of almost equal time commutators at infinite momentum — the accepted orthodox approach — he could not resist relating the inferred scaling property to the possible presence of point-like constituents, something which was then meeting strong resistance from many. He has been given much credit by the Nobel laureates for his rôle in helping the experimentalists analyze their data and assess its implications.

The part played by R.P. Feynman at the time is also of great significance. Starting from a different corner of particle physics, namely the properties of particle production in high energy hadron collisions, he had reached the idea that hadrons were made of point-like partons. Thanks to his inspiring talks, these partons were soon recognized by many as the agents at the origin of the scaling property. They were later identified with quarks. To quote Riordan in his book "The Hunting of the Quark", "partons swept through SLAC like a brushfire" after Feynman's first presentation. Feynman could explain scaling in a language which everybody understood. But perhaps more important was the respectability he brought to an idea which seemed unorthodox to many.

Eliminating Doubt

The results of the SLAC-MIT inelastic scattering experiment were at first believed to be misinterpreted owing to possible errors introduced mainly by the radiative corrections that took account of the energy that an incident or outgoing electron could radiate as light. The scaling property eventually helped a great deal in making the observed rates much higher than those anticipated from a "soft" proton with a charge spread over its volume. By 1968 the statistics were such that it was clear that a major new effect had been found.

It still took a considerable effort by the same team to fully establish the scaling property through an extension of their analysis to larger angles, and therefore lower cross-sections, and to eliminate experimentally all other "explanations" which were of course readily ventured to avoid the need for point-like structures.

The behaviours of the two independent structure functions which contain the dynamical part of the scattering cross-section had to be separated. Scattering off deuterons had to be done in addition to the initial experiments on hydrogen to compare the proton and neutron responses in terms of these structure functions. By 1972, the point-like constituents were there to stay; they could also be identified with quarks. Moreover, CERN's experiments on deep inelastic neutrino scattering in the Gargamelle bubble chamber started to provide strong supporting evidence for the identification of the point-like scatterers as quarks.

Into The Future

We understand today how each of the quark types with their different flavours exists in three states differing by a property called colour. The quarks interact strongly *via* the exchange of massless vector bosons (or gluons) which themselves exist in eight colour states, and the quantum field theory of quarks and gluons, called Quantum Chromodynamics (QCD), represents the modern approach to the strong interaction. Quarks have never been detected as free particles owing to the long-distance nature of the strong force between coloured particles which confines quarks within the colourless hadrons that are observed. We appreciate therefore how coloured objects like quarks can form colourless hadrons and yet never appear as free particles. One also understands how the scaling property emerges at large transferred energy and large q^2, but not as an exact property since logarithmic deviations originating from the radiation of gluons by the scattered quarks have to be acknowledged.

With the great steps forward of the seventies and early eighties, and the successes of the Standard Model, the electroweak theory of Glashow, Salem and Weinberg combined with QCD, which recently emerged with flying colours from the first round of LEP experiments (see *Europhysics News* **21** (1990) 166), one now understands rather well the deep structure of hadrons in terms of point-like quarks. Indeed, many predictions thus inferred have been verified. Hadrons containing at least one quark or antiquark of the first five flavours have been observed. The sixth quark, the heaviest called "top", remains unidentified (see page 203) and collisions between quarks in future colliders are expected to probe much deeper into the structure of matter (see below). And all of these past and future developments started with the beautiful experimental result of 1968 which has now been acknowledged with the 1990 Nobel Prize in Physics.

LHC Physics

CERN's Theory Division looks beyond LEP and the Standard Model in describing the physics potential of a future proton-proton collider.

The LEP accelerator at CERN is now fully operational so it is legitimate to prepare for the steps beyond the machine's further development (which is in progress and mainly involves boosting the energy to 200 GeV by installing superconducting RF cavities). The underlying rationale is clear-cut — to reach a more profound understanding of the way the world is built and works, physicists seek greater unity and simplicity in descriptions of the physical world by probing the structure of matter to increasing depth. For behind the enormous variety and complexity of structures met in our everyday experience, there is a basic description in terms of fundamental constituents and interactions. At today's level of scrutiny of 10^{-18} m we have found quarks and leptons — fundamental point-like components. Their interactions as summarized by the Standard Model are the building blocks of matter — hadrons, nuclei and eventually atoms and molecules — and they show a cohesion never met before in physics.

The Standard Model is a relatively recent achievement which must be thoroughly tested. CERN's LEP machine that began operating in July 1989 was designed with this in mind, by continuing with greater accuracy the exploration started at the organization's $\bar{p}p$ collider. For according to the quantum rules governing sub-atomic physics, the price to pay for resolution is energy. So to probe in detail the structure of matter at the level of 10^{-18} m one needs the 100 to 200 GeV provided by LEP. The physics we meet is the one which prevailed when the expanding Universe was a tenth of a nanosecond old. It is only in this distant past that the many questions raised by the observation of the Cosmos at large can find their answers.

Despite the Standard Model's relative simplicity it is not the ultimate in physics. A natural progression in expanding the model is an order of magnitude increase in resolution, with an analysis of the structure of matter at the level of 10^{-19} m and, accordingly, an understanding of the physics of the Universe when it was 10^{-12} s old.

Symmetry Breaking

In both the electroweak theory, which provides a unifying framework to such diverse phenomena as electromagnetism and radioactivity, and modern descriptions of strong interactions in terms of quantum chromodynamics, the vacuum behaves as a medium. However, the symmetries fundamental to the three basic modes of interaction in the model (Fig. 1), which satisfy the quest for unity and simplicity, are broken when applied to the vacuum. The properties of the vacuum in fact seem to be similar to those met in superconductors, although in a more involved and complicated fashion. To provide the appropriate dynamics we have the complexity of the medium in the case of superconductivity: for the Standard Model there is merely a "twist" in the vacuum with an unknown dynamics, a feature which remains one of the great open problems in physics.

An effect analogous to the disappearance of superconductivity at high temperatures owing to a phase transition is expected in the vacuum. It has been predicted that the vacuum should change phase at temperatures above those equivalent to 200 GeV, whereupon the heavy masses of the W and the Z particles would disappear. As it is the vacuum that generates the masses, in seeking to identify the structure of vacuum one will thus be exploring the dynamic origin of the masses of particles. It is therefore extremely important to extend observations well beyond such energies to discover the way physics works. Studying collisions at several TeV of W's and Z's, where quarks will be radiated with a reasonable probability, is especially important as dramatic new results are anticipated at energies approaching 1 TeV.

A second objective also has to do with symmetry breaking, but in a different sense. The remarkable unity of the Standard Model naturally leads us to envisage a still greater symmetry — one that would combine quarks and leptons coupled through a unique interaction mode. We have good reasons to think that symmetry of this type indeed exists, but that such a so-called Grand Unified Theory could only operate at energies on the order of 10^{15} GeV or higher, *i.e.* at least twelve orders of magnitude beyond the TeV levels now being sought. As only fragmented remnants of such a full symmetry are detected at today's energies of 100 GeV, its realm may appear too removed from our capabilities. However, the presence of full symmetry is not an academic question since quantum theory tells us that manifestations of interactions at extreme energies can be felt as damped but quite sizable quantum fluctuations at much lower energies. Indeed, more order is observed at 100 GeV than expected, implying that disturbances by residual quantum effects from much higher energy phenomena are not as large as predicted.

Compensating mechanisms may of course arise, but these mechanisms, perhaps together with new particles and new interactions, should involve effects which manifest themselves at energies that are not much above today's limit of about 100 GeV. For if this is not the case they would not shield what is observed today from perturbations originating at much higher energies. These mechanisms, if they exist, are definitely expected to show up before reaching one TeV.

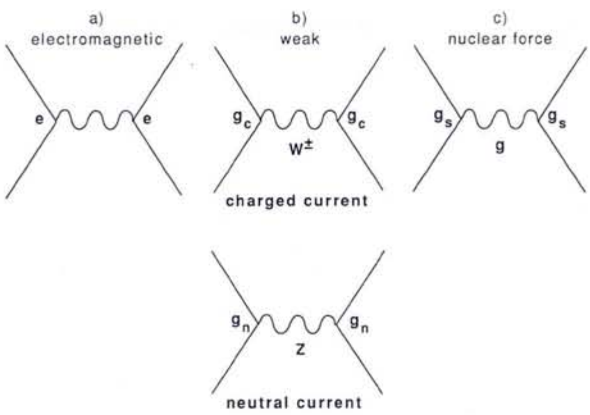

Fig. 1 — The three basic modes of interaction in the Standard Model. Although the forces are transmitted by different particles, they all have the same fundamental character: a) electrons exchanging a photon; b) quark and lepton exchanging a W or a Z; c) quarks exchanging a gluon.

To summarize, entirely new phenomena are expected to appear at energies not too far above LEP's 200 GeV, and certainly in the TeV range. At stake is the way Nature breaks its basic symmetries through "twists" of the vacuum and provides particles with their masses through two very different mechanisms, thirteen orders of magnitude apart on the energy scale. This, together with the natural curiosity to explore new ground, are the main motivations for the LHC. Moreover, in contrast to the lead up to the discovery of the W and the Z, where one was fairly confident that these particles existed, we at present have much less well-defined ideas of how Nature may work at a deeper level. The search is therefore perhaps even more interesting.

A Proton Collider for 10^{-19} m.

While the Standard Model tells us, for example, that the W's and Z's acquired their heavy masses between 10^{-12} and 10^{-10} seconds to eventually disappear from the cosmic scene, we have to understand how and why. This and many other questions presently being raised owing to the success of the Standard Model cannot be answered with LEP as its resolution is limited to 10^{-18} m. They could in principle continue to be tackled with electron-positron collisions, where a straightforward extrapolation shows that the energy must be increased tenfold (to about one TeV) to reach a resolution of 10^{-19} m. But the LEP design, while well suited to an energy of about 100 GeV, would entail much larger costs if one were to construct a similar, circular machine of much higher energy. The alternative is a linear collider which is widely recognized to be out of the question as it would be so complicated that its construction cannot be readily envisaged. Indeed, preliminary design work and feasibility studies could extend well into the next decade before construction started, cost notwithstanding.

The other route to attaining greater spatial resolutions is to use protons. They can be accelerated in circular machines to much higher energies than electrons where a considerable amount of energy is lost as radiation. Protons, however, are complicated objects comprising several constituents. What matters most when probing the structure of matter to increasing depth is the collision energy between the point-like quarks and gluons inside the proton. For quark-quark collisions, this energy is typically only one-tenth of the nominal machine energy at the proton-proton level. A machine developing several TeV is therefore required to probe structures smaller than the 10^{-10} m target at the crucial quark level.

The Importance of Hadronic Jets

Since the proton can be considered as a wide band beam of quarks, antiquarks and gluons with a large energy spread, collisions between these constituents take place over a range of energies. By raising the luminosity or beam intensity, it is possible to increase the number of observable events where the relevant quarks or gluons carry a large fraction of the energy of the protons they belong to. The clarity and spectacular character of the so-called hadronic jets (see cover illustration), a major discovery of CERN's $\bar{p}p$ collider, emerging from these collisions indicate that their observation will allow the study of quark and gluon interactions in the midst of the large amount of flying debris associated with a proton-proton collisions at such high energies. A high luminosity proton-proton accelerator would thus be the ideal instrument to explore the structure of matter at the level of 10^{-19} m.

The LHC

The LHC project involves extending CERN's proton-antiproton collider to form two separate proton beams, circulating in opposite directions, whose collision would generate the required energies and beam intensities. By being mounted on top of the LEP machine within the existing LEP tunnel, LHC would benefit from the injector system used for CERN's PS and the SPS accelerator rings, and from the cryogenic equipment that is being installed progressively to raise LEP's collision energy to 200 GeV. Powerful 10 tesla superconducting magnets for the beam lines (see *Europhysics News* **21** (1990) 90) would yield a collision energy of 16 TeV in the centre-of-mass for proton-proton collisions, with a luminosity of typically 10^{33} cm^{-2} s^{-1} and the ability to in-

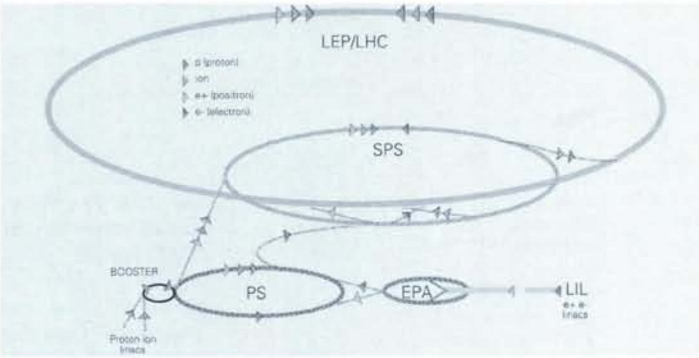

Fig. 2 — The injector complex for the proposed LHC proton-proton collider that would be mounted above the existing LEP electron-positron collider.

crease it to beyond 10^{34} cm^{-2} s^{-1} for specific purposes (the injector system is illustrated in Fig. 2).

Complementary to SSC

Important goals call for action everywhere and the United States has launched the construction of the SSC, a 40 TeV proton-proton collider with a circumference of 87 km, on a completely new site in Texas (the DoE approved US budget calls for $318 million to be spent in fiscal 1991). By exploiting important existing infrastructure, the LHC is in a position to be completed early enough to be competitive as its energy of 16 TeV is sufficient to cover the promising ground around the one TeV level. Moreover, the machine's higher luminosity would ensure an important complementarity, by compensating for the lower energy in making better use of infrequent collisions where the active constituents, quarks and gluons, take a large fraction of the energy of the protons they belong to. Indeed, CERN's $\bar{p}p$ collider remained competitive with Fermilab's Tevatron in the exploration of W and Z production despite its lower energy. It is only because this physics is well understood after eight years of detailed research that the CERN machine is now falling behind.

By the time SSC comes fully on stream with its higher energy as an overwhelming asset, one will still have the unique opportunity to collide LHC's protons against the LEP's electrons and positrons, thus continuing HERA's study of electron-proton collisions which starts shortly, but at three times the energy (1.7 GeV).

CERN's existing accelerator complex also accelerates heavy ions — a capability which will be extended to lead. The LHC could therefore be used to provide lead-lead collisions at 1312 TeV per nucleus — over 30 times the energy developed by RHIC, a new accelerator in the US. RHIC is set to receive funding for construction in the 1991 budget, and specific as opposed to broader, generic detector projects are now starting to be supported. Research is to focus on the quark-gluon plasma, a new state of matter which should have existed at high temperature and density during the first microseconds after the Big Bang. The corresponding phase transition of the vacuum will thus be achievable in the laboratory.

With electron-proton and lead-lead collisions, the physics potential of the LHC shows both versatility and complementarity in addition to its primary goal of shedding light on the puzzling aspect of the vacuum. The latter was also the motive for Newton to understand action at a distance, for Einstein to overthrow the ether, and for Dirac to propose antimatter. In each case, meeting properly the challenges inevitably heralded remarkable developments.

John Stewart Bell

The prominent CERN theoretical physicist J.S. Bell died on 1 October of a stroke at 62 years of age. Though he left us far too soon, his contributions to quantum physics will remain as a lasting testimonial. He is universally known for the inequalities that go by his name. Reported in 1964, they showed that the specific probability correlations imposed by quantum mechanics could not be obtained from any set of preset values for hidden variables, and that any local realistic model was thus ruled out. Together they represent a major advance in the understanding of quantum mechanics starting from the famous paradox of Einstein, Podolsky and Rosen formulated in 1935. With characteristic modesty, he described the outcome of this advance into an intellectual territory where few dare to tread as a "dilemma".

In a convincing series of experiments, A. Aspect demonstrated in 1982 that the Bell inequalities are indeed violated by photon polarization correlations, and that the observations are in full agreement with quantum mechanics.

John Bell was born and educated in Belfast, Northern Ireland, graduating from Queen's University in Experimental Physics in 1948, and in Theoretical Physics a year later. His scientific career is rich with famous contributions other than his clarification of the deep and puzzling nature of the quantum state. His independent derivation of the CPT theorem was part of his thesis work in the mid-fifties under R. Peierls at the University of Birmingham, UK during a leave of absence from the UK Atomic Energy Authority, Harwell which he had joined in 1949. But for a leave of absence at the Stanford Linear Accelerator Center, California, USA in 1964, he worked in the CERN Theory Division from 1960. This period led to the discovery, in 1969, of the Adler-Bell-Jackiw anomaly pointing out a profound question in field theory. The effect of this anomaly, which spoils a symmetry at the quantum radiation level and challenges the renormalizability of the theory, has to be eliminated. The quark-lepton symmetry of the standard model responds to this demand.

Although a deep thinker in quantum physics, he fully understood those he called "why bother'ers" who merely use quantum mechanics as a tool to obtain physically meaningful results. His own work along such a line developing the violation of CP symmetry, completed in the mid-sixties, is a masterpiece. Other important contributions across a remarkably broad range of interests included work in accelerator physics, some of which he co-authored with his wife Mary, an accelerator engineer at CERN. His major achievements have been recognized by the Dirac Medal (1988) and the Heinemann Prize (1989).

John Bell was profound and much could be learnt from him. Yet his modesty, particularly with respect to the philosophical causes supported by some of his ideas, was impressive. As he himself said: "What I really wanted was a clean argument rather than to justify any particular conception of the world. From what I know of my own character, which is somewhat stubborn, I am often more concerned with the conduct of the debate and its logic than the actual truth". On his success with the inequalities: "Then people started doing the experiments: the results confirmed ordinary quantum mechanics and therefore disconfirmed Einstein's hopes. Then there was more and more publicity."

Despite the publicity, his approach to physics, epitomizing depth, modesty, rigour and imagination, stands as an enduring model: "What we deal with in physics are the simplest situations. We simplify questions to the limit in the hope of finding that the laws of simple things can be built up into the laws of complicated things."

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