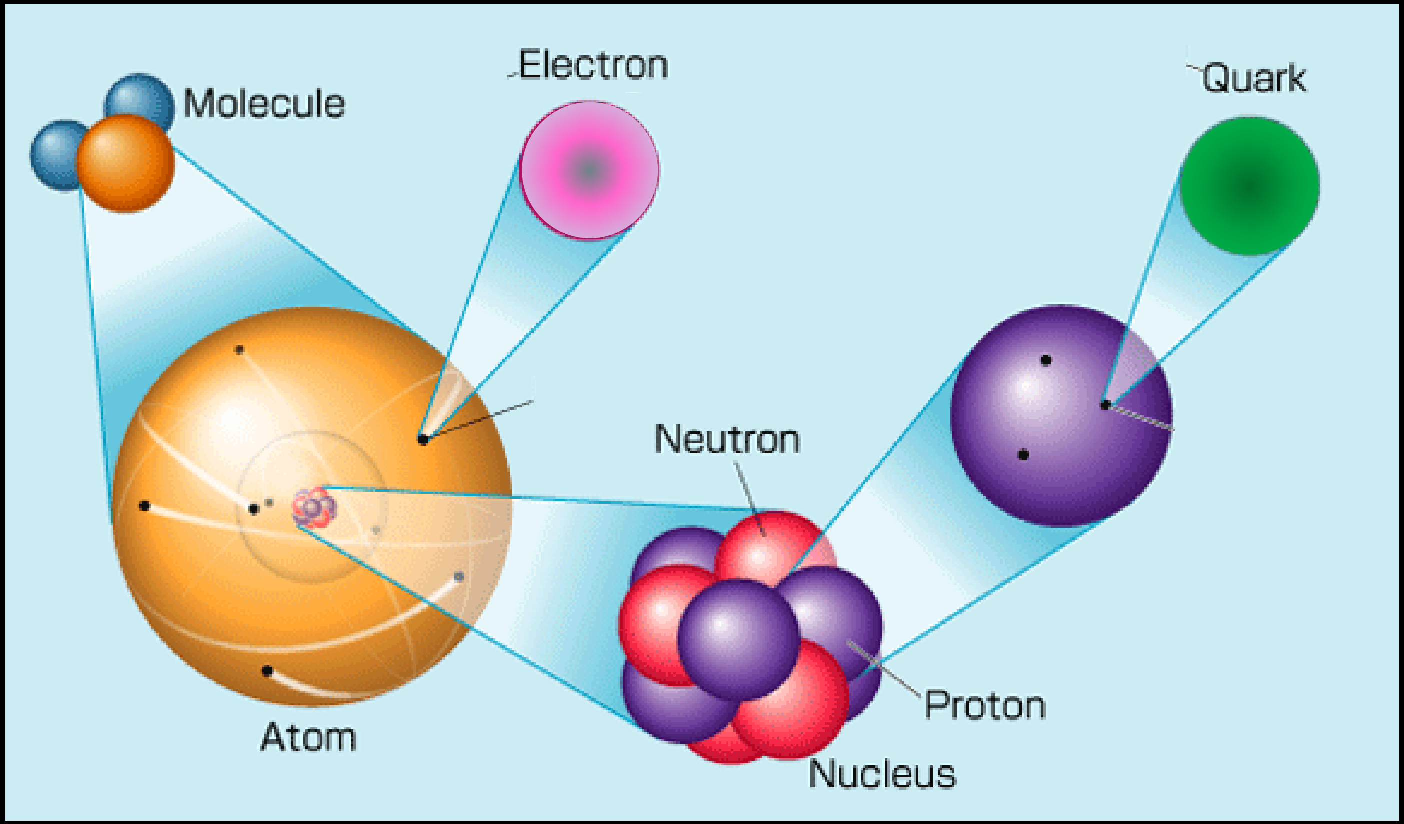
Mitglied der Helmholtz-Gemeinschaft

2nd Autumn Lectures – Tbilisi 2015

Structure of Matter (SoM)
Part 2

October, 2015 | Hans Ströher (Forschungszentrum Jülich)

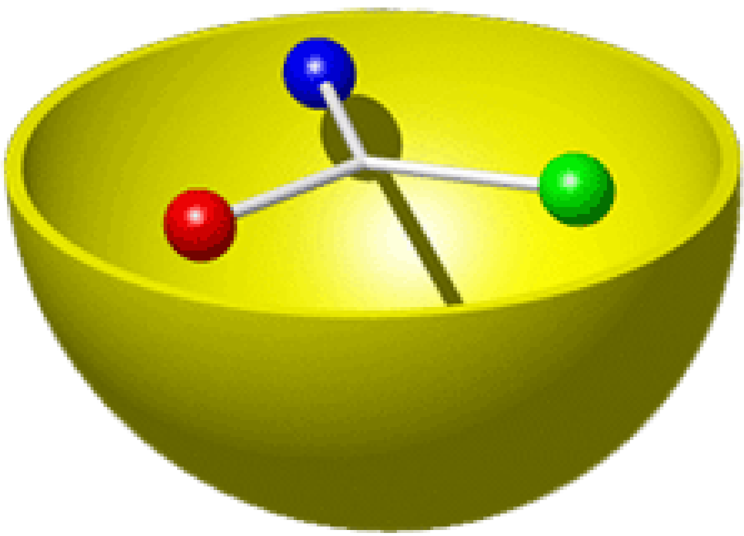
Part 1: Atoms, Nuclei



Protons, Neutrons, etc.

Part 2 – **Hadrons** – Introduction

Nucleons (protons (p) and neutrons (n)) are made of 3 “**quarks**”; the one´s that build the nucleon are called “**up**” (u) and “**down**” (d); they have **electric charge** (units of the elementary charge e_0) of +2/3 (u) and -1/3 (d):



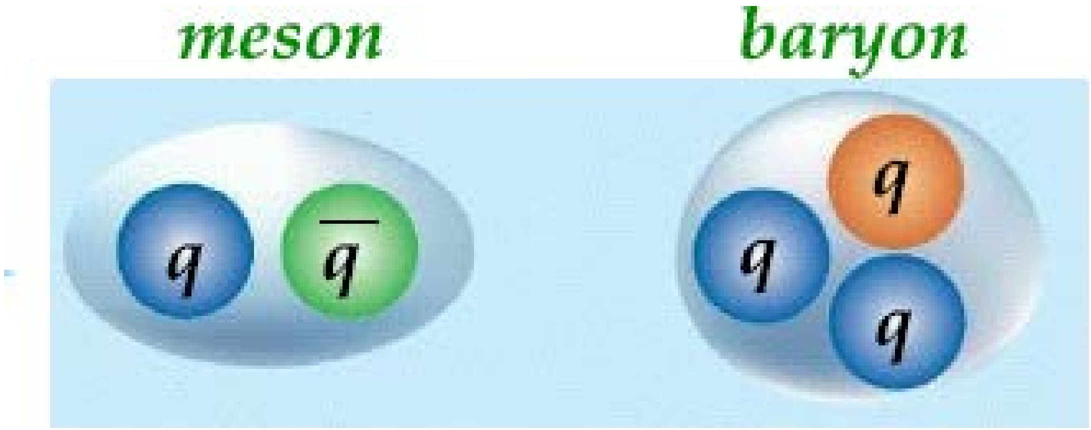
p = 2/3 + 2/3 – 1/3 = +1
p = uud

n = 2/3 – 1/3 – 1/3 = 0
n = udd

(quarks also have “**color charge**” … later)

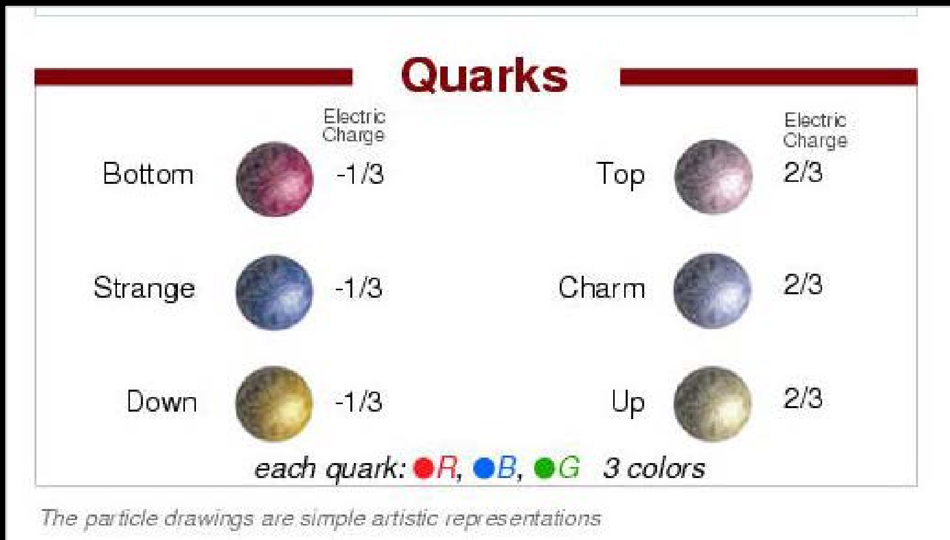
Part 2 – **Hadrons** – Introduction

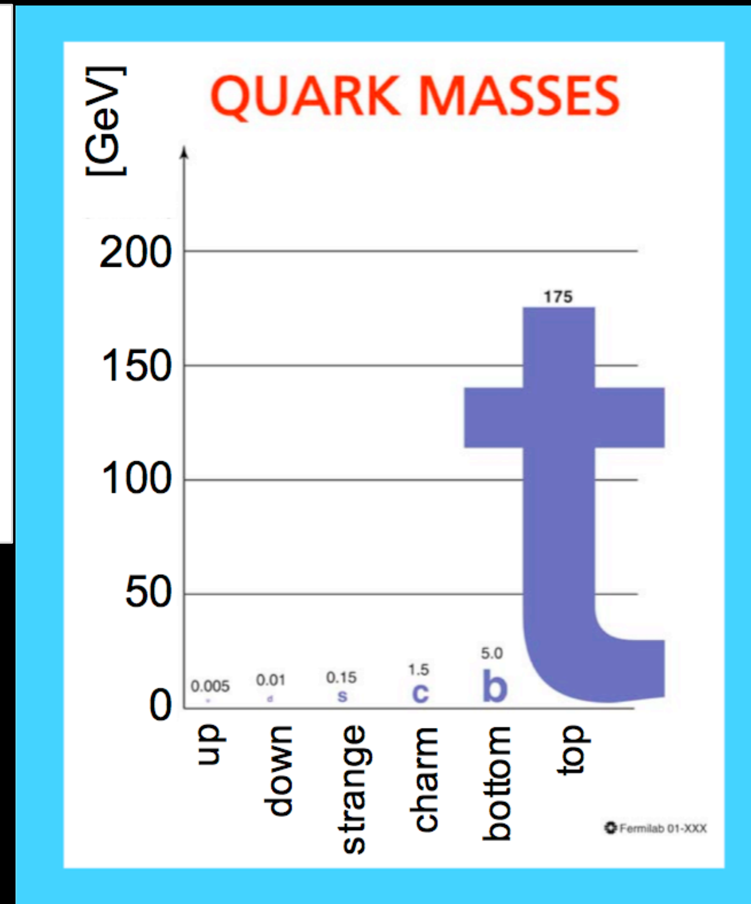
Nucleons are not the only systems made from quarks; more generally objects comprised of 3 quarks (qqq) are called “**baryons**”, while quark-antiquark systems ($q\bar{q}$) are called “**mesons**”; the two species together are named “**hadrons**”:



Since there are actually **6 different quarks** (“quark-flavor”), a lot of hadrons can be made; however, the world around us contains only up- and down-quarks; others are produced in energetic collisions and the corresponding particles are unstable.

Part 2 – Hadrons – Introduction



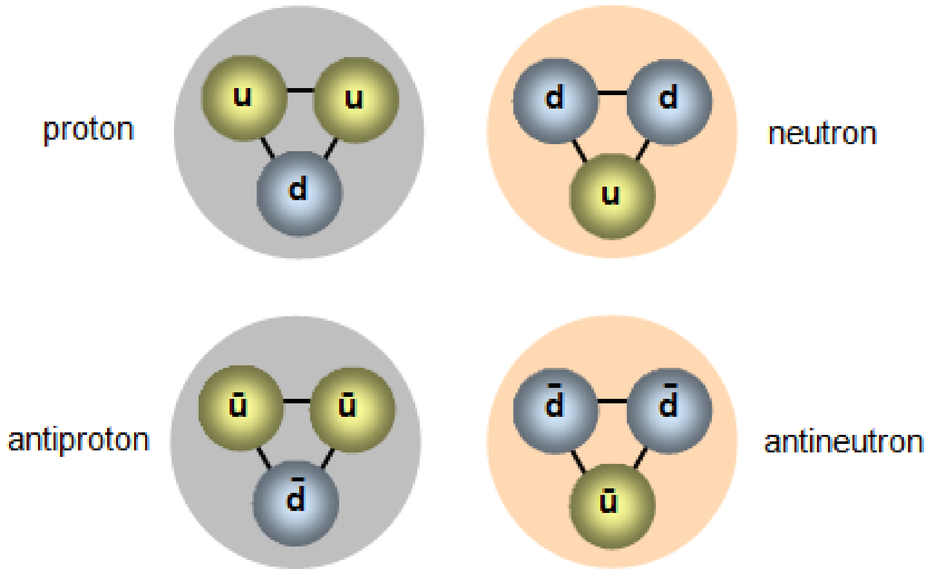


Note: anti-quarks
(charge: + ←→ -)

Quark Flavours

Part 2 – **Hadrons** – Introduction

The corresponding **anti-quarks** ($\bar{q}$) are the partial building blocks of the mesons ($q\bar{q}$) and the building blocks of the anti-baryons ($\bar{q}\,\bar{q}\,\bar{q}$); because of the reversed quark-charges, charged particles and anti-particles exhibit a charge change as well:



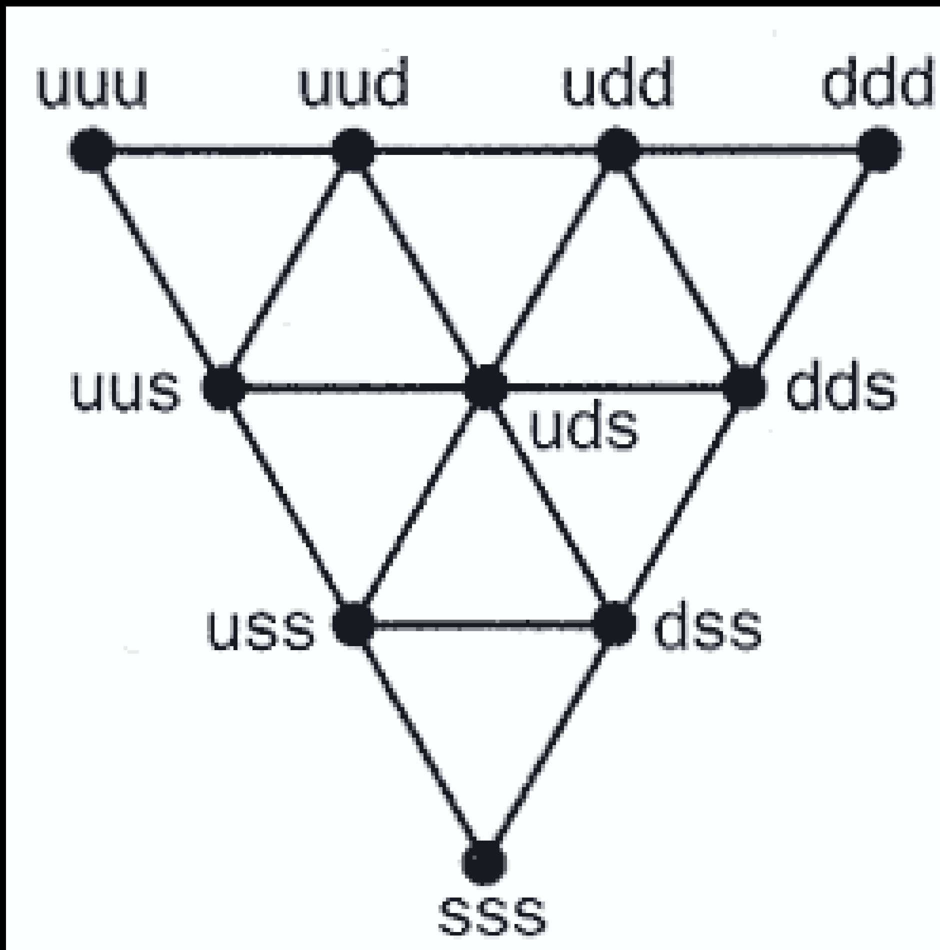
Part 2 – Hadrons – Multiplets

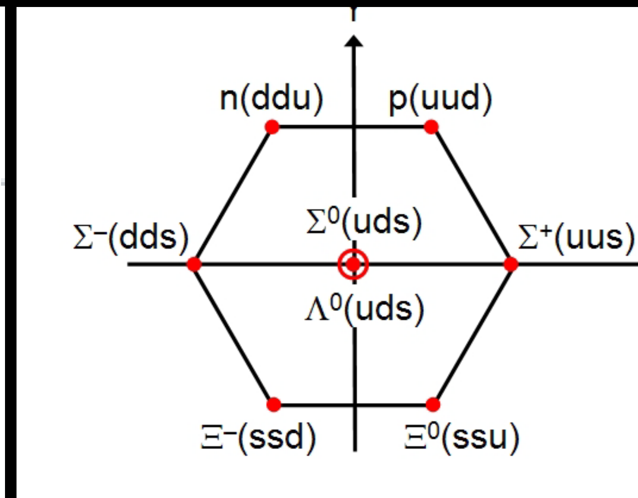
If only the **3 lightest quarks (u, d, s)** are considered, the following **baryons** are possible (note: 10 quark and 10 antiquark combinations):

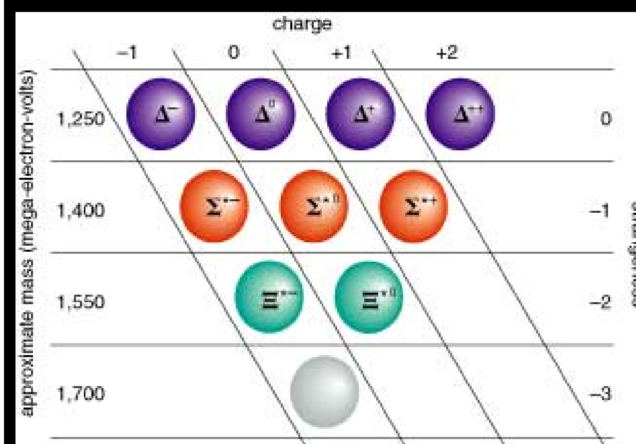
+3				$\overline{sss}$		Omega-Plus
+2			$\overline{dss}$	$\overline{dss}$		Anti-Xi
+1		$\overline{uus}$	$\overline{uds}$	$\overline{dds}$		Anti-Lambda, Anti-Sigma
0	$\overline{uuu}$	$\overline{uud}$	$\overline{udd}$	$\overline{ddd}$		Anti-Nukleon, Anti-Delta
0		ddd	udd	uud	uuu	Nukleon, Delta
-1		dds	uds	uus		Lambda, Sigma
-2		dss	uss			Xi
-3		sss				Omega-Minus
	-2	-1	0	+1	+2	

→ Can you find out (guess) what the numbers on the axes mean?

Taking into account that $\mathbf{m_u \sim m_d}$ and $\mathbf{m_{u,d} < m_s}$, the lines of the matrix discriminate the **particle masses**.







Baryon Multiplet

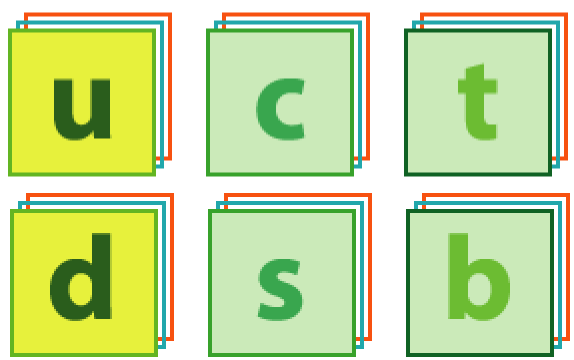
Part 2 – Hadrons – Color

The **significance of the Ω^-** was twofold:

- it was predicted within the quark model (mass, properties)
- it demonstrated the need for a property called "color” (charge)

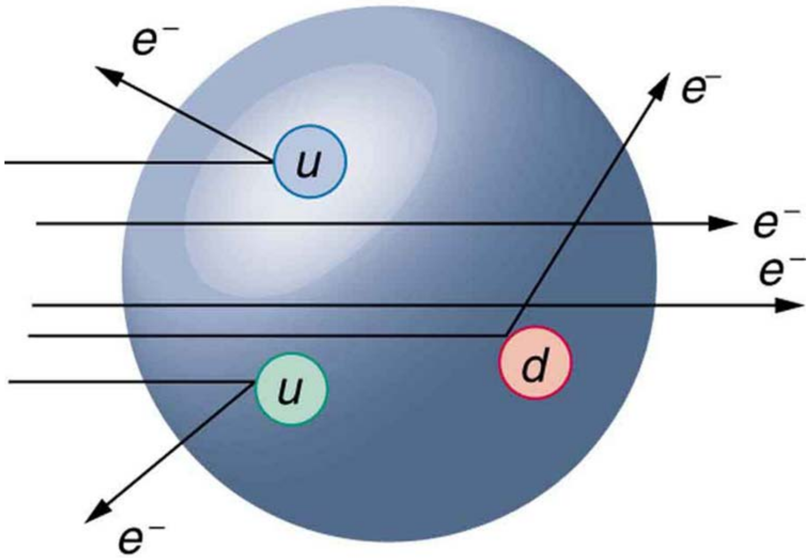
Since **quarks** are fermions with spin 1/2, they must obey the **Pauli exclusion principle** and cannot exist in identical states. So with three strange quarks, the property which distinguishes them must be capable of at least three distinct values – this is usually visualized by the three colors **red (R), green (G)** and **blue (B)**.

It turns out that all quarks have this property and it´s implications are very profound!



Part 2 – **Hadrons** – Color

Quarks are the **constituents of hadrons** as can be shown, e.g., in scattering experiments of high energy electrons on protons:

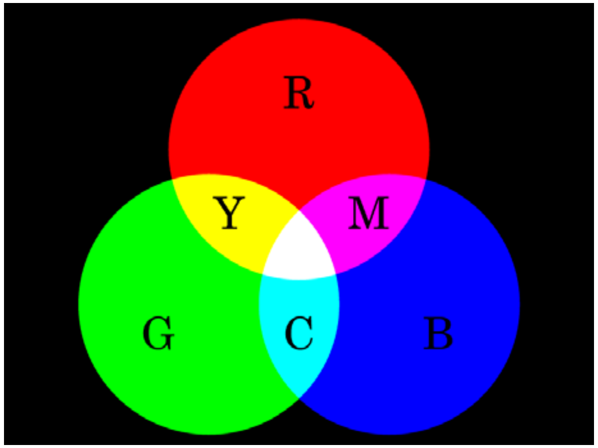


Proton

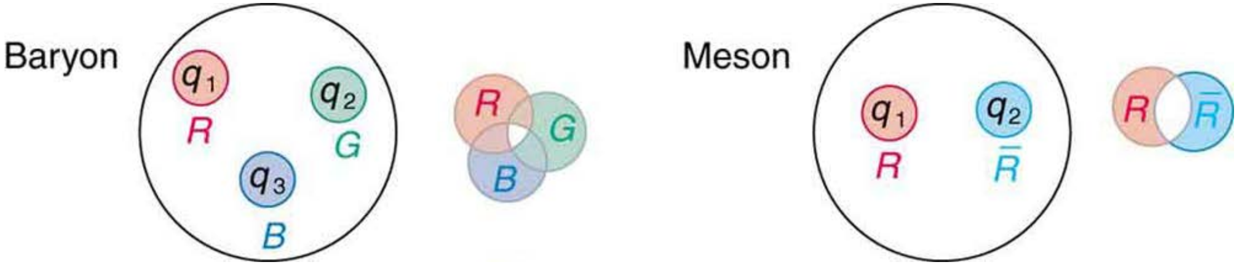
But, in spite of very intense searches, **no free quarks** have ever been observed → it is asserted that quarks cannot be isolated (they are said to be “**confined**” in hadrons)!

Part 2 – Hadrons – Color

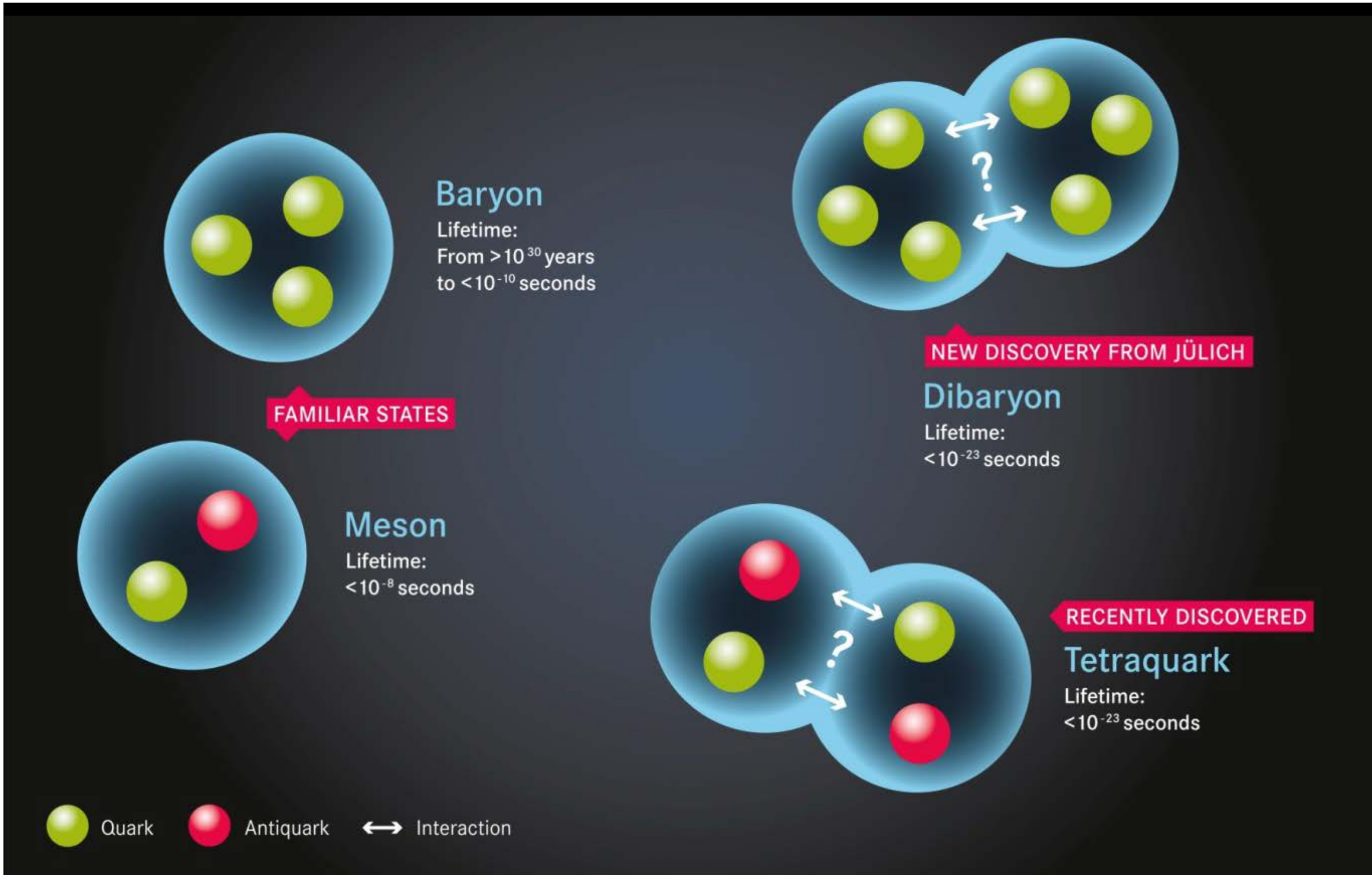
The “reason” for quark-confinement is that **only color-neutral** (“white”) hadrons do exist in Nature (thus the analogy with colors …):



This is possible, e.g., for baryons (if each of the quarks has one color) and also for mesons (assuming that **anti-quarks** have **anti-color**):



Part 2 – **Hadrons** – Color

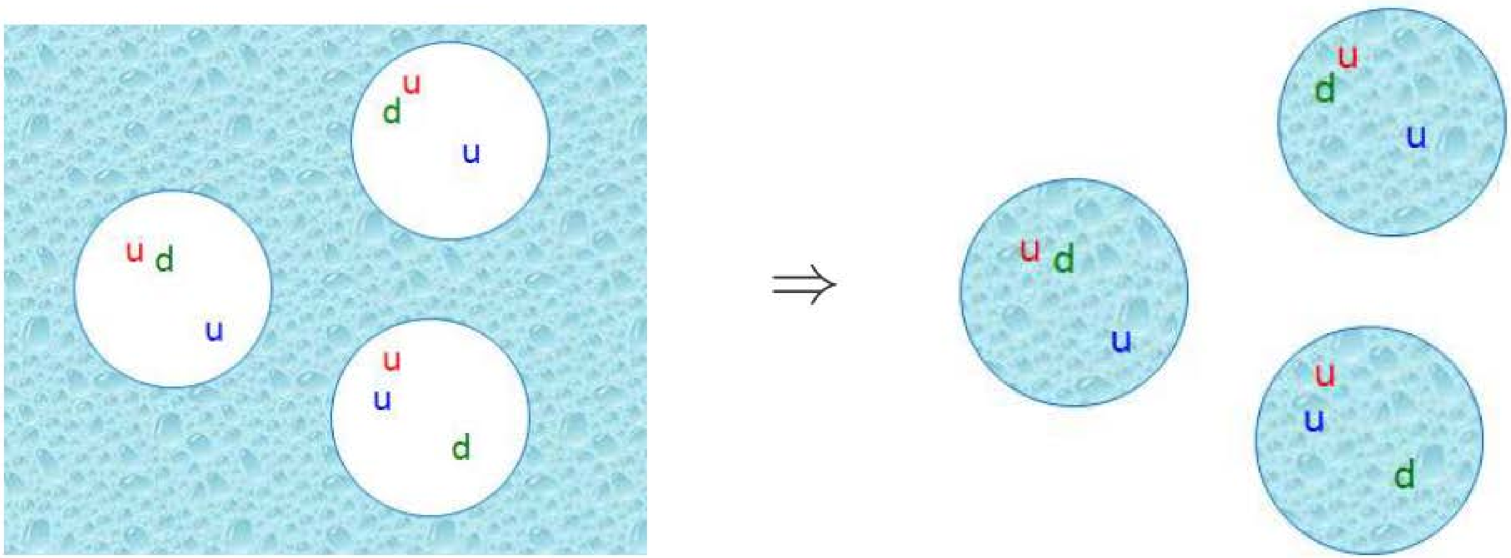


(…)

Quark Bound States

Part 2 – **Hadrons** – Nucleons

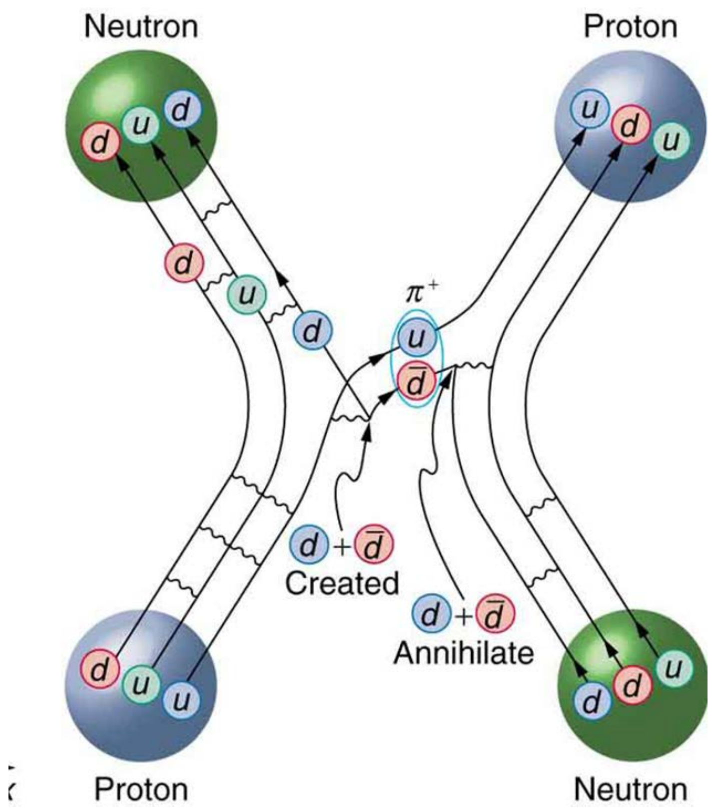
Nucleons (and other hadrons) were originally thought to be **bags** inside the vacuum (MIT quark-bag model; R ~ 1 fm); in recent years the picture has changed completely: the space between quarks is empty (except for quantum fluctuations) while the inside is extremely complex:



Quarks cannot escape the bag in either picture (**quark confinement**) due to the interaction between the quarks … later.

Part 2 – **Hadrons** – Nucleons

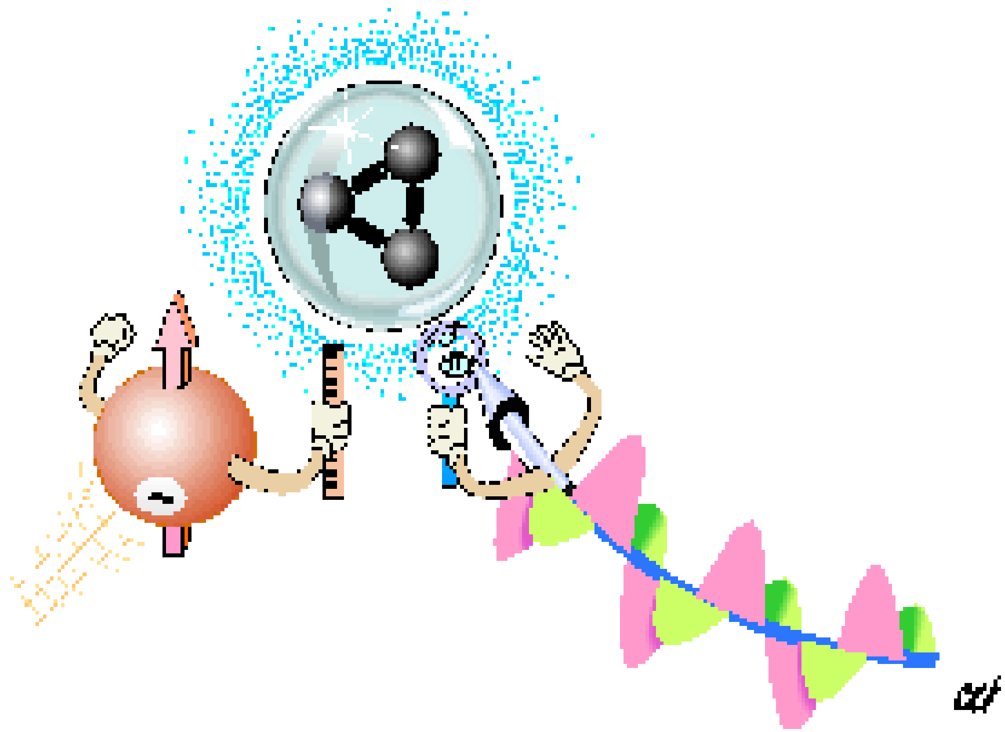
Because of the nucleon substructure, **the nuclear force** via the exchange of particles called "pion" is also more complex:



→ Note: force between quarks … later

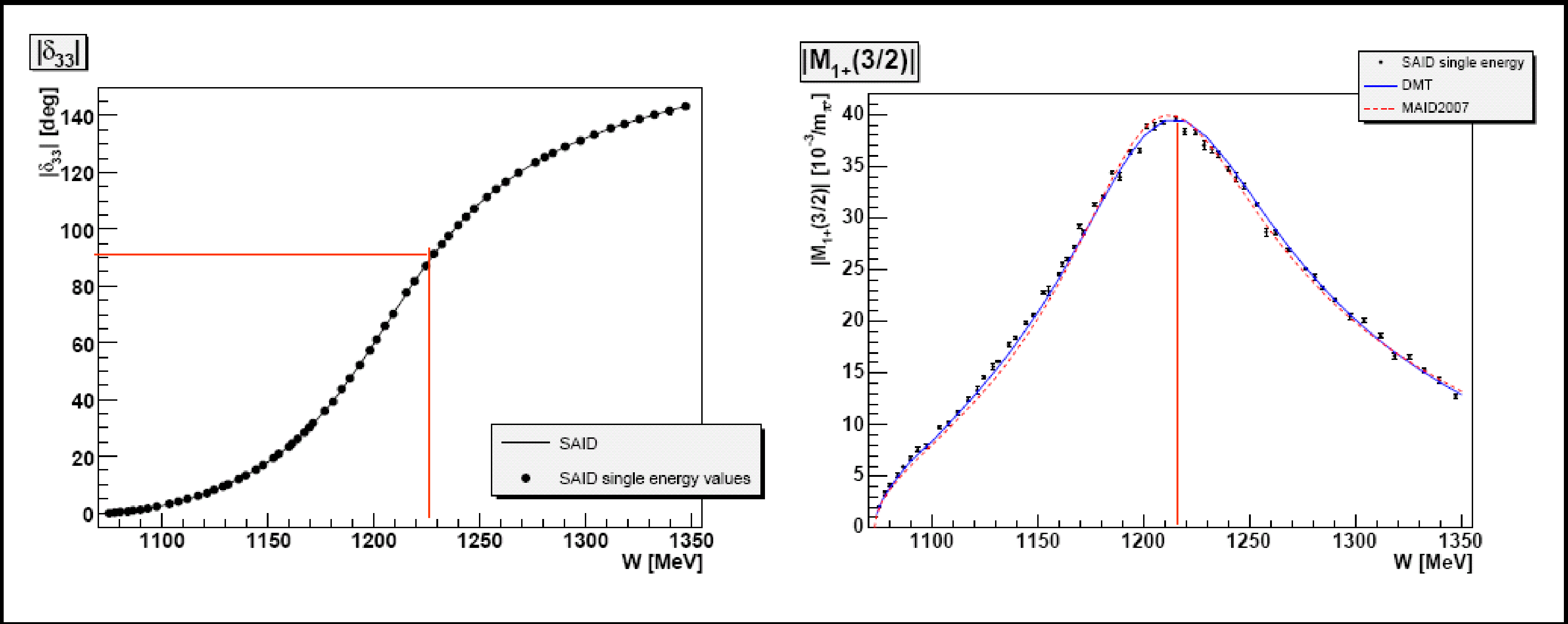
Part 2 – **Hadrons** – Nucleons

By injecting energy into hadrons (baryons, mesons) via photons, electrons or other projectiles (pions, nucleons, …), they can be excited to so called **resonances**:



They exhibit a spectrum of internal excitations (like atoms and nuclei):

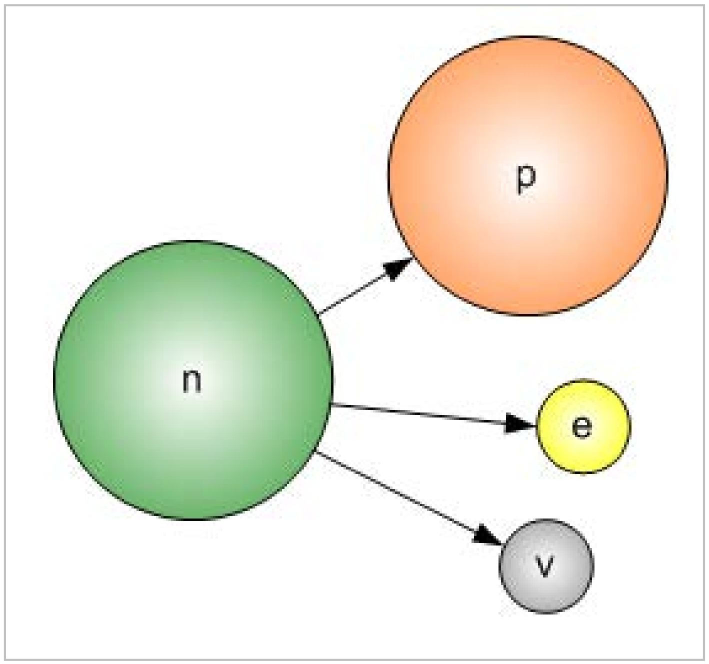
Part 2 – **Hadrons** – Nucleons



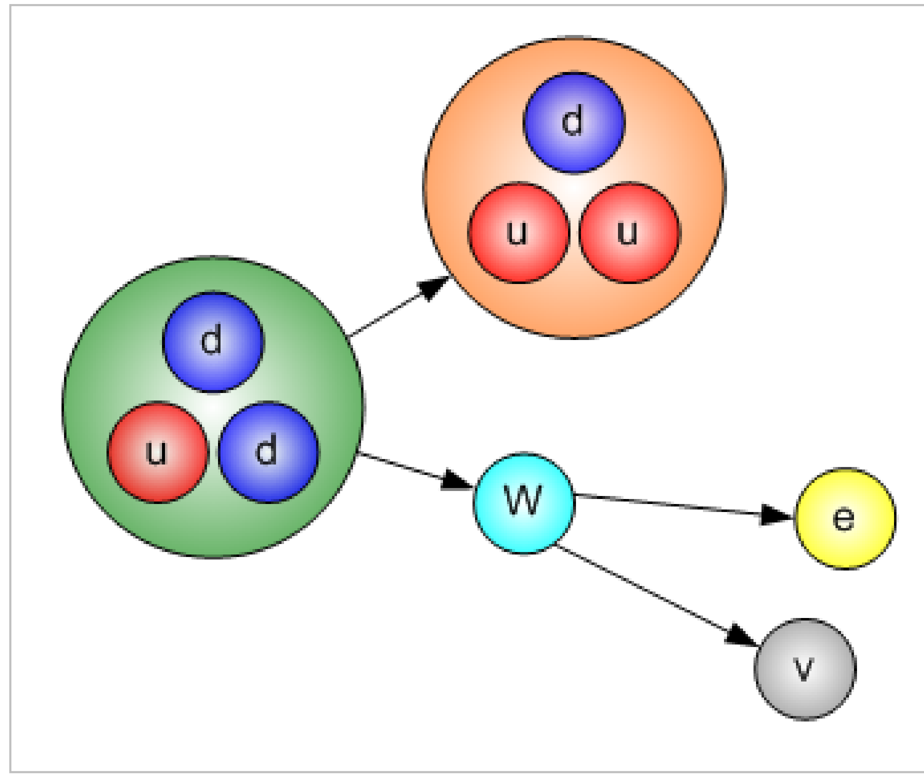
„Delta“ (Δ) Resonance

Part 2 – **Hadrons** – Nucleons

The **free neutron is unstable** (ß-decay)

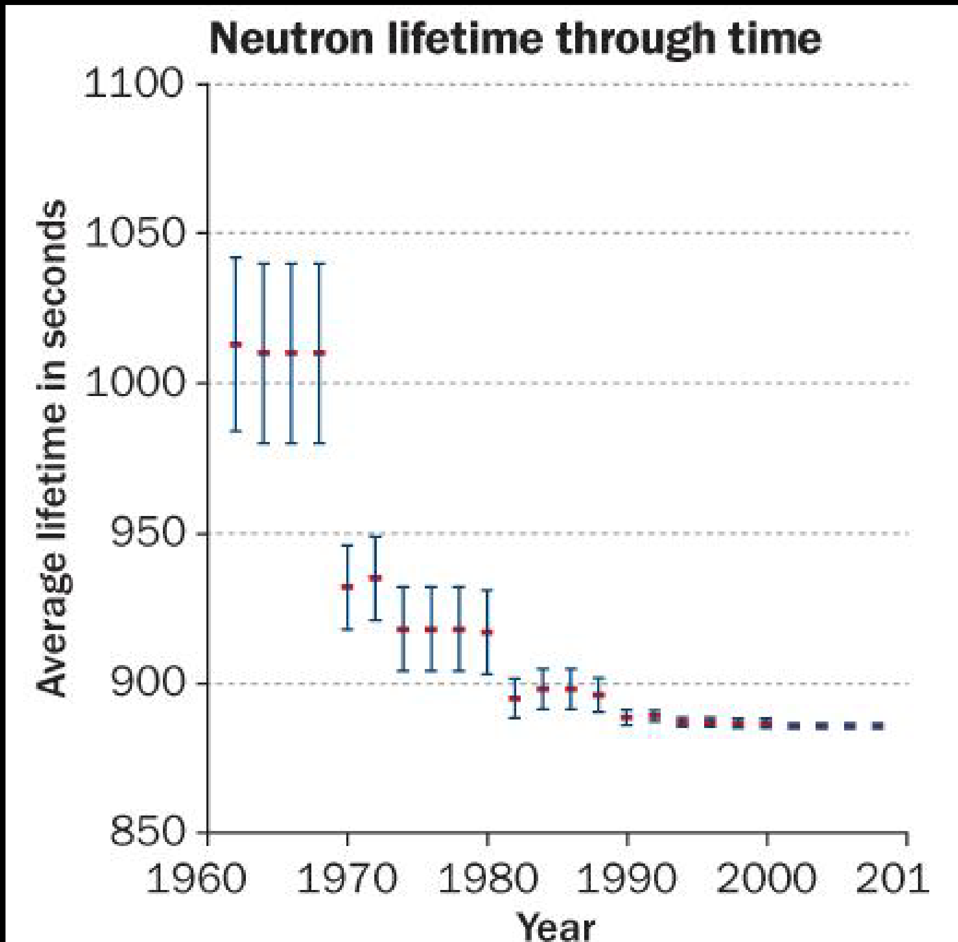


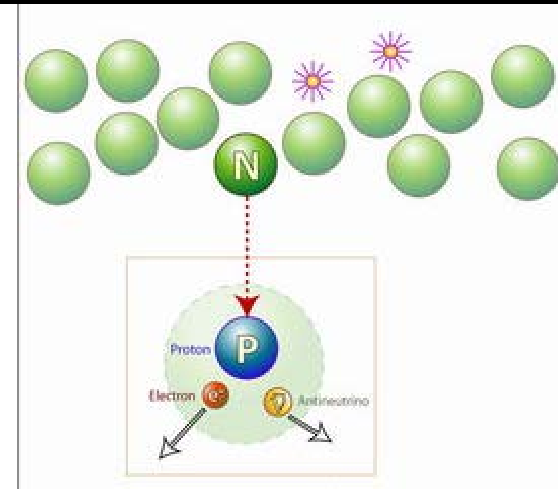
$$n \rightarrow p^{+} + e^{-} + \bar{\nu}_e + 782\ \mathrm{keV}$$



Inside many nuclei it is stabilized because of the **Pauli exclusion principle** (no energetically possible empty proton level). If, however, such a level is empty, nuclear ß-decay will happen!

Part 2 – **Hadrons** – Nucleons





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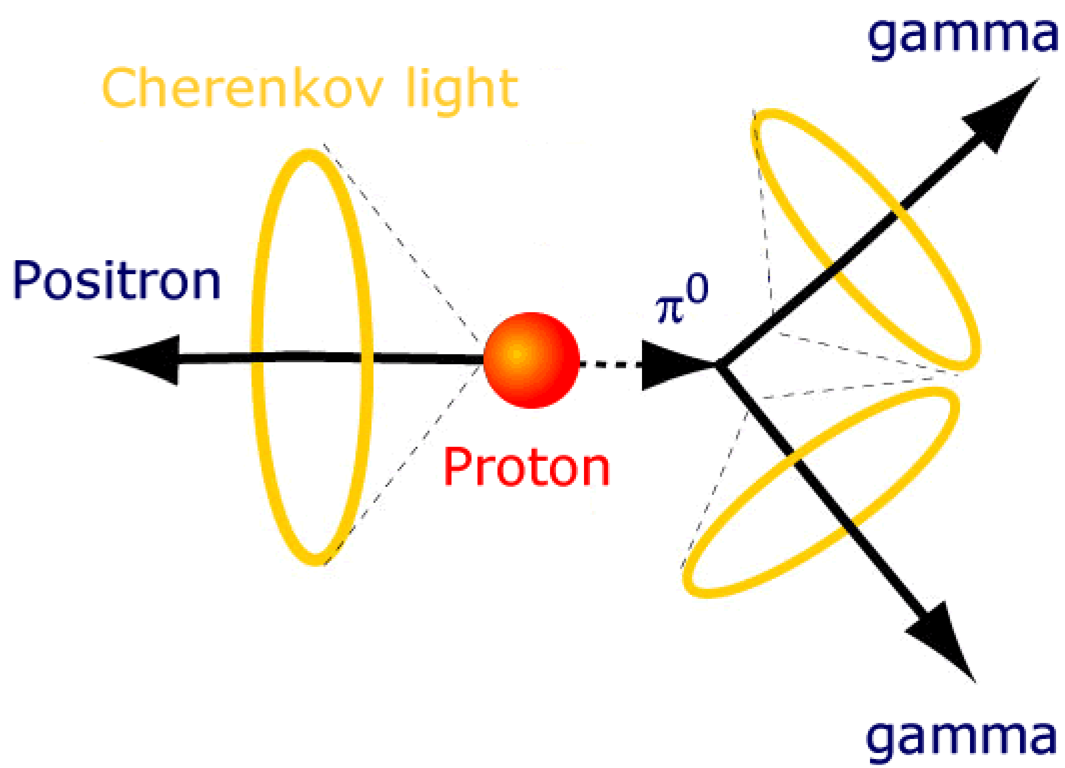
882.6± 2.7	MAMPE	93
888.4± 3.1± 1.1	NESVIZHEV...	92
887.6± 3.0	MAMPE	89
891 ± 9	SPIVAK	88

Neutron Lifetime

Part 2 – **Hadrons** – Nucleons

The **free proton** is **very stable** – it´s lifetime is much larger than the age of the universe. It is not clear whether it decays at all, for example in the following way:



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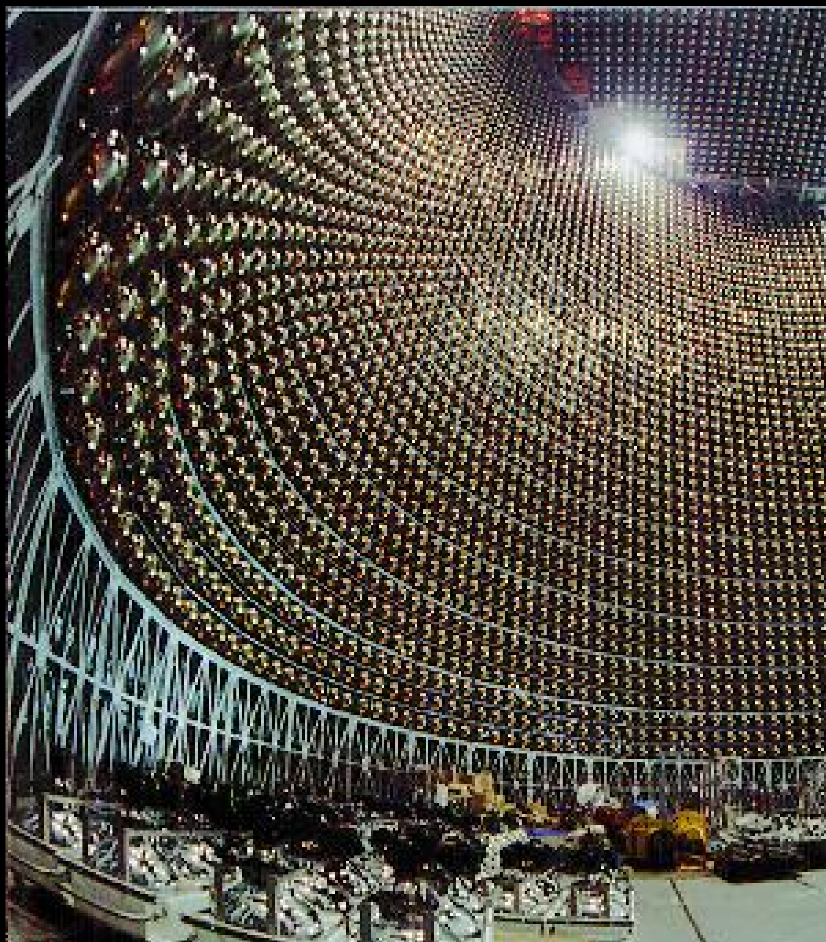
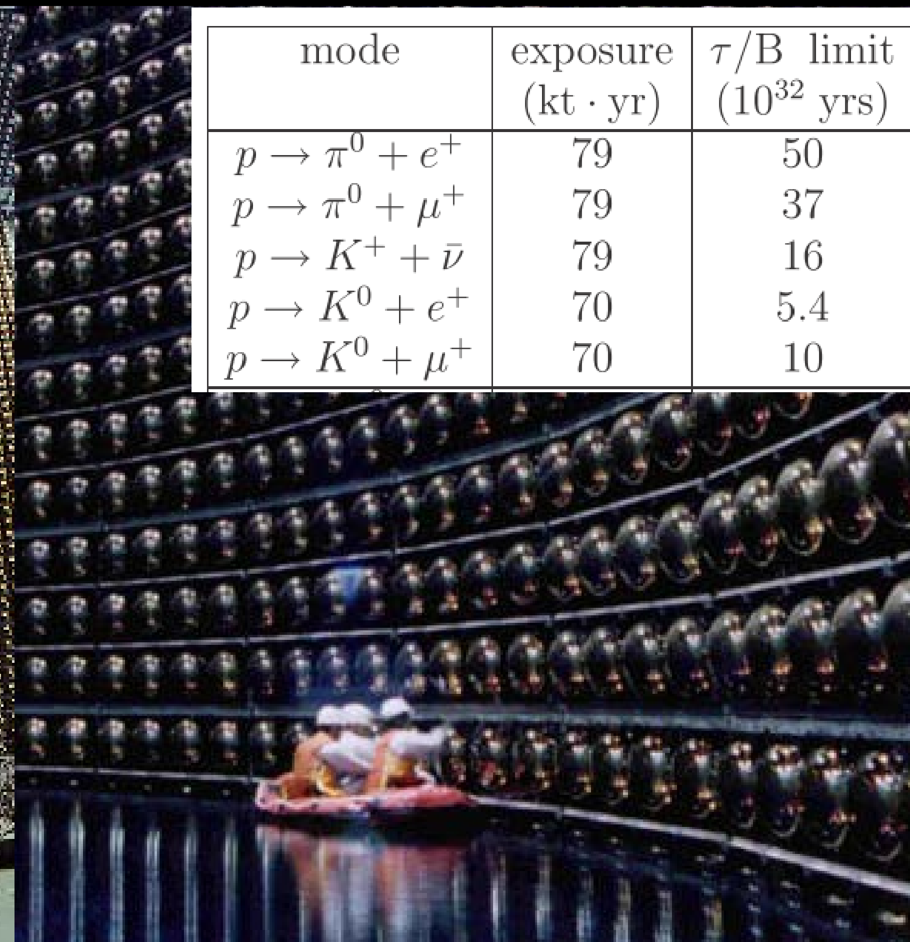


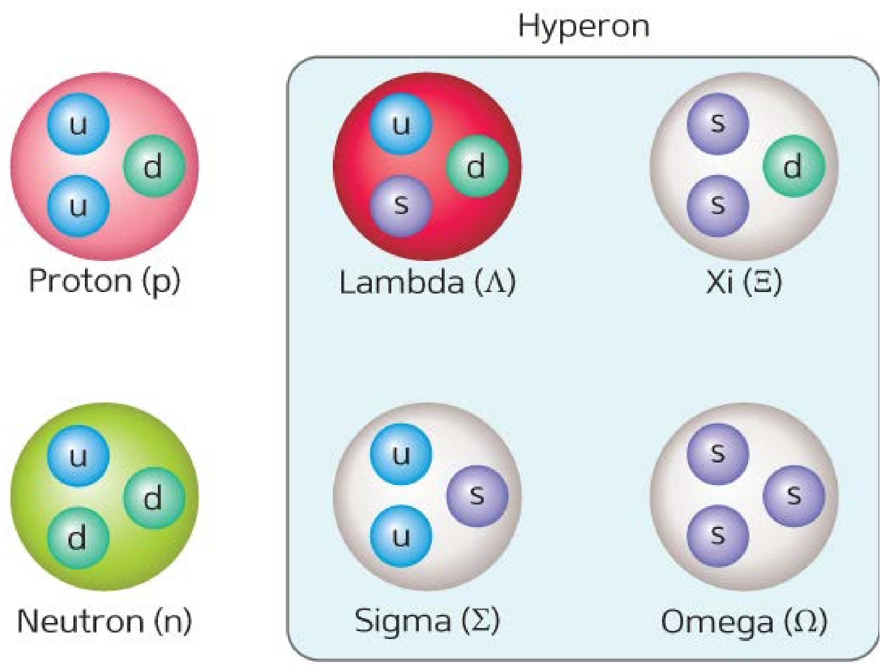


mode	exposure (kt · yr)	τ/B limit (10^{32} yrs)
$p \rightarrow \pi^0 + e^+$	79	50
$p \rightarrow \pi^0 + \mu^+$	79	37
$p \rightarrow K^+ + \bar{\nu}$	79	16
$p \rightarrow K^0 + e^+$	70	5.4
$p \rightarrow K^0 + \mu^+$	70	10

Proton Lifetime

Part 2 – **Hadrons** – Hyperons

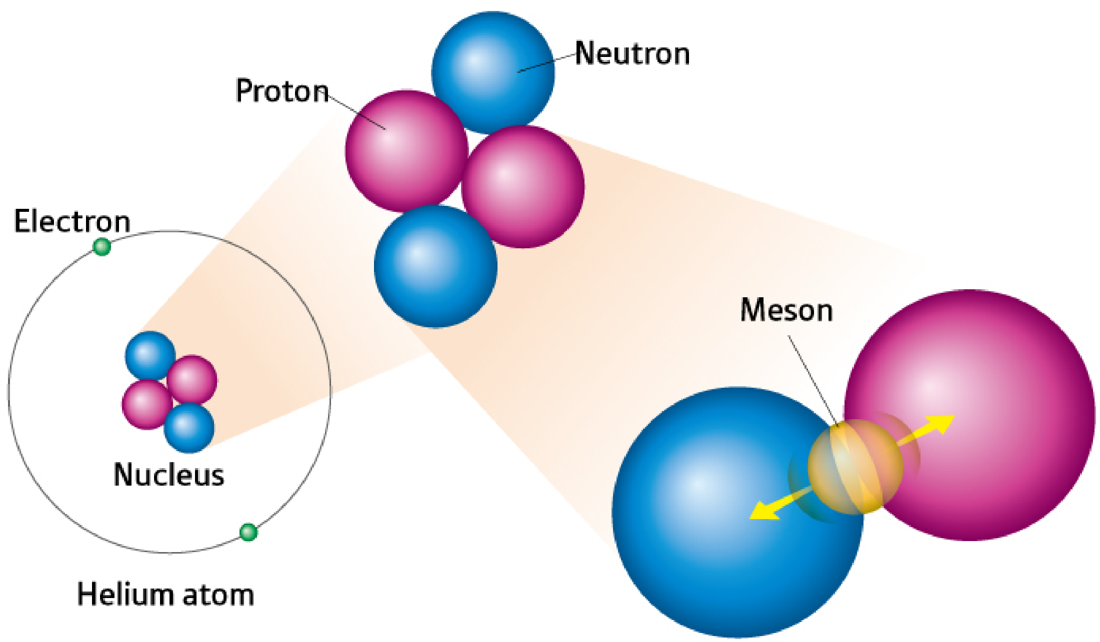
A **hyperon** is any baryon containing one or more **strange quarks** (s):



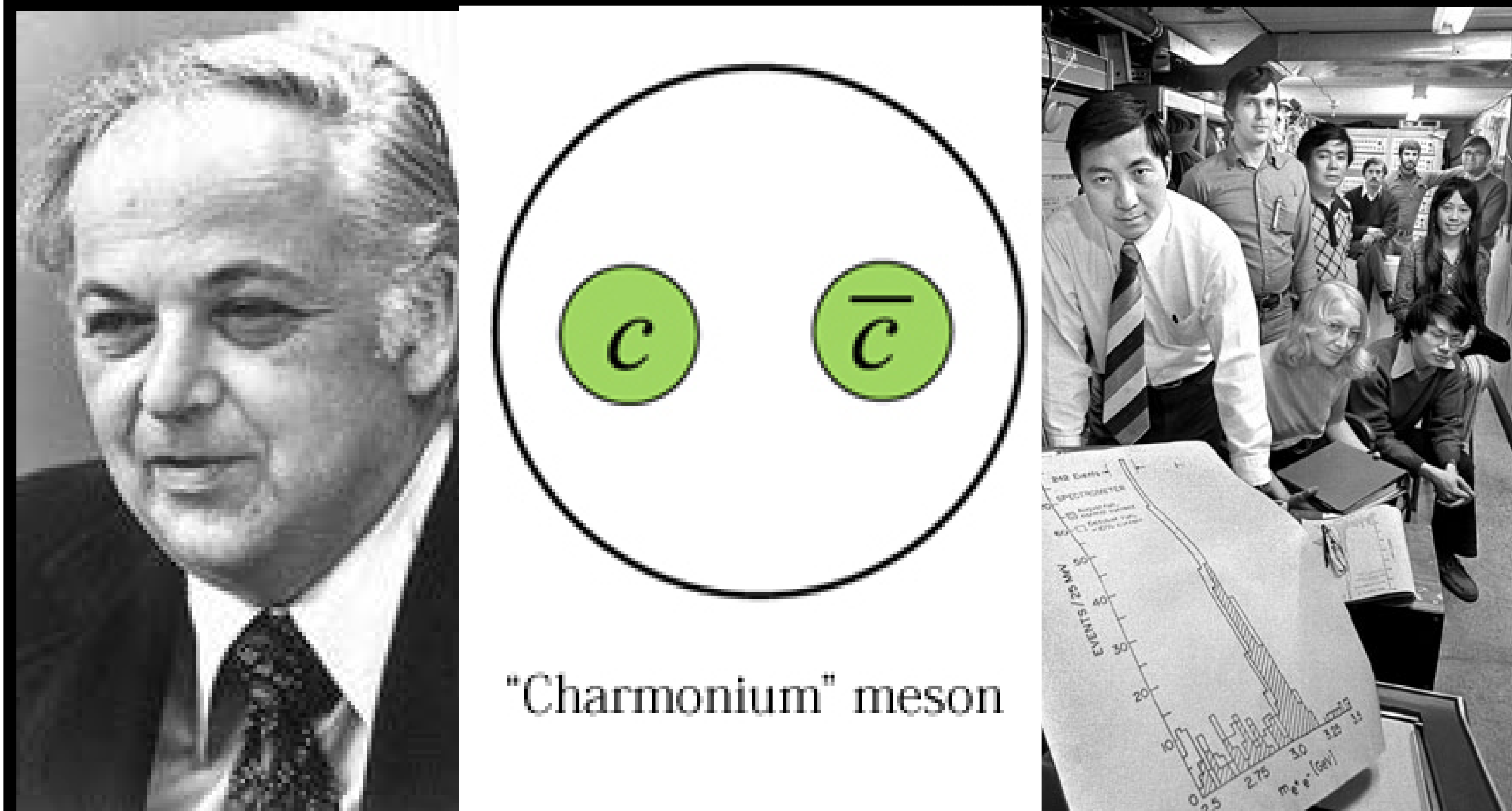
They were called "**strange**" particles, because by the time of their discovery, it was not understood, why many of them have such a long lifetime (10^{-10} - 10^{-11} s instead of $<10^{-19}$ s); the reason is "strangeness conservation" in strong interactions.

Part 2 – **Hadrons** – Mesons

Mesons are hadronic subatomic particles composed of one quark and one antiquark; all mesons are unstable, with the longest-lived lasting for only a few hundredths of a microsecond. The importance of lighter mesons is that they are the particles that **transmit the nuclear force**:



Part 2 – Hadrons – Mesons

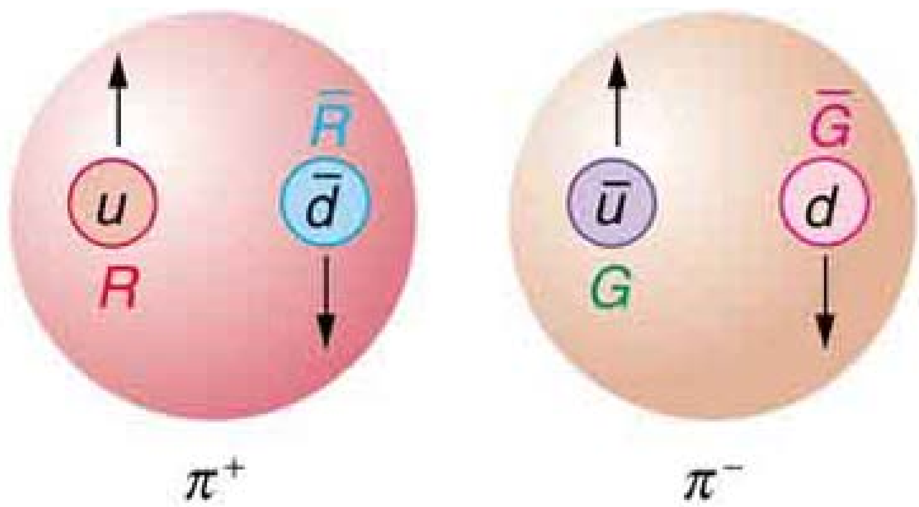


The Story of the J/Ψ Meson

Part 2 – **Hadrons** – Mesons

Mesons can only have charges **+(e_0)**, **0**, and **-(e_0)**; the charged mesons are particle and antiparticle, respectively:

Example:



Since for every particle, there exists an antiparticle, **neutral mesons** are their own antiparticles (as usual, in some cases it turns out to be more complicated …).

Part 2 – Hadrons – Summary

Hadrons are atomic **particles made of quarks** in a way that they are color-neutral (“white”).

Many hadrons exist; they are subdivided into **baryons** (3 quark states) and **mesons** (quark-antiquark states), “multiplets”, but other combinations (e.g., tetraquarks, …) do also exist.

Hadrons can be excited into **resonances**, which decay by emission of particles (mesons) and photons.

All hadrons (except the lightest one – the proton – which has not yet been shown to decay) are **unstable**.

Protons and neutrons (nucleons) have **spin ½** and thus have to obey the Pauli exclusion principle, which leads to the structure of the nucleus.

We now know 6 quarks and the electron – is this all?

Part 2 – Particles – Introduction

Situation in 1960

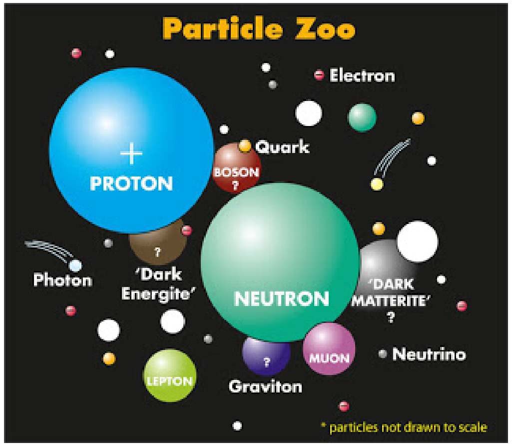
Part 2 – Particles – Introduction

Particles are (or are comprised of) the **fundamental constituents of matter** (i.e. to our current knowledge they have no internal structure); in the context of atoms, nuclei and hadrons, we have discussed:

- **Electron** (e)
- Baryons (e.g. **proton** (p) and **neutron** (n))
- Mesons (e.g. **pion** (π) …)

} **quarks**

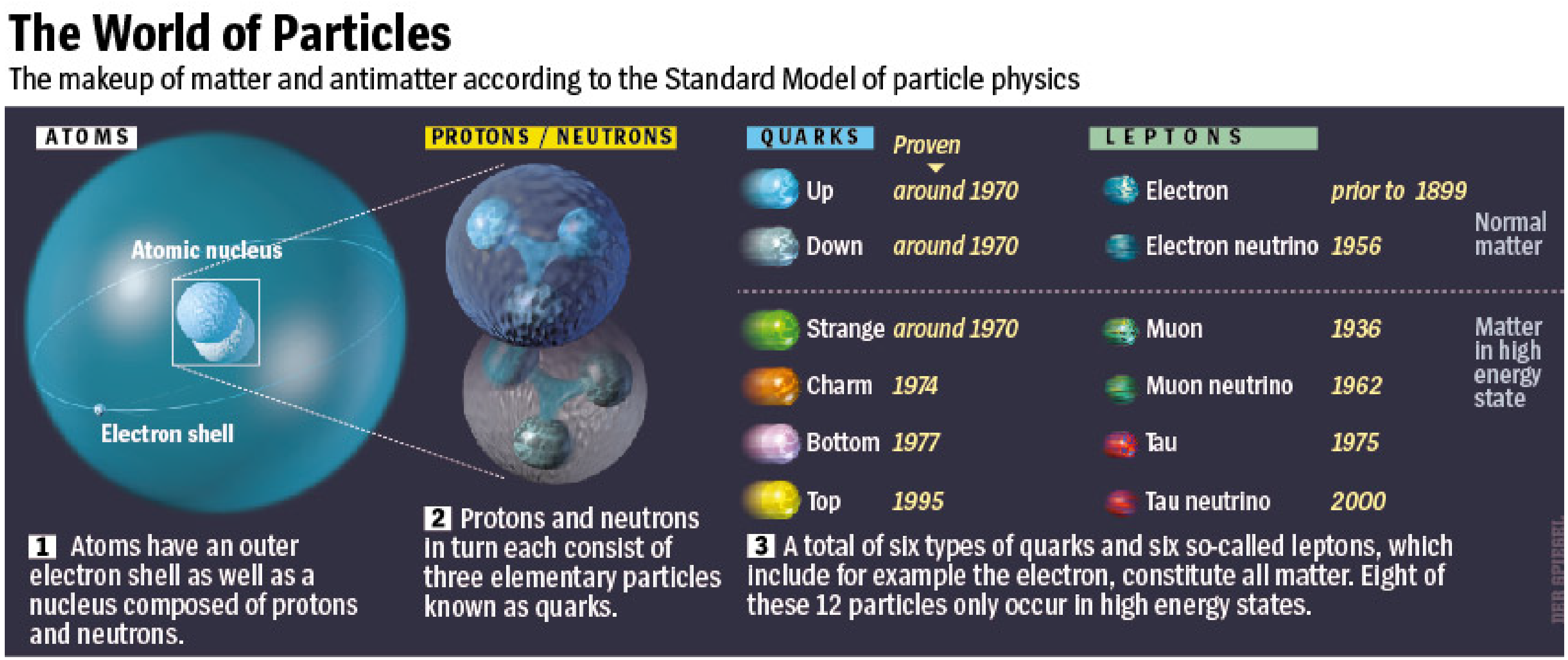
and mentioned some other: **photon** (γ), **muon** (μ), and **neutrino** (ν).



The question is whether (and how) this all fits together in a common framework (→ "**Standard Model**" of elementary particle physics)

Part 2 – **Particles** – Constituents

In the Standard Model, the **matter particles** are the **quarks** and the **leptons**; each come in 3 “families” or “generations” of charge states and with increasing mass:



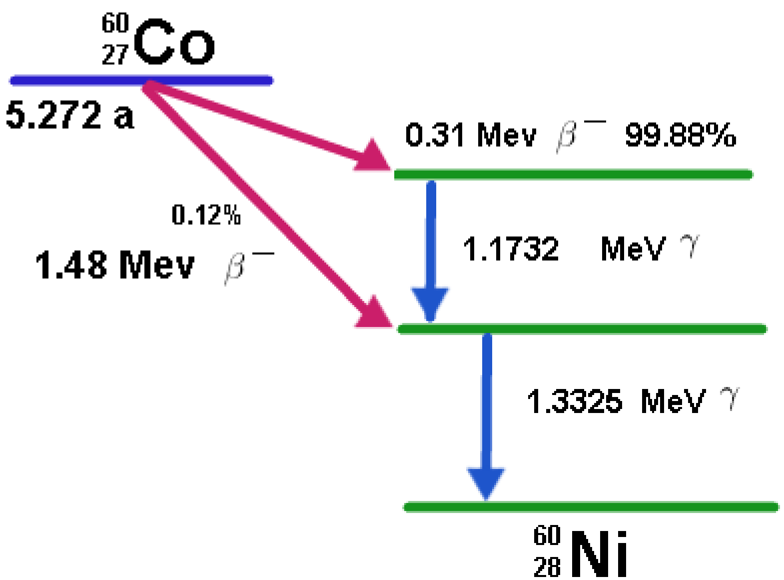
Normal matter consists of up- and down-quarks and electron and it´s neutrino.

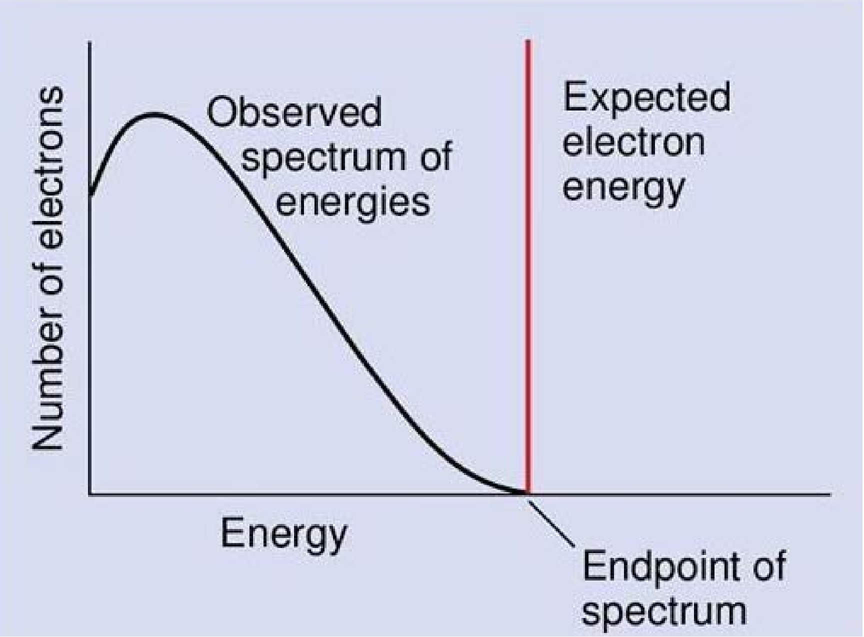
Part 2 – Particles – Constituents

Neutrinos are the electrically neutral leptons, affiliated with the corresponding charged ones: e - ν_e, μ - ν_μ, τ - ν_τ

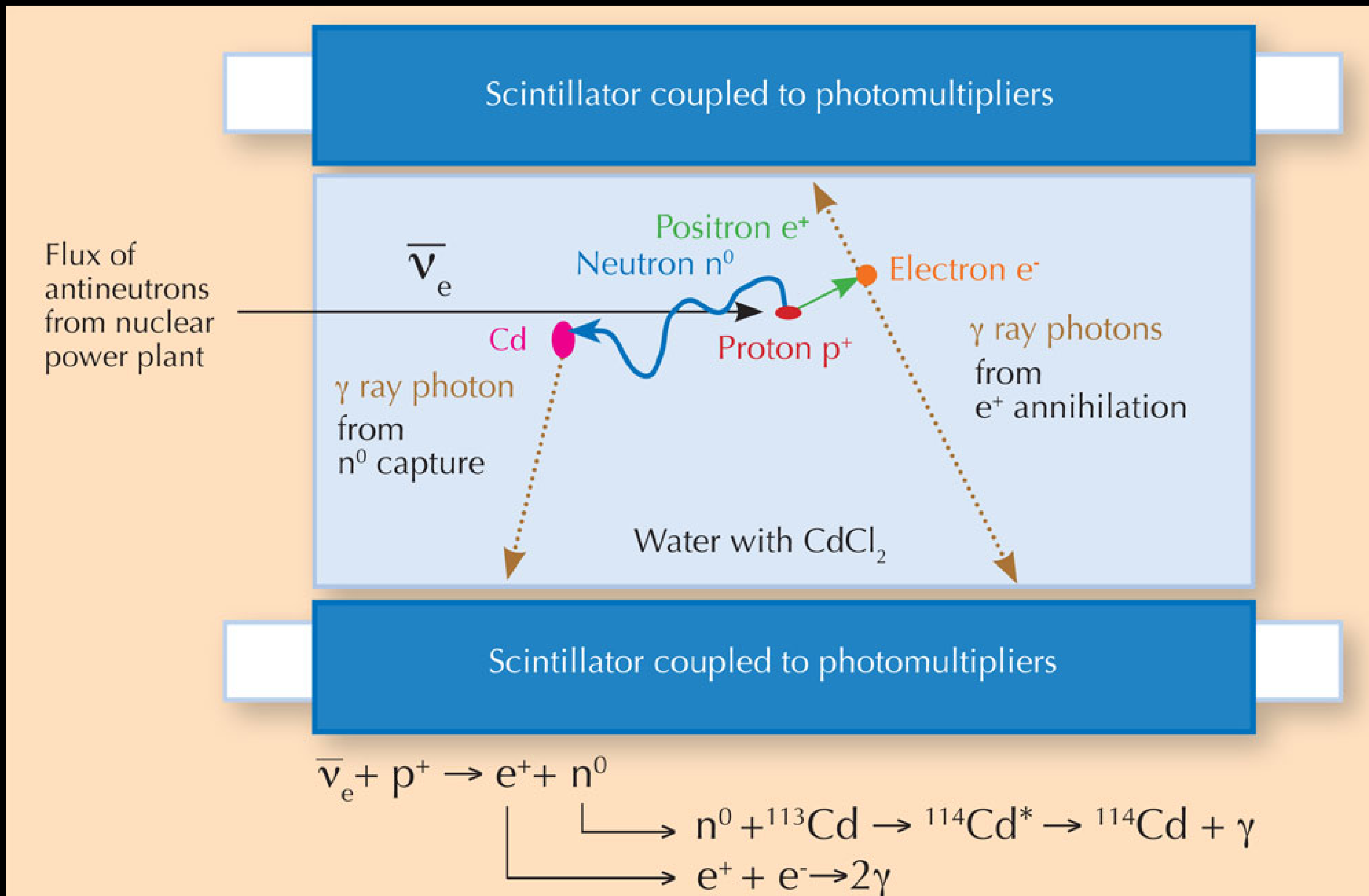
The neutrino was postulated first by Wolfgang Pauli in 1930 to explain how nuclear **ß- decay** could **conserve energy**, **momentum**, and **spin**;

Example:





Part 2 – Particles – Constituents



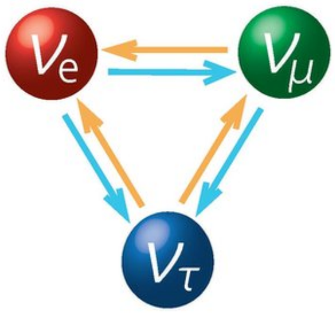
(First) Neutrino Detection

Part 2 – **Particles** – Constituents

Neutrinos are very abundant in the Universe (second most after photons): **~ 37 ν´s per cm^3**; the neutrino flux from the **sun** is calculated to be **5 x 10^6 cm^{-2} s^{-1}** ; every second trillions of neutrinos pass our bodies

Neutrinos **interact very little** with matter (→ reason why they were discovered so late); gigantic detectors have been built to measure their properties: AMANDA (Mediteranian Sea), IceCube (Antartica), Super-Kamiokande (Japan), Daya Bay (China), …

Neutrinos **have a mass** > 0 (although no finite neutrino mass has been measured yet; this is inferred from the fact that the different neutrino flavors can change into others ("neutrino oscillations"):



Part 2 – Particles – Force Carriers

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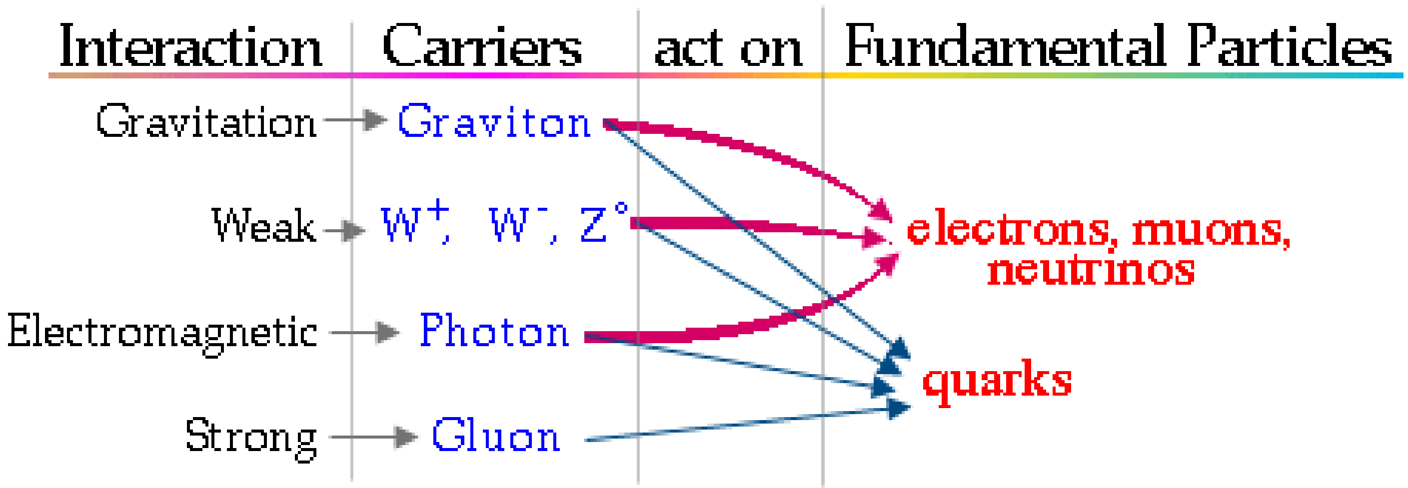
The Standard Model particles have to be extended by **force carriers**, i.e. particles which mediate the **interactions** between particles:

force	boson symbol	boson name
strong	g	*gluon*
electromagnetic	γ	*photon*
weak	W^+, W^-	*W bosons*
	Z°	*Z boson*

Scientists have discovered force carriers for three of the four known forces: **electromagnetism**, the **strong force** and the **weak force**. (They are still searching for experimental evidence of the force carrier for the fourth force, **gravity**. Note: gravitation will not be discussed here further.)

Part 2 – **Particles** – Force Carriers

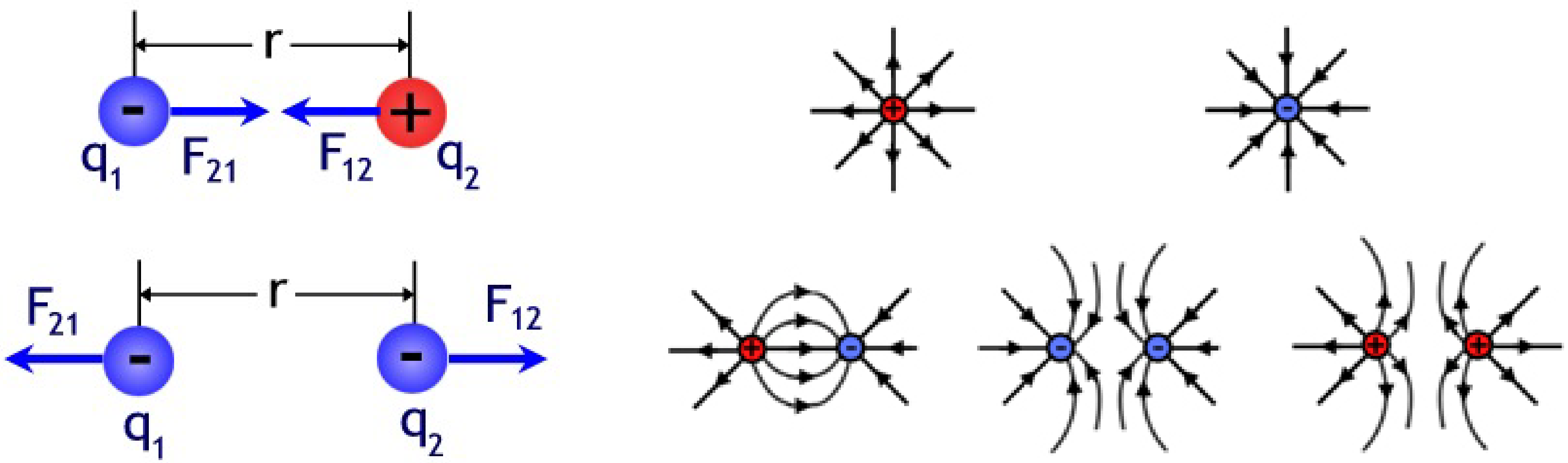
Not all fundamental particles take part in all of the interactions:



The **strong interaction** only acts between quarks, the **electromagnetic interaction** does not influence the uncharged neutrinos, but the **weak** and the **gravitational interaction** act on all fundamental particles.

Part 2 – **Particles** – Force Carriers

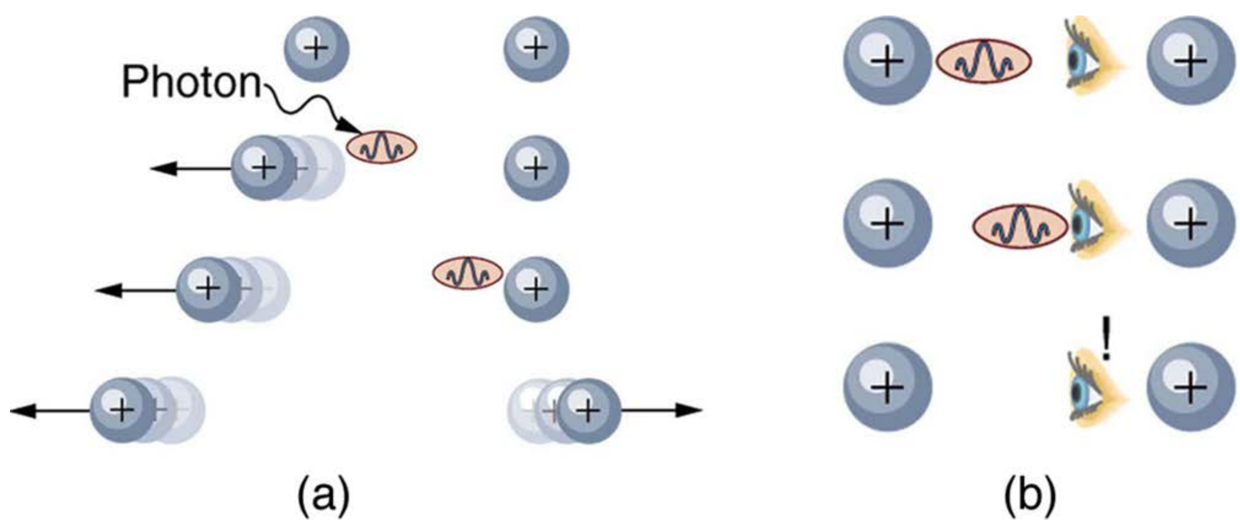
The **electromagnetic force** is a fundamental interactions in nature; it is described by electromagnetic fields, and has innumerable physical instances including the interaction of electrically **charged particles**:



The electromagnetic force is the interaction responsible for almost all the phenomena encountered in daily life, with the exception of gravity: molecular and atomic binding, electromagnetic waves (light) …
The foundation of **classical electrodynamics** is provided by the "Maxwell Equations"

Part 2 – **Particles** – Force Carriers

Maxwell's equations (along with the rest of classical electromagnetism) are extraordinarily successful at explaining and predicting a large variety of phenomena; however, they are **not exact laws** of Nature, but merely **approximations**; for example, Maxwell's equations do not involve “**photons**”.
For accurate predictions in all situations, Maxwell's equations have been superseded by quantum electro-dynamics (QED): the interaction happens by the **exchange of** force carrier bosons called **photons**:

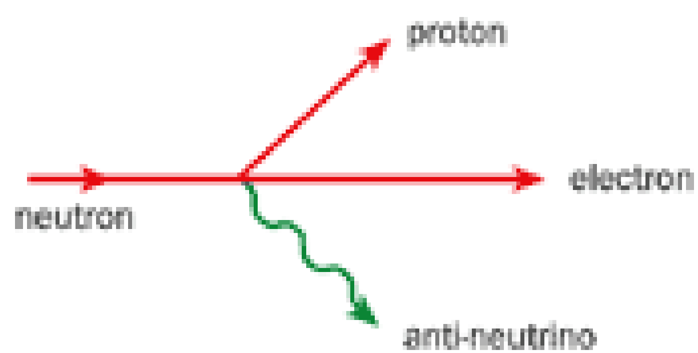


Part 2 – **Particles** – Force Carriers

The **weak force** underlies some forms of **radioactivity** (ß-decay), governs the **decay of unstable** subatomic **particles** (such as mesons), and initiates the nuclear **fusion reaction** (e.g., in the Sun)

The weak force **acts upon all known fermions**, i.e., elementary particles with half-integer values of intrinsic angular momentum (spin)

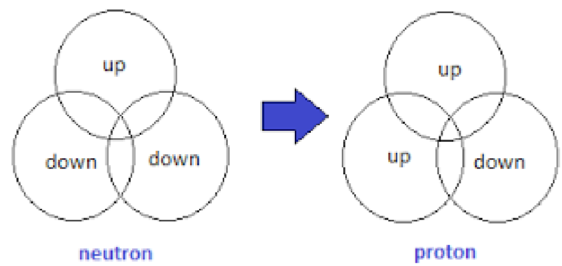
Enrico Fermi proposed the first theory of the weak interaction, known as Fermi's interaction by suggesting that beta decay could be explained by a four-fermion interaction, involving a contact force with no range; example: **neutron-decay**



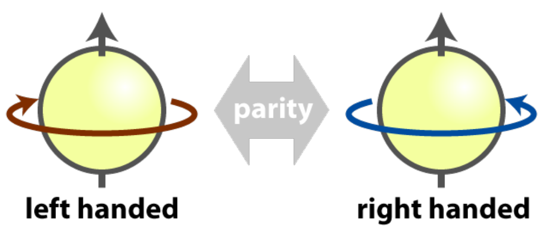
Part 2 – **Particles** – Force Carriers

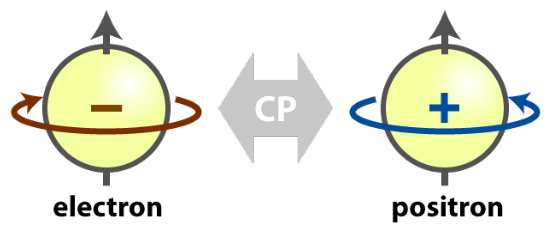
The **weak force** is unique in a number of respects:

- It is the only interaction capable of **changing the flavor of quarks** (i.e., of changing one type of quark into another)



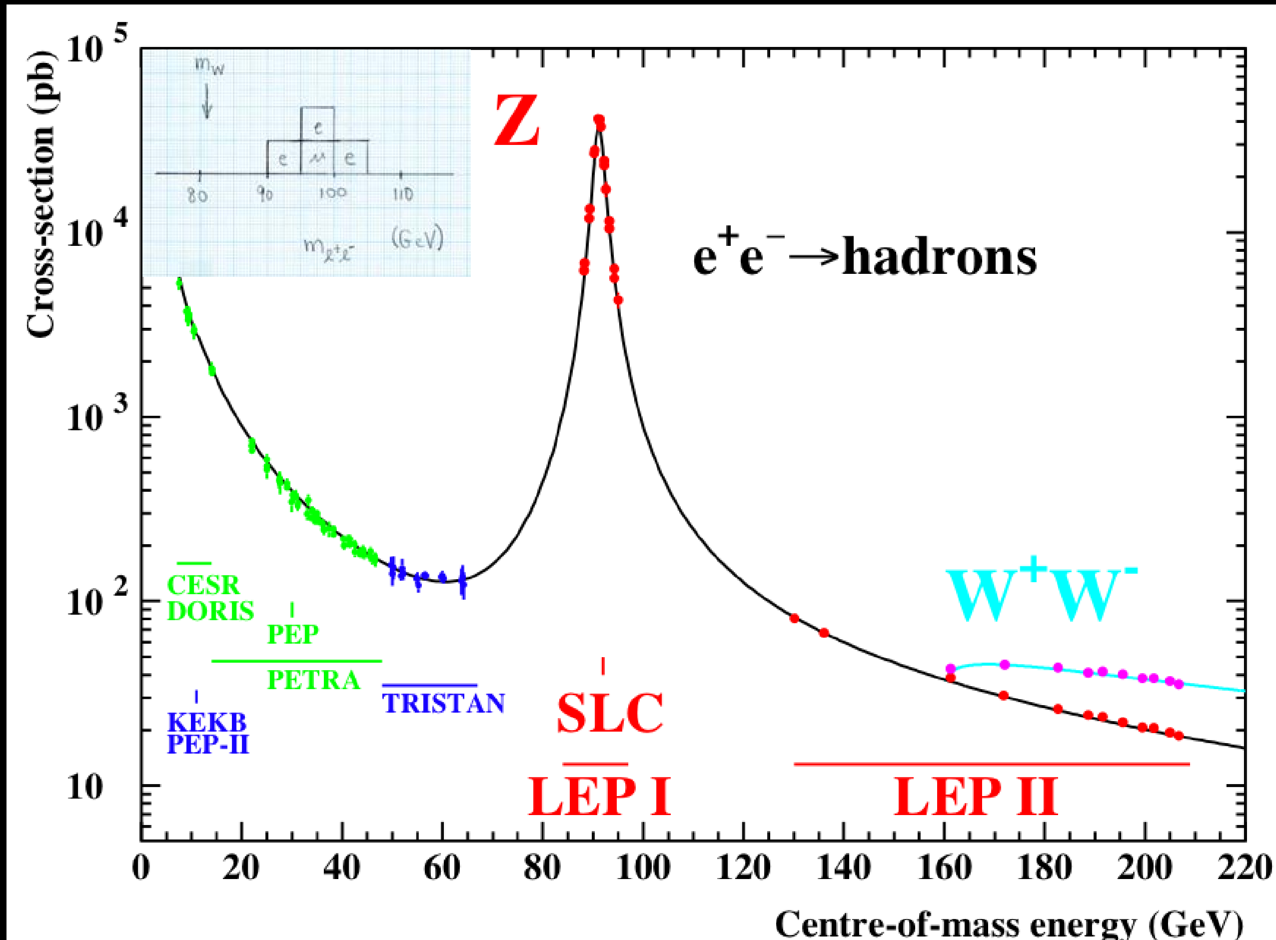
- It is the only interaction which **violates P** or parity-symmetry. It is also the only one which violates **CP symmetry**





- It is propagated by carrier particles (known as **gauge bosons**) that have significant masses (~ 100 x mass of the nucleon)

Part 2 – **Particles** – Force Carriers

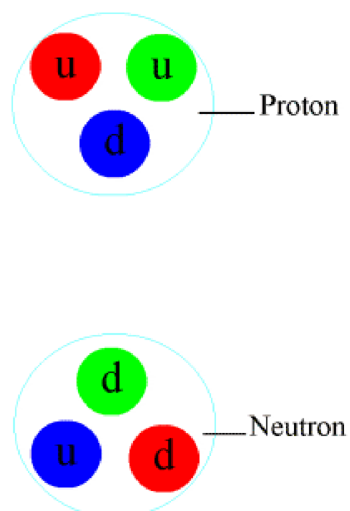


Discovery of Gauge Bosons

Part 2 – **Particles** – Force Carriers

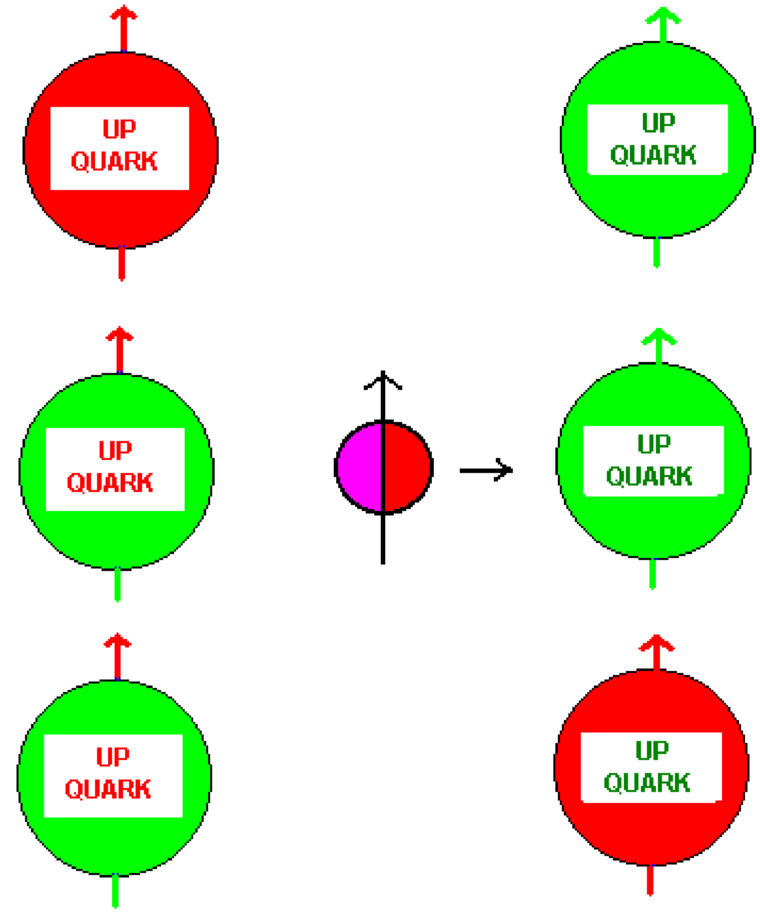
The **strong force** (interaction) is observable in two areas:

- on a larger scale (about 1 to 3 femtometers (fm)), it is the force that binds protons and neutrons (nucleons) together to form the nucleus of an atom - in this form, it is often referred to as the **nuclear force**
- on the smaller scale (less than about 0.8 fm, the radius of a nucleon), it is the force (carried by "**gluons**") that holds quarks together to form protons, neutrons and other hadron particles (→ **color force**)



Part 2 – **Particles** – Force Carriers

Quark-quark takes place by colored gluon-exchange:

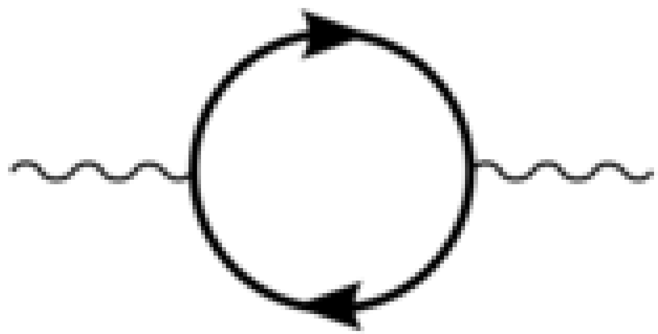


Gluons have color-anticolor (in this case **red-antigreen**)

Strong Interaction (Gluon Exchange)

Part 2 – **Particles** – Virtual Particles

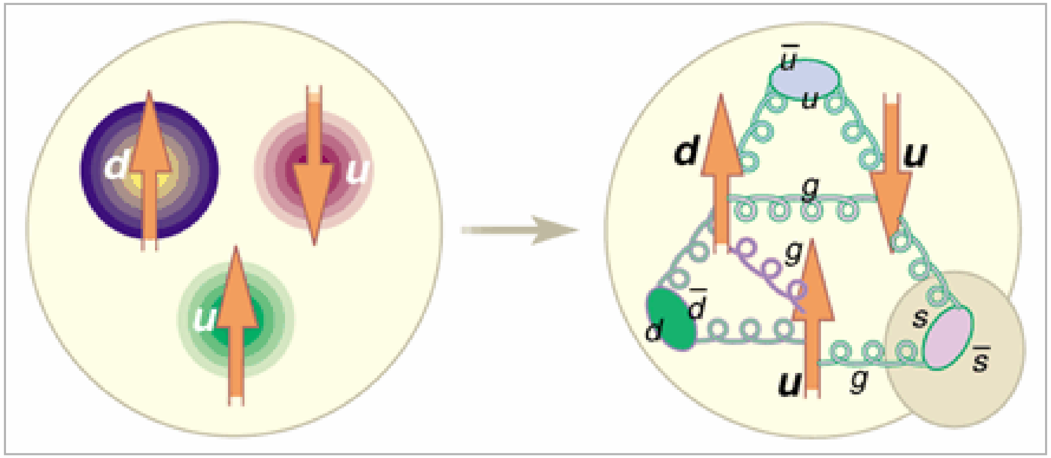
Quantum mechanics allows, and indeed requires, temporary **violations of conservation of energy** in quantum fluctuations, so one particle can become a pair of heavier particles (the so-called "virtual particles"), which quickly rejoin into the original particle as if they had never been there:



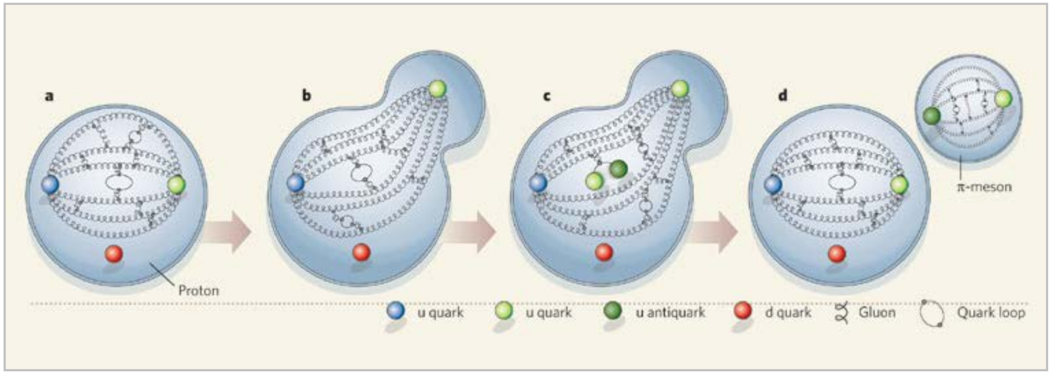
While the virtual particles are briefly part of our world they can interact with other particles, and that leads to a number of tests of the quantum-mechanical predictions about virtual particles: one example is the **Lamb-shift** in hydrogen (see: "atoms").

Part 2 – **Particles** – Force Carriers

Hadrons are thus much more **complicated multi-particle systems**;
Example: proton



… and **meson production** can be “more realistically” pictured as:



Part 2 – Particles – Bottomline

Force	Electromagnetism	Weak Nuclear	Strong Nuclear	Gravity
Number of Bosons	1	3	8	1
Bosons	Photon	W^+, W^-, Z^0	Gluon	Graviton**
Boson Mass*	0	80	0	0
Boson Charge	0	±1, 0	0	0
Acts on	Anything With Charge	Left Handed particle or Right Handed anti-particle with Flavour	Anything With Colour	Anything With Mass

Forces

Part 2 – Particles – Bottomline

Table S4.2 The Four Forces

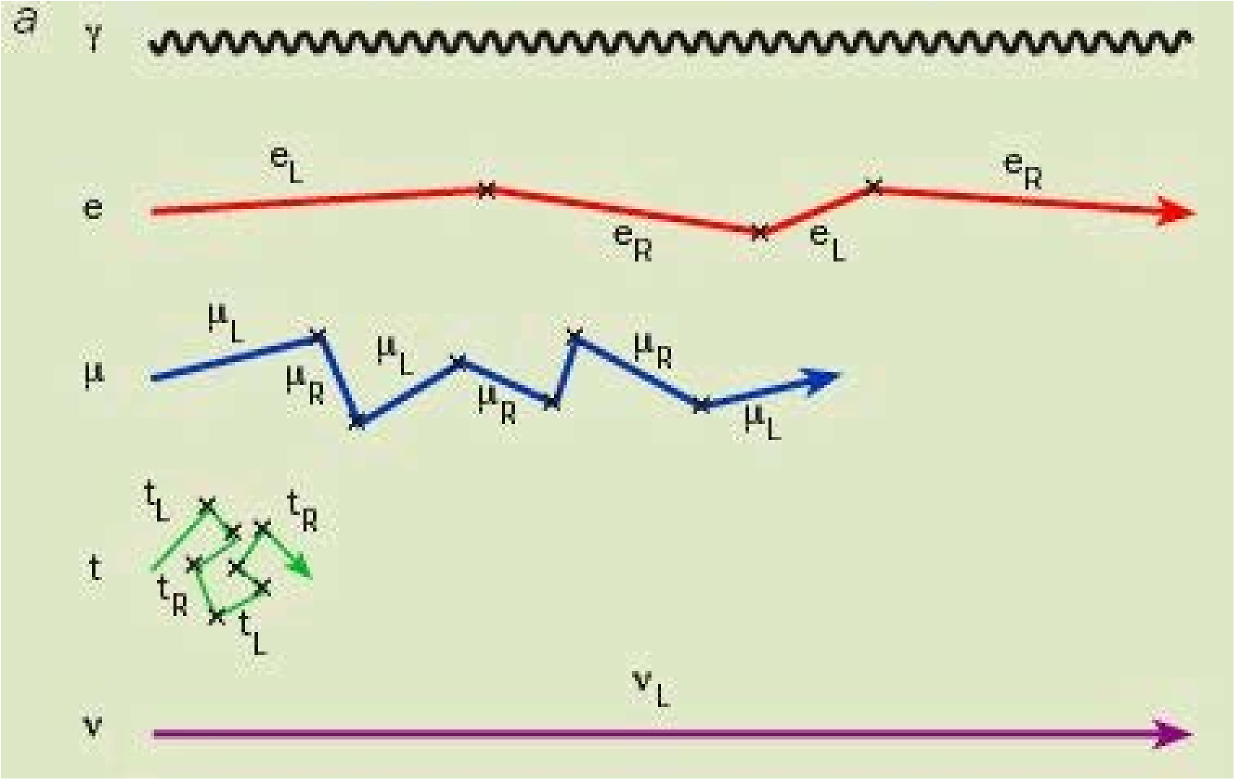
Force	Relative Strength Within Nucleus*	Relative Strength Beyond Nucleus	Exchange Particles	Major Role
Strong	100	0	Gluons	Holding nuclei together
Electromagnetic	1	1	Photons	Chemistry and biology
Weak	10^{-5}	0	Weak bosons	Nuclear reactions
Gravity	10^{-43}	10^{-43}	Gravitons	Large-scale structure

* The force laws for the strong and weak forces are more complex than the inverse square laws for the electromagnetic force and gravity; hence the numbers given for the strong and weak forces are very rough.

Forces

Part 2 – Particles – Higgs Boson

The **Higgs boson** or **Higgs particle** is an elementary particle, which is associated with the **Higgs field** and is pivotal to the Standard Model, since it explains why some fundamental particles have **mass** and why the **weak force** has a much shorter range than the electromagnetic force:



Part 2 – **Particles** – Standard Model

The **Standard Model** of elementary particle physics is a triumph of 20^{th} century science – but it is not without problems; for one thing it has too many elementary constituents:

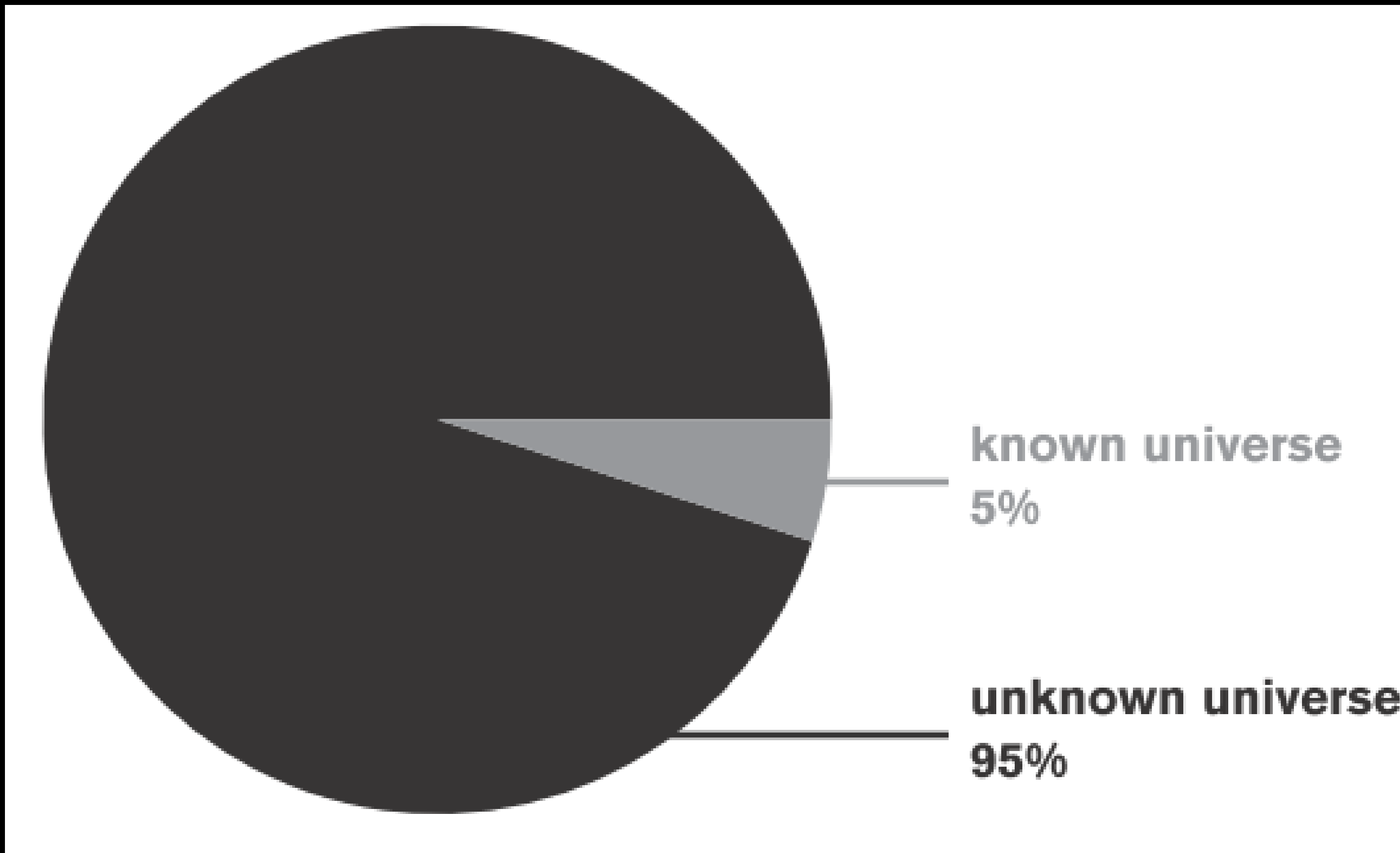
18 = (6 x 3)	quarks
6 = (2 x 3)	leptons
8	gluons
3	gauge bosons
1	photon
1 (at least)	Higgs boson

+ anti-particles

61

It does not attempt to explain **gravitation**; it needs to be modified in order to accommodate the fact that **neutrinos have mass**, and it cannot explain "**dark matter**" – there must be "**physics beyond the Standard Model**" (BSM) …

Part 2 – **Particles** – Kown and Unknown



„Dark Universe“

გმადლობთ