Particle Physics

The Basics

- Particle Physics arises from the combination of special relativity and quantum mechanics

Particles are described by a list of properties:

$$E^2 = (\vec{p}c)^2 + (mc^2)^2$$

- Mass, a positive number or zero, describing the minimum energy of the particle
  - Always given in metric multiples of eV/c^2, like MeV/c^2 and GeV/c^2

- Spin, which describes the internal angular momentum of the particle
  - Written as $s\hbar$, but we abbreviate this by just giving s, where $s > 0$
  - s is always an integer (0,1,2,3,…) or half-integer (1/2,3/2,5/2,…)

- Electric charge, which is a multiple of the fundamental charge e
  - We normally give just Q, and the charge is Qe
  - Q is an integer. It can be positive, negative, or zero

- Other properties exist, which we will discuss as they come up

Fermions and Bosons

- *Fermions* are particles that obey the Pauli Exclusion Principle
  - You can't put two of the same kind in the same quantum state
  - Fermions always have half-integer spin

- *Bosons* are particles that violate the Pauli Exclusion Principle
  - They actually *prefer* being in the same quantum state
  - Bosons always have integer spin

Some Particles (masses in MeV/c^2)

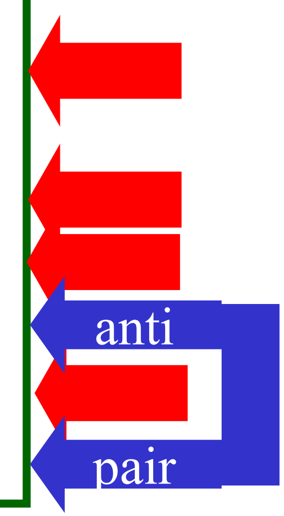
	Name	Sym.	Spin	Q	Mass
Fermions	Proton	p^+	½	+1	938.27
	Neutron	n^0	½	0	939.57
	Electron	e^-	½	-1	0.511
	Neutrino	ν	½	0	$\lesssim 2\times10^{-6}$
Bosons	Photon	γ	1	0	0
	Pi-plus	π^+	0	+1	139.57
	Pi-zero	π^0	0	0	134.98
	Pi-minus	π^-	0	-1	139.57

Anti-Particles

- All particles have anti-particles
- Anti-particles have the same mass and spin, but opposite charge
- Usually named by prefixing with "anti-"
- Some particles are their own anti-particles

For each of the particles below
- **What is the spin, charge, and mass of the anti-particle**
- **Which might be their own anti-particles?**
- **Which might be anti-particles of each other?**

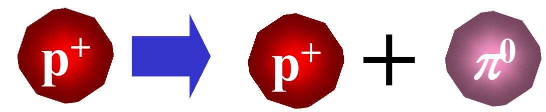
Name	Sym.	Spin	Q	Mass	Spin	Q	Mass
Proton	p^+	½	+1	938.27	½	–1	938.27
Neutron	n^0	½	0	939.57	½	0	939.57
Electron	e^-	½	–1	0.511	½	+1	0.511
Neutrino	ν	½	0	$\lesssim 2\times10^{-6}$	½	0	$\lesssim 2\times10^{-6}$
Photon	γ	1	0	0	1	0	0
Pi-plus	π^+	0	+1	139.57	0	–1	139.57
Pi-zero	π^0	0	0	134.98	0	0	134.98
Pi-minus	π^-	0	–1	139.57	0	+1	139.57



Conservation Laws

Energy and Momentum

- Energy and Momentum are conserved
- We'll use only energy conservation

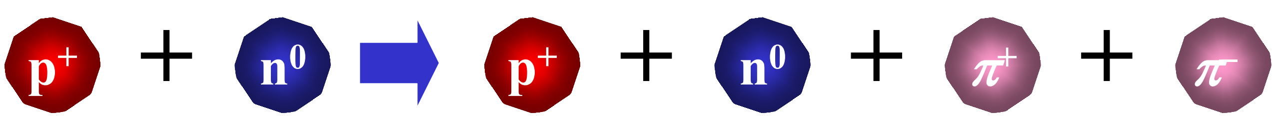


- Energy
- Momentum
- Angular Momentum
- Electric Charge
- Baryon Number
- Strangeness

- Consider a frame where the initial proton is at rest

$$E_i = E_p = m_p c^2 \qquad E_f = E'_p + E_\pi \geq m_p c^2 + m_\pi c^2 > m_p c^2$$

- Is the following interaction possible?



- Energy doesn't preclude it because the particles on the left can have kinetic energy in addition to their rest energy
  - There is not necessarily any frame where these particles are at rest

<u>For decays only</u>: Mass of initial particle must exceed sum of masses of final particles

Angular Momentum

- Total angular momentum is conserved

$$n^0 \rightarrow p^+ + e^-$$

- Consider angular momentum around *z*-axis

$$L_{nz} + S_{nz} = L_{pz} + S_{pz} + L_{ez} + S_{ez}$$

- All of the orbital angular momenta (L's) are integer multiples of $\hbar$

- Because the neutron, proton and electron are all fermions, the internal angular momenta (S's) are all half-integer multiples of $\hbar$

$$n_1\hbar \pm \tfrac{1}{2}\hbar = n_2\hbar \pm \tfrac{1}{2}\hbar + n_3\hbar \pm \tfrac{1}{2}\hbar$$

$$n_1 \pm \tfrac{1}{2} = n_2 \pm \tfrac{1}{2} + n_3 \pm \tfrac{1}{2}$$

- Right side is an integer, left side is not

- Energy
- Momentum
- Angular Momentum
- Electric Charge
- Baryon Number
- Strangeness

Total number of fermions (particles with half-integer spin) on left plus right must be even

Electric Charge

- Electric charge is conserved

Charge is conserved

- Energy
- Momentum
- Angular Momentum
- Electric Charge
- Baryon Number
- Strangeness

Why is the electron stable?

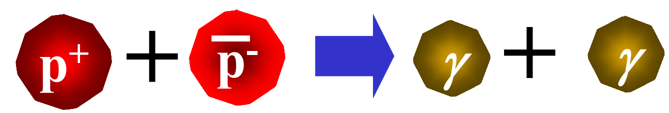
$e^- \Rightarrow$?

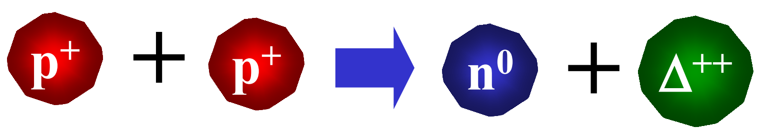
- By energy conservation, whatever is on the right must be lighter
- By charge conservation, something on the right must be charged
- No such particle exists, so electron is stable

Baryon Number

- Energy
- Momentum
- Angular Momentum
- Electric Charge
- Baryon Number
- Strangeness

- Consider nuclear reactions
  - β^- decay: $(Z,A) \rightarrow (Z+1,A)$
  - β^+ decay: $(Z,A) \rightarrow (Z-1,A)$
  - α decay: $(Z,A) \rightarrow (Z-2,A-4) + (2,4)$
  - γ decay: (Z,A)* → (Z,A)
- Total protons plus neutrons (call this baryons) remains constant?
- Maybe anti-protons count as negative baryons?





Baryon number is conserved

- Maybe there are other particles that count as baryons too?
- There are a group of particles called *baryons*
  - They each have baryon number +1
- For every baryon, there is an anti-baryon
  - They each have baryon number –1

Why is the proton stable?

- There is no lighter baryon

Baryons, Anti-Baryons, and Mesons

- The strong nuclear force is what holds the nucleus together
  - It is must be strong and fast to do so
- Some particles (photon, electron, neutrino) do not seem to be affected by it

The particles that feel strong forces come in three categories:

- *Baryons* have baryon number +1
- *Anti-baryons* are their anti-particles and have baryon number –1
- *Mesons* have baryon number 0
  - Anti-mesons are mesons

Reactions that occur very quickly are believed to be mediated by this strong force

- The rho-mesons, for example, decay very fast

$\rho^+ \Rightarrow \pi^+ + \pi^0$ $\quad t \approx 4\times10^{-24}\ \text{s}$

A strong interaction

- The kaons, by comparison, decay very slowly

$K^+ \Rightarrow \pi^+ + \pi^0$ $\quad t \approx 1.24\times10^{-8}\ \text{s}$

A weak interaction

Strangeness

- Energy
- Momentum
- Angular Momentum
- Electric Charge
- Baryon Number
- Strangeness

- Why do some reactions involving strongly interacting particles occur so slowly?
- It was speculated that some baryons and mesons had a property called *strangeness* that also had to be violated only in weak interactions

Strangeness is conserved in all interactions except weak interactions

Symbol	S
ρ^+, ρ^0, ρ^-	0
π^+, π^0, π^-	0
K^+, K^0	+1
$K^-, \overline{K^0}$	-1
p^+, n^0	0
$\Sigma^+, \Sigma^0, \Sigma^-$	-1
Λ^0	-1
Ξ^0, Ξ^-	-2

Important notes:

- Strangeness *only* applies to strongly interacting particles; other particles have $S = 0$
- Strangeness can *only* be changed by weak interactions
- The strangeness of an anti-particle is the opposite of the strangeness of the particle

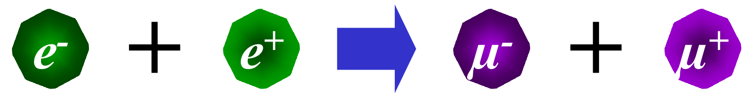
Types of Interactions

THE STRONG FORCE

- Involves only strongly interacting particles: baryons, anti-baryons, and mesons
- Conserves strangeness

ELECTROMAGNETISM

- Affects all charged particles
- Always involves photons (though this isn't always obvious)



THE WEAK FORCE

- Affects essentially all particles except photons
- The only force that affects neutrinos
- The only force that violates strangeness

Which force is at work in a given reaction?

- The stronger a force is, the more likely it is to be at work
  - Strong > Electromagnetism > Weak

Which Force?

A step-by-step procedure for determining which force is at work

- If charge conservation is violated → Impossible
- Else if baryon number is violated → Impossible
- Else if odd # fermions (left + right) → Impossible
- Else if decay <u>and</u> insufficient energy → Impossible
- Else if strangeness violated → Weak
- Else if all particles are strong → Strong
- Else if neutrinos are involved → Weak
- Else → Electromagnetism

Sample Problems

Classify the reactions below:

$p^+ + K^- \rightarrow \Xi^0 + K^0$

Strong

- Charge: (+1) + (-1) = 0 + 0 ☑
- Baryons: (+1) + 0 = (+1) + 0 ☑
- Fermions: [1+0] + [1+0] = 2 = even ☑
- Not a decay ☑
- Strangeness: 0 + (-1) = (-2) + (+1) ☑
- All particles are strong ☑

$\Sigma^0 \rightarrow \Lambda^0 + e^+ + e^-$

Electromagnetism

- Charge: 0 = 0 + (+1) + (-1) ☑
- Baryons: (+1) = (+1) + 0 + 0 ☑
- Fermions: [1] + [1+1+1] = 4 = even ☑
- Energy: 1193 > 1116 + 0.5 + 0.5 ☑
- Strangeness: 1 = 1 + 0 + 0 ☑
- All particles are strong ☒
- Neutrinos are involved ☒

$\overline{n}^0 \rightarrow \overline{p}^- + e^+$

(the $\overline{n}^0$ and the $\overline{p}^-$ are the anti-particles of the neutron and proton)

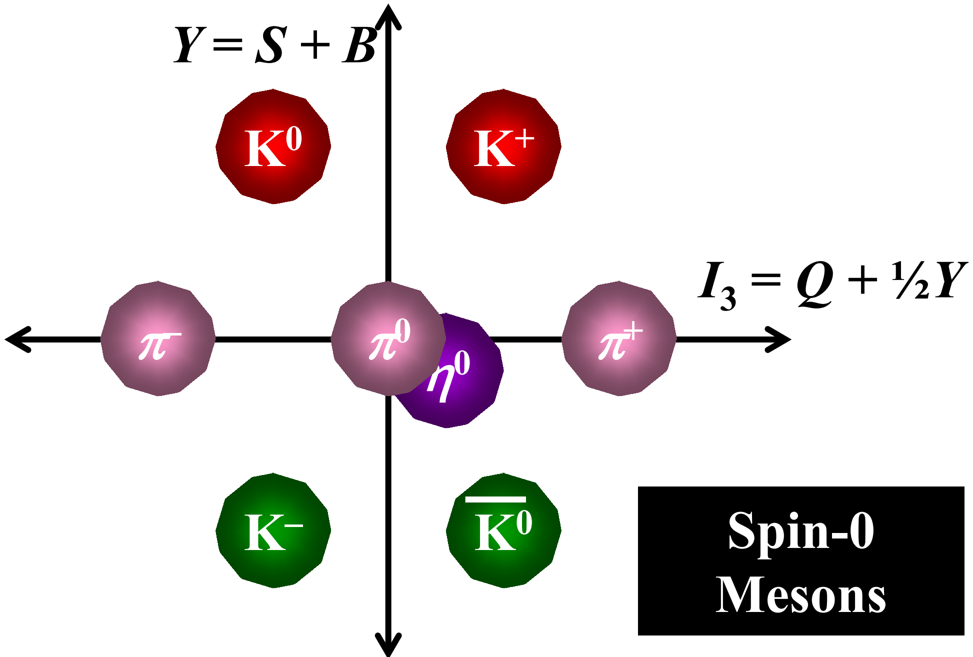
- Charge: 0 = (-1) + (+1) ☑
- Baryons: (-1) = (-1) + 0 ☑
- Fermions: [1] + [1+1] = 3 = odd ☒

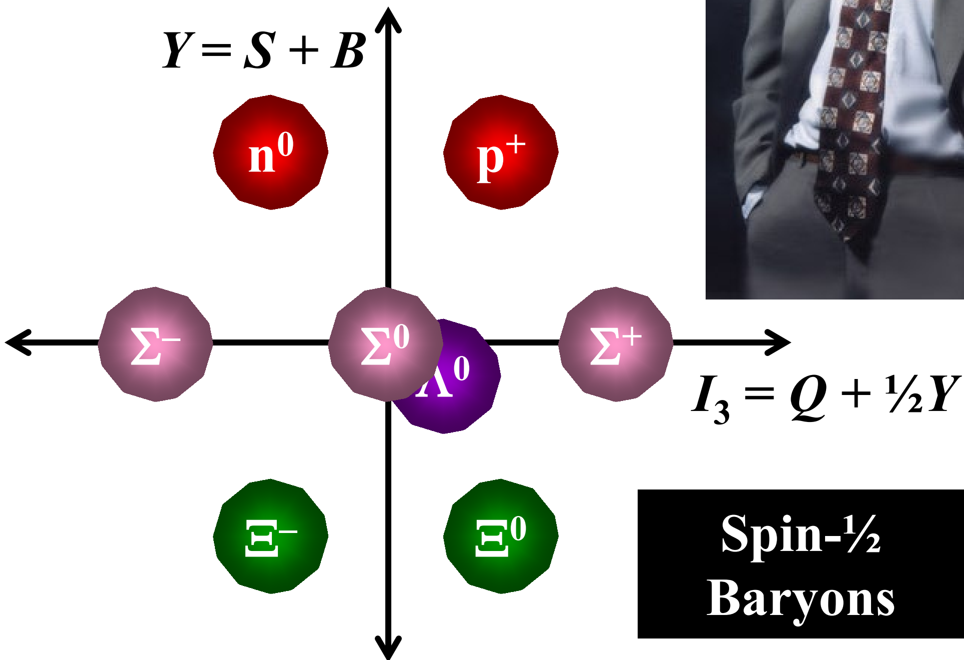
Impossible

The Standard Model

Patterns in Baryons and Mesons

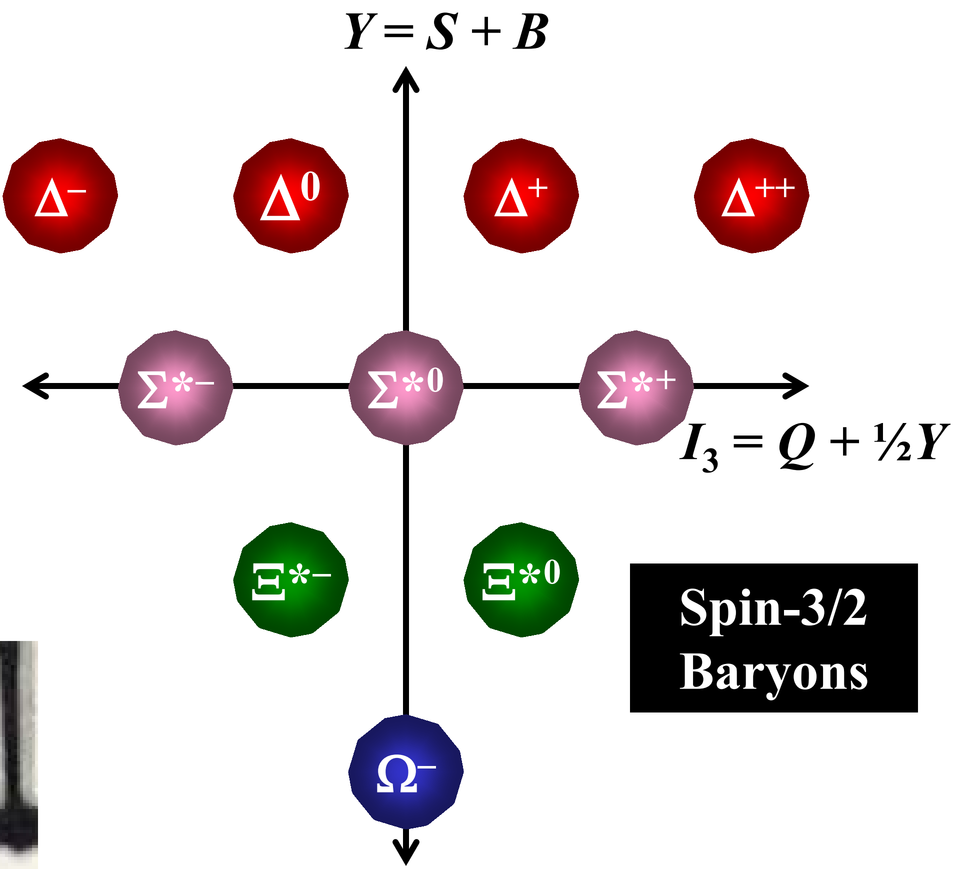
- In the 50's and 60's, the number of baryons and mesons was growing out of control
  - There are currently hundreds known
- In 1961, Murray Gell-Mann noticed a series of mathematical relationships between the various particles





Quarks

- In 1962, based on the patterns, Gell-Mann predicted a new particle, the Ω^-



- In 1964, Gell-Mann and George Zweig independently proposed that all these particles could be explained if there were underlying particles called *quarks*
  - There were three of them, and in baryons, they always come in threes
- There are also anti-quarks for every quark

Quark	Spin	charge	*S*
u Up	½	+2/3	0
d Down	½	–1/3	0
s Strange	½	–1/3	–1

anti-Quark	Spin	charge	*S*
$\bar{u}$ anti-Up	½	–2/3	0
$\bar{d}$ anti-Down	½	+1/3	0
$\bar{s}$ anti-Strange	½	+1/3	+1

Baryons and Mesons from Quarks

- To make a baryon, combine three quarks
- To make an anti-baryon, combine three anti-quarks
- To make a meson, combine a quark and an anti-quark

- Composition can generally be determined from strangeness and charge

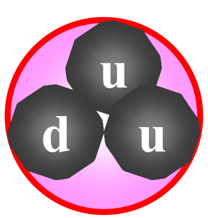
	Quark	Spin	charge	*S*
u	Up	½	+2/3	0
d	Down	½	–1/3	0
s	Strange	½	– /3	–1

What is a proton made from?

- It is a baryon: three quarks
- It has strangeness 0, so no strange quarks
- It has charge +1, so to get this, must take:

$$+\tfrac{2}{3}+\tfrac{2}{3}-\tfrac{1}{3}=+1$$

p^+ = [uud]

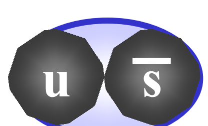


What is a K^+ made from?

- It is a meson: quark + anti-quark
- It has strangeness +1, so must have an anti-strange quark
- To get charge +1, the other quark must have charge +2/3

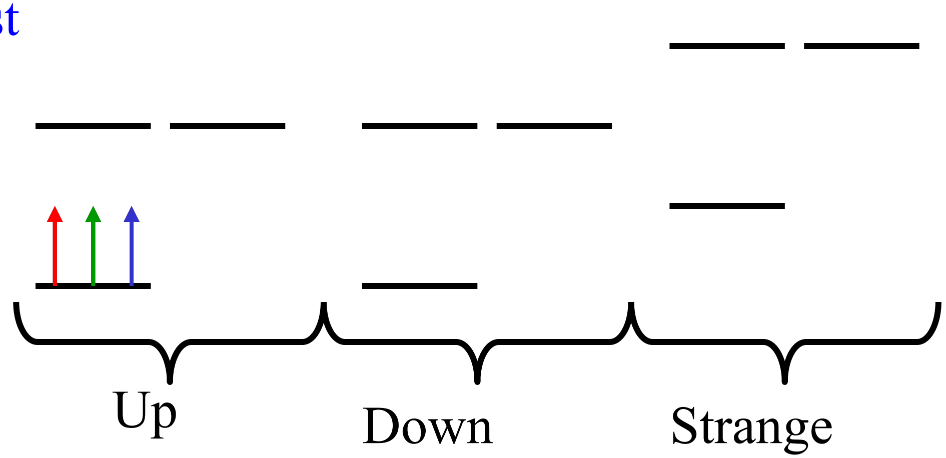
$$-\left(-\tfrac{1}{3}\right)+\tfrac{2}{3}=+1$$

$K^+ = [u\bar{s}]$



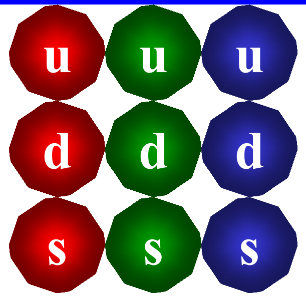
The Problem with Quarks

- Can we "predict" which baryons and mesons are lightest from the quark model?
- How about, say, the Δ^{++}?
  - Spin 3/2, three up quarks
- Seems to violate Pauli principle
- Some people abandoned the quark model, others, in desperation, dreamed up color



Color

- Maybe there is another property, call it color, that describes an individual quark
- Need three colors: typically called red, green, and blue
- Every type of quark comes in three colors
- You must always combine quarks in colorless combinations
- Anti-quarks come in anti-red, anti-green, and anti-blue
- Everything worked fine, but looked awfully arbitrary



The Secret of the Strong Force

- Where does the arbitrary rule, "make it colorless" come from?
- Consider, by analogy, atoms:
  - Electrons and nuclei have a property called "charge"
  - However, atoms are *almost always* neutral, they are "charge-free"
- This is because there is a force (electromagnetism) mediated by a particle (the photon) that prefers when charges cancel out

- Maybe color is associated with a new force that also prefers colorless combinations

- Particles called "gluons" carry the real strong force back and forth between the three quarks in a baryon or quark and anti-quark in a meson

More About the Strong Force

- The real strong force is this force between quarks, mediated by gluons
  - There are eight different gluons in all (don’t worry about it)
- The force we have been calling the “strong” force is just a weaker version of it
  - Analogy – nuclear force : strong force :: chemistry : electric force
- All calculations are <u>very difficult</u> involving the strong force
  - “Perturbation theory,” the usual technique, fails
- A few conclusions have been drawn from the theory
  - Quark confinement – quarks never escape
  - The force gets weaker – slowly – at very high energies
  - Only colorless combinations – baryons, mesons, anti-baryons – are possible
  - The type of quark – like strange quarks – weren’t changed; this is why strangeness is conserved
- With the advent of modern supercomputers, we are getting good match of theory and experiment

Two Down, One to Go

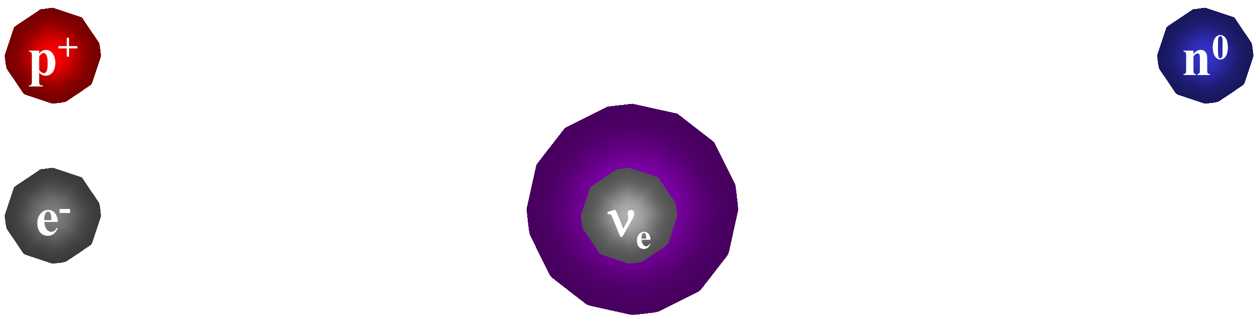
- The **electromagnetic force** was the first to be described quantum mechanically
  - Quantum Electrodynamics (QED) is the most accurately tested theory, ever

- The **strong force** was successfully described in terms of colors and gluons
  - Quantum Chromodynamics (QCD) is now pretty well tested

- The **weak force** was still being worked on
  - Actually, much of this work was simultaneous with strong force

Clues to the Weak Force

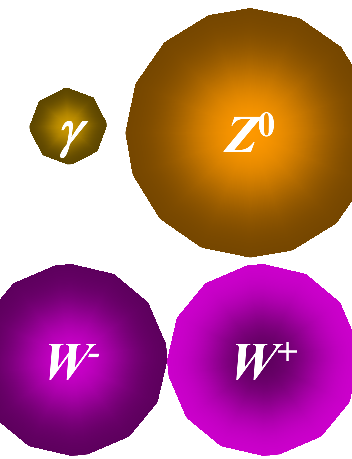
- The **<u>weak force</u>** changed the nature of particles in a more fundamental way than did the strong or the electromagnetic force
- It had a very short range, which is why it was so weak
- It was guessed it also involved exchange of a particle
  - Called the $W^{\pm}$, it was apparently <u>very</u> massive
  - It changed particles into ones with different identities



- Weak interactions changed the electron into an electron neutrino
  - This worked fine
  - These two particles were called leptons
- Another pair of leptons had also been discovered
  - The muon and muon neutrino were two more leptons
  - Just like the electron, but heavier

The Electroweak Theory

- During the 1960's, the modern electroweak theory was developed
  - It is a partial unification of the electromagnetic and weak forces
- In 1960 Sheldon Glashow proposed that the theory could be understood if there were also another neutral massive particle called the *Z*

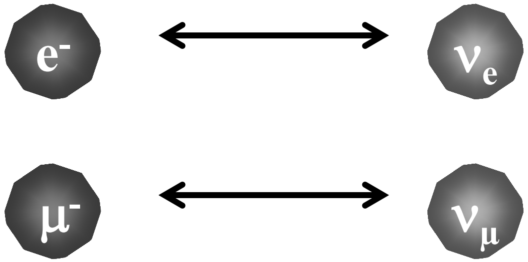


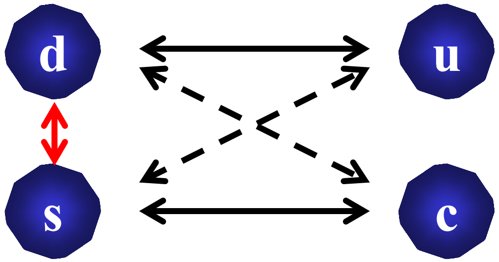
- There were theoretical problems with this approach
  - The *W*'s and *Z*'s were not massless like the photon
  - The *W*'s were connecting particles of different masses
- In 1967, Steven Weinberg and Abdus Salam independently proposed a solution to these problems

- The mass of the *W* and the *Z*, as well as all the quarks and leptons, had to come from a background field that pervades the universe, now called the Higgs field

Weak Interactions in the Quark Sector

- In the leptons, we had two charged leptons and two neutrinos
- Emission or absorption of a $W^{\pm}$ could convert them back and forth





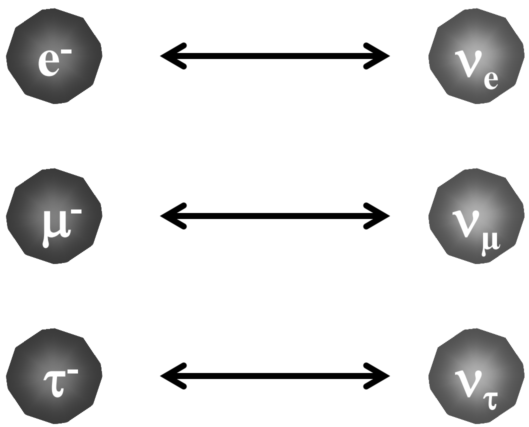
- In the quarks, we had three quarks
- Emission or absorption of a $W^{\pm}$ could convert them back and forth, but not equally
- The Z particle should also cause transitions that don't change the charge
  - This should cause d ←→ s transitions
  - But they weren't observed

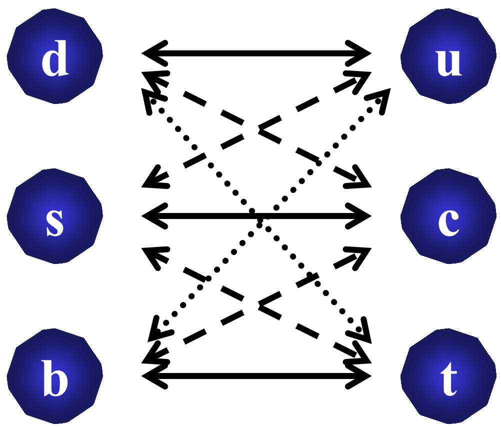
- In 1970, Glashow, Iliopoulos and Maiani found a solution
  - They had to assume there was a fourth quark, called charm

- In 1974, the charmed quark was discovered by Richter and Ting

The List Grows . . . But Not Forever

- In 1975, a new lepton was discovered, named the τ
  - It is just like the electron and muon, only heavier





- There was associated evidence for a new neutrino
  - Finally proven in 2001

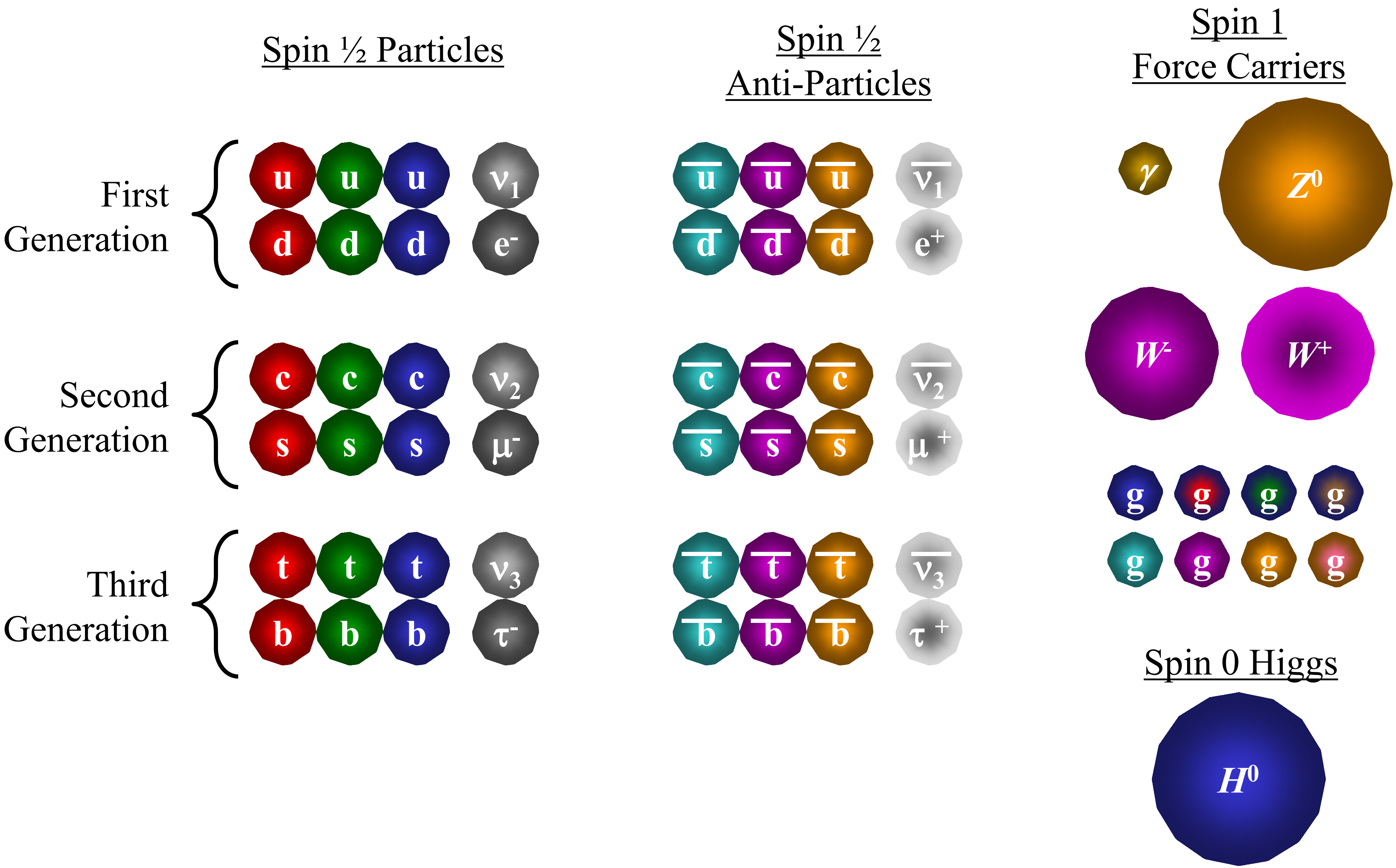
- Complicated arguments suggested it was likely there was another pair of quarks, too
  - Bottom quark (originally beauty) discovered in 1977
  - Top quark (originally truth) discovered in 1995

- Around 1989, measurements of the *Z* established that there were no new neutrinos
  - We now think this means we didn't miss anything

All Standard Model Particles

		Particle	symbols	spin	charge	Mass (MeV/c^2)
Fermions (add anti-particles)	leptons	Electron	e^-	½	-1	0.511
		Neutrino 1	ν_1	½	0	0?
		Muon	μ^-	½	-1	105.7
		Neutrino 2	ν_2	½	0	9×10^{-9} ?
		Tau	τ_μ	½	-1	1777
		Neutrino 3	ν_3	½	0	5×10^{-8} ?
	quarks	Up quark	*uuu*	½	+2/3	3
		Down quark	*ddd*	½	-1/3	5
		Charm quark	*ccc*	½	+2/3	1,300
		Strange quark	*sss*	½	-1/3	120
		Top quark	*ttt*	½	+2/3	174,200
		Bottom quark	*bbb*	½	-1/3	4,300
force carriers		Photon	γ	1	0	0
		Gluon	*gggggggg*	1	0	0
		W-boson	$W^\pm$	1	±1	80,400
		Z-boson	Z^0	1	0	91,188
		Higgs	H	0	0	125,100

All Standard Model Particles



The Standard Model Lagrangian:

What part of

$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} - \tfrac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \tfrac{1}{2}W^{+}_{\mu\nu}W^{-\mu\nu} - \tfrac{1}{4}G^{(a)}_{\mu\nu}G^{(a)\mu\nu} + \sum_f \overline{\psi}_f\left(i\gamma^{\mu}D_{\mu} - m_f\left(1+\frac{H}{v}\right)\right)\psi_f$$

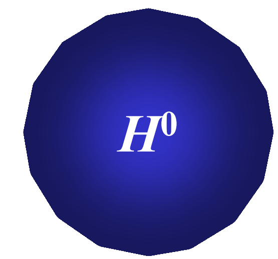
$$+\left(m_W^2 W^{+}_{\mu}W^{-\mu} + \tfrac{1}{2}m_Z^2 Z_{\mu}Z^{\mu}\right)\left(1+\frac{H}{v}\right)^2 + \tfrac{1}{2}\partial_{\mu}H\partial^{\mu}H - \tfrac{1}{2}m_H^2 H^2\left(1+\frac{H}{2v}\right)^2$$

don’t you understand?

What's Missing?

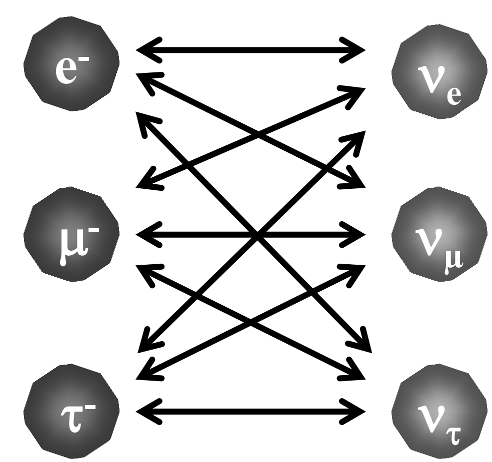
- There are 18 numbers in this theory that must be put in by hand
  - 9 quark and lepton masses
  - 3 strengths of the forces (strong, weak, electromagnetic)
  - 4 describing the mixings in weak interactions
  - 2 describe the mass and strength of the Higgs field

- The Higgs particle: discovery announced July 4, 2012



- The three neutrinos are massless in the standard model
  - Experimental evidence for masses and mixing

- It is easy to fix this – too easy



Gravity

Outline of History of Universe

Time	T or $k_B T$	Events
10^{-43} s	10^{18} GeV	Planck Era; time becomes meaningless?
10^{-39} s	10^{16} GeV	Inflation begins; forces unified
10^{-35} s	10^{15} GeV	Inflation ends; reheating; forces separate; baryosynthesis (?)
10^{-13} s	1500 GeV	Supersymmetry breaking, LSP (dark matter)
10^{-11} s	160 GeV	Electroweak symmetry breaking
14 μs	150 MeV	Quark Confinement
0.4 s	1.5 MeV	Neutrino Decoupling
1.5 s	0.7 MeV	Neutron/Proton freezeout
20 s	170 keV	Electron/Positron annihilation
200 s	80 keV	Nucleosynthesis
57 ky	0.76 eV	Matter-Radiation equality
370 ky	0.26 eV	Recombination
600 My	30 K	First Structure/First Stars
13.8 Gy	2.725 K	Today

Known Particle Physics

The Era of Particle Physics

More Particles Become Relevant

- At temperatures of 0.2 – 30 MeV, photons, neutrinos, and electrons (and their anti-particles) are effectively massless, and appear in high numbers
- Above 35 – 50 MeV (~0.3 ms) the muons and pions are relevant
- The pions are strongly interacting, and start to affect how all strongly interacting particles appear
- Theory says that the strong force becomes weaker at higher energy
- At 150 MeV quarks shift from being trapped in baryons and mesons to being free
    - Universe is filled with "quark soup"

Quark Confinement

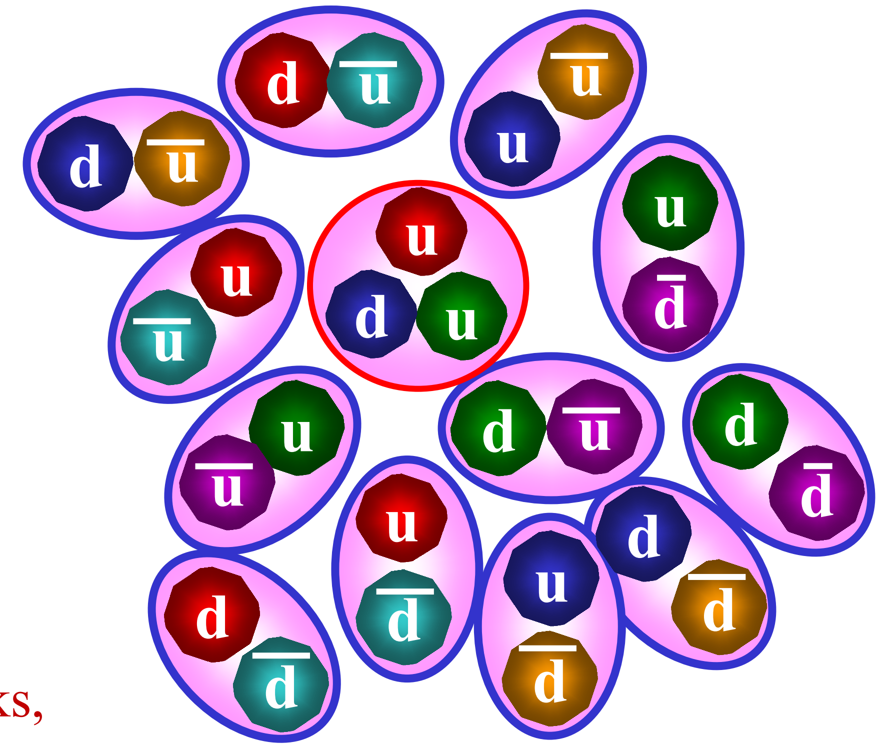
- At low temperatures (< 40 MeV) just an occasional baryon

- At 45 MeV, pions start to appear
- At 150 MeV, the pions are so thick that they start overlapping with each other
- Quarks can jump from one pion to the next

- Strong force gets weaker at higher energy
  - Effectively confinement doesn't apply

- Quarks go from free to confined at 150 MeV

- At this temperature there are up, down, and strange quarks, and gluons
- In addition to the photons, neutrinos, electrons, and muons



Time	T or $k_B T$	Events
14 μs	150 MeV	Quark Confinement

$$t = \frac{2.42\ \text{s}}{\sqrt{g_{\text{eff}}}}\left(\frac{\text{MeV}}{k_B T}\right)^2 = \frac{2.42\ \text{s}}{\sqrt{61.75}}\left(\frac{\text{MeV}}{150\ \text{MeV}}\right)^2$$

$$= 1.4\times 10^{-5}\ \text{s}$$

Particles in the Early Universe

$$g_{\text{eff}} = g_b + \tfrac{7}{8} g_f$$

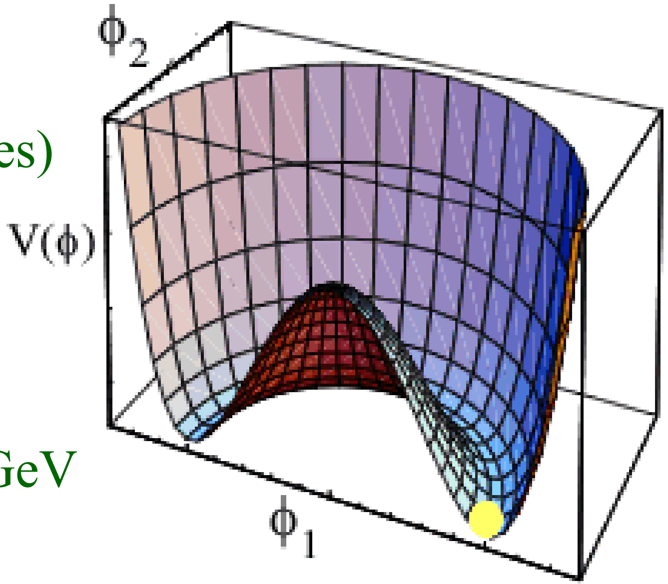
- For $k_B T < 150$ MeV, quarks are bound and it's complicated
- Above 150 MeV, all particles are in thermal equilibrium
- As temperature rises, particles get included when $3k_B T > mc^2$
- For 150 – 400 MeV, include e, μ, u, d, s, ν_1, ν_2, ν_3, γ, and g
- At 400 MeV, add c; at 600 add τ
- At 1.5 GeV add b
- At 30 GeV, add W and Z
- At 40 GeV, add H; at 60 add t
- Above 60 GeV, we have

$$g_{\text{eff}} = 28 + \tfrac{7}{8}(90) = 106.75$$

Particle	symbols	spin	g	mc^2 (MeV)
Electron	e	½	4	0.511
Neutrino 1	ν_1	½	2	~0
Up quark	uuu	½	12	~5
Down quark	ddd	½	12	~10
Muon	μ	½	4	105.7
Neutrino 2	ν_2	½	2	~0
Charm quark	ccc	½	12	1,270
Strange quark	sss	½	12	~100
Tau	τ	½	4	1,777
Neutrino 3	ν_3	½	2	~0
Top quark	ttt	½	12	173,000
Bottom quark	bbb	½	12	4,700
Photon	γ	1	2	0
Gluon	$gggggggg$	1	16	0
W-boson	W	1	6	80,400
Z-boson	Z	1	3	91,200
Higgs	H	0	1	125,100

Electroweak Phase Transition

- There are three forces that particle physicists understand:
  - Strong, electromagnetic, and weak
- Electromagnetic and weak forces affected by a field called the *Higgs field*
- The shape of the Higgs potential is interesting:
  - Sometimes called a Mexican Hat potential



- At low temperatures (us), one direction is easy to move (EM forces) and one is very hard (weak forces)
- At high temperatures, (early universe) you naturally move to the middle of the potential
- All directions are created equal
- Electroweak unification becomes apparent at perhaps $k_B T = 160$ GeV

$$t = \frac{2.42\text{ s}}{\sqrt{g_{\text{eff}}}}\left(\frac{\text{MeV}}{k_B T}\right)^2 = \frac{2.42\text{ s}}{\sqrt{106.75}}\left(\frac{\text{MeV}}{160{,}000\text{ MeV}}\right)^2 \approx 10^{-11}\text{ s}$$

Time	T or $k_B T$	Events
10^{-11} s	160 GeV	Electroweak Symmetry Breaking

Outline of History of Universe

Time	T or $k_B T$	Events
10^{-43} s	10^{18} GeV	Planck Era; time becomes meaningless?
10^{-39} s	10^{16} GeV	Inflation begins; forces unified
10^{-35} s	10^{15} GeV	Inflation ends; reheating; forces separate; baryosynthesis (?)
10^{-13} s	1500 GeV	Supersymmetry breaking, LSP (dark matter)
10^{-11} s	160 GeV	Electroweak symmetry breaking
14 μs	150 MeV	Quark Confinement
0.4 s	1.5 MeV	Neutrino Decoupling
1.5 s	0.7 MeV	Neutron/Proton freezeout
20 s	170 keV	Electron/Positron annihilation
200 s	80 keV	Nucleosynthesis
57 ky	0.76 eV	Matter-Radiation equality
370 ky	0.26 eV	Recombination
600 My	30 K	First Structure/First Stars
13.8 Gy	2.725 K	Today

Unknown Particle Physics