New Phenomena and New Physics

Presented by R. Petronzio, CERN

No written contribution received.

Supercollider Physics

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1. Introduction

Amid all the talk at this Symposium about anomalies past and present, I have been deeply impressed with how far we have come -- by virtue of experiments at the CERN S$\bar{p}$pS Collider and elsewhere -- toward establishing the essential elements of the "standard model." In preparing this talk last night I reread one of my old papers[1] (an exercise guaranteed to produce humility) and was struck by how much was only speculation just a few years ago. In 1977, hadron production at large transverse momentum had been observed, but the idea of jet structure was seriously in question, and the connection to QCD was unclear. The Drell-Yan mechanism was still hypothetical, and the factorization of perturbative QCD cross sections had not been demonstrated. For that matter, the pattern of scaling violations in deeply inelastic scattering was not clearly established. The correctness of the Weinberg-Salam theory as a description of both charged-current and neutral-current phenomena was under experimental challenge. At a less lofty level, because the idea of $\bar{p}p$ colliders was itself a novelty, the charge asymmetry in $\bar{p}p \rightarrow W^{\pm} \rightarrow$ leptons was an exotic notion. Today, all of these ideas are firmly grounded in experimental reality, and serve as points of departure for more incisive analysis. The $W^{\pm}$ charge asymmetry itself has passed from the realm of exotica to a standard question in graduate student qualifying exams.

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†Operated by Universities Research Association under contract with the United States Department of Energy.

If we have come very far, we still have very far to go. For us in 1985, the success of the standard $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ model prompts new questions:

- Why does it work?
- Can it be complete?
- Where will it fail?

The standard model itself hints that the frontier of our ignorance lies at ~1 TeV for collisions among the fundamental constituents. In more general terms, the success of our theoretical framework suggests that a significant step beyond present-day energies is required, to see breakdowns of the theory.

Beyond these generalities, there are many specific issues to be faced. There is, for example, our incomplete understanding of electroweak symmetry breaking and the suggestion (from the "bound" $M_{Higgs} < 1\ \mathrm{TeV}/c^2$) that the 1 TeV scale will be crucial to a resolution of this problem. The Higgs mechanism provides a means for generating quark and lepton masses and mixing angles, but leaves the values as free parameters. We do not understand what CP violation means. The idea of quark-lepton generations is suggested by the necessity for anomaly cancellation in the electroweak theory, but the meaning of generations is unclear. We may even dare to ask what is the origin of the gauge symmetries themselves.

Such questions -- and this is but a partial list -- are stimulated by the standard model itself, and by our aspiration not only to describe the world as we find it, but also to understand why it is as it is.

What I shall have to say today is taken largely from the article by Eichten, Hinchliffe, Lane, and myself (EHLQ),[2] and from the many workshops on supercollider physics[3] held during the past year. I will try to stress some of the progress made since the publication of EHLQ.

The objectives of our work were to set out the conventional physics possibilities in some detail, to determine the discovery reach of supercolliders, and to identify areas in which more work is needed. The conventional possibilities are important because they are of interest in their own right, and because they provide backgrounds to new or unexpected physics. In assessing what can be explored with a new machine, we considered as examples several of the conventional exotic ideas: technicolor, supersymmetry, and compositeness. Our calculations are a starting point for considering questions of collider energy and luminosity, and the relative merits of pp and $\bar{p}p$ collisions. We hope they will also serve as a point of reference for the design of detectors and experiments.

Our paper includes treatments of parton distributions, hadron jet production, the standard electroweak theory and minimal extensions to it, technicolor, supersymmetry, and compositeness. We have not dealt with fixed-target physics, log(s) physics, or exotic states of matter (QCD plasma), nor have we carried out detailed Monte Carlo calculations.

2. Parton Distributions

We compute hard-scattering cross sections using standard methods of the renormalization-group-improved parton model, for which we must know the distributions of quarks and gluons in the proton as functions of x and Q^2. The relevant values of Q^2 are typically of order $\hat{s}$ for the parton subprocess of interest, which implies a range $(10\ \text{GeV})^2 \lesssim Q^2 \lesssim (10^4\ \text{GeV})^2$. For colliders with c.m. energies between 10 and 100 TeV, typical values of x may be as small as $\langle x \rangle \approx 10^{-4}$. The very broad kinematic range implied means that distributions in the preëxisting literature are not useful for our purposes, because they are parametrizations valid over a limited range of Q^2. In addition, we require for some purposes the heavy quark (c,b, and t) distributions of the proton. Finally, the structure functions are essentially unmeasured at values of

$x \lesssim 0.01$, so it is important to assess how reliably the distributions may be considered to be known there.

We produced two sets of distributions functions that behave sensibly over the kinematic range of interest. This was done by constructing initial distributions at $Q_0^2 = 5\ GeV^2$ using the CDHS structure functions,[4] subject to the constraints of momentum and flavor sum rules, and under the assumption that there are no "intrinsic" heavy flavor components. We then evolved the distributions to $Q^2 > Q_0^2$ using the (first-order) Altarelli-Parisi equations. We studied in detail two distributions, characterized by the QCD scale parameters $\Lambda = 200$ MeV and 290 MeV, and gave a detailed discussion of the uncertainties.

The uncertainties fall into several classes. The first has to do with uncertainties in the input. We studied with some care the effect of our ignorance at small x and small Q^2, and found that at moderate to large values of Q^2, the small-x structure functions could be computed without great ambiguity. The size of the input sea distribution is subject to question, both because of other measurements[5] and the EMC effect.[6] The ratio of down to up valence quarks in our parameterizations do not perfectly reproduce the SLAC-MIT measurements,[7] but are in acceptable agreement with the EMC data.[8] At the factor-of-two level of reliability for which one hopes in making supercollider projections, none of this matters. It would still be desirable, particularly for S$\bar{p}$pS and Tevatron applications, to do better. We expect that final data from the CDHS and CCFR neutrino experiments will soon be available, and we intend to make use of these to produce revised distributions. In the longer term, results from the fixed-target Tevatron experiments should be helpful. We may also ask whether collider determinations of structure functions can become quantitative, instead of merely (already very interesting) consistency checks.

A second area of uncertainty surrounds the treatment of heavy flavors. The EHLQ distributions include only the perturbative evolution of heavy quark components. The treatment of thresholds is somewhat uncertain. More complete data on $\mu N \to \mu c\bar{c}X$ (perhaps eventually $\mu N \to \mu b\bar{b}X$) will provide useful guidance. We did not include any contribution of "intrinsic" heavy flavors. The experimental situation for charm is so confused[9] that one is free to believe almost anything. However, there is now general agreement[10] that this component would scale as $1/M^4$, and so be completely irrelevant for heavier flavors than charm. We may note here that the existence of light squarks or gluinos would make a (small) difference in the evolution of structure functions.

A final uncertainty concerns a question of principle: does QCD perturbation theory, as embodied in the Altarelli-Parisi equations, make sense as $x \to 0$? The concern here is that the pileup of ln(x) factors might make the perturbation series meaningless for x very close to zero. How close? Gribov, Levin, and Ryskin[11] have given a careful, and very physical, analysis of this problem. They argue that if the quantity

$$D(x,Q^2) = \frac{x f_i(x,Q^2) m_\pi^2}{Q^2} \gtrsim 1 \quad ,$$

partons overlap and cease to act individually so that conventional "free-parton" perturbation theory cannot be trusted. It was shown at Snowmass[12] that the EHLQ structure functions evade the dangerous regime for all values of $x > 10^{-4}$ and for $5\ \text{GeV}^2 < Q^2 < 10^8\ \text{GeV}^2$, the range in which it was hoped to apply them.

The general conclusion is that we know enough to make reasonably reliable projections to supercollider energies. Our knowledge of the parton distributions is well matched to our knowledge of the elementary cross sections, and to our current needs. Refinements seem both interesting and possible.

3. QCD Jets

Data from the S$\bar{p}$pS collider provide a useful check on the consistency of the general approach we follow and on the structure functions used. Fig. 1 shows the calculated inclusive cross section for jet production in $\bar{p}p$ collisions at (a) 540 GeV and (b) 630 GeV. The predictions nicely fit the published data at 540 GeV, and, as we have seen in Froidevaux's talk at this meeting,[13] also reproduce the preliminary UA2 data at 630 GeV. Similar results for the invariant mass distribution of two jets are shown in Fig. 2.

It is straightforward to extrapolate these calculations to supercollider energies, and the expectations have been presented in considerable detail in EHLQ. Figure 3 shows the values of transverse energy E_T that distinguish the regimes in which the two-gluon, quark-gluon, and quark-quark final states are dominant. Some promising work on enriching samples of quark jets and gluon jets was reported at this meeting by Ghez.[14] This is an area in which there is room for very fruitful iteration between calculations and experimental analysis.

An important task begun but not completed at Snowmass and Lausanne is confronting the challenges of trigger rates at high luminosity. The point to emphasize is that there are substantial rates for hard-scattering processes, and not merely for the fluff generated by peripheral collisions. For example, at $\sqrt{s}$ = 40 TeV and $\mathscr{L} = 10^{33}$ cm^{-2} sec^{-1}, a "high-E_T" trigger with threshold set at 2 TeV will count at 1 Hz from two-jet QCD events. The E_T-trigger rate is shown in Fig. 4 for pp collisions at 10, 40, and 100 TeV.

4. Electroweak Physics

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 a 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. 5 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

($\mathcal{L} \approx 2\times10^{31}$ cm^{-2}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. 6. The mapping from rapidity to c.m. angles is given in Fig. 7. In a machine with an average luminosity of 10^{33} cm^{-2} sec^{-1}, there will be a flux of approximately 10 W^+/second emitted within 2° of the beam direction, in each hemisphere.

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^0Z^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^0Z^0 and $Z^0\gamma$ reactions do not probe trilinear gauge 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^0Z^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 $q_i\bar{q}_i \to W^+W^-$ are shown in Fig. 8. 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 term, the cross section for production of a pair of longitudinally polarized intermediate bosons is proportional to $\hat{s}$, 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. 9. 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.

5. Heavy Higgs Bosons

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. 10, where the partial widths for the decay $H \to Q\bar{Q}$ 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 discussed by Georgi, et al.[15] and the intermediate boson fusion process investigated by Cahn and Dawson.[16] The rate for gluon fusion is sensitive to the masses of the quarks circulating in the loop, and particularly to the top quark mass. I show in Fig. 11 the cross section for W^+W^- pairs arising in the process

$$pp \to H + \text{anything}$$
$$\hookrightarrow W^+W^-$$

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/c^2. The contributions from gluon fusion and intermediate 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 $d\sigma/d\mathcal{M}$ for W-pair production with $|y_W| < 2.5$ (Fig. 9), and multiplying by the greater of 10 GeV and the Higgs boson width (Fig. 10). The signal exceeds the background for $M_H < 630$ GeV/c^2. The signal to background ratio is improved if the top quark is heavier, or if the rapidity cut is tightened to $|y_i|<1.5$.

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/c^2, if the $W^\pm$ can be observed with high efficiency. If both W's must be detected in their 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

$$H \to W^+W^-$$
$$\hookrightarrow \text{jet}_3 + \text{jet}_4$$
$$\hookrightarrow \text{jet}_1 + \text{jet}_2$$

final state. Second, the angular distributions are different for the isotropic $H \to VV$ decay and the forward-backward peaked $q\bar{q} \to W^+W^-$ 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 $q\bar{q} \to Z^0Z^0$ is a factor of five to ten smaller than the corresponding W^+W^- rate. Although the $Z^0 \to \ell^+\ell^-$ 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.

We have seen in the foregoing discussion that the 4-jet final state in QCD is a crucial background to the detection of intermediate boson pairs in their nonleptonic decay modes. It is also a necessary ingredient for the full understanding of three-jet phenomena about which we have heard from Scott[17] and Froidevaux.[13] Unfortunately, it is terribly hard to compute. For example, the process $gg \to gggg$ involves many diagrams, each of which generates a huge number of terms. Direct evaluation may be unthinkable, at least until AI Machines are developed as expert systems for perturbation theory.

There is, however, some reason for optimism, with the observation by Stephen Parke and Tom Taylor[18] that supersymmetry has a practical value. In N=2 supersymmetric QCD, the gluon is accompanied by a massless spin-1/2 gluino and a massless scalar gluon. All interactions, and indeed all helicity amplitudes, are simply related, so one may hope to read off the amplitude of interest from a simpler case. The method has been tested on the 2-to-3 process, for which the amplitude has been given in compact form by Berends and collaborators.[19] In this case the amplitude for external scalars is relatively easy to compute, and embodies by itself the combinatorics of crossing symmetry found by Berends, et al. The full amplitude for $gg \to ggg$ follows directly, and the amplitude for $gg \to g\tilde{g}\tilde{g}$ (massless gluinos) is a by-product. This insight gives hope that $gg \to 4g$ can be computed by human hands.

6. Some Conclusions

In this talk, I have been able to mention only a few of the physics possibilities considered by EHLQ (and others). It remains our hope that the calculations we carried out will be of value to others in reaching their own conclusions about desirable parameters for a hadron supercollider. Our own most important conclusion is the conviction that a high-luminosity multi-TeV hadron collider will meet the objective of exploring the TeV energy scale and illuminating the nature of electroweak symmetry breaking. In more detail, we have come to the following conclusions:

- We are confident that a 40 TeV collider which permits experimentation at integrated luminosities of 10^{39} cm^{-2} will make possible a detailed exploration of the 1 TeV scale.
- For a 10 TeV device, the same guarantees cannot so comfortably be made. At this lower energy, the upper reaches of the expected mass ranges for new phenomena are inaccessible, even at an integrated luminosity of 10^{40} cm^{-2}.

We are not so foolish as to say that a 10 TeV collider is without interest, or to assert that our calculations prove that it is inadequate to the task of sorting out the physics of electroweak symmetry breaking. We cannot state the precise location of the dividing line between our confidence at (40 TeV, 10^{39} cm^{-2}) and our trepidation at (10 TeV, 10^{40} cm^{-2}).

- Beyond the 1 TeV electroweak scale, we do not have specific landmarks in sight. However, the $1/\hat{s}$ behavior of hard-scattering cross sections suggests that to fully exploit collider energies higher than about 40 TeV requires an increase in luminosity as well as energy.
- For hard-scattering processes, the advantage of $\bar{p}p$ over pp collisions (at the same energy and luminosity) for the production of massive states is limited to a few special situations in which the presence of valence antiquarks is important. The choice between pp and $\bar{p}p$ colliders should thus be based on accelerator and detector considerations.

In our paper we have called attention to areas in which further work is required. Many of these have to do with simulations of signals and backgrounds in the context of projected detector performance. A few are of such general importance that I restate them here.

The detection and measurement of intermediate bosons $W^{\pm}$ and Z^0 in their nonleptonic decays should be a priority in detector development. Even if this can only be achieved for specific topologies, the potential rewards in terms of reconstruction efficiency for new phenomena are considerable.

Missing transverse momentum is an important signal (or trigger) for a number of new phenomena. This places a premium on the development of "hermetic" detectors which detect with high efficiency all the hadronic and electromagnetic energy emitted in the central rapidity region characterized by $|y| \lesssim 3$.

The ability to tag and measure heavy quarks and tau leptons would significantly enhance the incisiveness of many searches.

The new developments in collider physics presented at this meeting are representative of the continued promise of the field. I look forward with eager anticipation to more important results from the $Sp\bar{p}S$, to the first data from the Tevatron Collider, and to the Supercollider era that lies before us.

It is a great pleasure to thank Kuni Kondo and his colleagues at KEK and the University of Tsukuba for their warm and generous hospitality, and to compliment them on a very stimulating and productive symposium. My collaborators Estia Eichten, Ian Hinchliffe, and Ken Lane have contributed immeasurably to my understanding of supercollider physics.

Footnotes and References

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Captions

Fig. 1: Differential cross section for jet production at y=0 (90° c.m.) in $\bar{p}p$ collisions at (a) 540 GeV, (b) 630 GeV, according to the parton distributions of Set 2 of EHLQ. The 540 GeV data are from G. Arnison, et al., Phys. Lett. 126B, 115 (1983) and Phys. Lett. 132B, 214 (1983); and from P. Bagnaia, et al., Z. Phys. C20, 117 (1983) and Phys. Lett. 138B, 430 (1984).

Fig. 2: Invariant mass spectrum for two-jet events produced in proton-antiproton collisions at (a) $\sqrt{s}$ = 540 GeV, and (b) 630 GeV, according to the parton distributions of Set 1 of EHLQ. Both jets must satisfy $|y_i|<0.85$. Errors shown are statistical only.

Fig. 3: Parton composition of the two-jet final states produced in pp collisions at 90° in the c.m. The curves separate the regions in which gg, gq, and qq final states are dominant.

Fig. 4: Counting rate for an E_T-trigger in pp collisions at an instantaneous luminosity of 10^{33} cm^{-2} sec^{-1} (after EHLQ).

Fig. 5: 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 EHLQ was used.

Fig. 6: Rapidity distribution for W^{+} produced in pp collisions at $\sqrt{s}$ = 40 TeV, according to Set 2 of the parton distributions of EHLQ.

Fig. 7: Correspondence of angles to the c.m. rapidity scale used in Fig. 6. Also shown is the maximum rapidity, $y_{max} = \ln(\sqrt{s}/M_{proton})$ accessible for light secondaries.

Fig. 8: 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.

Fig. 9: Mass spectrum of W^+W^- pairs produced in pp collisions, according to the parton distributions of Set 2 from EHLQ. Both W^+ and W^- must satisfy $|y| < 2.5$.

Fig. 10: Partial decay widths of the Higgs boson into intermediate boson pairs vs. the Higgs-boson mass. For this illustration we have taken $M_W = 82$ GeV/c^2 and $M_Z = 93$ GeV/c^2.

Fig. 11: Cross section for the reaction $pp \rightarrow (H \rightarrow W^+W^-)$ + anything, with $m_t = 30$ GeV/c^2, according to the parton distributions of Set 2 of EHLQ, 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 $\Gamma_H d\sigma(pp \rightarrow W^+W^- + X)/d\mathcal{M}$, with $|y_W| < 2.5$ and $\mathcal{M} = M_H$. (See Fig. 9).

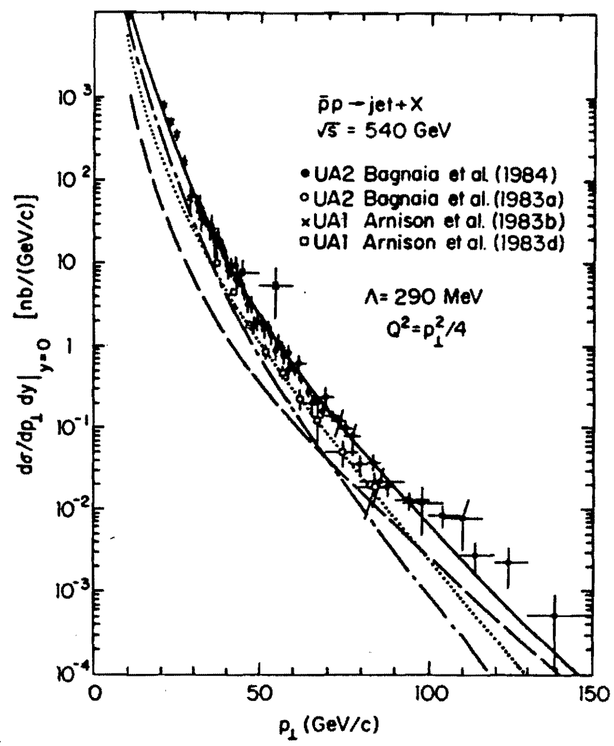


Fig. 1(a)

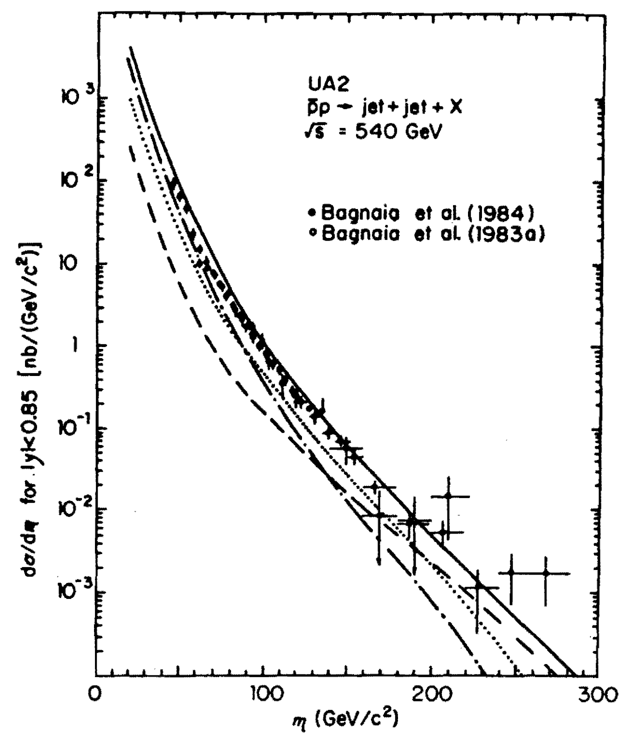
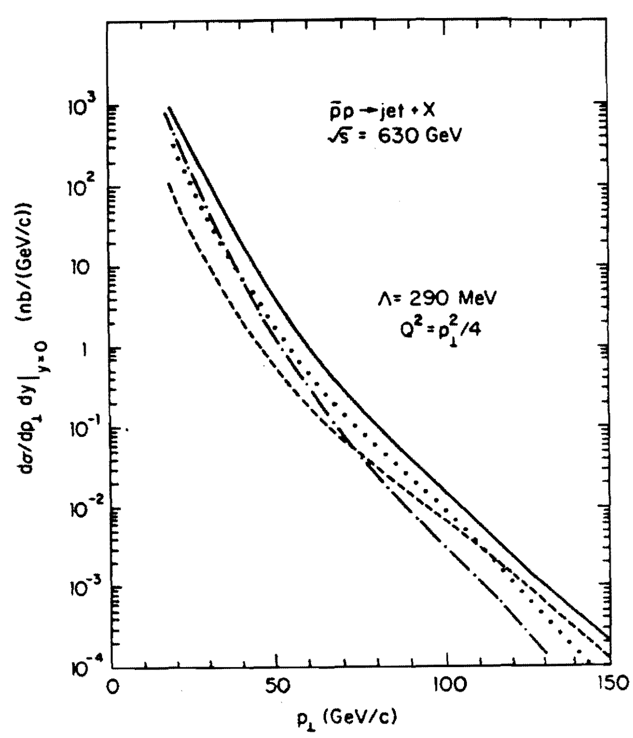


Fig. 2(a)



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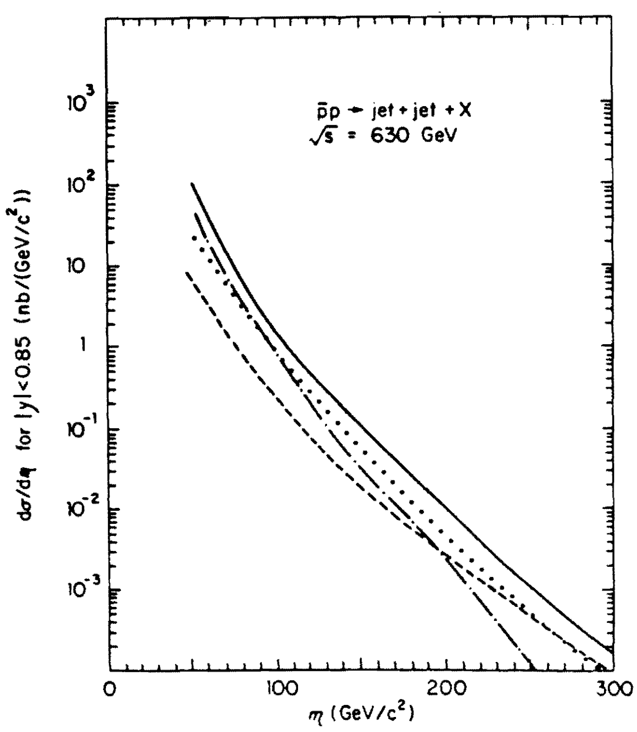

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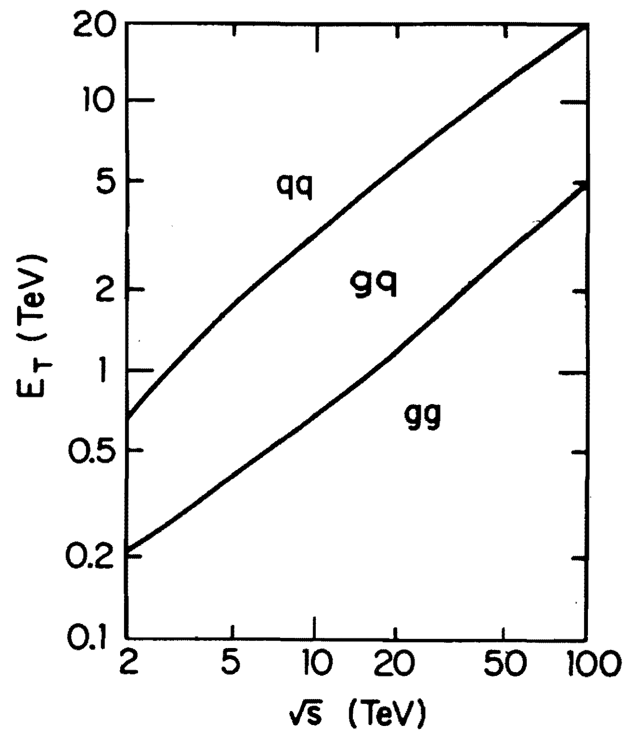

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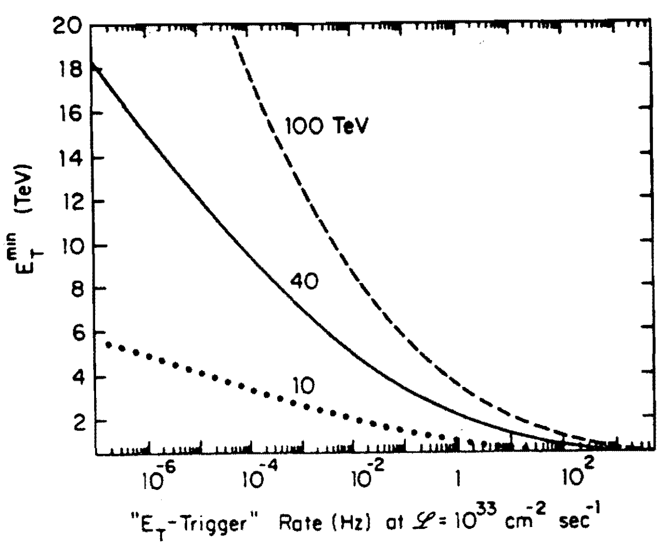

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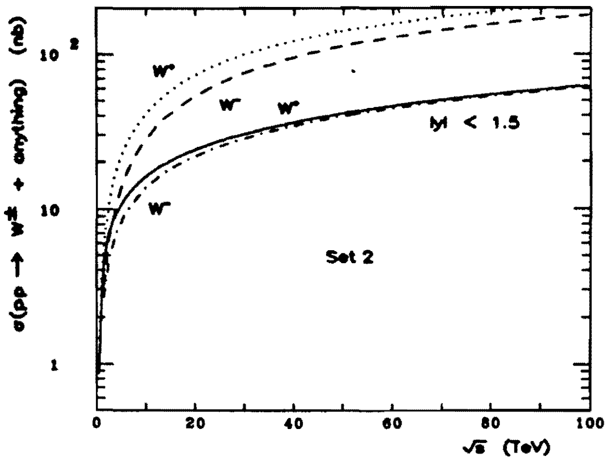

Fig. 5

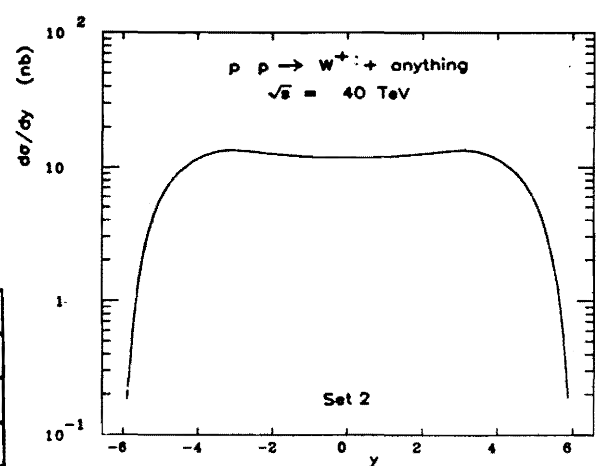

Fig. 6

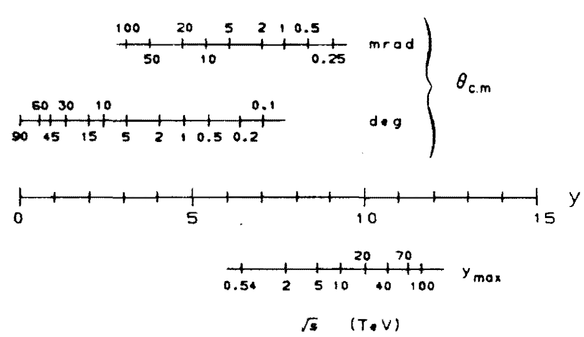

Fig. 7

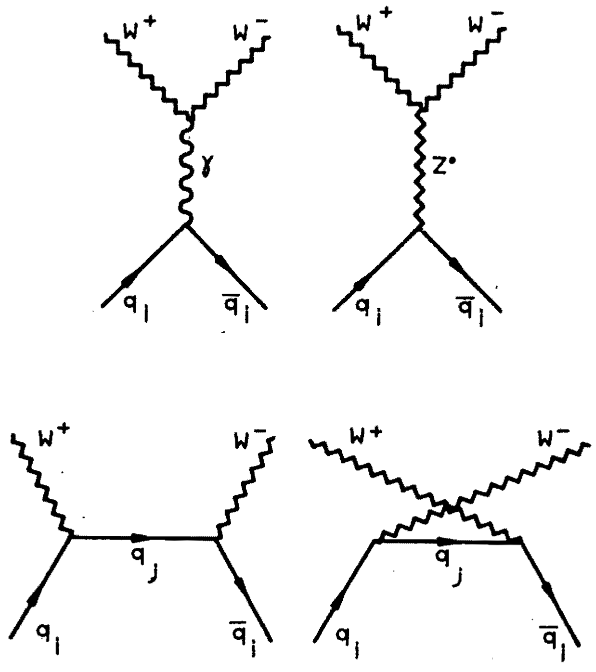

Fig. 8

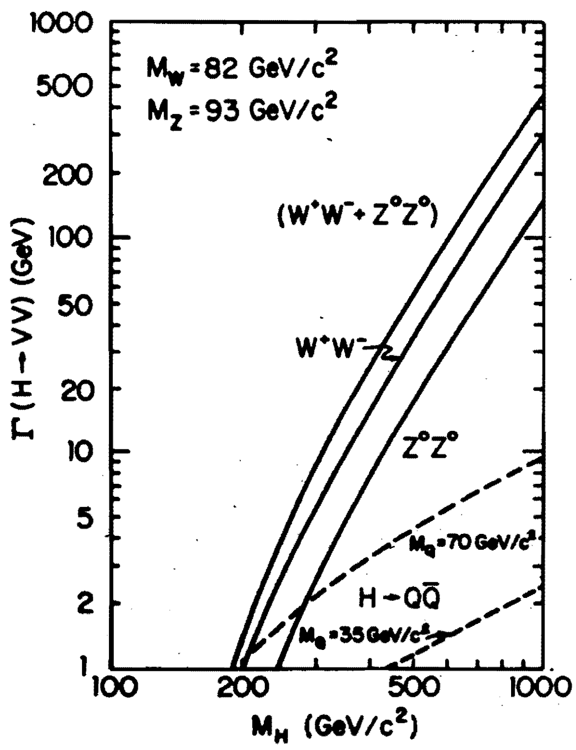

Fig. 10

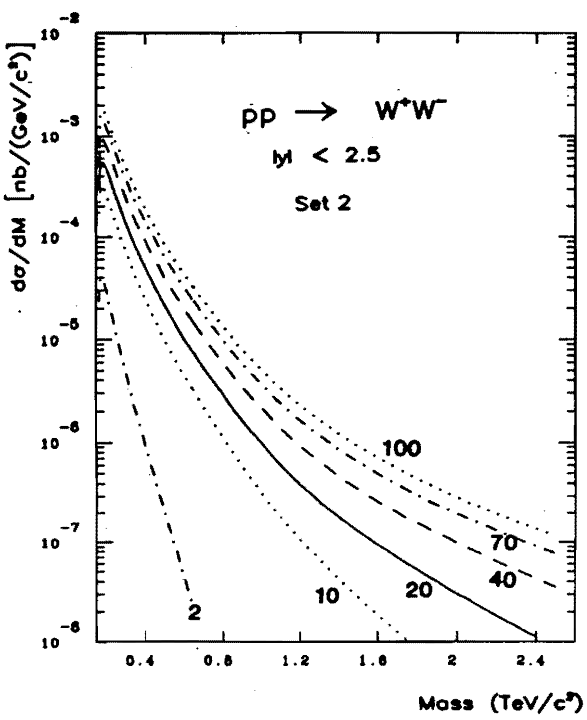

Fig. 9

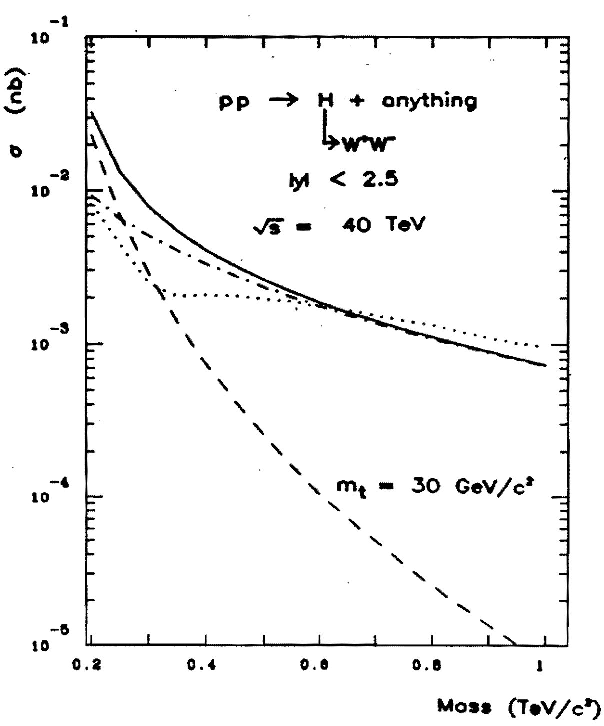

Fig. 11