Modern Aspects of Nuclear Physics, SS 2020

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

Tuesday, April 21, 2020

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 22 lectures and 5 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 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.

OUTLINE of the lectures

part 1

1. April 21 introduction, units, quick reminder of standard model
2. April 24 the nucleon, static properties
3. April 28 the nucleon radius, a crisis and its resolution
4. May 5 deep inelastic scattering and the parton model
5. May 8 recitation 1
6. May 12 how many gluons in a proton?
7. May 15 gluon saturation at low x
8. May 19 proton tomography
9. May 22 recitation 2
10. May 26 the quark model and surprizes in hadron structure

part 2

11. May 29 the structure of atomic nuclei
12. June 2 the chart of nuclides
13. June 5 recitation 2
14. June 9 nuclear structure near the drip lines
15. June 12 element formation in stars, from H and He to Fe
16. June 16 heavy element production, the r and s process
17. June 19 recitation 3
18. June 23 super-nova explosions and heavy element production
19. June 26 the structure of neutron stars
20. June 30 neutron star mergers
21. July 3 recitation 4

Outline of the lecture

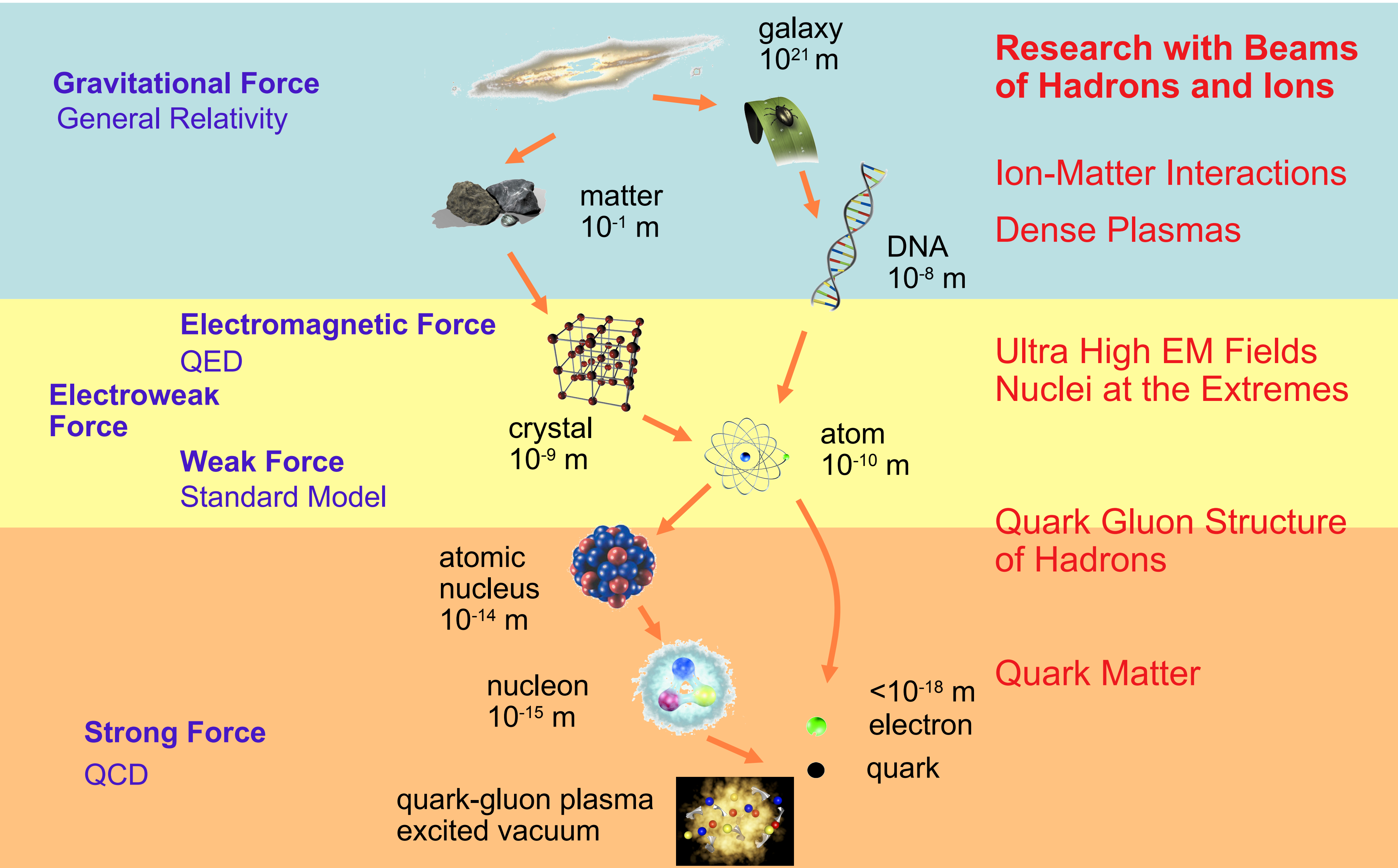
part 3

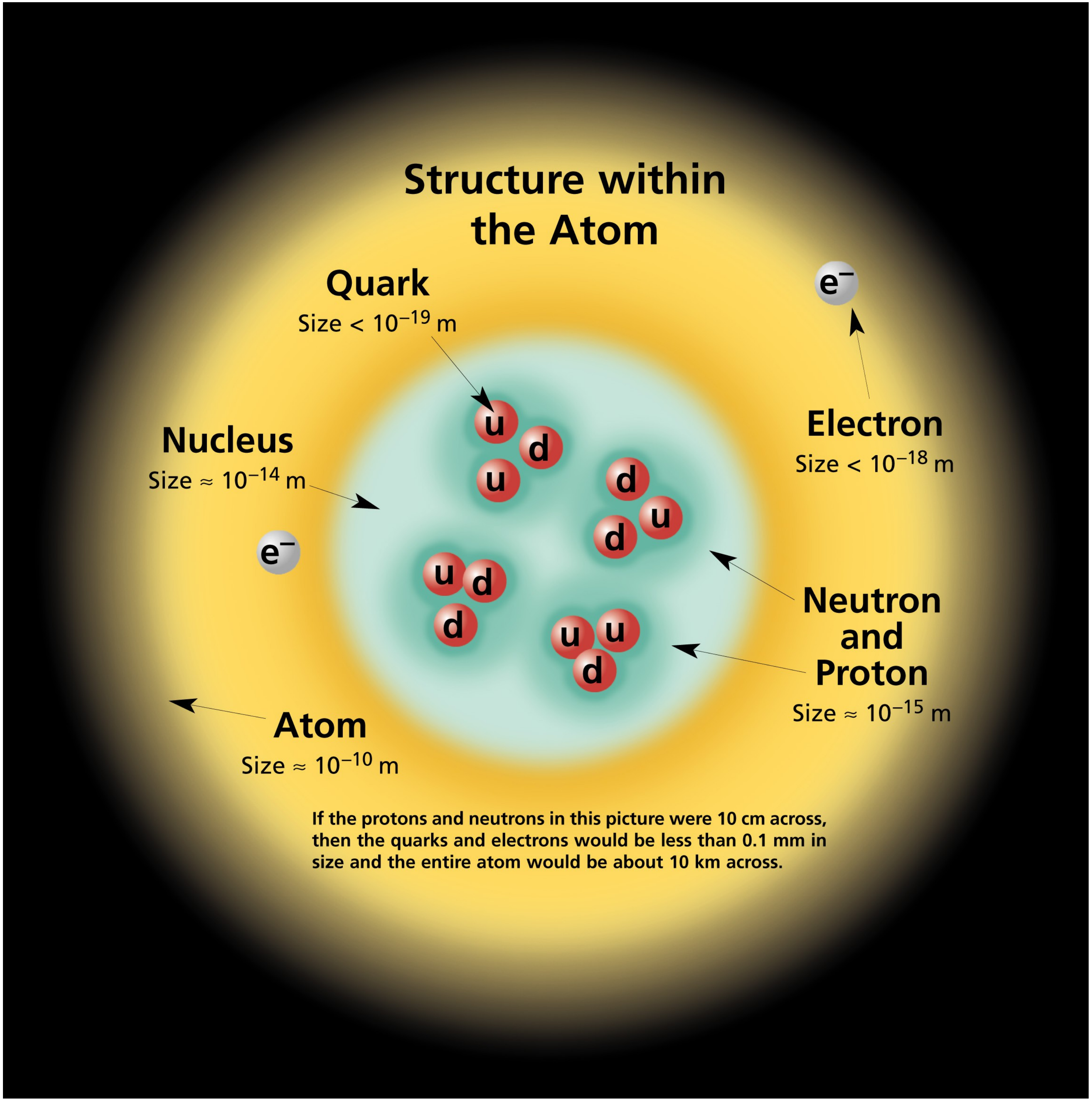
22. July 7 collisions of relativistic nuclei
23. July 10 hadron production and the phase diagram of QCD
24. July 14 the equation of state of the quark-gluon plasma
25. July 17 recitation 5
26. July 21 charmonium production and deconfinement of quarks
27. July 24 phase transitions in the early universe

Lect. 1

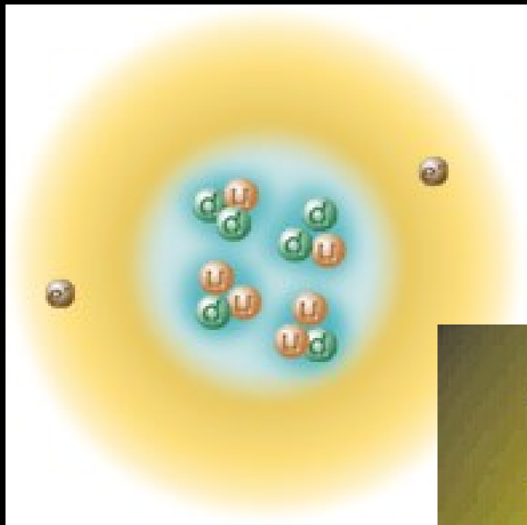
- Historical remarks
- Orders of magnitude
- 'Natural' units $\hbar = c = 1$
- Some non-relativistic and relativistic kinematics
- Survey of interactions

Structure of Matter

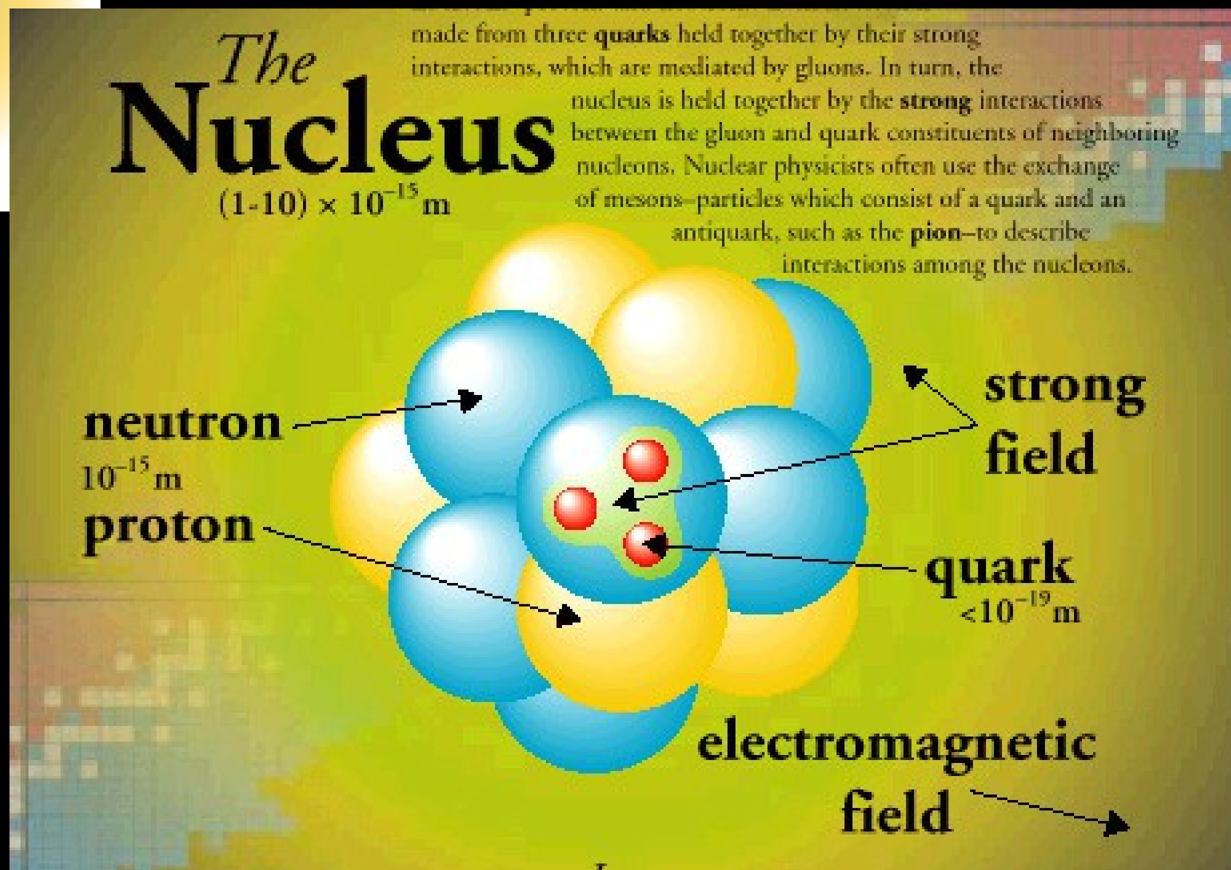




Structure within the Atom
Quark
Size < 10^{-19} m
e⁻
Electron
Size < 10^{-18} m
Nucleus
Size ≈ 10^{-14} m
u
d
u
d
u
d
e⁻
u
d
d
u
u
d
Neutron and Proton
Size ≈ 10^{-15} m
Atom
Size ≈ 10^{-10} m
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.



d u d
d d u
u d u
u u d



The Nucleus
(1-10) × 10^-15 m
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.
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}
3 lepton masses m_e, m_μ, m_τ
3 neutrino masses

note: $m_\gamma = m_g = 0$

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

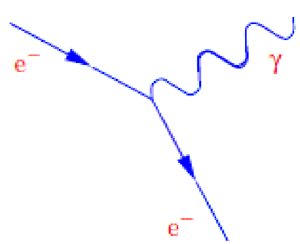
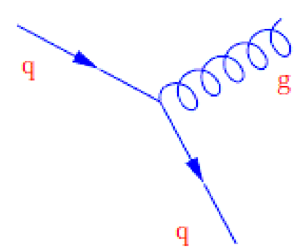
4 electroweak mixing parameters (lept.) θ_1 θ_2 θ_3 δ

mixing angles CP-viol. param.

4 electroweak mixing parameters (neutr.)

+ Λ_{QCD}

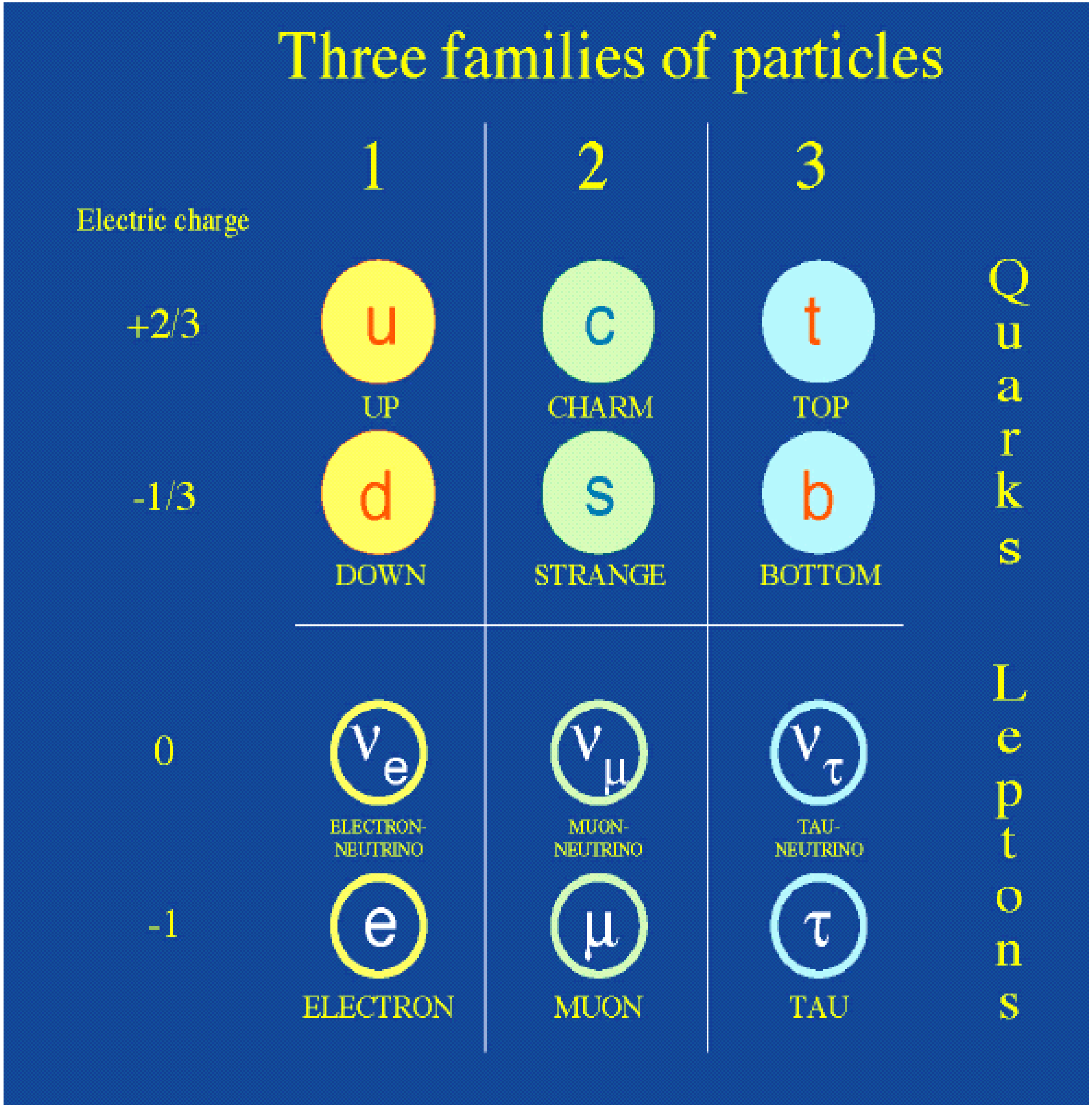
26 external parameters

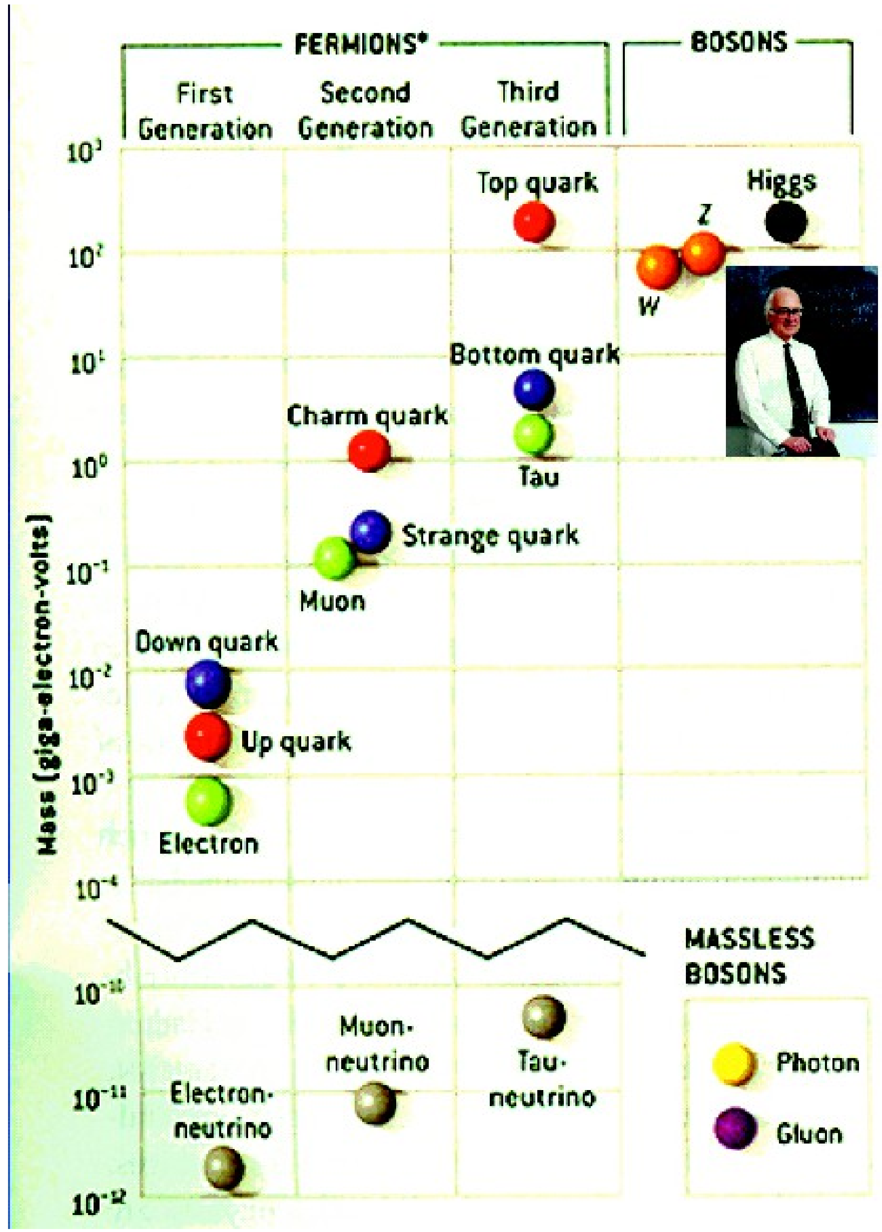
QED	QCD
Gauge symmetry $U(1)_{EM}$	Gauge symmetry $SU(3)_{COL}$
Electric charge e	Colour charge (r, g, b)
1 Massless Gauge Boson (Photon)	8 Massless Gauge Bosons (Gluons)
Photon carries no electric charge (no self-interaction)	Gluons carry colour charge (self-interact)
Basic Vertex (Bremsstrahlung)	Basic 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
νe
ELECTRON-NEUTRINO
νμ
MUON-NEUTRINO
ντ
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

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	$1\text{–}5 \times 10^{-3}$	2/3	0	0	0	0
e^-	0.511	−1	1	0	0	d	$3\text{–}9 \times 10^{-3}$	−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	$75\text{–}170 \times 10^{-3}$	−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
$\bar{\mathbf{p}}$	antiproton	$\bar{\mathbf{u}}\bar{\mathbf{u}}\bar{\mathbf{d}}$	–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

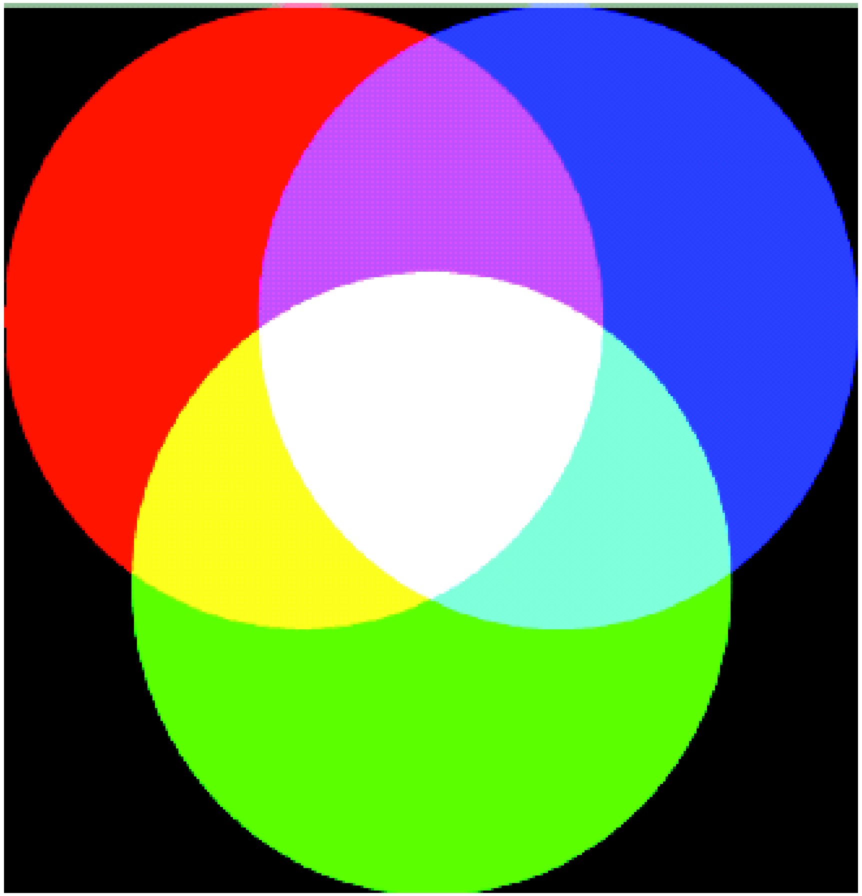
Mesons $q\bar{q}$

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

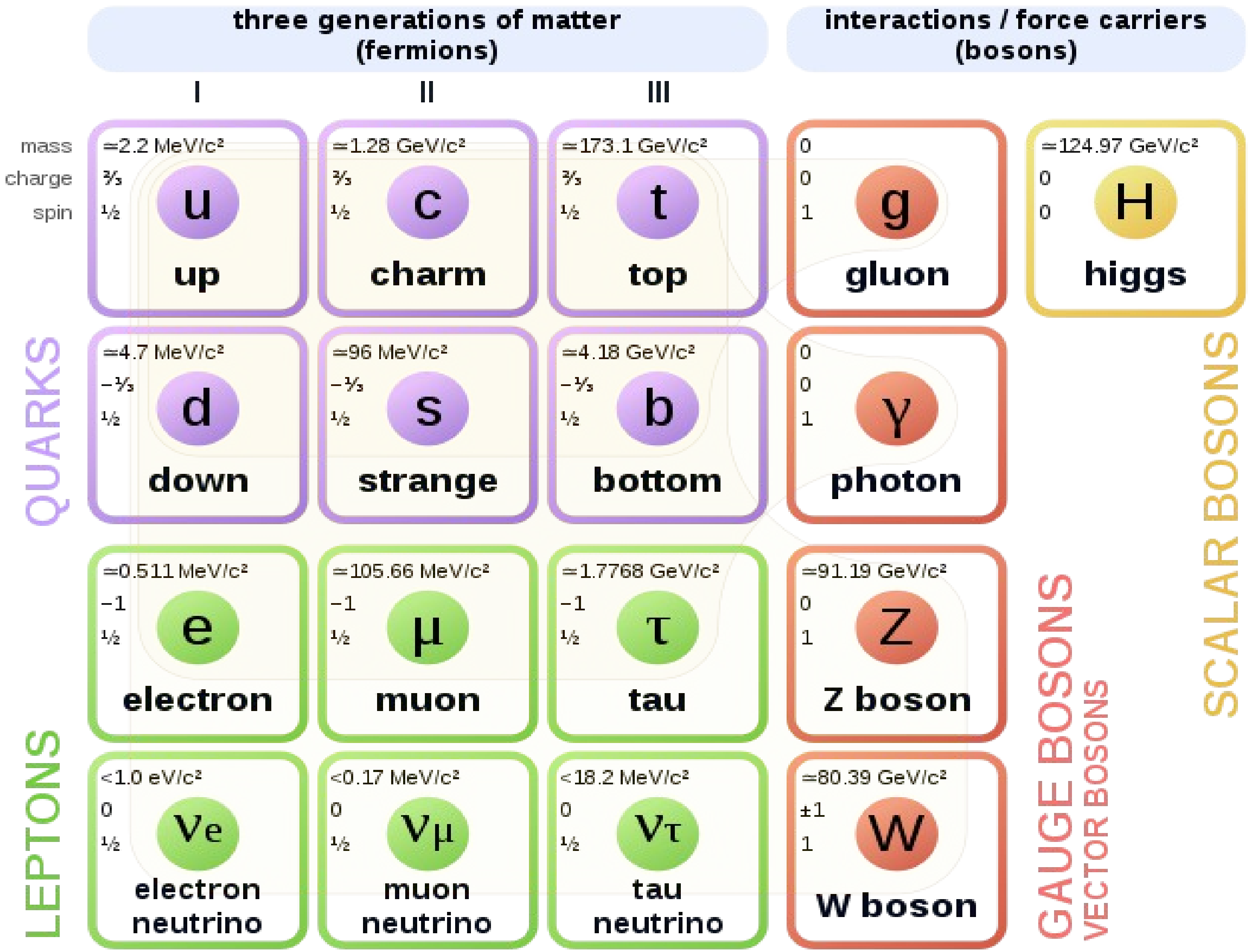


Properties of the Interactions

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 (Electroweak)	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

Standard Model of Elementary Particles



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	$\sim 10^{-3}$	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	$\sim 10^{-5}$	BOSONS Z^{0}, W^{+}, W^{-} (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES

Phenomenology of Collisions at High Energy

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

relativistic Kinematics

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

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

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 $\vec{\beta}_f$

center of mass energy ! $\sqrt{s}$

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

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

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 · fm ≈ 200 MeV · 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 $\Rightarrow$ multiply with $(\hbar c)^2$

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

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