

Searching for the Building Blocks of Matter

Building Blocks of Matter

The Smallest Scales

Physicists at Fermilab are searching for the smallest building blocks of matter and determining how they interact with one another.

Building Blocks of a Dew Drop

A dew drop is made up of many molecules of water (10^{21} or a billion trillion). Each molecule is made of an oxygen atom and two hydrogen atoms (H_2O). At the start of the 20th century, atoms were the smallest known building blocks of matter.

Smaller than the Atom

Each atom consists of a nucleus surrounded by electrons. Electrons are leptons that are bound to the nucleus by photons, which are bosons. The nucleus of a hydrogen atom is just a single proton. Protons consist of three quarks. In the proton, gluons hold the quarks together just as photons hold the electron to the nucleus in the atom.

Quarks, Leptons, and Bosons

Physicists currently believe there are three types of basic building blocks of matter: quarks, leptons, and bosons. Quarks and leptons make up everyday matter, which is held together by bosons. Each boson is associated with a force. The photon, the unit of the electromagnetic force, holds the electron to the nucleus in the atom. The way these particles combine dictates the structure of matter.

Cosmic Rays

Early particle physicists studied cosmic rays, a naturally occurring stream of high energy particles from outer space. Cosmic rays were the first source of unstable, short-lived particles. Later, physicists discovered that most of the building blocks of matter live for so short a time that we do not see them in everyday matter. One of the unstable particles they found was the muon (μ), a lepton.

A Strange New Particle: The Lambda

One particle discovered in cosmic rays was the lambda, identified by particle tracks forming the Greek symbol λ in the cloud chamber. The lambda has no electric charge so it leaves no trace until it decays into one positively and one negatively charged particle. They leave a λ pattern, as seen on the left. Lambdas were the first of a group of particles called “Strange” because they decayed more slowly than expected.

Cosmic Ray Detector

In this particle detector, you can see cosmic rays as they pass through a bundle of scintillating fibers. You see the light produced in the fiber by the cosmic rays.

Accelerators and the Particle Zoo

New technology in the early 1960s allowed physicists to build accelerators to create many new particles by shooting energetic particles at targets. These particles were short-lived and decayed quickly into offspring particles. With even higher energy accelerators, physicists found an exotic array of new particles. They developed theories to explain how all the particles in this “Particle Zoo” could be made from a few basic building blocks.

Accelerators

Physicists used accelerators to discover more and more particles in the “Particle Zoo.” An example is the 88-inch cyclotron at Lawrence Berkeley Laboratory, completed in 1961.

The Particle Zoo

These graphs from physics papers of the early 1960s represent the discovery of many new particles. Each peak indicates a possible new particle.

The Quark Model

In 1964, physicists proposed quarks as the building blocks of many of the particles in the “Particle Zoo.” In this theory all everyday objects, such as our bodies and the homes we live in, could be made from three basic particles: up and down quarks and electrons. At that time the Quark Model was one of many possible explanations and was not accepted for over a decade.

The Bottom Quark

Discovery of a New Quark at Fermilab

New accelerators with higher energies smashed beams of particles into fixed targets to produce short-lived particles with high masses. One of these particles, the ψ , had properties that implied that it could not be made of the known four quarks: up, down, strange and charm. Physicists concluded that the ψ was made of a new quark, the bottom quark, and its antiquark. Leon Lederman, the second director of Fermilab, headed this 1977 experiment. Today there are accelerators dedicated to the production of ψ 's and studies of the bottom quark.

Building Blocks in 1977

By early 1977, two complete generations of particles had been discovered. With the discovery of the ψ that summer, physicists saw the possibility of a third generation of particles.

The Experiment

Physicists built a large apparatus to detect muon pairs (μ^+ , μ^-), the decay products of the short-lived particles they were trying to discover. Those particles existed for such a short time that the detector could not see them. The longer-lived muon pairs were much easier to detect.

The Apparatus

Physicists used the apparatus in the photograph to detect the muon pairs. The drawing to the left shows the layers of materials used to detect the particles. The colored lines highlight the target and the paths of the proton beam and the resulting muon pair. The inset depicts what happened when the beam hit the target and produced the ψ (the bound bottom and antibottom pair) that decayed into the muon pair.

Interpreting the Results

If the muon pairs were produced in the decay of a new short-lived particle, physicists could calculate the mass of the new particle by measuring the energies and directions of the muons. In a plot of the mass found from all muon pairs, the particle would appear as a bump at a particular mass. Other muon pairs unrelated to the new particle, the “background,” would form a smooth curve on this plot.

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Background

Backgrounds to observations are a general problem in science. Think of trying to hear a friend speak in a noisy place. You use your expectation of how your friend's voice should sound to separate the voice from background noise.

To find the ψ in the noisy background, physicists used their expectation that a new particle would appear as a bump in the plot of the mass of all muon pairs.

Plots of Actual Data

The initial data, shown on the left, had a bump at a mass of about 9.5 GeV. It was plotted with and without subtracting the background. The bump indicated to the experimenters the presence of a new particle which they called the ψ .

On the right is a plot of later data without the background. The three bumps revealed a whole family of ψ 's, particles made from one bottom and one antibottom quark.

On to Top: the Accelerator

Implications of the b Quark Discovery

Physicists grouped quarks in pairs (up and down, charm and strange). When they discovered the bottom quark, the search was on for its partner. They believed superconductivity and colliding particle beams would provide the high energies required to produce the top quark.

Bottom to Top

The quarks come in three generations with the mass increasing with each generation. Physicists had not seen evidence of the top quark in existing accelerators, but they knew that if it were much heavier than the bottom quark, they would need far more energetic collisions to produce it.

The Need for a Collider

The fixed-target method used to discover the bottom quark could not produce energies high enough to make the top quark. Slamming highly energetic protons against a stationary atom transferred most of the energy into the motion of the newly created particles. By making the beams of energetic protons and antiprotons collide, more of their energy could go into creating new, more massive particles than into their motion.

Accelerator Fundamentals

To understand the accelerator improvements necessary to discover the top quark, it is important to understand how an accelerator works.

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A Basic Accelerator

The Fermilab accelerator has two basic parts: the magnets and the RF cavities. The magnets keep charged particles moving in a circular path. The RF cavities pump energy into the particles each time they pass through the cavities. Particles complete many laps around the accelerator ring and receive a small boost in energy with every lap. Examples of a Tevatron magnet and an RF cavity for the Linac are on the exhibit floor.

RF Cavity (Particle Pusher)

RF stands for Radio Frequency. The Tevatron accelerator uses electric fields that alternate at 53 MHz (million cycles per second), half the frequency of FM radio signals. The electric field pushes the particles at just the right time, similar to the way a parent pushes a child on a swing.

Magnets (Particle Benders)

The path of charged particles bends in a magnetic field. A ring of electromagnets sends the particle beams in a circle. As the particles get more energetic, we need stronger electromagnets to keep them in their circular path. To build a more powerful accelerator would have required putting so much current into the existing electromagnets they might melt. A magnet technology had to be developed based on superconductivity.

Antiprotons

Another key ingredient in building a particle accelerator powerful enough to discover the top quark was the production and acceleration of antiprotons to collide with high energy protons.

Antimatter

For every quark and lepton, physicists have discovered a corresponding antiparticle. These particles are referred to as antimatter. Antimatter was first observed in decays of radioactive nuclei. Antiprotons are composed of two antiup quarks and one antidown quark. Antihydrogen (an antiproton and a positron) was created at the European laboratory, CERN, and at Fermilab in 1996.

What's Special about Antimatter?

You get more energy for making new particles by colliding the protons and antiprotons head on. At the Tevatron's energy by colliding the antiquarks in the antiprotons with the quarks in the protons, we make about ten times more top and anti-top quarks than we would if we just used the quarks in protons.

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Collecting Antiprotons

Antiprotons are produced, although very rarely, in collisions of high-energy protons on a target. A lithium lens focuses the antiprotons into a beam. The beam goes into the Accumulator, which stores large numbers of antiprotons until they are needed. Magnets bend the antiprotons in a circular path.

Accelerating Antiprotons

Because antiprotons have the opposite electric charge of protons, they bend in the opposite direction as they move through a magnetic field. This means that antiprotons can circulate in the same accelerator as the protons, but in the opposite direction. This is exactly what is needed to make protons and antiprotons collide. It's two accelerators for the price of one!

Collisions

As they travel around the accelerator ring, the proton and antiproton beams are slightly separated. At points where physicists observe collisions, the two beams are made to cross. Special magnets focus the beams down to as small a size as possible to maximize the chances of a collision.

Superconducting Magnets

To build the superconducting magnets needed to keep the protons and antiprotons moving in a circular path at high energies, Fermilab had to develop two critical technologies: a reliable superconducting cable for the manufacturing the magnets and the process for maintaining superconducting temperatures in the magnets.

Superconductivity

Electricity flows with relative ease through metals, but there is small resistance. In 1911, H. K. Onnes discovered that this resistance disappears entirely at extremely low temperatures. Niobium, for example, superconducts at 9 kelvins (- 443° F). These data, from Onnes, show the resistance of mercury in ohms versus temperature. The resistance drops to zero ohms at about 4.2 kelvins, nearly absolute zero.

Cooling

To cool 135,000 pounds of wire down to superconducting temperature is no small job. Heat flows from the magnet cable, shown in red on the diagram, boiling some of the helium. The gaseous helium is then re-liquefied in the central helium liquefier. You can see the central helium liquefier building and the colorful helium tank farm from the east window.

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Fabrication

The manufacture of the Tevatron magnets required more than 135,000 pounds of niobium-titanium alloy; at the project's start in 1974, the worldwide annual production was a few hundred pounds. The manufacturing technology and capacity developed in response to this demand was later used to help make possible and commercially viable a new medical diagnostic method, magnetic resonance imaging, MRI.

On to Top: Experiments

Searching for Top at the Tevatron

In the Tevatron protons and antiprotons collide in a flash of energy. Other particles condense out that energy. Physicists use detectors to “see” these particles, including the top quark.

Needles in a Haystack

The search for top is akin to looking for needles in a haystack. Out of every trillion proton-antiproton collisions, about ten top-antitop quark pairs are produced. Physicists must search out these desirable events.

Top's Family Tree

Physicists identify a top quark by looking at its descendants. A top quark decays almost immediately into a bottom quark and a W boson. The W, in turn, decays immediately either into two quarks or into a lepton and a neutrino. Quarks and gluons appear as a narrow spray of particles called a jet. When physicists observe the second and third generations in top's family tree, they can infer that top has been created.

Detectors: Seeing Particles

Detectors are the tools that particle physicists use to “see” the products of a collision. Each collision seen by the detector is called an event. Two basic types of detectors observe the particles in an event: tracking detectors and calorimeters. Tracking detectors record the path of a particle and calorimeters absorb particles and measure their energy. Physicists assemble these two types of detectors in layers around the collision point as shown in the diagram of the DØ Detector, one of two detectors used in the discovery of the top quark.

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Detector

Look at the diagram of the DØ detector, one of two detectors used in the discovery of the top quark.

Identifying Particles

In calorimeters different particles travel different distances before being absorbed. Photons and electrons lose energy very quickly and stop in the first layers of a calorimeter. Muons, by contrast, can pass through many feet of steel before losing their energy. Jets from quarks have an intermediate range. Physicists use the distance a particle travels in a calorimeter to identify the particle.

Tracking

Tracking detectors record the path of a particle. When particles pass through material, they leave a trail which can be picked up as an electrical signal in a wire grid. Each signal represents a point on a path, and connecting these points traces out the full path. By measuring the curvature of the path of a charged particle in a magnetic field, physicists can calculate the energy of a particle. Take a look at the CDF SVX and DØ central wire trackers in the exhibit area.

Calorimetry

Calorimetric (energy-measuring) detectors absorb the energy of a particle. As the particle enters a slab of dense material, it will form a shower of secondary particles. The more energetic the incident particle the deeper the shower will extend into the slab. By layering the slab (absorber) with a detector, physicists measure the energy of the particle. In the CDF detector, the energy is converted into light which can be observed by light-sensitive detectors. The amount of light observed measures the energy of the particle. Absorbing high-energy particles requires a lot of material, typically many feet of dense material. The calorimeter surrounds the point of interaction in a collider detector.

Electronics and Computing

Particle physicists use sophisticated electronics to convert detector information into digital signals and use powerful computers to process this information. With over several million interactions per second at the Tevatron, physicists need all the help they can get!

Amplification and Digitization

Electrical signals produced by a detector must be amplified before being transmitted outside the detector or they will be lost. The amplified signal is digitized, converted into a format that can be understood by computers. The electronics required for these steps is highly specialized and complex, often requiring custom chips, developed by a collaboration of physicists, electrical engineers, and outside corporations.

Selection and Collection

Physicists can store only one in 100,000 collisions at the Tevatron for later analysis so they rely on specialized hardware and software called "triggers" to select the most interesting events. Even with this enormous reduction, the CDF and DØ experiments plan to record about 20 megabytes per second which must be shipped over computer networks for storage.

Storage

The detector data is written to permanent storage for later analysis. Physicists write their data onto commercial, high capacity, magnetic tapes similar to the tapes used in portable video cameras. In the experimental run that discovered the top quark, each experiment recorded 40 terabytes of data on 8000 tapes, a stack of tapes 500 feet tall, over twice the height of Wilson Hall.

Computing

Data analysis is done by computers. Special programs find patterns in the data that match those expected in events of interest. The events are complex, and physicists use a lot of computing power to do the job. But instead of one big computer, physicists use a large number of small computers, networked together, each of which analyzes a small fraction of the data. Today's most powerful computer "farms" use hundreds of desktop PCs.

Discovery of Top

In 1995, physicists from the CDF and DØ collaborations discovered the top quark. Each experiment had observed approximately ten pairs of top-antitop quarks from the proton-antiproton collisions, enough events to state with certainty that they were not products from other sources which might be confused with top.

The top quark had a mass much larger than physicists had expected when the bottom quark was discovered. At the end of the search, top was determined to have a mass similar to that of a gold atom—an enormous mass for a fundamental particle.

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Experimental Teams

At Fermilab's two collider detectors, more than 900 scientists from 21 states and 12 foreign countries worked in partnership to find the top quark.

Identifying Top

Physicists recognize the particles produced in proton-antiproton collisions by their electronic signatures, shown graphically by computers as “lego” plots. In the plot below from the DØ experiment, the height of each object represents its energy after a particle collision. The object's color represents the layer(s) of the calorimeter where it was detected and a clue to its identity. By looking at the objects, physicists can reconstruct what happened in the kind of collisions that produces a top quark. On the left is an artist's rendering of what took place to create the lego plot on the bottom right.

What Have We Learned From Top

Physicists believe they have found all the quarks. However, the discovery of the top quark has led to more questions because it is so much heavier than the other quarks. Why is top so massive? Why does any fundamental particle have mass? Physicists believe the answer to these questions is connected with the interactions that govern the behavior of particles.

By the Way . . .

Spinoffs

The quest for knowledge drives Fermilab research. Building a collider and finding particles is like building a telescope and finding new galaxies, we do it for the joy of discovery. However, we know from experience that the impact of our new understanding can have profound consequences for the way we will live. For example, our present-day electronic world would be utterly impossible without the discovery of the electron a century ago. More recently the MRI (Magnetic Resonance Imaging) technology relied on the development of superconducting magnets for the Tevatron.

Synchrotron Radiation

X-rays, one side effect of synchrotrons, are an indispensable tool with applications in many fields—for example, in the production of integrated circuits and in the study of the gene responsible for Lou Gehrig's disease and enzymes involved in replication of the AIDS virus.

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Birthplace of the Web

What started as a tool for scientists at high-energy physics laboratories to collaborate with colleagues world-wide may ultimately count among high-energy physics' most significant contribution to modern technology.

Medical Applications

Particle physics research has contributed to Computer-Aided Tomography (CAT Scan), Magnetic Resonance Imaging (MRI), Positron Emission Tomography (PET scan), and cancer treatment. At Fermilab, patients receive cancer treatment from the Linac; at Loma Linda University Medical Center, over 100 patients each day receive treatment from a synchrotron designed and built at Fermilab.

Superconductivity

Building Fermilab's Tevatron, the world's first superconducting synchrotron, helped lay the foundation for a new industry—superconducting technology. This power-conserving technology has applications in the fields of energy, transportation, medicine, the environment and electronics. Pictured is the niobium titanium and copper braid used as the superconducting coil in the Tevatron.

The Search Goes On

Undiscovered

Fermilab continues to advance knowledge of the basic building blocks of matter and how they interact to make the universe what it is.

Feedback Loop

A theory describes what experiments see and makes predictions for future experiments. New experiments test the predictions which are sometimes confirmed, other times not. There can be surprises! Theorists use that information to refine their theories.

Why is there Mass?

Stars, people, and insects all have mass because the particles they are made of have mass. But, not all types of particles have mass. Why do some have mass and others don't? Why does a top quark have about 40 times as much mass as a bottom quark? One theory for mass requires a new heavy boson, called the Higgs, which has yet to be discovered. With the new Main Injector, the Tevatron will be the world's most powerful tool to search for the Higgs.

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Unification Theories

Electricity and magnetism are different manifestations of a unified "electromagnetic" force. Electromagnetism, gravity, and the nuclear forces may be parts of a single unified force or interaction. Grand Unification and Superstring theories attempt to describe this unified force and make predictions which can be tested with the Tevatron.

Matter and Antimatter

Why is the universe made of matter and not equal parts of matter and antimatter? The reason is not clear, but we know that there are some small differences between matter and antimatter. Two Fermilab experiments, KTeV and HyperCP (inset), use the Tevatron beam to study these differences in the decay of strange particles made up of strange quarks.

Experiments are also looking for similar evidence in the decays of particles made up of bottom quarks. The CDF experiment has found an indication of a matter-antimatter asymmetry in B meson decays, and the CDF and DØ experiments will be able to make detailed studies in the next Tevatron Collider run. New experiments are also proposed to look for more clues.

Better and Better Tools

To learn more about the top quark and to look for new particles, physicists develop new tools—new accelerators and new detectors—with capabilities beyond those now available.

Accelerator Upgrades

To increase the number of proton-antiproton collisions, Fermilab has constructed two new accelerators. The Main Injector and Recycler will come into operation in 1999. Other improvements will raise the energy of the Tevatron and increase the number of antiprotons produced and stored.

Fermilab Participation in CERN

Opening new horizons requires machines of much higher energy. Physicists from across the U.S., including Fermilab staff, are part of the Large Hadron Collider (LHC) project at CERN, a multinational laboratory near Geneva, Switzerland. The LHC will have seven times the energy of the Tevatron.

Detector Upgrades

Major improvements in the CDF (right) and DØ (left) detectors will handle the vastly increased data rates that the accelerator will produce.

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A Collider Beyond the LHC

Fermilab scientists are working on designs for new machines, more powerful microscopes, that will explore the energy frontier further. A Very Large Hadron Collider (VLHC) would have seven times the energy of the LHC, fifty times the energy of the Tevatron. A muon accelerator would collide beams of muons, electron's heavy cousins. These two machines explore inner space in complementary ways.

The Cosmos

Particle physics discoveries carry major implications for understanding the present structure and early history of the physical universe.

High-Energy Cosmic Rays

Fermilab scientists participate in the Pierre Auger Observatory Project which will study the particles striking the earth from space at energies far greater than any accelerator can achieve. These cosmic rays will be measured with an array of 1600 detectors such as the one pictured.

Mapping the Universe

Fermilab collaborates in the Sloan Digital Sky Survey which will create a map of the universe of unprecedented detail. The distribution of galaxies in space today tells us about the early universe. Fermilab contributes expertise in detector design and in handling large amounts of data gathered for this map.