

# STANDARD MODEL PHYSICS

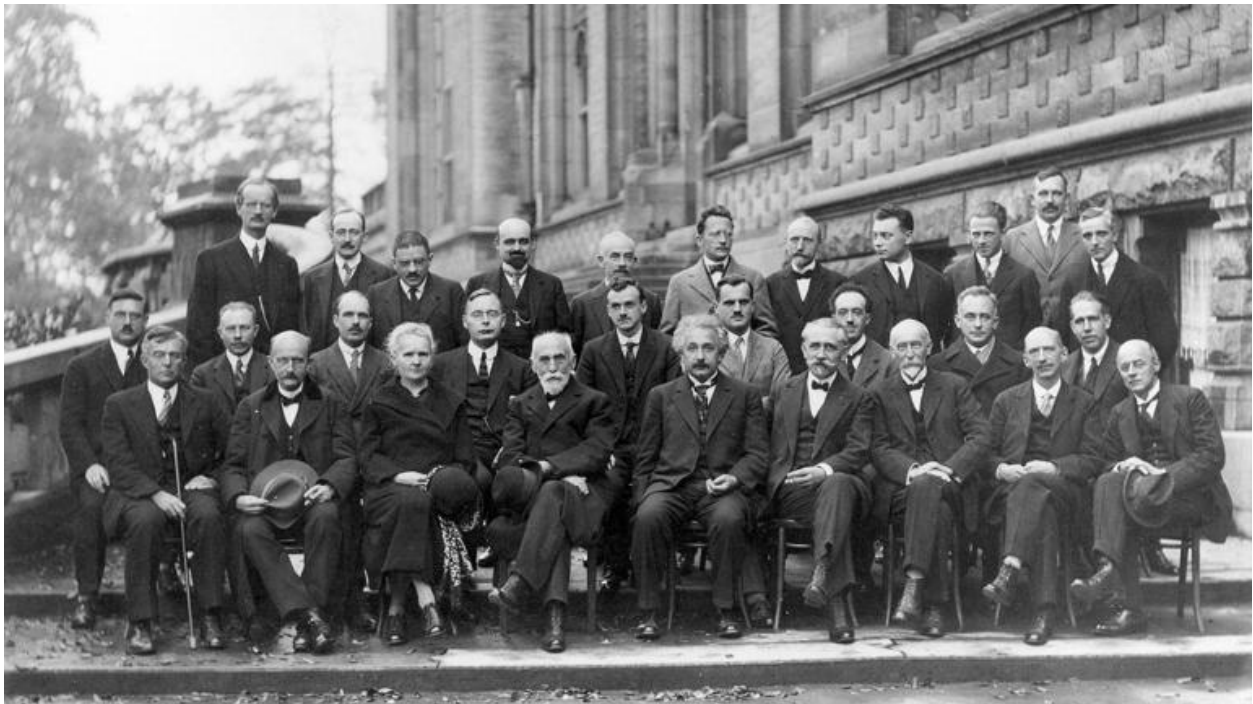
## **Einstein's theory of relativity: A deep dive into modern physics – part I**

Physics is a continually advancing field, with new discoveries occurring daily.

Newton's theory of gravity and Galileo's description of planetary motion are key components of classical physics.

Isaac Newton, Gottfried Leibniz, and Galileo Galilei established the foundations of classical mechanics. Two centuries later, James Clerk Maxwell formulated a theory of electromagnetism, explaining the behavior of electricity and magnetism.

These theories are considered classical, indicating they do not account for phenomena under extreme conditions, such as at the quantum level or on the scale of galaxies and the universe.



Some of the pioneers of modern physics, including Einstein, at the Solvay Conference on Quantum Mechanics in 1927. Credit: Benjamin Couprie, Institut International de Physique Solvay, Brussels, Belgium .© Provided by Interesting Engineering

Enter modern physics. A branch of physics that involves more radical thinking to explain things at microscopic and macroscopic levels. This way of approaching physical theories started in the late 19th century with pioneers like [Albert Einstein](#), Paul Dirac, and Neils Bohr.

Modern physics stands on two pillars: Einstein's theory of relativity and the [Standard Model](#) of particle physics. The theory of relativity encompasses the gravitational force, one of the four fundamental forces in the Universe.

Conversely, the Standard Model encompasses the other three forces—nuclear weak and strong and electromagnetic forces.

In this two-part article, we break down these pillars of modern physics and gain a deeper understanding of why they are so integral in science today.

In part one, we will focus on the theories of relativity.

## **Shortcomings of classical physics**

While classical physics successfully explains many day-to-day phenomena—before the development of modern physics—there were several instances where it failed.

One of them was the motion of Mercury around the Sun. Astronomers had observed a shift (or precession) in Mercury's orbit around the Sun over time. Newton's gravitation could not explain this observed shift.

Classical physics also couldn't explain why the speed of light was always constant.

At that time, the prevailing belief was that the universe was filled with ether, a substance through which light waves propagated. This was based on the understanding that waves could only travel through a medium.

Two scientists (Albert A. Michelson and Edward W. Morley) undertook the [Michelson-Morley experiment](#) in 1887 to put this hypothesis to the test. Their experiment showed that the speed of light remained constant, contrary to what would happen if the Earth moved through ether.

# Einstein's propositions

Einstein's motivation to understand the nature of light began when he was just 16 years old. His theory of special relativity stemmed from his desire to understand the nature of light and what would happen to objects moving near or at the speed of light. This led him to develop the photoelectric effect, which won him the Nobel Prize.

## Special relativity

In 1905, Einstein published the first of his many papers addressing the shortcomings of classical physics about light and spacetime. This was his theory of [special relativity](#).

Einstein introduced two main postulates in his special relativity theory.

1. The first postulate is about the laws of physics in inertial frames of reference. According to Einstein, the laws of physics do not change, no matter which inertial frame you are in. Galileo Galilei originally presented this postulate.

An object in an inertial frame remains in motion or at rest until an external force acts upon it.

2. The second postulate concerns the speed of light. Einstein showed that the speed of light is the same in a vacuum, despite the motion of the light itself or the observer. This value ( $c$ ) is equal to 299,792,458 meters per second.

These postulates have several implications for observed phenomena.

## Time dilation

One of the most fascinating implications of these postulates is that [time passes](#) more slowly for objects traveling near the speed of light than when the object would be at rest.

Several [experiments](#) involving muons (a type of subatomic particle) and high-precision atomic clocks have confirmed this.

In other words, a person traveling in a spaceship near the speed of light would age slower than if they were on Earth.

## **Relativity of simultaneity**

According to Einstein's theory, simultaneous events in one reference frame may not be simultaneous in another, which is in motion relative to the first.

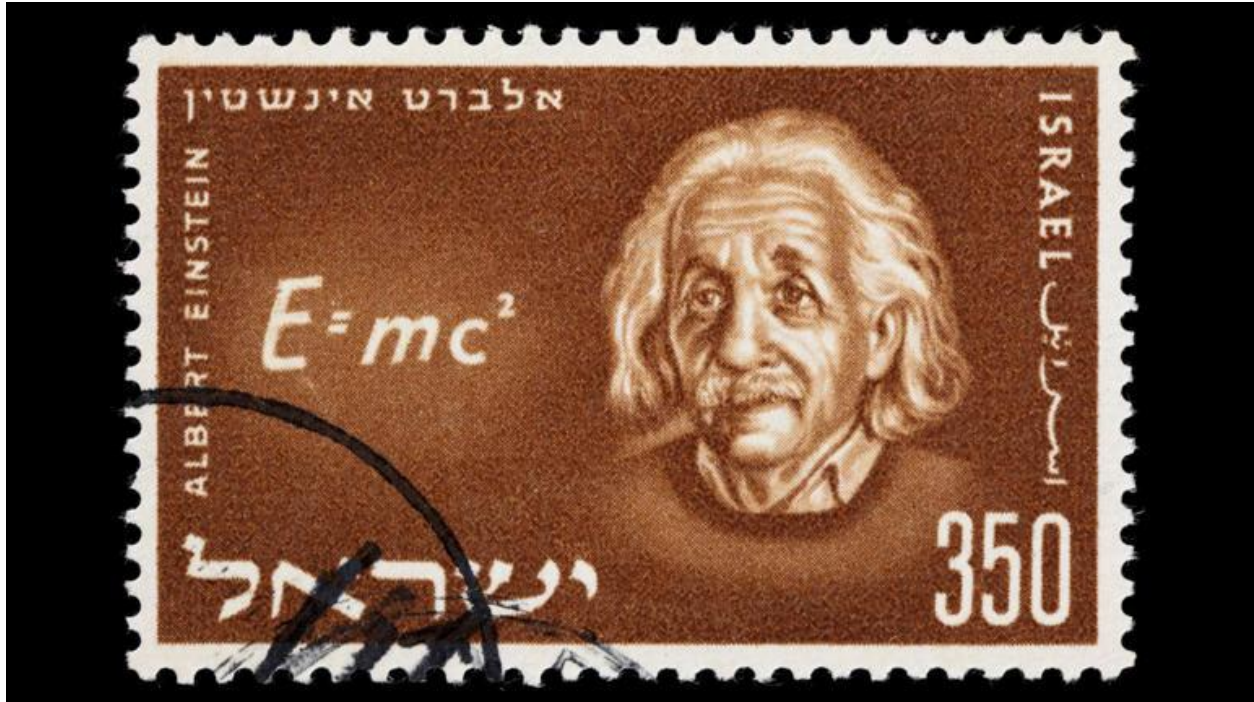
For example, a person standing on a train platform might see two [lightning strikes](#) simultaneously, but a passenger on a moving train might see one strike before the other.

This is because it takes time for the light to travel. So when the train is in motion, the light will have to cover that extra distance to reach the passenger on the train.

## **Mass-energy equivalence**

$E = mc^2$  is possibly the most famous equation in [physics](#) and probably the work Einstein is best known for.

According to this equation, mass and energy are interchangeable, meaning they are different forms of the same thing. However, the conversion factor is the square of the speed of light, which is a huge number.



A postal stamp from 1956 featuring Einstein and his mass-energy equation. Credit: PictureLake/iStock .© Provided by Interesting Engineering

This means that it is very hard to change one to another. According to [PBS Nova](#), if one atom in a paper clip were converted to pure energy, we would have the same amount of energy that 18 kilotons of TNT would produce!

This equation is how atomic bombs and nuclear fission reactors work.

## Minkowski's contributions

In 1908, before Einstein published his work on general relativity, mathematician Hermann Minkowski introduced the concept of four-dimensional space, called Minkowski spacetime.

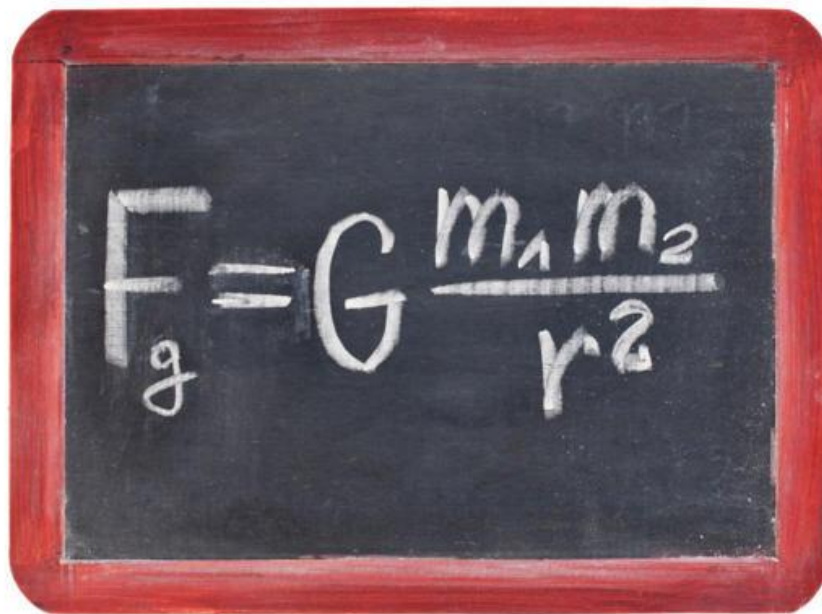
This [four-dimensional space](#) consists of the three spatial dimensions that we are familiar with and added time to it.

Minkowski's work gave us a geometric understanding of why different observers can disagree on the simultaneity of events, and how time can appear dilated depending on relative velocities.

It also laid down the mathematical foundation upon which Einstein built his theory of general relativity.

## General relativity

In 1915, Einstein published his paper on [general relativity](#), a theory of gravitation. While Newton's gravity explained everyday phenomena, it did not explain the nature of gravity itself.


$$F_g = G \frac{m_1 m_2}{r^2}$$

Newton's law of gravitation describing the gravitational forces between two objects. Credit: marekuliasz/iStock  
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Einstein knew that his theory of special relativity was partial. It couldn't be applied to accelerating (or non-inertial) objects or gravity.

### Equivalence principle

This led Einstein to formulate the Equivalence Principle, a cornerstone of general relativity. According to the [equivalence principle](#), the effects of gravity are *indistinguishable* from the effects of acceleration for an observer in a small region of spacetime.

So, if you were in a closed room on Earth, the force you would feel would be the same if the room were accelerating upwards in space at 9.8 meters per second squared.

This led Einstein to explore the idea [that gravity](#) may not be a force in the traditional sense of pulling or pushing of objects and might be a manifestation of spacetime.

## **Curved spacetime**

From 1912 to 1915, Einstein worked on his theory of gravity, collaborating with mathematician Marcel Grossman. In 1915, he [published four papers](#) on general relativity.

The central idea of his work was that mass and energy cause spacetime, which can be thought of as a fabric, to curve or bend.

To illustrate this, let's look at an example. Consider a heavy item (such as a bowling ball) resting on a trampoline. It results in the surface bending. Now, if we were to drop some lighter objects, like marbles, they would move toward the bowling ball as they followed the curves on the trampoline surface.

Einstein formulated [The Field Equations](#) to mathematically describe the relation between curvature of spacetime and mass and energy.

## **Geodesics**

Einstein also introduced the concept of geodesics in his theory of general relativity.

A geodesic is the path along which an object moves in curved spacetime, and this is the shortest path in curved spacetime. These paths appear curved when seen in our three-dimensional space. This is equivalent to a [straight line](#) being the shortest distance between two points on a flat surface.

For example, the paths taken by planets around the Sun follow geodesics and appear as elliptical orbits.

# From black hole to GPS

Einstein's special and general relativity theories have been repeatedly tested and consistently proven right.

## Mercury's orbit

Einstein [published a paper](#) in which he used his theory of general relativity to correctly predict that Mercury's orbit precesses by 43 arcseconds per century.

Arcseconds are a measure of angle used in astronomy, with 60 arcseconds in one arc minute and 60 arcminutes in one degree. This means that Mercury's orbit shifts by 43 arcseconds every century, as observed from Earth, due to [gravitational forces](#).

## Black holes

Black holes are regions of spacetime where the gravitational force is so strong that not even light can escape. Einstein's theory of general relativity allowed for the existence of black holes.

A few months after Einstein published his work, physicist Karl Schwarzschild found a solution to Einstein's field equations that described what we now call a [black hole](#).

However, the term "black hole" was not only coined in 1967 by astronomer John Wheeler.

Independent researchers made the first [confirmed observations](#) of a black hole in 1971, and it was named [Cygnus X-1](#).

## Gravitational waves

Einstein's theory of general relativity also predicted gravitational waves, which are ripples caused by spacetimes. According to this, massive accelerating objects (like black holes or neutron stars) disrupt spacetime, causing ripples to spread in all directions at the speed of light.

These ripples carry information about their origins and were first observed in 2015 by the [LIGO observatory](#) in the US. The observatory used laser interferometers to [detect the ripples](#) in spacetime caused by the collision of two massive black holes.

## GPS

The [global positioning system](#) (or GPS) is a system of satellites in orbit around the Earth that provide precise time and location information.

The technology works by constantly transmitting time and position signals from satellites, forming the basis of many modern technologies, such as navigation systems and emergency response services.

Einstein's theories of relativity are crucial to its functioning due to time dilation effects, which would cause the satellite clocks to go out of sync and run at rates different from the [clocks on Earth](#).

If it weren't for Einstein's theories of relativity, GPS systems would not work.

## Conclusion

There we have it, folks! Einstein's theories of relativity have revolutionized our understanding of spacetime and gravity, paving the way for discoveries and technology.

Despite its overall success, the theory has some limitations under extreme conditions. For example, Einstein's field equations break down at singularities, regions in spacetime where the gravitational force is infinite, such as at the center of black holes and the [Big Bang](#).

Additionally, they still need to fully integrate with the Standard Model, leaving the quest for a Unified Theory of Everything open.

# The Standard Model explained: A deep dive into modern physics – part II

Einstein's theories of relativity successfully explain the behavior of gravity. However, it does not account for the other three fundamental forces.

The Standard Model of particle physics explains the electromagnetic, nuclear strong, and nuclear weak forces. It describes the forces and behavior of the Universe's fundamental particles: quarks, leptons, and bosons.

It is a very comprehensive framework backed by extensive experimental evidence and is the foundation of modern particle physics.

[The Standard Model](#) extends the principles of quantum mechanics—which describes nature at the smallest scales—to provide a comprehensive picture of how the fundamental particles and forces work (except for gravity).

Together with Einstein's theories of relativity, they form the pillars of modern physics.

Let's start at the beginning.

## The birth of quantum mechanics

### Max Planck

One of the first contributions came from Max Planck, who introduced the concept of [quantized energy](#). Planck showed that energy could only be exchanged in discrete units or packets, which he termed *quanta*.

### Albert Einstein

In 1905, Einstein proposed the photon theory of light. According to this, light consists of discrete packets of energy called photons. His work on the [photoelectric effect](#) introduced us to wave-particle duality, where light can exhibit both particle and wave-like properties.

## Bohr and de Broglie

In 1913, [Neils Bohr proposed](#) that electrons in an atom orbit the nucleus in discrete energy levels. The introduction of discretized electron orbits addressed the stability of the atom and explained the atomic spectra of materials.

Following this, in 1924, [Louis de Broglie extended](#) Einstein's concept of wave-particle duality to the electron, proposing that it also has dual properties.

## Schrödinger, Dirac, and beyond

In 1926, Erwin Schrödinger developed a mathematical framework to describe quantum systems and introduced the [Schrodinger equation](#). Schrödinger provided a unified framework that accounted for both the wave and particle nature of quantum particles and systems.

In the same year, [Paul Dirac extended](#) Schrödinger's work by introducing Dirac notation. He also introduced the Dirac equation, combining Einstein's special relativity with quantum mechanics, which predicted the existence of positrons (antiparticle of the electron) and antimatter in general.

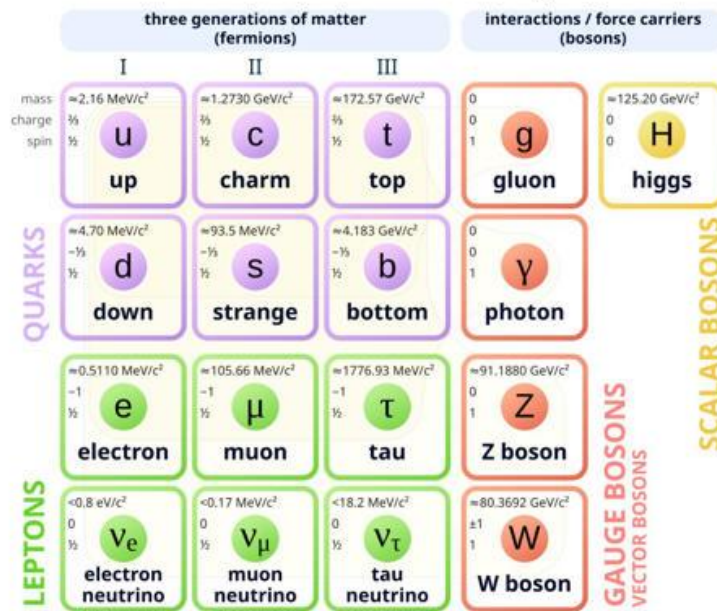
# The Standard Model

## Fundamental particles

Matter in the Universe is made of fundamental particles, essentially the building blocks. It was assumed that [atoms were indivisible](#) for the longest time, but we discovered electrons, protons, and neutrons.

Now we know that particles like neutrons and protons can be further divided into quarks, one of the three fundamental particles.

## Standard Model of Elementary Particles



The fundamental particles. Credit: Cush/Wikimedia Commons© Provided by Interesting Engineering

### Quarks

There are six types of quarks: up, down, charm, strange, top, and bottom. [Quarks combine](#) to form hadrons. Hadrons can further be categorized depending on the types of quarks that make up the hadron.

We have baryons, which are made of three quarks, like the neutron and proton, and we have mesons, which are made of one quark and one antiquark.

### Leptons

Apart from quarks, we have six leptons: electron, muon, tau and their [corresponding neutrinos](#), electron neutrino, muon neutrino, and tau neutrino.

One of the main differences between quarks and leptons is that leptons do not interact via the nuclear strong force and ultimately do not combine to form larger particles like quarks do.

Quarks and leptons both fall under the category of fermions.

## **Bosons**

Finally, we have bosons. There are gauge bosons (photon, W and Z bosons, gluons), which act as mediators of the fundamental forces, and the Higgs boson, which gives mass to the quarks and leptons.

Bosons are also known as force carriers because they mediate the interaction of these fundamental particles via one of the three forces: electromagnetic, [nuclear strong](#), and weak forces.

## **Fundamental forces**

The Standard Model accounts for three of the four fundamental forces, each with a carrier particle that helps mediate it.

### **Electromagnetic force**

The electromagnetic force is responsible for many phenomena we see day-to-day, like a lightning strike, a bulb lighting up, or a magnet sticking to a fridge. It is the interaction of any two charged particles.

The mediator of the electromagnetic force is the photon, the particle of light. This is because light itself is an electromagnetic wave. Whenever two charged particles interact via the [electromagnetic force](#), it occurs through the exchange of photons.

### **Nuclear strong force**

The nuclear strong force, or strong force, binds quarks to form hadrons. The force carrier for the strong force is the gluon.

This force is responsible for holding the protons and neutrons together in the nucleus of the atoms against the repulsive electromagnetic forces. Therefore, the strong force is much stronger than the electromagnetic force.

### **Nuclear weak force**

The weak force is seen in [radioactive decay](#) and neutrino interactions. As the name suggests, the nuclear weak force is weaker than the strong and electromagnetic force.

Its weaker strength compared to the other two is its short range. This means that its effects are less noticeable at the macroscopic level.

It is mediated by the W and Z bosons, which are massive particles. This affects the range of interaction of the nuclear weak force (discussed in detail later in the article).

However, the weak force is stronger than the [gravitational force](#), albeit over shorter distances.

## **Quantum field theory (QFT)**

The Standard Model is built on the mathematical framework of quantum field theory (QFT), combining the principles of quantum mechanics with special relativity.

QFT assumes the fundamental particles are disturbances or excitations (quanta) of their respective [quantum fields](#). The notion is that the quantum fields are the fundamental entities that exist throughout spacetime.

Think of a stone being dropped in a pond or a lake, causing ripples. The waves are the particles, and the water is the quantum field. For instance, photons are quanta of the electromagnetic field, and the quarks and leptons are quanta of their respective quantum fields.

Then we have the Higgs field, which gives rise to the Higgs boson. The Higgs boson has a pivotal role for the fundamental particles.

Enrico Fermi, Richard Feynman, Hans Bethe, and Steven Weinberg are among the contributors to QFT.

## **The role of the Higgs field**

The Higgs field plays a unique role compared to other quantum fields. While its excitations, like those of other fields, produce a fundamental particle—the Higgs boson—it is distinct in that it imparts mass to fundamental particles.

When the fundamental particles interact with the [Higgs field](#), they gain mass. The more strongly they interact with the Higgs field, the heavier they are.

The W and Z bosons, the carriers of the weak force, interact very strongly with the Higgs field, which is why they are so massive. Conversely, photons do not interact with the [Higgs field](#), which is why they are massless.

Because the photon doesn't have mass, it is the fastest-moving particle in the Universe, traveling at the speed of light ( $c$ ) in a vacuum. This is by Einstein's theory of relativity.

## Higgs boson

The Higgs boson, a physical manifestation of the Higgs field, was first theorized in 1964 through a series of three papers published in [Physical Review Letters](#).

The particle was named after [Peter Higgs](#), the author of one of the papers. Along with François Englert (co-author of one of the papers), he won the Nobel Prize for laying down the theoretical groundwork for the mechanism by which particles acquire mass.

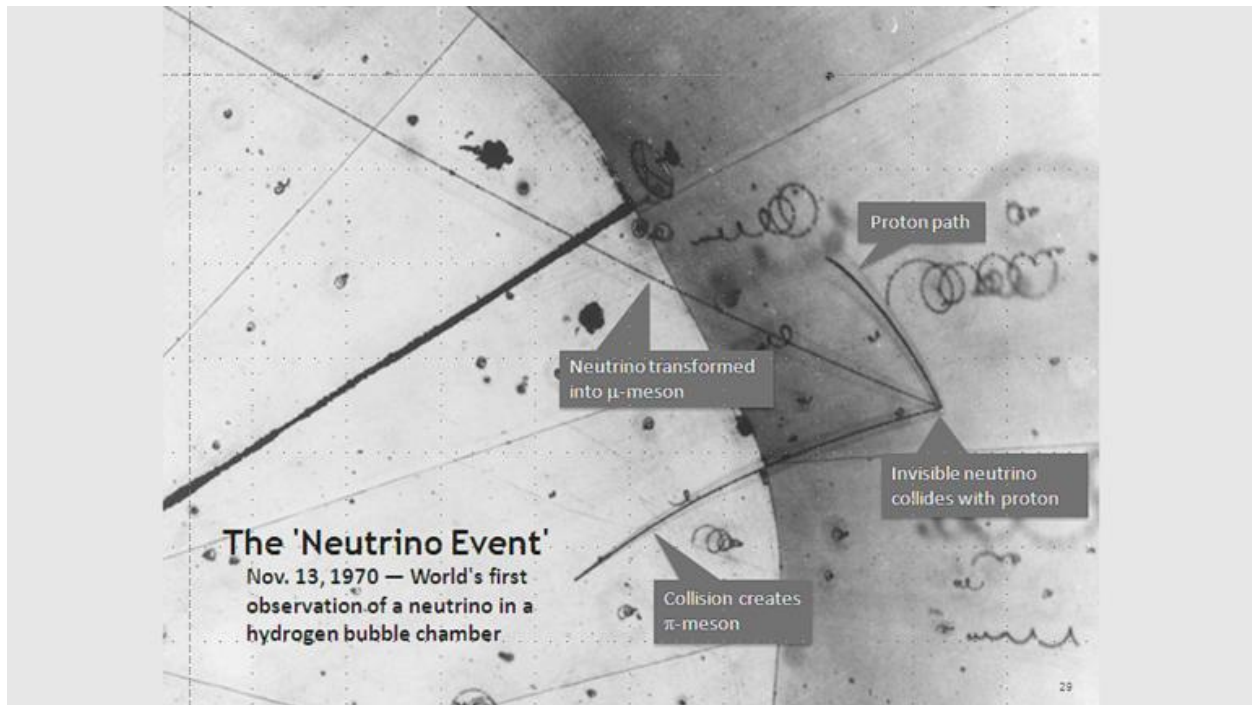
The [Large Hadron Collider](#) at CERN was built to find the Higgs particle and test other predictions made by the Standard Model. In 2012, the ATLAS and CMS experiments confirmed the discovery of the Higgs Boson.

## Predictions and limitations of the Standard Model

Apart from the Higgs boson, the model predicted the force carriers for the strong and weak forces long before their discovery. Two of the quarks (top and charm) were also predicted by the model, and the model has also predicted the behavior of particles in [high-energy collisions](#).

Although the Standard Model successfully unifies three fundamental forces, it is nonetheless limited by several limitations. The most obvious one is its non-inclusion of gravity.

This hinders the efforts to develop a [unified theory of everything](#), which some physicists argue may need to be more idealistic.



The first ever neutrino observation in the 1970s. © Provided by Interesting Engineering

The Standard Model also struggles to explain dark matter and dark energy, which is one of its limitations.

Also unexplained is the dilemma about the neutrino's mass. According to the Standard Model, neutrinos are assumed to be massless particles; however, experiments and observations have demonstrated that they possess a small, non-zero mass.

The Standard Model also fails to explain the abundance of matter over antimatter ([baryon asymmetry problem](#)).

## Physics beyond the Standard Model

The challenges with the Standard Model have prompted the suggestion of several alternate theories. Among the more well-known are [String Theory](#), Loop Quantum Gravity, Supersymmetry, and Grand Unified Theories.

However, they remain “theoretical” frameworks due to insufficient experimental evidence.

## Standard Model

[Particle physics](#)

Standard Model

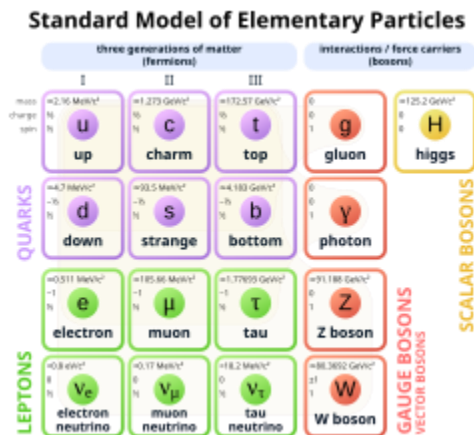
[Quantum field theory](#)

[Gauge theory](#)

[Spontaneous symmetry breaking](#)

[Higgs mechanism](#)

### Standard Model of [particle physics](#)



[Elementary particles](#) of the Standard Model

The **Standard Model** of [particle physics](#) is the [theory](#) describing three of the four known [fundamental forces](#) ([electromagnetic](#), [weak](#) and [strong interactions](#) – excluding [gravity](#)) in the [universe](#) and classifying all known [elementary particles](#). It was developed in stages throughout the latter half of the 20th century, through the work of many scientists worldwide,<sup>[1]</sup> with the current formulation being finalized in the mid-1970s upon [experimental confirmation](#) of the existence of [quarks](#). Since then, proof of the [top quark](#) (1995), the [tau neutrino](#) (2000), and the [Higgs boson](#) (2012) have added further credence to the Standard Model. In addition, the Standard Model has predicted

various properties of [weak neutral currents](#) and the [W and Z bosons](#) with great accuracy.

Although the Standard Model is believed to be theoretically self-consistent<sup>[note 1]</sup> and has demonstrated some success in providing [experimental predictions](#), it leaves some [physical phenomena unexplained](#) and so falls short of being a [complete theory of fundamental interactions](#).<sup>[3]</sup> For example, it does not fully explain [why there is more matter than anti-matter](#), incorporate the full [theory of gravitation](#)<sup>[4]</sup> as described by [general relativity](#), or account for the [universe's accelerating expansion](#) as possibly described by [dark energy](#). The model does not contain any viable [dark matter](#) particle that possesses all of the required properties deduced from observational [cosmology](#). It also does not incorporate [neutrino oscillations](#) and their non-zero masses.

The development of the Standard Model was driven by [theoretical](#) and [experimental](#) particle physicists alike. The Standard Model is a paradigm of a [quantum field theory](#) for theorists, exhibiting a wide range of phenomena, including [spontaneous symmetry breaking](#), [anomalies](#), and non-perturbative behavior. It is used as a basis for building more exotic models that incorporate [hypothetical particles](#), [extra dimensions](#), and elaborate symmetries (such as [supersymmetry](#)) to explain experimental results at variance with the Standard Model, such as the existence of dark matter and neutrino oscillations.

## Historical background

See also: [History of quantum field theory](#), [History of subatomic physics](#), [Julian Schwinger](#), and [John Clive Ward](#)

In 1928, [Paul Dirac](#) introduced the [Dirac equation](#), which implied the existence of [antimatter](#).

In 1954, [Yang Chen-Ning](#) and [Robert Mills](#) extended the concept of [gauge theory](#) for [abelian groups](#), e.g. [quantum electrodynamics](#), to [nonabelian groups](#) to provide an explanation for [strong interactions](#).<sup>[5]</sup> In 1957, [Chien-Shiung Wu](#) demonstrated [parity](#) was not conserved in the [weak interaction](#).<sup>[6]</sup>

In 1961, [Sheldon Glashow](#) combined the [electromagnetic](#) and [weak interactions](#).<sup>[7]</sup> In 1964, Murray Gell-Mann and George Zweig introduced quarks and that same year [Oscar W. Greenberg](#) implicitly introduced color charge of quarks.<sup>[8]</sup> In 1967 [Steven Weinberg](#)<sup>[9]</sup> and [Abdus Salam](#)<sup>[10]</sup> incorporated the [Higgs mechanism](#)<sup>[11][12][13]</sup> into Glashow's [electroweak interaction](#), giving it its modern form.

In 1970, Sheldon Glashow, John Iliopoulos, and Luciano Maiani introduced the [GIM mechanism](#), predicting the [charm quark](#).<sup>[14]</sup> In 1973 Gross and Wilczek and Politzer independently discovered that non-Abelian gauge theories, like the color theory of the strong force, have [asymptotic freedom](#).<sup>[14]</sup> In 1976, Martin Perl discovered the [tau lepton](#) at the [SLAC](#).<sup>[15][16]</sup> In 1977, a team led by Leon Lederman at Fermilab discovered the bottom quark.<sup>[17]</sup>

The Higgs mechanism is believed to give rise to the [masses](#) of all the [elementary particles](#) in the Standard Model. This includes the masses of the [W and Z bosons](#), and the masses of the [fermions](#), i.e. the [quarks](#) and [leptons](#).

After the [neutral weak currents](#) caused by [Z boson](#) exchange were [discovered](#) at [CERN](#) in 1973,<sup>[18][19][20][21]</sup> the electroweak theory became widely accepted and Glashow, Salam, and Weinberg shared the 1979 [Nobel Prize in Physics](#) for discovering it. The  $W^\pm$  and  $Z^0$  [bosons](#) were discovered experimentally in 1983; and the ratio of their masses was found to be as the Standard Model predicted.<sup>[22]</sup>

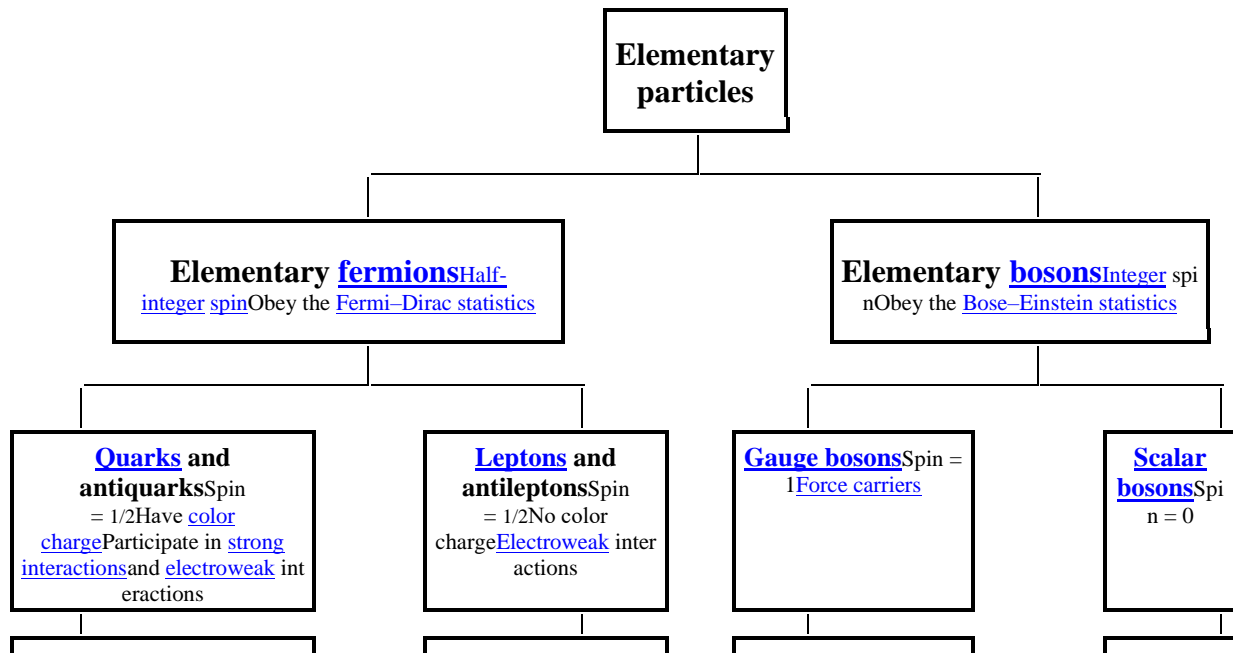
The theory of the [strong interaction](#) (i.e. [quantum chromodynamics](#), QCD), to which many contributed, acquired its modern form in 1973–74 when [asymptotic freedom](#) was proposed<sup>[23][24]</sup> (a development that made QCD the main focus of theoretical research)<sup>[25]</sup> and experiments confirmed that the [hadrons](#) were composed of fractionally charged quarks.<sup>[26][27]</sup>

The term "Standard Model" was introduced by [Abraham Pais](#) and [Sam Treiman](#) in 1975,<sup>[28]</sup> with reference to the electroweak theory with four quarks.<sup>[29]</sup> [Steven Weinberg](#), has since claimed priority, explaining that he chose the term Standard [Model](#) out of a sense of modesty<sup>[30][31][32][better source needed]</sup> and used it in 1973 during a talk in Aix-en-Provence in France.<sup>[33]</sup>

## Particle content

The Standard Model includes members of several classes of elementary particles, which in turn can be distinguished by other characteristics, such as [color charge](#).

All particles can be summarized as follows:



	Three generations	Three kinds	
<p><u>Three generations</u></p> <ol style="list-style-type: none"> <li><u>Up</u> (u), <u>Down</u> (d)</li> <li><u>Charm</u> (c), <u>Strange</u> (s)</li> <li><u>Top</u> (t), <u>Bottom</u> (b)</li> </ol>	<ol style="list-style-type: none"> <li><u>Electron</u> ( e<sup>-</sup> )<sup>[†]</sup>, <u>Electron neutrino</u> ( ν<sub>e</sub>)</li> <li><u>Muon</u> ( μ<sup>-</sup> ) , <u>Muon neutrino</u> ( ν<sub>μ</sub>)</li> <li><u>Tau</u> ( τ<sup>-</sup> ) , <u>Tau neutrino</u> ( ν<sub>τ</sub>)</li> </ol>	<ol style="list-style-type: none"> <li><u>Photon</u> ( γ ; <u>electroma gnetic interaction</u>)</li> <li><u>W and Z bosons</u> ( W<sup>+</sup> , W<sup>-</sup> , Z<sup>0</sup> ; <u>weak interaction</u>)</li> <li>Eight types of <u>gluons</u> ( g ; <u>strong interaction</u>)</li> </ol>	<p><b>One kind</b></p> <ol style="list-style-type: none"> <li><u>Higgs boson</u> ( H<sup>0</sup> )</li> </ol>

Notes:

[†] An anti-electron (  
e<sup>+</sup>

) is conventionally called a "positron".

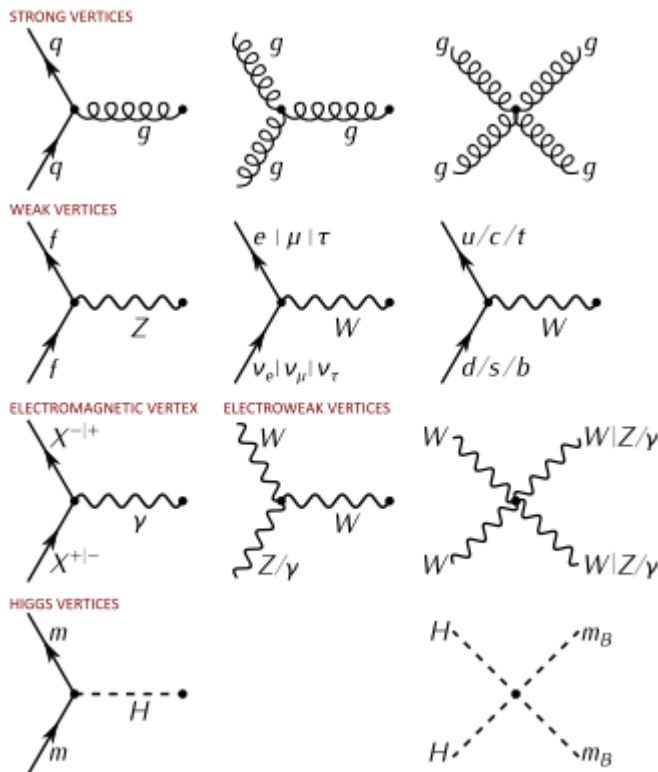
## Fermions

The Standard Model includes 12 elementary particles of spin 1/2, known as fermions.<sup>[34]</sup> Fermions respect the Pauli exclusion principle, meaning that two identical fermions cannot simultaneously occupy the same quantum state in the same atom.<sup>[35]</sup> Each fermion has a corresponding antiparticle, which are particles that have corresponding properties with the exception of opposite charges.<sup>[36]</sup> Fermions are classified based on how they interact, which is determined by the charges they carry, into two groups: quarks and leptons. Within each group, pairs of particles that exhibit similar physical behaviors are then grouped into generations (see the table). Each member of a generation has a greater mass than the corresponding particle of generations prior. Thus, there are three generations of quarks and leptons.<sup>[37]</sup> As first-generation particles do not decay, they comprise all of ordinary (baryonic) matter. Specifically, all atoms consist of electrons orbiting around the atomic nucleus, ultimately constituted of up and down quarks. On the other hand, second- and third-generation charged particles decay with very short half-lives and can only be observed in high-energy environments. Neutrinos of all generations also do not decay, and pervade the universe, but rarely interact with baryonic matter.

There are six quarks: up, down, charm, strange, top, and bottom.<sup>[34][37]</sup> Quarks carry color charge, and hence interact via the strong interaction. The color confinement phenomenon results in quarks being strongly bound together such that they form color-neutral composite particles called hadrons; quarks cannot individually

exist and must always bind with other quarks. Hadrons can contain either a quark-antiquark pair ([mesons](#)) or three quarks ([baryons](#)).<sup>[38]</sup> The lightest baryons are the [nucleons](#): the [proton](#) and [neutron](#). Quarks also carry [electric charge](#) and [weak isospin](#), and thus interact with other fermions through [electromagnetism](#) and [weak interaction](#). The six leptons consist of the [electron](#), [electron neutrino](#), [muon](#), [muon neutrino](#), [tau](#), and [tau neutrino](#). The leptons do not carry color charge, and do not respond to strong interaction. The charged leptons carry an [electric charge](#) of  $-1 e$ , while the three [neutrinos](#) carry zero electric charge. Thus, the neutrinos' motions are influenced by only the [weak interaction](#) and [gravity](#), making them difficult to observe.

## Gauge bosons



Interactions in the Standard Model. All

Feynman diagrams in the model are built from combinations of these vertices.  $q$  is any quark,  $g$  is a gluon,  $X$  is any charged particle,  $\gamma$  is a photon,  $f$  is any fermion,  $m$  is any particle with mass (with the possible exception of the neutrinos),  $m_b$  is any boson with mass. In diagrams with multiple particle labels separated by '/', one particle label is chosen. In diagrams with particle labels separated by '|', the labels must be chosen in the same order. For example, in the four boson electroweak case the valid diagrams are  $WWWW$ ,  $WWZZ$ ,  $WW\gamma\gamma$ ,  $WWZ\gamma$ . The conjugate of each listed vertex (reversing the direction of arrows) is also allowed.<sup>[39]</sup>

The Standard Model includes 4 kinds of [gauge bosons](#) of [spin 1](#),<sup>[34]</sup> with bosons being quantum particles containing an integer spin. The gauge bosons are defined as [force carriers](#), as they are responsible for mediating the [fundamental interactions](#). The Standard Model explains the four fundamental forces as arising from the interactions, with fermions [exchanging virtual](#) force carrier particles, thus mediating the forces. At a

macroscopic scale, this manifests as a [force](#).<sup>[40]</sup> As a result, they do not follow the Pauli exclusion principle that constrains fermions; bosons do not have a theoretical limit on their [spatial density](#). The types of gauge bosons are described below.

- **Electromagnetism:** [Photons](#) mediate the electromagnetic force, responsible for interactions between electrically charged particles. The photon is massless and is described by the theory of [quantum electrodynamics](#) (QED).
- **Strong Interactions:** [Gluons](#) mediate the strong interactions, which binds quarks to each other by influencing the [color charge](#), with the interactions being described in the theory of [quantum chromodynamics](#) (QCD). They have no mass, and there are eight distinct gluons, with each being denoted through a color-anticolor charge combination (e.g. red–antigreen).<sup>[note 2]</sup> As gluons have an effective color charge, they can also interact amongst themselves.
- **Weak Interactions:** The [W<sup>+</sup>](#), [W<sup>-</sup>](#), and [Z](#) gauge bosons mediate the weak interactions between all fermions, being responsible for [radioactivity](#). They contain mass, with the [Z](#) having more mass than the [W<sup>±</sup>](#). The weak interactions involving the [W<sup>±</sup>](#) act only on [left-handed particles and right-handed antiparticles](#). The [W<sup>±</sup>](#) carries an electric charge of +1 and −1 and couples to the electromagnetic interaction. The electrically neutral [Z](#) boson interacts with both left-handed particles and right-handed antiparticles. These three gauge bosons along with the photons are grouped together, as collectively mediating the [electroweak](#) interaction.
- **Gravity:** It is currently unexplained in the Standard Model, as the hypothetical mediating particle [graviton](#) has been proposed, but not observed.<sup>[42]</sup> This is due to the incompatibility of quantum mechanics and [Einstein's theory of general relativity](#), regarded as being the best explanation for gravity. In general relativity, gravity is explained as being the geometric curving of spacetime.<sup>[43]</sup>

The [Feynman diagram](#) calculations, which are a graphical representation of the [perturbation theory](#) approximation, invoke "force mediating particles", and when applied to analyze [high-energy scattering experiments](#) are in reasonable agreement with the data. However, perturbation theory (and with it the concept of a "force-mediating particle") fails in other situations. These include low-energy quantum

chromodynamics, [bound states](#), and [solitons](#). The interactions between all the particles described by the Standard Model are summarized by the diagrams on the right of this section.

## Higgs boson

*Main article:* [Higgs boson](#)

The Higgs particle is a massive [scalar](#) elementary particle theorized by [Peter Higgs \(and others\)](#) in 1964, when he showed that Goldstone's 1962 theorem (generic continuous symmetry, which is spontaneously broken) provides a third polarisation of a massive vector field. Hence, Goldstone's original scalar doublet, the massive spin-zero particle, was [proposed as the Higgs boson](#), and is a key building block in the Standard Model.<sup>[44]</sup> It has no intrinsic [spin](#), and for that reason is classified as a [boson](#) with spin-0.<sup>[34]</sup>

The Higgs boson plays a unique role in the Standard Model, by explaining why the other elementary particles, except the [photon](#) and [gluon](#), are massive. In particular, the Higgs boson explains why the photon has no mass, while the [W and Z bosons](#) are very heavy. Elementary-particle masses and the differences between [electromagnetism](#) (mediated by the photon) and the [weak force](#) (mediated by the W and Z bosons) are critical to many aspects of the structure of microscopic (and hence macroscopic) matter. In [electroweak theory](#), the Higgs boson generates the masses of the leptons (electron, muon, and tau) and quarks. As the Higgs boson is massive, it must interact with itself.

Because the Higgs boson is a very massive particle and also decays almost immediately when created, only a very high-energy [particle accelerator](#) can observe and record it. Experiments to confirm and determine the nature of the Higgs boson using the [Large Hadron Collider](#) (LHC) at [CERN](#) began in early 2010 and were performed at [Fermilab's Tevatron](#) until its closure in late 2011. Mathematical consistency of the Standard Model requires that any mechanism capable of generating the masses of elementary particles must become visible<sup>[clarification needed]</sup> at energies above 1.4 [TeV](#);<sup>[45]</sup> therefore, the LHC (designed to collide two 7 TeV proton beams) was built to answer the question of whether the Higgs boson actually exists.<sup>[46]</sup>

On 4 July 2012, two of the experiments at the LHC ([ATLAS](#) and [CMS](#)) both reported independently that they had found a new particle with a mass of about 125 [GeV/c<sup>2</sup>](#) (about 133 proton masses, on the order of 10<sup>-25</sup> kg), which is "consistent with the Higgs boson".<sup>[47][48]</sup> On 13 March 2013, it was confirmed to be the searched-for Higgs boson.<sup>[49][50]</sup>

## Theoretical aspects

*Main article:* [Mathematical formulation of the Standard Model](#)

### Construction of the Standard Model Lagrangian

#### Parameters of the Standard Model

Technically, [quantum field theory](#) provides the mathematical framework for the Standard Model, in which a [Lagrangian](#) controls the dynamics and kinematics of the theory. Each kind of particle is described in terms of a dynamical [field](#) that pervades [space-time](#).<sup>[51]</sup> The construction of the Standard Model proceeds following the modern method of constructing most field theories: by first postulating a set of symmetries of the system, and then by writing down the most general [renormalizable](#) Lagrangian from its particle (field) content that observes these symmetries.

The [global Poincaré symmetry](#) is postulated for all relativistic quantum field theories. It consists of the familiar [translational symmetry](#), [rotational symmetry](#) and the inertial reference frame invariance central to the theory of [special relativity](#). The [local](#)  $SU(3) \times SU(2) \times U(1)$  [gauge symmetry](#) is an [internal symmetry](#) that essentially defines the Standard Model. Roughly, the three factors of the gauge symmetry give rise to the three fundamental interactions. The fields fall into different [representations](#) of the various symmetry groups of the Standard Model (see table). Upon writing the most general Lagrangian, one finds that the dynamics depends on 19 parameters, whose numerical values are established by experiment. The parameters are summarized in the table (made visible by clicking "show") above.

### Quantum chromodynamics sector

*Main article:* [Quantum chromodynamics](#)

The quantum chromodynamics (QCD) sector defines the interactions between quarks and gluons, which is a [Yang–Mills gauge theory](#) with  $SU(3)$  symmetry, generated by  $G^a$ . Since leptons do not interact with gluons, they are not affected by this sector.

The Dirac Lagrangian of the quarks coupled to the gluon fields is given by

where  $\psi$  is a three component column vector of [Dirac spinors](#), each element of which refers to a quark field with a specific [color charge](#) (i.e. red, blue, and green) and summation over [flavor](#) (i.e. up, down, strange, etc.) is implied.

The gauge covariant derivative of QCD is defined by  $D_\mu = \partial_\mu - ig_s G^a_\mu \lambda^a$ , where

- $\gamma^\mu$  are the [Dirac matrices](#),
- $G^a$
- $A^a_\mu$  is the 8-component (  $\mathbf{8}$  )  $SU(3)$  gauge field,
- $\lambda^a$  are the  $3 \times 3$  [Gell-Mann matrices](#), generators of the  $SU(3)$  color group,
- $G^a$
- $G^a_{\mu\nu}$  represents the [gluon field strength tensor](#), and
- $g_s$  is the strong coupling constant.

The QCD Lagrangian is invariant under local SU(3) gauge transformations; i.e., transformations of the form  $\psi \rightarrow U(x)\psi$ , where  $U$  is  $3 \times 3$  unitary matrix with determinant 1, making it a member of the group SU(3), and  $\psi$  is an arbitrary function of spacetime.

### Electroweak sector

*Main article:* [Electroweak interaction](#)

The electroweak sector is a [Yang–Mills gauge theory](#) with the symmetry group  $U(1) \times SU(2)_L$ , where the subscript  $L$  sums over the three generations of fermions;  $\psi_L$ ,  $\psi_R^u$ , and  $\psi_R^d$  are the left-handed doublet, right-handed singlet up type, and right handed singlet down type quark fields; and  $\psi_L^e$  and  $\psi_R^e$  are the left-handed doublet and right-handed singlet lepton fields.

The electroweak [gauge covariant derivative](#) is defined as  $D_\mu = \partial_\mu - ig' Y_W - ig \vec{\tau}_L \cdot \vec{W}_\mu$ , where

- $B_\mu$  is the U(1) gauge field,
- $Y_W$  is the [weak hypercharge](#) – the generator of the U(1) group,
- $W_{\rightarrow\mu}$  is the 3-component SU(2) gauge field,
- $\tau_L$  are the [Pauli matrices](#) – infinitesimal generators of the SU(2) group – with subscript L to indicate that they only act on *left*-chiral fermions,
- $g'$  and  $g$  are the U(1) and SU(2) coupling constants respectively,
- $\vec{W}_\mu$  and  $B_\mu$  are the [field strength tensors](#) for the weak isospin and weak hypercharge fields.

Notice that the addition of fermion mass terms into the electroweak Lagrangian is

forbidden, since terms of the form  $\bar{\psi}\psi$  do not respect  $U(1) \times SU(2)_L$  gauge invariance. Neither is it possible to add explicit mass terms for the U(1) and SU(2) gauge fields. The Higgs mechanism is responsible for the generation of the gauge boson masses, and the fermion masses result from Yukawa-type interactions with the Higgs field.

### Higgs sector

*Main article:* [Higgs mechanism](#)

In the Standard Model, the [Higgs field](#) is an  $SU(2)_L$  doublet of complex [scalar](#) fields with four degrees of freedom:  $\phi^\pm, \phi^0$  where the superscripts + and 0 indicate the electric

charge of the components. The weak hypercharge of both components is 1.

Before symmetry breaking, the Higgs Lagrangian is  $\mathcal{L}_H = \partial_\mu \phi^\dagger \partial^\mu \phi - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$  where  $\mu$  is the electroweak

gauge covariant derivative defined above and  $V(\phi)$  is the potential of the Higgs field. The square of the covariant derivative leads to three and four point interactions between the electroweak gauge fields  $W_\mu^a$  and  $Z_\mu$  and the scalar field  $\phi$ . The scalar potential is given by  $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$ , where  $\mu^2 > 0$ , so that  $\phi$  acquires a non-zero [Vacuum expectation value](#), which generates masses for the Electroweak gauge fields (the Higgs mechanism), and  $\lambda > 0$ , so that the potential is bounded from below. The quartic term describes self-interactions of the scalar field  $\phi$ . The minimum of the potential is degenerate with an infinite number of equivalent [ground state](#) solutions, which occurs when  $\phi^\dagger \phi = v^2/2$ . It is possible to perform a [gauge transformation](#) on  $\phi$  such that the ground state is transformed to a basis where  $\phi = \begin{pmatrix} 0 \\ v \end{pmatrix}$  and  $\phi^\dagger = \begin{pmatrix} v & 0 \end{pmatrix}$ . This breaks the symmetry of the ground state. The expectation value of  $\phi^\dagger \phi$  now becomes  $v^2/2$  where  $v$  has units of mass and sets the scale of electroweak physics. This is the only dimensional parameter of the Standard Model and has a measured value of  $\sim 246 \text{ GeV}/c^2$ .

After symmetry breaking, the masses of the W and Z are given by  $M_W = gv/2$  and  $M_Z = \sqrt{g^2 + g'^2}v/2$ , which can be viewed as predictions of the theory. The photon remains massless. The mass of the [Higgs boson](#) is  $M_H = \sqrt{2\lambda}v$ . Since  $g$  and  $g'$  are free parameters, the Higgs's mass could not be predicted beforehand and had to be determined experimentally.

### Yukawa sector

The [Yukawa interaction](#) terms are:  $\bar{\psi}_L Y \phi \psi_R + \text{h.c.}$  where  $Y$ ,  $Y'$ , and  $Y''$  are  $3 \times 3$  matrices of Yukawa couplings, with the  $mn$  term giving the coupling of the generations  $m$  and  $n$ , and h.c. means Hermitian conjugate of preceding terms. The fields  $Q_L$  and  $L_L$  are left-handed quark and lepton doublets. Likewise,  $u_R$  and  $d_R$  are right-handed up-type quark, down-type quark, and lepton singlets. Finally  $\phi$  is the Higgs doublet and  $\phi^c$  is its charge conjugate state.

The Yukawa terms are invariant under the  $SU(2)_L \times U(1)_Y$  gauge symmetry of the Standard Model and generate masses for all fermions after spontaneous symmetry breaking.

# Fundamental interactions

Main article: [Fundamental interaction](#)

The Standard Model describes three of the four fundamental interactions in nature; only gravity remains unexplained. In the Standard Model, such an interaction is described as an exchange of [bosons](#) between the objects affected, such as a [photon](#) for the electromagnetic force and a [gluon](#) for the strong interaction. Those particles are called [force carriers](#) or messenger [particles](#).<sup>[52]</sup>

The four fundamental interactions of nature<sup>[53]</sup>

Property/Interaction	Gravitation	Electroweak		Strong	
		Weak	Electromagnetic	Fundamental	Residual
Mediating particles	Not yet observed ( <a href="#">Graviton</a> hypothesised)	<a href="#">W<sup>+</sup>, W<sup>-</sup> and Z<sup>0</sup></a>	<a href="#">γ</a> (photon)	Gluons	<a href="#">π, ρ and ω mesons</a>
Affected particles	All particles	Left-handed <a href="#">fermions</a>	Electrically charged	Quarks, <a href="#">gluons</a>	<a href="#">Hadrons</a>
Acts on	<a href="#">Stress–energy tensor</a>	<a href="#">Flavor</a>	Electric charge	<a href="#">Color charge</a>	
Bound states formed	Planets, stars, galaxies, galaxy groups	—	Atoms, molecules	Hadrons	Atomic nuclei
Strength at the scale of quarks (relative to electromagnetism)	10 <sup>-41</sup> (predicted)	10 <sup>-4</sup>	1	60	Not applicable to quarks

Strength at the scale of protons/neutrons (relative to electromagnetism)

$10^{-36}$  (predicted)

$10^{-7}$

1

Not applicable to hadrons

20

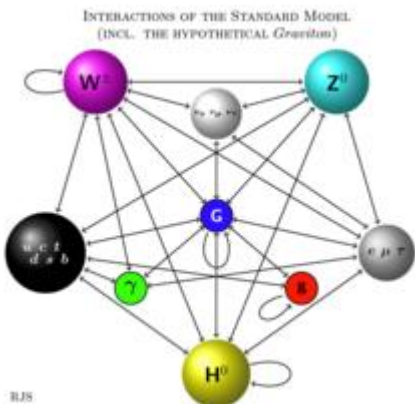


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## Gravity

[\[edit\]](#)

See also: [Quantum gravity](#) and [Gravity](#)



Fundamental Interactions of the Standard Model

including the hypothetical graviton

Despite being perhaps the most familiar fundamental interaction, gravity is not described by the Standard Model, due to contradictions that arise when combining general relativity, the modern theory of gravity, and quantum mechanics. However, gravity is so weak at microscopic scales, that it is essentially unmeasurable.

The [graviton](#) is postulated to be the mediating particle, but has not yet been proved to exist.

## Electromagnetism

See also: [Electromagnetism](#) and [Quantum electrodynamics](#)

Electromagnetism is the only long-range force in the Standard Model. It is mediated by photons and couples to electric charge.<sup>[54]</sup> Electromagnetism is responsible for a wide range of phenomena including [atomic electron shell structure](#), [chemical bonds](#), [electric circuits](#) and [electronics](#). Electromagnetic interactions in the Standard Model are described by quantum electrodynamics.

## Weak nuclear force

See also: [Weak interaction](#) and [Electroweak interaction](#)

The weak interaction is responsible for various forms of [particle decay](#), such as [beta decay](#). It is weak and short-range, due to the fact that the weak mediating particles, W and Z bosons, have mass. W bosons have electric charge and mediate interactions that change the particle type (referred to as flavor) and charge. Interactions mediated by W bosons are [charged current interactions](#). Z bosons are neutral and mediate neutral current interactions, which do not change particle flavor. Thus Z bosons are similar to the photon, aside from them being massive and interacting with the neutrino. The weak interaction is also the only interaction to violate [parity](#) and [CP](#). Parity violation is maximal for charged current interactions, since the W boson interacts exclusively with left-handed fermions and right-handed antifermions.

In the Standard Model, the weak force is understood in terms of the electroweak theory, which states that the weak and electromagnetic interactions become united into a single *electroweak* interaction at high energies.

## Strong nuclear force

See also: [Strong interaction](#), [Nuclear force](#), and [Quantum chromodynamics](#)

The strong nuclear force is responsible for hadronic and [nuclear binding](#). It is mediated by gluons, which couple to color charge. Since gluons themselves have color charge, the strong force exhibits [confinement](#) and [asymptotic freedom](#). Confinement means that only color-neutral particles can exist in isolation, therefore quarks can only exist in hadrons and never in isolation, at low energies. Asymptotic freedom means that the strong force becomes weaker, as the energy scale increases. The strong force overpowers the [electrostatic](#) repulsion of protons and quarks in nuclei and hadrons respectively, at their respective scales.

While quarks are bound in hadrons by the fundamental strong interaction, which is mediated by gluons, nucleons are bound by an emergent phenomenon termed the *residual strong force* or [nuclear force](#). This interaction is mediated by mesons, such as the [pion](#). The color charges inside the nucleon cancel out, meaning most of the gluon and quark fields cancel out outside of the nucleon. However, some residue is "leaked", which appears as the exchange of virtual mesons, that causes the attractive force between nucleons. The (fundamental) strong interaction is described by quantum chromodynamics, which is a component of the Standard Model.

## Tests and predictions

The Standard Model predicted the existence of the [W and Z bosons](#), [gluon](#), [top quark](#) and [charm quark](#), and predicted many of their properties before these particles were observed. The predictions were experimentally confirmed with good precision.<sup>[55]</sup>

The Standard Model also predicted the existence of the [Higgs boson](#), which was found in 2012 at the [Large Hadron Collider](#), the final fundamental particle predicted by the Standard Model to be experimentally confirmed.<sup>[56]</sup>

# Challenges

See also: [Physics beyond the Standard Model](#)

## Unsolved problem in physics:

- *What gives rise to the Standard Model of particle physics?*
- *Why do particle masses and [coupling constants](#) have the values that we measure?*
- *Why are there three [generations](#) of particles?*
- *Why is there more matter than [antimatter](#) in the universe?*
- *Where does [dark matter](#) fit into the model? Does it even consist of one or more new particles?*

[\(more unsolved problems in physics\)](#)

Self-consistency of the Standard Model (currently formulated as a non-[abelian](#) gauge theory quantized through path-integrals) has not been mathematically proved. While regularized versions useful for approximate computations (for example [lattice gauge theory](#)) exist, it is not known whether they converge (in the sense of S-matrix elements) in the limit that the regulator is removed. A key question related to the consistency is the [Yang–Mills existence and mass gap](#) problem.

Experiments indicate that [neutrinos](#) have [mass](#), which the classic Standard Model did not allow.<sup>[57]</sup> To accommodate this finding, the classic Standard Model can be modified to include neutrino mass, although it is not obvious exactly how this should be done.

If one insists on using only Standard Model particles, this can be achieved by adding a non-renormalizable interaction of leptons with the Higgs boson.<sup>[58]</sup> On a fundamental level, such an interaction emerges in the [seesaw mechanism](#) where heavy right-handed neutrinos are added to the theory. This is natural in the [left-right symmetric](#) extension of the Standard Model<sup>[59][60]</sup> and in certain [grand unified theories](#).<sup>[61]</sup> As long as new physics appears below or around  $10^{14}$  [GeV](#), the neutrino masses can be of the right order of magnitude.

Theoretical and experimental research has attempted to extend the Standard Model into a [unified field theory](#) or a [theory of everything](#), a complete theory explaining all physical phenomena including constants. Inadequacies of the Standard Model that motivate such research include:

- The model does not explain [gravitation](#), although physical confirmation of a theoretical particle known as a [graviton](#) would account for it to a degree. Though it addresses strong and electroweak interactions, the Standard Model does not consistently explain the canonical theory of gravitation, [general relativity](#), in terms of [quantum field theory](#). The reason for this is, among other things, that quantum field theories of gravity generally break down before reaching the [Planck scale](#). As a consequence, we have no reliable theory for the very early universe.

- Some physicists consider it to be *ad hoc* and inelegant, requiring 19 numerical constants whose values are unrelated and arbitrary.<sup>[62]</sup> Although the Standard Model, as it now stands, can explain why neutrinos have masses, the specifics of neutrino mass are still unclear. It is believed that explaining neutrino mass will require an additional 7 or 8 constants, which are also arbitrary parameters.<sup>[63]</sup>
- The Higgs mechanism gives rise to the [hierarchy problem](#) if some new physics (coupled to the Higgs) is present at high energy scales. In these cases, in order for the weak scale to be much smaller than the [Planck scale](#), severe fine tuning of the parameters is required; there are, however, other scenarios that include [quantum gravity](#) in which such fine tuning can be avoided.<sup>[64]</sup> There are also issues of [quantum triviality](#), which suggests that it may not be possible to create a consistent quantum field theory involving elementary scalar particles.<sup>[65]</sup>
- The model is inconsistent with the emerging [Lambda-CDM model](#) of cosmology. Contentions include the absence of an explanation in the Standard Model of particle physics for the observed amount of [cold dark matter](#) (CDM) and its contributions to [dark energy](#), which are many orders of magnitude too large. It is also difficult to accommodate the observed predominance of matter over antimatter ([matter/antimatter asymmetry](#)). The [isotropy](#) and [homogeneity](#) of the visible universe over large distances seems to require a mechanism like cosmic [inflation](#), which would also constitute an extension of the Standard Model.

Currently, no proposed [theory of everything](#) has been widely accepted or verified.

## See also

- [Yang–Mills theory](#)
- [Fundamental interaction](#):
  - [Quantum electrodynamics](#)
  - [Strong interaction](#): [Color charge](#), [Quantum chromodynamics](#), [Quark model](#)
  - [Weak interaction](#): [Electroweak interaction](#), [Fermi's interaction](#), [Weak hypercharge](#), [Weak isospin](#)
- [Gauge theory](#): [Introduction to gauge theory](#)
- [Generation](#)
- [Higgs mechanism](#): [Higgs boson](#), [Alternatives to the Standard Higgs Model](#)
- [Lagrangian](#)
- Open questions: [CP violation](#), [Neutrino masses](#), [QCD matter](#), [Quantum triviality](#)
- [Quantum field theory](#)
- Standard Model: [Mathematical formulation of](#), [Physics beyond the Standard Model](#)
- [Electron electric dipole moment](#)

# The Standard Model explained: A deep dive into modern physics – part II

Einstein's theories of relativity successfully explain the behavior of gravity. However, it does not account for the other three fundamental forces.

The Standard Model of particle physics explains the electromagnetic, nuclear strong, and nuclear weak forces. It describes the forces and behavior of the Universe's fundamental particles: quarks, leptons, and bosons.

It is a very comprehensive framework backed by extensive experimental evidence and is the foundation of modern particle physics.

[The Standard Model](#) extends the principles of quantum mechanics—which describes nature at the smallest scales—to provide a comprehensive picture of how the fundamental particles and forces work (except for gravity).

Together with Einstein's theories of relativity, they form the pillars of modern physics.

Let's start at the beginning.

## The birth of quantum mechanics

### Max Planck

One of the first contributions came from Max Planck, who introduced the concept of [quantized energy](#). Planck showed that energy could only be exchanged in discrete units or packets, which he termed *quanta*.

### Albert Einstein

In 1905, Einstein proposed the photon theory of light. According to this, light consists of discrete packets of energy called photons. His work on the [photoelectric effect](#) introduced us to wave-particle duality, where light can exhibit both particle and wave-like properties.

## Bohr and de Broglie

In 1913, [Niels Bohr proposed](#) that electrons in an atom orbit the nucleus in discrete energy levels. The introduction of discretized electron orbits addressed the stability of the atom and explained the atomic spectra of materials.

Following this, in 1924, [Louis de Broglie extended](#) Einstein's concept of wave-particle duality to the electron, proposing that it also has dual properties.

## Schrödinger, Dirac, and beyond

In 1926, Erwin Schrödinger developed a mathematical framework to describe quantum systems and introduced the [Schrodinger equation](#). Schrödinger provided a unified framework that accounted for both the wave and particle nature of quantum particles and systems.

In the same year, [Paul Dirac extended](#) Schrödinger's work by introducing Dirac notation. He also introduced the Dirac equation, combining Einstein's special relativity with quantum mechanics, which predicted the existence of positrons (antiparticle of the electron) and antimatter in general.

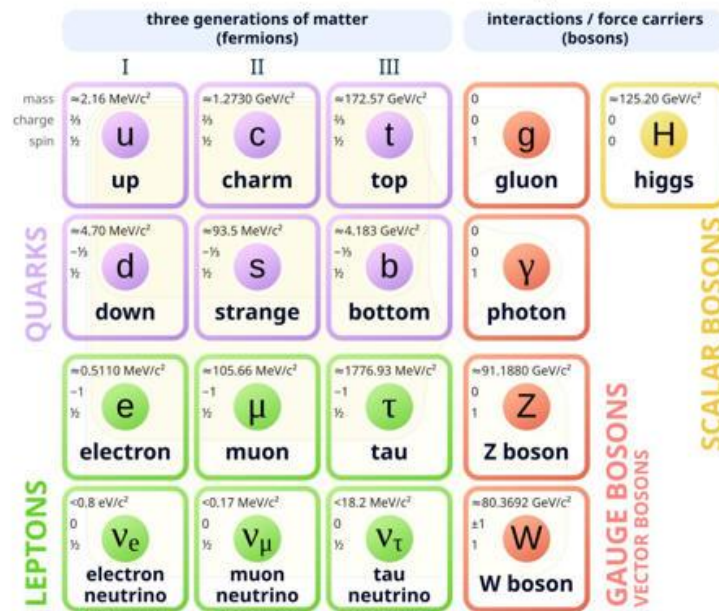
## The Standard Model

### Fundamental particles

Matter in the Universe is made of fundamental particles, essentially the building blocks. It was assumed that [atoms were indivisible](#) for the longest time, but we discovered electrons, protons, and neutrons.

Now we know that particles like neutrons and protons can be further divided into quarks, one of the three fundamental particles.

## Standard Model of Elementary Particles



The fundamental particles. Credit: Cush/Wikimedia Commons© Provided by Interesting Engineering

## Quarks

There are six types of quarks: up, down, charm, strange, top, and bottom. [Quarks combine](#) to form hadrons. Hadrons can further be categorized depending on the types of quarks that make up the hadron.

We have baryons, which are made of three quarks, like the neutron and proton, and we have mesons, which are made of one quark and one antiquark.

## Leptons

Apart from quarks, we have six leptons: electron, muon, tau and their [corresponding neutrinos](#), electron neutrino, muon neutrino, and tau neutrino.

One of the main differences between quarks and leptons is that leptons do not interact via the nuclear strong force and ultimately do not combine to form larger particles like quarks do.

Quarks and leptons both fall under the category of fermions.

## Bosons

Finally, we have bosons. There are gauge bosons (photon, W and Z bosons, gluons), which act as mediators of the fundamental forces, and the Higgs boson, which gives mass to the quarks and leptons.

Bosons are also known as force carriers because they mediate the interaction of these fundamental particles via one of the three forces: electromagnetic, [nuclear strong](#), and weak forces.

## Fundamental forces

The Standard Model accounts for three of the four fundamental forces, each with a carrier particle that helps mediate it.

### Electromagnetic force

The electromagnetic force is responsible for many phenomena we see day-to-day, like a lightning strike, a bulb lighting up, or a magnet sticking to a fridge. It is the interaction of any two charged particles.

The mediator of the electromagnetic force is the photon, the particle of light. This is because light itself is an electromagnetic wave. Whenever two charged particles interact via the [electromagnetic force](#), it occurs through the exchange of photons.

### Nuclear strong force

The nuclear strong force, or strong force, binds quarks to form hadrons. The force carrier for the strong force is the gluon.

This force is responsible for holding the protons and neutrons together in the nucleus of the atoms against the repulsive electromagnetic forces. Therefore, the strong force is much stronger than the electromagnetic force.

## Nuclear weak force

The weak force is seen in [radioactive decay](#) and neutrino interactions. As the name suggests, the nuclear weak force is weaker than the strong and electromagnetic force.

Its weaker strength compared to the other two is its short range. This means that its effects are less noticeable at the macroscopic level.

It is mediated by the W and Z bosons, which are massive particles. This affects the range of interaction of the nuclear weak force (discussed in detail later in the article).

However, the weak force is stronger than the [gravitational force](#), albeit over shorter distances.

## Quantum field theory (QFT)

The Standard Model is built on the mathematical framework of quantum field theory (QFT), combining the principles of quantum mechanics with special relativity.

QFT assumes the fundamental particles are disturbances or excitations (quanta) of their respective [quantum fields](#). The notion is that the quantum fields are the fundamental entities that exist throughout spacetime.

Think of a stone being dropped in a pond or a lake, causing ripples. The waves are the particles, and the water is the quantum field. For instance, photons are quanta of the electromagnetic field, and the quarks and leptons are quanta of their respective quantum fields.

Then we have the Higgs field, which gives rise to the Higgs boson. The Higgs boson has a pivotal role for the fundamental particles.

Enrico Fermi, Richard Feynman, Hans Bethe, and Steven Weinberg are among the contributors to QFT.

## The role of the Higgs field

The Higgs field plays a unique role compared to other quantum fields. While its excitations, like those of other fields, produce a fundamental particle—the Higgs boson—it is distinct in that it imparts mass to fundamental particles.

When the fundamental particles interact with the [Higgs field](#), they gain mass. The more strongly they interact with the Higgs field, the heavier they are.

The W and Z bosons, the carriers of the weak force, interact very strongly with the Higgs field, which is why they are so massive. Conversely, photons do not interact with the [Higgs field](#), which is why they are massless.

Because the photon doesn't have mass, it is the fastest-moving particle in the Universe, traveling at the speed of light ( $c$ ) in a vacuum. This is by Einstein's theory of relativity.

## Higgs boson

The Higgs boson, a physical manifestation of the Higgs field, was first theorized in 1964 through a series of three papers published in [Physical Review Letters](#).

The particle was named after [Peter Higgs](#), the author of one of the papers. Along with François Englert (co-author of one of the papers), he won the Nobel Prize for laying down the theoretical groundwork for the mechanism by which particles acquire mass.

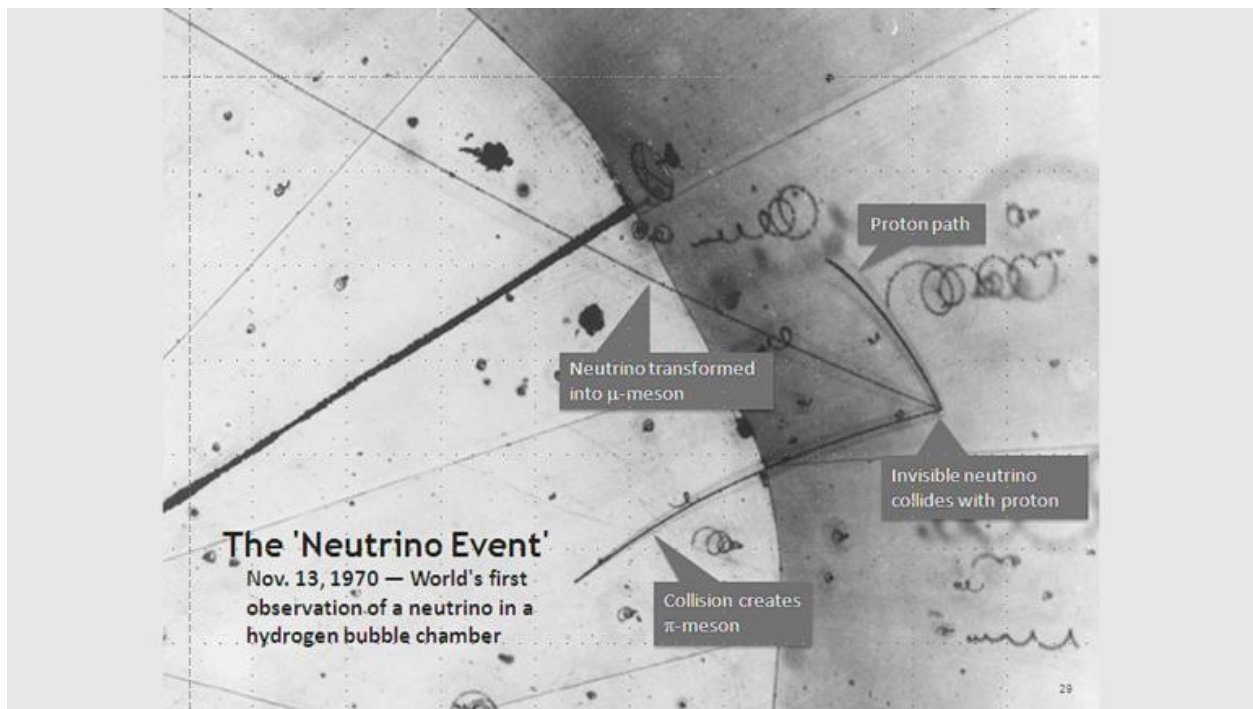
The [Large Hadron Collider](#) at CERN was built to find the Higgs particle and test other predictions made by the Standard Model. In 2012, the ATLAS and CMS experiments confirmed the discovery of the Higgs Boson.

# Predictions and limitations of the Standard Model

Apart from the Higgs boson, the model predicted the force carriers for the strong and weak forces long before their discovery. Two of the quarks (top and charm) were also predicted by the model, and the model has also predicted the behavior of particles in [high-energy collisions](#).

Although the Standard Model successfully unifies three fundamental forces, it is nonetheless limited by several limitations. The most obvious one is its non-inclusion of gravity.

This hinders the efforts to develop a [unified theory of everything](#), which some physicists argue may need to be more idealistic.



The first ever neutrino observation in the 1970s. © Provided by Interesting Engineering

The Standard Model also struggles to explain dark matter and dark energy, which is one of its limitations.

Also unexplained is the dilemma about the neutrino's mass. According to the Standard Model, neutrinos are assumed to be massless particles; however,

experiments and observations have demonstrated that they possess a small, non-zero mass.

The Standard Model also fails to explain the abundance of matter over antimatter ([baryon asymmetry problem](#)).

## **Physics beyond the Standard Model**

The challenges with the Standard Model have prompted the suggestion of several alternate theories. Among the more well-known are [String Theory](#), Loop Quantum Gravity, Supersymmetry, and Grand Unified Theories.

However, they remain “theoretical” frameworks due to insufficient experimental evidence.