EXPERIMENTAL SUMMARY

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The experimental results presented at the XXXVI Rencontres de Moriond Electroweak Inter-
actions and Unified Theories are summarized. The results range from possible evidence for the
Standard Model Higgs boson at LEP2 to searches for new physics at LEP, the Tevatron and
HERA, to precision electroweak and weak decay measurements, and to the strong evidence
for neutrino oscillations.

1 Introduction

This XXXVIth Rencontres de Moriond Electroweak Interactions and Unified Theories offered
some intense speculations on the recent past and the next few years, occurring just a few months
after the shutdown of LEP and at the beginning of the new Tevatron run at Fermilab. There
were 49 experimental contributions to this conference, so I cannot possibly do justice to them
all. I can only try to touch on what seemed to me to be some of the highlights.

This summary begins with the tantalizing evidence from LEP for the Standard Model Higgs
boson, and then continues with the precision electroweak and top quark mass measurements
from LEP, the Tevatron, SLD, BEPC, and HERA. Searches for non-Standard-Model Higgses at
LEP and prospects for Higgs searches at future colliders are then discussed. Searches for supers-
symmetry and other new physics at LEP, Fermilab, and DESY are reviewed. The measurement
of positron polarization at PSI is summarized, and the AMANDA and DAMA searches for ex-
traterrestrial interactions are briefly mentioned, as are the antimatter experiments at CERN.
The beautiful evidence for neutrino oscillations from Super-Kamiokande and preliminary K2K
results are presented. Rare kaon and charm decays are summarized. The LEP and SLD B
physics measurements are then discussed. The measurements of the $CP$ violation parameter
sin$2\beta$ from Belle and BaBar are presented, followed by measurements of rare $B$ decays from
CLEO, Belle, and BaBar. Finally the precision measurement of the anomalous magnetic moment
of the muon from Brookhaven National Laboratory E821 is summarized.
2 Evidence for the Standard Model Higgs Boson

The results of searches for the Standard Model Higgs boson at LEP were presented by Nakamura, Moretini, and Teixeira-Dias. At LEP the SM Higgs boson is expected to be produced mainly through the Higgs-strahlung process $e^+e^- \rightarrow H^0Z^0$, with contributions from the $WW$ fusion channel below 10%. Searches are performed in the channels $HZ \rightarrow b\bar{b}q\bar{q}$ (four jet), $HZ \rightarrow b\bar{b}\nu\bar{\nu}$ (missing energy), $HZ \rightarrow b\bar{b}\tau^+\tau^-$ or $\tau^+\tau^-q\bar{q}$ (tau), and $HZ \rightarrow b\bar{b}e^+e^-$ or $b\bar{b}\mu^+\mu^-$ (leptonic). All four LEP experiments have published results of the searches using the 2000 data. ALEPH, DELPHI, and OPAL presented results here that are the same as their publications and very similar to those presented at the November 3, 2000, meeting of the LEP Experiments Committee (LEPC), for which the only official combination of the four LEP experiments exists.

Table 1: Comparison of results presented here (published) with those used in the November 3 LEP combination.

| Experiment | Nov. 3 LEPC (combination) | Presented here (published) |
|------------|---------------------------|-----------------------------|
| ALEPH      | 3.4$\sigma$               | 3.2$\sigma$ (1 − $CL_b = 0.0015$ at $m_H \sim 115$ GeV) |
| DELPHI     | −1.0$\sigma$              | −1.0$\sigma$, $m_H > 114.3$ GeV (113.5 GeV expected) |
| L3         | 1.7$\sigma$               | − (reanalysis by summer conferences) |
| OPAL       | 1.3$\sigma$               | 1.3$\sigma$, $m_H > 109.7$ GeV (112.5 GeV expected) signal slightly favored |

The combination of the four LEP experiments presented at the November 3 LEPC meeting showed an excess of 2.9$\sigma$ significance, or $1 − CL_b = 0.0042$ at $m_H \sim 115$ GeV. The value of the mass is $m_H = 115 \pm 1.3^{+1.3}_{-0.9}$ GeV (2$\sigma$ errors). The probability density distributions for signal and background for $m_H = 115$ GeV for each experiment as presented at the November 3 LEP meeting are shown in Fig. 1. The confidence level for background for the LEP combination is shown in Fig. 2. For background only, $1 − CL_b$ will be 0.50 on the average. The log likelihood distribution for the LEP combination is shown in Fig. 3. The value of $m_H$ is given by the point at which the observed log likelihood intersects the predicted signal plus background curve.

The final combination of the four LEP experiments will be produced after the L3 Experiment reanalyzes its data and releases the results, in time for the 2001 summer conferences.

3 Electroweak and Top Measurements at LEP, SLD and Tevatron

The masses of the $W$ boson and the top quark obtained in Tevatron Run I by CDF and D0 were presented by Glenzinski. The combined values are $m_W = 80.452 \pm 0.062$ GeV and $m_t = 174.3 \pm 5.1$ GeV. Watson presented $m_W = 80.446 \pm 0.040$ GeV, a preliminary combination based on 82% of all LEP2 data. The world average, including LEP1, SLD, $\nu N$, and $m_t$ is $m_W = 80.368 \pm 0.023$ GeV. Verzi presented results on $WW$, $ZZ$, $Z\gamma$ and single $W$ production (triple gauge boson couplings) from LEP. Quartic gauge boson coupling results were presented by Musy.

De Groot presented new or updated results on $R_b$, $R_c$, $A_b$, and $A_c$ from SLD. The new SLD average for $A_b$ is 0.913 ± 0.021, compared with the LEP average of 0.873 ± 0.018, derived from the measurements of the $b\bar{b}$ forward-backward asymmetry ($A_{FB}^{0,b}$) and $A_c$.

Tournefier reported on the fits of the LEP electroweak data to the Standard Model including the running of $\alpha_s$, the latest $m_W$ from LEPT2, the new $R$ measurement from BES, the new measurements of $A_{FB}^{0,b}$ from ALEPH and DELPHI, and the new values of $R_b$, $R_c$, $A_b$, and $A_c$ from SLD. The results of the fit are shown in Fig. 4. The $\chi^2$ of the fit, including the top
mass measurement, as a function of $m_H$ is shown in Fig. 3. The fit gives $m_H = 98^{+58}_{-38}$ GeV and $m_H < 212$ GeV at 95% C.L. However, the probability of the fit is only 4% ($\chi^2$/d.o.f. = 25/15). The largest deviation is due to $A_{FB}$. The data favor a light Higgs boson.
Figure 3: Log likelihood distributions for the combined LEP experiments as shown at the November 3 LEPC meeting.

Winter 2001

| Measurement     | Pull | Pull |
|-----------------|------|------|
| $m_Z$ [GeV]     | $91.1875 \pm 0.0021$ | .04  |
| $\Gamma_Z$ [GeV]| $2.4952 \pm 0.0023$  | -.46 |
| $\sigma_{hadr}$ [nb] | $41.540 \pm 0.037$   | 1.62 |
| $R_l$           | $20.767 \pm 0.025$   | 1.09 |
| $A^l_l$         | $0.01714 \pm 0.00095$| .79  |
| $A^e$           | $0.1498 \pm 0.0048$  | .41  |
| $A^t$           | $0.1439 \pm 0.0041$  | -.96 |
| $\sin^2\theta_{lep}$ | $0.2322 \pm 0.0010$ | .78  |
| $m_W$ [GeV]     | $80.446 \pm 0.040$   | 1.32 |
| $R_b$           | $0.21664 \pm 0.00068$| 1.32 |
| $A^{0,b}_b$     | $0.1729 \pm 0.0032$  | .20  |
| $A^{0,c}_c$     | $0.0982 \pm 0.0017$  | -.32 |
| $A^{0,c}_c$     | $0.0689 \pm 0.0035$  | -1.48|
| $A^c$           | $0.921 \pm 0.020$    | -.68 |
| $A^c$           | $0.667 \pm 0.026$    | -.05 |
| $A^l$           | $0.1513 \pm 0.0021$  | 1.68 |
| $\sin^2\theta_W$ | $0.2255 \pm 0.0021$ | 1.20 |
| $m_W$ [GeV]     | $80.452 \pm 0.062$   | .95  |
| $m_t$ [GeV]     | $174.3 \pm 5.1$      | -.27 |
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | $0.02761 \pm 0.00036$| -.36 |

Figure 4: Fit to precision electroweak data pulls.
4 \( R \) Measurement at BES

A precision measurement of

\[ R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \]

from 2 to 5 GeV center-of-mass energy (\( E_{cm} \)) reduces the uncertainty on \( \alpha(m_Z^2) \), reduces the width of \( \chi^2 \) vs. \( m_H \) in the electroweak fits, and reduces the uncertainty in the theoretical value of the muon (\( g - 2 \)). Previous measurements of \( R \) had uncertainties of 15-20\% in the 2-5 GeV \( E_{cm} \) range. A new set of measurements was made using the Upgraded BEijing Spectrometer (BES-II) at the Beijing Electron-Positron Collider (BEPC) and presented by Huang. The uncertainties in the new measurements range from 6 to 10\% (average 6.6\%), a factor of two improvement over the old measurements. Values of \( R \) vs. \( E_{cm} \) are shown in Fig. 6.

5 Electroweak Tests at High \( Q^2 \) at HERA

Fusayasu presented recent results on high-\( Q^2 \) neutral and charged currents at HERA. Measurements of \( xF_3^{NC} \) have been extracted from the difference of the neutral current differential cross sections for \( e^-p \) and \( e^+p \). The first space-like measurement of \( m_W \) has been extracted from the slopes of the charged current differential cross sections for \( e^+p \). Electroweak unification is observed from the equality of the neutral current and charged current cross sections at high \( Q^2 \gg m_W^2, m_Z^2 \). One fb\(^{-1} \) integrated luminosity is expected from a luminosity upgrade with left-handed and right-handed longitudinally polarized beams in 2001 – 2005.
Non-SM Higgses at LEP

Teuscher and Holzner discussed the status of searches for non-Standard Model Higgs bosons at LEP. For the fermiophobic Higgs boson ($h^0 \rightarrow \gamma \gamma$) the preliminary LEP combined limit is $m_{h^0} > 107.7$ GeV, 95% C.L. L3 has also combined their search for $h \rightarrow \gamma \gamma$ with a search for $h \rightarrow WW^*$ to obtain a limit of $m_{h^0} > 104.8$ GeV.

Preliminary combined MSSM Higgs search results give $0.52 < \tan \beta < 2.25$ excluded and limits on the $h^0$ and $A^0$ masses of $m_{h^0} > 89.9$ GeV and $m_{A^0} > 90.5$ GeV in the conservative $m_{h^0}$-max scenario.

In general Type II Two-Higgs Doublet Models (2HDM(II)), Higgs boson decays to $b\bar{b}$ and $\tau^+\tau^-$ can be suppressed, leaving $c\bar{c}$ and $gg$ decays dominant. Flavor-independent searches for Higgs bosons have been carried out and give preliminary limits of $m_{h^0} > 102 \rightarrow 109$ GeV assuming Standard Model cross sections for Higgs boson production. Complete flavor-independent 2HDM(II) scans over the parameter space of the Higgs boson masses $m_{h^0}$ and $m_{A^0}$, $\tan \beta$ and $\alpha$ have been performed. For any value of $\alpha$ between $-\pi/2$ and 0, the region $13 < m_{A^0} < 56$ GeV and $m_{h^0} < 44$ GeV is excluded for $0.4 \leq \tan \beta \leq 58$.

Searches for Higgs bosons decaying into invisible particles (e.g., $h \rightarrow \tilde{\chi}_0^0\tilde{\chi}_0^0$) give $m_{h^0} > 113.7$ GeV for a Standard Model Higgs boson production cross section and 100% branching ratio for decay into invisible particles.

In the MSSM $m_{H^0} > 330$ GeV from the absence of flavor-changing neutral currents (from $b \rightarrow s\gamma$ measurements). Thus searches for $H^\pm$ at LEPT2 are non-MSSM searches. For $\tan \beta < 1$, decays to $c\bar{s}$ and $\tau^+\nu$ dominate, whereas for $\tan \beta > 1$, $W^*A$ dominates. L3 has observed for years a significant excess (now 4.4$\sigma$) at 68 GeV in the four-jet channel, but the other LEP experiments have not confirmed it. The combined preliminary LEP limit for $H^\pm \rightarrow c\bar{s}$ and $\tau^+\tau^-$ is $m_{H^\pm} > 78.5$ GeV. A search for $H^\pm \rightarrow W^*A$ has been performed by OPAL with no significant excess observed.

Prospects for Higgs at Future Colliders

Upgrades to the luminosity of the Tevatron at Fermilab were discussed by Church. Run IIa started the week before the conference with the goal of 2 fb$^{-1}$ by 2003. Run IIb will begin...
in 2003 with the luminosity goal of 13 fb$^{-1}$ by 2006+, and many upgrades (mostly increasing antiproton production) will be implemented to achieve this goal:

- Radiation due to beam losses will be decreased so that the Booster intensity can be increased.
- Slip stacking will be used to increase the intensity in the Main Injector.
- The $\bar{p}$ yield will be increased by increasing the gradient of the lithium lens.
- $\bar{p}$'s are cooled in the Debuncher Ring, the Accumulator Ring and the Recycler. Higher bandwidth stochastic cooling will be used in the Debuncher and the Accumulator. Electron cooling in the Recycler Ring will be installed in 2003.
- Electron lens compensation (an electron beam coaxial with the $\bar{p}$ beam) will be used to compensate the beam-beam tune shift that limits the proton intensity in the Tevatron. The first electron lens is installed in one straight section and will be commissioned over the next few months.
- The bunch spacing will be reduced from 396 ns to 132 ns, which will also require introducing a crossing angle at the IR’s.
- The Tevatron beam energy will be increased to 980 GeV.

The total luminosity goal by 2006 with all upgrades is 15 fb$^{-1}$.

In Run II at the Tevatron the Standard Model Higgs boson will be searched for in associated production in the modes $\ell\nu b\bar{b}$, $e^+e^-b\bar{b}$, and $\nu\bar{\nu}b\bar{b}$ for $90 < m_H < 130$ GeV. For $130 < m_H < 190$ GeV, the Higgs decay modes searched will be $WW^*$ and $ZZ^*$. For an integrated luminosity of 15 fb$^{-1}$, the Higgs boson signal should be significant by 5σ for $m_H < 120$ GeV. A 3σ effect can be observed for $m_H < 130$ GeV and $150 < m_H < 175$ GeV, and a 95% C.L. upper limit can be determined for $m_H < 185$ GeV.

Costanzo presented the prospects for Higgs searches at the LHC. The SM Higgs can be searched for in the channels $H \rightarrow \gamma\gamma$ and $t\bar{t}H \rightarrow t\bar{t}b\bar{b}$ for $m_H < 130$ GeV, in $H \rightarrow ZZ^* \rightarrow 4\ell$ for $m_H > 130$ GeV, and in $H \rightarrow WW$ and $WH \rightarrow WW$ for $m_H > 160$ GeV. The Higgs boson can be discovered at 5σ for ATLAS plus CMS together for $m_H < 130$ GeV with 10 fb$^{-1}$ integrated luminosity per experiment (~ one year, the first year of physics running, 2006-2007). For 100 fb$^{-1}$ (four years running) the Higgs signal will be significant at 10σ per experiment over the entire $m_H$ mass range.

Schumacher discussed Higgs physics at a future $e^+e^-$ linear collider, which would have a center-of-mass energy of 350-800 GeV and a luminosity of $2.5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ (several 100 fb$^{-1}$/year). An $e^+e^-$ linear collider would be complementary to the LHC: the LHC would discover an SM Higgs boson for $100 < m_H < 1000$ GeV and could discover at least one MSSM Higgs boson, and the linear collider would measure the properties, such as mass, width, and couplings, with more precision than the LHC. For example, $m_H$ could be measured to ~ 50 MeV for $m_H \sim 150$ GeV. Branching ratios to $b\bar{b}$, $gg$, $WW$, etc., can be measured to ~ 5%. $CP$ properties can be measured from angular distributions in $e^+e^- \rightarrow ZH$. Holes in the LHC region for discovery of MSSM Higgs bosons can be closed.

Murray presented the possibilities with a muon collider Higgs factory. The beam energy in a muon collider can be measured to $10^{-6}$ via $(g - 2)$, and a $10^{-5}$ beam energy spread is possible. Since muons are 200 times heavier than electrons, the storage ring can be smaller. The Higgs boson is produced through the $s$-channel, so the cross section is 40,000 times the electron equivalent. With such a machine one could measure $m_H$ to 100’s of keV and the width to 1 MeV. $CP$ properties can be measured from transverse polarization asymmetries. A muon
collider Higgs factory can offer many advantages in the case of MSSM or other non-standard-model Higgs bosons through, for example, precise measurement of the Higgs width and resolution of degenerate states. However, several technical difficulties must be overcome. The muons decay, so cooling of the beams must take place quickly. The proposed method is ionization cooling. Ionization cooling schemes typically cool in the transverse phase space. This cooling then needs to be transferred to the longitudinal direction by emittance exchange. These cooling ideas are being developed but have not yet been shown to be feasible.

8 Searches for SUSY and Exotics at LEP

Jakobs presented preliminary results on MSSM SUSY searches, including data from 2000. With gravity mediated SUSY breaking and R-parity conservation, the lightest supersymmetric particle (LSP) is assumed to be the lightest neutralino ($\tilde{\chi}^0_1$). The combined LEP limits for slepton searches are $m_{\tilde{e}} > 99.4$ GeV, $m_{\tilde{\mu}} > 96.4$ GeV, and $m_{\tilde{\tau}} > 87.1$ GeV, all for $m_{\tilde{\chi}^0_1} = 40$ GeV. There was no $\tau$ excess in the 2000 data. The combined LEP limits for squarks are $m_{\tilde{t}_1} > 95$ GeV for $\tilde{t}_1 \rightarrow c\tilde{\chi}^0_1$ and $\Delta M = 40$ GeV, $m_{\tilde{t}_1} > 97$ GeV for $\tilde{t}_1 \rightarrow b\tilde{\nu}$ and $\Delta M = 40$ GeV, and $m_{\tilde{b}_1} > 95$ GeV for $\tilde{b} \rightarrow b\tilde{\chi}^0_1$, and $\Delta M = 20$ GeV, all independent of mixing angle. The limit on the mass of the lightest chargino is $m_{\tilde{\chi}^+}_1 > 103.5$ GeV for $\Delta M > 10$ GeV. The low $\Delta M$ regions are covered by dedicated searches. The limit on the mass of the LSP is $m_{\tilde{\chi}^0_1} > 39.6$ GeV for large $m_0$. A new DELPHI result includes slepton and Higgs searches.

De Min summarized the preliminary results of searches at LEP for R-parity violating (RpV) SUSY, gauge mediated SUSY breaking, and exotic final states. In gauge mediated SUSY breaking, $\tilde{\chi}^0_1 \rightarrow \tilde{G}\gamma$ or $\tilde{\ell} \rightarrow \tilde{G}\ell$, where $\tilde{G}$ is the gravitino. Single $\gamma$ final states are often used. Searches have also been performed for light sgoldstinos ($\Phi$): $e^+e^- \rightarrow \Phi\gamma$, with $\Phi \rightarrow gg$ or $\gamma\gamma$. Unfortunately, no significant excesses have been seen. A new LEP Working Group on Exotic Searches has been formed.

9 New Phenomena at the Tevatron

CDF and D0 collected ~ 110 pb$^{-1}$ integrated luminosity during the Tevatron Run I 1992–1996. Büscher reported the results of a new MSSM scalar top search by D0 in the mode $\tilde{t}_1 \rightarrow b\tilde{\nu}$. The excluded region will be greatly extended with Run II data. CDF searched for RpV scalar top in the mode $\tilde{t}_1 \rightarrow \tau^+b$. D0 carried out a search for large extra dimensions using di-fermion/di-photon events and found consistency with Standard Model expectations; limits were set at the $\geq 1$ TeV level. D0 has developed a model independent search (SLEUTH) for excesses at high-$p_T$ and has tested it for Monte Carlo samples of new physics, such as leptoquarks, and on data. Berryhill reported on a model independent search developed by CDF based on leptons, photons, multiple jets and missing transverse energy ($E_T$). A new CDF search for scalar quarks excludes $m_{\tilde{q}} \sim m_{\tilde{g}} < 300$ GeV, as shown in Fig. 6. A search for events with electrons, large missing $E_T$, and large mass of the electron-missing-$E_T$ system excludes $m_{\tilde{\nu}V} < 755$ GeV and compositeness scales $\Lambda_+, \Lambda_- < 2.8$ TeV. A D0 search for high-mass $ee$ events excludes $m_{Z'} < 670$ GeV and technicolor $m_{\rho_T}, m_{\omega_T} < 207$ GeV.

10 Searches for Extra Dimensions at LEP

Searches for extra dimensions were also carried out at LEP, as presented by Gataullin. Direct searches consisted of looking for one $\gamma$ or one $Z^0$ plus missing energy due to a missing graviton ($G$), and indirect searches looked for deviations from $(\sigma/d\Omega)_{SM}$ due to $G$ exchange ($\lambda = \pm 1$ refers to the different signs of the interference term). All four LEP experiments searched for $e^+e^- \rightarrow G^* \rightarrow \gamma\gamma$ with combined limits on the fundamental mass scale $M_S > 0.95$ TeV for
11 Searches Beyond the Standard Model at HERA

New search results from HERA were presented by Schöning for leptoquarks, large extra dimensions, lepton flavor violation, R-parity violating supersymmetry, and excited fermions. H1 has observed an excess of events with isolated leptons with large transverse momentum and large missing transverse momentum in both the 1994–97 $e^+p$ data and the 1999–2000 $e^+p$ data. ZEUS, however, finds consistency with Standard Model expectations. Leptoquarks are excluded up to $\sim 260$ GeV. New R-parity violating limits in mSUGRA improve the limits from the Tevatron for Yukawa couplings $\lambda_{ij1} \sim \alpha_{em}$. New limits on anomalous production of top quarks were obtained: HERA is very sensitive to such production. The HERA upgrade starts in September and will produce five times higher luminosity and polarized $e^{\pm}$ beams. In four years running, an integrated luminosity of 800 pb$^{-1}$ is anticipated, giving a large potential to discover leptoquarks, as shown in Fig. 8.
12 NuTeV: Heavy Lepton Anomaly

Shaevitz reported results from the NuTeV experiment at Fermilab. The experiment uses 800 GeV protons on target to produce $\nu_\mu$ and $\bar{\nu}_\mu$ beams and measures $\sin^2 \theta_W = 0.2253 \pm 0.0019 \pm 0.0010$ (preliminary), corresponding to $M_W = 80.26 \pm 0.110$ GeV. They have implemented a decay detector consisting of a 35 m helium bag instrumented with drift chambers to search for heavy neutral leptons. They observed three $\mu\mu$ events with vertices in the helium and transverse mass $> 2.2$ GeV compared with an expected background of 0.04 events. They do not observe any $\mu e$ or $\mu\pi$ events although the expected background for these is about three times larger. The events have the characteristics of neutrino interactions because the energies are asymmetric. They do not seem to be consistent with any known background or other physics process. The events are used to set limits for heavy neutral lepton and neutralino production.

13 Polarization of $e$ from $\mu$ Decays at PSI

The purposes of the $\mu P_T$ Experiment at PSI, discussed by Köhler, are a search for additional couplings in muon decays, a model independent determination of $G_F$, and a search for violation of time-reversal invariance. All three components of the positron’s polarization vector are measured. No evidence for additional scalar couplings in muon decay were found. The model independent measurement of $G_F$ gives

$$G_F = (1.16532 \pm 0.00069) \times 10^{-5} (\hbar c)^3 \text{GeV}^{-2}.$$ 

14 AMANDA, DAMA and Antimatter Experiments

Hill reported on the latest results from AMANDA, which is an experiment at the South Pole that looks at atmospheric neutrinos that penetrate the Earth. The results are consistent with
expectations. They have also set limits on extraterrestrial neutrinos, WIMPs, and gamma-ray bursts.

DAMA is an experiment that uses NaI(Tl) to search for dark matter sources. Belli\(^2\) gave the current status of the analysis, which shows an annual modulation with the proper features to be compatible with the presence of WIMPs in the Galactic halo. No systematics or side reactions were found to be able to give the observed modulation.

Tan described several antimatter experiments at CERN.\(^3\) Low energy antiprotons (5.3 MeV) are extracted from the Antiproton Decelerator (AD) Ring. The three experiments are ATRAP, ATHENA, and ASACUSA. ATRAP has produced the world’s coldest \(\bar{p}\)'s. The \(\bar{p}\)'s are trapped in the world’s most intricate Penning Trap. ATRAP also accumulated the first cold positrons. The cold \(\bar{p}\)'s and cold \(e^+\)'s are then used to produce cold antihydrogen for high resolution spectroscopy. Experiments studying transitions in antihydrogen as compared with hydrogen test CPT invariance.

15 Neutrinos

15.1 \(\nu\) Mass Measurement at Mainz

The best measurement of the \(\nu_e\) mass is being carried out at Mainz using the tritium \(\beta\) decay endpoint. Bonn\(^4\) reported that they have the world’s best sensitivity and have measured \(m_{\nu_e} < 2.2 \text{ eV}/c^2\), 95% C.L., using 1998/99 data. They have seen no evidence of the “Troitsk anomaly.” Changing the design of their apparatus will allow them to reach a sensitivity of \(\leq 0.4 \text{ eV}/c^2\).

15.2 DONUT

Sielaff\(^5\) reported results from the DONUT Experiment, Fermilab E872, which has observed four events due to \(\nu_\tau\) interactions in nuclear emulsion targets with an expected background of 0.3 events. The \(\nu_\tau\) interaction produces a \(\tau\), which then decays to a single charged track and a \(\nu_\tau\) (86% of \(\tau\) decays). The decay results in a kink in the reconstructed emulsion track. The probability that all four events are background is \(8.0 \times 10^{-5}\). Phase 2 of the analysis, with relaxed cuts for the \(\nu_\tau\) interaction, including three-prong decays, is in progress. An interesting event was located on February 21, 2001.

15.3 Super-Kamiokande Results

Super-Kamiokande results on solar neutrinos were presented by Smy.\(^6\) Super-Kamiokande has reached its design threshold of 5 MeV. The total observed flux compared with the Standard Solar Model is \(0.451 \pm 0.005\) (stat.)\(^+0.016\)\(^{-0.014}\) (syst.). The day-night asymmetry is \(1.5\sigma\) away from zero. A new oscillation analysis has been performed, including zenith angle and new information on the \(^8\)B spectrum. The results of the global fit to \(\nu_e \leftrightarrow \nu_{\mu,\tau}\) are shown in Fig.\(^7\) The Small Mixing Angle solution is mostly disfavored at about 95% C.L. Mixing to sterile neutrinos alone is also disfavored at 95% C.L.

Atmospheric neutrino results from Super-Kamiokande were presented by Toshito.\(^8\) For 79 kton-years of data

\[
\text{Sub – GeV contained events : } \frac{(\mu/e)_{\text{DATA}}}{(\mu/e)_{\text{MC}}} = 0.638 \pm 0.017 \pm 0.050
\]

\[
\text{Multi – GeV events : } \frac{(\mu/e)_{\text{DATA}}}{(\mu/e)_{\text{MC}}} = 0.675^{+0.034}_{-0.032} \pm 0.080.
\]
A two-flavor oscillation analysis for $\nu_\mu \rightarrow \nu_\tau$ gives $\sin^2 2\theta > 0.88$ and $1.6 \times 10^{-3} < \Delta m^2 < 4 \times 10^{-3}$ eV$^2$ at 90% C.L. Pure $\nu_\mu \rightarrow \nu_\mu$ is disfavored at 99% C.L. Three different analyses are consistent with charged current $\nu_\tau$ appearance, with 74 events expected so far.

15.4 K2K Results

The goal of K2K is to establish neutrino oscillations through $\nu_\mu$ disappearance and $\nu_e$ appearance. The flight length is 250 km from KEK to Super-Kamiokande. The $\nu_\mu$ beam flux and $\nu_e$ contamination are measured in the near detector at KEK. GPS is used for time synchronization between the near and far sites. Ishii reported results for the data from June 1999 to June 2000, corresponding to $2.29 \times 10^{19}$ pot. The number of fully contained events observed in the fiducial volume of Super-Kamiokande was 28, with $37.8^{+3.5}_{-3.8}$ events expected without oscillation. There is a deficit of $\sim 1$ GeV $\nu_\mu$ after the 250 km flight path at 90% significance. The experiment resumed in January 2001.

15.5 Solar and Atmospheric Three $\nu$ Analysis

A fit to the standard three neutrino mixing matrix, including CHOOZ reactor data and the updated analyses of Super-Kamiokande data, was presented by Montanino. It was found that maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing is preferred from atmospheric $\nu$ data. Maximal $\nu_1 \leftrightarrow \nu_2$ mixing is preferred from solar $\nu$ data. The best fit for solar plus atmospheric plus CHOOZ data gives $U^2_{e3} = \sin^2 \theta_{13} \simeq 0$. There is a multiplicity of solutions to the solar $\nu$ problem.
15.6 CHORUS and NOMAD Results

CHORUS and NOMAD were designed to detect $\nu_e$ CC interactions: $\nu_e + N \rightarrow \tau^- + X$. These short baseline experiments at CERN have found no evidence for neutrino oscillations in the cosmologically relevant region $\Delta m^2 > 1$ eV$^2$, as reported by Cocco. Mixing angles down to $\sin^2(2\theta_{13}) \approx O(10^{-4})$ have been explored. The NOMAD analysis is completed, and CHORUS has started “phase II” emulsion data analysis.

16 Rare Kaon Decays

Recent results from NA48 were presented by T. Cuhadar-Dönszelmann. Based on the 1999 $K_S$ high intensity data (2.3 $\times$ $10^6$ $K_S$), $\text{BR}(K_S \rightarrow \gamma\gamma)$ was measured to be $(2.58 \pm 0.36$ stat. $\pm 0.22$ syst.) $\times 10^{-6}$. Using the 1998 and 1999 data, preliminary results are $\text{BR}(K_S \rightarrow \pi^+\pi^-e^+e^-) = (4.3 \pm 0.2$ stat. $\pm 0.3$ syst.) $\times 10^{-5}$ with no asymmetry ($A_{\pi\pi ee} = (-0.2 \pm 3.4$ stat. $\pm 1.4$ syst.%)). $\text{BR}(K_L \rightarrow \pi^+\pi^-e^+e^-) = (3.1 \pm 0.1$ stat. $\pm 0.2$ syst.) $\times 10^{-7}$ with $A_{\pi\pi ee} = (13.9 \pm 2.7$ stat. $\pm 2.0$ syst.)%. Again using the 1999 $K_S$ high intensity data, no events survive after all cuts, giving the final result $\text{BR}(K_S \rightarrow \pi^0e^+e^-) < 1.4 \times 10^{-7}$, 90% C.L.

Preliminary results using $300 \times 10^6$ events from the 1997 KTeV data were given by Bellanenti. The charge asymmetry in $K_{e3}$ decays ($\delta_L$): $\delta_L = (3.320 \pm 0.058$ stat. $\pm 0.046$ syst.) $\times 10^{-3}$, giving a new world average of $(3.305 \pm 0.063) \times 10^{-3}$, in agreement with no CP violation. The charge radius for $K_L^0 \rightarrow \pi^+\pi^-e^+e^-$ was measured to be $< R^2 > = (-0.047 \pm 0.008$ stat. $\pm 0.006$ syst.) fm$^2$, which implies a mass difference $m_s - m_d \sim 100$ MeV. From one event passing the cuts, a limit of $\text{BR}(K_L^0 \rightarrow \pi^0\pi^0e^+e^-) < 5.4 \times 10^{-9}$, 90% C.L., was found. $\text{BR}(K_L^0 \rightarrow \mu^+\mu^-\gamma) = (3.66 \pm 0.04$ stat. $\pm 0.07$ syst.) $\times 10^{-7}$. This measurement puts the tightest constraints on the $K_L^0 \rightarrow \gamma^{(*)}\gamma^{(*)}$ vertex factor $\rho_{\text{CKM}}$. The data are used to find limits on $\rho_{\text{CKM}}$ for two models: $\rho_{\text{CKM}} > -1.0$ using the BMS model and $\rho_{\text{CKM}} > -0.2$ using the DIP model. A limit was placed on the lepton flavor violating decay $K_L^0 \rightarrow \pi^0\mu^+\pi^-$ at $< 4.40 \times 10^{-10}$ at 90% C.L. for two events found in the data. The 1999 data will improve the statistics by a factor of 2.5 for $\pi^0e^+e^-$, $\pi^0\mu^+\mu^-$, and $\pi^0\mu^+\pi^-$ and by a factor of 3.2 for $\pi^+\pi^-e^+e^-$, $\mu^+\mu^-e^+e^-$, and $e^+e^-e^+e^-$. However $K_L^0 \rightarrow \pi^0e^+e^-$ and $K_L^0 \rightarrow \pi^0\mu^+\mu^-$ are reaching background limits already. Future goals are the measurements of $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$ in KaMI and $K^+ \rightarrow \pi^+\nu\bar{\nu}$ in CKM.

17 Charm Results

New results for charm physics were presented by Link, Hans, and Sanders. The FOCUS Experiment looks for charm mixing through lifetime differences between $CP$-even and $CP$-odd eigenstates in decays of the $D^0$. $D^0 \rightarrow K^+\pi^-$ can occur through a doubly-Cabibbo-suppressed process or through mixing followed by a Cabibbo favored decay. They measure a lifetime difference $y = (3.42 \pm 1.39 \pm 0.74)%$ and a ratio of wrong-sign to right-sign branching ratios of $(0.404 \pm 0.085 \pm 0.025)%$ in the limit of no mixing; this is a possible indication of $D^0\bar{D}^0$ mixing at the 2$\sigma$ level.

The CLEO Experiment reported $CP$ asymmetries consistent with zero for five $D^0$ decays $(K^+K^-, \pi^+\pi^-, K_L^0\pi^0, \pi^0\pi^0,$ and $K_L^0K_s^0)$. They reported the first observation of $D^0 \rightarrow K^-\pi^+\pi^0$. They also measured the time difference $y_{CP} = (-0.011 \pm 0.025 \pm 0.014)$ from $K^+K^-$ and $\pi^+\pi^-$ decays as a limit on $D^0\bar{D}^0$ mixing.

E791 at Fermilab reported limits on many rare or forbidden two-, three- and four-body decays of $D$ mesons, some of which have not previously been reported. A few measurements are improvements on the previous upper limits by an order of magnitude or more.
Lin reported on recent heavy flavor results from LEP and SLD. A new preliminary measurement of the charm multiplicity in $B$ decays from SLD gives $\eta_c = 1.238 \pm 0.055$, which is in agreement with measurements from CLEO and LEP but slightly higher and brings the average into better agreement with the prediction.

The measurements of the CKM matrix elements from LEP give $|V_{cb}| = (40.4 \pm 1.8) \times 10^{-3}$ (average of inclusive and exclusive measurements) and $|V_{ub}| = (4.1 \pm 0.7) \times 10^{-3}$. The $B_d^0$ mixing oscillation frequency is the most direct method to extract $|V_{td}|$. The $B$ Oscillations Working Group (LEP, SLD and CDF) value for $\Delta m_d$ is $(0.486 \pm 0.015)$ ps$^{-1}$. Only a lower limit has been obtained for $B_s^0$ mixing oscillations: $\Delta m_s > 15$ ps$^{-1}$ at 95% C.L., with a sensitivity of 18 ps$^{-1}$. These measurements can be used to constrain the unitarity triangle, as discussed in the presentation by M. Ciuchini. It will have to be left to Fermilab to measure $\Delta m_s$.

![Figure 10: Compilation of measurements of the $CP$ violation parameter $\sin 2\beta$.](image)

### 19 $CP$ Violation and $B - \bar{B}$ Mixing Results from Belle and BaBar

Belle, presented by Hanagaki, and BaBar, presented by Faccini, have made measurements of the unitarity triangle angle $\sin 2\beta (\phi_1 \equiv \beta)$ at the $B$ factories at KEK and SLAC, respectively:

- Belle: $\sin 2\phi_1 = 0.58_{-0.34}^{+0.32}$ (stat.) $^{+0.09}_{-0.10}$ (syst.)
- BaBar: $\sin 2\beta = 0.34 \pm 0.20$ (stat.) $\pm 0.05$ (syst.)
Both experiments also measure $\Delta m_d$; the value for BaBar is $\Delta m_d = (0.519 \pm 0.020 \text{ (stat.)} 
\pm 0.016 \text{ (syst.)}) \text{ ps}^{-1}$ (preliminary) giving a new world average including Belle of $\Delta m_d = (0.484 \pm 0.010) \text{ ps}^{-1}$.

A compilation of sin $2\beta$ measurements is shown in Fig. 10. After the next run ending August 2001 the uncertainty on sin $2\beta$ should be 0.015.

## 20 $B$ Decay Results from CLEO, Belle, and BaBar

Results on rare $B$ decays were presented by CLEO, Belle, and BaBar. CLEO has a new limit on $B^0 \rightarrow \pi^0\pi^0$ and has observed $B \rightarrow \phi K^(*)$, as presented by Blanc. The $b \rightarrow s\gamma$ branching ratio has been measured, and $|V_{cb}|$ has been determined from the $\gamma$ energy spectrum to be $|V_{cb}| = (40.6 \pm 1.1 \text{ (exp.)} \pm 0.7 \text{ (theor.)}) \times 10^{-3}$ with a $CP$ asymmetry $-0.27 < A_{CP} < +0.10$, 90% C.L.

Results for gluonic penguin, electroweak penguin, and $B \rightarrow hh$ decays are shown in Tables 2, 3 and 4, respectively. Belle results were presented by Taylor, based on an integrated luminosity of 10.5 fb$^{-1}$. They have made the first observation of the Cabibbo-suppressed decays $B \rightarrow D^+ K^-, D^{*0} K^-, D^{*-} K^-$, and $D^0 K^{*-}$. Measurements for $B \rightarrow \eta'h$ give BR($B^+ \rightarrow \eta'h$) = $(6.8^{+1.3}_{-1.2} + 0.7) \times 10^{-5}$ and BR($B^+ \rightarrow \eta'\pi^+$) < $1.2 \times 10^{-5}$. Results for electroweak penguin and $B \rightarrow hh$ decays are shown in Tables 2 and 3.

Roberts reported BaBar results on $B$ decays to double charm. BaBar took 20.7 fb$^{-1}$ of data on the $\Upsilon(4S)$ resonance. The branching ratio for $B^+ \rightarrow D^{*+} D^{*-} K^+$, a color-suppressed decay, was measured to be $(0.34 \pm 0.16 \pm 0.09)$%. $B^0 \rightarrow D^{(*)+} D^{(*)-} K_S$, a potentially useful mode for $CP$ violation measurements, was also observed. Charmless hadronic $B$ decays from BaBar were discussed by Wilson. Results for gluonic penguin, electroweak penguin, and $B \rightarrow hh$ decays are shown in Tables 2, 3 and 4.

All three experiments reported $CP$ asymmetry measurements that were all consistent with zero.

| Experiment | Decay | $BR \times 10^{-6}$ |
|------------|-------|---------------------|
| CLEO       | $b \rightarrow s\gamma$ | 2.85 ± 0.35 ± 0.22 |
| Belle      | $B \rightarrow X_s\gamma$ | 3.37 ± 0.53 ± 0.42$^{+0.50}_{-0.54}$ (theor.) |
| BaBar      | $B^0 \rightarrow K^{*0}\gamma$ | 0.439 ± 0.041 ± 0.027 |

Table 2: Gluonic penguin decays.

| BR $\times 10^{-6}$ | CLEO | BaBar |
|---------------------|------|-------|
| $\phi K^-$          | $5.5^{+2.1}_{-1.8} \pm 0.6$ | $7.7^{+1.6}_{-1.4} \pm 0.8$ |
| $\phi K^0$          | $< 12.3$, 90% C.L. | $8.1^{+3.1}_{-2.5} \pm 0.8$ |
| $\phi K^{*-}$       | $10.6^{+6.4}_{-4.9} + 1.8$ | $9.6^{+4.1}_{-3.3} \pm 1.7$ |
| $\phi K^{*0}$       | $11.5^{+4.5}_{-3.7} + 1.8$ | $-^{+4.1}_{-3.3} \pm 1.7$ |
| $\phi \pi^-$        | $-^{+4.5}_{-3.7} + 1.8$ | $< 1.3$ |

Table 3: Electroweak penguin decays. The Standard Model prediction is $(3.28 \pm 0.33) \times 10^{-4}$. 
Table 4: Charmless hadronic $B$ decays.

| BR $\times 10^{-8}$ | CLEO | Belle | BaBar |
|----------------------|-------|-------|-------|
| $K^+\pi^-$           | $1.79^{+0.25}_{-0.24} \pm 0.12$ | $1.87^{+0.33}_{-0.31} \pm 0.16$ | $1.67 \pm 0.16^{+0.12}_{-0.17}$ |
| $K^+\pi^0$           | $1.16^{+0.30}_{-0.27} +0.14$    | $1.70^{+0.37}_{-0.33} +0.20$    | $- 0.24$ |
| $K^0\pi^+$           | $1.82^{+0.46}_{-0.40} \pm 0.16$ | $1.31^{+0.55}_{-0.46} \pm 0.26$ | $- 0.24$ |
| $K^0\pi^0$           | $1.46^{+0.59}_{-0.51} +0.24$    | $1.46^{+0.61}_{-0.51} \pm 0.27$ | $- 0.24$ |
| $\pi^+\pi^-$         | $0.43^{+0.16}_{-0.14} \pm 0.05$ | $0.59^{+0.24}_{-0.21} \pm 0.05$ | $0.41 \pm 0.10 \pm 0.07$ |
| $\pi^+\pi^0$         | $< 1.27, 90\%$  C.L.            | $0.71^{+0.36}_{-0.30} +0.09$    | $- 0.6$ |
| $\pi^0\pi^0$         | $< 0.57, 90\%$  C.L.            | $- 0.6$                         | $- 0.6$ |
| $K^+K^-$              | $< 0.19, 90\%$  C.L.            | $- 0.6$                         | $< 0.25$ |

21 Muon $(g - 2)$ Measurement at BNL E821

The anomalous magnetic moment of the muon is given by $a_\mu \equiv (g - 2)/2$. For a point-like spin one-half particle, $g = 2$.

$$a_\mu^{\text{theory}} = a_\mu^{\text{QED}} + a_\mu^{\text{had}} + a_\mu^{\text{weak}} + a_\mu^{\text{New Physics}}$$

where

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{had}} + a_\mu^{\text{weak}}.$$ 

The contributions to $a_\mu^{\text{SM}}$ are shown in Table 5.

Table 5: Contributions to the muon anomalous magnetic moment.

| Contribution | $\times 10^{-11}$ | ppm |
|--------------|-------------------|-----|
| $a_\mu^{\text{QED}}$ | $116584706 \pm 3$ | $10^6 \pm 0.025$ |
| $a_\mu^{\text{had}}$ | $6739 \pm 67$ | $57.8 \pm 0.6$ |
| $a_\mu^{\text{weak}}$ | $151 \pm 4$ | $1.30 \pm 0.03$ |
| $a_\mu^{\text{SM}}$ | $116591596 \pm 67$ | $\pm 0.6$ |

Results from Experiment E821 at Brookhaven National Laboratory were reported by On-derwater. To measure the anomalous magnetic moment of the muon, polarized muons from $\pi$ decay precess in a magnetic field produced by a storage ring with a 1.45 T superconducting magnet uniform to 10 ppm. The magnetic field is measured to 1 ppm by an NMR probe on a trolley. The precession frequency of the NMR protons is $\omega_p/2\pi = 61,791, 256 \pm 25$ Hz. The precession frequency of the muons is measured to be $\omega_a/2\pi = 229,072.8 \pm 0.3$ Hz. There are several internal consistency checks, shown in Fig. [11].
The result is $a^\text{exp}_\mu - a^\text{theory}_\mu = (43 \pm 16) \times 10^{-10}$, a $2.6\sigma$ deviation. The total error is statistics dominated, with a systematic error of 0.25 ppm. Data equivalent to four times that presented here have been recorded but not yet analyzed, and the goal is to improve the final error to 0.3 ppm. The largest contribution to the theoretical error is the hadronic contribution, which is being redone to include the BES $R$ measurement and new $\tau$ results from ALEPH. The deviation from the Standard Model expectation is consistent with contributions from loops due to supersymmetric particles. It is hoped to have a new result by the end of the year.

22 Conclusions and Future Prospects

The evidence for the Standard Model Higgs boson from LEP has a significance of only 2.9$\sigma$. Unfortunately a LEP run for 2001 was not approved, so we will have to wait until at least $\sim$ 2007 to find out from the LHC experiments, or possibly the Fermilab Tevatron, whether there is really anything there. The significance of the deviation of the muon anomalous magnetic moment from the Standard Model prediction is even less, 2.6$\sigma$; however, in this case we should have more information soon from the analysis of the rest of the E821 data from 2000. If both of these possibilities are verified, then the evidence for supersymmetry will be rather strong. If the 115 GeV Higgs boson is the lightest supersymmetric Higgs, we should be able to find the heavier Higgs bosons or supersymmetric particles at the LHC. However, there are cases in which the observation of the heavier Higgses at the LHC or at a future $e^+e^-$ linear will be difficult.

The evidence for neutrino oscillations seems to be strong; more measurements will be reported in the near future. An exciting program of neutrino physics awaits us, as we measure the masses and mixing angles, and possibly even CP violation.

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