The Standard Model of Particle Physics

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Overview of the Standard Model

-The Standard Model incorporates 6 quarks, 6 leptons, 4 gauge bosons, and the Higgs Boson

-There are three families of quarks and leptons, differing from each other by mass

-Gauge bosons act as force carriers. Elementary particles interact with each other by exchanging gauge bosons

-The Higgs Boson is the quantum excitation of the Higgs field, where the Higgs mechanism gives rise to mass

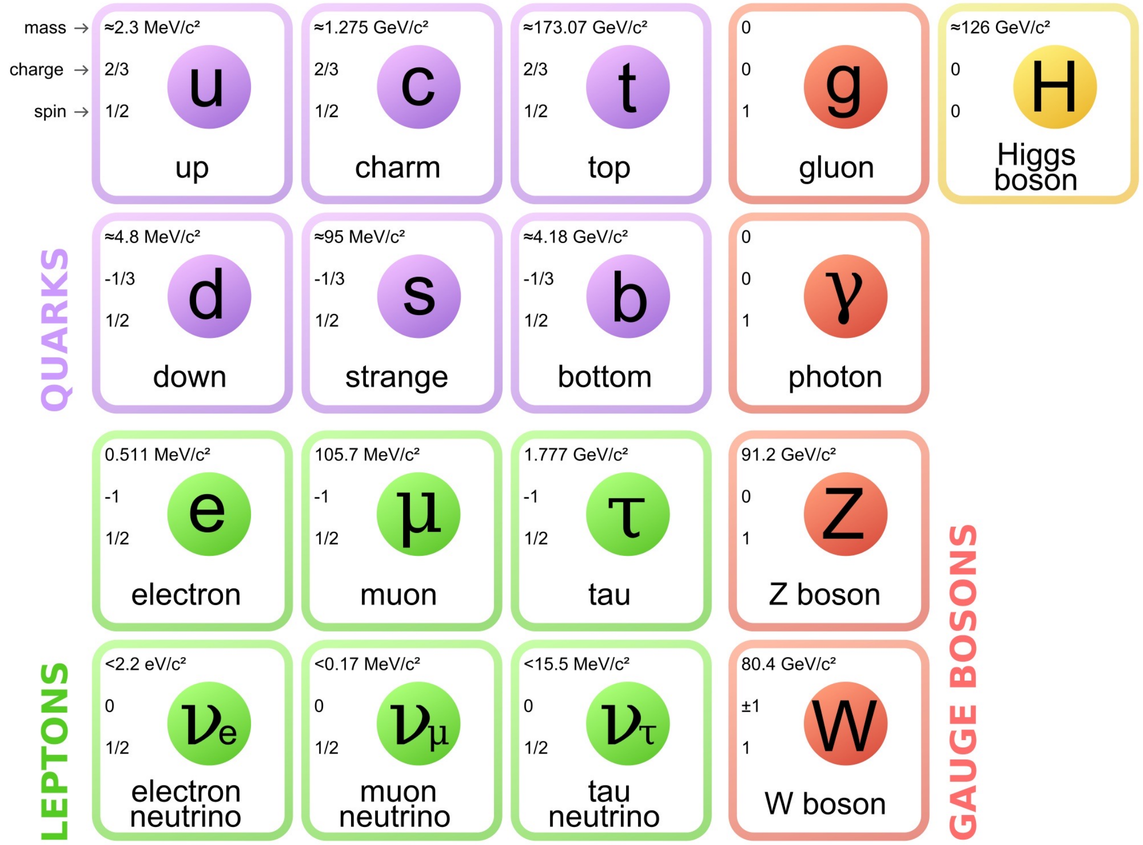


Image from *The Standard Model: a beautiful but flawed theory*, by Pauline Gagnon.

http://www.quantumdiaries.org/2014/03/14/the-standard-model-a-beautiful-but-flawed-theory

Overview of the Standard Model

-Four fundamental forces:

-Strength: Gravity < Weak Force

< Electromagnetism < Strong Force

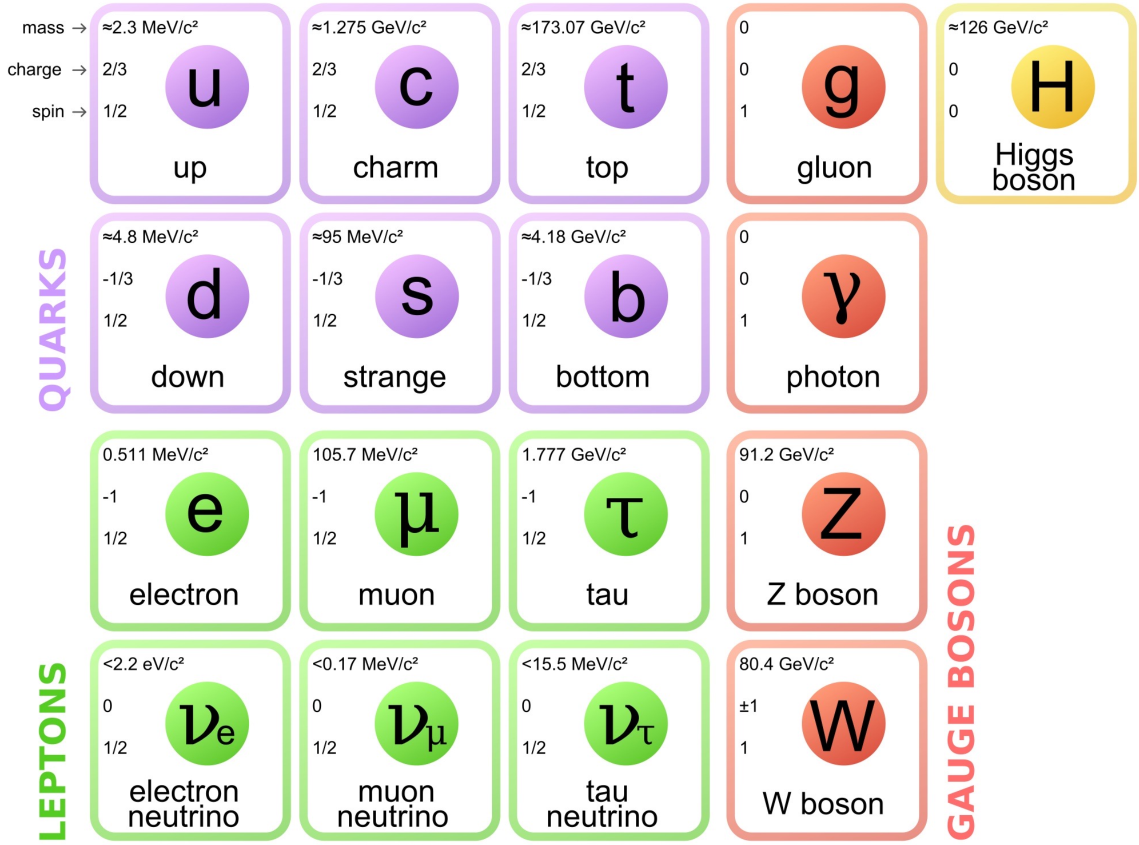
-Force Carriers:

-*Gravity* --- graviton (conjectured)

-Weak Force --- W and Z bosons (observed)

-Electromagnetism --- photon (observed)

-Strong Force --- gluon (permanently confined)



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Overview of the Standard Model

<u>Fermions</u>

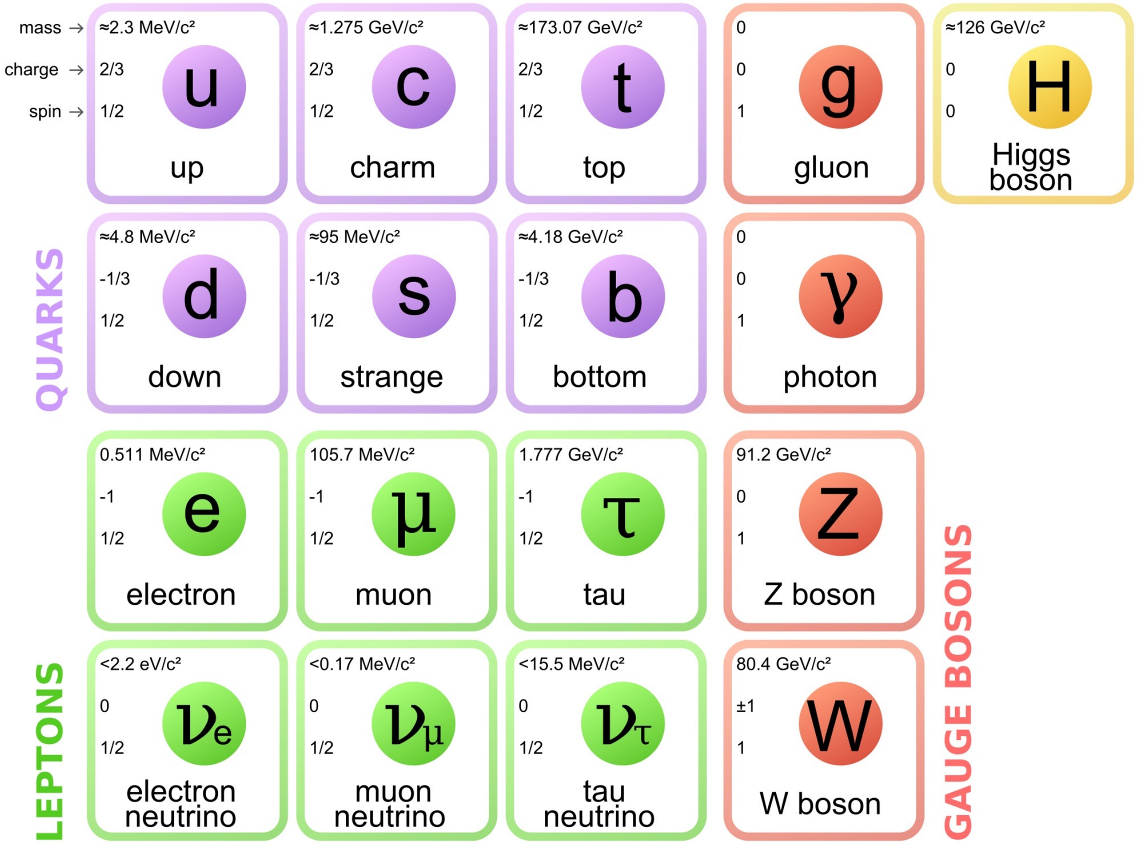
-Have **half-odd-integer spin** (e.g. spin 1/2, 3/2)

-Include all quarks and leptons and all particles made of an odd number of them

<u>Bosons</u>

-Subatomic particles with **integer-value spin**

-Some (g, γ, Z, W) act as force carriers, one (the Higgs Boson) contributes to mass, and others (e.g. mesons) are composite particles



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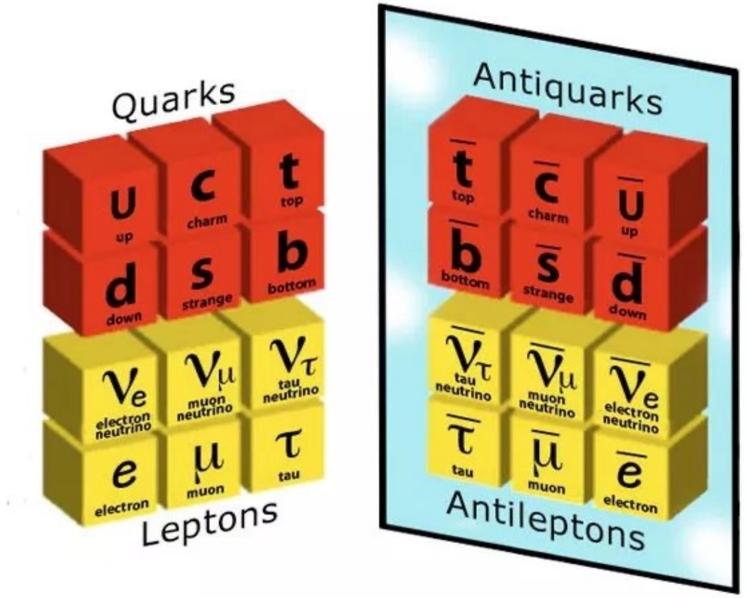
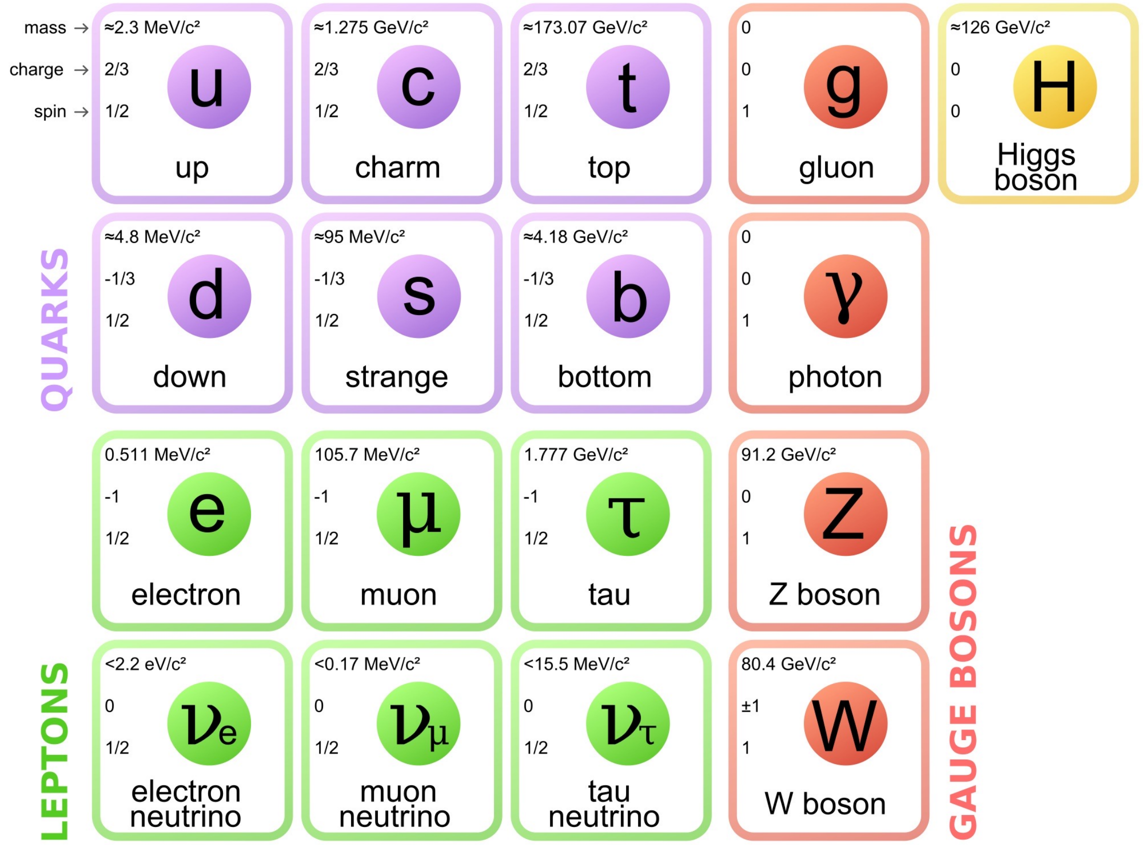
Overview of the Standard Model

-Antiparticles

-Every particle is associated with an **antiparticle** with the same mass and spin but carry opposite values for other properties (e.g. electric charge)





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Leptons

-Particles not affected by the Strong Force

-Lepton numbers

-An additive quantum number

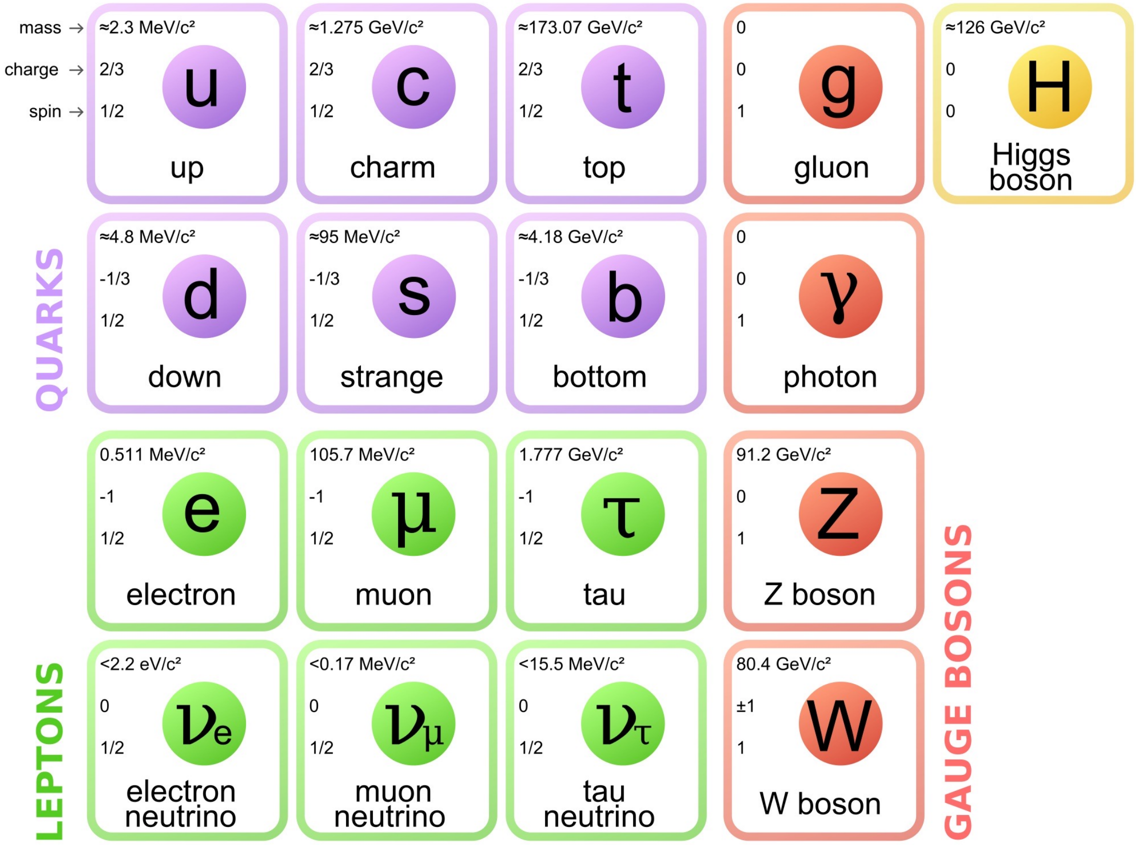
-There are three families of leptons, each with own lepton numbers:

-Electron number: $e^{-}, \nu_{e} \rightarrow +1$ and $e^{+}, \overline{\nu_{e}} \rightarrow -1$

-Similar for Muon/Tau numbers

-The total **lepton number is conserved** during particle processes

-Example: $\mu^{-} \rightarrow e^{-} + \overline{\nu_{e}} + \nu_{\mu}$



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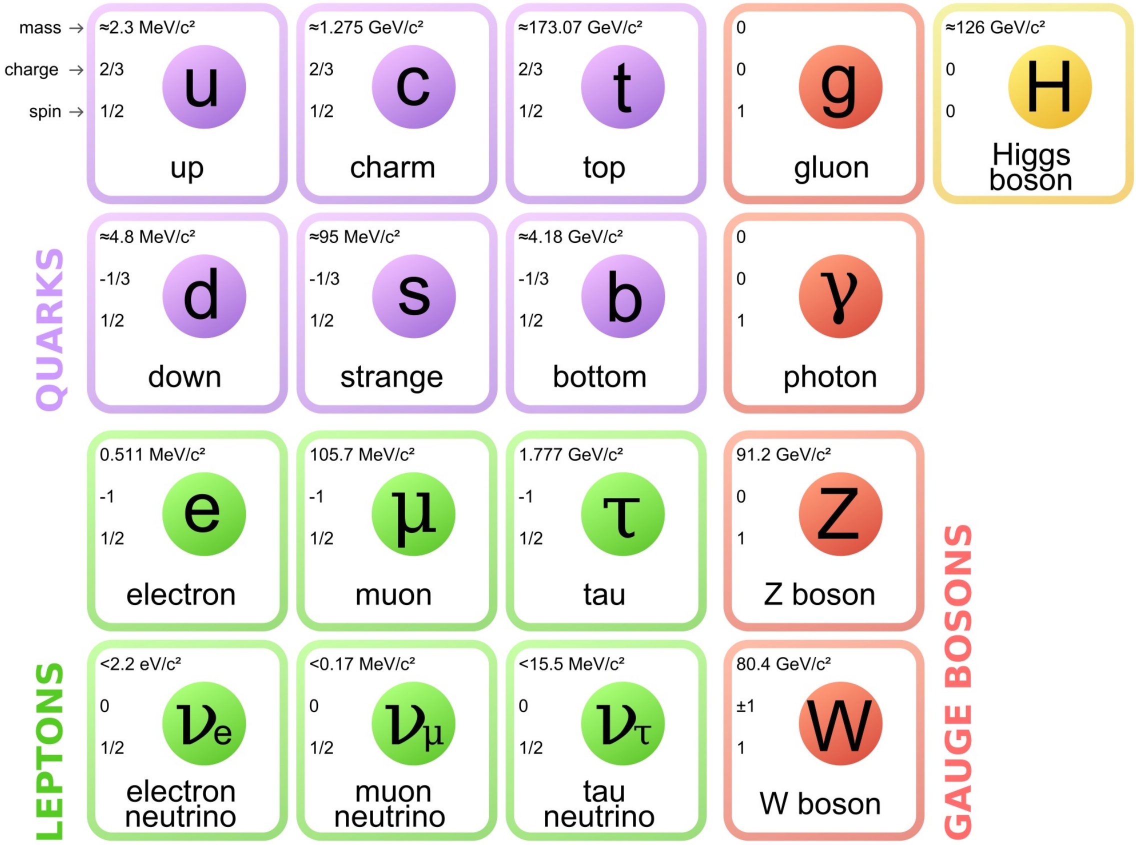
Leptons

-The heavier leptons, muon and tau, are not found in ordinary matter because they are unstable and decay quickly into lighter leptons

-The electron is stable since there is no less massive charged particle into which it can decay (if it decays then it violates the conservation of charge)



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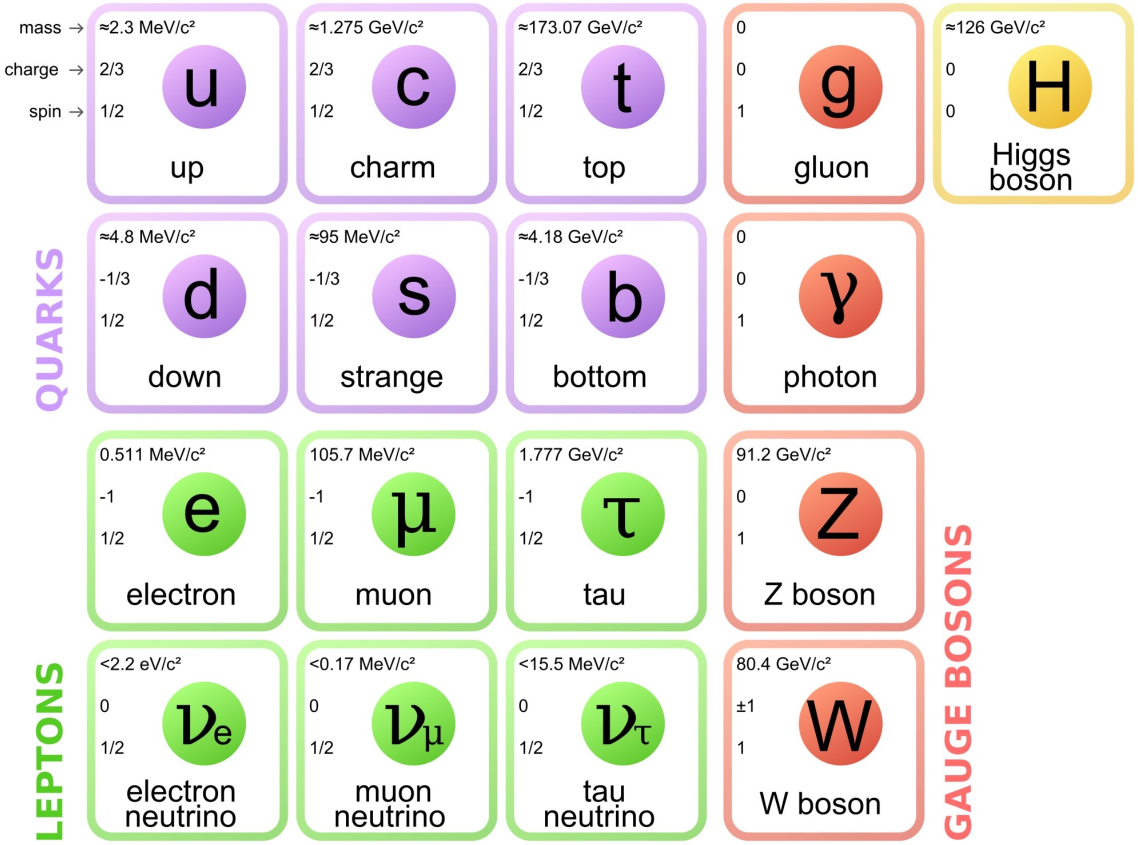
Quarks

-They carry electric charge equal to a precise fraction of an electron's charge

-Quarks form combinations in which the sum of their charges is integer

-Like leptons, quarks experience weak interactions that change flavor

-Example: $n \to p^{+} + e^{-} + \overline{\nu}_e \ (d \to u)$



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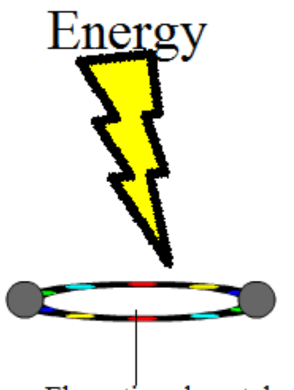
Quarks

-Free quarks have never been observed

-One indication of the soundness of the quark model

is its prediction of electron-positron annihilation



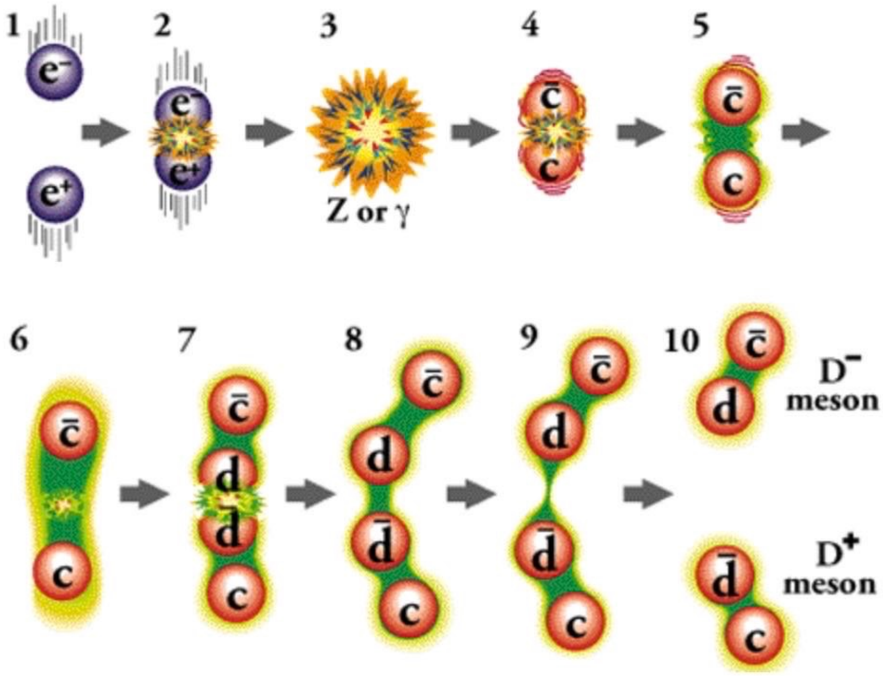


Image from *The Particle Adventure, Particle Decays and Annihilations, Electron/Positron Annihilation*. https://ccwww.kek.jp/pdg/particleadventure/frameless/eedd.html

Hadrons

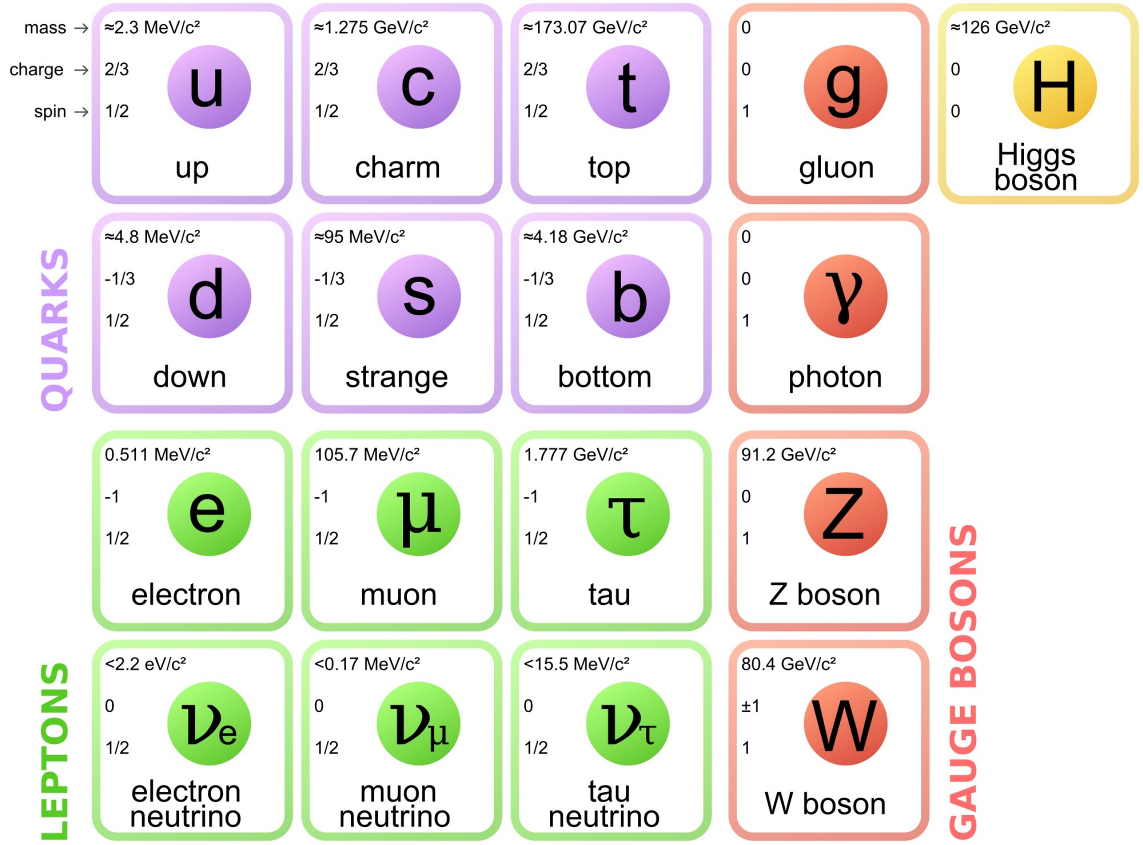
-Composite subatomic particles made of two or more quarks held by the Strong Force

-Protons, neutrons, mesons, etc.

-Quarks form combinations in which the sum of their charges is integer

-Two families of hadrons: **Baryons** and **Mesons**

-No other combinations of quarks (e.g. hadrons that consists of 2 or 4 quarks) have been observed



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Hadrons: Baryons and Mesons

Baryons

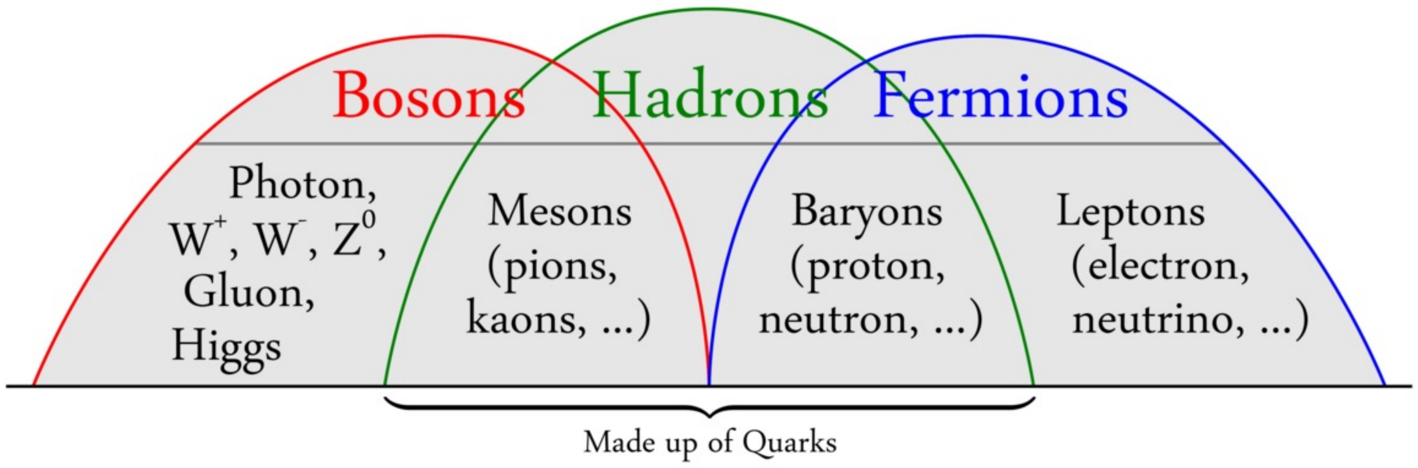
-Composite subatomic particles made of an **odd number of quarks**

-Since quarks are spin-1/2, baryons can only have half-odd-integer spin, so they are **fermions**

Mesons

-Composite subatomic particles made of **one quark and one antiquark**

-Again, since quarks are spin-1/2, mesons can only have integer spin, so they are **bosons**



Quarks and Gluons: Color Charge

-Each flavor of quark can carry one of the three colors:

red, green, or blue

-Each antiquark carries one of the three “anti-colors”:

anti-red, anti-green, or anti-blue

-Gluons are mixtures of two colors, e.g. blue and anti-green

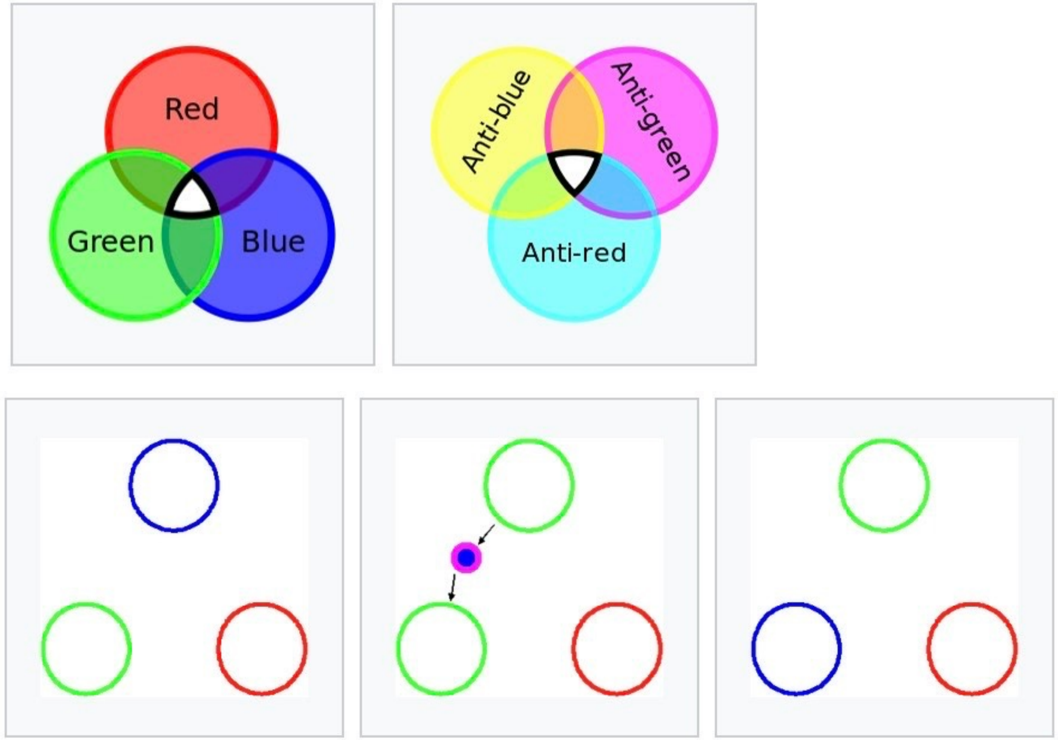


Image from *Color charge, Wikipedia.* https://en.wikipedia.org/wiki/Color_charge

Quarks and Gluons: Color Charge

- A composite particle is “colorless” if

    -Its components are of three different colors/anti-colors

    OR

    -Its components are one color and the corresponding anti-color (e.g. blue + anti-blue)

-The **color confinement** of the Strong Interaction says that free particles must be “colorless” (net color charge of zero)

-This explains why baryons and mesons are the only possible composite of quarks and why free quarks are never observed.

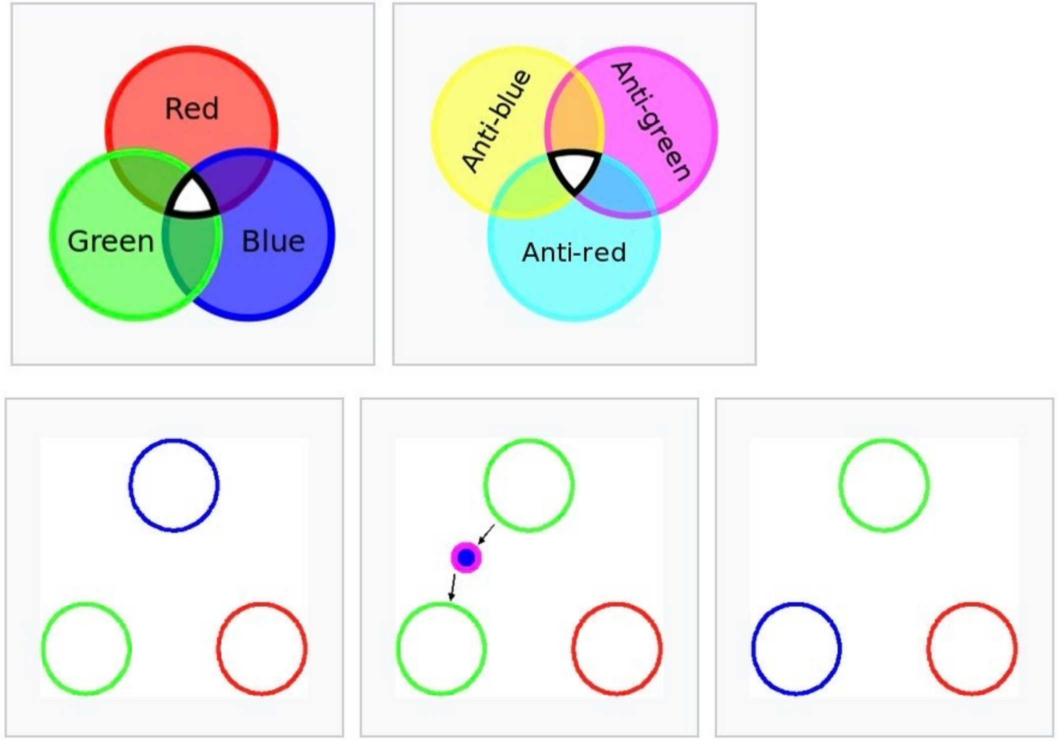


Image from *Color charge, Wikipedia.* https://en.wikipedia.org/wiki/Color_charge

Why is the Standard Model successful?

1) It predicts the existence of the W and Z bosons, the gluon, and the charm and top quarks, all of which are subsequently found and with properties as predicted.

2) It is observed that the electroweak mixing angle is the same everywhere. If the Standard Model were wrong, the angle would have different values for different processes.

3) Every one of the 20 million Z bosons at which the Large Electron-Positron collider has looked decayed in the same manner as the SM has predicted (energies, directions of the outgoing particles, etc.)

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Why must the Standard Model be extended?

1) The Standard Model is incompatible with General Relativity, which describes gravity as a property of spacetime and is the most successful theory of gravity to date.

2) If the universe began in the big bang as a huge burst of energy, it should have evolved into equal parts matter and antimatter. But instead, the stars and nebulae are made of protons, neutrons and electrons and not their antiparticles. This matter asymmetry cannot be explained by the Standard Model.

3) The expansion of the universe was long believed to be slowing down because of the mutual gravitational attraction of all the matter in the universe. We now know that the expansion is accelerating and that whatever causes the acceleration (“dark energy”) cannot be Standard Model physics.

Why must the Standard Model be extended?

4) Dark matter cannot be particles of the Standard Model.

5) The values of the masses of the quarks and leptons (such as the electron and neutrinos) cannot be explained by the Standard Model.

6) The Standard Model has three “generations” of particles. The everyday world is made up entirely of first-generation particles, and that generation appears to form a consistent theory on its own. The Standard Model describes all three generations, but it cannot explain why more than one exists.

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Example of Physics beyond the Standard Model

—— Supersymmetry

-Supersymmetry is a conjectured symmetry of space and time, and an automatic consequence of it is that every particle in the Standard Model has a partner particle.

-Why supersymmetry?

-Interactions between the Higgs Boson and other Standard-Model particles tend to make it very heavy, but it turns out to be very light.

-The extra particles predicted by supersymmetry would cancel out the contribution to the Higgs mass from their Standard-Model partners.

Illustration by Sandbox Studio, Chicago with Steve Shanabruch

Example of Physics beyond the Standard Model

—— Supersymmetry

-Supersymmetry would also link the two different classes of particles known as fermions and bosons. If a particle is a fermion, its super-partner is a boson. If a particle is a boson, its super-partner is a fermion.

-Furthermore, it was proven mathematically that supersymmetry is the only symmetry that can be added to Einstein's Relativity without producing inconsistency with the known Universe.

-Finally, in many theories scientists predict the lightest supersymmetric particle to be stable and electrically neutral and to interact weakly with the particles of the Standard Model. These are exactly the characteristics required for dark matter.

Illustration by Sandbox Studio, Chicago with Steve Shanabruch

Example of Physics beyond the Standard Model

—— Supersymmetry

-Why no supersymmetric particles have been found so far?

-They are too heavy to be produced at current energies of the particle accelerators?

-They are created but escaped detection?

Illustration by Sandbox Studio,
Chicago with Steve Shanabruch

References

[1] Quigg, C. (1985). *Elementary Particles and Forces*. Scientific American (Vol. 252, No. 4, p. 84). Doi:10.1038/scientificamerican0485-84

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[5] Strassler, M. (2011). *Supersymmetry – What Is It?* Of Particular Significance. https://profmattstrassler.com/articles-and-posts/some-speculative-theoretical-ideas-for-the-lhc/supersymmetry/supersymmetry-what-is-it/