SUMMARY AND OUTLOOK ON THE FUTURE*

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ABSTRACT

Highlights of the Physics in Collision Conference are reviewed. Selected topics which address the important questions in the future are discussed. Projections and predictions for the future are given.

I. SUMMARY

This conference has been an extremely interesting and enjoyable one, and has continued a fine tradition in the Physics in Collision series. I want to thank the organizers for the opportunity to be here and to celebrate with you the rapid turn-on of the TRISTAN machine and the first physics results from VENUS, TOPAZ and AMY. The accomplishments are impressive for the short time since turn-on. The integrated luminosity achieved to date is approximately 0.5 pb^{-1} at $\sqrt{s} = 50$ GeV and 3.5 pb^{-1} at $\sqrt{s} = 52$ GeV, in the three detectors. The peak luminosity of 7×10^{30} achieved is excellent for the first year of operation of a new machine.

Early results from VENUS, TOPAZ, and AMY for the QED processes ee, $\gamma\gamma$, $\mu\mu$, and $\tau\tau$ final states are internally consistent and consistent with the Standard Model. Large forward-backward asymmetries show the importance of this energy region to the studies of weak-electromagnetic interference effects. Small numbers of events will provide sensitive tests of electroweak coupling parameters and tests of universality.

Hadronic studies show that event production rate and event shapes are consistent with five quark flavors being produced, and no open top quark being present. No evidence for a b' quark, representing a new quark flavor, has been seen, although this possibility was not as easy to exclude.

No sequential heavy leptons are seen in the data, and masses below 26 GeV are excluded. The tantalizing events seen in PETRA experiments at the highest energies, where isolated μ's were seen in hadronic events, are not confirmed at TRISTAN.

Most impressive for this new facility was the rapid and smooth operation of TRISTAN, and the rapid turn-around from raw data to physics results by the three collaborations. We welcome this new facility to the field and to the study of particle production at the front doorstep of the Z^0 .

We have seen at this conference new results confirming the validity of the Standard Model. As far as we know, all results at high energy are compatible with the Standard Model, although not all Standard Model parameters are measured. The uncertainties of the Higgs particle(s) and the whereabouts of the top quark await resolution at future conferences. This year, however, has been a very productive year for experimental physics. This has been the year of the B's. Strong indications of $B\bar{B}$ mixing has been reported by UA1, based on analyses of di-lepton production, and ARGUS now shows clear evidence of the same in reconstructed events. In addition, ARGUS reports observation of a direct charmless decay of the b quark in certain clean final states where background processes are under control. Average b-quark lifetime measurements are in good agreement in a number of experiments with a lifetime of about 1.1 psec. These exciting results have rapidly provided us a good experimental base upon which our future b physics will be based. By the early 90's, the b-quark will be as well-known to us as the charm quark is today.

UA1 presented to us a long list of results based on a solid understanding of the QCD processes in their detector at CERN collider energies. Refined values of M_W and M_Z exist. W decays into τ leptons are seen. Electron-muon-tau universality is supported by the data. Limits on the number of neutrino types were given. Searches and mass limits for "new physics" not included in Standard Model phenomenology were given. Compositeness searches, heavy W''s and Z''s, search for top, lepto-quarks, SUSY particles all were discussed. However, no anomalous patterns indicating new physics were reported. Limits on top production were derived from studies of μ's in jets. Two limits on the top mass were given, $M_t > 44$ GeV and $M_t > 56$ GeV. The first limit is a conservative estimate based on comparison to QCD calculations of backgrounds. The second limit is probably valid, but requires confidence in the Monte Carlo calculation (Eurojet QCD). These results supersede the recent TRISTAN results, $M_t > 26$ GeV. UA1 also reports no evidence for b' production, and places two limits $M_{b'} > 25$ GeV (conservative) and $M_{b'} > 41$ GeV (likely).

Latest results from UA2 were also presented. Values for M_W and M_Z, Γ_Z and $M_Z - M_W$ were given. Evaluation of Γ_Z/Γ_W and the relation with M_t and the number of neutrinos were discussed. They reported $N_\nu \leq 7$ (which lowers to

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$N_\nu \leq 3$ if $M_t > 74$ GeV). Evidence for reconstruction of W's and Z's by calorimetry techniques were shown and a search for jets accompanying W or Z production was reported to be consistent with QCD backgrounds. New particle searches yielded mass limits, but no signals. UA2 will soon run with ACOL operating and the detector upgraded. Improved measurements in all areas are expected in 1988.

The Tevatron at FERMILAB has now come into operation and the first detector at this collider, the CDF, reported on performance of the detector and early physics results. Jet events have been clearly observed in 1.8 TeV $\bar{p}p$ collisions. Inclusive jet distributions were reported. Nineteen W candidates and a few Z candidates exist in the early data. Upcoming runs in 1988 anticipate ten times more data, better trigger capability, better detector shielding, and a completed detector.

The FERMILAB experiment, E691, which studies charmed particle production by photoproduction, has stunned the particle physics world and revitalized the arguments for more fixed target experiments. This experiment demonstrates the power of technological advances in particle detection techniques, and set a new scale of precision in charmed particle experiments. The lifetime distributions are classics, and the breadth of results coming from the data is very large. That experiment alone recorded 10^8 triggers and processed these through the FERMILAB ACP computer farm in three months. That accomplishment demonstrates the power of processor farms for future computing in the field.

Finally I would like to acknowledge the very careful and thorough work of NA31 at CERN on CP-violation in $K_L \to 2\pi$ decays. The group reported the CP violating parameter $\epsilon'/\epsilon = (3.5 \pm 0.66) \times 10^{-3}$ with a Monte Carlo error of 0.4×10^{-3} and a systematic error of 1.2×10^{-3}. This non-zero result appears to be consistent with the Standard Model and our knowledge of $K - M$ matrix elements. This result provides us further understanding of the CP-violation mechanism.

The results of 1987 fall against the backdrop of a very exciting year for physics in general. The supernova SN1987a is an event of the century, and many generations hence SN1987a will be noted in the text books. We were very lucky to see the neutrino burst in two of our detectors, KAMIOKE and IMB. The observations were unplanned, but we can claim those results as ours and celebrate what they mean for human knowledge and the ability to understand such distant phenomena from high energy observations in earth's laboratories. Solar neutrinos can also be seen in KAMIOKE, and soon we should learn more about the solar neutrino flux, with perhaps improved limits or observation of a signal. The year 1987 was also the year of high T_c superconductors. That is not our business, but it may become important to us, and we could well benefit by this dramatic breakthrough. So

overall, Physics in 1987 is very much alive and well, and I expect 1988 to be even more exciting.

II. OUTLOOK FOR THE FUTURE

I would like to now look at prospects for physics in the near future and beyond. To focus this discussion I would like to list a few of the important and outstanding issues, and to see how we may learn more about these questions as new facilities open up. Then I would like to end with projections and predictions.

Among the currently interesting and outstanding questions within and beyond the framework of the Standard Model are the following:

1. Supersymmetry?

2. The Higgs particles; the existence? the mass? charged and neutral?

3. Heavy quarks and leptons?

4. Compositeness in quarks and leptons?

Progress in understanding these questions and how to find the answers has been painfully slow. Nevertheless, there has been significant progress, and a beautiful example of progress in the field in the past ten years is given in Table 1, where neutral current and electroweak processes have converged to a dramatic and important agreement. Table 1[1] lists seven experiments or collection of experiments in widely different processes which can determine the electroweak mixing parameter, $sin^2\theta_W$. The processes listed include the masses of the W and Z , inelastic neutrino and polarized electron scattering, elastic anti-neutrino-proton and electron scattering, and atomic parity violation (an average). These processes, if higher order corrections are ignored, show a disagreement "at the 3σ level", but with radiative corrections applied are fully consistent with an average value of $sin^2\theta_W = 0.230 \pm 0.0044$. The authors of the report note that a simple SU(5) grand-unification theory predicts for this parameter $0.216^{+0.003}_{-0.004}$ which is disfavored by 2.5σ , but supersymmetry models predict a higher value $0.237^{+0.003}_{-0.004}$, which is not disfavored by the world average. This observation is indeed tantalizing in it's disfavoring of SU(5), already in trouble because of the proton decay experiments. The SU(5) model led to prediction of a "great desert" above the W and Z, and the data of Table 1 may be further very indirect indication of new physics with a mass scale below 1 TeV. Whatever these results may mean for the future, this is surely a great accomplishment by a large number of experimental and theoretical colleagues in our field working in different areas over a number of years.

The future promises to bring precision tests in some of these processes. Precision measurements of the W and Z masses at LEP and SLC and precision measurements of neutral current couplings will provide further tests of the Standard

Table 1. A global summary of neutral current experiments (from Ref. 1). The experimental results are characterized by the electroweak parameter $sin^2\theta_W$ uncorrected and after radiative corrections have been applied.

Radiative Corrections: (using $M_t = 45$ GeV and $M_H = 100$ GeV.[1]

Experiment	$\sin^2\theta_W^{unc}$	Rad. Corr.	$\sin^2\theta_W \equiv 1 - m_W^2/m_Z^2$
Atomic P. V.	$0.201 \pm 0.018 \pm 0.014$	+0.008	$0.209 \pm 0.018 \pm 0.014$
$\overset{(-)}{\nu}_\mu e$	0.221 ± 0.019	+0.002	0.223 ± 0.019
$\overset{(-)}{\nu}_\mu p$	0.208 ± 0.033	+0.002	0.210 ± 0.033
eD asym.	$0.226 \pm 0.015 \pm 0.013$	-0.005	$0.221 \pm 0.015 \pm 0.013$
$\nu_\mu N$	$0.242 \pm 0.003 \pm 0.005$	-0.009	$0.233 \pm 0.003 \pm 0.005$
$M_W = 80.9 \pm 1.4$ GeV	0.212 ± 0.008	+0.017	0.229 ± 0.008
$M_Z = 91.9 \pm 1.8$ GeV	0.208 ± 0.011	+0.022	0.230 ± 0.011
		Ave.	0.230 ± 0.0044

Model. Already we see limits on the top quark mass from below coming from PETRA/PEP, TRISTAN, and UA1. The UA1 results report $M_t > 44$ GeV. Contributions to the masses of the W and Z from virtual processes containing t-quarks limits the mass $M_t < 200$ GeV (from UA2 data and $\nu-$ scattering data). Future precision measurements could further constrain the top-quark mass and the Higgs mass. The mass of the Z should be known to ± 50 MeV at the SLC, and to ± 10 MeV at LEP I. The mass of the W can be measured to ± 350 MeV in UA2, and to ± 100 MeV at LEP II.

The W and Z masses are somewhat insensitive to the value of the Higgs mass, and we cannot learn much about the Higgs boson by accurate measurements of M_W/M_Z . However, couplings of particles to the Z° are more sensitive to this parameter. The most sensitive measurement of neutral current couplings comes in a simple measurement at the SLC with polarized beams. With longitudinally polarized electrons, one measures the asymmetry at the Z° :

$$A_{LR} = \frac{\sigma_{vis}(e_L) - \sigma_{vis}(e_R)}{\sigma_{vis}(e_L) + \sigma_{vis}(e_R)}$$

where $\sigma_{vis}(e_R)$ and $\sigma_{vis}(e_L)$ refer to the total visible cross section with right and left-handed polarized electrons. Errors in A_{LR} are expected to reach $\lesssim 0.005$.[2]

Figure 1[3] shows the Standard Model predictions for A_{LR} versus M_W with M_t and M_H left as free parameters. A single point on the graph represents the accuracy of precision possible in these measurements. At a future date, these combined results would be the culmination of the work on Standard Model tests could provide indirect measurements of the top mass and the Higgs mass, and could challenge or confirm the Standard Model in its ability to predict parameters including higher order corrections.

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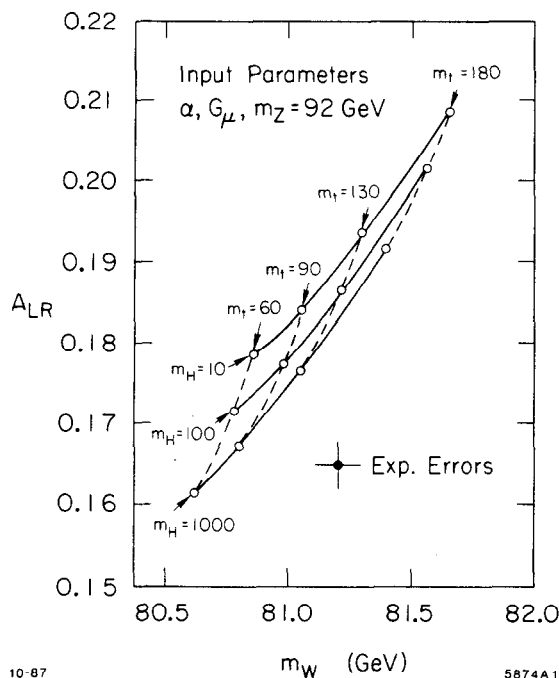
Fig. 1. A_{LR} vs M_W (from Ref. 3) as predicted in the Standard Model assuming other parameters are known. The sensitivity to top quark mass and Higgs mass shows that accurate measurements can constrain these parameters. The point labelled "Exp. Errors" gives estimates of errors possible for M_W at LEP II and A_{LR} at the SLC.

Searches for the Higgs, however, will undoubtedly proceed through many techniques. In e^+e^- colliders, the process

$$e^+e^- \rightarrow H^\circ e^+e^- \quad \text{and} \quad H^\circ \mu^+ \mu^-$$

appears to offer the cleanest signal. At the SLC, the above process will give a visible signature for M_H up to 40 GeV, and at LEP II to around 80 GeV. For

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a TeV linear collider, the mass limits where a signal would be visible approach $\sqrt{s}/2$.

Identifying the decays of the $H°$ would significantly enhance the cleanliness of a search. Since the Higgs couples most strongly to the heavy particles, the Higgs would be seen in

$$H° \rightarrow q\bar{q}$$

for M_H below $2M_W$, and in

$$H° \rightarrow W^+W^-$$

for M_H above the WW threshold. For the case of $M_H < 2M_W$, the decay of $H°$ is predominantly into the heavy quarks, and silicon vertex detectors are likely to be required. For the case where $M_H > 2M_W$, detection of the W's from the $H°$ decay would require good calorimetry.

These cases have separately been studied in simulations for SLC and for a TeV linear collider.

Detection of heavy quarks in an event relies on the long lifetime of the b-quark. In events containing b-quarks, a high resolution vertex detector can observe multiple tracks emanating from displaced vertices. If t-quarks are produced they will decay predominantly into b's, so the event topology also contains displaced vertices. One can define a "pseudo vertex" parameter for every event. Take an event containing N charged tracks and take all possible track pairs, giving $N(N-1)/2$ combinations. For each track pair, the points of closest approach form a line segment in space, of length ℓ . The midpoint falls a distance δ from the event interaction point, which is well defined in linear colliders. For the event, the number of track combinations for which $\delta > \delta_0$ and $\ell < \ell_0$ is counted. This number is the pseudo vertex count for the event. This number can be large for events containing heavy quarks because of the long lifetimes and high track multiplicities, while for light quarks the number should be small. A detailed simulation which incorporates SLC beam geometry and silicon vertex detector resolutions is shown in Figure 2.[4] Three curves are identified; the u, d, and s events from the $Z°$ fall to the left. The c-quark events fall in the middle, and the b-quark events fall to the right. Cuts appropriately placed give good separation of the b-quarks from all else with high efficiency. This simple tracking algorithm is an excellent inclusive b-quark discrimination which could substantially enhance the search for the Higgs.

In the case where $M_H > 2M_W$, higher energy beams and calorimetry seem to be required. Searches in this mass range become possible with a TeV linear collider. Studies of the capabilities to identify $W^\pm$'s with calorimetry in colliders have been
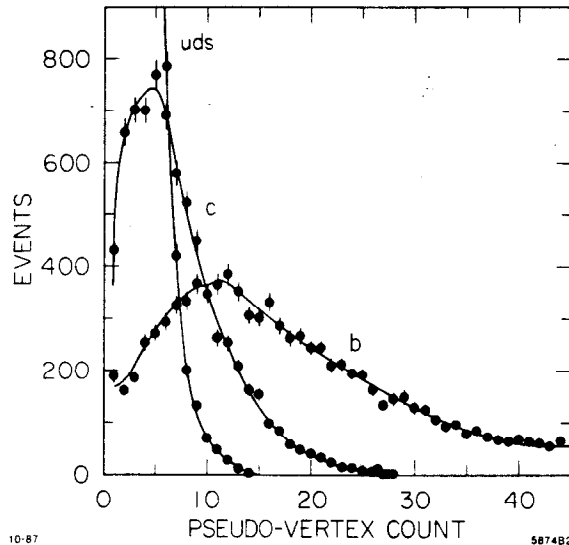
Fig. 2. A Monte Carlo calculation (from Ref. 4) of the distribution of pseudo vertex count (defined in text) for light quark, charmed quark, and b-quark events coming from Z° decays. A simple track reconstruction algorithm using the precise tracking of silicon pixel vertex devices is expected to give good separation between heavy quarks and light quarks with high efficiencies.

reported using data and Monte Carlo simulation. From the UA2 report in this conference we see the reconstruction of W and Z's from jets.[5] This signal sits on a large QCD background, but in TeV linear colliders, the signals are expected to be relatively clean. Figure 3a shows the simulated reconstruction of two W's from $e^+e^- \to W^+W^-$ at 1 TeV[6]. The corresponding $q\bar{q}$ background is shown in Fig. 3b. The mass resolution in realistic calorimeters (this study used the SLD calorimeter parameters) is expected to be around 10 GeV. Figure 4 shows a reconstructed H°, of mass 300 GeV, in the presence of a heavy lepton "background". A clear, distinct H° signal is seen. For the TeV energy scale of the future, W bosons become the "light mesons" of the new physics.

In comparisons between e^+e^- and hadron colliders, much emphasis has been placed on discovery potential for various processes. M. Peskin[7] argues that the threshold for discovery for selected process in e^+e^- colliders increases as approximately $k\sqrt{E_{cm}(pp)}$, where $E_{cm}(pp)$ is the threshold energy in the hadron collider, and k varies from 0.1 to 1 typically, depending on the specific process. He does not discuss discovery potential for the case of Higgs particles. This case is more complicated by the nature of the Higgs decays for $M_H < 2M_W$. In hadron colliders, the QCD backgrounds may mask the Higgs for $M_H < 2M_W$, and only e^+e^- colliders would find such a Higgs. Furthermore, if charged Higgs exist, they decay
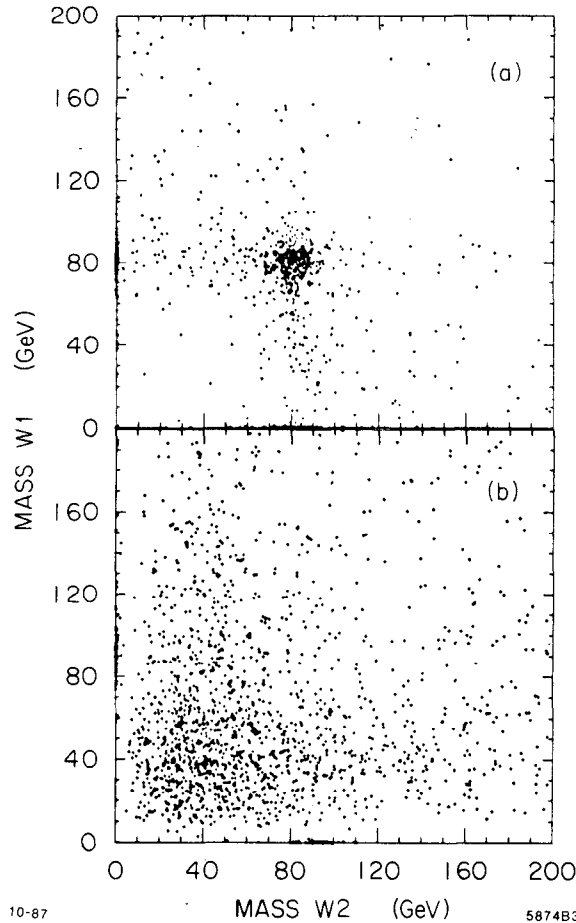
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Fig. 3. (a) Simulated invariant mass reconstruction from the SLD calorime-
ter for W's from $e^+e^- \to W^+W^-$ at $\sqrt{s} = 1$ TeV. The signal consists of
calorimetric reconstruction of $q\bar{q}$ and $\ell\nu$ decays of the W's (from Ref. 6). (b)
Simulated invariant mass reconstruction for $e^+e^- \to q\bar{q}$ giving hadronic jets
at $\sqrt{s} = 1$ TeV. This is the normal QCD background under the W signals
(from Ref. 6).

through heavy quark modes only, independent of mass, and therefore are hidden
in hadron colliders by the normal QCD processes. Only e^+e^- colliders have a clear
shot at discovery of light mass Higgs and charged Higgs.

The conclusions of such comparative studies is that e^+e^- colliders and hadron
colliders are complementary tools in the search for new physics, and the future
physics world needs both.

Hadron colliders of sufficient luminosity to see these interesting processes will
swamp present detectors with uninteresting events at an enormous rate. Raw
trigger rates may reach 10^8/sec, and processing of data to filter out the unwanted
events from the interesting events looks very difficult. In addition QCD back-
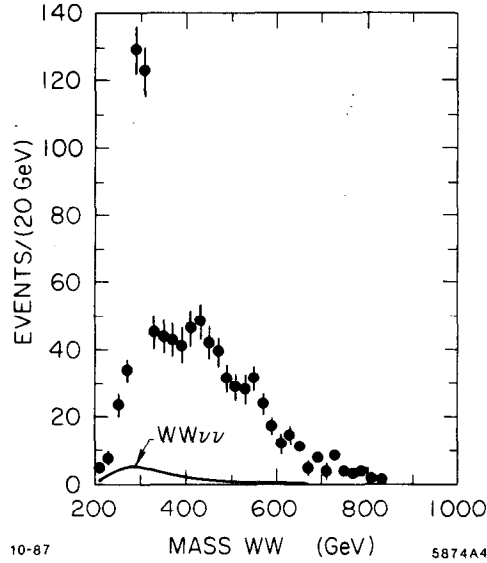grounds may remain large, and radiation hardness eliminates many otherwise in-

Fig. 4. Reconstruction of $H^\circ \rightarrow W^+W^-$ by calorimetry techniques.

teresting devices and techniques as candidates for future detectors. Much detector research and development work is needed before we can proceed with detectors for the future hadron colliders.

For e^+e^- colliders, the requirements for high energy and high luminosity are beyond present day technology. Accelerator research and development must proceed if we are to realize e^+e^- collisions at the TeV scale. These problems leave us at present with some serious work ahead. Progress toward new physics may be slower than we would like, but efforts in solving these problems are intense. However, there is one new activity which promises to bring us to the regime of new physics in the near future. That is HERA.

HERA is presently actively in construction. The tunnel excavation is now complete, as we have heard at this conference. Electrons will be operational soon, and the proton ring will follow shortly. The accelerator complex will begin to operate for physics in the early 1990's. I hold the highest hope and expectations for new physics to come from this bold adventure. After all, deep inelastic scattering started the revolution in particle physics that has now become our Standard Model. The inelastic scattering of electrons from protons gave us our first look at nucleon structure. From those experiments, "precocious scaling" was observed, and with it our first glimpse at the world of quarks. Further deep inelastic scattering uncovered scale breaking phenomena and supported the picture of QCD and indirectly the existence of gluons. Inelastic scattering of neutrinos led us to the discovery of the neutral currents, and polarized electron scattering demonstrated

weak-electromagnetic interference and completed the electroweak unification picture. In retrospect, inelastic scattering has been extremely important. I predict history will repeat, and that HERA will lead us into new physics at the TeV scale.

III. PROJECTIONS AND PREDICTIONS

Figure 5 shows the growth of center-of-mass energy in the constituent frame for accelerators from 1960 to the present and beyond. This graph, the so-called "Livingston Plot", includes hadron colliders and e^+e^- colliders. The solid curve represents the growth curve for hadron colliders, and includes the ISR, the CERN $S\bar{p}pS$, and FERMILAB's Tevatron I. The plot also shows SSC, in 1995, arriving ahead of its time by a few years. A similar curve for e^+e^- colliders passes through ADONE, PEP, SLC and LEP I and LEP II. The next linear collider, the TLC, is predicted to reach 1 TeV in the year 1999. The slopes of these growth curves are not quite equal. The e^+e^- growth is presently slightly faster than for the hadron colliders, although an early SSC will change that trend.
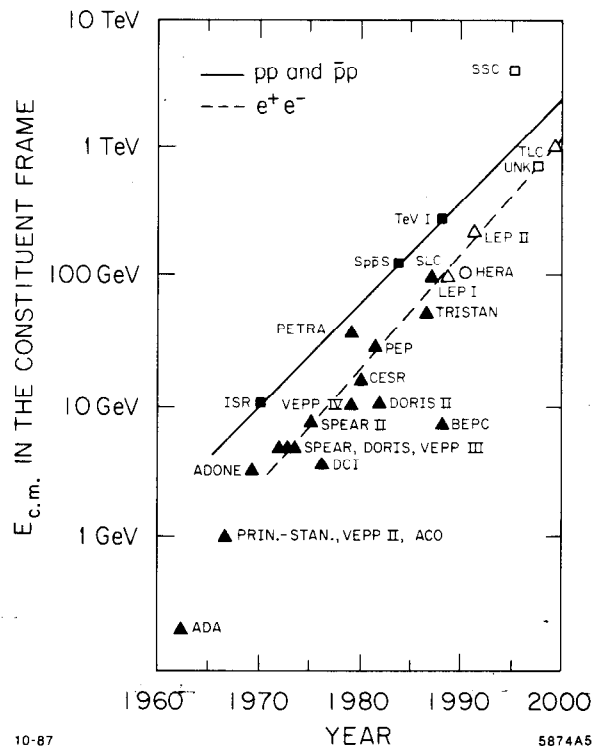

Fig. 5. The growth in center-of-mass energies in various colliders. The hadron colliders have been adjusted to the constituent center-of-mass energies. The solid line represents the trend for hadron colliders, while the dashed line is the trend for e^+e^- colliders.

Figure 6 shows a comparable growth curve for detectors[8]. The measure of detector size used here is channels of electronics. The same two lines used for accelerators in Figure 6 are shown here for comparison. The growth in detectors is faster than for accelerators, and large detectors in the SSC era will exceed 10^6 channels.
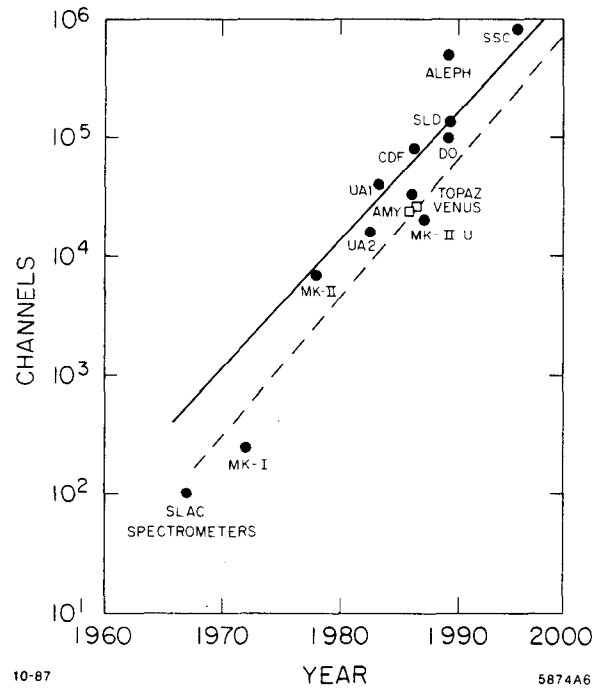

Fig. 6. The growth curve for detector size (from Ref. 8). The parameter chosen to represent detector size is electronic channel count. The two lines of accelerator growth in Figure 5 have been scaled and overlayed for comparison with detectors. This representation for detector size shows a trend which is steeper than for accelerators.

Figure 7 shows the same trends in computing. Again, the same two curves for accelerators are shown on this graph for comparison. Growth in computing power exceeds the growth in accelerator energy, but follows the trends for detector size. By the time SSC detectors go into operations, 500 MIPS will be in vogue for computers associated with large detectors in high energy physics.

In none of these trends do I see a tendency to flatten or level out. If anything is to be learned, it is that the growth rate in our field is probably increasing.

I would thus like to end with my predictions for the year 2000. I make these predictions in the spirit of a note in a time capsule. It will be interesting to see which, if any, come to pass.
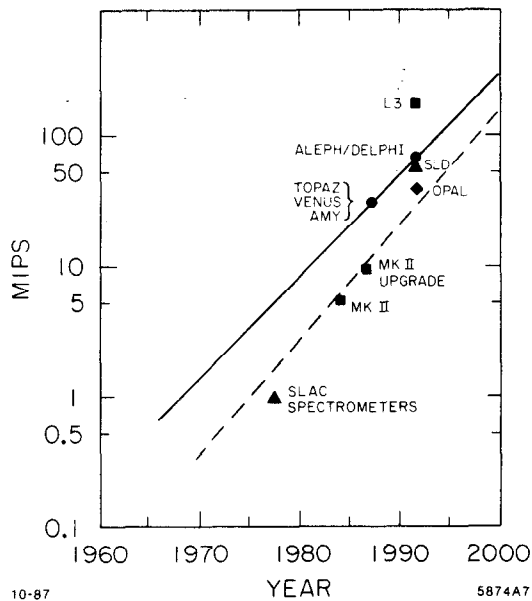
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Fig. 7. The growth curve for computer size. The unit MIPS refers to "million instructions per second" for the computers associated with the indicated detectors. The two lines for accelerator growth have been scaled and overlayed for comparison.

The first prediction: The SSC and a TLC (a TeV linear e^+e^- collider) will be the new frontier facilities operating near 40 TeV and 1 TeV, respectively.

The second prediction: Detectors will be very large, exceeding 10^6 channels of electronics, and computers for data analysis will exceed 500 MIPS for a large detector.

The third prediction: HERA will be an "old machine" but will be leading us into the new physics of the TeV scale.

Finally, a fourth prediction: A rich new physics will exist at the TeV scale and a new Standard Model will supersede our present one.

Let me end by again thanking the organizers for their warm hospitality and their efforts in making this a successful and enjoyable conference. Let us now go back to work to help make the future come about.

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