INTRODUCTION TO PARTICLE PHYSICS

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Web resources

- **http://particleadventure.org/index.html**
  - Especially designed for a very wide audience
  - A lot of links from this web page –please try as many as you can
- **http://quarknet.fnal.gov/**
  - Again, a lot of links from this web page – to modern experiments, and to more practical materials
- **http://eddata.fnal.gov/lasso/quarknet_g_activities/detail.lasso?ID=18**
  - This is specific link from the previous web page that I consider as a most important for implementation of an information about particle physics into your sillabus

What is particle physics or HEP?

- Particle physics is a branch of physics that studies the elementary constituents of matter and radiation, and the interactions between them. It is also called "high energy physics", because many elementary particles do not occur under normal circumstances in nature, but can be created and detected during energetic collisions of other particles, as is done in particle accelerators
- Particle physics is a journey into the heart of matter.
- Everything in the universe, from stars and planets, to us is made from the same basic building blocks - particles of matter.
  Some particles were last seen only billionths of a second after the Big Bang. Others form most of the matter around us today.
- Particle physics studies these very small building block particles and works out how they interact to make the universe look and behave the way it does

What is the universe made of?

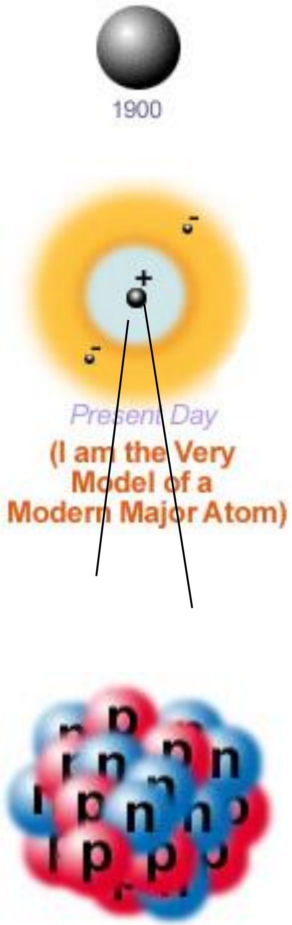
- **A very old question, and one that has been approached in many ways**
- **The only <u>reliable</u> way to answer this question is by directly enquiring of nature, through experiments**
  - not necessarily a “natural human activity”, but perhaps the greatest human invention
- **While it is often claimed that humans display a natural curiosity, this does not always seem to translate into a natural affinity for an experimental approach**
  - Despite hundreds of years of experience, science is not understood, and not particularly liked, by many people
  - often tolerated mainly because it is useful
  - Something to think about, especially when we are trying to explain scientific projects that do not, a priori, seem to be useful

Experiment has taught us:

- **Complex structures in the universe are made by combining simple objects in different ways**
  - Periodic Table
- **Apparently diverse phenomena are often different manifestations of the same underlying physics**
  - Orbits of planets and apples falling from trees
- **Almost everything is made of small objects that like to stick together**
  - Particles and Forces
- **Everyday intuition is not necessarily a good guide**
  - We live in a quantum world, even if it's not obvious to us

History of the particle physics

- Modern particle physics began in the early 20th century as an exploration into the structure of the atom. The discovery of the atomic nucleus in the gold foil experiment of Geiger, Marsden, and Rutherford was the foundation of the field. The components of the nucleus were subsequently discovered in 1919 (the proton) and 1932 (the neutron). In the 1920s the field of quantum physics was developed to explain the structure of the atom. The binding of the nucleus could not be understood by the physical laws known at the time. Based on electromagnetism alone, one would expect the protons to repel each other. In the mid-1930s, Yukawa proposed a new force to hold the nucleus together, which would eventually become known as the strong nuclear force. He speculated that this force was mediated by a new particle called a meson.



Search for fundamental particles

- Also in the 1930s, Fermi postulated the neutrino as an explanation for the observed energy spectrum of β-decay, and proposed an effective theory of the weak force. Separately, the positron and the muon were discovered by Anderson. Yukawa's meson was discovered in the form of the pion in 1947. Over time, the focus of the field shifted from understanding the nucleus to the more fundamental particles and their interactions, and particle physics became a distinct field from nuclear physics.
- Throughout the 1950-1960’s, a huge variety of additional particles was found in scattering experiments. This was referred to as the "particle zoo".

Are protons and neutrons fundamental?

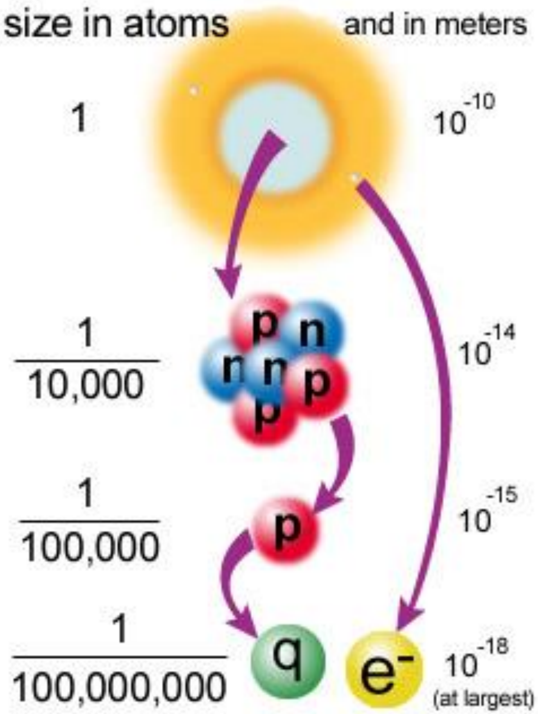
- To escape the "Particle Zoo," the next logical step was to investigate whether these patterns could be explained by postulating that all Baryons and Mesons are made of other particles. These particles were named Quarks

- As far as we know, quarks are like points in geometry. They're not made up of anything else.
- **After extensively testing this theory, scientists now suspect that quarks and the electron (and a few other things we'll see in a minute) are fundamental.**

- An elementary particle or *fundamental particle* is a particle not known to have substructure; that is, it is not known to be made up of smaller particles. If an elementary particle truly has no substructure, then it is one of the basic particles of the universe from which all larger particles are made.

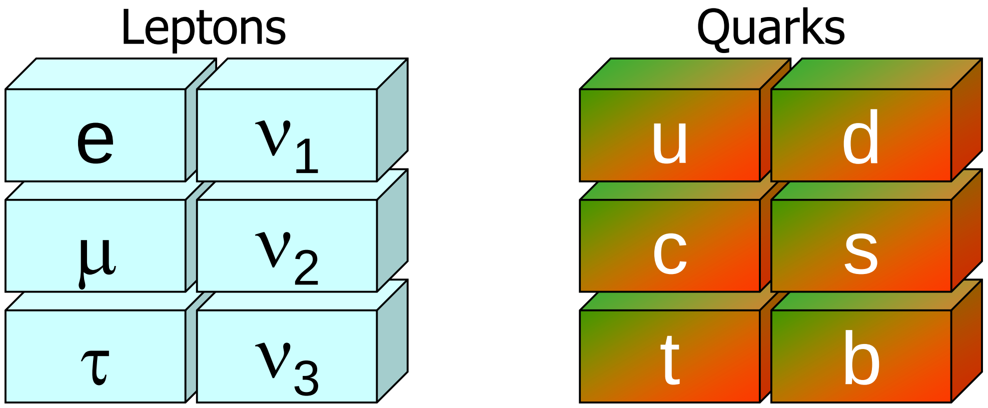
Scale of the atom

- While an atom is tiny, the nucleus is ten thousand times smaller than the atom and the quarks and electrons are at least ten thousand times smaller than that. We don't know exactly how small quarks and electrons are; they are definitely smaller than 10^{-18} meters, and they might literally be points, but we do not know.
- It is also possible that quarks and electrons are not fundamental after all, and will turn out to be made up of other, more fundamental particles.



Fundamental blocks

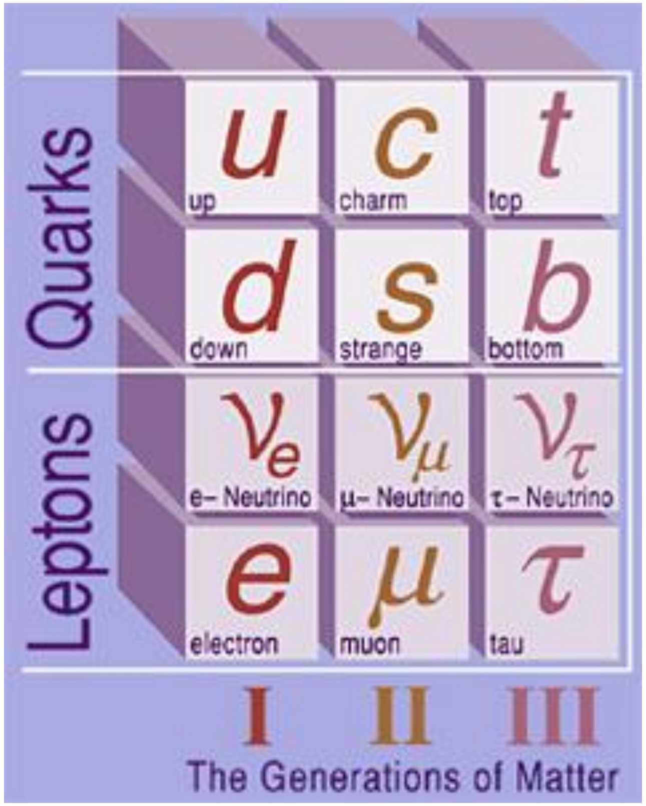
- Two types of point like constituents



- **Plus force carriers (will come to them later)**
- For every type of matter particle we've found, there also exists a corresponding **antimatter** particle, or **antiparticle**.
- Antiparticles look and behave just like their corresponding matter particles, except they have opposite charges.

Generations of quarks and leptons

- Note that both quarks and leptons exist in three distinct sets. Each set of quark and lepton charge types is called a **generation** of matter (charges +2/3, -1/3, 0, and -1 as you go down each generation). The generations are organized by increasing mass.
- All visible matter in the universe is made from the first generation of matter particles -- up quarks, down quarks, and electrons. This is because all second and third generation particles are unstable and quickly decay into stable first generation particles.



Spin: a property of particle

- Spin is a value of angular momentum assigned to all particles. When a top spins, it has a certain amount of angular momentum. The faster it spins, the greater the angular momentum. This idea of angular momentum is also applied to particles, but it appeared to be an intrinsic, unchangeable property. For example, an electron has and will always have 1/2 of spin.
- In quantum theories, angular momentum is measured in units of h = h/2p = 1.05 x 10^{-34} Js (Max Planck). (Js is joule-seconds, and is pronounced "h bar.")
- Classification of particles according to spin:
  - **Fermions: have spin ½**
  - **Bosons: : have spin 1**
  - **Scalar particles: have spin = 0**

Quarks

- Most of the matter we see around us is made from protons and neutrons, which are composed of up and down quarks.
- There are six quarks, but physicists usually talk about them in terms of three pairs: up/down, charm/strange, and top/bottom. (Also, for each of these quarks, there is a corresponding antiquark.)
- Quarks have the unusual characteristic of having a fractional electric charge, unlike the proton and electron, which have integer charges of +1 and -1 respectively. Quarks also carry another type of charge called color charge, which we will discuss later.

Quantum numbers of quarks

Type of quark	Charge	Spin
u (up)	+2/3	1/2
d (down)	-1/3	1/2
s (strange), S = 1	-1/3	1/2
c (charm), C =1	+2/3	1/2
b (bottom), B = 1	-1/3	1/2
t (top)	+2/3	1/2

Fractional charges and unseen quarks

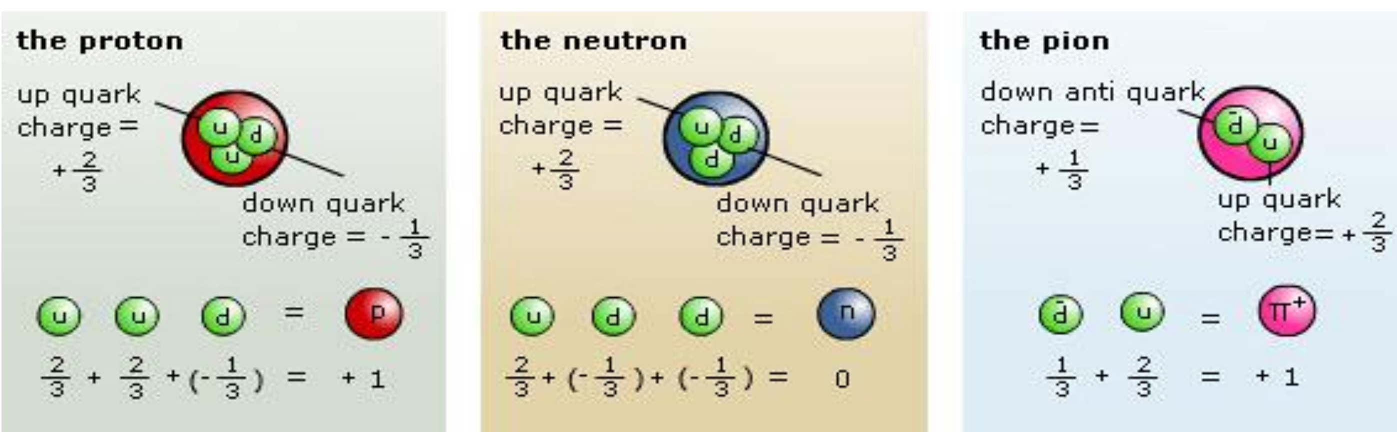
- Murray Gell-Mann and George Zwieg proposed the idea of the quarks to find some order in the chaos of particles:
  - baryons are particles consisting of three quarks (qqq),
  - mesons are particles consisting of a quark and anti-quark (q q-bar).

qqq	Q	S	Bar.
uuu	2	0	Δ^{++}
uud	1	0	Δ^{+}
udd	0	0	Δ^{0}
ddd	-1	0	Δ^{-}
uus	1	-1	Σ^{*+}
uds	0	-1	Σ^{*0}
dds	-1	-1	Σ^{*-}
uss	0	-2	Ξ^{*0}
dss	-1	-2	Ξ^{*0}
sss	-1	-3	Ω^{-}

qqbar	Q	S	Mes.
uubar	0	0	π^{0}
udbar	1	0	π^{+}
ubar d	-1	0	π^{-}
ddbar	0	0	η
uus	1	-1	K^{+}
uds	0	-1	K^{0}
dds	-1	-1	K^{-}
uss	0	-2	K^{0}
dss	-1	-2	η'

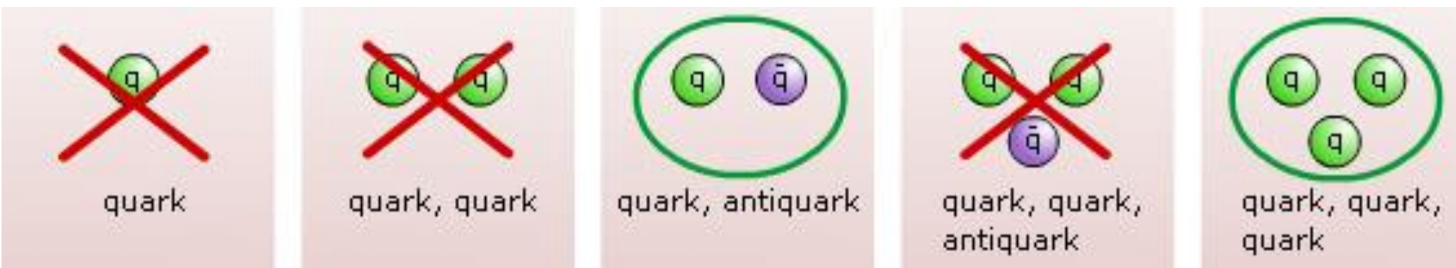
Fractional charges and unseen quarks

- **Problems arose with introducing quarks:**
  - Fractional charge – never seen before
  - Quarks are not observable
  - Not all quark combinations exist in nature
- **It appears to violate the Pauli exclusion principle**
  - Originally was formulated for two electrons.
  - Later realized that the same rule applies to all particles with spin ½.
  - Consider Δ^{++}(uuu): is supposed to consist of three u quarks in the same state – inconsistent with Pauli principle!



Color charge of quarks (1)

- So one had to explain why one saw only those combinations of quarks and antiquarks that had integer charge, and why no one ever saw a q, qq, qqqbar, or countless other combinations.

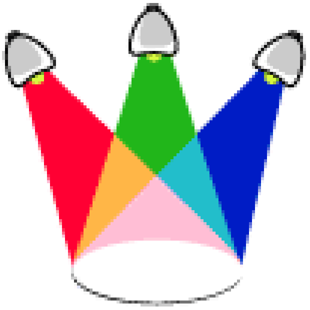


- Gell-Mann and others thought that the answer had to lie in the nature of forces between quarks. This force is the so-called "strong" force, and the new charges that feel the force are called "color" charges, even though they have nothing to do with ordinary colors.

Color charge of quarks (2)

- They proposed that quarks can have three color charges. This type of charge was called "color" because certain combinations of quark colors would be "neutral" in the sense that three ordinary colors can yield white, a neutral color.
- Only particles that are color neutral can exist, which is why only qqq and q q-bar are seen.
- This also resolve a problem with Pauli principle

Just like the combination of red and blue gives purple, the combination of certain colors give white. One example is the combination of red, green and blue.



Summary of L.1

- **There are 6 quarks and 6 leptons which we believe are fundamental blocks of nature**
- **They have antiparticles, i.e. the same quantum numbers except electric charge**
- **Quarks have fractional electric charges**
- **A new charge for quarks has been introduced: this charge is color**

Forces

Although there are apparently many types of forces in the Universe, they are all based on four fundamental forces:
Gravity, Electromagnetic force, Weak force and Strong force.

The strong and weak forces only act at very short distances and are responsible for holding nuclei together.

The electromagnetic force acts between electric charges.
The gravitational force acts between masses.

Pauli's exclusion principle is responsible for the tendency of atoms not to overlap each other, and is thus responsible for the "stiffness" or "rigidness" of matter, but this also depends on the electromagnetic force which binds the constituents of every atom.

Forces

All other forces are based on these four. For example, friction is a manifestation of the electromagnetic force acting between the atoms of two surfaces, and the Pauli exclusion principle, which does not allow atoms to pass through each other.

The forces in springs modeled by Hooke’s law are also the result of electromagnetic forces and the exclusion principle acting together to return the object to its equilibrium position.

Centrifugal forces are acceleration forces which arise simply from the acceleration of rotating frames of reference

Forces at the fundamental level

- The particles (quarks and leptons) interact through different “forces”, which we understand as due to the exchange of “field quanta” known as “gauge bosons”.

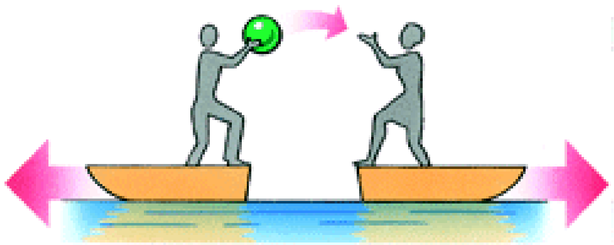
Electromagnetism (QED)	**Photon (γ) exchange**
Strong interactions (QCD)	**Gluon (g) exchange**
Weak interactions	**W and Z bosons exchange**
Gravitational interactions	**Graviton (G) exchange ?**

Forces

- The Standard Model describes the interaction of quarks and leptons via these gauge bosons.
- There is also postulated but not yet discovered scalar (i.e. spin of this particle = 0)
- What's the difference between a force and an interaction?
  - This is a hard distinction to make. Strictly speaking, a force is the effect on a particle due to the presence of other particles. The interactions of a particle include all the forces that affect it, but also include decays and annihilations that the particle might go through. (We will spend the next chapter discussing these decays and annihilations in more depth.)
  - The reason this gets confusing is that most people, even most physicists, usually use "force" and "interaction" interchangeably, although "interaction" is more correct. For instance, we call the particles which carry the interactions force carrier particles. You will usually be okay using the terms interchangeably, but you should know that they are different.

Exchange forces

- You can think about forces as being analogous to the following situation:
  - **Two people are standing in boats. One person moves their arm and is pushed backwards; a moment later the other person grabs at an invisible object and is driven backwards. Even though you cannot see a basketball, you can assume that one person threw a basketball to the other person because you see its effect on the people.**



- It turns out that all interactions which affect matter particles are due to an exchange of **force carrier particles**, a different type of particle altogether. These particles are like basketballs tossed between matter particles (which are like the basketball players). What we normally think of as "forces" are actually the effects of force carrier particles on matter particles.

Exchange forces

- We see examples of attractive forces in everyday life (such as magnets and gravity), and so we generally take it for granted that an object's presence can just affect another object. It is when we approach the deeper question, "How can two objects affect one another without touching?" that we propose that the invisible force could be an exchange of force carrier particles. Particle physicists have found that we can explain the force of one particle acting on another to INCREDIBLE precision by the exchange of these force carrier particles.
- One important thing to know about force carriers is that a particular force carrier particle can only be absorbed or produced by a matter particle which is affected by that particular force. For instance, electrons and protons have electric charge, so they can produce and absorb the electromagnetic force carrier, the photon. Neutrinos, on the other hand, have no electric charge, so they cannot absorb or produce photons.

Range of forces

The range of forces is related to the mass of exchange particle M.

An amount of energy $\Delta E = Mc^2$ borrowed for a time Δt is governed by the Uncertainty Principle:

$$\Delta E \times \Delta t \sim \hbar$$

The maximum distance the particle can travel is $\Delta x = c\,\Delta t$, where c is velocity of light.

$$\Delta x = \hbar c / \Delta E$$

$$\boxed{\Delta x = \hbar c / Mc^2}$$

The photon has M=0 → infinite range of EM force.

W boson has a mass of 80 GeV/c2 → Range of weak force is 197 MeV fm/ 8×10^5 MeV = 2×10^{-3} fm

Which forces act on which particles?

- The weak force acts between all quarks and leptons
- The electromagnetic force acts between all charged particles
- The strong force acts between all quarks (i.e. objects that have color charge)
- Gravity does not play any role in particle physics

	Weak	**EM**	**Strong**
Quarks	+	+	+
Charged leptons	+	+	–
Neutral leptons	+	–	–

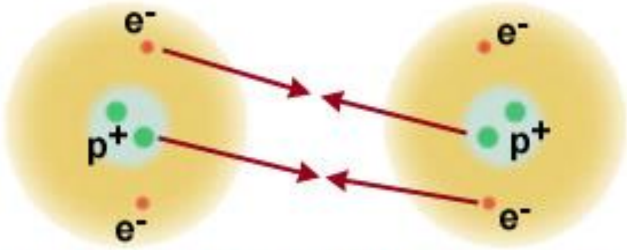
Electromagnetism

- The electromagnetic force causes like-charged things to repel and oppositely-charged things to attract. Many everyday forces, such as friction, are caused by the electromagnetic, or E-M force. For instance, the force that keeps us from falling through the floor is the electromagnetic force which causes the atoms making up the matter in our feet and the floor to resist being displaced.

- Photons of different energies span the electromagnetic spectrum of x rays, visible light, radio waves, and so forth.

Residual EM force

- Atoms usually have the same numbers of protons and electrons. They are electrically neutral, because the positive protons cancel out the negative electrons. Since they are neutral, what causes them to stick together to form stable molecules?
- The answer is a bit strange: we've discovered that the charged parts of one atom can interact with the charged parts of another atom. This allows different atoms to bind together, an effect called the **residual electromagnetic force**.
- So the electromagnetic force is what allows atoms to bond and form molecules, allowing the world to stay together and create the matter. All the structures of the world exist simply because protons and electrons have opposite charges!



Residual E-M force in action: the atoms are electrically neutral, but the electrons in one are attracted to the protons in another, and vice versa!

What about nucleus?

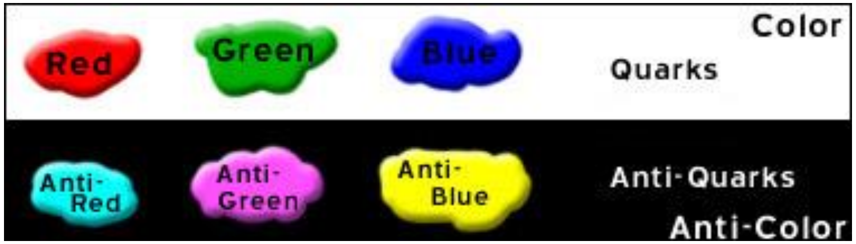
- We have another problem with atoms, though. What binds the nucleus together?
- The nucleus of an atom consists of a bunch of protons and neutrons crammed together. Since neutrons have no charge and the positively-charged protons repel one another, **why doesn't the nucleus blow apart?**
- We cannot account for the nucleus staying together with just electromagnetic force. What else could there be?

Strong interactions

- To understand what is happening inside the nucleus, we need to understand more about the quarks that make up the protons and neutrons in the nucleus. Quarks have electromagnetic charge, and they also have an altogether different kind of charge called color charge. The force between color-charged particles is very strong, so this force is "creatively" called strong.
- The strong force holds quarks together to form hadrons, so its carrier particles are whimsically called **gluons** because they so tightly "glue" quarks together.
- **Color charge** behaves differently than electromagnetic charge. Gluons, themselves, have color charge, which is weird and not at all like photons which do not have electromagnetic charge. And while quarks have color charge, composite particles made out of quarks have **no net color charge** (they are color neutral). For this reason, the strong force only takes place on the really small level of quark interactions.

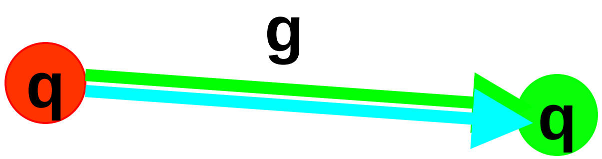
Color charge

- There are three color charges and three corresponding anticolor (complementary color) charges. Each quark has one of the three color charges and each antiquark has one of the three anticolor charges. Just as a mix of red, green, and blue light yields white light, in a baryon a combination of "red," "green," and "blue" color charges is color neutral, and in an antibaryon "antired," "antigreen," and "antiblue" is also color neutral. Mesons are color neutral because they carry combinations such as "red" and "antired.“
- Because gluon-emission and -absorption always changes color, and -in addition - color is a conserved quantity - *gluons can be thought of as carrying a color and an anticolor charge*. Since there are nine possible color-anticolor combinations we might expect nine different gluon charges, but the mathematics works out such that there are only *eight combinations*. Unfortunately, there is no intuitive explanation for this result.



Color charge (2)

- When two quarks are close to one another, they exchange gluons and create a very strong color force field that binds the quarks together. The force field gets stronger as the quarks get further apart. Quarks constantly change their color charges as they exchange gluons with other quarks.



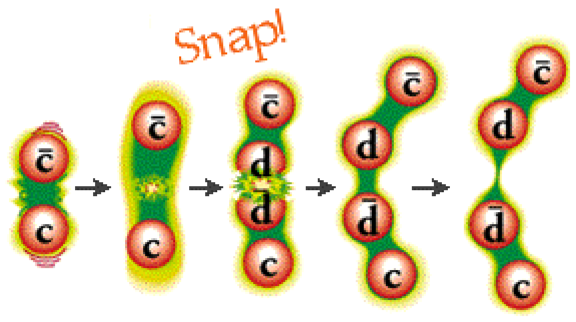
Anti-red-green gluon transforms the red quark into the green quark

Quark Confinement

- **Color confinement** is the physics phenomenon that color charged particles like quarks cannot be isolated. Quarks are confined with other quarks by the strong interaction to form pairs of triplets so the net color is neutral. The force between quarks increases as the distance between them increases, so no quarks can be found individually.
  - As any of two electrically-charged particles separate, the electric fields between them diminish quickly, allowing electrons to become unbound from nuclei.
  - However, as two *quarks* separate, the gluon fields form narrow tubes (or strings) of color charge) – quite different from EM!
  - Because of this behavior, the color *force* experienced by the quarks in the direction to hold them together, remains constant, regardless of their distance from each other.
  - Since energy is calculated as force times distance, ***the total energy increases linearly with distance.***

Quark Confinement (2)

- When two quarks become separated, as happens in accelerator collisions, at some point it is more energetically favorable for a new quark/anti-quark pair to "pop" out of the vacuum.



- In so doing, energy is conserved because the energy of the color-force field is converted into the mass of the new quarks, and the color-force field can "relax" back to an unstretched state.

Residual strong force

- So now we know that the **strong force** binds quarks together because quarks have **color charge**. But that still does not explain what holds the nucleus together, since positive protons repel each other with electromagnetic force, and protons and neutrons are color-neutral.
- The answer is that, in short, they don't call it the strong force for nothing. The strong force between the quarks in one proton and the quarks in another proton is strong enough to overwhelm the repulsive electromagnetic force

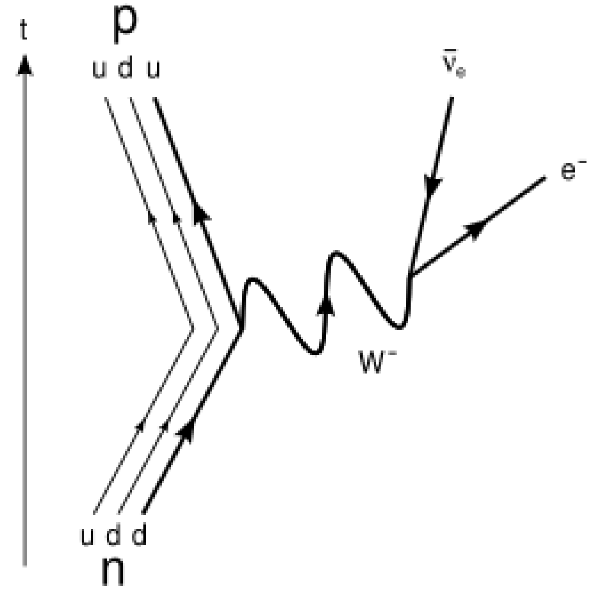
- This is called the residual strong interaction, and it is what "glues" the nucleus

Weak interactions

- There are six kinds of quarks and six kinds of leptons. But all the stable matter of the universe appears to be made of just the two least-massive quarks (up quark and down quark), the least-massive charged lepton (the electron), and the neutrinos.
- It is the only interaction capable of changing **flavor.**
- It is mediated by *heavy* gauge bosons W and Z.
  - Due to the large mass of the weak interaction's carrier particles (about 90 GeV/c2), their mean life is limited to 3×10^{-25} s by the Uncertainty principle. This effectively limits the range of weak interaction to 10^{-18} m (1000 times smaller than the diameter of an atomic nucleus)
- It is the only force affecting neutrinos.

Weak interactions (2)

- Since the weak interaction is both very weak and very short range, its most noticeable effect is due to its other unique feature: **flavor changing.**
- Consider a neutron **n(udd) β-decay.** Although the neutron is heavier than its sister proton **p(uud)**, it cannot decay to proton without changing the flavor of one of its **down quarks d.**
- Neither EM nor strong interactions allow to change the flavor changing, so that must proceed through weak interaction.
- Here $d \rightarrow u + W \rightarrow u + e + \bar{\nu}_e$



$$n \rightarrow p + e + \bar{\nu}_e$$

Gravity

- Gravitons are postulated because of the great success of the quantum field theory at modeling the behavior of all other forces of nature with similar particles: EM with the photon, the strong interaction with the gluons, and the weak interaction with the W and Z bosons. In this framework, the gravitational interaction is mediated by gravitons, instead of being described in terms of curved spacetime like in general relativity.
- Gravitons should be massless since the gravitational force acts on infinite distances.
- Gravitons should have spin 2 (because gravity is a second-rank tensor field)
- Gravitons have not been observed so far.
- For particle physics, it is very weak interaction to worry about.

Introduction

- One of the most striking general properties of elementary particles is their tendency to disintegrate.
- Universal principle: Every particle decays into lighter particles, unless prevented from doing so by some conservation law.
- Obvious conservation laws:
  - **Momentum conservation**
  - **Energy conservation**
  - **Charge conservation**
- Stable particles: neutrinos, photon, electron and proton.
  - **Neutrinos and photon are massless, there is nothing to decay for them into**
  - **The electron is lightest charged particle, so conservation of charge prevents its decay.**
  - **Why proton is stable?**

Baryon number

- **Baryon number:** $B = (n_q - n_{\bar{q}})/3$
  - **all baryons have baryon number +1, and antibaryons have baryon number -1. The baryon number is conserved in all interactions, i.e. the sum of the baryon number of all incoming particles is the same as the sum of the baryon numbers of all particles resulting from the reaction.**
- For example, the process $p \rightarrow e^+ + \gamma$ does not violate the conservation laws of charge, energy, linear momentum, or angular momentum. However, it does not occur because it violates the conservation of baryon number, i.e., $B = 1$ on the left and 0 on the right. It is fortunate that this process "never" happens, since otherwise all protons in the universe would gradually change into positrons! The apparent stability of the proton, and the lack of many other processes that might otherwise occur, are thus correctly described by introducing the baryon number B together with a law of conservation of baryon number.
- However, having stated that protons do not decay, it must also be noted that supersymmetric theories predict that protons actually do decay, although with a half-life of at least 10^{32} years, which is longer than the age of the universe. All attempts to detect the decay of protons have thus far been unsuccessful.

Lepton Number

- **Lepton number:** $L = n_\ell - n_{\bar{\ell}}$
  - leptons have assigned a value of +1, antileptons −1, and non-leptonic particles 0. Lepton number (sometimes also called lepton charge) is an additive quantum number.
  - **The lepton number is conserved in all interactions, i.e. the sum of the lepton number of all incoming particles is the same as the sum of the lepton numbers of all particles resulting from the reaction.**

Other quantum numbers

- **Strangeness:** $S = N_{\bar{s}} - N_s$ is a property of particles, expressed as a quantum number for describing decay of particles. Strangeness of anti-particles is referred to as +1, and particles as -1 as per the original definition.
  - Strangeness is conserved in strong and electromagnetic interactions but not during weak interactions.
  - $\Delta S=1$ in weak interactions. $\Delta S>1$ are forbidden.
- **Charm:** $C = N_c - N_{\bar{c}}$
  - Charm is conserved in strong and electromagnetic interactions, but not in weak interactions. $\Delta C=1$ in weak interactions.
  - Examples of charm particles: D meson contains charm quark and D_s meson contains c and s quarks, J/ψ is (cc) combination, charmonium; Baryon (but not the only one): Λ_c contains both s and c quarks

What governs the particle decay? (1)

- Each unstable particle has a characteristic mean lifetime. Lifetime τ is related to the half-life $t_{1/2}$ by the formula $t_{1/2}=(\ln 2)\tau = 0.693\tau$. The half-time is the time it takes for half the particles in a large sample to disintegrate.
- For muons μ it's $2.2\mathrm{x}10^{-6}$ sec, for the π^+ it's $2.6\mathrm{X}10^{-8}$ sec; for π^0 it's $8.3\mathrm{x}10^{-17}$ sec.
- Most of the particles exhibit several different decay modes
  - **Example: 63.4% of K^+'s decay into $\mu^+ + \nu_\mu$, but 21% go to $\pi^+ + \pi^0$, 5.6% to $\pi^+ + \pi^+ + \pi^-$ and so on.**
- One of the goals of the elementary particle physics is to calculate these lifetimes and branching ratios
- A given decay is governed by one of the 3 fundamental forces:
  - **Strong decay: $\Delta^{++} \rightarrow p^+ + \pi^+$**
  - **EM decay: $\pi^0 \rightarrow \gamma + \gamma$**
  - **Weak decay: $\Sigma^- \rightarrow n + e + \bar{\nu}_e$**

Branching fractions

- In particle physics, the branching fraction for a decay is the fraction of particles which decay by an individual decay mode with respect to the total number of particles which decay. It is equal to the ratio of the partial decay constant to the overall decay constant. Sometimes a partial half-life is given, but this term is misleading; due to competing modes it is not true that half of the particles will decay through a particular decay mode after its partial half-life.

What governs the particle decay? (2)

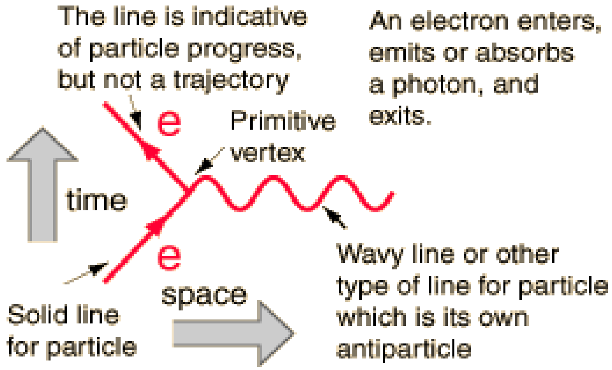
- **Momentum/energy conservation law in particle physics. Example: is decay Λ^0(uds)$\rightarrow\pi^- + p^+$ allowed?**
  - m_Λ = 1116 MeV ; m_p = 938 MeV ; m_π = 140 MeV, so $m_\Lambda > m_p + m_\pi$ and decay is allowed. $Q = m_\Lambda - m_p - m_\pi$ = 38 MeV, so the total kinetic energy of the decay products must be $K_p + K_\pi$ = 38 MeV. Using relativistic formula for kinetic energy, we can write this as

$$K_p + K_\pi = \sqrt{p_p^2 + m_p^2} - m_p + \sqrt{p_\pi^2 + m_\pi^2} - m_\pi = 38MeV$$

  - Conservation of of momentum requires $p_p = p_\pi$.
  - The kinetic energies can be found: K_p = 33 MeV, K_π = 5 MeV

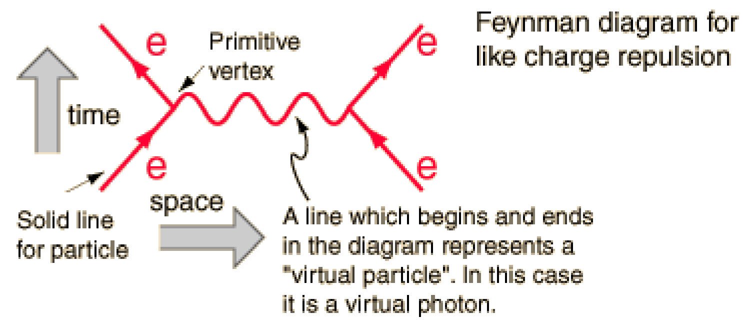
Feynman diagrams

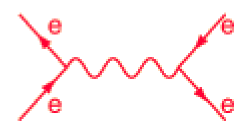
- Feynman diagrams are graphical ways to represent exchange forces. Each point at which lines come together is called a vertex, and at each vertex one may examine the conservation laws which govern particle interactions. Each vertex must conserve charge, baryon number and lepton number.
- Developed by Feynman to describe the interactions in quantum electrodynamics (QED), the diagrams have found use in describing a variety of particle interactions. They are spacetime diagrams, ct vs x. The time axis points upward and the space axis to the right. Particles are represented by lines with arrows to denote the direction of their travel, with antiparticles having their arrows reversed. Virtual particles are represented by wavy or broken lines and have no arrows. All electromagnetic interactions can be described with combinations of primitive diagrams like this one.



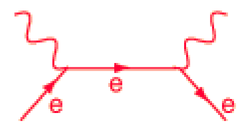
Feynman diagrams

- Only lines entering or leaving the diagram represent observable particles. Here two electrons enter, exchange a photon, and then exit. The time and space axes are usually not indicated. The vertical direction indicates the progress of time upward, but the horizontal spacing does not give the distance between the particles.
- After being introduced for electromagnetic processes, Feynman diagrams were developed for the weak and strong interactions as well. Forms of primitive vertices for these three interactions are

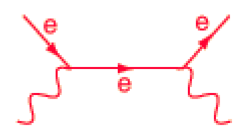




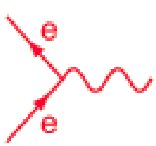
electron-positron
attraction



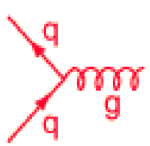
electron-positron
annihilation



electron-positron
pair production



charges
electromagnetic



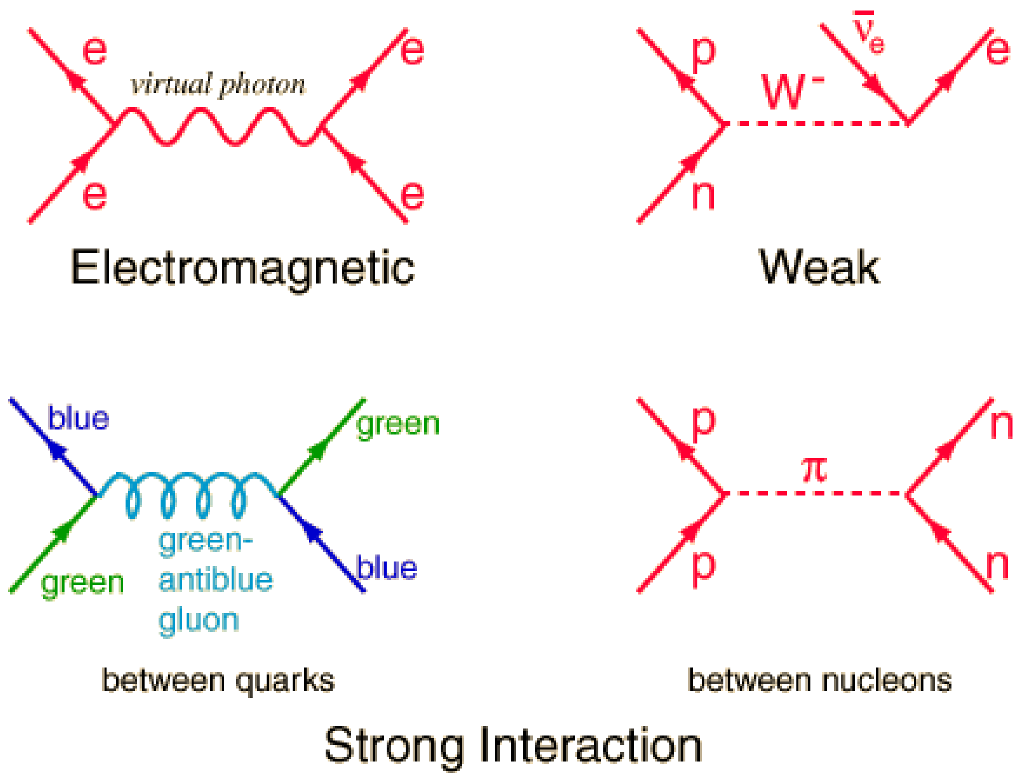
quarks
strong

quarks

leptons

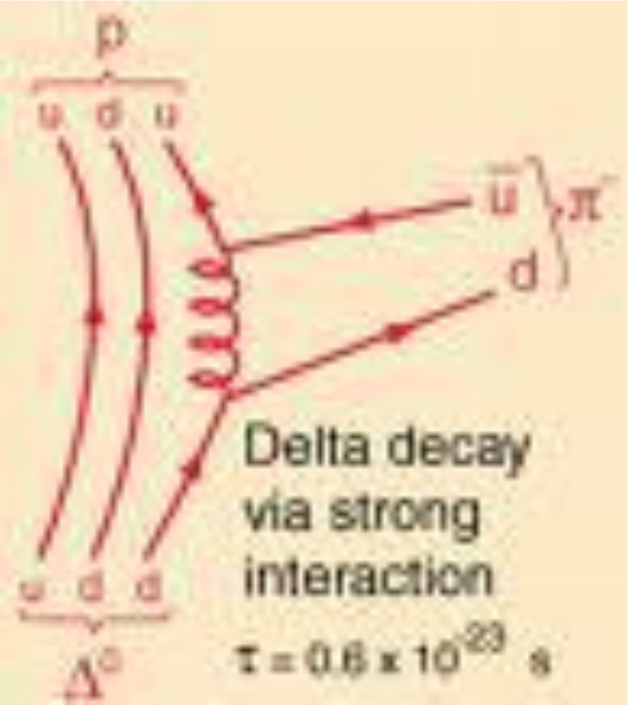
weak interaction

Examples of Feynman diagrams



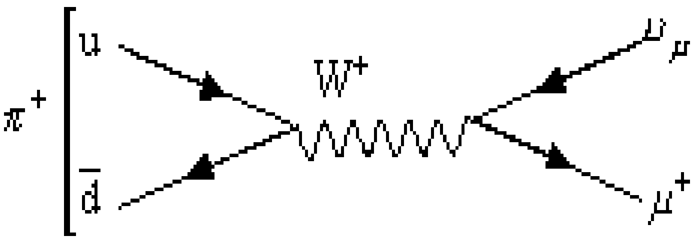
Feynman diagrams for some decays (1)

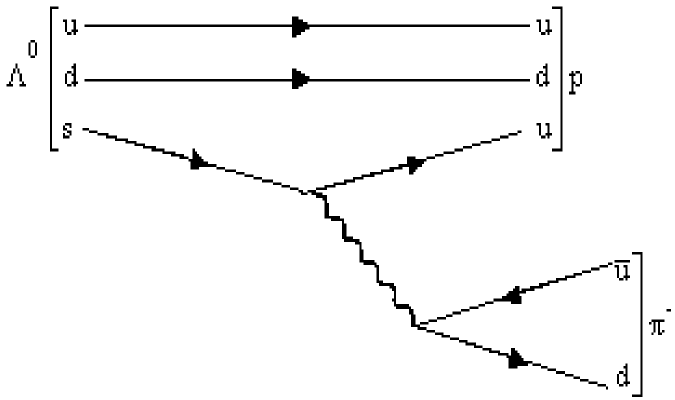
- **Consider decay $\Delta^0 \rightarrow p + \pi^-$:** This is **strong decay**, i.e. it occurs due to emission of gluon by one of the d-quarks in Δ^0 baryon. The emitted gluon does not change the flavor of the quark, so we still have a d-quark in the final state (it went to pion). Then this gluon is split into two quarks, u and anti-u. The u-quark combines with initial u and d quarks in Δ^0, and this leads to arising of a proton, p. The anti-u quark combines with d quark and together they form a negatively charged pion.



Feynman diagrams for some decays (2)

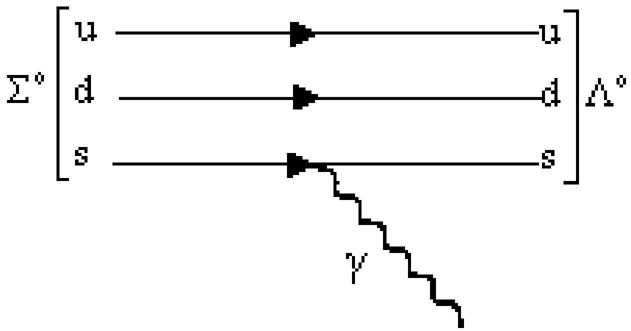
- **Consider decays $\pi^+ \rightarrow \nu_\mu + \mu^+$ and $\Lambda^0 \rightarrow p + \pi^-$:** In both cases one of the quarks changed its flavor via emitting a charged W boson. This is the main feature of the weak interactions, so these decays are weak decays.
- In both cases we have a ***virtual*** W bosons, i.e. they arise for a very short time and decay.
- As you can see, W boson can decay into a pair of leptons (first case) or into a pair of quarks (second diagram)





Feynman diagrams for some decays (3)

- **Consider decay $\Sigma^0 \rightarrow \Lambda^0 + \gamma$:** In this case the quark composition does not change. So it is not a weak decay. It is also not a strong decay – it does not involve any exchange with gluons. So this is radiative decay, that is caused by EM force.
- In general, having a photon in the final state means that we have an electromagnetic decay – usually call them radiative decays.



Which decays are allowed?

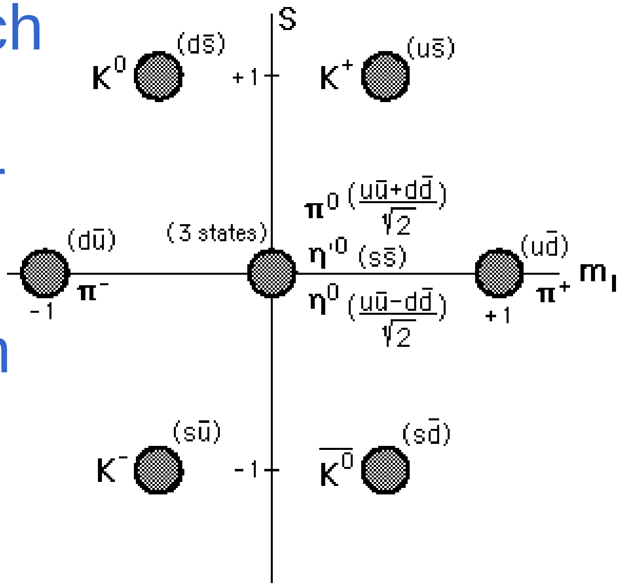
- $\Sigma^0 \rightarrow \Lambda + \pi^0$
  - Σ^0(uds), Λ(uds), π^0(u ubar). M(Σ) = 1197.45 MeV, M(Λ) = 1115.68 MeV, M(π^0) = 134.98 MeV;
- $\Sigma^- \rightarrow$ **n +** π^-
  - Σ^-(dds), n(udd), π^-(ubar d). M(Σ) = 1197.45 MeV, M(n) = 939.56 MeV, M(π-) = 139.57 MeV ;
- $\Xi^0 \rightarrow \pi^-$ **+p**
  - uss, ubar d, uud correspondingly. M(Ξ^0) =1314.83 MeV , M(p) = 938.27 MeV
- $\Xi^- \rightarrow \pi^- + \Lambda$
  - dss, ubar d, uds correspondingly. M(Ξ^-) =1321.31 MeV
- **N** $\rightarrow$ **e +** π^-
  - M(e) = 0.511 MeV

Parity

- One of the conservation laws which applies to particle interactions is associated with **parity.**
- Quarks have an intrinsic parity which is defined to be +1 and for an antiquark parity = -1. Nucleons are defined to have intrinsic parity +1. For a meson with quark and antiquark with antiparallel spins (s=0), then the parity is given by $P = P_q P_{\bar{q}} (-1)^{\ell}$, where l = orbital angular momentum.
- The meson parity is given by $P = -(-1)^{\ell} = (-1)^{\ell+1}$
- The lowest energy states for quark-antiquark pairs (mesons) will have zero spin and negative parity and are called pseudoscalar mesons. The nine pseudoscalar mesons can be shown on a meson diagram. One kind of notation for these states indicates their angular momentum and parity $J^P = 0^{-1}$

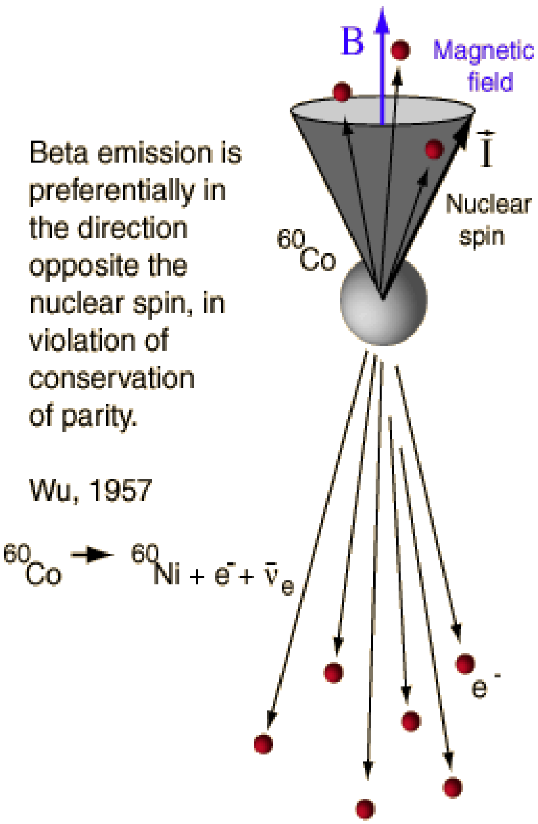
Parity (2)

- Excited states of the mesons occur in which the quark spins are aligned, which with zero orbital angular momentum gives j=1. Such states are called vector mesons, $J^P = 1^{-1}$
- The vector mesons have the same spin and parity as photons.
- All neutrinos are found to be "left-handed", with an intrinsic parity of -1 while antineutrinos are right-handed, parity =+1.
- Parity conserves in strong and EM interactions, but not in weak interactions.



Non-conservation of parity

- The electromagnetic and strong interactions are invariant under the parity transformation. It was a reasonable assumption that this was just the way nature behaved, oblivious to whether the coordinate system was right-handed or left-handed. In 1956, T. D. Lee and C. N. Yang predicted the non-conservation of parity in the weak interaction. Their prediction was quickly tested when C. S. Wu and collaborators studied the β-decay of Cobalt-60 in 1957.
- By lowering the temperature of cobalt atoms to about 0.01K, Wu was able to "polarize" the nuclear spins along the direction of an applied magnetic field. The directions of the emitted electrons were then measured. Equal numbers of electrons should be emitted parallel and antiparallel to the magnetic field if parity is conserved, but they found that more electrons were emitted in the direction opposite to the magnetic field and therefore opposite to the nuclear spin.



Non-conservation of parity

- This and subsequent experiments have consistently shown that a neutrino always has its intrinsic angular momentum (spin) pointed in the direction opposite its velocity. It is called a left-handed particle as a result. Anti-neutrinos have their spins parallel to their velocity and are therefore right-handed particles. Therefore we say that the neutrino has an intrinsic parity.
- When non-conservation of parity was discovered, theorists tried to “fix” the problem assuming that physics laws are invariant under CP transformations
- *CP* is the product of two symmetries: C for charge conjugation, which transforms a particle into its antiparticle, and P for parity, which creates the mirror image of a physical system.

CP symmetry and its violation

- *CP* violation is a violation of the postulated *CP* symmetry of the laws of physics. It plays an important role in theories of cosmology that attempt to explain the dominance of matter over antimatter in the present Universe. The discovery of *CP* violation in 1964 in the decays of neutral kaons resulted in the Nobel Prize in Physics in 1980 for its discoverers James Cronin and Val Fitch. The study of *CP* violation remains a vibrant area of theoretical and experimental work today.
- The strong interaction and electromagnetic interaction seem to be invariant under the combined CP transformation operation, but this symmetry is slightly violated during certain types of weak decay. Historically, CP-symmetry was proposed to restore order after the discovery of parity violation in the 1950s

CP violation

- Overall, the symmetry of a quantum mechanical system can be restored if another symmetry *S* can be found such that the combined symmetry *PS* remains unbroken. This rather subtle point about the structure of Hilbert space was realized shortly after the discovery of *P* violation, and it was proposed that charge conjugation was the desired symmetry to restore order.
- Simply speaking, charge conjugation is a simple symmetry between particles and antiparticles, and so CP symmetry was proposed in 1957 by Lev Landau as the true symmetry between matter and antimatter. In other words a process in which all particles are exchanged with their antiparticles was assumed to be equivalent to the mirror image of the original process
- In 1964, James Croninand Val Fitch provided clear evidence that CP symmetry could be broken, too. Their discovery showed that weak interactions violate not only the charge-conjugation symmetry C between particles and antiparticles and the P or parity, but also their combination. .

CP violation

- The kind of CP violation discovered in 1964 was linked to the fact that neutral kaons can transform into their antiparticles (in which each quark is replaced with its antiquark) and vice versa, but such transformation does not occur with exactly the same probability in both directions; this is called *indirect* CP violation.
- Only a weaker version of the symmetry could be preserved by physical phenomena, which was CPT symmetry. Besides C and P, there is a third operation, time reversal (T), which corresponds to reversal of motion. Invariance under time reversal implies that whenever a motion is allowed by the laws of physics, the reversed motion is also an allowed one. The combination of CPT is thought to constitute an exact symmetry of all types of fundamental interactions. Because of the CPT-symmetry, a violation of the CP-symmetry is equivalent to a violation of the T-symmetry. CP violation implied nonconservation of T, provided that the long-held CPT theorem was valid. In this theorem, regarded as one of the basic principles of quantum field theory, charge conjugation, parity, and time reversal are applied together.

CPT invariance (1)

- Many of the profound ideas in nature manifest themselves as symmetries. A symmetry in a physical experiment suggests that something is conserved, or remains constant, during the experiment. So conservation laws and symmetries are strongly linked.
- Three of the symmetries which usually, but not always, hold are those of charge conjugation (C), parity (P), and time reversal (T):
  - **Charge conjugation (C) : reversing the electric charge and all the internal quantum numbers.**
  - **Parity (P): space inversion; reversal of the space coordinates, but not the time.**
  - **Time reversal (T): replacing t by -t. This reverses time derivatives like momentum and angular momentum.**

CPT invariance (1)

- P, CP symmetries are violated in weak interaction. We are left with the combination of all three, CPT, a profound symmetry consistent with all known experimental observations.
- On the theoretical side, CPT invariance has received a great deal of attention. Georg Ludens, Wolfgang Pauli and Julian Schwinger independently showed that invariance under Lorentz transformations implies CPT invariance. CPT invariance itself has implications which are at the heart of our understanding of nature and which do not easily arise from other types of considerations.
  - **Integer spin particles obey Bose-Einstein statistics and half-integer spin particles obey Fermi-Dirac statistics. Particles and antiparticles have identical masses and lifetimes. This arises from CPT invariance of physical theories.**
  - **All the internal quantum numbers of antiparticles are opposite to those of the particles.**

CP violation and matter/antimatter

- The CPT Theorem guarantees that a particle and its anti-particle have exactly the same mass and lifetime, and exactly opposite charge. Given this symmetry, it is puzzling that the universe does not have equal amounts of matter and antimatter. Indeed, there is no experimental evidence that there are any significant concentrations of antimatter in the observable universe.
- There are two main interpretations for this disparity: either when the universe began there was already a small preference for matter, with the total baryonic number of the universe different from zero; or, the universe was originally perfectly symmetric ($B(time = 0) = 0$), but somehow a set of phenomena contributed to a small imbalance. The second point of view is preferred, although there is no clear experimental evidence indicating either of them to be the correct one.

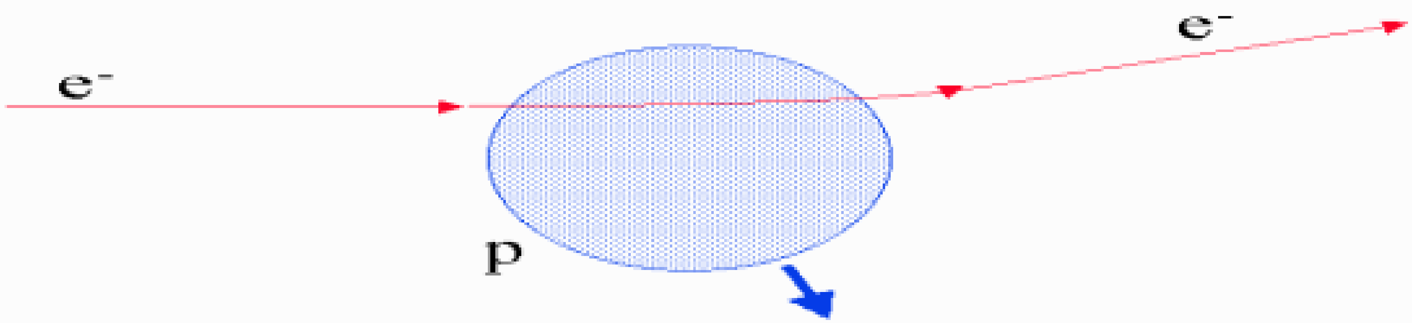
The Sakharov conditions

- In 1967, Andrei Sakharov proposed a set of three necessary conditions that a baryon-generating interaction must satisfy to produce matter and antimatter at different rates.
  - **Baryon number *B* violation. –** Do not have any experimental confirmations
  - **C-symmetry and CP-symmetry violation. –** Observed experimentally
  - **Interactions out of thermal equilibrium.**
- The last condition states that the rate of a reaction which generates baryon-asymmetry must be less than the rate of expansion of the universe. In this situation the particles and their corresponding antiparticles do not achieve thermal equilibrium due to rapid expansion decreasing the occurrence of pair-annihilation.

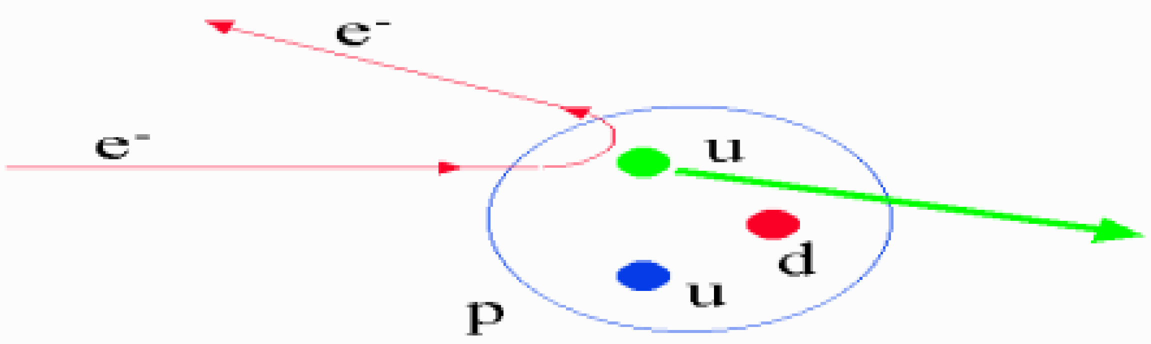
- There are competing theories to explain this aspect of the phenomena of baryogenesis, but there is no one consensus theory to explain the phenomenon at this time

Evidence for Quarks: The Basic Idea

- Fire electrons at protons.
- If proton "charge cloud":

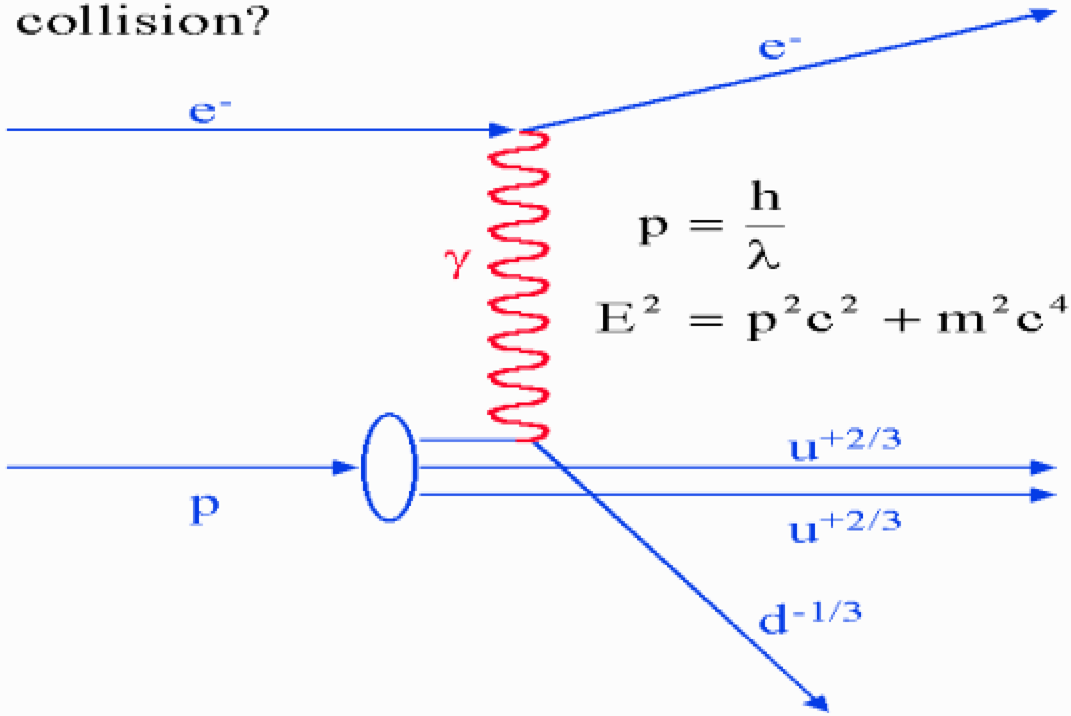


- If proton contains point charges, some of time see:



Evidence for Quarks: More Detail

- Look at protons using "electron microscope".
- Resolution dependent on wavelength.
- What is happening in electron proton collision?

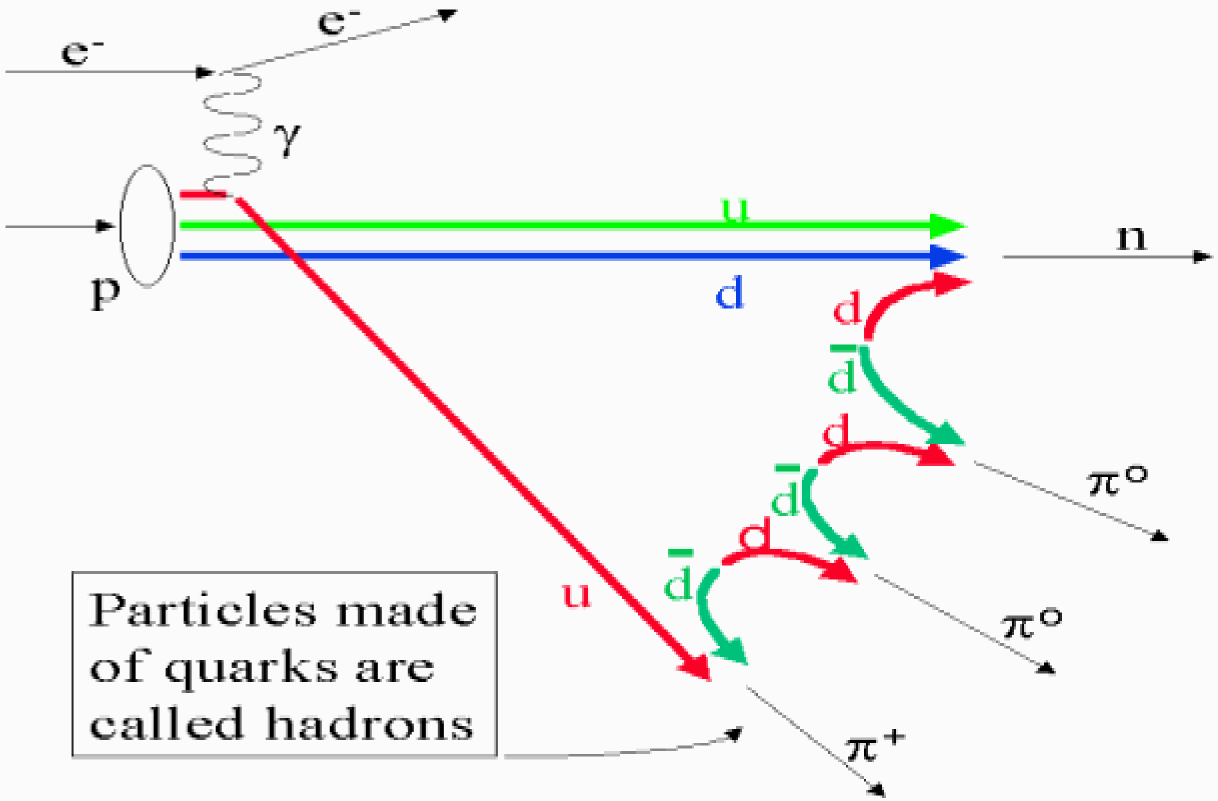


$$p = \frac{h}{\lambda}$$

$$E^2 = p^2c^2 + m^2c^4$$

But we don't see quarks…

- Strength of force between colour charges increases with separation.
- Never see "free" quarks!

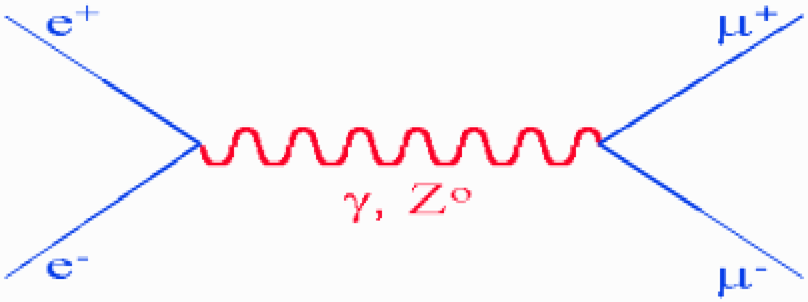


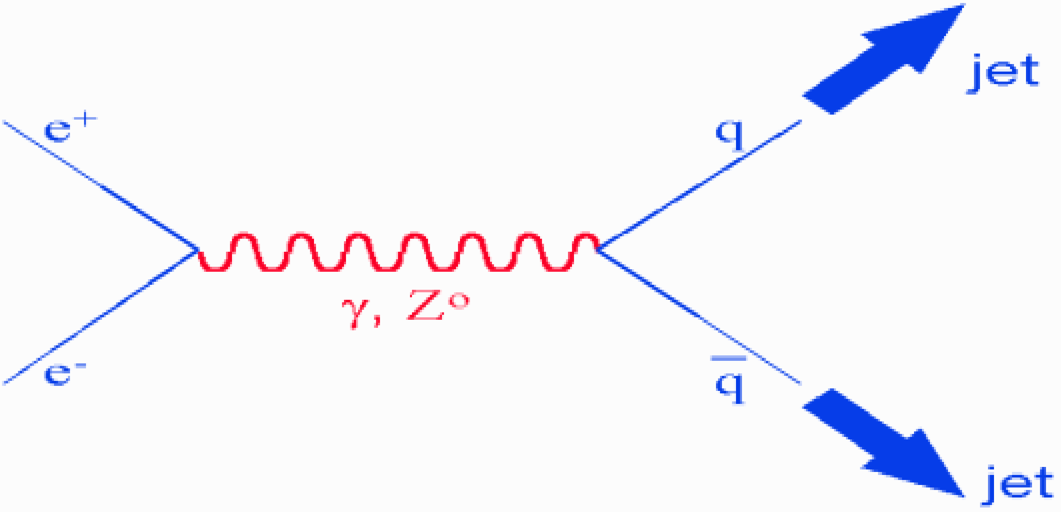
LEPI

- Collide electrons (e^-) with positrons (e^+) at 45 GeV.
- Matter and anti-matter annihilate.
- Energy appears as force carrying particle.
- "Freezes out" into matter/anti-matter.
- Produce all energetically allowed matter particles.
- $2m_tc^2 > 2 \times 45$ GeV, so top quark not produced.

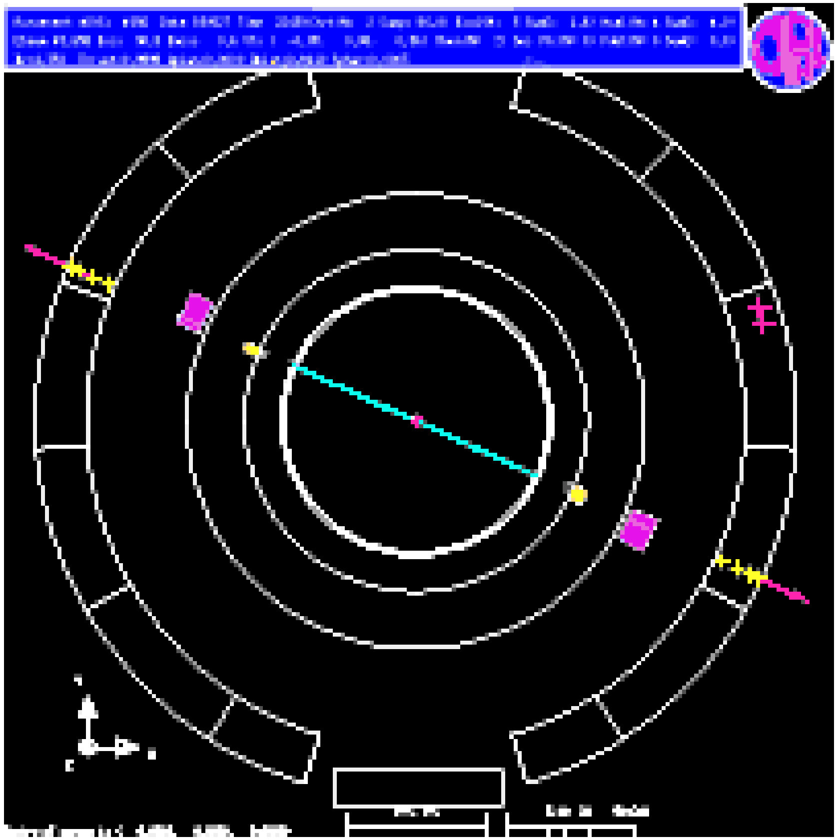
LEPI cont.

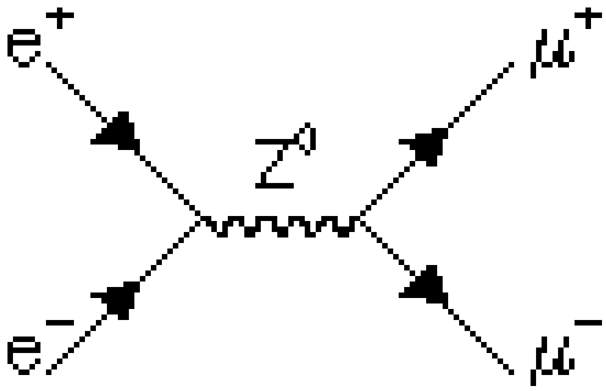
- Important Feynman diagrams at LEPI





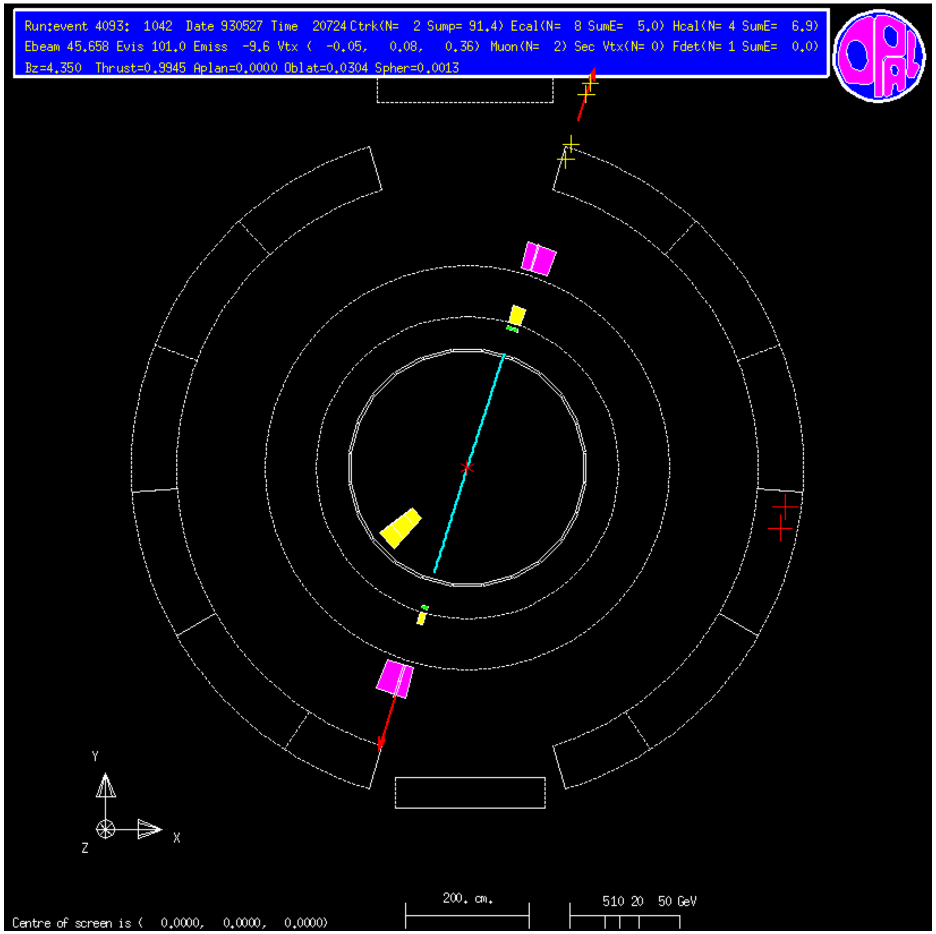
Event displays from OPAL experiment at LEP

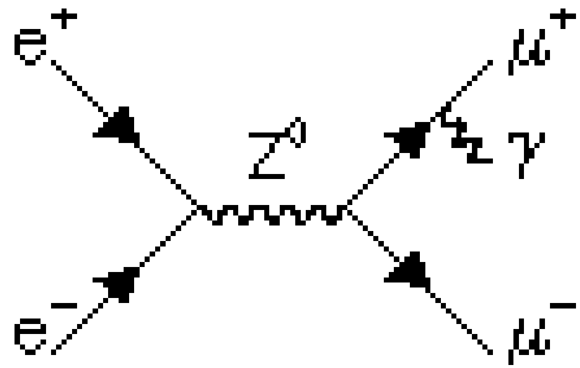




In the first event, the decay of a Z boson into a pair of muons is seen. The muons are identified by their penetration right through the detector.

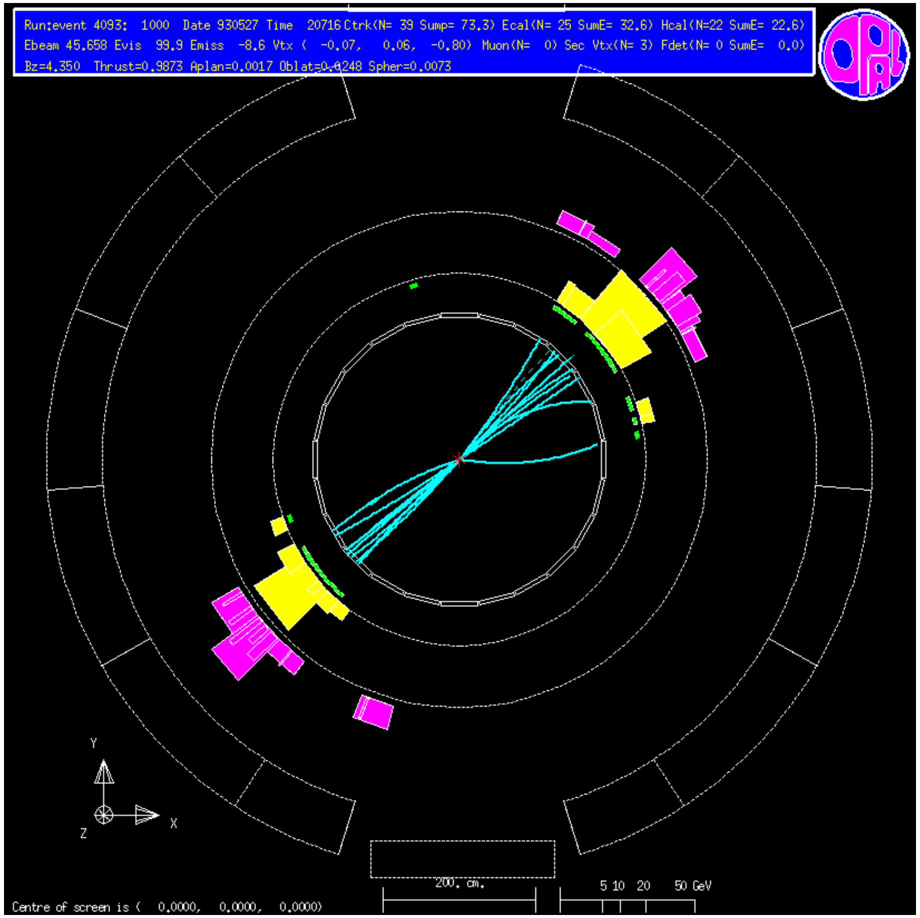
Event displays from OPAL experiment at LEP

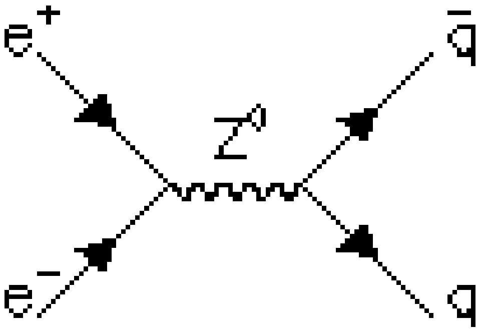




A similar event is shown here but in this case a photon has been emitted by one of the muons, shown as a cluster in the electromagnetic calorimeter with no associated track.

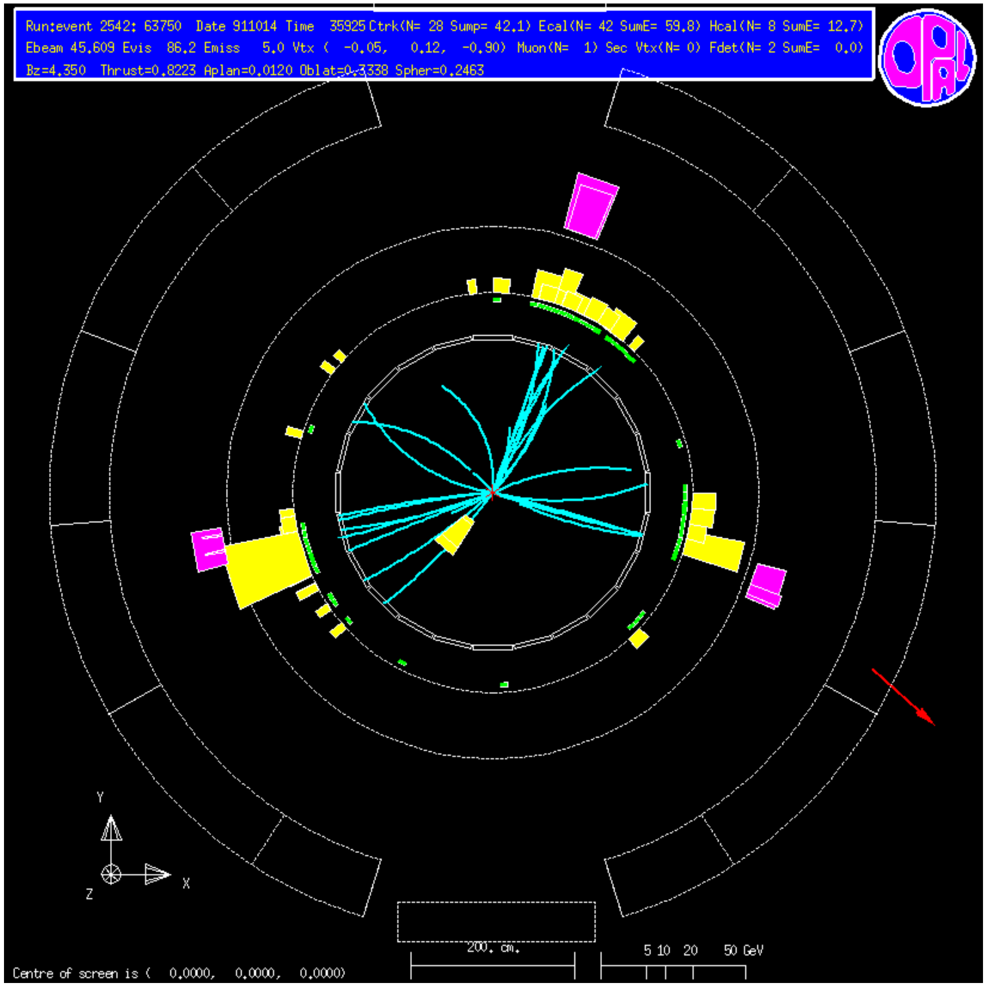
Event displays from OPAL experiment at LEP

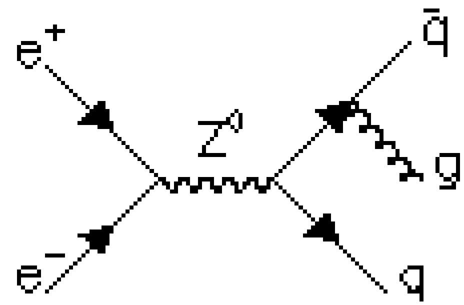




The Z boson may also decay to a pair of quarks. As the quarks move apart, the energy in the field between them caused by their "colour" charge builds up and further quarks and antiquarks are formed. Finally, the quarks are seen in the detector as two collimated back-to-back "jets" of hadrons (bound states of quarks and antiquarks), as in this event

Event displays from OPAL experiment at LEP





Sometimes, an energetic gluon (a quantum of the colour field) may be emitted by one of the quarks. In an event like this, a third jet may be seen. The study of events like these allow us to test the theory of the strong interactions, Quantum ChromoDynamics (QCD).

Production cross section (1)

- The strength of a particular interaction between two particles is specified by interaction cross section.
- The concept of cross section is the crucial key that opens the communication between the real world of experiment and the abstract, idealized world of theoretical models. The cross section is the probability that an interaction will occur between a projectile particle and a target particle, which could be an antiproton, or perhaps a proton or neutron in a piece of metal foil.
- We can measure the probability that two particles will interact in experiments. We can also calculate this quantity in a model that incorporates our understanding of the forces acting on a subatomic level. In the famous experiment in which Rutherford studied the scattering of alpha particles off a foil target, the cross section gives the probability that the alpha particle is deflected from its path straight through the target. The cross section for large-angle scattering is the fraction of alpha particles that bounce back from the target, divided by the density of nuclei in the target and the target thickness. The comparison of the measured cross section with the calculated one verified the model of the atom with a massive center, carrying an electrical charge.

Production cross section (2)

- We can picture the cross section as the effective area that a target presents to the projected particle. If an interaction is highly probable, it's as if the target particle is large compared to the whole target area, while if the interaction is very rare, it's as if the target is small. The cross section for an interaction to occur does not necessarily depend on the geometric area of a particle. It's possible for two particles to have the same geometric area (sometimes known as geometric cross section) and yet have very different interaction cross section or probability for interacting with a projectile particle.
- During wartime research on the atomic bomb, American physicists who were bouncing neutrons off uranium nuclei described the uranium nucleus as "big as a barn." Physicists working on the project adopted the name barn for a unit equal to 10^{-24} square centimeters, about the size of a uranium nucleus. Initially they hoped the American slang name would obscure any reference to the study of nuclear structure; eventually, the word became a standard unit in particle physics.

Proof of color (1)

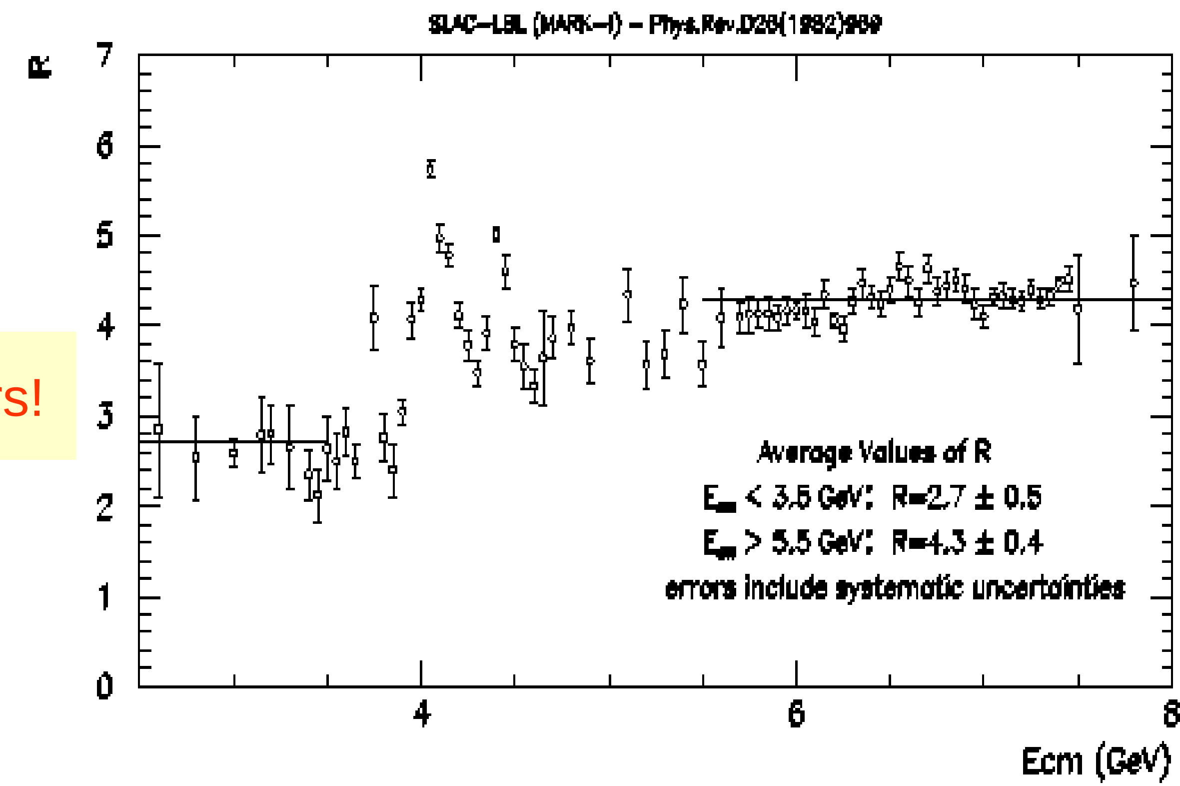
- SLAC (SPEAR), Brookhaven lab (p on Be) and Cambridge Electron Accelerator were measuring R
- R is ratio of the production cross sections to hadrons and to muons

$$R = \sigma(e^+e^- \to q\bar{q}) / \sigma(e^+e^- \to \mu^+\mu^-)$$

$$R \equiv \frac{\sigma\left(e^+e^- \to \text{hadrons}\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)} = 3 \sum_{\text{flavour}} e_{q_i}^2$$

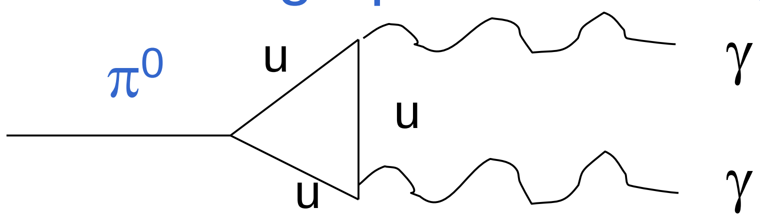
3 stands for number of colors!

- R should be 2 for low energies, where we have u, d, s quarks: R = 3x(1/9+1/9+4/9) = 3x2/3 =2



Proof of color (2)

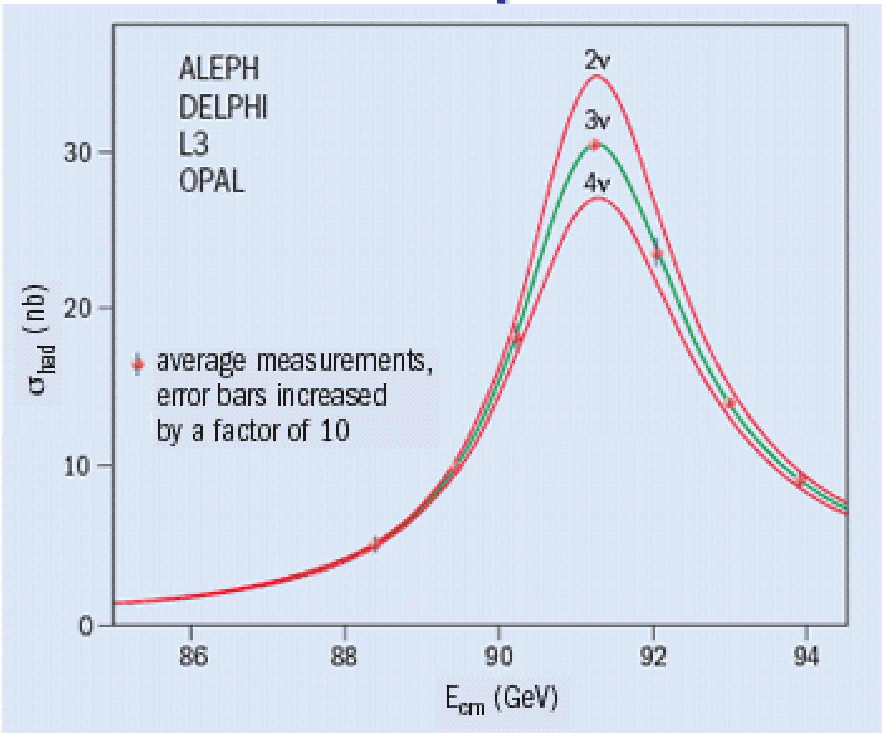
- Another example of the effect of color is in the neutral pion decay $\pi^0 \to \gamma\gamma$.
- Dominant graph is the triangle diagram:



- In this case colors involved in the decay are not distinguishable, so the three amplitudes should be added coherently, and the rate acquires a factor $N_c^2=9$.
- Theory predicts $\Gamma(\pi^0 \rightarrow 2\gamma)=7.73$ eV, experimentally measured $\Gamma(\pi^0 \rightarrow 2\gamma)=7.7 \pm 0.6$ eV
- If N_c would be 1, the theoretical prediction would be 9 times smaller.

Proof of three generations of leptons

- Z boson can decay to hadrons and leptons.
- Z boson can decay to the pair of neutrino and antineutrino.
- Since neutrinos assumed to be massless or at least have very small masses, we can try to use this fact to determine number of neutrino flavors (corresponding leptons might be heavy, so Z might not have enough mass to decay into pair of such leptons

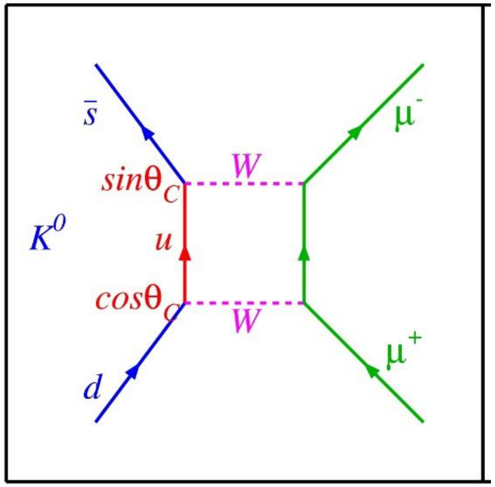


- Theoretical prediction for the Z boson width (it depends on number of neutrino flavors) and experimental data obtained at LEP.
- Agreement with assumption of 3 flavors of netrinos → 3 generations.

Introduction

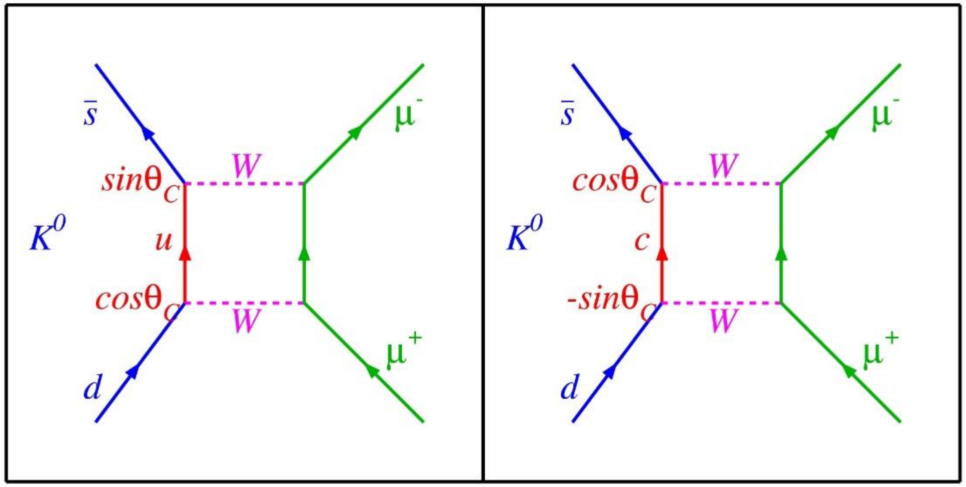
- By 1960's a lot of particles were discovered
- In 1964, Gell-Mann has proposed a model that explained all particles as consisting of three types of quarks, u,d and s, and their anitquarks.
- But in 1970's, there was a problem with the flavor changing decay of $K^0_L(d\bar{s})$:

- Measured decay rate turned out to be much smaller compared to the predicted



Theoretical prediction

- To fix the problem, Glashow, Illiopolus and Maiani have suggested to introduce the fourth quark named charm (c) quark.
- So we have to add another diagram into calculation of the $K \to \mu^+ \mu^-$ decay.



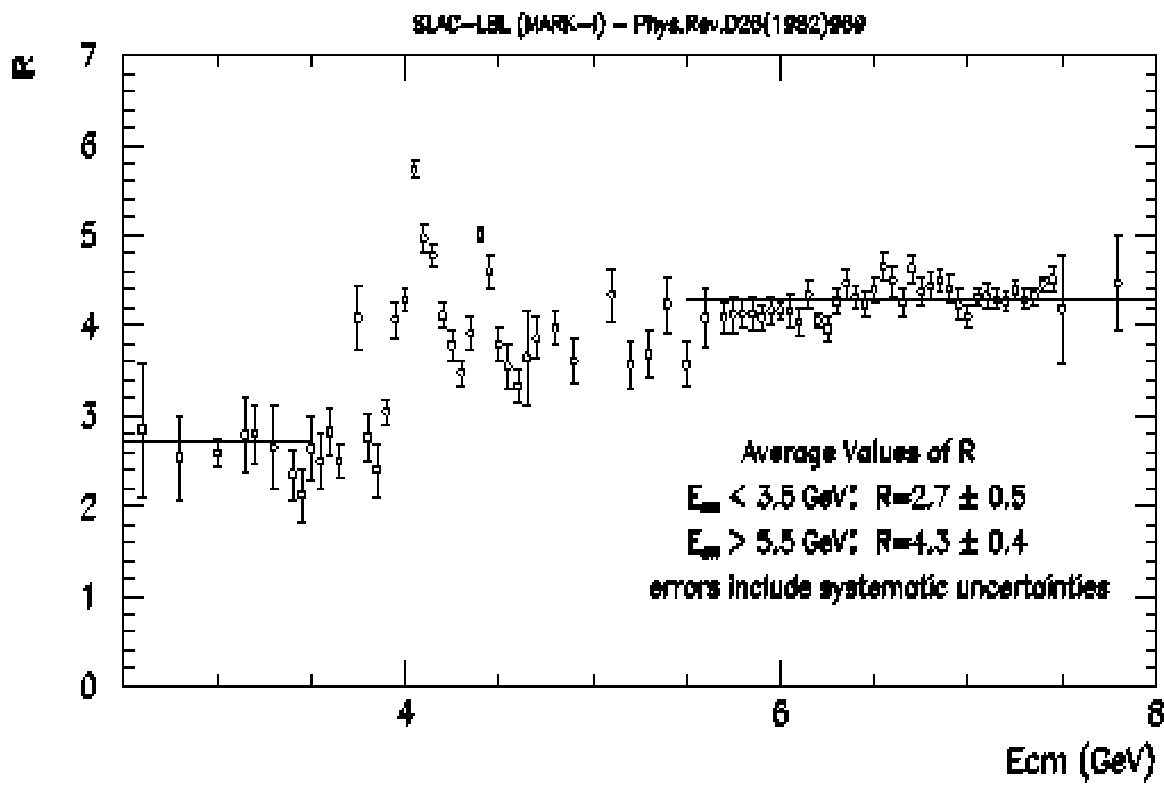
- These two diagrams almost completely compensate each other, and we do not see this decay.
- Now, how we can prove that c quark exists?

R and new quarks

- SLAC (SPEAR), Brookhaven lab (p on Be) and Cambridge Electron Accelerator were measuring R
- Ratio $R = \sigma(e^+e^- \to q\bar{q}) / \sigma(e^+e^- \to \mu^+\mu^-)$

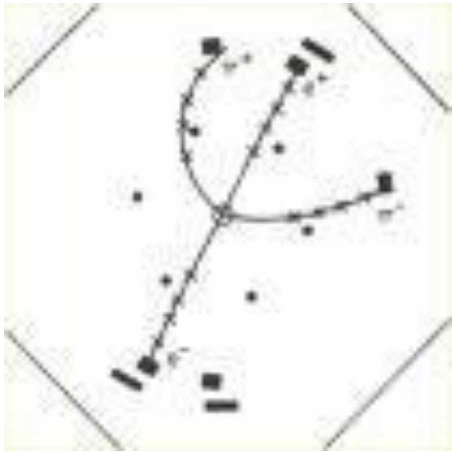
$$R = \frac{\sigma\left(e^+e^- \to \text{hadrons}\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)} = 3 \sum_{\text{flavour}} e_{q_i}^2$$

- At low energies, R = 2 confirming that all particles produced at these energies consist of 3 quarks.
- As energy increases, new quarks can be created from vacuum, resulting in increase of R



Discovery of J/ψ

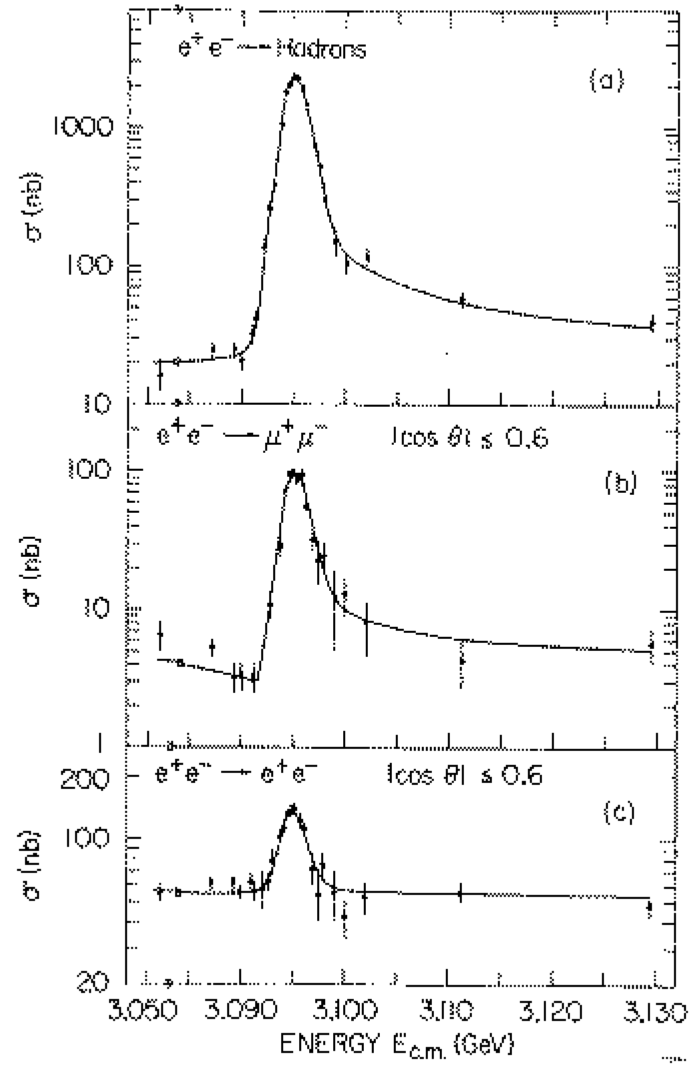
- A new particle has been discovered in 1974 by two independent experiments at SLAC and Brookhaven.
- SLAC: $e^+e^- \to \psi \to hadrons$
  $$\psi \to e^+e^-, \mu^+\mu^-$$



- SLAC called it ψ
- BNL: $p + Be \to J/\psi + anything$
  $$J/\psi \to e^+e^-$$
- BNL team called it J (after Ting?)
- This is the only particle that has double name

Discovery of J/ψ

- These are original plots showing the observation of the J/ψ resonance with mass of 3.1 GeV/c2. Here (a) corresponds to case $e^+e^- \to q\bar{q}$ (b) $e^+e^- \to \mu^+\mu^-$ and (c) $e^+e^- \to e^+e^-$
- One can see that this resonance is well pronounced in all channels and peak is at the same mass
- Why they were sure that this particle has charm and anti-charm quarks?



What is the quark composition of J/ψ ?

Particle	Mass	J^P, I	Γ, MeV	Branching ratio	
J/ψ	3097.88 ± 0.04	1^-,0	0.087	Hadrons	88%
	Lifetime			e^+e^-	6%
	~10^{-20} sec			$\mu^+\mu^-$	6%

- The extreme narrowness of the J/ψ resonance in comparison with those of other meson resonances indicated that there was no possibility of understanding them in terms of u, d, s quarks only.
- The mass of the particle was extremely large compared to masses of known particles.
- A new type of quark postulated by GIM in 1970 → this particle is a combination of ccbar - charmonium

Some details about J/ψ

- **Charmonium is a bound state of a charmed quark and antiquark**
- **The attractive force between them has two pieces**
  - A Coulomb-like part, which dominates at short distances
  - A spring-like part, which dominates at long distances
- **The charmonium wavefunctions**
  - Are Hydrogen-atom like
  - Can be described with H-atom like quantum numbers, e.g. $^3S_1$
  - Drive the production properties
- **Charmonium production**
  - Is not a simple story

Semi-Classical Quark Confinement

Yesterday's not-too-terrible model of the quark-antiquark force law:

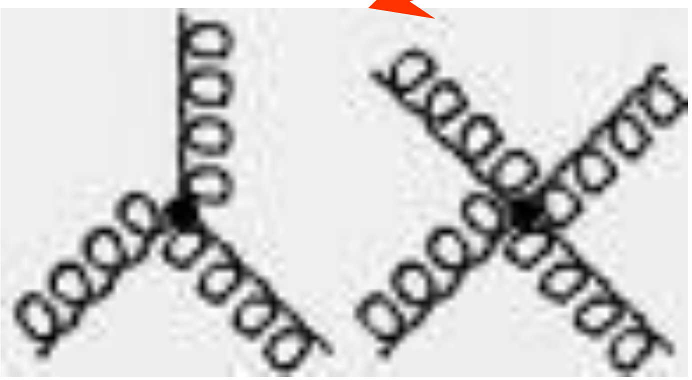
A spring-like part

$$F = \frac{A}{r^2} + Br$$

A Coulomb-like part

This piece comes from the non-Abelian nature of QCD: the fact that you have 3-gluon and 4-gluon couplings.

In QED, there is no $\gamma\gamma$ coupling, so this term is absent

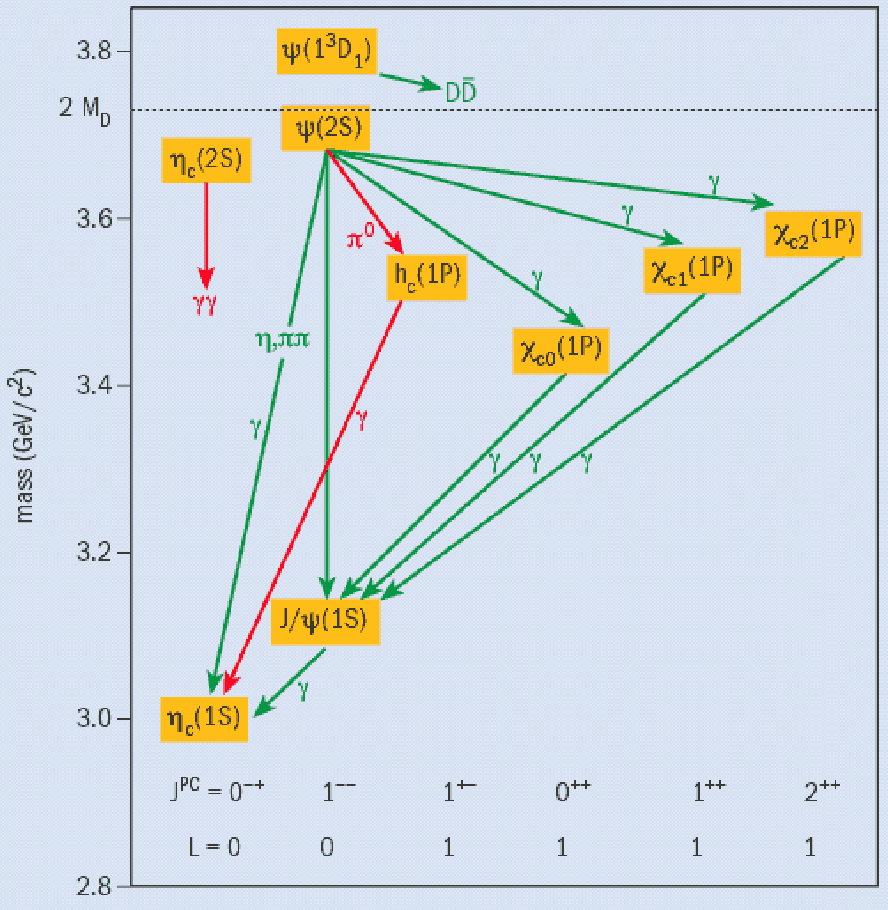


Charmonium states

- As the mass of the charmed quark is quite large, the velocities of the c and cbar in a bound state are small enough that many important features of these states can be described using non-relativistic potential models. Also, at typical separations of the quark and antiquark, the shape of the ccbar potential is somewhat like that of the Coulomb potential. Hence, many features of ccbar states - collectively called charmonium - are familiar from the physics of the hydrogen atom, or more precisely, from the spectroscopy and dynamics of positronium, a bound state of an electron and a positron.
- The charmonium spectrum provides fundamental information about the nature of the strong force holding quarks together.

Charmonium states

- After its discovery, the J/ψ was soon identified as a $^3S_1$ ccbar bound state, that is, a spin-triplet (S = 1) S-wave (L = 0) level with total spin J = 1. Several other ccbar levels were observed soon after. This figure illustrates the low-mass charmonium spectrum and the principal transitions between charmonium states expected from the analogy of ccbar states with positronium states. Among the low-mass states expected, only the $\eta_c(2S)$, an excited version of the $\eta_c(1S)$, and the h_c, a spin-singlet P-wave $^1P_1$ level, steadfastly refused to make significant appearances, despite reported sightings that were not confirmed.



Importance of charmonium studies

- If current ideas about the nature of the interquark force are correct, the mass of the h_c, $M(h_c)$, is expected to be near the average of the masses of the χ_{cJ} levels, $\langle M(^3P_J)\rangle \approx 3525$ MeV/c^2. This prediction for $M(h_c)$ is based on the expectation that the dominant spin-dependent interquark force is Coulomb-like, as predicted by quantum chromodynamics (QCD).
- Charm and charmonium data taken at CLEO by year 2005 include a sample of slightly more than 3 million $\psi(2S)$ decays. The $\psi(2S)$ data were used to search for the transition $\psi(2S) \rightarrow \pi^0 h_c$.
- **Analyses of this inclusive signature yielded $M(h_c) = 3524.9 \pm 0.7 \pm 0.4$ MeV/c^2 in good agreement with expectations**

Examples of other charmed particles

- **Decay of D^+ meson:** $D^+ \to \overline{K}^0 + e^+ + \nu_e$
  - $D^+(c\overline{d})$, mass $M(D^+) = 1869.7$ MeV, mean lifetime $t = 1.04 \times 10^{-12}$ sec
  - $\overline{K}^0(\overline{d}s)$, mass $M(K^0) = 497.7$ MeV
- **Decay of Λ^+_c baryon:** $\Lambda_c \to p + \overline{K}^0$
  - $\Lambda_c(udc)$ – lightest charmed baryon.
  - What about $\Lambda^+_c \to \pi^+ + \overline{K}^0$ decay? Is it allowed?
  - Can Λ^+_c decay strongly, i.e. via strong interactions only?
- **Decay of Σ_c baryon: $\Sigma^+_c \rightarrow \Lambda^+_c + \pi^0$ – what kind of the decay is that?**