Title: The Quest for Supersymmetry

Date: Apr 06, 2005 07:00 PM

URL: http://pirsa.org/05040046

Abstract: Edward Witten is one of the worldÂ’s preeminent string theorists. Among his many accomplishments, he is widely known for showing how five different variations of string theory all belong within a single framework. His awards range from a MacArthur \'genius grant\' to the Fields Medal - the highest honour in the world of mathematics. Professor Witten will examine key discoveries made by physicists in the 20th century such as the detection of antimatter. He will then describe how many of todayÂ’s leading scientists are working at the high energy frontier of elementary particle accelerators in their quest to uncover the quantum structures of space and time. <kw> supersymmetry, Edward Witten, particle physics, quantum mechanics, waves, Rutherford, antimatter, antiparticle, quantum uncertainty principle, accelerator, space-time </kw>

PARTICLE PHYSICS

Edward Witten
Institute for Advanced Studies

“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.

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:

Rutherford was very surprised to see that his particles were sometimes scattered at large angles – the atom contained a hard "nucleus."

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.

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

Rutherford was very surprised to see that his particles were sometimes scattered at large angles – the atom contained a hard "nucleus."

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.

The energy of the alpha particles in Rutherford's beam was large – roughly a Million Electron Volts, that is a million times the energy of an electron that comes from a one volt battery. This is the abbreviated MeV.

We also write GeV as an abbreviation for a Billion Electron Volts.

Rutherford's experiment was done at roughly the same time that Einstein was learning that

$$E = mc^2$$

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.

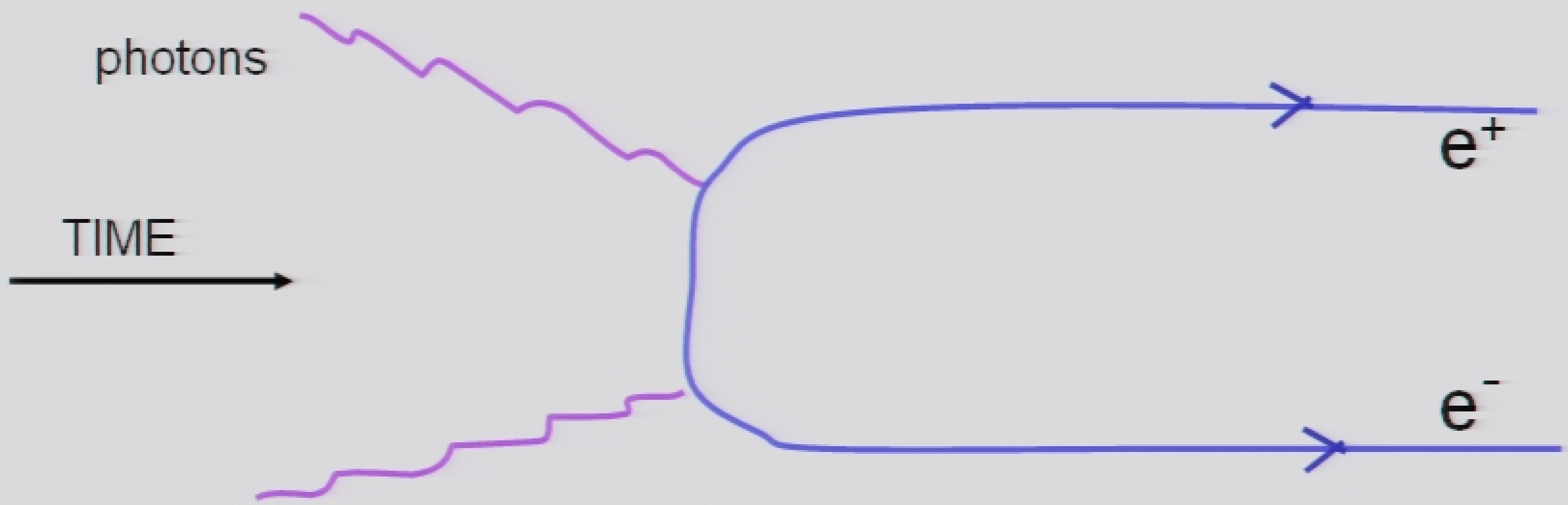
The next one, by the way, is a TeV, and this stands for a Trillion Electron Volts!

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 – around 1930 – 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.

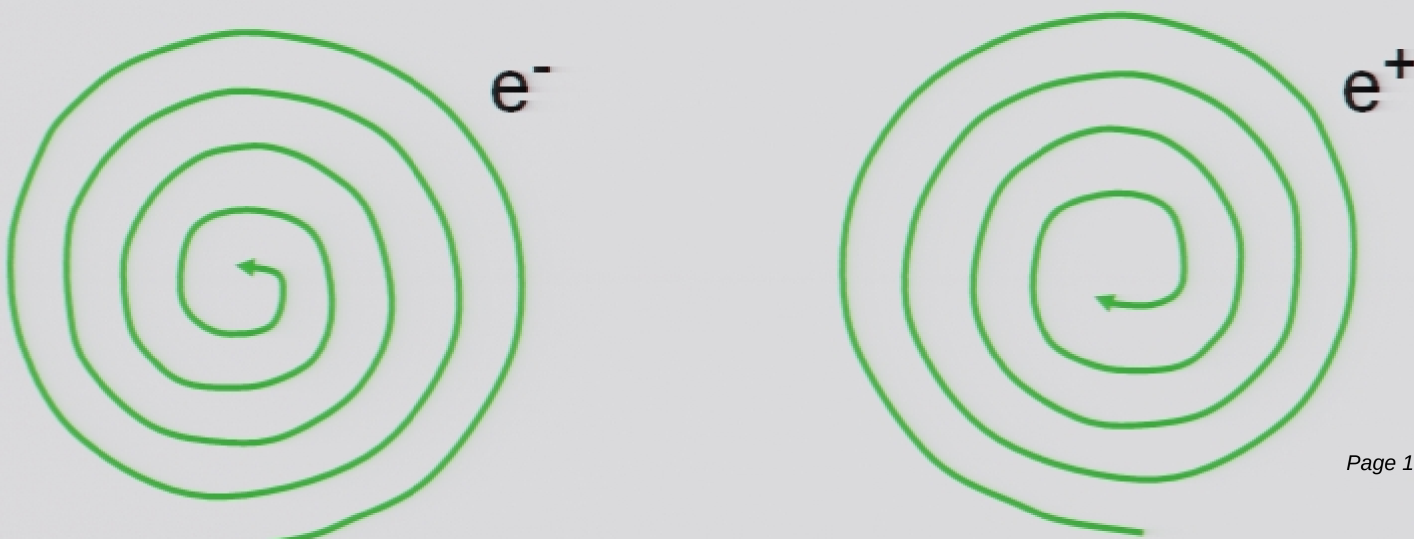
The most basic property of "antimatter" is that matter-

antimatter pairs can be created and annihilated.



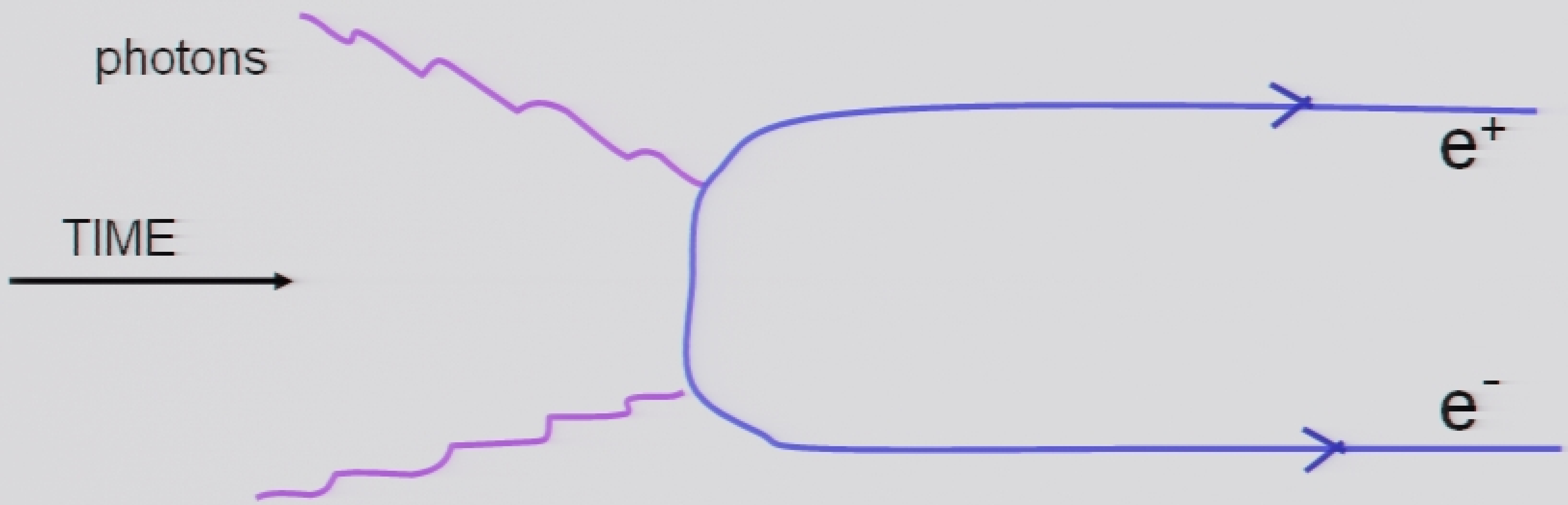
For example, photons – which are as close to pure energy as it gets – can be converted to electron-positron pairs.

One of the first big discoveries made using cosmic rays – around 1930 – 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.



The most basic property of “antimatter” is that matter-

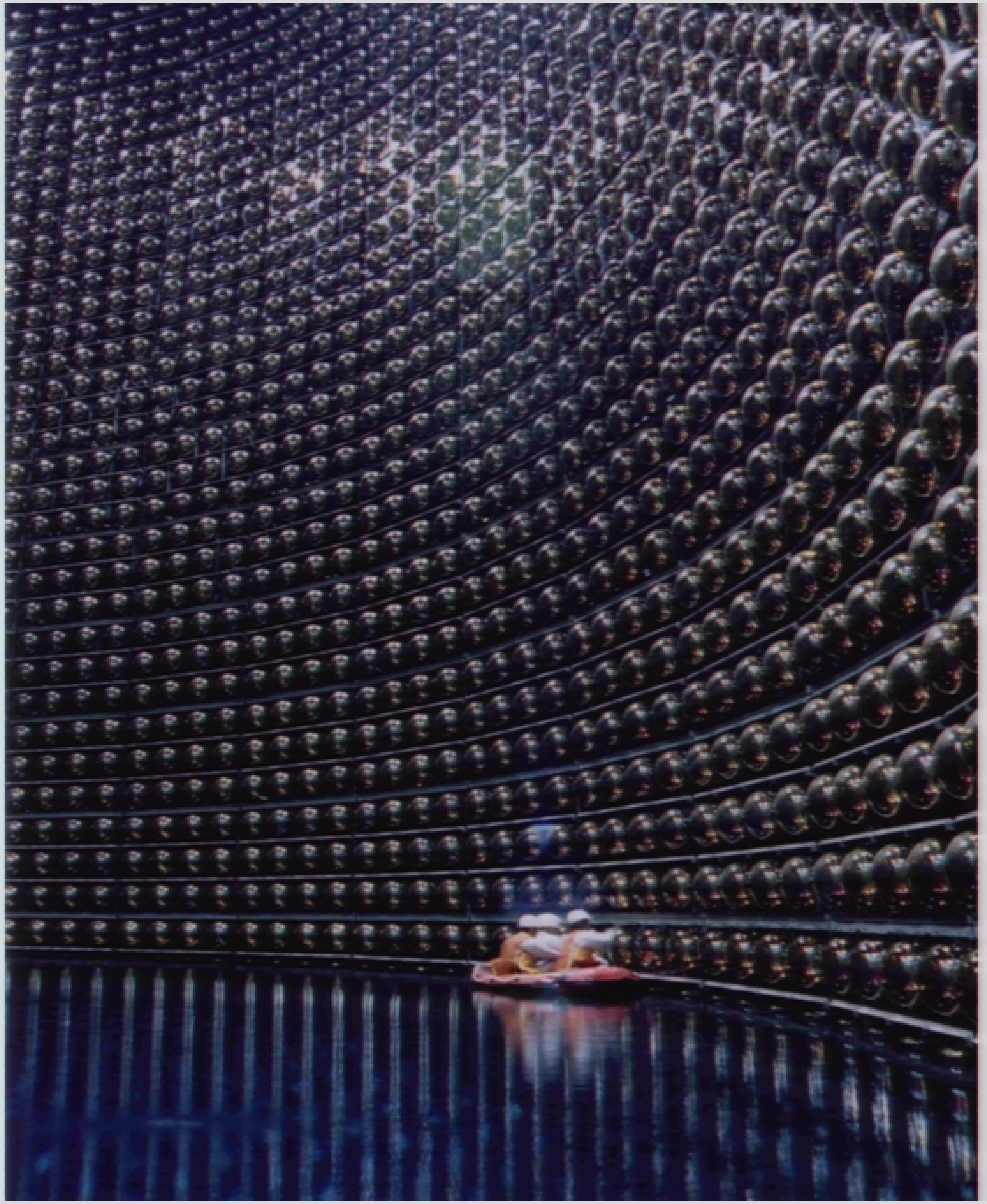
antimatter pairs can be created and annihilated.

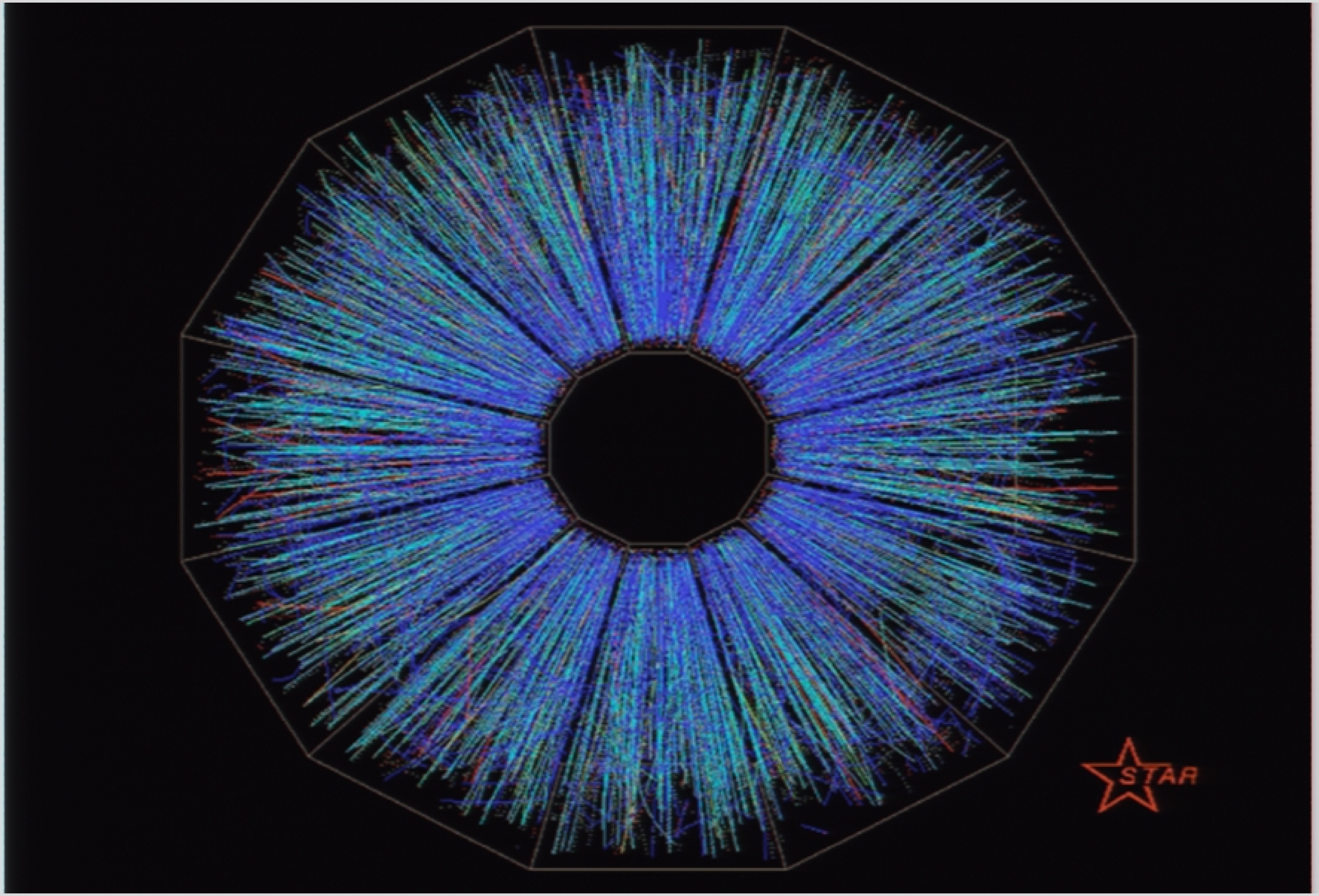


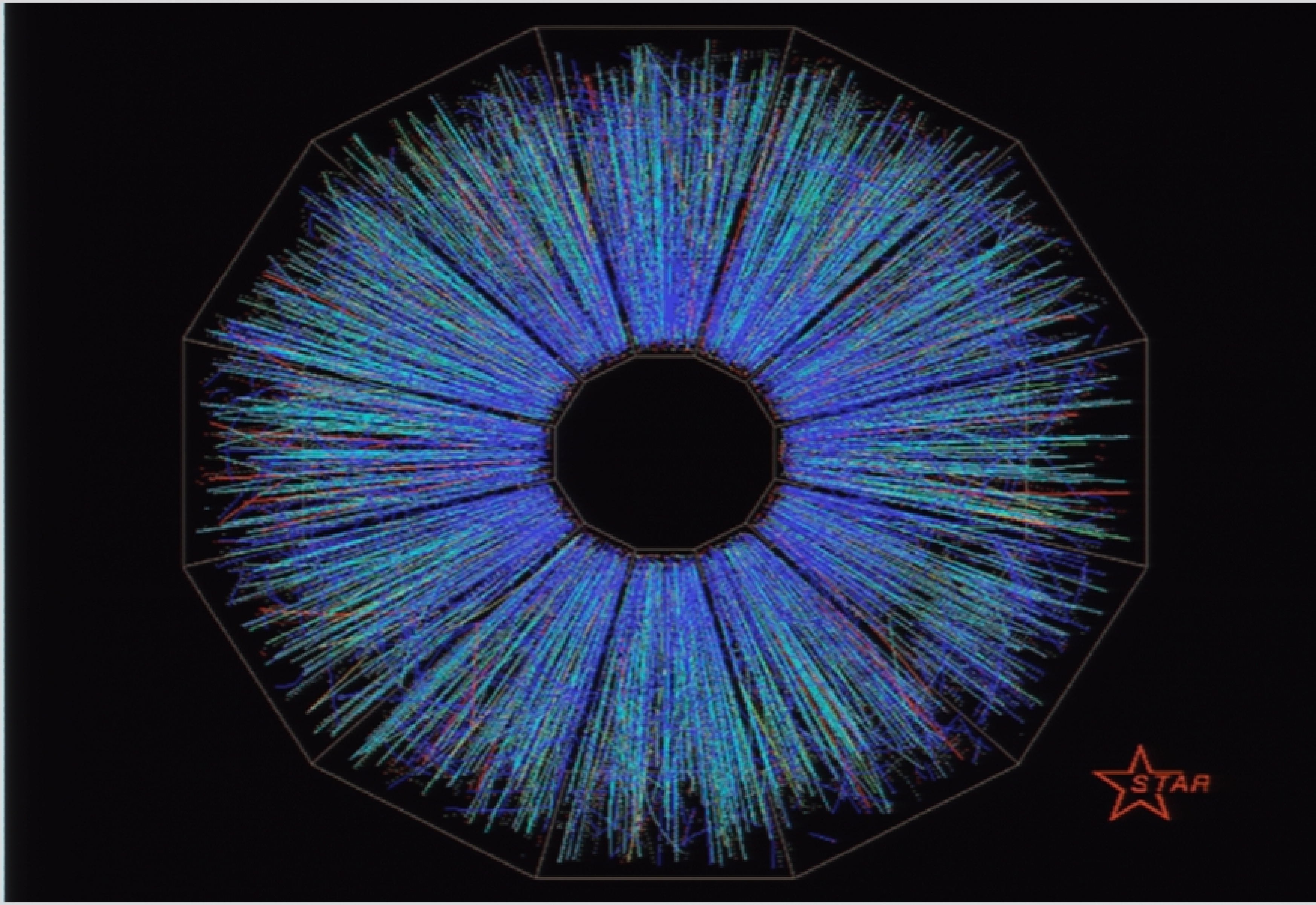
For example, photons – which are as close to pure energy as it gets – can be converted to electron-positron pairs.

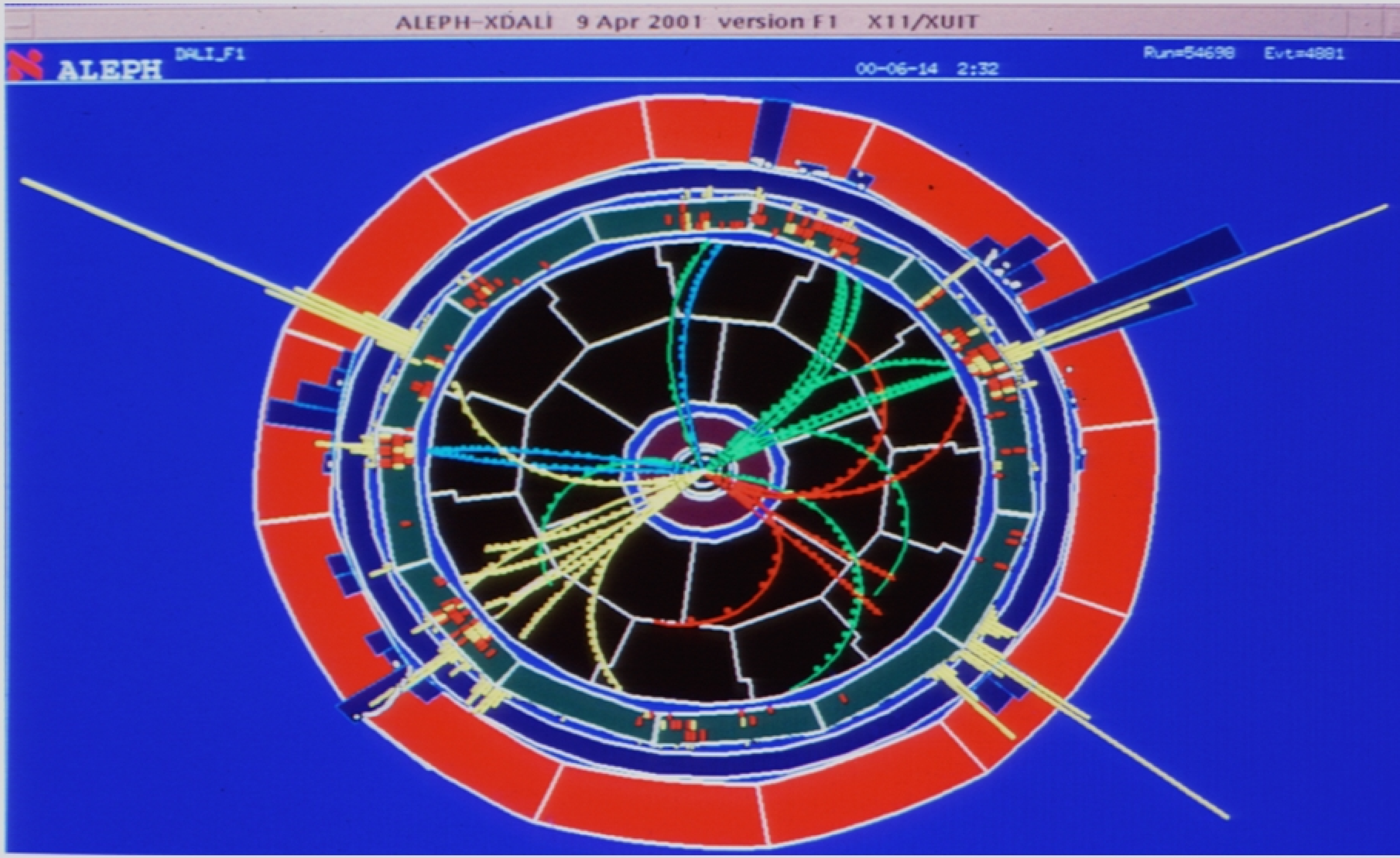
And similarly electron-positron pairs can annihilate into photons.

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



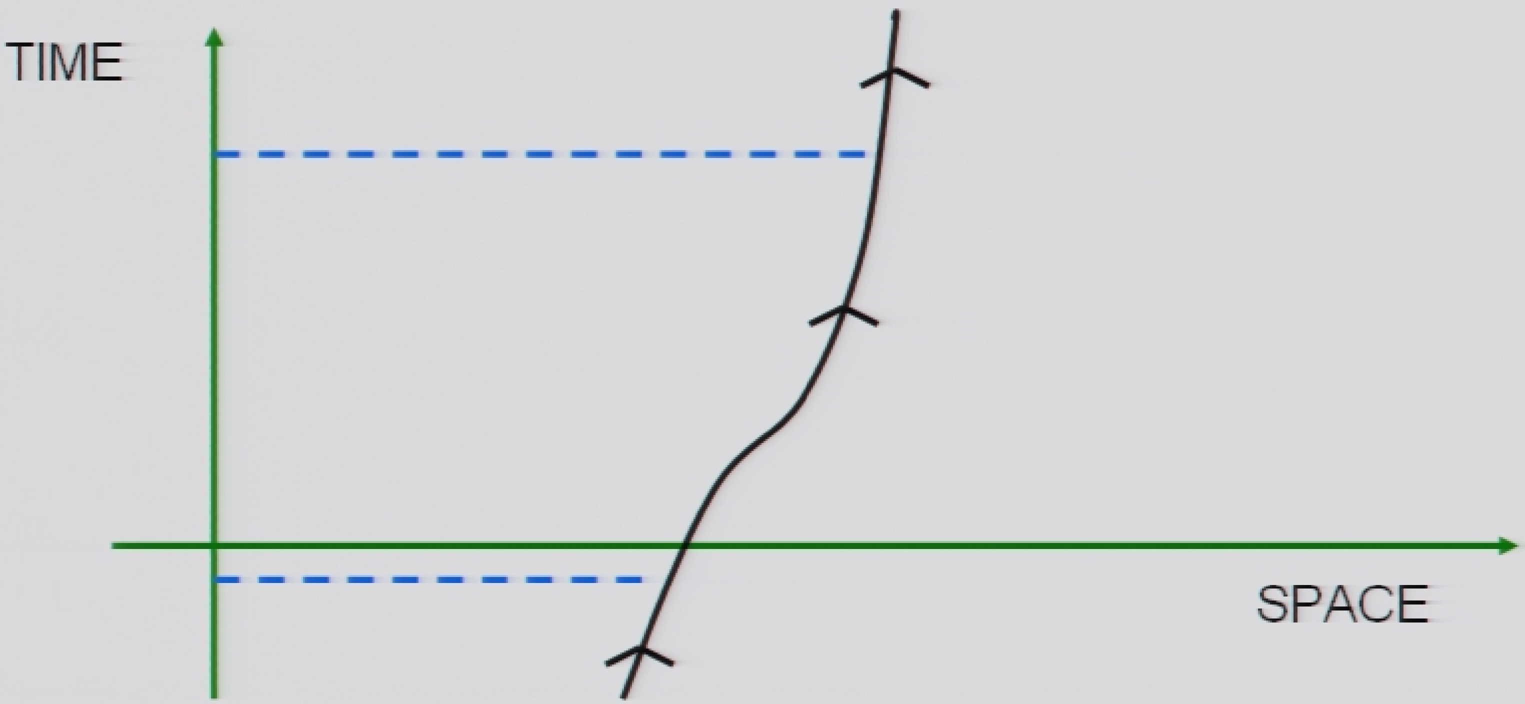

STAR


STAR


ALEPH-XDALI 9 Apr 2001 version F1 X11/XUIT
ALEPH
DALI_F1
00-06-14 2:32
Run=54698 Evt=4881

Apart from antimatter, another strange discovery in 20th century physics was "quantum mechanics," maybe the strangest of all.

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

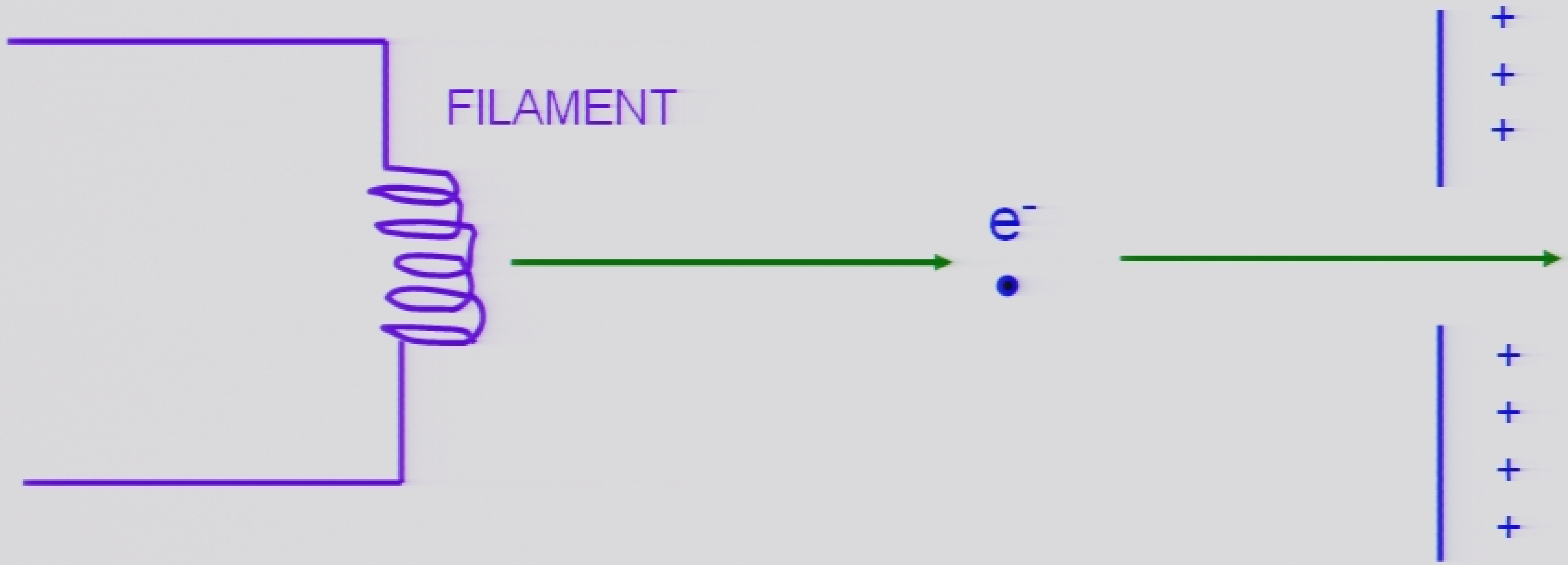


The “quantum uncertainty principle” implies that to discover small things (like an atomic nucleus), one requires a probe with high energy (like the radioactive beam used by Rutherford).

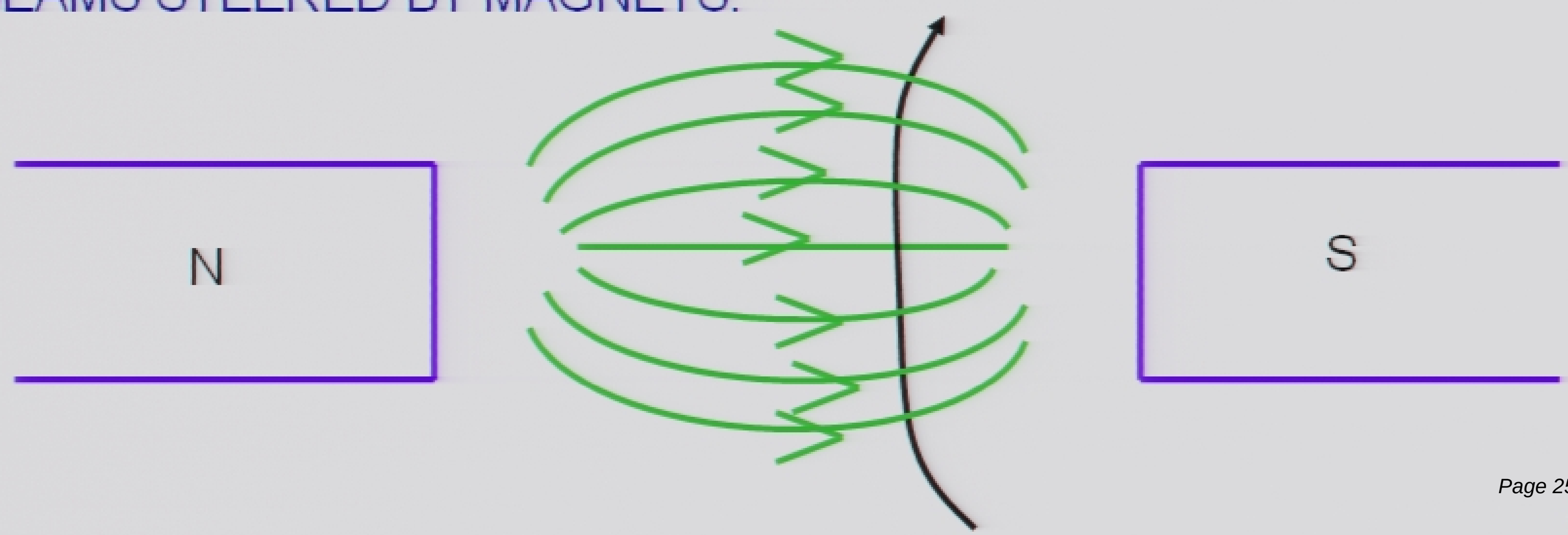
Many discoveries were made using natural sources of high energy particles, but because of the uncertainty principle, to get farther physicists had to make artificial accelerators, to reach even higher energies.

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

SIMPLEST VERSION

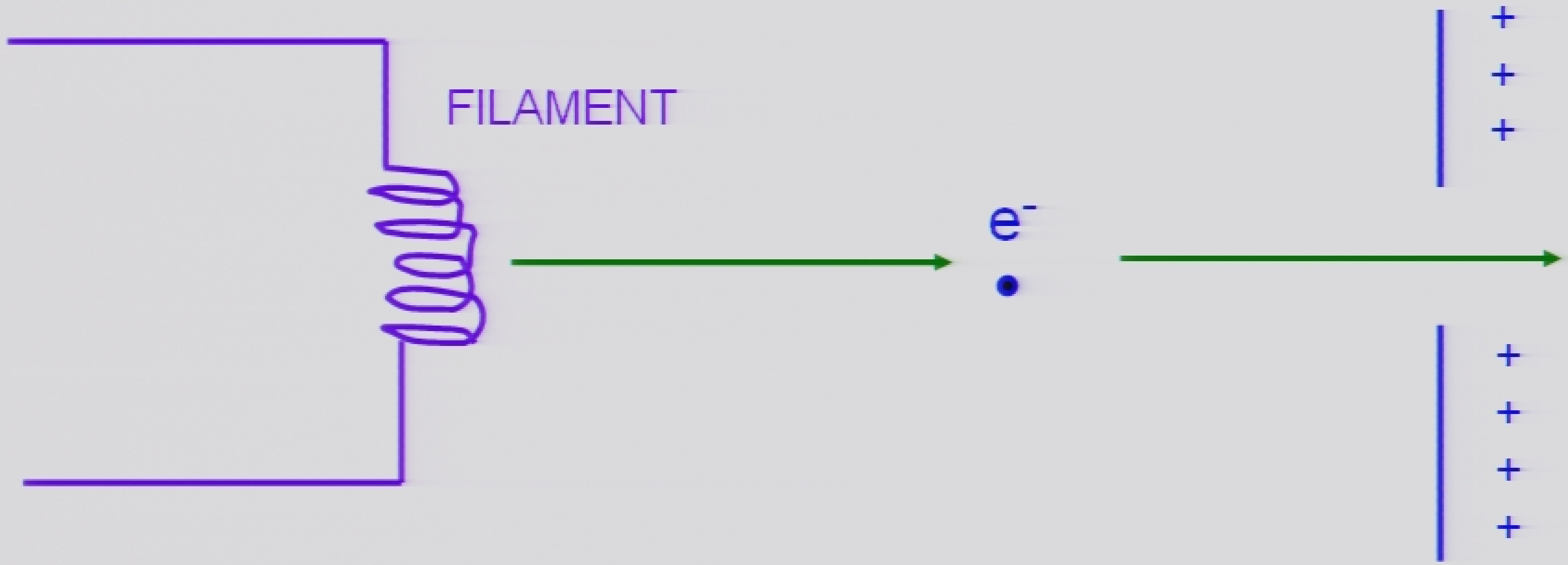


BEAMS STEERED BY MAGNETS:

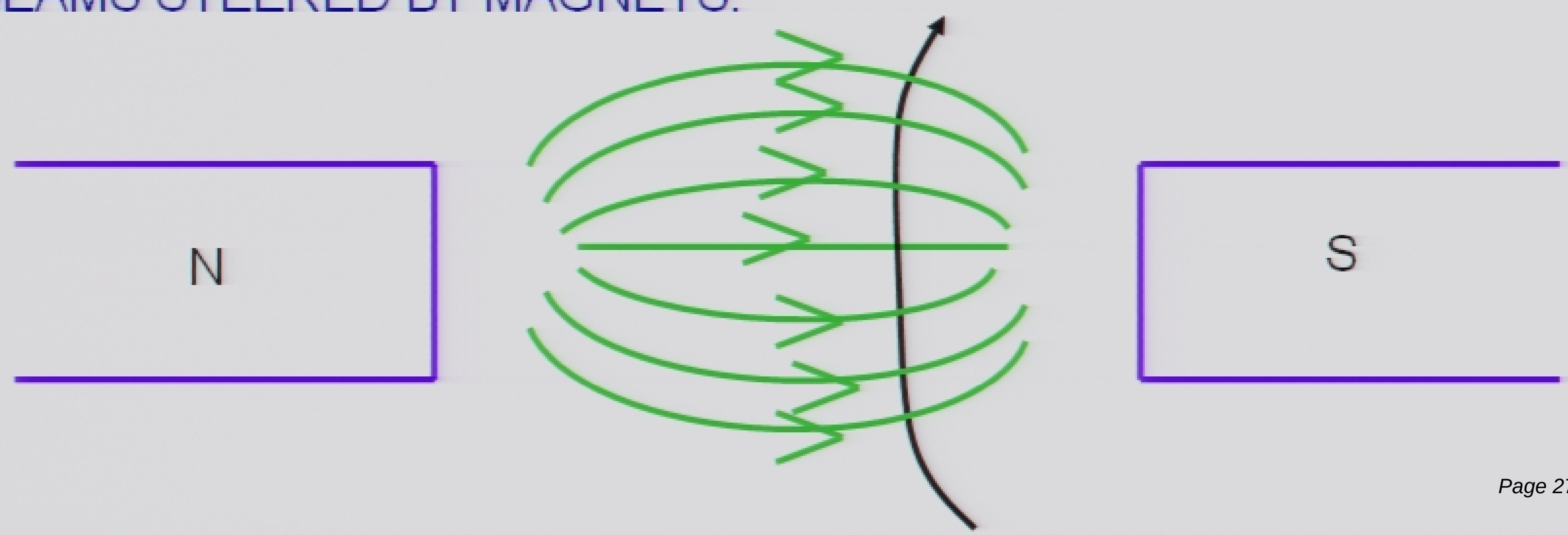


Because there is a limit on the strength of the electromagnetic fields that we can use to accelerate or steer the particle beams, to reach higher energies, we need a bigger accelerator…that is why accelerators have become quite large and expensive.

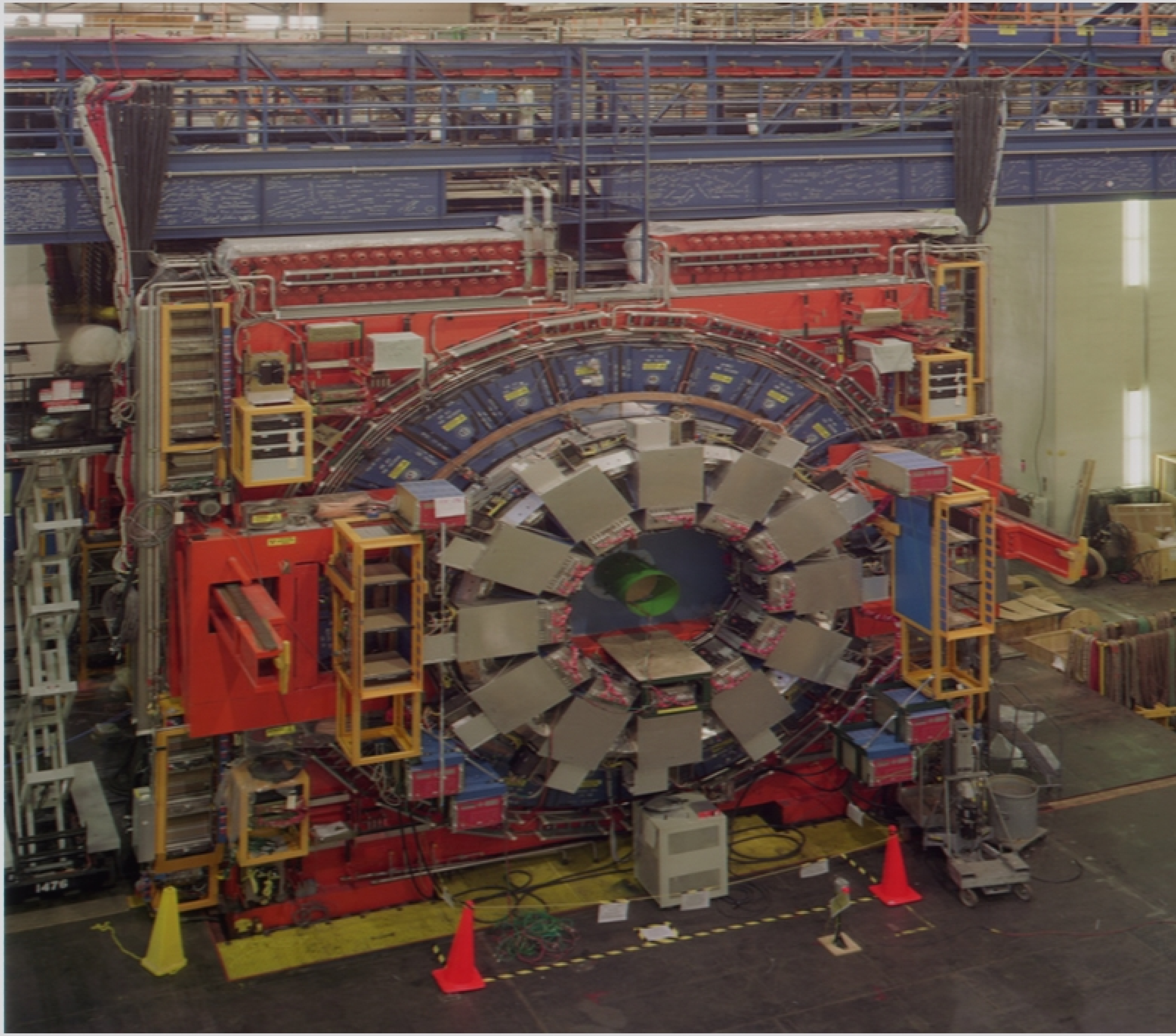
SIMPLEST VERSION

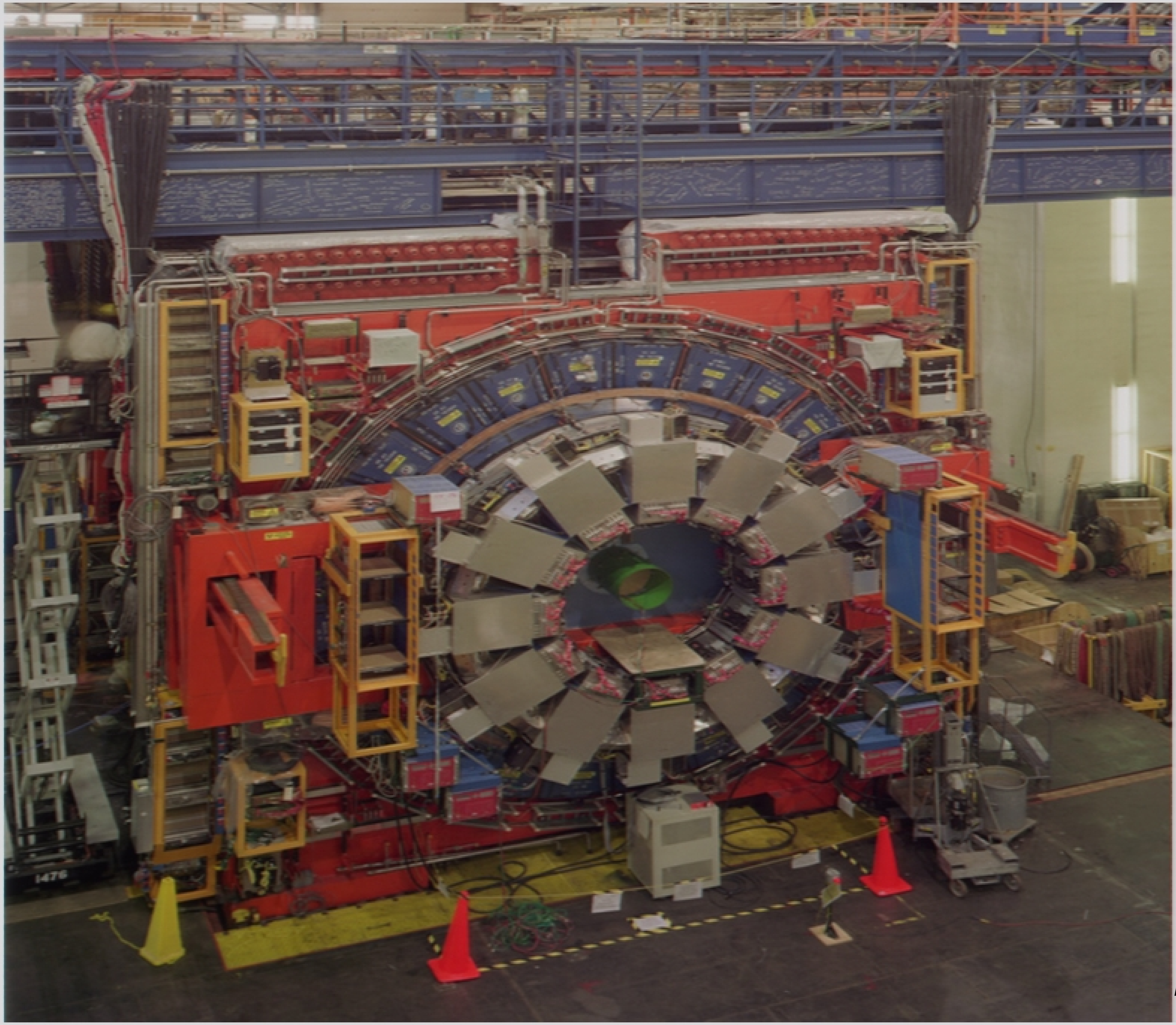


BEAMS STEERED BY MAGNETS:

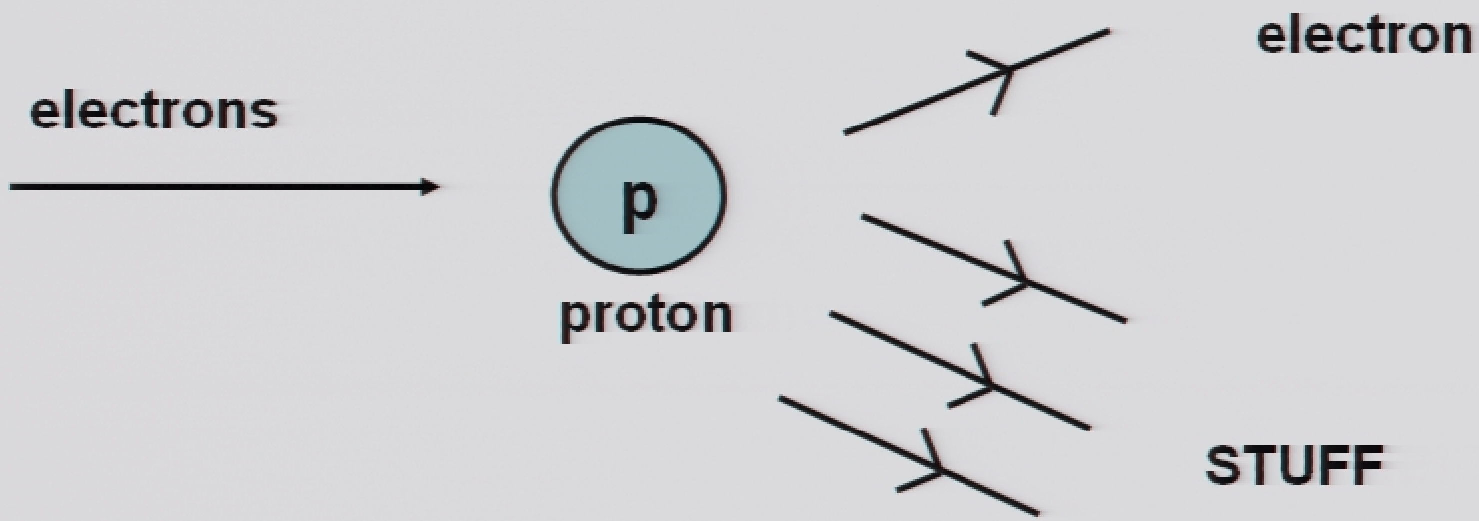


Because there is a limit on the strength of the electromagnetic fields that we can use to accelerate or steer the particle beams, to reach higher energies, we need a bigger accelerator…that is why accelerators have become quite large and expensive.





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 ⅔ e

d -⅓ e

Actually, protons and neutrons are made of "up" and "down" quarks, but altogether there are (at least) six different types of quark. The first particles containing a "strange" quark were discovered in cosmic rays (around 1950), and the other quarks (charm, bottom, top) were discovered in accelerators.

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

u ⅔ e
d -⅓ e

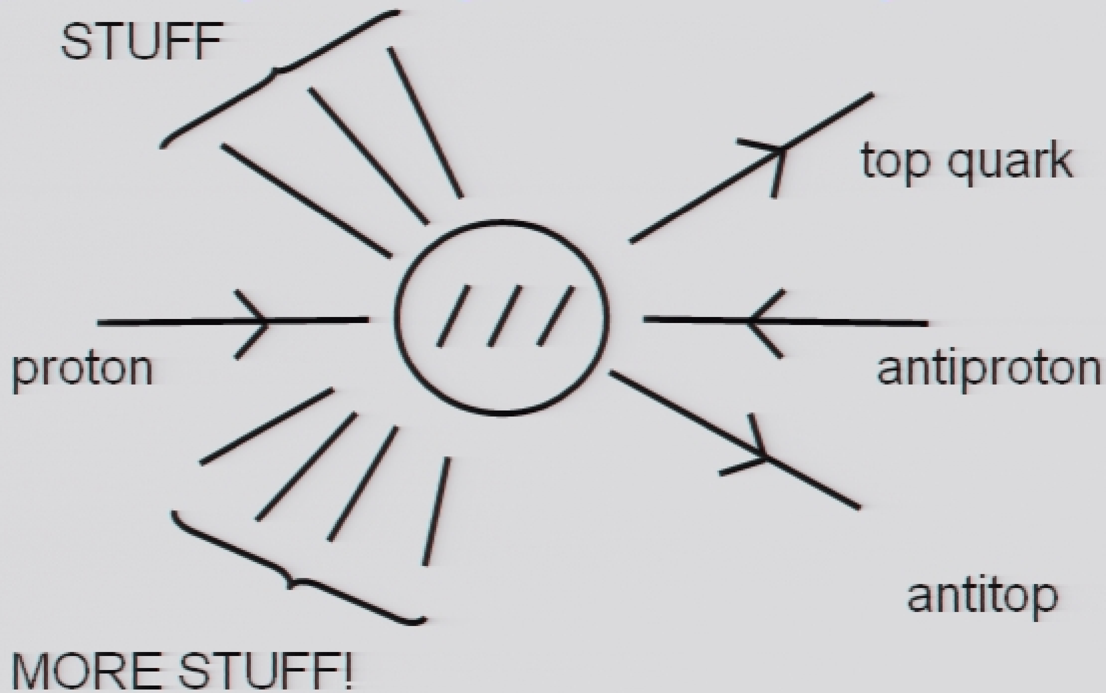
Actually, protons and neutrons are made of “up” and “down” quarks, but altogether there are (at least) six different types of quark. The first particles containing a “strange” quark were discovered in cosmic rays (around 1950), and the other quarks (charm, bottom, top) were discovered in accelerators.

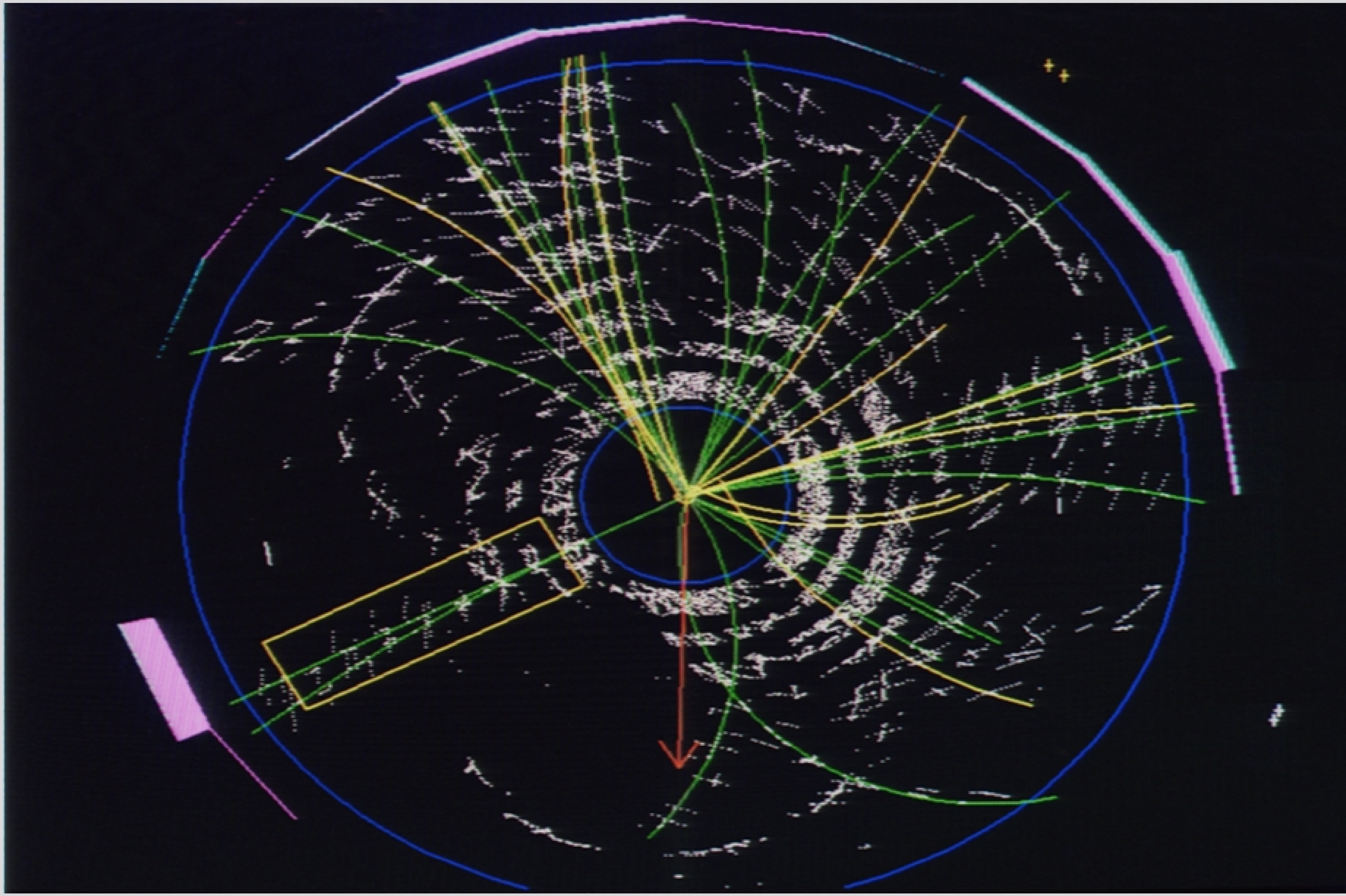
Most recently, the world's biggest accelerator, the Tevatron, was used to discover the heaviest quark, the top quark.

The Tevatron collides protons and antiprotons with about 1 TeV in each beam.

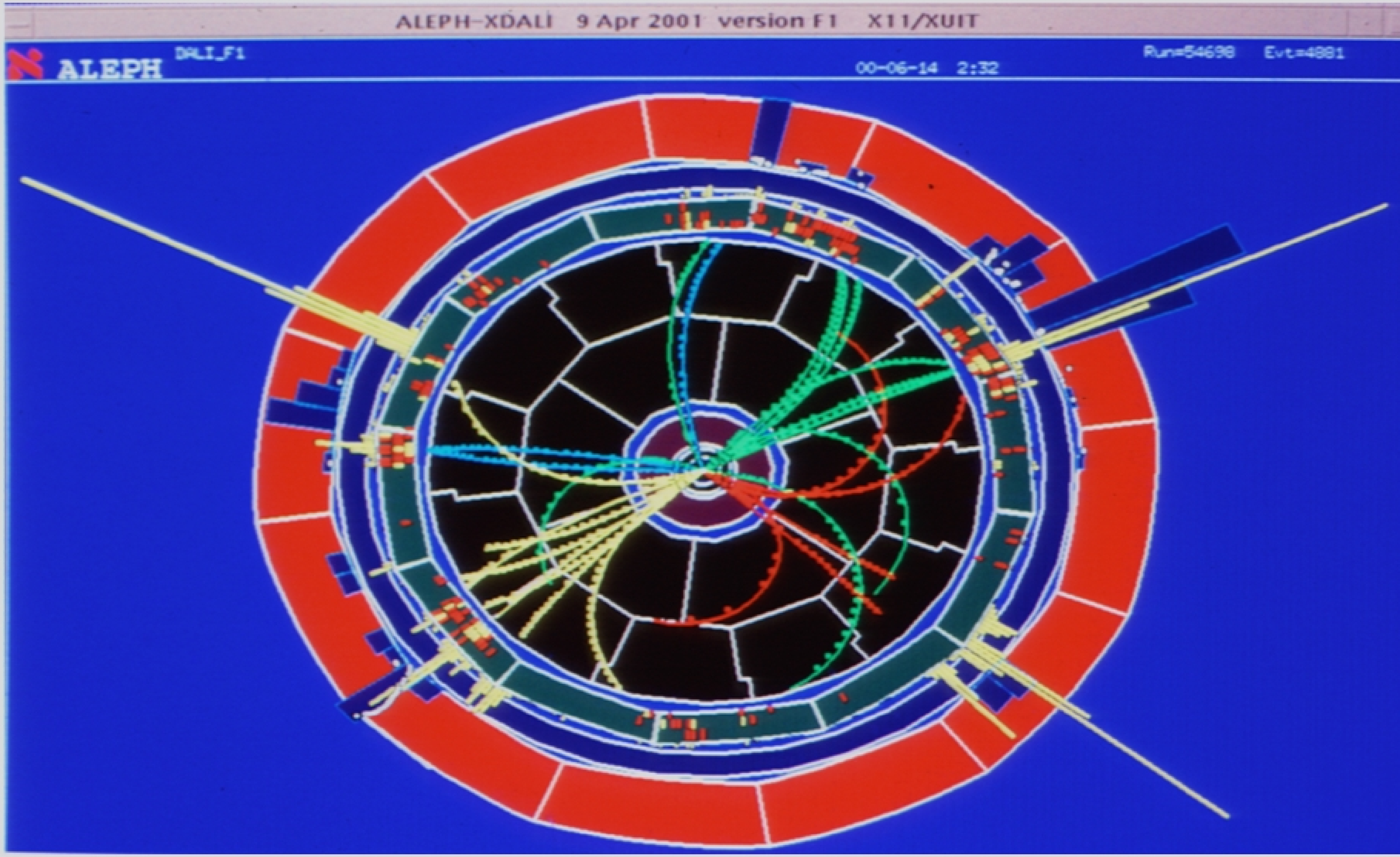
The top quark itself has mc^2 of about 175 GeV.

It is discovered in a reaction in which proton plus antiproton produce top quark plus top antiquark plus other particles:



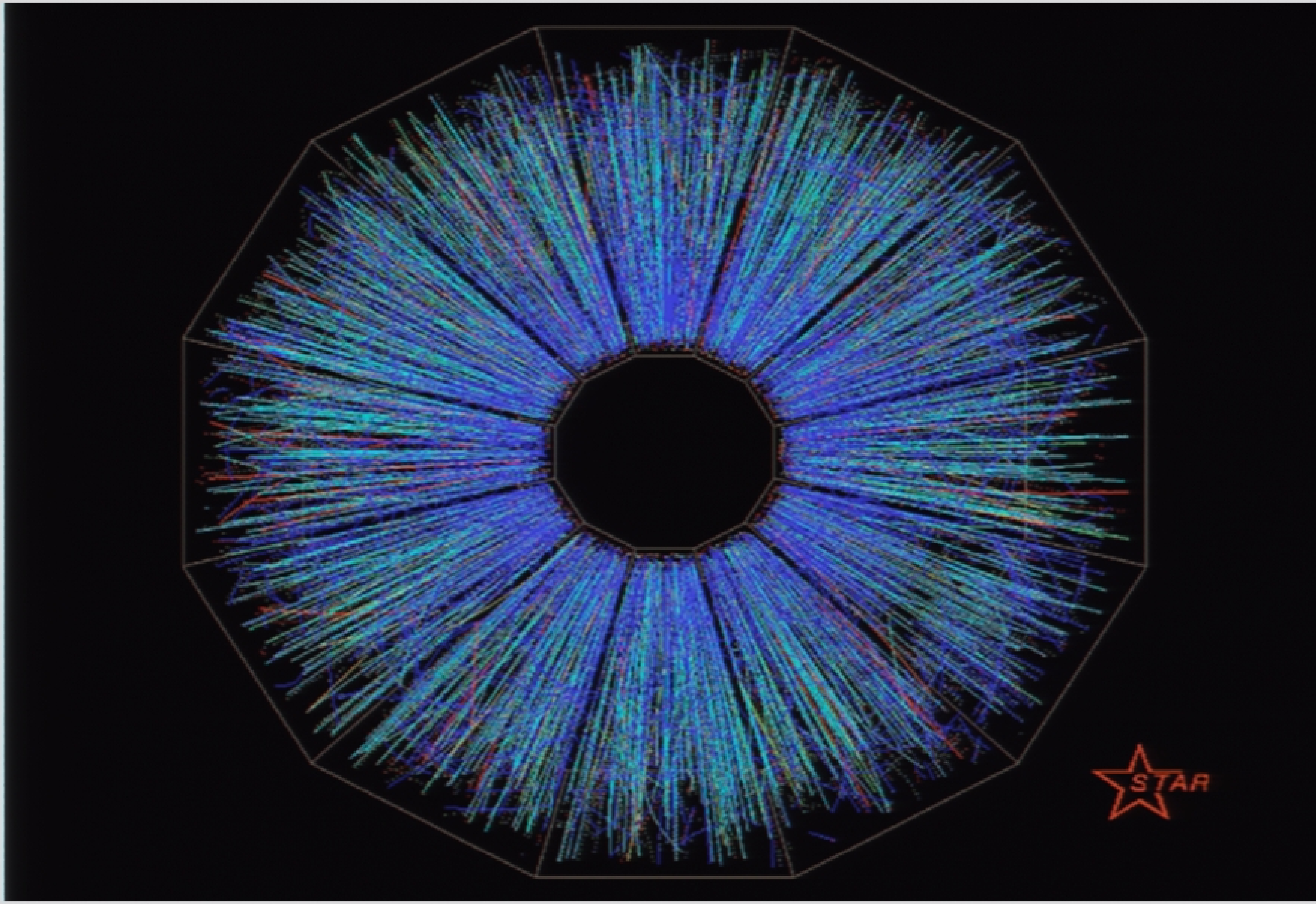


In the twentieth century, physicists learned that the laws of nature are really very strange when you look closely. Objects behave strangely near the speed of light.


ALEPH-XDALI 9 Apr 2001 version F1 X11/XUIT
ALEPH
DALI_F1
00-06-14 2:32
Run=54698 Evt=4881

Apart from antimatter, another strange discovery in 20th century physics was "quantum mechanics," maybe the strangest of all.

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


STAR

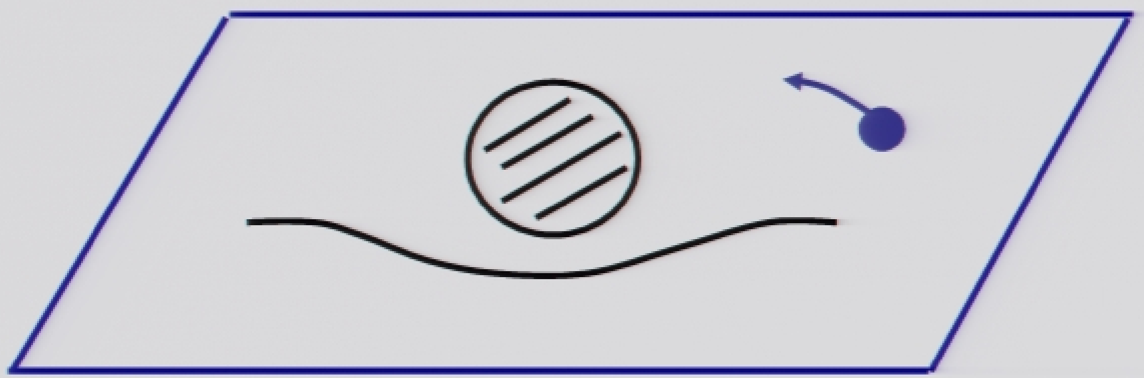
In the twentieth century, physicists learned that the laws of nature are really very strange when you look closely. Objects behave strangely near the speed of light.

In the twentieth century, physicists learned that the laws of nature are really very strange when you look closely. Objects behave strangely near the speed of light.

Waves are really made of particles.

Particles, if you look at them closely, obey the strange and fuzzy laws of quantum mechanics.

And according to Einstein's greatest discovery, which is his General Theory of Relativity, spacetime is curved and gravity results from this curvature.



With the exception of the curvature of space, all these strange laws – relativity, antimatter, quantum mechanics – are everyday facts of life in the world of high energy elementary particles.

Waves are really made of particles.

Particles, if you look at them closely, obey the strange and fuzzy laws of quantum mechanics.

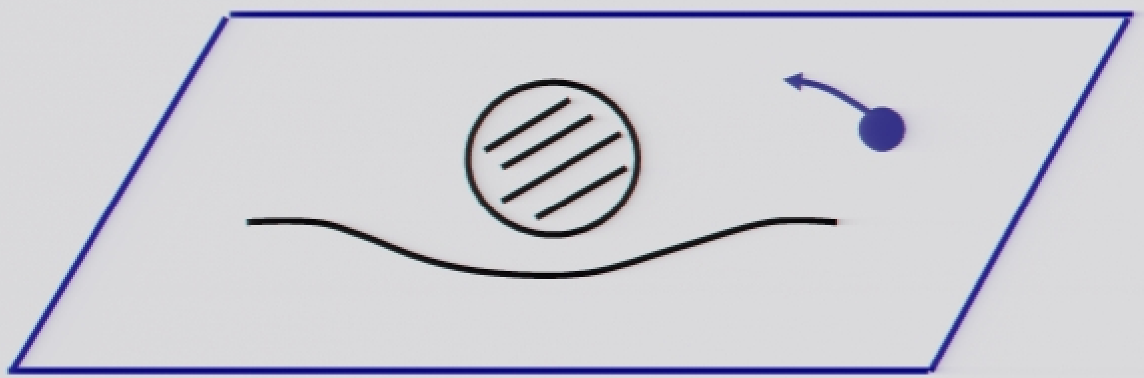
And according to Einstein's greatest discovery, which is his General Theory of Relativity, spacetime is curved and gravity results from this curvature.

In the twentieth century, physicists learned that the laws of nature are really very strange when you look closely. Objects behave strangely near the speed of light.

Waves are really made of particles.

Particles, if you look at them closely, obey the strange and fuzzy laws of quantum mechanics.

And according to Einstein's greatest discovery, which is his General Theory of Relativity, spacetime is curved and gravity results from this curvature.



With the exception of the curvature of space, all these strange laws – relativity, antimatter, quantum mechanics – are everyday facts of life in the world of high energy elementary particles.

This is what makes elementary particle physics exciting – it gives us our best window in discovering the strange laws by which our Universe works.

What physicists really care about is not so much the particles themselves, but the laws and principles that describe them – the laws of nature that we uncover by studying the particles.

What discoveries can we hope to make in the coming years?

To my thinking, the most exciting quest in particle physics for the next few years is the search for “supersymmetry”.

If a physicist who lived near the beginning of the twentieth century were to come back today…

He or she would find that almost everything in our understanding of physics has changed radically…

because of the discovery of quantum mechanics, antimatter, quarks, and a host of other surprising discoveries that I have not really had time to explain.

But one key facet of our understanding of physics has not changed much in almost a hundred years … this is our conception of spacetime, where we still use the ideas introduced by Einstein. Einstein did away with Newton’s notions of universal time, action at a distance, and the like … he introduced us to a strange new world in which moving bodies shrink, moving clocks slow down, in which $E=mc^2$, all this is in his original theory, “Special Relativity” (1905), and then in the finished product, “General Relativity” (1915) things got stranger …

Mass causes a curvature of space and time, a ticking clock slows down in a gravitational field, an accelerating mass emits gravitational waves that travel at the speed of light …

And perhaps strangest of all are the Black Holes and the expansion of the Universe …

But (almost) all this was in place by 1915 … so it predates Quantum Mechanics (which took shape by 1925). Quantum Mechanics radically changed our understanding of almost everything in physics.

The only part of our pre-quantum understanding of physics that still survives in much the same form is that we still think about spacetime using the concepts that Einstein introduced in the years up until 1915 … the quantum revolution has not yet affected the way we understand space and time.

Many physicists believe that this may change in the next couple of decades … that to make more progress with fundamental physics, we need to understand the quantum nature of spacetime …

A new theory called supersymmetry has been proposed that may be the beginning of incorporating quantum variables in the way we describe spacetime.

In physics, there are objects measured by numbers – like temperature, energy, electric field – and there are stranger quantities, like the spin of an electron, that are really quantum mechanical in nature … they cannot be properly measured by numbers … the description really needs "matrices," which we learn about in high school.

In everyday life, we measure spacetime by numbers …

It is now 3 o'clock, we are 200 meters above sea level at 40 degrees north latitude.

Measuring spacetime by numbers is one bit of common sense that Einstein preserved … while he overturned so many other "obvious" ideas.

Einstein hardly had a choice, because Quantum Mechanics wasn’t yet known. Einstein couldn’t use quantum variables to measure space and time!

Supersymmetry, however, introduces, apart from the three obvious dimensions plus time, new "quantum" dimensions that cannot be measured by numbers; they are "quantum" (or "fermionic") dimensions, like the spin of the electron.

Particles vibrating in the new dimensions look in our accelerators and detectors like new elementary particles.

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.

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:

There are hints that supersymmetry is correct, but we don't yet have a decisive proof.

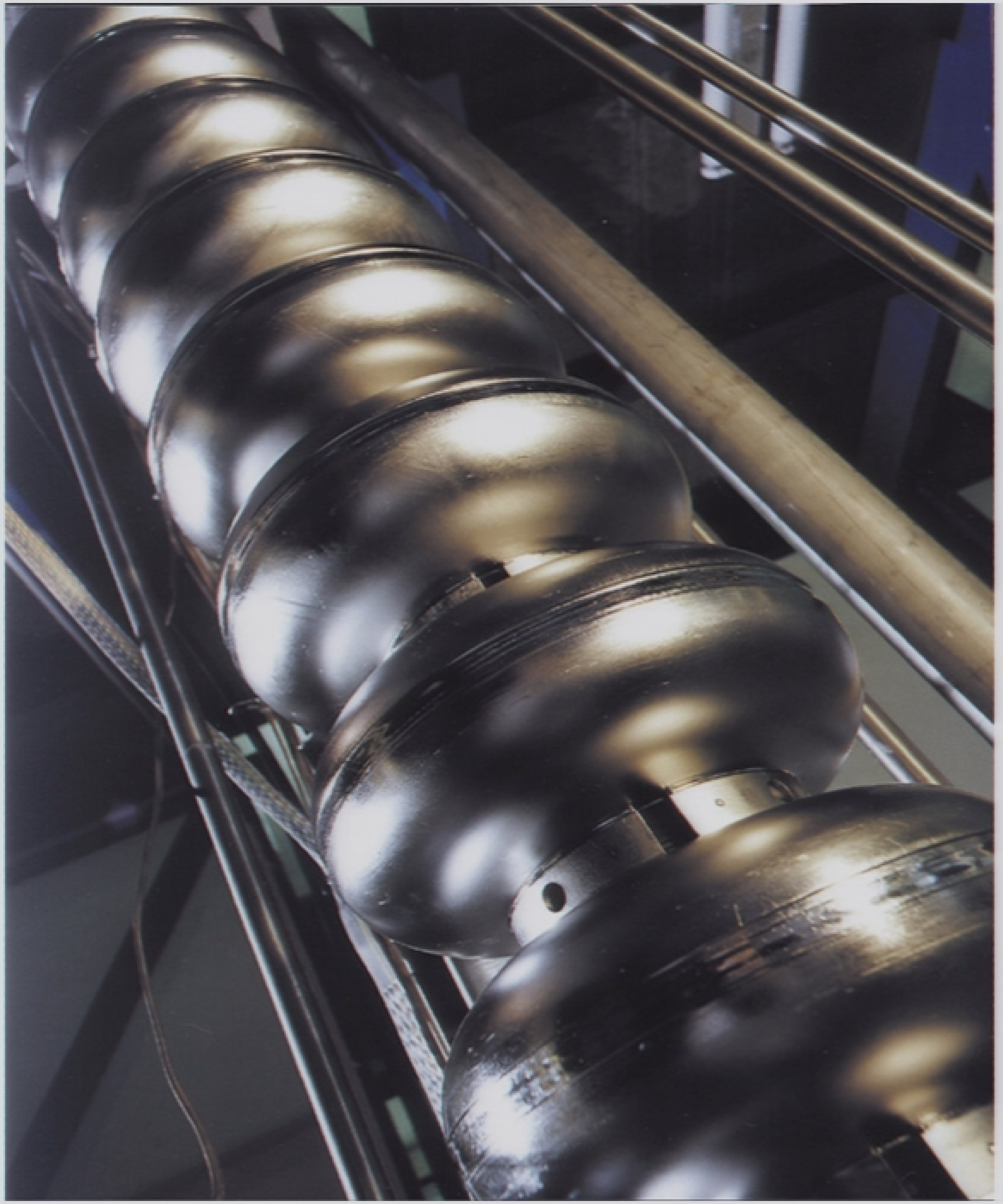
However, a new accelerator, the Large Hadron Collider (LHC) is being built in Switzerland … it will study proton-proton collisions with an energy of 7 TeV (that is 7,000 times mc^2) per beam. According to most calculations, this will be enough to produce the new supersymmetric particles, if they exist.

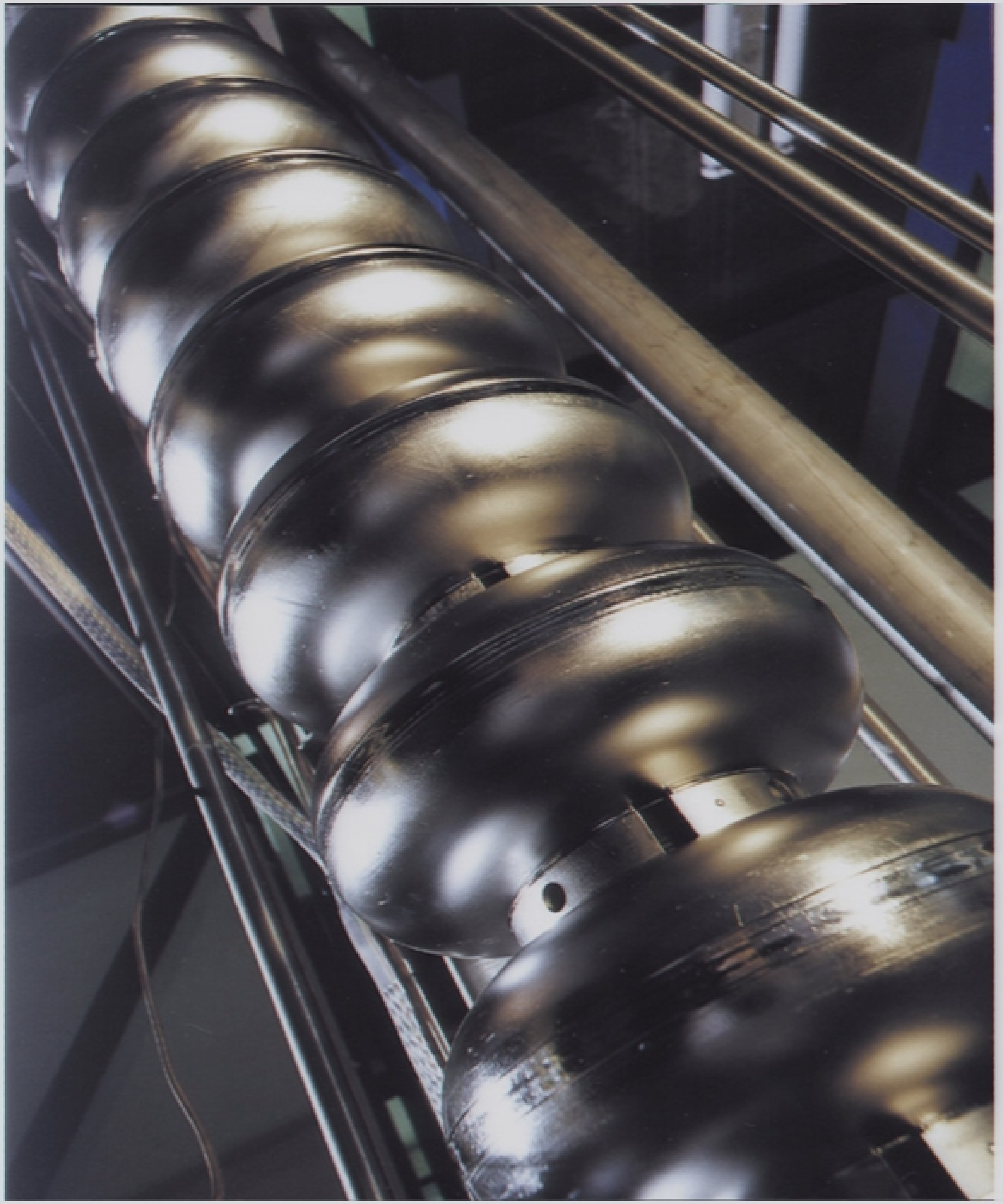
If supersymmetry is correct, then the electron also has a new cousin, not yet discovered, which is "spinless" and hence non-magnetic:

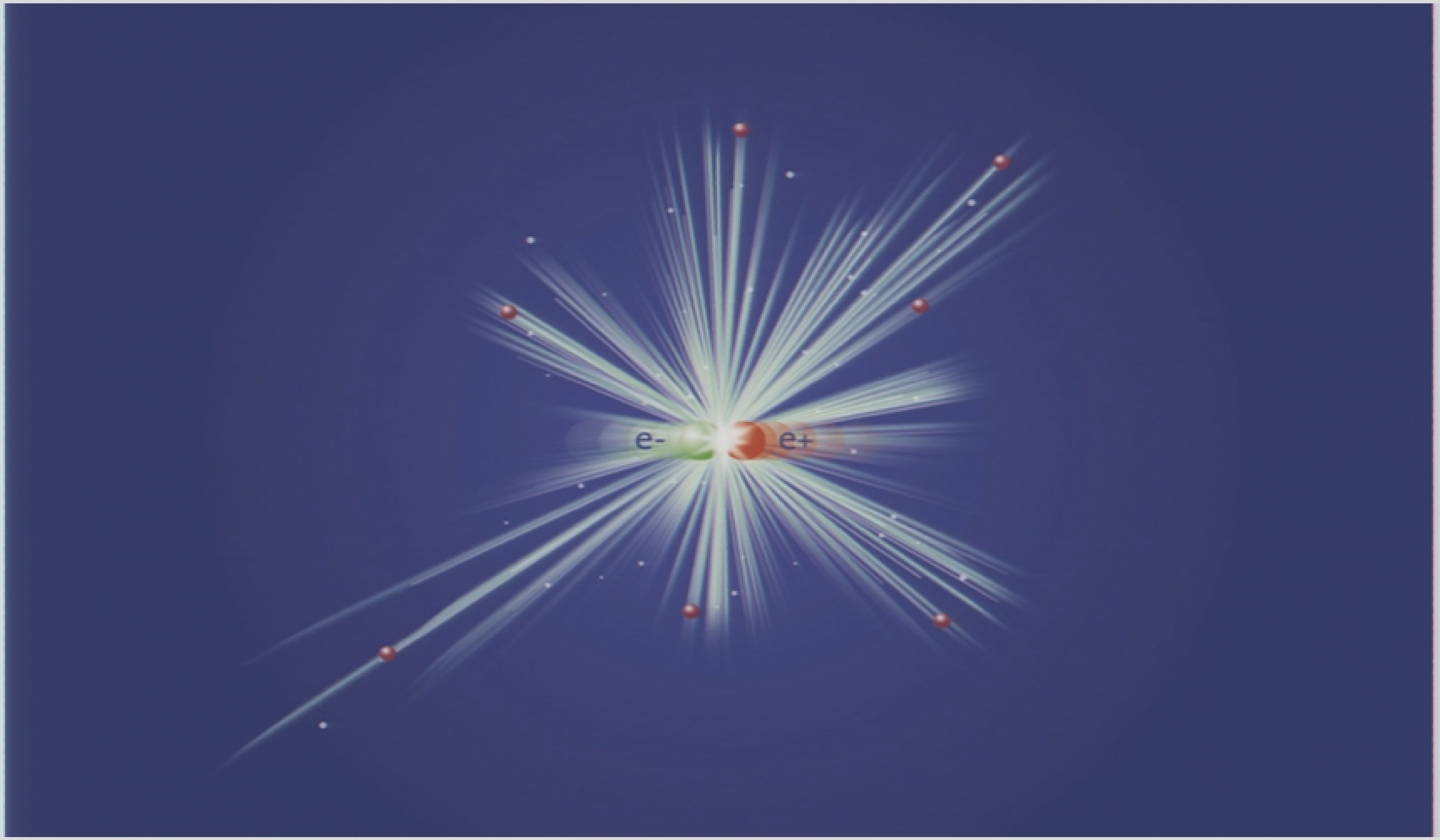
There are hints that supersymmetry is correct, but we don't yet have a decisive proof.

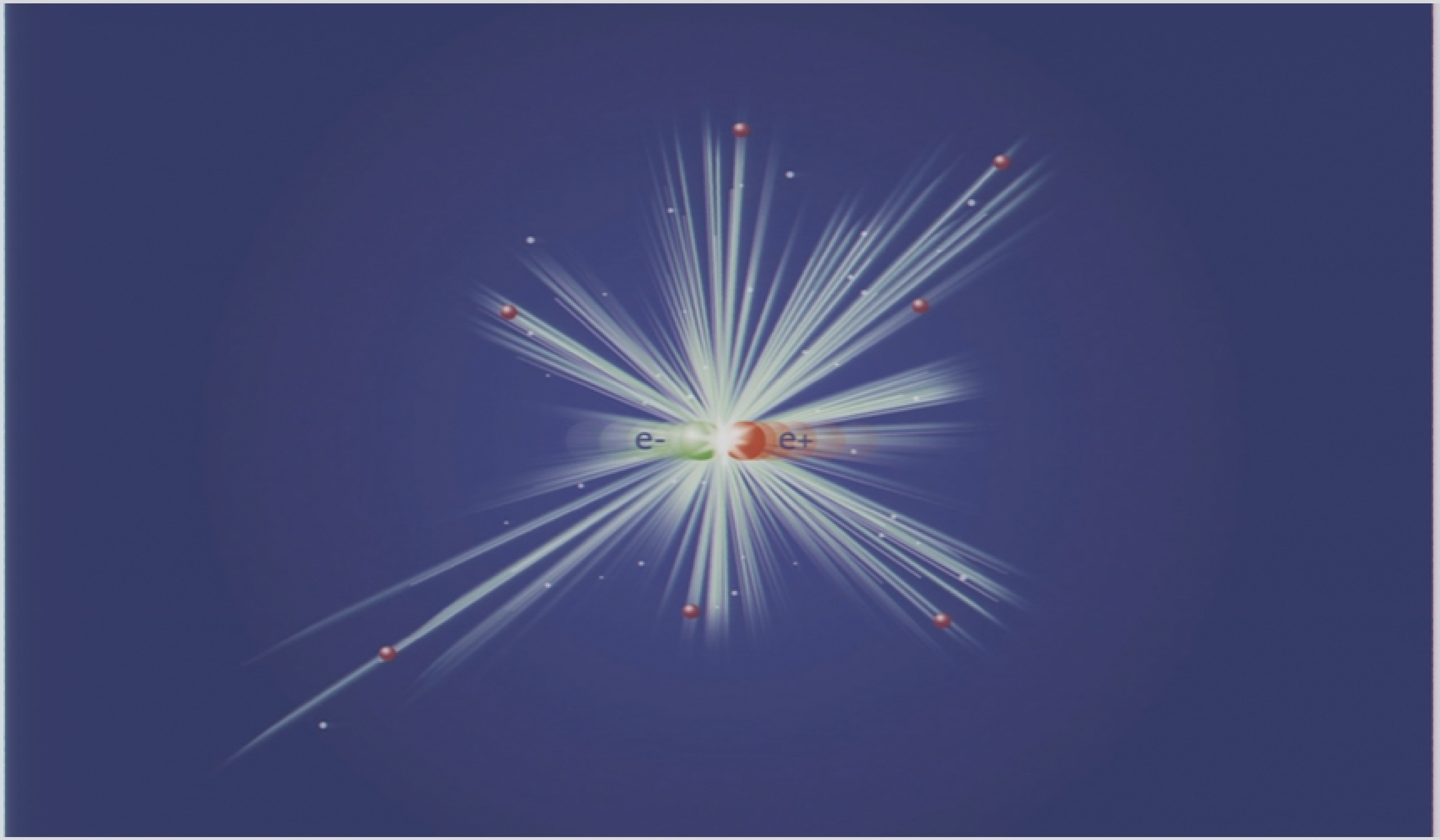
However, a new accelerator, the Large Hadron Collider (LHC) is being built in Switzerland … it will study proton-proton collisions with an energy of 7 TeV (that is 7,000 times mc^2) per beam. According to most calculations, this will be enough to produce the new supersymmetric particles, if they exist.

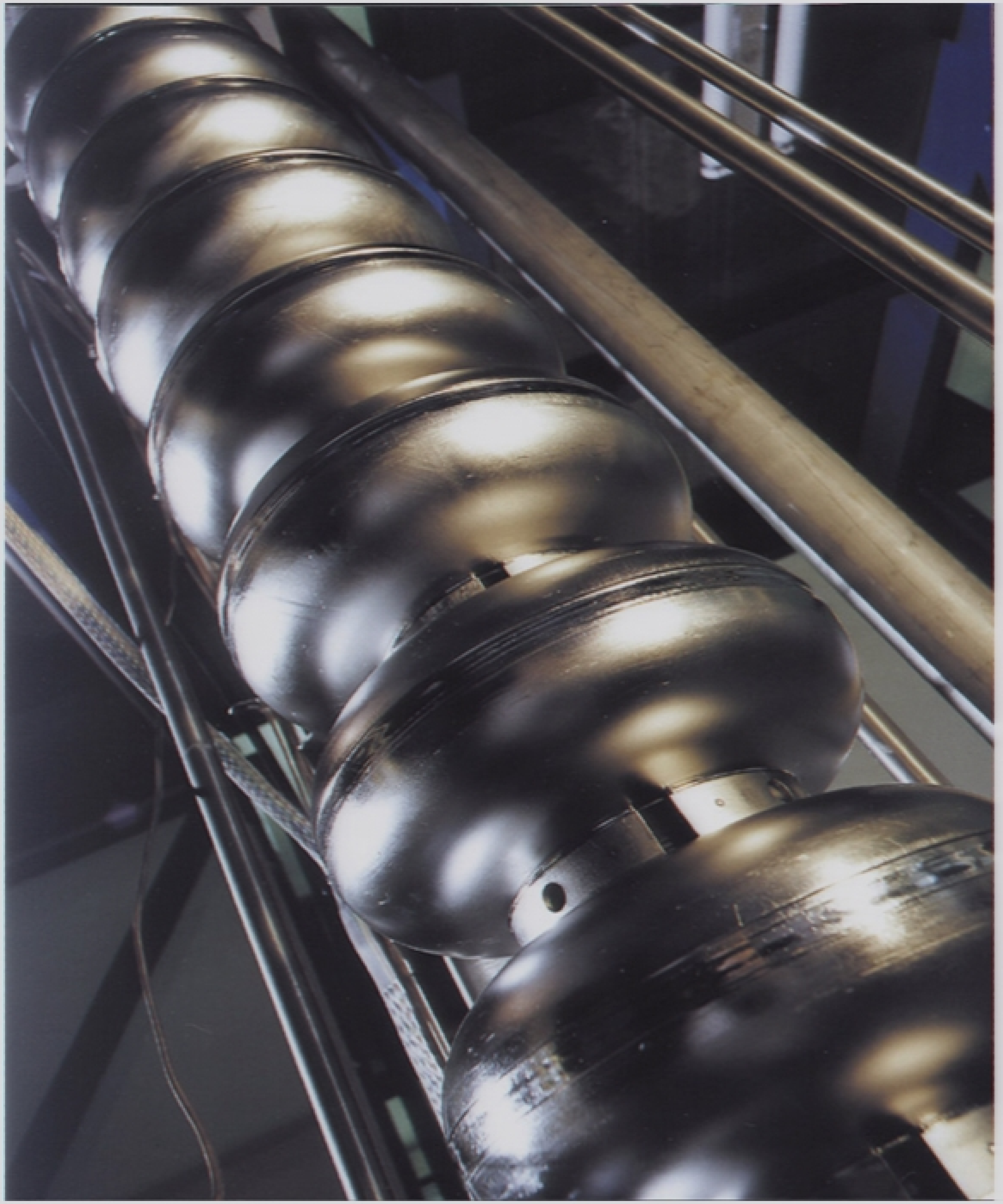
If supersymmetry is indeed discovered, what then? Supersymmetry would “modernize” Einstein’s early theory, Special Relativity, to include Quantum Mechanics. We would still need a quantum version of his greatest achievement, General Relativity. That is what physicists are looking for in String Theory, but I will have to leave String Theory for another occasion.

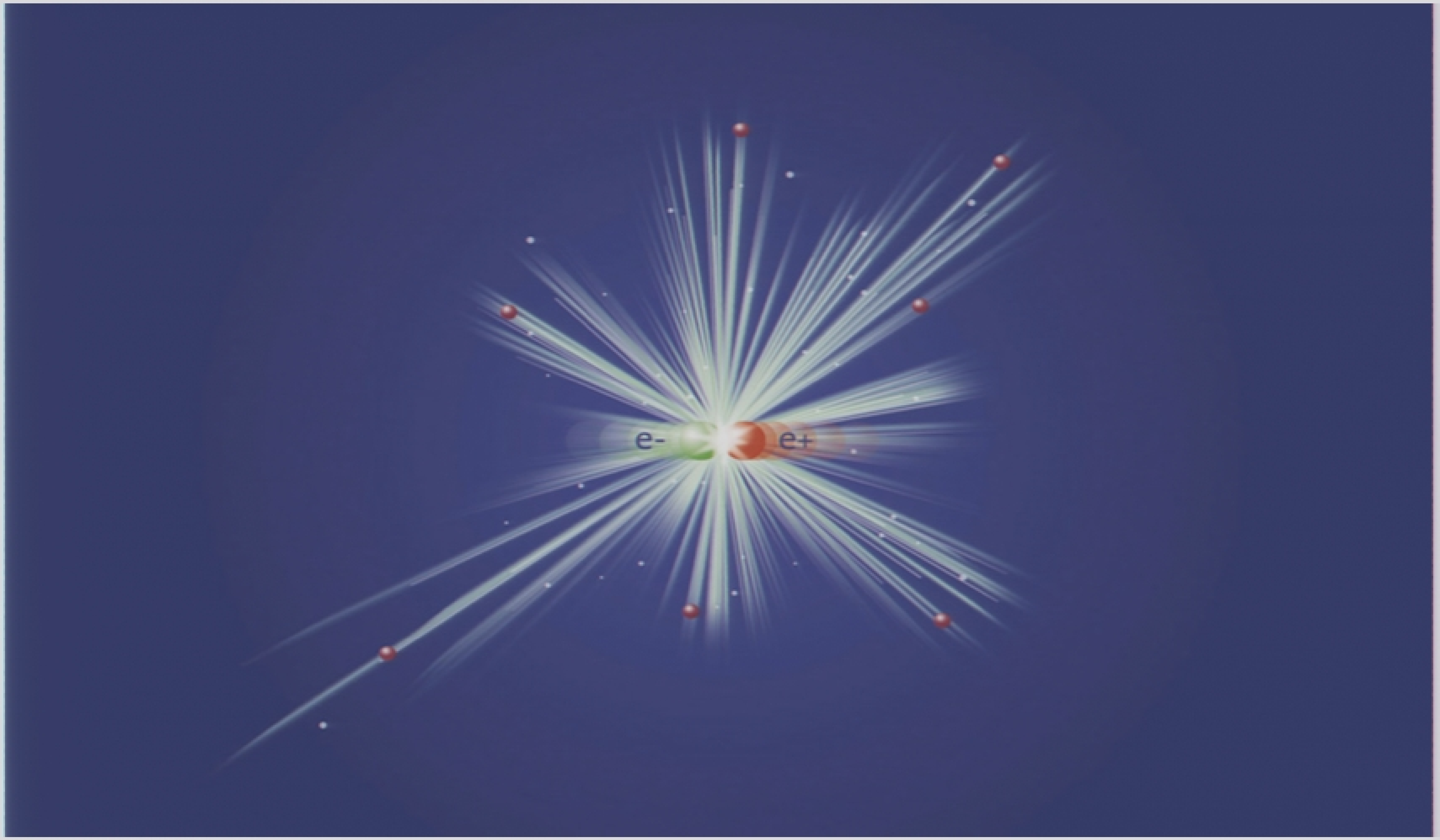


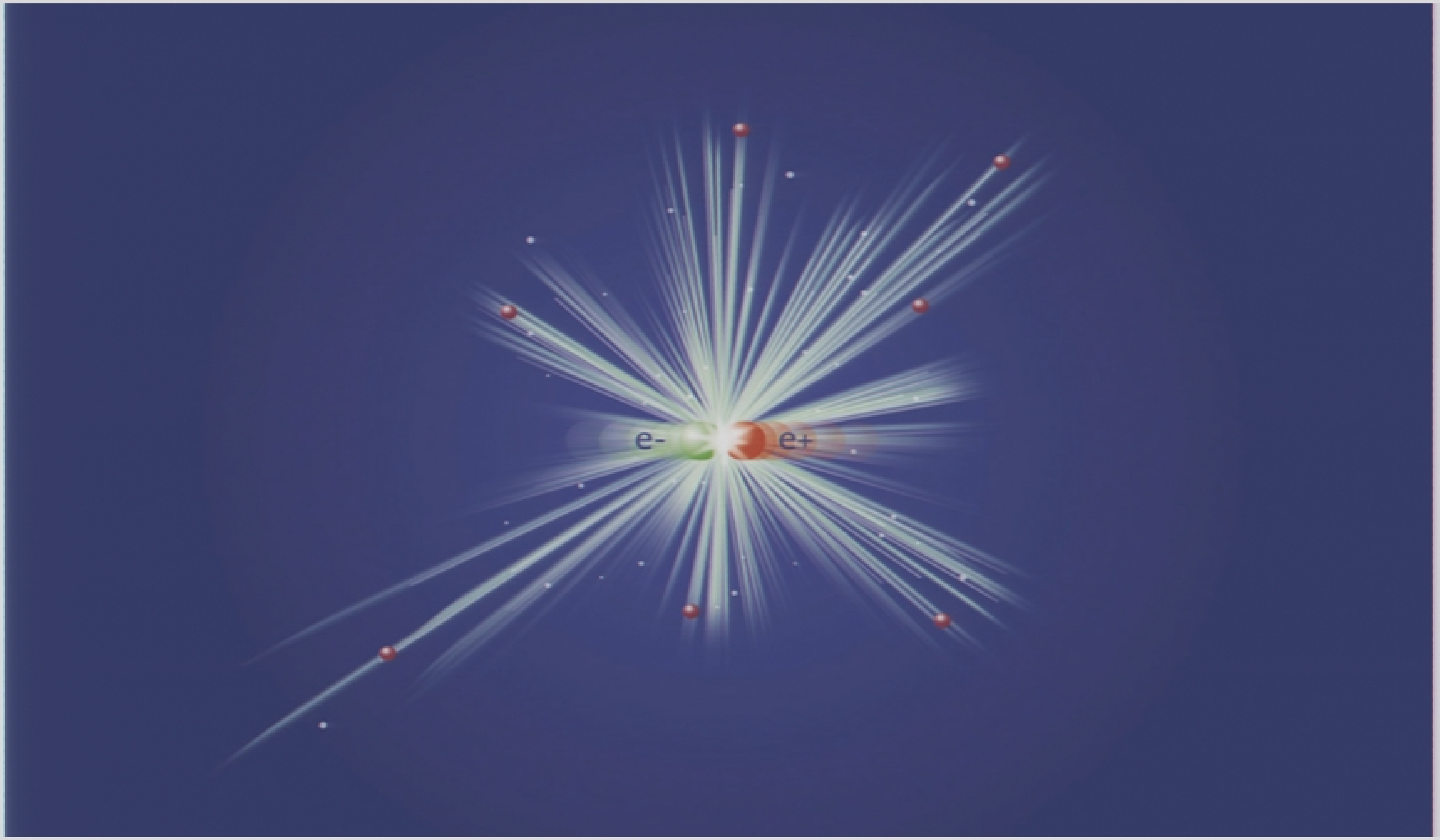



e-
e+


e-
e+




e-
e+


e-
e+