Hadrones y quarks

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THE STANDARD MODEL OF

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c² (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c² $= 1.67\times10^{-27}$ kg.

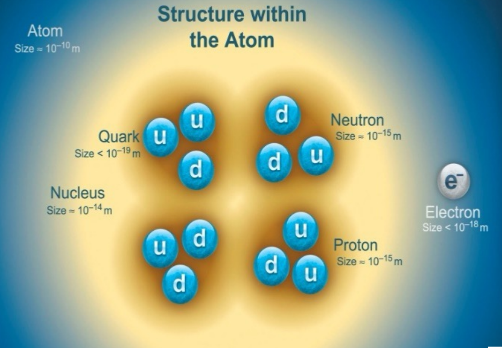
Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c²	Electric charge
H Higgs	126	0

Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), and B^0 ($d\bar{b}$).

Learn more at ParticleAdventure.org

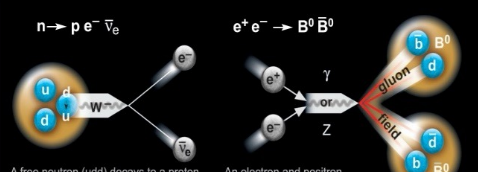
Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Particle Processes

These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

Why is the Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

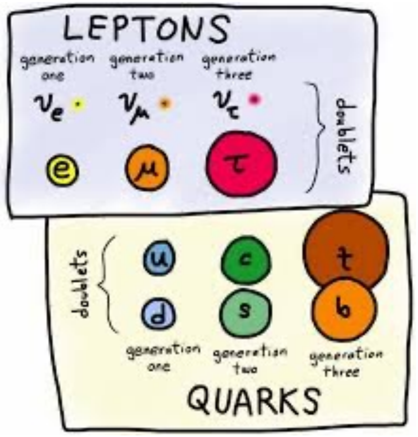
What is Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

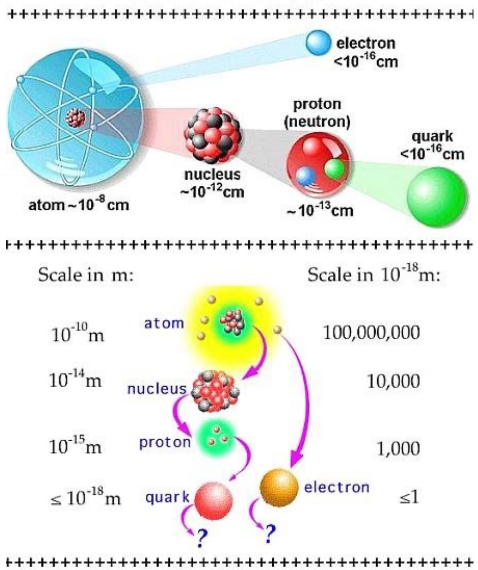
Are there Extra Dimensions?

An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).

U.S. Department of Energy, U.S. National Science Foundation, & Lawrence Berkeley National Laboratory.



Particle Physics: Probing the fundamental interactions of elementary particles



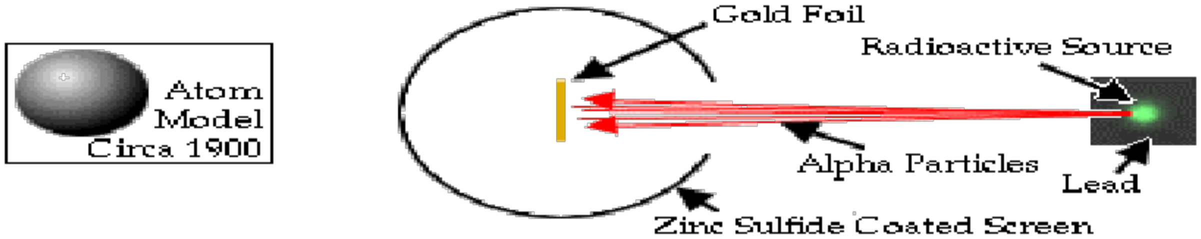
PROPERTIES OF THE INTERACTIONS

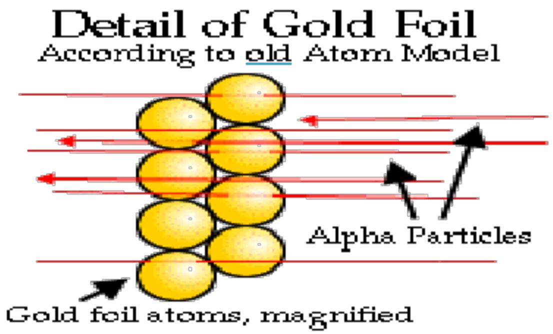
Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
Strength relative to electromag for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Fundamental Force Particles

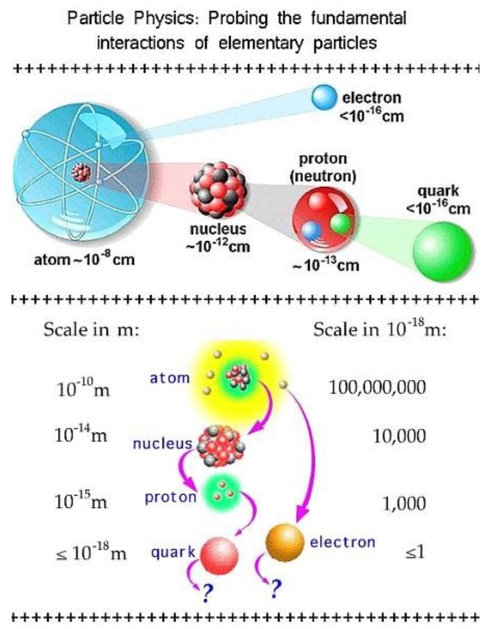
Force	Particles Experiencing	Force Carrier Particle	Range	Relative Strength*
Gravity acts between objects with mass	all particles with mass	graviton (not yet observed)	infinity	much weaker
Weak Force governs particle decay	quarks and leptons	W^+, W^-, Z^0 (W and Z)	short range	↓
Electromagnetism acts between electrically charged particles	electrically charged	γ (photon)	infinity	↓
Strong Force** binds quarks together	quarks and gluons	g (gluon)	short range	much stronger

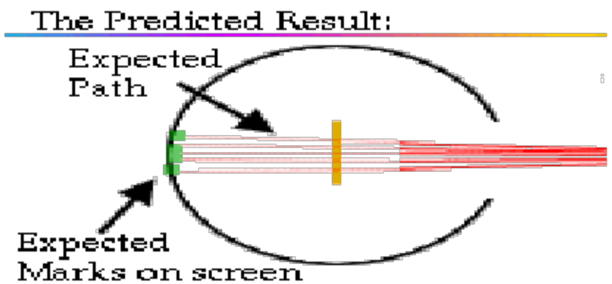
Rutherford Scattering

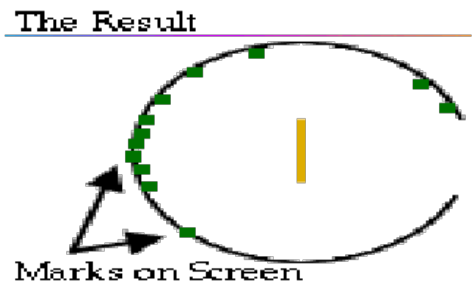




Experiments by Geiger & Marsden in 1909

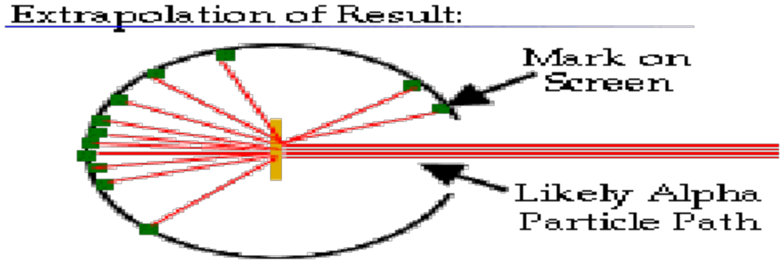


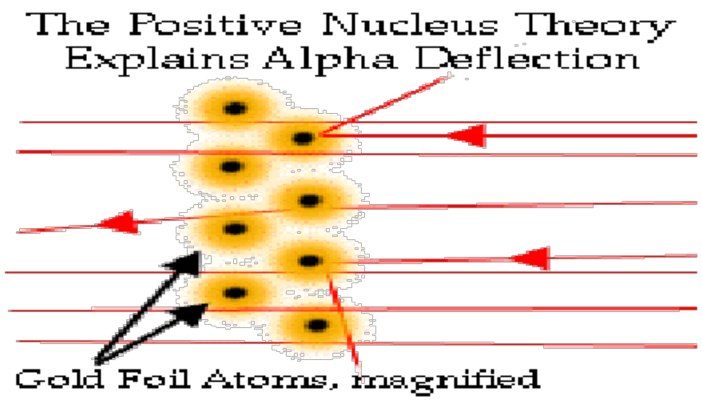




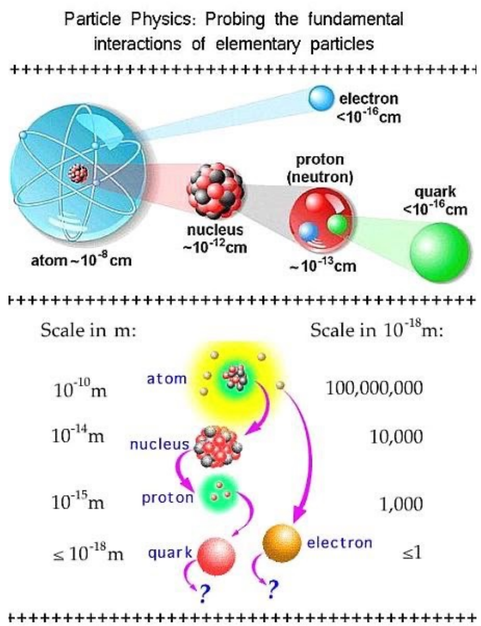
From D. Acosta (U. Florida)

Rutherford Model of the Atom



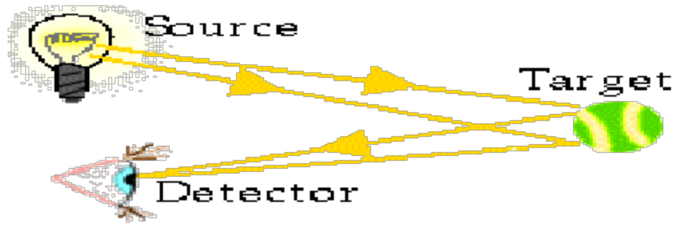


Conclusion: the atom contains a positive nucleus < 10 fm in size (1 fm = 10^{-15} m)

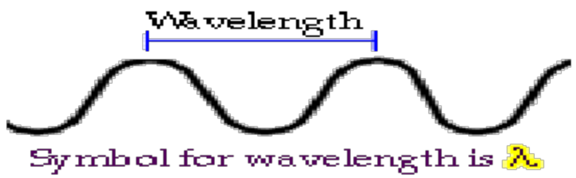


From D. Acosta (U. Florida)

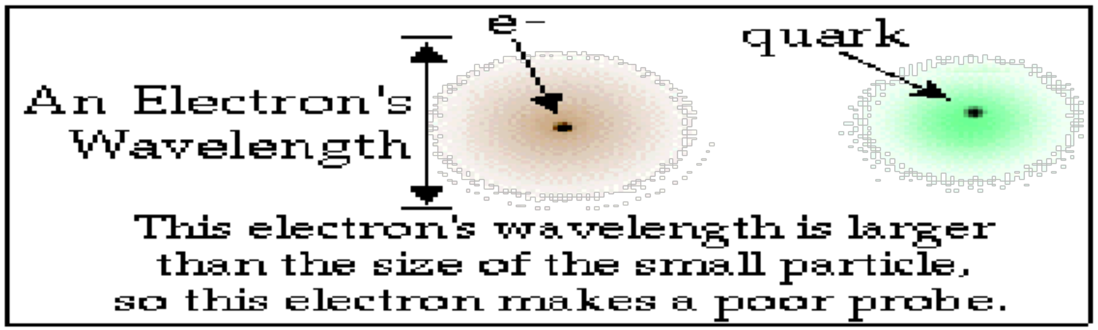
How we "see" particles



The smaller the wavelength, the smaller the features observed.



Recall that the deBoglie wavelength of a particle is $\lambda = h / p$



So we need high energies to probe quarks

PARTICLE ACELERATORS

From D. Acosta (U. Florida)

Size of Nuclei

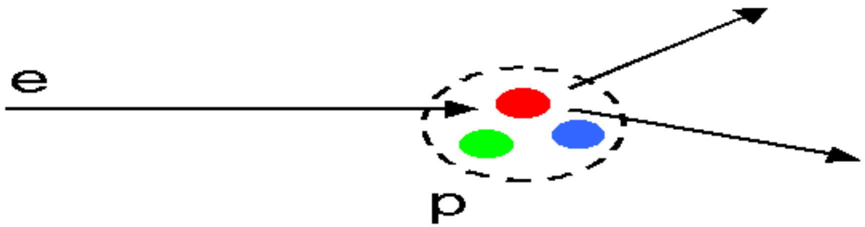
- Robert Hofstadter performs experiment at Stanford using new linear accelerator for electrons in 1950s
- E = 100 -- 500 MeV
- λ = 2.5 fm
- The proton is not a point! (Deviation of *elastic* scattering rate from Rutherford Scattering)
- Proton and nuclei have extended charge distributions
- Nobel prize in 1961

proton

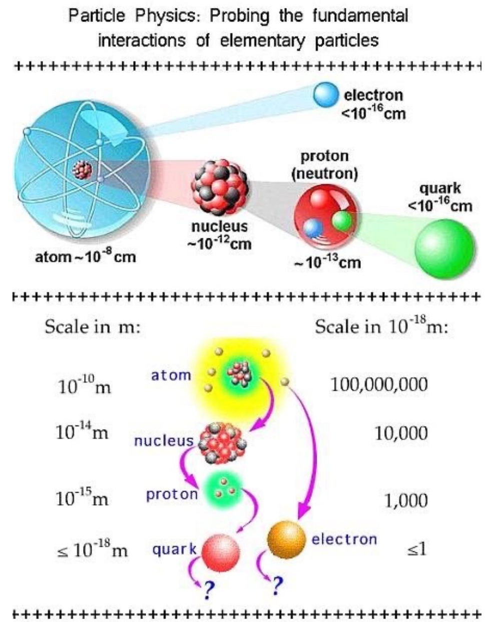
From D. Acosta (U. Florida)

Deep Inelastic Scattering

- Stanford Linear Accelerator Center (SLAC) constructs 2 mile long accelerator in 1966
- E = 20 GeV
- Experiment by SLAC and MIT (Friedman, Kendall, Taylor -- Nobel in 1990) cracks the proton (*inelastic* scattering) in 1967
- Surprise when scattering rate follows Rutherford formula for scattering between point particles!
- Richard Feynman dubs proton consituents *partons*
- *Quarks are real!*



High-energy collisions between electrons and protons produced the first indications, published in 1969, that smaller constituent particles lurked inside protons.



From D. Acosta (U. Florida)

MODELO ESTÁNDAR DE FÍSICA DE PARTÍCULAS

interacción fuerte

Las tres generaciones de materia (Fermiones)

QUARKS

Símbolo	Nombre	Masa	Carga	Espín
u	ARRIBA	2.4 Mev	2/3	1/2
d	ABAJO	4.8 MeV	-1/3	1/2
c	ENCANTO	1.27 GeV	2/3	1/2
s	EXTRAÑO	104 MeV	-1/3	1/2
t	CIMA	171.2 GeV	2/3	1/2
b	FONDO	4.2 GeV	-1/3	1/2

LEPTONES

Símbolo	Nombre	Masa	Carga	Espín
ν_e	NEUTRINO ELECTRÓNICO	< 2.2 eV	0	1/2
e	ELECTRÓN	0.511 MeV	-1	1/2
ν_μ	NEUTRINO MUÓNICO	< 0.17 MeV	0	1/2
μ	MUÓN	105.7 MeV	-1	1/2
ν_τ	NEUTRINO TAUÓNICO	< 15.5 MeV	0	1/2
τ	TAU	1.777 GeV	-1	1/2

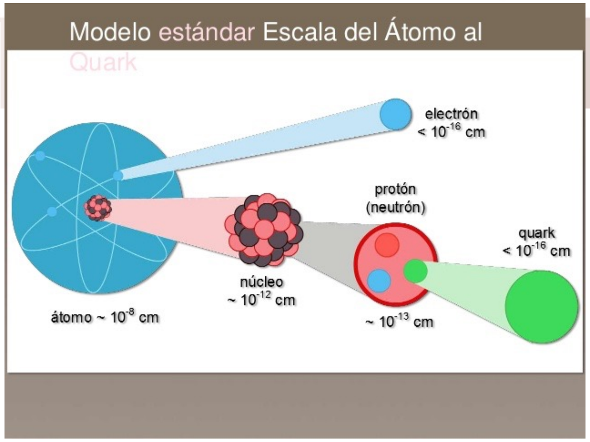
BOSONES (Fuerzas)

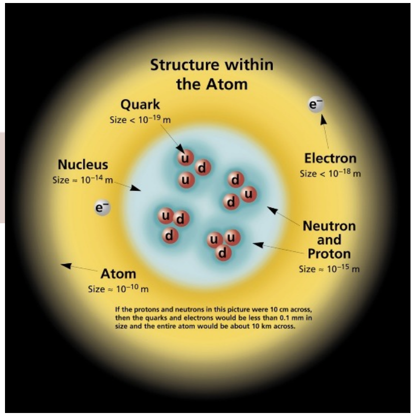
Símbolo	Nombre	Masa	Carga	Espín
γ	FOTÓN	0	0	1
g	GLUÓN	0	0	1
Z^0	BOSÓN Z	91.2 GeV	0	1
$W^\pm$	BOSÓN W	80.4 GeV	±1	1
H	BOSÓN DE HIGGS	125 GeV	0	0

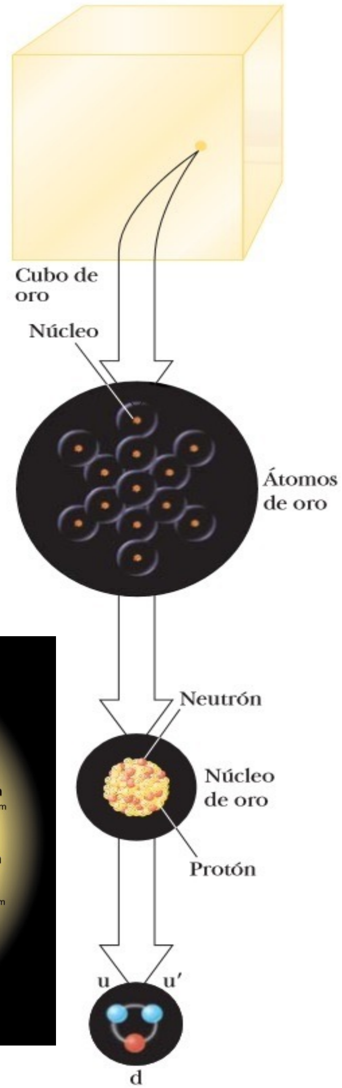
MODELO ESTÁNDAR

		LEPTONES		QUARKS	
Partículas presentes en la materia ordinaria.	Primera familia	Electrón m=0,51 q=-1	Neutrino electrónico m~0 q=0	*Up* m=1,5–5 q=2/3	*Down* m=3–9 $q=-\frac{1}{3}$
Partículas existentes poco después del *Big Bang*. Actualmente están presentes en los rayos cósmicos y se obtienen en los aceleradores de partículas.	Segunda familia	Muón m=105 q=-1	Neutrino muónico m~0 q=0	*Charm* m=1.100–1.400 q=2/3	*Strange* m=60–170 $q=-\frac{1}{3}$
	Tercera familia	Tau m=1.777 q=-1	Neutrino tau m~0 q=0	*Top* m=170.000 q=2/3	*Bottom* m=4.100–4.400 $q=-\frac{1}{3}$

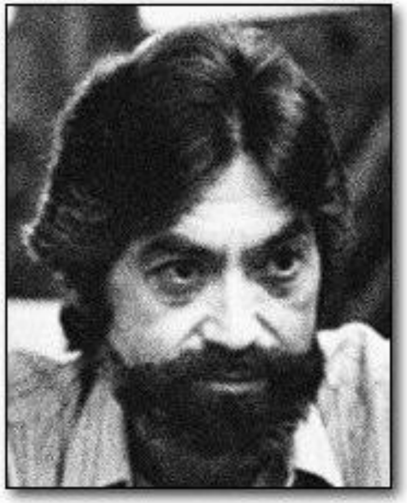
m = masa en MeV/c^2 (MeV, millones de electronvoltios; c, velocidad de la luz)







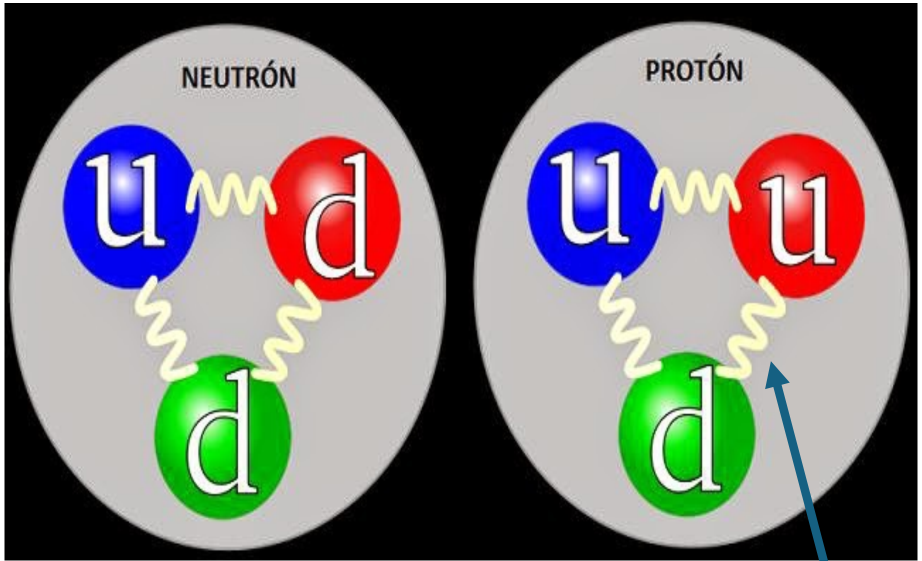
QUARKS

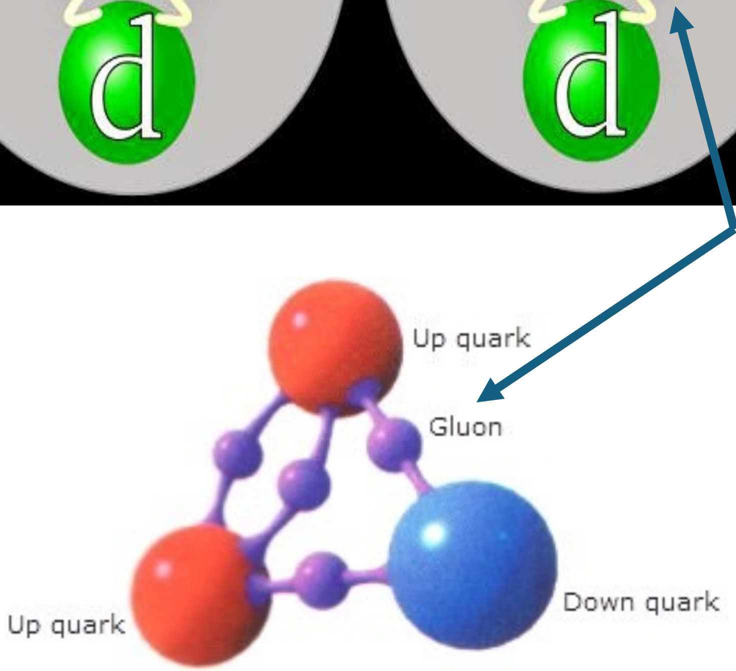


En 1964 Murray Gell-Mann y George Zweig sugirieron que muchas de las partículas conocidas hasta el momento podrían ser explicadas como una combinación de solo 3 partículas (y sus antipartículas) fundamentales

Gell-Mann eligió el nombre de **“quarks”** para estos constituyentes fundamentales

Esta palabra aparece en la frase “three quarks for Muster Mark” en la novela de James Joyce, *Finnegan’s Wake*





Gluons holding quarks together to form a proton (diagram from *Scientific American*)

Modelo de hadrones.

<u>Sienten la interacción fuerte</u>

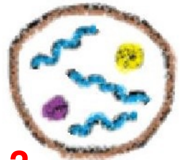
Bariones.

3 quarks.

spin: 1/2, 3/2, ...

Mesones.

1 quark + 1 antiquark.



spin: 0, 1, 2, ...

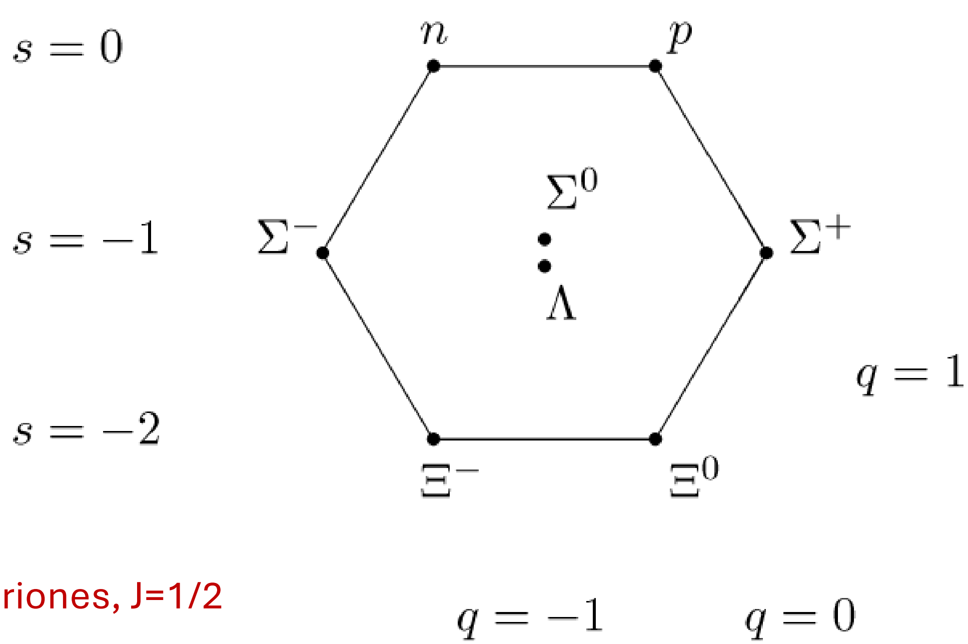
Quark u: masivo, carga 2/3, spin 1/2.

Quark d: masivo, carga -1/3, spin 1/2.

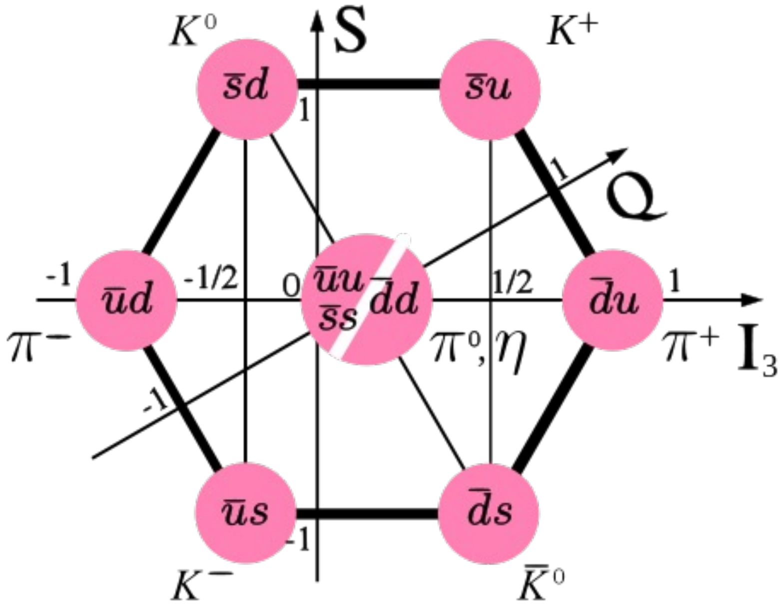
Protón: u u d.

Neutrón: u d d.

<u>Cromodinámica Cuántica</u> (QCD): interacción entre quarks y gluones que forman los hadrones.

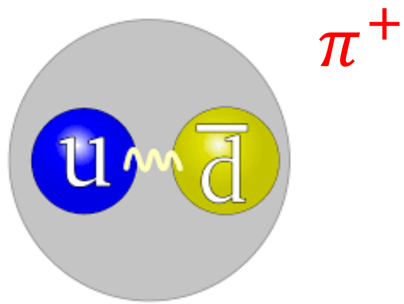


bariones, J=1/2

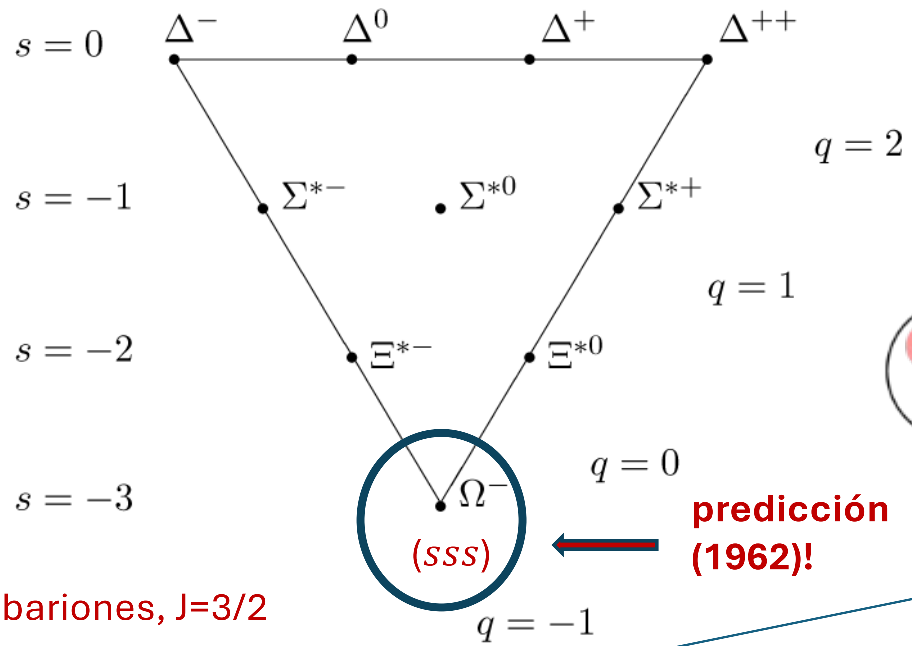


mesones, J=0

Hacia 1947, y no por primera vez, los físicos opinaban que su disciplina estaba casi cerrada. El mundo estaba compuesto por protones, neutrones, electrones y sus antipartículas. Además, más o menos a regañadientes se aceptaba al muón y su neutrino. En diciembre de ese año se descubrió (G.D. Rochester y C.C. Butler) una partícula neutra que se desintegra en un par de piones cargados y de signo opuesto: $K^0 \to \pi^+ \pi^-$.
Otras desintegraciones,
$K^+ \to \pi^+ \pi^+ \pi^-$ (Powel 1949) , $\Lambda \longrightarrow p\, \pi^-$ (Anderson 1950), ... **Partículas extrañas!**
En 1953, Gell-Mann y Nishima introdujeron un nuevo número cuántico, la extrañeza, con la peculiaridad de que se conserva en las interacciones fuertes, pero se viola en las débiles.



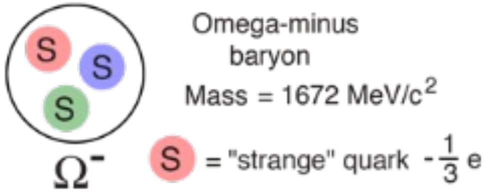
Hadrones se podían clasificar en multipletes del grupo de tres sabores (u,d,s) SU(3)

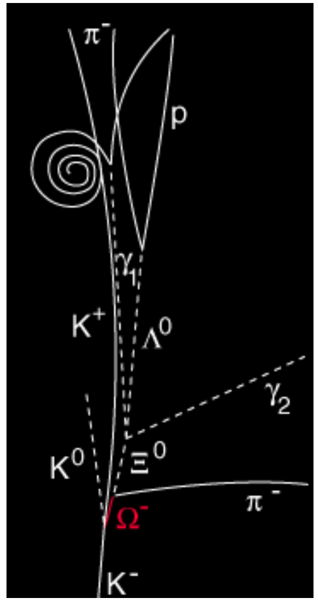


predicción (1962)!

bariones, J=3/2

Murray Gell-Mann

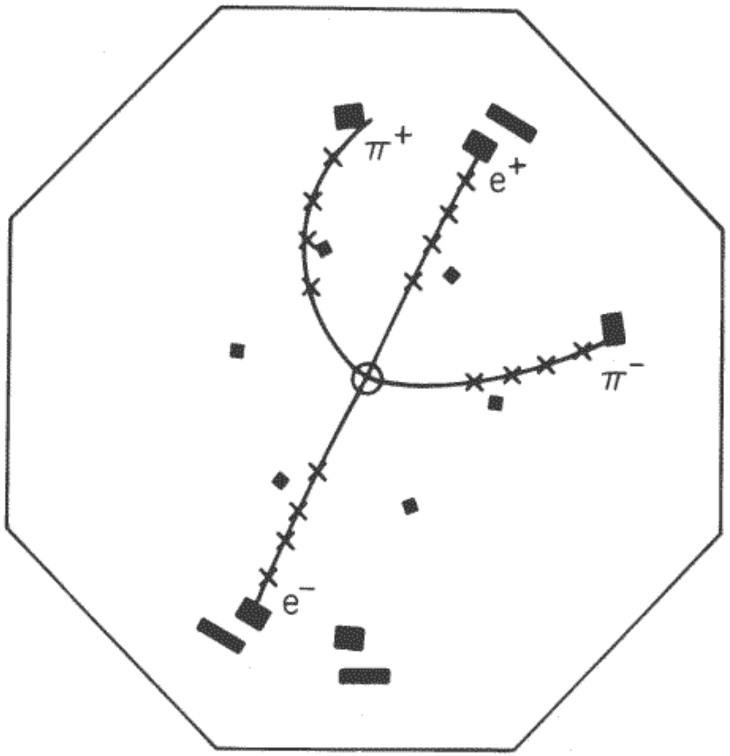




V. E. Barnes et al., Phys. Rev. Lett. 12, 204 (1964)

$$pK^- \longrightarrow \Omega^- K^+ K^0$$
$$uud + s\bar{u} \longrightarrow sss + u\bar{s} + d\bar{s}$$

El **descubrimiento (1964)** de la partícula Ω^- (sss) a partir de la predicción obtenida del multiplete de SU(3) supuso la evidencia incontrovertible de que existía una estructura en los hadrones controlada por el sabor de los quarks



J/ψ tiene espín-paridad 1^-, masa alrededor de 3.1 GeV (3.3 veces la masa del protón y una anchura muy pequeña de alrededor de 90 keV (estable ante desintegraciones fuertes)

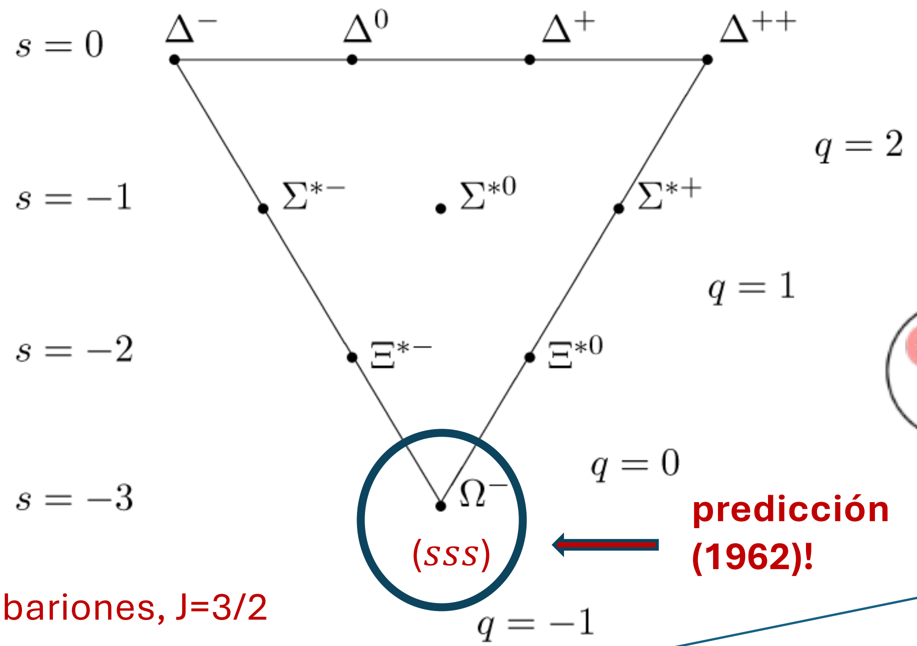
Noviembre 1974: estado ligado $c\bar{c}$ de nuevo quark [Samuel Ting (Brookhaven) y Burton Richter (SLAC)]

confirmación espectacular de la predicción de 1970 de Glashow–Iliopoulos–Maiani (mecanismo GIM)

1977 descubrimiento quark bottom (*b*) en FermiLab .....

QUARK	Masa (GeV/c^2)	Carga eléctrica (e)
u up	0,002	+2/3
d down	0,005	-1/3
c charm	1,3	+2/3
s strange	0,1	-1/3
t top	173	+2/3
b bottom	4,2	-1/3

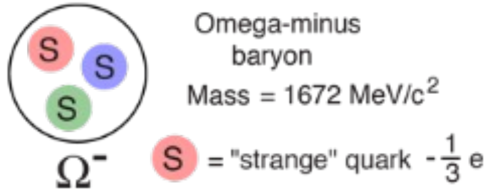
Espín 1/2 y carga fraccionaria!

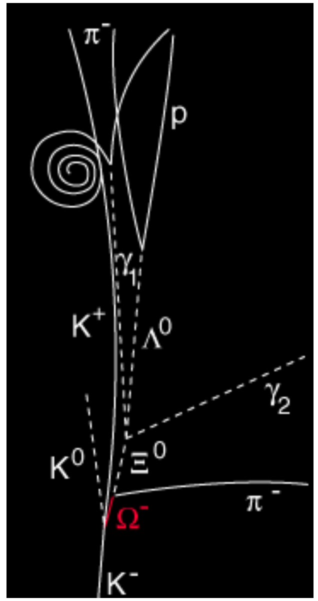


predicción (1962)!

bariones, J=3/2

Murray Gell-Mann





V. E. Barnes et al., Phys. Rev. Lett. 12, 204 (1964)

El **descubrimiento (1964)** de la partícula Ω^- (sss) a partir de la predicción obtenida del multiplete de SU(3) supuso la evidencia incontrovertible de que existía una estructura en los hadrones controlada por el sabor de los quarks

$$pK^- \longrightarrow \Omega^- K^+ K^0$$
$$uud + s\bar{u} \longrightarrow sss + u\bar{s} + d\bar{s}$$

$\Omega(J = {}^3/_2, J_z = {}^3/_2) = s\uparrow s\uparrow s\uparrow$ en onda S. Quark extraño es un fermión (J=1/2), aparece un problema porque la función de ondas spin-sabor de este sistema de tres fermiones es completamente simetríca. Solución una nueva "carga" (número cuántico) que permita antisimetrizas la función de ondas total: <u>color</u> (debe tomar al menos 3 valores)

a,b,c indices de color

$$s_a\uparrow s_b\uparrow s_c\uparrow \frac{\epsilon_{abc}}{\sqrt{6}}$$

FRANK WILCZEK:
AUGUST 2000 PHYSICS TODAY

F.W. junto con David Gross y David Politzer recibió el ***Premio Nobel de Física 2004*** *por el descubrimiento de la libertad asintótica en la teoría de la interacción fuerte.*

Dinámica de color: QCD

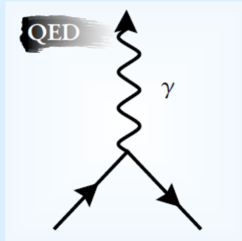
Quantum chromodynamics is conceptually simple. Its realization in nature, however, is usually very complex. But not always.

Quarks are spin-1/2 point particles, very much like electrons. But instead of electric charge, they carry color charge. **To be more precise, quarks carry *fractional* electric charge** (+ 2e/3 for the u, c, and t quarks, and – e/3 for the d, s, and b quarks) in addition to their **color charge**.

Gluons can also change one color charge into another. All possible changes of this kind are allowed, and yet color charge is conserved. So the **gluons themselves must be able to carry unbalanced color charges. Photons, of course, are electrically neutral.**

Hadrones no tienen carga neta de color: bariones y mesones forman estados ligados sin carga de color (interacción entre hadrones sería similar a una fuerza electromagnética tipo Van der Waals entre sistemas con carga eléctrica neta cero.

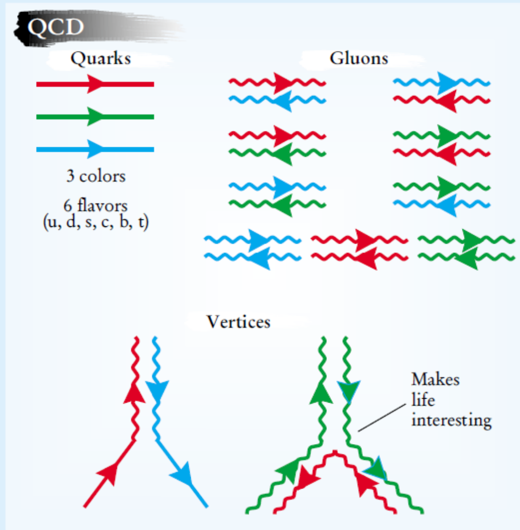
QED and QCD in Pictures.



The physical content of quantum electrodynamics is summarized in the algorithm that associates a probability amplitude with each of its Feynman graphs, depicting a possible process in spacetime. The Feynman graphs are constructed by linking together interaction vertices of the type at left, which represents a point charged particle (lepton or quark) radiating a photon. To get the amplitude, one multiplies together a kinematic "propagator" factor for each line and an interaction factor for each vertex. Reversing a line's direction is equivalent to replacing a particle by its antiparticle.

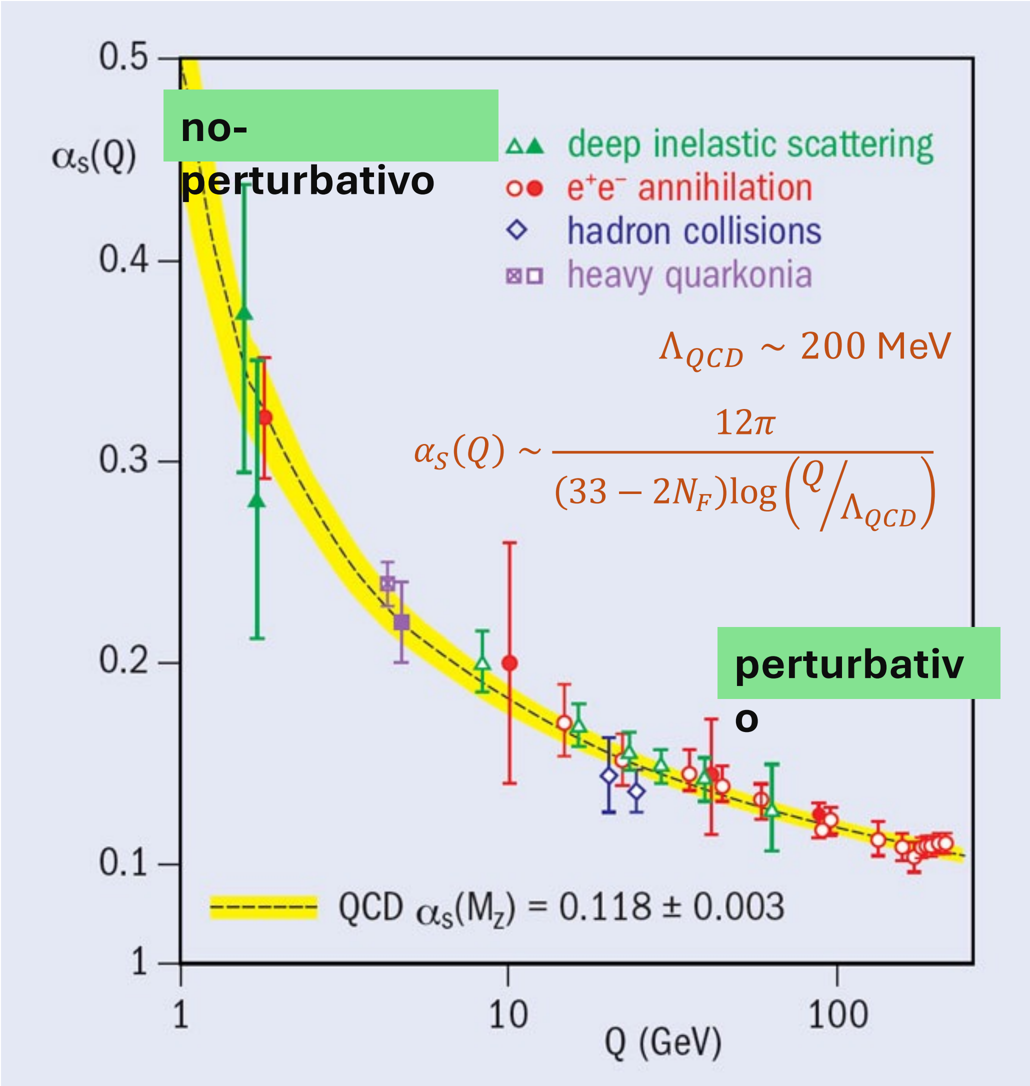
Quantum chromodynamics can be similarly summarized, but with a more elaborate set of ingredients and vertices, as shown below. Quarks (antiquarks) carry one positive (negative) unit of color charge. Linear superpositions of the 9 possible combinations of gluon colors shown below form an SU(3) octet of 8 physical gluon types.

A qualitatively new feature of QCD is that there are vertices describing direct interactions of color gluons with one another. Photons, by contrast, couple only to electric charge, of which they carry none themselves.

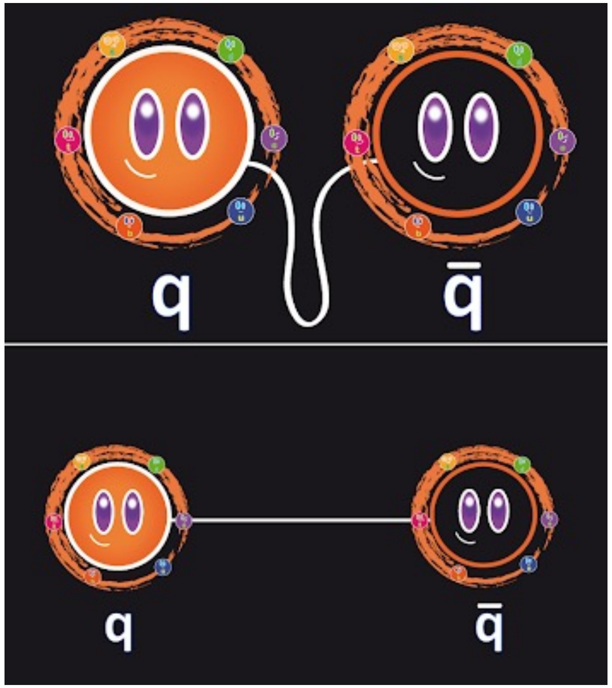


LIBERTAD ASINTOTICA & CONFINAMIENTO

No es posible encontrar quarks libres y siempre aparecen formando hadrones (partículas sin color)

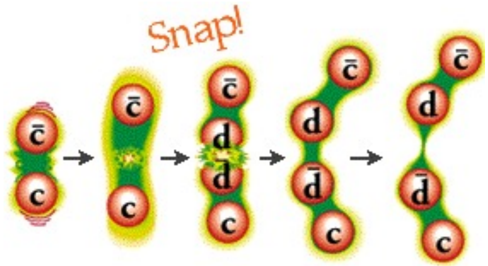


← distancia entre quarks



a cortas distancias la interacción entre quarks es muy débil, pero a distancias grandes ….

La energía potencial para separar dos quarks aumenta linealmente con su distancia
Más favorable energéticamente la creación de un par $q\bar{q}$ del vacío: formación de nuevos hadrones



QUARK	Masa (GeV/c^2)	Carga eléctrica (e)
u up	0,002	+2/3
d down	0,005	-1/3
c charm	1,3	+2/3
s strange	0,1	-1/3
t top	173	+2/3
b bottom	4,2	-1/3

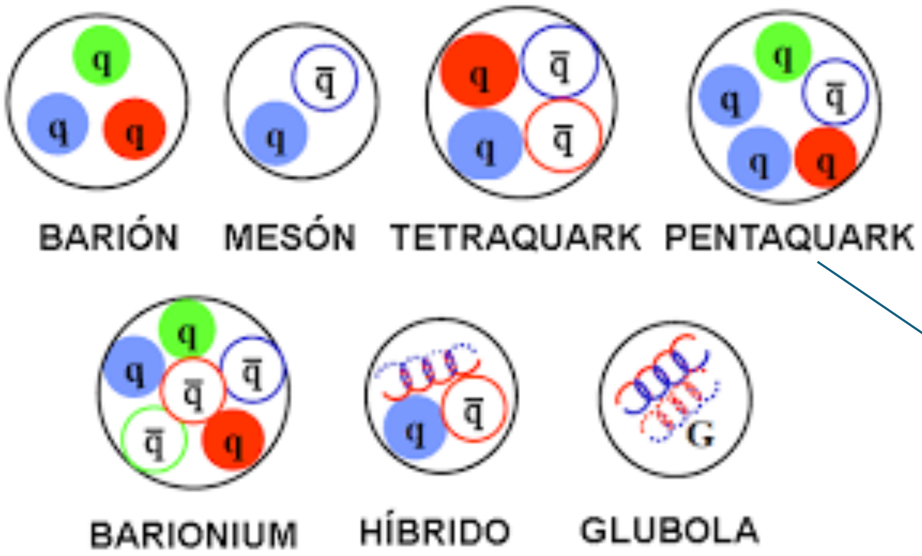
Simetrías exactas de QCD

- Invariancia bajo rotaciones gauge del grupo SU(3) de color (aparecen los gluones)
- Conservación del número de quarks (número bariónico)
- Conservación de cada sabor por separado

Simetrías aproximadas de QCD

- $m_u \sim m_d \Rightarrow$ simetría de isospín (pej. protones y neutrones: Física Nuclear)
- $m_u \sim m_d \sim m_s \Rightarrow$ simetría SU(3) de sabor
- $m_{u,d,s} \ll m_p \Rightarrow$ simetría quiral (relacionado con los bosones de Goldstone)
- $m_{c,b} \gg$ escala de confinamiento ($\sim$ 200-250 MeV) $\Rightarrow$ simetría (espín-sabor) quarks pesados

otras estructuras que dan lugar a singletes de color

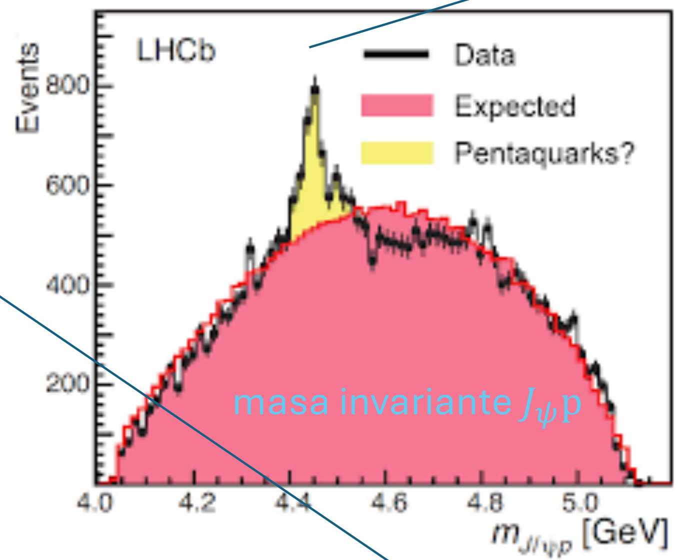


LHCb Collaboration, Phys. Rev.Lett. 115 (2015) 072001

$$\Lambda_b \rightarrow J_\psi K^- \, p$$

Otros tipos de configuraciones de hadrones (con carga neta de color?)

$P_c^+(4450)$



Con contenido $c\bar{c}$, no puede ser un barión ordinario qqq