Modern Aspects of Nuclear Physics, SS 2022

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Lecture 1: introduction, units, quick reminder of standard model

Friday, April 22, 2022

Idea behind and rational of this course:

in the bachelor course 'Experimentalphysik IV, Kern- und Teilchenphysik' you have all been exposed to a concise introduction into these two fields.

The current course builds on this and provides a survey, from a mainly experimental point of view, of selected highlights in the field of nuclear physics.

Altogether, there will be 21 lectures and 6 recitations. Copies of the lecture files as well as material for the recitations can be found on the lecture web pages. There you will also find info on relevant textbooks as well as some recent review papers on the subjects of the course.

The course outline is given in the next 2 slides.

The recitations will deal with homework problems built around the lecture material. Successful participation in the course will be demonstrated by active participation in the recitations and by completing a take-home exam. There you will be asked to answer, in writing, a number of specific questions about a research paper dealing with a topic treated in the course. The take-home exam will be distributed on July 22, 2022 and answers should be returned by email on July 29, 2022. Successful completion of the course requirements will earn you 4 ECTS points .

OUTLINE of the lectures

part 1

1. April 22 introduction, units, quick reminder of standard model
2. April 26 the nucleon, static properties
3. April 29 the nucleon radius, a crisis and its resolution
4. May 3 deep inelastic scattering and the parton model
5. May 6 recitation 1
6. May 10 how many gluons in a proton?
7. May 13 gluon saturation at low x
8. May 17 proton tomography
9. May 20 recitation 2
10. May 24 the quark model, news and surprizes in hadron structure

part 2

11. May 27 the structure of atomic nuclei
12. May 31 the chart of nuclides
13. June 3 recitation 3
14. June 7 nuclear structure near the drip lines
15. June 10 element formation in stars, from H and He to Fe
16. June 14 heavy element production, the r and s process
17. June 17 recitation 4

part 3

18. June 21 super-nova explosions and heavy element production 1
19. June 24 super-nova explosions and heavy element production 2
20. June 28 the structure of neutron stars
21. July 1 recitation 5

Outline of the lecture

part 3

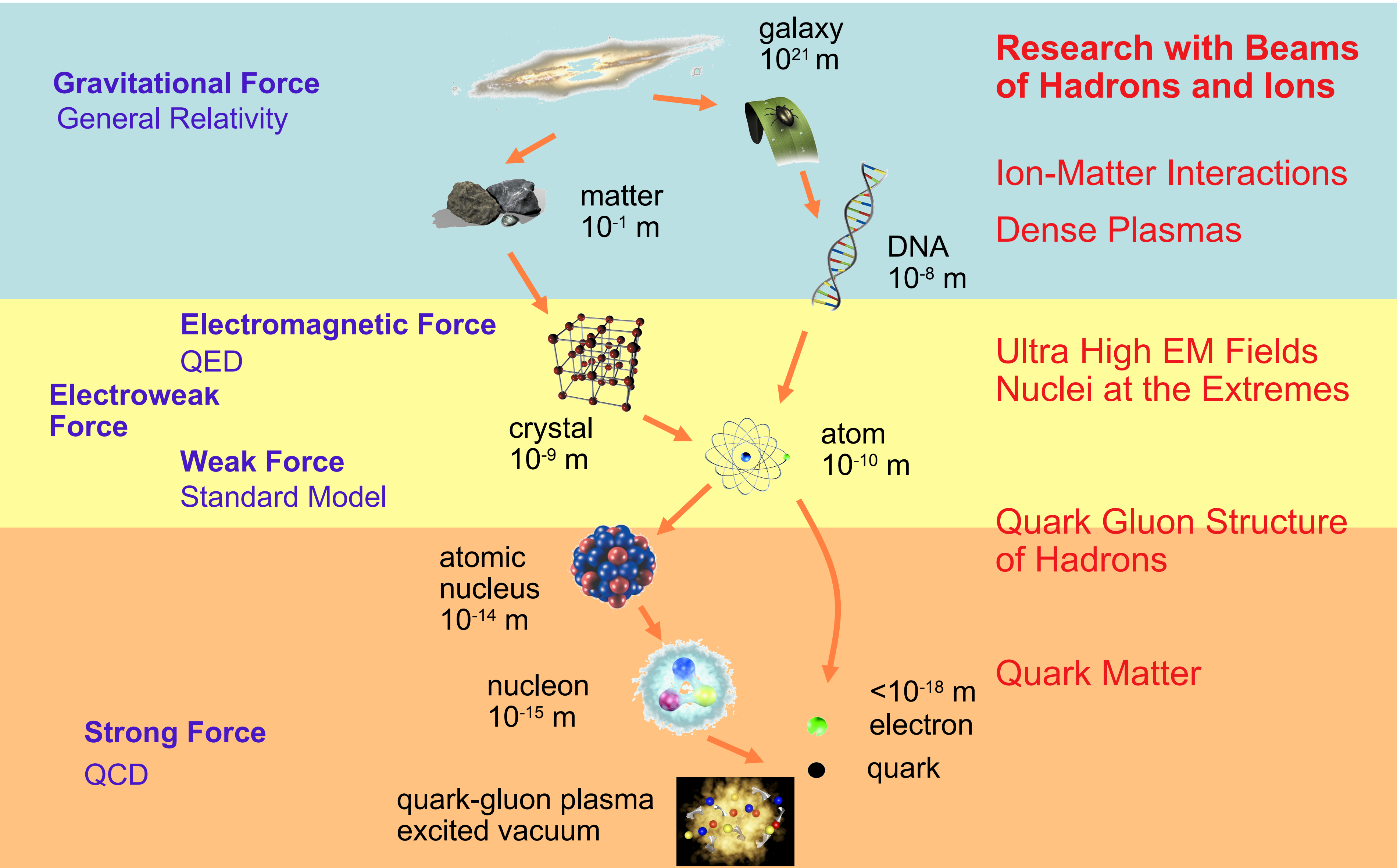
22. July 5 neutron star mergers
23. July 8 collisions of relativistic nuclei
24. July 12 decoding the QCD phase structure with relativistic nuclear coillisions
25. July 15 extreme matter: from cold quantum gases to the quark-gluon plasma via black holes
26. July 19 recitation 6
27. July 22 multi-charm hadrons and quark deconfinement

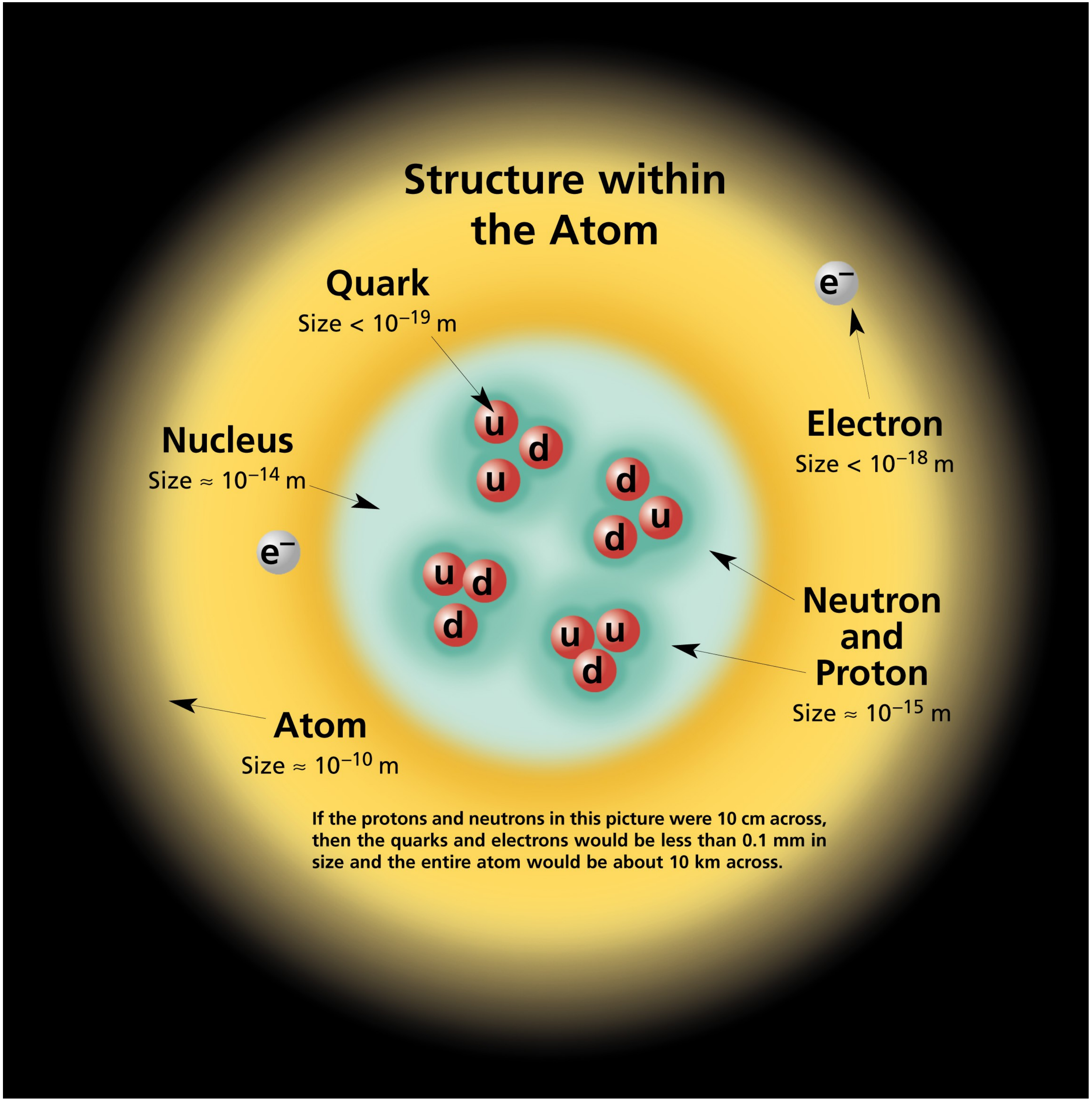
July 26 exam week
July 29 exam week

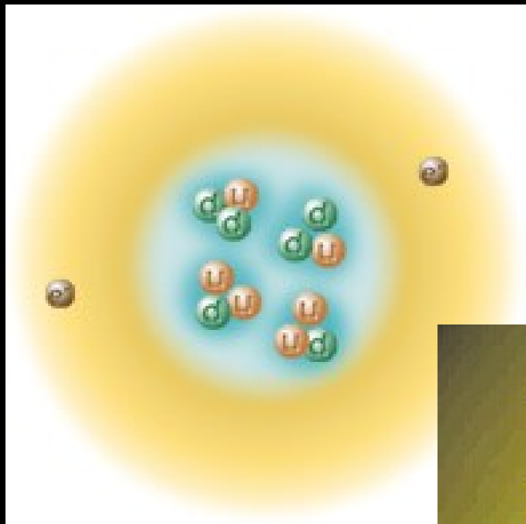
Lect. 1

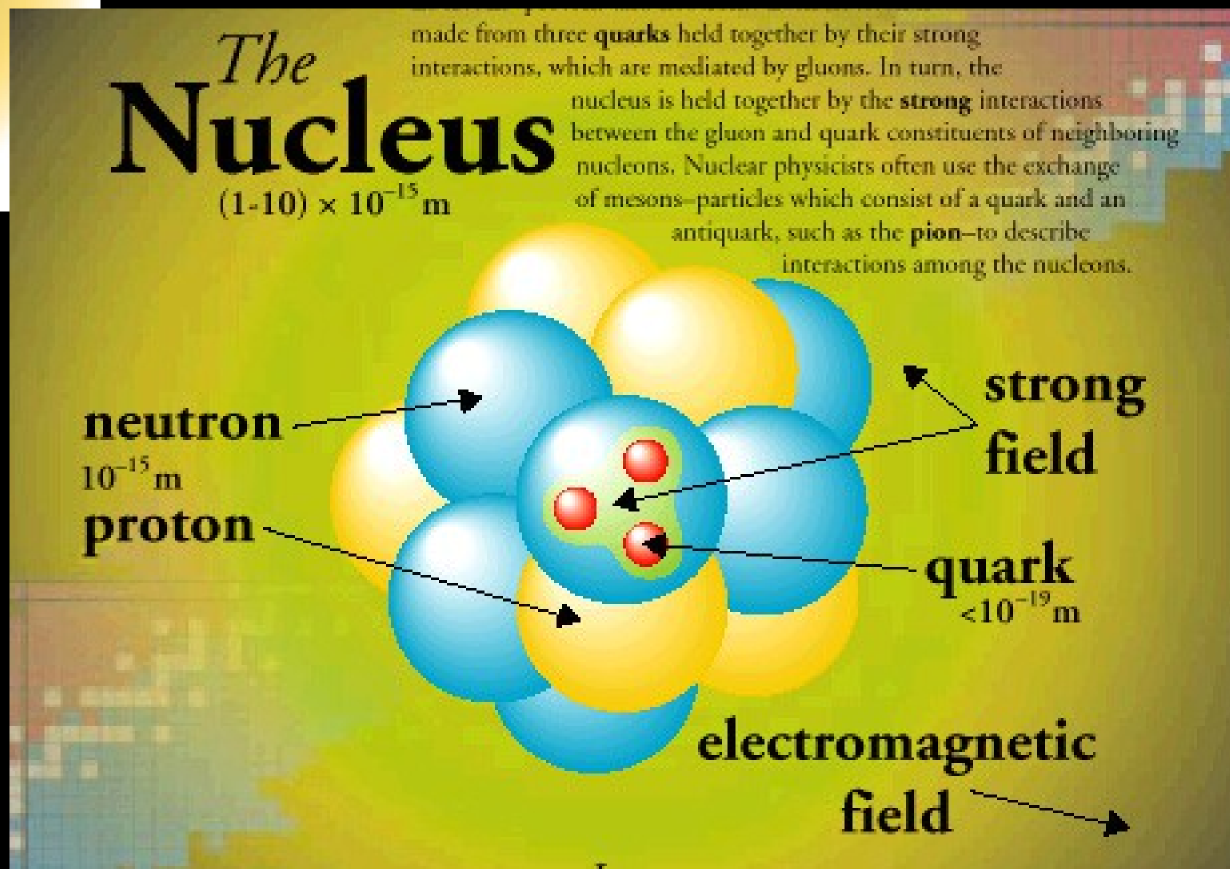
- Historical remarks
- Orders of magnitude
- 'Natural' units $\hbar = c = 1$
- Some non-relativistic and relativistic kinematics
- Survey of interactions

Structure of Matter




Structure within
the Atom
Quark
Size < 10⁻¹⁹ m
e⁻
Electron
Size < 10⁻¹⁸ m
Nucleus
Size ≈ 10⁻¹⁴ m
u
d
u
d
u
d
u
d
d
u
u
d
e⁻
Neutron
and
Proton
Size ≈ 10⁻¹⁵ m
Atom
Size ≈ 10⁻¹⁰ m
If the protons 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.




made from three **quarks** held together by their strong
interactions, which are mediated by gluons. In turn, the
nucleus is held together by the **strong** interactions
between the gluon and quark constituents of neighboring
nucleons. Nuclear physicists often use the exchange
of mesons–particles which consist of a quark and an
antiquark, such as the **pion**–to describe
interactions among the nucleons.
The
Nucleus
$(1\text{-}10) \times 10^{-15}$ m
neutron
10^{-15} m
proton
strong
field
quark
$<10^{-19}$ m
electromagnetic
field

THE STANDARD MODEL

The Standard Model expresses our present understanding of the known fundamental fermions (quarks and leptons) and the forces between them:

- The Electromagnetic force
- The Weak force
- The Strong force

It does not incorporate gravity.

The forces are mediated by fundamental "gauge" bosons: the photon, the $W^{\pm}$ and Z^0, and the gluons.

The symmetry of the model is expressed mathematically as

$SU(2) \times U(1) \times SU(3)$

Parameters of the Standard Model

15 masses (6 quark masses $m_u, m_d, m_s, m_c, m_b, m_t$)
3 vector bosons m_W, m_Z, m_{Higgs}

note: $m_\gamma = m_g = 0$

3 lepton masses m_e, m_μ, m_τ

3 neutrino masses

2 coupling constants $\alpha(q \approx 0)$ $\alpha_s(q \approx m_Z)$

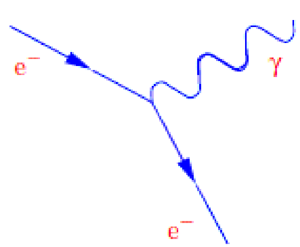
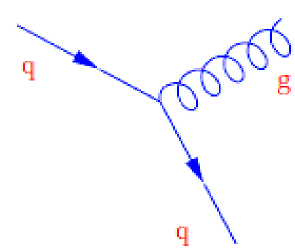
4 electroweak mixing parameters (lept.) Θ_1 Θ_2 Θ_3 δ

mixing angles CP-viol. param.

4 electroweak mixing parameters (neutr.)

+ Λ_{QCD}

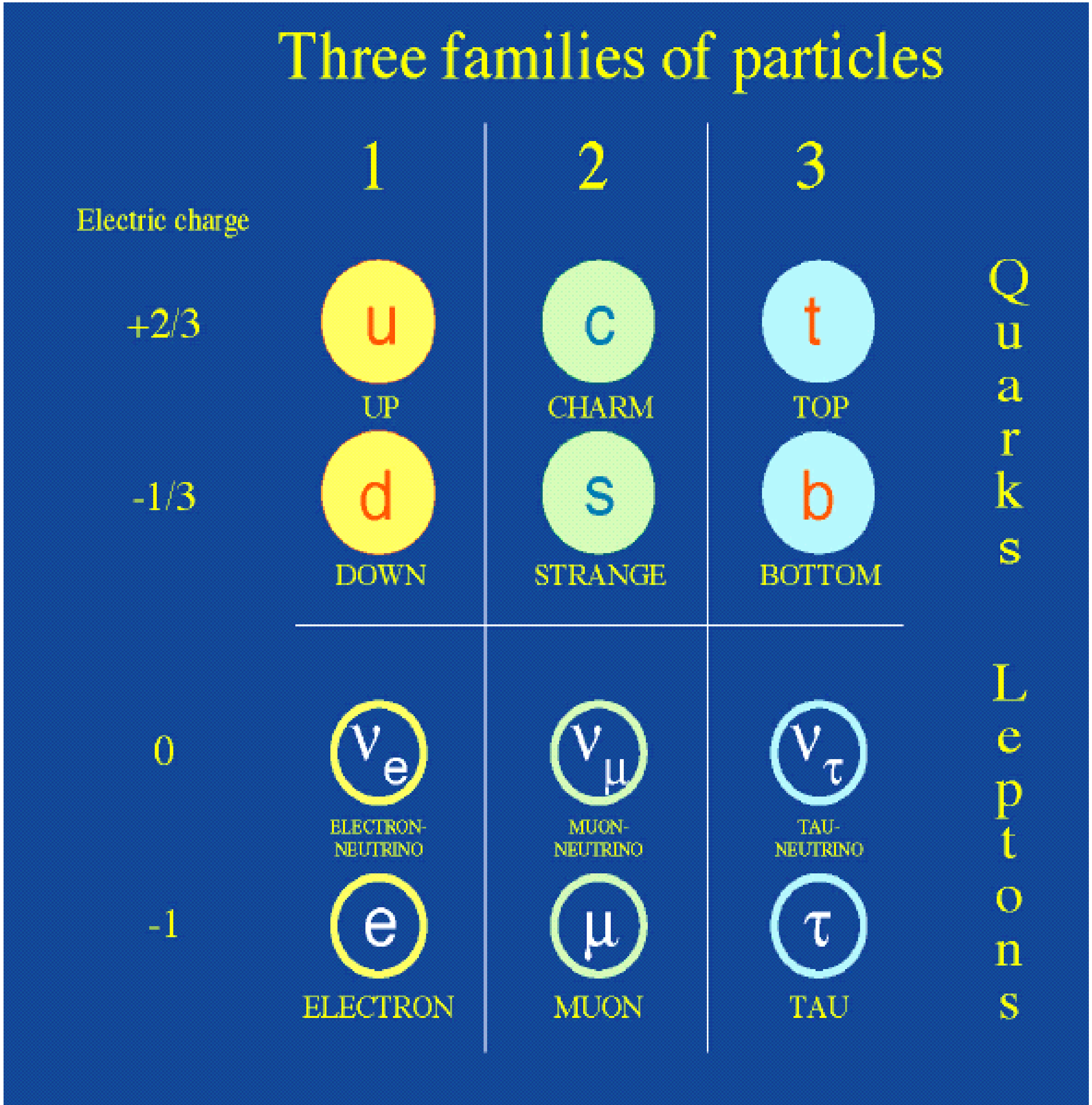
26 external parameters

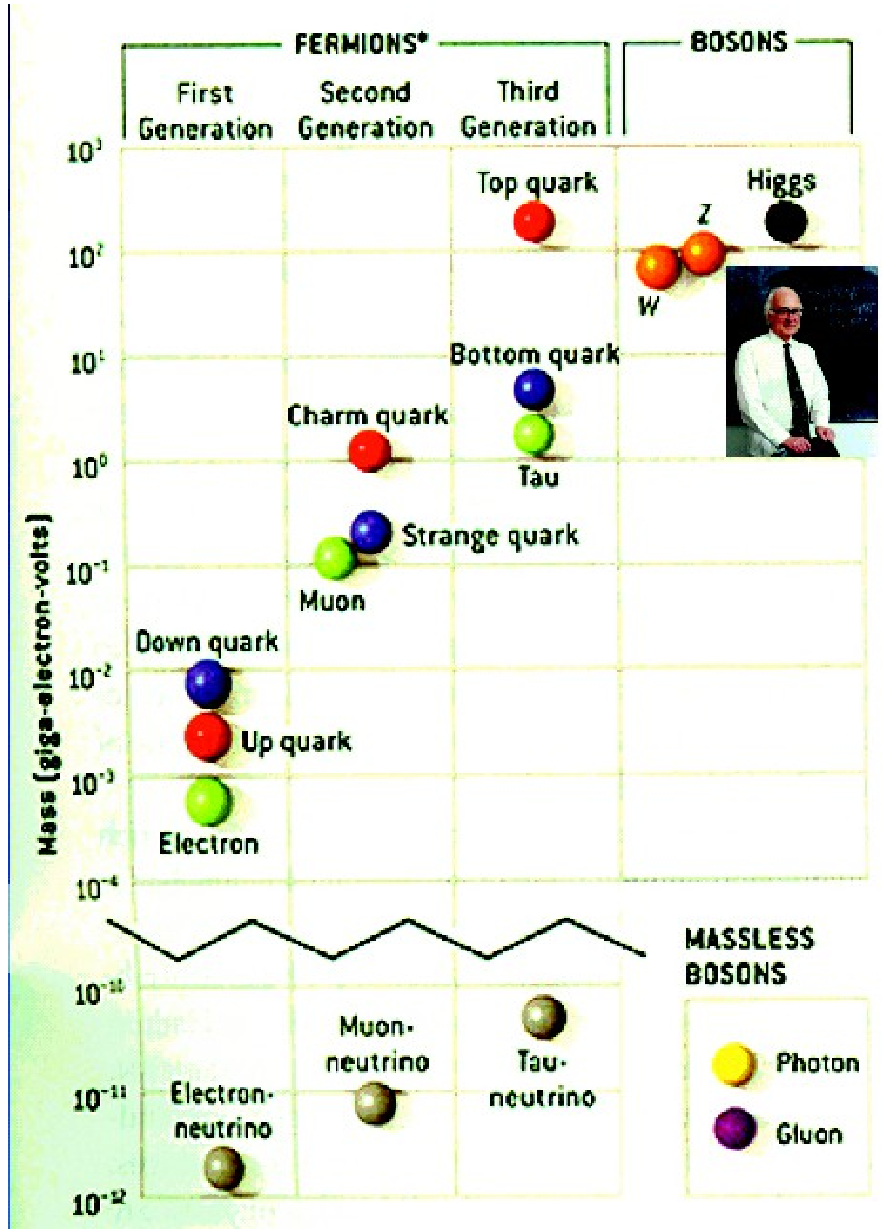
QED	QCD
Gauge symmetry $U(1)_{EM}$	Gauge symmetry $SU(3)_{COL}$
Electric charge e	Colour charge (r, g, b)
1 Massless Gauge Boson (Photon)	8 Massless Gauge Bosons (Gluons)
Photon carries no electric charge (no self-interaction)	Gluons carry colour charge (self-interact)
Basic Vertex (Bremsstrahlung)	Basic Vertex (Gluon Bremsstrahlung)
	
Infinite range force	Confinement of Quarks

Brief history of QCD

- 1954 non-abelian gauge theories --- Yang & Mills
- 1964 quark model (8-fold way) --- Gell-Mann & Zweig
- 1964 color degree of freedom --- O. Greenberg
- 1969 deep inelastic scattering at SLAC
  Bjorken: scaling from current algebra – point like constituents
  Feynman: infinite momentum frame – partons
- 1970 GIM mechanism, 4^{th} (charm) quark
  Glashow, Iliopoulos, Maiani
- 1971 non-abelian gauge theory is renormalizable
  t'Hooft & Veltman
- 1973 SU(3)c --- Gell-Mann, Fritzsch, Leutwyler
- 1973 asymptotic freedom --- Gross & Wilczek, Politzer
- 1974 discovery of charmonia --- bound states of QCD

- 1975 hadron jets in e+e- --- SPEAR
- 1976 prediction of gluon jets --- Ellis, Gaillard, Ross
- 1979 discovery of the gluon --- PETRA experiments at DESY
- 1980 running of alpha_s --- PETRA
- 1988 – 2005 --- DIS and HERA@DESY
- 2003 – 2020+ 'exotic' hadrons at Belle, Babar, LHCb, ...
- 2005 'perfect fluid' scenario for QGP at RHIC
- 2009 - Hadron structure, QCD and LHC@CERN
-
- 2012 discovery of Higgs particle by ATLAS and CMS
- 2017 deconfined quarks in the QGP


Three families of particles
1
2
3
Electric charge
+2/3
-1/3
0
-1
u
UP
c
CHARM
t
TOP
d
DOWN
s
STRANGE
b
BOTTOM
Quarks
ν_e
ELECTRON-NEUTRINO
ν_μ
MUON-NEUTRINO
ν_τ
TAU-NEUTRINO
e
ELECTRON
μ
MUON
τ
TAU
Leptons


FERMIONS*
BOSONS
First Generation
Second Generation
Third Generation
Mass (giga-electron-volts)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-10}
10^{-11}
10^{-12}
Top quark
Higgs
Z
W
Bottom quark
Charm quark
Tau
Strange quark
Muon
Down quark
Up quark
Electron
MASSLESS BOSONS
Muon-neutrino
Tau-neutrino
Electron-neutrino
Photon
Gluon

FERMIONS

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

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

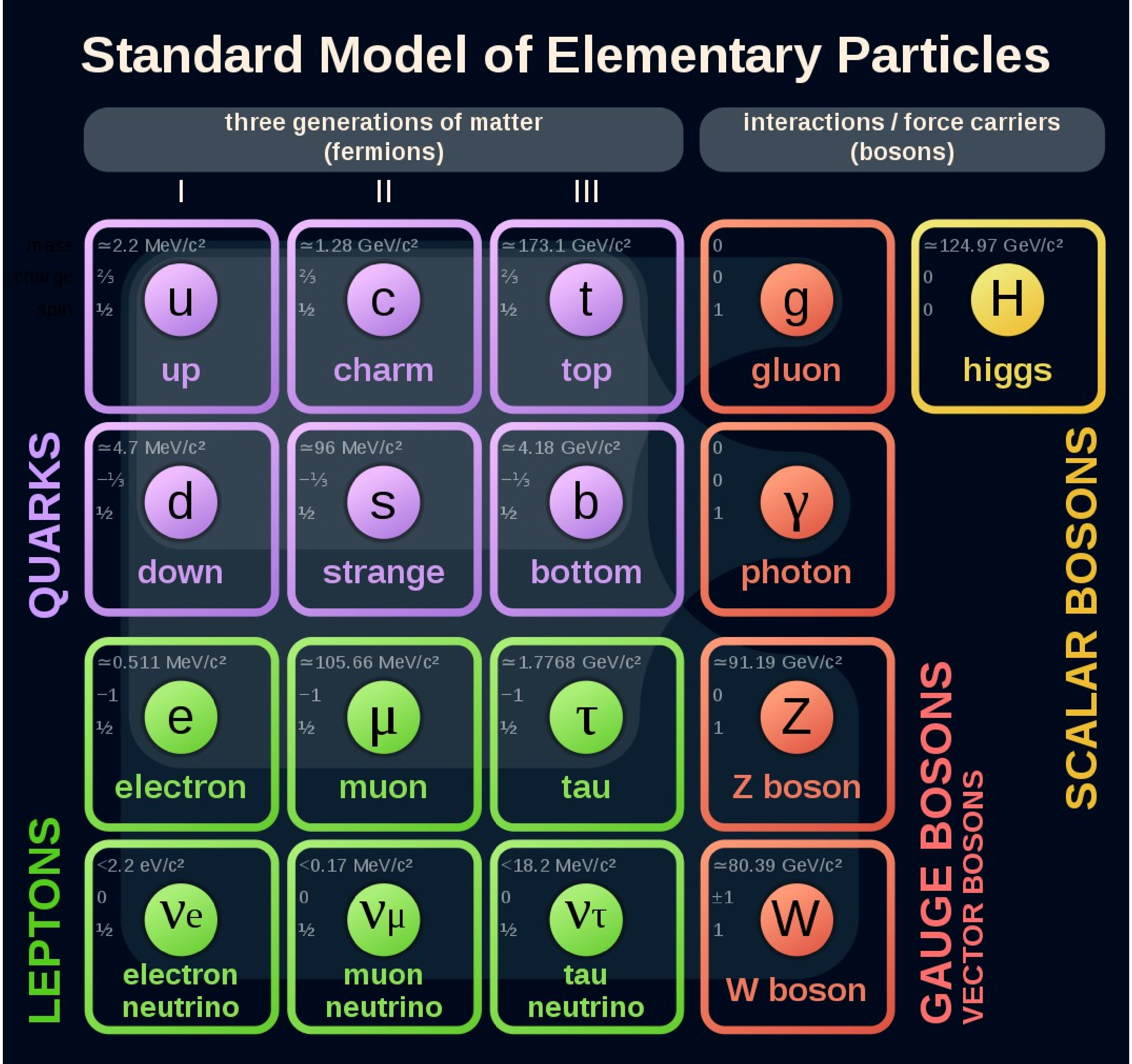
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	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/c^2	Electric charge
g gluon	0	0



Standard Model of Elementary Particles
three generations of matter (fermions)
interactions / force carriers (bosons)
I
II
III
mass
charge
spin
≃2.2 MeV/c² ⅔ ½ u up
≃1.28 GeV/c² ⅔ ½ c charm
≃173.1 GeV/c² ⅔ ½ t top
0 0 1 g gluon
≃124.97 GeV/c² 0 0 H higgs
≃4.7 MeV/c² −⅓ ½ d down
≃96 MeV/c² −⅓ ½ s strange
≃4.18 GeV/c² −⅓ ½ b bottom
0 0 1 γ photon
≃0.511 MeV/c² −1 ½ e electron
≃105.66 MeV/c² −1 ½ μ muon
≃1.7768 GeV/c² −1 ½ τ tau
≃91.19 GeV/c² 0 1 Z Z boson
<2.2 eV/c² 0 ½ νe electron neutrino
<0.17 MeV/c² 0 ½ νμ muon neutrino
<18.2 MeV/c² 0 ½ ντ tau neutrino
≃80.39 GeV/c² ±1 1 W W boson
QUARKS
LEPTONS
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS

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

Quarks spin =1/2

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u up	0.002	2/3
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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/c^2 (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

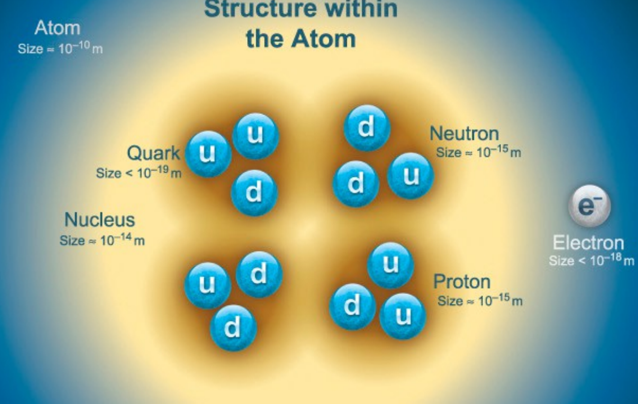
Neutrinos

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/c^2	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/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	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

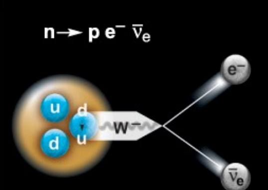
Properties of the Interactions

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.

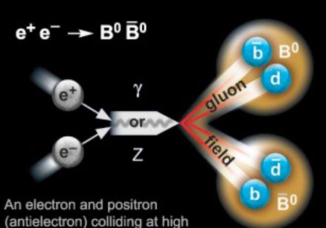
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	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).

 Made possible by the generous support of:
U.S. Department of Energy, U.S. National Science Foundation, & Lawrence Berkeley National Laboratory.

Table 1. Properties of quarks and leptons.

Leptons						Quarks						
Particle	Mass (MeV/c^2)	Q/e	L_e	L_μ	L_τ	Particle	Mass (GeV/c^2)	Q/e	S	C	$\tilde{B}$	T
ν_e	$< 3 \times 10^{-6}$	0	1	0	0	u	$1–5 \times 10^{-3}$	2/3	0	0	0	0
e^-	0.511	−1	1	0	0	d	$3–9 \times 10^{-3}$	−1/3	0	0	0	0
ν_μ	< 0.19	0	0	1	0	c	1.15–1.35	2/3	0	1	0	0
μ^-	105.66	−1	0	1	0	s	$75–170 \times 10^{-3}$	−1/3	−1	0	0	0
ν_τ	< 18.2	0	0	0	1	t	174.3 ± 5.1	2/3	0	0	0	1
τ^-	1777.0	−1	0	0	1	b	4–4.4	−1/3	0	0	−1	0

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

Baryons are fermionic hadrons.

These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–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

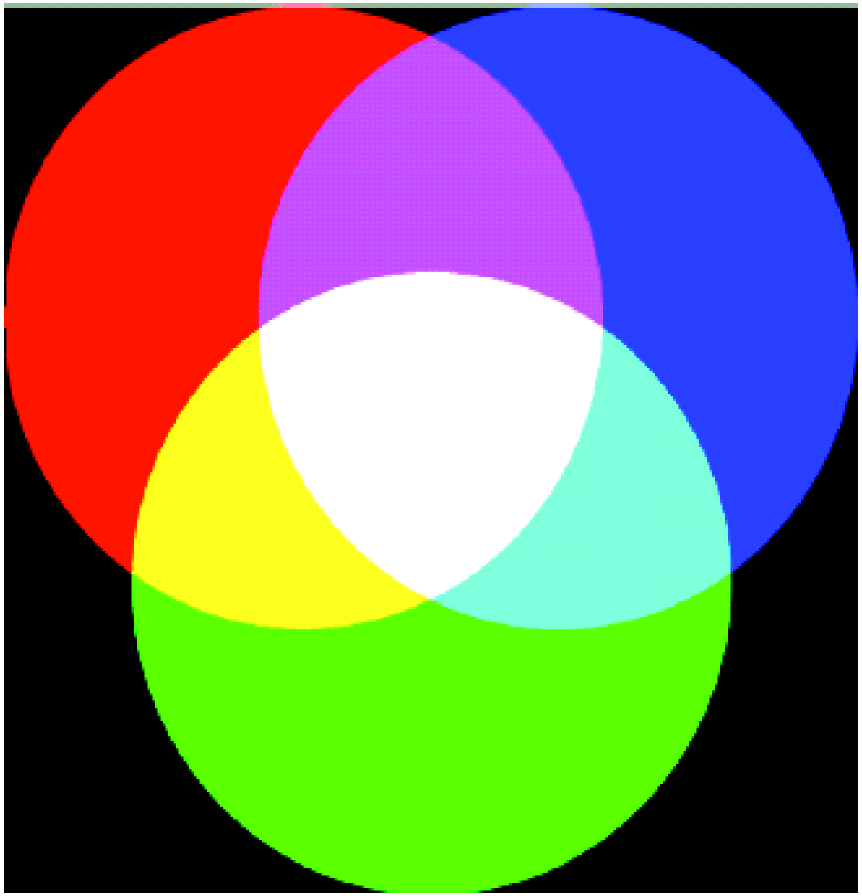
Mesons $q\bar{q}$

Mesons are bosonic hadrons

These are a few of the many types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$\mathbf{u\bar{d}}$	+1	0.140	0
$\mathbf{K^-}$	kaon	$\mathbf{s\bar{u}}$	–1	0.494	0
ρ^+	rho	$\mathbf{u\bar{d}}$	+1	0.776	1
B^0	B-zero	$\mathbf{d\bar{b}}$	0	5.279	0
η_c	eta-c	$\mathbf{c\bar{c}}$	0	2.980	0

Baryons and Mesons are colorless Objects



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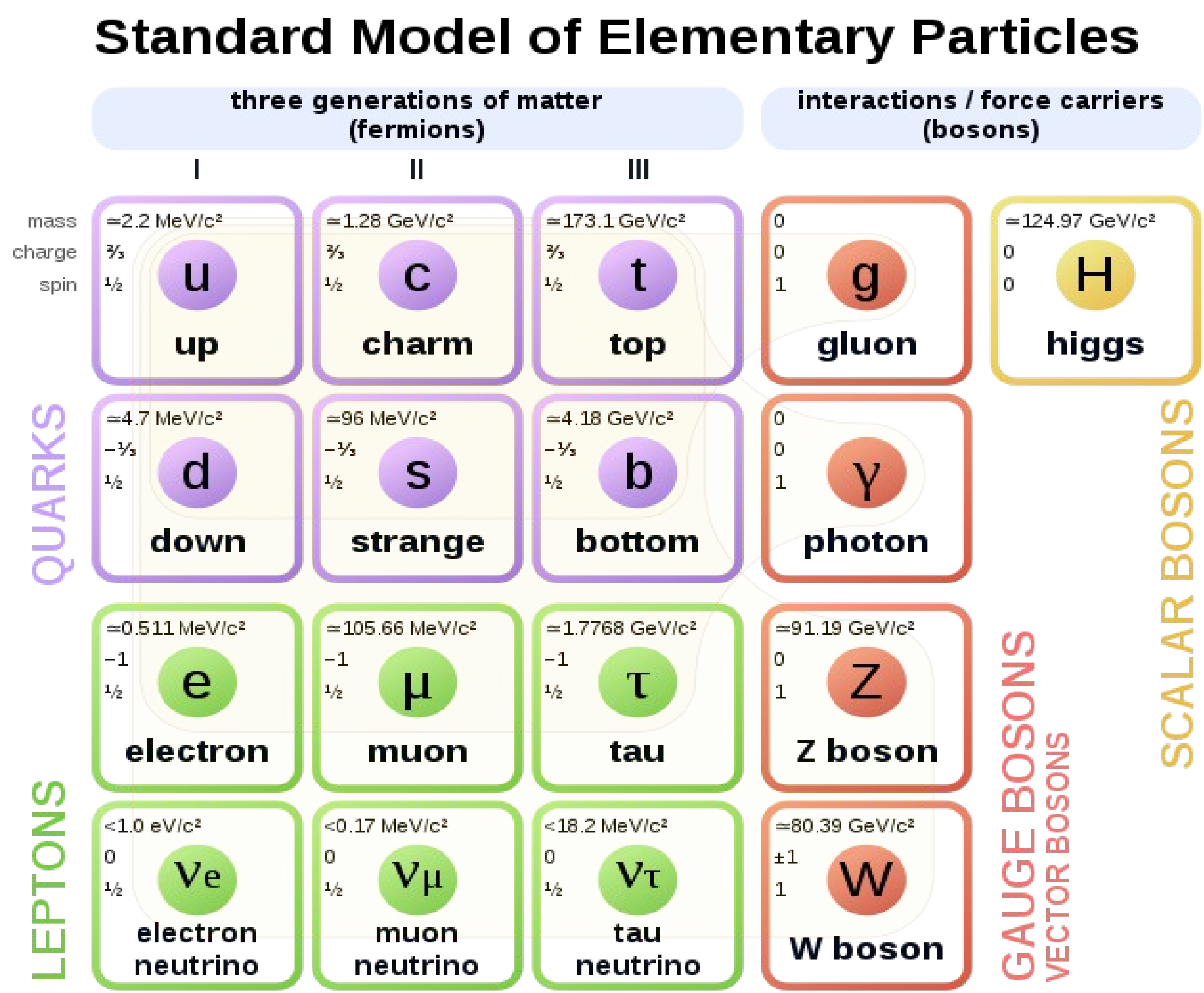

source:
PDG
Wikipedia

TYPE	INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	~ 10^{-3}	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	~ 10^{-5}	BOSONS Z^0 , W+ , W- (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	~ 10^{-38}	GRAVITONS (?)	HEAVENLY BODIES

Phenomenology of Collisions at High Energy

from now on, use units of $\hbar = c = 1$

relativistic Kinematics

$E^2 = \vec{p}^{\,2} + m^2$, 4 vector $p = (E, \vec{p})$

$p^2 = m^2$ velocity $\vec{\beta} = \frac{\vec{p}}{E}$, $\gamma^2 = \frac{1}{1-\beta^2}$

viewed from a frame moving with velocity $\vec{\beta}_f$, we get

$$\begin{pmatrix} E^* \\ p_{\parallel}^* \end{pmatrix} = \begin{pmatrix} \gamma_f & -\gamma_f\beta_f \\ -\gamma_f\beta_f & \gamma_f \end{pmatrix} \begin{pmatrix} E \\ p_{\parallel} \end{pmatrix} \qquad p_{\perp}^* = p_{\perp}$$

$p_{\parallel(\perp)}$ is component of $\vec{p}$ parallel or perpendicular to $\vec{\beta}_f$

$E_{cm} = \sqrt{s}$ $s = (p_1 + p_2)^2$

center of mass energy

$$E_{cm} = \sqrt{(p_1 + p_2)^2} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

$$= \sqrt{m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2 \cos\theta_{12})}$$

in a frame with particle 2 at rest ($\vec{p}_2 = 0$,

$$E_{cm} = \sqrt{m_1^2 + m_2^2 + 2E_1^{lab} \cdot m_2}$$

velocity of center of mass in lab frame

$$\vec{\beta}_{cm} = \frac{\vec{p}_1^{\,lab}}{E_1^{lab} + m_2} \qquad \gamma_{cm} = \frac{E_1^{lab} + m_2}{E_{cm}}$$

Natural Units

$\hbar = c = 1 \Rightarrow$ mass, energy, momentum is measured in energy units

goes back to Planck's 1899 suggestion: (Annalen Physik 4 (1901) 553)

$c = G = \hbar = k_B = k_e = 1$

then length and time are measured in $\frac{1}{\text{energy}}$ ~ distance

(see also: Nick van Remortel, Nature Physics 12 (2016) 1082)

useful constants to convert (via dimensional analysis) into 'physical units': $\hbar c = 197.3$ MeV $\cdot$ fm ≈ 200 MeV $\cdot$ fm

$e^2 = 1.44$ MeV fm

non-interacting gluon gas

energy density $\varepsilon_g = g_{gluon} \cdot \frac{\pi^2}{30} T^4$

degeneracy factor $g_{gluon} = 2 \times 8 = 16$

$\Rightarrow$ at $T = 200$ MeV

$$\varepsilon_g = 16 \cdot \frac{\pi^2}{30} \cdot \frac{T^4}{(\hbar c)^3} \simeq 1 \frac{\text{GeV}}{\text{fm}^3}$$

$$n_g = g_{gluon} \frac{\zeta(3)}{\pi^2} \cdot \frac{T^3}{(\hbar c)^3} = 16 \cdot \frac{1.202}{\pi^2} \approx 2/\text{fm}^3$$

$\zeta(3) \approx 1.202$

examples — dimensional analysis

$$\sigma_{e^+e^-\to\mu^+\mu^-} = \frac{4\pi}{3}\alpha^2\frac{1}{s} \qquad s = (p_{e^+} + p_{e^-})^2 \qquad \sqrt{s} = E_{cm}$$

$$\sigma_{e^+e^-\to\mu^+\mu^-} = \frac{4\pi}{3}\alpha^2 \cdot \frac{1}{s\,(\mathrm{GeV}^2)}$$

but: cross section is area => multiply with $(\hbar c)^2$

$$\Rightarrow \sigma_{e^+e^-} = 87\ \mathrm{nb}\ \frac{1}{s\,(\mathrm{GeV}^2)}$$

$$1\ \mathrm{fm}^2 = 10^{-26}\ \mathrm{cm}^2 = 10\ \mathrm{mb}$$