics, physicists' best theory for how particles and forces interact. Instead, some say it might be the first hint of a new force of nature, called technicolour, which would resolve some problems with the standard model but would leave others unanswered.

The observation was made by Fermilab's CDF experiment, which smashes together protons and antiprotons 2 million times every second. The data, collected over a span of eight years, looks at collisions that produce a W boson, the carrier of the weak nuclear force, and a pair of jets of subatomic particles called quarks.

Physicists predicted that the number of these events – producing a W boson and a pair of jets – would fall off as the mass of the jet pair increased. But the CDF data showed something strange (see graph): a bump in the number of events when the mass of the jet pair was about 145 GeV.

Just a fluke?

That suggests that the additional jet pairs were produced by a new particle weighing about 145 GeV. "We expected to see a smooth shape that decreases for increasing values of the mass," says CDF team member Pierluigi Catastini of Harvard University in Cambridge, Massachusetts. "Instead we observe an excess of events concentrated in one region, and it seems to be a bump – the typical signature of a particle."

Intriguing as it sounds, there is a 1 in 1000 chance that the bump is simply a statistical fluke. Those odds make it a so-called three-sigma result, falling short of the gold standard for a discovery – five sigma, or a 1 in a million chance of error. "I've seen three-sigma effects come and go," says Kenneth Lane of Boston University in Massachusetts. Still, physicists are 99.9 per cent sure it is not a fluke, so they are understandably anxious to pin down the particle's identity.

Most agree that the mysterious particle is not the long-sought Higgs boson, believed by many to endow particles with mass. "It's definitely not a Higgs-like object," says Rob Roser, a CDF spokesperson at Fermilab. If it were, the bump in the data would be 300 times smaller. What's more, a Higgs particle should most often decay into bottom quarks, which do not seem to make an appearance in the Fermilab data.

Fifth force

"There's no version of a Higgs in any model that I know of where the production rate would be this large," says Lane. "It has to be something else." And Lane is confident that he knows exactly what it is.

Just over 20 years ago, Lane, along with Fermilab physicist Estia Eichten, predicted that experiments would see just such a signal. Lane and Eichten were working on a theory known as technicolour, which proposes the existence of a fifth fundamental force in addition to the four already known: gravity, electromagnetism, and the strong and weak nuclear forces. Technicolour is very similar to the strong force, which binds quarks together in the nuclei of atoms, only it operates at much higher energies. It is also able to give particles their mass – rendering the Higgs boson unnecessary.

The new force comes with a zoo of new particles. Lane and Eichten's model predicted that a technicolour particle called a technirho would often decay into a W boson and another particle called a technipion.

In a new paper, Lane, Eichten and Fermilab physicist Adam Martin suggest that a technipion with a mass of about 160 GeV could be the mysterious particle producing the two jets. "If this is real, I think people will give up on the idea of looking for the Higgs and begin exploring this rich world of new particles," Lane says.

Future tests

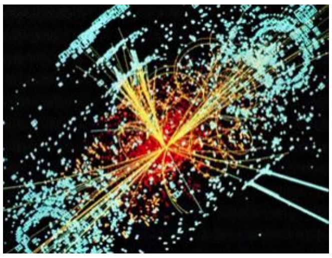
But if technicolour is correct, it would not be able to resolve all the questions left unanswered by the standard model. For example, physicists believe that at the high energies found in the early universe, the fundamental forces of nature were unified into a single superforce. Supersymmetry, physicists' leading contender for a theory beyond the standard model, paves a way for the forces to unite at high energies, but technicolour does not.

Figuring out which theory – if either – is right means combing through more heaps of data to determine if the new signal is real. Budget constraints mean the Tevatron will shut down this year, but fortunately the CDF team, which made the find, is already "sitting on almost twice the data that went into this analysis", says Roser. "Over the coming months we will redo the analysis with double the data."

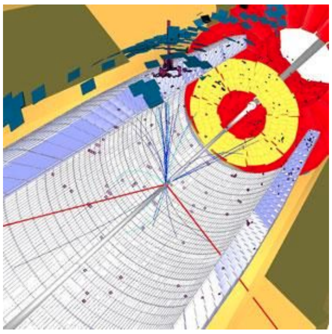
Meanwhile, DZero, Fermilab's other detector, will analyse its own data to provide independent corroboration or refutation of the bump. And at CERN's Large Hadron Collider near Geneva, Switzerland, physicists will soon collect enough data to perform their own search. In their paper, Lane and his colleagues suggest ways to look for other techniparticles.

"I haven't been sleeping very well for the past six months," says Lane, who found out about the bump long before the team went public with the result. "If this is what we think it is, it's a whole new world beyond quarks and leptons. It'll be great! And if it's not, it's not."

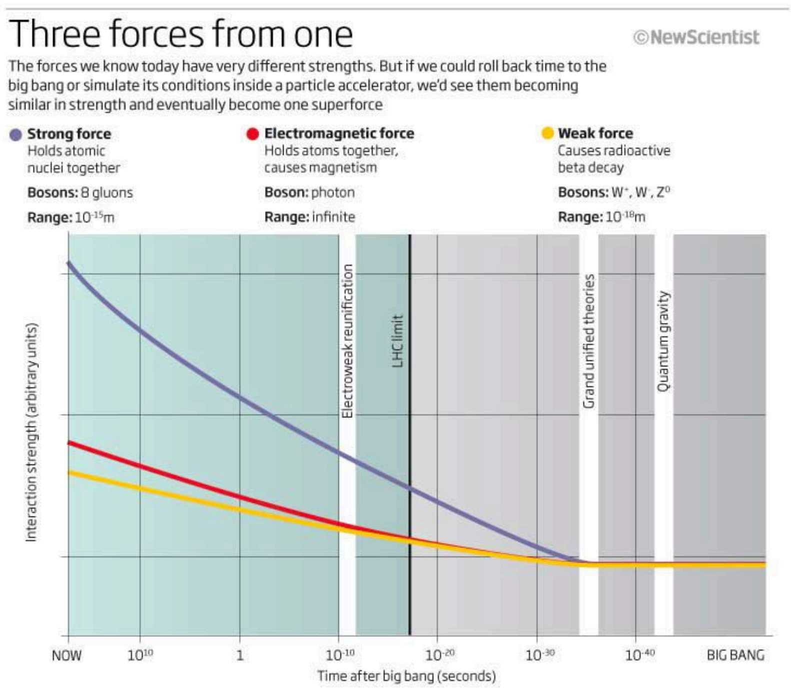
Journal reference: arxiv.org/abs/1104.0699

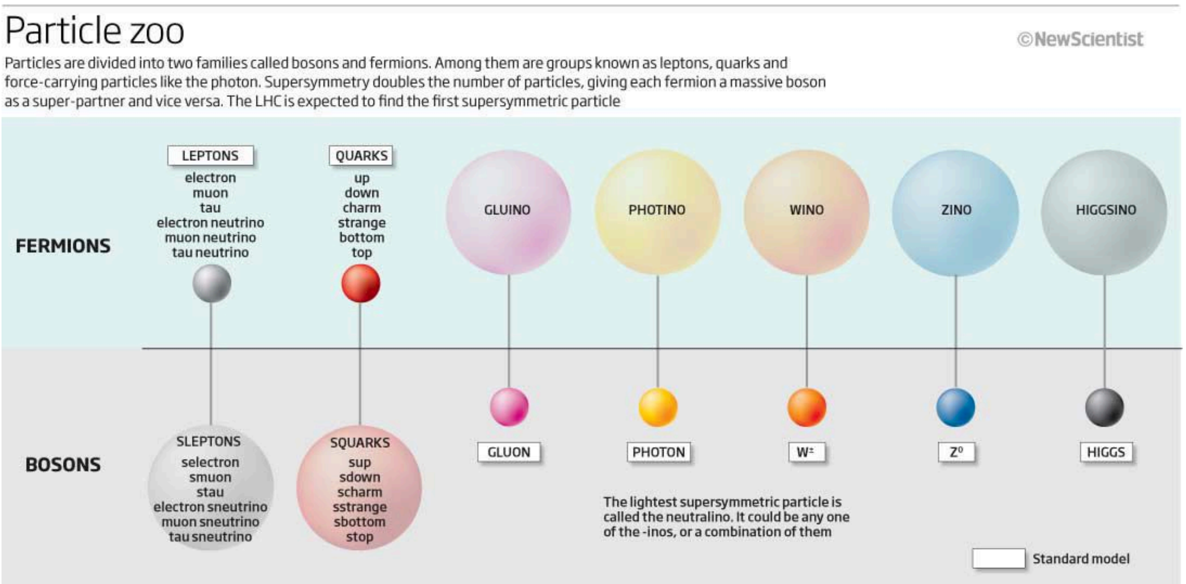


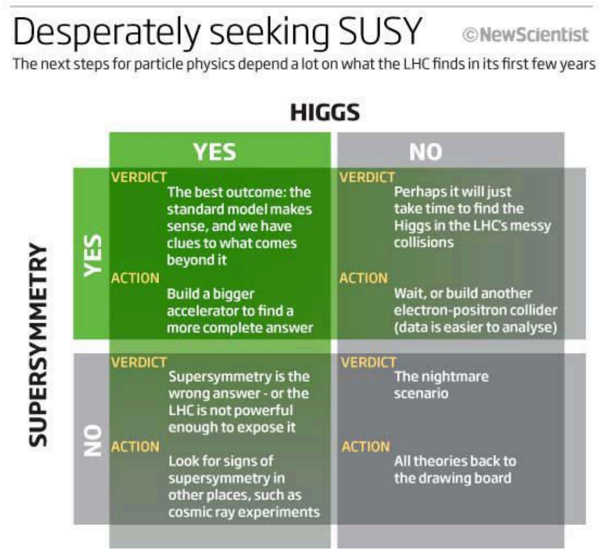
This simulation depicts the decay of a Higgs particle following a collision of two protons in the CMS experiment (Image: CMS)



This image shows the decay of a neutralino into a Z particle and a lightest supersymmetric particle (LSP). The Z decays into two muons. This experiment was from the Compact Muon Solenoid (CMS) at CERN (Image: Maria Spiropulu; Stephan Wynhoff)







In SUSY we trust: What the LHC is really looking for

- 11 November 2009 by **Anil Ananthaswamy**
- Magazine issue 2734. **Subscribe** and get 4 free issues.
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AS DAMP squibs go, it was quite a spectacular one. Amid great pomp and ceremony - not to mention dark offstage rumblings that the end of the world was nigh - the Large Hadron Collider (LHC), the world's mightiest particle smasher, fired up in September last year. Nine days later a short circuit and a catastrophic leak of liquid helium ignominiously shut the machine down.

Now for take two. Any day now, if all goes to plan, proton beams will start racing all the way round the ring deep beneath CERN, the LHC's home on the outskirts of Geneva, Switzerland.

Nobel laureate Steven Weinberg is worried. It's not that he thinks the LHC will create a black hole that will engulf the planet, or even that the restart will end in a technical debacle like last year's. No: he's actually worried that the LHC will find what some call the "God particle", the popular and embarrassingly grandiose moniker for the hitherto undetected Higgs boson.

"I'm terrified," he says. "Discovering just the Higgs would really be a crisis."

Why so? Evidence for the Higgs would be the capstone of an edifice that particle physicists have been building for half a century - the phenomenally successful theory known simply as the standard model. It describes all known particles, as well as three of the four forces that act on them: electromagnetism and the weak and strong nuclear forces.

It is also manifestly incomplete. We know from what the theory doesn't explain that it must be just part of something much bigger. So if the LHC finds the Higgs and nothing but the Higgs, the standard model will be sewn up. But then particle physics will be at a dead end, with no clues where to turn next.

Hence Weinberg's fears. However, if the theorists are right, before it ever finds the Higgs, the LHC will see the first outline of something far bigger: the grand, overarching theory known as supersymmetry. SUSY, as it is endearingly called, is a daring theory that doubles the number of particles needed to explain the world. And it could be just what particle physicists need to set them on the path to fresh enlightenment.

So what's so wrong with the standard model? First off, there are some obvious sins of omission. It has nothing whatsoever to say about the fourth fundamental force of nature, gravity, and it is also silent on the nature of dark matter. Dark matter is no trivial matter: if our interpretation of certain astronomical observations is correct, the stuff outweighs conventional matter in the cosmos by more than 4 to 1.

Ironically enough, though, the real trouble begins with the Higgs. The Higgs came about to solve a truly massive problem: the fact that the basic building blocks of ordinary matter (things such as electrons and quarks, collectively known as fermions) and the particles that carry forces (collectively called bosons) all have a property we call mass. Theories could see no rhyme or reason in particles' masses and could not predict them; they had to be measured in experiments and added into the theory by hand.

These "free parameters" were embarrassing loose threads in the theories that were being woven together to form what eventually became the standard model. In 1964,Peter Higgs of the University of Edinburgh, UK, and François Englert and Robert Brout of the Free University of Brussels (ULB) in Belgium independently hit upon a way to tie them up.

That mechanism was an unseen quantum field that suffuses the entire cosmos. Later dubbed the Higgs field, it imparts mass to all particles. The mass an elementary particle such as an electron or quark acquires depends on the strength of its interactions with the Higgs field, whose "quanta" are Higgs bosons.

Fields like this are key to the standard model as they describe how the electromagnetic and the weak and strong nuclear forces act on particles through the exchange of various bosons - the W and Z particles, gluons and photons. But the Higgs theory, though elegant, comes with a nasty sting in its tail: what is the mass of the Higgs itself? It should consist of a core mass plus contributions from its interactions with all the other elementary particles. When you tot up those contributions, the Higgs mass balloons out of control.

The experimental clues we already have suggest that the Higgs's mass should lie somewhere between 114 and 180 gigaelectronvolts - between 120 and 190 times the mass of a proton or neutron, and easily the sort of energy the LHC can reach. Theory, however, comes up with values 17 or 18 orders of magnitude greater - a catastrophic discrepancy dubbed "the hierarchy problem". The only way to get rid of it in the standard model is to fine-tune certain parameters with an accuracy of 1 part in 10^{34}, something that physicists find unnatural and abhorrent.

Three into one

The hierarchy problem is not the only defect in the standard model. There is also the problem of how to reunite all the forces. In today's universe, the three forces dealt with by the standard model have very different strengths and ranges. At a subatomic level, the strong force is the strongest, the weak the weakest and the electromagnetic force somewhere in between.

Towards the end of the 1960s, though, Weinberg, then at Harvard University, showed with Abdus Salam and Sheldon Glashow that this hadn't always been the case. At the kind of high energies prevalent in the early universe, the weak and electromagnetic forces have one and the same strength; in fact they unify into one force. The expectation was that if you extrapolated back far enough towards the big bang, the strong force would also succumb, and be unified with the electromagnetic and weak force in one single super-force (see graph).

In 1974 Weinberg and his colleagues Helen Quinn and Howard Georgi showed that the standard model could indeed make that happen - but only approximately. Hailed initially as a great success, this not-so-exact reunification soon began to bug physicists working on "grand unified theories" of nature's interactions.

It was around this time that supersymmetry made its appearance, debuting in the work of Soviet physicists Yuri Golfand and Evgeny Likhtman that never quite made it to the west. It was left to Julius Wess of Karlsruhe University in Germany and Bruno Zumino of the University of California, Berkeley, to bring its radical prescriptions to wider attention a few years later.

Wess and Zumino were trying to apply physicists' favourite simplifying principle, symmetry, to the zoo of subatomic particles. Their aim was to show that the division of the particle domain into fermions and bosons is the result of a lost symmetry that existed in the early universe.

According to supersymmetry, each fermion is paired with a more massive supersymmetric boson, and each boson with a fermionic super-sibling. For example, the electron has the selectron (a boson) as its supersymmetric partner, while the photon is partnered with the photino (a fermion). In essence, the particles we know now are merely the runts of a litter double the size (see diagram).

The key to the theory is that in the high-energy soup of the early universe, particles and their super-partners were indistinguishable. Each pair co-existed as single massless entities. As the universe expanded and cooled, though, this supersymmetry broke down. Partners and super-partners went their separate ways, becoming individual particles with a distinctive mass all their own.

Supersymmetry was a bold idea, but one with seemingly little to commend it other than its appeal to the symmetry fetishists. Until, that is, you apply it to the hierarchy problem. It turned out that supersymmetry could tame all the pesky contributions from the Higgs's interactions with elementary particles, the ones that cause its mass to run out of control. They are simply cancelled out by contributions from their supersymmetric partners. "Supersymmetry makes the cancellation very natural," says Nathan Seiberg of Princeton University.

That wasn't all. In 1981 Georgi, together with Savas Dimopoulos of Stanford University, redid the force reunification calculations that he had done with Weinberg and Quinn, but with supersymmetry added to the mix. They found that the curves representing the strengths of all three forces could be made to come together with stunning accuracy in the early universe. "If you have two curves, it's not surprising that they intersect somewhere," says Weinberg. "But if you have three curves that intersect at the same point, then that's not trivial."

This second strike for supersymmetry was enough to convert many physicists into true believers. But it was when they began studying some of the questions raised by the new theory that things became really interesting.

One pressing question concerned the present-day whereabouts of supersymmetric particles. Electrons, photons and the like are all around us, but of selectrons and photinos there is no sign, either in nature or in any high-energy accelerator experiments so far. If such particles exist, they must be extremely massive indeed, requiring huge amounts of energy to fabricate.

Such huge particles would long since have decayed into a residue of the lightest, stable supersymmetric particles, dubbed neutralinos. Still massive, the neutralino has no electric charge and interacts with normal matter extremely timorously by means of the weak nuclear force. No surprise then that it is has eluded detection so far.

When physicists calculated exactly how much of the neutralino residue there should be, they were taken aback. It was a huge amount - far more than all the normal matter in the universe.

Beginning to sound familiar? Yes, indeed: it seemed that neutralinos fulfilled all the requirements for the dark matter that astronomical observations persuade us must dominate the cosmos. A third strike for supersymmetry.

Each of the three questions that supersymmetry purports to solve - the hierarchy problem, the reunification problem and the dark-matter problem - might have its own unique answer. But physicists are always inclined to favour an all-purpose theory if they can find one. "It's really reassuring that there is one idea that solves these three logically independent things," says Seiberg.

Supersymmetry solves problems with the standard model, helps to unify nature's forces and explains the origin of dark matter
Supersymmetry's scope does not end there. As Seiberg and his Princeton colleague Edward Witten have shown, the theory can also explain why quarks are never seen on their own, but are always corralled together by the strong force into larger particles such as protons and neutrons. In the standard model, there is no mathematical indication why that should be; with supersymmetry, it drops out of the equations naturally. Similarly, mathematics derived from supersymmetry can tell you how many ways can you fold a four-dimensional surface, an otherwise intractable problem in topology.

All this seems to point to some fundamental truth locked up within the theory. "When something has applications beyond those that you designed it for, then you say, 'well this looks deep'," says Seiberg. "The beauty of supersymmetry is really overwhelming."

Sadly, neither mathematical beauty nor promise are enough on their own. You also need experimental evidence. "It is embarrassing," says Michael Dine of the University of California, Santa Cruz. "It is a lot of paper expended on something that is holding on by these threads."

Circumstantial evidence for supersymmetry might be found in various experiments designed to find and characterise dark matter in cosmic rays passing through Earth. These include the Cryogenic Dark Matter Search experiment inside the Soudan Mine in northern Minnesota and the Xenon experiment beneath the Gran Sasso mountain in central Italy. Space probes like NASA's Fermi satellite are also scouring the Milky Way for the telltale signs expected to be produced when two neutralinos meet and annihilate.

The best proof would come, however, if we could produce neutralinos directly through collisions in an accelerator. The trouble is that we are not entirely sure how muscular that accelerator would need to be. The mass of the super-partners depends on precisely when supersymmetry broke apart as the universe cooled and the standard particles and their super-partners parted company. Various versions of the theory have not come up with a consistent timing. Some variants even suggest that certain super-partners are light enough to have already turned up in accelerators such as the Large Electron-Positron collider - the LHC's predecessor at CERN - or the Tevatron collider in Batavia, Illinois. Yet neither accelerator found anything.

The reason physicists are so excited about the LHC, though, is that the kind of supersymmetry that best solves the hierarchy problem will become visible at the higher energies the LHC will explore. Similarly, if neutralinos have the right mass to make up dark matter, they should be produced in great numbers at the LHC.

Since the accident during the accelerator's commissioning last year, CERN has adopted a softly-softly approach to the LHC's restart. For the first year it will smash together two beams of protons with a total energy of 7 teraelectronvolts (TeV), half its design energy. Even that is quite a step up from the 1.96 TeV that the Tevatron, the previous record holder, could manage. "If the heaviest supersymmetric particles weigh less than a teraelectronvolt, then they could be produced quite copiously in the early stages of LHC's running," says CERN theorist John Ellis.

If that is so, events after the accelerator is fired up again could take a paradoxical turn. The protons that the LHC smashes together are composite particles made up of quarks and gluons, and produce extremely messy debris. It could take rather a long time to dig the Higgs out of the rubble, says Ellis.

Any supersymmetric particles, on the other hand, will decay in as little as 10^{-16} seconds into a slew of secondary particles, culminating in a cascade of neutralinos. Because neutralinos barely interact with other particles, they will evade the LHC's detectors. Paradoxically, this may make them relatively easy to find as the energy and momentum they carry will appear to be missing. "This, in principle, is something quite distinctive," says Ellis.

So if evidence for supersymmetry does exist in the form most theorists expect, it could be discovered well before the Higgs particle, whose problems SUSY purports to solve. Any sighting of something that looks like a neutralino would be very big news indeed. At the very least it would be the best sighting yet of a dark-matter particle. Even better, it would tell us that nature is fundamentally supersymmetric.

There is a palpable sense of excitement about what the LHC might find in the coming years. "I'll be delighted if it is supersymmetry," says Seiberg. "But I'll also be delighted if it is something else. We need more clues from nature. The LHC will give us these clues."

Blood brothers?

String theory and supersymmetry are two as-yet unproved theories about the make-up of the universe. But they are not necessarily related.

It is true that most popular variants of string theory take a supersymmetric universe as their starting point. String theorists, who have taken considerable flak for advocating a theory that has consistently struggled to make testable predictions, will breathe a huge sigh of relief if supersymmetry is found.

That might be premature: the universe could still be supersymmetric without string theory being correct. Conversely, at the kind of energies probed by the LHC, it is not clear that supersymmetry is a precondition for string theory. "It is easier to understand string theory if there is supersymmetry at the LHC," says Edward Witten, a theorist at Princeton University, "but it is not clear that it is a logical requirement."

If supersymmetry does smooth the way for string theory, however, that could be a decisive step towards a theory that solves the greatest unsolved problem of physics: why gravity seems so different to all the rest of the forces in nature. If so, supersymmetry really could have all the answers.

Anil Ananthaswamy is a consulting editor for New Scientist

12 November 2012 Last updated at 13:30 GMT
Popular physics theory running out of hiding places

By Pallab Ghosh Science correspondent, BBC News

Supersymmetry predicts the existence of enigmatic "super particles"

Researchers at the Large Hadron Collider have detected one of the rarest particle decays seen in Nature.

The finding deals a significant blow to the theory of physics known as supersymmetry.

Many researchers had hoped the LHC would have confirmed this by now.

Supersymmetry, or SUSY, has gained popularity as a way to explain some of the inconsistencies in the traditional theory of subatomic physics known as the Standard Model.

The new observation, reported at the Hadron Collider Physics conference in Kyoto, is not consistent with many of the most likely models of SUSY.

Prof Chris Parkes, who is the spokesperson for the UK Participation in the LHCb experiment, told BBC News: "Supersymmetry may not be dead but these latest results have certainly put it into hospital."

"Supersymmetry may not be dead but these latest results have certainly put it into hospital"

Prof Chris Parkes LHCb Experiment
Supersymmetry theorises the existence of more massive versions of particles that have already been detected.

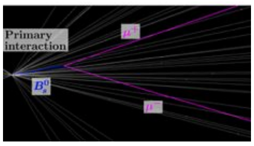
Their existence would help explain why galaxies appear to rotate faster than the Standard Model would suggest. Physicists have speculated that as well as the particles we know about, galaxies contain invisible, undetected dark matter made up of super particles. The galaxies therefore contain more mass than we can detect and so spin faster.

Researchers at the LHCb detector have dealt a serious blow to this idea. They have measured the decay between a particle known as a Bs Meson into two particles known as muons. It is the first time that this decay has been observed and the team has calculated that for every billion times that the Bs Meson decays it only decays in this way three times.

If superparticles were to exist the decay would happen far more often. This test is one of the "golden" tests for supersymmetry and it is one that on the face of it this hugely popular theory among physicists has failed.

Prof Val Gibson, leader of the Cambridge LHCb team, said that the new result was "putting our supersymmetry theory colleagues in a spin".

The results are in fact completely in line with what one would expect from the Standard Model. There is already concern that the LHCb's sister detectors might have expected to have detected superparticles by now, yet none have been found so far.



A Bs Meson decays into two muons: a rare event that undermines physics's favourite theory
If supersymmetry is not an explanation for dark matter, then theorists will have to find alternative ideas to explain those inconsistencies in the Standard Model. So far researchers who are racing to find evidence of so called "new physics" have run into a series of dead ends.

"If new physics exists, then it is hiding very well behind the Standard Model," commented Cambridge physicist Dr Marc-Olivier Bettler, a member of the analysis team.

The result does not rule out the possibility that super particles exist. But according to Prof Parkes, "they are running out of places to hide".

Supporters of supersymmetry, however, such as Prof John Ellis of King's College London said that the observation is "quite consistent with supersymmetry".

"In fact," he said "(it) was actually expected in (some) supersymmetric models. I certainly won't lose any sleep over the result."

27 August 2011 Last updated at 06:41 GMT

LHC results put supersymmetry theory 'on the spot'

By Pallab Ghosh Science correspondent, BBC News

Results from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

Researchers failed to find evidence of so-called "supersymmetric" particles, which many physicists had hoped would plug holes in the current theory.

Theorists working in the field have told BBC News that they may have to come up with a completely new idea.

Data were presented at the Lepton Photon science meeting in Mumbai.

They come from the LHC Beauty (LHCb) experiment, one of the four main detectors situated around the collider ring at the European Organisation for Nuclear Research (Cern) on the Swiss-French border.

According to Dr Tara Shears of Liverpool University, a spokesman for the LHCb experiment: "It does rather put supersymmetry on the spot".

"There's a certain amount of worry that's creeping into our discussions"
Dr Joseph Lykken Fermilab
The experiment looked at the decay of particles called "B-mesons" in hitherto unprecedented detail.

If supersymmetric particles exist, B-mesons ought to decay far more often than if they do not exist.

There also ought to be a greater difference in the way matter and antimatter versions of these particles decay.

The results had been eagerly awaited following hints from earlier results, most notably from the Tevatron particle accelerator in the US, that the decay of B-mesons was influenced by supersymmetric particles.

LHCb's more detailed analysis however has failed to find this effect.

Bitten the dust

This failure to find indirect evidence of supersymmetry, coupled with the fact that two of the collider's other main experiments have not yet detected supersymmetic particles, means that the simplest version of the theory has in effect bitten the dust.

Collisions inside the LHC should have found some evidence of Supersymmetry by now

The theory of supersymmetry in its simplest form is that as well as the subatomic particles we know about, there are "super-particles" that are similar, but have slightly different characteristics.

The theory, which was developed 20 years ago, can help to explain why there is more material in the Universe than we can detect - so-called "dark matter".

According to Professor Jordan Nash of Imperial College London, who is working on one of the LHC's experiments, researchers could have seen some evidence of supersymmetry by now.

"The fact that we haven't seen any evidence of it tells us that either our understanding of it is incomplete, or it's a little different to what we thought - or maybe it doesn't exist at all," he said.

Disappointed

The timing of the announcement could not be worse for advocates of supersymmetry, who begin their annual international meeting at Fermilab, near Chicago, this weekend.

"Supersymmetry… has got symmetry and its super - but there's no experimental data to say it is correct"

Professor George Smoot Nobel Laureate

Dr Joseph Lykken of Fermilab, who is among the conference organisers, says he and others working in the field are "disappointed" by the results - or rather, the lack of them.

"There's a certain amount of worry that's creeping into our discussions," he told BBC News.

The worry is that the basic idea of supersymmetry might be wrong.

"It's a beautiful idea. It explains dark matter, it explains the Higgs boson, it explains some aspects of cosmology; but that doesn't mean it's right.

"It could be that this whole framework has some fundamental flaws and we have to start over again and figure out a new direction," he said.

Down the drain

Experimental physicists working at the LHC, such as Professor Nash, say the results are forcing their theoretical colleagues to think again.

"For the last 20 years or so, theorists have been a step ahead in that they've had ideas and said 'now you need to go and look for it'.

"Now we've done that, and they need to go scratch their heads," he said.

That is not to say that it is all over for supersymmetry. There are many other, albeit more complex, versions of the theory that have not been ruled out by the LHC results.

These more complex versions suggest that super-particles might be harder to find and could take years to detect.

Some old ideas that emerged around the same time as supersymmetry are being resurrected now there is a prospect that supersymmetry may be on the wane.

One has the whimsical name of "Technicolor".

According to Dr Lykken, some younger theoretical physicists are beginning to develop completely novel ideas because they believe supersymmetry to be "old hat" .

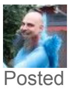
"Young theorists especially would love to see supersymmetry go down the drain, because it means that the real thing is something they could invent - not something that was invented by the older generation," he said.

And the new generation has the backing of an old hand - Professor George Smoot, Nobel prizewinner for his work on the cosmic microwave background and one of the world's most respected physicists.

"Supersymmetry is an extremely beautiful model," he said.

"It's got symmetry, it's super and it's been taught in Europe for decades as the correct model because it is so beautiful; but there's no experimental data to say that it is correct."

The Rise and Fall of Supersymmetry



Posted by **Ethan** on May 15, 2013

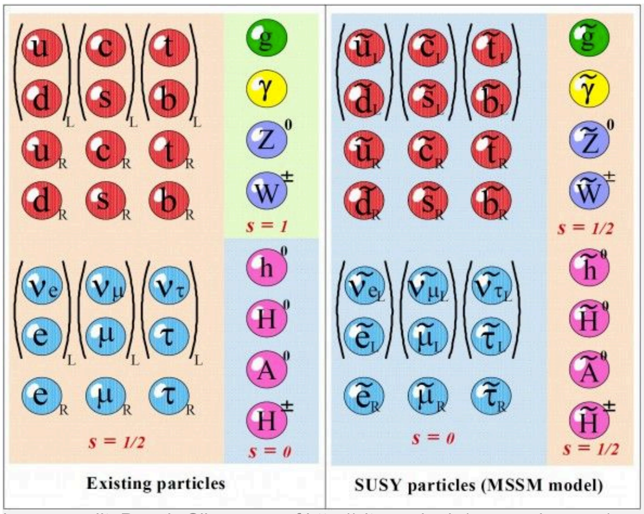


Image credit: Dennis Silverman, of http://sites.uci.edu/energyobserver/.

"Supposedly she'd died, but here she was again–somewhat changed, but you couldn't kill her. Not when the truest part of her hadn't even been born." -Denis Johnson

Over the past 100 years, our picture of the Universe has changed dramatically, on both the largest scales and the smallest.


Image credit: Richard Payne.

On the large-scales, we've gone from a Newtonian Universe of unknown age populated only by the stars in our own Milky Way to a Universe governed by General Relativity, containing hundreds of billions of galaxies.

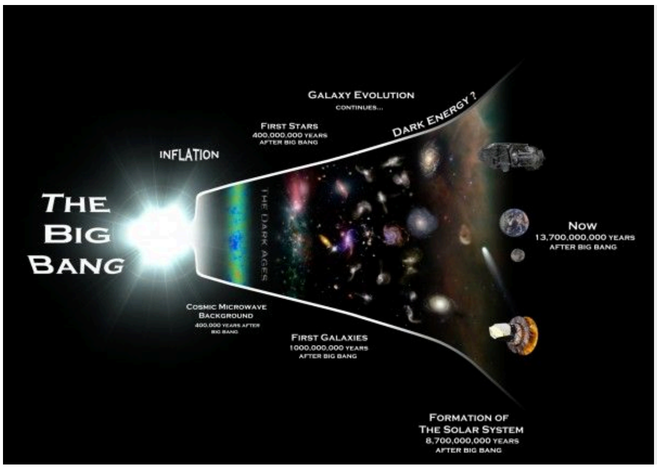


Image credit: Rhys Taylor, Cardiff University.

The age of this Universe is dated at 13.8 billion years since the Big Bang, the observable part of which is some 92 billion light-years in diameter, filled with normal matter (and not antimatter), dark matter, and dark energy.

On the small scales, the revolution has been just as dramatic.

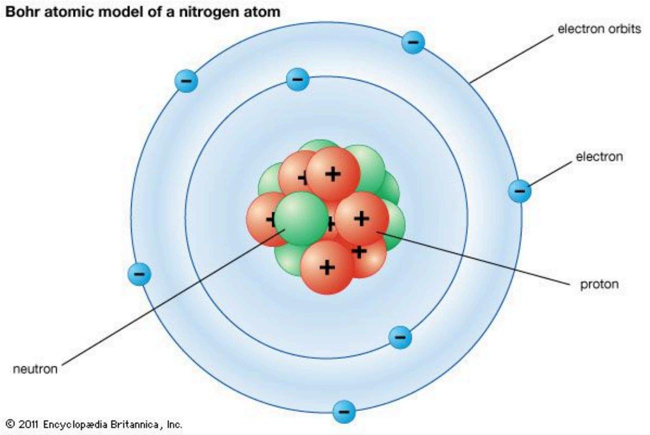


Image credit: 2011 Encyclopaedia Britannica.

We've gone from a Universe made up of atomic nuclei, electrons and photons, where the only known forces were gravitational and electromagnetic, to a much more fundamental understanding of the smallest particles and interactions that make up the Universe. Nuclei are made up of protons and neutrons, which — in turn — are made up of quarks and gluons. There are two types of nuclear forces, the strong and the weak forces, and three generations of particles, including the leptons (electrons, neutrinos, and their heavier counterparts) and quarks (up, down, and their heavier counterparts). There are gauge bosons governing the strong, weak, and electromagnetic forces, and finally there's the Higgs, bringing this all together under the framework of the Standard Model.

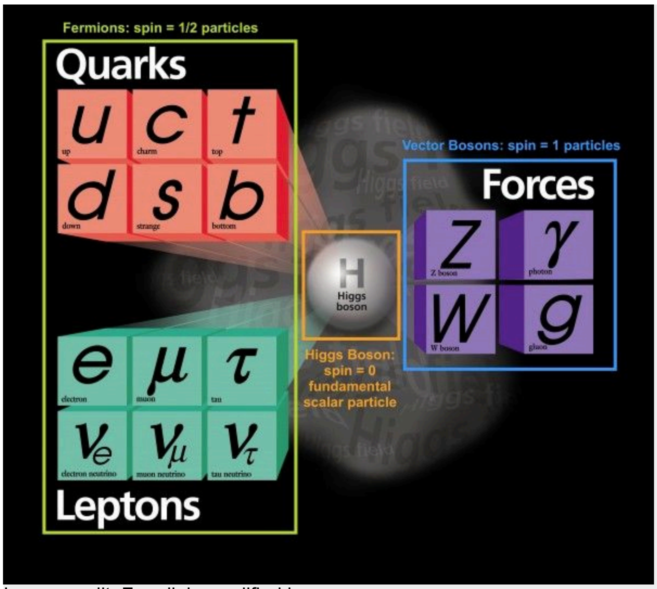
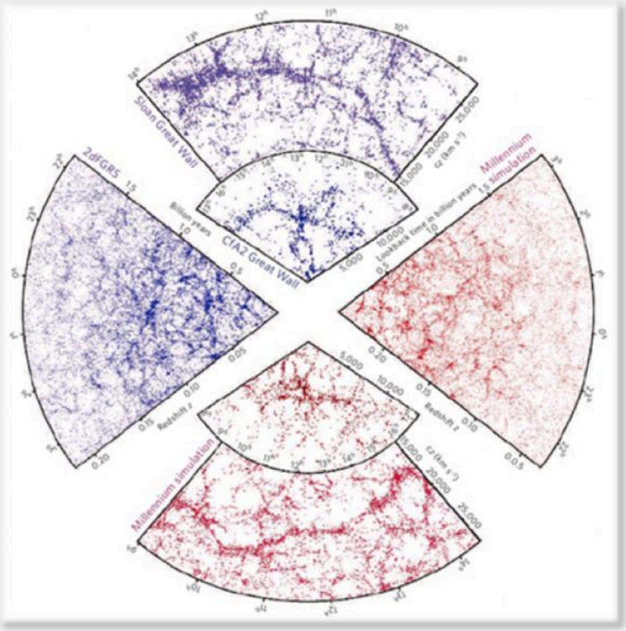


Image credit: Fermilab, modified by me.

And combining the Standard Model of particle physics with General Relativity and the standard model of modern cosmology means that we can *nearly* explain the entire physical Universe! By beginning with a Universe that had slightly more matter than antimatter, and starting just some 10^{-10} seconds after the Big Bang, we can account for all of the observed phenomena using *only* the already-established laws of physics. We can reproduce — with simulations — a Universe that is, in all meaningful ways, physically indistinguishable from our own.



Images credit: 2dF Galaxy Redshift Survey (blue) and Millenium Simulation (red), which agree!

And yet, there are some very fundamental questions we still don’t understand. Among them are:

1. *Why* is there more matter than antimatter? Where did the asymmetry (of the observed magnitude) come from?
2. What is the nature of dark energy? What is the field/property responsible for it?
3. What is the nature of dark matter? What is the particle responsible for it?
4. We know that, at very high energies, the electromagnetic and the weak force **unify**, and are actually a manifestation of the electroweak force, whose symmetry is broken at low energies. Do the other forces — the strong force and maybe even gravity — unify at some even higher energy?
5. And finally, *why* do the fundamental particles — the ones in the Standard Model — have the masses that they do?

This last one is a problem known as the hierarchy problem in physics, and it goes something like this.

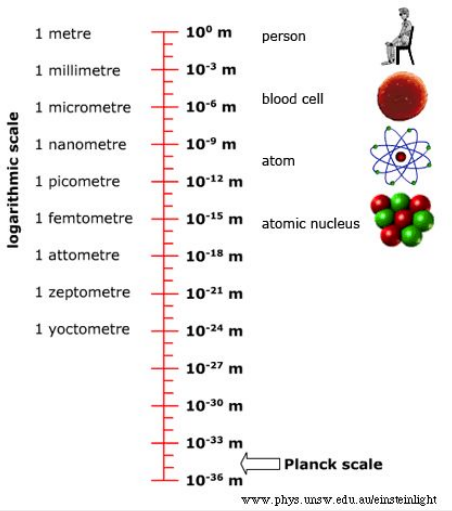


Image credit: © School of Physics UNSW.

There are a few fundamental constants in nature: the gravitational constant (G), Planck’s constant(h or ħ, which is h/2π), and the speed of light (c). There are different combinations of these constants we can create to get values for time, length, and mass; these are known as Planck units.

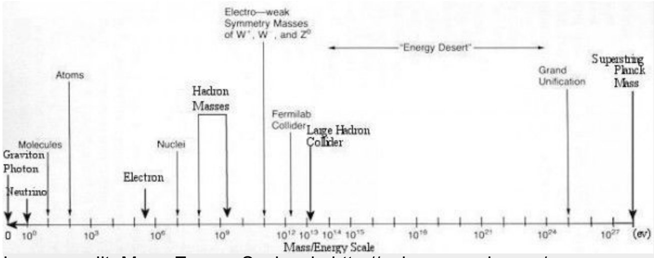


Image credit: Mass-Energy Scale, via http://universe-review.ca/.

If you were to predict the mass of the particles in the Standard Model from first principles, they ought to be on the order of the Planck mass, which has an energy of around 10^{28} eV. The major problem is that this mass is **17 orders of magnitude**, or a factor of 100,000,000,000,000,000 *larger* than the heaviest observed particle in the Universe. The Higgs boson, in particular, should have the Planck mass, and — since the Higgs field couples to the other particles, giving them mass — so should all the others.

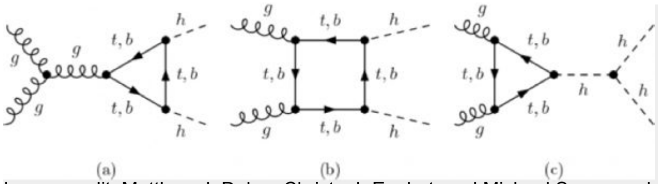


Image credit: Matthew J. Dolan, Christoph Englert, and Michael Spannowsky, via JHEP 1210 (2012) 112.

So *why*, we ask, do the particles have the mass that they do, and not much, much larger ones? The best, most elegant solution is that there's an extra *symmetry* that cancels out all those Planck-scale contributions, and protects the mass down to a much lower energy.

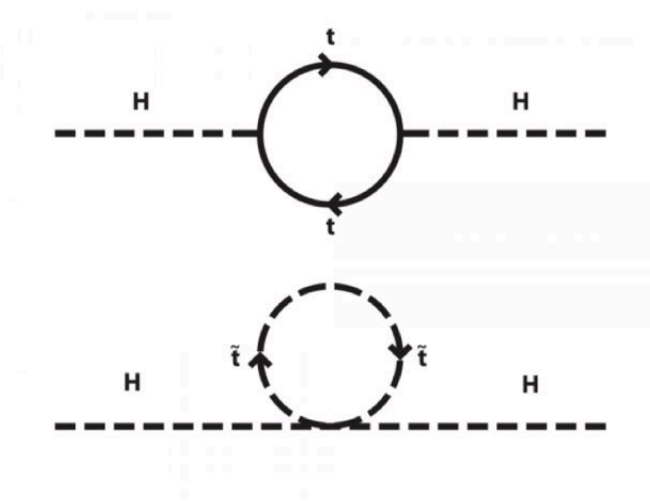


Image credit: wikimedia commons user VermillionBird.

That's the idea behind Supersymmetry, known as SUSY for short. Supersymmetry makes the very bold prediction that every one of the Standard Model particles has a partner particle — a superpartner — that has nearly identical properties, except has a spin that's different by a value of ±½ from its Standard Model counterpart.

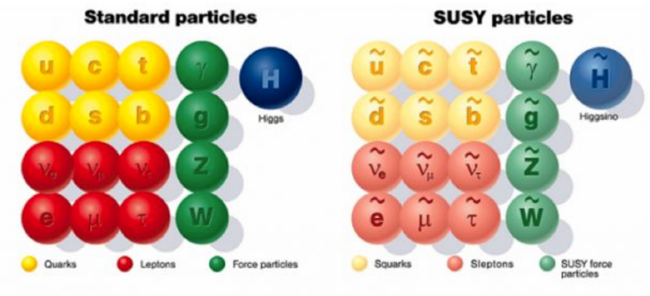


Image credit: DESY at Hamburg.

This superpartner should *protect* the mass of all the particles — the Standard Model ones and the SUSY ones — all the way down to the scale at which SUSY is broken, at which point the superpartners acquire a heavier mass than the normal ones.

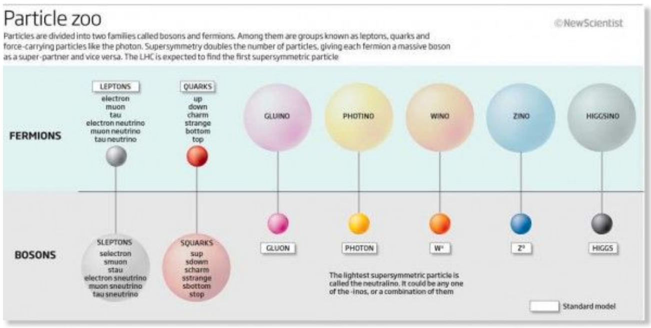


Image credit: © New Scientist.

If SUSY is broken at the right scale to solve the hierarchy problem, somewhere between 100 GeV and 1 TeV, then the lightest supersymmetric particles should be accessible by the LHC.

But there's more.

There are a bunch of things that are known *not* to happen in the Standard Model to very high precision: baryon number isn't violated, lepton number isn't violated, and there are no flavor-changing neutral currents. In order to make these things *also* not happen in SUSY, you need a new symmetry called R-parity, which comes along with an added feature. If R-parity is real and SUSY is real, then the lightest supersymmetric particle is **stable**, which means, if enough of them are left over from the hot Big Bang, *it could be the dark matter*!


Image credit: CDMS experiment, Fermilab / Dept. of Energy, via http://www.fnal.gov/.

There's even one more cool thing that happens: if you take all the particles in the standard model, and you look at the interaction strength of the three forces, you'll find that the strength of the forces — parametrized by their coupling constants — changes with energy. They change in such as way that, in the Standard Model, they *almost* meet at some high energy (around 10^{15} GeV), but just miss, slightly, if you put them on a log-log scale. But if you add in supersymmetry, the addition of these new particles changes the way the coupling constants evolve. And therefore, if SUSY is right, it could indicate a place where the electromagnetic, weak and strong forces *all unify* at a high energy!

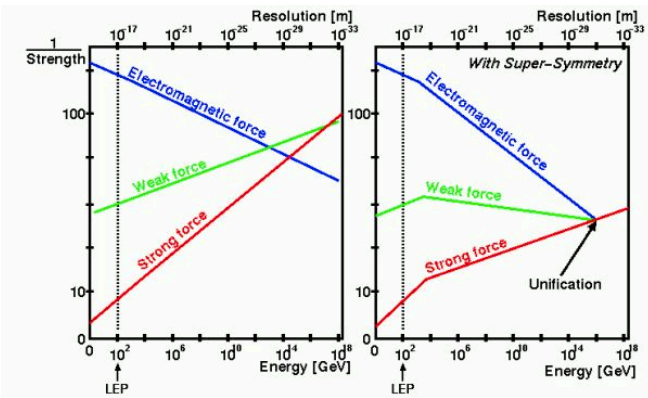


Image credit: CERN (European Organization for Nuclear Research), 2001. Via http://edu.pyhajoki.fi/.

In other words, there are three major problems that could *all* be solved by the existence of supersymmetry; it's a **great** idea! (There are four if you count the problem of the Coleman-Mandula theorem, which many do, but I'm not one of them.)

But there's also a few problems with each of these three problems that SUSY looks like it solves:

1. If it solves the hierarchy problem, then there should *definitely* be new supersymmetric particles discovered at the LHC. In fact, if the LHC doesn't discover supersymmetric particles, then *even if SUSY exists*, there must be some other solution to the hierarchy problem, because SUSY alone won't do it.
2. If the lightest supersymmetric particle is, in fact, the dark matter in the Universe, then experiments designed to see it, such as CDMS and XENON, ought to have seen it by now. In addition, SUSY dark matter should annihilate in a very particular way, which we haven't seen. The null-detection status of these experiments (among others) is a big red flag against this. Plus, there are plenty of other good dark matter candidates as far as astrophysics is concerned; SUSY is hardly the only horse in the race.
3. The strong force *may not unify* with the other forces! There's no reason, other than our predisposition towards liking more symmetric things, for that to be the case. There's also the issue that if you put any three curves on a log-log scale and zoom out far enough, they will *always* look like a triangle where the three lines "just barely" miss coming together to a point.

But the biggest failures of SUSY are not theoretical ones; they're experimental.

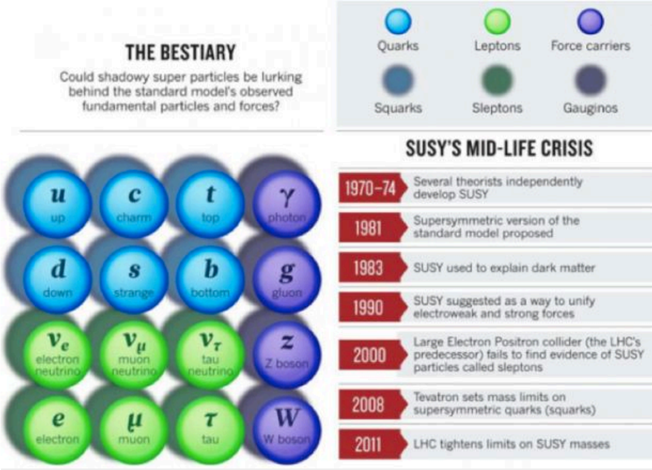


Image credit: Geoff Brumfiel from Nature.

And there are a lot of different ways of representing just how difficult it is to reconcile what SUSY expects with what we actually have — and *haven't* — seen.

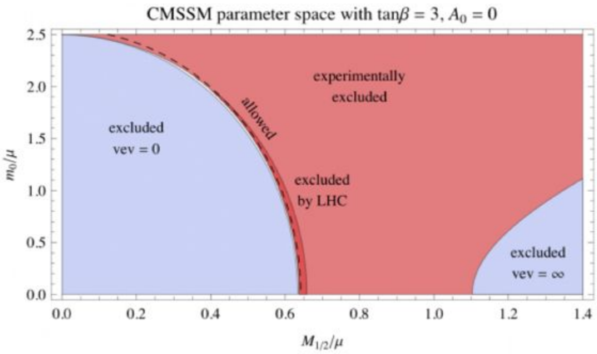


Image credit: Alessandro Strumia, via http://resonaances.blogspot.com/.

At the LHC, supersymmetric particles should have been detected by now, if they exist. There are plenty of theorists and experimentalists who are still optimistic about SUSY, but nearly all models that successfully solve the hierarchy problem have been ruled out.

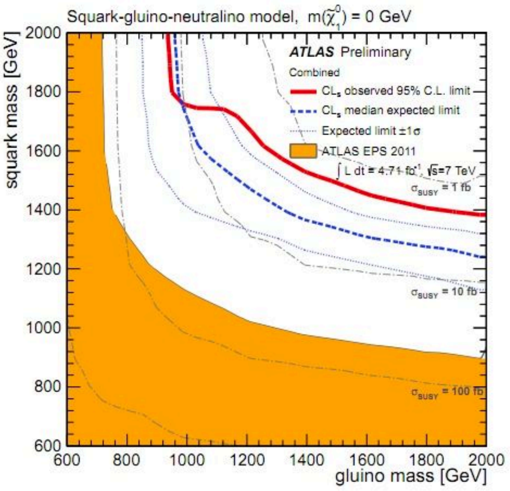


Figure 4: Limits on the masses of gluinos and first and second generation squarks, at 95% C.L., derived by ATLAS using simplified models with a massless neutralino, and assuming that the masses of all other SUSY particles are very large.

Image credit: Particle Data Group (2012), O. Buchmueller and P. de Jong.

At this point in the game, based on what we've seen (and *haven't* seen) so far, it would be *shocking* if the LHC turned up evidence for supersymmetry. As always, continued experimentation will be the ultimate arbiter of nature, but I think it's fair to say that the only reason SUSY gets as much positive press as it does is for two simple reasons.

1. A lot of people have invested their entire careers in SUSY, and if it's not a part of nature, then a *lot* of what they've invested in is nothing more than a blind alley. For example, if there is no SUSY in nature, at any energy scale, then string theory is wrong. Plain and simple.
2. There are no other *good* solutions to the hierarchy problem that are as satisfying as SUSY. If there's no SUSY, then we have to admit that we have no idea why the masses of the standard model particles have the value that they do.

Which is to say, SUSY or not, physics still has a lot of explaining to do, and there's work to be done. But the biggest problem is that SUSY predicts new particles, and it predicts their existence to occur in a fairly specific range of energies.

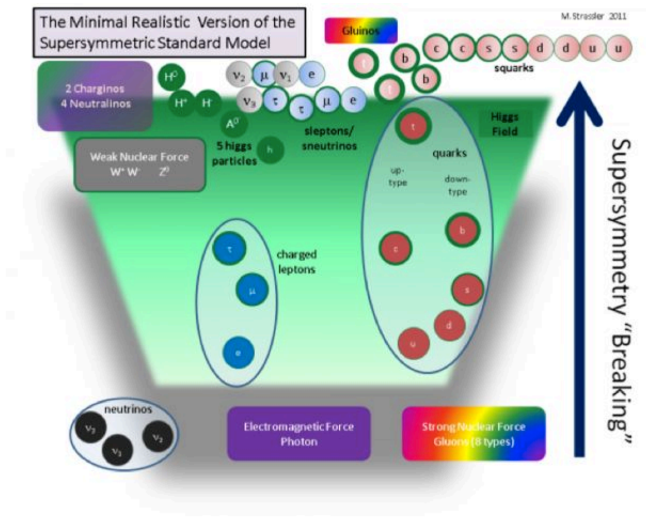


Image credit: Matt Strassler of http://profmattstrassler.com/.

If they're not there, then this isn't the right story. At this point, the theoretical hoops being jumped through to keep SUSY "viable" (and yes, that belongs in air quotes) given our experimental null results are getting progressively more and more extravagant. I'm not much of a betting man, but if I were, I'd say that SUSY is already dead. It's just waiting for the coffin nails to be hammered in.