# PARITY VIOLATING TOTAL CROSS SECTIONS

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## Abstract

A diquark-quark scattering model for the parity-violating asymmetry in nucleon-nucleon scattering is described. Criticism of the model by Simonius and Unger is refuted. The strong energy dependence of the result, and the possibility of important non-valence contributions to the nucleon polarization, both support the need for further measurements at Fermilab and at Brookhaven energies.

Until recently, parity violating total cross sections of the form

$$PVA = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} , \tag{1}$$

where $\sigma_{+(-)}$ is the total cross section for positive (negative) helicity particles on an unpolarized target, were mostly of interest only at low energies. There, elegant experiments have found effects at the $10^{-7}$ level. Only one higher energy experiment, at 6 GeV/c, has been performed[1]. This found an effect at the $10^{-6}$ level, which is difficult to comprehend in the context of low energy, meson exchange pictures. From a high energy, quark point of view, however, this would seem natural since the strong amplitude A is schematically

$$A \sim \alpha_s/q^2 \tag{2}$$

where $\alpha_s$ is the strong coupling, and $q^2$ is the four-momentum transfer, and the weak parity-violating amplitude is similarly

$$B \sim G_F \tag{3}$$

Then, since $\alpha_s \lesssim 1$ and $\langle q^2 \rangle \sim 0.1\ \mathrm{GeV}^2/c^2$,

$$\begin{aligned} PVA &\sim \frac{|A^* B|}{|A|^2} \\ &\sim G_F \langle q^2 \rangle / \alpha_s \quad . \\ &\sim 10^{-6} \end{aligned} \tag{4}$$

Detailed calculations require studying the strong and weak amplitudes as shown in Figs. 1-3. In Fig. 1, we show QCD gluonic exchange amplitudes for quark-quark ($A_q$) and quark-diquark scattering ($A_d$). To leading logarithm order, to all orders in perturbation theory, we can drop the first three types of graphs by replacing the vertex strength in all of the others by the running coupling constant. For consistency, we must make the (QCD) leading log corrections to the weak parity-violating quark-quark interaction, $B_q$, which is indicated by the graphs in Fig. 2. However, when considering strong corrections to weak amplitudes, there are also the quark-diquark amplitudes $B_d$ shown in Fig. 3, (which also include the running coupling constant.)

We have found[2] that all of the contributions of these graphs to the PVA are $\lesssim 10^{-7}$, with the possible exception of those of the form

$$\mathrm{PVA} \simeq \frac{B_d^* A_d + A_d^* B_d}{|\Sigma A_i|^2} \tag{5}$$

where the sum in the denominator runs over <u>all</u> QCD graphs. To the extent that QCD provides a correct representation of the strong interactions, the denominator can be replaced by the spin averaged total nucleon-nucleon cross section, provided only that QCD parameters fitted to experiment are used in the numerator of (5).

We use a renormalization scale of order 1 $\mathrm{GeV}^2 \equiv \mu^2$ and set $\alpha_s \sim 1$ there corresponding to $\Lambda_{QCD} \sim 400$ MeV at the one-loop level. This is consist with $\Lambda_{\overline{MS}} \simeq 100$ MeV at the two-loop level, and so represents well-accepted parameters.

We should also note here that the use of diquarks and of gluons requires representations of their confinement. We do this by giving a finite width $\Gamma$ to the diquark in the final state, thus representing its confinement as a unitarity loss into other (confined) channels. The gluon we give an effective mass $\lambda$ which nicely limits the range of its virtual propagation. We have found that, by setting $\lambda = \mu$, (which gives a very short gluon range and so can be expected to underestimate the size of the following amplitudes), an analytic calculation can be made for the dominant (polarized) diquark contribution to the PVA. This contribution is shown in general in the graphs in Fig. 4, (all other diquark overlaps vanish due to tracelessness of the QCD coupling matrices), but in fact, three of these vanish and the entire result is due to the first overlap alone.

Before giving the specific form of the result, we comment on the physical interpretation of the relevant graph. On the $B_d$ side of the intermediate state cut, the graph would represent solely wavefunction mixing of the polarized diquark component of the nucleon. However, the distorting strong interaction in the initial state, due to the gluon exchanged between the quark from one nucleon and the diquark from the other, injects a four-momentum which raises the intermediate state (final in the actual scattering) diquark to larger mass scales. As such, this calculation includes all relevant parity violating <u>mixing</u> between the nucleon and higher mass baryonic states. It is <u>not</u> constrained by (low energy) nuclear data on (diagonal) parity violating components of the nucleon itself.

Explicitly, we find[2]

$$\mathrm{PVA} = \frac{8G_F}{\sqrt{2}} \left(\frac{\eta\chi}{\sigma}\right) \left[F_d\left(\frac{S}{\mu^2}, b\right) + F_q\left(\frac{S}{\mu^2}, b\right)\right] \tag{6}$$

where $1.6 \leq \eta \leq 6$ represents the uncertainty in the short distance QCD (loop) enhancement of the weak vertex operator, $\sigma \simeq 40$ mb, and

$$\chi \equiv |\psi_d(0)|^2/m\Gamma \simeq 30 \tag{7}$$

taking reasonable values for the diquark wavefunction at the origin $\psi_d(0)$, the current quark mass m for light quarks, and the diquark width $\Gamma$ referred to above. The parameter b comes from the one-loop QCD evolution of the strong coupling; we have used b = 1.4 for our central results below. Finally, S is the total squared energy in the center of momentum frame for the nucleon-nucleon collision.

The explicit analytic forms of the F's are as follows:

$$\begin{aligned} F_d(x,y) = (32\pi/9x^2y^3)\{&1296G(2,x,y) \\ &- 36(x + 54)G(1,x,y) \\ &+ (x^2 + 36x + 648)G(-1,x,y) \\ &- \tfrac{1}{2}x^3y(1 + \ln H(x,y))/(x + 36)H(x,y)\}, \end{aligned} \tag{8}$$

$$\begin{aligned} F_q(x,y) = 32\pi/9x^2y^3)\{&-216G(2,x,y) \\ &+ 6(x + 54)G(1,x,y) - 6(x + 18)G(-1,x,y) \\ &- \tfrac{1}{12}x^3y(1 + \ln H(x,y))/(x + 36)H(x,y)\}, \end{aligned} \tag{9}$$

where

$$H(x,y) \equiv 1 + y\ \ln(1 + x/36) \tag{10}$$

and

$$\begin{aligned} G(n,x,y) = e^{-n/y}\{&(1 + \ln H(x,y))\mathrm{Ei}(nH(x,y)/y) \\ &- \mathrm{Ei}_2(-nH(x,y)/y) - \mathrm{Ei}(n/y) + \mathrm{Ei}_2(-n/y)\}\ , \end{aligned} \tag{11}$$

where Ei is the conventional exponential integral function[3] and $Ei_2$ is defined in Ref. 4 as $Ei_1^{(2)}$. We also note the limiting high energy behaviour, for $x \gg 1$

$$F_d(x,y) \sim (32\pi/9y^2)\{(1/y)\exp(1/y)$$
$$\times [Ei_2(1/y) - Ei(-1/y)]$$
$$\cdot[1 + \ln\{1 + y \ln(x/36)\}/[1 + y \ln (x/36)] + \ldots] \qquad (12)$$

and

$$F_q(x,y) \sim (4\pi/9y)$$
$$\times \ln [1 + y \ln(x/36)]/[1 + y \ln (x/36)]^2 + \ldots] \qquad (13)$$

Before presenting our numerical results and some conclusions, we note that Simonius and Unger (SU) have taken exception to what has been described thus far[5]. We take this opportunity to respond to these critisisms:

Where we take the measured total cross section for the PVA denominator, SU take only one graph, corresponding to the sole surviving numerator graph, but with a gluon exchange replacing the weak (four-fermion) vertex operator. It is straightforward to see that this is not consistent as there is no reason to assume that the other QCD graphs vanish. In fact, this graph represents neither a complete set nor even a gauge invariant subset of graphs, and hence, the procedure is not sensible. Beyond this, SU have not included the running QCD coupling constant, which we found significantly affects our results -- damping the high energy growth of the F-functions.

That there is some difference is apparent from the fact that SU find <u>8 barns</u> for the nucleon-nucleon total cross section at $S = 13$ GeV$^2$. If this were true, QCD would have proven false! But the SU calculation cannot be correct since it is well known that such subleading graphs in a renormalizable theory must <u>fall</u> with increasing S and theirs does not. In fact, our results fall as lnlnS/lnS despite the nonrenormalizable weak vertex (which, by the way, limits the applicability of our results to $\sqrt{S} \lesssim$ 1 TeV, where the effect of the W-boson propagator should become apparent), and so the SU result should fall even faster; again, it does not fall but rather increases with S. We are unable to trace the source of the error, since they present only numerical results. Note further that they claim agreement with our PVA numerator calculation for $\chi \simeq 1/2$, whereas in fact, we have used $\chi \simeq 30$.

This problem is reminiscent of others in QED where gauge invariance has not been properly implemented. There, as here, a single graph at a given order can be larger than the sum, showing that there, as here, arbitrarily picking out one graph is completely unjustified. Our effectively single graph result for the weak PVA numerator came from examining <u>all</u> graphs to this order, and finding that, <u>in that particular case</u>, the rest were negligible, or vanished. It is clear this would not be the case for the QCD denominator.

We regret the necessity of making these strong, pejorative remarks. However, in view of the published comments of SU, we could not avoid making a response.

We now turn to our numerical results[2] shown in Fig. 5 as curve c). The experimental points are from Refs. [1] and [6]. The a) and b) curves are a Regge wavefunction mixing calculation due to Nardulli and Preparata[7], which have been criticized elsewhere[8]. Our curve has been normalized to the high energy data due to the difficulty in ascertaining a precise value for $\chi$.

To estimate the uncertainty in our prediction, which is really a prediction of the energy dependence of the PVA, we show Fig. 6. Here, curve b) represents all of the smaller effects not discussed explicitly in this presentation. Curves a) represent the total effect, dominated by the diquark contributions of Eq. (6). As can be seen from that equation, once the overall normalization is fixed (at $P_{lab}$ = 6 GeV/c by the experimental result), all of the uncertainty is due to the parameter b, which effectively represents the strength of the QCD coupling at the $\mu^2$-scale. Although this is rarely taken to vary by more than 50% from the value we have used, we have presented an extreme (almost factor of three) variation to show that our prediction of a strong (but eventually saturating) increase of the PVA with S cannot be avoided in our diquark picture. A Brookhaven experiment should expect PVA ~ $10^{-5}$ and a Fermilab experiment, almost $10^{-4}$. Naturally, the prudent experimenter will design for an order of magnitude better sensitivity than these predictions, if possible.

In summary, we have presented a crude model which, as for deep inelastic structure functions, cannot supply an accurate prediction of the PVA at a given energy, but which should be valid for the (strong) energy dependence of the PVA at high energies. An upper bound of 1 TeV applies due to approximations made in evaluating the model. Amazingly, it is even consistent with data between 6 and 1.5 GeV/c, when the variation of the total nucleon-nucleon cross section between those beam momenta is taken crudely into account.

This is where this manuscript would have ended, except for the startling experimental results presented at this conference regarding the spin fraction of the nucleon carried by non-valence constituents. Our model is based on the heretofore conventional wisdom that all of the nucleon spin is carried by the valence quarks. If the sea and gluons are highly polarized, then graphs for B which we have ignored (see Fig. 7) could be come important. We would find this hard to credit except for one consideration: the two-phase vacuum model of confinement involves chromo-electric and -magnetic fields. These could carry significant spin, polarizing the sea quarks to produce a precise cancellation for an "empty" perturbative vacuum bubble. Introduction of polarized valence quarks would certainly disturb this cancellation, and it is precisely at small Bjorken x where one would expect the largest effect. We speculate that this is related to high-$p_T$ polarization phenomena[9] when the $P_T$ is large enough that the hard scattering involved occurred in one polarization region. However, this speculation and the effect of these considerations on the PVA require considerable additional effort before any conclusions can be drawn. The measured high energy PVA will be an important constraint for interpreting the results of such a theoretical study.

## References

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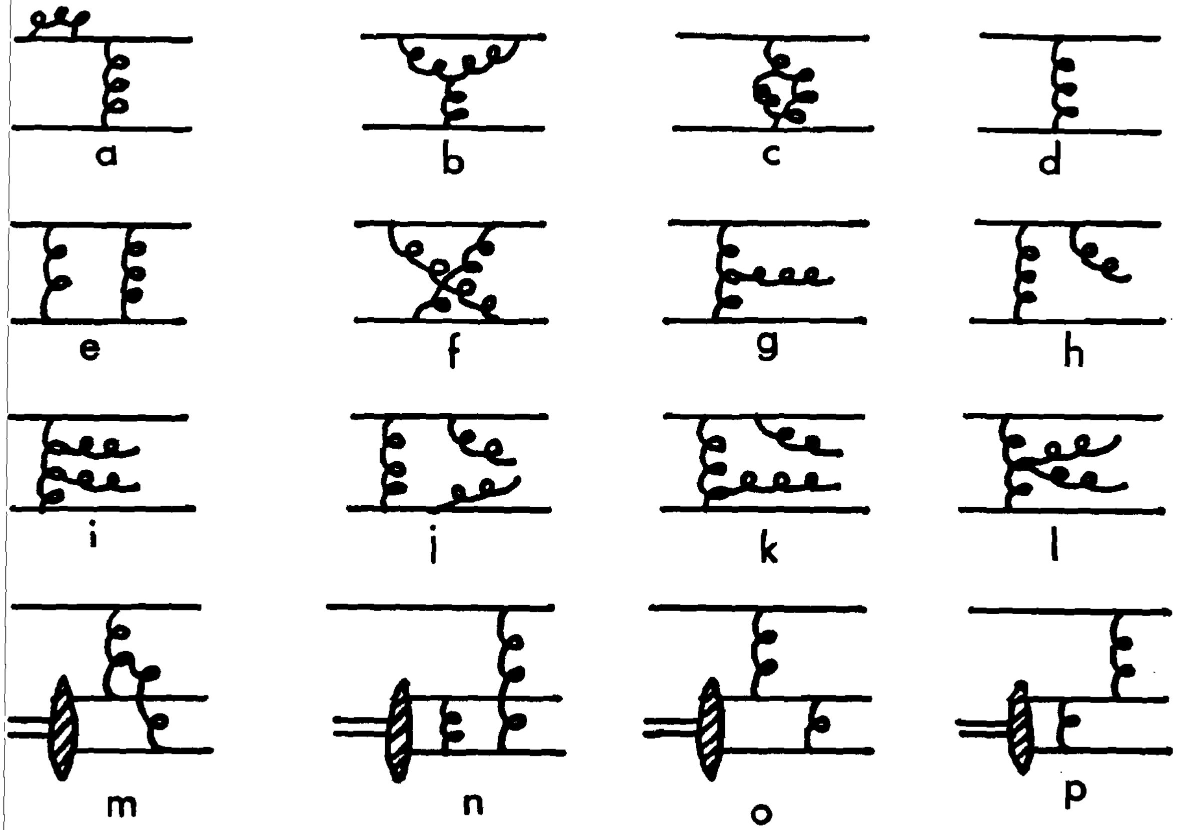


Fig. 1. Quark-quark [a) - ℓ] and quark-diquark [m) - p)] scattering amplitudes in QCD.

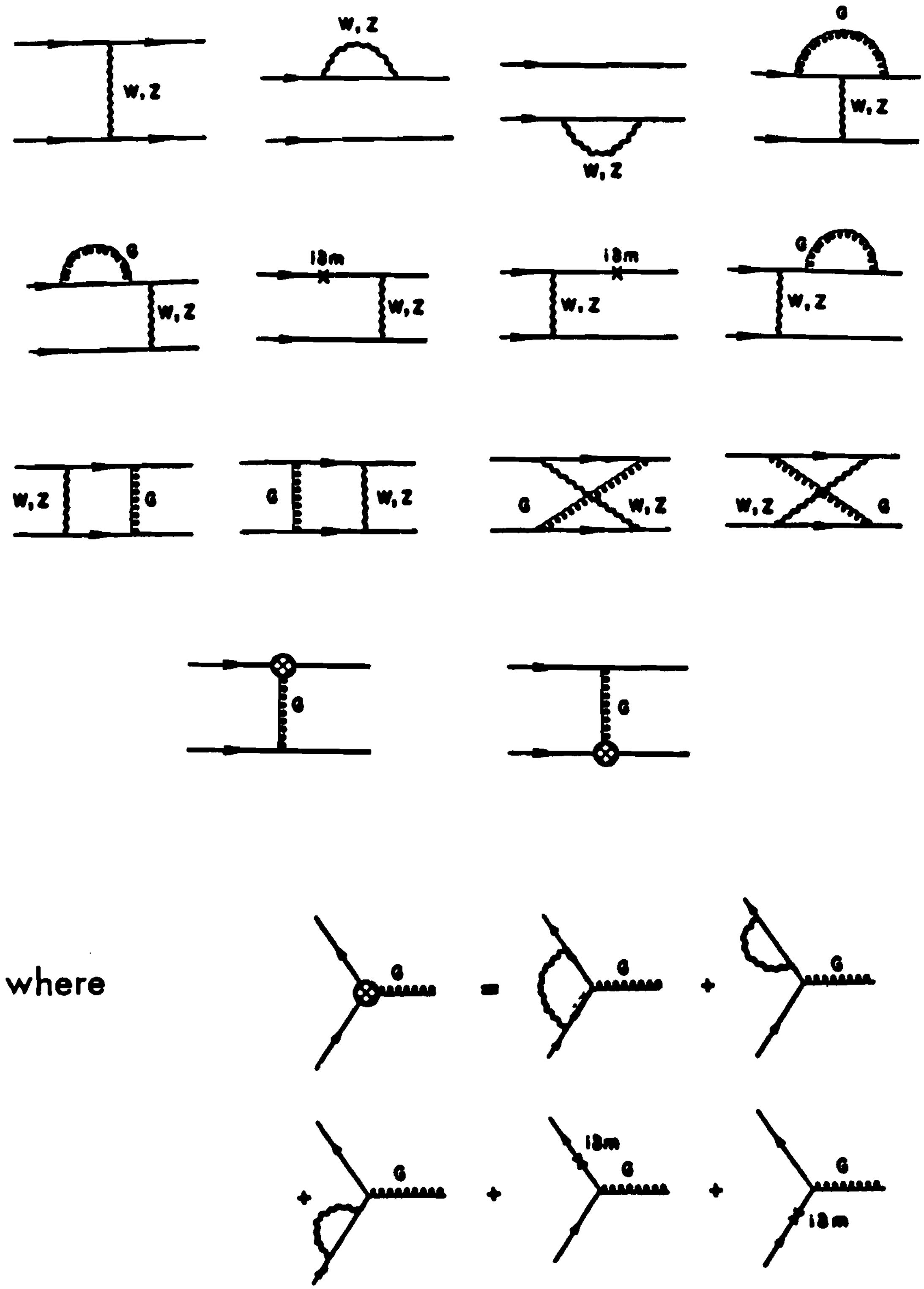


**Fig. 2. Quark-quark weak scattering amplitudes and their one-loop QCD corrections.**

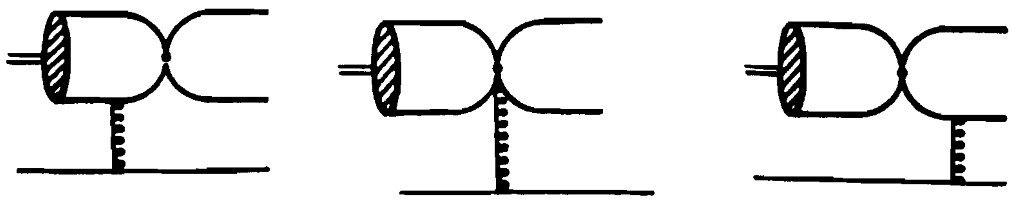

Fig. 3. QCD correction to weak quark-quark scattering within a diquark due to the presence of a quark from another hadron. The dot at the point four-fermion interaction vertex represents the (leading log) sum of all of the graphs in Fig. 2 for four-momentum transfers squared much less than $M_W^2$ or $M_Z^2$.

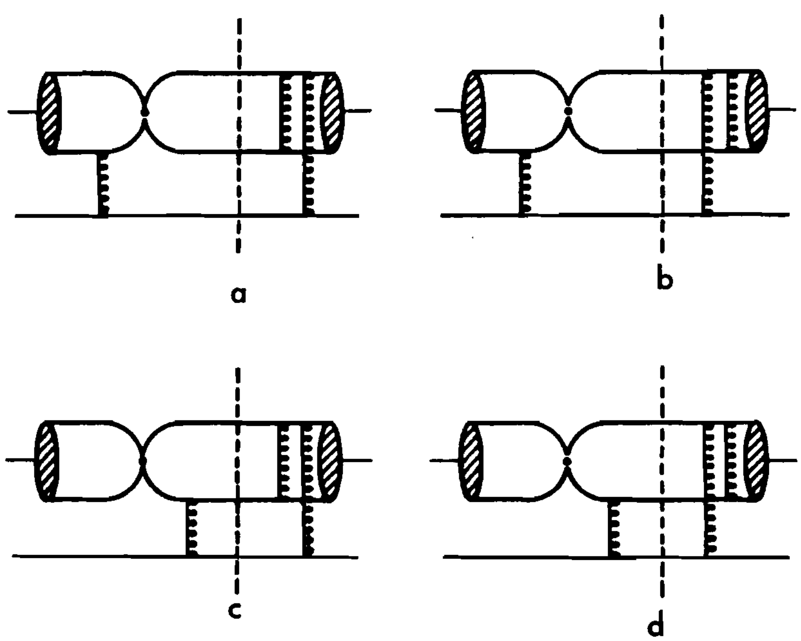


Fig. 4. Quark-diquark contributions to the PVA which do not vanish simply due to tracelessness of the QCD coupling matrices.

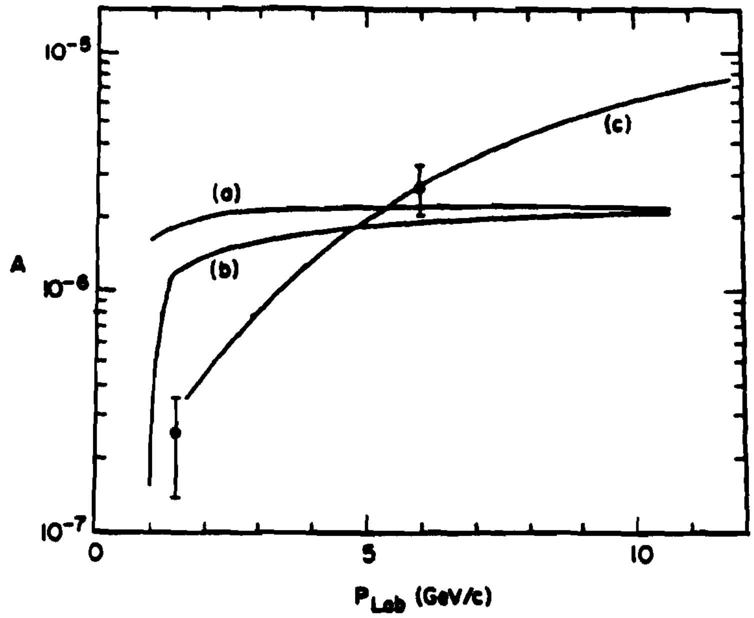


Fig. 5. PVA in N-N scattering: Curve c) from Ref. 2 and this work; curves a) - b) from Ref. 7; experimental points from Refs. 1 and 6.

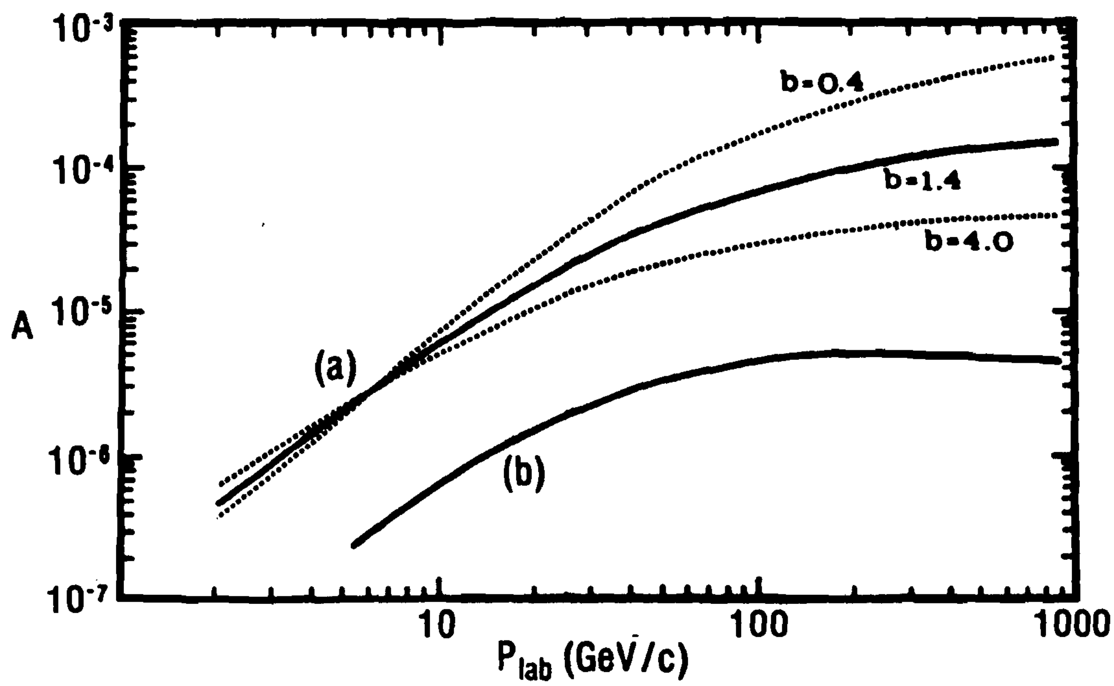


Fig. 6. a) Beam-momentum dependence of the PVA in this model for 3 values of the parameter, b. Curve b) shows the contribution to a) from quark-quark scattering terms not explicitly discussed here.

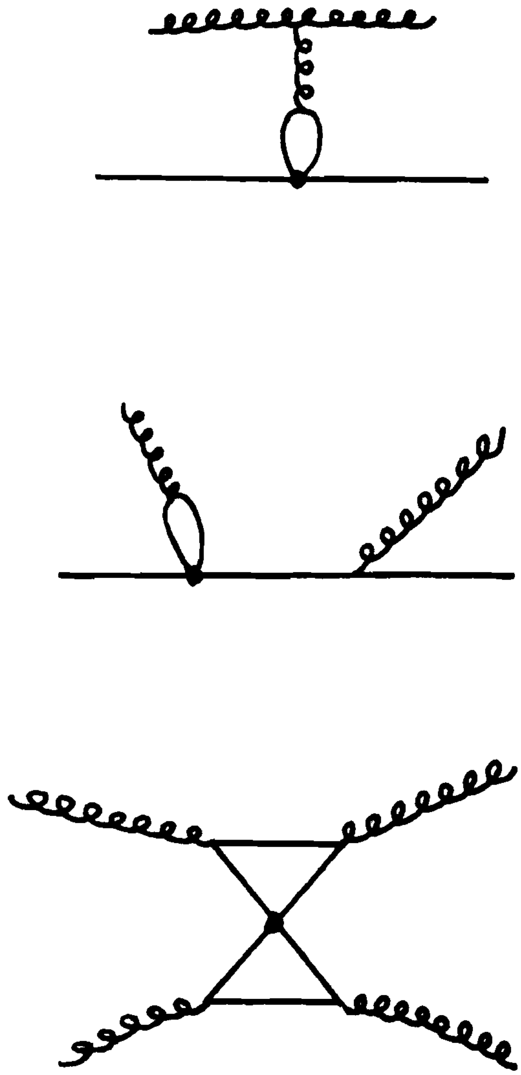

Fig. 7. Additional contributions to PVA amplitudes which arise if non-valence partons contribute significantly to the nucleon polarization.