FUNDAMENTAL ROLE OF EXPERIMENTS IN HIGH ENERGY PHYSICS

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Abstract

An introductory talk at a Meeting on results and prospects of collaboration of Russian research organizations with European organization for nuclear research (CERN), which took place at the Ministry of science and technical policy of Russia on 8 July, 1996.

Introduction.

The purpose of this talk is to give a general review of High Energy Physics, of its basic notions and terminology. The terminological barrier is a serious obstacle in understanding any science. I will be unable to destroy it, but I hope, that I will help you, at least partly, to overcome it. The talk is organized as answers to 12 questions:

1. When was the High Energy Physics born?
2. Why do we need the highest energies?
3. Which particles are called fundamental (elementary)?
4. What is the difference between bosons and fermions?
5. How does the "Mendeleev Table" of fundamental particles look like?
6. Why are the fundamental bosons needed?

7. Why is the first generation of fermions needed?

8. Why are the second and the third generations needed?

9. What is a collider? What has been discovered with colliders?

10. What do we expect from the future colliders?

11. Experiments not at the highest energies – are they needed?

12. To understand the fundamental particles – why is it necessary for the mankind?

1  When was the High Energy Physics born?

It was born twice. First time – 100 years ago, when in 1896 the radioactivity was discovered. Second time – 50 years ago, after World War II, when the first large accelerators of charged particles started to create new elementary particles.

At the dawn of the century – when X-rays, radioactivity and atomic nucleus were discovered – high energies stretched from thousands to millions of electrovolts (from KeV’s to MeV’s). At present they stretch from billions to trillions of eV’s (from GeV’s to TeV’s). Let me comment the notations: K – kilo, M – mega, G – giga, T – tera; 1KeV = 10³ eV, 1MeV = 10⁶ eV, 1GeV = 10⁹ eV, 1TeV = 10¹² eV. 1eV = 1e × 1V – is the energy, which an electron acquires by crossing in accelerating difference of potentials of 1 Volt. Let me remind that 1Amper = 6·10¹⁸ electrons/sec. Thus the values of energies under discussion may seem to be quite non-impressive. But they are very large, if one takes into account, that they are carried by single particles!

2  Why do we need the highest energies?

In order to create and to study fundamental particles. You know, of course, the famous formula by Einstein, which literally, shook the world:

\[ E_0 = mc^2 \]
where

\[ E_0 = E \text{ is the rest energy of a body (the index zero indicates that the body is at rest, its velocity being equal to zero)}, \]
\[ m = \text{is the mass of the body}, \]
\[ c = 3 \cdot 10^8 \text{ m/sec} \] is the velocity of light.

In experiments on accelerators the kinetic energy of accelerated particles is transformed, during collisions, into the rest energy (mass) of created particles. The higher is the energy of an accelerator, the heavier are the particles which it can produce.

3 Which particles are called fundamental (elementary)?

Those, which at present level of knowledge do not consist of more fundamental ones ("the smallest matreshkas"). Atoms are not elementary: they consist of electrons and nuclei. Nuclei consist of protons \( p \) and neutrons \( n \). Protons and neutrons are also not elementary, they consist of quarks of two types, \( u \)-quarks and \( d \)-quarks:

\[ p = uud, \quad n = ddu. \]

Quarks and electrons are elementary at present level of knowledge. Photons – the particles of light – are elementary as well. Quarks and electrons belong to a family of particles called fundamental fermions. Photons belong to another family, that of fundamental bosons.

4 What is the difference between bosons and fermions?

They differ by the value of their spin. Particles are like miniature tops. Spin is the proper rotational (angular) momentum of a particle. Spin is measured in units of \( \hbar \):

\[ \hbar = 10^{-34} \text{ Joules} \cdot \text{sec} = 10^{-34} \text{ kg} \cdot (\text{m/sec}) \cdot \text{m} \]
In order to visualize the value of $\hbar$, imagine one gram weight, which is fixed on a rotating 1 cm long stick so that its velocity is 1 cm/sec. And now reduce the mass by 27 orders of magnitude, the length by 10 orders, and increase the velocity by 10 orders. (In order to reduce a stick by 10 orders, one has to break it into two halves, then to break, in the same way, one of the halves, and to repeat this procedure 31 times ”only”.)

The constant $\hbar$ – one of the most fundamental constants of nature. It was introduced by German physicist Max Planck in 1900.

Bosons (named after Indian physicist Bose) have integer values of spin in units of $\hbar$. Fermions (named after Italian physicist Fermi) have half-integer spin. The spin of photon is $1\hbar$, or simply 1; the spin of electron is $1/2$.

Fermions are individualists: there can exist, in a given state, only one fermion of a given type. This property explains the pattern of atomic levels and hence the Mendeleev Table.

Bosons are collectivists: all bosons of a given type prefer to be in one state. This property is the basis of the laser.

The amazing properties of bosons and fermions are connected with basic principles of the modern quantum physics. I do not know of any simple graphic explanation of these properties.

Now we are ready to answer the key question of this talk.

5 How does the ”Mendeleev Table” of fundamental particles look like?

The Table contains 16 particles: 4 bosons and 12 fermions.
**Fundamental bosons.**

The photon, $\gamma$, the $W$ and $Z$ bosons, the gluon, $g$. All of them have spin 1. The photon, gluon and $Z$ boson are electrically neutral: their electric charge $Q$ is equal to zero. For $W$ bosons $Q = \pm 1$.

**Fundamental fermions.**

Twelve fermions are subdivided into three generations, two quarks and two leptons in each. (The term leptons means electron and its ”relatives”.) The first three columns of the following table represent three generations of fundamental fermions. The fourth column shows their electric charges $Q$.

| generation     | 1st | 2nd | 3d | $Q$   |
|----------------|-----|-----|-----|-------|
| quarks         |     |     |     |       |
| upper          | $u$ | $c$ | $t$ | +2/3  |
| lower          | $d$ | $s$ | $b$ | -1/3  |
| neutrinos      | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ | 0     |
| charged leptons| $e$ | $\mu$ | $\tau$ | -1    |

As seen from the table, there are two types of quarks: ”upper” and ”lower”. (The symbols $u$ and $d$ stem from ”up” and ”down”, whilst $t$ and $b$ – from ”top” and ”bottom”; $c$ and $s$ denote so called ”charmed” and ”strange” quarks.) As for leptons, they are subdivided into neutral (neutrinos) and charged ones.

Each charged fermion has its antiparticle: $\bar{u}$, $\bar{d}$, $\bar{c}$, $\bar{s}$, $\bar{t}$, $\bar{b}$, $e^+$, $\mu^+$, $\tau^+$. About neutrinos this is still uncertain. It is one of the important problems – to establish whether or not antineutrinos are identical with neutrinos.

Let us note that 5 fundamental fermions ($c, b, t, \tau, \nu_\tau$) and 3 fundamental bosons ($g, W, Z$) have been discovered after 1973.

**6 Why are the fundamental bosons needed?**

The main role of the known fundamental bosons is to serve as mediators of forces.
The exchange of photons creates electromagnetic forces which underlie the atomic and molecular physics, physics of solid state and plasma, optics, acoustics, chemistry, biology.

The exchange of gluons creates strong interactions which confine quarks inside protons, neutrons and hundreds of other particles which are built of quarks and gluons and which are called hadrons.

The exchange of $W$ and $Z$ bosons creates weak forces.

Theorists have no doubt that gravity is produced by exchange of gravitons, fundamental bosons with spin equal 2. However to observe these particles is extremely difficult. Even our grand-grand children will be unable to detect them.

7 Why is the first generation of fermions needed?

The world around us and we ourselves are built from electrons and $u$- and $d$-quarks. Without weak interactions with participation of $\nu_e$ there would be no stars, no sun, no life. A complex chain of nuclear reactions involving electron neutrinos inside the sun transforms hydrogen into helium and then into heavy elements. Protons ”burn” with release of energy and neutrinos:

$$2e^- + 4p \rightarrow ^4He + 2\nu_e + 27\text{ MeV}.$$  

The flux of solar neutrinos is enormous: 70 billion per second per each cm$^2$ on the earth. But we are practically transparent for them. Only special multikilotonne detectors can capture a few particles from this flux. (One of such detectors operates in our country, in the Baksan valley.) The number of captured $\nu_e$’s turned out to be approximately a factor of two less, than had been expected. Maybe, on their way from the center of the sun to the earth, $\nu_e$’s partly transform into $\nu_\mu$’s or $\nu_\tau$’s, which leave no trace in detectors, which are sensitive only to $\nu_e$’s?

8 Why are the second and the third generations of fermions needed?

We have no definite answer to this question. Maybe, they are needed in order to preserve some amount of electrons and protons from the time of the ”big
bang”. Otherwise the world would consist only of photons and neutrinos. (On an average per one proton, there is one electron, one billion of photons, with energy $3 \cdot 10^{-4}$ eV in the form of radiowaves, and approximately the same number of neutrinos.)

9 What is a collider? What has been discovered by using colliders?

Collider is a machine for accelerating, storing (not always) and head-on colliding two beams of particles. (In an ordinary accelerator, not a collider, there is only one beam, which hits a fixed target.) In the head-on collisions in colliders the kinetic energy is transformed into the rest energy of created particles in the most effective way.

The particles discovered with colliders are: $t$- and partly $c$-quark, $\tau$-lepton, gluon, $W$ and $Z$-bosons.

The masses of $W$ and $Z$ bosons are 80 GeV and 91 GeV, respectively. These bosons have been discovered at CERN on a specially built for this purpose proton-antiproton collider, with energies of particles in each beam 270 GeV.

20 million $Z$ bosons have been created and detected at CERN, in 1989–1995, on the LEP I collider. In a circular tunnel of LEP I, with 27 km circumference, beams of electrons and positrons with energies 45.5 GeV collided head-on. Their energy was fully used to create $Z$ bosons.

In 1994 at the proton-antiproton collider Tevatron (USA), the heaviest of known particles have been created – $t$-quark, its mass being about 175 GeV. The energy of particles in each of the two beams of Tevatron is about one TeV, hence the name of the collider. May I remind you that the mass of a proton is 0.94 GeV, while that of electron is 0.5 MeV.

10 What do we expect from the future colliders?

In the same ring, where LEP I was operating, a new collider started to run in the fall of 1999. The energies of $e^-$ and $e^+$ will reach in it 96 GeV. In year
2000, in the same tunnel the construction of a new machine – Large Hadron Collider (LHC) – will start. The colliding particles in this machine will be protons with energy 7 TeV.

First of all, physicists expect, that with the new colliders, a new particle called Higgs boson (or simply, higgs) will be discovered. (P.Higgs is a contemporary British theorist.) The spin of the higgs must be equal to zero. Its mass cannot be predicted in a definite way. Most probable, however, that higgs is heavier than W boson, but lighter than the top-quark. The higgs plays a central role in the modern theory of matter. According to the theory, all fundamental particles acquire their masses through their interaction with the higgs. The discovery of the higgs would allow physicists to come closer to understanding the nature of mass.

Another promising direction is supersymmetry, according to which to each of the known particles there correspond a ”superpartner”: a particle with spin differing by 1/2. Thus superpartner of a fermion is a boson, whilst superpartner of a boson is a fermion. The supersymmetry is strongly broken in the nature. It is expected, that the masses of ”superpartners” of the known particles lie mainly in the interval from 100 GeV to 1 TeV.

Third direction is the possible compositness of our fundamental particles, which may reveal itself at higher energies.

Finally, one has not to forget about ”expected surprises”. In the past, many important phenomena were unexpectedly discovered at accelerators, which had been built for other purposes and did not have these phenomena on their ”to be discovered” lists.

11 Experiments not at the highest energies – are they needed?

Yes! The idea that all efforts should be concentrated on the highest energy colliders is an erroneous one.

The colliders represent the direction of the principle attack, but we are fighting simultaneously on several fronts. The answers to many crucial questions cannot be, in principle, obtained with colliders. They might be obtained either in non-accelerator experiments, or in experiments on low energy fixed target accelerators. (In the latter case they may be considered as ”pockets
of resistance”. Here are a few examples:

- Search for neutrino masses.
- Study of solar neutrinos (the neutrino monitoring of the sun could be exceptionally important from practical point of view).
- Search for proton decay.
- Search for transformation of neutrons into antineutrons in vacuum.
- Study of the asymmetry between particles and antiparticles.
- Study of light hadrons in order to understand the mechanism of confinement of quarks in hadrons.

It should be stressed that for the study of light hadrons the existing accelerators in Russia could be highly effective.

12 To understand the fundamental particles – why is it necessary for the mankind?

In order to ascertain the basic principles of nature (as an ideal – one principle, from which follow all fundamental laws).

In order to understand the birth of the universe and its future. (One TeV corresponds to the temperature of the universe at the age of one picosecond).

High Energy Physics is a tuning fork of the intellectual sphere of mankind. There exists at present a unique community of engineers, experimental and theoretical physicists, which can solve these problems. It should not be lost!