SLAC-PUB-2041
November 1977
(T/E)

FUTURE ACCELERATORS: PHYSICS ISSUES*

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As the energy scale explored by particle physics increases, so also does the time scale for planning and constructing the larger machines now projected for the future. It becomes correspondingly more difficult to apply the criteria of today's physics to such future facilities: we should expect that the most exciting physics issues of the next decade will not be easily anticipated today. Indeed the safest prediction about the future is that we shall encounter major surprises; it is a prediction which has always worked well before. Under such circumstances wise theorists, when considering the future, find that the most prudent course is to keep their mouths shut. And wise experimentalists and machine-builders choose not to take overly seriously the words of those theorists who do open their mouths.

So here I am, a verbose futurist, exhorting you not to take too seriously what I am to say. Yet I am compelled to defend my right to say it. It would be irresponsible for theory not to provide its best estimates of future directions of our science. In addition to providing some general guidance as to parameters for machines, it is also necessary to identify specific regions of study where manifest progress will be made in order to guarantee that the great cost of such machines is justified--at least from the point of view of scientific output. Of course any decision to build such facilities depends as well on questions broader than the scientific goals of high energy physics. These considerations, while extremely important, are beyond the scope of these remarks.

* Work supported by The Department of Energy

(Presented to 1977 International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, Germany, August 25-31, 1977)

Before staring into this treacherous business of prophecy, I tried to look back at what must have been the prognostications physicists made for the accelerators of the past. While this is not the place to elaborate all that in detail, I came to the opinion that the prophets of the past did not do so badly, in the sense that the broad directions for future progress were properly perceived.[1] However, the manner in which that progress was manifested was often quite unexpected. In addition most prophets predicted major surprises--and we have not been disappointed. There have, of course, been unfulfilled expectations as well--for example, no weak intermediate bosons, quarks, tachyons, or monopoles have been discovered from our accelerators, despite the considerable PR devoted to them in proposals and the like. But these all had been long-shots; on the whole, the field has moved forward step by step in ways which have, in a broad sense, been those anticipated in advance of the construction of the accelerators and instruments.

One final introductory remark: this report is based on work done in conjunction with the International Study Group on Very Big Accelerators, which met[2] in Serpukhov in 1976 to consider the question of accelerators (VBA) so big as to require international or world collaboration for their construction and utilization. It, therefore, is not addressed to the more immediate question of relative priorities for the next machines, but only for a global view of the future, as measured in decades.

I. PROPOSED MACHINES AND INSTRUMENTS OF THE FUTURE

Figure 1 lays out the energy level diagram for machines, past, present, and future. The energy scale is equivalent lab energy: log s. I have also displaced the energy scales, somewhat arbitrarily, for the three classes of collisions [pp ($\bar{p}$p), ep (μp, νp), and e^+e^-] by factors of two in s because of the relative inefficiency of a proton in converting its energy into interesting physics. This puts ADONE ($s \sim 10$ GeV^2) roughly equivalent to the AGS ($s \sim 40$ GeV^2); they both are at ψ-production threshold.

There are a remarkable variety of future options to consider. Impressive to me is the large range in energy which is available for future exploration. The increase in equivalent lab energy in going from the ISR to the VBC (very big collider: 10 TeV + 10 TeV colliding pp (p$\bar{p}$) beams) is comparable to going from a 20 MeV proton linac to the ISR. It has been said that because of the size and scale of the new accelerators, the field is heading toward stagnation--a dead end. If there were to be no further technological breakthrough, this could be true when considering the long run. But in the meantime, there is plenty of room at the top.

As a guide to the acronyms, most of the new machines on Fig. 1 are tabulated in Table 1. It is largely taken from a report[2] written by the VBA study group last year. It is very likely that any future conventional proton machine will also be a storage ring; hence, one can entertain the option of either pp or p$\bar{p}$ colliding beams, as well as ep rings, with electrons of energy at least ~ 20 GeV. Thus already with the FNAL doubler-Tevatron program, there are several possible colliding-beam schemes. In addition, there exists the CERN $\bar{p}$ option using collisions in the SPS.

While I think most of us agree that energy is the number one commodity, it isn't everything. Luminosity, as well as flexibility in the choice of incident beam and target, is a strong argument in favor of the conventional fixed-target synchrotrons. The supreme cleanliness of the e^+e^- physics argues strongly in its favor, even at the expense of center-of-mass energy. Not only is the capability of the machines with regard to energy, luminosity and types of collision of importance, but also the capability which exists for extracting the physics. How will instrumentation develop? Are the phenomena detectable? Are backgrounds manageable?? These kinds of questions are not for a theorist to consider. However, a few things are clear: detection of hadrons with calorimeters becomes more accurate at higher energies and should gain in importance for practical as well as for physics reasons. Study of specific exclusive channels: i.e., 1C-4C physics, probably will dwindle in importance (except for elastic and diffractive processes). Neutrino detection via missing energy and/or $p_\perp$ becomes easier.

II. PHYSICS ISSUES AND OPPORTUNITIES

What kind of physics will dominate our interest at multi-TeV energies ? The most immediate answer, and one which carries much truth, is the one obtained by making the obvious extensions of our present interests to higher energies. To pursue this answer here is also to create great tedium: long lists of topics are generated, along with a recitation which amounts to a review of the present status of particle physics. I would prefer to avoid that as much as possible. Nevertheless, by omitting the obvious is to invite a chorus of complaints of experimentalists whose area of expertise I have totally ignored. Therefore, a list of such topics is compiled in Appendix A in the hopes of minimizing this phenomenon. I shall try to stay beyond the bread-and-butter topics, and have organized them as follows: (A) strong-interaction dynamics, (B) weak-electromagnetic dynamics, (C) symmetries and new-particle zoos, and (D) more fundamental questions.

A. Strong Interaction Dynamics and Cosmic Rays

Beyond the obvious areas of strong interaction dynamics available at higher energies (such as log s and high $p_\perp$ physics), there is the possibility that quite new directions open up. One way of considering such a possibility is to look at what is said by those who have already made studies of this region with cosmic-rays. While cosmic-ray results tend to be fraught with difficulties and uncertainties, I feel it is wrong to ignore such evidence. On the other hand, a sharp, critical analysis of some of the results I discuss would be of use. Unfortunately, this is something I cannot myself provide.

There seems to be general agreement within the cosmic-ray community[3] that new phenomena seem to appear at a laboratory energy of order $10^{2\pm1}$ TeV. Individual events of peculiar character, as well as changes in the characteristics of extensive air showers and of hadron penetration, have been reported. My favorite examples are those which are most direct, for which little interpretation need intervene. They are:

i) The Niu Charm Event. This celebrated event,[4] observed in an emulsion chamber flown in an airplane by Niu's group in Japan, is an interaction at a primary energy ~ 20 TeV, containing a leading charged secondary, with mass 1.5-2 GeV and lifetime $\sim 10^{-13}$ sec, which apparently decays into a π^0 or γ and another charged particle (cf Fig. 2). But this is not the only reason I find the event interesting. Within ~ 2 units of rapidity, there exists a "fireball" of ~ 25 charged particles. These are leading particles with $\theta < 10$ mrad., and they are not nuclear fragments, inasmuch as the event is initiated by a neutral particle. Such large charged multiplicity in a limited rapidity range is to my knowledge very difficult to obtain from extrapolation of the presently accepted pictures of particle production.

Since the original event was reported there have been other similar events reported by Niu's group.[5,6] Two of these are shown in Figs. 3 and 4. Again, high leading multiplicity seems to be present.

ii) "Centauro" This event (Fig 5), observed[7] in the large emulsion experiment of the Brazil-Japan collaboration on Mt. Chacaltaya, is interpreted as production of a leading "fireball" (i.e., a group of hadrons within two units of rapidity of each other) containing ~ 100 hadrons with $p_\perp$ ~ 1.5 to 2 GeV, and with, at best, only a few of them π^0's. The experimentalists triangulate tracks to a production height ~ 50 m. above the emulsion; this argues against a heavy primary such as Fe as initiator of the event. While the favored interpretation of "Centauro" strains credibility, I have not heard any better alternative. The primary energy is estimated to be ~ 250 TeV.

iii) Tien-Shan Calorimeter Experiment. A very large calorimeter array in the Tien Shan region of the USSR has been used to estimate the mean penetration of hadron cascades as a function of their energy.[8] A sharp rise in the absorption length from 700 gm cm^{-2} to ~ 1100 gm cm^{-2} is observed at an energy ~ 100 TeV (Fig. 6). Even if this is only due to the presence of mere charm in the cascades, it still signals an unexpectedly copious production mechanism for charm.

This is only a sample of the evidence. Studies[9] of extensive air showers indicate that extrapolations of the limiting-fragmentation behavior and approximately constant central plateau to energies above 100 TeV fail badly in accounting for properties of the air shower development. It is not clear what is needed to bring Monte-Carlo shower simulations in agreement with observations, especially given the lack of knowledge of primary composition (protons vs. Fe). Nevertheless, the inadequacy of scaling concepts to account for the properties of extensive air showers seems to be generally agreed upon.

Thus high multiplicity of leading hadrons may well be a new direction in high energy strong interactions. Another may be peculiar composition: e.g., presence of charm or some other relatively penetrating component, and absence of π^o's. One should also watch for multilepton or multigamma events. There is also cosmic ray evidence[10] for the presence of high-$p_\perp$ hadrons at high energies. These may or may not be a consequence of binary hard collisions of constituents, the hypothesis popular at present energies. Experiments which measure pairs (or more) of acoplanar high-$p_\perp$ hadrons are already needed at present energies, and it would not surprise me if this phenomenon became very significant at the future energies.

B. Weak and Electromagnetic Dynamics

The popular and very successful gauge theories[11] have provided a strong argument for the synthesis of weak and electromagnetic phenomena at center-of-mass energies $\sim$50-100 GeV. Whether or not this argument is true or false, it is a certainty[12] that by the time we reach $E_{c.m.} \sim 1$ TeV, the inner dynamical structure of the weak force must reveal itself. Let us review the options for, say the process $e^+e^- \to \mu^+\mu^-$:

i) If W, Z do not exist, then the J=1 cross section rises linearly until cut off by unitarity. If this is true, lepton-lepton scattering is strong at those energies.

ii) If W and Z do exist, but there are no gauge-theory type cancellations, then WW scattering, etc., become strong at high energies.

iii) If W and Z exist, and if there exists a renormalizable theory, there must also exist J=0 Higgs bosons.[13] These Higgs-bosons are usually presumed to be weakly coupled to each other (so that there exists a convergent perturbation theory). If Higgs-bosons are strongly coupled to each other, then their masses would be estimated to be $\gtrsim G_F^{-1/2} \sim 300$ GeV.

We conclude that in any case there probably exist non-gauge bosons with $J \neq 1$; in case (i) they are $\ell\bar{\ell}$ resonances, in case (ii) they are $W\bar{W}$ resonances, and in case (iii) they are the Higgs-bosons. We may also conclude that there is a good possibility that there is a new regime of strong interactions at cms energies $\gtrsim 1$ TeV. (Note that this corresponds to $E_{lab} \sim 10^3$ TeV in pp collisions; perhaps the cosmic-ray phenomena are somehow connected??)

What do these options imply for the dynamics of weak interactions? Consider again $e^+e^- \to \mu^+\mu^-$: in case (i), as shown in Fig. 7, σ_{tot} rises linearly up to $E_{c.m.s.} \sim 1$ GeV. In cases (ii) and (iii), there is the Z^0 resonance which occurs when the electromagnetic contribution (falling as s^{-1}) is comparable with the weak (rising as s); thereafter weak and electromagnetic contributions become indistinguishable. In case (iii) the cross section falls as s^{-1} thereafter, and will be related (neglecting correction of order m_Z^2/s) to other lepton-lepton scattering processes by the unbroken $SU(2) \otimes U(1)$ symmetry. Case (ii) is more conjectural; one guess is that $\sigma(ee \to \mu\mu)$ would possess considerable structure, but perhaps be even roughly independent of s for large s.

An important point is that our interest should be focused beyond the question of existence of W and Z. If they are not found with the expected mass, the pursuit to higher mass will be obvious and of great necessity. I find it remarkable (but true) that nondiscovery of W and Z in the 50-100 GeV mass range would be a more revolutionary development than discovery of a 65 GeV W and 80 GeV Z with all the expected properties. If W and Z are found, with properties anticipated by the gauge theories, there will be an even greater urge than at present to enlarge the gauge group; in general there will be predicted a number of Z's mediating neutral currents, along with strong motivation to search them out over a much higher mass range. Finally there will be increased motivation in locating and studying the properties of the Higgs sector.[14]

C. Symmetry and Group Structure of Strong and Weak Interactions

The number of lepton and quark types (flavors) is already large and can be expected to expand. If quantum chromodynamics is a correct way of approaching strong interactions, then we are rapidly learning how to search and discover new quark flavors by means of the production of onium, thanks to the large branching ratio of onium into dileptons (perhaps in the future we may include digammas as well). If, as widely expected, the Υ turns out to be onium associated with a fifth quark, we will soon have at our disposal a relatively reliable basis for extrapolation of production mechanisms and decay schemes. However study of the production and decay of hadrons of new flavors may well greatly increase in difficulty relative to the physics of F's and D's (even for the e^+e^- storage rings), if for no other reason than the greater variety of decay modes available. We either will have to be lucky or will have to figure out better ways of isolating such particles from the general background.

We should not tacitly assume that all such new flavored hadrons decay via W-exchange mechanisms. If there is no coupling to W, they may decay via heavier gauge boson exchanges, with correspondingly longer lifetimes.[15] There may be complex cascade chains involving several heavy quarks or heavy leptons, or they may even decay via emission of real Higgs bosons[16] or (if they are really heavy) of gauge bosons. Indeed clean production of something very heavy (e.g., $e^+e^- \rightarrow Z^0$) may well reveal all kinds of new objects via cascade chains.

However, there seems already not much economy of description in flavor physics. With proliferation of leptons and of hadron flavors very probable, a synthesis is much to be sought. There is not much to go on in this regard: perhaps we must penetrate another layer of compositeness and find pre-quarks and the like,[17] or perhaps a large flavor group is intrinsic and not to be further dissected.[18] Perhaps even weak gauge bosons are not fundamental. Here history may have a lesson for us: were theorists more prescient and had developed gauge principles and the theory of spontaneous symmetry breakdown before experimentalists had advanced beyond 50 MeV, the (undiscovered) π might have been treated the way we now treat Higgs-bosons, and the (undiscovered) ρ and ω might have been treated the way we now treat gauge gluons, or even W and Z.

The question of strong and weak symmetries and basic degrees of freedom is an area where we must expect to be surprised. Given the cosmic ray hints, we may simply be thinking in completely inappropriate terms. But new theoretical ideas and new concepts seem most of the time to end up in predictions of a zoo of new particles. But, as before, to review all the beasts in that zoo is an exercise in tedium. A partial catalogue of these is given in Appendix B, along with a brief guide to the uninitiated.

D. Fundamental Issues

Futurists seldom resist waxing eloquent on the possibilities of discovering something absolutely revolutionary about the structure of space-time, causality, etc., by going to still higher energies. Such speculations have not borne fruit so far, and as a result most of us nowadays tend to forget them. Nevertheless, just because they are so unlikely, yet so basic, we should still remember them and put them to the test. A short list is given below:

i) Violation of Causality: Here a test may be made either through dispersion relations or discovery of a Lee-Wick particle.[19] What would we do were $\sigma_{\bar{p}p} - \sigma_{pp}$ not to tend to zero but begin to increase with increasing s?

ii) Breakdown of quantum electrodynamics: In the next generation of energies, we expect standard QED to break down because of the weak-electromagnetic synthesis. But aside from such mundane effects, what happens if we find something inexplicable in those terms?

iii) Deterioration of conservation laws at short distances: Here theory already gives examples of quite unexpected effects from nonperturbative causes.[20] Maybe there are more.

iv) Nonlinearity of quantum mechanics at short distances: I don't know what that means. It was, however, entertained at the time of the $K_L \rightarrow \mu\mu$ crisis.[21]

v) Breakdown of Poincare invariance at short distances: The Poincare group is the greatest sacred cow in physics. It ought to be put to experimental test. The problem is that one is hard put to butcher a covariant theory in a credible way in order to study and limit the size of any presumed cutoff. However, the recent development of lattice electrodynamics[22] provides a prototype of a realistic theory with built-in cutoff. I would like to see an analysis which presumes that space or space-time is a lattice structure and which determines the best limit on the lattice constant and lattice velocity relative to our local coordinate system. I personally like to entertain this idea of a real physical lattice. However, when the subject comes up I start seeing that patronizing look come over my colleagues' faces: "Well, bj is finally cracking up."

III. HOW THE PROPOSED MACHINES ADDRESS THESE ISSUES

The physics issues we have discussed are attacked in different ways by the different machines. In making comparisons, we invariably find a class of contributions unique to a given type of machine. Some of the most important of these have been culled from Appendix A and are listed below (this list is not meant to be comprehensive. I suspect I left out important items.):

A. Multi-TeV Fixed Target Program

i) Higher luminosity by a factor $\gtrsim 10^4$ or so means greater selectivity in studying both common and rare processes.

ii) High-$p_\perp$ hadron physics. In storage rings the limitation on the maximum attainable $p_\perp$ for secondary hadrons is likely to be luminosity, not energy. The ability to study these processes for $p_\perp$ comparable to $E_{c.m.s.}$ also provides additional inputs for understanding production dynamics. Diversity of incident beams is also an important advantage.

iii) Neutrino and muon physics. The closest competition here comes from ep colliding beams; ep physics may be qualitatively similar to νp physics when momentum transfers $\sqrt{Q^2}$ exceed 50-100 GeV and weak interactions become as important as electromagnetic interactions. However $\nu_\mu e$ and $\nu_e e$ interactions, and processes such as $\gamma + \nu_\mu \rightarrow X$ through the nuclear Coulomb field have no competitors whatsoever.

iv) Diversity of beams, especially meson versus baryon. This has always provided important qualitative information, and there is no reason for the situation to be different at higher energies.

v) Nuclear targets: Because of the large longitudinal distances which characterize the internal dynamics of collisions at high energy, there are expected to be a variety of A-dependent effects in strong interaction processes, high $p_\perp$ hadron collisions, dilepton production by hadrons and deep inelastic lepton-induced phenomena. This is not dirty physics; it has direct impact upon basic dynamical questions.[23] It can only begin to be studied at energies $\gtrsim$100 GeV. Its importance these days is, I believe, generally underrated.

vi) Availability of 4π visual detectors (bubble chambers; streamer chambers, etc.,) to see the entire event.

vii) Exotic beams: Creation of Y, Σ, Ξ, Ω, (...?) beams should become even more feasible and useful as energy increases.

viii) Atomic electrons at targets: study of electroproduction structure functions of π, K, Σ, Λ, etc., begins to be possible for $E > 5$ TeV (corresponding to $W^2 \gtrsim 5$-$6\ GeV^2$).

ix) Photon targets (via Primakoff effect) can study photoproduction from π, K, Λ, Σ, Ξ, etc.

B. Proton-Proton or Proton-Antiproton Colliding Beams

i) Highest available energy: the name of the game is energy, and the value of this cannot be underestimated--and especially if the cosmic-ray hints really are true.

ii) Log-s strong interactions physics requires a large energy increase; this includes measurements of σ_{tot}, σ_{el} diffraction excitation, inclusive distributions, rapidity correlations, multiplicity distributions and moments, multiple Pomeron exchange, etc.

C. Electron-Proton Colliding Beams[24]

i) Deep inelastic scaling tests: Present ideas using QCD predict small violations of scaling behavior which vary logarithmically with energy.[25] A large lever-arm in energy and momentum transfer, along with clean experimental conditions are essential. The ep colliding-beam option appears to be a unique way of testing this kind of behavior. Of course we might also be surprised and find unexpected substructure to the proton constituents as well.

ii) Photoproduction at the very highest energy, via the quasi-real photons accompanying the electron.

iii) Leptoquark production. In general there seems no special advantage in using ep colliding beams for production of new particles (although an exception is weak production of a neutral lepton E^o). The center-of-mass energy is not as large as in pp or $\bar{p}p$ collisions, and one generally creates a secondary lepton and/or baryon in addition to the system of interest. Thus in comparison to e^+e^- collisions the production mechanism is likely to be inefficient in $E_{c.m.s.}$ and not as clean. A far-fetched exception would be finding an object carrying both lepton-number and baryon-number, produced by s-channel "fusion" of the electron with something in the proton; e.g., a leptoquark. This would involve drastic theoretical revisions[26] such as integer-charge constituents, broken color symmetry, etc.

D. Electron-Positron Collisions

i) Tests of quantum electrodynamics. Precision measurements of Bhabha scattering and muon-pair production provide a firm calibration of our basic concepts at extremely short distances.

ii) Exploitation of narrow resonances and sharp thresholds. While we need only to cite recent history, it is also necessary to warn that it will be harder in the future. Onium peaks are not likely to be as prominent as the ψ, and steps in the cross-section will have to be discerned in the presence of a larger background. The Υ situation provides an instructive example. We expect $\int \sigma \, dE$ to decrease with increasing onium mass; also the machine energy resolution ΔE increases with E as well. Thus signal-to-noise decreases rather sharply with increasing mass.

iii) Photon-photon collisions can be studied at very high energies, providing a good test of vector dominance and a comparison of photon internal structure with hadron structure.

iv) Electron scattering from a virtual photon can give a more microscopic look at the internal structure of photons.[27]

We now turn to the major themes which are common to all machines:

a) Search for narrow, heavy states. This is of course a central theme for the exploratory side of particle physics. We begin by considering states which can decay into e^+e^- and/or $q\bar{q}$ pairs. They can be produced resonantly by e^+e^- colliding beams or by quark-antiquark annihilation according to the Drell-Yan mechanism.[28] Fig. 8 exhibits, in width-mass space, the location of some of the more familiar beasts in the (real or imagined) elementary particle zoo. One must recognize that the relation between width and mass of W and Z

$$\Gamma \sim G_F m^3$$

ceases to hold for gauge-bosons beyond W and Z (assuming the gauge theories to be correct). The relationship becomes $\Gamma \sim \alpha m$, and we shall see that this implies a relatively smaller production cross section for superheavy gauge bosons than conventional estimates give. The leptonic width of onium is expected to decrease with increasing mass. The estimates of leptonic width of Υ, along the known value of the ψ, provide some basis for extrapolation. I have used the calculations of Carlson and Suaya,[29] which give $\Gamma_{\ell\bar{\ell}} \sim m^{-1}$ as long as the linear potential model is correct. If a QCD potential takes over, one expects $\Gamma_{\ell\bar{\ell}} \sim m(\log m)^{-3}$ which is roughly constant from 5 to 100 GeV. Normalizing at ~ 5 GeV gives the shaded region in the figure for the leptonic width. The total width would not be expected to be much more than a factor 10 larger. Of importance in considering superheavy onium is the possibility that one of its constituents may decay weakly before the onium annihilates. This probability increases in proportion to m^5; thus the dilepton branching ratio very rapidly becomes unobservably small. However, in pp collisions the production cross section depends only upon $\sigma_{\ell\bar{\ell}}$, so that this only affects the final state observability of the process. This is also the case for e^+e^- annihilation provided

$$\frac{\Gamma_{tot}}{m} \lesssim \frac{\Delta E}{E}$$

where $\Delta E/E$ is the energy width of the e^+e^- machine, typically $\sim 10^{-3}$. This is satisfied up to $m_Q \sim m_W$; if thereafter one has $Q \to qW$, then $\Gamma/m \sim \alpha$ and the observability of $Q\bar{Q}$ onium would be severely compromised.

Properties of Higgs bosons are an uncertain matter indeed.[14] If the standard SU(2) ⊗ U(1) model is a reliable guide, then the leptonic Yukawa coupling is $\sim G_F^{1/2} m_\ell$ and leptonic width $\Gamma \approx G_F m_\ell^2 m_h$. This means the Higgs boson chooses to decay into the most massive object available to it; e.g.,

$$\Gamma(h \to e^+e^-) \ll \Gamma(h \to \mu^+\mu^-) \ll \Gamma(h \to \tau^+\tau^-) \ll \Gamma(h \to Q_\Upsilon Q_\Upsilon) \ll \cdots$$

where Q_Υ is the quark inside the Υ (cf Fig. 9). Probably the Higgs h is best produced via cascade decay of something else, although there is an outside chance of finding it in direct production by very high energy neutrinos or other leptons.[30]

What portion of Γ -m space can we see with these machines ? To estimate this for e^+e^- machines, we assume that the luminosity $\mathscr{L}$ is $10^{32}\text{cm}^{-2}\text{sec}^{-1}$, the energy resolution $\Delta E/E$ is 10^{-3}, and that a peak cross section of 10^{-36}cm^2 is observable. A simple calculation then shows that we must have (for a J=1 resonance)

$$\Gamma_{\ell\bar{\ell}} \gtrsim 2\times 10^{-14}\, s^{3/2}$$

with all units in GeV. This provides no problem, provided one known where the resonance is and also has some way of cleanly separating signal from background. In contrast with this overoptimistic estimate, we may also make a conservative estimate by presuming that it is necessary to scan over energy, using one hour per point, in order to measure a peak in σ_{tot}. A similar exercise yields the estimate

$$\Gamma_{\ell\bar{\ell}} \gtrsim 10^{-11}\, s\sqrt{R}$$

again with all units in GeV, and with

$$R = \frac{\sigma_{tot}}{"\sigma_{\mu\mu}"} = \sigma_{tot}\left[\frac{4}{3}\pi\,\alpha^{2}\,s^{-1}\right]^{-1}$$

This is shown in Fig. 10. It is quite possible that the sensitivity of an energy scan could be increased by using some property of the onium signal not shared by the background. In balance, it appears that for masses up to 50-100 GeV, e^+e^- rings remain a very powerful tool for discovery and study of any onia which exist in that range.

But most impressive is the resonant production of Z^o or other neutral weak bosons.[31] For the standard SU(2) ⊗ U(1) Z^o, and for luminosity $\mathscr{L} \sim 10^{32} cm^{-2} sec^{-1}$, one estimates about ten Z^o's produced per second. This would be an extremely rich source of all leptons of mass $\lesssim 40$ GeV which couple to Z^o, as well as of new quarks in a similar mass range. In addition, if there are Higgs bosons h^o of mass $\lesssim 40$ GeV, the decay $Z^o \to h^o h^o$ has branching ratio comparable to the decay into a lepton pair. In addition the decay $Z^o \to h^o \mu^+ \mu^-$ (or $Z^o \to h^o e^+ e^-$) also has branching ratio $\gtrsim 10^{-4}$ for $m_h \lesssim 40$ GeV. This mode is especially useful because detection of the lepton pair suffices to detect the h^o irrespective of its decay modes.

To estimate production of narrow resonances in pp and/or $p\bar{p}$ collisions, we rely on the parton model and the Drell-Yan mechanism of parton-antiparton annihilation. There are apparent dangers in so doing. Nevertheless, the Drell-Yan model seems to be reasonably successful in accounting for electromagnetic production of dileptons. There is a need for more incisive tests of the scaling behavior; it is this which is most crucial for giving us the confidence to extrapolate to higher energies.

The Drell-Yan formula for lepton-pair electromagnetic production at y=0 may be written

$$m^3 \left.\frac{d\sigma}{dm\,dy}\right|_{y=0} = 5\times 10^{-31}\left[u(x)\bar{u}(x)+\cdots\right]\mathrm{cm}^2\mathrm{GeV}^2$$

$$x = \frac{m}{\sqrt{s}}$$

For resonance-production (assuming a J = 1 X particle)

$$m^3 \left.\frac{d\sigma}{dy}\right|_{y=0} \approx 3\times 10^{-27}\left[\Gamma(X\rightarrow u\bar{u})u(x)\bar{u}(x)+\ldots\right]\mathrm{cm}^2\mathrm{GeV}^2$$

The recent muon-pair data[32] provides a measurement of $u(x)\bar{u}(x)$ for $0.2<x<0.5$. Over that range it falls exponentially from a value $\sim 4\times 10^{-2}$ to $\sim 2\times 10^{-4}$. As $x\rightarrow 0$ we expect $u(x)\sim\bar{u}(x)\sim 0.3$. If we assume that $\gtrsim 10\%$ of all W or Z decays are observable and that two units of rapidity y (about 90°) can be fully covered with detector, it should suffice to have

$$\mathscr{L}\frac{d\sigma}{dy} > 5\times 10^{-4}$$

(This gives ~10 observed decays per day). The region of Γ -m space which can be seen is shown in Figs. 11-15, corresponding to various choices of parameters. For the different machines we chose luminosity (rather arbitrarily) as follows:

Machine	Luminosity ($cm^2 sec^{-1}$)
ISR	10^{31}
pp rings of higher energy	10^{33}
$p\bar{p}$ rings	10^{30}
Fixed-target VBA	10^{37}

One sees that the shape of the boundary is universal; an overlay is provided in Fig. 16, along with instructions for use, so that any choice of luminosity and machine may be made.

The function $f_{\bar{p}p}$ appropriate to pp storage-rings will be larger[33] than the corresponding function f_{pp}. This is shown as the dashed line on the template in Fig. 16.

We see that pp rings suffice not only to find the W, but also to explore the territory up to much higher mass values; the VBC (very big collider) could reach masses in excess of 1000 GeV, even given the smaller couplings of such heavier objects expected from the unified gauge theories. For $\bar{p}p$ rings, high luminosity is quite crucial, and if there is a factor ~100 less luminosity for $\bar{p}p$ than for pp, the limit on mass of heavier Z's is decreased by a factor ~2-3.

Turning now to the question of onium, it is not clear whether its production proceeds via a quark-antiquark annihilation mechanism, or whether the mechanism is entirely different. The success[29] of the two-gluon mechanism in roughly accounting for Υ production argues, at the least, for a scale-invariant mechanism of production. But in any case, as long as $\gtrsim 10\%$ of the onium width is electromagnetic, we can get a lower limit on onium production via the quark-antiquark annihilation mechanism. Then scaling might imply that the ratio of the true answer to the conservative estimate is roughly energy independent. Evidently the conservative estimate (conservative by no more than a factor ~10) can be read off Figs. 11-15, indicating onium production might be observable in high luminosity colliding-beam experiments up to masses ~20-40 GeV. [However, we have not taken into consideration backgrounds]. As we mentioned before, once the onium mass exceeds ~30-50 GeV, its probable weak decay into other channels provides a much more difficult problem than the size of the production cross section.

We have not discussed states not coupled to $q\bar{q}$ or gg or $\ell\bar{\ell}$. Such objects might best be found as decay modes of Z or other particles we have discussed.

Also a possibly important source is single production by leptons in deep inelastic processes.

b) Direct leptons, photons, multileptons, and multiphotons as signature for new physics or new particles. Here the issues are luminosity, available cms energy, and the expected signal-to-noise. The theoretical considerations are here too diffuse to help too much. Even if production mechanisms are available from theory, decay mechanisms and branching ratios tend to be much more uncertain. Here I choose to remain silent; such experiments hold promise for all machines of the future.

c) Properties of hadron final states in deep inelastic νp, ep, μp reactions, $e^+e^- \rightarrow$ hadrons, W, Z decay, and high-$p_\perp$ hard collisions in pp and $p\bar{p}$. The principal figure of merit here is W^2, and the next is ease of studying the final state in detail. The issues center about the nature of "parton fragmentation," i.e., how (and, at higher energies, if) the struck quark evolves into hadrons. It appears that e^+e^- and especially ep rings are superior here; for example, $W \lesssim 10^3$ GeV is attainable with 25 GeV electrons colliding with 10 TeV protons.

The high $p_\perp$ jets produced in pp collisions may also be a useful source of information. They are limited somewhat by luminosity and are also more complex; low-$p_\perp$ ordinary hadrons not associated with the jet structure produce extra confusion right in the midst of the rapidity space of the interesting jets. However, one unique contribution proton-proton collisions can provide is a study of the hadron final states produced in association with massive dileptions. In such a case one again has fractionally charged multiquark systems leaving the interaction region, and it would be interesting and incisive to study in detail the remanent hadrons.

Finally one must also remember that pp collisions may be a source of high-$p_\perp$ partons which are not quarks; e.g., gluons.

d) Properties of hadron-currents coupled to leptons. This is almost a corollary of the previous item. But here one is concerned with the scaling behavior and internal symmetry structure of the underlying production mechanism; e.g., old currents vs. new currents, charged weak currents and neutral weak currents and how, if at all, they are coupled to new leptons and quarks. [There are similar issues for the electromagnetic current. But at $Q^2 \gtrsim 2500$ GeV^2 we may not even be allowed to talk of electromagnetic currents, only SU(2) currents and U(1) currents.] In comparing different machines, we make only a miscellany of observations.

α) The maximum Q^2 attainable is of special importance for scaling tests. The cross section for all events greater than some Q^2 is, assuming naive scaling (good enough for these purposes)

$$\sigma(>Q^2) = \frac{1}{Q^2} F\left(\frac{Q^2}{W^2}\right)$$

One can check[24] that for $\mathscr{L} \geq 10^{32}$ cm^{-2}sec^{-1} it is W^2 which is the limiting factor, not Q^2 (for the next-generation machines). We compare

	$\mathscr{L}$(cm^{-2}sec^{-1})	W^2_{max}(GeV^2)	Q^2_{max}(GeV^2)
25 × 400 GeV ep rings	10^{32}	4×10^4	10^4
VBA: $10^6 \mu$/sec. at 5 TeV into 20 m Fe target.	10^{34}	10^4	7×10^3
25 GeV e × 10TeV p	10^{32}	10^6	7×10^4

β) As we mentioned earlier, for weak processes much depends upon whether the gauge theories are correct. If they are, weak processes do not get systematically larger than the nominal electromagnetic ones (except at Z resonances). The study of energy dependence is especially clean in e^+e^- reactions, quite good in ep $\rightarrow$ hadrons, and more difficult in pp collisions. If there is no gauge theory cutoff, then weak jets from ud $\rightarrow$ du with $p_\perp > 100$ GeV could become very prominent in a VBC.

Another clean way of studying quantum numbers of weak currents is by diffractive production of ρ, ω, A_1, ψ, ..., etc., by neutrinos. The cross sections are not large and high energy is useful.[34]

γ) Leptoproduction of flavored quarks Q becomes interesting for ep collisions: it may be that the ratio R_{ep}

$$R_{ep}(\omega, Q^2) = \frac{\sigma(e^-p \rightarrow e^-Q\bar{Q} + \text{all})}{\sigma(e^-p \rightarrow e^- + \text{all})}$$

becomes as large as the corresponding $R_{e^+e^-}$ when ω is large and $Q^2 > 4m_Q^2$. I suspect that a detailed comparison of, say, 25 GeV × 10 TeV ep with 100 GeV × 100 GeV e^+e^- would favor the e^+e^-; however, this is only a guess.

e) New particles as decay products of other heavy particles. It is difficult for anything to compete with the Z-factory (e^+e^- colliding beams at Z resonance). One possibility is creation of exotic neutrino beams via decay of very heavy Q states produced in pp collisions. Here only VBA can help, and only by a relatively modest step in center of mass energy. However, if the Q_Υ conjectured to be associated with Υ has such decay modes (e.g., into ν_τ), that energy increase might be quite significant. Another is the multilepton and γ-production discussed in item (b).

f) New lepton production: We are accustomed to e^+e^- collisions as being a good way to produce new charged leptons. But as the energy approaches and exceeds the Z^0 mass, neutral lepton pairs coupled to the neutral current are also produced with comparable cross section. ep and νp collisions offer possibilities for single production up to $m_\ell \sim 0.3\sqrt{s}$. Proton-proton collisions, while less clean, may also compete, although it looks less promising.

IV. CONCLUDING OPINIONS

It is hard to avoid the conclusion that weak interactions will be the dominant theme in the next energy regime. We shall learn how the low energy structure is modified at high energies. In addition we may expect to have a much better understanding of weak symmetries, especially through the search for new leptons and new flavors. The existence of W and Z, with masses between 50 and 100 GeV, is so widely accepted that it would be a more revolutionary discovery if they were not discovered than were they to be found with all the expected properties. And we must, in fact, be setting our sights not only on the discovery of the "standard" W and Z, but upon the region beyond. If there is no standard W with mass less than 100 GeV, the push will go onward. If a standard W and Z do exist, we will be going beyond in order to find more.

The discovery of a Z would imply great progress through study of its decays. Resonant electron-positron annihilation into the Z would provide a clean, copious source of all its decay products. Thus pp and/or $p\bar{p}$ rings play a role complementary to the e^+e^- rings; their relatively large center-of-mass energy allows searches for W's and Z's over a relatively broad energy range. On the other hand, a large e^+e^- ring should provide much more detailed information--provided there is a Z^0 within its sensitive energy range.

However, in considering pp and/or $p\bar{p}$ collisions, we are basing our optimism on the extrapolation of not-completely-established scaling concepts which utilize the parton-model and the Drell-Yan mechanism. Certainly the recent experiments on dilepton production by protons strengthen this optimism. However, we must still make a rather large extrapolation, and there always remains the possibility of an unexpected breakdown. It is especially at this point that the hints from cosmic-rays give us pause. If it is true that the character of even typical hadron collisions changes drastically at energies $\gtrsim 10^5$ GeV (about 500 GeV in the center-of-mass), we can hardly trust parton-model or other conventional considerations. Furthermore, the existence of copious high-$p_\perp$ hadron production (corresponding to $p_\perp^{-4}$ behavior--or with even lower exponent), as hinted at by the cosmic-ray data, would provide more serious background problems for any kind of heavy particle searches.

But along with that unpleasant news would come the good news of revolutionary changes in strong interaction phenomenology to study instead. The cosmic-ray evidence for very high multiplicity, along with exotic events such as Centauro, remind us that the high energy world above 10^5 GeV may just be very different from what is familiar to us at accelerator energies. And, provided energies above 100 TeV are attainable, <u>any</u> luminosity above $10^{26} cm^{-2} sec^{-1}$ would already provide us a meaningful view of that world.

Finally, while in the future the cutting energy probably will rest with pp, pp, and perhaps e^+e^- machines, we should not forget that e^-p machines will provide clean and very sensitive information on hadron structure. And the fixed-target experiments, while in the future no longer competitive in terms of center-of-mass energy, will remain the backbone of high energy physics because of the depth and diversity of the research opportunities they offer.

V. ACKNOWLEDGMENT

The speaker originally invited to give this report was L. B. Okun of the Institute of Theoretical and Experimental Physics, Moscow, USSR. I know we all regret very much that he was unable to attend this meeting. Professor Okun, at about the same time I was making this study, also studied these issues along parallel lines. I wish to acknowledge his most helpful and wise counsel on these questions.

Appendix A:
Some Predictable Extensions of Present Interests

Strong Interactions

σ_{el} and σ_{tot}

Diffraction dissociation

Double and triple Pomeron exchange

Multiplicity distributions

Inclusive spectra

Correlations (clusters, etc.)

Exotic beams (Y, etc.)

Onium searches

Searches for new flavors

Nuclear cascading and A-dependence studies

Search for missing energy; direct ν production

Direct leptons and multileptons

High-$p_\perp$ jet production; high-$p_\perp$ inclusive spectra

Correlation studies at high-$p_\perp$

Direct γ and multigammas

ψ, Υ, ... production studies

Studies of charm production in hadron collisions

Electromagnetic Interactions

QED tests

W_1, W_2 scaling tests

Deep-inelastic hadron final states

Photoproduction:

- $\rho, \omega, \phi, \psi, \Upsilon, \ldots$
- Inclusive spectra, correlations, $\bar{n}$, ...
- Charm and direct lepton production
- A-dependence studies
- In general, program parallel to strong interactions

Deep-inelastic Compton scattering

Nuclear effects in high-ω electroproduction

Primakoff processes

e target (πe, Ke, Σe, ... scattering)

Virtual-γ target (in colliding beam experiments)

Electromagnetic production of heavy leptons, other charged objects

$e^+e^- \longrightarrow$ hadrons

R, inclusive spectra, $\bar{n}$, correlations,...

Spectroscopy of new flavors

Flavor searches

Scans for new resonances

$\gamma\gamma$ physics (as in photoproduction)

Weak Interactions

W_1, W_2, W_3 scaling tests

Deep-inelastic hadron final states

Weak diffractive production of ρ, ω, A1, K*, ... by ν

Similar neutral-current studies

Dileptons and multileptons

ν oscillations

ν-e interactions

ν_e interactions

Weak-electromagnetic interferences

Polarized e/μ beams

$e^+e^- \rightarrow \mu^+\mu^-$

Charge-asymmetries in deep-inelastic scattering

ep $\longrightarrow \nu$ hadrons; μp $\longrightarrow \nu$ hadrons

ep $\longrightarrow N^o$ hadrons; μp $\longrightarrow N^o$ hadrons

W and Z production

Weak jets in pp collisions

Weak decays of new particles

Hyperon decays

Appendix B:
A Zoo of Unobserved Particles

i) Well-established

- Quarks
- Monopoles
- Tachyons
- W and Z
- Dyons
- Gluons
- Gravitons

[Most of these appear in the compilations of the Particle Data Group]

ii) Familiar

- New leptons
- New-flavored hadrons
- Onium [as in positronium, charmonium, Υ, ...]
- Heavier gauge bosons
- Higgs bosons
  - Scalons (cf Weinberg's talk)
  - Pseudogoldstone bosons (like scalons, relatively light)
- Glueballs [bound states of gluon pairs]
- Super-high-spin hadrons [high-spin members of leading trajectories don't decay strongly]

iii) Others

- Massless spin 3/2 Goldstone fermions (present in spontaneously broken super gravity)
- Leptoquarks (gauge bosons which couple to $\ell\bar{q}$)
- Colored bosons, Colored fermions [cf Pati & Salam, collected works]
- Diotons [colored gauge-bosons in integer-charge theories; cf Fritsch & Minkowski.[18]]
- Prequarks [Constituents of quarks]
- Wakems, Hakems, Chroms [Particular prequarks espoused by Terazawa]

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Tabie I

Machines Under Construction
Or Reasonably Likely to be in Near Future

	pp	$p\bar{p}$	ep	e^+e^-
ISABELLE (Proposed at Brookhaven; some preliminary funding obtained)	400 × 400	? ?	20 × 400 (later)	
SPS Collider (See Van Hove's talk)		270 × 270		
FNAL Colliders	270 × 1000	400 × 400 1000 × 1000		
PETRA				18 × 18
PEP				18 × 18
VEPP - IV				7 × 7
CESR				8 × 8
Other Projects Under Discussion				
TRISTAN (Japan; uses KEK as injector)	180 × 180		17 × 180	17 × 17
POPAE (FNAL; uses Tevatron as injector)	1000 × 1000	1000 × 1000	20 × 1000	
UNK (under discussion in USSR; uses IHEP accelerator as injector)	2000 × 2000	2000 × 2000	20 × 2000	14 × 14
LEP (future European project)				70 × 70? 100 × 100?
DUMAND (Deep underwater neutrino project)			$E^{\nu p}_{lab} > 10^4$ GeV	
VBA (or VBC) either	$>10^4 \times 10^4$	$>10^4 \times 10^4$		
or				$>100 \times 100$

FIGURE CAPTIONS

1. Energy levels of machines. The acronyms are identified in Table I.

2. The event of Niu, Mikumo, and Maeda.[4] Note the large leading multiplicity.

3. Another candidate for new-particle production from the Niu emulsion-chamber.[5]

4. A third candidate from the Niu emulsion chamber.[6]

5. The "Centauro" event of the Brazil-Japan collaboration 5m × 8m emulsion-chamber on Mt. Chacaltaya.[7] This picture of the event is only schematic.

6. Data from the large Pb-ionization chamber calorimeter at the Tien-Shan installation:[8]

   a) Mean ionization vs. depth into the calorimeter .

   The initial peak is the electromagnetic component. The slope of the remaining hadronic component measures the attenuation length of the cascades.

   b) Attenuation length vs. energy of the cascade.

   c) Electromagnetic component vs. energy.

7. Schematic description of elementary cross-sections. The heavy portions of the curves have some support from experiment.

8. Width-mass space. The fiducial marks (+) are of use in conjunction with the template; Fig. 16.

9. Width-mass space for the Higgs sector.

10. Region of width-mass space accessible to e^+e^- colliding beams of luminosity $10^{32} cm^{-2} sec^{-1}$.

11. Region of width-mass space accessible to the ISR: $\mathscr{L} = 10^{31} cm^{-2} sec^{-1}$, 10 events/day, ~10% final-state detection efficiency.

12. Region of width-mass space accessible to ISABELLE, 400 × 400 GeV; $\mathscr{L} = 10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

13. Region of width-mass space accessible to the Tevatron $p\bar{p}$ program; 1 TeV × 1 TeV; $\mathscr{L} = 10^{30}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

14. Region of width-mass space accessible to a Very Big Collider (VBC): 10 TeV × 10 TeV; $\mathscr{L} = 10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

15. Region of width-mass space accessible to a Very Big Accelerator of 10 TeV on a fixed target; $\mathscr{L} = 10^{37}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

16. Template for generating Figs. 11-15. First, copy this figure onto a transparent sheet. For a machine of luminosity $\mathscr{L} = 10^{33}$, line up the diagonal boundary with fiducials (+) on Fig. 8, then move until the vertical boundary on the right intercepts the horizontal axis of Fig. 8 at $m = \sqrt{s}$. For other luminosities, displace the template vertically by the appropriate factor. The dashed line shows the boundary for $p\bar{p}$ collisions, for which $q\bar{q}$ luminosity is higher.

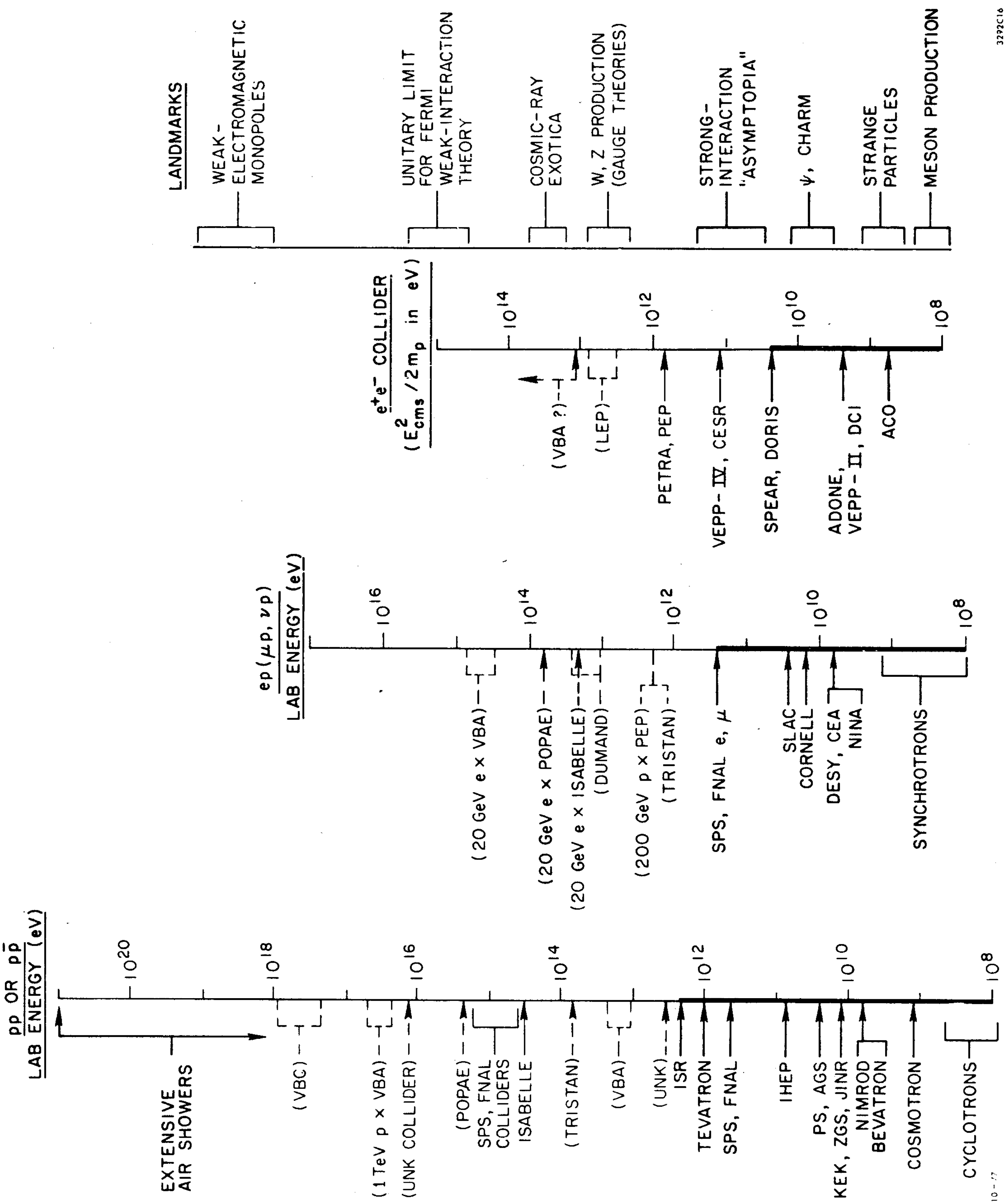

Fig. 1 Energy levels of machines. The acronyms are identified in Table I.

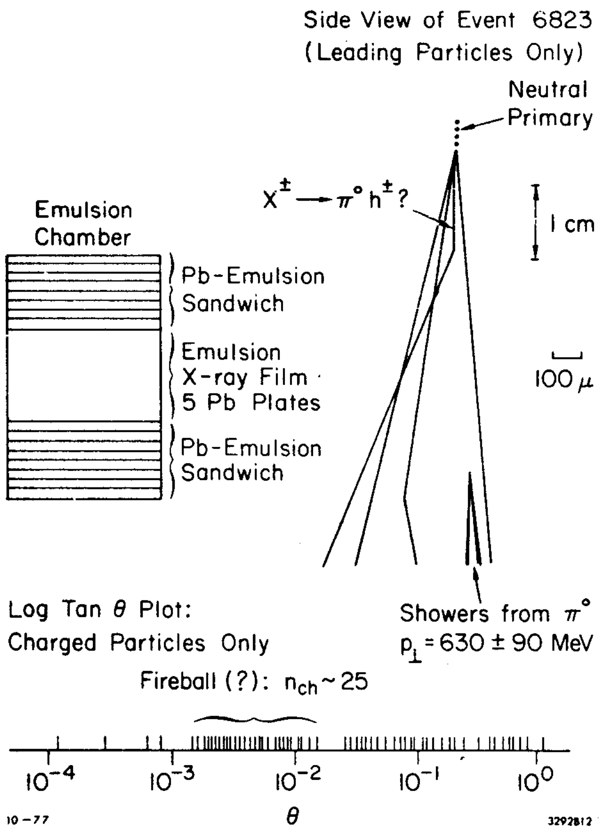

Fig. 2 The event of Niu, Mikumo, and Maeda.[4] Note the large leading multiplicity.

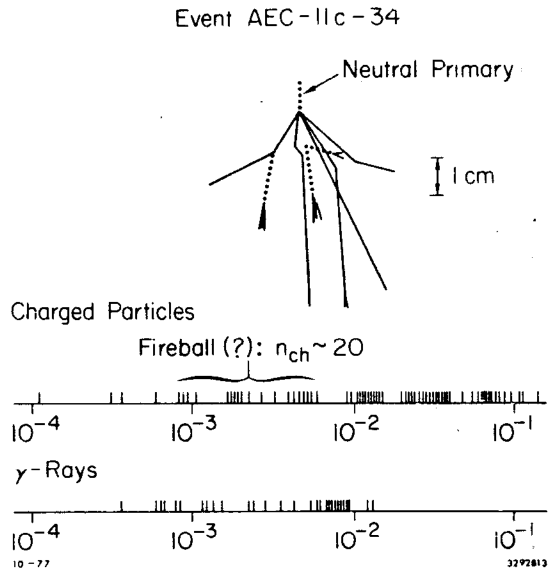

Fig. 3 Another candidate for new-particle production from the Niu emulsion-chamber.[5]

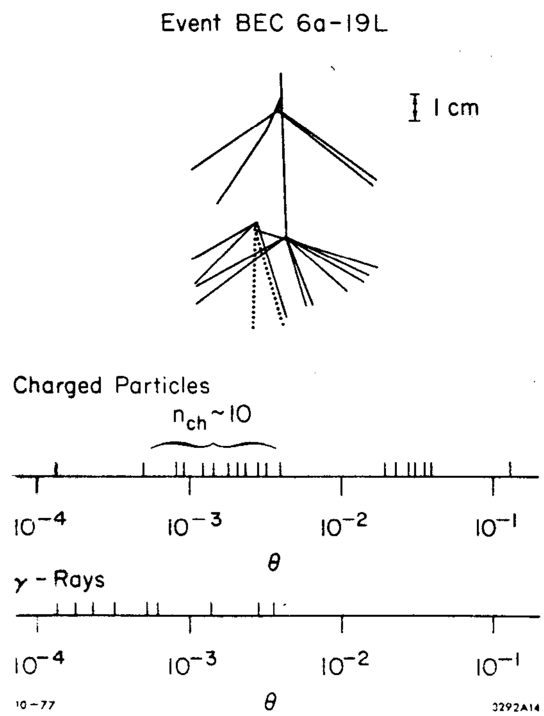

Fig. 4 A third candidate from the Niu emulsion chamber.[6]

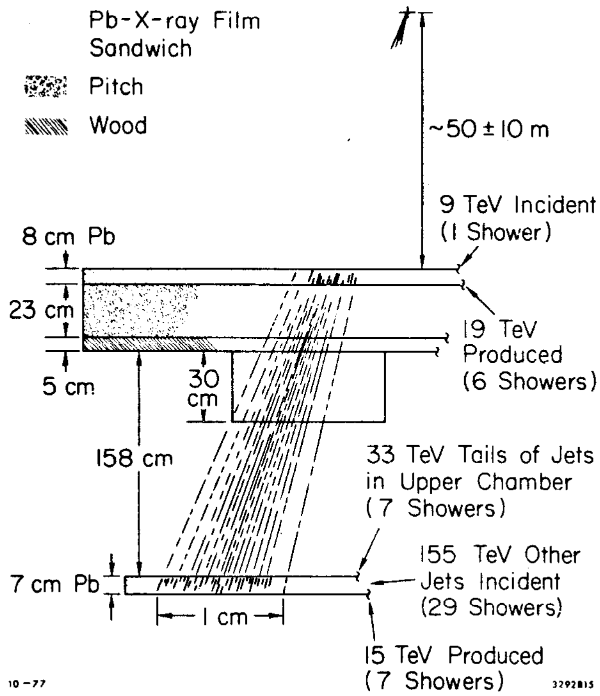

Fig. 5 The "Centauro" event of the Brazil-Japan collaboration 5m × 8m emulsion-chamber on Mt. Chacaltaya.[7] This picture of the event is only schematic.

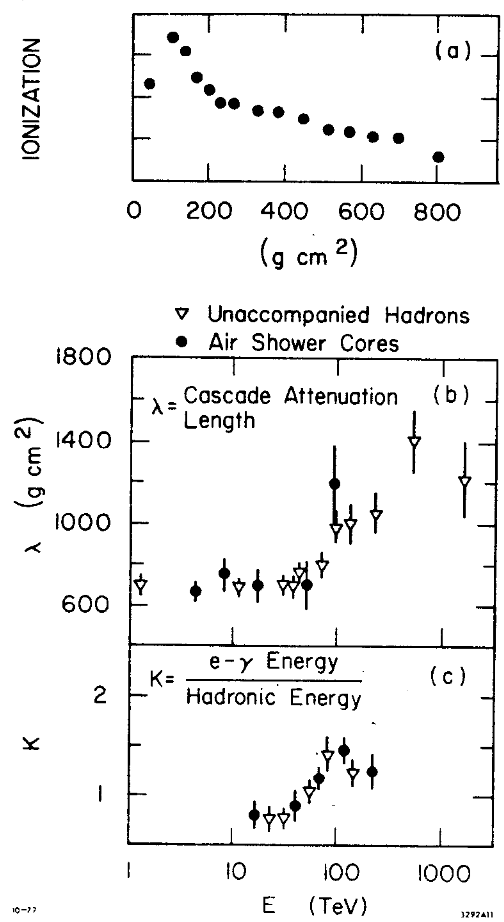

Fig. 6 Data from the large Pb-ionization chamber calorimeter at the Tien-Shan installation:[8]

a) Mean ionization vs. depth into the calorimeter. The initial peak is the electromagnetic component. The slope of the remaining hadronic component measures the attenuation length of the cascades.

b) Attenuation length vs. energy of the cascade.

c) Electromagnetic component vs. energy.

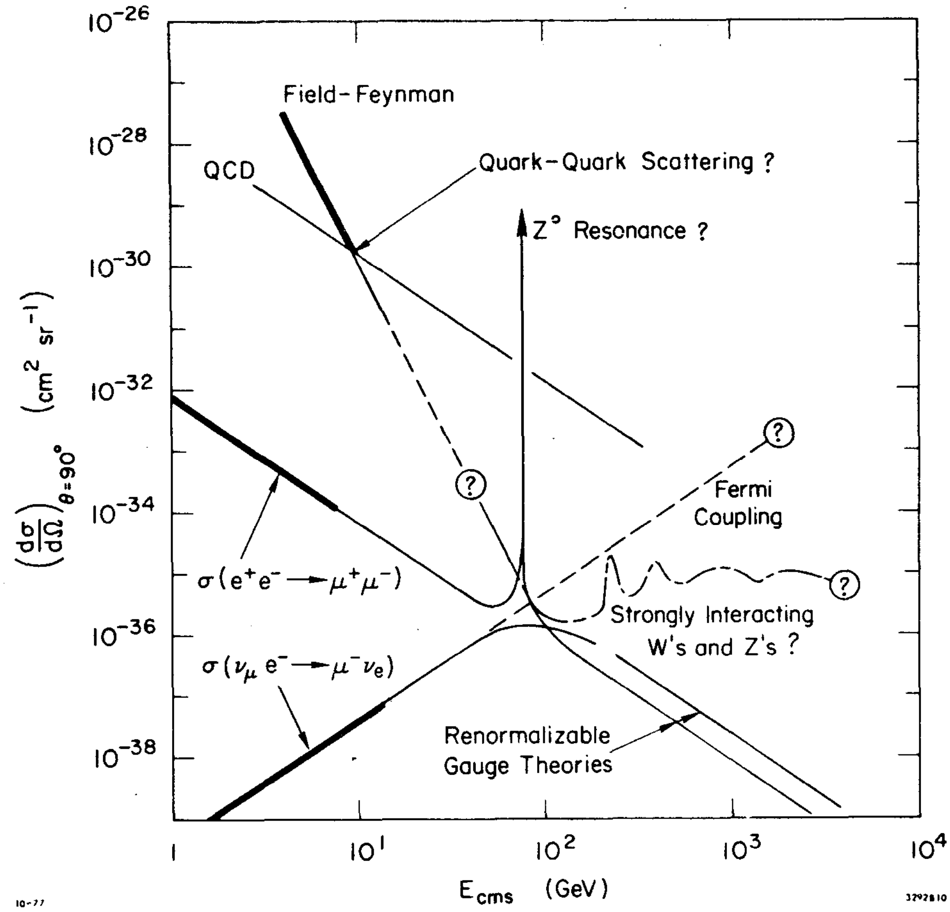

Fig. 7 Schematic description of elementary cross-sections. The heavy portions of the curves have some support from experiment.

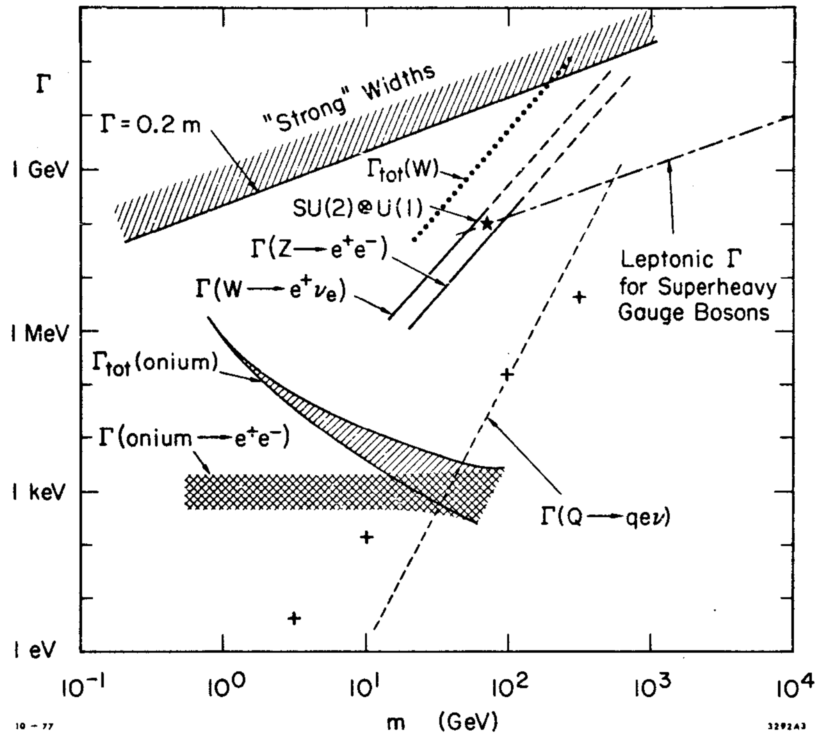

Fig. 8 Width-mass space. The fiducial marks (+) are of use in conjunction with the template; Fig. 16.

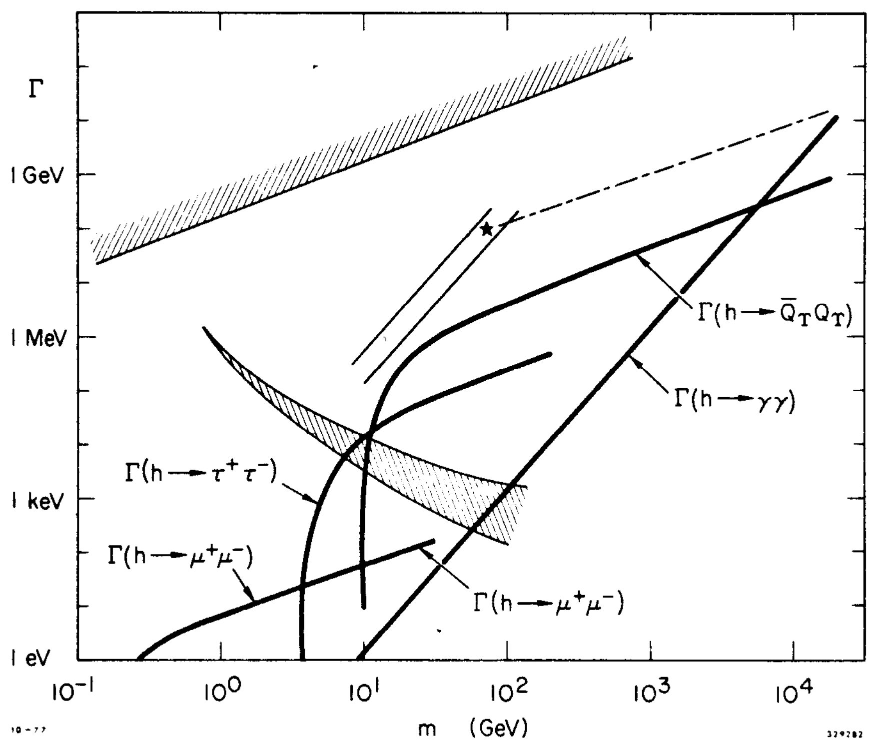

Fig. 9 Width-mass space for the Higgs sector.

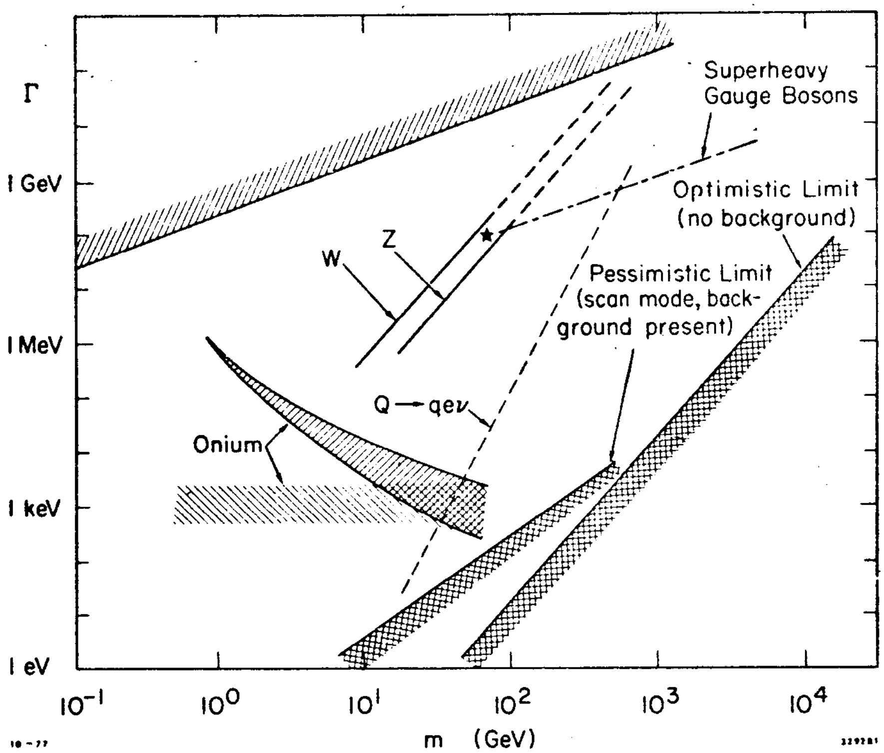

Fig. 10 Region of width-mass space accessible to e^+e^- colliding beams of luminosity $10^{32} cm^{-2} sec^{-1}$.

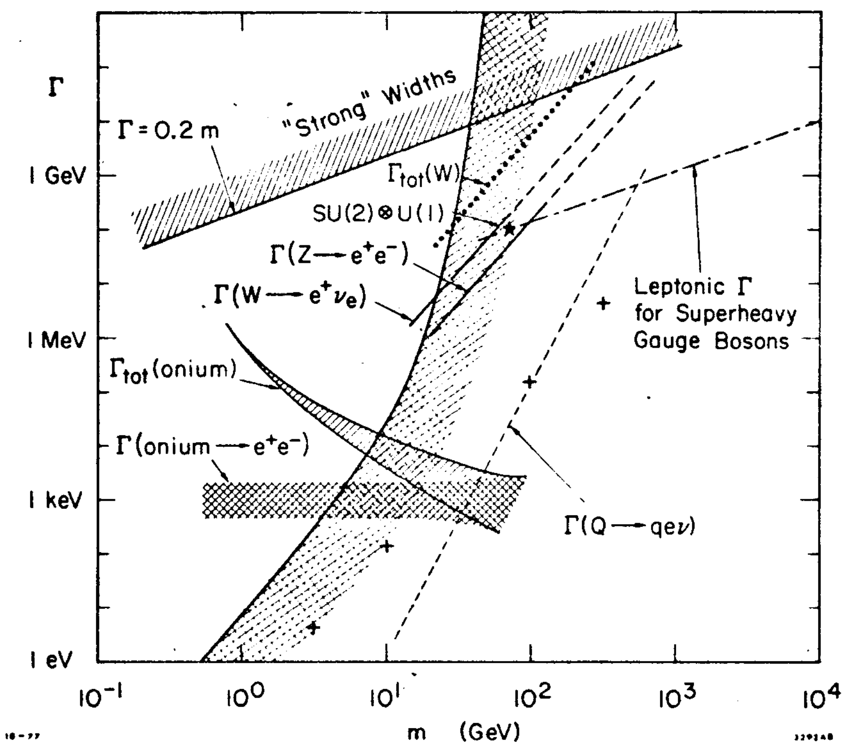

Fig. 11 Region of width-mass space accessible to the ISR: $\mathscr{L} = 10^{31} cm^{-2} sec^{-1}$, 10 events/day, ~10% final-state detection efficiency.

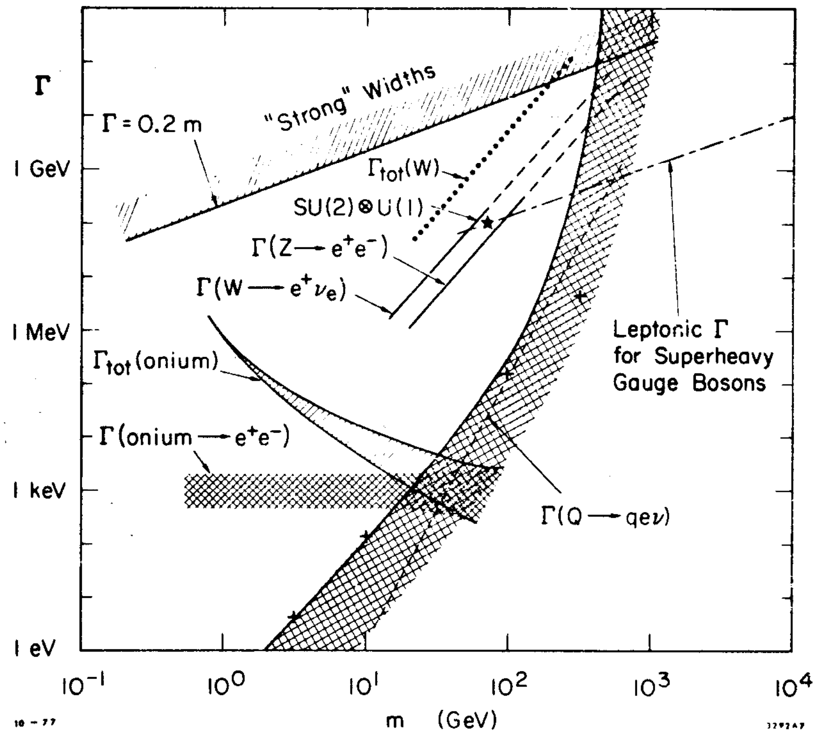

Fig. 12 Region of width-mass space accessible to ISABELLE, 400 × 400 GeV; $\mathscr{L}=10^{33}cm^{-2}sec^{-1}$.

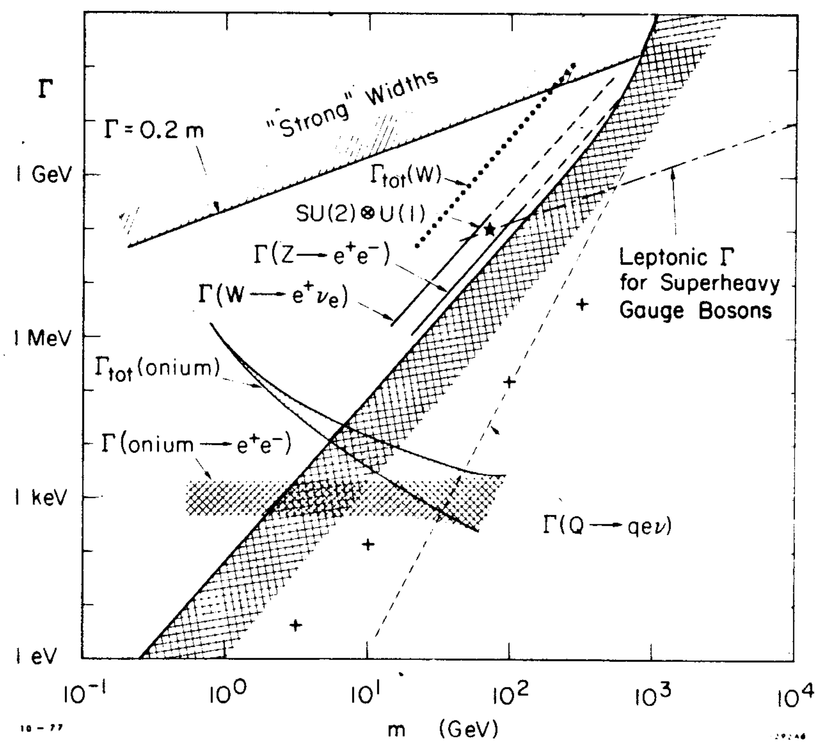

Fig. 13 Region of width-mass space accessible to the Tevatron $p\bar{p}$ program; 1 TeV × 1 TeV; $\mathscr{L}= 10^{30}cm^{-2}sec^{-1}$.

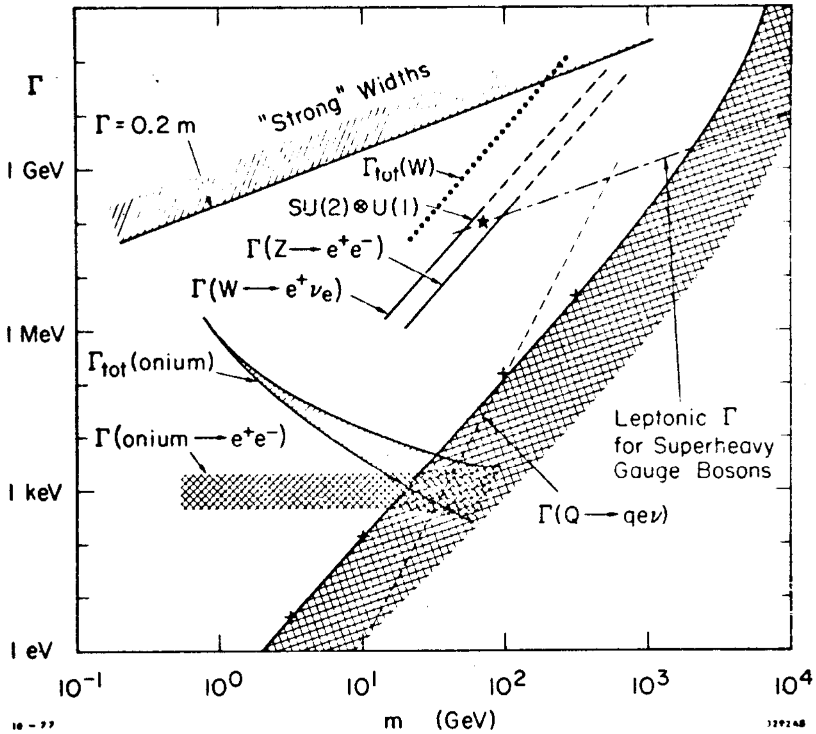

Fig. 14 Region of width-mass space accessible to a Very Big Collider (VBC): 10 TeV × 10 TeV; $\mathscr{L} = 10^{33}cm^{-2}sec^{-1}$.

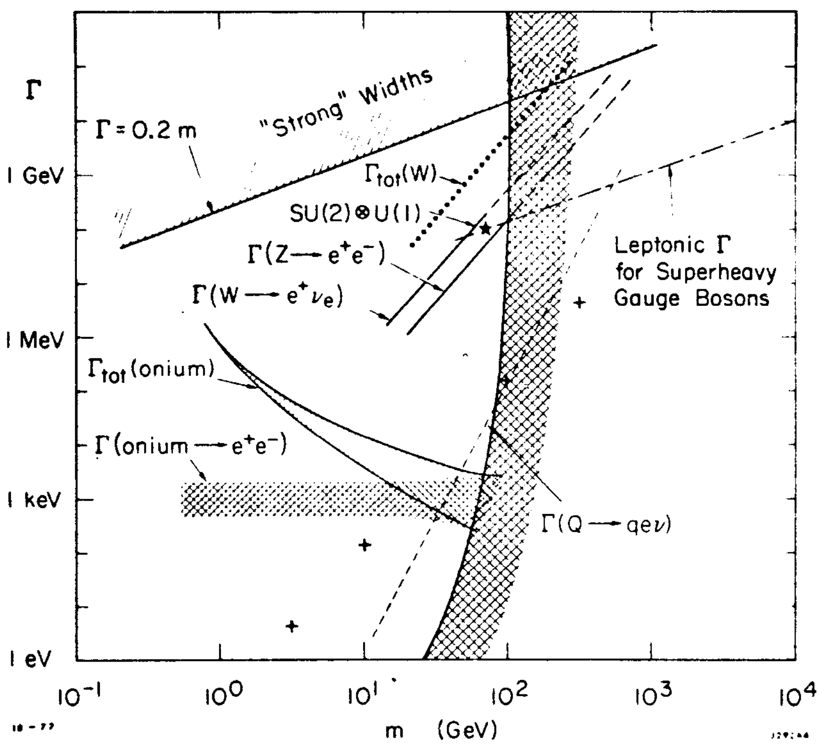

Fig. 15 Region of width-mass accessible to a Very Big Accelerator of 10 TeV on a fixed target; $\mathscr{L} = 10^{37}cm^{-2}sec^{-2}$.

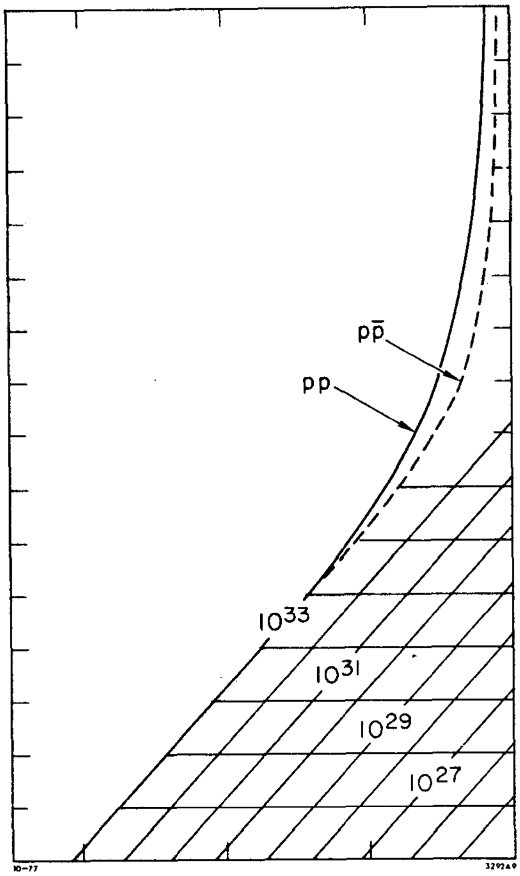

Fig. 16 Template for generating Figs. 11-15. First, copy this figure onto a transparent sheet. For a machine of luminosity $\mathscr{L} = 10^{33}$, line up the diagonal boundary with fiducials (+) on Fig. 8, then move until the vertical boundary on the right intercepts the horizontal axis of Fig. 8 at $m = \sqrt{s}$. For other luminosities, displace the template vertically by the appropriate factor. The dashed line shows the boundary for $p\bar{p}$ collisions, for which $q\bar{q}$ luminosity is higher.