

# Elementarne čestice i temeljna međudjelovanja

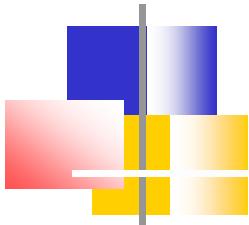
## Elementarne četice

### Uvod. Prve ideje o elementarnim česticama

- Prve ideje o elementarnim česticama došle su iz stare grčke i provlačile su se kroz čitavu filozofiju zapadnog svijeta
- Pismene dokumente o tome imamo od Anaksimena iz Smirne. Promatrao je vodu
- Kasnije su se razmatrala četiri elementa *voda*, *vatra*, *zrak* i *zemlja*
- Kombinacijom ovih četiriju elemenata filozofi su pokušali objasniti sve
- Istovremeno Demokrit dolazi na ideju da su sve tvari sastavljene od malih komadića koji se više ne daju dijeliti, a imaju svojstva krupne tvari
- Na grčkom *atōnoi* (atomi) znači nedjeljivi



# Elementarne čestice



- Oko početka XIX st. John Dalton uvodi ponovo ideju da je tvar sastavljena od atoma da bi objasnio zakone kemijskog spajanja
- Nastao je problem od čega su atomi građeni
- Rješenje koje je dao Ruđer Bošković bilo je da su **atomi centri sile**, da nisu tvar
- Rutherford je postavio planetarni model, a Bohr je kvantizirao atom
- Prve elementarne čestice bile su proton (jezgra vodika) i elektron (1895. godine ga je našao Thomson). 1932. godine pronađen je neutron (Chadwick)
- **Proton**, **elektron** i **neutron** grade čitavu nama blisku tvar
- Nukleoni imaju unutrašnju strukturu
- Jedan od najznačajnijih razvoja moderne fizike je standardni model elementarnih čestica i međudjelovanja
- U slici standardnog modela protoni i neutroni su čestice sastavljene od **kvarkova**
- Čestice sastavljene od kvarkova nazivaju se **hadroni** (one sastavljene od tri kvarka zovu se barioni, a one sastavljene od para kvark-antikvark zovu se **mezoni**).

## Pregled poznatih elementarnih čestica

- Danas znamo da protoni i neutroni nisu elementarne čestice , a da elektron jest

- Proton se sastoji od dva **up kvarka** i jednog **down kvarka**
- Neutron se sastoji od dva down kvarka i jednog up kvarka
- Simbolički

$$p=uud$$

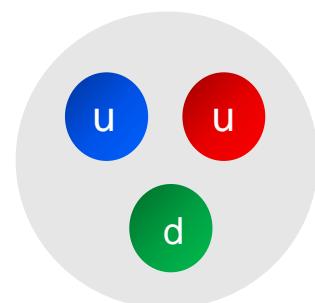
$$n=udd$$

- Naboji kvarkova moraju se složiti u kombinacije tako da se zbroje za proton, a ponište za neutron. Označimo li pripadne nabaje  $Q_u$  i  $Q_d$  mora vrijediti

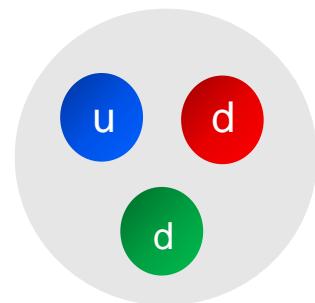
$$Q_u + Q_u + Q_d = 1e,$$

$$Q_u + Q_d + Q_d = 0$$

- Rješavanjem ovih jednadžbi dobije se  $Q_u = +2e/3$  i  $Q_d = -1e/3$



Proton



Neutron

# Elementarne čestice

Tablica prikazuje elementarne čestice u **standardnom modelu** fizike el. čestica

|               | LEPTONI        | NEUTRINI                    | KVARKOVSKI PAROVI |               |
|---------------|----------------|-----------------------------|-------------------|---------------|
| 1. generacija | $e$ (elektron) | $\nu_e$ (elektron neutrino) | $u$ (up)          | $d$ (down)    |
| 2. generacija | $\mu$ (mion)   | $\nu_\mu$ (mion neutrino)   | $c$ (charm)       | $s$ (strange) |
| 3. generacija | $\tau$ (tau)   | $\nu_\tau$ (tau neutrino)   | $t$ (top)         | $b$ (bottom)  |
|               | + antičestice  | + antičestice               | + antičestice     |               |

- Lepton dolazi od grčke riječi leptos (λεπτοσ) što znači malen, sitan, slab
- Mion i tau imaju isti naboј kao elektron
- Mion i tau mogu se raspasti na druge čestice dok je elektron stabilna čestica
- Neutrini su električni neutralni
- Neutrini imaju ekstremno malu masu (eksperimenti sugeriraju manje od 1/10000 mase elektrona)

## Čestice i antičestice

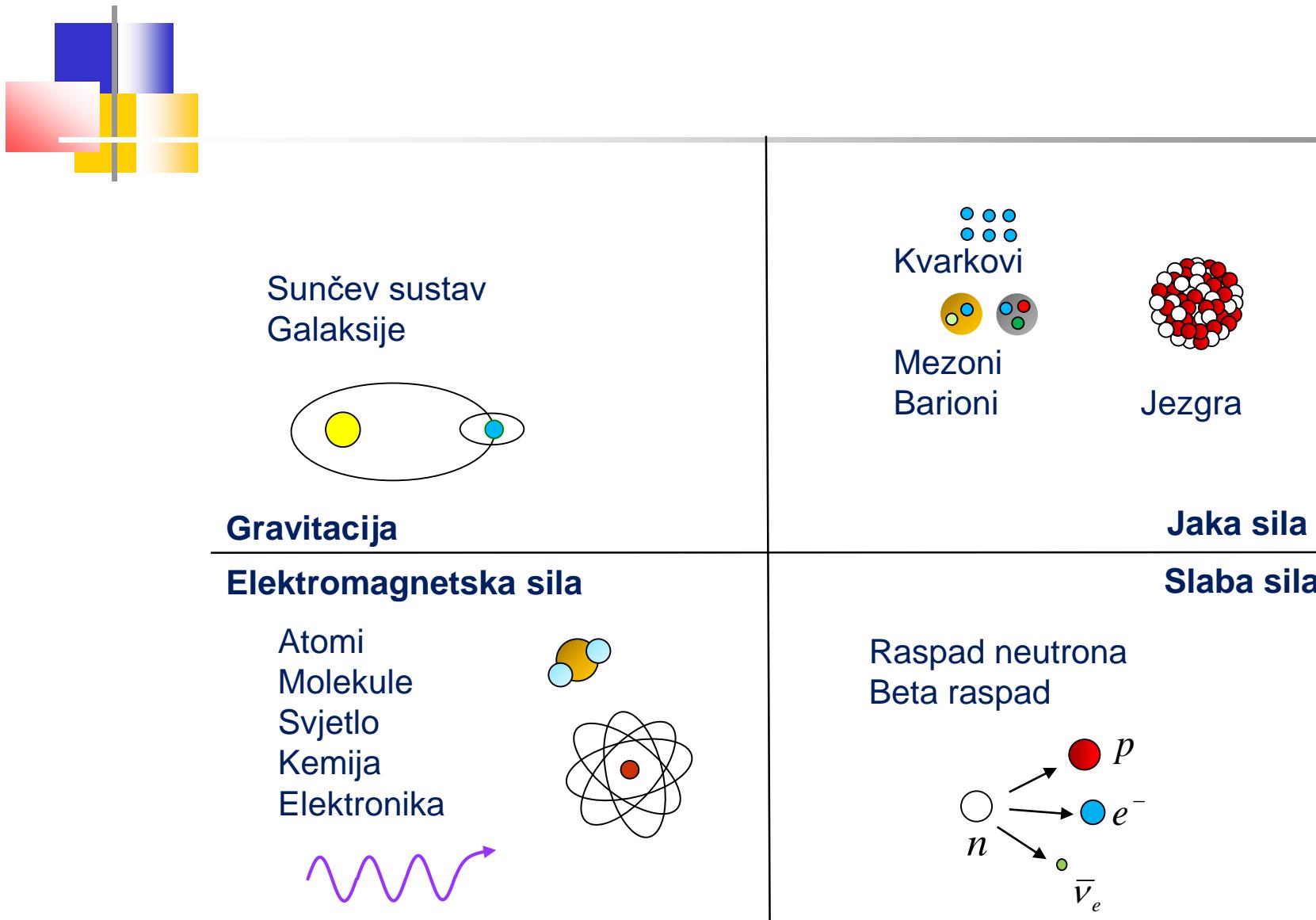
- 1928. godine Dirac je dobio za rješenje jednadžbi gibanja elektrona da elektron može imati stanja pozitivne i negativne energije u elektromagnetskom polju
- Dirac je prvi dao matematičku jednadžbu koja je korektno predviđala gibanje elektrona brzinom bliskom brzini svjetlosti ([Diracova jednadžba](#))
- Rekao je da su stanja negativne isto stvarna, međutim, da su ona potpuno popunjena
- Ako jednom elektronu negativne energije dovedemo energiju na njegovu mjestu ostane šupljina. Šupljina se ponaša kao čestica. On ju je nazvao [anti-elektron](#)
- 1932. godine C. Anderson pronalazi eksperimentalno [pozitron](#)
- Pozitron se pod djelovanjem magnetskog polja giba u smjeru suprotnom od elektrona
- Kad je pronađen pozitron, uočilo se da [sve čestice imaju antičestice](#) koje se od čestica razlikuju u onom svojstvu koje je karakteristično za polje čija se energijska stanja promatraju. Za elektron je to elektromagnetsko polje

## Temeljna međudjelovanja u prirodi i njihovo ujedinjenje

### Postavka problema. Dosadašnja ujedinjenja

- Temeljna sila je ona koja nije sastavljena od dijelova
- Prvo veliko ujedinjenje sila je ujedinjenje sile teže i sile gravitacije
- Maxwell je pokazao da su električna i magnetska sila jedna te ista sila, elektromagnetska, samo što se pojavljuju u različitim oblicima
- Kad je Hertz otkrio elektromagnetske valove, pokazalo se da je svjetlost elektromagnetski val
- Temeljne sile u prirodi su
  - gravitacijska
  - elektromagnetska
  - jaka nuklearna i
  - slaba nuklearna sila
- Uvijek je tendencija fizičara bila da se sve sile ujedine u jednu
- Danas znamo da su slaba nuklearna i elektromagnetska sila jedna sila
- Ujedinjenje se događa kad istim formulama možemo opisati i jednu i drugu silu
- Treba podići razinu energije do 1Gev-10GeV da bi se sve sile jednako ponašale

# Elementarne čestice



## Jaka nuklearna sila

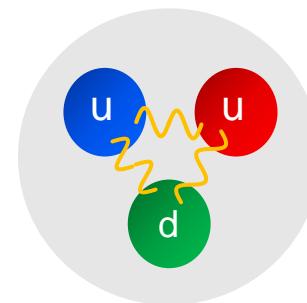
- Jezgre sadrže protone i neutrone
- Dva protona kao nabijene čestice **se odbijaju** jer je elektromagnetska sila među njima veća od gravitacijske
- Kako protoni ostaju blizu čineći jezgre mora postojati sila jača od elektromagnetske sile koja je odgovorna za postojanje jezgre. Nazivamo je **jaka sila**.
- **Jaka nuklearna sila djeluje među kvarkovima**
- **Lepotoni ne osjećaju jaku silu** (slično kao što neutralni objekti ne osjećaju elektromagnetsku silu)
- Ovo je razlog zašto čestice dijelimo na kvarkove i leptone
- Jaka sila među kvarkovima čini da oni tvore čestice kao što su protoni i neutroni

## Slaba nuklearna sila

- Slaba sila mijenja čestice iz jedne u drugu. Doseg joj je  $10^{-15}$  cm.
- Ako dva leptona dođu na udaljenost koja je reda veličine i manja od dosega sile mogu se promijeniti u druge leptone.
- Odgovorna je za većinu radioaktivnih raspada

## Izmjenjene čestice i boja kvarkova

- Za elektromagnetsku silu su izmjenjene čestice **fotoni**, za slabu  $Z^0$ ,  $W^-$  i  $W^+$ , a za gravitacijsku **gravitonii** (još nisu opaženi). Izmjenjene čestice za jaku silu su **gluoni**
- Gluoni su električno neutralni, bez mase i imaju spin 1, baš kao i fotoni
- Gluoni se razlikuju od fotona jer imaju „**boju**”, svojstvo koje razlikuje kvarkove od leptona
- Gluoni se vežu samo na kvarkove (koji imaju boju), a ne na leptone (koji nemaju boju)
- Kvarkovi imaju **crvenu**, **zelenu** i **plavu boju**
- „Boja“ je samo način da se izrazi svojstvo koje dolazi u tri oblika (dok naboj recimo dolazi u dva oblika, plus i minus)
- Sile se prenose kvantima- **izmjenjenim česticama**
- **Kvantna kromodinamika** za jaku silu je teorija ekvivalentna kvantnoj elektrodinamici za elektromagnetsku silu



## Fermioni i bozoni

- **Fermioni** – imaju polucjelobrojni spin

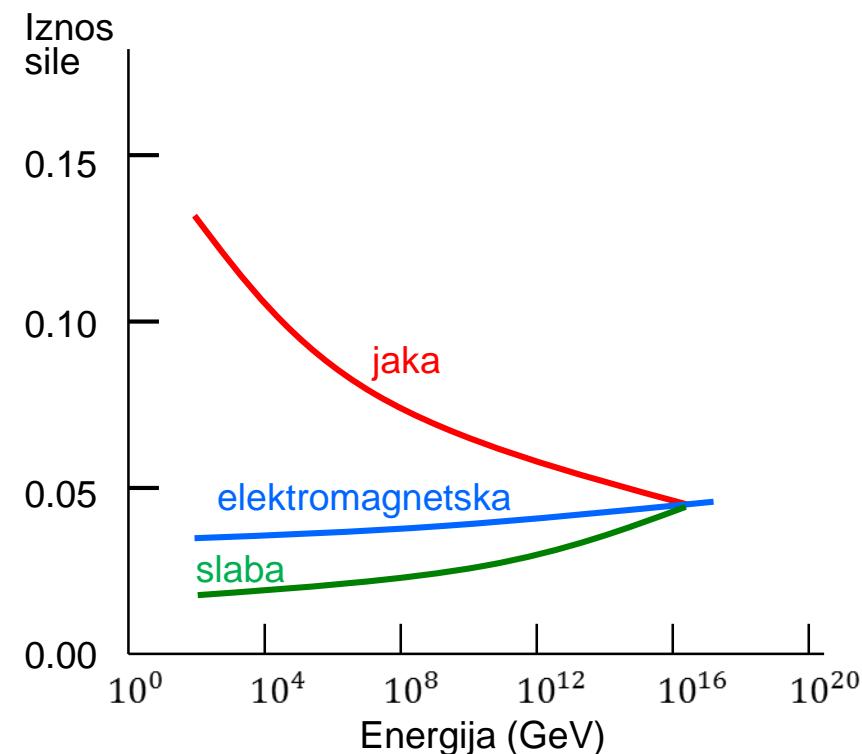
- grade materiju
  - leptoni ( $s=1/2$ )
  - kvarkovi ( $s=1/2$ )
- dobili ime po Enricu Fermiju koji je istovremeno s Paul Diracom otkrio njihovo statističko ponašanje – zadovoljavaju Fermi-Diracovu statističku raspodjelu po energetskim stanjima
  - za njih vrijedi Paulijev princip isključenja (u jednom kvantnom stanju može postojati samo jedan fermion)

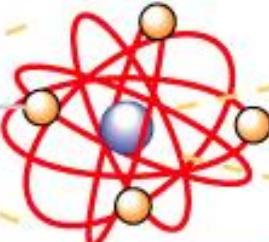
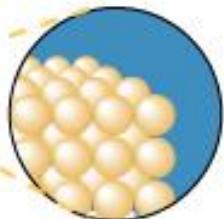
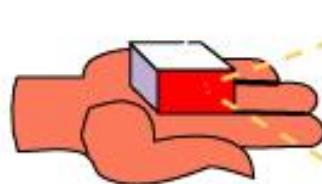
- **Bozoni** - imaju cijelobrojni spin

- nositelji sile (čestice izmjene)
  - fotoni ( $s=1$ )
  - $Z^0$ ,  $W^-$  i  $W^+$  ( $s=1$ )
  - gluoni ( $s=1$ )
- dobili su ime po Nath Boseu koji je istovremeno s Einsteinom otkrio njihovo statističko ponašanje - zadovoljavaju Bose-Einsteinovu statističku raspodjelu po energetskim stanjima
  - Paulijev princip isključenja ne odnosi se na bozone (u jednom kvantnom stanju može postojati proizvoljno mnogo bozona) i oni se mogu nakupljati u stanju najniže energije

## Veliko ujedinjenje (GUT - Grand Unified Theory)

- Iznos jake sile smanjuje se kad energija čestice raste
- Iznos elektromagnetske i slabe sile također se mijenjaju s energijom
- Postoji vjerojatnost da sve sile mogu imati isti iznos pri istoj energiji
- Sve tri sile postaju usporedive po iznosu pri energiji  $10^{14}$  GeV
- Ova energija je izvan dosega ubrzivača čestica
- Ujedinjenje s gravitacijom se očekuje na  $10^{40}$  GeV





## Mass Particles

All ordinary particles belong to this group

These particles only existed just after the Big Bang. Now they are found in cosmic rays or produced in scientific laboratories such as CERN.

## LEPTONS

### Electron

Responsible for electricity and chemical reactions  
It has a charge of -1  
Its anti-particle, the positron, has a charge of +1

### Electron Neutrino

Particle with no electric charge, and possibly no mass. Billions fly through your body every second.

### Muon

It is heavier than the electron. It lives for two millionths of a second  
It has a charge of  $\pm 1$

### Muon Neutrino

Created along with muons when some particles decay. It has no electric charge.

### Tau

Heavier still; it is extremely unstable. It was discovered in 1975.  
It has a charge of  $\pm 1$

### Tau Neutrino

Discovered in 2000.  
It has no electric charge.

## QUARKS

### Up

It has an electric charge of +2/3.  
Protons contain 2, neutrons contain 1.

### Down

It has an electric charge of -1/3  
Protons contain 1, neutrons contain 2.

### Charm

Discovered in 1974.  
It is heavier than the Up.  
It has a charge of +2/3

### Strange

Discovered in 1963.  
It is heavier than the Down. It has a charge of -1/3

### Top

Heavier still.  
Discovered in 1995.  
Electric charge +2/3

### Bottom

Heavier still; measuring bottom quarks is an important test of electroweak theory.  
Discovered in 1977.  
Electric charge -1/3

## Force Particles

These particles transmit the four fundamental forces of nature. Gravitons have so far not been discovered.

### Gluons

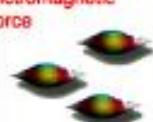
Carriers of the strong force between quarks



Felt by: quarks and gluons

### Photons

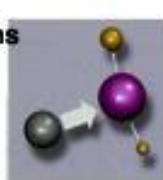
Particles that make up light. They carry the electromagnetic force



Felt by: charged particles

### Intermediate vector bosons

Carriers of the weak force



Felt by: quarks and leptons

Some forms of radioactivity are the result of the weak force.

### Gravitons

Carriers of gravity



Felt by: all particles with mass

All the weight we experience is the result of the gravitational force.

The explosive release of nuclear energy is the result of the strong force.

Electricity, magnetism and chemistry are all the results of electromagnetic force.

**ANTIMATTER:** Each particle also has an antimatter counterpart... sort of a mirror image.



# Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

## FERMIONS

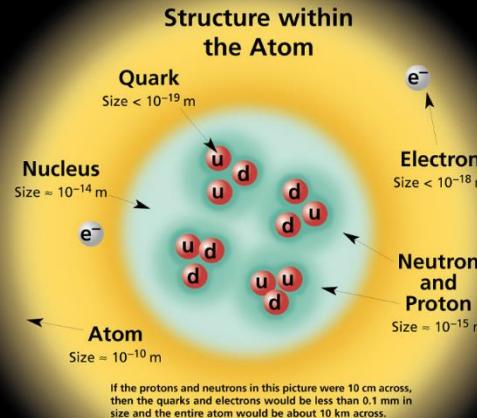
matter constituents  
spin = 1/2, 3/2, 5/2, ...

| Leptons spin = 1/2        |                         | Quarks spin = 1/2 |           |                                 |                 |
|---------------------------|-------------------------|-------------------|-----------|---------------------------------|-----------------|
| Flavor                    | Mass GeV/c <sup>2</sup> | Electric charge   | Flavor    | Approx. Mass GeV/c <sup>2</sup> | Electric charge |
| $\nu_e$ electron neutrino | <1x10 <sup>-8</sup>     | 0                 | u up      | 0.003                           | 2/3             |
| e electron                | 0.000511                | -1                | d down    | 0.006                           | -1/3            |
| $\nu_\mu$ muon neutrino   | <0.0002                 | 0                 | c charm   | 1.3                             | 2/3             |
| $\mu$ muon                | 0.106                   | -1                | s strange | 0.1                             | -1/3            |
| $\nu_\tau$ tau neutrino   | <0.02                   | 0                 | t top     | 175                             | 2/3             |
| $\tau$ tau                | 1.7771                  | -1                | b bottom  | 4.3                             | -1/3            |

Spin is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum, where  $\hbar = h/2\pi = 6.58 \times 10^{-25}$  GeV s =  $1.05 \times 10^{-34}$  J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  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/c<sup>2</sup> (remember  $E = mc^2$ ), where 1 GeV =  $10^9$  eV =  $1.60 \times 10^{-10}$  joule. The mass of the proton is 0.938 GeV/c<sup>2</sup> =  $1.67 \times 10^{-27}$  kg.



## BOSONS

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

| Unified Electroweak spin = 1 |                         |                 |
|------------------------------|-------------------------|-----------------|
| Name                         | Mass GeV/c <sup>2</sup> | Electric charge |
| $\gamma$ photon              | 0                       | 0               |
| W <sup>-</sup>               | 80.4                    | -1              |
| W <sup>+</sup>               | 80.4                    | +1              |
| Z <sup>0</sup>               | 91.187                  | 0               |

| Strong (color) spin = 1 |                         |                 |
|-------------------------|-------------------------|-----------------|
| Name                    | Mass GeV/c <sup>2</sup> | Electric charge |
| g gluon                 | 0                       | 0               |

**Color Charge**  
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

### Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; 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 (see figure below). 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**  $qqq$ .

### Residual Strong Interaction

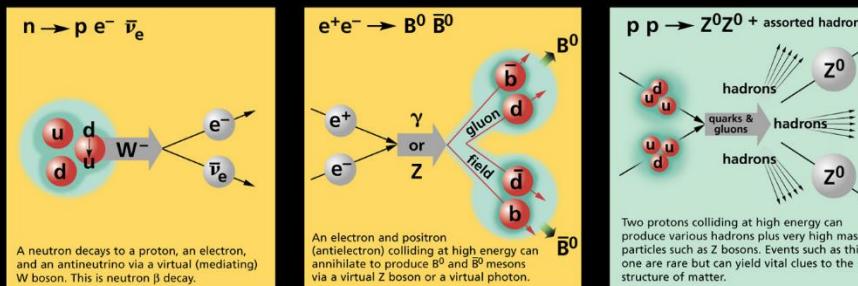
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

## PROPERTIES OF THE INTERACTIONS

| Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$                     |             |                         |                 |                         |      |
|---|-------------|-------------------------|-----------------|-------------------------|------|
| Baryons are fermionic hadrons.<br>There are about 120 types of baryons. |             |                         |                 |                         |      |
| Symbol  | Name        | Quark content           | Electric charge | Mass GeV/c <sup>2</sup> | Spin |
| p   | proton      | uud                     | 1               | 0.938                   | 1/2  |
| $\bar{p}$   | anti-proton | $\bar{u}\bar{u}\bar{d}$ | -1              | 0.938                   | 1/2  |
| n   | neutron     | udd                     | 0               | 0.940                   | 1/2  |
| $\Lambda$   | lambda      | uds                     | 0               | 1.116                   | 1/2  |
| $\Omega^-$  | omega       | sss                     | -1              | 1.672                   | 3/2  |

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

| Mesons $q\bar{q}$   |        |               |                 |                         |      |
|---|--------|---------------|-----------------|-------------------------|------|
| Mesons are bosonic hadrons.<br>There are about 140 types of mesons. |        |               |                 |                         |      |
| Symbol  | Name   | Quark content | Electric charge | Mass GeV/c <sup>2</sup> | Spin |
| $\pi^+$   | pion   | $u\bar{d}$    | +1              | 0.140                   | 0    |
| $K^-$   | kaon   | $s\bar{u}$    | -1              | 0.494                   | 0    |
| $\rho^+$  | rho    | $u\bar{d}$    | +1              | 0.770                   | 1    |
| $B^0$   | B-zero | $d\bar{u}$    | 0               | 5.279                   | 0    |
| $\eta_c$  | eta-c  | $c\bar{c}$    | 0               | 2.980                   | 0    |



**The Particle Adventure**  
Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>

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### Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines are the quark paths.