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POLARIZED $e^{\pm}$ - POLARIZED p COLLIDING BEAMS: PHYSICS ISSUES*

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ABSTRACT

The physics of collisions of polarized electrons with polarized protons at storage-ring energies is examined, with emphasis on polarization asymmetries of structure functions. The usefulness of positron-proton as well as electron-proton collisions is underlined.

I. INTRODUCTION

In the 1980 Spin Symposium, L. Sehgal[1] gave an excellent exposition of deep-inelastic phenomena at collider energies with polarized lepton beams. After the talk, E. Courant asked the following question:

"What would be the significance of having polarized proton beams as well as polarized electron beams available in the ep collider?"

Sehgal's answer, in part, was:
"...(it will give) additional information about the spin structure of the proton, but...not...anything fundamentally new about the structure of the weak interactions... It might make it easier to disentangle the parameters."

I am not sure there is the same interest today in the answer to Courant's question as then. But the question remains, and this talk is devoted to a somewhat more detailed look at the issues than in Sehgal's reply.

II. WHAT HAS BEEN DONE?

We begin with the briefest reminder of some of the salient measurements of polarized electroproduction:

1. Time-reversal test[2] utilizing elastic ep scattering, with proton spin polarized transverse to the scattering plane and electron unpolarized: null results.
2. Parallel-antiparallel asymmetry, with both electron and proton polarized along the beam direction. Here the measurements in the deep-inelastic regime (Fig. 1) show a very large asymmetry,[3] in accordance with general theoretical expectations.[4] However, detailed theoretical models in general do not do too well in determining the magnitude of the asymmetry and its dependence upon the scaling variable x.

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3. Parallel-antiparallel asymmetry in deep-inelastic electron-neutron scattering: these measurements are proposed[5] but not yet carried out. The asymmetry is, for moderate x, expected to be small,[4] while for large (perhaps unmeasurable) x, the neutron asymmetry must become nearly complete, and of the same sign as the proton asymmetry. As we shall see, this quantity is quite significant theoretically.
4. Longitudinally polarized electrons on transversely polarized protons with proton polarization in the scattering plane: these measurements are also proposed[5] but not yet carried out. The asymmetry parameter (the so-called A_2 parameter) is sensitive to σ_s/σ_t (it is bounded above by $\sqrt{\sigma_s/\sigma_t}$); hence a nonvanishing observed value has important theoretical implications for this rather poorly understood quantity.
5. The parity-violating electroweak asymmetry of longitudinally polarized leptons from unpolarized hadrons: the SLAC-YALE result[6] is so (justifiably) famous that no further mention need be made here. We must however, mention the new measurement from the CERN SPS muon beam.[7]

The theoretical expectation for a large parallel-antiparallel ep asymmetry is based upon a current-algebra sum rule,[4] which in modern form reads:

$$\int \frac{dx}{x}\left(\frac{A_p F_p(x)}{1+R_p} - \frac{A_n F_n(x)}{1+R_n}\right) = \frac{1}{3}\frac{|G_a|}{|G_v|}\left(1-\frac{\alpha_s}{\pi}(Q^2)\ldots\right) \cong 0.4 \qquad (2.1)$$

Here x is the deep-inelastic scaling variable, $A_{p,n}$ the polarization asymmetry, $F_{p,n}$ the usual structure functions F_2, and $R = \sigma_s/\sigma_t$ the ratio of longitudinal to transverse cross-sections.

The integrand for the first ("proton") term, on an appropriate logarithmic scale for x is shown in Fig. 2.

The "neutron" integrand is expected,[4,9] on moderately firm grounds, to be small. The data accounts for at least half the needed sum; what is needed to get it all is also shown in Fig. 2. It will be nice to check this point, which is quite a fundamental QCD test. Measurements at small x (pending[10] at CERN) will also shed some needed light on Regge asymptotics of <u>nonsinglet</u> structure functions. Here theory is not in good condition and some stimulation from experiment would be salutary.

III. THE ASYMMETRY FORMULAE

Deep-inelastic kinematics will not be reviewed here. We use the jargon of neutrino physicists and take as independent variables Q^2 = the squared invariant momentum transfer from lepton to hadron, and the scaling variables x and y. We also shamelessly use the simplest of quark-parton models, neglecting QCD scaling violations, as well as strange quarks and ocean quarks or antiquarks in the proton wave function. This can be valid quantitatively (at best) for

$x \gtrsim 0.2$. More professional assumptions are of course possible but less transparent.

Let us begin with charged - current weak processes, which become available for study at projected ep collider energies. In a hopefully self-evident notation we write for $e^- \; p \to \nu_e + \ldots$ with left-polarized e and p

$$\frac{d\sigma_{LL}^{(cc)}(e^-p)}{dx\ dy} = u_P(x)\sigma^{(cc)}(e^-u) \tag{3.1}$$

$u_P(x)$ = probability of finding, in the proton, an up quark with polarization parallel to proton polarization and with fraction x of the proton momentum (in the collider reference frame, for example)

$\sigma^{(cc)}$ = cross-section for the charged-current subprocess $e^-u \to \nu_e d$, with appropriate kinematic factors appended. (For asymmetries these kinematic factors will cancel out.)

Similarly,

$$\frac{d\sigma_{LR}^{(cc)}(e^-p)}{dx\ dy} = u_A(x)\sigma^{cc}(e^-u) \tag{3.2}$$

The asymmetry

$$\frac{d\sigma_{LL}^{(cc)} - d\sigma_{LR}^{(cc)}}{d\sigma_{LL}^{(cc)} + d\sigma_{LR}^{(cc)}} = A_p^{(cc)}(e^-p) = \frac{u_P - u_A}{u_P + u_A} \equiv a_u \tag{3.3}$$

directly measures an intrinsic quantity $a_u(x)$ which is the degree of polarization transfer from proton to up-quark. Positron-proton scattering is especially useful. We have

$$\frac{d\sigma_{RL}(e^+p)}{dx\ dy} = d_P(x)\sigma^{cc}(e^+d)(1-y)^2 \tag{3.4}$$

$$\frac{d\sigma_{RR}(e^+p)}{dx\ dy} = d_A(x)\sigma^{cc}(e^+d)(1-y)^2 \tag{3.5}$$

where the $(1-y)^2$ "angular" factor signals the helicity mismatch of right-handed positron and left-handed quark.

The proton asymmetry

$$A_p^{cc}(e^+p) = \frac{d_P-d_A}{d_P+d_A} \equiv a_d \tag{3.6}$$

again directly measures polarization transfer from proton to down quark. This quantity controls the parallel-antiparallel asymmetry in electron-neutron scattering, and is a difficult polarization parameter to determine. It also is sensitive to details of the quark structure in the proton wave function.

Cross-sections for neutral-current processes may be written down in a similar form. For example, for e^--p scattering,

$$\begin{aligned}\frac{d\sigma_{LL}(e^-p)}{dx\ dy} &= \left(u_P(x)\sigma_{LL}(e^-u) + d_P(x)\sigma_{LL}(e^-d)\right) \\ &+ \left(u_A(x)\sigma_{LR}(e^-u) + d_A(x)\sigma_{LR}(e^-d)\right)(1-y)^2\end{aligned} \tag{3.7}$$

Three more such equations can be easily written down. For e^+p scattering, there are similar expressions, related by crossing symmetry. For example:

$$\begin{aligned}\frac{d\sigma_{RL}(e^+p)}{dx\ dy} &= \left(u_P(x)\sigma_{LL}(e^-u) + d_P(x)\sigma_{LL}(e^-d)\right)(1-y)^2 \\ &+\left(u_A(x)\sigma_{LR}(e^-u) + d_A(x)\sigma_{LR}(e^-d)\right)\end{aligned} \tag{3.8}$$

Thus (given our simplifying assumptions of no "ocean" quarks, etc.) the positron measurements give in principle no new information. However, extraction of the two independent contributions, proportional to 1 and to $(1-y)^2$ respectively, can be troublesome. Here we shall go to the limit $y \to 0$ and use both e^-p and e^+p asymmetries. In this way all information is extracted.

In addition to the total $e^{\pm}p$ cross-sections there are six asymmetries which can be measured. Two asymmetries are the "old" single asymmetries with polarized lepton on unpolarized proton. In our simplified limit, these are:

$$A(e^-) = \left(\frac{\sigma_{LL}-\sigma_{RR}}{\sigma_{LL}+\sigma_{RR}}\right)_{e^-u} \frac{\{1+(d/u)[(\sigma_{LL}-\sigma_{RR})_{ed}]/[(\sigma_{LL}-\sigma_{RR})_{eu}]\}}{\{1+(d/u)[(\sigma_{LL}+\sigma_{RR})_{ed}]/[(\sigma_{LL}+\sigma_{RR})_{eu}]\}} \tag{3.9}$$

$$A(e^+) = \left(\frac{\sigma_{RL}-\sigma_{LR}}{\sigma_{RL}+\sigma_{LR}}\right)_{e^-u} \frac{\{1+(d/u)[(\sigma_{RL}-\sigma_{LR})_{ed}]/[(\sigma_{RL}-\sigma_{LR})_{eu}]\}}{\{1+(d/u)[(\sigma_{RL}+\sigma_{LR})_{ed}]/[(\sigma_{RL}+\sigma_{LR})_{eu}]\}} \tag{3.10}$$

Here the ratio d/u

$$d/u = \frac{d_p(x)+d_A(x)}{u_p(x)+u_A(x)} \tag{3.11}$$

has been determined[11] from (unpolarized) measurements of the ratio of electron-neutron and electron-proton deep-inelastic scattering. Within our simplified model

$$\frac{\sigma_{en}}{\sigma_{ep}} = \frac{4(d/u)+1}{4+(d/u)} \tag{3.12}$$

As $x \to 1$, this ratio experimentally tends to 1/4, implying

$$d/u \to 0 \quad \text{as} \quad x \to 1 \tag{3.13}$$

A reasonable fit is

$$d/u \simeq 1-x \tag{3.14}$$

The cross-section ratios appearing in the expressions for the asymmetries $A(e^{\pm})$ will be discussed later.

The four asymmetries directly relevant to the subject matter here involve polarized protons. It is convenient to compare the single asymmetries (unpolarized $e^{\pm}$, polarized p) with the "old" single asymmetries (polarized $e^{\pm}$, unpolarized p) to see what, if any, new information emerges. One easily finds, for e^-p scattering,

$$\frac{A(p)}{A(e^-)} = a_u \frac{\{1+(d/u)(a_d/a_u)[(\sigma_{LL}-\sigma_{RR})_{ed}]/[(\sigma_{LL}-\sigma_{RR})_{eu}]\}}{\{1+(d/u)[(\sigma_{LL}-\sigma_{RR})_{ed}]/[(\sigma_{LL}-\sigma_{RR})_{eu}]\}} \tag{3.15}$$

For e^+p scattering, we have

$$\frac{A(p)}{A(e^+)} = a_u \frac{\{1+(d/u)(a_d/a_u)[(\sigma_{RL}-\sigma_{LR})_{ed}]/[(\sigma_{RL}-\sigma_{LR})_{eu}]\}}{\{1+(d/u)[(\sigma_{RL}-\sigma_{LR})_{ed}]/[(\sigma_{RL}-\sigma_{LR})_{eu}]\}} \tag{3.16}$$

Assuming that a_u is "well-known" (as is essentially the case already!), the unknowns in these ratios are cross-section ratios, which depend only on Q^2, not x (or y). But they are accessible to single-asymmetry measurements with polarized leptons [eqns. (3.9) and (3.10)]. In principle, one looks at the asymmetry $A(e^{\pm})$ at fixed Q^2 as function of x. The other unknown is (a_d/a_u), which might be better determined from charged-current data. We also note that the cross-section ratios in the denominators $(\sigma_{LL}+\sigma_{RR})_{ed}/(\sigma_{LL}+\sigma_{RR})_{eu}$ and $(\sigma_{LR}+\sigma_{RL})_{ed}/(\sigma_{LR}+\sigma_{RL})_{eu}$ are each equal to 1/4 (the ratio of squared charges) for Q^2 small compared to the characteristic scale of the weak interaction ($\sim 10^4 \mathrm{GeV}^2$), and should not be considered unknown.

Finally, the last pair of asymmetries, the double asymmetries, are given by

$$A(e^-p) = a_u \frac{\{1+(d/u)(a_d/a_u)[(\sigma_{LL}+\sigma_{RR})_{ed}]/[(\sigma_{LL}+\sigma_{RR})_{eu}]\}}{\{1+(d/u)[(\sigma_{LL}+\sigma_{RR})_{ed}]/[(\sigma_{LL}+\sigma_{RR})_{eu}]\}} \tag{3.17}$$

$$A(e^+p) = a_u \frac{\{1+(d/u)(a_d/a_u)[(\sigma_{LR}+\sigma_{RL})_{ed}]/[(\sigma_{LR}+\sigma_{RL})_{eu}]\}}{\{1+(d/u)[(\sigma_{LR}+\sigma_{RL})_{ed}]/[(\sigma_{LR}+\sigma_{RL})_{eu}]\}} \tag{3.18}$$

Again the cross-section-ratios equal 1/4 (for $Q^2 \ll 10^4 \mathrm{GeV}^2$), and the ratio d/u is considerably less than 1. Thus, to good approximation, the asymmetry is insensitive to (a_d/a_u):

$$A(e^{\pm}p) \simeq a_u(x) \tag{3.19}$$

IV. PARTON CROSS-SECTION RATIOS IN THE STANDARD MODEL

Enough is already known[12] that it would be surprising were there a gross deviation at moderate Q^2 of the quark-lepton cross-sections from the standard SU(2)×U(1) electroweak theory. Therefore we evaluate the cross-section ratios appearing in the previous formulae in the standard model. The relevant part of the neutral-current electroweak amplitude may be conveniently written as

$$\mathcal{M} = \frac{e^2}{Q^2}\left[Q^{(1)}Q^{(2)} + \frac{Q^2}{(Q^2+M_z^2)}\left(\frac{T_3^{(1)}T_3^{(2)}}{\sin^2\Theta_W} + \frac{Y^{(1)}Y^{(2)}}{\cos^2\Theta_W} - Q^{(1)}Q^{(2)}\right)\right]$$

$$= \frac{e^2M_z^2}{Q^2(Q^2+M_z^2)}\left[Q^{(1)}Q^{(2)} + \frac{Q^2}{M_z^2}\left(\frac{T_3^{(1)}T_3^{(2)}}{\sin^2\Theta_W} + \frac{Y^{(1)}Y^{(2)}}{\cos^2\Theta_W}\right)\right] \tag{4.1}$$

with $Q^{(i)}$, $T_3^{(i)}$, and $Y^{(i)}$ the charge, third component of weak isospin, and weak hypercharge

$$Q^{(i)} = T_3^{(i)} + Y^{(i)} \tag{4.2}$$

of the i^{th} projectile. In order to obtain the cross-section ratios, only the square of the factor in the square brackets need be calculated for the various processes. The result is shown in Fig. 3. We see that the "parity-conserving" cross-section ratios do not grow with Q^2 by more than a factor two from their starting value of 1/4. The "parity-violating" ratios are typically of order unity, affording a much better opportunity for large observational effects.

V. POLARIZATION TRANSFERS TO THE DOWN-QUARK: THE PARAMETER a_d AND THE ELECTRON-NEUTRON ASYMMETRY

The parameter a_d is poorly known. Were it to vanish, the proton asymmetry measurement would yield very little beyond what we already know (except perhaps for scaling-violation studies of the a_u). As we already mentioned, the electron-neutron asymmetry is sensitive to a_d. Because of the current-algebra sum-rule combined with SU(6) estimates,[4] on average the neutron asymmetry should be near zero. In fact, with our omission of strange quarks, it can be estimated[9] to be $\backsim$-10% of the proton asymmetry. However, it follows from charge symmetry (and our simplified assumptions) that

$$A(e^-n)=a_u \frac{\{1+(d/u)(a_d/a_u)[\sigma_{LL}+\sigma_{RR})_{eu}]/[(\sigma_{LL}+\sigma_{RR})_{ed}]\}}{\{1+(d/u)[\sigma_{LL}+\sigma_{RR})_{eu}]/[(\sigma_{LL}+\sigma_{RR})_{ed}]\}} \tag{5.1}$$

Setting the cross-section ratio equal to 4, and solving for a_d in terms of the "observables" A(en), A(ep), and n/p, one finds

$$\left(\frac{n}{p} - \frac{1}{4}\right) a_d = \frac{n}{p} A(en) - \frac{1}{4} A(ep) \tag{5.2}$$

As $n/p \rightarrow 1/4$, i.e. as $x \rightarrow 1$, it follows that

$$A(en) \rightarrow A(ep) \quad \text{as } x \rightarrow 1 \tag{5.3}$$

i.e. from the data

$$A(en) \rightarrow 1 \tag{5.4}$$

Therefore, it is not everywhere small.* Also if A(en) in more predominant regions of x (say, 0.2-0.7) is very small, then

$$\left(\frac{a_d}{a_u}\right) \sim - \frac{1}{4(n/p)-1} \; ? \qquad (A(en) \sim 0) \tag{5.5}$$

suggesting a negative value of the ratio of intrinsic asymmetries. However, these remain speculations. Better would be some solid measurements.

VI. IMPLICATIONS

What measurements seem especially relevant and why? We may outline a few:

i) The double asymmetry at small x ($\gtrsim 10^{-3}$) helps test the electroproduction sum rule.

ii) At large x, the double asymmetry is insensitive to electroweak effects but gives a good determination of the polarization-transfer parameter a_u and its scaling behavior.

iii) The best way to obtain the parameter a_d might be (with sufficient energy and luminosity) to measure the proton polarization asymmetry in positron-proton charged-current interactions.

iv) If one assumes the validity of standard electroweak theory-or if the relevant parameters are measured via polarized-lepton asymmetries, then the single polarized proton asymmetries may be a good way to determine $a_d(x)$. A positive effect would be enhanced were $a_d(x)/a_u(x)$ negative - as we speculated in the previous section might well be the case (for moderate values of x).

In addition to these inferences, we should not forget the limited nature of the above considerations. Several other measurements come to mind.

i) We have ignored any possible polarization transfer to strange or to "ocean" quarks and antiquarks in the proton. Probably careful

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*One has the inequality

$$|A(en)| \geq p/4n \; |A(ep)| - \{1-p/4n\},$$

useful for (at least) $x \gtrsim 0.7$.

study of y-dependence of $e^{\pm}$-p asymmetries would be necessary to disentangle such effects.

ii) Measurement of the aforementioned A_2 asymmetry should be possible. Theory predicts[13] it to be quite small, although the situation is murky.

iii) The T-violating asymmetry (from lepton-quark scattering) may be studied, although theory, to my knowledge, offers little if any encouragement for finding a positive effect.

iv) If right-handed charged currents[14] were to be found, it would of course be nice to learn more about the hadron vertex using proton polarization. But this is a second-generation question.

v) There should be spin-dependent effects in the hadron final state. I have not looked into these, although there should be e.g., dependence of the angular distribution of gluon jets upon proton polarization. [The whole subject of hadronization, polarization or not, is an especially attractive feature of ep colliders: richer than e^+e^-, but not as complex as pp or $p\bar{p}$.]

VII. CONCLUDING COMMENTS

The most certain result of the addition of proton polarization to e^-p collisions appears to be the new information on the quark structure of the nucleon. The information thus far obtained, as one can see, already creates some problems for theory.

What are appropriate energy-scales for this kind of physics? The small-x asymmetries may still be measurable at $x \sim 10^{-3}$, which, if true, demands $s \gtrsim 10^4 \text{GeV}^2$, well above what is available in fixed target experiments. For large-x asymmetries, we have seen that positron-proton charged-current reactions are very useful. For these to be measurable, one would again like $Q^2 \sim 10^3\text{-}10^4 \text{GeV}^2$, hence $s \sim 10^4\text{-}10^5 \text{GeV}^2$.

For large-x neutral current parity-violating asymmetries, one could make good use of Q^2 values of $\sim 10^4$ GeV^2, where the asymmetries may be expected to be quite large and statistics not too much of a problem. For $Q^2 \gtrsim 10^4 - 10^5$ GeV^2 and typical luminosities of 10^{32} cm^{-2} sec^{-1}, there is not much rate remaining. This implies that for $s \gtrsim 10^5\text{-}10^6$ GeV^2 the large-x region is no longer accessible. However, this is hardly a restriction for a long time.

Thus for the foreseeable future, there is no saturation of physics interest with increasing energy-indeed quite the opposite. If a polarized-proton capability is not inordinately difficult or costly, it is clear that the physics menu is rich enough to easily justify the effort. If providing polarized protons becomes a major cost factor, much more careful study than contained in this short sketch is needed to see whether the physics benefits would justify the effort.

VIII. ACKNOWLEDGEMENTS

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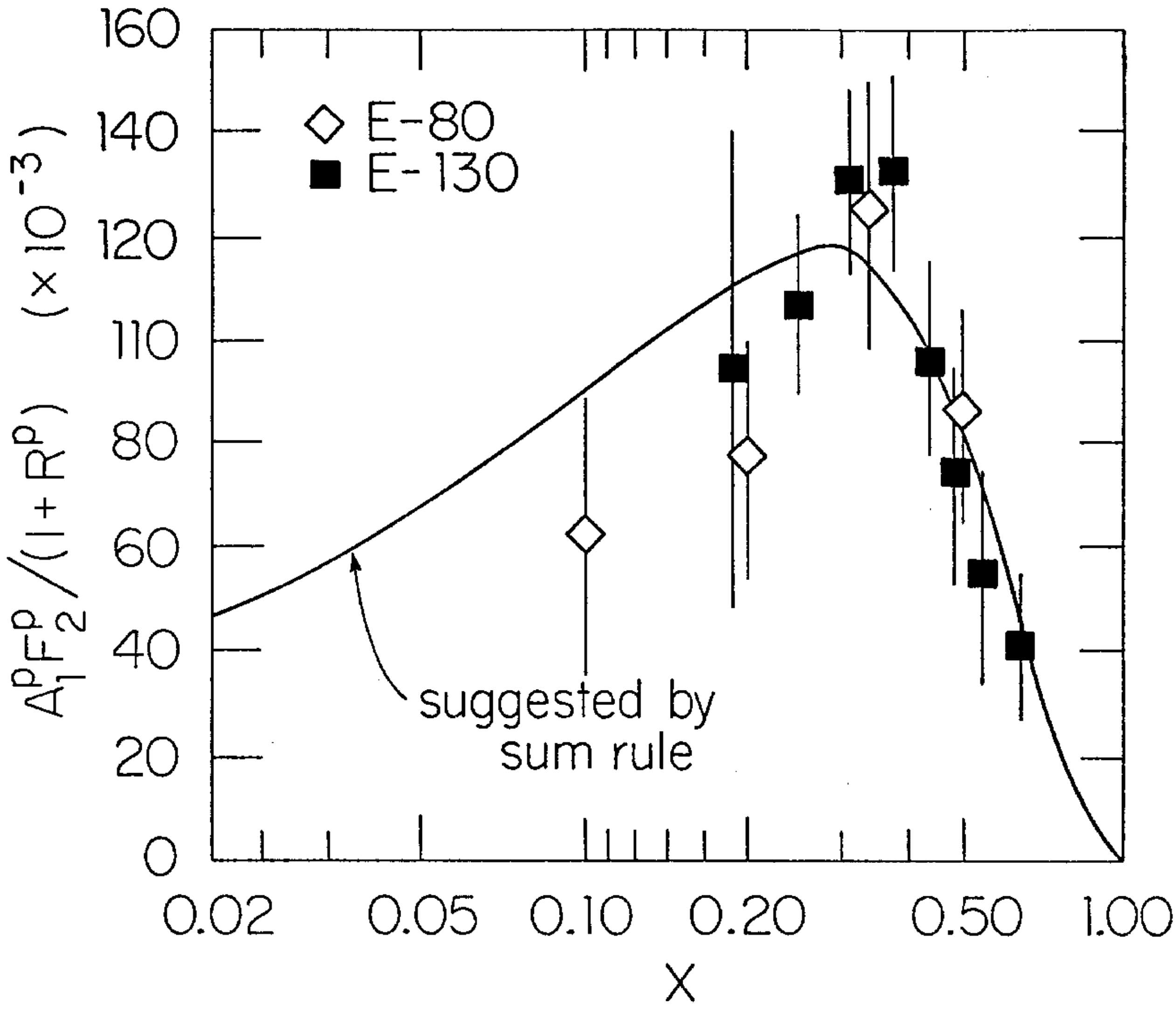
14. This is a popular goal of ep collider proponents. However, diagonal right handed currents involving e,u,and d alone are known to be small. Off-diagonal right-handed currents are, however, conceivable.

FIGURE CAPTIONS

Fig. 1: Double asymmetry in ep scattering, as measured in SLAC experiments E-80 and E-130. Also shown are various theoretical calculations: (1) J. Kuti and V. Weisskopf, Phys. Rev. D4, 3418 (1971); (2) F. Close, Nucl. Phys. B80, 269 (1974); (3) G. Look and E. Fischbach, Phys. Rev. D16, 211 (1977); L. Sehgal, Phys. Rev. D10, 1663 (1974); (4) R. Carlitz and J. Kaur, Phys. Rev. Letts. 38, 673; 1102(E) (1977); J. Kaur, Nucl. Phys. B128, 219 (1977); (5) R. Jaffe, Phys. Rev. D11, 1953 (1975); R.J. Hughes, Phys. Rev. D16, 662 (1977); (6) J. Schwinger, Nucl. Phys. B123, 223 (1977); (7) G. Preparata, ref. 1, p. 121.

Fig. 2: Integrand for polarization sum-rule versus x.

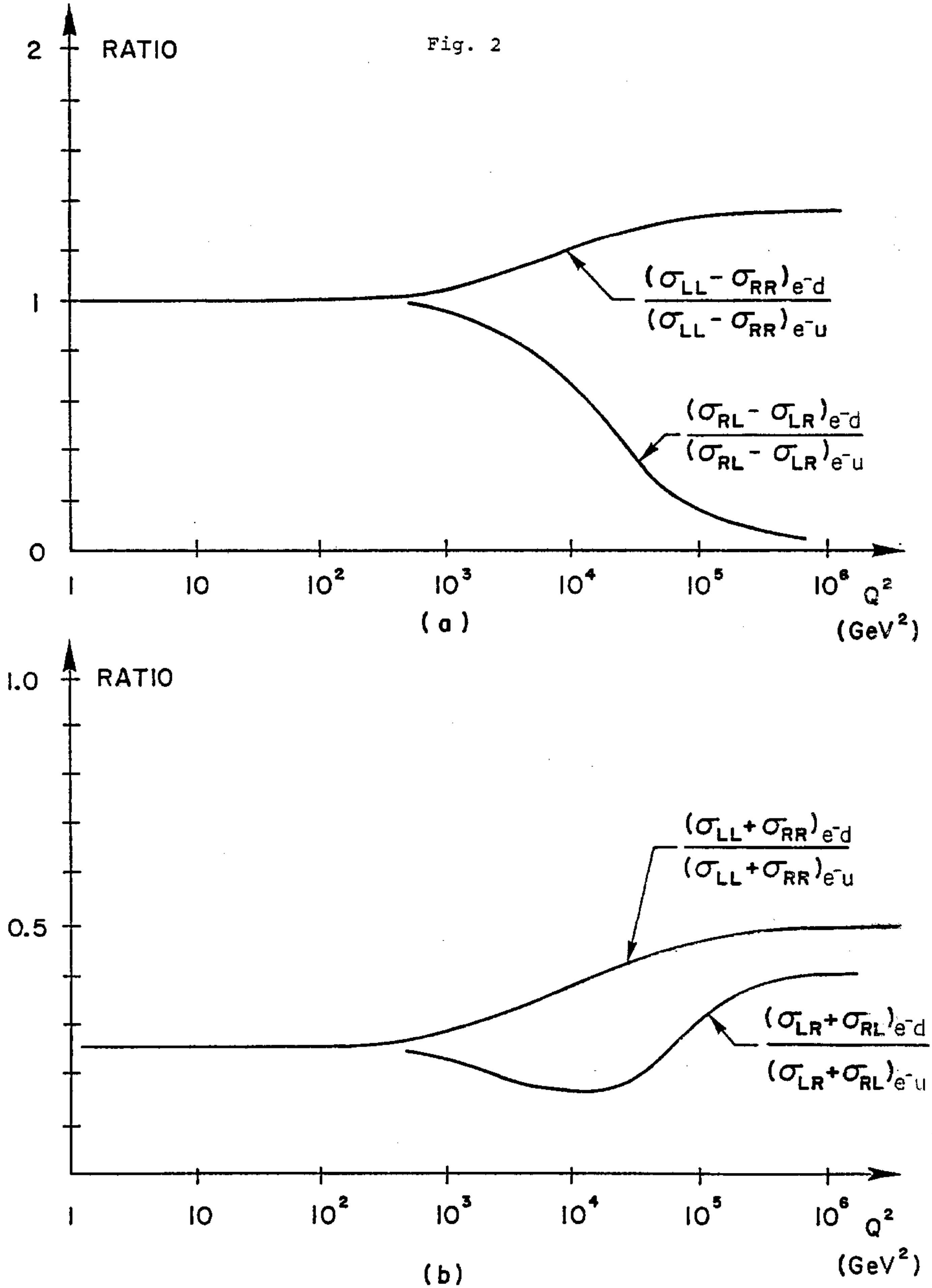
Fig. 3: Cross-section ratios relevant to spin asymmetry measurements: (a) "Parity-violating" ratios, and (b) "Parity-conserving" ratios. The standard SU(2)×U(1) electroweak model is assumed correct.



E-80
E-130
suggested by
sum rule
$A_1^p F_2^p / (1 + R^p)$ $(\times 10^{-3})$
160
140
120
110
80
60
40
20
0
0.02
0.05
0.10
0.20
0.50
1.00
X

Fig. 1

Fig. 2


RATIO
2
1
0
$\frac{(\sigma_{LL} - \sigma_{RR})_{e^-d}}{(\sigma_{LL} - \sigma_{RR})_{e^-u}}$
$\frac{(\sigma_{RL} - \sigma_{LR})_{e^-d}}{(\sigma_{RL} - \sigma_{LR})_{e^-u}}$
1 10 10^2 10^3 10^4 10^5 10^6 Q^2 (GeV^2)
(a)
RATIO
1.0
0.5
$\frac{(\sigma_{LL} + \sigma_{RR})_{e^-d}}{(\sigma_{LL} + \sigma_{RR})_{e^-u}}$
$\frac{(\sigma_{LR} + \sigma_{RL})_{e^-d}}{(\sigma_{LR} + \sigma_{RL})_{e^-u}}$
1 10 10^2 10^3 10^4 10^5 10^6 Q^2 (GeV^2)
(b)

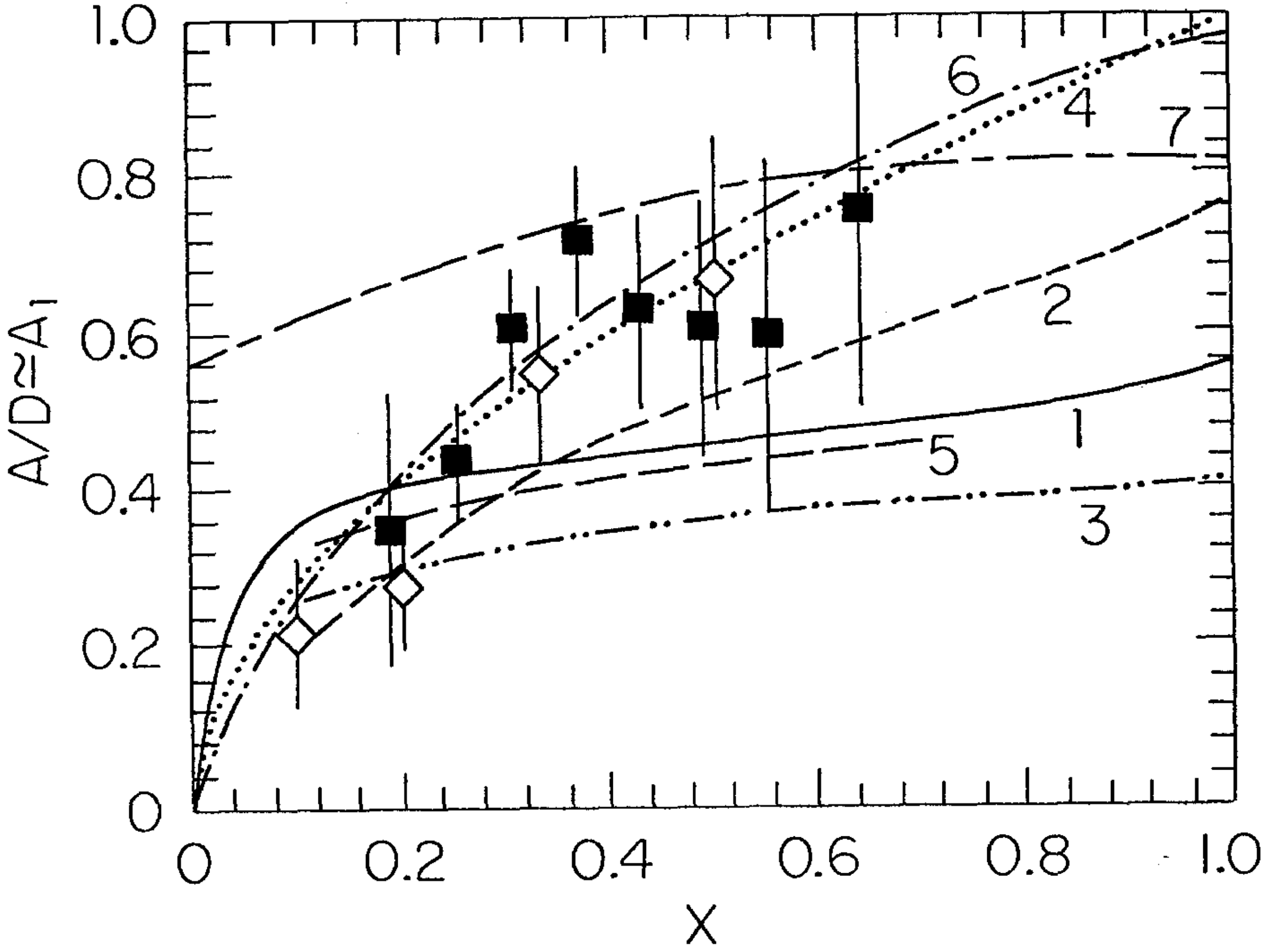


Fig. 3