Review of Experiments

Superconducting Super Collider Laboratory
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Review of Experiments*

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While progress in particle physics may not be as swift as most of us would like it to be, the data sample presently available have brought us a wealth of new information, all of which appears to cement the Standard Model. This report summarizes the most important results extracted from the many excellent review talks presented at this Symposium.

INTRODUCTION

This year marks the 30th anniversary of the birth of this series of high energy conferences, and while we are trying to assess the progress that has been made in the two years since the last Lepton-Photon Symposium, it may be of interest to look back and see how far we have progressed in the course of the last three decades.

Thirty years ago, elastic e-p scattering and the study of proton form factors extended to $-Q^2 < 2 \text{ GeV}^2$ and photo-production covered the resonance region up to $W^2 = 3 \text{ GeV}^2$. The vast range of higher $Q^2$ and $W^2$ remained untouched and the time-like region of $Q^2 > 0$ had just been opened to exploration by the first generation of $e^+e^-$ storage rings at Orsay, Novosibirsk, Frascati, CEA and Stanford. The properties of the $\eta$ meson had been clarified by photo-production and QED was confirmed at the 1 GeV momentum scale, i.e. down to distances of a few tenths of a fermi by the precision $g-2$ experiments.

Ten years later at Bonn, impressive new data on deep inelastic e-p scattering and $e^+e^-$ annihilation dramatically changed our understanding of matter. The observation of scaling in deep inelastic scattering suggested that hadrons were composed of point-like constituents, and questions were raised about the extension of scaling into the time-like domain of $Q^2$. Neutrino interactions observed in Gargamelle gave first evidence for the weak neutral current, and various theoretical models placed upper limits on the mass of the intermediate vector bosons at 13 GeV/c$^2$ or less.

During the next decade, the Standard Model (SM) developed largely to its present form, supported by the observation of charm and beauty hadrons and the τ lepton. At the 1983 Symposium here at Cornell, the first direct measurements of the W and Z mass were presented by UA1 and UA2, namely $M_Z = 95.6 \pm 1.5 \text{ GeV}/c^2$ and $M_W = 81.0 \pm 2.0 \text{ GeV}/c^2$. The first measurements of the average lifetime of beauty particles were reported with a surprisingly large average value. Two other results puzzled the community at that time, the observation of like-sign di-leptons in neutrino interactions at a level of $10^{-3}$ (this puzzle went away) and the emergence of a meson resonance that did not fit into the quark model and that was interpreted as a potential glueball. This and other states of similar nature are still puzzling us today.

So, where do we stand another decade later? From the experimental point of view, we have accumulated an enormous amount of new information from experiments at a number of accelerators with excellent performance: $\bar{p}p$ interactions at LEAR, the TEVATRON and the anti-proton accumulator ring at Fermilab, muon and electron scattering at CERN and SLAC, and most recently at HERA, neutral and charged kaon decays at CERN and Fermilab, hadro- and photo-production of charm particles at Fermilab, and $e^+e^-$ annihilation at BEPC in Beijing, CESR at Cornell, LEP at CERN, and SLC at SLAC. Most of these experiments operate electromagnetic and hadronic calorimeters and muon detectors of high resolution and hermeticity, employ highly selective triggers and advanced on-line computing to cope with high data rates, and they use precision vertex detectors to select charm and beauty decays. In addition, the analysis techniques have advanced a new level of sophistication and complexity.

The present period of particle physics can be described as the period of consolidation of the Standard Model. The electromagnetic and weak interactions have been unified in the $SU_2 \times U_1$. Electroweak Theory and Quantum Chromodynamics (QCD) stands unchallenged as the description of strong interactions. Experimenters continue to probe the predictions of this theory by more and more precise measurements of electroweak and strong interactions, and by searches for processes that are not expected or predicted to occur within the framework of the Standard Model. In the following, a brief summary of the wide range of measurements and tests will be given.

**PROPERTIES OF NEUTRAL AND CHARGED LEPTONS**

In spite of the important role neutrinos have played in the study of electroweak interactions, rather little is known about their basic properties like mass and lifetime, their electric or magnetic moment. From LEP experiments, we have a precise determination of the number of families of light Standard Model neutrinos, $N_V = 2.980 \pm 0.027$. To everybody's relief, the puzzle of the 17 keV neutrino has been solved! A reanalysis of the earlier measurement revealed that the kink in the electron spectrum could be attributed to
second-order contributions to scattering on slits and baffles. All other experimental tests performed have so far been consistent with a zero rest mass.

Cosmological arguments which attribute the mass of the universe largely to neutrinos require neutrino masses in the range of 15 to 30 eV, a range that will be very difficult to reach by the direct measurements of neutrino masses which are presently limited by systematic uncertainties in calibration and resolution functions, as well as by uncertainties in the spectrum near the endpoint.

Neutrino oscillation experiments which are sensitive to mass differences between neutrinos of different generations may provide the necessary information provided such oscillations exist. So far, there is no convincing evidence for neutrino oscillations in terrestrial experiments. Accelerator experiments produce $v_\mu$ and provide sensitivity to small mixing angles, $\sin^22\theta > 10^{-3}$, but they allow for only modest sensitivity to small mass parameters $\Delta m^2$. This is in contrast to reactors which are a copious source of $v_\alpha$ and permit limits of $\Delta m^2 < 10^{-2}$ eV$^2$. Very long baseline experiments are being considered to extend these limits to lower masses.

Due to the large distances solar neutrinos travel within the sun and in open space experiments, measurements of the flux of solar neutrinos can, in principal, provide higher sensitivity to mass and mixing parameters than terrestrial observation, $\Delta m^2$ below $10^{-4}$ eV$^2$. At present there are four experiments measuring solar neutrino fluxes, four more are under construction, and others are still in the development phase. So far, all four experiments observe fluxes that are substantially lower than predictions by the Standard Solar Model, although year by year the measured rates appear to increase. While earlier measurements in the Homestake mine and by Kamiokande were only sensitive to the high energy portion of the solar spectrum, the two more recent measurements by the European GALLEX group and Soviet-American SAGE collaboration can detect the p-p portion of the spectrum which is responsible for 98% of the solar energy release. Both of these recent experiments use the inverse $\beta$-decay reaction $^{71}$Ga($v_\alpha$,e$^-$$^{71}$Ge for detection. The results are listed in Table 1. The measurements are to be compared with predicted rates of 132 SNU by Bahcall and 125 SNU by Turck-Chieze. Both $^{71}$Ge experiments continue to suffer from limited statistics and poorly known systematic uncertainties. None of the radiochemical experiments can demonstrate that the signals originate from the sun. Long awaited calibrations of their detection efficiency and study of background sources are scheduled for next year.
Table 1. Recent measurements of solar neutrino fluxes.

<table>
<thead>
<tr>
<th></th>
<th>Year</th>
<th>Flux (SNU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAGE</td>
<td>1990</td>
<td>$20 \pm 16 \pm 32$</td>
</tr>
<tr>
<td></td>
<td>1991</td>
<td>$85 \pm 22 \pm 20$</td>
</tr>
<tr>
<td>GALLEX</td>
<td>1991</td>
<td>$81 \pm 17 \pm 9$</td>
</tr>
<tr>
<td></td>
<td>1992</td>
<td>$97 \pm 23 \pm 7$</td>
</tr>
</tbody>
</table>

Remarkable progress has been reported in the measurement of one of the slowest weak processes, double $\beta$-decay. There are now observations of $2\nu$ $\beta\beta$-decay in four isotopes: $^{76}\text{Ge}$, $^{82}\text{Se}$, $^{100}\text{Mo}$, and $^{150}\text{Nd}$. Such processes, which are allowed in standard weak interactions, are merely of nuclear physics interest. The search for neutrinoless double $\beta$-decay provides sensitive tests of lepton number conservation and has resulted in limits on the effective mass of the Majorana neutrino at the level of 2 eV. Substantial improvements can be expected from measurements with enriched $^{76}\text{Ge}$ planned in the Gran Sasso Laboratory.

Among the charged leptons, the $\tau$ is the most massive and the most interesting. The best measurement of the $\tau$ mass was reported last year by the BES group, which measured the $\tau^+\tau^-$ pair production by $e^+e^-$ annihilation near threshold with the beam energy calibrated relative to the very well known mass of the $J/\psi$ resonance. The resulting value of $1.776.9 \pm 0.3 \pm 0.2$ MeV/$c^2$ is significantly below previous measurements. Both CLEO and the four LEP experiments reported new measurements of the leptonic branching ratios of the $\tau$, based on much improved statistics, cleaner samples, and better normalization. The average values are $B_e = (17.89 \pm 0.14)\%$ and $B_\mu = (17.24 \pm 0.16)\%$. The lifetime of the $\tau$ has been measured with improved precision at LEP using silicon micro-vertex detectors. The average value is $0.2947 \pm 0.003$ ps. With these measurements of the mass, branching ratio, and lifetime, the universality of the charged weak coupling has been tested, $g_\tau/g_\mu = 0.996 \pm 0.006$. As a result of these new measurements, the apparent deviation from $\mu - \tau$ universality is much reduced, with the principal uncertainty now coming from the error in the leptonic branching ratio.

For several years there has been a lingering suspicion that the sum of the branching ratios for exclusive $\tau$ decays with a single final state charged particle is significantly smaller than the inclusively measured branching ratio for one-prong decays of the $\tau$. There appear to have been several reasons for this discrepancy: in the past, only a few decay modes
were measured with rather poor statistical errors. Decays with more than one neutral particle, \(\pi^0\) or \(\eta^0\), were unmeasurable and their contribution was inferred by isospin symmetry from the few measured decay modes. Also, measurements from different experiments relying on different efficiencies and normalization had to be combined. Now several groups have presented a complete analysis with a large number of measured exclusive decay modes. Major improvements are due to statistics as well as new detector components, for instance the e.m. calorimeter in CLEO and the hadron identification in DELPHI. As a result, we have a more consistent picture with a smaller discrepancy and smaller overall errors, leaving us with a problem that is less compelling, but still needs further study. In the future, more information on \(\tau\) decays involving kaons will become available, exploiting the uniqueness of \(\tau\) decays for studying weak hadronic interactions.

**SEARCH FOR RARE DECAYS**

Experiments designed to study decays of leptons and hadrons that are highly suppressed or forbidden by Standard Model interactions can provide clues to the existence of interactions or particles that are not included in the Standard Model. Examples of such processes are higher order processes like flavor changing neutral currents (FCNC) and lepton flavor violating interactions which require an extension of the SM, for instance SUSY, extended Technicolor, or composite quarks or leptons.

Experimentally, we now have a number of sensitive tests from the study of rare decays of \(K\) and \(B\) mesons, leptons, and the \(Z^0\). At Brookhaven, KEK and Fermilab experiments are examining charged and neutral kaon decays and have resulted in the observation of decays like \(K_L \rightarrow \mu^+\mu^-\) and \(K^+ \rightarrow \pi^+e^+e^-\) at levels consistent with expectations. Limits on FCNC processes are presently at the level of \(10^{-10}\), still more than one order of magnitude above the Standard Model predictions. It is hoped that the next round of experiments under preparation at BNL and FNAL will reach sensitivities close to the level of predicted rates. Of particular interest is the decay \(K_L \rightarrow \pi^0e^+e^-\) which is CP violating in leading order.

The four LEP experiments are well suited for searches for new particles and new interactions. From the accurate measurement of the \(Z^0\) total width and the hadronic and leptonic widths, limits for the pair production of new particles have been derived that now extend to the kinematic limit, i.e. half the \(Z^0\) mass (unless dynamic suppression occurs). Searches have resulted in the exclusion of the minimal Standard Model Higgs up to masses of 63.5 GeV/c². However, in a total sample of about \(10^6\) \(Z^0\) decays, ALEPH found one candidate for a non-minimal Higgs in the process \(Z^0 \rightarrow e^+e^-X\) with the mass \(M_X = 61.3 \pm 0.5\) GeV/c². Extensive searches for SUSY particles have not produced any positive results, but the existence of light gluinos cannot be fully excluded. The first data
from HERA have been used to search for lepto-quarks and lepto-gluons excluding mass
regions of 92 to 192 GeV/c² and greater than 100 GeV/c², respectively.

LEP experiments have also looked for evidence for lepton flavor violation and rare
τ decays, placing branching ratio limits in the range of 10⁻⁵ for Z⁰ → ℓ⁺ ℓ⁻ and 8 · 10⁻⁵ for
τ⁺ → μ⁺γ. The L3 experiment reported recently the observation of four events of the type
Z⁰ → ℓ⁺ ℓ⁻γγ in a sample of 1.6 million Z⁰. In all four events the invariant mass of the
two photons was close to 60 GeV/c². Similar events were observed by the other LEP
experiments, but without a significant clustering in the γγ mass distribution. ALEPH also
observed one event of the type Z → ℓ⁺ ℓ⁻νν with Mνν = 58.5 ± 1.9 GeV / c². No
anomaly was detected at TRISTAN. Thus, the most likely explanation is that the L3 events
are due to a statistical fluctuation of the rate in the QED process e⁺e⁻ → ℓ⁺ ℓ⁻(nγ).

HADRON STRUCTURE AND QCD

A subject of substantial interest over many years has been the study of the spin
structure of the nucleon based on data from deep inelastic scattering of polarized electrons
and muons by polarized targets. At this conference, measurements on polarized ³He and
solid deuteron targets were presented, allowing for the long awaited test of the Bjorken and
Ellis-Jaffe sum rules. The Bjorken sum rule is fundamental to QCD (consequence of
current algebra) and it relates the nucleon spin structure function integrals to the weak
coupling constants g₇ and g₅. The Ellis-Jaffe sum rule is based on SU₃ flavor symmetry (it
ignores the effects of strange quarks) and it relates the spin structure function integrals to
the spin of the quarks in the nucleon. In Table 2 the theoretical predictions and the mea-
surements are listed. The comparison shows that within the 15% errors the data are consis-
tent with both the Bjorken and the Ellis-Jaffe sum rules. Combining the SLAC measure-
ments of the spin quark distributions with the weak coupling constants measured in baryon
decay implies that the total quark contribution to the nucleon spin is 0.57 ± 0.11. Thus the
non-strange quarks contribute about half the nucleon spin. On the basis of the earlier pro-
ton data alone, one had concluded that this contribution was much smaller and thus the
gluons, strange quarks, and/or angular momenta had to contribute appreciably. The com-
bined EMC/SMC result is consistent with the earlier measurements and also with the SLAC
result. The experimenters expect new data on the proton next year, to be followed by a
series of experiments that are planned for SLAC, as well as the for the polarized electron
beam at HERA.
Table 2. Measurements of Nucleon Spin Structure

<table>
<thead>
<tr>
<th></th>
<th>Bjorken Sum Rule</th>
<th>Ellis-Jaffe Sum Rule</th>
<th>Quark Spin Integral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prediction</td>
<td>0.183 ± 0.007</td>
<td>-0.021 ± 0.018</td>
<td></td>
</tr>
<tr>
<td>EMC/SMC</td>
<td>0.20 ± 0.06</td>
<td>-0.08 ± 0.05</td>
<td>0.06 ± 0.25</td>
</tr>
<tr>
<td>SLAC</td>
<td>0.148 ± 0.021</td>
<td>-0.022 ± 0.011</td>
<td>0.57 ± 0.11</td>
</tr>
</tbody>
</table>

While previous experiments studying deep inelastic scattering have been limited to the kinematic range of \( x > 10^{-3} \) and \( Q^2 < 4 \) GeV\(^2\), the e-p storage ring HERA, with its current c.m. energy of 296 GeV, allows measurements to extend down to \( x > 10^{-4} \) and \( Q^2 > 10,000 \) GeV\(^2\). While the data are still too limited to perform precision QCD tests in the high \( Q^2 \) regime, they permit a study of the very low \( x \) region which is expected to show effects of saturation and gluon recombination due to extremely high gluon densities. The data from H1 and ZEUS show a substantial rise in the structure function \( F_2(x,Q^2) \) with decreasing \( x \). While it is premature to draw any definite conclusions, it is exciting to observe the predicted breakdown of the GLAP gluon distribution function. Much more data are expected in the next few months.

Both HERA experiments observe neutral current events in which the scattered proton is well separated from the remaining hadrons. The \( x \), \( Q^2 \), and \( M_X \) distributions are similar to standard deep inelastic scattering events. The \( W \) dependence and the rapidity distribution are flat. Such events are not expected for hard scattering of the incident lepton from a colored quark in which one expects substantial energy flow in the direction of the proton. On the other hand, such events are expected in diffractive processes which are described by the exchange of a pomeron. It has been suggested that the pomeron may have partonic structure and this could in fact be probed with virtual photons at HERA.

Perturbative QCD has been highly successful in describing experimental data of larger and larger variety and of increasing quality. Jet definition and hadron fragmentation have received much attention, and their effects are generally understood and taken into account. Difficulties remain due to the fact that calculations are limited to second order and thus become sensitive to the mass scale. The most impressive examples of comparisons between perturbative QCD predictions and data are the jet cross section measurements by CDF and D0 which now extend over nine orders of magnitude, two-jet rates in \( e^+e^- \) annihilation at LEP and TRISTAN, and scaling violations in deep inelastic lepton scattering. We also saw improved measurements of direct photon production from E-706 and D0 at...
Fermilab which agree well with NLO calculations, and in the future can serve as a tool to study the gluon distribution function \( G(x,Q^2) \). The measurement of \( \alpha_s(Q^2) \), in many processes using a multitude of variables, has become an industry, in particular at LEP where the data also permit tests of its flavor independence. The best value is \( \alpha_s(M_Z) = 0.123 \pm 0.006 \).

**STANDARD MODEL PARAMETERS**

The measurements at the \( Z^0 \) resonance continue to produce the most stringent test of the electro-weak theory and the most severe constraints on its variations. The total cross sections for hadronic final states, and the differential cross sections for lepton pairs measured at energies near the \( Z^0 \) peak, are the basis for multi-parameter analyses. There are nine independent parameters to be fitted: the mass and the total width of the \( Z^0 \), the hadronic cross section at the peak, and for each lepton, the ratio \( R \) of the hadronic to leptonic partial width and the forward backward asymmetry. The four LEP experiments give consistent results for all fitted quantities. The combined results are given in Table 3. The values of other \( Z^0 \) parameters can be derived from the fitted ones, they are listed in Table 4. It is expected that for the data presently recorded at LEP, the error on the energy calibration and on the luminosity measurement will be substantially reduced.

Table 3. Results of the global fit to the combined \( Z^0 \) data from all four LEP experiments. Lepton universality is assumed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_Z (\text{GeV}) )</td>
<td>91.187 ± 0.007</td>
</tr>
<tr>
<td>( \Gamma_Z (\text{GeV}) )</td>
<td>2.489 ± 0.007</td>
</tr>
<tr>
<td>( \sigma_H^0 (\text{nb}) )</td>
<td>41.56 ± 0.14</td>
</tr>
<tr>
<td>( R )</td>
<td>20.763 ± 0.049</td>
</tr>
<tr>
<td>( A_{FB}^{0,\ell} )</td>
<td>0.0158 ± 0.0018</td>
</tr>
</tbody>
</table>
Table 4. List of parameters derived from the global fit to the $Z^0$ data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_\ell$ (MeV)</td>
<td>83.82 ± 0.27</td>
</tr>
<tr>
<td>$\Gamma_{\text{had}}$ (MeV)</td>
<td>1740.3 ± 5.9</td>
</tr>
<tr>
<td>$\Gamma_{\text{inv}}$ (MeV)</td>
<td>497.6 ± 4.3</td>
</tr>
<tr>
<td>$g_V^2$</td>
<td>0.00134 ± 0.00015</td>
</tr>
<tr>
<td>$g_A^2$</td>
<td>0.25088 ± 0.00083</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}}^\text{lept}$</td>
<td>0.2318 ± 0.0010</td>
</tr>
</tbody>
</table>

The vector and axial-vector coupling constants can be derived independently for the charged leptons allowing for a test of the universality of the coupling to the neutral current. The lepton forward-backward asymmetries measure the ratio, the partial widths measure the sum of the squares of the couplings, and the $\tau$ polarization allows for determination of the relative sign. The combined LEP data confirm the universality at the level of 0.3%.

With the installation of silicon vertex detectors, LEP experiments have significantly improved the detection of $c\bar{c}$ and $b\bar{b}$ decays of the $Z^0$ and thus can provide sensitive tests of the flavor dependence of the vector and axial vector coupling. Average values of the heavy flavor forward-backward asymmetries $A_{FB}^c = 0.075 ± 0.015$ and $A_{FB}^b = 0.098 ± 0.006$ translate to effective couplings $\sin^2 \Theta_w^c = 0.2313 ± 0.0036$ and $\sin^2 \Theta_w^b = 0.2322 ± 0.0011$.

Since the $t$-quark contributions to the decay $Z \to b\bar{b}$ are unsuppressed by CKM factors, the measurement of the ratio $R_b = \Gamma_{b\bar{b}} / \Gamma_{\text{had}}$ can probe the mass of the top quark (largely independent of the Higgs mass). The present average of the LEP and SLD measurements of $R_b = 0.2203 ± 0.0027$ translates to an upper limit on the top mass of 210 GeV/$c^2$.

The SLD group at SLAC measures the polarization asymmetry $A_{LR}$ of the $Z^0$ production cross section with left and right-handed electrons. This quantity is directly proportional to the beam polarization and the electroweak mixing parameter $\sin^2 \Theta_w$. $A_{LR}$ is expected to be relatively large, in the range of 10%, it is sensitive to the initial state couplings.
and insensitive to final state coupling and real radiative corrections. The measurement implies simply a counting of events for each of the two longitudinal polarization states of the electron beam. It does not require an absolute luminosity measurement or any knowledge of the detector acceptance and efficiency. At the time of this Symposium, the SLD group had collected a sample of 50,000 Z^0 events with a beam polarization of 65% to 75%. Unfortunately the group had not obtained a sufficient understanding of the beam polarization and therefore refrained from citing a new measurement of sin^2 θ_W.

The global fit of all LEP measurements of widths, cross sections and asymmetries permits the determination of the top quark mass and α_s in the context of the Standard

\[ m_t = 164 \pm 16 \pm 21 \text{ GeV} / \text{c}^2 \quad \text{and} \quad \alpha_s = 0.120 \pm 0.006 \pm 0.002, \]

for a Higgs mass of 300 GeV/c^2. The fit also predicts the mass of W^+ at 80.24 GeV/c^2, with an error of 0.09 GeV/c^2 that is significantly better than presently available from direct measurements.

While the measurements of Γ_{bb} at LEP confirm the weak isospin of the b quark and the absence of FCNC demands a GIM partner of the b quark, the top quark has so far escaped direct observation. At Tevatron energies, top quarks are produced in pairs, dominantly via q̅q annihilation and gluon fusion, and they decay via the process t → W + b. While the hadronic W decays have the largest branching ratio, they are very hard to distinguish from multi-jet QCD background. Events with one of the two W's decaying leptonically have a cleaner signature, but may still require tagging of the b-decay by secondary vertices or by an additional low momentum lepton from its semileptonic decay. Both CDF and D0 find candidate events with opposite sign di-leptons plus jets, but at a rate that is fully compatible with the expected background from W^+W^- and Drell-Yan production. The observed rate can be translated to a lower limit on the mass of the top quark of 93 GeV/c^2 and 113 GeV/c^2 at 95% C.L. for CDF and D0, respectively. In addition, CDF has analyzed events with a single high p_T lepton and three or more jets. By requiring several tracks with significant impact parameters relative to the production vertex, the sample is reduced to 3 events compared to an expected background level of 1.2 events. It is hoped that further analysis will clarify this tantalizing situation. Both CDF and D0 expect to increase their data samples by a factor of 4 within a year.

**CP AND CPT VIOLATION**

Two experiments, NA31 at CERN and E731 at FNAL, continue their effort to establish direct CP violation in the weak decay amplitude as predicted by the Standard
Model. The most recent result derived from the double ratio of the two-pion decay of the neutral kaon is

\[
\text{Re } \frac{\epsilon'}{\epsilon} = \frac{1}{6} \left\{ 1 - \frac{\eta_{00}}{\eta_{+-}} \right\} = 2.30 \pm 0.65 \cdot 10^{-3} \quad \text{NA-31}
\]

\[
= 0.74 \pm 0.59 \cdot 10^{-3} \quad \text{E 731}
\]

Standard Model calculations predict that \(\epsilon'/\epsilon\) should be finite, with a value estimated to be of the order of \(10^{-3}\), decreasing monotonically as the mass of the top quark increases. The difference in the two measurements is not significant. Both experiments are presently being rebuilt to further reduce systematic uncertainties and allow for higher rates.

There is a small \(\bar{p}p\) experiment operating at LEAR in which the flavor of the neutral kaon and its momentum are tagged by the kinematics of the fully constrained final state, \(\bar{p}p \rightarrow K^0 K^+ \pi^-\). At this Symposium, data of high statistics were presented that promise precise measurements of the mass difference \(\Delta m\), \(\eta_{+-}\) and \(\eta_{00}\), as well as the phases \(\Phi_{+-}\) and \(\Phi_{00}\), and the complex amplitude \(x\) for transitions violating the \(\Delta S = \Delta Q\) rule. This experiment will also measure several other decay modes of the neutral kaons and test CP and CPT in a variety of different ways. In Frascati, DAΦNE, a low energy \(e^+e^-\) storage ring, is under construction, which is designed to operate at the \(\Phi\) resonance, a state that decays exclusively into \(K_L K_S\) or \(K^+ K^-\), and thus provides pairs of kaons of well defined momentum. This facility will address physics questions not dissimilar from those of the CP experiment at LEAR.

HEAVY FLAVOR PHYSICS

Heavy flavor physics has become one of the most active fields of research in particle physics. It comprises searches for new phenomena as well as the measurements of the fundamental parameters of the electroweak theory, and also quantitative tests of QCD as well as non-perturbative processes in strong interactions. A number of very large experiments are contributing to very sizable data sets which have produced a large variety of interesting results, only a few of which can be mentioned here.

CHARM PHYSICS

Until recently, almost all of the information on charmonium states originated from \(e^+e^-\) experiments. Now there are impressive data from \(E 760\), a gas jet experiment operating in the anti-proton accumulator ring at Fermilab. Stochastic cooling results in a mass resolution of 0.25 MeV/c^2 and has lead to substantial improvements in the accuracy of the \(\chi\) resonance parameters. Recently, the group announced the discovery of the long missing \(^1P_1\) state, which can be considered a pure QCD analog to positronium, at a mass of 3526.4 ± 0.15 ± 0.2 MeV/c^2.
There is also remarkable progress in the unraveling of charm spectroscopy. Sizable samples of events exist for the L=1 charm mesons from ARGUS and CLEO as well as the photoproduction experiments at Fermilab. Spin parity analyses have lead to the identification of four of the twelve D** states. The CLEO group reported the observation of a new state, \( \Lambda_c^{*+}(2590) \), below the \( \Lambda_c^{*+}(2630) \) previously observed by ARGUS.

The study of charm meson and baryon decays has focused on the measurement of branching ratios and lifetimes, and the study of the nonperturbative strong interactions inevitably involved in both semileptonic and hadronic decays. A wealth of new information, based on very large samples from the Fermilab photoproduction experiments and a multitude of decay modes measured by ARGUS and CLEO, was presented here. While most of the branching ratios are cited relative to one of the standard decay modes, there are now new accurate measurements of absolute branching ratios for \( D^0 \), and to a lesser extent also for \( D^+ \) and \( D_s^+ \). These results are also important for the determination of a wide range of B branching ratios.

Precision lifetime measurements have been performed by Fermilab experiment E 687, with errors that are in many cases dominated by systematic uncertainties as small as 1.5%. The lifetimes of different charm particles can be understood fairly well in terms of the simple quark diagrams and factorization of the decay amplitudes. For charm mesons, the two-body spectator diagrams dominate, and the two spectator diagrams interfere destructively in decays with two identical quarks. This leads to a lifetime pattern of the form \( \tau(D^+) > \tau(D^0) \equiv \tau(D_s^+) \). Charm baryon lifetimes are influenced by additional spectator diagrams and a non-helicity suppressed exchange diagram. The relative sign and size of these amplitudes determines the lifetime of different charm baryons. At present, the measurements are consistent with \( \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Sigma_c^+) \).

Simple models do not reproduce exclusive hadronic branching ratios, but the data now available have substantially contributed to an improved understanding, in particular the importance of final state interactions. It has always been considerably easier to interpret measurements of exclusive semileptonic decays, which proceed via the single spectator amplitude, with form factors describing the formation of the final state kaon. In complete analogy to semileptonic K decays measured some 25 years ago, we now have measurements of the \( Q^2 \) dependence of the scalar form factor by CLEO for the decay \( D^0 \rightarrow K^-\ell^+\nu \). The results can be well parameterized by a pole mass of \( M^*=2.00 \pm 0.11 \pm 0.16 \) GeV. The decay amplitude for the decays \( D \rightarrow K^*\ell\nu \) involves three form factors for which we also have much improved measurements, \( f_+(0) = 0.77 \pm 0.04, V(0) = 1.16 \pm 0.06, A_1(0) = 0.61 \pm 0.05 \) and \( A_2(0) = 0.45 \pm 0.09 \). Theoretical models differ in their predictions, most of them agree with measured values for \( f_+ \) and \( V \), but are somewhat high on \( A_1 \) and \( A_2 \), resulting in branching ratios that are substantially larger than the measurements for both \( D^0 \) and \( D^+ \).
One of the most impressive analyses presented at the Symposium was the observation of $38 \pm 8$ purely leptonic decays $D^+_s \rightarrow \mu^+ \nu$. The measured relative branching ratio of $\Gamma(D^+_s \rightarrow \mu^+ \nu) / \Gamma(D^+_s \rightarrow \phi \pi^+) = 0.245 \pm 0.052 \pm 0.074$ translates to a decay constant $f_{D_s} = 344 \pm 37 \pm 42$ MeV, which is at the upper end of the theoretical predictions. This constant is of great interest for the study of mixing and CP violation in B decays, because the charm decay constant can be related to the beauty decay constant which is deemed to be very difficult to measure.

**BEAUTY PHYSICS**

Among the lowest lying B mesons, the $B_s$ was recently discovered by experiments at LEP and CDF at the Tevatron, all of which relied heavily on precision vertex detection. The mass measurement is at present dominated by a single event with the decay $B_s \rightarrow \Psi' \Phi \rightarrow \mu^+ \mu^- K^+ K^-$, the average mass is $M(B_s) = 5382.3 \pm 4.2$ MeV/c$^2$. The observation of an excited meson $B^{**}(5610)$ by CDF lead to the speculation that this state, if produced copiously, could be used to tag the particle/anti-particle nature of neutral B mesons, a feature that is of great importance to the measurement of CP violation in the neutral B system. Experiments at LEP have used correlations between the charge of high $p_t$ leptons and $\Lambda^0$ and $\Xi^-$ baryons to detect semileptonic decays of the beauty baryons $\Lambda_b^0$ and $\Xi_b^0$ and have also derived lifetime estimates. As for charm mesons, lifetime measurements test the importance of various tree level decay diagrams. The average B lifetime is $\langle \tau(B) \rangle = 1.49 \pm 0.04$ ps, a value consistent with the lifetimes for the individual B mesons. The lifetimes of the charged and neutral B mesons are equal, their ratio was also derived by CLEO from the ratio of semileptonic decay branching ratios, $\tau^+/\tau^0 = 1.05 \pm 0.16 \pm 0.15$. The B baryon lifetime is somewhat shorter, $\tau(\Lambda_b) = 1.07 \pm 0.16$ ps.

Extensive studies of exclusive hadronic decays have been performed. While there is clear indication for factorization of decay amplitudes in some decays modes, the concept does not appear to work for others.

As is the case for charm mesons, the semileptonic B meson decays are better understood than hydronic decays, both theoretically and experimentally. They provide the best method for the measurement of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$. The so-called Heavy Quark Effective Theory or HQET has attracted large interest because it promises to provide model independent predictions for beauty, and perhaps even charm hadrons. According to HQET, the Dalitz plot distribution depends only on $|V_{cb}|$ and a single universal function $\xi(y)$, and thus $V_{cb}$ can be derived by extrapolation of the data to the edge of the Dalitz plot where $\xi(y=1)=1.0$ and all major corrections vanish. Even though the exact functional form of $\xi(y)$ is not known, the resulting value of $|V_{cb}| = 0.037 \pm 0.005 \pm 0.004$ does not vary significantly as long as reasonable parameterizations are used.
The existence of charmless semileptonic decays is now reliably established. The most recent analysis by the CLEO group is based on one million $\bar{B}B$ events and attributes $107 \pm 15 \pm 11$ high momentum leptons to $b \to u/\nu$ transitions. The derivation of $V_{ub}$ requires knowledge of the lepton spectrum, and thus is model dependent. The average value is $|V_{ub}/V_{cb}| = 0.08 \pm 0.02$, where the error is set to cover the theoretical uncertainty. It is hoped that as the data samples grow in the next few years, more detailed studies will permit a distinction between the theoretical alternatives, and thus will lead to substantial improvement.

Among the rare decays of $B$ mesons, two classes of events which are important for future studies of CP violation have been discovered by the CLEO collaboration. There is now compelling evidence for the existence of the decay $B^0 \to K^* \gamma$. The branching ratio of $4.5 \pm 1.5 \pm 0.9 \cdot 10^{-5}$ is compatible with predictions based on the existence of one-loop, flavor changing neutral current diagrams, commonly referred to as penguin diagrams. The observed rate is an order of magnitude larger than would be expected, if such diagrams did not exist, and this is taken as conclusive evidence for these diagrams, that were originally introduced in 1975 to explain the $\Delta l=1/2$ rule in kaon decays.

A similarly difficult analysis lead to the observation of decays of two charmless mesons, $\pi^+\pi^-$ and $K^+\pi^-$. The total signal above background for the sum of both decay modes is $13.6 \pm 4.7$ decays, corresponding to a branching ratio of $2.4 \pm 0.8 \pm 0.2 \cdot 10^{-5}$. This measurement is evidence for the existence of charmless hadronic $B$ decays, the branching ratio is in good agreement with theoretical predictions of $1-2 \cdot 10^{-5}$.

$B^0 - \bar{B}^0$ MIXING

The observation of an unexpected, large signal of like-sign di-leptons was first reported by UA1 in 1984. It was received with considerable skepticism, given that the observed signal required a large contribution from a particle that had not been observed at that time, the $B_s$. Since then, many groups have measured the same effect and largely confirmed the UA1 result. $B\bar{B}$ mixing is a measure of the mass difference $\Delta m$ between the CP eigenstates in the neutral $B$ system and it is related directly to the CKM matrix element $V_{td}$. At this Symposium, two of the LEP experiments, ALEPH and DELPHI, presented clear evidence that the observed mixing rate is dependent on the $B$ decay time. The observed time distribution of the mixed events was fit to the expected $\cos(\Delta m t)$ term to determine the mass difference, $\Delta m = 3.42 \pm 0.51 \cdot 10^{-4}$ eV. By pure coincidence, this value happens to be exactly a factor 100 larger than the mass difference in the $K^0$ system! The derived value for $x_d = \Delta m/\Gamma$ agrees well with the time-integrated measurements obtained from CLEO and ARGUS. The average of all measurements is $x_d = \Delta m/\Gamma = 0.71 \pm 0.07$. Measurements near $B\bar{B}$ threshold are only sensitive to $B_d$. This is in contrast to LEP and Tevatron experiments which are sensitive to mixing of both $B_d$ and $B_s$. 

mesons, with their relative fraction unknown. From the observed rate of mixed events at 
LEP, \( \chi = 0.40 \chi_{ud} + 0.12 \chi_{s} = 0.120 \pm 0.010 \), and the measured fraction of mixed 
events of \( \chi_{ud} = 0.158 \pm 0.026 \) from ARGUS and CLEO, \( \chi_{s} = 0.47 \pm 0.12 \), which translates 
to a value of \( x_s = 4.0 \pm 2.5 \). Thus these recent results confirm the expectation that \( B_s \) 
mixes more readily than \( B_d \), as was implicated by the first measurement by UA1. 
Unfortunately, with the present large errors, very little useful information on \( |V_{ub}| \) can be 
derived.

**UNITARITY TRIANGLE**

The recent measurements of charm and beauty decays have substantially improved 
our knowledge of the CKM mixing matrix which describes the coupling of the quarks to 
the charged weak current. Based on the LEP measurements, we can now be more certain 
that there are only three generations of quarks and leptons. Thus, the unitarity of the CKM 
matrix implies that

\[
V_{ub}^* + V_{td} - \sin \Theta_c V_{cb} = 0,
\]

a relation that can be represented geometrically by a triangle in the complex plane. 
Constraints on the sides of this so-called unitarity triangle come from measurements of 
\( B^0 \bar{B}^0 \) mixing (\( V_{td} \)), charmless semileptonic decays of B mesons (\( V_{ub} \)), and a combination 
of the B lifetime, B meson mass, and semileptonic branching ratios (\( V_{cb} \)), as well as 
\( \varepsilon_K = 2.26 \pm 0.02 \cdot 10^{-3} \), a measure of CP violation in \( K^0 \) decay. These constraints depend 
on the top mass \( m_t \), the decay constant \( f_B \) of the B mesons and the so-called bag parameters 
\( B_K \) and \( B_B \). Unfortunately, these parameters are not too well known, the best estimates are 
\( B_K = 0.8 \pm 0.2 \), and \( B_B = 1.0 \pm 0.2 \). From the \( Z^0 \) line shape analysis we have \( m_t = 164 \pm 
17 \pm 21 \) GeV/c². The recently measured value of the \( D_s \) decay constant is considerably 
higher than most theoretical estimates. It is thus even more uncertain how this measure-
ments of \( f_{Ds} \) translates to \( f_B \). A reasonable guess appears to be \( f_B = 0.22 \pm 0.04 \) MeV. 
From the semileptonic decays, we take \( |V_{ub}|/|V_{cb}| = 0.08 \pm 0.03 \), with a rather large error to 
cover the model dependence of the derivation. The new average for the mixing parameter 
is \( x_d = 0.71 \pm 0.07 \). If the orientation of the triangle is chosen such that \( V_{cb} \) and \( V_{cd} \) be-
come almost real, then the vertex of the triangle is constrained to the shaded region indi-
cated in Figure 1.

It is hoped that in the next few years substantial improvements can be made that will 
allow for more stringent tests of the Standard Model. It is hoped that with substantially 
higher statistics, the experimental and theoretical error on \( |V_{ub}|/|V_{cb}| \) can be reduced to the 
level of 0.01. Improvement on the knowledge of \( f_B \) will require a measurement of the 
decay \( B^+ \rightarrow \tau^+ \nu \), an enormous challenge to experimenters. Measurements of mixing in 
both the \( B_d \) and \( B_s \) system will determine the ratio \( |V_{ts}|/|V_{td}| \), and thus largely eliminate the 
dependence on the bag parameters and the decay constants. It is hoped that with larger
statistics and improved vertex detection experiments at LEP and SLC will perform these measurements in the next few years. Knowledge of the top mass will further improve the constraints.

Another way to constrain the triangle is to measure the three angles. These angles are directly related to CP asymmetries in different classes of $B_d$ and $B_s$ decays, for instance $B \to \Psi K_S$ measures $\beta$, $B \to \pi^+ \pi^-$ measures $\alpha$, and various $B_s$ decays are sensitive to $\gamma$. All these decays have branching ratios of $10^{-4}$ or less, and thus very large samples of $B$ decays are needed with the beauty flavor tagged event by event. These high rates of $B$ decays will become available at the Tevatron and at the recently approved $e^+e^-$ asymmetric $B$ Factories at KEK and SLAC, and in the longer term future at hadron colliders like LHC.

While at $e^+e^-$ $B$ factories the rates are expected to be mostly limited by the achievable luminosity, at hadron colliders, the principal difficulty will be the detection and flavor tagging of $B$ decays.

![Graph](image)

**FIG 1.** Constraints for the apex of the unitarity triangle formed by the CKM matrix elements $V_{ub}^*$, $V_{td}$ and $V_{cb}$. The values for the input parameters are $m_t = 160 \text{ GeV}/c^2$, $\epsilon_K = 2.26 \pm 0.02 \cdot 10^{-3}$, $B_K = 0.8 \pm 0.2$, $B_B = 1.0 \pm 0.2$, $f_B = 0.22 \pm 0.04 \text{ GeV}$, $x_d = 0.71 \pm 0.07$, and $|V_{ub}/V_{cb}| = 0.8 \pm 0.3$.

**CONCLUSIONS**

From an experimenter's point of view, this has been an exiting Symposium, although not without some disappointments. We had hoped to hear about the discovery of the top quark. Instead, we ended up with some enticing events from the Tevatron experiments and a mass estimate from LEP. There were new results on CP violation in kaon decay, but we really do not know any more about the origin of this phenomenon. On the other hand, the study of $B$ decay has revealed the non-exponential decay distributions expected from mixing, decays to CP eigenstates, and processes contributed by penguin diagrams, all of which are necessary for future studies of CP violation in the decay of neutral...
B mesons. Many experiments have been searching for the Higgs and SUSY particles, but with the exception of a few tantalizing events, nothing was found. We also continue to be puzzling over the spin of the nucleons. The solar neutrino deficit may be real, although there remain serious uncertainties in the experimental techniques.

The good news is that many of the answers to most of these questions and the resolution to many of today’s puzzles can probably found in the next decade! LEP in its present and future form will continue to offer the best tests of electro-weak theory and the best constraints on potential departures from it. HERA may or may not find the lepto-quarks, but is will certainly lead to precision tests of QCD, and a better understanding of the proton, the photon, and possibly the pomeron. Experiments at the Fermilab collider have their task cut out. With future improvements and upgrades of the machine and the detectors, the discovery of the top quark and many other results are reasonably assured. The $e^+e^-B$ Factories, symmetric in energy at Cornell, asymmetric at KEK and SLAC, will be essential to enhance our knowledge of the CKM parameters and to clarify whether the origin of CP violation does or does not lie within the Standard Model. These experiments will face fierce competition from present and future experiments at hadron machines, both with colliding beams and high intensity external beams.

At the time of this Symposium, much of the hallway discussions focused on the status of the SSC Project. Everybody knew that the budget for the next year was uncertain, but very few of us imagined that this project, in which thousands of scientists saw the future of particle physics, could be wiped out by a simple budget cutting action of the U.S. Congress.

The termination of the SSC Project blocks the only path to the exploration of what lies beyond the Standard Model, which in spite of its unprecedented success in accommodating all experimental observations, must be superseded by phenomena that are certain to be revealed at the highest energies.

Like any crisis, the present situation offers new opportunities. It represents a chance for us scientists to demonstrate that through increased international cooperation we can continue to strive for large projects. This will, however, be very difficult, if not impossible, if the attitude of the public and lawmakers spreads, becomes epidemic and affects other projects in particle physics and other fields of science, in this country and elsewhere. It is our responsibility as members of the scientific community to examine the reason for the decision by our fellow citizens to cut off support for the SSC. It is our responsibility to do more to explain our raison d’être, the need for research as part of our human endeavor, and the close connection between the basic science of today and the technology of tomorrow.
ACKNOWLEDGMENTS

This report is a summary of many excellent summary talks and I am indebted to the other speakers who made my task a lot easier. Furthermore, I refer the reader to their reports for proper reference to the contributed papers. I would like to take this opportunity to thank the organizers of this Symposium, in particular Rich Galik and his staff, for an exceptionally well conceived and well run conference. I owe special thanks to my scientific secretary, Frank Würthwein, for his help in the preparation of the material for this presentation.