LEPTON-HADRON COLLIDERS

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The general emphasis of this meeting has been on the physics to be studied with future high energy facilities. This is generally considered to be synonomous with an extension to higher energies. Any lepton hadron collider will be a future high energy facility and will entail an extension to higher energies. The emphasis that we wish to make, however, is not the extension to higher energies, but the extended momentum transfer which now becomes available. We can see this in Figures 1 and 2 where we compare the yield of events/day for lepton hadron interactions for the fixed target program that will become operational with the turning on of the Tevatron program and a modest 10 x 1000 GeV electron proton machine. The figures clearly indicate that even a modest investment in an electron proton collider will enable us to study this fundamental interaction at momentum transfers of approximately 10^4 GeV^2, a significant increase since the weak and electromagnetic interactions will be of comparable strength.

I am going to summarize the work at Snowmass under six subheadings.

a) Structure functions and the ability of an e-p collider to measure them.

b) Deviations from the structure functions.

c) Test of the propagator and searches for additional Z^o's and W's.

d) Limits on right handed currents.

e) Search for heavy flavor states.

f) New particle production and exotic states.

I will not cover some of the topics covered at this meeting such as lepto-quark and lepto-gluon production which Jim Wiss has covered in an accompanying paper. As a basis for our discussion, I will use the proposal for a 10 x 1000 GeV e-p collider proposed for Fermilab, P-659. The luminosity of this detector was calculated to be 4×10^{31} cm^{-2} sec^{-1}. The proposal was for a run of 10^{38} cm^{-2} subdivided into 4 equal runs with left-handed, right-handed positrons and electrons.

One of the essential tests of the standard model is a measurement of the structure functions as a function of x and Q^2. The results for the proposed run are shown in Figure 3. In order to appreciate the new kinematic range that will be studied, we note that the kinematic limit for x = 0.1 is Q^2 = 190 GeV^2. We see clearly that an electron proton collider has the ability to measure the structure function with appreciable statistics an order of magnitude beyond this. The other fact that becomes apparent is that the extension to lower values of x enables us to study the variation of the structure function over larger values of Q^2. The value of Λ^2 used for these calculations was 0.7. Recent data indicate that this may be too high. During this workshop J. Friedman and G. Tzanakos estimated the sensitivity of such a run to lower values of Λ. They estimate that for $s = 4 \times 10^4$ GeV^2 and $\int L\,d\,t = 4 \times 10^{38}$cm^{-2} with $Q^2 > 110$ GeV^2 and $0.3 < x < 0.75$ the error on Λ would be:

Λ (GeV)	$\delta\Lambda/\Lambda$
0.1	$\approx \pm 0.3$
0.3	$\approx \pm 0.2$

Structure functions may also be affected by the threshold behavior of new resonances. While these effects were not studied in detail, it was noted that the increased range in Q^2 accompanied by adequate statistics enabled the experimenters to make cuts on the data which would eliminate any threshold behavior.

The structure functions, of course, could also vary from the expected standard model behavior due to some new effect. A simple example would be the presence of quark substructure. In order to examine this we reexamine the standard model with an extra term:

$$F(Q^2) = \left(\frac{1}{1 + Q^2/M^2}\right)$$

This term is analogous to the elastic scattering form factor. The results expected are shown in Figure 4. We see that the data will clearly allow us to see the effect up to a mass, M, of 300 GeV. Again the more than adequate statistics will enable us to separate this from other effects by looking at the Q^2 behavior of the data as a function of Q^2. All x values, for example, should be modified by only a simple Q^2 modification.

The effect of the propagator can be separated by measuring positron and electron scattering separately. We can measure the charge asymmetry defined by:

$$A = \frac{\sigma_{e^-} - \sigma_{e^+}}{\sigma_{e^-} + \sigma_{e^+}}$$

$$\equiv \frac{2\sqrt{2}\, G_F}{e^2} \quad \frac{Q^2}{1 + Q^2/M^2} \quad \frac{f^-}{f^+} \quad \frac{xF_3^{INT}(x,Q^2)}{F_2^{em}(x,Q^2)}$$

where

$$f^{\pm} = \frac{1 \pm (1-y)^2}{2}$$

and $\frac{x\,F_3^{INT}}{F_2^{em}}$ are the usual structure functions and their interference terms which are constant to ~ 1% over the Q^2 range being considered for the collider. (Any departure from this would be interesting.) The results are shown in Figure 5. The calculations indicate that such a detector will measure the Z^o mass with an error of ± 20 GeV. The error, of course, does not compare with the mass determination of an electron-positron collider but would be a useful corroboration.

The $W^{\pm}$ mass can also be determined by an $e^{\pm}$ collider, but will not become feasible until LEP II is available. Here an e-p collider can make an early measurement. The mass can be determined using the relationship

$$4\pi \frac{d\sigma}{dxdy}(e^{\pm}) = \frac{4\ G_F^2}{(1 + Q^2/M_W^2)} \left[W_1 + (1-y)^2\ W_2\right]$$

It is necessary to know the luminosity, but for a measurement $\Delta L/L = \pm\ 20\%$, we obtain $M_W = 78 \pm 5$ GeV. In Figure 6 we show the modification of the propagator and the statistical errors on the data.

The e-p collider will also give us the first indication of the presence of additional $W^{\pm}$ bosons. In order to measure this we simply rewrite the coupling constant as:

$$\frac{G_F}{1 + Q^2/M_W{}^2} \longrightarrow \frac{C_1}{Q^2 + M_1{}^2} + \frac{C_2}{Q^2 + M_2{}^2}$$

C_1 and C_2 are the new coupling constants which, for simplicity, we take to be equal and consistent with present low energy data. The collider will be able to search for masses up to 200 GeV, assuming a mass for the current lowest W to be slightly lower than the mass expected from the standard models. This is clearly shown in Figure 7 where we have assumed a value of 50 GeV for M. The limitation here is due to a combination of energy and luminosity. If we were to have a modest increase in s to $\sim 10^5$ GeV^2 and increase our integrated luminosity to $\sim 10^{39}$ cm^{-2} the mass determination for M_2 would be extended to 400-500 GeV.

The machine can also be utilized to search for W bosons which couple to right handed currents. While we currently exist in a left handed world as far as the weak interaction is concerned, complete symmetry may exist, but higher energies are required to detect them. We are searching for a higher mass right handed intermediate vector boson. In order to do this with an e-p collider, it is necessary to polarize the electrons and positrons. Calculations by S. Holmes, P. Coteus, A. Cho, and E. Courant for P659 indicate that P = 80% is possible. We have used that value for all calculations. Defining

$$R\left(\frac{e_R^-}{e_L^-}\right) = \frac{(1 + P)\ e_R^- - (1 - P)\ e_L^-}{(1 - P)\ e_R^- + (1 + P)\ e_L^-}$$

we can consider 3 cases. Consider first the cases of a zero mass neutral lepton:

a) Consider a V + A charged current which couples to right handed quarks. We measure the quantity $R(e_R^-/e_L^-)$ as defined above. We find that the experiment is sensitive up to a mass of 250 GeV.

b) We can assume that right handed charged currents couple to left handed quarks. If we assume, as we did before, that the strengths of the couplings remain the same, we need only change definition of R which we now define as $R(e_L^+/e_R^+)$, we can again measure the mass of W_R. The results for both of these cases are shown in Figure 8. These values of about 200-300 GeV for the determination of the right handed charged current are lower than the values of 500 GeV claimed for experiments at LAMPF and TRIUMF, but the systematic errors are significantly different. The observation of a charged current interaction by a right handed lepton is an unambiguous observation of right handed currents subject to many experimental cuts and tests.

c) There is, however, another example of right handed currents which is completely unique to a lepton hadron detector. If the right handed current couples to a neutral massive lepton, then an electron collider is the only feasible way to observe such an interaction. The production rate is prodigious. We see the yield in Figure 9 as a function of lepton mass assuming conventional couplings since it is no longer necessary to have a large mass for W_R once we invoke the massive lepton. Figure 10 indicates the ability of a conventional detector to determine the mass of the heavy lepton with various decay modes. The search for massive heavy neutral leptons is essentially a unique feature of a lepton hadron collider and could be of great physical significance.

Let me conclude this summary by commenting on another feature of an e-p machine. The machine will provide us with a photon beam that has a flux equivalent to the wide band beam from a 20 TeV accelerator. The experimental area for this region of physics would be somewhat different from a conventional colliding beam detector. It would resemble the detectors we are familiar with at fixed target machines. We can make reasonable estimates of the yields. We assume that the cross section for virtual photon interactions is given by

$$\sigma_{\gamma^* p} = \frac{M_V{}^4}{(Q^2 + M_V{}^2)^2}\ \sigma_0\left(1 - \frac{\nu_{TH}}{\nu}\right)$$

where

M_V = mass of vector meson

ν_{TH} = threshold energy of the photon for production of m_c.

σ_0 is the asymptotic cross section for the heavy quark and is the measured number 500nb for charm and is scaled for higher massed quarks. i.e.,

$$\sigma_0 \propto (q/M_q)^2$$

Table 1 shows the yield for 2 machines $s = 4 \times 10^4$ GeV^2 and $s = 8 \times 10^6$ GeV^2 for an integrated luminosity of 5×10^{-38} cm^{-2}.

Acknowledgements

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TABLE I

Meson	$s = 4 \times 10^4$	$s = 8 \times 10^6$
D	80 M	1 85 M
B	3 M	8.5 M
t (20 GeV)	315 K	1.6 M
t (50 GeV)	11 K	200 K
t (60 GeV)	4 K	120 K
t (200 GeV)	-	6 K

TABLE II

Lepton-Hadron Collider Discussion Group

M. Abolins	J. Martin
B. Blumenfeld	M. Month
Y. Cho	T. O'Halloran
E. Courant	F. Taylor
M. Derrick	J. Trischuk
J. Friedman	G. Trilling
R. Gustafson	G. Tzanakos
D. Johnson	H. White
W. Ko	R. R. Wilson
W. Lee	J. Wiss

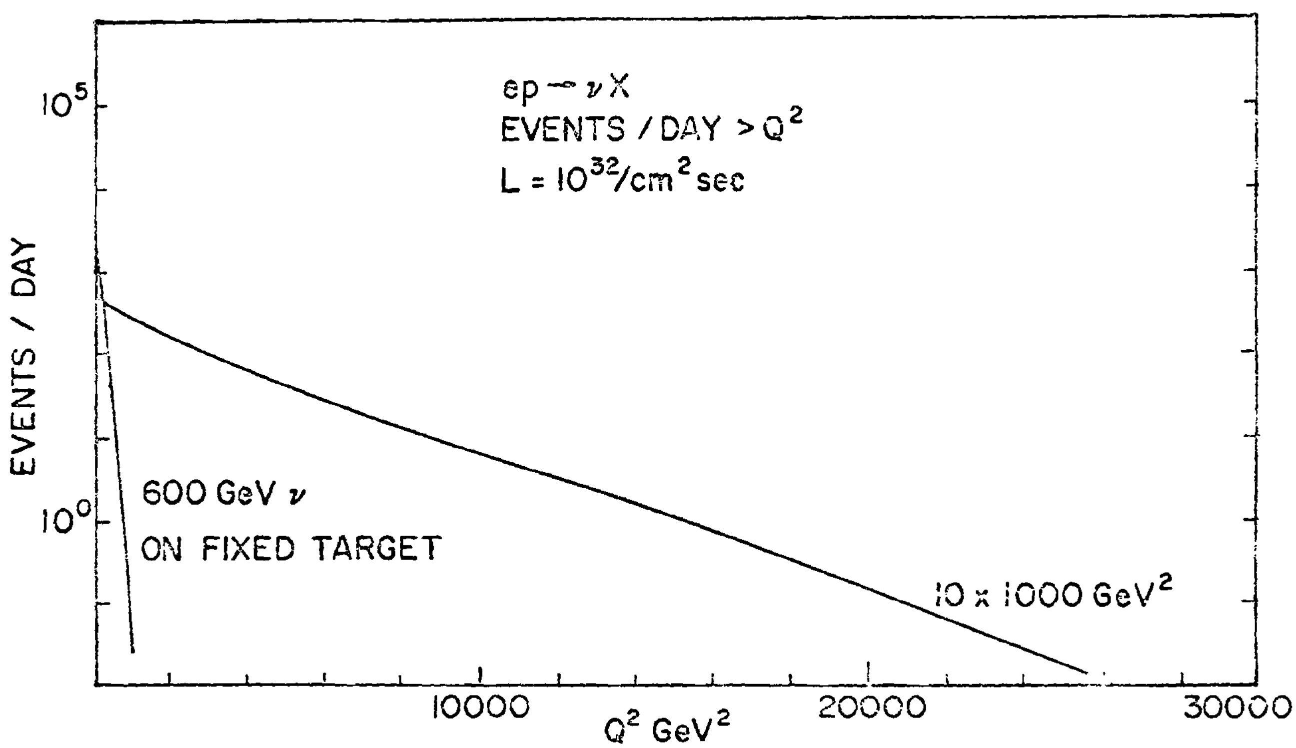

Figure 1

Event yield of 10 x 1000 GeV^2 collider compared with 600 GeV ν fixed target yield.

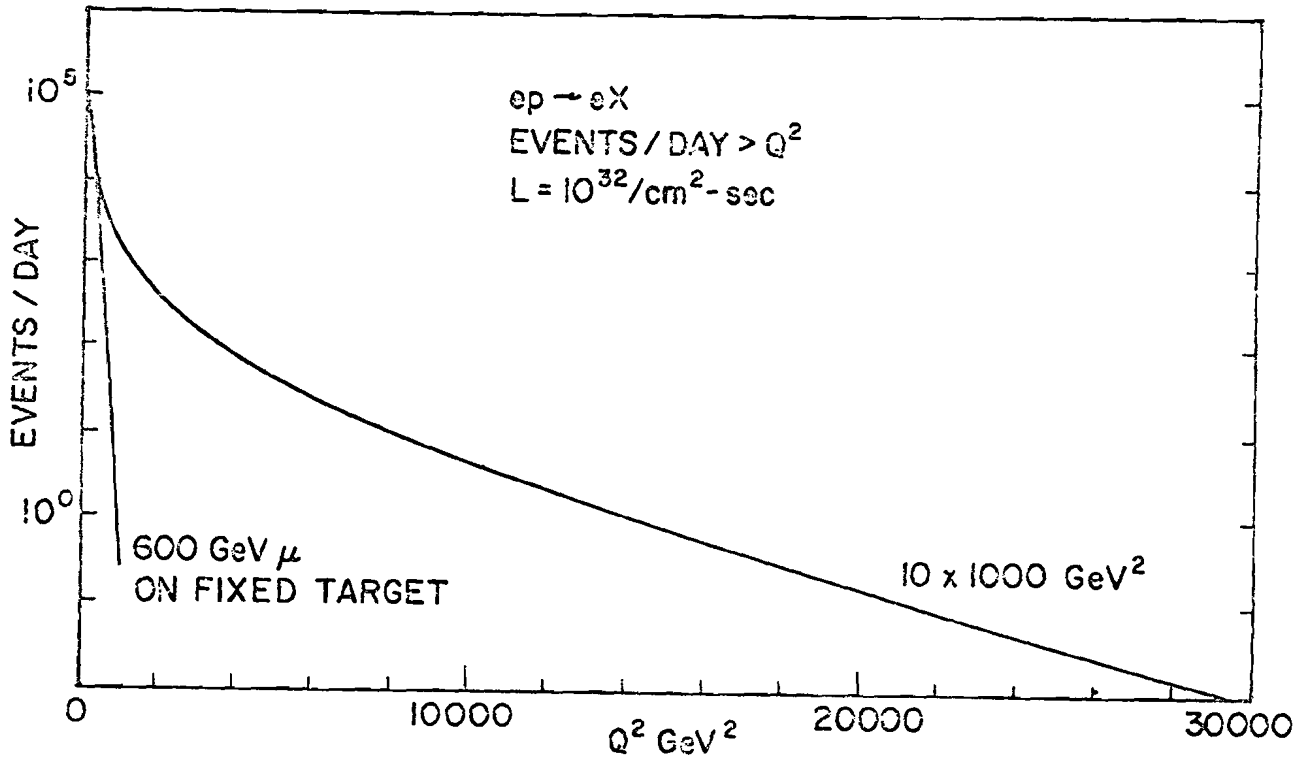

Figure 2

Event yield of 10 x 1000 GeV^2 collider compared with 600 GeV μ fixed target yield.

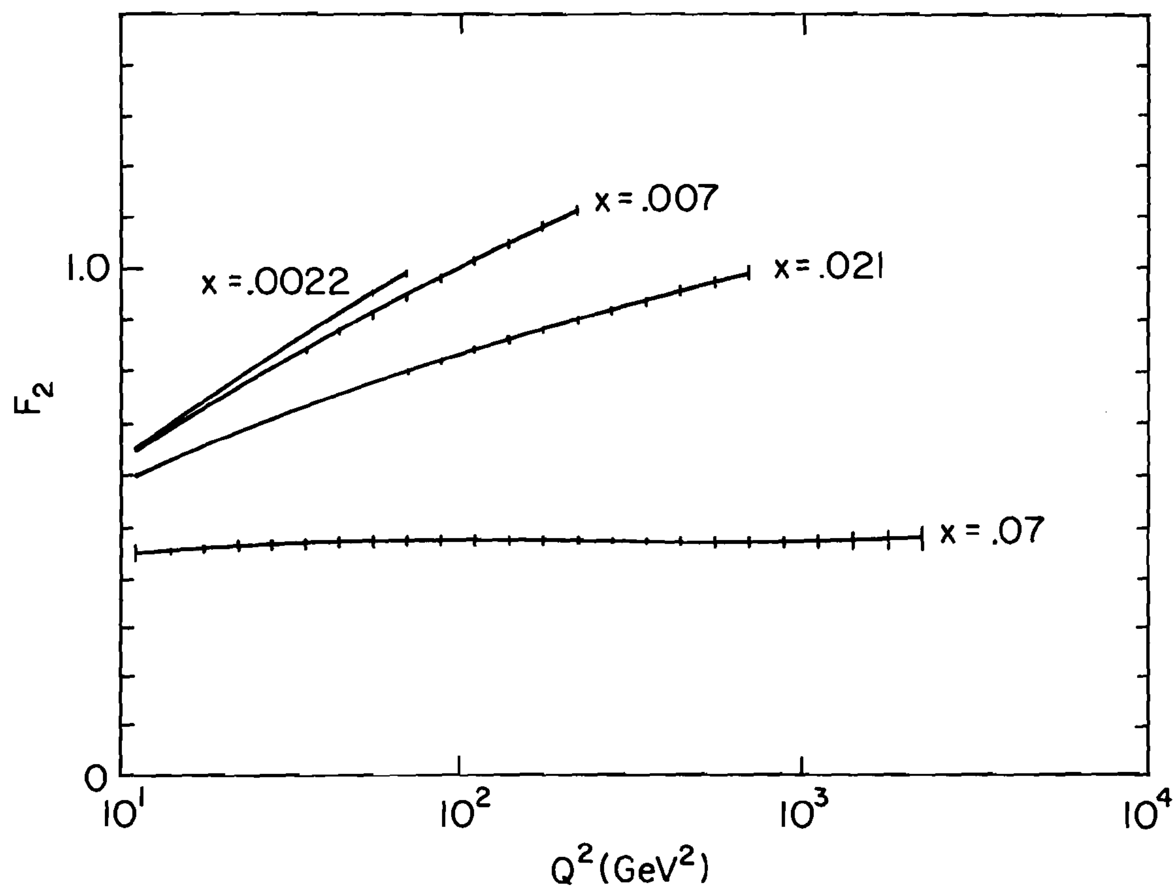

Figure 3

Variation of F_2 as a function of Q^2 for various values of x.

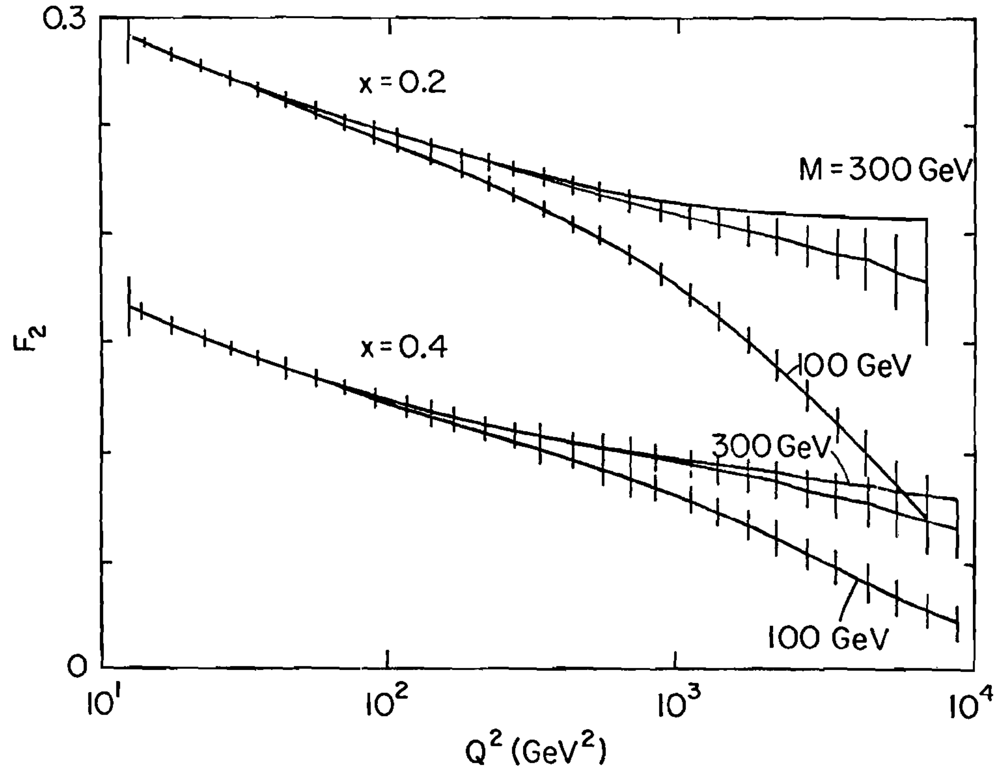

Figure 4

Sensitivity of F_2 to quark substructure.

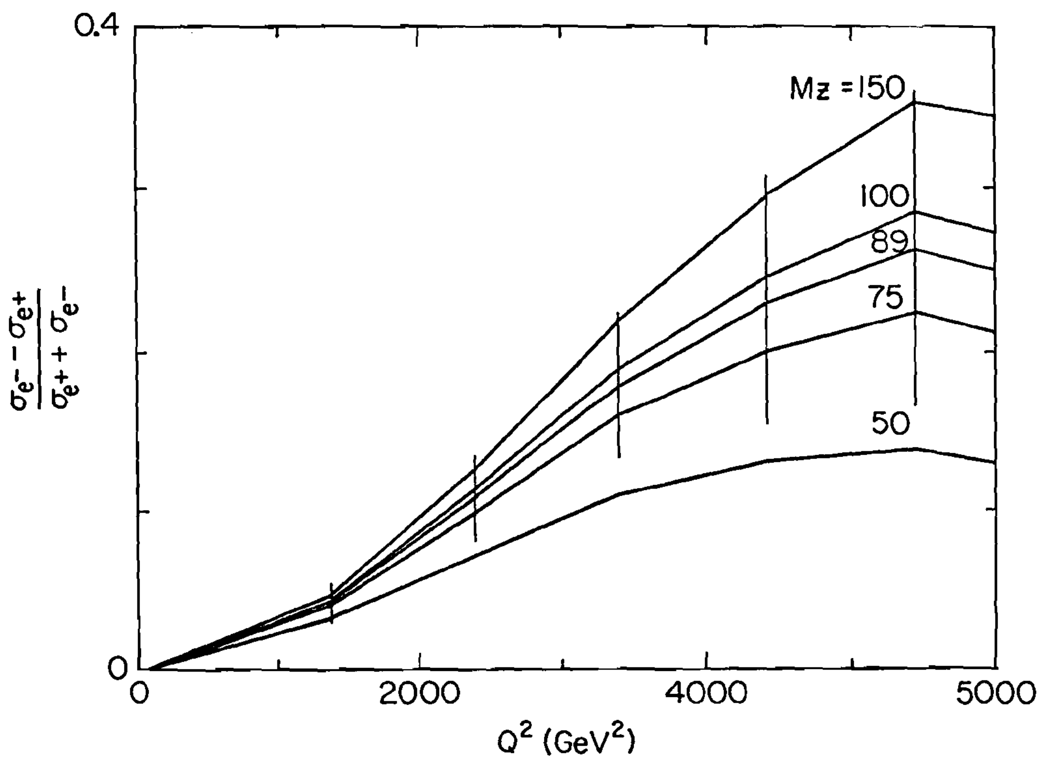

Figure 5

Charge asymmetry expected for several values of the Z^o mass as a function of Q^2.

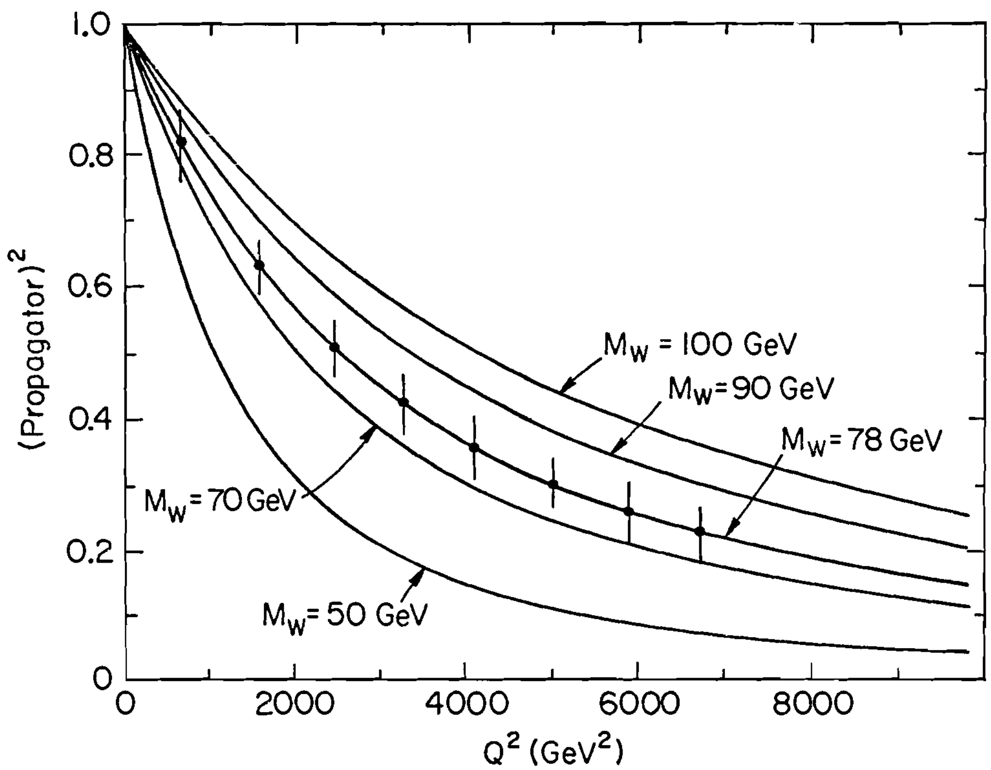

Figure 6

The Q^2 evolution of the charged current propagation for different W masses.

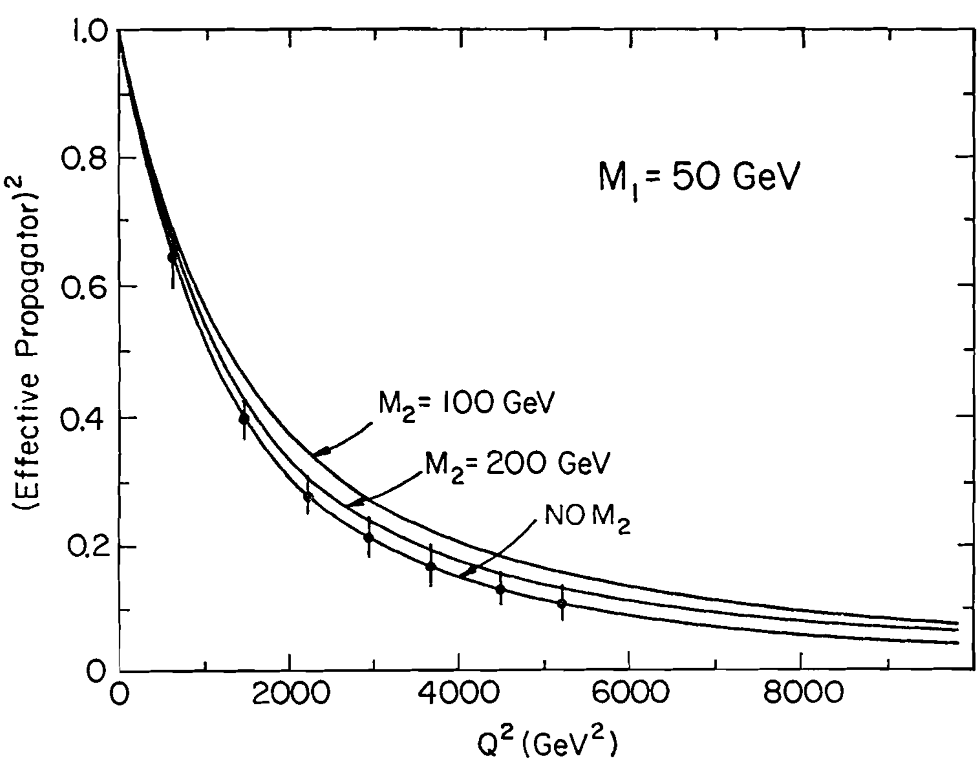

Figure 7: The Q^2 evolution of the charged current propagator is there are 2 W's as described in the text. The mass of the first W is fixed at 50 GeV; the second is allowed to vary. We will be sensitive to additional W's of masses up to 200 GeV.

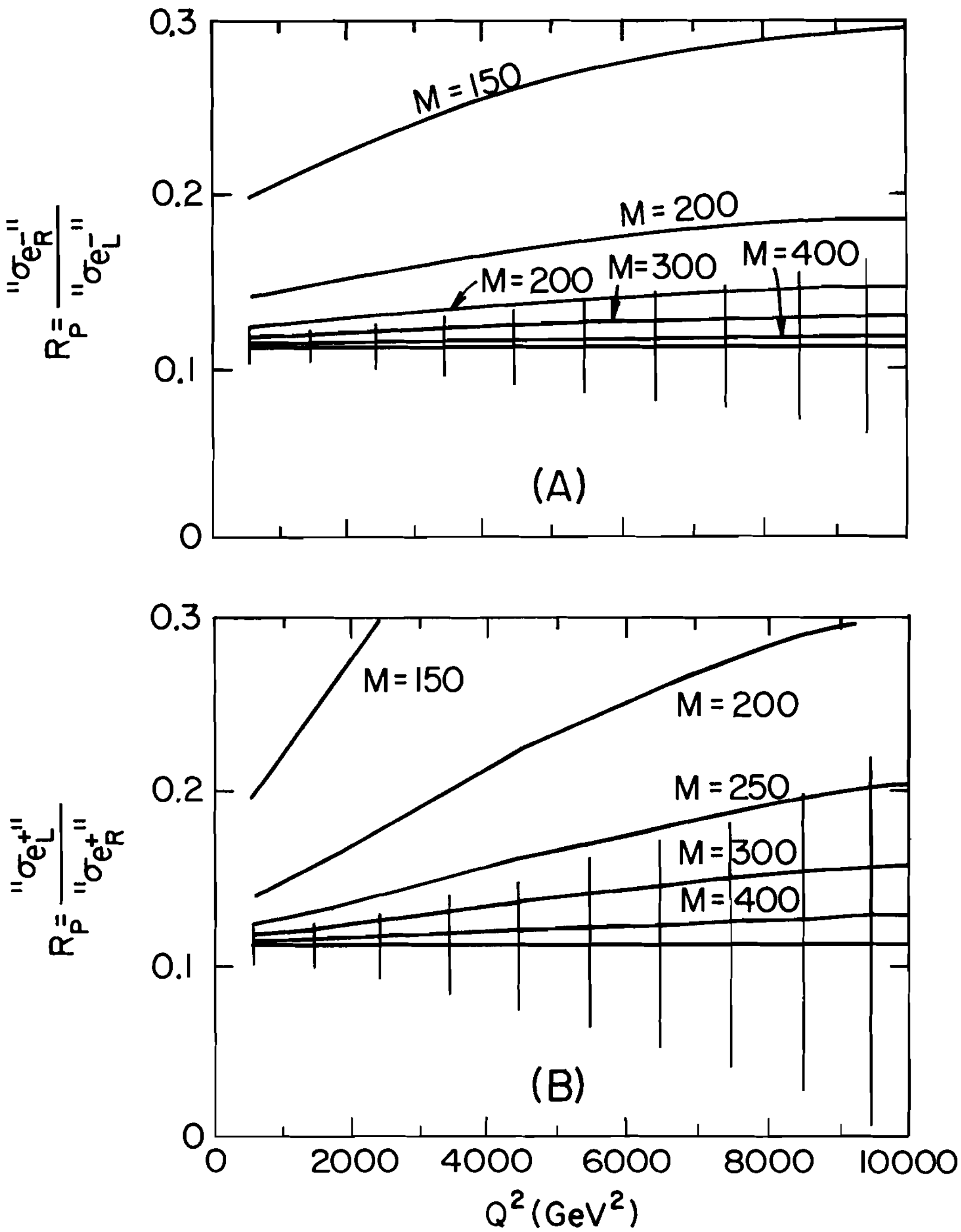

Figure 8

(A) The ratio of 80% polarized righthanded electron events to 80% polarized lefthanded electron events in a model with a new W of mass M which has a V+A coupling to leptons and a V+A coupling to quarks. We will be sensitive to these effects up to masses of 250 GeV.

(B) The ratio of 80% polarized lefthanded positron events to 80% polarized righthanded positron events in a model with a new W of mass M which has a V+A coupling to leptons and a V-A coupling to quarks. We will be sensitive to these effects up to masses of 300 GeV.

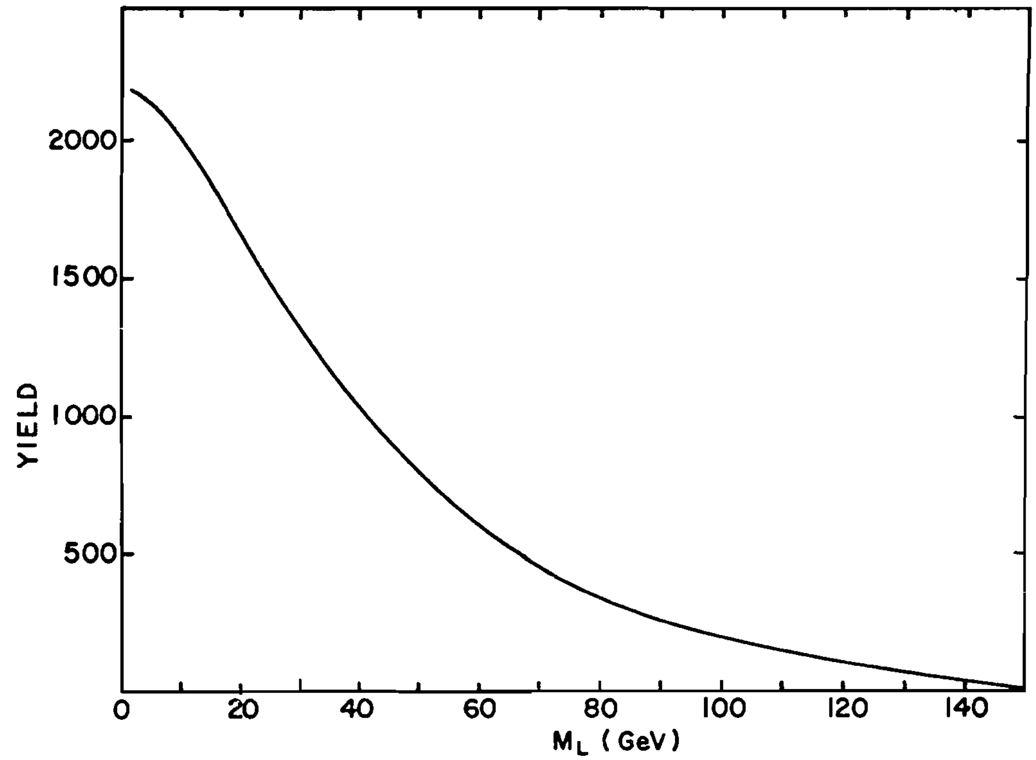

Figure 9: Expected yield of neutral heavy electrons for our assumed run as a function of heavy electron mass.

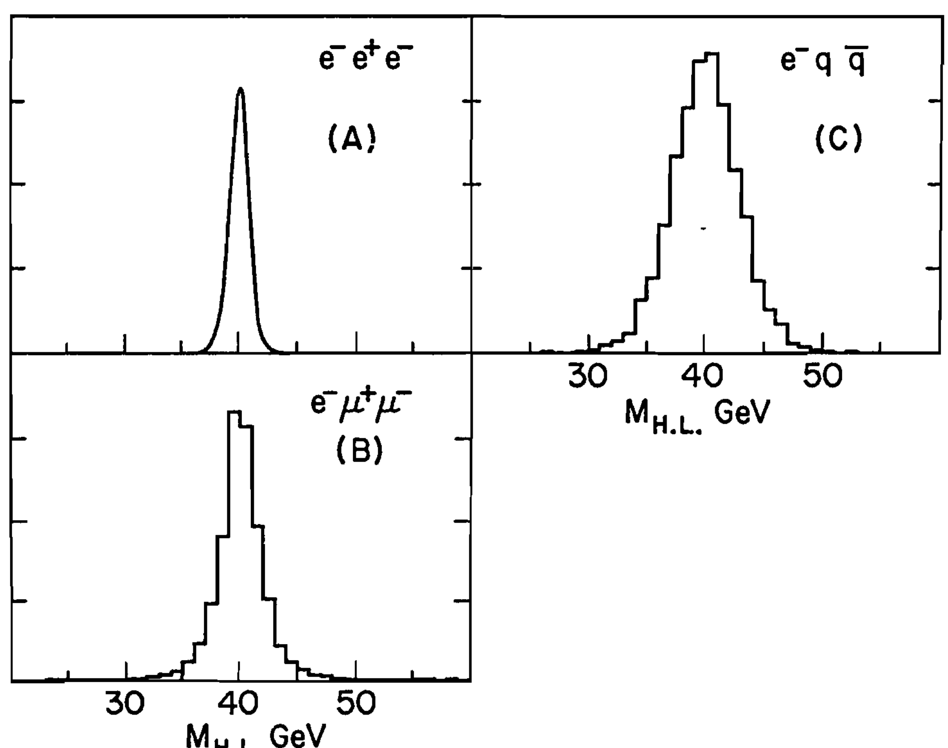

Figure 10: Mass resolution for decay of a 40 GeV heavy electron decaying into the indicated neutrino less final states.