This superbly organized workshop invited the participants to focus on four outstanding questions in weak interactions:

i) is the electroweak model correct at the quantum level?

ii) supersymmetry?

iii) neutrino mass?

iv) what is the nature of CP-violation?

The meeting demonstrated how weak-interaction physics has become a terrain successfully covered by accelerator and non-accelerator experiments in a very complimentary way.

1. **Electroweak Theory**

A massive experimental effort is under way to test the Standard Electroweak Model at the quantum level. High precision measurements of the properties of the Z at LEP and of the W at p̅p colliders spearhead this effort. Okun[1] keeps reminding us that all electroweak observables are still consistent with the “Born-level” predictions provided these are evaluated using the relevant coupling $\alpha(M_Z) (= 1/128.87(12))$ and not the low energy Thomson charge $\alpha(0) (= 1/137.0359895(61))$. How does one obtain precise determinations of the top mass (less than 20 GeV error in the analysis presented in Ref.[2]; see also Refs.[3, 4, 5]) from 1 $\sigma$ measurements of the loop contributions to the measured observables such as $\sin^2\theta_W$, asymmetries and the decay widths of the Z-boson? The small 1$\sigma$ effects result from cancellation of large positive contributions involving top with large negative corrections from all other virtual particles in the loop: other quarks, weak bosons and the Higgs. It is precisely the non-observation of electroweak corrections that places stringent limits on the top mass.
This point should not be overemphasized. It is scheme-dependent, i.e. the statements are only true in on-mass-shell renormalization. It is nevertheless useful to measure quantities that depend on the top mass in an essentially different way, i.e. not via purely oblique $t\bar{t}$ loop corrections. The obvious observable is the decay width of the $Z$ into $b\bar{b}$. At this conference the first measurements of this width were presented which achieved a precision comparable to those of other LEP observables (Ref.[3]). Using $b$-tagging vertex detectors measurements of the forward-backward asymmetry for $b$-quarks have also achieved a similarly high accuracy. Exploiting polarization of the beams SLC has recently produced a measurement of the Weinberg angle with a precision matching LEP.

This naturally raises the question of how far one can push the precision of the determination of the top mass. Can one achieve sensitivity to the Higgs mass? The significance of any determination of the Higgs mass with present statistics is clearly illusionary. With steadily shrinking experimental errors it is important, however, to remember that the theory has only made predictions at the one-loop level. All the dominant two-loop effects have been evaluated and computed but a complete calculation is unlikely. Two-loop effects are important. For a given value of $M_W$ they shift the top mass by 5–20 GeV for $m_t = 120–200$ GeV. For a fixed value of $\sin^2\theta_W$ the mass shifts associated with two-loop order are yet a factor 2 larger. If one is going to make any claims on $m_t$ with precision 20 GeV, or on the value of the Higgs mass, one must worry about the extend to which we know the two-loop radiative corrections. The Achilles heel of the perturbative expansion is the threshold contribution to the $t\bar{t}$ loop, symbolically shown below:

![Fig. 1](image_url)

Although calculation to $O(\alpha \alpha_s)$, i.e. the first two diagrams is straightforward, contributions from resonances below threshold and enhancement of the cross section just above threshold are significant and their explicit evaluation has turned out to be a problem. For the other quarks $q = u \ldots b$ the problem is finessed by computing the loops directly from $e^+e^- \rightarrow q\bar{q}$ data using dispersion relations. This procedure sums all orders of perturbation theory. It, obviously, does not work for top. Although for heavy tops the calculation of the threshold enhancements can be computed perturbatively, such a computation is only possible in the non-relativistic approximation. This turns out to be a problem when evaluating the threshold contribution to the loop because of the slow convergence of the dispersion relation[5]. Moreover, the required subtraction of the dispersion relation is not unique[7]. Two proposals in the literature
do not even yield the same sign of the top threshold contribution to the running of \( \alpha \). There is theoretical work to do in order to keep pace with experiment!

2. Supersymmetry?

Once SU(5) predicted proton decay and it was not there. So, maybe there is no unification, no desert and lots of physics at an energy scale just exceeding those probed by our present accelerators. Strangely, theorists do not think this way, they fix up the wrong prediction. It is clear what is needed:\[i\):

i) introduce color exotics, e.g. leptoquarks, to extend the proton lifetime;

ii) introduce multiple Higgses.

Step i) cures rapid proton decay but also drives the Weinberg angle to unacceptably low values and this can be fixed by introducing an extended Higgs sector. Supersymmetry nicely provides both steps in a neatly packaged form (Refs.\[5, 8\]). The package also delivers:

a) a resolution of the bad behavior of radiative corrections in the Standard Model. As for every boson there is a companion fermion, the bad divergence associated with the Higgs loop shown below is cancelled by a fermion loop with opposite sign,

\[H\]

Fig. 2

b) the lightest supersymmetric particle may be stable (\(R\)-parity) thus providing us with an outstanding cold dark matter candidate (Refs.\[9, 10\]).

Most importantly, in order to design future detectors we need dreams about physics beyond the standard model. Supersymmetry is an intellectually pleasing, yet specific and calculable dream. It takes some of the mystery out of the puzzling separation of matter (half-integer spin) and forces (integer spin) in the Standard Model. And, unlike the Standard Model, it can accommodate all empirical constraints on the strong and electroweak couplings which nicely unifies in the vicinity of \(10^{16}\) GeV.
3. Neutrino Mass

Heroic efforts are pushing $\beta$-decay experiments towards their ultimate sensitivity corresponding to an upper limit on the $\nu_e$ mass of a few eV (Ref.\cite{11}). The 17 KeV neutrino is no longer (Ref.\cite{10}). “Evidence” for neutrino mass is now based on the solar and atmospheric “anomalies.” The experimental evidence is, in both cases, conceptually very similar. Underground experiments, sometimes the same experiment as in the case of KAMIOKANDE, count a deficit of neutrinos from the sun and from the atmospheric neutrino beam compared to the rate predicted by theoretical calculations. The statistical weight of the evidence is very similar, with several experiments supporting the existence of an anomalously low event count in each case. I really do not see any reason to put these observations on a different footing. The potential weakness of both is systematics. This is not a criticism. Experimentalists are keenly aware of this fact and tackling the problem, e.g. by the calibration of the KAMIOKANDE detector in a particle beam. Another potential weakness is that the evidence, in both cases, is based on the comparison of an experimental counting rate with a calculated one. Although I have no special insights or any reasons to question the reliability of the solar flux estimates, I do know as a particle physicist that one can predict the ratio of electron-to-muon neutrinos in the atmospheric beam with total confidence. Cosmic ray ambiguities drop out in the ratio which is determined by textbook particle physics. So, here the atmospheric “anomaly” may be given a slight edge.

The opportunity exists, in principle, to eliminate the model dependence in establishing the solar “anomaly.” The counting rate of solar neutrinos is obtained by multiplying their solar flux with the detection cross section, symbolically

$$ N = \sum_i \sigma_i \phi_i .$$

Here the sum is over the various cycles $i = pp, pep, \ldots$ Be, Bo. One can convert this relation into an inequality which only involves the total flux of the sun, which is unambiguously known\cite{12}

$$ N < \sigma_{pp} \sum_i \phi_i = \sigma_{pp} \phi_\odot = 80 \text{ SNU}. $$

If an experiment like GALLEX or SAGE were to establish a flux below 80 SNU we would be able to conclude that the solar “anomaly” is a particle physics problem without having to rely on modelling of solar fluxes. Unfortunately, with the present values this is not the case, e.g. for GALLEX $N = 97 \pm 23$ (Ref.\cite{13}).

The problem with taking both anomalies seriously is that their interpretation in terms of massive oscillating neutrinos predicts different mass values with

$$ 10^{-6} - 10^{-10} \text{ eV}^2 \quad \text{for the sun and,} $$

$$ 10^{-2} - 10^{-3} \text{ eV}^2 \quad \text{for the atmosphere.} $$
It is far from obvious how to incorporate both “results” into a coherent model (Ref.[14]). If you do not want to wait it out you have to be pretty imaginative. Someone was (Ref.[17]).

4. CP-violation and other weak interaction windows on high energy

CP-problems come in the weak and strong variety (Refs.[16, 17, 18]). In these talks and in a very lengthy and exciting discussion session organized by C. S. Kim, the strategy was reviewed in detail on how a $B$-factory can establish the fact that CP-violation is just a consequence of the presence of a complex phase in the CKM matrix. Confirmation of the Standard Model origin of CP-violation will make the question loom very big why Nature supplied us with exactly the three generations needed to introduce one complex phase allowing us to break CP and make possible a ratio of baryon number to entropy of $(4-6) \times 10^{-11}$ in the Universe, which is responsible for the fact that we are here pondering the question. Alternatively, $B$-factories may disprove the Standard Model origin of CP-violation, providing us with a new window on physics beyond its reach.

With supercolliders embroiled in political turmoil and the technical feasibility of linear electron-positron colliders unproven, it is good to reassure ourselves that precision measurements in weak interactions have the potential to indeed give us a glimpse of physics beyond the reach of accelerators. Besides CP-violation, there is neutrino mass, double $\beta$ decay (Ref.[19]), $\mu \to e + \gamma$ experiments (Ref.[20]). Even though evidence for Majorons or Majorana neutrinos has been lacking, progress in double $\beta$ decay experiments has moved them into a position to probe supersymmetry, for example, with a sensitivity competitive with accelerators. On the theoretical side the power of non-accelerator experiments to probe physics beyond the Standard Model is pointedly illustrated by the intriguing result of the see-saw model[14]

\[ \begin{align*}
0.05 \frac{m_{\nu_2}}{m_I} : 0.08 \frac{m_{\nu_2}}{m_I} : 0.28 \frac{m_{\nu_3}}{m_I} = m_{\nu_1} : m_{\nu_2} : m_{\nu_3},
\end{align*} \]

which for $m_I = 10^{13}$ GeV incorporates a 10 eV $\tau$-neutrino — a perfect candidate for the hot dark matter required by the COBE measurements of the granularity of the cosmic photon background (Ref.[14]). The coefficients in front of the mass ratios represent the running of the Yukawa couplings. They were obtained by averaging the SU(5) and SO(10) predictions which are, in fact, very similar.
5. Return of the weak interactions and neutrinos as our window on high energy

One must conclude that the future of this field is bright. The variety of experiments and the qualitative improvement in their sensitivity guarantee an exciting transition period to the supercolliders. Even second generation non-accelerator experiments will be commissioned for a price which is less than 1% of the SSC. Cheap experiments mean short timelines and data soon. At the risk of omissions I close with a preview:

- **CP-violation:**
  - $B$-factories,
  - $B$’s after Tevatron upgrade,
  - $\epsilon$ and $\epsilon'$ measurements.

- **Neutrino mass:**
  - oscillation experiments (CHORUS, NOMAD, new underground experiments using the atmospheric beam),
  - long-baseline oscillation experiments (BNL and various combinations of accelerator beams and deep underground detectors),
  - neutrino mass measurements, solar neutrino experiments (here we enter the era of experiments with more that 10 events per day: SNO, BOREXINO, ICARUS…; observation of all neutrino types via neutral current detection),
  - high energy neutrino telescopes (AMANDA, BAIKAL, DUMAND and NESTOR),
  - supernova beams. Even in the latter case the timeline might be comparable with the SSC if the error on their anticipated frequency in our galaxy is such that one explodes every 25 years rather than once a century. A large variety of much improved detectors will be ready (Ref.[21]).

- **Other:**
  - the Universe,
  - edm moments,
  - rare decays with new $K$ and $\Phi$ factories,
  - double $\beta$ decay,
  - atomic parity violation, and
  - bolometric dark matter detectors.

A lot of exciting results will await us in Talloires in two years!
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