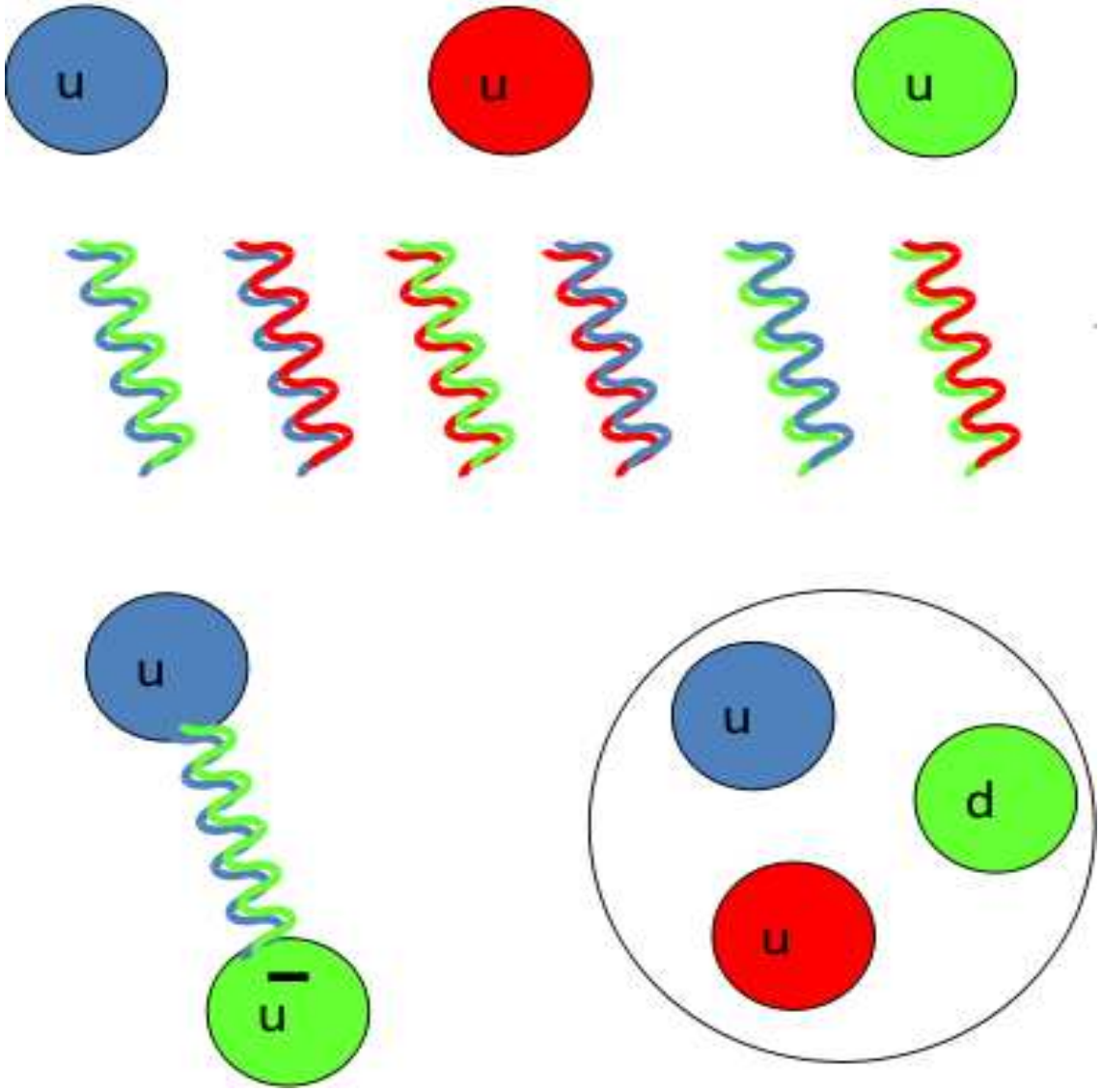
Introduction to Quark-Gluon Matter



A.B. Borissov

Why

- Investigation of Quark-Gluon Matter is the subject at "the edge of what we know about the density and compression of the most extreme state of the matter", F. Antinori, MEPhI, 15.09.2016.

- LHC program is scheduled up to 2035 including five running periods.

- In addtion, RHIC, GSI and Dubna already have or will have its own experiments on heavy ion collisions.

$\Longrightarrow$ Actions are needed and the new results are anticipated.

Introduction to the course

- Subject of Quark-Gluon Matter
- How it is studied
- Accelerators and experiments
- ALICE in details
- Observables and current researches

...Slides have been borrowing heavily from many lectures uploaded in internet.
Slides in russian are from the previous lecture course of Prof. V.I. Manko.

Introduction to the course

Papers:

- H. Satz *The Quark-Gluon Plasma, A Short Intorduction*, arXive:1101.3937 [hep-ph].

- G-M. Garsia *Advances in Quark Gluon Plasma*, arXiv:1304.1452 [nucl-ex].

- A. Andronic and P. Braun-Munzinger *Ultrarelativistic nucleus-nucleus collisions and the quark-gluon plasma*, arXiv:hep-ph/0402291.

- C.A. Salgado *Lectires on high-energy heavy-ion collisions at the LHC*, https://cds.cern.ch/record/1183649/files/p239.pdf.

- L. McLerran *Relativistic heavy-ion physics: three lectures*, https://cds.cern.ch/record/1009274/files/p75.pdf

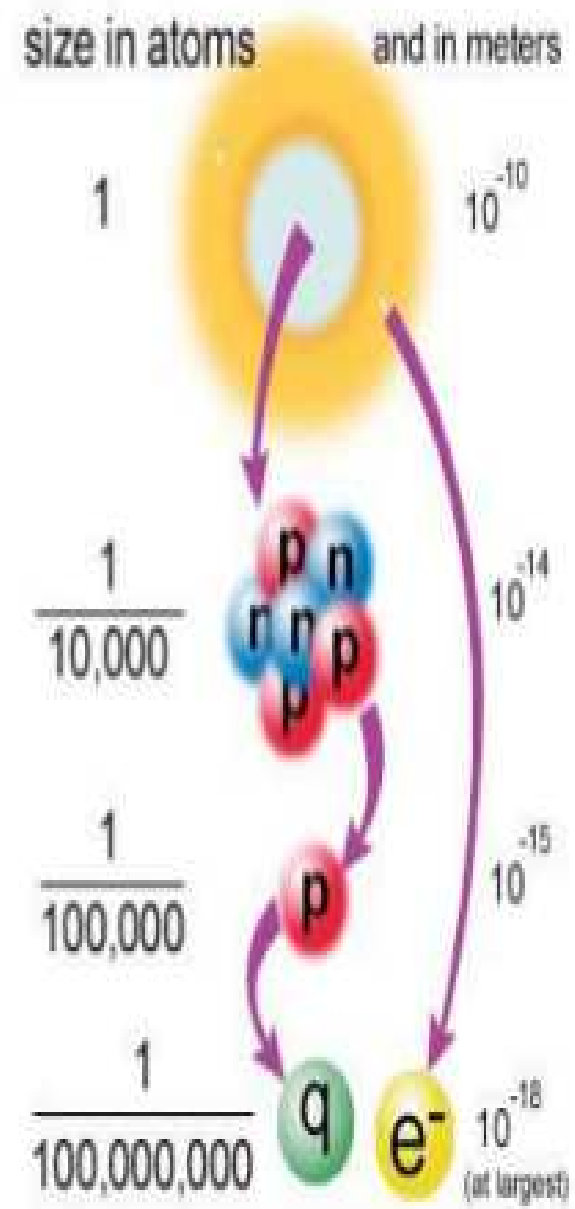
Fundamental Particles and Interactions

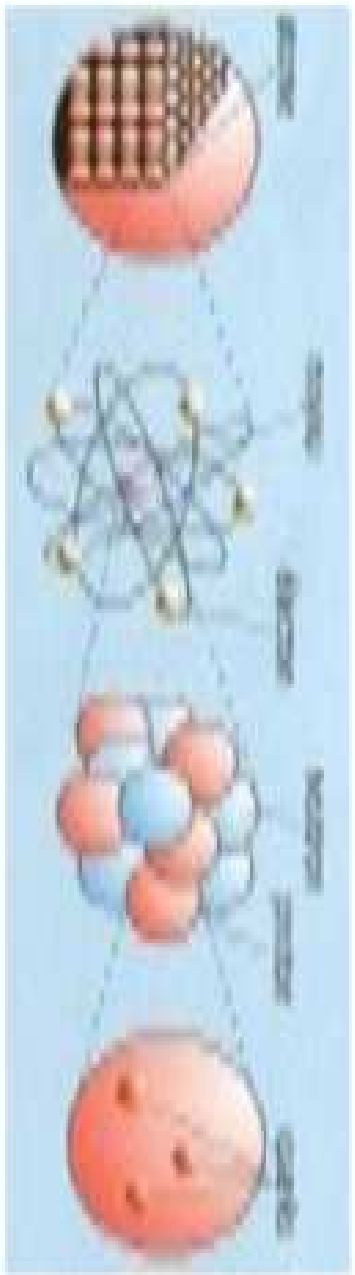
Introduction

People have long asked:
"*What is the world made of?*" and "*What holds it together?*"

Building blocks of matter

- Matter is made of molecules
- Molecules are built out of atoms
- Atoms are made of nuclei and electrons
- Nuclei are assemblies of protons and neutrons
- Protons and neutrons are quarks bound together...





Constituents of matter

FERMIONS

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

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS

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

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Basic ingredients of nuclear matter

Heavy quarks appear in hot nuclear matter

Fundamental Particles: Quarks & Leptons

FERMIONS

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

Leptons spin = 1/2

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Not-so-fundamental: Mesons & Baryons

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

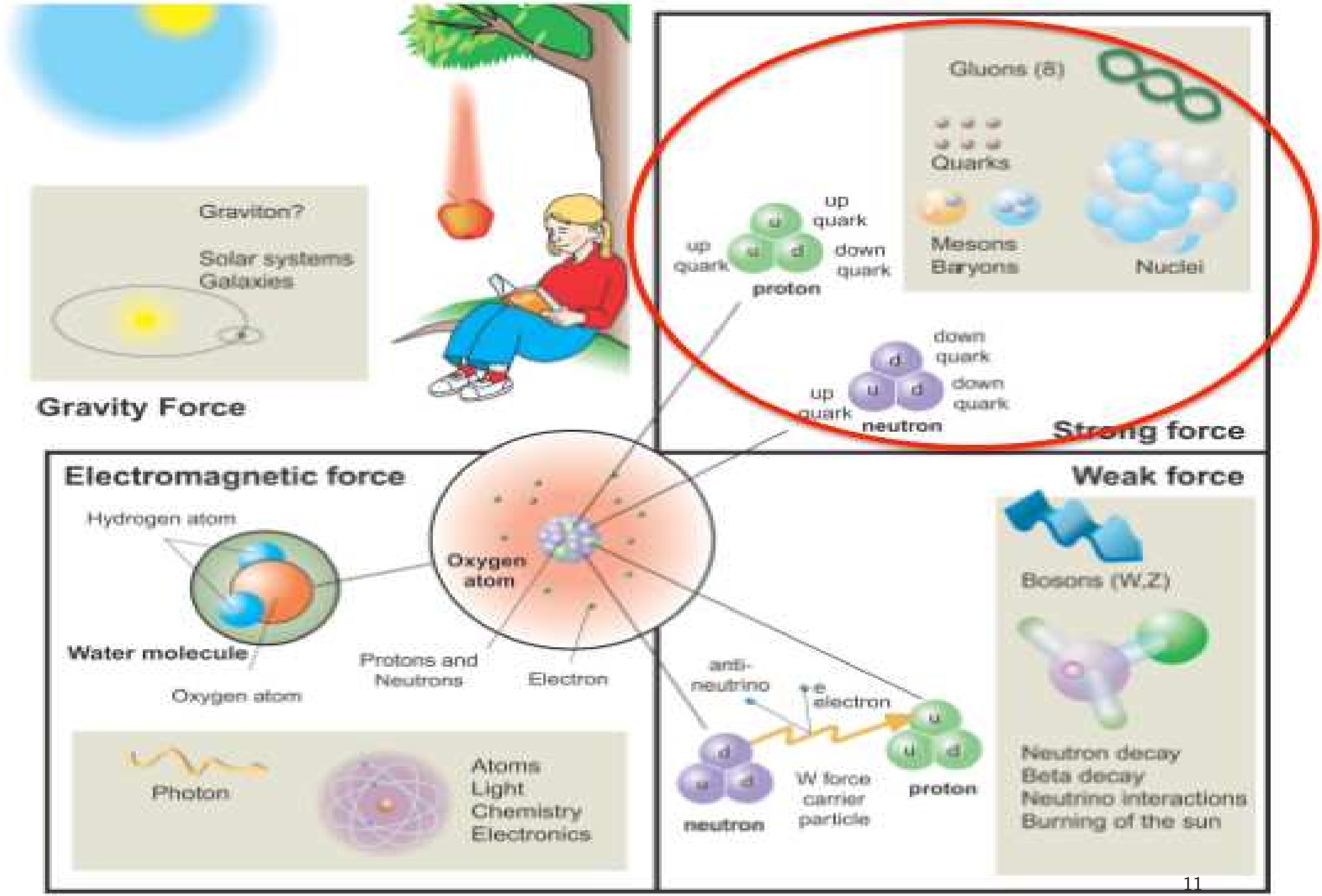
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	-1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Fundamental interactions



Interactions

PROPERTIES OF THE INTERACTIONS

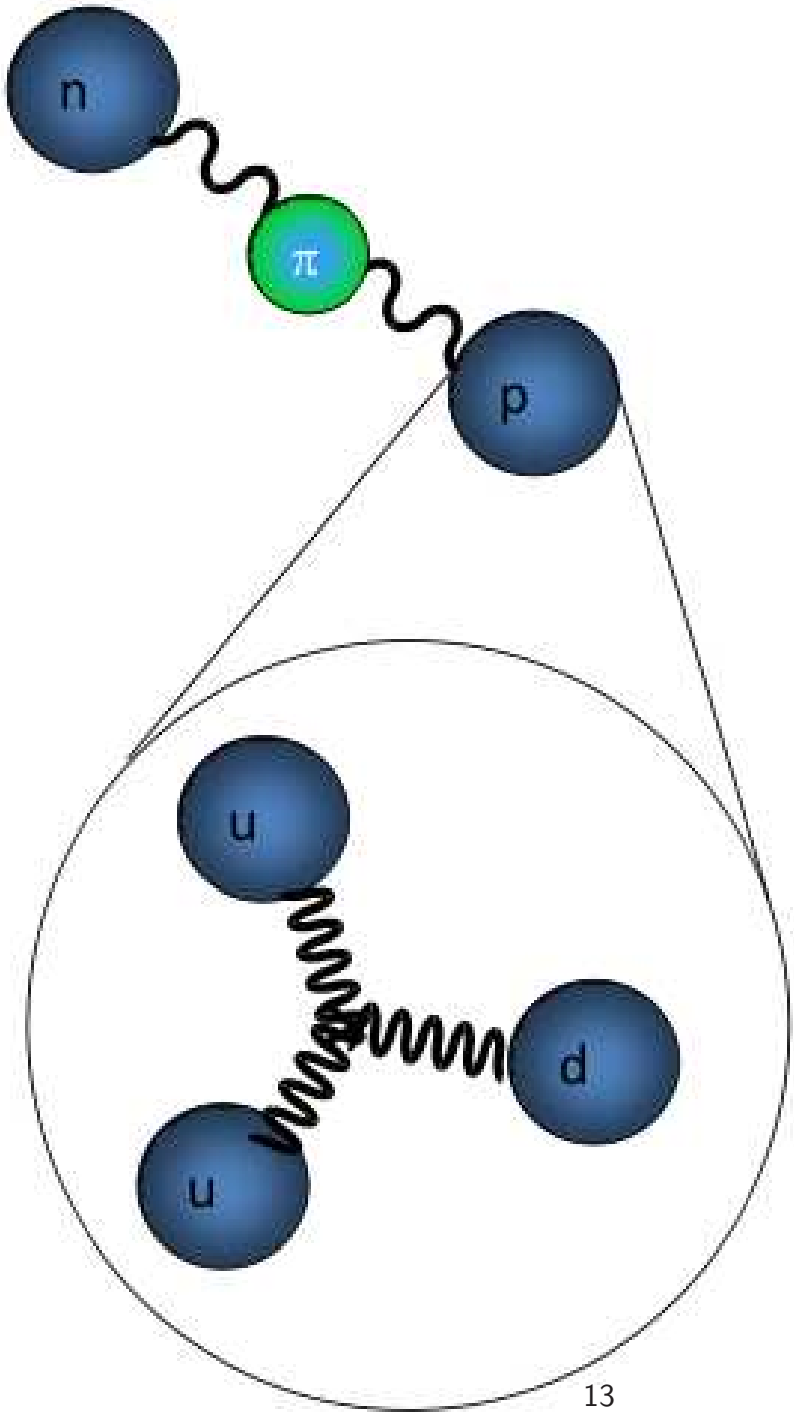
Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
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	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

The Strong Force

Nuclei are held together by exchanging mesons (but deuterons are easy to break apart)

Nucleons are held together by exchanging gluons

Both are two manifestations of the "strong" force, but nucleons and quarks are very different…



The Strong Force

The nuclei are composed of:

- protons (positive electric charge)
- neutrons (no electric charge)

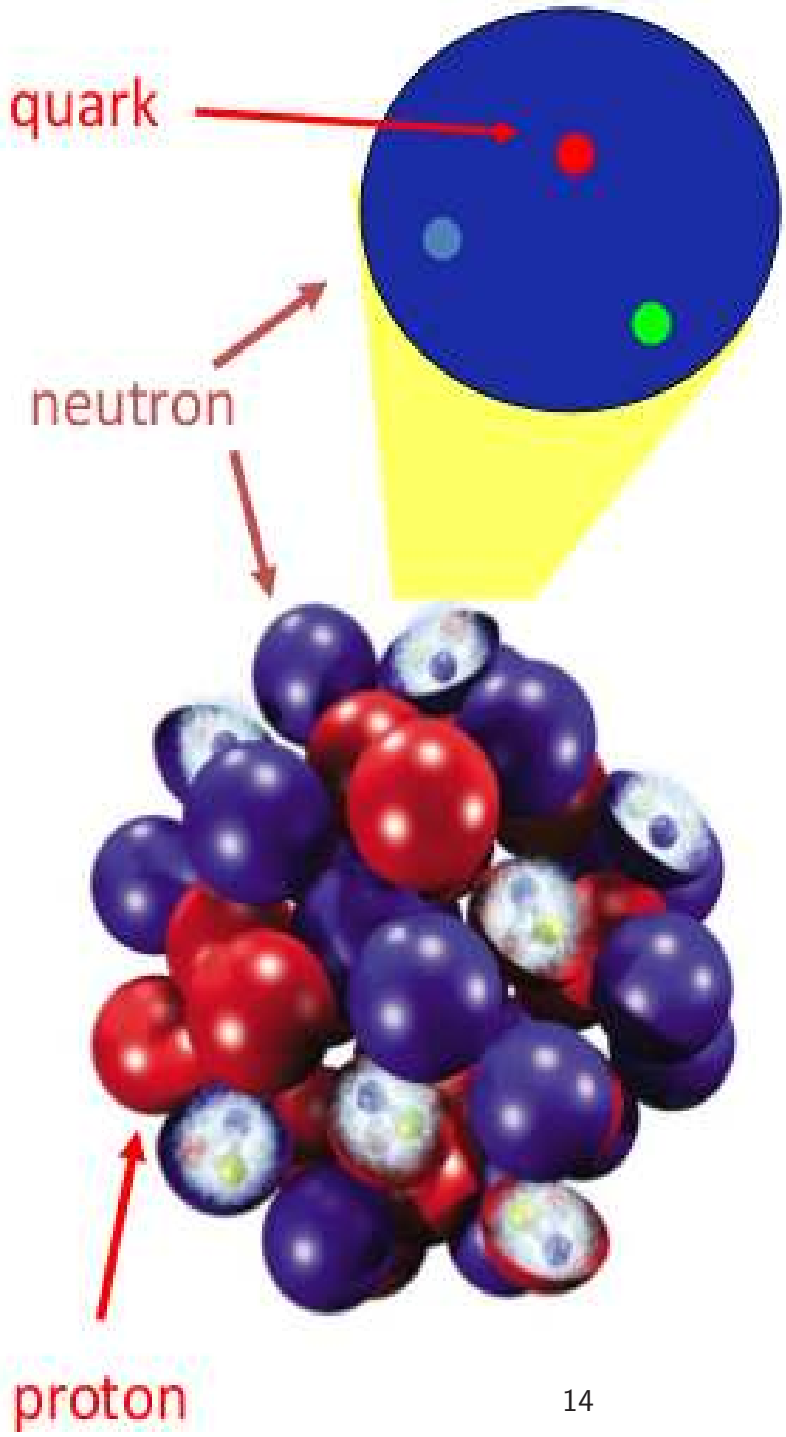
They do not blow up thanks to the "strong nuclear force"

- overcomes electrical repulsion
- determines nuclear reactions

- results from the more fundamental colour force (QCD)

→ acts on the colour charge of **quarks** (and gluons!)

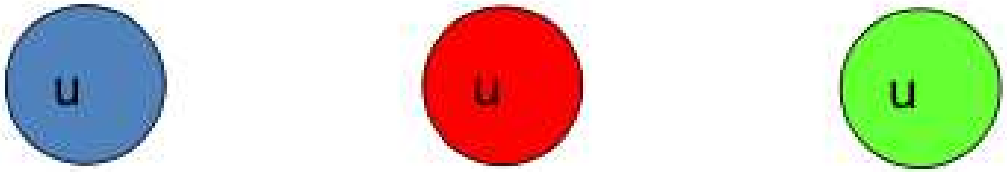
→ it is the least well understood force in Nature



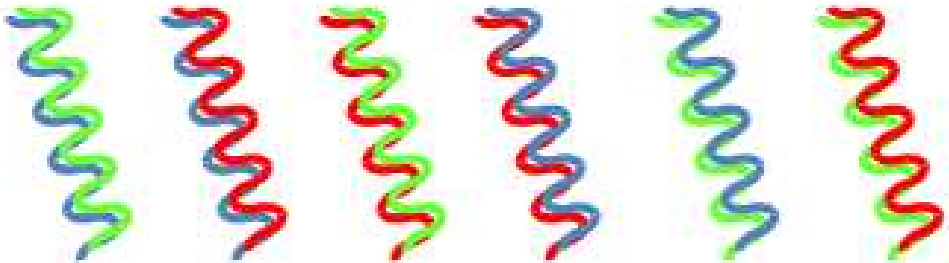
Quarks and gluons (q & g)

Quarks and gluons are both "coloured" objects!
Colour is "simply" a "charge" (but more complicated)

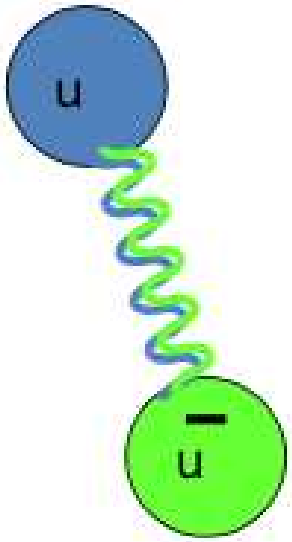
Quarks carry a single colour

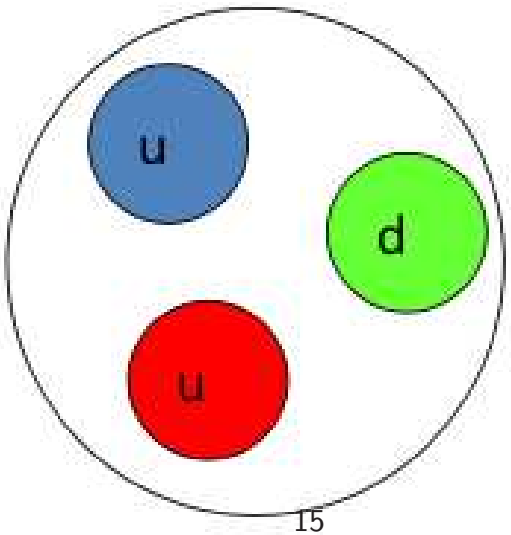


Gluons carry color & anti-colour



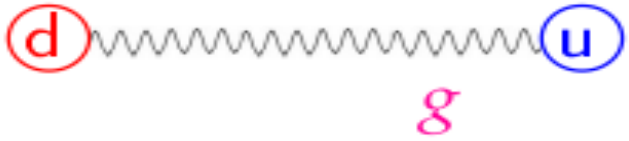
Mesons & Baryons are "colourless" objects (RBG or R+(anti-R), etc.)





Elementary interactions

- gluon is the exchange boson of the strong interaction between quarks



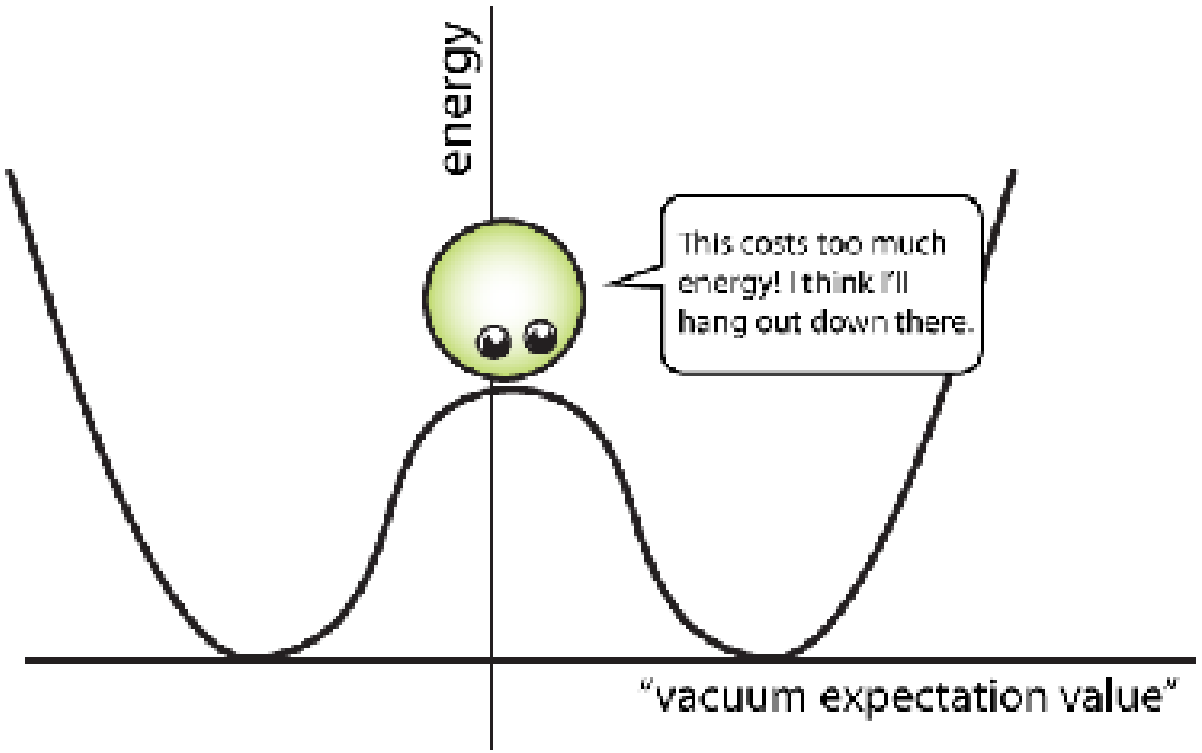
- weak bosons ($W^{\pm}$, W^0, Z) carry the weak interaction

Two complementary interpretation: Bosons are elementary excitations of the field; on the other hand, the field is a condensate of bosons, e.g. the electron is surrounded by a cloud of the so called virtual photons.

Higgs field

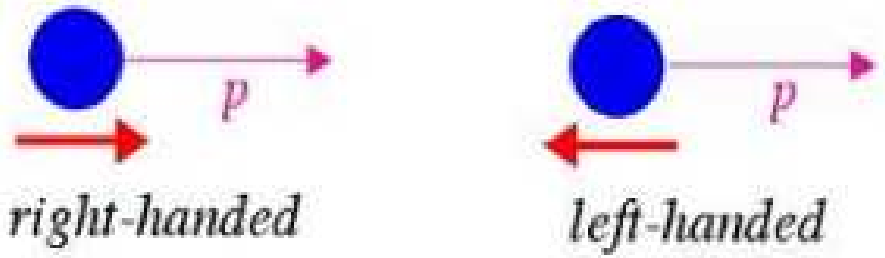
Higgs assumed the existence of a new field, – the Higgs field –, that fills all of space and has no external source. The Higgs boson is an elementary excitation of the field.

The source of the Higgs field is the Higgs field itself. In the alternative picture, the Higgs bosons in the condensate attract each other. The resulting potential energy of the system has its minimum at a non-zero value of the field.



Spontaneous breaking of chiral symmetry

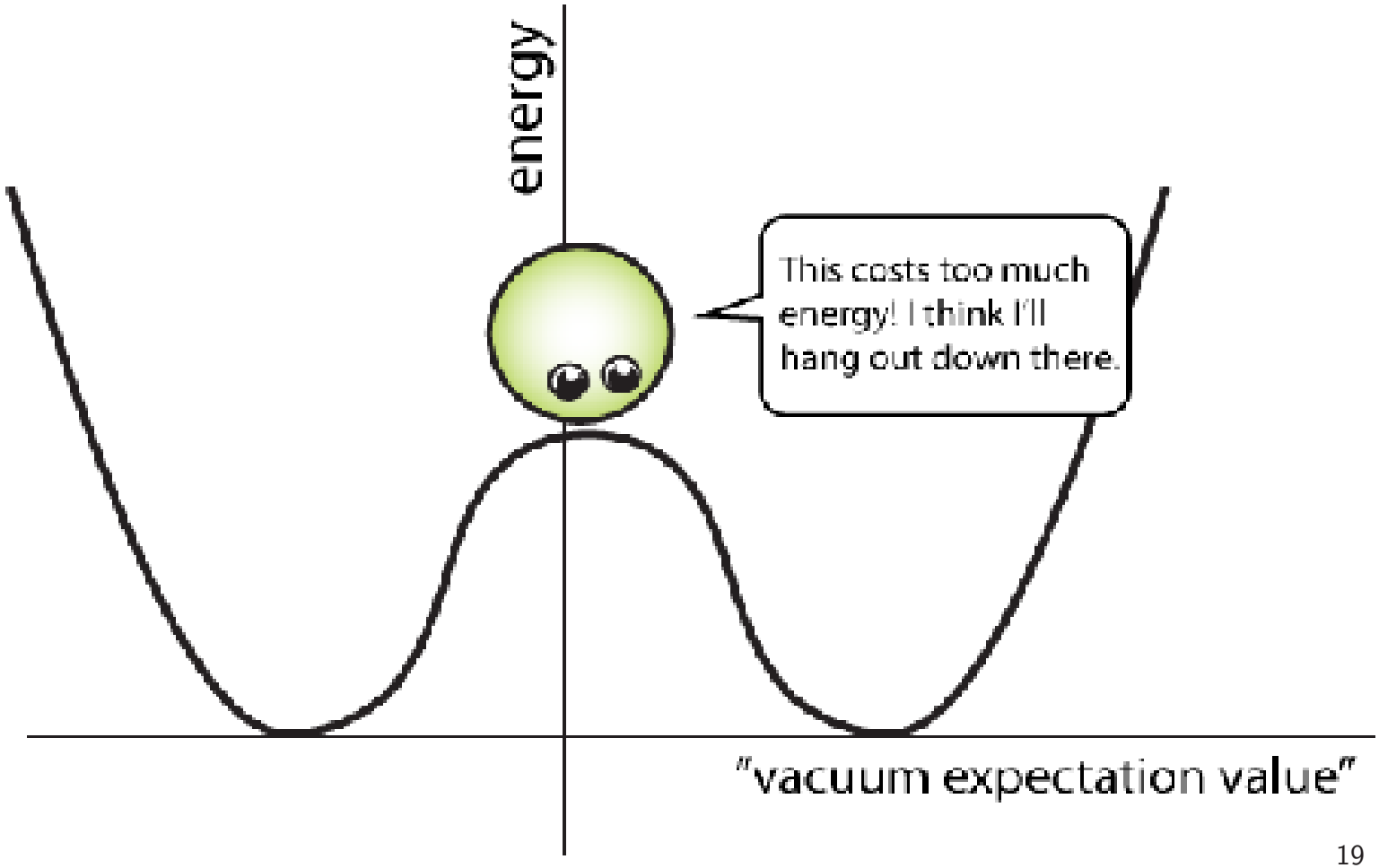
The reason for introducing the Higgs field actually lies in the observation that the equations of motion preserve the chiral symmetry while in nature this symmetry is violated.
The symmetry requires that the helicity, i.e. the projection of particle spin onto the direction of motion, is a good quantum number, and the elementary particles are supposed to be either left- or right-handed.



This solution is however not realized in nature: if one observer sees a right handed electron then for another observer, moving with the velocity greater than the electron velocity in the same direction, the electron has opposite helicity. The helicity is preserved only for massless particles moving with the speed of light; massive particles violate the symmetry.

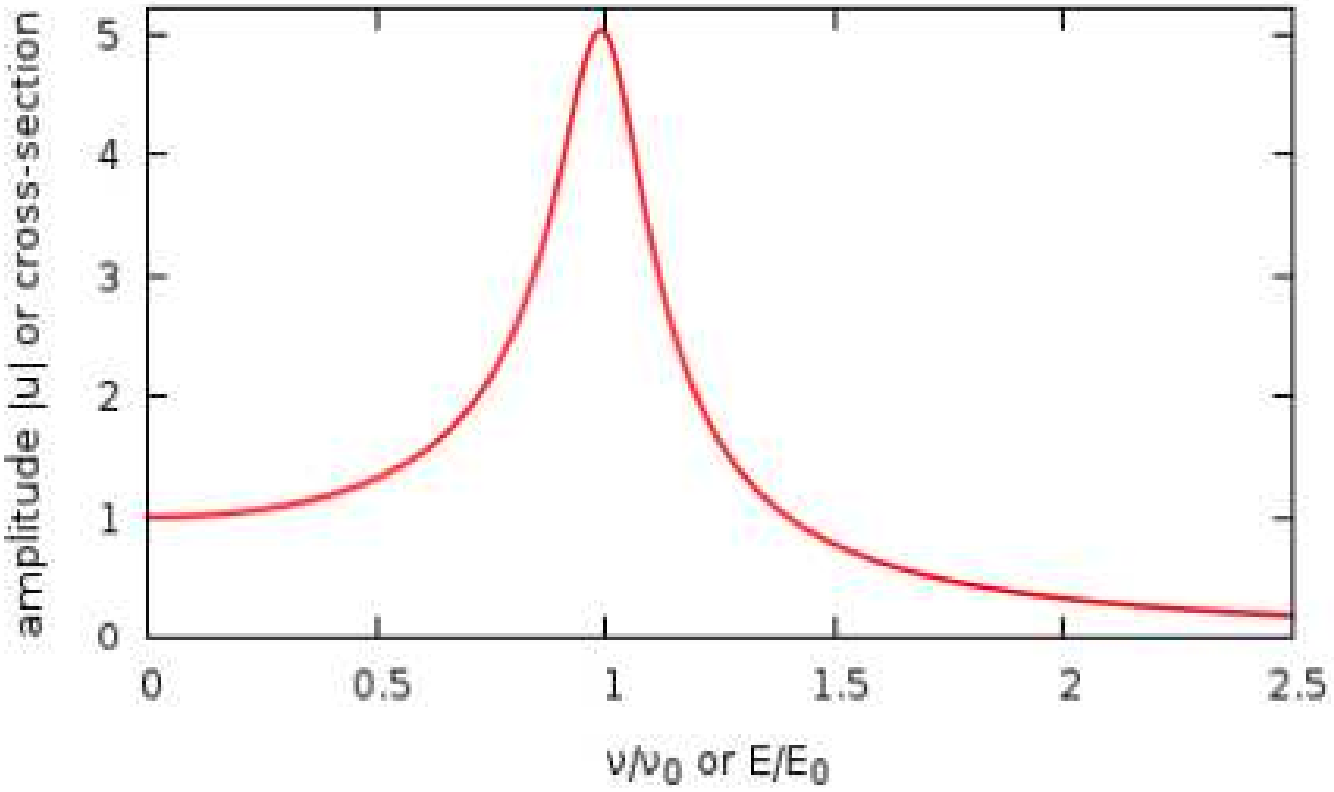
Spontaneous breaking of chiral symmetry

The situation in which the underlying laws are invariant under some symmetry while the solution is not is called "spontaneous symmetry breaking" and the Higgs mechanism is a model that describes such breaking.

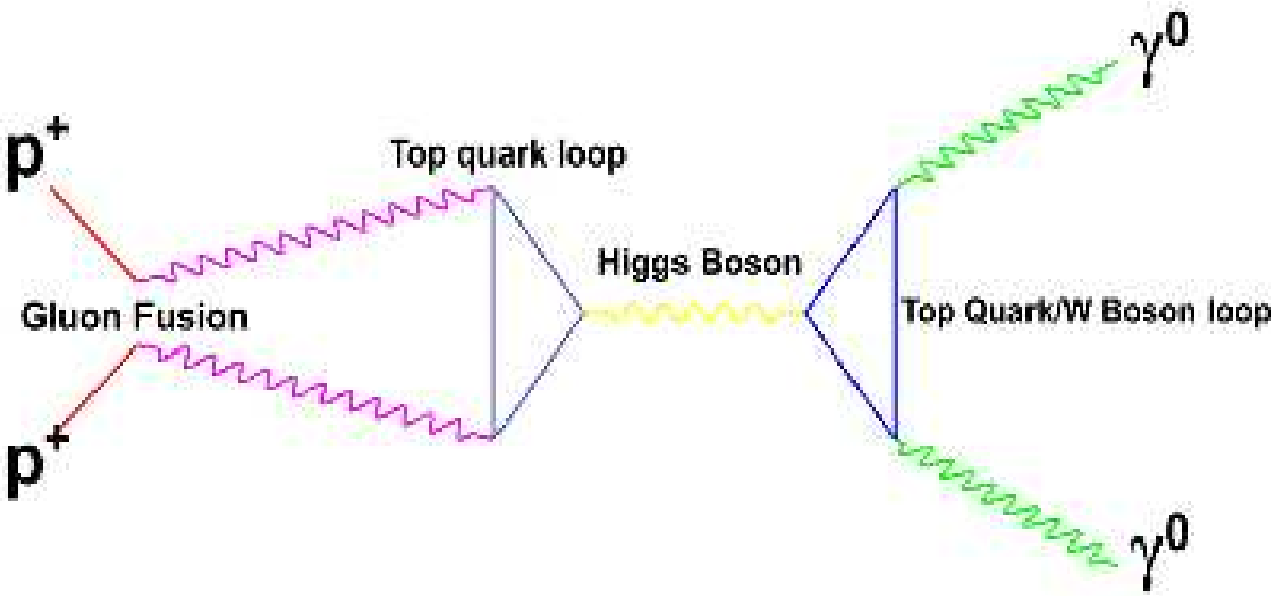


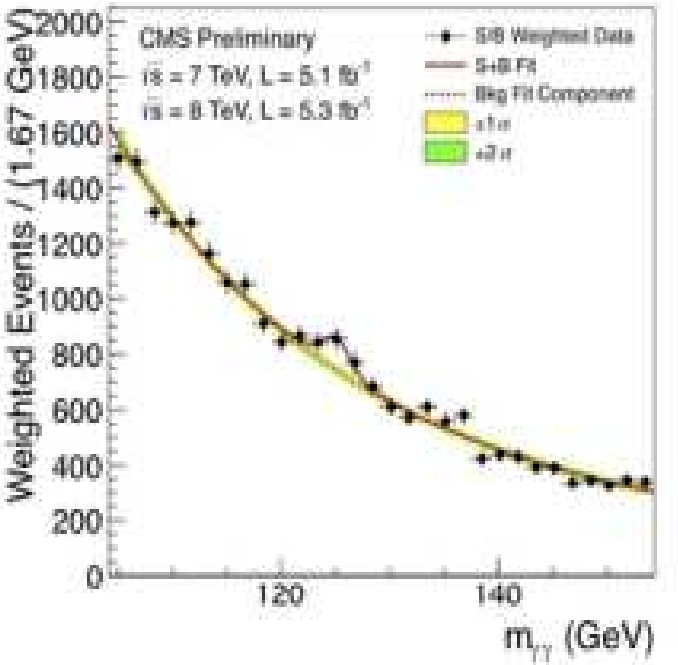
Production of the Higgs boson

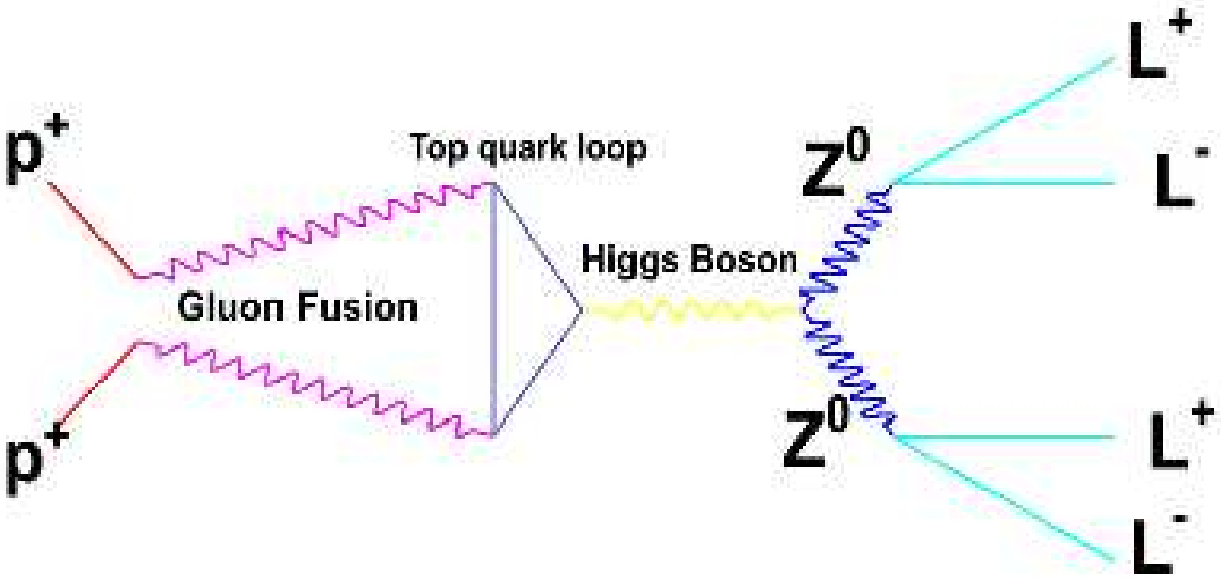
In order to observe a free Higgs boson, a huge amount of energy has to be transferred to the vacuum (i.e to the Higgs field). A particle in quantum mechanics is described as a wave with frequency $\nu = E/h$ (h is the Planck constant). The largest probability to excite an oscillation is at the resonance – i.e. when the transferred energy is equal to the energy (mass) of the particle.

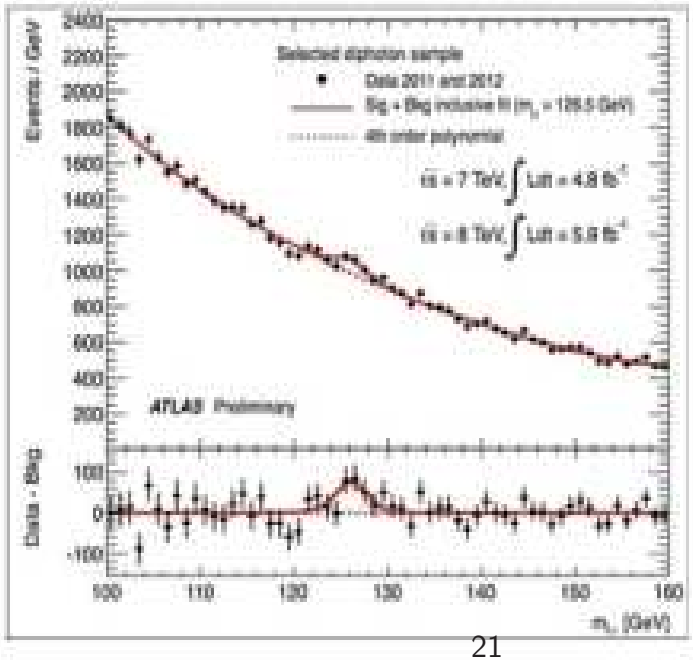


Production of the Higgs boson

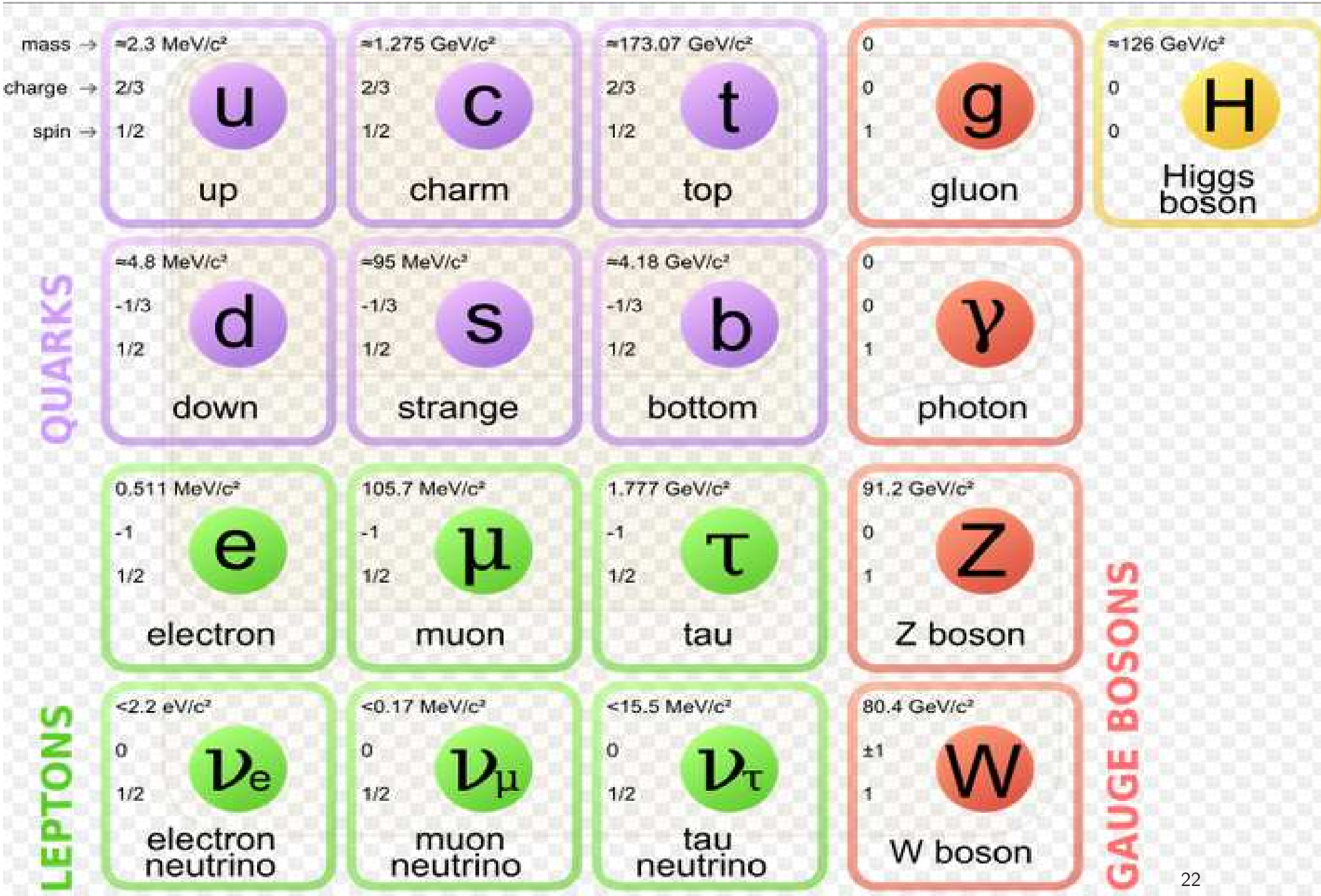


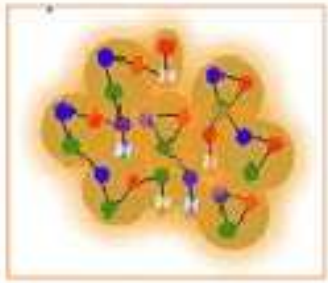






Summary


mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
QUARKS
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
LEPTONS
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
GAUGE BOSONS



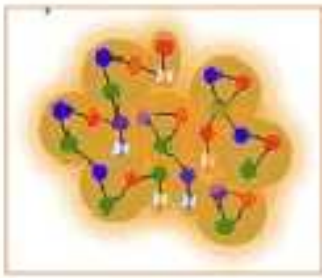
Лептоны

Лептоны - элементарные частицы, испытывающие только электромагнитное и слабое взаимодействия

→ 3 поколения, 6 частиц и столько же античастиц

Электрический заряд	**-1**	**0**
Окружающий мир	**Электрон (e)** **Масса M = 0.511 MeV/c^2**	**Электронное нейтрино (ν_e)** **Масса > 0** **β - распад ядер, Солнце**
Большой Взрыв, космос, ускорители	**Мюон (μ) – аналог электрона** **Масса 106 MeV/c^2** **Время жизни 2×10^{-6} сек** **мюона**	**Мюонное нейтрино (ν_μ)** **Масса > 0** **рождение и распад**
	Тау (τ) – аналог электрона **Масса 1777 MeV/c^2** **Время жизни 3×10^{-13} сек**	**Тау нейтрино (ν_τ)** **Масса > 0** **рождение и распад тау**

Кварки



Кварки - элементарные частицы, испытывающие сильное (цветовое) взаимодействие

→ 3 поколения, 6 ароматов, 3 цветовых заряда *(“красный”, “синий”, “зелёный”)*

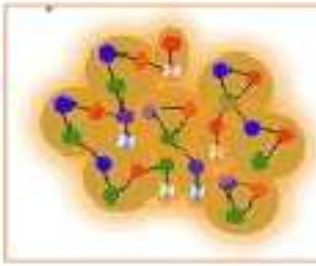
→ всего 18 кварков и столько же антикварков

Электрический заряд	**+2/3**	**-1/3**
Окружающий мир	-	
	u - кварк (up) **Масса M ≈ 3 MeV/c^2**	**d - кварк (down)** **Масса ≈ 6 MeV/c^2**
Большой Взрыв, космос, ускорители	**c – кварк (charm)** **Масса ≈1300 MeV/c^2**	**s – кварк (strange)** **Масса ≈ 100 MeV/c^2**
	t – кварк (top) **Масса ≈ 175000 MeV/c^2**	**b – кварк (beauty)** **Масса ≈ 4300 MeV/c^2**

❖ **Глюоны, 8 типов – переносчики цветового взаимодействия**

⇒ ***масса 0, электр. заряд 0, имеют цветовой заряд***

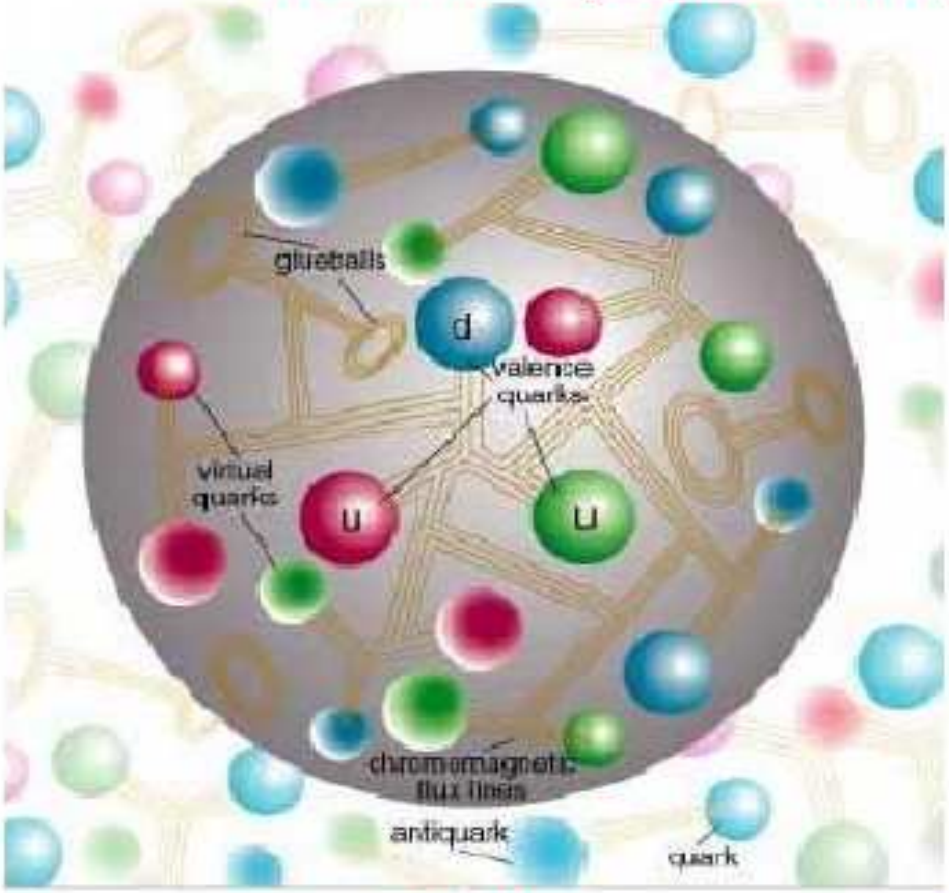
Hadrons



Адроны – сильно взаимодействующие частицы

Барионы – полуцелый спин (фермионы)

Мезоны – целый спин (бозоны)



протон

❖ **Все адроны состоят из кварков, антикварков и глюонов.**

✓ ***Барион ⇒ 3 разноцветных кварка (нейтрон ⇒ udd, протон ⇒ uud)***

✓ ***Мезон ⇒ кварк-антикварк***

❖ **Все адроны бесцветны**

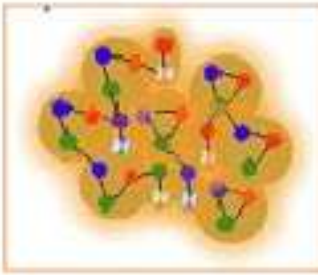
✓ ***Адрон не несёт цветового заряда***

Размер ≈ 0.5 фм

Валентные кварки, виртуальные кварки

Кварковая модель с большой точностью объясняет спектр адронов по массам и различным квантовым числам

Фундаментальные силы (поля, взаимодействия)



Взаимодействие	Переносчики	Объекты, *процессы*
Гравитационное	Гравитоны	Вселенная *притяжение тел*
Электромагнитное	Фотоны (кванты)	Атомы, молекулы *электромагнетизм, свет*
Слабое	W^-, W^+, Z^0	Элементарные частицы *β - распад ядер, мюона*
Сильное	Глюоны (glue)	Ядерные частицы *деление и синтез ядер*