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Future Particle-Physics Projects in the United States

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Abstract—Basic proposals of experiments aimed at precision measurements of Standard Model parameters and at searches for new particles, including dark-matter particles, are described along with future experimental projects considered by American Physical Society at the meeting in the summer of 2013 and intended for implementation within the next ten to twenty years.

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INTRODUCTION

In modern science, the planning of scientific investigations is of great importance, since the majority of projects require capital expenditures and since the time of their implementation is frequently very long, amounting to many years or sometimes decades. In the United States, physicists working in the realms of particle physics organize a discussion of future projects every five to ten years, and this makes it possible to choose the most important line of research for subsequent ten to twenty years. The process in question is coordinated by the American Physical Society, which is a community-based organization, rather than by the government or financing institutions, and this permits focusing discussions on priority problems.

The notion of particle physics covers somewhat different fields of research in different countries. For example, studies on heavy-ion physics refer in the United States to nuclear rather than to particle physics.

For the reasons of space, all proposals concerning future projects and experiments considered at the meeting in the summer of 2013 (in which involve more than 1000 physicists) cannot be described in a short article. The entire body of respective information can be found in [1, 2].

The process described above takes into account not only scientific priorities but also financing realities.

The present article gives only an overview of basic lines of the experimental program planned in the United States. The references quoted above permit the reader to get acquainted with all of the projects.

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HOW ARE PRIORITIES ESTABLISHED?

In the United States, the procedure for reaching a decision on the priority lines of investigations consists of the following main steps. First, a group of scientists proposes an experiment or a project. All proposals (sometimes, there are a few hundred of them) are examined at a meeting of the American Physical Society, where physicists ask questions on all details of the proposals—from scientific ones to those concerning the cost and the time of implementation. After that, a committee, called P5, which consists of about 25 leading scientists from the United States and other countries, examines all proposals, sets priorities on the basis of the expected financing, and presents a recommendation at governmental organs that finance projects and experiments in particle physics. A conclusive decision is taken by governmental organs (such as the US Department of Energy) on the basis of these recommendations.

The process described above relies on scientific priorities but also takes into consideration the realities of financing.

BASIC PROBLEMS IN PARTICLE PHYSICS

In order to specify the most promising projects, it is important to have a list of the most important problems in particle physics. Presented immediately below is the list of such problems that was composed on the basis of the results of discussions at the American Physical Society in the summer of 2013.

(i) What is the extent to which we understand the discovered Higgs boson? Which are the principles underlying its coupling to quarks and leptons? How many are there Higgs bosons (one versus many)? Is the Higgs boson an elementary or a composite particle?

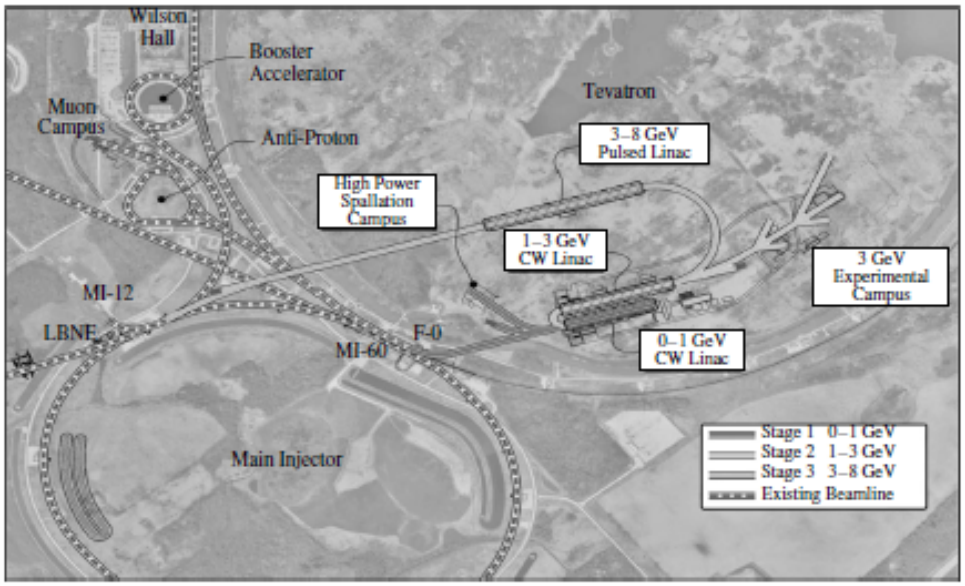

Fig. 1. Layout of a high-current proton accelerator—Project X.

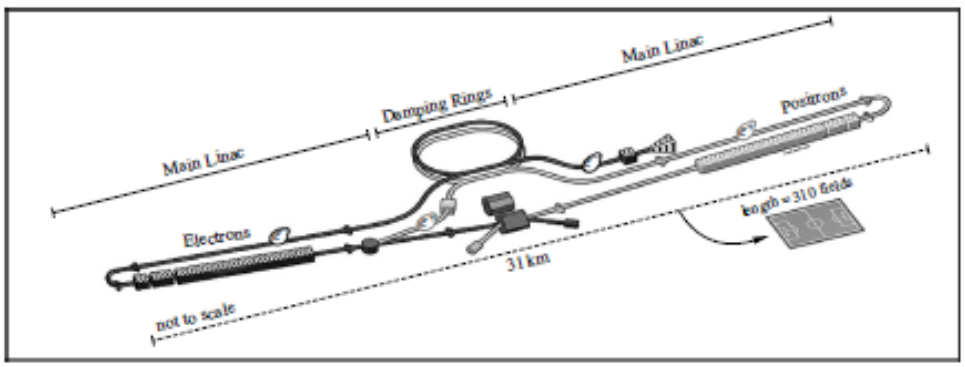

Fig. 2. International Linear Collider (ILC), which is planned to be constructed in Japan.

(ii) Which are the principles that determine the masses and mixing of quarks and leptons? Why is the mixing of quarks is different from the mixing of leptons? Why is the CP-violation phase unequal to zero? Is there CP violation in the lepton sector?

(iii) Why is the neutrino much lighter than the other particles? Are the low neutrino masses due to the existence of a very large mass scale? Are there new interactions in which only neutrinos are involved?

(iv) Which mechanism was responsible for the matter–antimatter asymmetry in the Universe? Why are the interactions of particles and antiparticles not fully symmetric?

(v) The mass of the Universe is dominated by dark matter. Of what does it consist? Does it consist of particles of the same type or of particles of different types? What principle determines the dark-matter density in the Universe? Are dark-matter particles coupled to Standard Model particles or are they part of a totally new "dark" sector?

(vi) What is dark energy? Is it a static energy per unit volume of the vacuum or is it dynamical, changing with the Universe? Which principles determine the magnitude of the observed dark energy?

(vii) How did the Universe look at the earliest instants and how did it evolve to the current state? The inflation model of the Universe requires the presence of new fields at the early stages of Universe evolution. What are sources of these fields and how can they be discovered in modern Universe?

The aforementioned problems concern not only particle physics but also science as a whole.

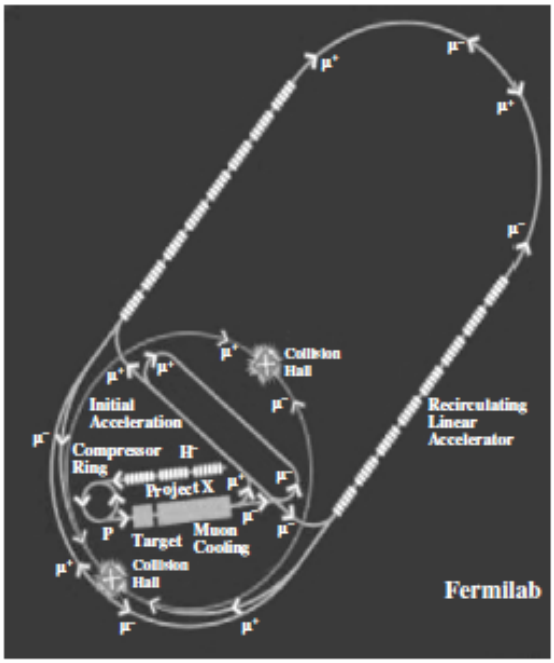

Fig. 3. Project of a muon collider that is rated to an energy of up to 10 TeV and which will be deployed within the Fermilab territory.

FUTURE PARTICLE ACCELERATORS

In order to answer many of the questions listed above, physicists need new powerful particle accelerators. These may be accelerators of very high energy or very high intensity, depending on the problem at hand. Listed immediately below are the most important questions for scientists involved in designing modern accelerators:

(i) In which way is it possible to create a 100-TeV proton–proton collider?

(ii) In which way is it possible to construct a lepton collider of energy in excess 1 TeV?

(iii) How can one obtain a low-energy proton beam of power 100 MW?

(iv) Is it possible to fabricate targets for beams of power equal to many megawatt units? How long will such targets be able to work?

(v) Will plasma-based accelerators prove be useful in particle physics?

(vi) Is it possible to construct an accelerator that would be ten times cheaper than the existing accelerators of energy 1 TeV or power 1 MW?

The accelerator projects actively discussed in the summer of 2013 include Project X, which is a 1 to 8-GeV high-current linear proton accelerator, its power at the energy of 1 GeV being 1 MW. This accelerator will provide a large number of low-energy experiments with particle beams and will serve as a source of protons for future accelerators, such as the muon collider. The layout of Project X is shown in Fig. 1.

The participation in the project of the International Linear Collider (ILC) is widely supported in the United States. This collider will be deployed in Japan. Its planned c.m. electron–positron collision energy and luminosity are 500 GeV and about 10^{34} cm^{-2} s^{-1}, respectively. Such an accelerator will make it possible to study all Standard Model particles, including the Higgs boson and top quark, to a unique precision. The layout of the ILC accelerator is shown in Fig. 2.

A collider on the basis of muons is an interesting project vigorously developed in the United States. A ring muon accelerator does not run into synchrotron-radiation problems characteristic of electron accelerators belonging to this type. The problem of fast muon production and "cooling" (creation of beams whose phase space is small) is the main problem here since the muon lifetime at rest is as short as 2 μs. Muon colliders of energy up to 10 TeV are thought to be realistic, and one of the possible versions is shown in Fig. 3.

HIGH ENERGIES AND INTENSITIES AND ASTROPHYSICS

The set of basic proposed projects (whose start is planned for about the next ten years) was broken down in accordance with the following lines of research: high energies, intense particle beams, and astrophysics.

The following projects were considered in the region of ultrahigh energies: (i) the LHC at a luminosity as high as 5×10^{34} cm^{-2} s^{-1} (such an accelerator will make it possible to study Higgs bosons, to perform direct searches for particles of mass up to 5 TeV, to study the scattering of vector bosons, and to conduct a number of other interesting investigations); (ii) a linear electon–positron collider of energy 500 GeV (such a collider will make it possible to determine Higgs boson couplings to all Standard Model particles and to perform a precision study of all Standard Model particles, including the top quark, which is the heaviest of them); and (iii) a muon collider of energy 3 to 10 TeV (its tasks are similar to those of the electron–positron collider, but it can produce higher mass particles; moreover, it is potentially cheaper).

Three experiments were widely discussed in the realms of experiments that require high-intensity particle beams. The Long Baseline Neutrino Experiment (LBNE) is an experiment aimed at neutrino-oscillation studies—in particular, at a determination

Fig. 4. Layout of the LBNE experiment aimed at studying neutrino oscillations.

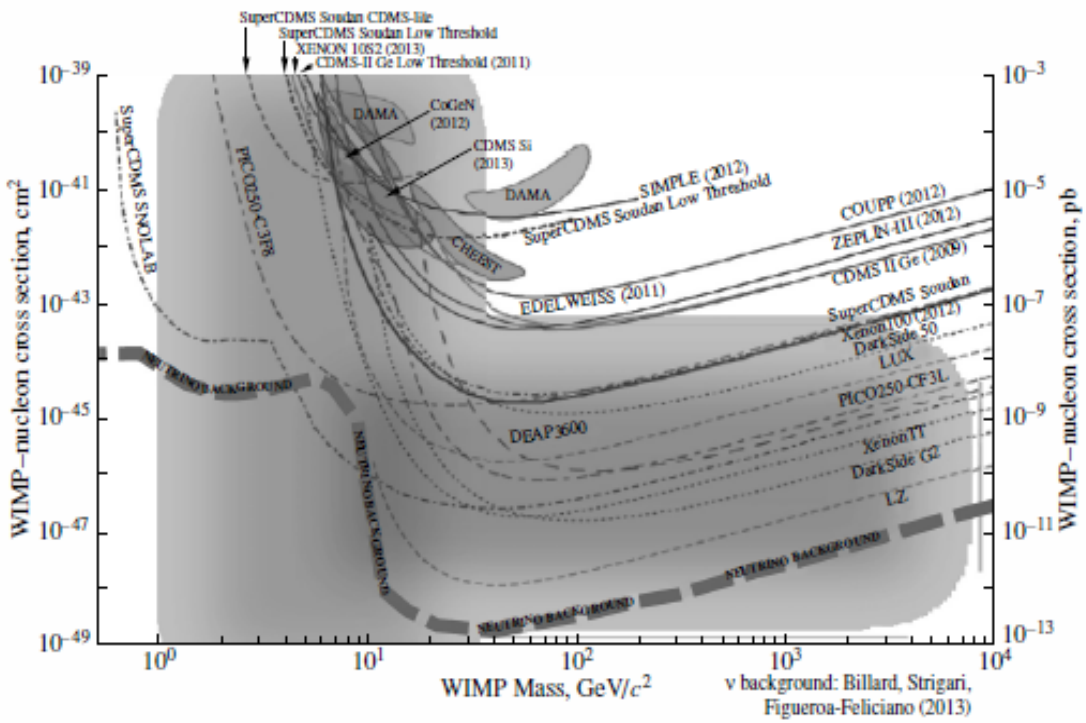

Fig. 5. Survey of the results on dark-matter searches and potential of future experiments (shaded regions).

the neutrino-mass hierarchy and at an observation of CP violation in the lepton sector. The layout of this experiment, where the neutrino base flight is 1300 km, is shown in Fig. 4. An experiment devoted to searches for a lepton-number nonconservation in muon decay to an electron and a photon would make it possible to improve constraints on the probability for this decay by four orders of magnitude or to discover it. This experiment is planned at the Fermilab and is referred to as Mu2e. Measurement of the quantity $g-2$ for the muon to a high degree of precision would make it possible to obtain an answer to the question of whether the previous indications of deviations of the experimental $g-2$ value from the

Standard Model prediction are true or whether they are due to the experimental errors or uncertainties in respective theoretical calculations. This experiment, referred to as a g-2 one, is also planned to be performed at the Fermilab.

Many experiments of great interest are planned in the realms of astrophysics. They will deal with searches for dark matter and dark energy (in many cases, by methods developed for particle detection at accelerators) and searches for sources of very high-energy cosmic rays and will also address issues associated with the origin and evolution of the Universe. Figure 5 shows the results of searches for dark matter and the potential of future experiments (shaded regions).

FUTURE PROJECTS

The total cost of all proposed experiments and projects examined by the American Physical Society in the summer of 2013 (about seven billion dollars) exceeds the expected financing by a factor of three to four. This is indicative of a large number of interesting ideas, among which it is necessary to choose only the most important ones. The results of work of the P5 committee on the choice of projects became known in May 2014.

CONCLUDING COMMENTS

Particle physics in the United States passes through an intermediate period after the large accelerators at the SLAC and Fermilab ceased operations. In the summer of 2013, the American Physical Society performed an extensive work on the preparation and discussion of products in high-energy physics. The most important problems in particle physics were formulated for the next ten to twenty years. Project X, ILC, and LHC with a high luminosity were recognized as the most promising projects with the next ten years. A large number of proposals for experiments not only at accelerators but also in astrophysics, basically aimed at searches for dark-matter particles, were examined. So large a number of interesting problems creates a sound basis for a continuation of an active collaboration between Russian and American physicists.

REFERENCES

1. J. L. Rosner et al., Report FERMILAB-CONF-13-648 (Fermilab, Batavia, 2013); arXiv:1401.6075 [hep-ex].
2. http://www.snowmass2013.org/tiki-index.php