TESTS OF QUARK-LEPTON COMPOSITE STRUCTURE USING A HIGH ENERGY eP COLLIDER

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Summary

A high energy eP collider offers the ability to test several of the ideas on lepton, quark, and gluon structure discussed during the DPF Summer Workshop on Future Facilities. In this contribution, I will discuss how the presence of such substructure will effect the Q^2 and x dependence of the eP neutral current cross section in three ways. If either quarks or electrons have form factors, the yield of high Q^2 neutral current events will be damped in an x independent way. Alternatively the existence of a (vector) leptoquark or leptogluon which could be formed by the S channel fusion of an electron with a proton constituent would create a Q^2 independent narrow bump in the neutral current yield as a function of x at $x=M^2/S$ where M is the mass of the lepto(quark or gluon). Finally, one can imagine a new contact-like interaction where composite quarks and leptons undergo large angle scatterings by constituent exchange, which at moderate Q^2 will be Q^2 independent. This process can be essentially viewed as t channel leptoquark exchange. As I will show, the eP colliders being contemplated in the near future can probe substructure at distance scales of about 1 TeV^{-1}.

Quark Form Factors

In this section we consider the high Q^2 damping of the eP neutral current cross section due to the presence of either a quark (or electron) form factor parameterized as:

$$|F(Q^2)|^2 = \left(\frac{\Lambda^2}{Q^2+\Lambda^2}\right)^2 \qquad \text{(Eqn. 1)}$$

The presence of this form factor will cause the neutral current structure function $F_2(x,Q^2)$ at fixed x to fall with increasing Q^2 faster than the logarithmic fall due to QCD scale breaking effects. The behavior of $F_2(x,Q^2)$ as $Q^2 >> \Lambda^2$ in such a composite model is highly speculative. Perhaps as Q^2 grows large enough, the structure functions will begin to rise again with increasing Q^2 and scale at a new level as elastic quark or lepton constituent scattering begins to dominate the eP neutral current process.

Figure 1 shows how the simple form factor parameterized by Eqn. 1 (for the cases $\Lambda = 100$ and 300 GeV) effect the behavior of $F_2(x,Q^2)$ in a hypothetical S=40000 GeV eP collider for two x regions.[1] The error bars reflect the statistics appropriate to a run of 10^{-38} cm^{-2} integrated luminosity. Even with this modest run, a sensitivity to form factors down to distance scales of $(300\ \text{GeV})^{-1}$ is possible. In order to separate the scale breaking due to composite effects from that due to possible other effects (such as new quark thresholds, or unforseen QCD complications) it will be neccessary to study the scale breaking in several different x bins. Scale breaking due to substructure effects should be x independent, whereas other scale breaking mechanisms would dominate in particular x regions. Once sufficiently large Q^2 are reached, and constituent scattering dominates eP scattering one might expect dramatic changes in the appearance of the final hadronic state. For example the current jet may appear to be unusually broad as the p_t scale changes from the fermi momentum of a quark within the proton to the fermi momentum of a subquark within a quark.

Leptoquark and Leptogluon Production

Several models[2] which construct quarks, leptons, and even gauge bosons from constituents predict the existence of narrow leptoquarks with masses possibly in the vicinity of hundreds of GeV. Leptoquarks, of course, play a central role in Grand Unified Theories but at the stratospheric mass scales of 10^{14} GeV. In this section, I will discuss production and signatures for leptoquarks produced by the fusion of an incident electron and either the quark or gluon constituents of the proton. Production of such states by a high energy eP collider is possible for lepto-objects with squared masses less than the S of the facility.

Experimental Signatures

Because leptoquarks or leptogluons will appear as S-channel resonances in high energy eP collisions, experimental signatures are dramatic and unambiguous. One can imagine the formation of an electron and quark resonance and its subsequent nearly isotropic decay into a quark jet and electron. The final state will consist of an electron, a wide angle jet and zero degree proton fragmentation jet. Such a final state closely resembles the final state present in ordinary neutral current scattering; however the leptoquark will produce a narrow peak in the distribution of the invariant mass of the electron-quark jet system at the mass of the leptoquark. If one neglects the p_t of the partons within the proton due to gluon emission, one can readily show that $M_{ej}^2 = S\,x$, where M_{ej} is the electron-quark jet invariant mass, and x is the usual $x=Q^2/(2P\cdot Q)$. This observation means that the M_{ej} distribution measured in ordinary neutral current events will be smooth and rapidly falling since the M_{ej} distribution is trivially related to the neutral current x distribution. Furthermore, the relationship between x and M_{ej} in the naive model allows one to dispense with the measurement of M_{ej} and the attendant problems of jet measurement altogether, since according to this relationship the leptoquark M_{ej} peak reflects into a peak in x at $x=M_{ej}^2/S$. A measurement of the scattered lepton suffices to measure x in eP scattering.

Assuming that leptoquarks and leptogluons will have a narrow natural width, the sharpness of the x or M_{ej} peak will be determined primarily by jet measurement error (in the case of an M_{ej} peak) or by parton p_t effects within the proton (in the case of an x peak). In either case the width of the peak will be about 10% of its central value. For the case of an x peak, I have done a kinematics calculation which indicates that parton p_t effects will broaden the x peak by:

$$\frac{\sigma_x}{x} \simeq \frac{p_t}{\sqrt{Q^2}}$$

QCD motivated fits of present data[3] indicate that the p_t of the parton should grow with increasing p_t as:

$$\langle P_t^{\,2} \rangle = (.5)^2 + \frac{1}{8}\,\frac{(1-x)Q^2}{\text{Log}\; Q^2/\Lambda^2}$$

where $\Lambda^2 = .01\ \text{GeV}^2$.

This formula implies a p_t broadening of the leptoquark x peak of $\sigma_x/x \simeq 10\%$ for $Q^2 > 2500\ \text{GeV}^2$ events. As we shall show shortly one would require such a Q^2 cut in searching for leptoquarks for additional resolution and signal to background reasons for an $S = 40000\ \text{GeV}^2$ machine. In addition to p_t broadening of the x peak, there will be x measurement error primarily due to electron energy resolution which is particularly large at low $y = Q^2/(S\ x)$. The error is :

$$\frac{\sigma_x}{x} = \frac{1}{y}\,\frac{\sigma_{\varepsilon'}}{\varepsilon'}$$

where y ranges from 0 to 1. In order to limit the x measurement error one should exclude low y events by requiring $y > .25$ for example. At $S = 40000\ \text{GeV}^2$ this is equivalent to a $Q^2 > 2500\ \text{GeV}^2$ cut for 100 GeV massed leptoquarks. With this cut, the scattered electron in a 10 x 1000 GeV collider has an energy greater than 70 GeV, and hence x measurment errors for the case of a 100 GeV leptoquark can be kept below 5%. Hence parton p_t broadening will dominate the width of the leptoquark x peak. A $y > .25$ cut has the additional virtue of greatly increasing the signal to background. The y distribution for an isotropically decaying leptoquark will be flat and thus the cut $y > .25$ eliminates only 25% of the signal events, whereas it greatly reduces the ordinary neutral current background which for fixed x falls faster than y^{-4}.

Figure 2 shows the effects on the $S = 40000\ \text{GeV}^2$ neutral current yield with a peak contribution from a 100 GeV leptogluon for data with the cut $y > .25$. The yield has been computed using the formulae presented in the next section assuming a 1 TeV energy compositeness scale. I have assumed a 10% x broadening due to p_t effects.

Yields

During the DPF workshop, M. Peskin provided models for the production of scalar leptoquarks, vector leptoquarks, and color octet leptogluons. I have made estimates of the production of vector leptoquarks and leptogluons using his cross section calculations and Buras-Gaemers parton distributions.

1) Scalar Leptoquarks

For scalar leptoquarks the quark electron coupling is expected to be proportional to the quark mass divided by a compositeness mass scale. For this reason, production of scalar leptoquarks is highly suppressed relative to their vector counterparts. Explicitly:

$$\sigma = \sum_q \frac{\pi}{2M_{LQ}^2}\left(\frac{m_q}{\Lambda}\right)^2 z\ f(z);\quad z = \frac{M_{LQ}^2}{S}$$

For the case of order 100 GeV leptoquark masses, and a compositeness scale of about 100 GeV, the factor multiplying the parton distribution ranges from about 10^{-4} picobarns for production off of valence quarks (M_q = 10 MeV) to 10^{-2} picobarn for production off the strange quark sea (M_q = 150 MeV). Even under the optimistic compositeness scale assumptions, scalar leptoquark production appears to be negligible.

2) Vector Leptoquarks

The quark mass dependent couplings are not present for the case of vector leptoquark production. Hence the cross section is essentially pointlike with an effective coupling constant of α_{LQ}:

$$\sigma = \sum_q \frac{4\pi^2\,\alpha_{LQ}}{M_{LQ}^2}\ z\ f_q(z);\quad z = \frac{M_{LQ}^2}{S}$$

Present knowlege of the weak interaction limits the strength of this effective coupling constant by the relation:

$$\frac{\alpha}{M_W^2} \gg \frac{\alpha_{LQ}}{M_{LQ}^2}$$

Hence optimistically one might expect: $\alpha_{LQ} \simeq \frac{\alpha}{10}$. Figure 3 gives the yield of vector leptoquarks as a function of the leptoquark mass for S= 40000 GeV^2, 100000 GeV^2 and a (pie in the sky) $S = 8 \times 10^6\ \text{GeV}^2$ machine where we have assumed $\alpha_{LQ} = .1\ \alpha$. To calibrate, note that the previously discussed Figure 2 showing the peak expected for a 100 GeV leptogluon assumed 10000 signal events over the neutral current background appropriate to a $5 \times 10^{38}\ \text{cm}^{-2}$ integrated luminosity. Hence Figure 3 indicates that vector leptoquarks should be visible up to nearly the kinematic limit or about up to masses of 175 GeV for the $S = 40000\ \text{GeV}^2$ machine or 275 GeV for the $S = 100000\ \text{GeV}^2$ machine.

3) Leptogluons

A wide variety of new states with masses from 10 GeV to several hundred GeV can be accomodated in technicolor theories. These states created from techniquark and technilepton constituents include color singlet states such as the technipions, leptoquark color triplet states, and techiquark composite states of higher color representation (octets, and sextets). In this framework it is possible to conceive of color octet leptogluons in the hundred GeV mass range. Such states could be produced in high energy eP collisions via magnetic form factor couplings leading to a formation cross section given by:

$$\sigma = 4\pi^2\ \alpha_s\left(\frac{M_{Lg}}{\Lambda^2}\right)^2 z\ f_g(z)\ ;\ z = \frac{M_{Lg}^2}{S}$$

where we consider a gluon compositeness scale of $\Lambda = 1$ TeV, and take $\alpha_s = .15$.

Figure 4 shows the yield of such leptogluons as a function of the leptogluon mass for an S=40000 GeV^2 and S=100000 GeV^2 machine for a run with 5 x 10^{38} cm^{-2} integrated luminosity. We have used a gluon distribution $f(x) = A(1.-x)^7$ with A chosen so that half the momentum of a nucleon is in gluons. We see that the yield grows to quite respectable values with increasing M_{lg} because the coupling proportional to M and then falls as one runs out of high $x = M_{lg}^2/S$ partons. In light of Figure 2, it appears that a high S eP machine is eminently suited to discovering leptogluons in the interesting hundred GeV mass range.

New Interactions

If quarks and leptons are constructed from similar building blocks (such as a fermion-boson pair) one can anticipate new interactions where quark lepton scattering takes place by the rearrangement of constituents rather than by photon (and Z_o exchange). At momentum transfers significantly less than Λ where Λ^{-1} is the scale of quark or lepton structure, such a scattering process should be contact-like (in analogy with neutrino quark scattering at $Q^2 << M_W^2$) which has a differential cross section in the quark lepton center of mass system given by:

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi}\frac{\hat{S}}{\Lambda^4}$$

where $\hat{S}$ is the squared total energy in the quark lepton CM frame. Such an interaction (in isolation) would produce a neutral current cross section of the form:

$$\frac{d\sigma}{dQ^2} = \frac{1}{\Lambda^4}\sum_q \int_{x_{min}}^1 f_q(x,Q^2)\,dx$$

where $f(x,Q^2)$ is the parton momentum fraction distribution for the qth quark and $x_{min} = Q^2/S$. This should be contrasted with the Q^2 dependence of the ordinary neutral current cross section which falls in Q^2 according to:

$$\frac{d\sigma}{dQ^2} = \frac{A\alpha^2}{Q^4}\sum_q \int_{x_{min}}^1 f_q(x,Q^2)dx$$

where A is a constant on the order of unity. In the presence of both effects one will obtain an interference term in addition:

$$\frac{d\sigma}{dQ^2} = \left(\frac{A\alpha^2}{Q^4} \pm \frac{\sqrt{A}\,\alpha}{Q^2\,\Lambda^2} + \frac{1}{\Lambda 4}\right)\sum_q \int_{x_{min}}^1 f(x,Q^2)dx$$

where the +/- choice depends on the relative phase between the ordinary neutral current and the contact amplitude. For the case of large Λ and moderate Q^2 the contact interaction will be primarily observable in the interference term:

$$\frac{d\sigma/dQ^2}{d\sigma/dQ^2)_{\Lambda=\infty}} = 1 \pm \frac{A^{-1/2}Q^2}{\Lambda^2}$$

Thus, in this simple picture, if the compositeness scale were Λ = 4 TeV, the yield of events with $Q^2 > 60000$ GeV^2 would be more than 50% higher than anticipated.

M. Peskin, at this workshop, developed neutral current cross section formulae incorporating the amplitudes for one photon exchange, the Z pole, as well as the new contact interactions. In general, the neutral current cross section can be written as:

$$\frac{d\sigma}{dxdy} = \frac{2\pi\alpha^2}{Sx^2y^2}\sum_q x\, f_q(x,Q^2)\left[A_q(Q^2)+(1-y)^2B_q(Q^2)\right]$$

where $Q^2 = S\,x\,y$. The presence of a contact term adds a coupling of the form:

$$\frac{8\pi}{\Lambda^2}\;\bar{e}_L\,\gamma^\mu e_L\,\bar{q}_L\,\gamma_\nu\,q_L$$

This term adds the underlined contribution to the $A(Q^2)$ amplitude:

$$A_q(Q^2) = \left(q_q + {}^1C_q^A\frac{Q^2}{Q^2+M_z^2} - \underline{\frac{nQ^2}{\alpha\Lambda^2}}\right)^2 + \left(q_q + {}^2C_q^A\frac{Q^2}{Q^2+M_z^2}\right)^2 \qquad \text{(Eqn. 2)}$$

where q_q is the quark charge (1/3 or 2/3) and ${}^{1,2}C_q^A$ are coupling constants which are functions of the Weinberg angle, and η is a relative phase factor ($\eta = \pm 1$). The $B(Q^2)$ factors are unaffected in Peskin's model:

$$B_q(Q^2) = \left(q_q - {}^1C_q^B\frac{Q^2}{Q^2+M_z^2}\right)^2 + \left(q_q - {}^2C_q^B\frac{Q^2}{Q^2+M_z^2}\right)^2$$

I have used M. Peskin's cross sections, and the Buras-Gaemer quark distributions to evaluate the effects of a contact interaction with $\alpha\Lambda^2 = 10^5$ GeV^2 (i.e., Λ = 4 TeV) in the total neutral current yield as a function of Q^2 for S = 40000 GeV^2 and S = 100000 GeV^2 colliders. In Figure 5 the dashed curves show the neutral current yield with the contact interaction present; the solid curves show the yield with the contact interaction absent. If the relative phase between one photon exchange and the contact term were reversed, the dashed curve would lie beneath the solid curve.

Figure 6 shows the ratio of the yield of neutral current events with $Q^2 > Q_0^2$ when a contact term is present over the yield of neutral current events when the contact term is absent. The statistical error bars reflect a run of 10^{39} cm^{-2} integrated luminosity of a S = 100000 GeV^2 collider. Since Figure 6 represents integrals of the Q^2 distribution past certain Q^2 points the error bars are not statistically independent -- however, the effects of a contact interaction with $\alpha\Lambda^2 = 10^5$ GeV^2 will be apparent. For example, Figure 6 shows that the yield of $Q^2 > 40000$ GeV^2 events will be a factor of about 1.75 times higher than expected -- about a six standard deviation effect. Much larger statistical sensitivity to contact effects can be obtained by comparing theoretical predictions to the observed yield at lower Q^2. Eventually, however, the deviation due to contact effects will approach the level of systematic uncertainties. Probably an S = 100000 GeV^2 machine will be sensitive to contact effects in the range

$\Lambda < 5 10^5$ GeV^2.

Shifts in the Z mass?

Can contact effects be separated from the effects in the neutral current cross section due to unexpected shifts in the mass or the Z? As Eqn. 1 demonstrates, for $Q^2 \ll M_Z{}^2$, the effect of a contact term could be absorbed by changing the position of the Z pole from M_Z to $M_Z{}'$ where:

$$\frac{1}{M_{z'}^2} = \frac{1}{M_z^2} \pm \frac{1}{{}^1C_q^A} \frac{1}{\alpha\Lambda^2}$$

where ${}^1C_q{}^A = 1/2$, assuming $\sin^2\theta = .23$. At $\alpha\Lambda^2 = 10^5$ GeV^2 this shift would be about 10% which would present difficulties with present limits on the Sakurai-Hung parameter:

$$\rho = \frac{M_W^2}{M_z^2 \cos^2\theta_W}$$

which is measured to be nearly unity using present low energy neutrino data. Hence high energy eP colliders have sensitivity to the direct presence of a contact term where limits deduced from the standard model begin to run out.

If the presence of a contact term is observed in high energy eP collisions at $\alpha\Lambda^2 = 10^5$ to 10^6 GeV^2, Figure 6 shows that significant deviations from the expected neutral current yield will occur beyond $Q^2 > 20000$ GeV^2. At this point the Z pole contribution to the $A(Q^2)$ amplitude flattens out, whereas the contact contribution continues to rise with increasing Q^2 relative to the one photon exchange amplitude. Hence by seeing that the ratio of the observed to expected neutral current cross section continues to deviate from unity in a fashion which is linear in Q^2 far above $Q^2 > M_Z{}^2$, one will be able to separate pole shift from contact terms.

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References

[1] Fermilab Proposal 659: Electron-Proton Interaction Experiment.

[2] L. F. Abbott, Edward Fahri, and S.-H. Tye, "Alternatives to the Standard Model: Experimental Signatures", contributed to these Proceedings.

[3] H. D. Politzer, Phys. Lett. 70B, 430 (1977).

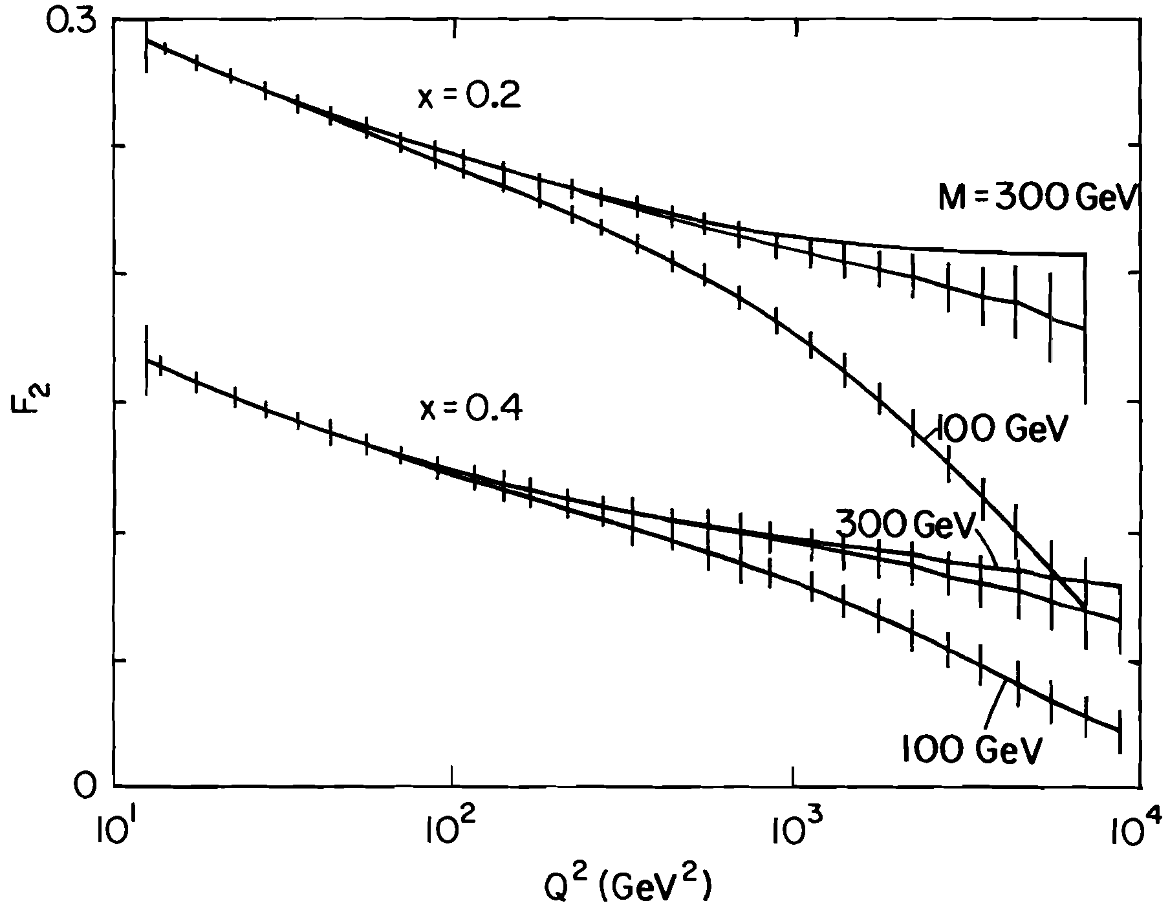

Figure 1

The Q^2 dependence of F_2 for events with $0.1 < x < 0.5$ in the absence of quark substructure (unlabeled curves) and in the presence of quark substructure with characteristic mass scales of 100 and 300 GeV. We will be sensitive to up to mass scales of 300 GeV.

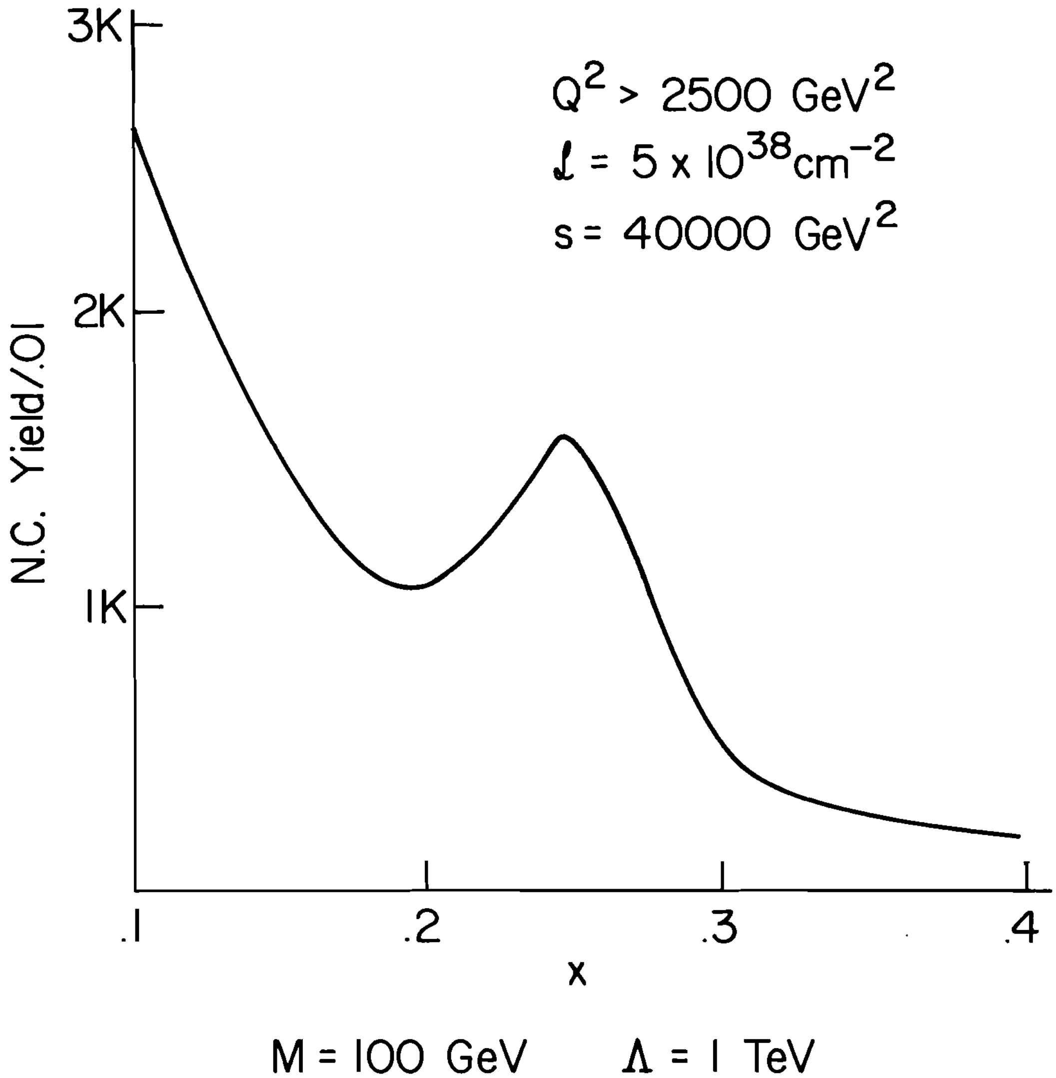

Figure 2

The effects of a 100 GeV leptogluon on the yield of $Q^2 > 2500$ GeV^2 neutral current events as a function of x. If the leptogluon compositeness scale is 1 TeV, about 10000 signal events will be produced in a run of 5×10^{38}cm^{-2} integrated luminosity of an $S = 40000$ GeV^2 eP collider. These signal events will form a peak at $x = .25$ in the neutral current yield which will lie over a smooth background of ordinary neutral current events.

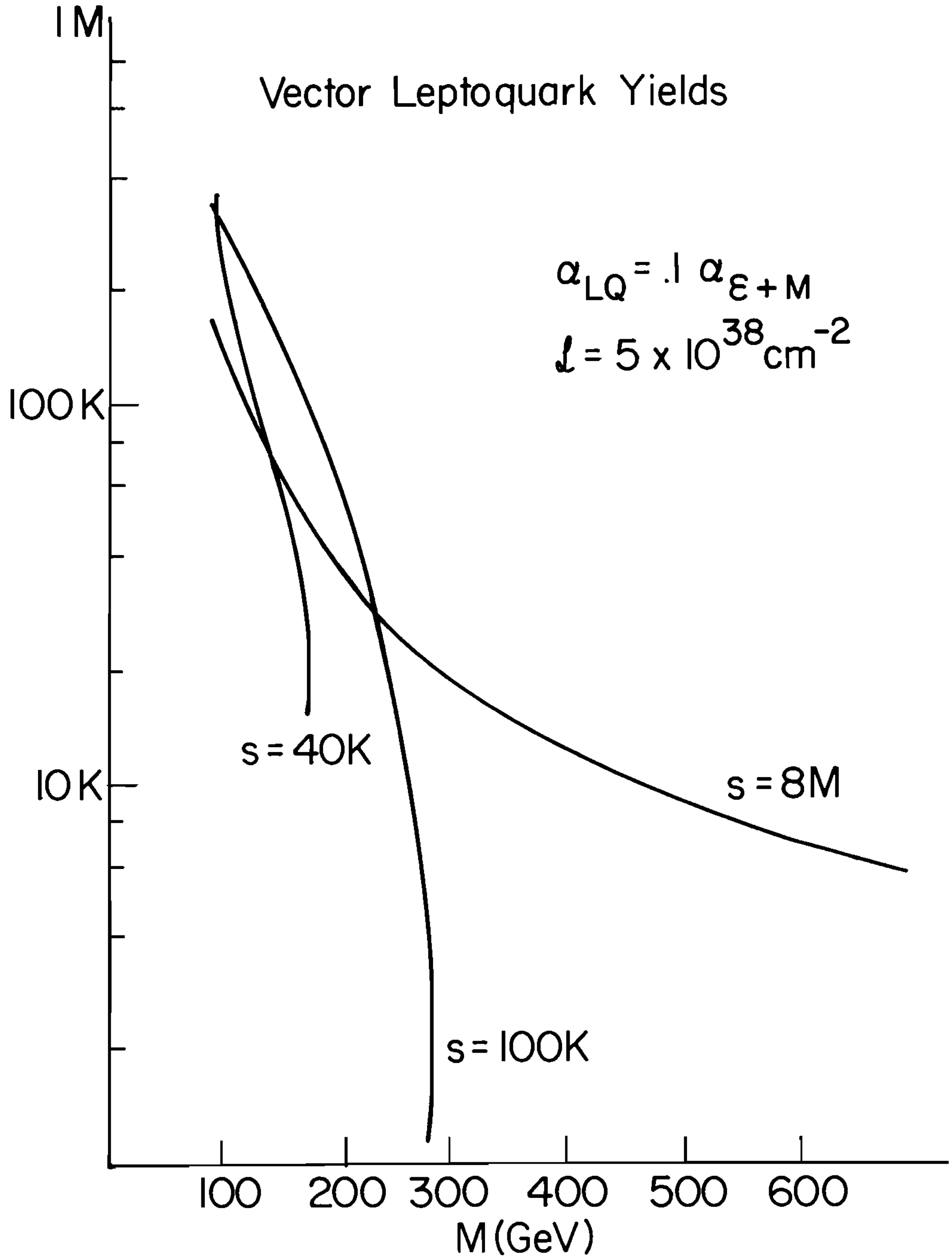

Figure 3

Vector leptoquark yields as a function of vector leptoquark mass for a run of $5 \times 10^{38} cm^{-2}$ integrated luminosity for S = 40K, 100K, and 8M GeV^2 colliders. We assume $\alpha_{L.Q.} = .1\alpha$ where $\alpha \simeq 1/137$.

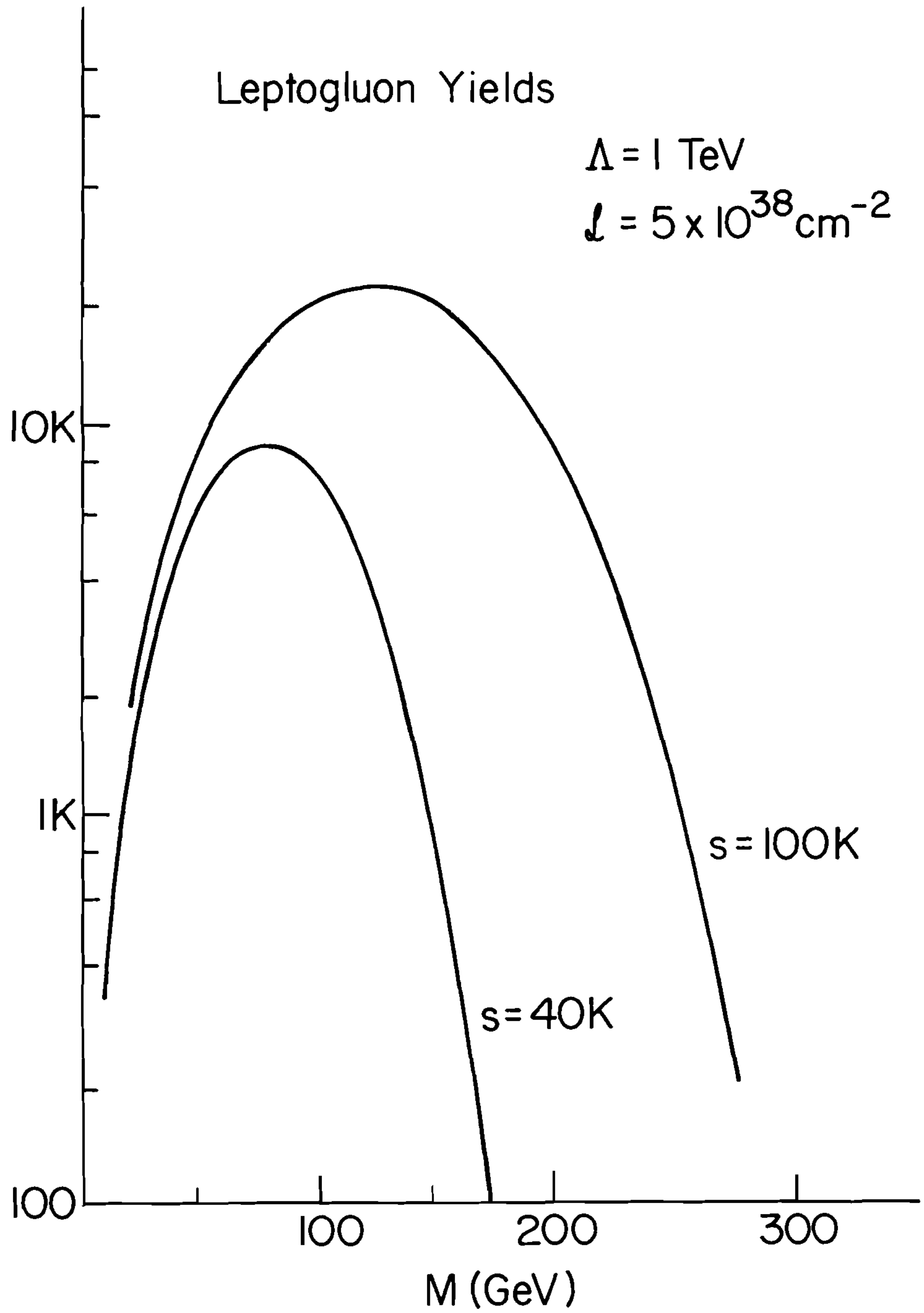

Figure 4

Leptogluon yield as a function of leptogluon mass for a run of $5 \times 10^{38} cm^{-2}$ integrated luminosity in an S = 100K GeV^2 and S = 40K GeV^2 eP collider. This figure assumes a compositeness scale of 1 TeV.

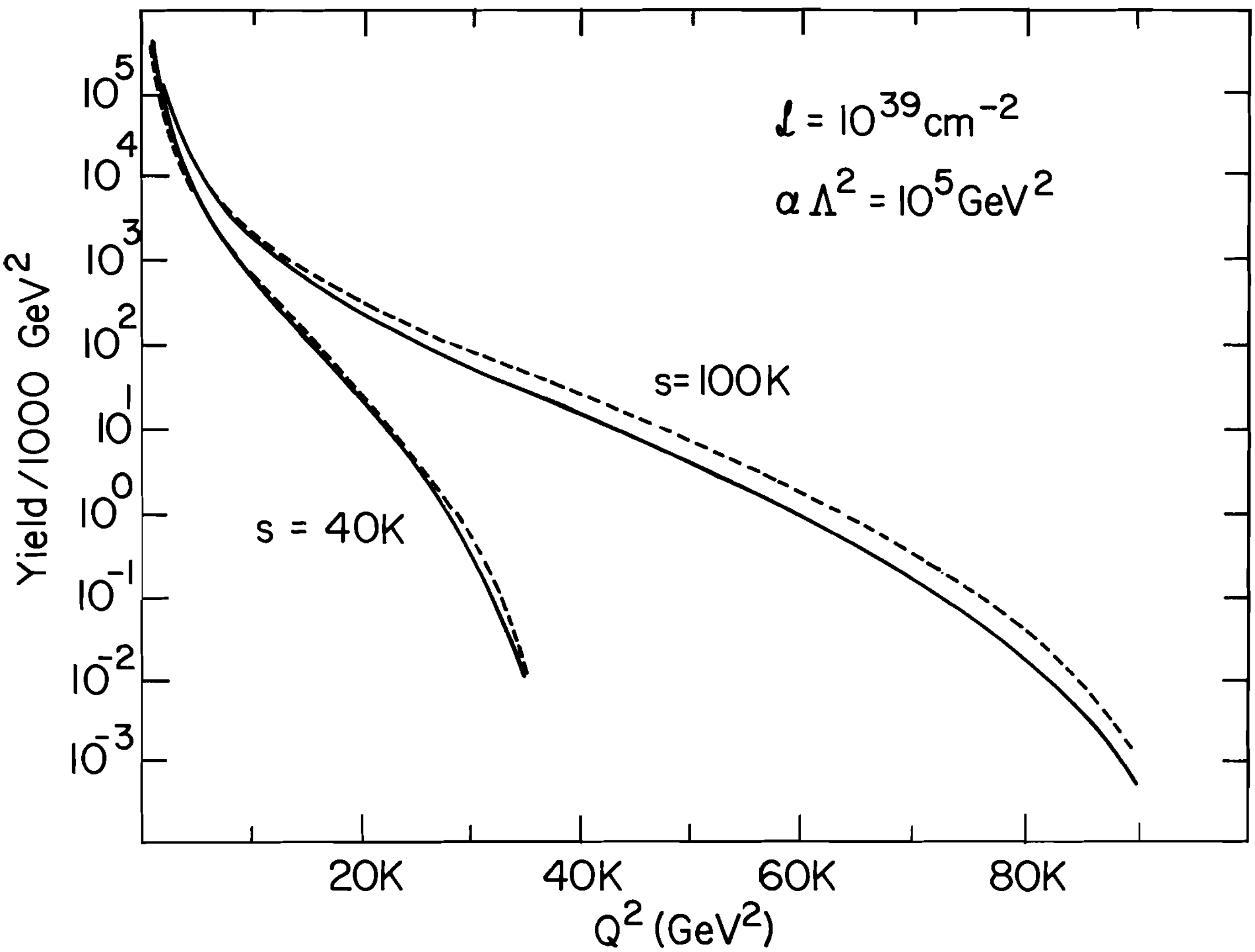

Figure 5

Effects of a contact interaction on the neutral current yield as a function of Q^2 for an S = 40000 GeV^2 eP collider. We have assumed a compositeness scale of $\alpha\Lambda^2 = 10^5 GeV^2$. The dashed curves give the yield in the presence of a contact interaction; the solid curves give the yield in the absence of the contact interaction.

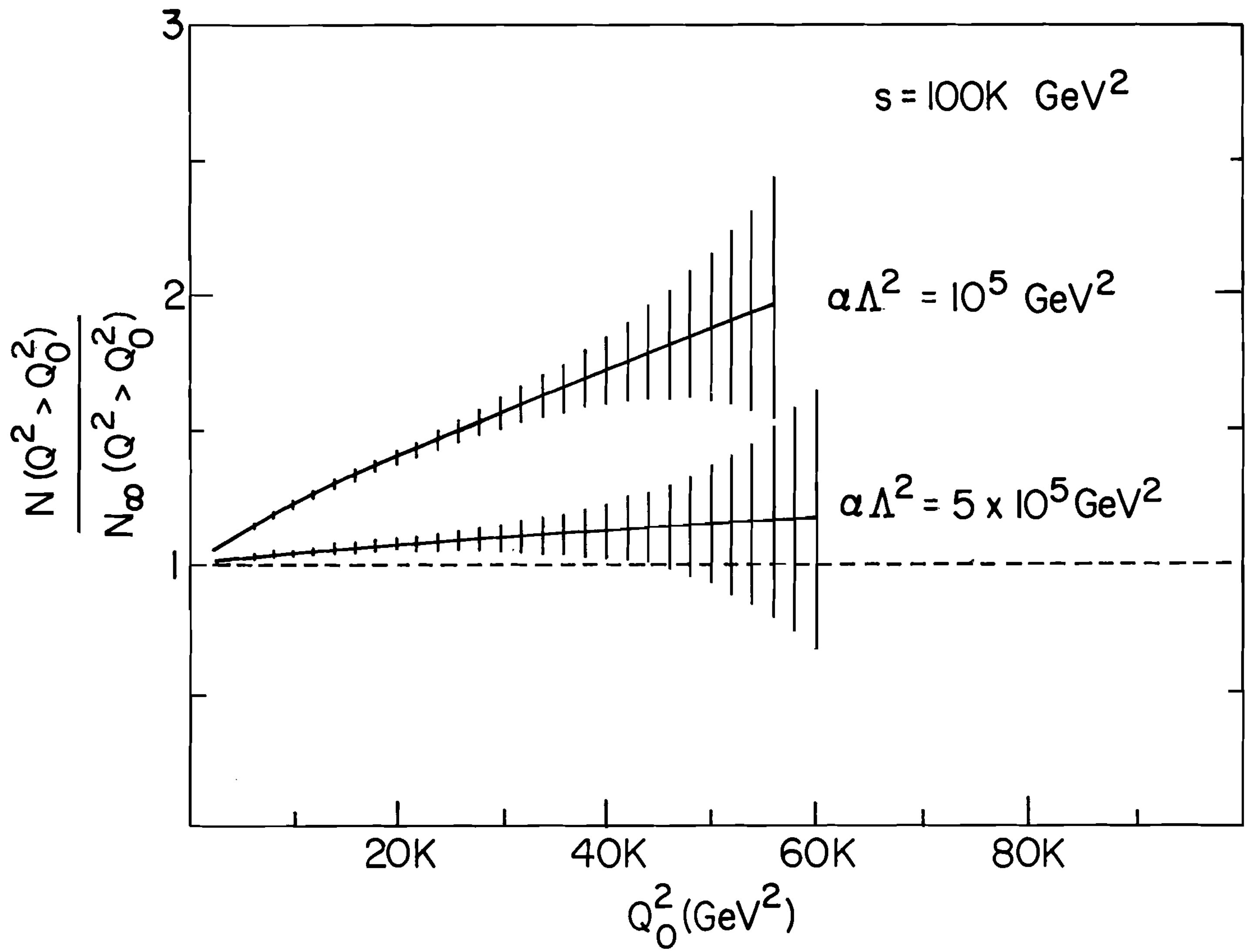

Figure 6

The ratio of the yield of neutral current events with $Q^2 > Q_0^2$ in the presence of a contact interaction over the yield of $Q^2 > Q_0^2$ events in the absence of a contact interaction. The error bars are computed for a run of 10^{39}cm^{-2} integrated luminosity for an S = 100000 GeV^2. We consider the cases of a compositeness scale of $\alpha\Lambda^2 = 10^5$ GeV^2 and $\alpha\Lambda^2 = 5 \times 10^5$ GeV^2. These error bars are not statistically independent since, for example, a fluctuation in the number of events beyond Q^2 = 40000 GeV^2 is correlated with the fluctuation in the number of events beyond Q^2 = 30000 GeV^2.