Research at CERN To-day and To-morrow

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Located near Geneva on the border between France and Switzerland, CERN is a European laboratory for the study of particle physics serving over 5000 users from all over the world.

An asset of the Laboratory has always been the diversity of the experimental programmes which it offers to the research community. Alongside the flagship experiments at the high-energy frontier (yesterday at the SPS, to-day at LEP and to-morrow at the LHC) the pursuit of research activities at lower energies on the accelerators of the older generations is an important element in the success of CERN. The motivation is not merely the cost-effective exploitation of the existing accelerator infrastructure used in the injection chain to the highest energy collider. It is the recognition that the high-energy frontier is not the exclusive domain for new discoveries. For lower-energy research programmes to be welcome, excellence is the main criterion, and the resources they draw from CERN must be sufficiently modest not to impair the pursuit of the higher-energy programme in adequate conditions. In addition, there must exist very strong reasons for accommodating such programmes at CERN rather than elsewhere.

The current users community is split more or less evenly between LEP and the lower-energy programmes, which include ISOLDE, LEAR, the fixed-target SPS programme and the heavy-ion programme. A significant migration of nuclear physicists from national accelerators to the latter programmes has taken place during the past ten years and is expected to continue. In the decade in front of us, 1995 to 2005, the evolution of the research programmes will follow scientific priorities while, at the same time, leaving free resources for the preparation of LHC experiments.

The LEP Programme

Currently operated on the Z peak, LEP will have its energy doubled in 1995 in order to explore the region above the W pair threshold and to extend further its reach for new particle searches. At the end of the century it will shut down for LHC installation. Physics at LEP will therefore cover the first half of the period under consideration.

In its current mode of operation LEP will have collected an integrated luminosity nearing 150 pb^{-1} in each of the four experiments by the end of 1994 and will have given unique and outstanding contributions to a very rich set of physics issues:

- Very high precision measurements of the electroweak parameters of the Standard Model at the level of a few per mil, including that of the Z width resulting from the 1993 energy scan. They severely constrain the number of neutrino families, the mass of the top quark, and the lower mass sector of whatever may exist beyond the Standard Model. An accuracy of 7 MeV on the Z mass and width has been achieved from the very precise measurement of the beam energy. The method consists in fine-tuning the frequency of an horizontal oscillating magnetic field to destroy the natural transverse polarization (up to 50%) which builds up from the emission of synchrotron radiation. A detailed understanding of systematic effects affecting this measurement has recently been obtained, providing spectacular evidence for the deformation of the earth crust induced by the moon and sun. An accuracy of 2 MeV should be ultimately obtained.
- Detailed studies of quantum chromodynamics in its perturbative regime, taking full advantage of the unprecedented laboratory provided by hadronic Z decays. Accurate and consistent measurements of the strong coupling constant have been obtained from several independent methods, providing clear evidence for its q^2 dependence.
- Searches for new particles, including Higgs bosons and supersymmetric partners of the particles which are known to-day. The current limit on the standard Higgs boson mass exceeds 50 GeV.
- Sudies of short-lived particles, tau lepton and B hadrons, with important contributions to the knowledge of their lifetimes and decay modes. The exploration of the B sector has been particularly successful with the observation of individual B_s decays and the evidence for B^0-$\bar{B}^0$ oscillations at a confidence level of 99%. The measurement of

their frequency makes it possible to evaluate the B_1-B_2 mass differences

$$\Delta m_d = (3.3\,^{+.5}_{-.4} \pm .7)\,10^{-4}\ \text{eV}$$

and $\Delta m_s > 12\,10^{-4}$ eV.

By the end of 1994, LEP will start its conversion to higher energies where W pairs can be produced. Together with the detailed study of the Z, this was an essential motivation in the decision to construct a collider of such an ambitious design. By then, significant further progress at the Z peak could not rely on simply increasing the statistics, as this would take far too long with present luminosities. Our current understanding of the limitations in reaching high luminosities seems to imply that a major increase, say by an order of magnitude, is out of reach. An attractive possibility, which has been the subject of detailed studies, would have been the performance of a high precision measurement of the left-right asymmetry parameter, A_{LR}, using longitudinally polarized beams. However, the success of SLC in reaching high polarizations makes this option much less competitive than previously assumed.

Doubling LEP energy is a project on which the Laboratory has concentrated major efforts and resources for several years now. It will open a new region to exploration with three major physics issues to be addressed:

- A major extension of LEP's reach for new particle searches. Particularly appealing in this context is the existence of supersymmetric models which predict a low-mass Higgs boson with properties very similar to the standard Higgs boson. At tree level the mass of such a supersymmetric Higgs should not exceed the Z mass, but radiative corrections raise its upper limit to 150 GeV or so. The reach of LEP in this regime being approximately $\sqrt{s}$ - 100 GeV, the exploration of a major fraction of the supersymmetric Higgs domain will be possible. However, its higher energy part, requiring beam energies up to 130 GeV, will obviously remain out of LEP reach but will be open to LHC experiments.
- A direct study of the ZW W coupling, which interferes destructively with neutrino exchange in the t-channel, and is of fundamental importance for the understanding of electroweak interactions.

- A precision measurement of the W mass, improving the error on the ultimate $\bar{p}p$ collider result by a factor of at least 2.

Technically, doubling LEP energy is a major enterprise which implies the installation in the LEP tunnel of 192 superconducting cavities which should make it possible to operate at nearly 90 GeV per beam from 1996 onward. It must be noted that the LEP research programme will be at least as demanding on luminosity as on energy, the relevant cross sections being typically three to four orders of magnitude below those at the Z peak. For this reason, it has been decided to replace the present copper cavities by 32 additional superconducting cavities of lower impedance, which can therefore accept higher beam currents. It is hoped in this way to reach $4\ 10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ and to collect of the order of $500\ \mathrm{pb}^{-1}$ per experiment during the period under consideration. It is premature to-day to be more specific on the optimal working point in the energy-luminosity space. Experience with the operation of a large number of superconducting cavities and running the machine with very large synchrotron radiation losses per turn are necessary prerequisites to more detailed considerations.

The four LEP detectors are in the process of getting prepared to approach the exploitation of higher energy collisions in optimal conditions. In particular they will all be equipped with high performance silicon microvertex detectors which considerably enhance their discovery potential. Special attention is currently being given to the design of adequate systems of collimators in order to protect the detectors from the intense synchrotron radiation background which will prevail at higher energies. The experimental programme will benefit to an even greater extent than now from the existence of four detectors because of the need to collect the highest possible integrated luminosity.

The Heavy-Ion Programme

After a pause of two years to allow for the installation of the new injector constructed in collaboration with several European institutes the ion programme will resume operation in 1994 with much heavier projectiles than was previously possible. During the first years of the period under consideration a run will be scheduled at the end of each year with a typical duration of two months to feed a number of experiments which are currently preparing for the event.

Ion experiments have been an important element of the CERN research programme for several years now. In a first phase they have used medium-mass ion beams, first oxygen and then sulphur, accelerated in the SPS to approximately 200 GeV per nucleon. Their main motivation has been the study of a region of temperature and density where quarks and gluons are no longer expected to be confined inside hadrons, an essential prediction of non-perturbative quantum chromodynamics. The challenge of exploring this new domain, which must have played an important rôle in the genesis of the Universe, was two-fold. On the theoretical front, our inability to perform accurate calculations in this regime prevents quantitative predictions and provides at most qualitative guidance to name signatures of the deconfined phase in which the colliding ions spend only a very short period of time. On the experimental front, the very high multiplicities which characterize the final state are a major difficulty which the detectors and the data analysis techniques must overcome. These challenges have been taken up successfully by the oxygen/sulphur experiments, which have provided evidence for the production of high temperature-density intermediate states and which have identified signals within reach of their experimental capabilities which are good candidates for signatures of the deconfined phase.

As a result, the programme has naturally developed into a second generation phase using projectiles in the lead region with the aim of increasing considerably the volume and lifetime of the quark-gluon plasma in the hope of making the effects of its existence more clearly visible than was previously possible.

In order to approach this new phase of ion physics, some experiments require only modest upgrades which are currently nearing completion. Such is the case of NA44 which measures the size of the plasma when it cools down into hadrons using interferometric techniques, NA50 which studies J/ψ production and measures the mass spectrum of muon pairs, WA97 which detects strange baryons in the OMEGA spectrometer, and WA98 which focuses on photon production. Other experiments could not have survived the very high multiplicities characteristic of heavy ion collisions and had to be completely redesigned. Such is the case of NA49 which will use large Time Projection Chambers to disentangle the complex pattern of charged particles produced in the final state. While some experiments will be completed after a few years, NA49 can be expected to run much longer and eventually to serve as a facility for performing more advanced experimental studies.

The heavy-ion programme will pave the way for the exploitation of the LHC as an ion collider and its development in time will allow for a smooth transfer of the community from the SPS to the LHC.

The SPS Fixed-Target Programme

Over the years, when high-energy colliders ($\mathrm{S\bar{p}pS}$ and LEP) became available, the number of experiments accommodated in the SPS fixed target programme has kept decreasing. To-day it focuses on a few experiments of very high quality which in their initial state require particles which cannot be stored in colliders, such as pions, hyperons, muons, neutrinos and neutral kaons.

A rich programme of spectroscopy is currently active in the OMEGA spectrometer with WA89, WA91 and WA92 but should not extend beyond 1996 when the West Area will shut down.

In EHN2 the SMC experiment (NA47) studies the spin structure of the nucleon via the deep inelastic scattering of longitudinally-polarized muons on a target of longitudinally-polarized nucleons. The interest in such studies was triggered from the observation that the spin carried by valence quarks is a small fraction of the total nucleon spin. Current results on proton and deuteron targets confirm this earlier observation and are consistent with the predicitons of the Bjorken and Ellis-Jaffe sum rules. Improved statistical accuracy will soon bring further insight in the problem and contribute to a better understanding of quantum chromodynamics in this sector.

Two neutrino experiments, CHORUS (WA95) and NOMAD (WA96) are currently being assembled and will detect the first interactions produced by the refurbished neutrino beam at the end of 1993. Their aim is to observe interactions induced by tau neutrinos generated from oscillations in the incident muon neutrino beam. They will be able to probe an unexplored region of neutrino masses and mixing parameters where astrophysical data suggest that oscillations may take place. CHORUS is an emulsion experiment and constraints on the exposure time impose a prompt completion by the end of 1995. Of course, a second exposure using new emulsions cannot be excluded if the performance of the first run demands such an extension. NOMAD is a counter experiment which uses the UA1 magnet and identifies tau neutrino interactions from the characteristic topology of their kinematics. Its approach to the problem is complementary to that of CHORUS.

A possible future of the neutrino research programme will be easier to plan when the results of CHORUS, NOMAD and various underground neutrino experiments are available. Physics will dictate how it could be pursued. In this context, mention must be made of the potential interest of producing neutrinos from one of the LHC transfer tunnels pointing to the Gran Sasso Laboratory, thus making possible the detection of oscillations over a very long time base.

The CP violation experiment NA48 completes the list of experiments currently scheduled in the SPS fixed target programme. It is the successor of a long series of experiments which have studied CP violation in the neutral kaon system with increased accuracy. Together with its American competitor, the CERN predecessor of NA48 has measured the direct CP violation parameter at only three standard deviations from zero ($\mathrm{Re}\ \varepsilon'/\varepsilon = 1.48 \pm 0.43\ 10^{-3}$). While this result is consistent with the expectations of the Standard Model with a mass of the top quark in the 150 GeV region, the challenge of establishing the evidence for direct CP violation on firmer ground is obvious. Such is the aim of NA48 which should start operation in ECN3 in 1995 with new beam and detector designs in order to reduce very significantly the effect of systematic uncertainties. It is difficult to-day to predict accurately how long NA48 will need to run in order to achieve its goal, but five years seem a reasonable guess.

Other smaller experiments, which are part of the current fixed-target SPS programme, and which should be completed by 1995, have not been mentioned. The feasibility of open-ended fixed-target operation will always make it possible to accommodate more experiments if physics demands it.

The LEAR programme

The LEAR research programme has now reached maturity and is currently producing important results in the fields of meson spectroscopy and CP violation in the neutral kaon system.

Three large experiments, OBELIX, Crystal Barrel and JETSET take advantage of the large gluon content of $\bar{p}p$ annihilation final states to search for light mesons which cannot be accommodated in the conventional nonets, such as glueballs, hybrids and multi-quark states. Particularly successful are Crystal Barrel and OBELIX, which efficiently complement each other in the study of multi-pion final states where evidence for new mesons has been found. In particular evidence has been obtained for the simultaneous presence in the 1500 MeV region of a 0^{++} and a 2^{++} state which can both decay into a pair of π^0's. While the former is an excellent glueball candidate, a likely interpretation of the latter is a nucleon-antinucleon bound state. A minimum of two additional years will be necessary to complete this study and to obtain a clean understanding of the properties of the newly discovered mesons.

The CPLEAR experiment studies CP violation in the decay of tagged neutral kaons, an approach complementary to that taken by NA48. While CPLEAR cannot compete with NA48 in giving evidence for direct CP violation, it brings significant improvements to the measurement of several other parameters which are determinant in our understanding of CP violation.

Many other experiments use LEAR to approach problems of atomic and nuclear physics from an original angle and their contributions to their respective fields are often outstanding. Of particular interest is experiment PS196 which traps very cold antiprotons for very long periods of time, making it possible to measure the $\bar{p}/p$ mass ratio to an accuracy of 10^{-9}. Such a result opens very attractive perspectives on the possible use of ultra-low energy antiprotons in atomic physics, such as the study of the spectroscopy of antihydrogen. However, the pursuit of such a programme would require many years before coming to fruition, and is incompatible with the planned termination of the LEAR research programme by the end of 1996.

A very elegant experiment, PS205, deserves a special mention. It has recently provided evidence for a $\bar{p}$He metastable atomic state populated by stopping antiprotons in helium. The transition to an Auger unstable state with very short lifetime is induced by laser excitation.

The ISOLDE programme

The ISOLDE facility was recently moved from the shut down synchrocyclotron to the PS Booster. It has now resumed operation successfully and the hopes which had been entertained in terms of production yields and background conditions have realized. Early difficulties experienced in the use of liquid targets in a high-intensity pulsed beam have now been overcome. While a rich programme is currently under way on the general-purpose separator, the preparation for the installation of the high-resolution separator is in progress.

The ISOLDE research programme covers a large number of topics which will certainly justify its pursuit until the end of the century. It includes

- broad systematic studies of nuclear ground state properties with laser techniques and ion traps;
- the study of exotic nuclear decay modes and nuclear structure at the limits of stability, where ISOLDE has played a pioneering rôle;
- experiments on nuclei which are important for the understanding of the r- and s- processes in astrophysics;
- low-energy studies of fundamental interactions at the interface between particle, nuclear and atomic physics;
- solid state surface physics and the investigation of impurities and defects in semi-conductors;
- production of isotopes for medical physics with a view to develop new diagnosis and therapy techniques.

The ISOLDE community has expressed interest in building at CERN a unique world facility for radioactive beams, providing exotic beams up to 6-10 MeV per nucleon for astrophysics and nuclear physics studies. If such a development cannot be *a priori* excluded, very good reasons would have to be given to accommodate such a facility at CERN rather than elsewhere. While the Laboratory is encouraging the participation of the ISOLDE community in design and R&D studies in this direction, it would exclude competing with other laboratories to accommodate it on its site.

The LHC Programme

Two essential elements of the Standard Model are still awaiting experimental confirmation: the top quark and the Higgs sector. The former is expected to emerge soon from the CDF and D0 data at Fermilab. The latter is central to the mass generation and SU(2) x U(1) symmetry breaking mechanisms. Without it the Standard Model fails to accommodate the non-zero mass of the weak boson triplet within a renormalizable framework. Its exploration is therefore of paramount importance. Fortunately its mass scale, related to the weak boson masses, is such that it seems within reach of our current technical possibilities as the phenomena associated with it are expected to occur below one TeV. In the most economic version of the Standard Model a single Higgs boson should exist within this range. In more elegant versions making use of supersymmetry several such bosons would be present, one of them below 160 GeV, together with at least some of the supersymmetric partners of the currently known particles. It is therefore not surprising that CERN has set as its next objective the exploration of this domain.

A new tool is required for this exploration, a collider covering the TeV mass range with adequate luminosity. The choice of a pp collider, rather than $\bar{p}p$ or e^+e^-, is dictated by straightforward technical considerations. The high luminosities required are out of reach of $\bar{p}p$ colliders and present linear collider technology makes it impractical to cover the required energy range with sufficient luminosity. Moreover, the traditional attractive features of e^+e^- colliders are of considerably lesser interest in this case where the most important processes occur in the collision of two bremsstrahled weak bosons rather than in the annihilation channel.

The CERN design, LHC (for Large Hadron Collider), is a proton-proton collider installed in the 27 km long LEP tunnel with beam energies reaching up to 7 TeV. Together with a very large luminosity in excess of 10^{34} cm^{-2} s^{-1}, this makes it possible for the whole TeV mass range to be covered in such a way that the processes which are expected to be of interest should be revealed in a reasonable amount of time. The guide dipoles are superconducting two-in-one magnets operated at superfluid helium temperature. The stored beam energy approaches 700 MJ, imposing severe constraints on the accelerator design. The use of existing infrastructure lowers considerably the cost of the collider, by a factor of two in comparison with what it would be if a new laboratory had to be constructed in a green field. Approval of the project is expected in 1994 which would enable physics to start in 2003.

Two large detectors, ATLAS and CMS, are being designed to address with complementary approaches the physics issues of interest. They should detect a standard Higgs boson having a mass below 800 GeV from its ZZ or $\gamma\gamma$ decay modes. New particles such as heavy leptons ($L \rightarrow W\nu$), heavy quarks ($Q \rightarrow Wq$), heavy gauge bosons (W/Z', W_R), leptoquarks ($D \rightarrow lq$), supersymmetric partners of new particles ($\tilde{q}, \tilde{g}, \tilde{e}, \tilde{w}$) should be revealed in mass ranges reaching between several 100 GeV and several TeV. The design and operation of ATLAS and CMS are very challenging as they need to cope with extremely high multiplicities and event rates. Fast, radiation hard electronics must be developed at sufficiently low cost to equip millions of channels.

In addition to the exploration of the TeV mass range, the LHC will also produce a crowd of B hadrons in a dedicated experiment which will be competitive with the B factories under construction at SLAC and KEK. Operation with colliding heavy ions will offer a new window on the deconfined phase of the quark-gluon matter, well above the reach of RHIC. A dedicated experiment, ALICE, is being designed for this purpose. Finally, in a more remote future, protons from LHC could be made to collide with electrons from LEP, thereby extending the current HERA domain up to $\sqrt{s} = 1.3$ TeV with a luminosity of $2\ 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

Summary

Physics at CERN to-day is dominated by the very rich LEP programme where Z bosons are produced copiously and make it possible to challenge the validity of the standard model with an unprecedented degree of precision. LEP has turned out to be also a superb laboratory for the study of perturbative QCD, of tau leptons and B mesons, and for searching for new particles.

From 1996 to 2000 its operation above the W pair threshold will make it possible to accumulate several 100 pb^{-1} and to explore a new window of masses where new particles might well be found, in particular if nature makes use of supersymmetry. In addition it will provide an accurate measurement of the W mass and offer a unique opportunity to probe the ZWW coupling directly.

Beside LEP, CERN offers a rich variety of other programmes with leading experiments in the domains of CP violation, neutrino oscillations and deep inelastic muon scattering.

Strong interactions in the non perturbative regime are explored from many different approaches including searches for glueballs and quark-gluon plasma.

ISOLDE and LEAR are the home of many elegant experiments in nuclear atomic and solid state physics.

The mass generation mechanism and the possible existence of supersymmetric partners of the known particles are undoubtedly the most fundamental question-marks of to-day's knowledge, the answers of which are almost within our reach. The construction of LHC in the coming years will allow CERN to enter the new millenium with a tool perfectly suited to the exploration of this fascinating domain of physics.