Full Circle - the physics and astronomy connection

- Physics, the study of our natural world, grew out of astronomy and especially the work of Kepler, Galileo and Newton which showed how we could describe and understand planetary motion.
- In the last hundred years has physics has yielded a completely new and unexpectedly strange view of the stuff the universe is made of.
- Currently, Physics and Astronomy are reuniting in the age old attempt to understand the origins of our universe and its remarkable evolution.

Illusions

- Our view of the world is shaped by experience that is limited to observing ordinary sized things moving at ordinary velocities. *Small things and things that move fast behave very differently*

- Our senses are finely tuned to give us the sharpest sight, hearing, touch and taste possible without revealing what the real world is like. *Stuff that looks solid is mostly empty space and the bits of it can behave like waves.*

- We think of space as something fixed and unchangeable -something that we and all things are in. *But space can be warped by massive objects.*

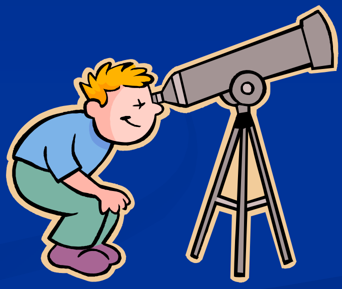
- Time seems to be something universal that is the same for everyone. *But atomic clocks kept on airplanes run slower than those on the ground.*

We are stuck with a lot of illusions!

Seeing with instruments

- Ever since Galileo wrote "The Starry Messenger" 390 years ago and described what he could see with a telescope, science has relied on instruments.

- Today we "see" a universe of 10^{26} m in size with the aid of radio telescopes and can trace the evolution of the universe back to a time of one part in 10^{43} of a second from the time of the big bang



- With the aid of accelerators we can "see" the minute particles called Quarks and Leptons that are the modern "Atoms" of which the material universe is made.

Unfortunately the things we "see" with instruments don't fit the neat world view of our illusions.

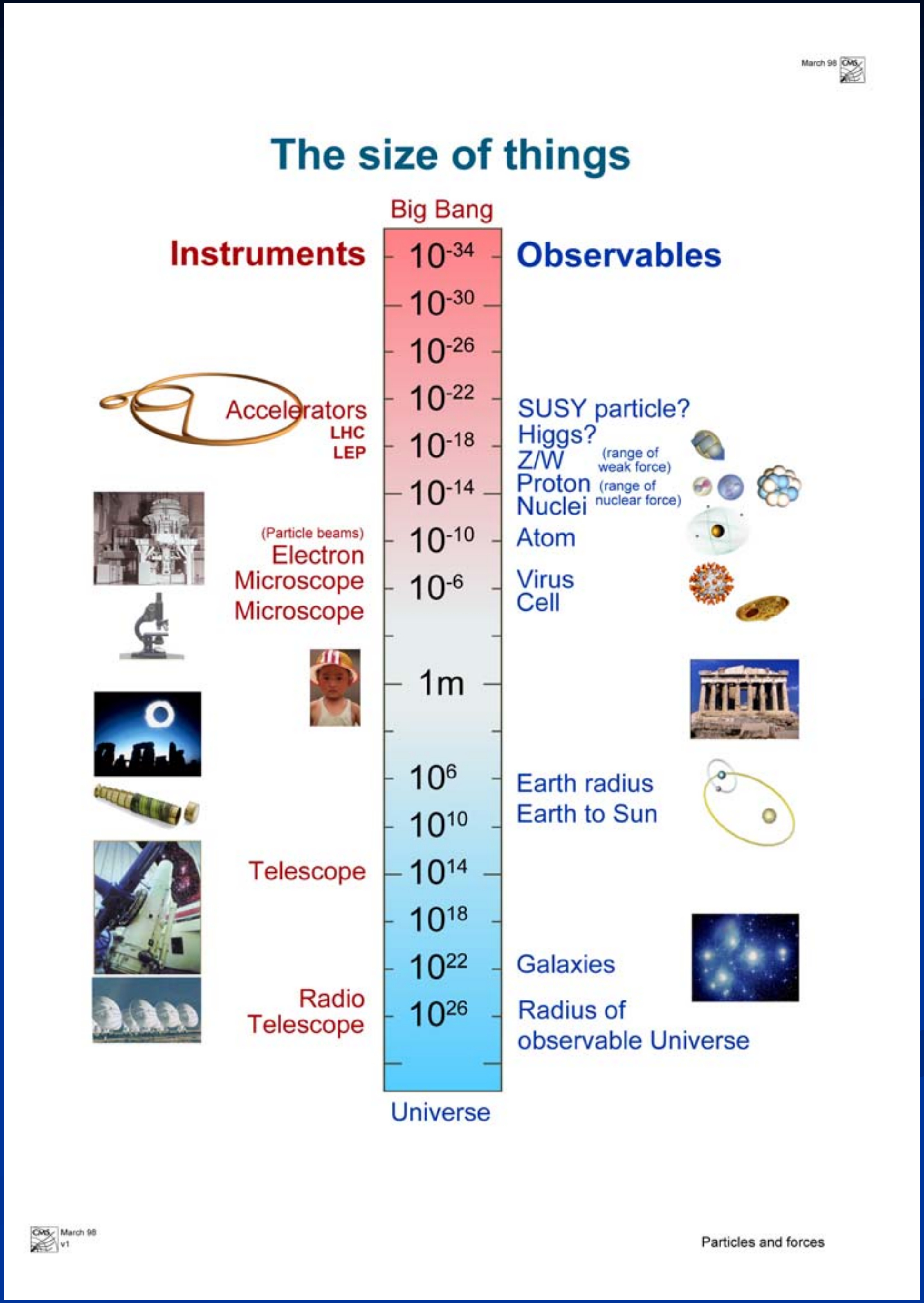
Big and Small Stuff

The largest thing we can "see" is the Universe. It is more than 10 billion light years across*.

The smallest things we can "see" so far are elementary particles with sizes of 10^{-22} m**.

We humans are 1 to 2 m in size. That puts us roughly in the middle of the range of sizes .

*100,000,000,000,000,000,000,000,000 m
**1/10,000,000,000,000,000,000,000 m

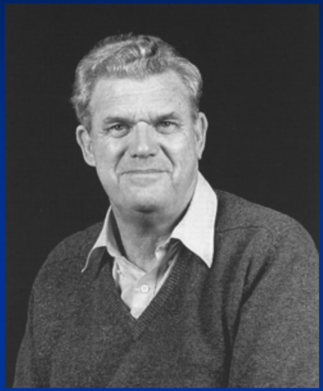


The Small Stuff

- The matter in the universe is made up of just 2 kinds of bits:-

Quarks Leptons

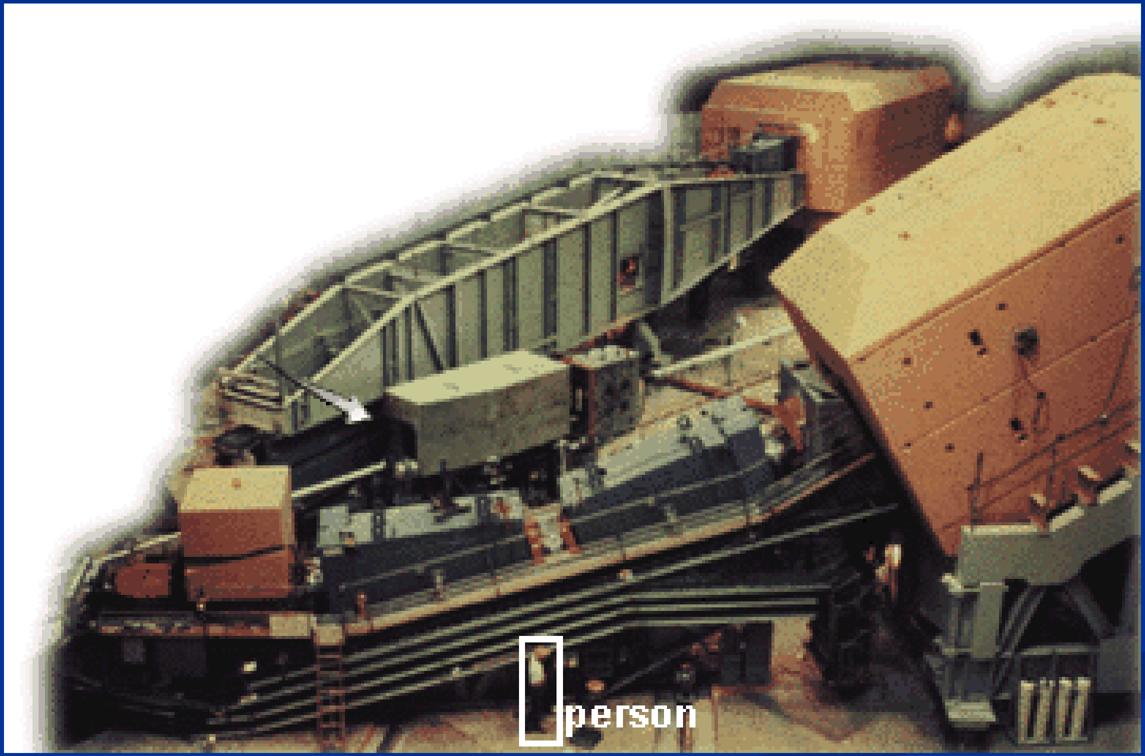
One of our guys helped discover the Quark



Dick Taylor

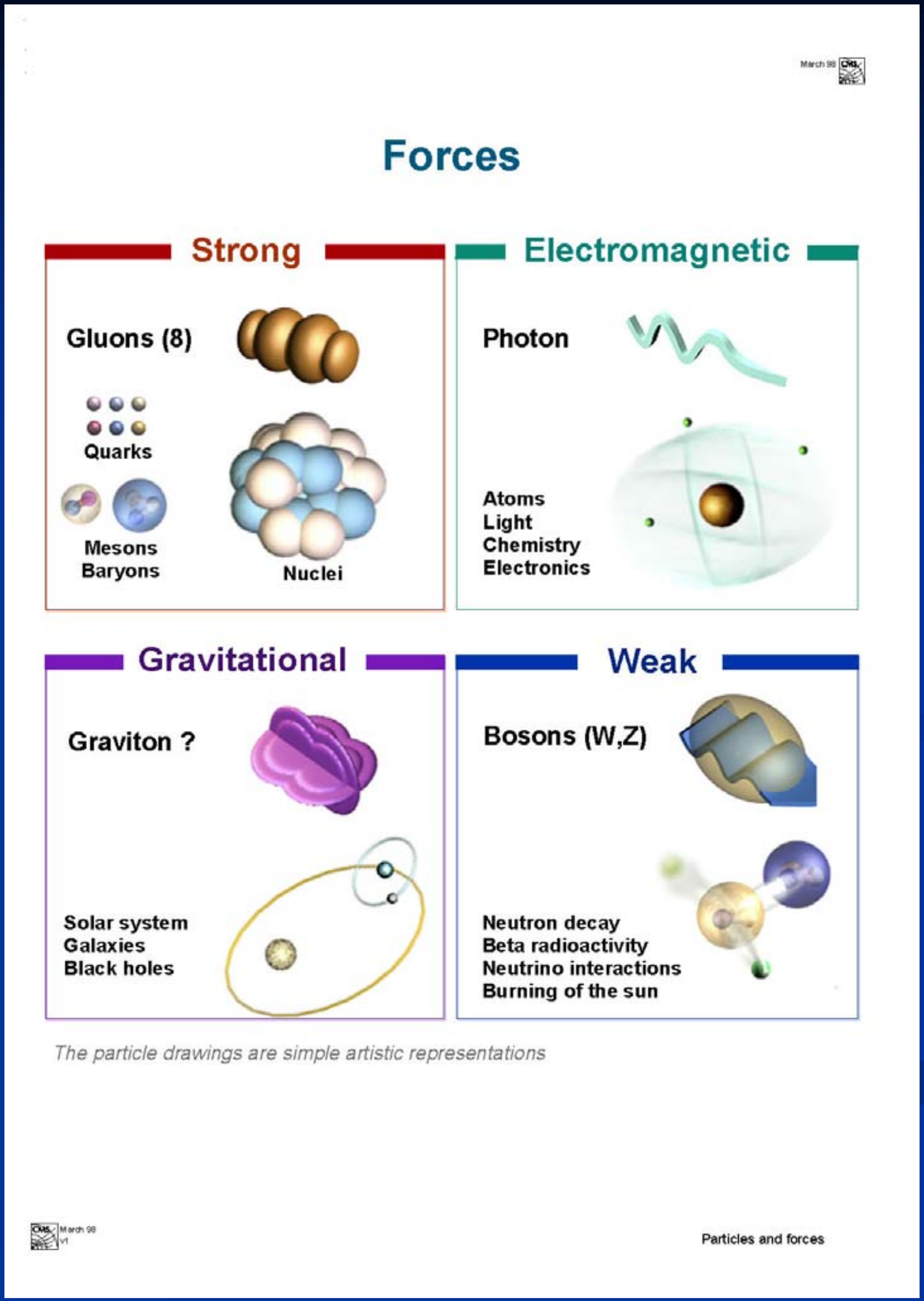
from Medicine Hat, Alberta shared a Nobel Prize the first experiment to “see” the bits we call quarks

And - he has an ETX scope



How Particles Interact

- There are just 4 forces responsible for the interactions between particles.
- Each Force works through an exchange of something - a boson

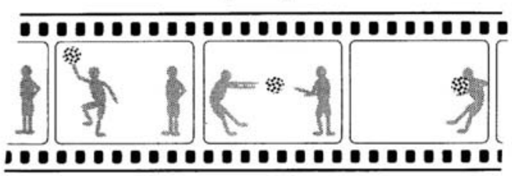


So how do exchange forces work?

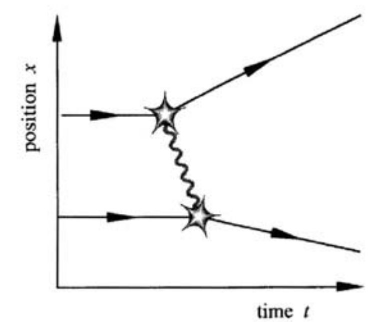
Imagine two people on ice skates tossing a bean bag back and forth. The sequence might go like this -

- The first person tosses a bag and recoils backward.
- The bag travels to the second person
- The second person catches it and recoils in the direction the bag was traveling.

Classical "Field" Interaction



Skaters exchange a beanbag



Positions of skaters changing with time

This graph is called a Feynman Diagram and can be used to describe the Quantum field interactions that elementary particles experience.

Now the tricky (and fun) part

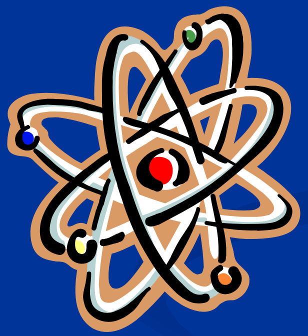
- The exchange forces between elementary particles involve very small things moving very fast.
- They have different rules of engagement –
  - *the Quantum nature of small stuff*

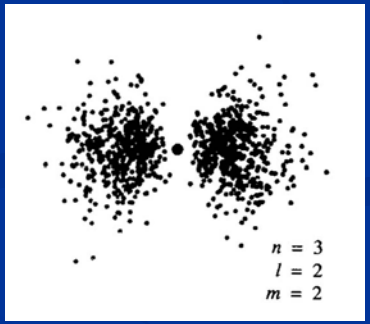
    and
  - *Relativity*

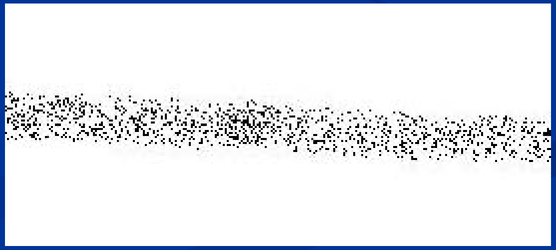
Quantum Uncertainty

- The exact locations and motions of small things are hard to pin down.
- Planets follow smooth and predictable orbits but electrons in an atom are all over the place .
- The paths of large things are predictable but those of electrons and quarks are fuzzy.

If it weren't for this stars would collapse under their own gravity

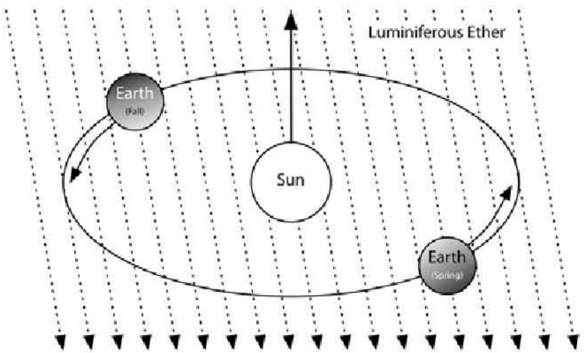






Relativity

The **Michelson–Morley experiment**, one of the most important and famous experiments in the history of physics, was performed in 1887 by Albert Michelson and Edward Morley and is generally considered to be the first strong evidence against the theory of a luminiferous aether.



The result was startling – adding a velocity to that of light (c) resulted in no change. ***Any*** velocity added to c results in no change. ***(even c+c+c=c)***

Albert Einstein worked out the implications which turned out to be unexpected and very weird.

- There is no absolute time. Observers can disagree about whether two events happened at the same time, before, or after each other.
- Energy and Mass are parts of the same thing
- Because no influence (force) can travel faster than c there can be no instantaneous "action at a distance". There has to be a ***field*** that moves at finite velocity between interacting objects!

Time of events?

- Different observers no longer agree on when something happens.

- Even the time sequence of events can differ.

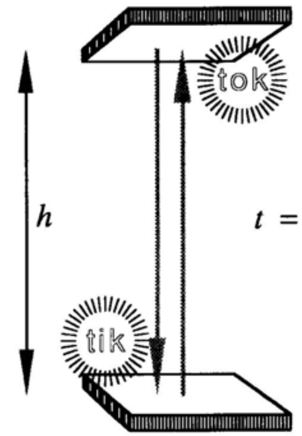


Fig. 8.1 Stationary Lorentz light clock: a light ray caught between two flat parallel mirrors, a distance h apart. Time t is measured by the transit time h/c between the mirrors. Because the speed c of light is always the same, such a clock is a perfect timepiece.

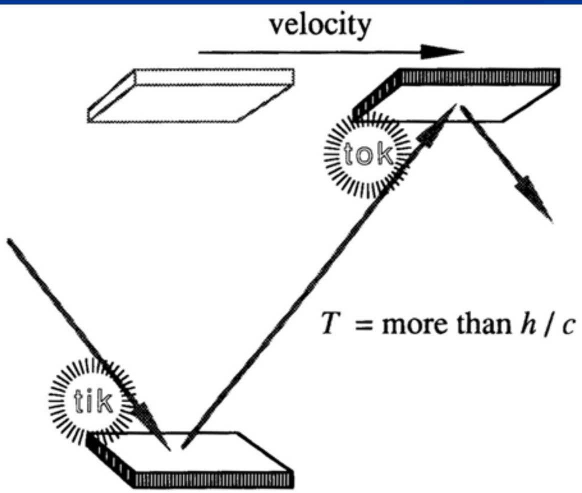


Fig. 8.2 Moving Lorentz light clock. When an observer sees a Lorentz clock move, the light ray between the mirrors must follow a slanted line, which is longer than the perpendicular distance between the mirrors. Because the speed of light is the same for all observers, the clock is seen to tick more slowly: it takes more time to traverse the slanted line than the perpendicular distance.

$E=mc^2$?

It is a necessary consequence of a maximum velocity.

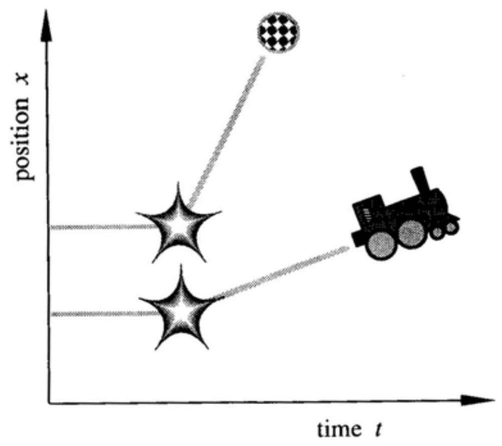


Fig. 1.5 Space-time diagrams of two different objects during a kick. The top track shows a football being kicked; its low mass shows up in a large change in velocity (i.e. a large acceleration, producing a sharp kink in the space-time track). The other track is not as sharply deflected, showing what happens when the same kick is delivered to a railway engine.

Beanbags (or Bosons)?

No action at a distance -even interactions have a maximum velocity.

Perhaps the strangest result of all - Space is warped

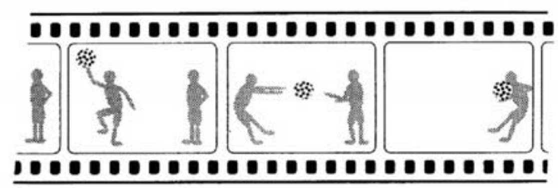
- When Einstein examined the full implications of a maximum velocity, he arrived at the conclusion that massive objects must warp the space around them.
- This was spectacularly confirmed when light from a star passing very close to the sun was bent exactly as Einstein predicted.

Back to the interactions

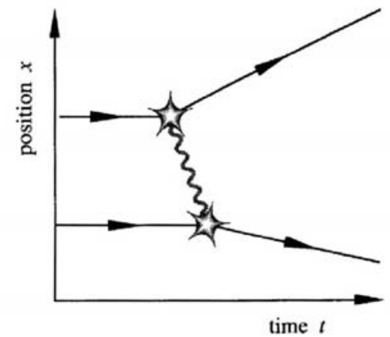
Rules of Engagement –

- Quantum uncertainty means we can’t be sure where the particles are exactly.
- Relativity means different observers will see the events differently.
- The maximum velocity of things means there is a maximum slope to the paths.

Classical “Field” Interaction



Skaters exchange a beanbag



Positions of skaters changing with time

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Quantum Spillover

An electron passes through an electric field. It is wavelike and refracted just as a light wave would be.

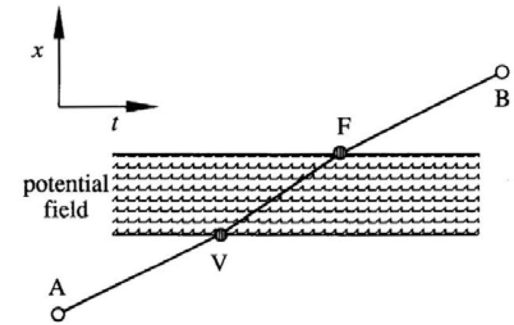


Fig. 8.6 Electron moving through a plane-parallel field, showing the space-time path of an electron that is accelerated at V and decelerated at F by a potential field (zone with wavy lines).

In the lower diagram, the maximum slope of the path is shown and the electron can't be deflected beyond that path – or can it?

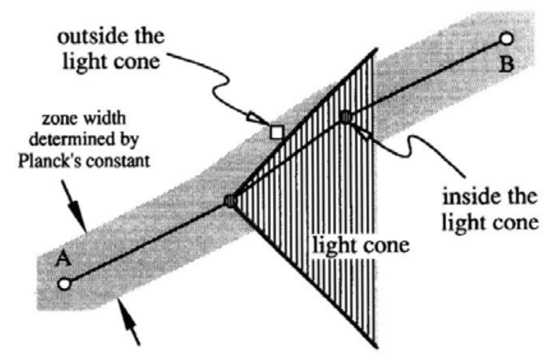
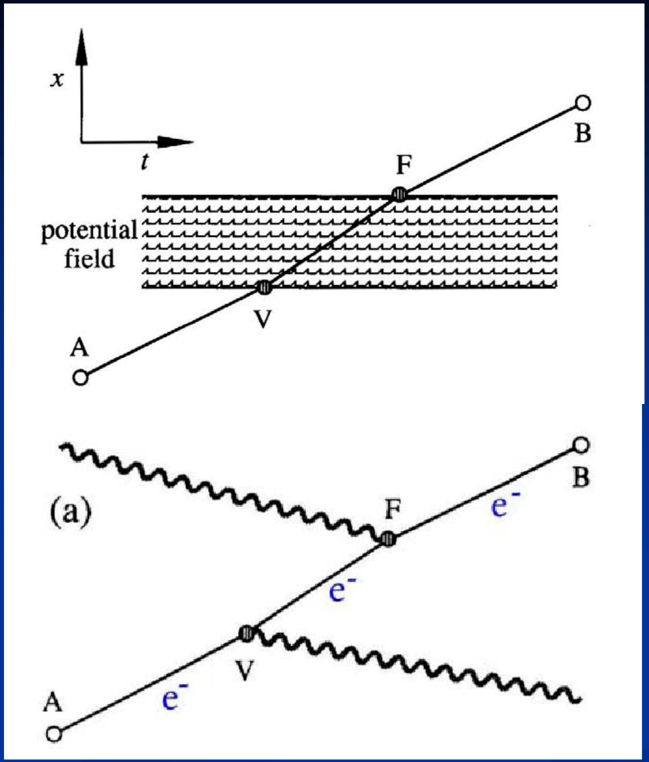
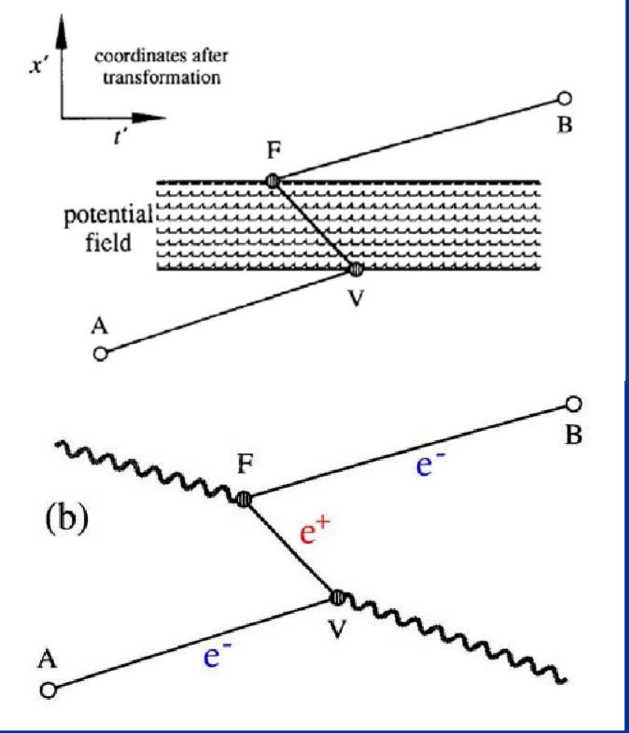


Fig. 8.7 Quantum spillover outside the light cone. Here we see the same electron path as in Fig. 8.6, but now it is a quantum path that is fuzzy due to Heisenberg uncertainty. Thus, some points of the path lie outside the light cone, as indicated by the white square.

Feynman to the rescue

Richard Feynman's interpretation - *The electron emits a photon as it enters the field and absorbs one as it leaves.*

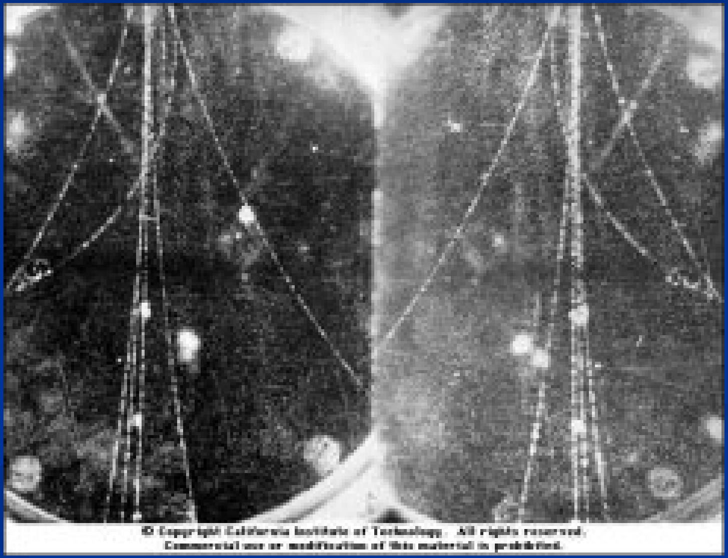




Here an electron goes backward in time! Feynman thought this might be equivalent to a positive electron or positron going forward. In that case a photon disappears to produce an electron positron pair. *This is creation of matter out of energy just as* $E=mc^2$ *implies.*

Positrons Found

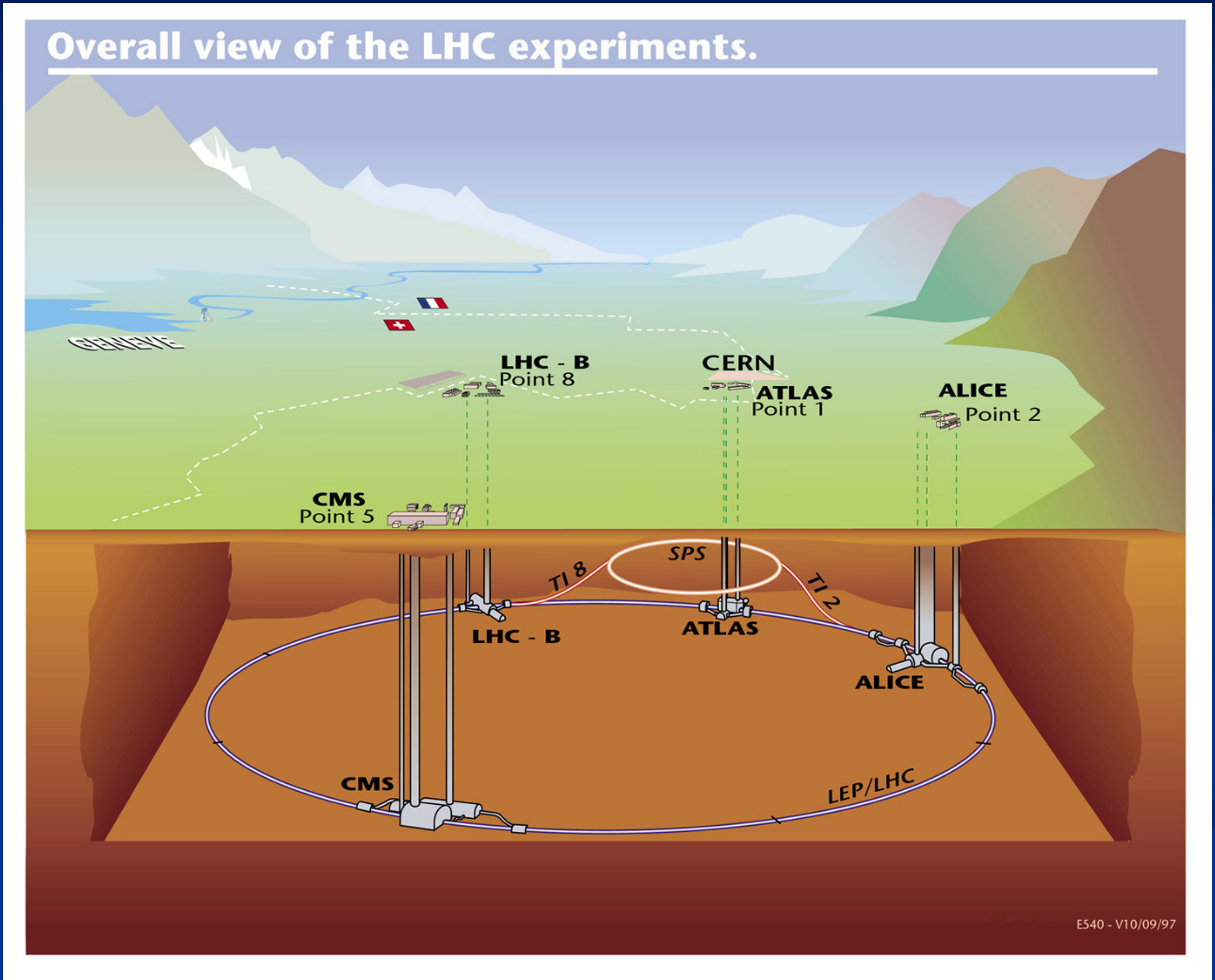
In 1932 **Carl Anderson**, a young professor at the California Institute of Technology, was studying showers of cosmic particles in a cloud chamber and saw a track left by *"something positively charged, and with the same mass as an electron"*. After nearly one year of effort and observation, he decided the tracks were actually **antielectrons**, each produced alongside an electron from the impact of cosmic rays in the cloud chamber. He called the antielectron a "**positron**", for its positive charge.



The discovery gave Anderson the **Nobel Prize** in **1936** and proved the existence of antiparticles as predicted by Dirac.

Today we can create all kinds of particles

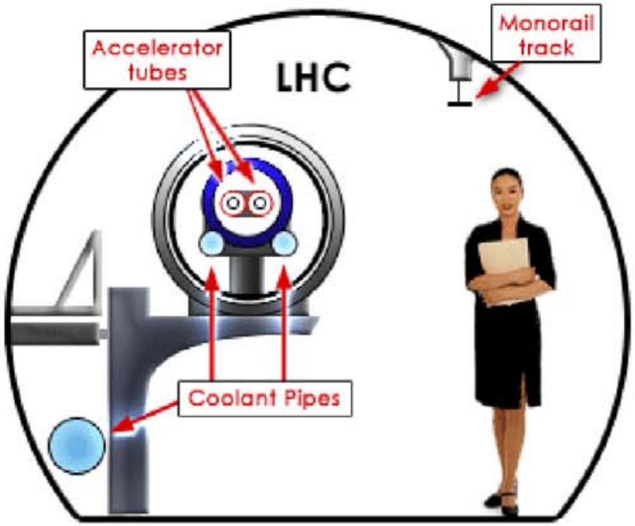
LEP (Large electron positron Collider)



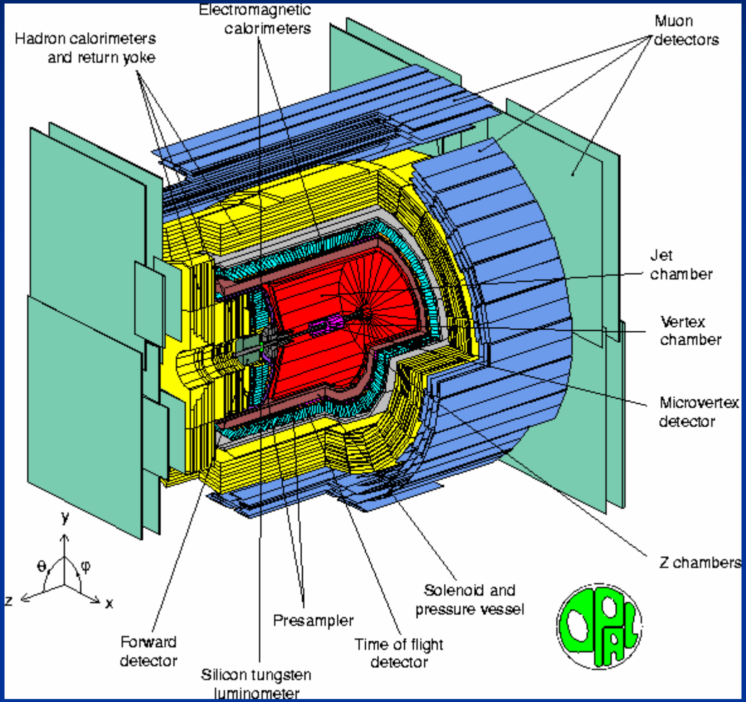
27 km Tunnel

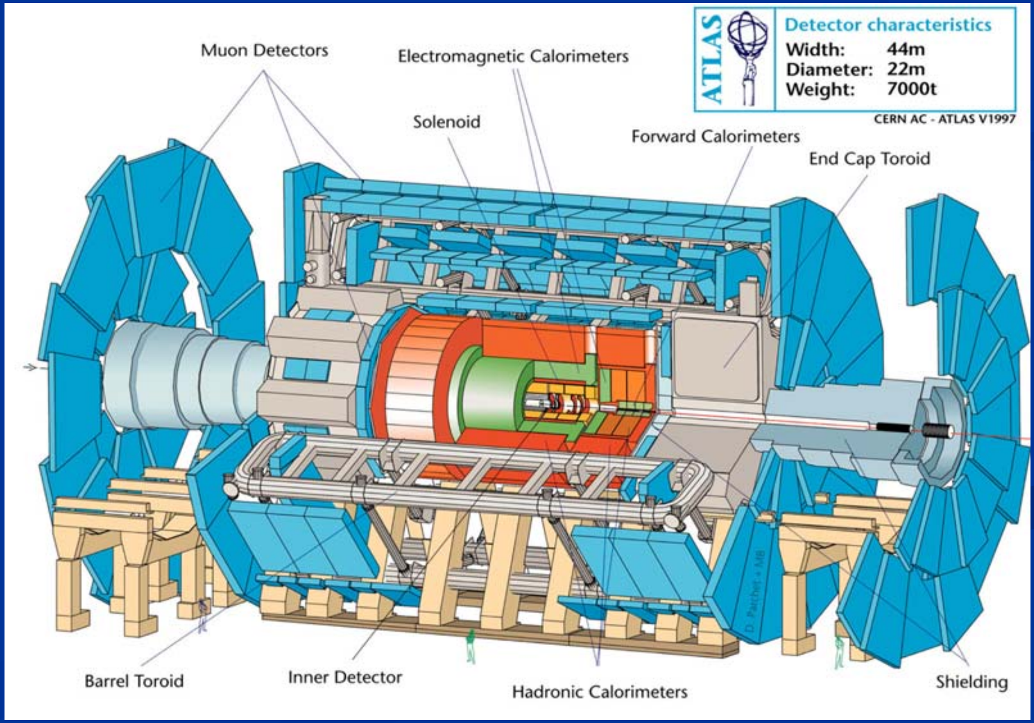
What Determines the LHC's Energy?

The high-energy protons travel inside vacuum pipes in an underground tunnel. They are kept in approximately circular orbits by strong magnetic fields produced by superconducting magnets. The higher the energy, the larger the orbit, the longer the tunnel, the more magnets needed, and the higher the cost. The 16-mile-long tunnel of the LHC is the largest for any particle accelerator in the world.



The detectors



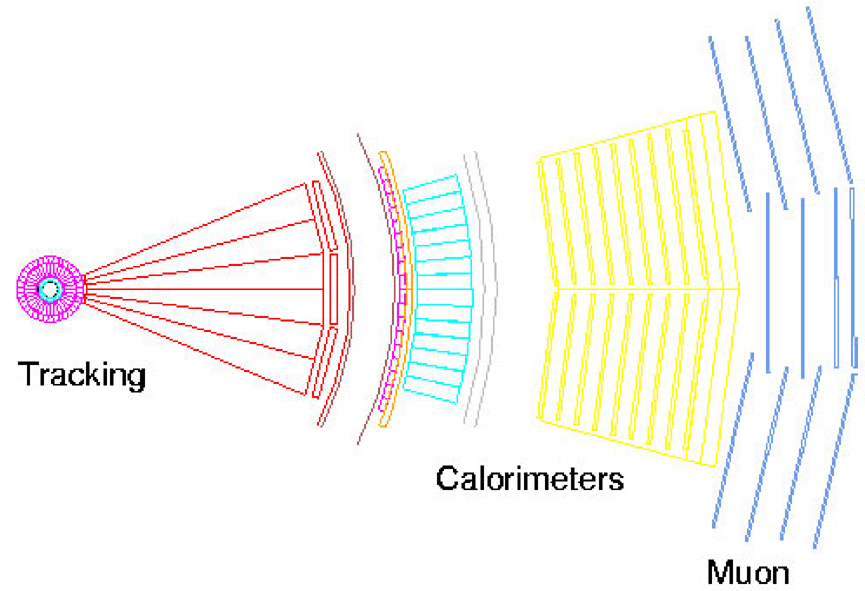


Detector Components

This is the inside structure of the OPAL detector.

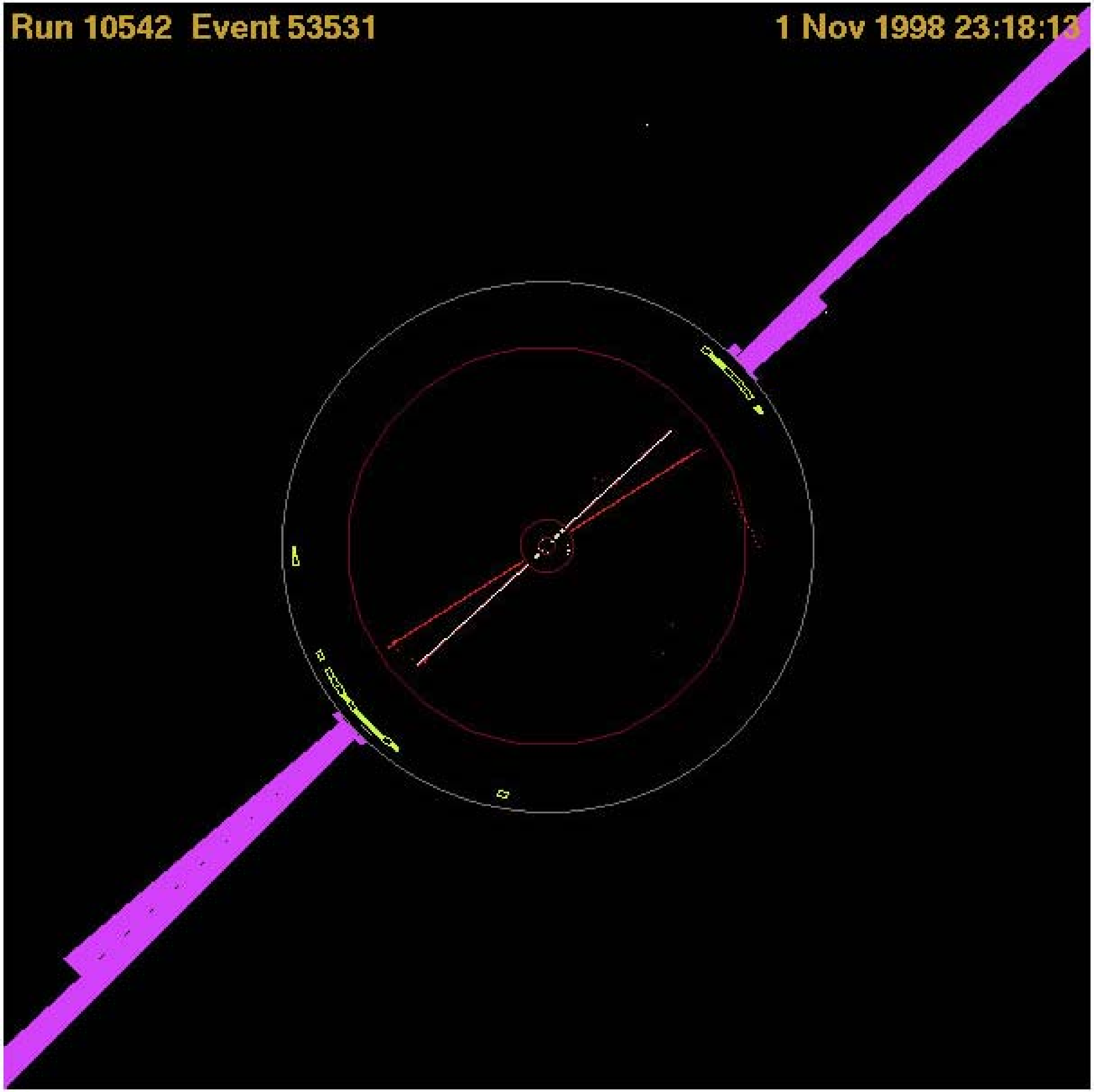
It consists of layers of sub-detectors, each of which is used to observe a different property of the outgoing particles

A Multi-Layer Detector

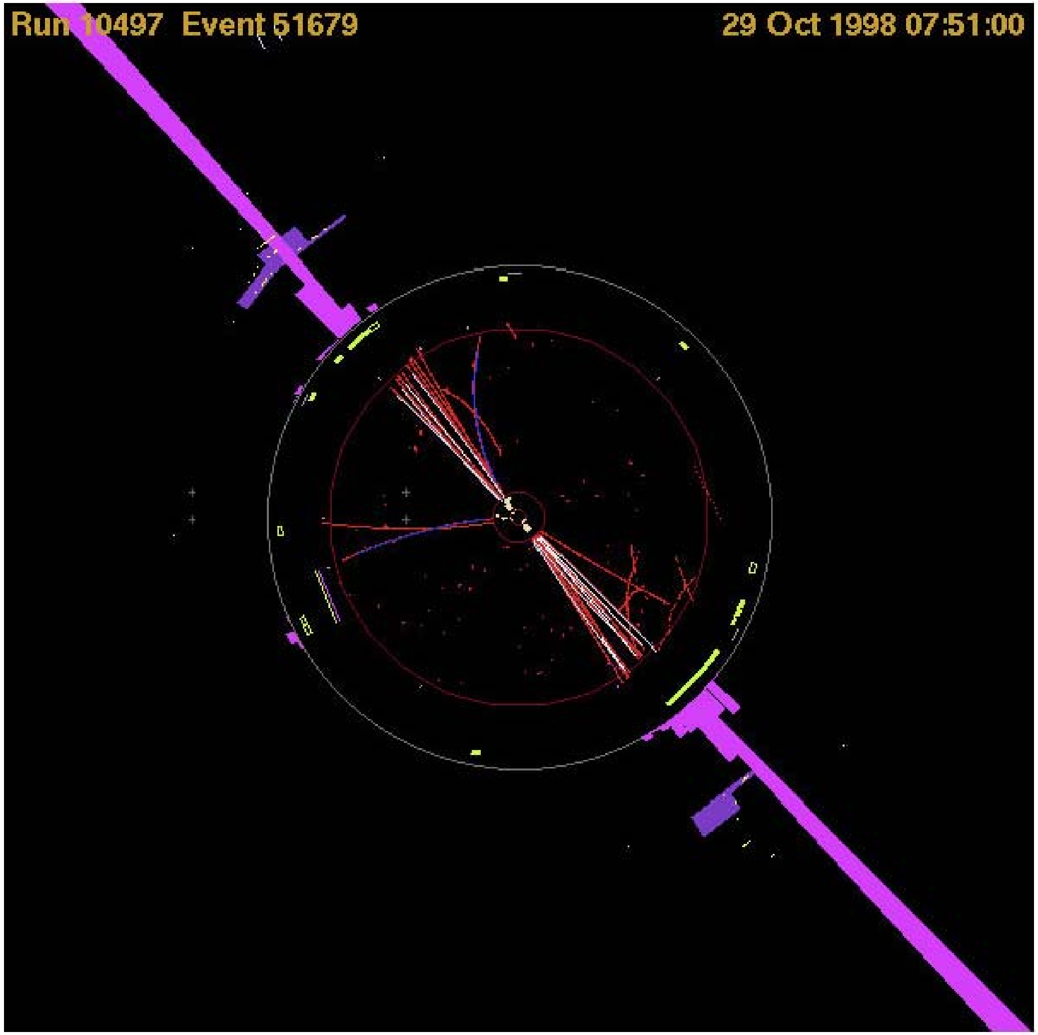


The detector is made up of three main layers, each of which is further subdivided:

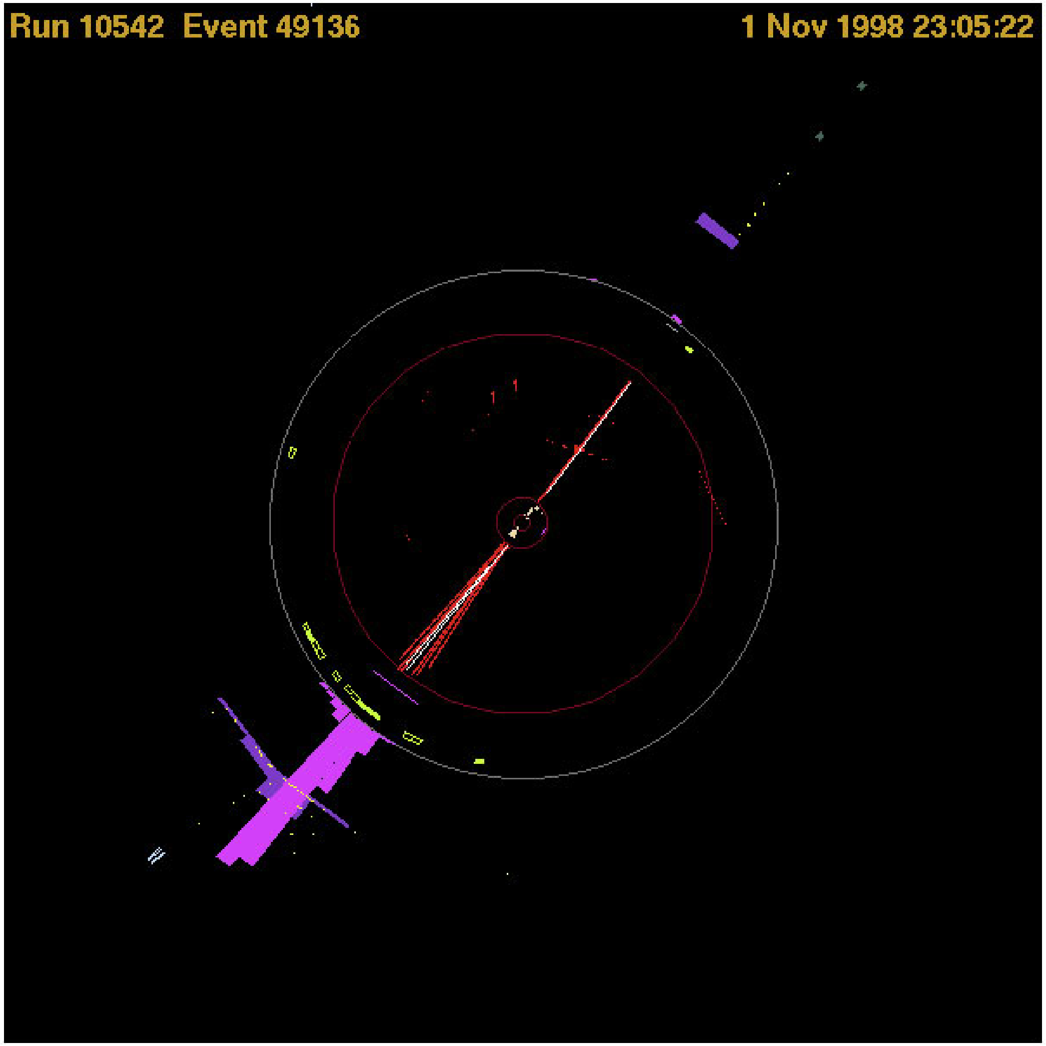
1. The tracking detectors are low-density devices. Particles produced in the electron-positron interaction just fly outwards through the tracking detectors, usually losing only a tiny part of their energy. However, if the particles are electrically charged, they cause ionisation of the tracking detector materials as they fly outwards: we detect this ionisation, and by measuring its position we can measure the path that the charged particle followed.
2. The calorimeters are made of high density material, and they are designed to stop most of the particles originating from the electron-positron interaction. When electrons, photons or hadrons stop in the material of the calorimeters, they give rise to *showers*. We can measure the energy of the incoming particle from the properties of these showers.
3. On the outside of the detector lies the muon system. The muon detectors are gas-filled chambers which detect the passage of charged particles, similarly to the central tracking detectors. Muons are very penetrating particles, and are the only ones which normally pass right through the detector as far as the muon system: so we can tell if a muon was present by looking for signals in these muon detectors.



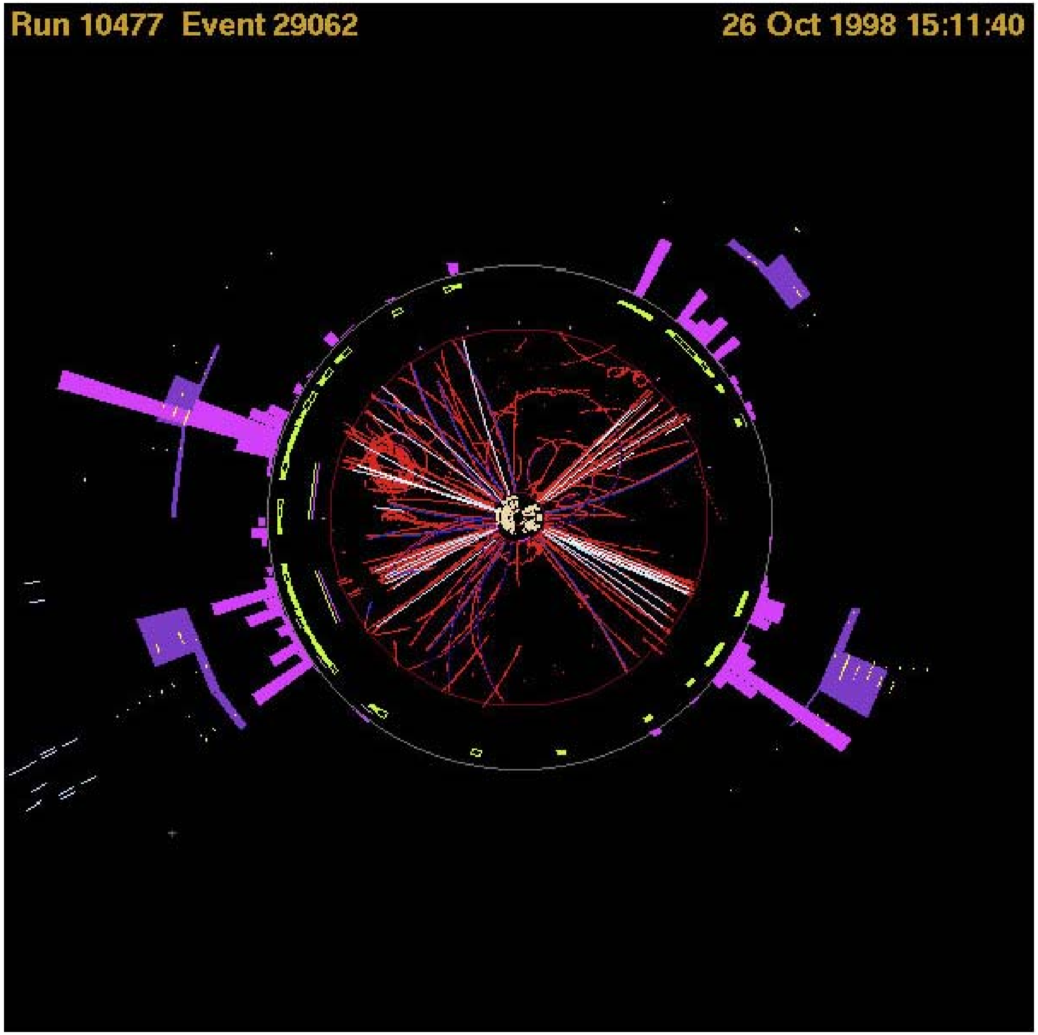
An example event of the kind $e^+e^- \rightarrow e^+e^-$



An example event of the type e^+e^- -> **quark (anti)quark**; The quarks materialise into a "jet" of hadronic particles. In this event two very clear narrow back-to-back jets are observed, which is why this type of event is known as a "two-jet event"



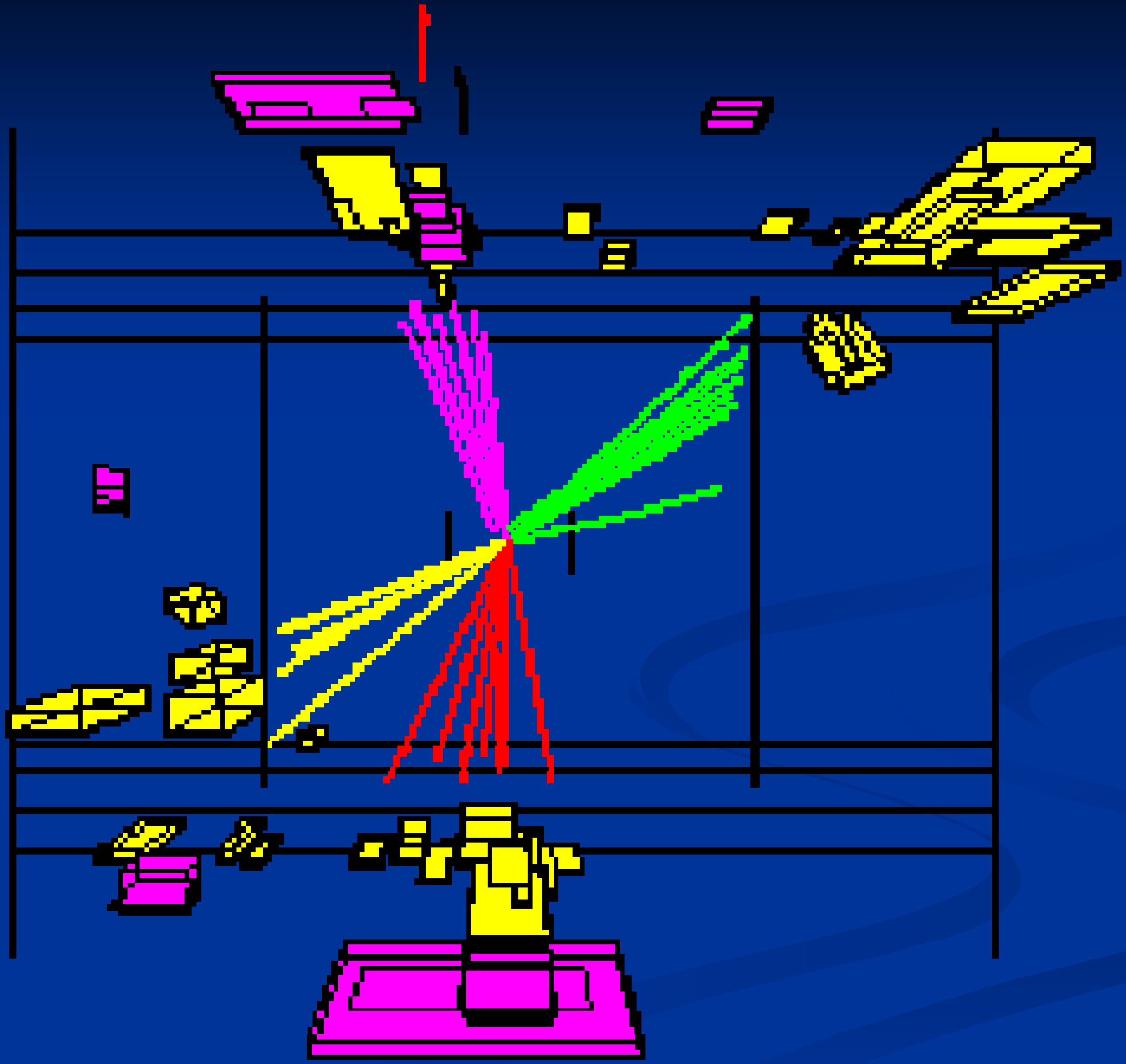
An example event of the kind e^+e^- -> **tau$^+$tau$^-$**;
The tau leptons decay very quickly: only their decay products are observed in the detector: in this case one tau has decayed to a muon (top right), the other to three charged particles (most likely pions; lower left)



At LEP2, we also produce events with pairs of W bosons: these are quite rare

This event is a candidate for $e^+e^- \to W^+W^-$, and where both W's decay quickly to quark-(anti)quark pairs.

Note that the event looks a bit like two of the two-jet events overlaid!

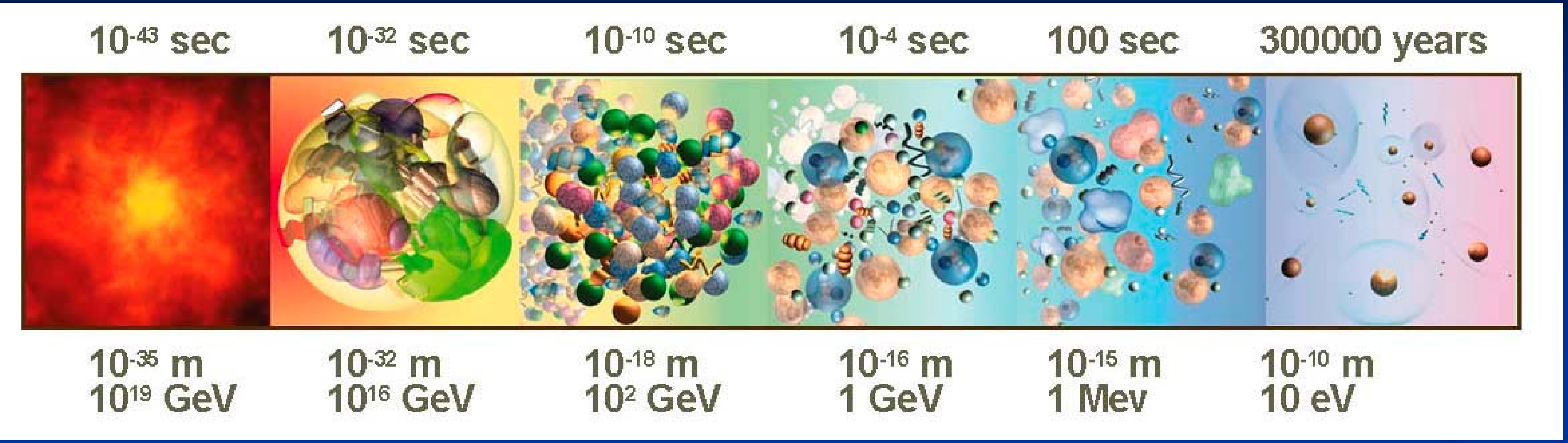


Surprisingly simple?

- One of the results of accelerator experiments is that the electromagnetic and weak forces are connected.
- It may be that all of the forces of nature are part of a single basic force.

What are the implications for the early Universe?

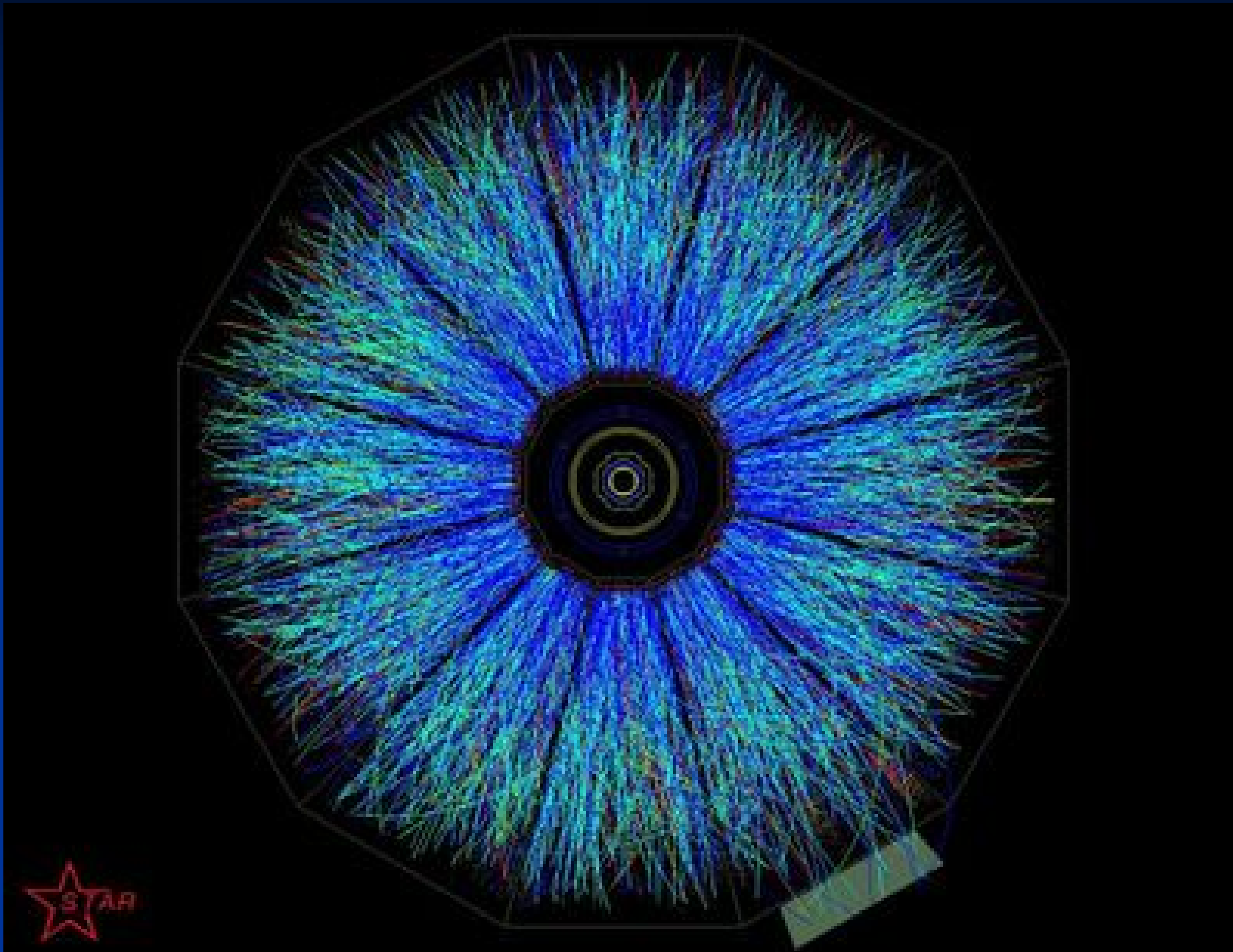
From particles to Universe



- 10^{-43}s - quarks and leptons. The universe doubles in size every 10^{-34}s.
- 10^{-32}s - Inflation stops.
- 10^{-4}s - Protons and Neutrons form from quarks.
- 3 min - Nuclei form.
- 300,000 yr. - Atoms form. Universe becomes transparent.
- 1B yr - Galaxies form
- *13B yr – Humans wonder where it all came from*

Current puzzles

- What is it that gives mass to the quarks and leptons?
  Search about to begin at CERN
- What about dark matter and dark energy?
  Lots of experiments in preparation and under way – stay tuned
- Can we make a back hole?
  We are about to try at CERN



So what have we learned?

- The “world” (ie: the Universe) is a very big place. It is unbelievably complex when we observe all the amazing things in it but astonishingly simple on the largest scale.

- The matter in the universe appears to be made of just two kinds of stuff, quarks and leptons.

- The forces that holds things together are of only 4 (now 3) kinds and there are hints that they may all be different aspects of a single force. (?)

Weird results but they work

Quantum and Relativity effects have made particle physics very different from what anyone expected. But the price of being a scientist is that you have to believe in observations and the observations bear out all of this and more.

Summary of some key points

- Matter is mostly empty space.
- There is no absolute time.
- Energy and Mass are interchangeable.
- At the microscopic level, interactions between particles involve the exchange of field particles.
- Quantum uncertainty makes the paths of particles and their locations fuzzy.
- Relativity and Quantum spillover conspire to change the order of events in time.
- Particles can be created from energy. They can also be annihilated to produce energy.
- The number of particles is not a constant.

If you like weird, this can be pretty cool stuff.

- Physics isn’t really hard but it is definitely weird.

I guess that’s why I like it.

the end