# *Particle physics: lecture 1*

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# Lecturer and coordinates

- I am a high energy particle experimentalist working at the Large Hadron Collider (LHC) at CERN, near Geneva.
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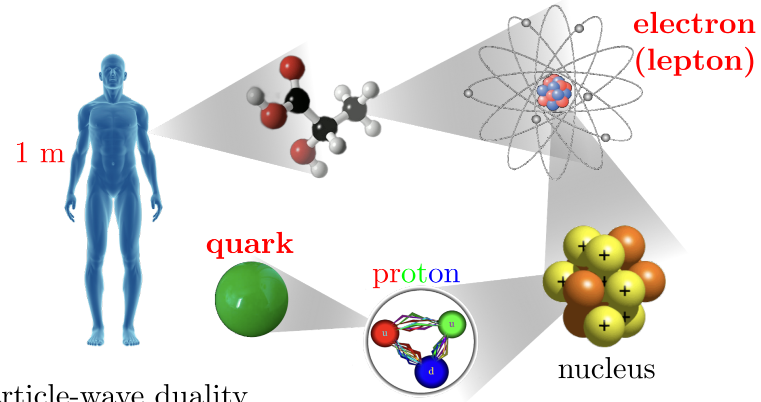
# Schedule and references

- Course page:
  http://bodri.elte.hu/∼giordano/partphys/index.html
- This week's schedule:
  - Lecture 1 (13th Sept): introduction to elementary particles
  - Lecture 2 (15th Sept): introduction to particle detectors
  - Lecture 3 (16th Sept): relativistic kinematics and exercises
- Introductory books:
  - D. Griffiths, *Introduction to Elementary Particles*
  - D. H. Perkins, *Introduction to High Energy Physics*

# What is elementary particle physics?

- Fundamental/indivisible constituents of matter.
- Understand their interactions $\Rightarrow$ biology, chemistry (in principle!).




particle-wave duality
top quark probes physics at $\sim 10^{-21}$ m

# Scales and elementarity

- What is "elementary" depends on the energy/length scale you are probing. Uncertainty principle: $\Delta x \sim \hbar/\Delta p$
    - Newtonian planetary motion: earth is point-like
    - Nuclear physics (NP): protons and neutrons
    - High energy physics (HEP): quarks and leptons (no known sub-structure yet)
- We will revisit the concept of effective-elementarity/range-of-interaction/degrees-of-freedom several times during this course.
- Nice website for a perspective: `https://scaleofuniverse.com`

# Natural units

- In HEP, it's convenient to use *natural units*, that set the values of physical constants to unity:

$$\boxed{\hbar = c = \varepsilon_0 = k = 1}$$

- Redefine all other units in terms of energy.
- Electron volt (eV): energy acquired by an electron accelerated over a potential of 1V. (MeV, GeV, TeV, ...).
- Mass and momentum $\propto E$ ($E = mc^2$).
- Length and time $\propto E^{-1}$ ($E = h\nu$).

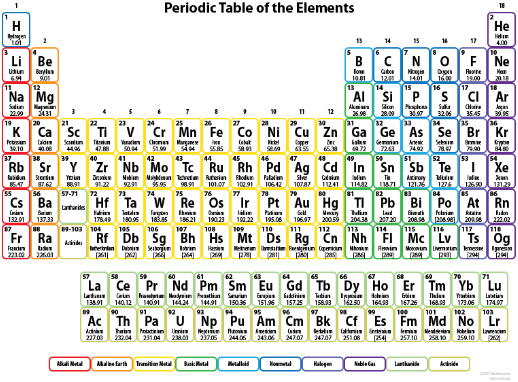
# Natural units (cont.)

- Connection with SI units: $\hbar c \sim 197$ MeV-fm.
- 1 Fermi (proton radius) $\sim 10^{-15}$ m $\sim \frac{1}{5}$ GeV$^{-1}$.
- Proton/neutron masses $\sim 1$ GeV.
- Electron mass is $\sim 0.5$ MeV.
- Charge (Coulomb) is redefined by choosing $\varepsilon_0 = 1$.
- Fine-structure constant $\alpha = \frac{1}{137} = \frac{e^2}{4\pi\varepsilon_0\hbar c} = \frac{e^2}{4\pi}$. Charge is dimensionless ($e = \sqrt{4\pi\alpha} \sim 0.3$).
- Temperature: $kT = E$ (Boltzmann const.). 1 GeV $\sim 1.16 \times 10^{16}$ K.

# Brief history: birth of particle physics

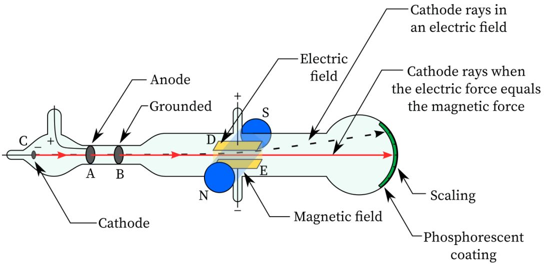
- What are we made of: a philosophical question for the ages.
- First scientific breakthrough was early 19th century chemist, John Dalton's "law of multiple proportions".
- One unit carbon and one unit oxygen makes CO. Two units of oxygen makes $CO_2$, ... theory of atoms ("indivisible" in Greek).

- Mendelev's periodic table (1869): each element has an integral atomic number ($Z$) and non-integral atomic weight ($A$).




- Pattern linked to the fact that atoms are very much "divisible", with internal structure.

# Electron: first sub-atomic particle

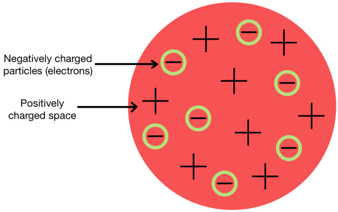



- 1897 *electron* ($e$), J. J. Thomson
- Cathode rays: negatively charged.

- Using perpendicular crossed electric and magnetic fields, tuned so that the stream was undeflected, $v/c = E/B$
- From the deflection in the presence of the electric field only, determined their charge-to-mass ratio
- Further, $m/e$ less than thousand times smaller than hydrogen ions.

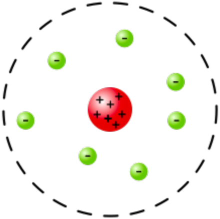
# Inside the nucleus

Thomson's
apple plum model




$\Rightarrow$

Rutherford's
planetary model



- 1908-1917: *proton* ($p$), E. Rutherford, H. Geiger, E. Marsden *et al.*
- planetary model of the atom: electrons orbiting around a positively charged *nucleus* containing almost all the mass
- each positive charge = one hydrogen nucleus = proton
- 1932: *neutron* ($n$), J. Chadwick
- mismatch between mass and charge of the nucleus
- fixed by neutron: neutral but essentially same mass as proton

# Meanwhile...radiation

1905: *photons* ($\gamma$), M. Planck, A. Einstein, *et al.*

- In subatomic processes, EM radiation comprises neutral, massless particles.
- Birth of quantum theory: $E \propto$ radiation frequency (photons)
- Only way to explain photoelectric effect (Einstein, 1905) and the scattering of light on particles at rest (Compton, 1926)
- *EM interaction* $\sim$ exchange of a stream of photons between electrically charged objects.

# Strong interactions: $\pi$-meson or pion

- Recall: Rutherford's gold-foil experiments showed a densely packed nuclear core.

  Q. How do protons (and neutrons) stay together in nuclei?

  A. *Strong interaction*: strong (overcome EM repulsion among protons), short-ranged (no macroscopic effects)

1934, H. Yukawa: strong interaction mediated by a new particle – the $\pi$-*meson* – in analogy with EM and the photon

- proton and neutron $\in$ *baryons*; baryons and mesons $\in$ *hadrons*
- estimate of mass from range of force $\sim 1/6$ of proton mass

1936: new particle, right mass found in cosmic rays by Anderson & Neddermeyer…but *not* Yukawa's meson!...

# Muons: "Who ordered that?"

1946-47 Powell, Lattes, Occhialini: *two* new particles in cosmic rays

- heavier one, shorter lifetime, disintegrated almost entirely in the upper atmosphere – the *pion* ($\pi$), the true Yukawa meson
- lighter one, longer lifetime, originally identified with the meson but interacts little with nuclei – the muon ($\mu$), into which the pion decays
- muon was not expected (I. Rabi: "Who ordered that?"): sort of heavier electron, grouped with it in the family of *leptons*

# Antiparticles

Theory:

1928-1931, P. A. M. Dirac: relativistic quantum mechanics predicts that to each particle corresponds its *antiparticle*: same mass but opposite electrical (and other) charge(s).
1928-1931, W. Pauli: AHAHAHAH LOL

Experiment:

- 1932: *positron*, C. D. Anderson
- 1955: *antiproton*, E. Segrè & O. Chamberlain
- 1955: *antineutron*, B. Cork

Some particles, like the photon, are their own antiparticles; electric neutrality is however a necessary but not sufficient condition

# Weak decays: the ghostly neutrino(s)

- Unstable nuclei undergo radioactive $\beta$-decay: $n \to p + e^-(+X)$.
- Problem was, this seemed to break momentum conservation.
- W. Pauli in 1930: additional neutral, very weakly interacting, almost massless particle is also emitted $\Rightarrow$ neutrino.
- Very hard to detect. 1956 Reines & Cowan: first observation
- 1950s-1960s: several experiments show
  - neutrino ($\nu$) $\neq$ antineutrino ($\bar{\nu}$)
  - two types of neutrinos, one corresponding to the electron ($\nu_e$), one corresponding to the muon ($\nu_\mu$), and respective antineutrinos ($\bar{\nu}_e, \bar{\nu}_\mu$)

# Strangeness and the hadron "zoo"

1947: kaon ($K$), G. D. Rochester & C. C. Butler

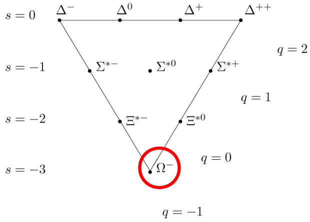
- Hadron of the meson subfamily, mass intermediate between $\pi$ and $p$
- "Strange" particle: created via strong interactions, decays slowly via weak interactions
- pre-1960: Hundreds of strongly interacting hadrons (strange and non-strange) found experimentally in the following years: the hadron "zoo"
- Clear that they were not all elementary, but underlying pattern unclear.

# The quark model

1964, Gell-Mann, Zweig: *quark model*

- Mesons and baryons not elementary but bound states of *quarks* and *antiquarks* – "more fundamental" particles
  - meson = quark+antiquark,
  - baryon = three quarks, antibaryon = three antiquarks

- Three types: *up* ($u$), *down* ($d$), and *strange* ($s$). Fractional charges. Has a property called "color".
- Neatly accommodates the hadron zoo spectra, predicts the $\Omega^-$ baryon (obs. 1964).




- Quarks as real objects (and not just a model) accepted only after discovery of the fourth quark: 1974, $J/\psi$ meson and *charm* quark ($c$), B. Richter *et al.*; S. Ting *et al.*

# The Standard Model: matter

From here on:

- 1975: tau lepton ($\tau$), M. Perl *et al.*, corresponding neutrino immediately theorised
- 1977: *bottom* or *beauty* quark ($b$), L. Lederman *et al.*, sixth quark immediately theorised
- 1995: *top* or *truth* ($t$) quark, CDF and DØ experiments at Fermilab
- 2000: $\nu_\tau$, DONUT experiment at Fermilab

Six quarks, six leptons and corresponding antiparticles = *matter particles*

# The Standard Model: interactions

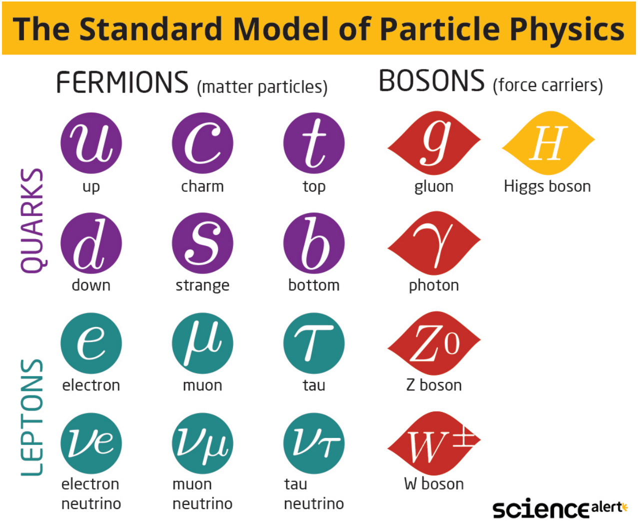
Weak and strong interactions modeled like the photon for EM.

- Mediator role of pion taken over by *gluons* ($g$), interactions described by Quantum Chromodynamics (QCD)
- Weak interactions mediated by *intermediate vector bosons*: $W$ (charged) and $Z$ (neutral), (1983, UA1 and UA2 experiments at CERN)
- Remaining problems fixed by *Higgs boson* ($H$), (2012, ATLAS and CMS experiments at CERN)
- Weak interactions unified with EM: Glashow-Salam-Weinberg model
- GSW+QCD= *Standard Model* of particle physics


- What properties uniquely identify particles – both elementary (electron) or composite (proton).
- Mass, type of interaction (strong, weak, EM) and charge
- + need several other "quantum numbers", in particular spin and parity. Lead to selection rules for decays.

# Spin and parity

- Spin ($\vec{S}$): rotational symmetry; Parity ($P$): mirror symmetry.
- Note: weak interaction breaks parity symmetry. Strong interaction preserves parity.
- Half-integer spin particles are called fermions (quarks + leptons).
- Spin-statistic theorem, 1940, W. Pauli: no two identical fermions can occupy the same quantum state. Holds up neutrons stars.
- Integer-spin particles are called bosons (photons). Identical particles can form Bose-Einstein Condensates.




- Other than gravity (a big problem!)...SM includes everything we currently understand about Nature.

# Matter particles: flavor sector

- All spin-$\frac{1}{2}$ fermions: *quarks* (interact strongly) and *leptons* ($e, \mu, \tau$ and neutrinos, do not interact strongly)

- To each particle $\rightarrow$ antiparticle with same mass and spin, and
  - opposite charge for charged particles (quarks, $e, \mu, \tau$)
  - opposite helicities (spin component in the direction of motion) for $\nu$

- Three *families* (or *generations*): hierarchical from lighter to heavier $[(u, d); (e, \nu_e)]$, $[(c, s); (\mu, \nu_\mu)]$, $[(t, b); (\tau, \nu_\tau)]$

- Masses span five orders of magnitude: $m_e = 0.5$ MeV, $m_t = 170$ MeV (and possibly more, since $m_\nu$ are small but yet unknown)

- Understanding *why* we have this structure: "flavor problem"

# Interaction particles: gauge sector

- All spin-1 bosons
- photon, $\gamma$: $m_\gamma = 0$, electrically neutral (i.e., it does not self-interact); mediates the electromagnetic interactions
- IVB, $W^\pm$ and $Z$: $m \neq 0$, $W$s electrically charged while $Z$ neutral; mediate the weak interactions;
- gluons, $g$: $m_g = 0$, electrically neutral; mediate the strong interactions
- IVB interact with each other and self-interact; $g$ interact with each other and self-interact; IVB and $g$ do not interact with each other

Bonus particle: Higgs boson $H$

- spin 0, massive, electrically neutral
- essentially provides mass to all other elementary particles
- interacts with IVB but not with the photon or with the gluons (hence these are massless)

*Graviton* ($G$): hypothetical quantum of gravitational interactions, not observed yet

# Building up hadronic matter

- Quarks are coloured objects. So $|u\rangle \Rightarrow |u\rangle + |u\rangle + |u\rangle$.
- Color confinement: stable objects (hadrons) are colour neutral. We never see free quarks in Nature.
- Note: antiquarks have opposite colour and parity, as quarks. Quark-antiquark $\Rightarrow$ colorless.
- Multi-particle system also has an orbital angular momentum ($\vec{L}$).
- Total angular momentum $\vec{J} = \vec{L} + \vec{S}$.
- All hadrons will have some value of $J^P$ that identifies it.

# Building up hadrons: mesons

$$\boxed{\text{Meson} \approx q\bar{q}}$$

- lightest mesons (also lightest hadrons): pions $\pi^-$,$\pi^0$,$\pi^+$
  - $m_\pi \approx 140$ MeV ($m_{\pi^0} < m_{\pi^\pm}$)
  - built from lightest quarks and antiquarks: $u$, $d$, $\bar{u}$ and $\bar{d}$
  - bound states with total quark spin $S_q = 0$ and orbital angular momentum $L_q = 0 \rightarrow$ pion spin $J = 0$
- meson state depends on $S_q$ and $L_q$ of $q\bar{q}$, so same quark content $\not\Longrightarrow$ same meson
  - $\rho$ mesons have the same quark content of the pions, but in a combination with $S_q = 1$ and $L_q = 0 \rightarrow \rho$ spin $J = 1$
- meson state depends on quark content
  - kaons $K$ (contain a strange quark)
  - $J/\psi$ ($|c\bar{c}\rangle$ state)

# Building up hadrons: baryons

$$\boxed{\text{Baryon} \approx qqq}$$

- lightest baryons: proton ($uud$), neutron ($udd$)
  - $m_{p,n} \approx 1$ GeV, $m_n > m_p$, with $|m_n - m_p|/m_p \ll 1$
  - $n$ decays into $p$ via $\beta$ decay, $p$ is stable
- $p$ is stable since lightest baryon: *baryon number* (number of baryons minus number of antibaryons) is conserved, $p$ cannot decay into anything $\rightarrow$ stability of ordinary matter
- no conserved meson number; in fact, even the pion is not stable and decays (mostly) into a muon and a muonic antineutrino
- heavier baryons exist with the same quark content but in different spin/orbital angular momentum states, and/or with different quark content
  - $\Delta^+$ and $\Delta^0$ have same quark content as $p$ and $n$ but $J = \frac{3}{2}$
  - $\Lambda = |uds\rangle$

| meson | quark content | spin | charge | mass |
|---|---|---|---|---|
| $\pi^+$ | $u\bar{d}$ | 0 | +1 | 135MeV |
| $\pi^-$ | $d\bar{u}$ | 0 | −1 | 140MeV |
| $\pi^0$ | $u\bar{u}, d\bar{d}$ | 0 | 0 | 140MeV |
| $\rho^+$ | $u\bar{d}$ | 1 | +1 | 775MeV |
| $\rho^-$ | $d\bar{u}$ | 1 | −1 | 775MeV |
| $\rho^0$ | $u\bar{u}, d\bar{d}$ | 1 | 0 | 775MeV |
| $K^+$ | $u\bar{s}$ | 0 | +1 | 494MeV |
| $K^-$ | $s\bar{u}$ | 0 | −1 | 494MeV |
| $K^0$ | $d\bar{s}$ | 0 | 0 | 498MeV |
| $\bar{K}^0$ | $s\bar{d}$ | 0 | 0 | 498MeV |
| $J/\psi$ | $c\bar{c}$ | 1 | 0 | 3.1GeV |

| baryon | quark content | spin | charge | mass |
|---|---|---|---|---|
| $p$ | $uud$ | $\frac{1}{2}$ | +1 | 0.938GeV |
| $n$ | $udd$ | $\frac{1}{2}$ | +1 | 0.940GeV |
| $\Delta^+$ | $uud$ | $\frac{3}{2}$ | +1 | 1.232GeV |
| $\Delta^0$ | $udd$ | $\frac{3}{2}$ | +1 | 1.232GeV |
| $\Lambda$ | $uds$ | $\frac{1}{2}$ | 0 | 1.1GeV |

# Particle Data Group (PDG)

- Most up-do-date reference: `https://pdglive.lbl.gov`