Introduction

Introduction to Elementary Particle Physics

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Course Outline

1. Introduction.
2. Discreet symmetries: P, C, T.
3. Isospin, strangeness, G-parity.
4. Quark Model (Hadron structure – I)
5. Electromagnetic interactions.
6. Weak interactions.
7. Strong interactions (Hadron structure – II)

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Introduction

Particle physics is concerned with the study of the elementary constituents of matter and their interactions.

An elementary particle is a particle with no internal structure.

Elementary particles can be found in cosmic rays.

They can be produced in the laboratory in collisions between high-energy particle beams, in accelerators.

For this reason Particle Physics is also called High-Energy Physics.

Why High Energy ?

To probe the internal structure of a particle we need high resolution. Assuming the probing beam itself consists of pointlike particles, the **resolution is limited by the De Broglie wavelength** of these particles.

$$\lambda = \frac{h}{p}$$

where p is the momentum of the probing particle and h is **Planck's constant.** In order to obtain high spatial resolutions, and thus resolve smaller and smaller structures, it is necessary to use high-energy particles as probes.

Furthermore many elementary particles have large masses and require correspondingly high-energies (mc^2) for their creation and study.

Units in High-Energy Physics

quantity	HEP unit	value in SI units	natural units $\hbar = c = 1$
length	1 fm	10^{-15} m	1 GeV^{-1} = 0.1975 fm
time	1 s	1 s	1 $GeV^{-1} = 6.59\times10^{-25}$ s
energy	1 GeV = 10^9 eV	1.602×10^{-10} J	1 GeV
mass (E/c^2)	1 GeV/c^2	1.78×10^{-27} Kg	1 GeV
momentum(E/c)	1 GeV/c	5.34×10^{-19} Kg m s^{-1}	1 GeV
$\hbar = h/2\pi$	6.588×10^{-25} GeV s	1.055×10^{-34} Js	1
c	2.998×10^{23} fm/s	2.998×10^{8}m/s	1
$\hbar c$	0.1975 GeV fm	3.162×10^{-26} Jm	1

Fine structure constant $\alpha = e^2/4\pi = 1/137.06$

Heaviside-Lorentz units $\varepsilon_0 = \mu_0 = \hbar = c = 1$

More Units and Conversion Factors

1 Kg = 5.61×10^{26} GeV

1 m = 5.07×10^{15} GeV^{-1}

1 s = 1.52×10^{24} GeV^{-1}

1 barn = 10^{-28} m^2 (cross section)

1 TeV = 10^3 GeV = 10^6 MeV = 10^9 KeV = 10^{12} eV

1 fm = 5.07 GeV^{-1}

1 fm^2 = 10 mb = 10^4 μb = 10^7 nb = 10^{10} pb

1GeV^{-2} = 0.389 mb

Particle Classification

Fermions

- Leptons ($e^{\pm}$, ν_e, $\mu^{\pm}$, ν_μ, $\tau^{\pm}$, ν_τ)
- Baryons (p, n, Λ ...)

Hadrons

Bosons

- Mesons (π, K, ...)
- Gauge Bosons (γ, $W^{\pm}$, Z°, g)

Hadrons = particles with strong interaction

Bosons and Fermions

Let us suppose that we have tow identical particles, defined by the sets of observables ξ_1 and ξ_2. Let $\psi(\xi_1,\xi_2)$ be their wave function.

$$\left|\psi(\xi_1,\xi_2)\right|^2 = \left|\psi(\xi_2,\xi_1)\right|^2$$

$$\psi(\xi_1,\xi_2) \xrightarrow{1\leftrightarrow 2} e^{i\alpha}\psi(\xi_2,\xi_1) \xrightarrow{1\leftrightarrow 2} \psi(\xi_1,\xi_2)$$

$$\therefore$$

$$e^{i2\alpha} = 1 \Rightarrow e^{i\alpha} = \pm 1$$

$$\therefore$$

$$\psi(\xi_1,\xi_2) = \pm\psi(\xi_2,\xi_1)$$

- Identical Bosons (integral spin):

  $\psi(\xi_1,\xi_2) = +\psi(\xi_2,\xi_1)$ symmetric wave function

- Identical Fermions (half-integral spin):

  $\psi(\xi_1,\xi_2) = -\psi(\xi_2,\xi_1)$ antisymmetric wave function

As a consequence of these rules we obtain Pauli's Exclusion Principle:

Two or more identical fermions cannot exist in the same quantum state.

If two identical particles are in the same quantum state, the wave function is necessarily *symmetric,* whereas for fermions it must be *antisymmetric.*

On the other hand there are no restrictions on the number of bosons in the same quantum state.

All matter is composed of fundamental spin ½ fermions (quarks and leptons), whereas particle interactions are mediated by bosons.

$$\textbf{Leptons} \begin{cases} e \quad \mu \quad \tau \qquad -1 \\ \nu_e \quad \nu_\mu \quad \nu_\tau \qquad 0 \end{cases}$$

$$\textbf{quarks} \begin{cases} u \quad c \quad t \qquad +2/3 \\ d \quad s \quad b \qquad -1/3 \end{cases}$$

Gauge Bosons

bosons	interaction	spin/parity(J^P)
gluon, G	strong	1^-
photon, γ	electromagnetic	1^-
$W^\pm$, Z^0	weak	$1^-, 1^+$
graviton, g	gravitational	2^+

Quarks

up (u) and down (d)	I = ½	$m_u \approx m_d \approx 0.31$ GeV/c^2
strange (s)	S=-1	$m_s \approx 0.50$ GeV/c^2
charm (c)	C= 1	$m_c \approx 1.6$ GeV/c^2
bottom or beauty (b)	B=-1	$m_b \approx 4.6$ GeV/c^2
top [or truth] (t)	T= 1	$m_t \approx 180$ GeV/c^2

Hadrons
- Baryons — $q_1q_2q_3$ — p(uud), n(udd), Λ(uds)
- Mesons — $q_1\,\bar{q}_2$ — $\pi^+(u\,\bar{d})$, $K^0(d\,\bar{s})$, $J/\psi\,(c\,\bar{c})$

Leptons

$e^{\pm}$	m_e = 0.511 MeV/c^2	ν_e	$m_{\nu e}$ < 3 eV
$\mu^{\pm}$	m_μ = 105.66 MeV/c^2	ν_μ	$m_{\nu\mu}$ < 0.19 MeV
$\tau^{\pm}$	m_τ = 1777 MeV/c^2	ν_τ	$m_{\nu\tau}$ < 18.2 MeV

- Neutrinos are *left-handed* (helicity H=-1)
  Antineutrinos are *right-handed* (helicity H=+1)
- Charged leptons undergo weak and electromagnetic interaction.
  Neutrinos can only have weak interaction.
- Lepton Numbers:

	π^+	$\rightarrow$ μ^+	+ ν_μ
L_μ	0	-1	+1

	μ^+	$\rightarrow$ e^+	+ ν_e	+ $\bar{\nu}_\mu$
L_μ	-1	0	0	-1
L_e	0	-1	1	0

Helicity

The quantity

$$H = \frac{\vec{\sigma} \cdot \vec{p}}{|\vec{p}|} = -1$$

is called **helicity (or handedness).** It measures the *sign of the component of the spin of the particle in the direction of motion*.

H = - 1 the particle is left-handed (LH)

H = +1 the particle is right-handed (RH)

Helicity is a well-defined, Lorentz-invariant quantity for a massless particle.

For interactions mediated by vector or axial vector bosons **helicity is conserved in the relativistic limit**.

For this reason helicity is conserved in strong, electromagnetic and weak interactions, which are all mediated by vector of axial vector bosons.

Relativistic Kinematics

The relativistic relation between the total energy E, the vector 3-momentum **p** and the rest mass m for a free particle is:

$$E^2 = \vec{p}^{\,2} c^2 + m^2 c^4$$

or, in natural units:

$$E^2 = \vec{p}^{\,2} + m^2$$

The components of the 3-momentum and the energy can be written as components of an energy-momentum 4-vector P :

$P_0 = E \quad P_1 = p_x \quad P_2 = p_y \quad P_3 = p_z$

whose square modulus equals the squared rest mass:

$$P^2 = P_0^2 - P_1^2 - P_2^2 - P_3^2 = E^2 - \vec{p}^{\,2} = m^2$$

in units $\hbar = c = 1$.

The square of a 4-vector is a relativistic invariant, i.e. it has the same value in all inertial reference frames.
If E,**p** are measured in a given reference frame, then in another frame moving along the x axis with velocity βc we have:

where

$$\begin{aligned} p'_x &= \gamma(p_x - \beta E) \\ p'_y &= p_y \\ p'_z &= p_z \\ E' &= \gamma(E - \beta p_x) \end{aligned}$$

$$\gamma = 1/\sqrt{1-\beta^2}$$

These are the so-called Lorentz transformations.

The square of a 4-vector is an example of a Lorentz scalar, i.e. the invariant scalar product of two 4-vectors.

A 4-vector q can be either space-like or time-like:

space-like	if	**$q^2 < 0$**
time-like	if	**$q^2 > 0$**

In the collision between a particle with energy E_A and momentum $\mathbf{p}_A$ and another one with energy E_B and momentum $\mathbf{p}_B$, the total 4-momentum squared is:

$$P^2 = (E_A + E_B)^2 - (\vec{p}_A + \vec{p}_B)^2$$

$$P^2 = m_A^2 + m_B^2 - 2\vec{p}_A \cdot \vec{p}_B + 2E_A E_B$$

The center-of-mass system (cms) is defined as the reference frame in which the total 3-momentum is zero.

If the total energy in the cms is denoted $\sqrt{s}$ we also have **$P^2 = s$**.

- If in the collision between two particles one is at rest in the lab frame ($E_B=m_B$) (*fixed target*) we have:

$$s = P^2 = m_A^2 + m_B^2 + 2m_B E_A \approx 2m_B E_A$$

- In the case of two particles travelling in opposite directions (*colliding beams*):

$$s = P^2 = 2(E_A E_B + p_A p_B) + m_A^2 + m_B^2$$

$$s \approx 4E_A E_B$$

($m_A, m_B << E_A, E_B$).

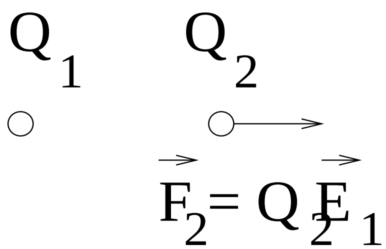
In a collider the total cms energy increases linearly with the beam energy, whereas in fixed targed it increases as the square root of the beam energy.

Interactions

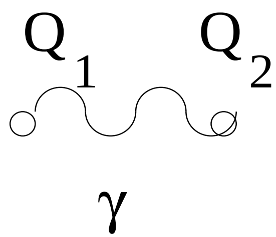
Classically interaction at a distance is described in terms of a potential or a *field*. In quantum theory it is viewed in terms of **exchange of quanta**. Quanta are bosons associated with the particular type of interaction.

<u>Example</u>: electrostatic interaction bewteen point charges.

Classica



Quantistica



we must have $\Delta E \cdot \Delta t \simeq \hbar$

In nature there are four types of interaction.

- The strong interaction binds quarks in hadrons and protons and neutrons in nuclei. It is mediated by gluons.
- The electromagnetic interaction binds electrons and nuclei in atoms, and it is also responsible for the intermolecular forces in liquids and solids. It is mediated by the photon.
- The weak interaction is typified by radioactive decays, for example the slow β decay. The quanta of the weak field are the $W^{\pm}$ and Z^0 bosons.
- The gravitational interaction acts between all types of massive particles. It is by far the weakest of all the fundamental interactions.

To indicate the relative magnitudes of the four types of interaction, the comparative strenghts of the force between two protons when just in contact are very roughly:

strong	electromagnetic	weak	gravity
1	10^{-2}	10^{-7}	10^{-39}

Ever since Einstein, physicists have speculated that the *4 interactions might be different manifestations of a unified force*. Up to now only electromagnetic and weak forces have been unified: these would have the same strength at very high energies, whereas at lower energies this symmetry is broken and the two forces have the same strength.

All four interactions play a fundamental role in our universe.

Electromagnetic Interactions

The coupling constant of the electromagnetic interaction is the fine structure constant α.

$$\alpha = \frac{\frac{1}{4\pi}\frac{e^2}{(\hbar / mc)}}{mc^2} = \frac{\text{electrostatic energy of two } e \text{ at a distance } (\hbar/mc)}{\text{rest mass of the electron}}$$

$$\alpha = \frac{e^2}{4\pi\hbar c} \approx \frac{1}{137}$$

$\pi^0 \rightarrow \gamma\gamma$ $\qquad \tau = (8.4 \pm 0.6) \times 10^{-17}$ s

The quantum of the electromagnetic interaction is the photon.

The field theory of the electromagnetic interaction is Quantum ElectroDynamics (QED).

Weak Interactions

$n \rightarrow p + e^- + \bar{\nu}_e$ β decay

$\bar{\nu}_e + p \rightarrow n + e^+$ $\bar{\nu}$ absorption

$\Sigma^- \rightarrow n + \pi^-$ $\tau \cong 10^{-10}$ s

(dds) (ddu)

$\Sigma^0 \rightarrow \Lambda + \gamma$ $\tau \cong 10^{-19}$ s

(e.m. viola isospin)

$$\frac{\alpha_W}{\alpha} \approx \sqrt{\frac{10^{-19}}{10^{-10}}} \approx 10^{-4} \div 10^{-5}$$

The quanta of the weak interaction are the $W^{\pm}$ and Z^0 bosons.

$M_W = (80.425 \pm 0.038)$ GeV/c^2

$M_Z = (91.1876 \pm 0.0021)$ GeV/c^2

Strong Interactions

$\Sigma^0(1385) \to \Lambda + \pi^0$ Γ=36 MeV $\tau \sim 10^{-23}$ s

$\Sigma^0(1192) \to \Lambda + \gamma$ $\tau \sim 10^{-19}$ s

$$\frac{\alpha_S}{\alpha} \approx \sqrt{\frac{10^{-19}}{10^{-23}}} \approx 100 \qquad \frac{e^2}{4\pi} = \frac{1}{137} \qquad \frac{g_s^2}{4\pi} \approx 1$$

The quanta of the strong interactions are the gluons. The strong charge is called color and it can assume 6 values R, G, B, $\bar{\text{R}}$, $\bar{\text{G}}$, $\bar{\text{B}}$.

Color symmetry is an exact symmetry, i.e. the force between quarks is color-independent.

The field theory of strong interactions is Quantum Chromodynamics (QCD).

Asymptotic freedom $V_s \to \alpha_s/r$ $q^2 \to \infty$

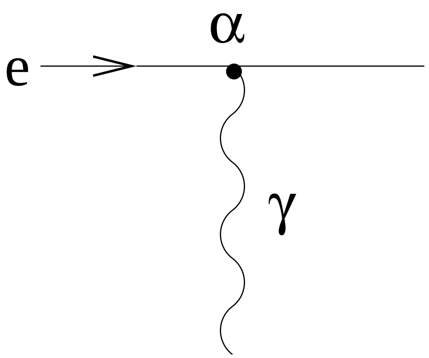
Confinement $V_s \to kr$ $q^2 \to 0$ $[r \to \infty]$

Feynman Diagrams

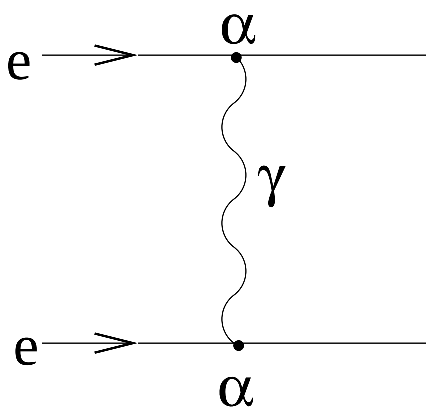
Feynman diagrams are a graphical way of representing the interaction between particles and fields.

- Solid straight lines represent fermions.
- Wavy, curly or broken lines represent bosons.
- Arrows along the lines indicate the time sense, with time increasing from left to right.
- Fermion and boson lines meet at **vertices** where charge, energy and momentum are conserved.
- The strength of the interaction is represented by a **coupling constant** associated to each vertex.
- Open lines (i.e. entering or leaving the boundaries of a diagram) represent real particles, closed lines and those joining vertices represent virtual particles.

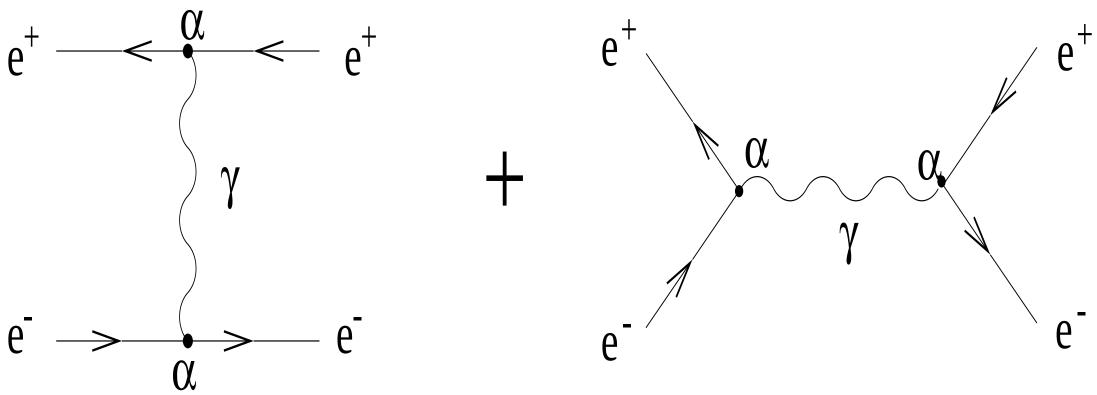
Feynman Diagrams



basic electron-photon vertex



ee scattering via γ exchange



e^+e^- scattering via photon exchange with two diagrams contributing in first order

Cross Section

Let us consider the two-body process:

$$\underbrace{a+b}_{i} \rightarrow \underbrace{c+d}_{f}$$

where:

n_a = number of incident particles per unit volume.

n_b = number of target particles per unit surface.

v_i = relative velocity of *a* with respect to *b*.

The number of interactions per unit surface and unit time is given by:

$$\frac{d^2N}{dAdt} = \sigma \cdot n_b \cdot n_a v_i$$

σ is the cross section for the process a+b $\rightarrow$ c+d