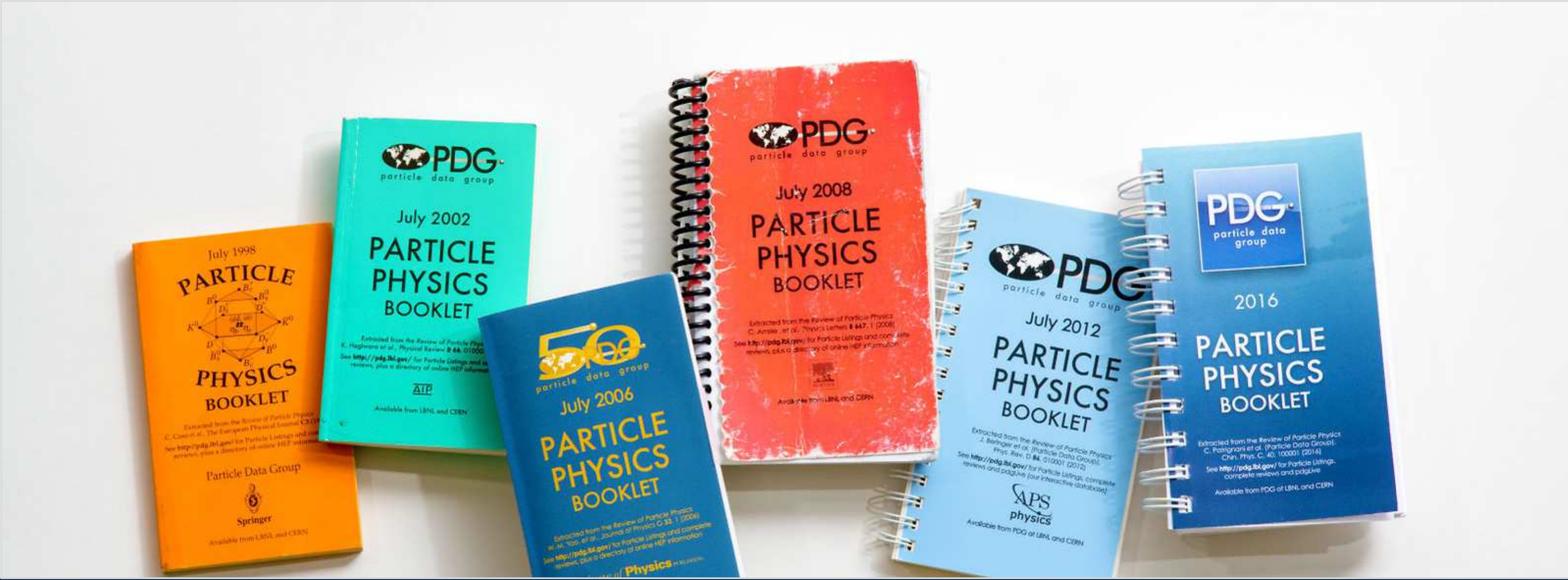


ELEMENTARY PARTICLE PHYSICS

THE FORCES OF NATURE (PART I)

MAY 2020 I HANS STRÖHER (FZ JÜLICH, UNIVERSITY OF COLOGNE)

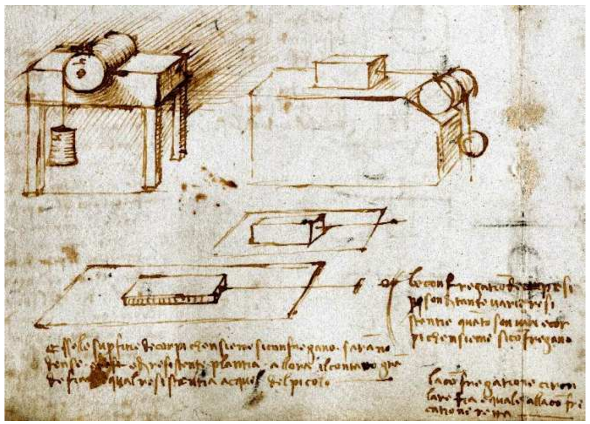
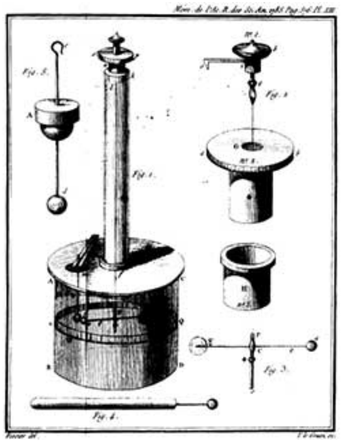
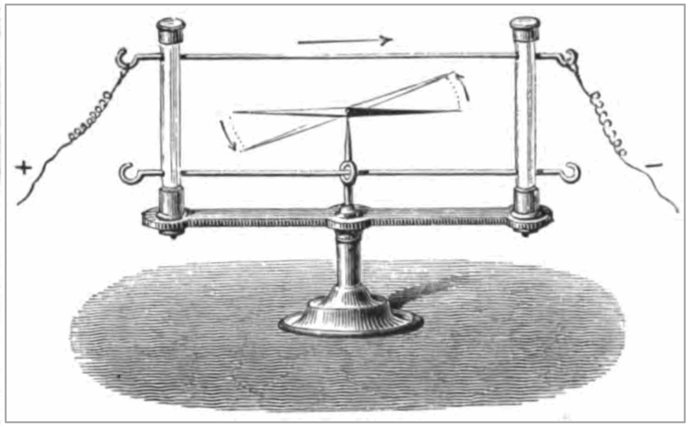
- Outline:
  - A brief **introduction** (history …)
  - The **tools** (accelerators, targets, detectors … kinematics, …)
  - The **particles** (hadrons, baryons, mesons …)
  - The ***fundamental* particles** (quarks, leptons)
  - The **forces** (gravitation, nuclear, weak forces)
  - The ***fundamental* interactions** (strong and electro-weak IA)
  - The **Standard Model** of EPP
  - Physics **Beyond the Standard Model** (BSM)
  - Spin-offs – **Applications** of EPP

THE FORCES

Prelude

History – the forces of daily life

- Gravitational force of the earth → Galileo Galilei
- Friction forces → Leonardo da Vinci
- Forces between charged objects → Charles-Augustin Coulomb
- Magnetism → Hans Christian Oersted

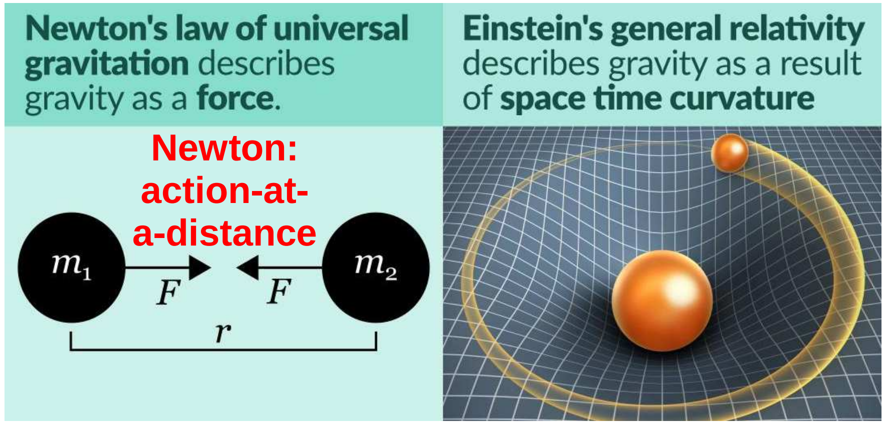





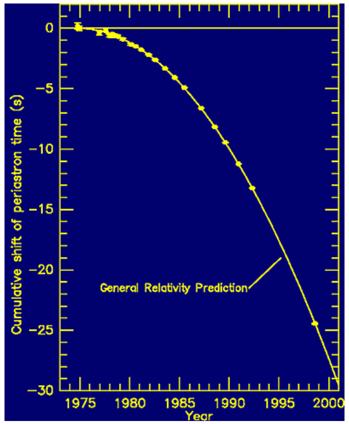
THE FORCES

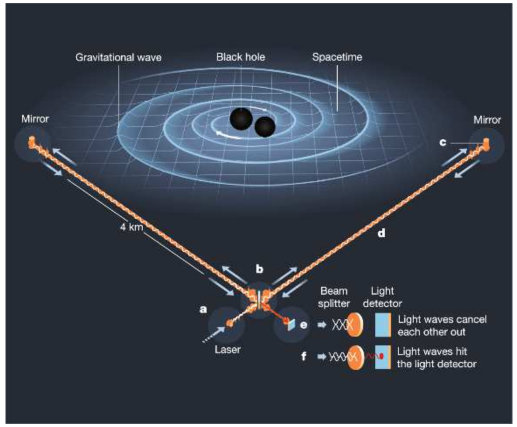
Prelude

Gravitational force – theories of Newton and Einstein

Gravity is the natural phenomenon that objects with mass or energy are attracted by each other. It is explained by the **law of universal gravitation** (Newton, 1686) and **general relativity** (Einstein, 1915):







→ GR predictions all experimentally verified, i.p. **gravitational waves** (2015)

<u>But:</u> inconsistent with quantum mechanics, …

THE FORCES

Prelude

Electromagnetic force – the Maxwell theory

Electromagnetism united the natural phenomena of electricity and magnetism (Maxwell, 1861/62); in the **electric** and **magnetic field** formulation there are four equations that determine the fields for given charge and current distribution:

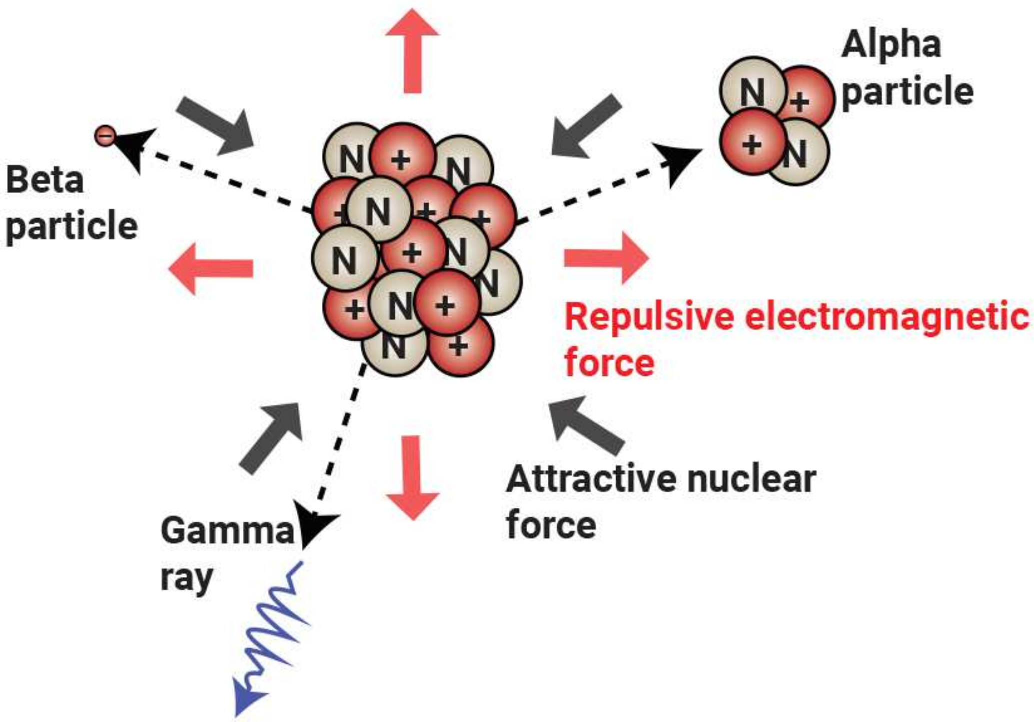
- Gauß´s law
- Gauß´s law for magnetism
- Faraday´s law of induction
- Ampere´s law with Maxwell´s addition

A separate law of nature, the **Lorentz force** law, describes how the electric and magnetic fields act on charged particles and currents. Maxwell´s eq.: existence of **electromagnetic waves** – first demonstrated by H. Hertz (1887)

→ Quantum Electrodynamics (QED) → Part II

THE FORCES

New Forces

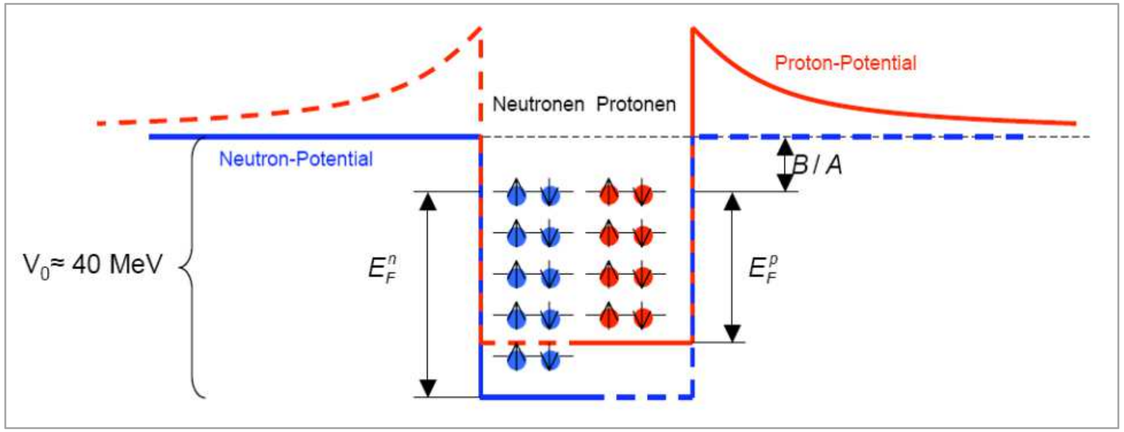


THE FORCES

New Forces

Nuclear force – binding and stability of nuclei (I)

From an energy point-of-view, protons and neutrons can be thought to fill potentials up to the **Fermi-energy** – which must be the same, since other-wise a corresponding decay would occur; it also implies that more neutrons are needed to stabilize a nucleus:

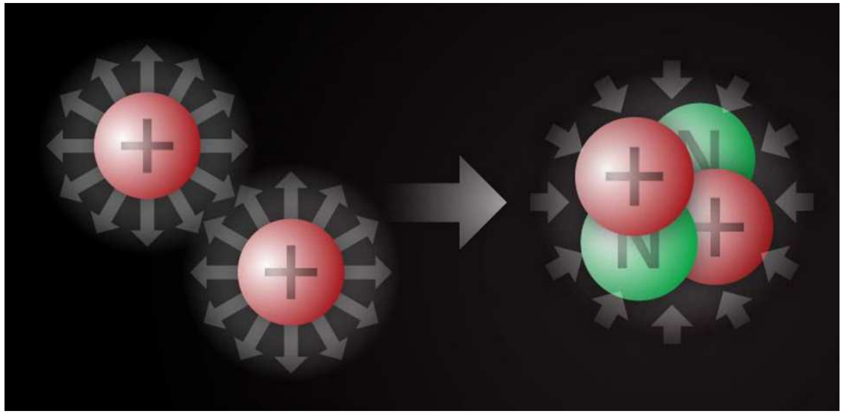


THE FORCES

New Forces

Nuclear force – binding and stability of nuclei (II)

Electric charges of like sign repell each other – in order to compensate the strong repulsion of protons inside nuclei, a new force (“strong nuclear force”) is required to stabilize them:



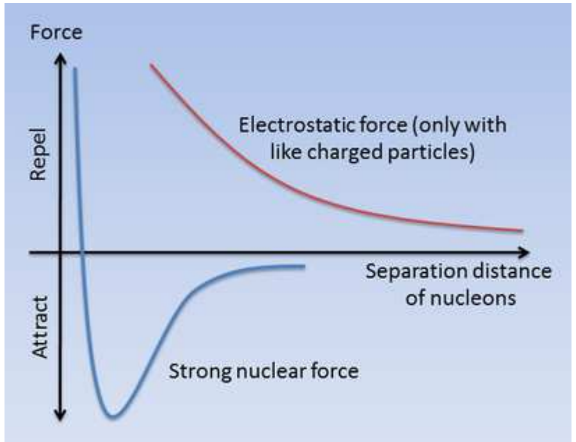
It acts between protons and neutrons (largely charge-independent) and it is also called the “**nucleon-nucleon force**” (NN-interaction)

THE FORCES

New Forces

Nuclear force – binding and stability of nuclei (III)

The nuclear force is **attractive** between nucleons at distances of about 1 fm (10^{-15} m), but it rapidly decreases to insignificance at distances beyond about 2.5 fm. At distances less than 0.7 fm, the nuclear force becomes **repulsive**:



… because of its range, the nuclear force is essentially a two-body (NN) interaction

The repulsive component is responsible for the physical **size and density of nuclei**, since the nucleons can come no closer than the force allows.

THE FORCES

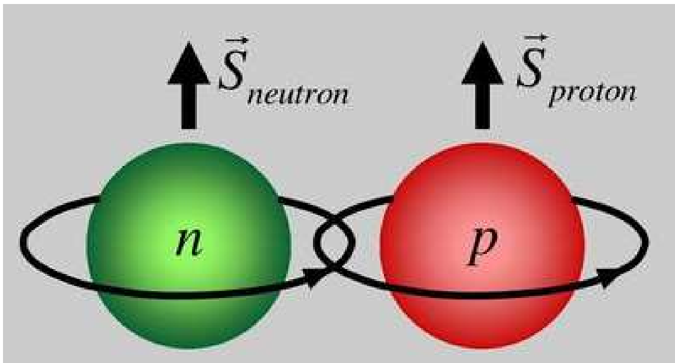
New Forces

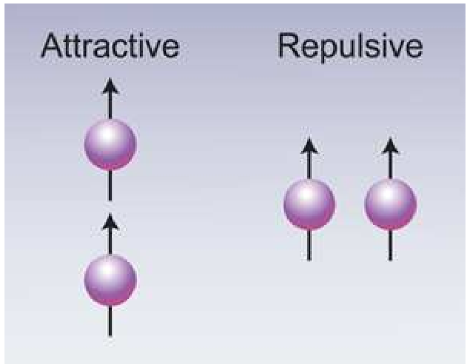
Nuclear force – binding and stability of nuclei (IV)

The nuclear force is complex, since for example it depends on the nucleon spins: the force is **stronger for particles with their spins aligned** than for those with their spins anti-aligned:

Example: d

Note: the np-system with antiparallel spins is unbound





The nuclear force also has a **tensor component** which depends on the interaction between the nucleon spins and the angular momentum of the nucleons, leading to deformation from a simple spherical **shape**

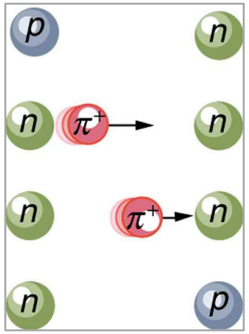
THE FORCES

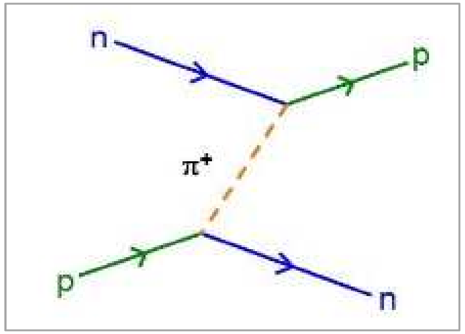
New Forces

Nuclear force – meson exchange model (Yukawa-picture) (I)

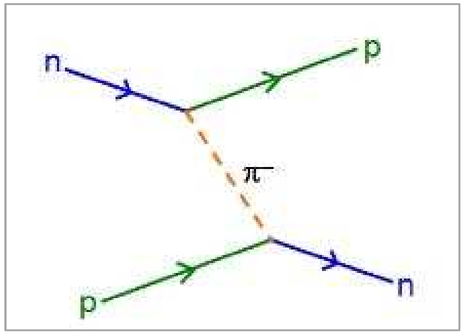
The nuclear force is created between nucleons by the **exchange of particles** called **mesons** (suggested in 1930´s by H. Yukawa):

Example: π^+-exchange





→also possible: π^--, π^0-exchange:



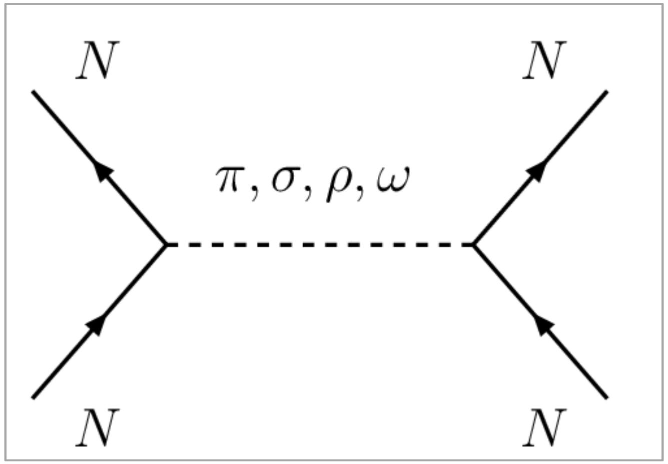
Feynman-diagrams

THE FORCES

New Forces

Nuclear force – meson exchange model (Yukawa-picture) (II)

It turns out that **pion-exchange** is not sufficient (describes only the long-range part); other mesons ($\sigma = \pi\pi$, ρ, ω) are required:



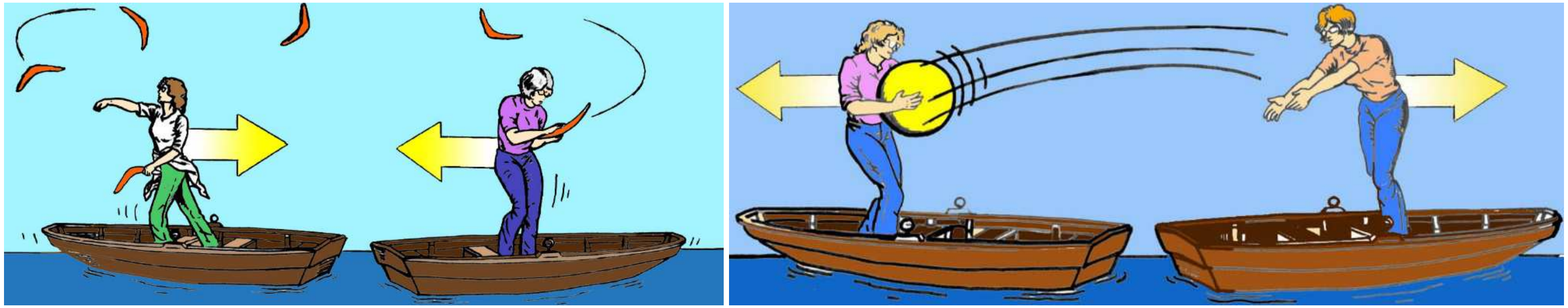
Note: The **range of the interaction** is related to the **mass of the exchange particle:** the heavier the particle, the shorter its interaction range

THE FORCES

New Forces

Nuclear force – meson exchange model (Yukawa-picture) (III)

The meson exchange model can lead to both **attraction** and **repulsion** (as indicated in this cartoon):



But: it is only a phenomenological description; the NN- (and the YN-, YY-) interaction is not fundamental, but it is the **residual force** of the **strong quark-quark interaction** (see later: “fundamental interactions”)

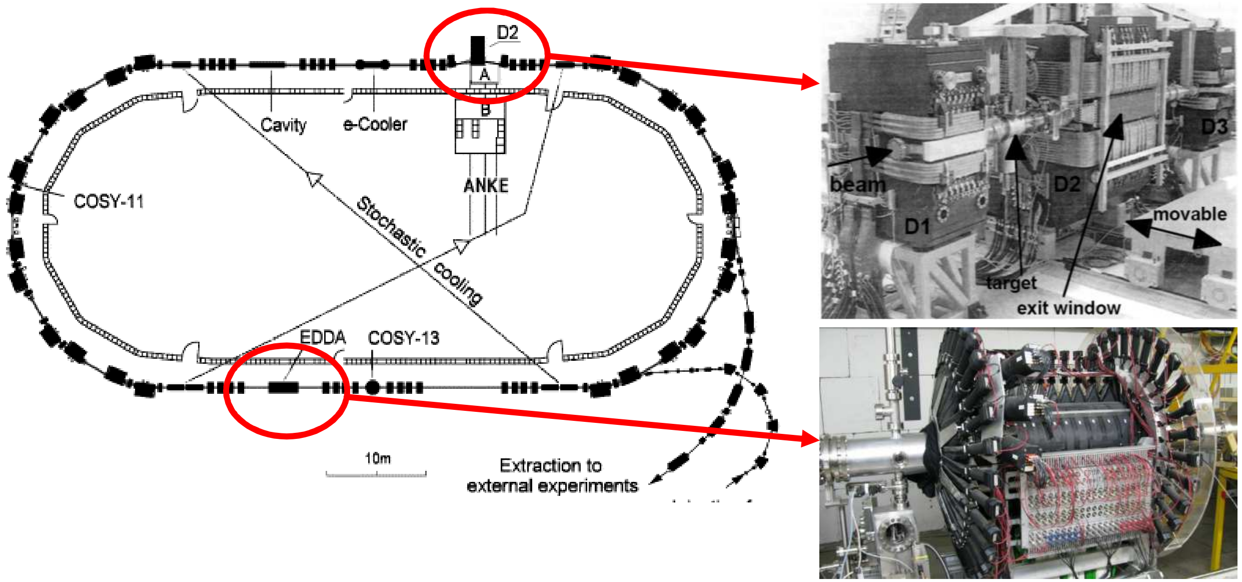
THE FORCES

New Forces

Nuclear force – experimental studies (I)

The nuclear force is studied in proton-proton and proton-neutron **scattering**; one can use **polarization** (of beam and/or target) to investigate it in great detail:

Example: COSY



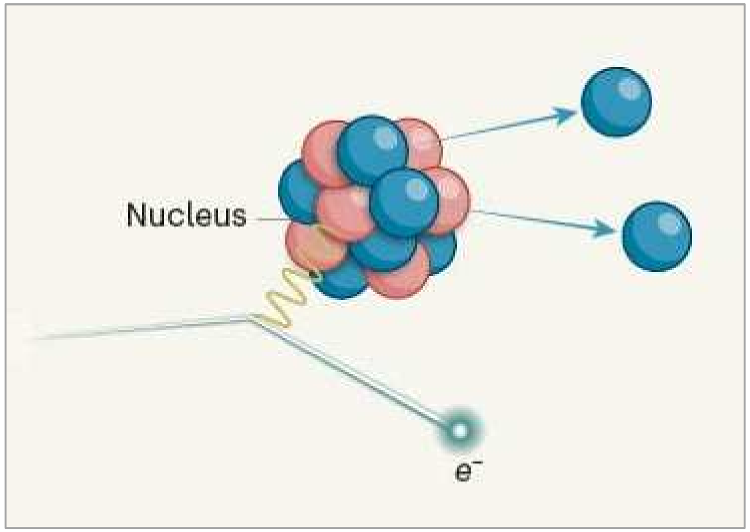
Result: a huge experimental data base of cross sections and single- and double polarization observables → phenomenology

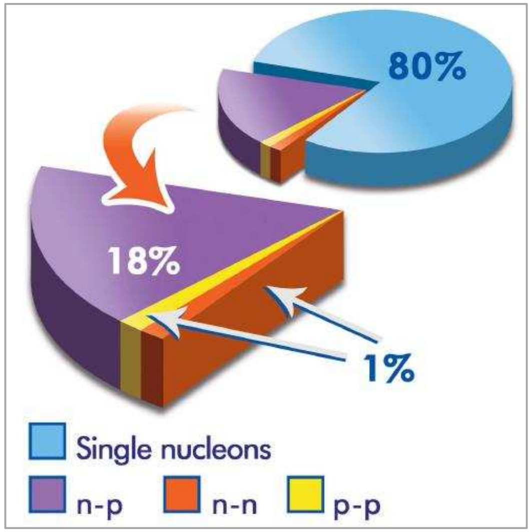
THE FORCES

New Forces

Nuclear force – experimental studies (II)

The protons and neutrons in a nucleus can form **strongly correlated nucleon pairs**:

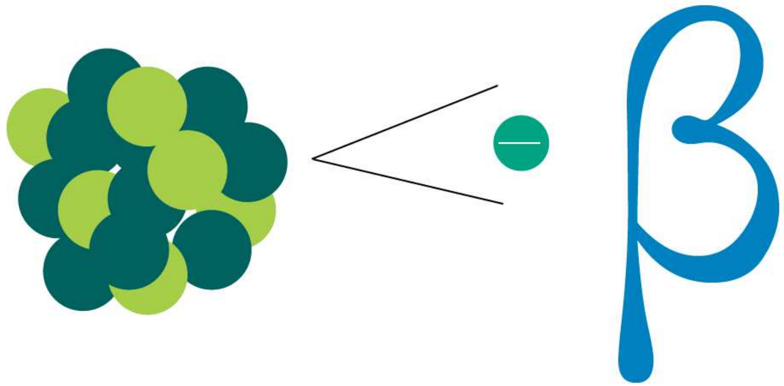




→ this is, e.g., studied in **electron scattering experiments** (Jlab, USA)

THE FORCES

New Forces

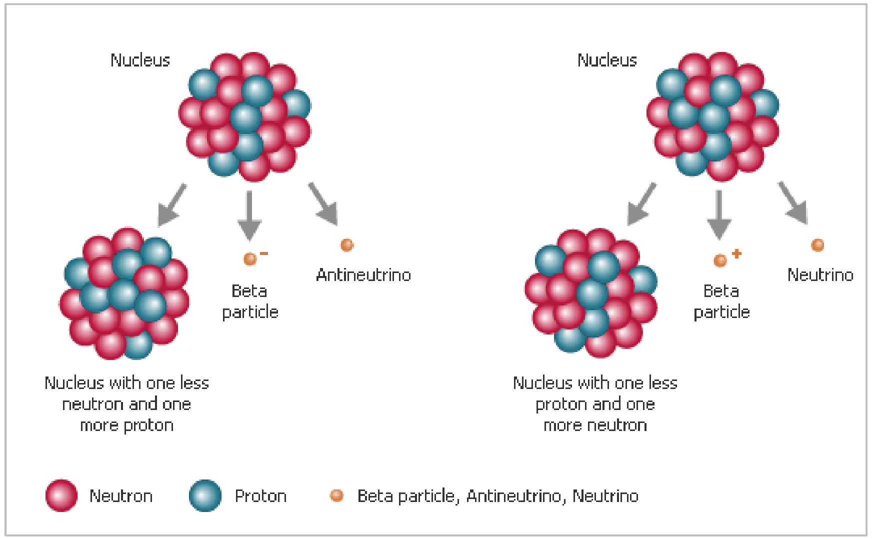


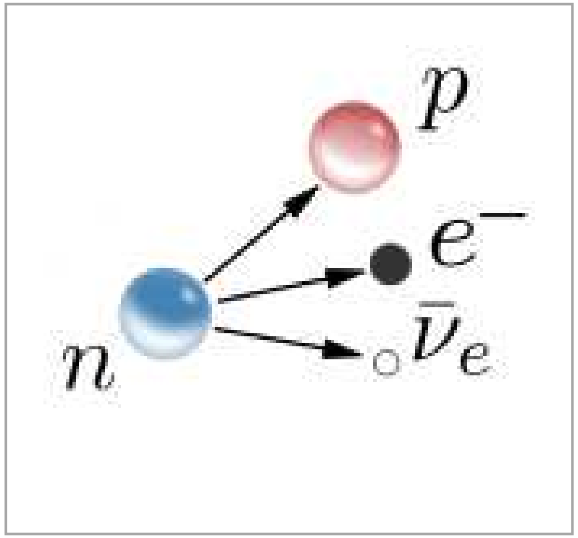
THE FORCES

New Forces

Weak force – nuclear beta-(β-) decay (I)

The weak force (weak nuclear force, weak interaction) is responsible for both a kind of **radioactive decay** and **nuclear fusion** of subatomic particles (e.g., in the sun). It was first observed in the slow process of nuclear β-decay (e^-; e^+ emission); the simplest one is the **free neutron decay**:



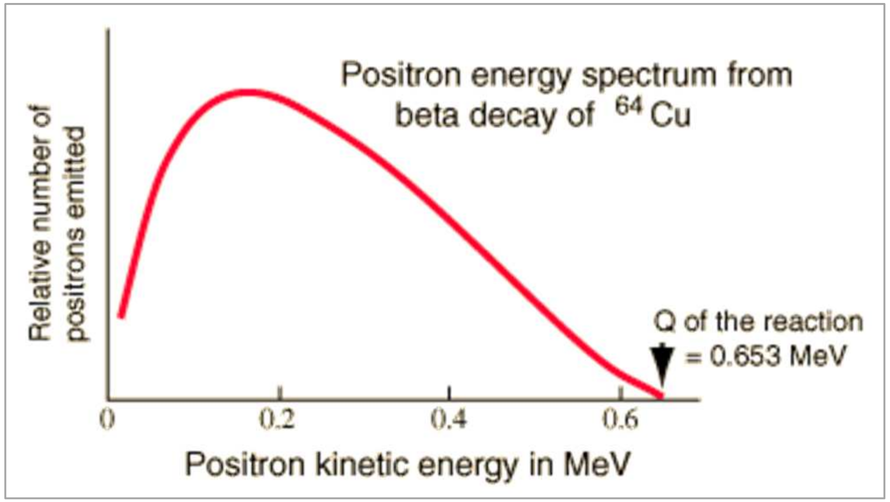


THE FORCES

New Forces

Weak force – nuclear beta-(β-) decay (II)

The nuclear β-decay results in a **continuous electron** (positron) energy distribution up to the maximum possible energy:



→ The decay is not a two-body but a **three-body decay** (the “invisible” 3rd particle is a(n) (anti-)**neutrino** (W. Pauli, 1930))

THE FORCES

New Forces

Weak force – classification of weak processes

The weak interaction is not restricted to β-decays – there is a surprising variety of effects :

(Purely) **leptonic** processes, e.g., muon decay $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

Semileptonic reactions, e.g., decay of the free neutron $n \rightarrow p + e^- + \bar{\nu}_e$

(Purely) **hadronic** reactions, e.g. decay of the Λ hyperon $\Lambda \rightarrow \pi^- + p$

Originally these (and other) reactions were assigned to the weak interaction because the corresponding **lifetimes were** too **long** to be due to the strong or the electromagnetic interaction (typically $<10^{-15}$ s).

THE FORCES

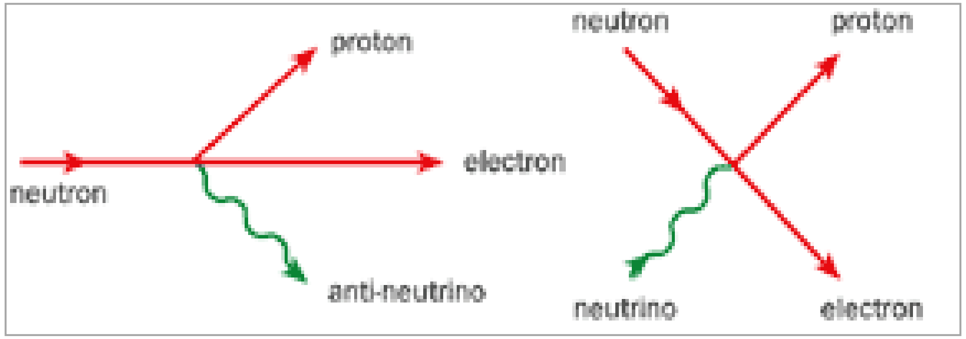
New Forces

Weak force – Fermi-theory (I)

In 1933, E. Fermi developed the **classical theory of β-decay** assuming mass- and charge-less neutrinos; contact-interaction

Example: n-decay

- Neutron decays spontaneously into a proton, an electron and an anti-neutrino (4 particles at same space-time point)
- Electric charge is shuffled around

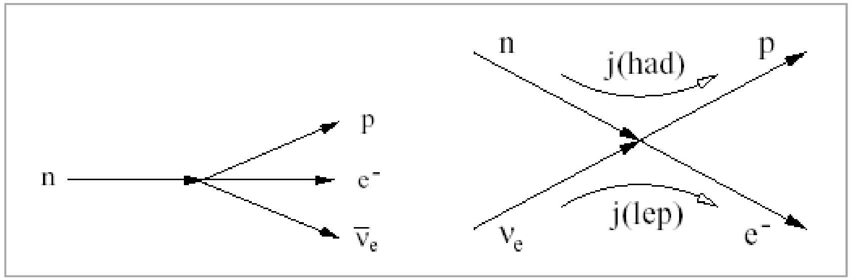


THE FORCES

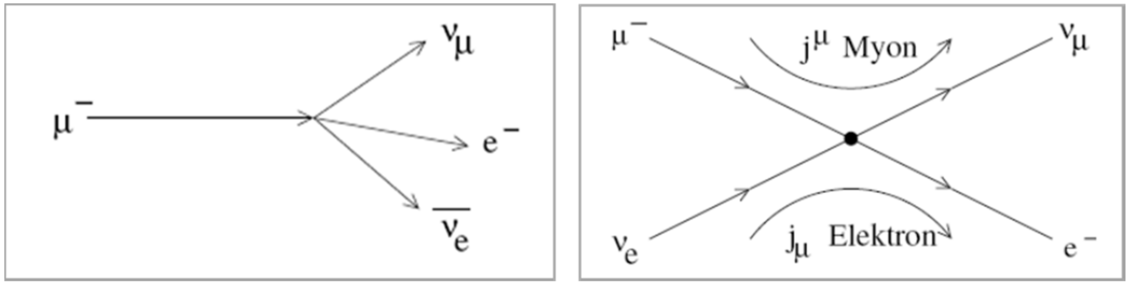
New Forces

Weak force – Fermi-theory (II)

The **neutron decay** was considered as an interaction between a **hadronic** and a **leptonic “current”**:



Likewise: μ**-decay** … **two leptonic currents**

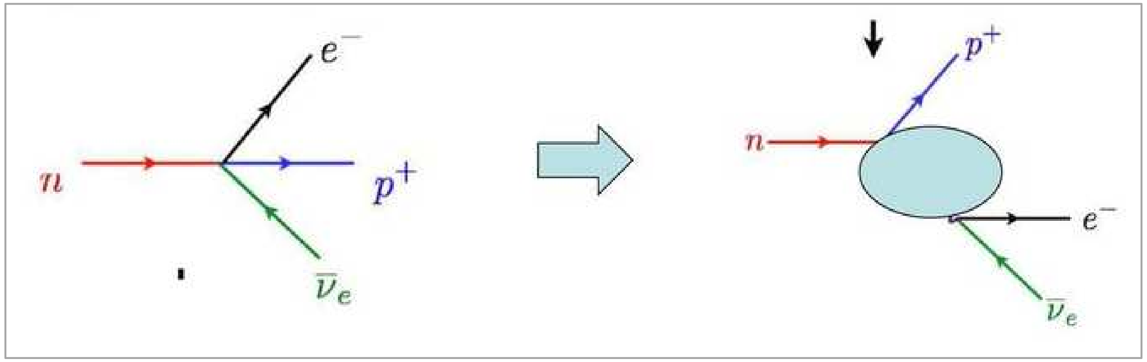


THE FORCES

New Forces

Weak force – Fermi-theory (III)

The weak interaction was first described as a **current-current point** interaction. However, there were problems at high energy (“unitarity violation”), i.e. the **cross section rises infinitely** with increasing energy: forced to re-think:



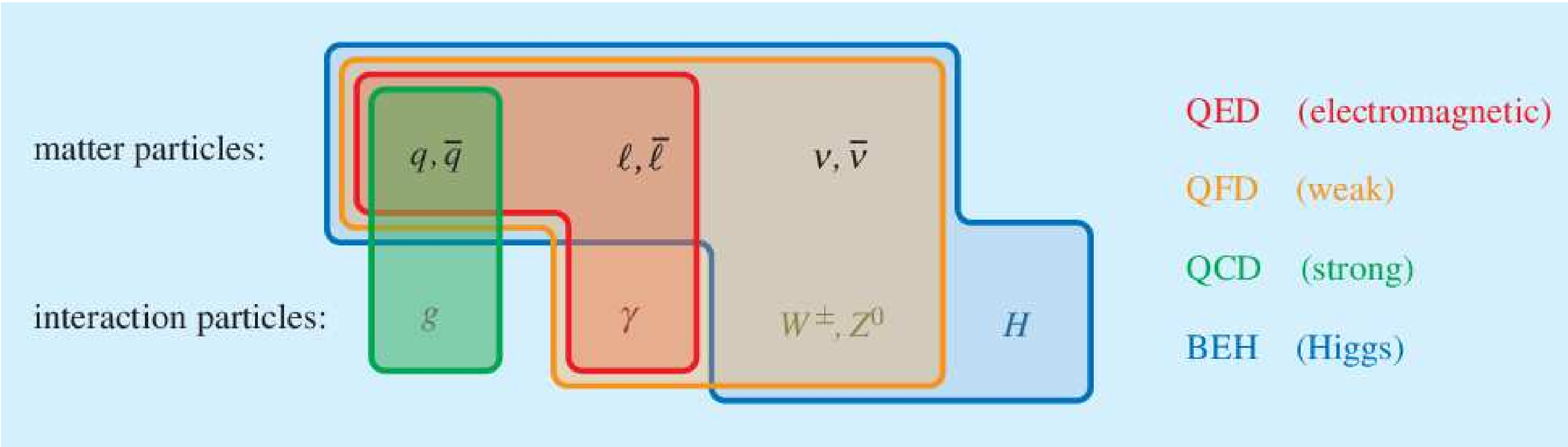
→ non-contact **exchange interaction** (see “fundamental interactions”); the Fermi-theory is the low-energy limit).

THE FORCES

New Forces

Weak force – noticible facts (I)

The weak interaction is actively involving both **hadrons** and **leptons** (like gravity – but wider than the nuclear force (only hadrons)):



THE FORCES

New Forces

Weak force – noticible facts (II)

The weak interaction **does not conserve** all **quantum numbers** of the particles: **isospin** ***I***

Example: K-decay ($K^+ \rightarrow \pi^+ \pi^+ \pi^-$)

$$\tfrac{1}{2} \rightarrow 1\ 1\ 1$$

and **strangeness** *S*:

Example: Λ-decay ($\Lambda \rightarrow \pi$ N):

$$\Lambda^0 \rightarrow p + \pi^- \qquad\qquad \Lambda^0 \rightarrow n + \pi^0$$
$$s = -1 \neq 0 + 0 \qquad\qquad s = -1 \neq 0 + 0$$

(in contrast to strong interaction)

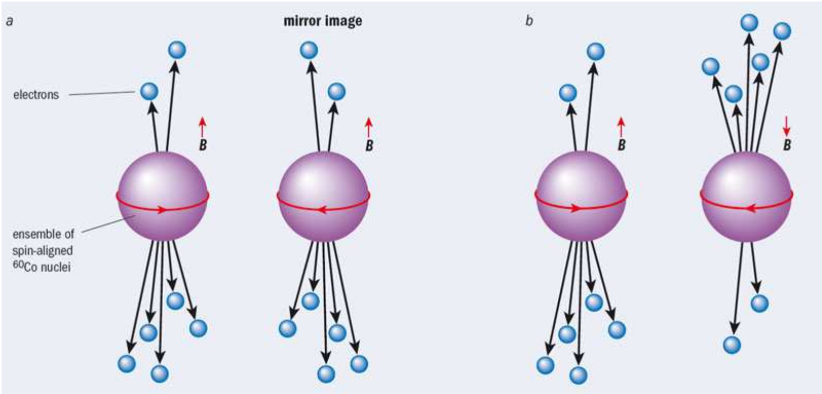
THE FORCES

New Forces

Weak force – noticible facts (III)

It also **does not conserve** all **discrete symmetries**: parity (P), charge conjugation (C) and CP:

- **P-violation:** Lee, Yang (theory, 1956) – Wu et al. (^{60}Co exp., 1957)



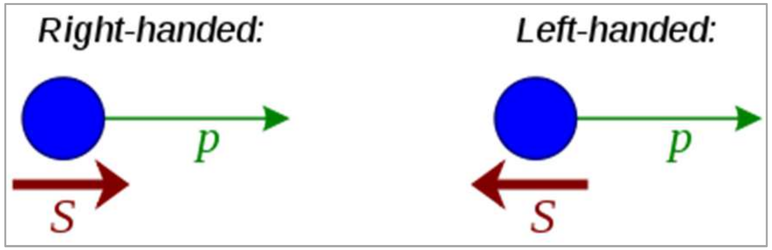
- **C-violation:** Garwin, Lederman, Weinrich (μ-decay, 1957)
- **CP-violation:** Christenson, Cronin, Fitch, Turlay (K^0 decay, 1964)

THE FORCES

New Forces

Weak force – implications of symmetry violations

The discovery of **parity violation** suggested that a new approach was needed. In 1957, R. Marshak and G. Sudarshan; R. Feynman and M. Gell-Mann proposed a **V−A** (“vector minus axial vector” or “left-handed”) **theory** for weak interactions:



In this theory, the **weak interaction acts only on left-handed particles** (and right-handed antiparticles). Since the mirror reflection of a left-handed particle is right-handed, this explains the maximal violation of parity. However, this theory allowed **CP symmetry to be conserved**.

THE FORCES

Exchange Forces

Virtual particles – Heisenberg uncertainty principle

All known forces of nature are “exchange forces”, i.e. it denotes a force produced by the **exchange of force carrier particles**; they are a different type of particle, a so called “**virtual particle**”:

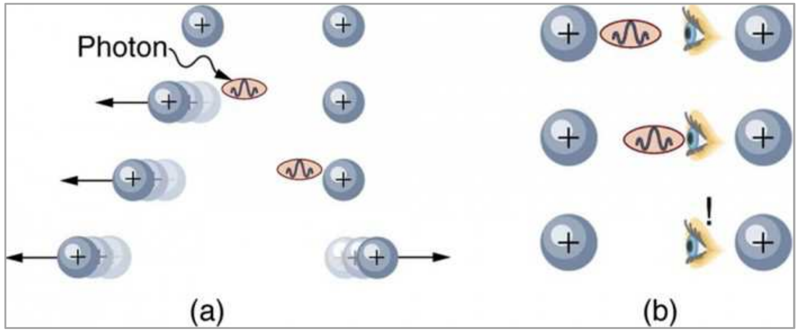


Image (a) shows the exchange of a **virtual photon** transmitting the electromagnetic force between charges, Image (b) shows that the photon cannot be directly observed in its passage, because this would disrupt it and alter the force. In this case it does not get to the other charge.

- A virtual particle is a transient quantum fluctuation that exhibits some of the characteristics of an ordinary particle, and its **existence is limited by** the **Heisenberg uncertainty principle**: $\Delta x \cdot \Delta p \sim \hbar$

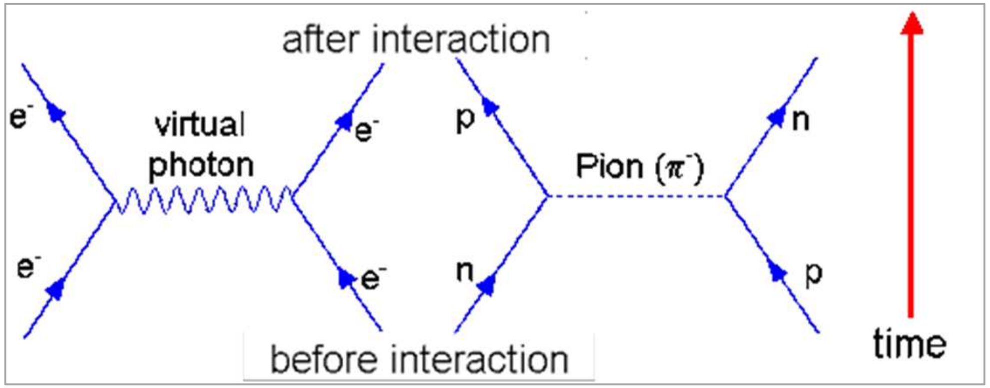
$$\Delta E \cdot \Delta t \sim \hbar$$

THE FORCES

Exchange Forces

Virtual particles – Feyman diagrams

- A virtual particle does **not precisely obey** the **energy–momentum relation** $m^2c^4 = E^2 - p^2c^2$. Its **kinetic energy** may not have the usual relationship to velocity. It **can be negative**. This is expressed by the phrase "off mass shell".
- Visualized in so called "**Feynman diagrams**":

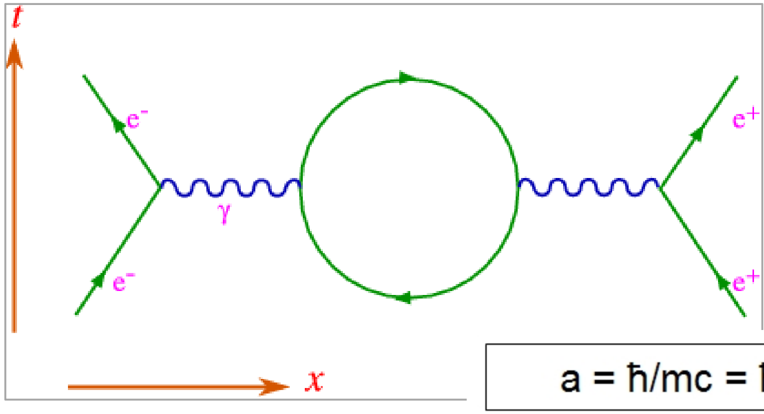


THE FORCES

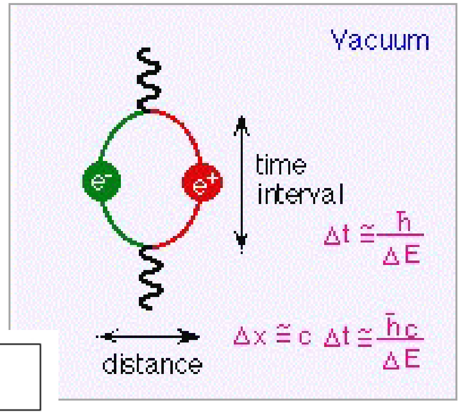
Exchange Forces

Virtual particles – virtual pairs of particles

- Quantum mechanics allows, and indeed requires, temporary violations of conservation of energy, so **one particle can become a pair of heavier particles** (so-called virtual particles), which quickly rejoin into the original particle as if they had never been there:



$$a = \hbar/mc = \hbar c/E$$



(Note: these are quantum-effects, not present in classical picture)

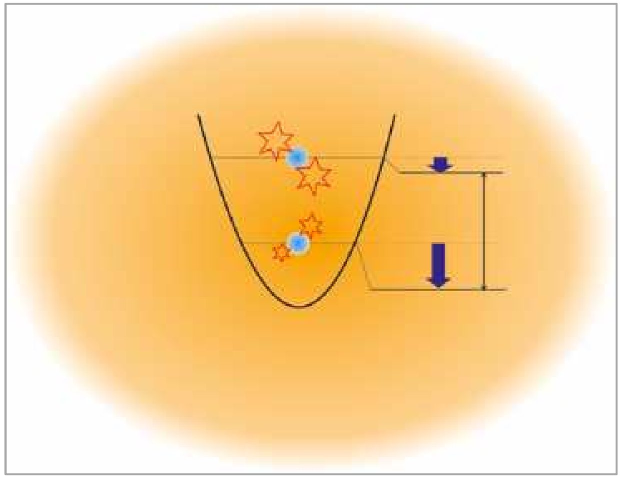
THE FORCES

Exchange Forces

Virtual particles – measurable effects (I)

- While the **virtual particles** are briefly part of our world they **can interact with other particles**, and that leads to a number of tests of the quantum-mechanical predictions about virtual particles:

  Example: Lamb-Shift in hydrogen atom



The **Lamb shift** is an energy shift of the energy levels of the hydrogen atom caused by the coupling of the atom's electron to fluctuations in the vacuum (→ "vacuum fluctuations")

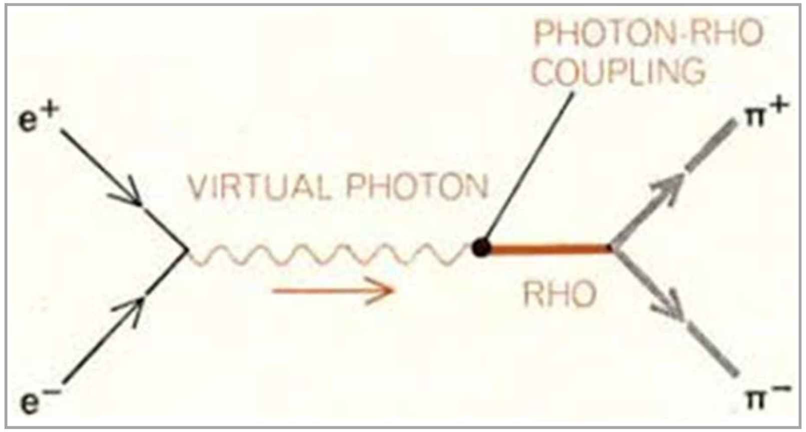
THE FORCES

Exchange Forces

Virtual particles – measurable effects (II)

- Electromagnetic processes (and other) are not as pure/simple any more:

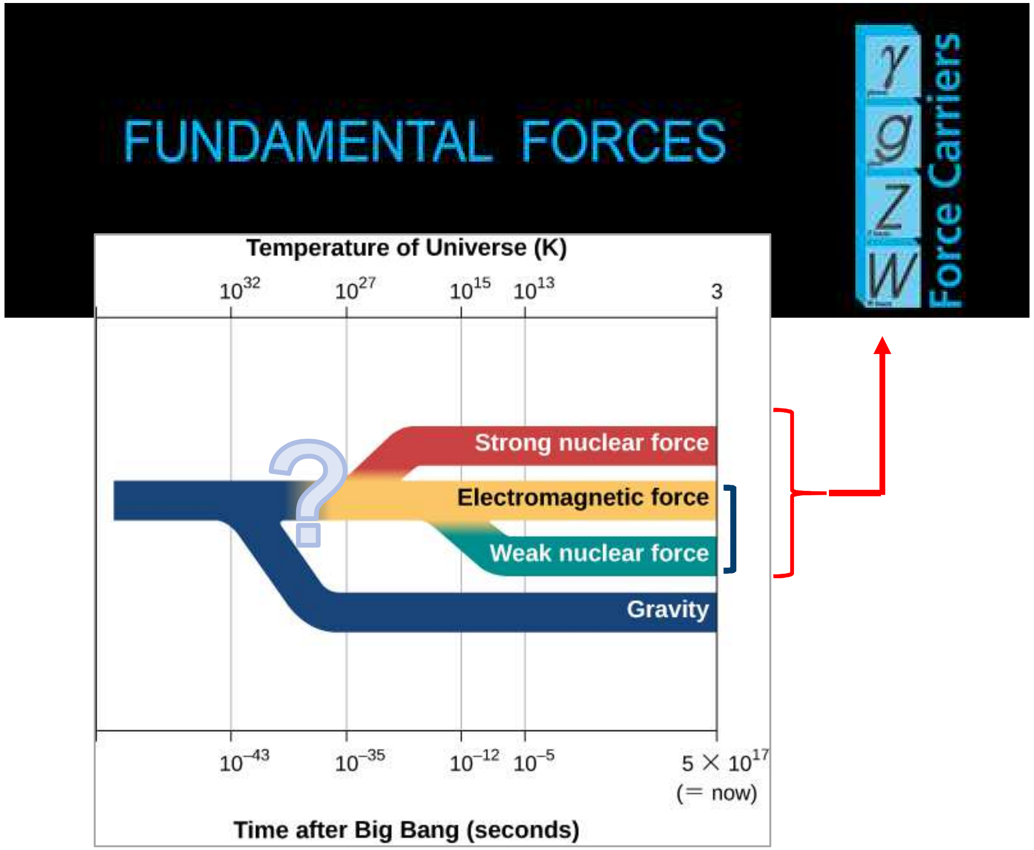
  Example: e^+e^- annihilation into a $(\pi^+\pi^-)$ pair



THE FORCES

Outlook

Fundamental forces



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THE FORCES

That´s it for today