



WHAT LIES AHEAD?*

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ABSTRACT

Open questions pertaining to the weak interactions are summarized, and the case for exploration of the 1 TeV scale is reviewed. The physics prospects for a multi-TeV hadron collider are briefly surveyed.

INTRODUCTION

It is an unusual privilege to share the platform with so many true heroes of our science. Many of the preceding talks have been reminiscences of the contributions that have shaped our understanding of the weak interactions, inspiring accounts of the triumphs of native guile and cunning, of determined persistence, and of what is too modestly described as good luck. I have been assigned the dubious honor of telling you what you have left undone, and how we hope to set about completing the elegant but unfinished intellectual edifice your work has given us. My presentation will begin with a discussion of some of the shortcomings of the "standard model" evolved in the theoretical work of Fermi,¹ Klein,² Feynman and Gell-Mann,³ Sudarshan and Marshak,⁴ Schwinger,⁵ Bludman,⁶ Glashow,⁷ Weinberg,⁸ Salam,⁹ 't Hooft,¹⁰ and others¹¹ under the spur of the experimental insights recounted over the past three days at Wingspread. I will then move toward the case for a very-high-energy proton-proton collider as an experimental instrument for resolving some of the outstanding puzzles, and summarize the capacities of such a device for both predicted and unexpected discoveries.

THE IMMEDIATE FUTURE

Before moving on to the issues that inspire our long-term aspirations, it is appropriate to mention some immediate experimental concerns. Our current understanding is founded on the identification of quarks and leptons as fundamental constituents of matter (at least at the current limits of resolution). The known quarks and leptons fit neatly into doublets

$$\begin{array}{ccc}
 \begin{bmatrix} u \\ d' \end{bmatrix}_L & \begin{bmatrix} c \\ s' \end{bmatrix}_L & \begin{bmatrix} t \\ b' \end{bmatrix}_L \\
 \begin{bmatrix} \nu_e \\ e \end{bmatrix}_L & \begin{bmatrix} \nu_\mu \\ \mu \end{bmatrix}_L & \begin{bmatrix} \nu_\tau \\ \tau \end{bmatrix}_L
 \end{array} \quad (1)$$

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The existence and weak-interaction properties of the top quark and the tau neutrino are strongly indicated by circumstantial evidence. It is important that they be found. The most promising experimental approaches appear to be a t-search in hadron colliders, and a "three neutrino experiment" proposed for the Tevatron direct neutral lepton facility.

The second key element of our current description is the gauge theory strategy for the construction of theories of the fundamental interactions. This line of work has led to the $SU(2)_L \times U(1)_Y$ electroweak theory, to quantum chromodynamics as a theory of the strong interactions, and to the prospect of a unified theory of the strong, weak, and electromagnetic interactions. It is extremely important, and within our experimental means, to test the $SU(2)_L \times U(1)_Y$ theory as stringently as quantum electrodynamics has been tested. This means refining our knowledge of the properties of the intermediate bosons W^\pm and Z^0 , and testing the radiative or "higher-order" corrections that are calculable in the theory. It also means continuing to challenge the experimental bases of the theory by testing CVC, searching for second-class currents, and checking the Cabibbo hypothesis for the flavor structure of the charged current. The outstanding experimental issue involves the status of the Cabibbo hypothesis for Σ^- β -decay; this should be resolved by an experiment under analysis at the Tevatron.

"ETERNAL" QUESTIONS

Beyond these concerns of the moment, there are many issues which have — in a sense — always been current. In the language of today's theoretical framework, some of these important questions are:

- (Why) is the charged current left-handed?
- (Why) are there quark-lepton generations?
- (Why) are the neutrinos massless?
- What does CP violation mean?
- How does nonleptonic enhancement arise?
- Are the "elementary particles" (the quarks and leptons) composite?

For many of these, existing experimental evidence and the theoretical paradigm give no particular clues about where to look for enlightenment. No energy scale is singled out.

THE NATURE OF ELECTROWEAK SYMMETRY BREAKING

The $SU(2)_L \times U(1)_Y$ electroweak gauge symmetry is not manifest in the world around us. It must be hidden or spontaneously broken. An understanding of spontaneous symmetry breaking has made possible the consistent application of the gauge principle to the weak interactions. This led to the successful predictions of W^\pm and Z^0 properties, and suggested a possible origin of fermion masses and mixing angles.

In the minimal electroweak model, the spontaneous symmetry breaking is set by the vacuum expectation value of the Higgs field,

$$\langle \phi \rangle_0 = (G_F \sqrt{8})^{-1/2} \approx 175 \text{ GeV} \quad . \quad (2)$$

Although the minimal model has given us impressive successes, it has obvious shortcomings: it is not predictive enough. The theory has many (>20) seemingly arbitrary parameters. Although the interactions of the scalars are consistent with local gauge invariance, the Yukawa couplings are not fixed by local gauge invariance. Field theories involving elementary scalars are viewed by many with mistrust because of the quadratically divergent mass shifts that arise. Finally, the mass of the Higgs boson, which is the physical relic of spontaneous symmetry breaking is a free parameter of the theory — unlike the masses of the W and Z intermediate bosons.

Self-consistency of the theory does impose some constraints on the Higgs boson mass. A lower bound¹² of

$$M_H \geq 7 \text{ GeV}/c^2 \quad (3)$$

arises from the requirement that the minimum of the Higgs potential occur for $\langle \phi \rangle_0 \neq 0$, not only classically but also in the presence of the first-order quantum corrections. An upper bound,

$$M_H \leq 1 \text{ TeV}/c^2 \quad (4)$$

has been deduced¹³ by demanding that partial-wave unitarity be respected in tree approximation for gauge boson scattering. If this condition is not met, the weak interactions will become strong at energies of about 1 TeV.

Since the properties of the Higgs scalar are so loosely prescribed in the theory, it is natural to ask whether the existence of the Higgs scalar is unavoidable. The answer is that something very like the Higgs boson is required to make the amplitudes for the reaction

$$e^+ e^- \rightarrow W^+ W^- \quad (5)$$

finite. This reaction is described, in lowest order in the Weinberg-Salam theory, by the four Feynman graphs in Fig. 1. The leading divergence in the p-wave amplitude of the neutrino-exchange diagram Fig. 1(a) is canceled by the contributions of the direct-channel γ - and Z^0 -exchange diagrams of Fig. 1(b) and (c). This is not the whole story, however. The s-wave scattering amplitude, which exists in this case because the electrons are massive and may therefore be found in the "wrong" helicity state, grows as \sqrt{s} for the production of longitudinally polarized gauge bosons. This residual divergence is precisely canceled by the Higgs boson graph of Fig. 1(d). If the Higgs boson did not exist, we should have to invent something very much like it. From the point of view of divergence cancellations in S-matrix theory, the $Hf\bar{f}$ coupling must be proportional to m_f because "wrong helicity" amplitudes are always proportional to m_f .

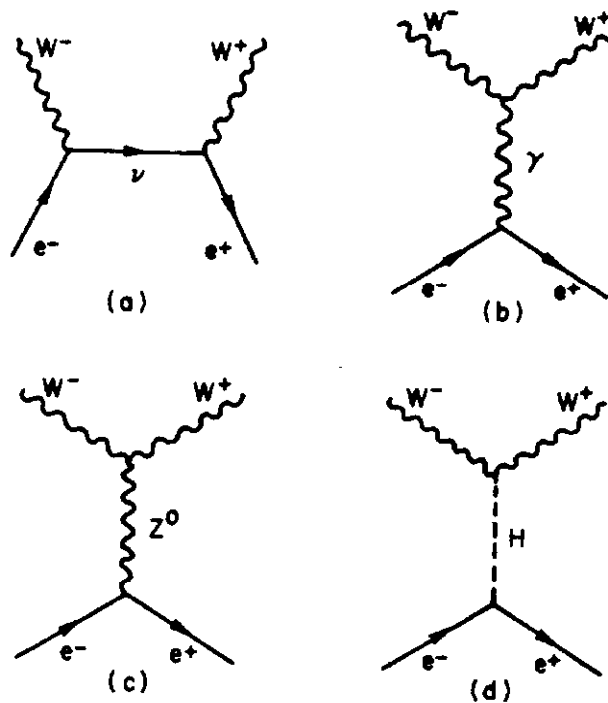


Fig. 1. Lowest-order contributions to the reaction $e^+e^- \rightarrow W^+W^-$, in the Weinberg-Salam model.

ALTERNATIVES TO THE MINIMAL MODEL

It is clearly of interest to seek ways of making the electroweak theory more complete and less arbitrary. One such approach is motivated by the observation that the Higgs sector of the standard model is the analog of the order parameter of the Ginzburg-Landau description of superconductivity.¹⁴ The Bardeen-Cooper-Schrieffer theory¹⁵ identifies the phenomenological order parameter with the density of Cooper pairs of electrons. In a similar fashion, it is appealing to identify the Higgs scalar as a composite of new elementary fermions. By solving the dynamics of the (new) interaction among these new constituents, it is hoped, one may calculate the properties of the Higgs scalar and reduce or eliminate the arbitrariness of the theory. Realizations of the dynamical symmetry breaking idea in particle physics are known as technicolor models.¹⁶ In the most realistic of these, there are many bound states with different quantum numbers. Many of these techniparticles, as they are called, occur in the mass regime around a few hundred GeV/c^2 .

A variant of this approach consists in relying upon strong interactions among the gauge bosons themselves to generate a low-mass Higgs scalar as a bound state. Setting aside some cart-before-horse questions, we can realize this scenario by considering the standard model with $M_H > 1 \text{ TeV}/c^2$. In some sense, the limit $M_H \rightarrow \infty$ corresponds to a theory without an elementary scalar. The strongly-interacting longitudinal components of the gauge bosons may form scalar WW and ZZ bound states, and additional p-wave WW and WZ bound states. The latter, with masses on the order of a few hundred GeV/c^2 , might be produced by mixing with the elementary W and Z.¹⁷

Unified theories of the strong, weak, and electromagnetic interactions represent another avenue for going beyond the standard electroweak theory. The simplest example of these theories is the SU(5) model proposed by Georgi and Glashow.¹⁸ Any such theory will display a more complicated pattern of symmetry breaking than the minimal electroweak theory. In the SU(5) model there are two scales of symmetry breaking: the electroweak scale of $\sim 1 \text{ TeV}$, and the unification scale of $\sim 10^{12} \text{ TeV}$. It is a challenge to sustain two such different mass scales in spontaneously broken theories. Although unified theories bring together quarks and leptons and place the strong, weak, and electromagnetic interactions on a common basis, the number of arbitrary parameters is no less than for the separate theories of quantum chromodynamics and the standard electroweak theory.

Still another approach to the problem of the scalar sector makes use of the fermion-boson symmetry known as supersymmetry.¹⁹ It is hoped that by relating particles of spin 1, spin 1/2, and spin 0, one will reduce the ambiguity of the standard model. Supersymmetry also eliminates the quadratic divergences that plague scalar field theories, and so makes more plausible a theory with elementary Higgs bosons. The price extracted for these services is a doubling of the particle spectrum, by the requirement that each known particle have a superpartner with spin differing by 1/2 unit. This implies the existence of many new particles at masses $\leq 1 \text{ TeV}/c^2$, if supersymmetry is to be the solution to the problem of electroweak symmetry breaking.

In this brief review, we have seen that both general arguments such as unitarity constraints and specific conjectures for improving or completing the standard electroweak model imply 1 TeV as an energy scale on which new phenomena crucial to our understanding of the fundamental interactions must occur. It is worth noting that simple unitarity arguments have provided reliable guidance before. The violation of partial-wave unitarity in the reaction

$$\nu_\mu e \rightarrow \mu \nu_e \quad (6)$$

in the old four-fermion theory at $\sqrt{s} = 600 \text{ GeV}$ approximately suggests the scale of the intermediate boson masses and the related vacuum expectation value of the Higgs field, $\langle \phi \rangle_0$. The region between 1/2 TeV and 2 TeV is a landmark in all models which defines the frontier of our ignorance.

The need to explore the 1 TeV scale is a primary motivation for the new hadron colliders now under consideration: the Superconducting Super Collider, or SSC, a machine of about 40 TeV in the United States; and the Large Hadron Collider, or LHC, which could be installed in the 27 km LEP tunnel at CERN and attain a c.m. energy of 1.6 TeV/Tesla.

SUPERCOLLIDER PHYSICS

To contribute to an understanding of what are the attributes of a desirable machine to explore the 1 TeV scale, Estia Eichten, Ian Hinchliffe, Ken Lane and I have undertaken a comprehensive study²⁰ of physics prospects for a supercollider. We have had three principal objectives. The first of these was to set out the conventional physics possibilities in some detail. These are required as we begin to make choices of energy, luminosity, and beams (pp vs. pp) for the SSC. They also provide a measure of the background rates for new or unexpected physics. Our second goal was to determine the discovery reach of a supercollider by considering a variety of new physics possibilities, and thereby to provide a reference point for the design of detectors and experiments. Finally, we have attempted to identify areas in which additional work is needed.

The following topics are discussed at considerable length in our paper:

- Parton Distributions
- Hadron jets - hard scattering
- Standard Electroweak Theory
- Minimal extensions of the standard model
- Technicolor
- Supersymmetry
- Quark and lepton compositeness.

These are representative of the hard-scattering phenomena that make the most stringent demands upon machine performance. We have not addressed the low transverse momentum phenomena known as "log s physics," nor have we considered the physics interest of quark-gluon plasma. We have also omitted any discussion of fixed-target physics with multi-TeV beams, for which the opportunities and concerns are rather different. We have not developed detailed Monte Carlo simulations of new and old physics processes.

Today I can give only a quick survey of our calculations and findings. I shall first discuss what we have done to develop reliable parton distributions, and then deal very briefly with a few physics topics. These will include the opportunities for detailed study of intermediate bosons, the search for additional intermediate bosons, the search for the Higgs boson of the standard model, and some manifestations of technicolor. The examples are chosen as much to illustrate the style of analysis we have carried out as to give prominence to specific collider capabilities.

PARTON DISTRIBUTION FUNCTIONS

The essence of the parton model²¹ is to regard a high-energy proton as a collection of quasifree partons which share its momentum. Thus we envisage a proton of momentum P as being made up of partons carrying longitudinal momenta $x_i P$, where the momentum fractions x_i satisfy

$$0 \leq x_i \leq 1 \quad (7)$$

and

$$\sum_{\text{partons } i} x_i = 1 \quad (8)$$

We make the idealization that the partons carry negligible transverse momentum.

The prototype hadron-hadron reaction is depicted in Fig. 2. The cross section for the hadronic reaction

$$a + b \rightarrow c + \text{anything} \quad (9)$$

is given by

$$d\sigma(a+b \rightarrow c+x) = \sum_{ij} f_i^{(a)}(x_a) f_j^{(b)}(x_b) d\hat{\sigma}(ij \rightarrow c+x') \quad (10)$$

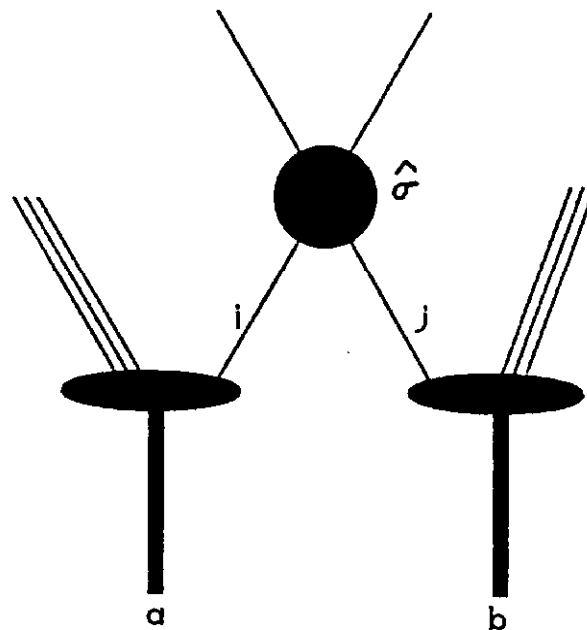


Fig. 2. Parton-model representation of a hadron-hadron reaction.

where $f_i^{(a)}(x_a)$ is the number distribution of partons of species i in hadron a . The summation runs over all contributing parton configurations. If we denote the invariant mass of the $i+j$ system as

$$\sqrt{s} = \sqrt{s\tau} \quad , \quad (11)$$

and its longitudinal momentum in the hadron-hadron c.m. by

$$p = x\sqrt{s}/2 \quad , \quad (12)$$

then the kinematic variables x_a, x_b of the elementary process are related to those of the hadronic process by

$$x_{a,b} = \frac{1}{2}[(x^2 + 4\tau)^{1/2} \pm x] \quad . \quad (13)$$

These parton momentum fractions satisfy the obvious requirements

$$x_a x_b = \tau \quad , \quad (14)$$

$$x_a - x_b = x \quad . \quad (15)$$

The elementary parton model sketched here is, at best, an approximation to reality. For the study of supercollider phenomena, the most important modification to the elementary picture is due to the strong-interaction (QCD) corrections to the parton distributions. To first approximation, these corrections are process-independent, and can be incorporated by the replacement

$$f_i^{(a)}(x_a) \rightarrow f_i^{(a)}(x_a, Q^2) \quad , \quad (16)$$

where the scale Q^2 on which the distributions are probed depends on the reaction under study. It is typically on the order of the subenergy

$$Q^2 \approx s \quad (17)$$

for the parton subprocess of interest. The typical momentum fraction contributing to such a process will be

$$\langle x \rangle \approx \sqrt{s/\tau} \quad . \quad (18)$$

For applications to processes with

$$(10 \text{ GeV})^2 \leq s \leq (10 \text{ TeV})^2 \quad (19)$$

at collider energies \sqrt{s} from 10 to 100 TeV, we require reliable parton distributions for

$$x \geq 10^{-4} \tag{20}$$

and

$$Q^2 \leq 10^8 \text{ GeV}^2 \tag{21}$$

Extensive measurements of the cross sections for deeply inelastic scattering of electrons, muons, and neutrinos from nucleons have made it possible to determine the parton distributions at modest values of Q^2 . When evolved to larger Q^2 according to the behavior prescribed by QCD, these yield parton distributions at any desired value of Q^2 . Many sets of distributions are available in the literature, but nearly all are inadequate for supercollider applications. Most are given in the form of parametrizations valid over limited ranges in Q^2 . As an example, we show in Fig. 3 the Q^2 -evolution of the gluon distribution $xG(x, Q^2)$ given by Baier, et al.,²² which behaves unreasonably for $Q^2 > 10^3 \text{ GeV}^2$. For large- Q^2 applications, we need heavy quark (c,b,t) distributions in the proton. These have been negligible at the values of Q^2 relevant for parametrizations in the literature. In addition, some of the well-known distributions violate number or momentum sum rules, or

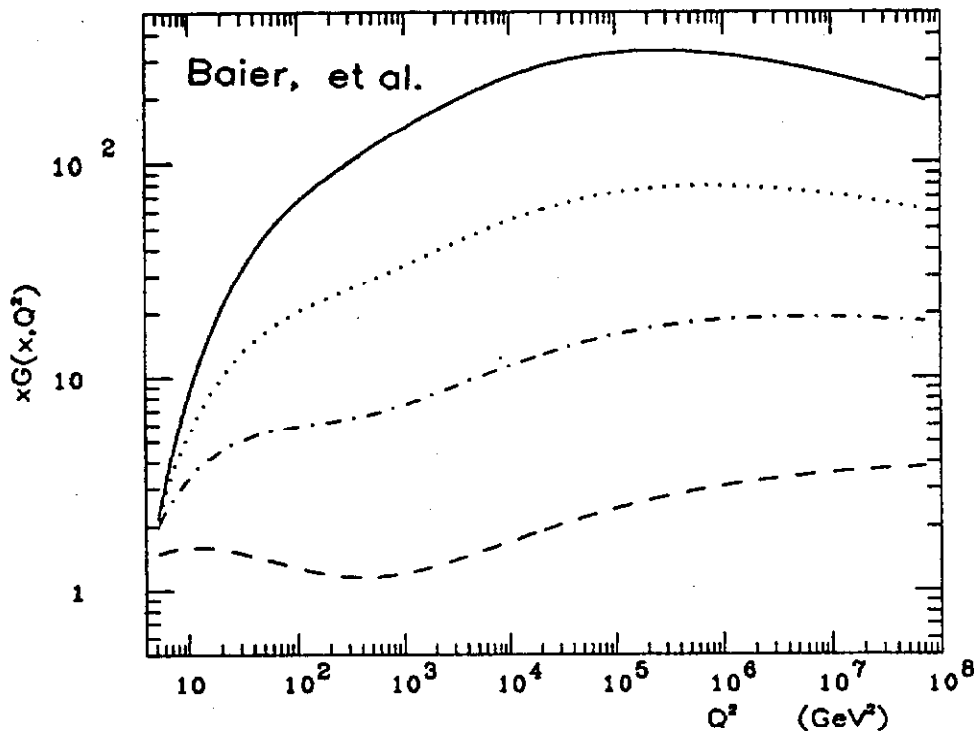


Fig. 3. Q^2 evolution of the gluon distribution $xG(x, Q^2)$ of Baier, Engels, and Petersson, Ref. 22: $x = 10^{-4}$ (solid line), 10^{-3} (dotted line), 10^{-2} (dotted-dashed line), 0.1 (dashed line).

fail to describe the ratio of u- and d-quarks. Finally, we wanted to pay particular attention to the reliability of parton distributions at small values of x ($x \leq 0.01$), where the structure functions are essentially unmeasured.

Our procedures are fully described in Ref. 20. As a measure of the reasonableness of the results, I show in Fig. 4 the Q^2 -evolution of $xG(x, Q^2)$ for one of the two sets of EHLQ structure functions. There we see the characteristic QCD evolution: a decrease of the structure function at large x , and a corresponding growth at small values of x .

A good measure of collider capabilities is the differential luminosity

$$\tau \frac{d\mathcal{L}}{d\tau} = \frac{\tau}{(1+\delta_{ij})} \int_{\tau}^1 dx [f_i^{(a)}(x, \hat{s}) f_j^{(b)}(\tau/x, \hat{s}) + i \leftrightarrow j] \quad , \quad (22)$$

which is proportional to the number of parton-parton collisions at c.m. energy $\sqrt{\hat{s}}$ per hadron-hadron collision at c.m. energy \sqrt{s} . Because elementary hard-scattering cross sections are of the form

$$\sigma = \frac{C}{\hat{s}} \quad , \quad (23)$$

the quantity $(\tau/\hat{s})d\mathcal{L}/d\tau$, which has the dimensions of a cross section, is particularly convenient for assessing in a general way the relative merits of different hadron energies, beams, and

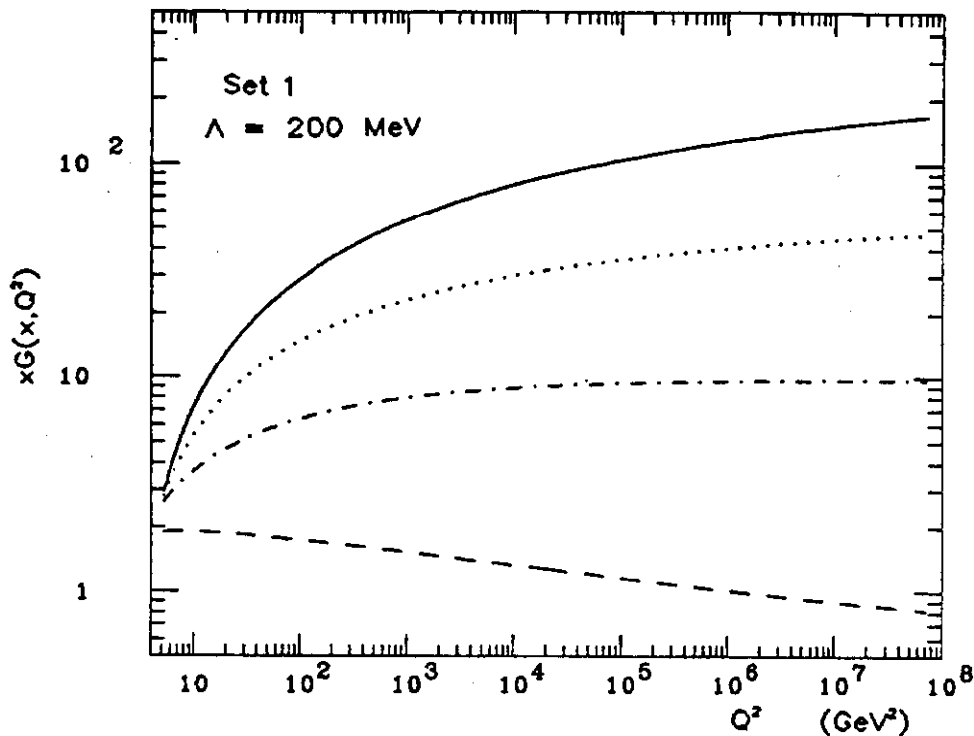


Fig. 4. Q^2 evolution of the gluon distribution $xG(x, Q^2)$ of Set 1 of EHLQ structure functions (Ref. 20). Same x values as Fig. 3.

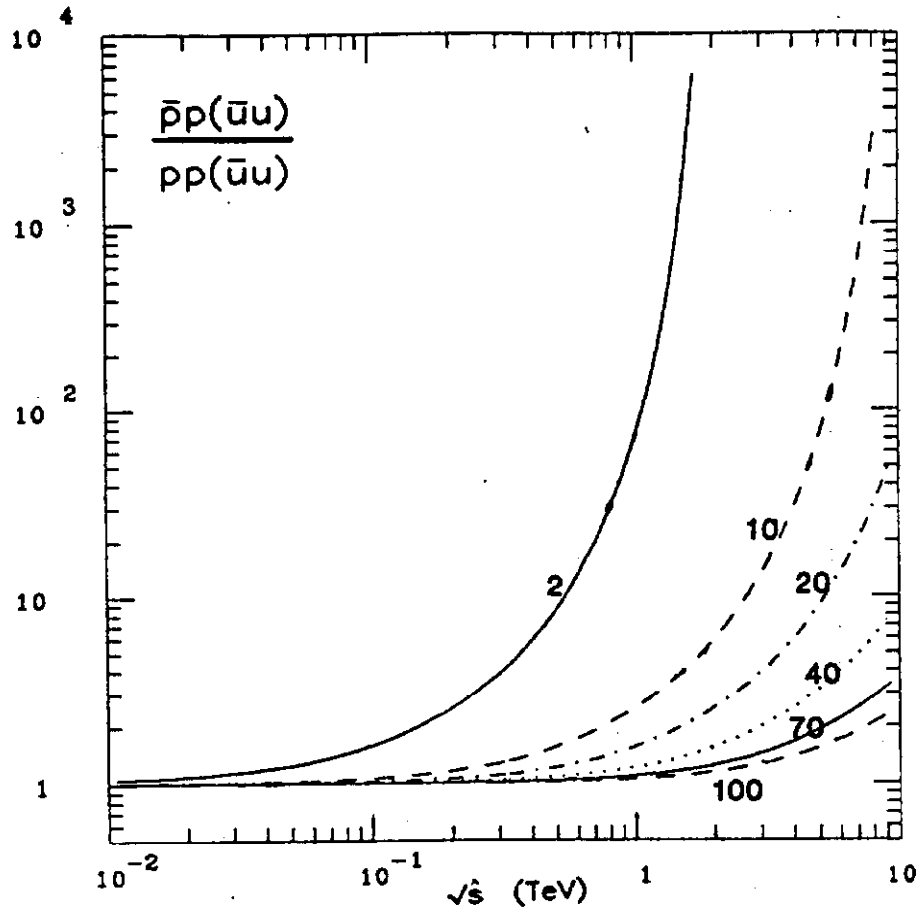


Fig. 5. Ratio of $(\tau/s)d\mathcal{L}/d\tau$ for $u\bar{u}$ interactions in $\bar{p}p$ and pp collisions, according to the parton distributions of Set 2 of EHLQ structure functions (Ref. 20). Collider energies \sqrt{s} are given in TeV.

luminosities. As one example, I show in Fig. 5 the ratio of $(\tau/s)d\mathcal{L}/d\tau$ for $u\bar{u}$ interactions in $\bar{p}p$ and pp collisions. Roughly speaking, the advantage of $\bar{p}p$ over pp collisions in this channel becomes appreciable for $\sqrt{\tau} = \sqrt{s}/s \geq 0.1$. Whether this advantage at large values of $\sqrt{\tau}$ can be exploited depends upon the event rate determined by cross section and luminosity.

To test our parton distributions and the reliability of the parton model, we compare in Fig. 6 the QCD prediction with recent measurements^{23,24} of large transverse momentum jets produced at 90° in the reaction

$$\bar{p}p \rightarrow \text{jet} + \text{anything} \quad (24)$$

at the CERN $S\bar{p}pS$ Collider. The errors plotted in Fig. 6 are statistical only. For the UA-1 data there is in addition a $\pm 7.5\%$ uncertainty in the p_\perp scale which has the effect of an overall normalization uncertainty of a factor of $(1.5)^{\pm 1}$. The overall

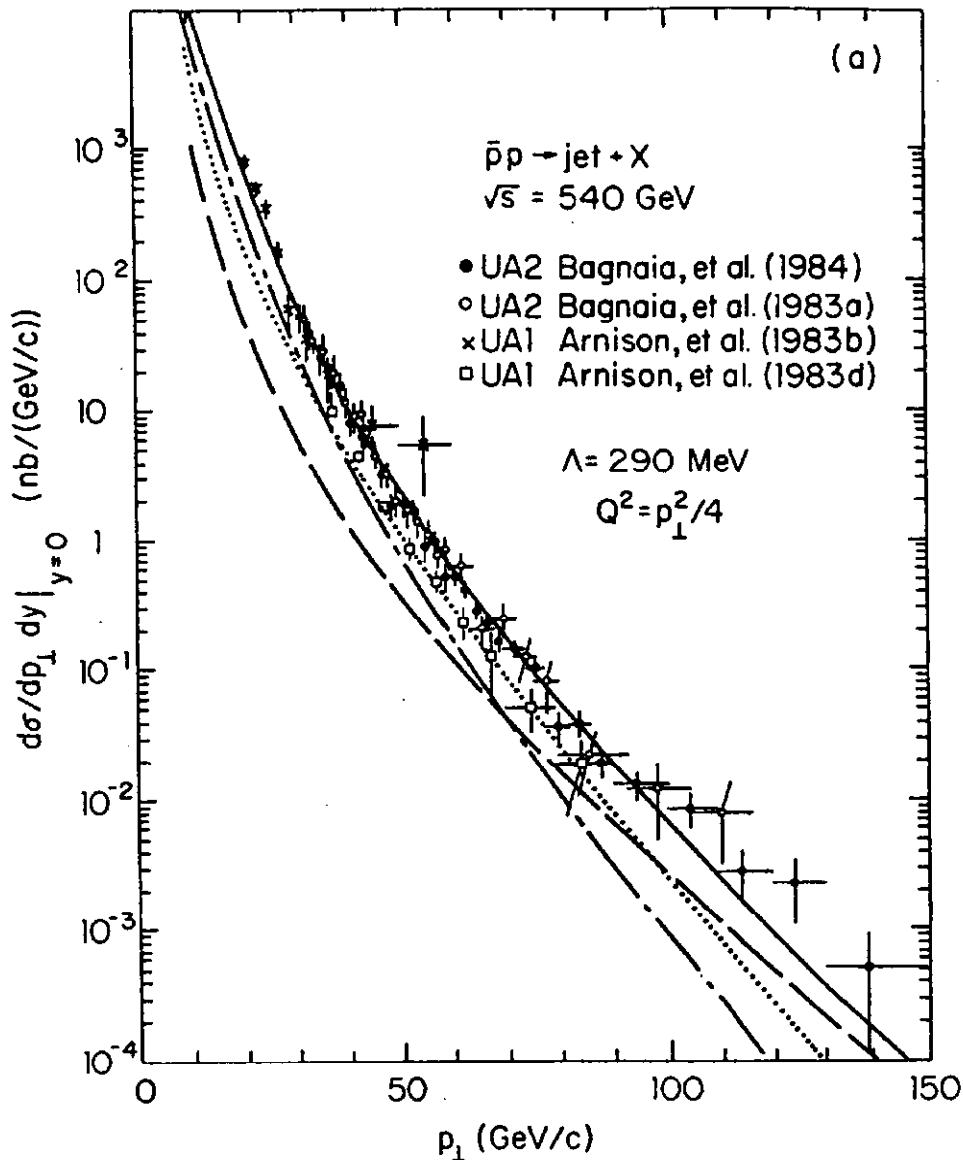


Fig. 6. Differential cross section for jet production at $y=0$ (90° c.m.) in $\bar{p}p$ collisions at 540 GeV, according to the parton distributions of Set 2 of Ref. 20. The data are from Arnison, et al. (Ref. 23) and Bagnaia, et al. (Ref. 24).

additional systematic uncertainty in the UA-2 data is $\pm 40\%$. The precise agreement between the data and our calculation is thus better than one has a right to expect.

Another interesting observable is the distribution of two-jet invariant masses M in the reaction

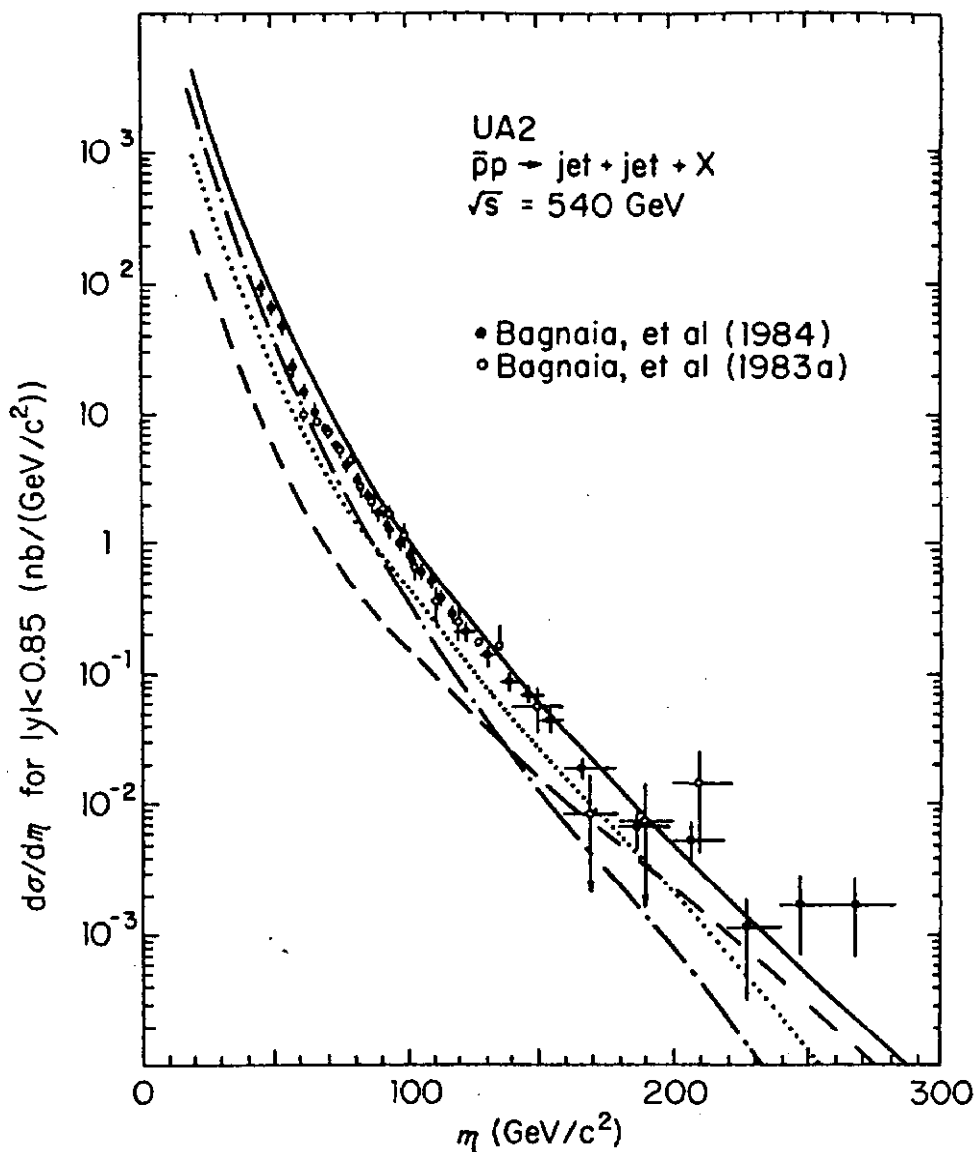


Fig. 7. Invariant mass spectrum for two-jet events produced in proton-antiproton collisions at $\sqrt{s} = 540$ GeV, according to the parton distributions of Set 1 of Ref. 20. Both jets must satisfy $|y_1| < 0.85$. The data are from Bagnaia, *et al.* (Ref. 24); errors are statistical only.

$$\bar{p}p \rightarrow \text{jet}_1 + \text{jet}_2 + \text{anything} \quad . \quad (25)$$

The invariant mass distribution $d\sigma/dm$ for jets produced with rapidities $|y_1|, |y_2| < 0.85$ is shown in Fig. 7. Again the UA-2 measurements²⁴ are in good agreement with the QCD prediction. We regard this as reassuring for our parton distributions in particular and for the parton model approach in general.

SUPERCOLLIDER PHENOMENA IN THE STANDARD ELECTROWEAK MODEL

The principal standard model issues to be addressed with a multi-TeV hadron collider are these:

- The rate of W^\pm and Z^0 production. This is chiefly of interest for investigations of the production mechanism itself and for the study of rare decays of the intermediate bosons. We expect that by the time supercollider comes into operation more basic measurements, such as precise determinations of the masses and widths of the intermediate bosons, will have been accomplished.
- The cross sections for pair production of gauge bosons. These are sensitive to the structure of the trilinear couplings among gauge bosons, and must be understood as potential backgrounds to the observation of heavy Higgs bosons, composite scalars, and other novel phenomena.
- The Higgs boson itself. In the standard electroweak model, this is the lone boson remaining to be found. Elucidating the structure of the Higgs sector is one of the fundamental goals of experimentation in the TeV regime.

In this brief tour, we shall touch briefly on each of these points.

The integrated cross sections for W^+ and W^- production in pp collisions are shown in Fig. 8 as functions of the c.m. energy \sqrt{s} . Also shown are the cross sections for production of W^\pm in the rapidity interval $-1.5 < y < 1.5$. The number of intermediate bosons produced at a high luminosity supercollider is impressively large. At a c.m. energy of 40 TeV, for example, a run with an integrated luminosity of 10^{40} cm^{-2} would yield approximately 6×10^8 Z^0 's and 2×10^9 W^\pm 's. For comparison, at a high luminosity Z^0 factory such as LEP ($\mathcal{L} \approx 2 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$) the number of Z^0 's expected in a year of running is approximately 10^7 . There is no competitive source of charged intermediate bosons.

The angular distribution of the produced W's is of great importance for the design of experiments. At supercollider energies, many intermediate bosons will be produced within a narrow cone about the beam direction.

Special-purpose detectors deployed near the forward direction may have significant advantages for the study of rare decays. This point is illustrated by the rapidity distribution $d\sigma/dy$ for W^+ production in proton-proton collisions at 40 TeV, shown in Fig. 9. The mapping from rapidity to c.m. angles is given in Fig. 10. In a machine with an average luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, there will be a flux of approximately 10 W^+ /second emitted within 2° of the beam direction, in each hemisphere.

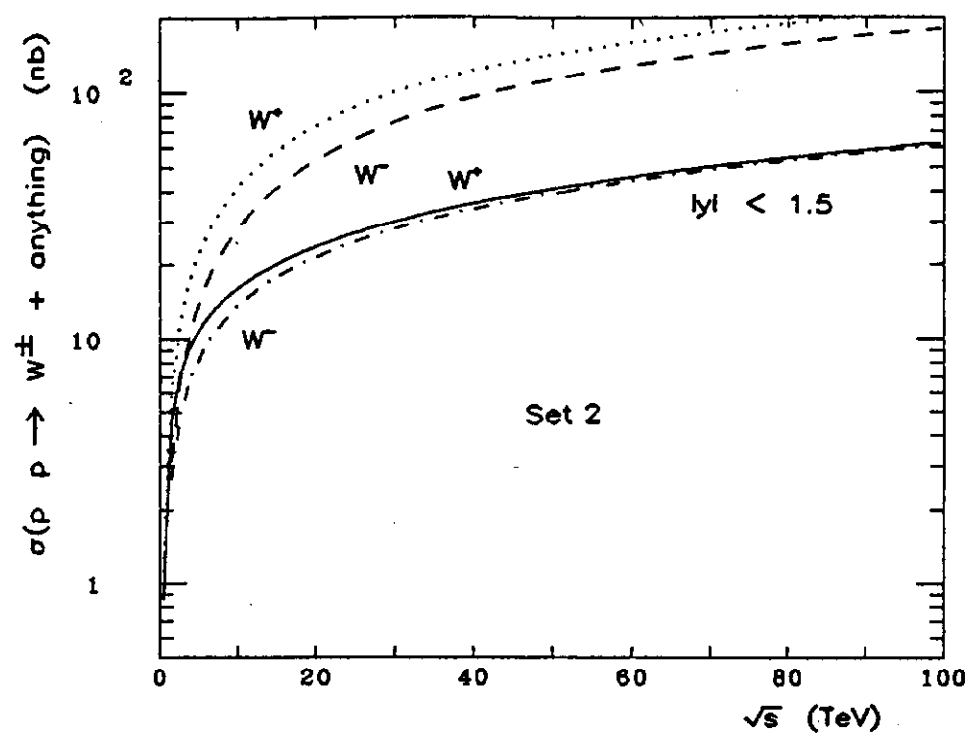


Fig. 8. Cross sections for W^\pm production in pp collisions in the Drell-Yan picture. Also shown are the cross sections for W^\pm produced in the rapidity interval $-1.5 < y < +1.5$. Set 2 of parton distributions of Ref. 20 was used.

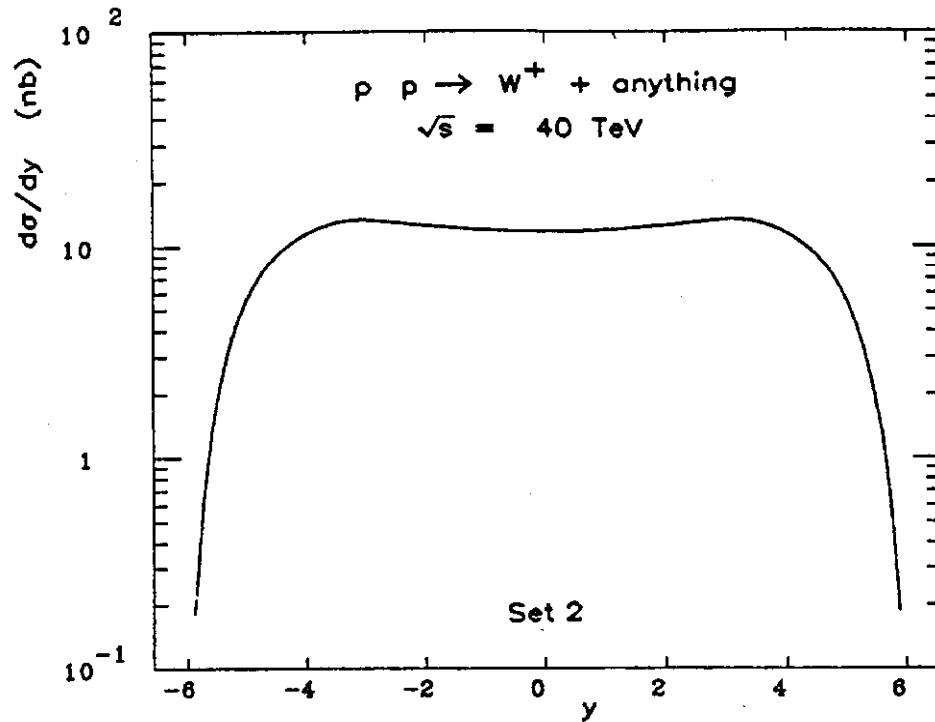


Fig. 9. Rapidity distribution for W^+ produced in pp collisions at $\sqrt{s} = 40$ TeV, according to Set 2 of the parton distributions of Ref. 20.

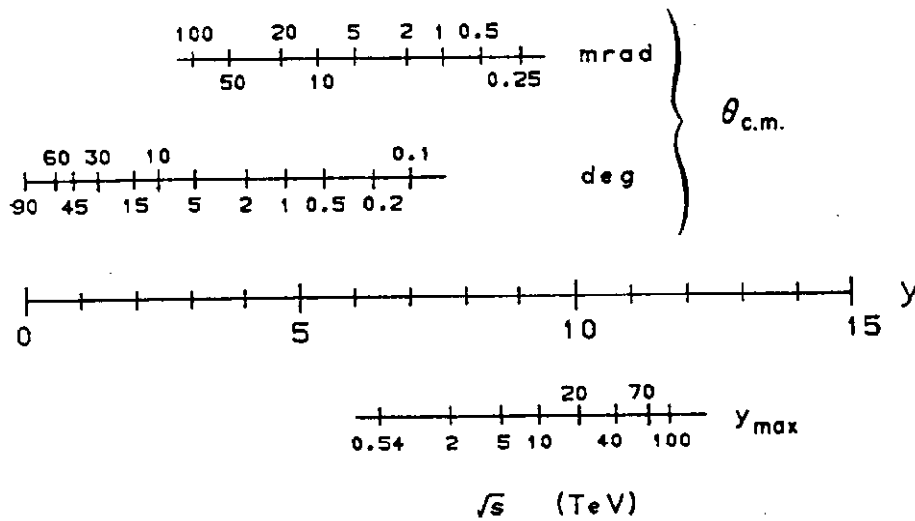


Fig. 10. Correspondence of angles to the c.m. rapidity scale used in Fig. 9. Also shown in the maximum rapidity, $y_{\max} = \ln(\sqrt{s}/M_{\text{proton}})$ accessible for light secondaries.

Incisive tests of the structure of the electroweak interactions may be achieved in detailed measurements of the cross sections for the production of W^+W^- , $W^\pm Z^0$, $Z^0 Z^0$, $W^\pm \gamma$ and $Z^0 \gamma$ pairs. The rate for $W^\pm \gamma$ production is sensitive to the magnetic moment of the intermediate boson. In the standard model there are important cancellations in the amplitudes for W^+W^- and $W^\pm Z^0$ production which rely on the gauge structure of the WWZ trilinear coupling. The $Z^0 Z^0$ and $Z^0 \gamma$ reactions do not probe trilinear couplings in the standard model, but are sensitive to nonstandard interactions such as, might arise if the gauge bosons were composite. In addition, the W^+W^- and $Z^0 Z^0$ final states may be significant backgrounds to the detection of heavy Higgs bosons and possible new degrees of freedom.

The Feynman diagrams for the process

$$q_i \bar{q}_i \rightarrow W^+ W^- \quad (26)$$

are shown in Fig. 11. The intrinsic interest in this process, which accounts in part for plans to study e^+e^- annihilations at c.m. energies around 180 GeV at LEP, is owed to the sensitivity of the cross section to the interplay among the γ -, Z^0 , and quark-exchange contributions. As is well known, in the absence of the Z^0 -exchange

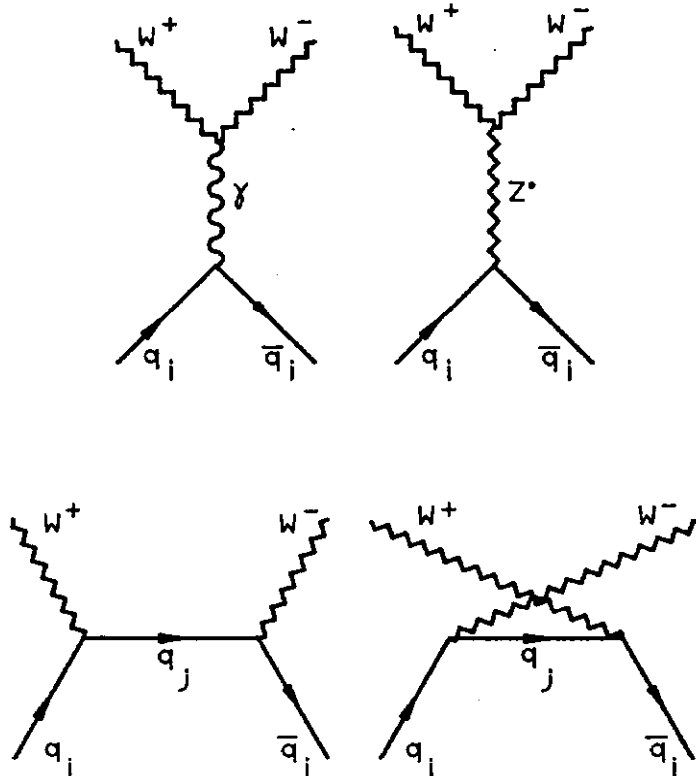


Fig. 11. Lowest-order Feynman diagrams for the reaction $q_i \bar{q}_i \rightarrow W^+ W^-$. A direct-channel Higgs boson diagram vanishes because the quarks are idealized as massless.

term, the cross section for production of a pair of longitudinally polarized intermediate bosons is proportional to s , in gross violation of unitarity. It is important to verify that the amplitude is damped as expected.

The mass spectrum of W^+W^- pairs is of interest both for the verification of gauge cancellations and for the assessment of backgrounds to heavy Higgs boson decays. This is shown for intermediate bosons satisfying $|y| < 2.5$ in Fig. 12. The number of pairs produced at high energies seems adequate for a test of the gauge cancellations, provided that the intermediate bosons can be detected with reasonable efficiency,

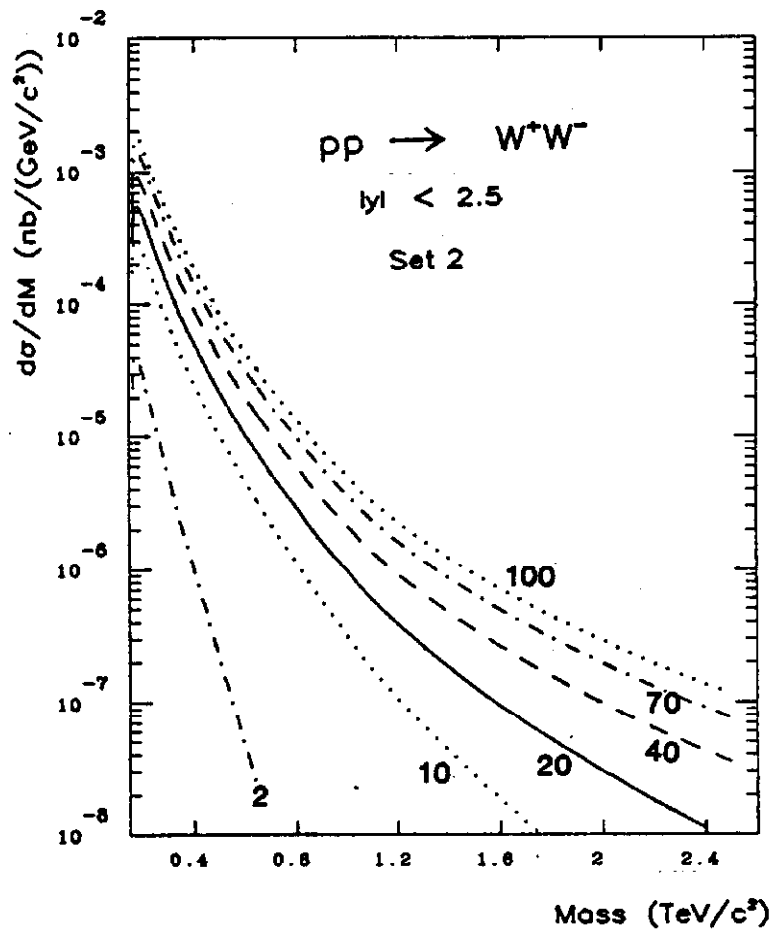


Fig. 12. Mass spectrum of W^+W^- pairs produced in pp collisions, according to the parton distributions of Set 2 from Ref. 20. Both W^+ and W^- must satisfy $|y| < 2.5$.

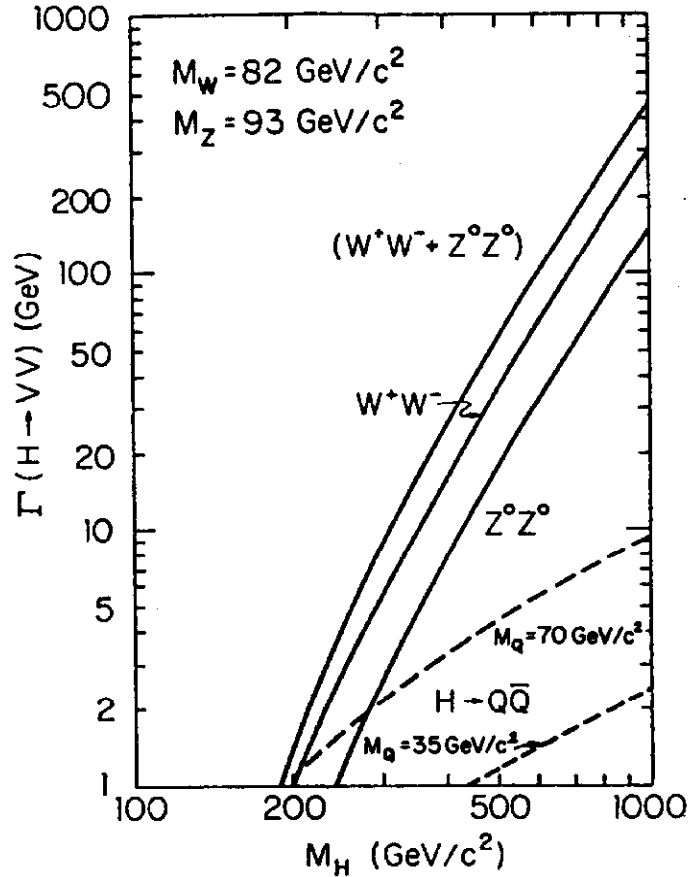


Fig. 13. Partial decay widths of the Higgs boson into intermediate boson pairs vs. the Higgs-boson mass. For this illustration we have taken $M_W = 82 \text{ GeV}/c^2$ and $M_Z = 93 \text{ GeV}/c^2$.

A Higgs boson with $M_H > 2M_W$ has the striking property that it will decay into pairs of gauge bosons. The resulting partial decay widths are shown in Fig. 13, where the partial widths for the decay $H \rightarrow Q\bar{Q}$ are also shown for heavy quark masses of 30 and 70 GeV/c^2 . The decay into pairs of intermediate bosons is dominant. If the perturbatively estimated width can be trusted, it may be difficult to establish a Higgs boson heavier than about 600 GeV/c^2 .

The most promising mechanisms for Higgs boson production are the gluon fusion process indicated in Fig. 14 and the intermediate boson fusion process depicted in Fig. 15. The rate for gluon fusion is sensitive to the masses of the quarks circulating in the loop in Fig. 14, and particularly to the top quark mass. I show in Fig. 16 the cross section for W^+W^- pairs arising in the process

$$pp \rightarrow H + \text{anything} \quad (27)$$

$$\quad \quad \quad \downarrow$$

$$\quad \quad \quad W^+W^-$$

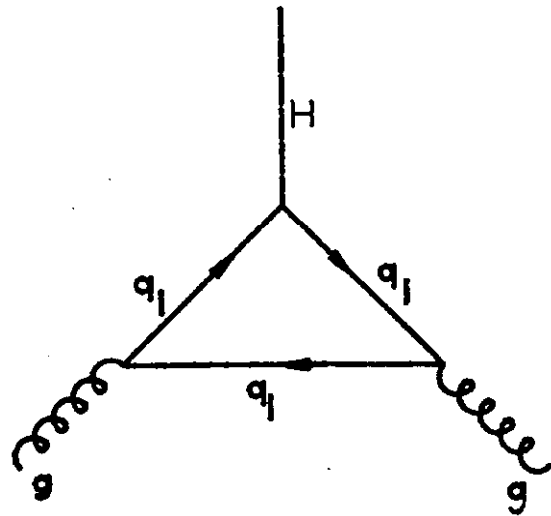


Fig. 14. Feynman diagram for the production of a Higgs boson in gluon-gluon fusion.

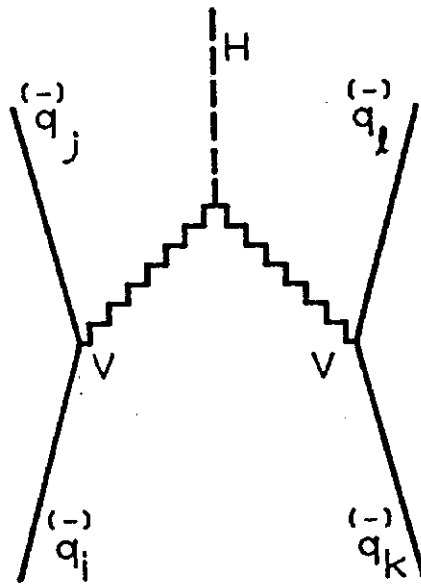


Fig. 15. Intermediate-boson fusion mechanism for Higgs-boson formation.

at $\sqrt{s} = 40$ TeV, as a function of the Higgs boson mass. The rapidity of the W^+ and W^- are restricted to the interval $|y| < 2.5$, and the example is for $m_t = 30$ GeV/c². The contributions from gluon fusion and intermediate t boson fusion are shown separately.

Assuming that the W 's can be identified, the background comes from W pair production. We have estimated this background by taking $d\sigma/dM$ for W -pair production with $|y_W| < 2.5$ (Fig. 12), and multiplying by the greater of 10 GeV and the Higgs boson width (Fig. 13). The signal exceeds the background for $M_H < 630$ GeV/c².

From these sorts of comparisons of expected signal and background we can draw the following lessons. First, the rates are reasonably large, even for $m_t = 30$ GeV/c², if the W^{\pm} can be observed with high efficiency. If both W 's must be detected in their

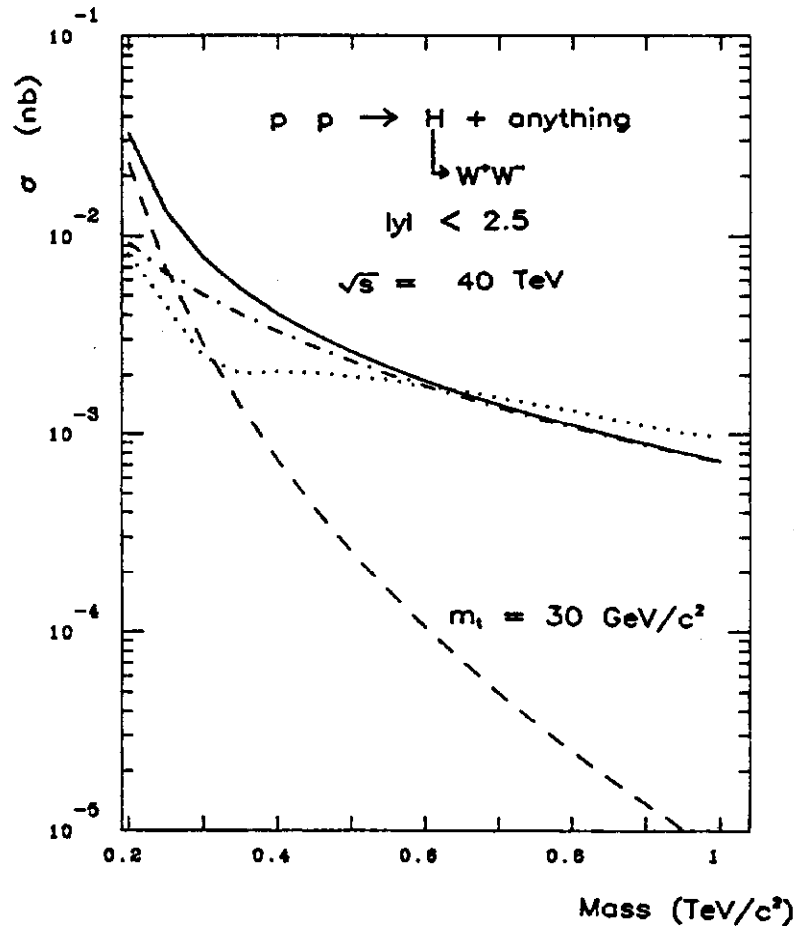


Fig. 16. Cross section for the reaction $pp \rightarrow (H \rightarrow W^+W^-) + \text{anything}$, with $m_t = 30$ GeV/c², according to the parton distributions of Set 2 of Ref. ^t20, for $\sqrt{s} = 40$ TeV. The intermediate bosons must satisfy $|y_W| < 2.5$. The contributions of gluon fusion [dashed line] and WW/ZZ fusion [dotted-dashed line] are shown separately. Also shown (dotted line) is $\Gamma_H d\sigma(pp \rightarrow W^+W^- + X)/dM$, with $|y_W| < 2.5$ and $M = M_H$. (See Fig. 12).

leptonic decays, the event rates will be down by two orders of magnitude. It is important to study the QCD four-jet background to the

$$\begin{array}{l}
 H \rightarrow W^+W^- \\
 \quad \swarrow \quad \searrow \\
 \quad \text{jet}_3 + \text{jet}_4 \\
 \quad \text{jet}_1 + \text{jet}_2
 \end{array}$$

final state. Second, the angular distributions are different for the isotropic $H \rightarrow VV$ decay and the forward-backward peaked $q\bar{q} \rightarrow W^+W^-$ reaction. Third, the rate for Higgs production in the Z^0Z^0 mode is one-half the W^+W^- rate, but the standard model background from the process $q\bar{q} \rightarrow Z^0Z^0$ is a factor of five to ten smaller than the corresponding W^+W^- rate. Although the $Z^0 \rightarrow \mu^+\mu^-$ channel may be easy to reconstruct, the price of detecting both Z's in the e^+e^- channel is about three orders of magnitude in rate.

NEW ELECTROWEAK GAUGE BOSONS

A number of proposals have been advanced for enlarging the electroweak gauge group beyond the $SU(2)_L \times U(1)_Y$ of the standard model. One class contains the "left-right symmetric" models based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_Y$, which restore parity invariance at high energies. Other models, notably the electroweak sector derived from the $SO(10)$ unified theory, exhibit additional $U(1)$ invariances. These will contain extra neutral gauge bosons.

All of these models have new gauge coupling constants which are of the order of the $SU(2)_L$ coupling constant of the standard model. They imply the existence of new gauge bosons with masses of a few hundred GeV/c^2 or more. In most interesting models, these new gauge bosons decay to the ordinary quarks and leptons, perhaps augmented by right-handed neutrinos. Roughly speaking, the decay rates of a W' will correspond to those of the familiar W , times $M_W/M_{W'}$. The heavier gauge bosons will therefore also be relatively narrow and prominent objects. To obtain a reasonable estimate of the cross sections for the production of additional W and Z bosons, we assume that the new bosons have the same gauge couplings to light leptons and quarks as do the known W^\pm and Z^0 , respectively.

We adopt as a discovery criterion the requirement that 1000 gauge bosons be produced in the rapidity interval $|y_{W'}| < 1.5$. This should be adequate to allow the establishment of a convincing signal in either the electron channel or the muon channel. The resulting "discovery limits" are shown in Fig. 17. The larger production rate for heavy gauge bosons in $\bar{p}p$ collisions makes itself apparent for integrated luminosities in excess of about 10^{39} cm^{-2} . For example, a 40 TeV $\bar{p}p$ collider can reach masses of 2.3, 4.1, and 6.5 TeV/c^2 for integrated luminosities of 10^{38} , 10^{39} , and 10^{40} cm^{-2} . A $\bar{p}p$ machine of the same energy can attain 2.4, 4.7, and 8.0 TeV/c^2 .

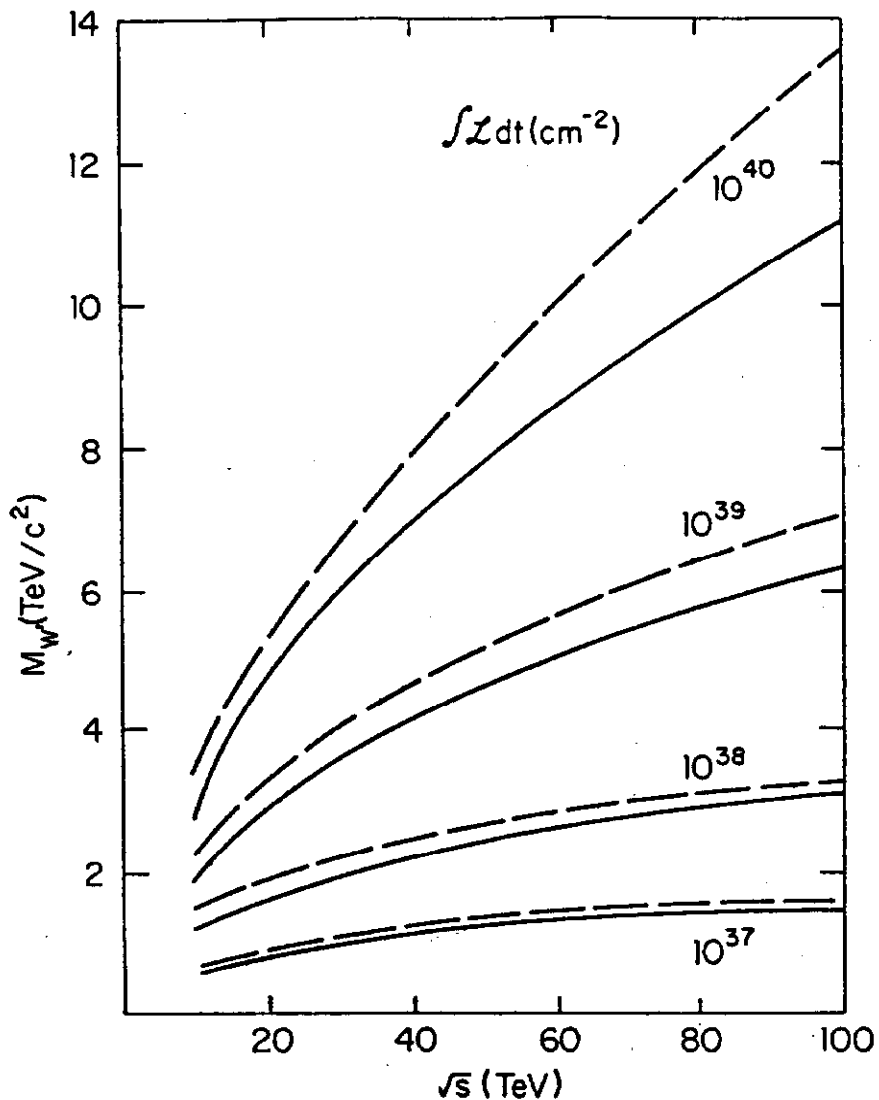


Fig. 17. Maximum mass of a new charged intermediate boson for which 10^3 events are produced with $|y_W| < 1.5$ at the stated integrated luminosities in proton-proton collisions (solid lines) and in proton-antiproton collisions (dashed lines).

TECHNICOLOR

We have already mentioned the idea that the Higgs boson might be replaced by a bound state of elementary fermions. The minimal, and unrealistic, example of this realization of dynamical symmetry breaking is based on the gauge symmetry

$$SU(4)_{\text{Technicolor}} \otimes SU(3)_{\text{Color}} \otimes SU(2)_L \otimes U(1)_Y \quad (28)$$

In addition to the usual quarks and leptons there is a chiral doublet of massless technifermions U and D which are assigned to the fundamental 4 representation of the technicolor group and are taken for simplicity to be color singlets. With these assignments the technicolor Lagrangian exhibits an exact chiral $SU(2)_L \times SU(2)_R$ symmetry. We suppose, in analogy with QCD, that at an energy scale of order $\Lambda_{TC} = O(1 \text{ TeV})$, the technicolor interactions become strong and the chiral symmetry is spontaneously broken down to (vector) $SU(2)$, the isospin group of the technifermions.

As a consequence of the spontaneous symmetry breaking, three Goldstone bosons appear. These are the massless technipions, $J^{PC} = 0^{-+}$ isovector states designated π_T^+ , π_T^0 , π_T^- .

If the technicolor scale Λ_{TC} is chosen so that the technipion decay constant is

$$F_\pi = (G_F \sqrt{2})^{-1/2} \quad , \quad (29)$$

then after the electroweak interaction is turned on, the W^\pm and Z^0 will acquire the canonical masses

$$M_W^2 = g^2 / 4G_F \sqrt{2} = \pi \alpha / G_F \sin^2 \theta_W \quad , \quad (30)$$

$$M_Z^2 = M_W^2 / \cos^2 \theta_W \quad . \quad (31)$$

The massless technipions disappear from the physical spectrum, having assumed the role of the longitudinal components of the intermediate bosons.

Knowing the spectrum of ordinary hadrons, and attributing its character to QCD, we may infer the remaining spectrum of technihadrons. It will include

- an isotopic triplet of $J^{PC} = 1^{--}$ technirhos, ρ_T^+ , ρ_T^0 , ρ_T^- , with $M(\rho_T) \approx O(1 \text{ TeV}/c^2)$;
- an isoscalar $J^{PC} = 1^{--}$ techniomega, ω_T , with $M(\omega_T) = O(1 \text{ TeV}/c^2)$;
- an isoscalar pseudoscalar technieta, η_T , with $M(\eta_T) = O(1 \text{ TeV}/c^2)$;
- an isoscalar $J^{PC} = 0^{++}$ technisigma, σ_T , with $M(\sigma_T) = O(1 \text{ TeV}/c^2)$,

plus other massive scalars, axial vectors, and tensors. The σ_T is the analog of the physical Higgs scalar in the Weinberg-Salam model. In addition to these ($\bar{T}T$) technimesons, there will be a rich spectrum of (T^*T^*) technibaryons. Some of these might well be stable against decay, within technicolor.

The mass of the technirho can be estimated in this model at about $1.77 \text{ GeV}/c^2$. The principal decay mode, with a (partial) width of about 325 GeV , is into a pair of technipions, which is to say

longitudinally polarized intermediate bosons. Because of the strong coupling of technirhos to pairs of intermediate bosons, the processes

$$q_1 \bar{q}_1 \rightarrow (\gamma \text{ or } Z^0) \rightarrow \rho_T^0 \rightarrow W_0^+ W_0^- \quad (32)$$

and

$$q_1 \bar{q}_j \rightarrow W^\pm \rightarrow \rho_T^\pm \rightarrow W_0^\pm Z_0^0 \quad , \quad (33)$$

will lead to substantial enhancements in the pair-production cross sections.

I show in Fig. 18 the mass spectrum of W^+W^- pairs produced in pp colliders at 20, 40, and 100 TeV, with and without the technirho enhancement. Both intermediate bosons are required to satisfy $|y| < 1.5$. The technirho enhancement amounts to nearly a doubling of the cross section in the resonance region. In more realistic technicolor models, the qualitative features are similar, but the technirho enhancement is generally moved to lower masses where the absolute rates are larger and convincing observations are easier. As in the earlier discussion of heavy Higgs bosons, a key remaining question is whether the 4-jet QCD background will compromise the detection of nonleptonic W and Z decays.

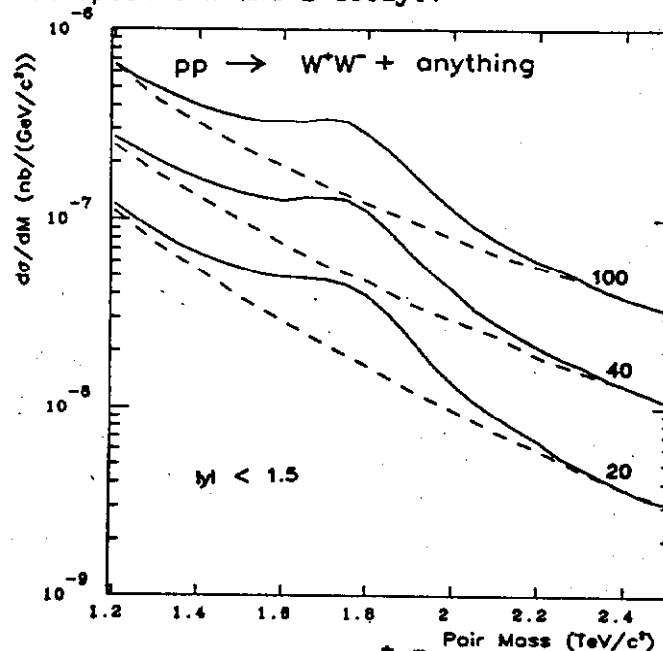


Fig. 18. Mass spectrum of W^+W^- pairs produced in pp collisions, according to the parton distributions of Set 2 of Ref. 20. Both W^+ and W^- must satisfy $|y| < 1.5$. The cross sections are shown with (solid lines) and without (dashed lines) the technirho enhancement.

CONCLUSIONS

The most important conclusion of the work reported in Ref. 20 is that a $p\bar{p}$ collider operating at a c.m. energy of tens of TeV with a luminosity of 10^{32} $\text{cm}^{-2} \text{sec}^{-1}$ or more will make possible a thorough exploration of the 1 TeV scale. We are confident that important clues toward a more complete understanding of the fundamental interactions are to be found on the scale of 1 TeV, and that a multi-TeV hadron supercollider will supply the means to reveal them.

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