String Theory And The Universe

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"Particle physicists" are really interested in understanding the laws of nature – the laws at work in biology, chemistry, astronomy – in the world around us.

The name "particle physics" comes because understanding elementary particles has proved to be an important part of this.

In the world around us, for example, there are waves – say, light waves.

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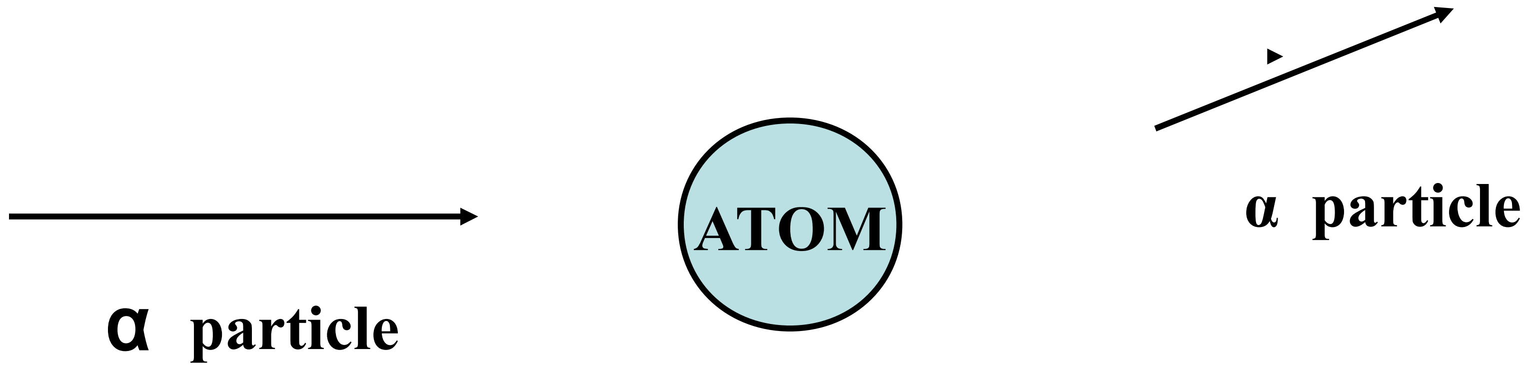
But according to quantum mechanics, if you look more closely, light waves are made of little packets of energy called "photons" – the photon is one of the important elementary particles.

Matter, when studied more closely, is made of atoms, and atoms are made of protons, neutrons, and electrons. When you look still more closely, the protons and neutrons are made of smaller things called "quarks."

The quarks and electrons are indivisible, as far as we know today, and they are some of our "elementary particles."

Early in the 20th century, Ernest Rutherford discovered the atomic nucleus in a famous experiment in which he bombarded atoms with energetic particles:



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To make this discovery, Rutherford did not need (or have) any method to accelerate the particles that made up his beam – he used a natural radioactive source.

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We also write GeV as an abbreviation for a Billion (10^9) Electron Volts.

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$$E = mc^2$$

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Another way to describe what is an MeV or a GeV is that an MeV is about 2 times mc^2 of an electron, and a GeV is about mc^2 for a proton.

The next one, by the way, which you heard about in the last lecture, is a TeV, and this stands for a Trillion (10^{12}) Electron Volts!

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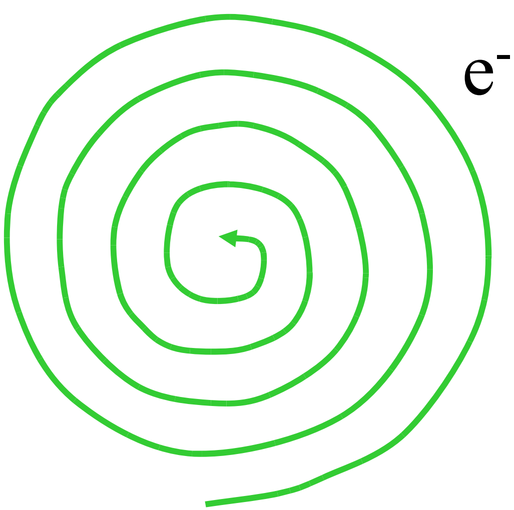
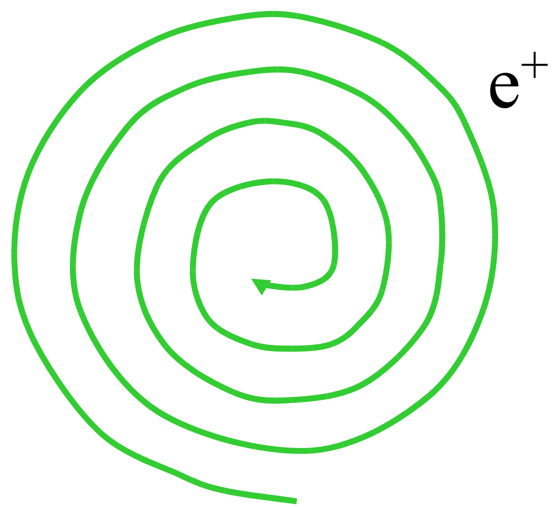
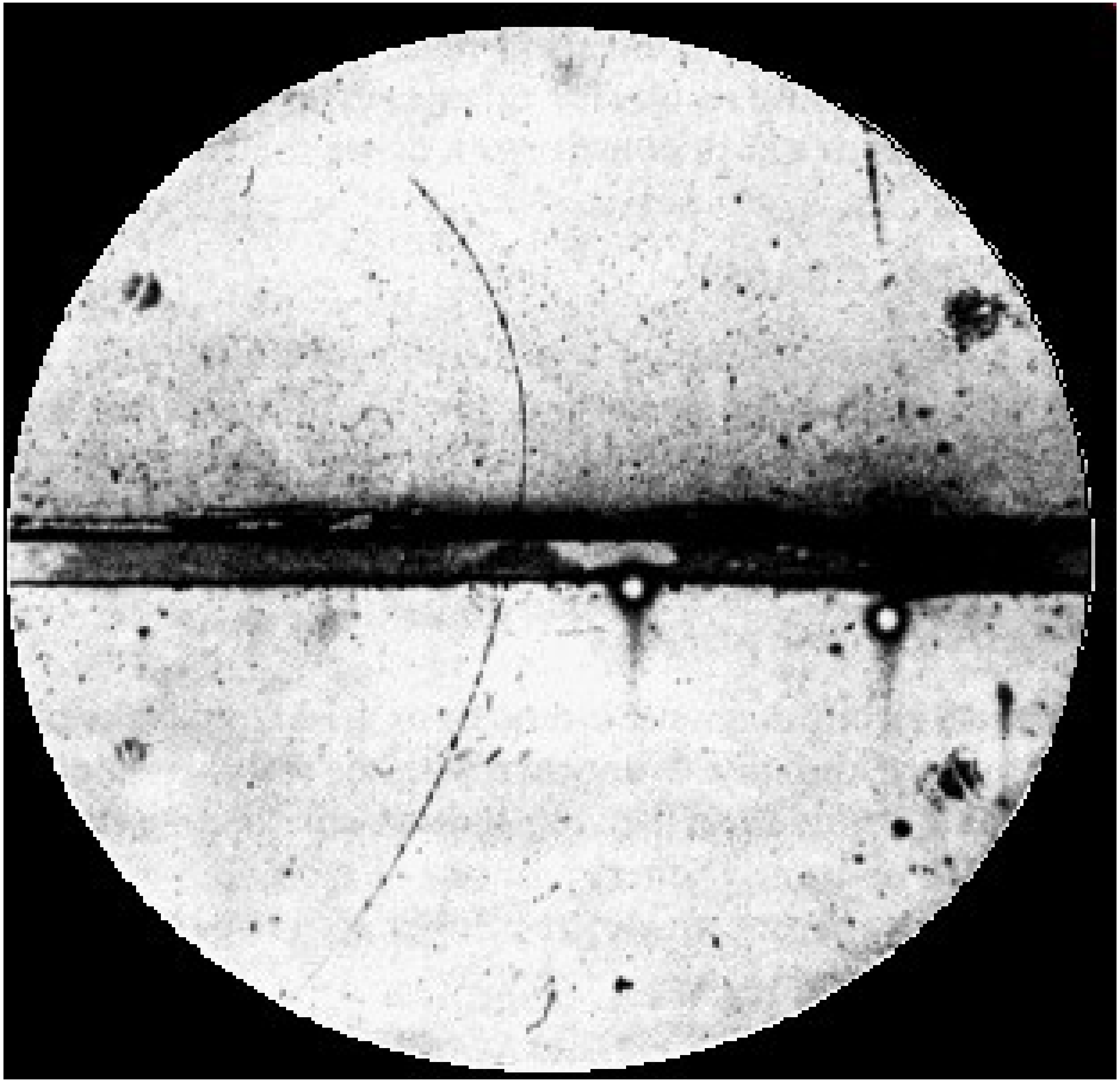
An energy of an MeV was enough for a lot of other exciting discoveries about the Universe. Apart from radioactive sources in the lab, high energy particles reach us from outer space – they are called cosmic rays.

One of the first big discoveries made using cosmic rays – in 1932 – was the existence of “antimatter.” It was found that cosmic ray particles reaching the earth included along with electrons also new particles called “positrons” that are like electrons, but have the opposite electric charge.

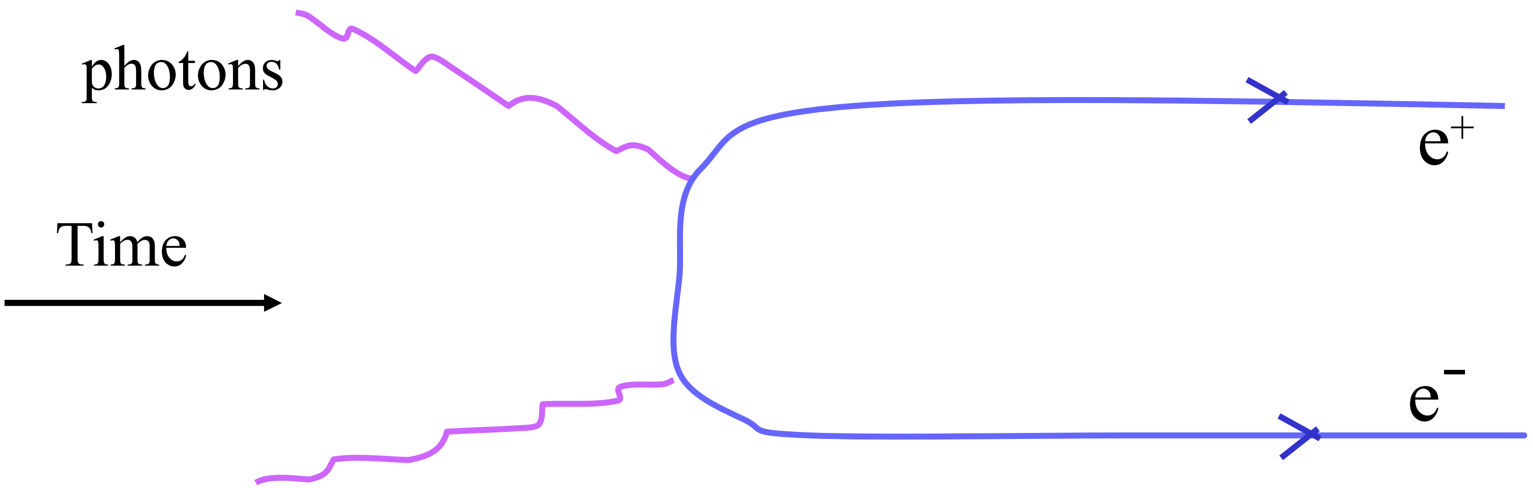






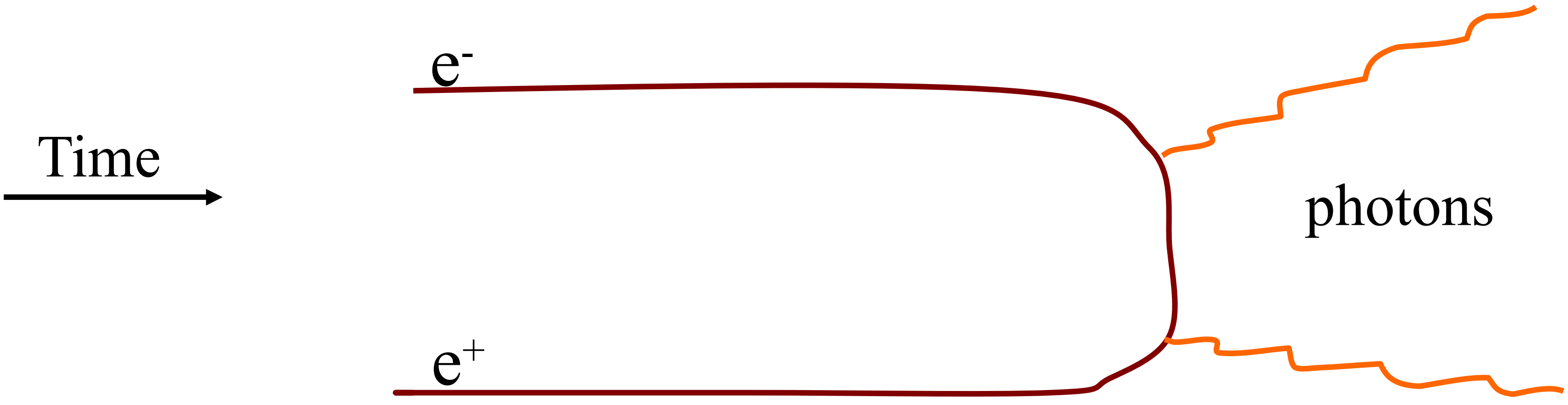
That was a schematic picture; here is a real one. This is what it looked like when antimatter was first discovered in 1932 by C. D. Anderson, leading to the 1936 Nobel Prize

The most basic property of “antimatter” is that matter-antimatter pairs can be created and annihilated.



For example, photons – which are as close to pure energy as it gets – can be converted to electron-positron pairs.

And similarly electron-positron pairs can annihilate into photons.



If you travel to a distant Solar System and meet a creature made of antimatter, don't shake his or her hand!

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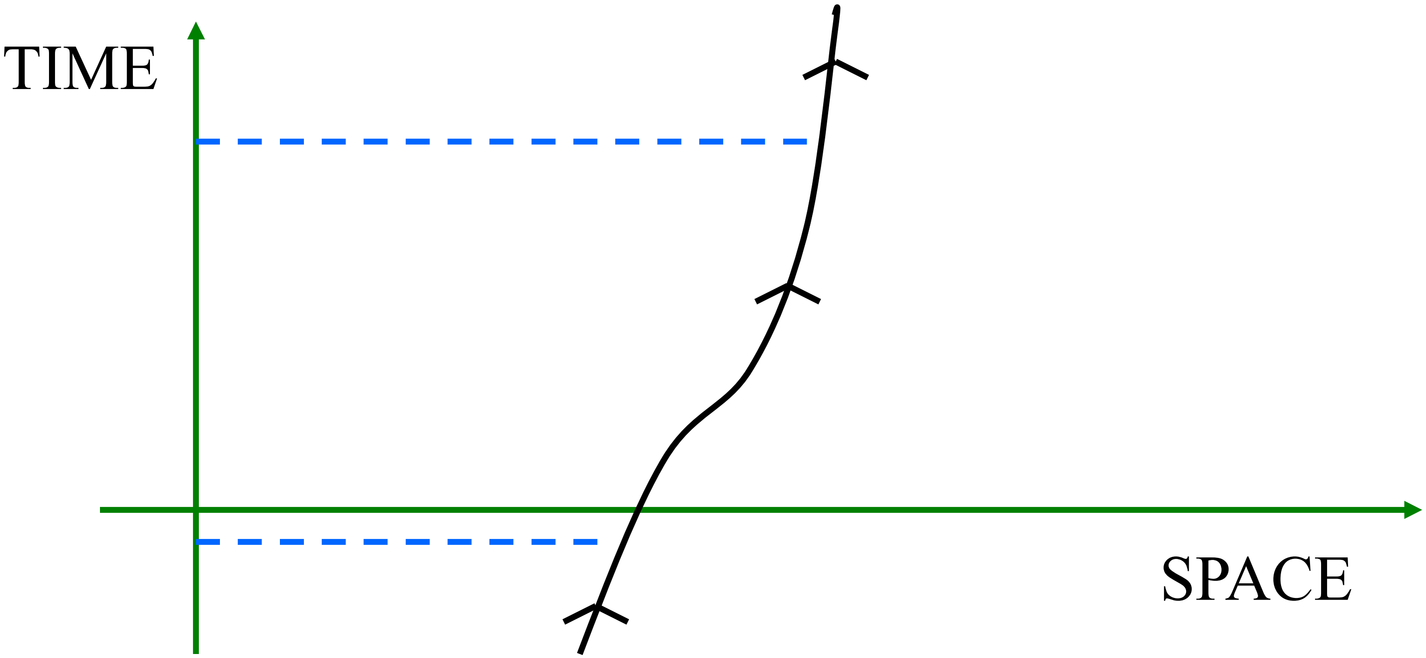
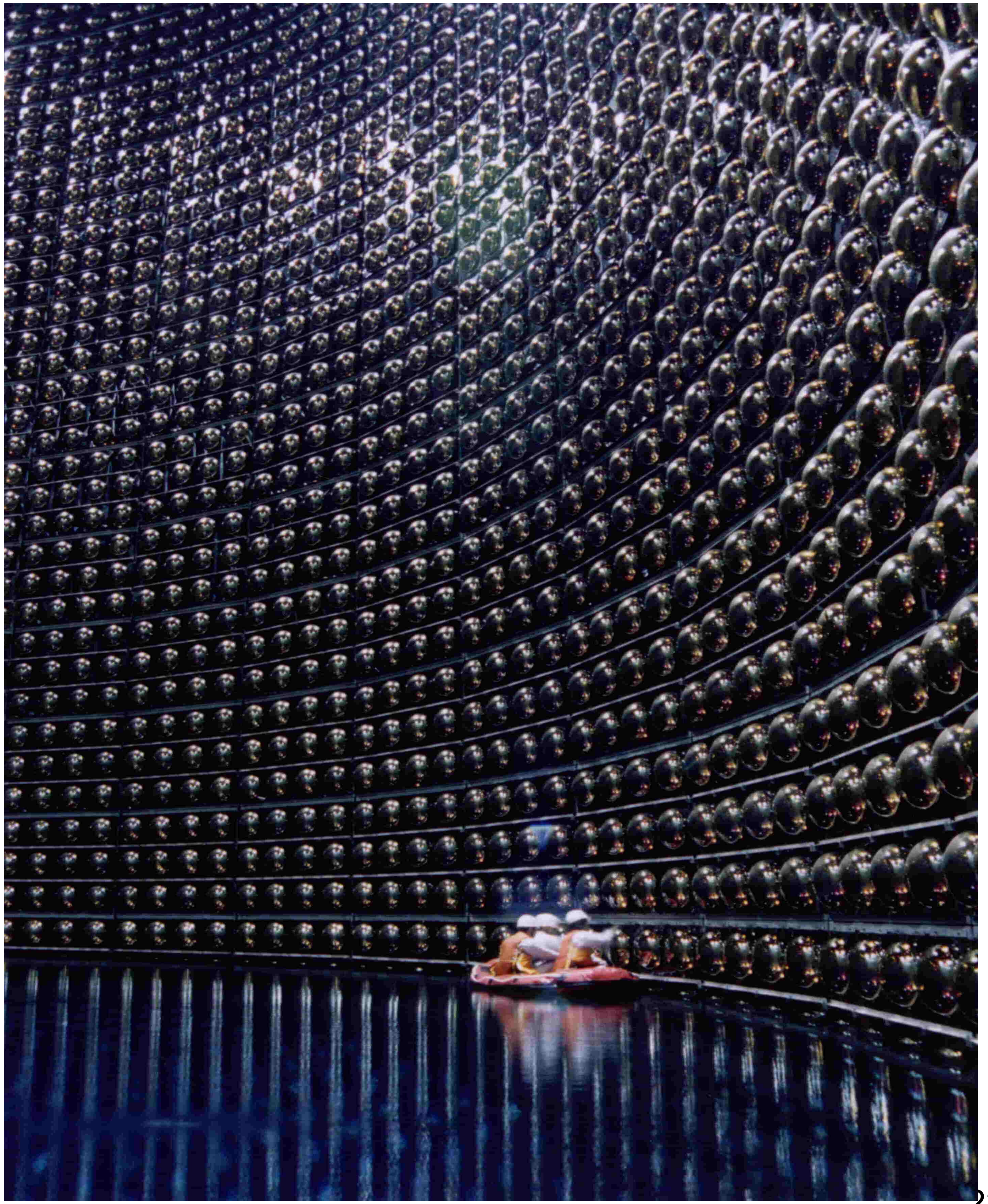
In the quantum world, everything is fuzzy – if you know where a particle is, you don't know how fast it is moving…



The “quantum uncertainty principle” implies that to discover small things (like an atomic nucleus), one requires a probe with high energy (like the radioactive beam used by Rutherford).

Discoveries are still made with cosmic ray particles … this is the SuperK detector in Japan



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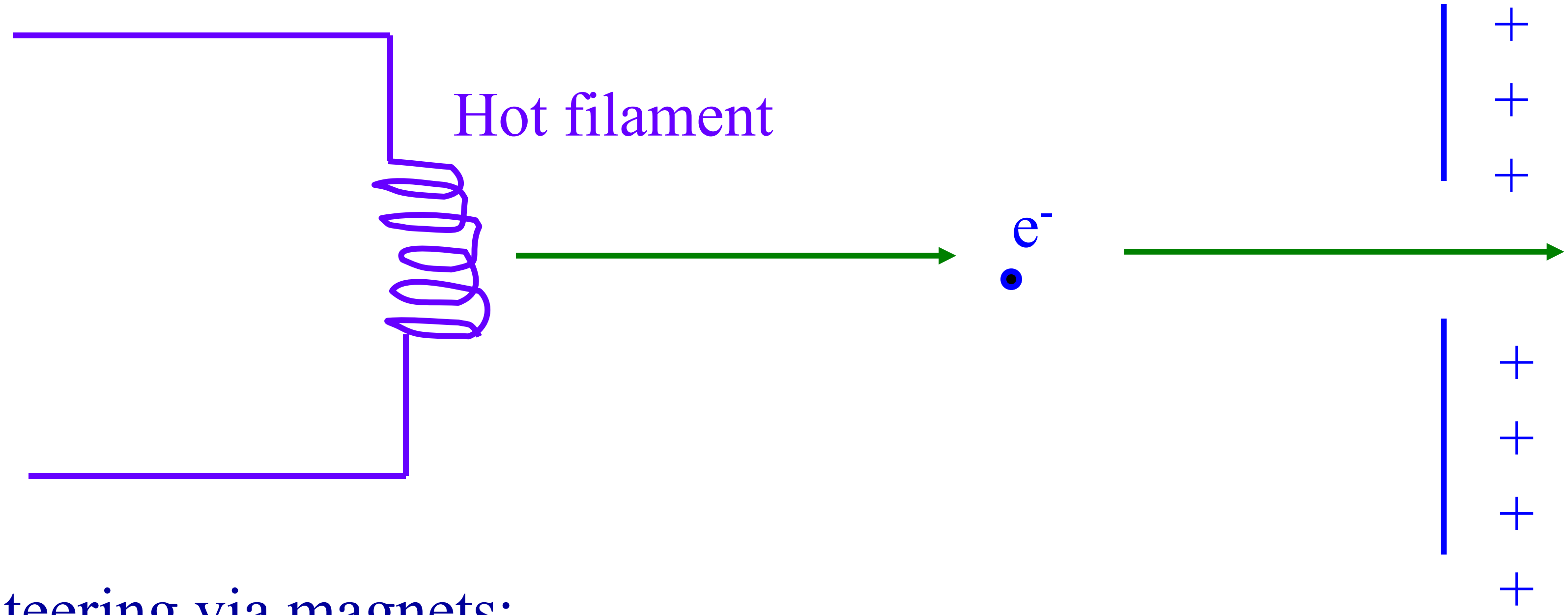
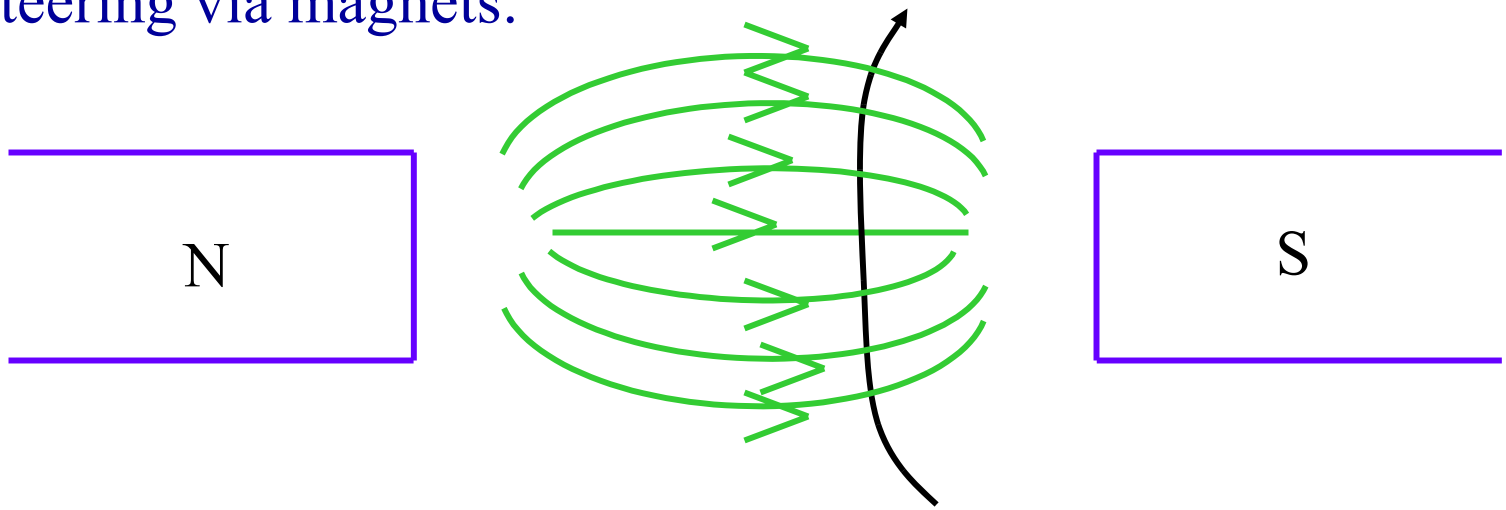
In accelerators, charged particles – usually electrons or protons or their antiparticles (positrons and antiprotons) are accelerated using electromagnetic fields.

Like many big things, it started with very simple ideas



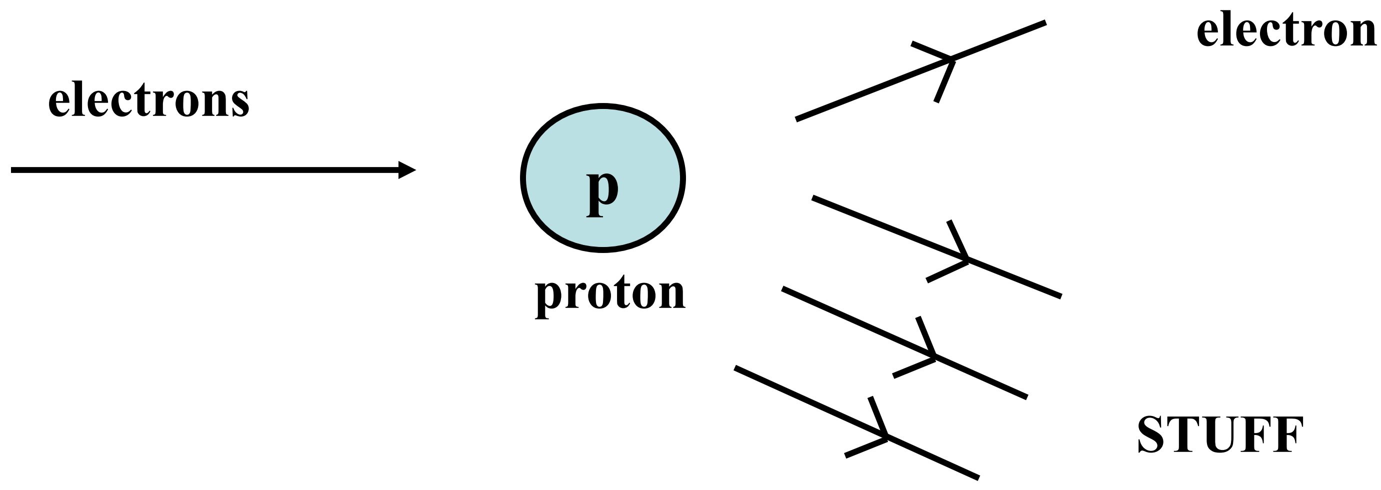
Steering via magnets:



Bit by bit, new techniques were found or old ones were improved and it was possible to go farther.

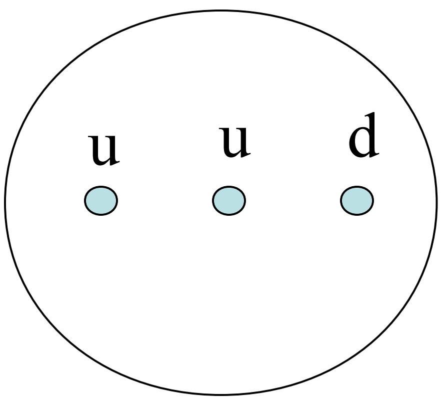
One surprise was discovered after another and each surprise raised new questions.

By the 1960's, electron beams with an energy of a few GeV were available. By smashing these beams into atomic nuclei, physicists repeated Rutherford's experiment at higher energies

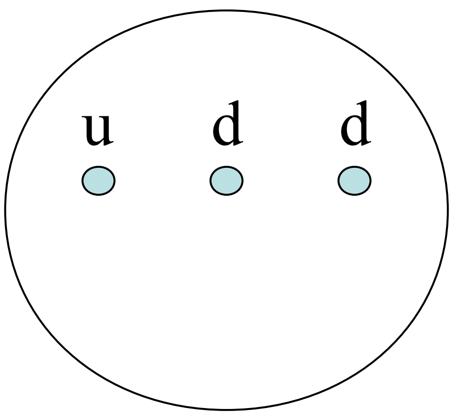


and discovered "quarks"

Modern picture, which emerged from this and other experiments: proton or neutron is made of three quarks (plus “gluons”)



proton



neutron

u $\frac{2}{3}$ e
d $-\frac{1}{3}$ e

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Because there is a limit on the strength of the electromagnetic fields that we can use to accelerate or steer the particle beams, to reach higher energies, we need a bigger accelerator…that is why accelerators have kept growing in size and cost, leading up to the Tevatron in the United States and now to today's LHC here in Europe.

The energy of the LHC is currently 4 TeV in each beam or 8 TeV in all.

Let us remember the characters:

1 eV typical energy of an electron coming out of an ordinary flashlight battery

1 MeV is mc^2 of an electron

1 GeV is mc^2 of a proton

1 TeV is 1000 times bigger still, or 10^{12}eV

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To discover quarks and *understand* the nucleus took GeV energies.

But to understand the mysterious “weak force” in Nature has required the TeV energies that we are only now reaching.

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I would like to explain what the Higgs particle is all about.

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Instead, it takes modern equipment to detect and study the weak interactions – whose most well-known manifestation is in certain forms of atomic radioactivity.

Yet according to our best understanding, the same type of equations describe electromagnetism and the weak interactions at a fundamental level.

Indeed, this is one of our most incisive insights about the unity of the most fundamental laws of nature.

To a large extent, this was proved 30 years ago when a previous accelerator at CERN discovered the W and Z particles, which are the basic quanta of the weak force in the same sense that the photon is the basic quantum of electromagnetism.

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(Incidentally, this discovery was made at a machine with an energy of about 500 GeV – roughly 100 times more than the energy needed to discover quarks and 1/16th of the current LHC energy.)

According to the fundamental laws, the W and Z are no different from the photoon …

but something has happened that hides two of them from our ordinary experience …

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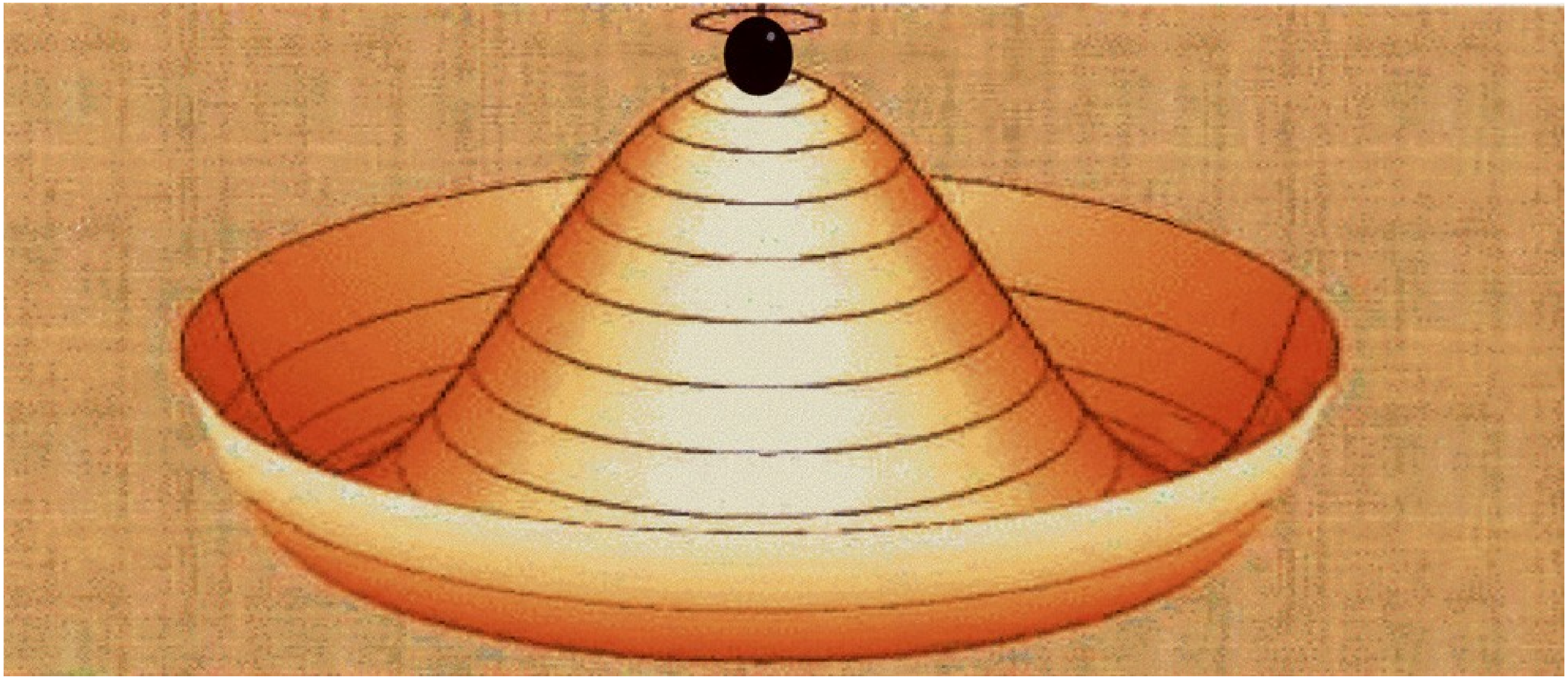
According to theory, that something is called “symmetry breaking.”



The little ball symbolizes the Universe …
about to roll down the hill and break the
symmetry between the different forces.

When the ball gets to the bottom of the hill, it can vibrate there …. According to quantum mechanics, vibrations of a field are what we interpret as “particles.”

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In the case of the little ball – or field – that rolled down the hill to break the symmetry between the forces, its vibrations are what we call the Higgs particle.

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Most of the particle masses arise when the ball rolls down the hill and breaks the symmetry between the forces …

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This goes for the W and Z masses, the electron mass, and the masses of the quarks (the proton and neutron are more complicated).

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So the little ball rolling down the hill hid the weak interactions, left us to see light waves, made it possible for atoms to exist, and in brief made the Universe the way it is.

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The particle masses are small!

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For us to be big and complicated enough to be able to think about an electron, we inevitably are made of many, many atoms so a single electron seems tiny to us.

To a physicist, it is more interesting to compare the electron mass to the constants of Nature.

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way to make this comparison is to compare the gravitational force between two electrons – which depends on the electron mass – to the electrical force between two electrons – which depends on the electron charge.

Gravity loses, by a lot. It is way weaker than even the weak force:

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The gravitational force between two electrons Gm^2/r^2

is less than the electric force e^2/r^2

by an unbelievably big factor 10^{42}.

That is why you sometimes feel an electrical shock from the doorknob even though you never feel the gravitational force of the doorknob.

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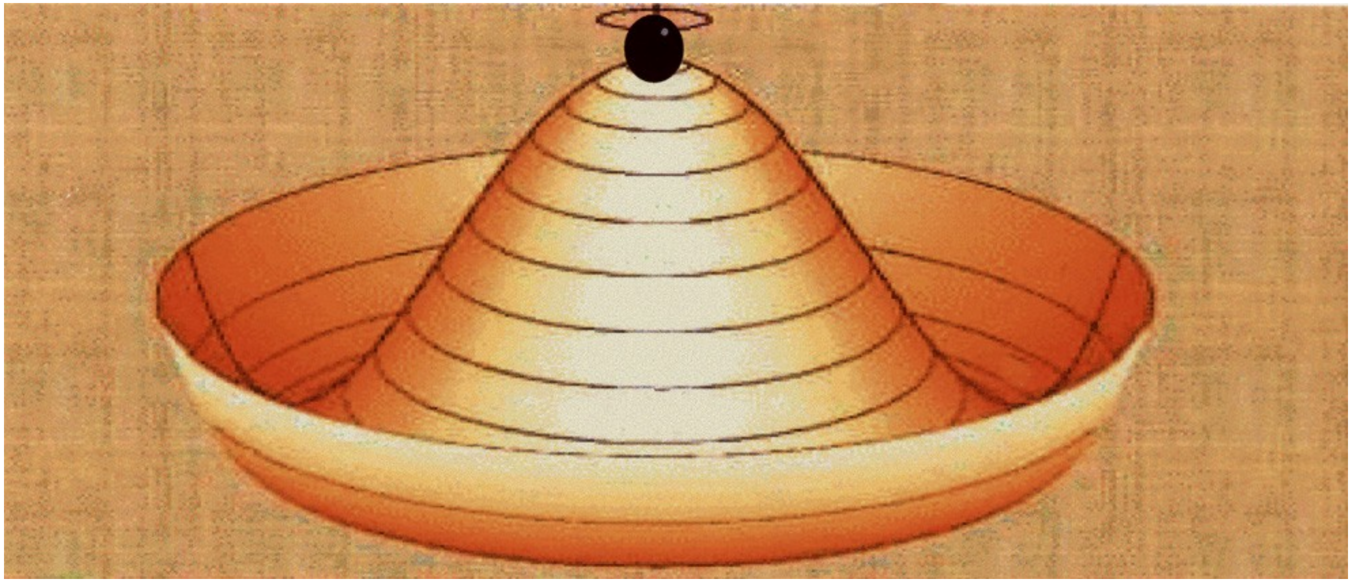
All the atoms in the doorknob are exerting a gravitational force on your hand, and only a few electrons (relatively) are giving you the shock, but gravity is very weak because the particle masses are so small, so you don't feel the gravitational force.

Particle physicists have put a huge effort into theories that try to explain why the little dip in the hat is so shallow



and hence why the particle masses are so little.

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Some have already run into trouble but others are still viable and will be tested in the next few years, as we learn more about the Higgs particle and about what happens at LHC energies.

One of the still viable explanations is something called “supersymmetry” …

to which I and many colleagues have devoted a very large effort.

Supersymmetry is roughly speaking an updating of Einstein’s Special Relativity in the light of quantum theory.

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According to supersymmetry, beyond the obvious dimensions of space and time, there is an additional "quantum dimension."

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One also needs quantum variables to describe spacetime.

An ordinary particle, like the electron, vibrating in the quantum dimension, would be observed as a new particle (electrically charged like the electron, but spinless and non-magnetic) that could be produced and detected at the LHC.

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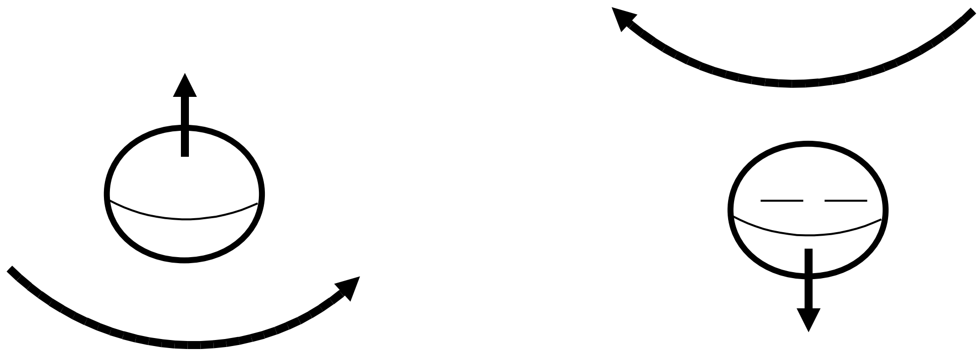
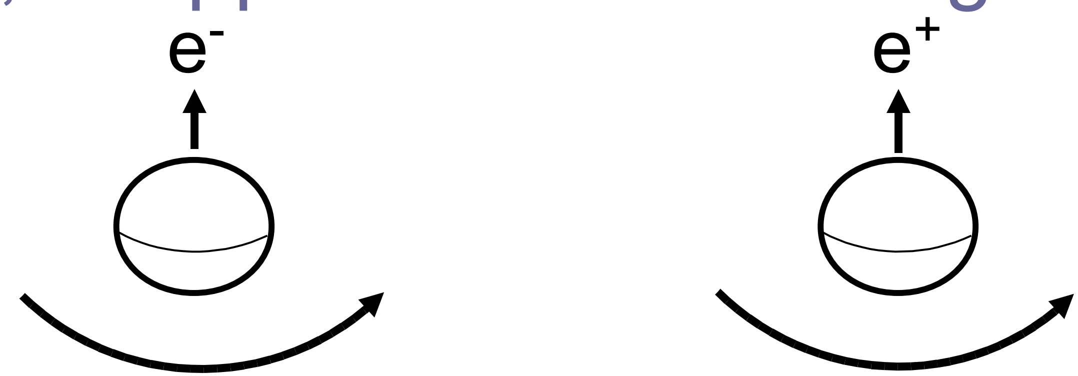
The zoo of elementary particles could potentially double in size if we could discover all of the “superpartners,” as it did when antimatter was discovered in 1932.

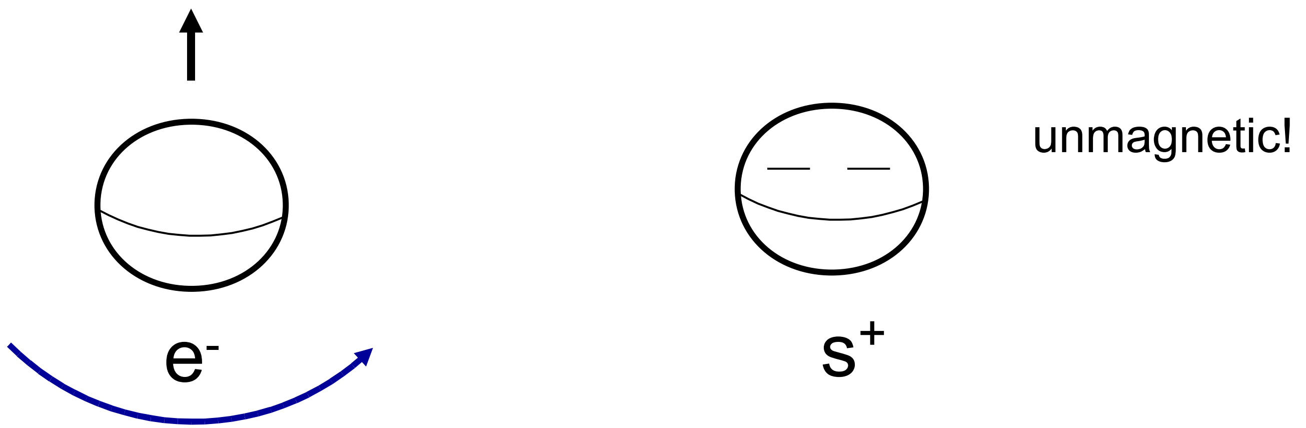
In the 1920's and 1930's, we learned that the electron spins like a tiny quantum magnet



and that it has an antimatter cousin, the positron, of opposite electric charge.



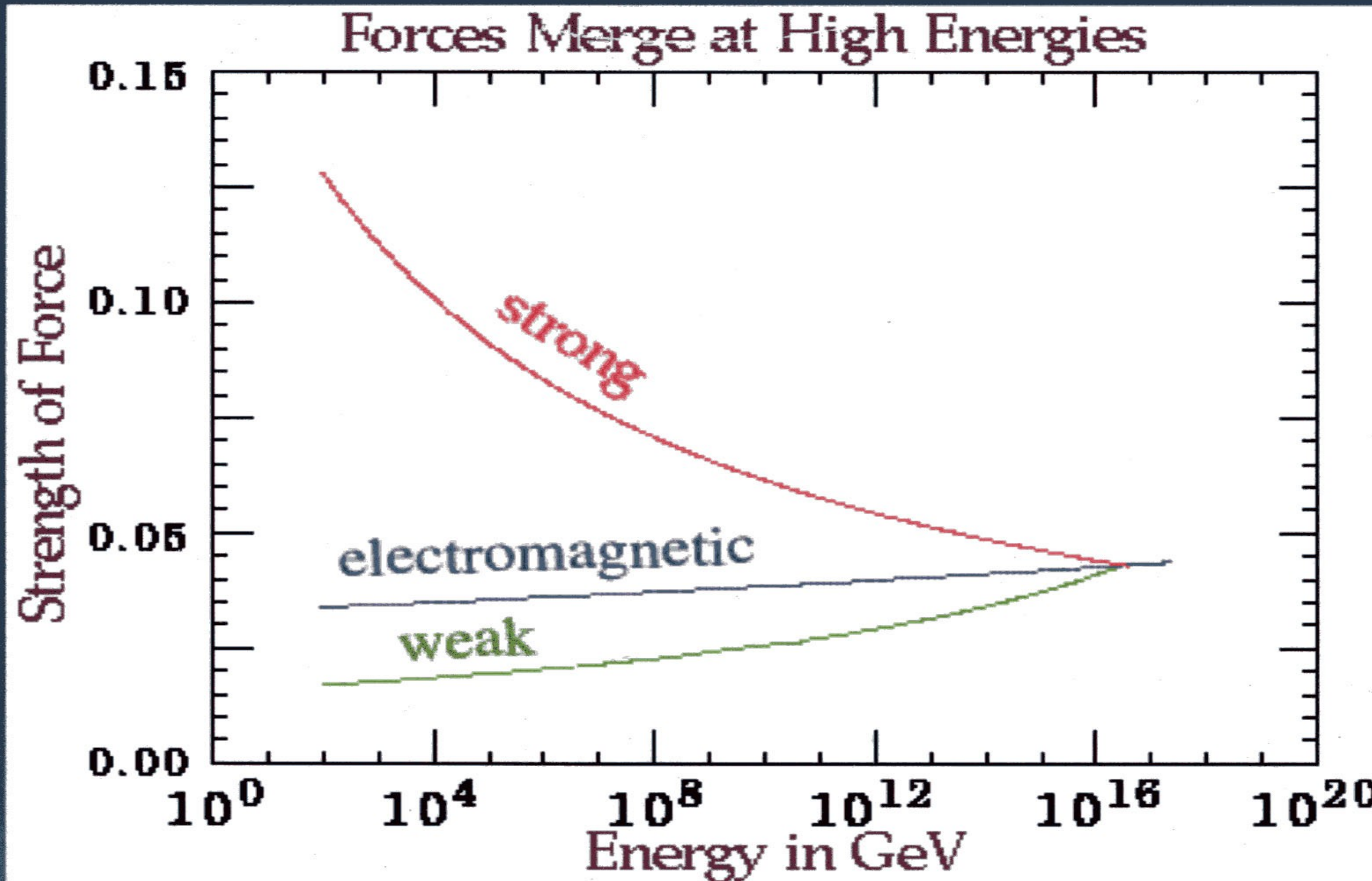
If supersymmetry is correct, then the electron also has a new cousin, not yet discovered, which is "spinless" and hence non-magnetic:



Supersymmetric particles have not been discovered yet – and in some versions of the theory, this should have happened already – but there is a possible hint of supersymmetry in data that we already have …

Supersymmetric particles have not been discovered yet – and in some versions of the theory, this should have happened already – but there is a possible hint of supersymmetry in data that we already have … this involves measuring the strengths of the different forces of Nature and extrapolating how they change as the energy is increased.

Running Couplings



A vast amount of experimental data are summarized in this one plot.

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And hopefully we will know within a few years.

Why do the three curves meet as if supersymmetry is real if we have not seen supersymmetric particles yet?

Why do the three curves meet as if supersymmetry is real if we have not seen supersymmetric particles yet? One suggestion is something called “split supersymmetry,” according to which we would probably not see at the LHC the supersymmetric partners of the electron or the quarks, but we would have a decent chance to see the partners of the photon, the W and Z particles, and the Higgs particle.

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Einstein based his concepts of space and time entirely on pre quantum mechanical ideas … it could not have been different, since quantum mechanics was still in the future when relativity theory was invented!

Finding supersymmetry would force us – and enable us – to at least begin to include quantum variables in the way that we think about space and time.

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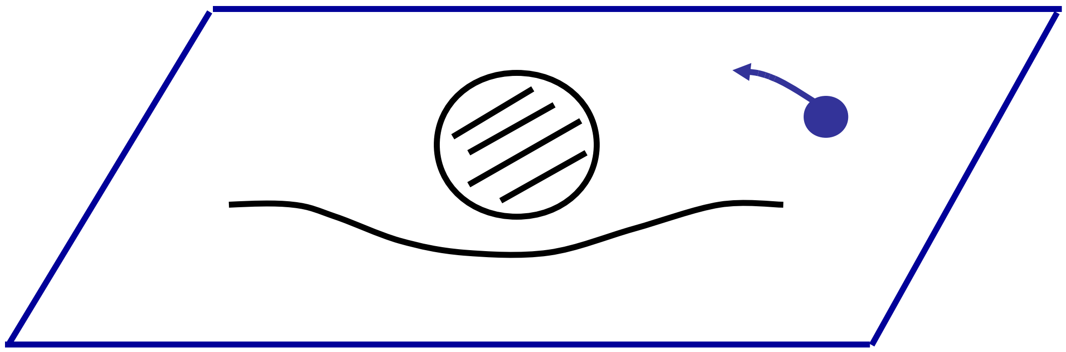
But it might potentially help with something even bigger.

Physics became very strange in the 20^{th} century ...

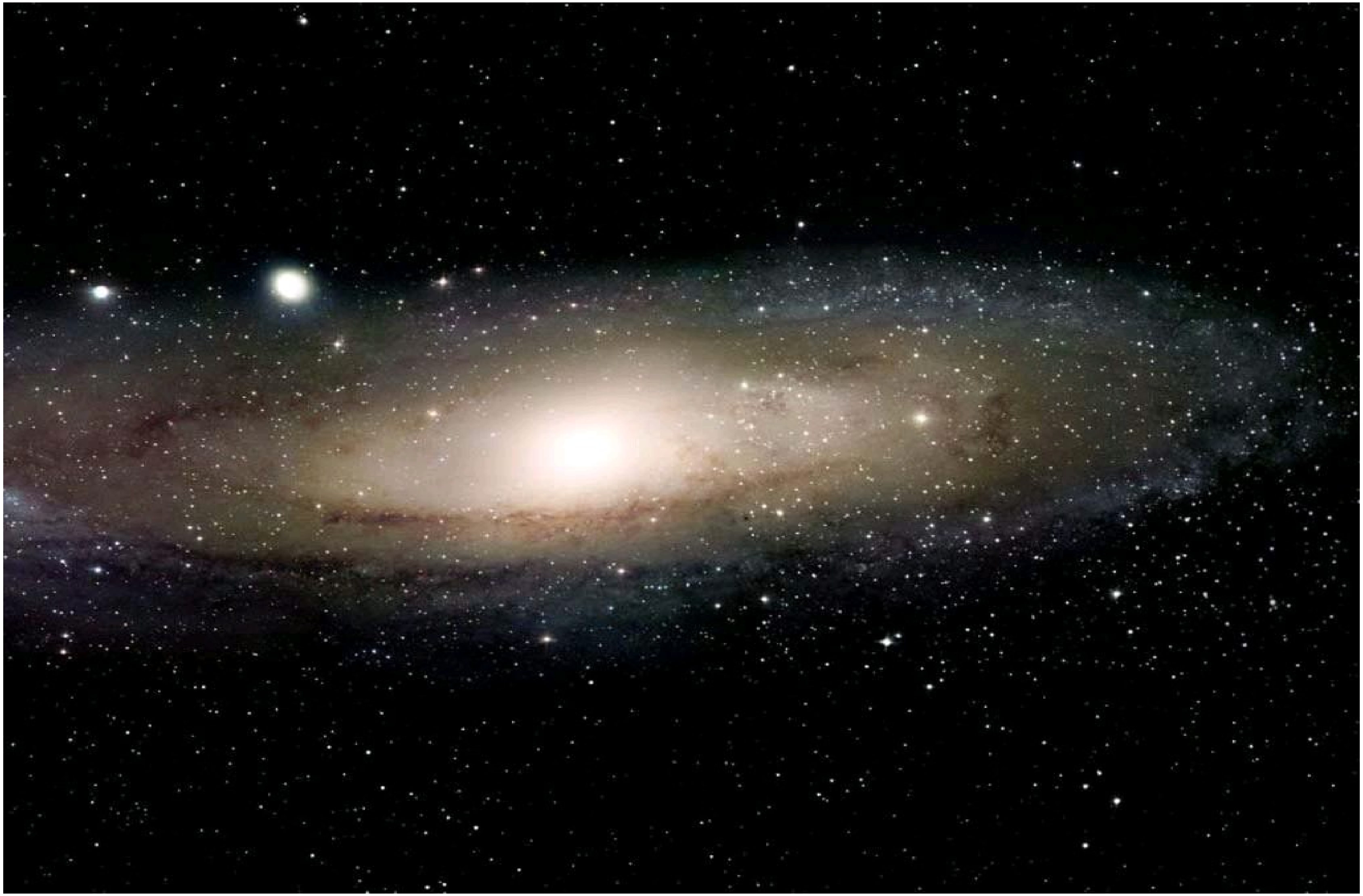
Objects behave strangely near the speed of light. Particles are waves. Energy can convert into matter.

Almost all of these strange things are everyday facts of life in the world of elementary particles.

There is really only one exception and this is Einstein's greatest achievement, his theory of gravity, which is known as General Relativity.



According to Einstein, gravity results from the curvature of spacetime, but we don't see this in particle physics just like you don't feel the gravitational force of your doorknob … the masses are too small.



Gravity is important when masses are big, so it is mostly studied by astronomers.

There is a problem with gravity: the nonlinear mathematics of Einstein's theory is not compatible with the quantum field theory that we use to describe elementary particles and their forces.

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So in practice, modern physics is based on quantum physics for atoms, while Einstein's general relativity is used for stars, galaxies, and the whole Universe.

It is hard to combine the two theories.

Something is wrong with this, since stars and galaxies are ultimately made out of atoms. They all have to be described by the same theory.

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And experience has taught us that problems like this one should be taken seriously.

But I think that this problem would simply have looked too difficult to me, had not an interesting approach fallen out of the sky

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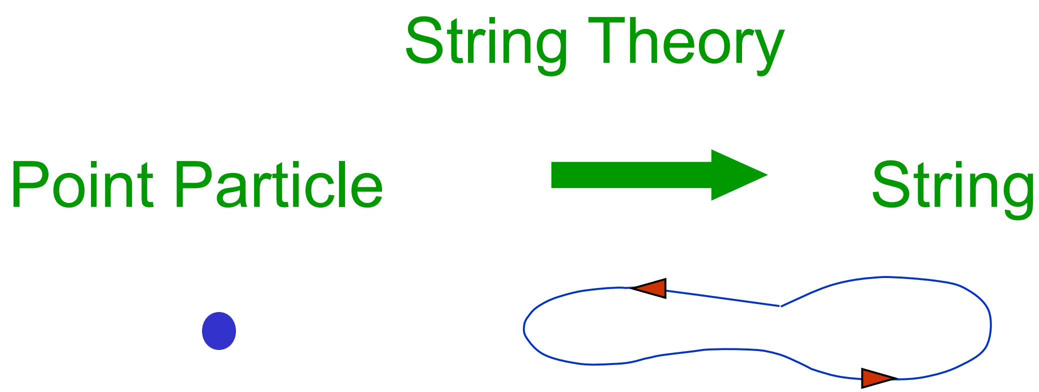
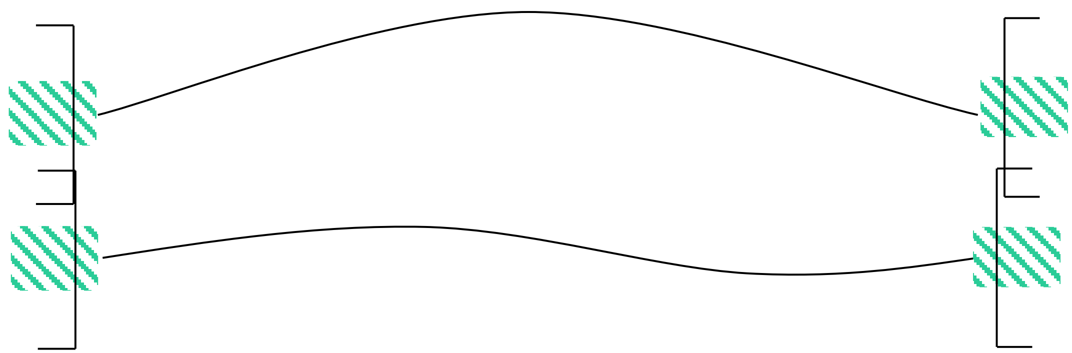
Or more accurately, had it not emerged as a lucky by-product from a not quite successful attempt in the late 1960's and early 1970's to understand the “strong force” that is responsible for binding quarks to make protons and neutrons

The one real idea about how to combine quantum mechanics with general relativity is “String Theory”:



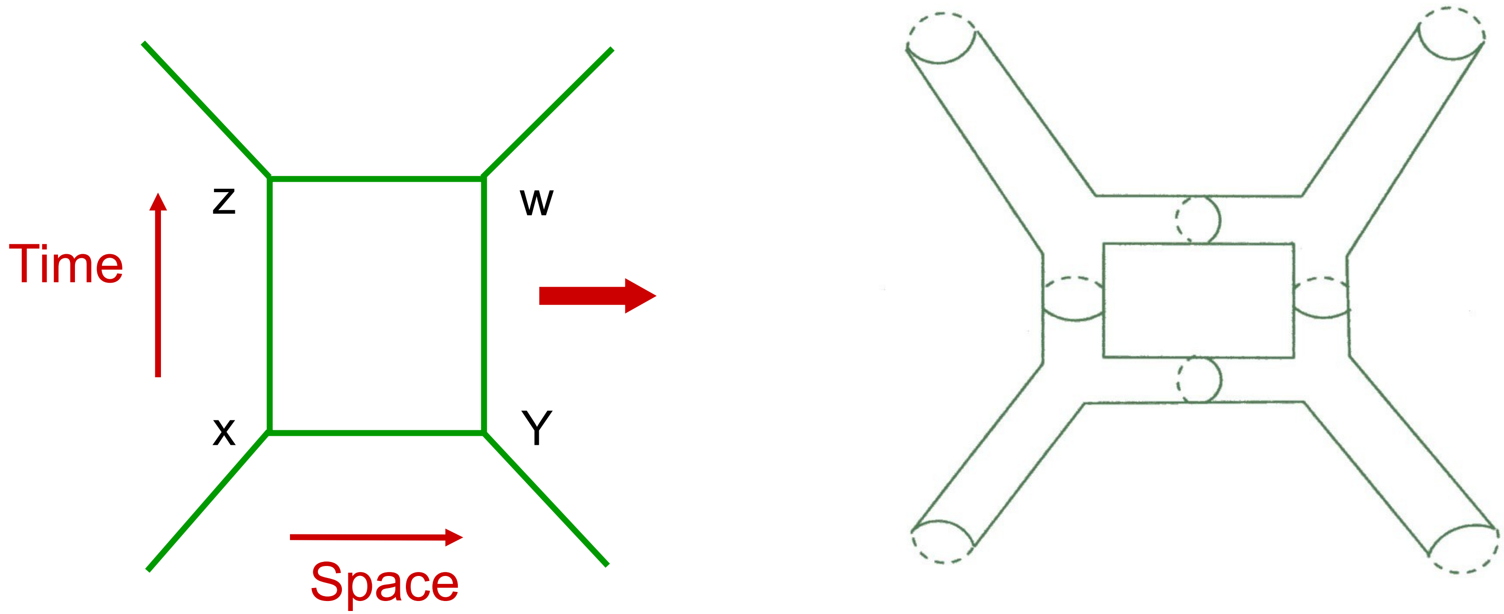
Like a violin string, one of these strings can vibrate in many ways:



Richness of music and unity of the elementary particles … they are all different forms of vibration of the same string.

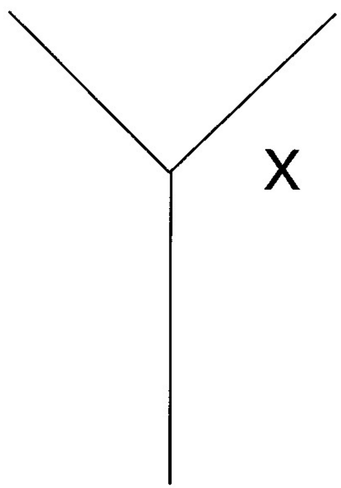
It sounds like an incredibly naive idea, but it has incredibly far-reaching consequences…which I have to explain in just a few minutes.

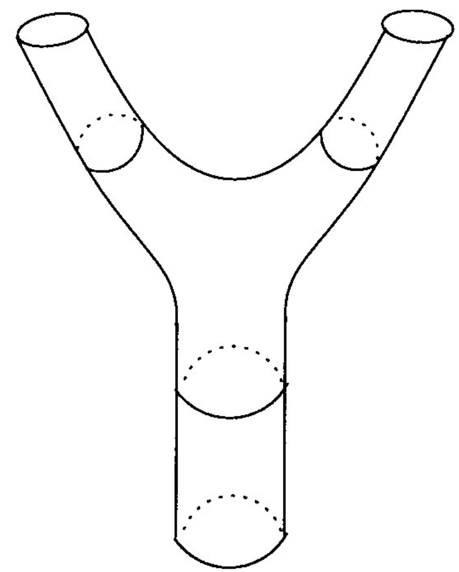
So I'll resort to a picture:



The particle interacts at special spacetime events x,y,z,w and we need rules for what happens there. As a result there are many possible theories, and trouble if x = y = z = w.

For the string, no special moment:





Any small piece of the picture on the right looks like any other.

Consequences:

For the string, spacetime becomes fuzzy—the string embodies new ideas in geometry that we don't yet understand.

The string makes its own rules—generates its own interactions.

String theory has a mind of its own and it does what it wants, regardless of what a physicist studying it may or may not want it to do.

Out pops Quantum Gravity—like it or not.

Out pops Gauge Symmetry …

the bread and butter of standard particle physics.

And out pop ten dimensions of spacetime — like it or not.

No one was looking for extra dimensions, but physicists studying string theory had no choice but to learn to live with them.

No one was looking for extra dimensions, but physicists studying string theory had no choice but to learn to live with them.

Nowadays, we see them as a blessing in disguise, since they give us more “room” to unify the particles and forces by interpreting the electron, the photon, the neutrino, the quarks, the W and Z and Higgs particles, and all the rest as different states of vibration of one basic “string”

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The last piece that pops out is Supersymmetry and this may be the piece that we have the best chance to test in the forseeable future – hopefully at the LHC!

Let us hope for good news in the coming years!