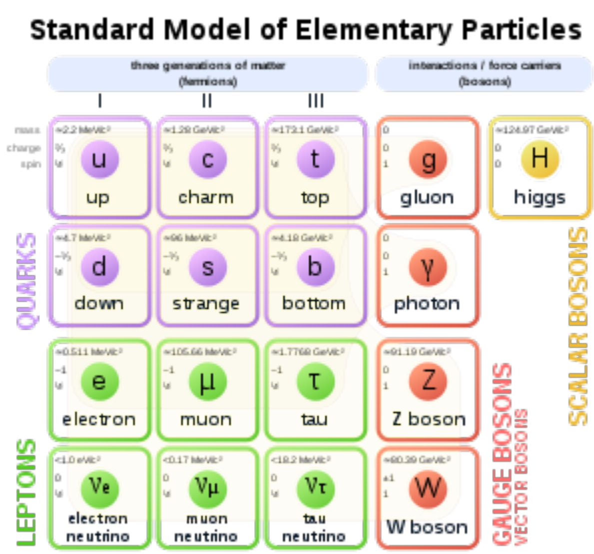
Discovery of the Top Quark

Abstract: The quark is a basic particle that participates in strong interactions, and is also the basic unit of matter. The quarks combine with each other to form a composite particle called a hadron. The most stable of hadrons are protons and neutrons, which are the units that make up the nucleus. Due to a phenomenon called "quark confinement", quarks cannot be directly observed or separated, and can only be found in hadrons. For this reason, most of what we know about quarks comes from indirect observations of hadrons. Top Quark is one of the elementary particles, belongs to the third generation of quarks in fermions, and is the heaviest elementary particle known, with a mass of 173.1 ± 0.6 GeV (equivalent to the mass of tungsten atoms), a charge of +2/3, and a very short life span. 1E-24s is much smaller than the time scale of strong interaction, so it will decay before forming hadrons (other quarks will have hadrons). On April 25, 1994, the CDF experimental group of the Fermi experiment in the United States published evidence of the existence of top quarks. After collecting more examples, the two experimental groups of CDF and DØ announced the discovery of top quarks in early 1995. This is The last quark found in the standard model of particle physics.

The Top Quark in the Standard Model

What kind of particle is the top quark? The top quark has a mass of 173.3 billion electron volts (173.3 GeV), which is about 175 times heavier than the hydrogen nucleus, almost the same weight as the tungsten nucleus, but its diameter is below one ten thousandth of the tungsten nucleus; the top quark is even heavier than the second The fermion-bottom quark-weighs nearly 40 times. Its huge mass is one of the hot spots of concern in particle physics; secondly, the life of the top quark is very short, only 5 × 10-25 seconds, so even the fastest light in such a short time has advanced by only one nucleus diameter The distance of 1/7 is so short that even the top quark does not even have time to react with other quarks, it will decay into other particles, and the other quarks have enough life to combine with each other to form hadrons. The top quark is the only quark that decays before forming hadrons, thus making it possible for us to experimentally study "naked" quarks.

These unique properties make top quark very important in particle physics. So, why these properties of the top quark are so important, we must start with the standard model. The standard model is a theory developed to describe the classification and interaction of elementary particles since the 1960s. The main point of view is that there are 17 kinds of the smallest inseparable particles (basic particles) that make up a substance (if considering the difference between fermions ’pros and cons, quarks, and the color charge carried by gluons, there are 61 kinds of basic particles) This includes three generations of fermions with a spin of 1/2, and each generation of fermions has two quarks, a lepton and the corresponding neutrino; the four vector bosons with a spin of 1 propagating the force , That is, photons that propagate electromagnetic interaction forces, W and Z particles that propagate weak interaction forces, and gluons that propagate strong interaction forces; and God particles that give the basic particles a mass of 0 spin—Higgs scalar glass Dice.



There are strong interactions between these elementary particles that follow quantum chromodynamics (QCD); electromagnetic interactions that follow quantum electrodynamics (QED); and weak interactions that follow V-A weak interaction theory. The gravitational interaction between these particles due to their mass is not considered by the standard model because their strength is much smaller than the above three forces. This set of theories explains almost all the phenomena of high-energy particles that we observe in the microscopic field, and their theoretical predictions exactly match the experimental observations. Therefore, the standard model is the most successful model in particle physics. However, the standard model cannot explain the dark matter and dark energy observed in astronomy. It cannot explain the neutrino mass problem and the natural problems in the model. It also makes us believe that there must be new physics outside the standard model. That is, we continue to increase the accuracy of experimental measurements and continue to explore the driving force behind all aspects of particle physics.

Properties

Quarks are attached together in two configurations to form hadrons. One configuration is two quarks attached together, another configuration is three quarks attached together. Two quarks together constitute a meson, and three quarks together constitute a baryon. Since quarks have positive and negative quarks, the mesons and baryons are composed of positive and negative particles. Quarks in hadrons also have quantum energy levels. It can be excited to enter a higher level by absorbing energy. Excited hadrons look like other hadrons, so many particles previously thought to be independent are considered as excited states of quark bonding.

In order to explain all known hadrons, it is necessary to imagine more than one quark. In the early 1970s, people imagined three "flavored" quarks. These three kinds of quarks are whimsically called "upper", "lower", and "odd". Later, there were more hadrons, and a fourth kind of quark was added, namely the "can" quark. In 1973, Kobayashi Makoto and Yichuan Minying predicted the existence of top and bottom quarks when explaining the symmetry breaking of CP, and thus won the 2008 Nobel Prize in Physics.

The basic presupposition of quark theory is that quark itself is a truly unified elementary particle, a point-like object with no internal structure. In this respect, quarks are quite like lepton, because lepton is not composed of quark, they seem to be elementary particles themselves. In fact, there is a natural correspondence between quark and lepton, giving people an unexpected opportunity to gain insight into the operation of nature. The systematic connection between quark and lepton is shown in Table 1 below. The right column of the table is the taste of quark, and the left is all known lepton. Remember, Lepton feels weak, while Quark feels strong. Another difference between lepton and quark is that lepton is either uncharged or only has 1 unit of charge; quark has 1/3 or 2/3 unit charge.

Despite the difference between Lepton and Quark, there is a deep mathematical symmetry between the two, so that Lepton and Quark have a layer-by-layer correspondence in the above chart. There are only four types of particles on the first level: upper and lower quarks, electrons, and electron neutrinos. Strangely, all ordinary matter is composed of these four particles. Both protons and neutrons are composed of three quarks, and electrons are just a subatomic particle that constitutes matter. Neutrinos just ran into the universe and did not participate in the construction of matter at all.

Subatomic particles can be divided into two categories: lepton and quark. Quark has not been found to exist alone, but together in two or three. Quark's charge is fractional. All ordinary matter is made up of particles at level I. Level II and Level III seem to be simple copies of Level I, in which the particles are highly unstable. Although the theoretical model does not rule out the existence of a new level, the experimental study of the decay of Z particles and the generation of Higgs particles basically ruled out the possibility of more levels.

The particles at the next level seem to be the first level of replication, but only heavier. The particles at the second level are extremely unstable (with the exception of neutrinos), and the various particles they form quickly decay into particles at level I. The same goes for particles at the third level.

The question then must arise: What is the use of particles other than level I? Why does nature need them? What role did they play in forming the universe? Are they redundant? Or are they part of a mysterious process that is not yet fully understood? The more puzzling question is, with the advent of particle accelerators with higher and higher energies in the future, are there only particles at these three levels? Will you find more or infinite levels?

There is also a complicated situation that deepens our confusion. In order to avoid conflict with one of the fundamental principles of quantum physics, we must assume that each flavor of quark actually has three different forms, known as "colors." Any given quark must be seen as a superposition of some kind of multi-layer electroplating (metaphor), constantly flashing (another metaphor) the colors of "red", "green", and "blue". In this way, everything looks like a messy zoo again. However, the way to clean up the situation is at hand. Symmetry is here to save the drive. However, this time the symmetry has a more subtle and more profound normative symmetry.

In order to understand the canonical symmetry, we have to talk about another big clue to the analysis of the basic structure of matter: force. No matter how complicated the particle zoo is, there seem to be only four basic forces: gravitation, electromagnetic force (which is widely known for its close relationship with daily life), weak force, and strong force. The nuclear force between neutrons and protons, of course, cannot be a fundamental force, because neutrons and protons are themselves complexes rather than elementary particles. When two protons attract each other, what we actually see is the resultant force of the interaction of the six quarks.

The force between quarks is the basic force. Similar to the description of electromagnetic fields, canonical symmetry can be used to describe the strong interaction between quarks, and the color of quarks is equivalent to electric charges. The photon counterpart is the so-called "gluon", whose function is to continuously bounce back and forth between quarks, like messengers, to glue quarks together. Physicists imitate electrodynamics and call this force field theory produced by "color" as chromatic dynamics. The effect of color dynamics is more complicated than that of electromagnetic forces. There are two reasons. First, quarks have three colors, but there is only one type of charge, so the eight different gluons correspond to one type of photon. Second, gluons also have colors, so they also have strong interactions with each other, and photons are not charged and are so irrelevant to each other.

History of discovery of top quark

The earliest prophecies about the existence of top quarks were Makoto Kobayashi and Toshihide Maskawa. In order to explain the phenomenon of CP destruction observed in the decay of K mesons, they proposed the CKM matrix theory and predicted the existence of the third-generation quarks—top and bottom quarks. However, this theory cannot predict the mass of the third-generation quarks, and it is not clear in which energy range they should be found. Four years later, the bottom quark was discovered in the Fermi laboratory, making people more convinced that the top quark exists. Many people are optimistic that the top quark will be discovered soon. In fact, due to its huge mass, the top quark is hidden for a long time outside the energy range that can be achieved by particle physics experiments. The search for the top quark on SLAC, DESY and CERN's SPS all ended in failure. Until 1995, 22 years later, Tevatron finally captured the accurate signal of the top quark. Kobayashi Makoto and Yichuan Minying also shared the 2008 Nobel Prize in Physics for predicting the work of the third-generation quark. However, this is not the end of finding the top quark story.

In the above process of discovering top quarks, top quarks are generated in pairs by strong interaction forces, while the standard model also predicts the process of top quarks being generated by weak interaction forces, that is, the process of a single top quark with other particles. The search continued until now. There are three generation modes for single-top quarks, namely t-mode, s-mode and tW concomitant generation mode. All three modes can verify whether the top quark participates in weak interaction and directly measure the matrix element | Vtb | in CKM matrix theory, thus further verifying the theoretical work of winning the Nobel Prize. The significant difference between the production of any single-quark model and the prediction of the standard model will indicate the existence of new physics. Obviously, the process of finding single-top quarks generated by weak forces is not easy. The strength of weak interactions is about 6 orders of magnitude smaller than the strength of strong interactions. The top quarks generated by weak interactions are stronger than strong interactions. The top quarks produced are rare.

It was not until 2009 that the t-pattern produced by a single top quark was discovered on Tevatron. But the roads of the other two modes are still tortuous. Greater hope is placed on the Large Hadron Collider, which began taking data in 2010. By 2012, the evidence of tW mode was observed on the Large Hadron Collider and confirmed in 2014. At the same time, Tevatron also announced the confirmation of the generation of the single-top quark s-mode after it ceased operation for 2 years. In June 2014, the American Physical Society published a related opinion article detailing the discovery process of the single-top quark. So far, the three modes produced by the top quark through the weak interaction force have all been confirmed. In the process of discovering each mode of top quark and single top quark, in addition to the final discovery of the s-mode is the result of combining CDF and D0, there are 2 different experimental release results for other discoveries, such as top quark and t -The mode was independently observed by the CDF experiment and D0 experiment on Tevatron; the tW mode was independently observed by the ATLAS experiment and CMS experiment on the Large Hadron Collider, respectively. There is a strong competitive relationship between multiple experiments with the same physical target on the same collider, making everyone in each experiment do their best. At the same time, because the two experiments are completely independent, they can verify each other's results, making the physical results issued by them more credible.

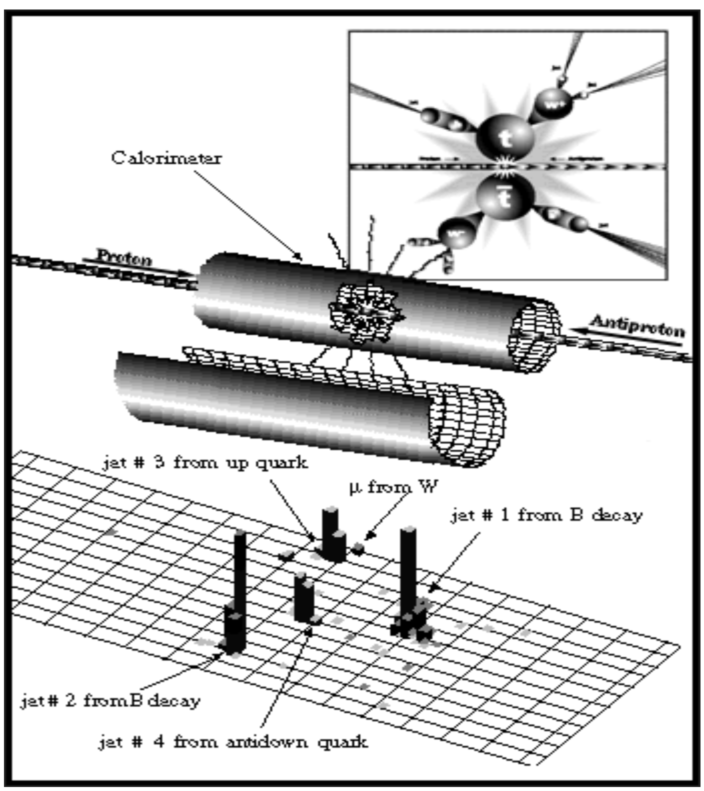
Assumptions and Experiment

Looking for the last kind of quark is the direction of the efforts of particle physicists in 19 years. Only by confirming the existence of the top quark can the standard model of particle physics be verified. The quality of the top quark exceeded the speculation of scientists, so Japan's TRISTAN, Germany's DESY, the United States' SLAC and the European Nuclear

Center's SPS failed to find it. The mass of the top quark is about 200 times the mass of the proton. According to the relativistic mass-to-energy conversion formula, the top quark is produced by the collision of protons, and the proton must be moved at a very high speed. The faster the speed and the higher the energy, the greater the possibility of generating top quarks at the moment of collision.

Fermilab's Tevatron accelerator has a circumference of 6.3km and uses 1,000 superconducting magnets to accelerate protons and antiprotons to an energy of 900 billion electron volts each, and then collide, with an average of 1 trillion collisions. One top quark may be observed. After the top quark appeared, "immediately" disappeared. The theory predicts that after the appearance of the top quark, it will decay into other particles in 1 × 10-24s.

In January 1994, the DØ experimental group published the limit of the top quark mass above 131GeV, and then in April the CDF experimental group gave the first evidence of top quark production, with a mass of 174 ± 10-12GeV. After a short rest, the problem of low brightness of Tevatron was solved. By the beginning of 1995, CDF and DØ collected enough cases to confirm the discovery of the top quark. The quality of the top quark given by CDF was 176 ± 13 GeV, while D0 The results given are 199 ± 30 GeV, and their results were published in the same issue of Phy. Rev. Lett.



With the continuous accumulation of Tevatron cases, CDF and DØ continue to improve the measurement accuracy of top quark properties. In 2010, CERN's Large Hadron Collider (LHC) began to operate, which is the highest energy collider and can produce a large number of top quark cases. Scientists combined data from Tevatron and LHC to obtain a more accurate top quark mass of 173.1 ± 0.6 GeV.

So far, only two particle colliders in the world have produced top quarks. One is the Tevatron, which has discovered the top quark, and it has ceased operation. The other is the large hadron collider, which discovered the Higgs boson. At the beginning of the construction of the Large Hadron Collider, the top quark has not been experimentally observed, but today the Large Hadron Collider is a veritable top quark factory. In the three years from 2010 to 2012 alone, the ATLS and CMS experiments on the Large Hadron Collider each recorded nearly 10 million top quark cases, far exceeding the sum of the top quark cases obtained by Tevatron after 28 years of operation. The top quark can be studied in more detail on the Large Hadron Collider. At present, the focus is on the quality measurement of top quarks, the use of top quarks to test the standard model, and the search for new physics related to top quarks.

The measurement accuracy of the top quark mass on the Large Hadron Collider has reached 1 GeV; all the top quark property measurements are consistent with the predictions of the standard model. Although no significant new physical signals were observed in all new physics related to the top quark, the asymmetry of the top quark 's charge on the hadron collider was observed to exceed the expectations of the standard model. Determine whether it is a signal of new physics, but related research has greatly promoted the development of top quark theory. The future of top quark detection With an in-depth understanding of top quarks, theorists expect to be able to make more accurate measurements of top quark properties, including the quality of top quarks, the properties of "naked" quarks, and so on, so as to accurately test the standard model , Looking for clues of new physics. The Large Hadron Collider currently in operation has already obtained the largest top quark sample in the world. In the next two decades or so, the Large Hadron Collider will obtain more top quark data, thus aligning the top quark Of the nature, and do a detailed study of the various modes of top quark production.

The relationship between top quark and new physics

Although the theory of the standard model gives the properties of quark's spin, parity, and whether it participates in various interactions, these properties need to be accurately compared with the experimental results to test. Many major discoveries in history are that experiments found inconsistencies with theoretical predictions, which led to the great development of theory. The quark confinement effect in the standard model prohibits us from observing a single quark. Of all the quarks, only the top quark decayed before forming hadron states with other quarks due to its ultra-short lifetime, thus keeping the information about a single top quark in its decay product. By studying the decay products of top quarks, one can understand the properties of individual top quarks. Such as spin, parity, and the information of the top quark decay, so as to compare with the predictions of the standard model. Therefore, the top quark is an ideal venue for testing the theory of standard models.

Since the mass of the top quark is at least 1 to 2 orders of magnitude higher than the mass of the other quarks, the top quark has a unique role in the new physics related to electroweak destruction (mass). For example, many new physics are more inclined to couple with the top quark and decay to the top quark. In this way, accurate study of the properties, generation, and decay of top quarks is more likely to discover signs of new physics. The top quark is a particle that is relatively easy to identify in high-energy physics experiments due to its huge mass and unique decay product, so from the experimental point of view, it is easier to distinguish it from the background. These factors determine the important position that top quark seeks in new physics.

Conclusion

However, both the Tevatron, which discovered the top quark for the first time, or the existing top quark factory, the Large Hadron Collider, suffers from the complicated background of the hadron collider in the accurate measurement of the top quark mass, and the theoretical calculation accuracy is limited. And other factors. Therefore, in order to greatly improve the measurement of the top quark properties, a new experimental scheme must be adopted. In the future, a number of positive and negative electron collider solutions have proposed physical targets to accurately measure the top quark mass, such as Japan 's International Linear Collider (ILC) and Europe 's Future Circular Collider (FCC-ee). The Higgs factory (CEPC) currently under pre-research in China, if the accelerator ring can be built to more than 80 kilometers, will also be able to achieve the 350 GeV centroid energy required for the top quark pair to produce accurate measurement of the top quark mass, etc. parameter. In any case, the detection of the top quark nature is far from over.

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