STRATEGY AND RECOMMENDATIONS FOR THE DEVELOPMENT OF PARTICLE PHYSICS IN GERMANY

Particle physics explores the innermost structure of matter, space and time and the fundamental forces of the universe. Initially an outgrowth of atomic and nuclear physics, it developed into a research field on its own through the construction of large particle accelerators in the second half of the 20th century. Particle physics has a long and successful tradition in Germany and, based on current technological and scientific developments, offers outstanding prospects for the future.

Experiments using high-energy particle beams have uncovered the intriguing facts that, in addition to the electrons in the atomic shell, other electron-related leptons exist, and that the protons and neutrons, which form the atomic nucleus, are made up of smaller objects, the quarks. According to our understanding, leptons and quarks are the elementary building blocks of matter as we know it. An equally astounding breakthrough occurred in the study of the fundamental forces. In addition to the long-known gravitational and electromagnetic forces, two other forces were discovered: the weak force, which is responsible for the decay of radioactive nuclei, and the strong nuclear force, which binds quarks together inside protons and neutrons, and which binds the protons and neutrons to each other inside the nuclei. Furthermore, precision measurements of the interactions of leptons and quarks led to the impressive confirmation of the theoretical prediction that the electromagnetic and weak forces are actually different manifestations of the same force. The knowledge of the outstanding role of symmetry and symmetry breaking in the microscopic world has equally profound and far-reaching consequences. They not only provide a decisive key to explaining the properties of leptons and quarks and their interactions but also, in their interplay, to the fundamental understanding for the inexhaustible variety of phenomena in the macroscopic world.

Research into the elementary building blocks of matter and the fundamental forces in the universe has revolutionised our understanding and knowledge of the origin, the structure and the future evolution of our world. A major factor in this success has been the high-energy accelerators: over the past ten years, these have been largely the LEP electron-positron accelerator at the European research laboratory CERN in Geneva, the SLC electron-positron collider at the Stanford Linear Accelerator Center SLAC in California, the HERA electron-proton facility at the *Deutsches Elektronen-Synchrotron* DESY in Hamburg, and the Tevatron proton-antiproton accelerator at the US research centre Fermilab in Chicago. More recently they were joined by the so-called “B-meson factories” PEP-II at SLAC and KEK-B at the KEK research centre in Tsukuba, Japan: both are electron-positron accelerators that run at a lower energy suited to their specific physics goals. Groundbreaking theoretical insights, analyses and precision calculations have played an equally important role in the successful development of particle physics. The results of the close collaboration between experiment and theory are manifested in the Standard Model of particle physics, a 20th-century achievement the significance of which ranks alongside that of Maxwell’s theory of electrodynamics and Einstein’s theory of relativity.

Driven by the extreme technological demands of high-energy particle accelerators and highly sensitive particle detectors, experimental particle physics quickly organised and coordinated itself at an international level in order to make effective and targeted use of the resources available. This international cooperation not only brought the desired success in deciphering the laws of nature. It also led to the development of new methods and technologies, with a broad potential for applications in other branches of science, the economy and everyday life.

As knowledge and technological know-how have increased, a phenomenon could be observed in particle physics that is typical for the fundamental sciences. Each new piece of knowledge generates new and deeper questions and new theoretical and experimental challenges. These are the motor for developing new ideas, theories and technologies, for planning and building new research projects and for training new generations of highly motivated and qualified scientists.

Despite the great advances in our understanding of the fascinating world of leptons and quarks, particle physics is anything but a completed field of science. Some of the central open questions being asked today, which touch on the very foundations of our world view, are as follows:

- How do elementary particles acquire their mass?
- Is there one universal interaction from which all known fundamental forces, including gravity, derive?
- Are there forms of matter undiscovered up to now, such as a whole new world of supersymmetric particles? Could this be the explanation of the “dark matter”, whose existence is suggested by the large scale structure formation of galaxies and the movement of the stars inside galaxies?
- What is the nature of the “dark energy” that causes the universe to expand at an ever-increasing rate?
- Are there hidden dimensions in addition to the three spatial dimensions that we are familiar with?

Compelling theoretical arguments and indirect experimental indications suggest that the answers to at least some of these questions ought to lie in the mass range between a few hundred giga-electronvolts (GeV) and several tera-electronvolts (TeV). That equates to more than a hundred to a thousand times the proton mass and, for the most part, lies outside the reach of today's accelerators. Comprehensive and precise investigation of physics at the TeV energy scale is *the* major challenge for particle physics in the coming 15 to 20 years – a challenge that can only be taken up through worldwide cooperation.

This document presents recommendations for the future development of particle physics in Germany in the next 15 to 20 years, based on the current status of knowledge, the theoretical perspectives and the experimental options, while taking into account the available resources.

The LHC proton-proton collider, with a centre-of-mass energy of 14 TeV, is presently being built at CERN in Geneva. Such a high energy is required in order to attain energies in the TeV range for the collisions of the elementary building blocks within the proton. In parallel, high-energy physicists throughout the world are constructing components for four large particle detectors for the LHC experiments. Operation should begin in 2007. For the time being, the LHC project has the highest potential for ground-breaking discoveries that will shed light on the open questions outlined above and to be discussed in greater detail later in this document.

Recommendation 1: *Highest priority is given to the swift completion of the Large Hadron Collider LHC under construction at CERN and of the LHC detectors, so that the facility can commence operation in 2007.*

The demands of the LHC experiments with respect to detection and measurement methods as well as data acquisition and processing are extreme. Indeed the huge quantity of data they will produce is comparable with the entire data volume processed by the world's telecommunications systems. As is well known from the past, the solutions to such problems will also create spin-offs in other fields and applications. Perhaps the greatest benefit of all will be the throngs of young people attracted by the prospect of excellent education and by the fascination for international teamwork.

Finding *all* answers to the above-mentioned questions through direct experimental investigations would call for energies far beyond those attainable with any particle accelerator. Nonetheless, access to these answers can be obtained indirectly at realisable high-energy accelerators by means of high-precision measurements. These precision measurements can reveal the structure of physics at very high energy scales after performing well-controlled extrapolations. The strength of this method has already been demonstrated by the LEP and SLC experiments, for instance, in the indirect determination of the mass of the top quark, later confirmed by direct measurement at Fermilab. The prerequisite for such extrapolations, however, is a far more accurate analysis of particle properties and processes than the LHC experiments alone are capable of providing. Moreover, a high level of sensitivity is required to corral the new physics beyond the Standard Model which cannot be investigated by the LHC, or at least not sufficiently. Detailed studies performed in international cooperation have shown that the required measurements can only be carried out at an electron-positron linear collider. For this reason it has been decided by worldwide consensus within the particle physics community, that the next major high-energy physics project should be the construction of a linear collider with a total energy of 0.5 to 1 TeV.

The new data and knowledge that can be expected from this linear collider will be greatly complementary to the results obtainable at the LHC. From the scientific viewpoint, an overlap in time with the physics programme at the LHC is imperative. Experience with electron-positron facilities such as LEP and the corresponding hadron accelerators such as the Tevatron demonstrate impressively the synergy effects that can be derived from such concurrent experimentation.

Recommendation 2: *The next large international particle physics project should be a high-energy and high beam-intensity electron-positron linear collider. Germany should make a significant contribution to such a facility, wherever it is built in the world under international cooperation.*

At the initiative of DESY, superconducting accelerating structures have been developed over years of international collaboration. This has laid the technological foundations for the TESLA project, an electron-positron linear collider with a centre-of-mass energy of 0.5 to 0.8 TeV. This successful accelerator development also makes feasible the construction of an X-ray laser, which opens up new interdisciplinary research fields in materials science, biology, chemistry and medicine. For many years DESY has been operating a number of unique machines allowing high-energy physics and synchrotron radiation studies to be performed in symbiosis. This is documented by its large international user community. Bearing in mind DESY's prominent role, the development work already undertaken, the available infrastructure and the highly attractive combination of particle accelerator and X-ray laser serving a broad field of scientific research, Hamburg is an excellent location for TESLA. Germany would profit as Host State from this worldwide project via the education and engagement of scientists, engineers and technicians. Leading researchers from home and abroad would be attracted, and new technologies would be developed and transferred to Industry. All of these benefits would more than offset the additional costs incurred to the Host State.

Recommendation 3: *The efforts to build the TESLA electron-positron linear collider under international cooperation at DESY in the near future are strongly supported.*

In July 2002, the German Science Council *("Wissenschaftsrat")* released a positive statement on the TESLA project.

A further investment essential to ensuring a successful future for particle physics in Germany is the continuation and successful completion of the ongoing experiments at HERA, the Tevatron and the B-factories. These accelerators and experiments continue to possess a high discovery potential. With these facilities an abundance of important new data can be collected that will also be of great use in the analysis and interpretation of measurements at the LHC and at a future electron-positron linear collider. One example is the measurement of the inner quark structure of the proton in electron-proton collisions at HERA, with a resolution of up to one-thousandth of the proton radius. Another is the search for new particles and for the fundamental mechanism for generating particle masses at the Tevatron. A further example is the research into the microscopic origin of the puzzling difference in behaviour between matter and antimatter, as is being conducted at the B-factories.

Finally the start-up of special experiments aimed at very specific questions in fields which cannot be covered by LHC and TESLA, such as neutrino physics, particle astrophysics and rare low-energy processes, is equally worthwhile. Neutrino experiments, above all, have substantially gained in scientific interest in the light of the recent discoveries of neutrino oscillations. Such a well-coordinated, diversified programme also ensures the continuing education of the upcoming generation of young scientists in all fields of particle physics. Despite the very long preparation times for future projects, this will preserve the expertise required to overcome their demands.

Recommendation 4: *Until the completion of the LHC, the continuation of the experiments at HERA and of German participation at the Tevatron is recommended. Furthermore, within the scope of available resources, participation in the B-factories and in neutrino and non-accelerator particle physics projects should be made possible.*

In the long term, accelerators will remain indispensable for the further development of particle physics. The studies relating to a multi-TeV electron-positron linear accelerator (CLIC), to a Very Large Hadron Collider (VLHC) or to the new concept of a neutrino factory and a muon collider still require many years of R&D. At present no detailed recommendation can be made on the construction of these large facilities which will extend well beyond the 15-20 year time span being considered in this document. But since new accelerator projects require decades of substantial R&D, the continuation of accelerator and detector technology research is necessary to prepare for the as yet unforeseeable challenges of particle physics.

Recommendation 5: *Research and development into accelerator and detector technologies must be continuously pursued.*

The strategy recommended here for the coming 15 to 20 years has its roots in the success achieved in this field of fundamental research over the past decades. Based on the present status of knowledge and technological progress, this strategy indicates a road towards a future full of promise. With particle physics groups in more than twenty universities and with CERN, the Helmholtz Centre DESY and the Max-Planck Institutes, Germany has reached a high scientific level by international standards. The universities have played an essential part in this process – without their leading role in the education of undergraduates and PhD students and without their contributions to the experiments and to the development of vigorous particle physics theory, the dynamics of this field could not be preserved.

As a knowledge-oriented field of fundamental research, particle physics in Germany is exclusively dependent on public financing from the Federal Government and the States *("Länder")*. The German contribution to CERN is financed by BMBF, the German Ministry for Education and Research, as is 90% of the budget for DESY. The other 10% of the costs for DESY Hamburg are carried by the State of Hamburg and 10% of the costs for DESY Zeuthen by the State of Brandenburg. The financing of the Max-Planck Society is shared between the Federal Government and the States. The States also provide considerable resources for personnel, basic equipment, workshops and general infrastructure in the university institutes. The Federal Government enables the university groups to participate in major particle physics projects within the framework of the integrated research system *("Verbundforschung")*. Indeed Germany's integrated research system has proven to be very successful and should definitely be maintained in future. Finally, theory groups and the education of graduates are sponsored by the German research foundation *("Deutsche Forschungsgemeinschaft")*.

By maintaining this well-focussed and highly efficient sponsorship system and with a strong participation in the LHC at CERN, a high level commitment towards an electron-positron linear collider, in particular TESLA at DESY, and a balanced accompanying programme, Germany will be able to continue playing a leading international role in the field of particle physics. In return, as we move ahead into the future, society can expect particle physics to be a source of new knowledge of great and enduring cultural value, of avant-garde technological developments, of spin-offs for other areas of science and economy, and of highly qualified young scientists, engineers and technicians.

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