Particle Physics
in a Nutshell

- All matter is made out of atoms. Atoms are organized into the Periodic Table.

- Rutherford scattering reveals the internal structure of atoms.

- Charged particles interact through fields. Fields convert the kinetic energy of moving particles into potential energy. In particle collisions, more kinetic energy means a closer approach, which means more detail.

- Focusing a lot of energy into a small volume can create new particles ($E = mc^2$). When matter is created out of energy, we also create antimatter.

- Technological improvements lead to increases in energy and rapid discovery of many new particles. The lack of an organizing structure leads to the "particle zoo".

- Patterns found in the particle zoo points to deeper structure – quarks. Quarks are fundamental particles that have fractional charge (e.g., ⅓ or ⅔) and new characteristics such as strangeness and colour.

- The quark model introduces a new force to hold quarks together—the strong force. The strong force acts on colour charge and gets stronger as distance increases.

- More exploration leads to more particles, requiring more quarks. The current model has six quarks (and six antiquarks), six leptons (and six antileptons), and four bosons.

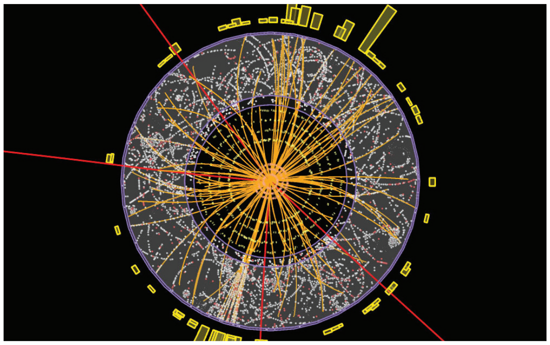
- The mass of the proton is mostly due to the binding energy of the quarks that make it up, not to the mass of the quarks. Why do quarks even have mass? This question leads to the Higgs field.

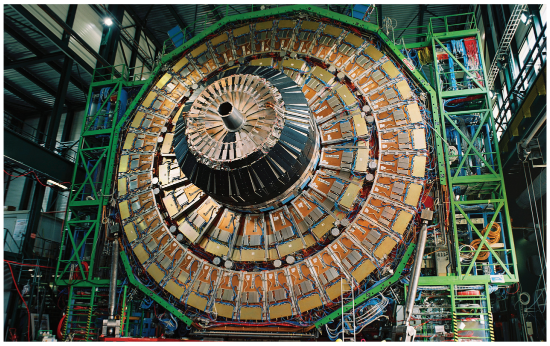
- Particles interact with the Higgs field, which impedes acceleration, giving inertia (mass). Massless particles like the photon do not couple to the Higgs field.

- Every field has a boson associated with it. The Higgs boson is like a ripple in the Higgs field. The Large Hadron Collider (LHC) will operate at high enough energy level (14 TeV) to generate Higgs bosons.

- The LHC will produce over 600 million collisions per second. Researchers expect to produce one Higgs event every three hours (talk about a needle in a haystack!).

- Four large detectors at the LHC will study the collisions for many different things: the Higgs boson, dark matter, quark-gluon plasma, matter-antimatter asymmetry, and supersymmetry.





Activity 01:
Video Summary

NAME :

01. The model of the atom has changed over the past 150 years as new evidence has been found. Draw labelled diagrams for a helium atom using each of these models.

Dalton's model of indivisible balls of matter	Thomson's model using electrons in a positive mass	Rutherford's model using electrons and nuclei

02. Rutherford fired alpha particles at gold foil and was surprised by the results.
He developed the nuclear model of the atom because
(a) most of the alpha particles went through
(b) most of the alpha particles bounced back
(c) a few of the alpha particles went through
(d) a few of the alpha particles bounced back
Explain your choice and make a labelled diagram of Rutherford's experiment.

03. The Large Hadron Collider (LHC) accelerates particles to unprecedented energy levels.
Higher-energy particles are used at the LHC because they can
(a) get closer to each other and probe smaller distances
(b) create massive particles from the energy
(c) both of the above
Explain your choice.

04. The most famous physics equation is Einstein's $E = mc^2$.
(a) Explain what each letter in the equation represents, and what the equation means.

(b) Draw a picture of what happens when an electron and a positron are created in a bubble chamber.
Where does the mass of the electron and positron come from?

05. Science was much simpler 80 years ago. Everything appeared to be made of just electron, protons, and neutrons.
Then physicists probed deeper into matter and detected new particles.
(a) Why was the discovery of new particles a problem?
(b) How was it solved?

06. The electromagnetic force pulls opposite charges together and pushes like charges apart. The strong force is different from the electromagnetic force in that the strong force is only attractive and it has
(a) three types of charge and gets weaker with distance
(b) three types of charge and gets stronger with distance
(c) two types of charge and gets weaker with distance
(d) two types of charge and gets stronger with distance

07. The Standard Model describes what is needed to make matter and the forces that hold it together.
(a) Fill in the table for the Standard Model.

	1st Generation	2nd Generation	3rd Generation	Bosons
Quarks				
Leptons				

(b) What is special about the first column?

(c) How are the next two columns different from the first?

(d) How is the last column different from the other three?

(e) Compare the periodic table of chemistry and the Standard Model of physics.

08. What particle in the Standard Model is the LHC designed to find? Why is it important?

09. What else might the LHC find? Make a list of all the possibilities mentioned.

Activity 03: Bubble Chamber Detective

NAME :

Physicists discovered dozens of different 'elementary' particles using bubble chambers. Bubble chambers are large vessels of super heated liquids in a uniform magnetic field. Identical charged particles are injected into the chamber where they collide inelastically with protons in the liquid to form new particles which may or may not decay. The following principles will allow you to analyze the events photographed in a bubble chamber:

Charge is always conserved.

- Only moving charged particles leave a trail. Neutral and stationary particles do not leave trails.
- The charged particles have a charge of either +1*e* or -1*e*, where *e* = 1.6 x 10^{-19} C
- Charge is determined by the direction the particle curves in a magnetic field.

Momentum is always conserved.

- The magnetic field bends the path of charged particles.
- The radius of a curved trail is proportional to particle's momentum.

Changes in the trails are evidence of an interaction

- A particle can collide with a proton to form new particles
- A particle can decay into new particles.

$$F_M = qvB = \frac{mv^2}{R}$$

$$mv = qBR$$

$$R = \frac{mv}{qB}$$

The radius of a curved trail is proportional to momentum

Part 1: CERN's Two Metre Hydrogen Bubble Chamber

Figure 1 is a photograph showing seven kaons entering a bubble chamber from the bottom. Kaons are unstable subatomic particles that can be produced in large quantities and decay into other particles, making them useful in bubble chamber experiments.There is a uniform magnetic field directed into the page. Answer each question and provide a brief written justification for your answer.

01. The kaon trails are curving slightly to the right. What is the charge of the kaons?
(a) –1 (b) +1 (c) 0 (d) not enough information

02. At point **P** the single trail of a kaon branches into two trails. What is the charge of the particle on the right?
(a) –1 (b) +1 (c) 0 (d) not enough information

03. Compare the total charge going into point **P** with the total charge going out. The single charged kaon
(a) has decayed into two oppositely charged particles.
(b) has decayed into two identically charged particles.
(c) has interacted with a proton and produced two oppositely charged particles.
(d) has interacted with a proton and produced two identically charged particles.

04. Compare the tracks going into point **P** with the tracks going out. What can you infer?
(a) A charged particle has been produced that moves up and to the left.
(b) A charged particle has been produced that moves up and to the right.
(c) A neutral particle has been produced that moves up and to the left.
(d) A neutral particle has been produced that moves up and to the right.

05. There is a kink in the track at point **T**. The particle making the track has
a) interacted with a neutral particle.
b) interacted with a positively charged particle.
c) decayed into a positively charged particle and a neutral particle.
d) decayed into a negatively charged particle and a neutral particle.

06. There is a very slight kink in the track at point **R** as the curvature increases. The particle making the track has
   a) interacted with a neutral particle.
   b) interacted with a positively charged particle.
   c) decayed into a positively charged particle and a neutral particle.
   d) decayed into a negatively charged particle and a neutral particle.

07. The two charged particles that appear at point **S** pass by each other at point **U**. Draw a straight line from this intersection to point **S**, where the particles were created from a neutral particle. This line gives the direction of the original neutral particle. Extend the line back down the page. Where did the neutral particle originate?
   a) at point P
   b) at point Q
   c) at point R
   d) not enough information

08. Two new particles appear at point **Q**. What can we infer about the event happening at point **Q**?
   a) A stationary charged particle has decayed into two new particles.
   b) A stationary neutral particle has decayed into two new particles.
   c) A charged particle moving up and to the left has decayed into two new particles.
   d) A neutral particle moving up and to the left has decayed into two new particles.

09. Extend the curved trails from point **Q** to find their intersection point by tracing the existing curve onto another piece of paper and using this to extend the path. Where did the neutral particle that decayed to form these particles originate?
   a) at point P
   b) at point Q
   c) at point R
   d) not enough information

10. Put it all together and give a complete description of the events that happen in this photograph.

Part 2: Brookhaven National Laboratory's Bubble Chamber

Figure 2 is an historic photograph. It provided the first evidence for the omega-minus particle which had been predicted two years earlier by Murray Gell-Mann. Negative kaons enter at the bottom. A uniform magnetic field is directed into the page. The essential trails have been darkened.

01. Identify the charges of the particles interacting at point **V**.

02. Identify the charges of the particles interacting at point **W**.

03. Two oppositely charged particles have been created from a neutral particle at point **Y**. The curves have been extended until they intersect. Draw a line to show where the neutral particle originated.

04. Oppositely charged particles have been produced from neutral particles at points **X** and **Z**. Find the origin of these neutral particles by extending the line that bisects the 'vee' formed by the charged particles. These lines should intersect with the line you drew in question 03 at a single point. What can you infer from this? Refer back to Question 02 in your explanation.

05. Reconstruct the interactions by labeling the visible and invisible particle trails on Figure 2. Begin at point **V** where a kaon (K^-) collides with a proton to produce the omega-minus (Ω^-), a neutral kaon (K^0) and a positive kaon (K^+). The omega decays at point **W** into a neutral xion (Ξ^0) and a negative pion (π^-). The xion then decays into a neutral lambda (Λ^0) and a neutral pion (π^0). The neutral pion decayed almost immediately into two photons (γ) which decay at points **X** and **V** into electron-positron (e^-, e^+) pairs. The lambda decays at point **Y** into a proton and a negative pion.

06. Nicholas Samios was the researcher who first analyzed this photograph in 1964. Imagine that it is three in the morning when he realizes that he has evidence for the omega-minus particle predicted by Gell-Mann in 1962. He wants to phone his boss with the news right away but his analysis is based on four invisible trails. What would you do? How would you explain your analysis over the phone?

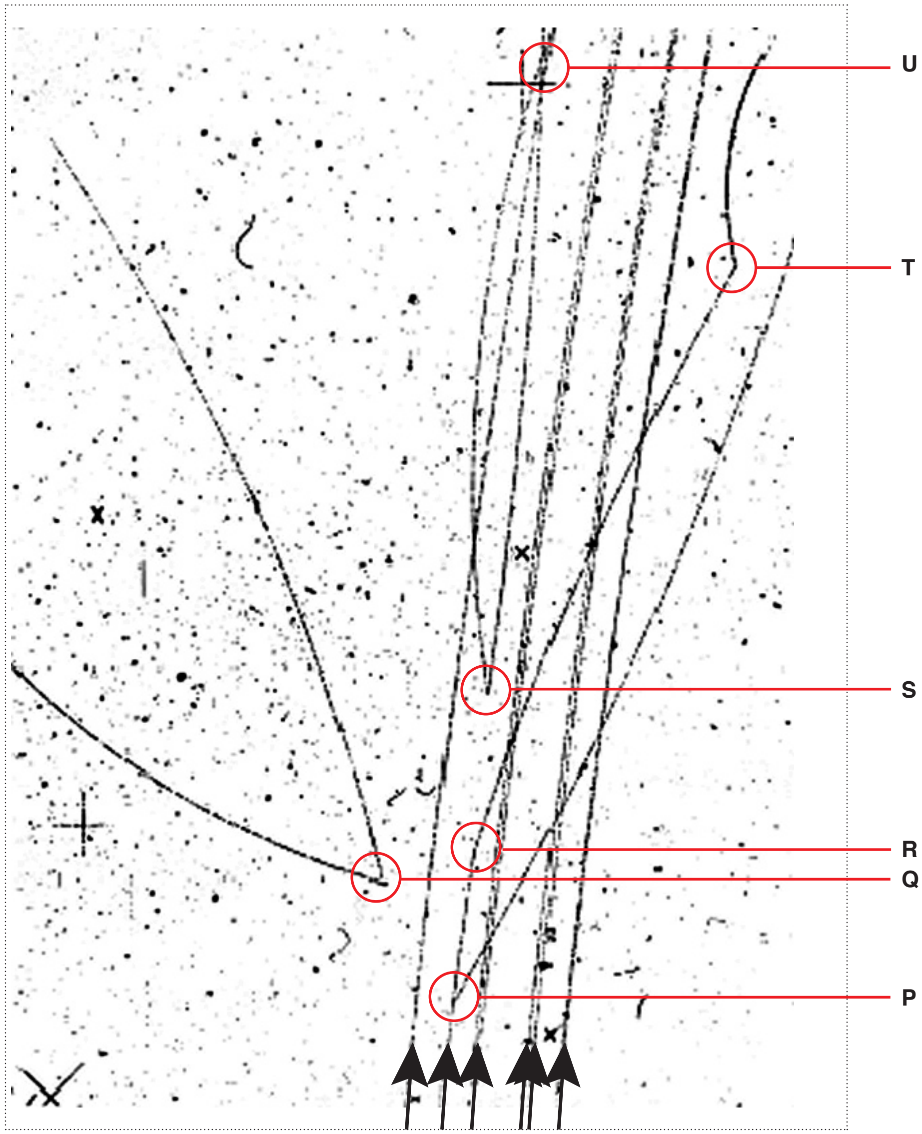


Figure 1 Photograph of CERN bubble chamber. Arrows indicate kaons moving up the page. There is a constant magnetic field into the page.

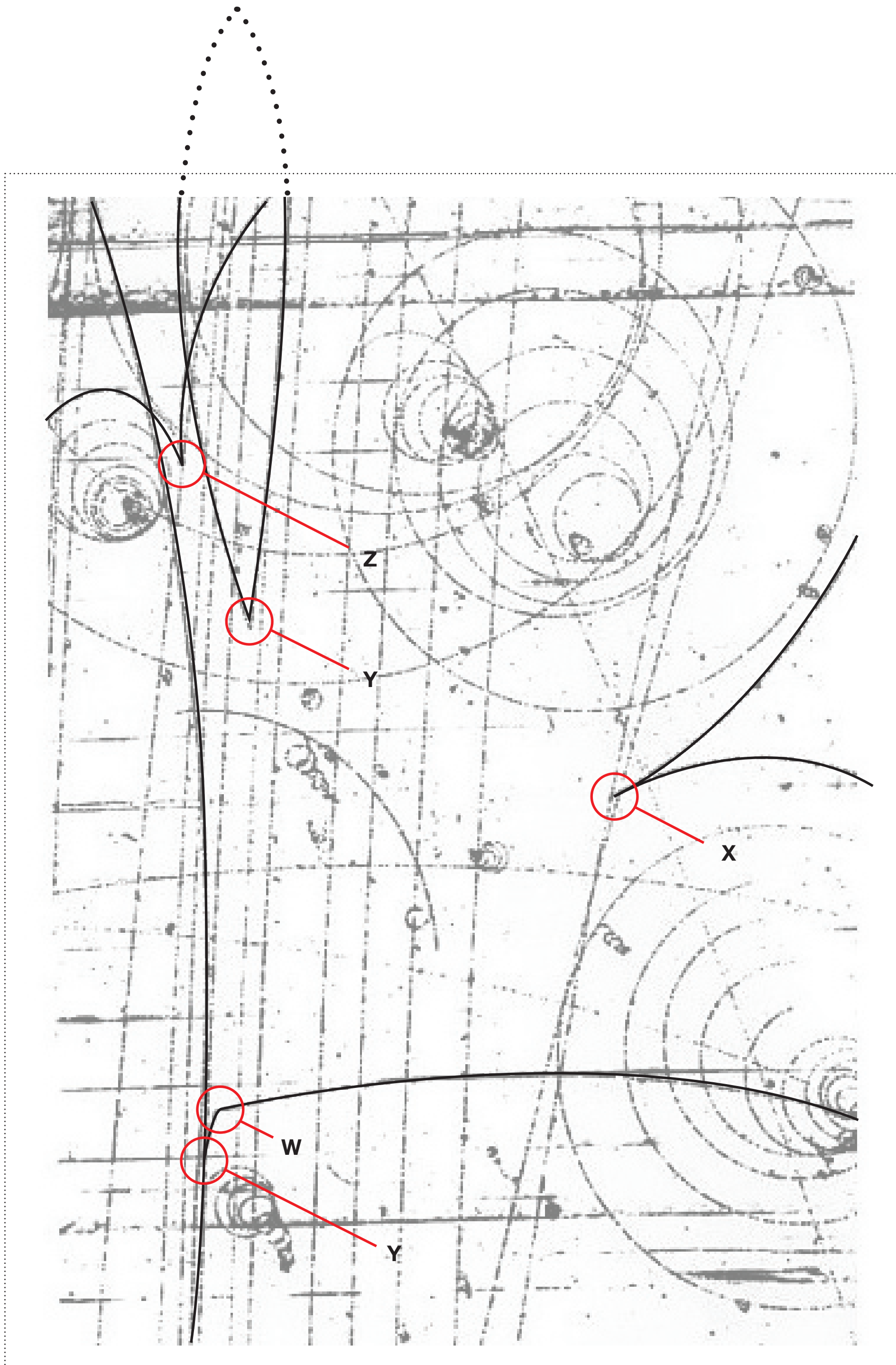


Figure 2 Photograph from Brookhaven National Laboratory. Negative kaons enter from the bottom of the image. There is a constant magnetic field directed into the page.

Activity 04:
Taming the Particle Zoo

NAME : ....

We have come a long way from Dalton and the indivisible atom. First, Thomson found the electron, Rutherford discovered the proton, and in 1932 Chadwick found the neutron. Then, the list expanded over the next 30 years to include over 90 different particles. Particle physics in the 50s and 60s was much like chemistry in the 1880s: a tremendous amount of data but no widely accepted theory to provide an organizing structure.

In this activity we will examine some of these particles, identify a pattern, and explore a theory that will help us tame the particle zoo, just as Mendeleev did for the elements when he built the first Periodic Table.

Part 1: Finding Patterns

01. Take a deck of particle cards and inspect the information on the cards. [Note: S is a new property called "strangeness".]

02. Sort the particles into **three** distinct groups based on information on the cards. Which characteristic is the best choice for this? Why?

03. Take one of the three groups. Organize its particles into rows and columns based on two of the other characteristics. Repeat for the other two groups.

04. Two of the groups should have eight members and look similar. The third group should look different and have nine members. Describe the geometric patterns that emerge from your arrangement of the cards. Patterns are often a clue to deeper structure.

05. Inspect the larger group. The pattern seems incomplete. You can complete the pattern by adding one more particle to the group. On a blank card, write down the characteristics (mass, spin, Q, S) you expect the missing piece will have. Show this prediction to your teacher.

Murray Gell-Mann won the Nobel Prize in 1969 for his theory explaining all of the known particles and predicting the omega-minus particle. Gell-Mann arranged the known particles into groups, much as you did in Part 1 of this activity. His theory was motivated by the geometric patterns that he found. He recognized that these patterns pointed to a deeper structure within matter. Just as the patterns in the Periodic Table can be explained using protons and electrons to build atoms, Gell-Mann's patterns suggested that the particles were made of smaller, more fundamental, particles which he called quarks. Each quark has a characteristic charge and strangeness. It also has a "mirror image" antiquark with the opposite charge and strangeness.

Quark Characteristics

Flavour	up (u)	down (d)	strange (s)	antiup ($\bar{u}$)	antidown ($\bar{d}$)	antistrange ($\bar{s}$)
Charge	$+\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{2}{3}$	$+\frac{1}{3}$	$+\frac{1}{3}$
Strangeness	0	0	−1	0	0	+1

All of the known particles can be constructed by arranging quarks according to a simple set of rules:

- Baryons are made of three quarks. (Antibaryons are made of three antiquarks)
- Mesons are made of one quark and one antiquark.
- Quarks have fractional charge and combine to produce integer charge (e.g., $\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$).
- Quarks have two distinct spin states: (½ or –½). When we combine quarks, the spins either add or subtract, just like the charges do to produce either spin-0, spin-½, or spin-³⁄₂ particles.

Part 2: Understanding Patterns

01. Mesons are a combination of one quark and one antiquark. The table below has all of the possible combinations of u, d, and s quarks and antiquarks. Determine the combined **Q** and **S** values for each combination. Then, match these values with the mesons in the spin-0 group that you built in Part 1.

Spin-0 Mesons

$q\bar{q}$	$u\bar{u}$	$u\bar{d}$	$u\bar{s}$	$d\bar{u}$	$d\bar{d}$	$d\bar{s}$	$s\bar{u}$	$s\bar{d}$	$s\bar{s}$
Q		+1							
S		0							
Particle Symbol		π^+							

What problems do you see in your results? How could you resolve them?

02. Baryons are a combination of three quarks. The table below has all of the possible combinations of u, d, and s quarks. Determine the combined Q and S values for each combination. Then, match these values with the baryons in the spin-3/2 group and the spin-1/2 group that you built in Part 1. Baryons

Baryons

qqq	uuu	uud	udd	ddd	uus	uds	dds	uss	dss	sss
Q		+1								
S		0								
Spin-3/2 Baryons		Δ^+								
Spin-1/2 Baryons		p								

What problems do you see in your results? How could you resolve them?

Supplementary Information

Introduction

Science is a process of learning about our universe through observation and explanation. We build models to explain our observations and then test these models using logic and experiment. Experiments are designed to test specific predictions made by the models and to provide new observations that the models must explain. Models that fail to predict or explain observations are modified or discarded. As observations improve, so do the models.

Particle physics is the study of the elementary building blocks of the universe and the forces through which they interact. Its origins go back to ancient times when philosophers considered what would happen if an object were cut into smaller and smaller pieces. Some felt that matter could be continuously divided into smaller and smaller pieces forever. Others concluded the logical answer was that eventually one would reach a point where the object could no longer be divided—our word **atom** comes from the Greek word for "uncuttable." This idea stood untested for almost two thousand years, until developments in chemistry and physics allowed scientists to probe deeper into matter.

One of the earliest developments was electrolysis: the process of applying an electric potential across a solution to separate the constituent parts. As researchers developed this tool, they modified their experiments to pull gases apart. This led to the development of the cathode ray tube (CRT). In a CRT, even when an electric potential is applied across a vacuum, something is still observed moving from one end of the tube to another: a flow of **electrons**. In a sense, the CRT acts like a very sharp knife, allowing scientists to "cut the uncuttable."

Figure 1 Early cathode ray tube.

The discovery of the electron by J. J. Thomson in 1897 showed that atoms were made of even smaller parts. This raised the question: What is the structure of the atom? Thomson knew that atoms were electrically neutral and that electrons were negatively charged. He imagined the atom looking like a "raisin bun," with the "bun" being a positive substance that held the tiny negatively charged electrons or "raisins" in place. It was this model that Ernest Rutherford set out to examine.

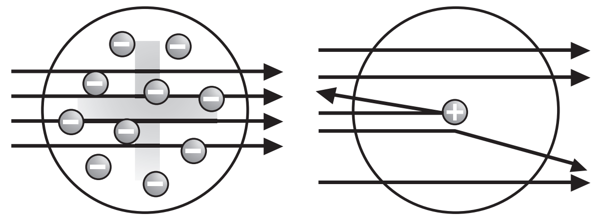


Figure 2 The "raisin bun" model fails to explain the observations

Rutherford's scattering experiment overthrew the raisin bun model and demonstrated that the positively charged part of the atom must be concentrated into a very small volume at the centre of the atom—the **nucleus**. The significance of Rutherford's discovery does not stop at the knowledge gained in the experiment. The technique that Rutherford used was revolutionary. Instead of pulling atoms apart by applying an electric potential across them, he probed the atom by firing particles at it—a technique that is still proving useful today.

Rutherford's Model and Fields

Electrically charged objects exert forces over a distance—a seemingly mysterious phenomenon. Somehow, the objects are able to reach out through space and affect each other without touching (as the students observe in the *Scattering Experiment*). This behaviour can be explained using fields. An electric field is a region of space surrounding charged objects in which other charged objects feel a force. Since fields exert forces, they are capable of doing work and transferring energy.

The strength of the field depends on the charge distribution of the object producing the field. In the raisin bun model, the atom was a lump of positive matter with little negative bits suspended in it. Rutherford knew that the field generated by such a dilute positive charge would barely disturb the trajectory of an alpha particle passing through the atom. To test this idea he fired positively charged alpha particles at a thin gold foil. He chose gold foil as his target because it can be made very thin, giving clean results. A scintillating screen surrounding the target flashed whenever struck by an alpha particle. Rutherford and his students observed the individual flashes through low-power microscopes. Eventually they accumulated enough data to determine that 1 out of every 8000 alpha particles was being deflected straight back. This was a huge surprise and a puzzle that took Rutherford over a year to solve.

> *"It was as though you had fired a 15-inch shell at a piece of tissue paper and it had bounced straight back and hit you."*
> *– Ernest Rutherford*

Rutherford knew that the strength of the electric field surrounding the gold nucleus decreases with distance. Alpha particles that travel straight through the gold must be far from any nuclei. Particles that are deflected slightly must have been closer to a nucleus and experienced a small force. Particles that bounce back must have traveled directly at a nucleus, slowed down, stopped and then reversed direction.

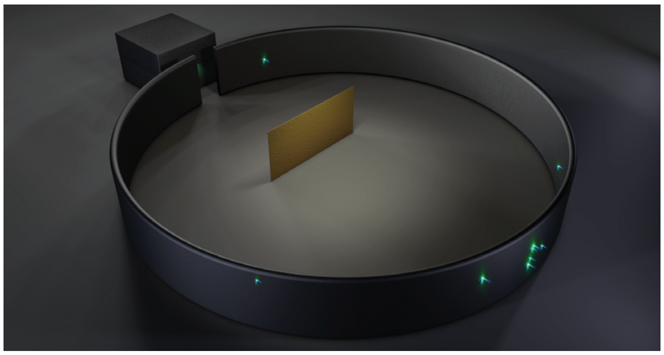


Figure 3 Flashes of light are produced when an alpha particle hits the screen.

The kinetic energy of the particle is stored up by the field as potential energy and then transformed back into kinetic energy as the alpha particle moves away. The initial energy of the alpha particle determines how close it gets to the gold nucleus, as the equation below shows. Rutherford's original experiment shows that the minimum separation distance between the alpha particles and the gold nucleus was 2.7×10^{-14} m, which is about 10 000 times smaller than the atom. This is not the actual radius of the nucleus, just the distance of closest approach for the particles that collided with the nucleus head-on.

$$\tfrac{1}{2}mv^2 = \frac{kQ_\alpha Q_{Au}}{r} \qquad r = \frac{2kQ_\alpha Q_{Au}}{mv^2}$$

Figure 4 Equations for distance of closest approach

In order to get closer to the nucleus, the alpha particle must start with more kinetic energy. To increase the kinetic energy of particles, we accelerate them. The increased energy allows them to penetrate into more intense regions of the electric field, giving researchers a more precise description of the nucleus. As the energy of the particles increases, we reach a point where there is so much energy in such a small region of space that new particles appear. In order to understand where these new particles come from, we must examine the nature of energy and mass.

Energy-Mass Equivalence

One result of Einstein's special theory of relativity is the unification of energy and mass. Einstein showed that energy and mass are equivalent and interchangeable. This can be seen in the general form of the relativistic energy-momentum expression $E^2 = (mc^2)^2 + (pc)^2$, where E is the total energy, m is the rest mass, c is the speed of light, and p is the relativistic momentum ($p = \gamma mv$, where γ is the relativistic factor due to the velocity v). For objects that are at rest ($p = 0$), this expression simplifies to the more familiar $E = mc^2$.

The relativistic energy-momentum expression encapsulates the fundamental physics behind the creation of particles in a collider. Conservation of energy dictates that the total energy before a collision must equal the total energy after a collision, but it does not say how that energy is distributed between rest mass and momentum. The particles produced in a collision are constrained by various conservation laws (charge, spin, etc) but within those parameters, anything that can happen, will happen with a certain probability. Due to quantum randomness, we cannot predict what particles will be produced in any one collision. We can, however, predict the probability of a given result. As long as the initial collision has enough energy to produce the total rest mass of a certain set of particles, then it will produce those particles some of the time.

Note that the rest mass of a particle does not change when it is accelerated—even to relativistic speeds. As energy is added to the system the first term in the energy-momentum expression will not change, so at relativistic speeds the contribution of rest mass to the total energy becomes negligible and the expression simplifies to $E = pc$. It is sometimes said that as objects approach the speed of light they get heavier and heavier, but that is misleading. As objects approach the speed of light they get harder to accelerate, which is the same effect as would occur due to an increase in mass, but does not actually mean that there is a change in the rest mass of the particle.

Consider the collision that produced the top quark at Fermilab in the United States, a discovery announced in 1995 (students analyze these results in the *Finding the Top Quark* activity). A proton and antiproton each having rest mass energy of 0.938 GeV were accelerated to energies of 900 GeV before colliding with a total energy of 1.8 TeV. With so much energy available there were many possible combinations of rest mass energy and momentum in the products of the collision. The combination that researchers were looking for was a spray of particles whose total momentum and energy pointed to a large rest mass. This rest mass was that of a top quark–antitop quark pair. The energy needed to produce this pair came from the momentum of the proton and antiproton. Notice how the analysis moves fluidly from momentum to energy to mass without really differentiating between them. Researchers are not being sloppy in their treatment of units—they are making use of deep connections between these three quantities.

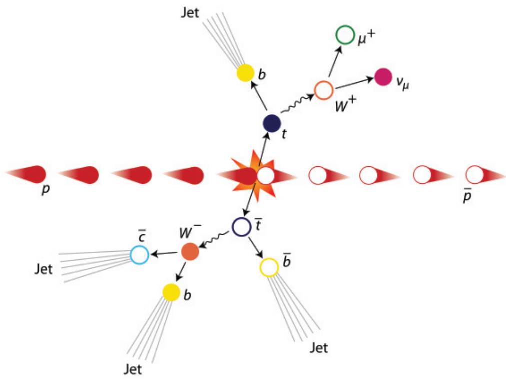


Figure 5 A Top Antitop Quark Event from the D-Zero Dectector at Fermilab

Antimatter

One of the more exotic results from particle physics is the discovery and production of antimatter. British physicist Paul Dirac predicted the existence of a positively charged version of the electron while deriving a relativistic version of the Schrodinger wave equation for electrons. The equation had two possible solutions: one solution was the electron, the other was a particle with the same mass as an electron but opposite charge—the **positron**. This new antimatter particle was discovered within four years of Dirac's prediction and antimatter has played a major role in particle physics ever since.

Antiparticles are fundamental particles that have the same mass as their counterparts but opposite properties (such as charge, colour, and strangeness). Thus, the positron is the antiparticle of the electron. When particles and antiparticles meet, they annihilate, releasing all of their rest mass energy as other particles according to $E = mc^2$. Science-fiction writers have long admired antimatter and routinely invoke it as a source of energy or as a weapon. In reality, however, it can be very difficult to produce. One of the largest producers of antimatter is CERN and they estimate that it would take 100 billion years and over 1000 trillion dollars to produce even a single gram of antiprotons. Antimatter does, however, have many applications in medicine. For example, positrons are used routinely in hospitals for positron electron topography (PET) scans.

The Eightfold Way

The first half of the 20th century was a very productive time for particle physics. At the beginning of the century, the electron was the only subatomic particle that had been discovered. By the mid 1960s, there were dozens of subatomic particles, but no underlying theory to explain this "particle zoo." The particles were grouped by behaviour into two categories: **leptons** and **hadrons**. Hadrons were further divided into **mesons** and **baryons**. Murray Gell-Mann won the Nobel Prize in 1969 for his "contributions and discoveries concerning the classification of elementary particles and their interactions". What Gell-Mann and several of his contemporaries did was to organize the known hadrons by their spin, charge, and strangeness (just as students do in the *Taming the Particle Zoo* activity). The pattern that emerged revealed a special symmetry among mesons and baryons, which Gell-Mann coined the "Eightfold Way".

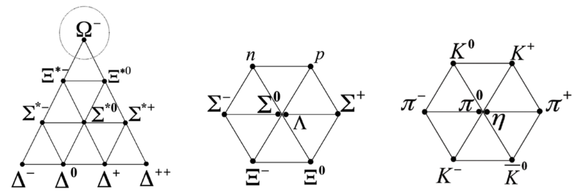


Figure 6 The Eightfold way brought order to the particle zoo.

Two things were apparent to Gell-Mann: first, one of the groups was missing a particle (the omega-minus), whose existence he was able to successfully predict; second, the basic structure of the patterns seemed to be built out of triangles. This pointed to the existence of three fundamental particles: the up, down, and strange **quarks**. Thus, the quark model was Gell-Mann's explanation for the Eightfold Way symmetry he had observed.

One of the compelling aspects of the Eightfold Way and the quark model behind it was the way they revealed order within the particle zoo via a simple set of rules. Two requirements of a scientific model are that it makes testable predictions and that it can accommodate new observations. The quark model has proven to be very robust in this regard. The early success of the model in predicting the existence of the omega-minus particle was further bolstered by the ability of the model to adapt to the discovery of new particles by incorporating three more quarks.

The Standard Model

The early quark model brought order to the hadrons in the particle zoo of the early 1960s, but as technology improved the number of particles increased. The quark model grew to four, then five, and finally six flavours of quarks organized into three generations. According to the **Standard Model** of particle physics, these six quarks (and their antiquark counterparts) produce all the observed hadrons: mesons are quark-antiquark pairs, baryons are quark triplets.

Quark	First generation		Second generation		Third generation	
Flavour	Down	Up	Strange	Charm	Bottom	Top
Symbol	d	u	s	c	b	t
Charge (e)	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$

Notice that quarks have fractional charges. In nature we do not find free particles with fractional charge; the smallest charge we find is the elementary charge *e*. The only quark combinations allowed in the Standard Model produce particles with an integer charge.

Quarks are spin-½ particles, which means they have two distinct spin states (up and down). The Pauli Exclusion Principle says that two identical particles of this type cannot occupy the same state. There are particles, like the delta-plus-plus, that have three apparently identical quarks in them which seems to violate the Pauli Exclusion Principle, so an additional quantum property, **colour charge**, was added to the quark model to further distinguish one quark from another. Quarks can have one of three “colours”: red, blue, and green. Of course, quarks do not actually have colour in the conventional sense; colour is used here to describe a property of quarks with three variations that combine to produce a neutral result, just as actual primary colours do. Colour charge is not observed in baryons and mesons, so quarks must combine in a way that produces only colour-neutral particles. In baryons, this is accomplished by adding a red quark, a blue quark, and a green quark together to get a white (colourless) particle. In mesons, this is accomplished by adding a quark that has colour with an antiquark that has the corresponding anticolour.

The Standard Model might appear quirky, with its language of quarks, flavour, colour, strangeness, and spin, but it is described by two very precise mathematical theories: **quantum chromodynamics (QCD)** and **electroweak theory**. These are two of the most successful and far-reaching theories ever produced by science. QCD gives a complete description of how the strong nuclear force works. It sets out the rules that govern how quarks combine to give hadrons. Electroweak theory unifies two of the fundamental forces (electromagnetic and weak nuclear). It describes how electrically charged particles behave and sets out the rules for the behaviour of leptons.

Leptons are fundamental particles that do not interact with the strong force (i.e. they do not have colour). Like quarks, they come in three generations, with each generation having a negatively charged particle, such as an electron, and a neutrino counterpart. **Neutrinos** are particles that are produced in prodigious numbers during fusion reactions inside stars. They are incredibly difficult to study because they interact so weakly with matter. There are many experiments being conducted around the world to learn more about these elusive particles.

Lepton	First generation		Second generation		Third generation	
Name	electron	electron neutrino	muon	muon neutrino	tau	tau neutrino
Symbol	e	ν_e	μ	ν_μ	τ	ν_τ
Charge (e)	−1	0	−1	0	−1	0

The Standard Model is not just about particles. It also gives a complete description of the strong, weak and electromagnetic forces. In the Standard Model, objects exert forces by exchanging particles called **bosons**. Bosons carry information about how strong the force is and whether it is attractive or repulsive. The electromagnetic force is mediated by photons, (i.e., electrostatic repulsion occurs when photons are exchanged between two like charges). The strong force is a short-range force that acts between coloured particles (i.e., quarks) by exchanging gluons, massless bosons that carry colour. The weak force is involved in radioactive decay and is mediated by the W and Z bosons.

Mediator	Electromagnetic Force	Strong Force	Weak Force	
Name	photon	gluon	$W^\pm$	Z^0
Symbol	γ	g	$W^\pm$	Z^0
Charge (e)	0	0	±1	0
Mass (MeV/c²)	0	0	81 800	92 600

The final particle in the Standard Model is the **Higgs boson**. The Higgs boson was introduced into the Standard Model to explain why fundamental particles have mass. It is the only particle in the Standard Model that has not been conclusively observed, as of January 2012.

The Higgs Mechanism

The Higgs mechanism is a concept that was first introduced into electroweak theory to solve a serious problem. The problem was that there was a theory of the weak interactions—a precursor of the Standard Model—that got many features right, but seemed to predict that all elementary particles were massless. But if they were massless they would all have to travel at precisely the speed of light, which they do not. What made this such a serious problem was that the same feature of the theory that made it successful—a particular symmetry of its equations—was also precisely what seemed to require particles to be massless.

The technical details of this symmetry use ideas that go beyond the scope of this resource, but the idea of the Higgs mechanism can be more simply understood. The idea is that the universe is permeated by a Higgs field, which breaks the symmetry that would otherwise make particles massless. The Higgs field permeates all of space even in the absence of any particles; it exists everywhere, even in a vacuum.

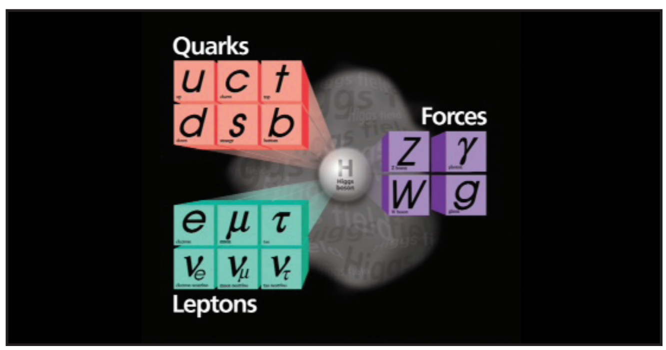


Figure 7 The Standard Model

Particles experience an energy of interaction with this ambient field, and it is this energy of interaction that we interpret as their mass (we are able to do this because energy and mass are interchangeable). Not all particles interact with, or couple to, the Higgs field with the same strength. Particles that couple more strongly are harder to accelerate and so have more inertial mass. Photons are massless despite the Higgs field because they do not couple to it at all. Why some particles couple to the field more strongly than others is still an open question: the coupling strength for each particle is an empirically derived parameter (i.e., we start with observed masses and work backwards to get the coupling strength, rather than predicting the coupling strength theoretically).

Because the Higgs mechanism determines every particle's mass, it plays a vital role in all physical processes. In particular it makes the weak force very short-ranged and this, in turn, is what makes the weak interactions experienced by nuclei so weak. Since the weak force is responsible for all reactions that change protons and neutrons into one another, it is responsible for the nuclear fusion reaction that releases energy by converting hydrogen into helium—a process that requires turning protons into neutrons. Since it is the strength of this force that controls the rate of nuclear fusion, the Higgs mechanism is partly responsible for the reactions that make stars shine. If the Higgs mechanism were slightly different, stars would either not shine at all or burn up rapidly. The Higgs mechanism also ultimately determines the fact that the proton is lighter than the neutron, which is why free neutrons decay into protons (plus other particles) rather than protons decaying into neutrons. Thus, the Higgs mechanism is a very important concept, and finding evidence for or against it will be an important step forward for science.

In quantum mechanics, every field has a particle associated with it. In the case of the Higgs field, this particle is the Higgs boson. This boson is like a small ripple in the Higgs field. If we sufficiently disturb the Higgs field in the vacuum, we can create a ripple in it–a Higgs boson. This boson would then decay rapidly into lighter particles, and it is these lighter particles that the detectors at the Large Hadron Collider will record and analyze.

The Large Hadron Collider (LHC)

The **Large Hadron Collider** or **LHC** is the world's largest particle accelerator—a 27 km-long ring buried 100 m below the Swiss-French border near Geneva. When running at full power, it will produce over 600 million collisions per second at unprecedented energies: 14 TeV for protons, 1150 TeV for lead ions. The collisions will occur at four different locations on the ring where enormously complicated and sensitive detectors will analyze the particles produced by the collisions. This data will be quickly filtered by several layers of computer analysis to about 100 events of interest per second. These events will then be recorded for further analysis at a rate of about 700 MB/s. At this rate the LHC would create enough data

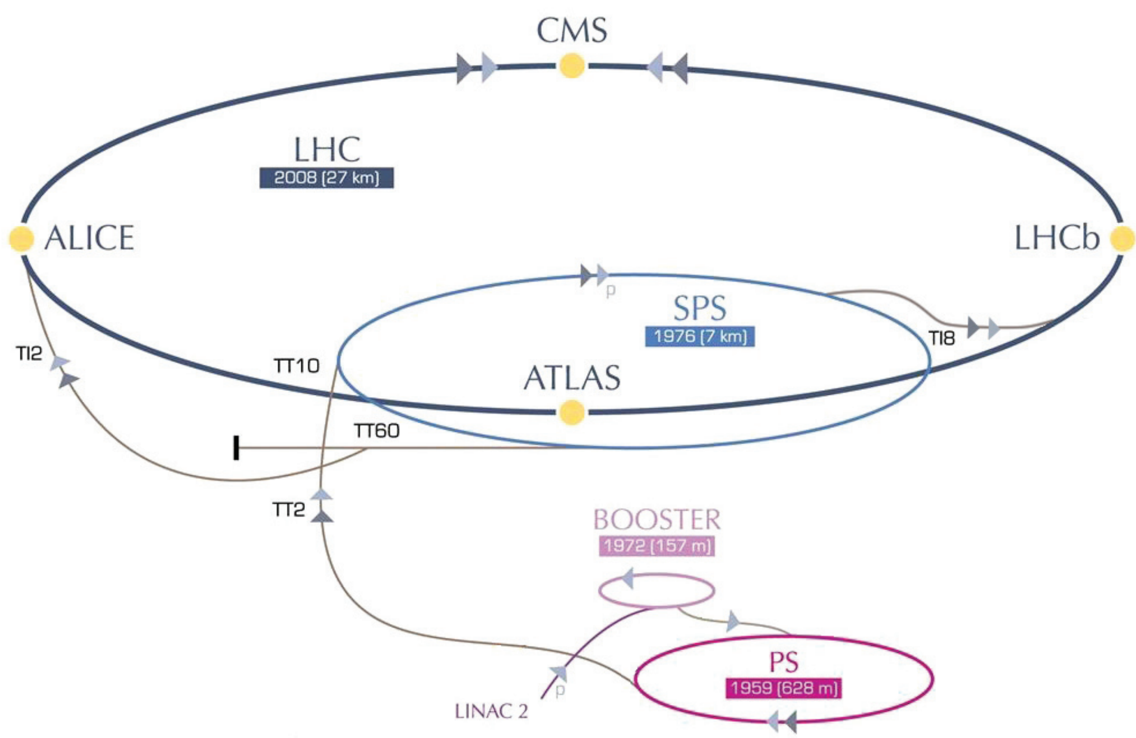


Figure 8 CERN acceleraor complex (simplified)

to fill a stack of CDs 20 km high every year! Even with this huge amount of data it is expected that it will take two to three years to accumulate enough data to produce reliable conclusions.

In the LHC's typical operating mode, two proton beams circulate in opposite directions. The protons are made by stripping the electrons from hydrogen. The protons start at LINAC-2, a linear accelerator that gives them a kinetic energy of 50 MeV. From LINAC-2 the protons pass through three accelerating rings: the Proton Synchrotron Booster, Proton Synchrotron, and Super Proton Synchrotron. At this point the protons are travelling at a speed of 0.999998c—this is before they have even entered the LHC! The protons are then injected into the LHC in two counter-circulating beams, and for the next 20 minutes they accelerate to their top speed of 0.999999991c.

Each proton beam consists of 2808 bunches that are a few centimetres long by a millimetre wide and contain about 100 billion protons apiece. As a bunch approaches a collision point, it gets squeezed into a 16 μm-wide beam by focussing magnets. It is then deflected by a kicking magnet to collide with a bunch of protons travelling in the opposite direction.

Protons are charged, so they respond to both electric and magnetic fields. Acceleration is achieved by exerting forces on the protons with radio waves. As the protons approach the speed of light they begin to display relativistic effects, making them increasingly difficult to steer. At the LHC the protons become so hard to steer that superconducting magnets with fields in excess of 8 T are used. The magnets have to be superconducting because it takes such a huge electric current (11 700 A) to generate this field that it would be impossible to do so with conventional conductors.

There are four large detectors attached to the LHC. Each detector records and examines the collisions in slightly different ways. The two largest detectors, ATLAS and CMS, are general-purpose detectors that are looking for the all kinds of new physics (including the Higgs boson). Another detector, ALICE, uses heavy ion collisions in an effort to study the behaviour of matter at very high temperatures and densities. LHCb is a specialized detector that is studying rare decays involving the bottom quark in an effort to test the Standard Model and to gain insight into the problem of matter-antimatter asymmetry: why there appears to be so much more matter than antimatter in the universe.

ATLAS:
A Toroidal LHC ApparatuS

CMS:
Compact Muon Solenoid

ALICE:
A Large Ion Collider Experiment

LHCb:
Large Hadron Collider beauty

Each detector has unique features but they are all trying to do the same basic task—measuring the position, speed, mass, charge, momentum, and energy of the particles created by collisions. To gather all this information, the detectors are built in layers that measure specific properties of the particles produced by the collision (except for the neutrinos).

Tracking devices, positioned both near the collision point and in the outer layers, record the trajectories of charged particles. Powerful magnetic fields bend the trajectories of charged particles as they pass through tracking chambers, revealing the charge and momentum of the particles. As the charged particles pass through the tracking chamber, electric signals are sent to a computer for analysis.

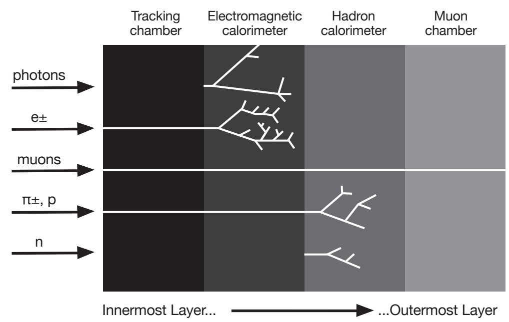


Figure 9 Layers of ATLAS detector

Calorimeters stop the particles and record the amount of energy deposited. Electromagnetic calorimeters (ECALs) measure particles like electrons, positrons, and photons. As these particles pass through an ECAL, they strike the atoms in the calorimeter and create an avalanche of lower-energy electrons, positrons, and photons that are detected by light-sensitive phototubes. Hadronic calorimeters (HCALs) stop the strongly interacting particles, such as protons, by having them collide with the atoms in a dense substance like iron. These collisions rip electrons out of the iron, and these electrons then radiate photons that in turn produce more electrons and positrons, in a cascading shower of particles that can be detected. A typical HCAL will alternate layers of iron with a less dense substance that will ionize or scintillate as the particles pass through, allowing the computer to track them.

Modern detectors produce copious amounts of data for each collision. Most of this data is filtered out by the computers in the detector hall. The LHC creates 600 million collisions every second, so the data analysis challenge is huge. One of the techniques being developed by CERN to cope with this challenge is called the Grid. The Grid is a huge global network of computing centres that share the workload using new data sharing and analysis techniques. CERN has already revolutionized the world through the development of the worldwide web. Who can predict what impact the Grid will have?

What Else Might the LHC Find?

At peak energy the LHC will be seven times more powerful than any previous particle accelerator. One goal of the LHC is to detect the Higgs boson, but at the energy levels the LHC reaches, there are some other very important phenomena that it will be able to explore:

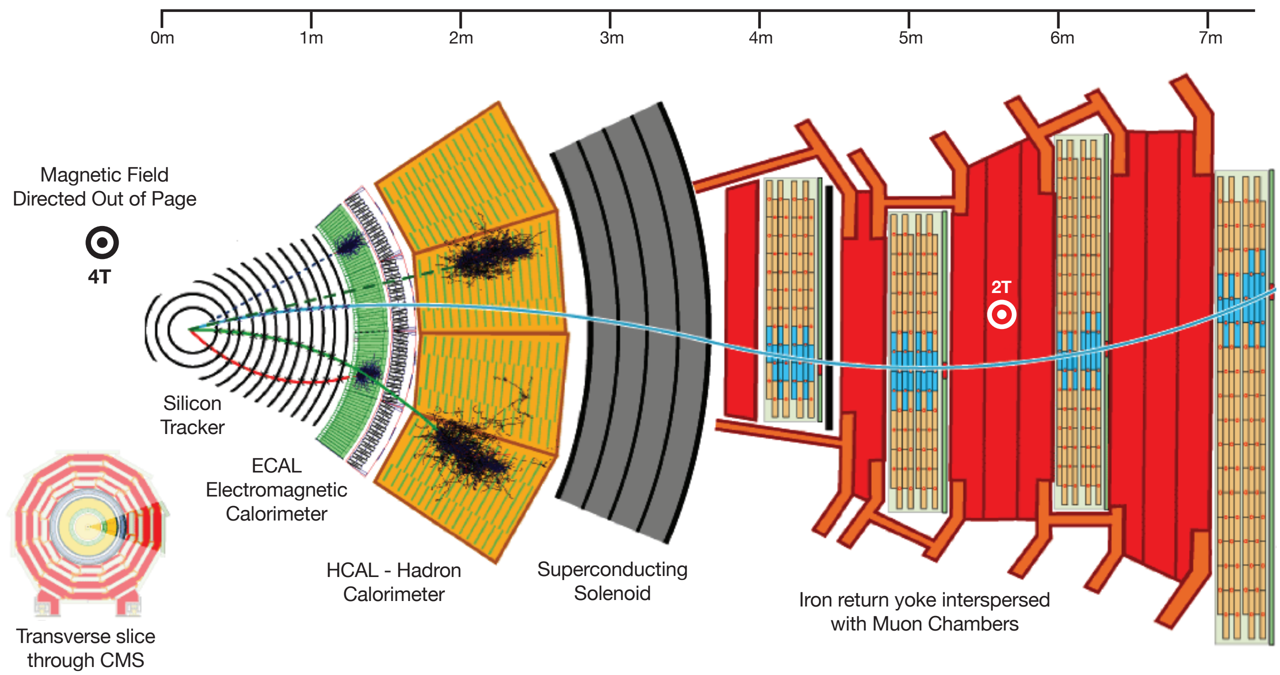


Figure 10 Layers of CMS detector

- Dark matter particles – Invisible particles that make up at least 90% of every galaxy in the universe
- Supersymmetry – A symmetry that predicts the existence of heavier partner particles for every particle in the Standard Model
- Matter-antimatter asymmetry – Why does the universe have more matter than antimatter?
- Quark-gluon plasma – An exotic state of matter that may shed light on the Big Bang

Dark Matter Particles

When astronomers look at the night sky, they see stars, planets, gas clouds, and other objects that emit light. Until a few decades ago, it was thought that these objects made up the bulk of the universe. However, recent observations, such as the rotation rates of galaxies, have revealed that light-emitting objects account for just a small fraction of the universe's contents. Physicists now think that most of the matter and energy in the universe is unseen. Ninety percent of the mass of every galaxy is thought to be made of an invisible substance called **dark matter**. The leading candidate for this dark matter is a new type of subatomic particle called a **weakly interacting massive particle (WIMP)**. Scientists are currently trying to directly detect WIMPs in a number of experiments. The LHC could potentially create and detect particles that would be good candidates for dark matter.

Supersymmetry

Supersymmetry proposes that each particle in the Standard Model has a partner particle with the same charge but different spin, and possibly with a much higher mass. For example, the electron would have a supersymmetric partner called a selectron that is spinless. The LHC should be able to detect the lowest-energy supersymmetric particles—if they exist. Note that some of these new particles could also fit the description for WIMPs and so supersymmetric theories might also shed light on the origin of dark matter.

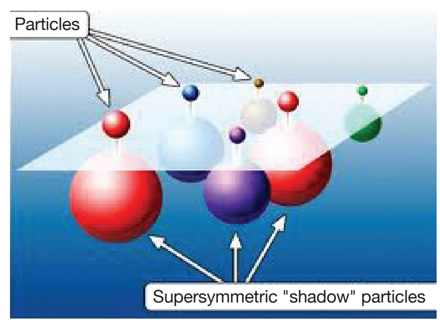


Figure 11 Schematic diagram of supersymmetric particles

Matter-Antimatter Asymmetry

Everything around us—buildings, trees, the Earth, and the entire solar system—is made of matter, not antimatter. From the perspective of fundamental physics, this is very puzzling. Matter and antimatter should have been created in equal amounts during Big Bang, but detailed observations and calculations show that there must have been an excess of matter particles. Why there is more matter than antimatter is an important open question in science today.
The LHCb detector will provide new insight into this problem by carefully observing reactions involving the b-quark that are slightly different for matter and antimatter.

Quark-Gluon Plasma

Ordinarily, quarks and gluons are bound inside the nuclei of atoms. But, in situations with extremely high temperatures or densities, there can be enough energy for them to be free. The gluons and quarks then move around freely in a "soup" called a **quark-gluon plasma**. According to current Big Bang theories, the universe went through a quark-gluon plasma stage before cooling to a point where the quarks and gluons became confined inside composite particles such as protons and neutrons. The LHC smashes lead ions together at such high energies that a quark-gluon plasma should be created. Physicists can then observe how matter behaved in the earliest stages of the universe.

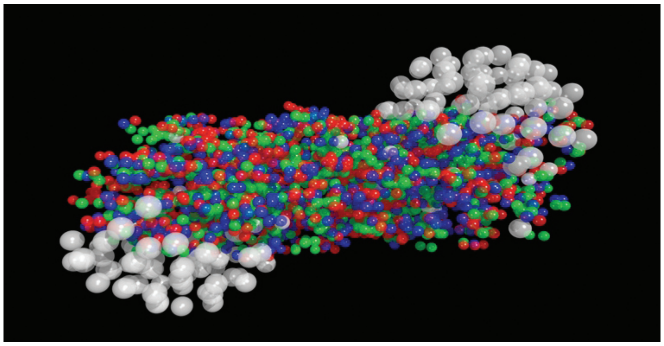


Figure 12 A lead-lead collision producing a quark-gluon plasma

In Summary

The Standard Model provides a very good description of matter and forces using a small number of fundamental particles. Scientists are aware of the limitations of this model, however, and are actively testing it so they can produce a better model. The Large Hadron Collider represents the latest test of the Standard Model. The LHC operates at such high energy that it is expected to exceed the limits of the Standard Model. New discoveries will undoubtedly be made. Results from the LHC will give us insight into why particles have mass, why the universe is made of matter, and even what the early universe was like. The LHC will move science forward to a new deeper understanding of the universe at the most fundamental level.

Further Reading

Facts and Mysteries in Elementary Particle Physics
by Martinus Veltman *(World Scientific, 2003)*

Understanding the Universe from Quarks to the Cosmos
by Don Lincoln *(World Scientific, 2004)*

The New Cosmic Onion
by Frank Close (Taylor & Francis, 2007)

Introduction to Elementary Particles
by David Griffiths *(Harper & Row, 1987)*

The Quantum World: Quantum Physics for Everyone
by Kenneth Ford *(Harvard Press, 2004)*

Appendix:
Particle Zoo Cards

p	**PROTON** **mass:** 938 MeV spin-½ Q = +1 S = 0 **discovered:** 1919
Σ^{*-}	**SIGMA STAR MINUS** **mass:** 1387 MeV spin-3/2 Q = -1 S = -1 **discovered:** 1960
π^0	**PION (PI ZERO)** **mass:** 135 MeV spin-0 Q = 0 S = 0 **discovered:** 1949
Δ^-	**DELTA MINUS** **mass:** 1232 MeV spin-3/2 Q = -1 S = 0 discovered: 1954
Ξ^0	**XI ZERO** **mass:** 1315 MeV spin-½ Q = 0 S = -2 **discovered:** 1959
Ξ^{*-}	**XI STAR MINUS** **mass:** 1535 MeV spin-3/2 Q = -1 S = -2 **discovered:** 1962
Σ^-	**SIGMA MINUS** **mass:** 1197 MeV spin-½ Q = -1 S = -1 **discovered:** 1953
K^0	**KAON (K ZERO)** **mass:** 498 MeV spin-0 Q = 0 S = +1 **discovered:** 1947
π^+	**PION (PI PLUS)** **mass:** 140 MeV spin-0 Q = +1 S = 0 **discovered:** 1947
Ξ^{*0}	**XI STAR ZERO** **mass:** 1532 MeV spin-3/2 Q = 0 S = -2 **discovered: 1962**
Σ^0	**SIGMA ZERO** **mass:** 1193 MeV spin-½ Q = 0 S = -1 **discovered:** 1956
n	**NEUTRON** **mass:** 940 MeV spin-½ Q = 0 S = 0 **discovered:** 1932
Σ^+	**SIGMA PLUS** **mass:** 1189 MeV spin-½ Q = +1 S = -1 **discovered:** 1953
K^-	**KAON (K MINUS)** **mass:** 494 MeV spin-0 Q = -1 S = -1 **discovered:** 1947
η	**ETA** **mass:** 548 MeV spin-0 Q = 0 S = 0 **discovered:** 1961

Appendix:
Particle Zoo Cards cont.

Ξ^-

XI MINUS
mass: 1322 MeV

spin-½
Q = -1
S = -2

discovered: 1952

Σ^{*-}

SIGMA STAR PLUS
mass: 1383 MeV

spin-3⁄2
Q = +1
S = -1

discovered: 1960

π^-

PION (PI MINUS)
mass: 140 MeV

spin-0
Q = -1
S = 0

discovered: 1947

Δ^0

DELTA ZERO
mass: 1231 MeV

spin-3⁄2
Q = 0
S = 0

discovered: 1954

$\overline{K}^0$

KAON (KBAR ZERO)
mass: 498 MeV

spin-0
Q = 0
S = -1

discovered: 1947

Δ^+

DELTA PLUS
mass: 1235 MeV

spin-3⁄2
Q = +1
S = 0

discovered: 1954

K^+

KAON (K PLUS)
mass: 494 MeV

spin-0
Q = +1
S = +1

discovered: 1947

Λ

LAMBDA
mass: 1116 MeV

spin-½
Q = 0
S = -1

discovered: 1951

Σ^{*0}

SIGMA STAR ZERO
mass: 1384 MeV

spin-3⁄2
Q = 0
S = -1

discovered: 1960

Δ^{++}

DELTA DOUBLE PLUS
mass: 1231 MeV

spin-3⁄2
Q = +2
S = 0

discovered: 1954

Ω^-

OMEGA MINUS
mass: 1672 MeV

spin-3⁄2
Q = -1
S = -3

discovered: 1964

η'

ETA PRIME
mass: 958 MeV

spin-0
Q = 0
S = 0

discovered: 1964

NOBEL PRIZE
Murray Gell-Mann