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POLARIZATION OBSERVABLES IN ϕ-MESON PHOTOPRODUCTION

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Introduction

Recently, the strangeness content of ordinary nucleons and nuclei has attracted considerable interest [1–4]. This is connected with experimental evidence of nonzero strangeness matrix elements in the proton which comes from the measurement of the pion-nucleon σ-term at low energies [5] and deep-inelastic polarized muon scattering from the proton [6]. At the same time, it has been argued [7] that both measurements could be understood with a little or without strangeness content in the nucleon. Therefore, it is natural to consider other independent tests related to the strangeness content [1,3,8]. One of them is to use the leptoproduction and photoproduction of the ϕ meson from a proton, as it has been suggested by Henley *et al.* [1,2]. The idea is to determine the amount of the $s\bar{s}$–admixture in the nucleon by isolating the direct knockout contribution to the measured cross section. Since the quark content of ϕ is purely $s\bar{s}$, other processes violating the OZI rule are suppressed. In Ref. [2], the calculation has been carried out in a non-relativistic quark model (NRQM) and the direct knockout contributions have been found to be comparable with the prediction of the vector-meson dominance model (VDM) [9] of diffractive production if a (10-20)% strange quark admixture is assumed.

In Ref. [10], this model has been improved including the Lorentz-contraction effect, where the form factors and other spatial integrals are calculated within the relativistic harmonic oscillator model [11]. The results show that even with a $1 \sim 2\%$ admixture of strange quarks, the direct knockout mechanisms are comparable with the diffractive VDM of ϕ meson electroproduction at large momentum transfers.

In this paper we show that the polarization observables are much more sensitive to the intrinsic content of the strangeness in the proton. As an example, we analyze two of them which can be measured experimentally: double beam–target polarization asymmetries, when the target is polarized normal to the scattering plane and beam-target asymmetry when the target is polarized along the photon momentum.

We denote the four momenta of the photon, initial and final proton, and the produced ϕ meson as q, p, p', and p_ϕ, respectively. In the laboratory frame, we write $q \equiv (\nu, \mathbf{q})$, $\nu = |\mathbf{q}|$, $p \equiv (E_p, \mathbf{p})$=$(M, \mathbf{0})$, where M is the nucleon mass, $p' \equiv (E_{p'}, \mathbf{p}')$, and $p_\phi \equiv (E_\phi, \mathbf{p}_\phi)$. We also represent the four-momentum transfer squared to the proton as $t \equiv (p-p')^2$ and the photon–proton c.m. energy as $W^2 = (p+q)^2$. The photoproduction cross section is related to the invariant amplitude squared by

$$\frac{d\sigma_{fi}}{dt} = \frac{1}{4\pi}\frac{M^2}{(W^2-M^2)^2}|T_{fi}|^2. \tag{1}$$

VDM diffractive photoproduction

Diffractive VDM ϕ photoproduction mechanism assumes that the incoming photon mixes into the ϕ meson and then scatters diffractively from the proton through the exchange of a Pomeron [9]. The corresponding amplitude has the form

$$T_{fi}^{\mathrm{VDM}} = T_0^{\mathrm{VDM}}\delta_{m_f,m_i}\hat{\mathbf{e}}^*_{\lambda_\phi}\cdot\hat{\mathbf{e}}_{\lambda_\gamma}, \tag{2}$$

where $m_{i,f}$ are the spin projections of the incoming and outgoing proton, and $\mathbf{e}_{\lambda_\gamma,\lambda_\phi}$ are the polarization vectors of the photon and ϕ meson, respectively. For simplicity, we restrict our consideration to the circularly polarized photon with helicity $\lambda_\gamma = \pm 1$. The amplitude T_0^V does not depend on the spin variables and is related to the unpolarized diffractive VDM photoproduction σ_0^{VDM} by Eq. (1). Using the usual exponential-like form with the parameters of Refs. [2,9] we find

$$T_0^V = \frac{W^2-M^2}{M}\sqrt{4\pi\sigma_\gamma(W)b_\phi}\,\exp(-\tfrac{b_\phi}{2}|t-t_{\mathbf{max}}|), \tag{3}$$

where $t_{\mathbf{max}}$ is a possible maximum value of t. The exponential slope b_ϕ and the total photoproduction cross section $\sigma_\gamma(W)$ are determined from experiment [12] as b_ϕ=4.01 GeV^2 and $\sigma_\gamma(W) \simeq 0.2$ μb at $E_\gamma = 2$ GeV. In the VDM diffractive photoproduction, the polarizations of incoming photon and target proton are transferred to the outgoing ϕ meson and recoil proton, respectively.

Knockout photoproduction

The main assumption of the "knockout" photoproduction model is the constituent quark wave function of hadrons with the momentum p_h written in the Fock space of the form [2]:

$$|\phi; p_h\rangle = |[s\bar{s}]^1, p_h\rangle,$$
$$|p; p_h\rangle =$$
$$\left|\left\{A[uud]^{\frac{1}{2}} + B\left(a_0[[uud]^{\frac{1}{2}} \otimes [s\bar{s}]^0]^{\frac{1}{2}} + a_1[[uud]^{\frac{1}{2}} \otimes [s\bar{s}]^1]^{\frac{1}{2}}\right)\right\}, p_h\right\rangle, \quad (4)$$

where B^2 is the strangeness admixture of the proton and (a_0^2, a_1^2) are the spin 0 and spin 1 fraction of $s\bar{s}$, respectively. It is supposed that the quarks in clusters are in a relative $1s$-state with respect to the cluster c.m.-coordinate and $s\bar{s}$ is in a relative p-wave about the uud-cluster, because of the parity. Symbol $\otimes$ in Eq. (4) means the vector addition of the orbital momentum $\mathbf{L}$, $(\ell = 1)$ and the momenta of uud and $s\bar{s}$ clusters in a proton. It is assumed that each quark cluster in Eq. (4) is described by a color-singlet spin-flavor wave function. The spatial structure of the hadron is specified by the effective confining quark-quark interaction which in the following is approximated by the relativistic harmonic oscillator potential [11].

Note that the relativistic harmonic oscillator model (RHOM) first considered in Ref. [11] enables one to take into account the Lorentz-contraction of the composite particle wave function. This essential relativistic effect becomes important at large $-q^2$ and provides an explanation of the dipole-type q^2 dependence of the elastic nucleon form factor. Due to this advantage, RHOM has been widely used for describing of the hadron properties at large momentum transfers [11,13,14], despite some theoretical difficulties which are inherent in the model [13].

For the hadron electromagnetic current, there are two ways of its construction: the first is the adoption of the non-relativistic electromagnetic current and the other is the development of some relativistic generalization [11,13,15]. For practical convenience, we use the non-relativistic expression for the hadron electromagnetic current in this calculation remembering that the main relativistic effect is related to the Lorentz-contraction of the hadron intrinsic wave functions. Its possible relativistic modification of Refs. [11,13] does not change the spin structure of the photoproduction amplitudes which determines the qualitative behavior of the polarization observables. Some quantitative difference between the two approaches associated with the relativistic normalization of the hadron center of mass – motion wave functions is not so essential at the initial photon energy $\nu \sim 2$ GeV and is within the accuracy of the model.

Considering interaction of the photon with the $s\bar{s}$ quarks in a proton, one can see that the amplitude does not vanish only when the initial proton state has the antisymmetric $s\bar{s}$ component with spin $j_{s\bar{s}} = 0$ [2,10]. When the initial photon interacts with the u or d quark in the proton, the $s\bar{s}$ cluster is a spectator so that only the component with $j_{s\bar{s}} = 1$ in the initial wave function contributes. The relevant knockout amplitudes evaluated in the laboratory frame reads

$$T_{fi}^{s\bar{s}} = -T_0^{s\bar{s}} \ \{\lambda_\gamma \left\langle \tfrac{1}{2}m_f 1\varrho | \tfrac{1}{2}m_i \right\rangle \sqrt{4\pi} Y_{1\varrho}(\hat{\mathbf{p}}')\hat{\mathbf{e}}_{\lambda_\phi} \cdot \hat{\mathbf{e}}_{\lambda_\gamma}\}, \tag{5}$$

$$T_{fi}^{uud} = T_0^{uud} \ \{ \sum_{i_c=\frac{1}{2},\frac{3}{2}} \left\langle \tfrac{1}{2}m' 1\varrho \middle| i_c m_c \right\rangle \left\langle i_c m_c 1 m_\phi \middle| \tfrac{1}{2}m_i \right\rangle \sqrt{4\pi} Y_{1\varrho}^*(\hat{\mathbf{p}}_\phi)$$
$$\times [\lambda_\gamma \tfrac{1}{2} \sin\varepsilon \delta_{m',m_f} + \cos\varepsilon \delta_{m',m_f-\lambda_\gamma}]\}, \tag{6}$$

where $\cos^2\varepsilon = (1 + 2(5p' \sin\theta_{\widehat{p'q}}/3\mu\nu)^2)^{-1}$. Note that $\sin\varepsilon$ in (6) may be neglected because ε is smaller than 10^{-1} over the whole area of the kinematic variables of our interest and decreases fast in the region of $t \to t_{min}$ where the uud knockout dominates the total amplitude.

The amplitudes $T_0^{s\bar{s}}$ and T_0^{uud} are related to the corresponding single unpolarized knockout cross section as in Eq. (1) and are of the forms

$$T_0^{s\bar{s}} = (\frac{8\pi\alpha E_\phi E_p'}{M})^{1/2} A^* B a_0 \frac{\mu_s \nu}{3M} F_{s\bar{s}}(\gamma_\phi, q_{\text{eff}}^{s\bar{s}}) F_{uud}(\gamma_{p'}, 0) V_{s\bar{s}}(\mathbf{p}'), \tag{7}$$

$$T_0^{uud} = (\frac{8\pi\alpha E_\phi E_p'}{M})^{1/2} A^* B a_1 \frac{\mu\nu}{2M\cos\varepsilon}$$
$$\times F_{s\bar{s}}(\gamma_\phi, 0) F_{uud}(\gamma_{p'}, q_{\text{eff}}^{uud}) V_{uud}(\mathbf{p}_\phi), \tag{8}$$

where $\alpha = \frac{e^2}{4\pi}$, $\mu = M/M_{u,d} \simeq 3$, and $\mu_s = M/M_s \simeq 1.88$. Here $M_{u,d,s}$ are the mean energies or "constituent" masses of the corresponding quarks. When RHOM is used (see, for example, Ref. [11]) the spatial integrals are given as

$$F_{s\bar{s}}(\gamma_\phi, q_{\text{eff}}^{s\bar{s}}) = (\gamma_\phi)^{-1} \exp(-\frac{r_{s\bar{s}}^2 q_{\text{eff}}^{s\bar{s}\,2}}{6}),$$

$$F_{uud}(\gamma_{p'}, q_{\text{eff}}^{uud}) = (\gamma_{p'})^{-2} \exp(-\frac{r_{uud}^2 q_{\text{eff}}^{uud\,2}}{6}),$$

$$\frac{1}{(2\pi)^3} V_g(\mathbf{p}) = \frac{v_g(\mathbf{p})}{\int d\mathbf{p} v_g(\mathbf{p})},$$

$$v_g(\mathbf{p}) = \mathbf{p}^2 \exp\left\{-\frac{1}{\omega}\left(\mathbf{p}^2 - x_g M\sqrt{\mathbf{p}^2 + M^2}\right)\right\}, \tag{9}$$

where

$$\gamma_\phi = \frac{E_\phi}{M_\phi}, \;\; q_{\rm eff}^{s\bar{s}2} = 2\nu^2 - \frac{\nu}{E_\phi}(\nu^2 - \mathbf{p}'^2 + \mathbf{p}_\phi^2),$$
$$\gamma_{p'} = \frac{E_{p'}}{M}, \;\; q_{\rm eff}^{uud\,2} = 2\nu^2 - \frac{\nu}{E_{p'}}(\nu^2 + \mathbf{p}'^2 - \mathbf{p}_\phi^2), \quad (10)$$

and the subscript g denotes $s\bar{s}$ or uud with ($x_{s\bar{s}} = \frac{3}{5}$, $x_{uud} = \frac{2}{5}$).

Fixing parameters. The dimensional parameter r_{uud} is chosen so that the proton (uud) magnetic form factors are reproduced up to $Q^2 \simeq 10$ GeV^2. This gives $r_{uud} = r_p/c = 0.53$ fm, or when the proton radius is used $r_p = 0.83$ fm, the scale factor c is $c = 1.57$. The parameter $r_{s\bar{s}}$ is chosen to be $r_{s\bar{s}} = r_\phi/c$ and $r_\phi = 0.45$ fm, with the same scale factor of the uud cluster. And ω is determined so that the distribution $V_{s\bar{s}}(\mathbf{p})$ reduces to that of NRQM [2] as $|\mathbf{p}| \to 0$. We perform calculations with different strangeness probabilities: B^2=0, 0.025, 1%, with assuming that $|a_0|$=$|a_1| = 1/\sqrt{2}$.

Displayed in Fig. 1 are unpolarized ϕ photoproduction cross sections of all the possible processes with B^2=1% and existing experimental data [12]. The main contribution comes from the diffractive VDM photoproduction. Only at large $|t|$ – near the kinematical limit, where the VDM photoproduction cross section is exponentially small, the uud knockout channel becomes dominant. But eliminating this extreme region we find, that the total unpolarized cross section is near VDM photoproduction and is not sensitive to a small admixture of the strangeness in a proton. The situation, however, changes dramatically for the polarization observables.

Transverse Polarization

Consider first the asymmetry of the double polarized cross section when the target proton and the produced ϕ meson are quantized normal to the scattering plane, i.e., *transverse polarization.* In the ϕ-meson helicity basis, the VDM, $s\bar{s}$, uud knockout amplitudes are written as

$$T_{fi}^{VDM} = T_0^V \delta_{m_f,m_i} d^{(1)}_{\lambda_\gamma,\lambda_\phi}(\theta_\phi),$$
$$T_{fi}^{s\bar{s}} = -T_0^{s\bar{s}}\sqrt{\frac{3}{2}}\langle\frac{1}{2}\, m_f\, 1\, \sigma \mid \frac{1}{2}\, m_i\rangle[\sqrt{2}\hat{p}'_\sigma]\lambda_\gamma d^{(1)}_{\lambda_\gamma,\lambda_\phi}(\theta_\phi), \quad (11)$$

$$T_{fi}^{uud} = T_0^{uud}\sqrt{\frac{3}{2}} \sum_{i_c,m_c,m_\phi} \langle \frac{1}{2}\, m'\, 1\, \sigma \mid i_c\, m_c\rangle\langle i_c\, m_c\, 1\, m_\phi \mid \frac{1}{2}\, m_i\rangle[\sqrt{2}\hat{p}^*_{\phi,\sigma}]$$
$$\times\delta_{m',m_f-\lambda_\gamma} d^{(1)}_{m_\phi,\lambda_\phi}(\theta^*_\phi). \qquad (12)$$

where

$$\hat{p}'_\sigma = -\frac{\sigma}{\sqrt{2}}\exp(-i\sigma\theta'_p), \qquad \hat{p}_{\phi,\sigma} = -\frac{\sigma}{\sqrt{2}}\exp(-i\sigma\theta_\phi), \qquad \theta^*_\phi = \frac{\pi}{2}, \quad (13)$$

and $\sigma = \pm 1, 0$. To express the polarized amplitudes, we use the following notation:

$$T^{t,r}_{b,v}, \qquad (14)$$

where t, r, b, and v represent the polarization of the target, recoil, beam, and vector meson, respectively. After some exercises, we find

$$\begin{aligned}
T^{++}_{+\lambda_\phi} &= T_0^V d^1_{1,\lambda_\phi}(\theta_\phi) &&+\ 0 &&+\ T_0^{uud}\sqrt{2}d_1 e^{i\theta_\phi} d^1_{0,\lambda_\phi}(\theta_\phi),\\
T^{++}_{-\lambda_\phi} &= T_0^V d^1_{-1,\lambda_\phi}(\theta_\phi) &&+\ 0 &&+\ 0,\\
T^{+-}_{+\lambda_\phi} &= 0 &&-\ T_0^{s\bar{s}} e^{-i\theta'_p} d^1_{1,\lambda_\phi}(\theta_\phi) &&+\ 0,\\
T^{+-}_{-\lambda_\phi} &= 0 &&+\ T_0^{s\bar{s}} e^{-i\theta'_p} d^1_{-1,\lambda_\phi}(\theta_\phi) &&-\ T_0^{uud} f(\theta_\phi),\\
T^{-+}_{+\lambda_\phi} &= 0 &&-\ T_0^{s\bar{s}} e^{i\theta'_p} d^1_{1,\lambda_\phi}(\theta_\phi) &&+\ T_0^{uud} f^*(\theta_\phi),\\
T^{-+}_{-\lambda_\phi} &= 0 &&+\ T_0^{s\bar{s}} e^{i\theta'_p} d^1_{-1,\lambda_\phi}(\theta_\phi) &&+\ 0,\\
T^{--}_{+\lambda_\phi} &= T_0^V d^1_{1,\lambda_\phi}(\theta_\phi) &&+\ 0 &&+\ 0,\\
T^{--}_{-\lambda_\phi} &= T_0^V d^1_{-1,\lambda_\phi}(\theta_\phi) &&+\ 0 &&-\ T_0^{uud}\sqrt{2}d_1 e^{-i\theta_\phi} d^1_{0,\lambda_\phi}(\theta_\phi),
\end{aligned} \qquad (15)$$

where $d_{1,2,3,4}$ are defined as

$$d_1 = \frac{1+\sqrt{2}}{\sqrt{12}}, \qquad d_2 = \frac{\sqrt{3}}{2}, \qquad d_3 = \frac{2\sqrt{2}-1}{\sqrt{12}}, \qquad d_4 = \frac{\sqrt{2}-1}{\sqrt{6}}. \quad (16)$$

and the function f is

$$f(\theta_\phi) = [d_2 e^{i\theta_\phi} d^1_{-1,\lambda_\phi}(\theta_\phi) + d_3 e^{-i\theta_\phi} d^1_{1,\lambda_\phi}(\theta_\phi)]. \qquad (17)$$

Here we use the rotation matrix elements $d^1_{m'm}$ as in textbook [16].

$m'(\downarrow)m(\rightarrow)$	$+1$	0	-1
$+1$	$\frac{1}{2}(1+\cos\theta)$	$\frac{1}{\sqrt{2}}\sin\theta$	$\frac{1}{2}(1-\cos\theta)$
0	$-\frac{1}{\sqrt{2}}\sin\theta$	$\cos\theta$	$\frac{1}{\sqrt{2}}\sin\theta$
-1	$\frac{1}{2}(1-\cos\theta)$	$-\frac{1}{\sqrt{2}}\sin\theta$	$\frac{1}{2}(1+\cos\theta)$

(18)

Also for $d^{1/2}_{m'm}$, we have

$m'(\downarrow)m(\rightarrow)$	$+1/2$	$-1/2$
$+1/2$	$\cos\frac{\theta}{2}$	$\sin\frac{\theta}{2}$
$-1/2$	$-\sin\frac{\theta}{2}$	$\cos\frac{\theta}{2}$

(19)

Beam–Vector-meson Asymmetry $\mathcal{T}_{BV}$

The beam–vector-meson asymmetry $\mathcal{T}_{BV}$ is defined as

$$\mathcal{T}_{BV} \equiv \frac{|T^{uu}_{++}|^2 - |T^{uu}_{+-}|^2}{|T^{uu}_{++}|^2 + |T^{uu}_{+-}|^2}, \tag{20}$$

where

$$|T^{uu}_{+\pm}|^2 \equiv |T^{++}_{+\pm}|^2 + |T^{+-}_{+\pm}|^2 + |T^{-+}_{+\pm}|^2 + |T^{--}_{+\pm}|^2. \tag{21}$$

Using the expressions for the amplitudes, we have

$$\begin{aligned} |T^{uu}_{++}|^2 = & \frac{1}{2}\{(T^V_0)^2 + (T^{s\bar{s}}_0)^2\}(1+\cos\theta_\phi)^2 \\ & +\frac{1}{2}(T^{uud}_0)^2\{1 + d_1^2 + (3d_1^2 - 1)\cos 2\theta_\phi\} \\ & -T^V_0 T^{uud}_0 d_1(1+\cos\theta_\phi)\cos\theta_\phi \\ & -\frac{1}{2}T^{s\bar{s}}_0 T^{uud}_0(1+\cos\theta_\phi)\{d_2\cos(\theta_{p'}+\theta_\phi) + d_3\cos(\theta_{p'}-\theta_\phi)\}, \end{aligned} \tag{22}$$

and

$$\begin{aligned} |T^{uu}_{+-}|^2 = & \frac{1}{2}\{(T^V_0)^2 + (T^{s\bar{s}}_0)^2\}(1-\cos\theta_\phi)^2 \\ & +\frac{1}{2}(T^{uud}_0)^2\{1 + d_1^2 + (3d_1^2 - 1)\cos 2\theta_\phi\} \\ & +T^V_0 T^{uud}_0 d_1(1-\cos\theta_\phi)\cos\theta_\phi \\ & -\frac{1}{2}T^{s\bar{s}}_0 T^{uud}_0(1-\cos\theta_\phi)\{d_2\cos(\theta_{p'}+\theta_\phi) + d_3\cos(\theta_{p'}-\theta_\phi)\}. \end{aligned} \tag{23}$$

Beam–Target Asymmetry $\mathcal{T}_{BT}$

The beam–target asymmetry $\mathcal{T}_{BT}$ is defined as

$$\mathcal{T}_{BT} \equiv \frac{|T^{+u}_{+u}|^2 - |T^{+u}_{-u}|^2}{|T^{+u}_{+u}|^2 + |T^{+u}_{-u}|^2}, \tag{24}$$

where

$$|T^{+u}_{\pm u}|^2 \equiv |T^{++}_{\pm +}|^2 + |T^{++}_{\pm 0}|^2 + |T^{++}_{\pm -}|^2 + |T^{+-}_{\pm +}|^2 + +|T^{+-}_{\pm 0}|^2 + |T^{+-}_{\pm -}|^2. \tag{25}$$

Again, we have

$$|T^{+u}_{+u}|^2 = (T^V_0)^2 + (T^{s\bar{s}}_0)^2 + (T^{uud}_0)^2 2d_1^2 - T^V_0 T^{uud}_0 2d_1 \cos^2\theta_\phi, \tag{26}$$

$$\begin{aligned} |T^{+u}_{-u}|^2 = {} & (T^V_0)^2 + (T^{s\bar{s}}_0)^2 + (T^{uud}_0)^2(d_2^2 + d_3^2) \\ & - T^{s\bar{s}}_0 T^{uud}_0 \{(1 + \sin\theta_\phi) d_2 \cos(\theta_{p'} + \theta_\phi) \\ & + (1 - \sin\theta_\phi) d_3 \cos(\theta_{p'} - \theta_\phi)\}. \end{aligned} \tag{27}$$

Target–Vector-meson Asymmetry $\mathcal{T}_{TV}$

The target–vector-meson asymmetry $\mathcal{T}_{TV}$ is defined as

$$\mathcal{T}_{TV} \equiv \frac{|T^{+u}_{u+}|^2 - |T^{+u}_{u-}|^2}{|T^{+u}_{u+}|^2 + |T^{+u}_{u-}|^2}, \tag{28}$$

where

$$|T^{+u}_{u\pm}|^2 \equiv |T^{++}_{+\pm}|^2 + |T^{+-}_{+\pm}|^2 + |T^{++}_{-\pm}|^2 + |T^{+-}_{-\pm}|^2. \tag{29}$$

And we get

$$\begin{aligned} |T^{+u}_{u+}|^2 = {} & \frac{1}{2}\{(T^V_0)^2 + (T^{s\bar{s}}_0)^2\}(1 + \cos^2\theta_\phi) \\ & + \frac{1}{2}(T^{uud}_0)^2\{1 + d_1^2 + (3d_1^2 - 1)\cos 2\theta_\phi\} \\ & - T^V_0 T^{uud}_0 d_1 (1 + \cos\theta_\phi)\cos\theta_\phi \\ & - \frac{1}{2} T^{s\bar{s}}_0 T^{uud}_0 (1 - \cos\theta_\phi)\{d_2 \cos(\theta_{p'} + \theta_\phi) + d_3 \cos(\theta_{p'} - \theta_\phi)\}, \end{aligned} \tag{30}$$

and

$$\begin{aligned} |T^{+u}_{u-}|^2 = {} & \frac{1}{2}\{(T^V_0)^2 + (T^{s\bar{s}}_0)^2\}(1 + \cos^2\theta_\phi) \\ & + \frac{1}{2}(T^{uud}_0)^2\{1 + d_1^2 + (3d_1^2 - 1)\cos 2\theta_\phi\} \\ & + T^V_0 T^{uud}_0 d_1 (1 - \cos\theta_\phi)\cos\theta_\phi \\ & - \frac{1}{2} T^{s\bar{s}}_0 T^{uud}_0 (1 + \cos\theta_\phi)\{d_2 \cos(\theta_{p'} + \theta_\phi) + d_3 \cos(\theta_{p'} - \theta_\phi)\}. \end{aligned} \tag{31}$$

Target–Recoil Asymmetry $\mathcal{T}_{TR}$

The target–recoil asymmetry $\mathcal{T}_{TR}$ is defined as

$$\mathcal{T}_{TR} \equiv \frac{|T^{++}_{uu}|^2 - |T^{+-}_{uu}|^2}{|T^{++}_{uu}|^2 + |T^{+-}_{uu}|^2}, \tag{32}$$

where

$$|T^{+\pm}_{uu}|^2 \equiv |T^{+\pm}_{++}|^2 + |T^{+\pm}_{+0}|^2 + |T^{+\pm}_{+-}|^2 + |T^{+\pm}_{-+}|^2 + +|T^{+\pm}_{-0}|^2 + |T^{+\pm}_{--}|^2. \tag{33}$$

Therefore, we get

$$|T^{++}_{uu}|^2 = 2(T^V_0)^2 + 2(T^{uud}_0)^2 d_1^2 - 2T^V_0 T^{uud}_0 d_1 \cos^2\theta_\phi, \tag{34}$$

and

$$\begin{aligned} |T^{+-}_{uu}|^2 = {} & 2(T^{s\bar{s}}_0)^2 + 2(T^{uud}_0)^2(1-d_1^2) \\ & -T^{s\bar{s}}_0 T^{uud}_0\{(1+\sin\theta_\phi)d_2\cos(\theta_{p'}+\theta_\phi) \\ & +(1-\sin\theta_\phi)d_3\cos(\theta_{p'}-\theta_\phi)\}. \end{aligned} \tag{35}$$

Inspection of the above expression shows that neither of the asymmeries contain interference between the VDM photoproduction and $s\bar{s}$ knockout which is proportional to $T^V_0 T^{s\bar{s}}_0$. This means that the asymmetries are not sensitive to the contribution of the $s\bar{s}$ knockout mechanism or to the amplitude a_0; Whereas they are sensitive to the uud- knockout (or the amplitude a_1), dominant at large $|t|$ where, however, the cross sections are exponentially small. As an example, Fig.2 shows the **target-recoil** asymmetry. At small $|t|$ it is proportional to $1\text{-}2(T^{s\bar{s}}_0/Tv)^2$. We choose $B^2 = 0, 0.0025, 0.01$; $a_0^2 = a_1^2 = 0.5$. At large $|t|$ it depends on the combination of $(T^{uud}_0)^2$ and $T^V_0 T^{uud}_0$, where the term proportional to $(T^{uud}_0)^2$ is dominant because of sharply decreasing T^V_0 with increasing $|t|$. So, at large $|t|$ the result is not responsive to the phase of a_1 qualitatively.

Longitudinal Polarization

In this case, the photon and the produced ϕ-meson are quantized parallel to the scattering plane. We choose the z-axis to be parallel to the photon momentum. In the helicity basis, the amplitudes read

$$T_{fi}^{VDM} = T_0^V d^{1/2}_{\lambda_i,\lambda_f}(\theta'_p)\, d^1_{\lambda_\gamma,\lambda_\phi}(\theta_\phi),$$
$$T_{fi}^{s\bar{s}} = -T_0^{s\bar{s}}\sqrt{\frac{3}{2}}\langle\frac{1}{2}m_f 1\sigma|\frac{1}{2}\lambda_i\rangle\lambda_\gamma[\sqrt{2}\hat{p}'_\sigma]\, d^{1/2}_{m_f,\lambda_f}(\theta'_p)\, d^1_{\lambda_\gamma,\lambda_\phi}(\theta_\phi),$$
$$T_{fi}^{uud} = T_0^{uud}\sqrt{\frac{3}{2}}\langle\frac{1}{2}m_f - \lambda_\gamma 1\sigma|i_c m_c\rangle\langle i_c m_c 1 m_\phi|\frac{1}{2}\lambda_i\rangle[\sqrt{2}\hat{p}^*_{\phi,\sigma}]$$
$$\times d^{1/2}_{m_f,\lambda_f}(\theta'_p)\, d^1_{m_\phi,\lambda_\phi}(\theta_\phi). \tag{36}$$

where

$$\hat{p}'_0 = \cos\theta_{p'}, \quad \hat{p}'_\pm = \mp\frac{1}{\sqrt{2}}\sin\theta_{p'},$$
$$\hat{p}_{\phi,0} = \cos\theta_{p_\phi}, \quad \hat{p}_{\phi,\pm} = \mp\frac{1}{\sqrt{2}}\sin\theta_{p_\phi}. \tag{37}$$

The polarized amplitudes are obtained as:

$$T^{++}_{+\lambda_\phi} = \{T_0^V\cos\tfrac{\theta_{p'}}{2} - T_0^{s\bar{s}}\cos\frac{3\theta_{p'}}{2}\}\, d^1_{1,\lambda_\phi}(\theta_\phi)$$
$$+d_1\, T_0^{uud}\cos\tfrac{\theta_{p'}}{2}\,[2\cos\theta_\phi\, d^1_{1,\lambda_\phi}(\theta_\phi) + \sqrt{2}\sin\theta_\phi\, d^1_{0,\lambda_\phi}(\theta_\phi)] \tag{38}$$

$$T^{++}_{-\lambda_\phi} = \{T_0^V\cos\tfrac{\theta_{p'}}{2} + T_0^{s\bar{s}}\cos\frac{3\theta_{p'}}{2}\}\, d^1_{-1,\lambda_\phi}(\theta_\phi)$$
$$+T_0^{uud}\sin\tfrac{\theta_{p'}}{2}\,[d_3\sin\theta_\phi\, d^1_{1,\lambda_\phi}(\theta_\phi)$$
$$+\sqrt{2}\, d_4\cos\theta_\phi\, d^1_{0,\lambda_\phi}(\theta_\phi) + d_2\sin\theta_\phi\, d^1_{-1,\lambda_\phi}(\theta_\phi)] \tag{39}$$

$$T^{+-}_{+\lambda_\phi} = \{T_0^V\sin\tfrac{\theta_{p'}}{2} - T_0^{s\bar{s}}\sin\frac{3\theta_{p'}}{2}\}\, d^1_{1,\lambda_\phi}(\theta_\phi)$$
$$+T_0^{uud}\, d_1\sin\tfrac{\theta_{p'}}{2}\,[2\cos\theta_\phi\, d^1_{1,\lambda_\phi}(\theta_\phi) + \sqrt{2}\sin\theta_\phi\, d^1_{0,\lambda_\phi}(\theta_\phi)] \tag{40}$$

$$T^{+-}_{-\lambda_\phi} = \{T_0^V\sin\tfrac{\theta_{p'}}{2} + T_0^{s\bar{s}}\sin\frac{3\theta_{p'}}{2}\}\, d^1_{-1,\lambda_\phi}(\theta_\phi)$$
$$-T_0^{uud}\cos\tfrac{\theta_{p'}}{2}\,[d_3\sin\theta_\phi\, d^1_{1,\lambda_\phi}(\theta_\phi) + \sqrt{2}\, d_4\cos\theta_\phi\, d^1_{0,\lambda_\phi}(\theta_\phi)$$
$$+d_2\sin\theta_\phi\, d^1_{-1,\lambda_\phi}(\theta_\phi)] \tag{41}$$

$$T^{-+}_{+\lambda_\phi} = -\{T_0^V\sin\tfrac{\theta_{p'}}{2} + T_0^{s\bar{s}}\sin\frac{3\theta_{p'}}{2}\}\, d^1_{1,\lambda_\phi}(\theta_\phi)$$
$$+T_0^{uud}\cos\tfrac{\theta_{p'}}{2}\,[d_2\sin\theta_\phi\, d^1_{1,\lambda_\phi}(\theta_\phi) - \sqrt{2}\, d_4\cos\theta_\phi\, d^1_{0,\lambda_\phi}(\theta_\phi)$$
$$+d_3\sin\theta_\phi\, d^1_{-1,\lambda_\phi}(\theta_\phi)] \tag{42}$$

$$T^{-+}_{-\lambda_\phi} = -\{T_0^V\sin\tfrac{\theta_{p'}}{2} - T_0^{s\bar{s}}\sin\frac{3\theta_{p'}}{2}\}\, d^1_{-1,\lambda_\phi}(\theta_\phi)$$

$$+T_0^{uud}\, d_1 \sin\tfrac{\theta_{p'}}{2}\,[\sqrt{2}\sin\theta_\phi\, d^1_{0,\lambda_\phi}(\theta_\phi) - 2\cos\theta_\phi\, d^1_{-1,\lambda_\phi}(\theta_\phi)] \quad (43)$$

$$T^{--}_{+\lambda_\phi} = \{T_0^V \cos\tfrac{\theta_{p'}}{2} + T_0^{s\bar{s}} \cos\frac{3\theta_{p'}}{2}\}\, d^1_{1,\lambda_\phi}(\theta_\phi)$$
$$+T_0^{uud} \sin\tfrac{\theta_{p'}}{2}\,[d_2 \sin\theta_\phi\, d^1_{1,\lambda_\phi}(\theta_\phi) - \sqrt{2}\, d_4 \cos\theta_\phi\, d^1_{0,\lambda_\phi}(\theta_\phi)$$
$$+d_3 \sin\theta_\phi\, d^1_{-1,\lambda_\phi}(\theta_\phi)] \quad (44)$$

$$T^{--}_{-\lambda_\phi} = \{T_0^V \cos\tfrac{\theta_{p'}}{2} - T_0^{s\bar{s}} \cos\frac{3\theta_{p'}}{2}\}\, d^1_{-1,\lambda_\phi}(\theta_\phi)$$
$$-T_0^{uud}\, d_1 \cos\tfrac{\theta_{p'}}{2}\,[\sqrt{2}\sin\theta_\phi\, d^1_{0,\lambda_\phi}(\theta_\phi) - 2\cos\theta_\phi\, d^1_{-1,\lambda_\phi}(\theta_\phi)] \quad (45)$$

Beam–Vector-meson Asymmetry $\mathcal{L}_{BV}$

The beam–vector-meson asymmetry $\mathcal{L}_{BV}$ is defined as

$$\mathcal{L}_{BV} \equiv \frac{|T^{uu}_{++}|^2 - |T^{uu}_{+-}|^2}{|T^{uu}_{++}|^2 + |T^{uu}_{+-}|^2}, \quad (46)$$

where

$$|T^{uu}_{+\pm}|^2 \equiv |T^{++}_{+\pm}|^2 + |T^{+-}_{+\pm}|^2 + |T^{-+}_{+\pm}|^2 + |T^{--}_{+\pm}|^2. \quad (47)$$

Using the expressions for the amplitudes, we have

$$\begin{aligned}|T^{uu}_{++}|^2 - |T^{uu}_{+-}|^2 = {} & 2\{(T_0^V)^2 + (T_0^{s\bar{s}})^2\}\cos\theta_\phi \\ & +4(T_0^{uud})^2 d_1\{d_1\cos\theta_\phi\cos 2\theta_\phi + d_4 \sin\theta_\phi \sin 2\theta_\phi\} \\ & +2(T_0^V)(T_0^{uud}) d_1(\cos^2\theta_\phi + \cos 2\theta_\phi) \\ & -2(T_0^{s\bar{s}})(T_0^{uud})\{\cos\theta_{p'} d_1(\cos^2\theta_\phi + \cos 2\theta_\phi) \\ & +\sin\theta_{p'}(d_1 \sin\theta_\phi\cos\theta_\phi + d_4 \sin 2\theta_\phi)\},\end{aligned} \quad (48)$$

$$\begin{aligned}|T^{uu}_{++}|^2 + |T^{uu}_{+-}|^2 = {} & \{(T_0^V)^2 + (T_0^{s\bar{s}})^2\}(1+\cos^2\theta_\phi) \\ & +2(T_0^{uud})^2\{d_1^2(1+\cos^2 2\theta_\phi) + d_4^2 \sin^2 2\theta_\phi\} \\ & +2(T_0^V)(T_0^{uud}) d_1 \cos\theta_\phi(1+\cos 2\theta_\phi) \\ & -2(T_0^{s\bar{s}})(T_0^{uud})\{\cos\theta_{p'} d_1 \cos\theta_\phi(1+\cos 2\theta_\phi) \\ & +\sin\theta_{p'}(d_1\sin\theta_\phi + d_4\cos\theta_\phi \sin 2\theta_\phi)\}.\end{aligned} \quad (49)$$

Beam–Target Asymmetry $\mathcal{L}_{BT}$

The beam–target asymmetry $\mathcal{L}_{BT}$ is defined as

$$\mathcal{L}_{BT} \equiv \frac{|T^{+u}_{+u}|^2 - |T^{+u}_{-u}|^2}{|T^{+u}_{+u}|^2 + |T^{+u}_{-u}|^2}, \tag{50}$$

where

$$|T^{+u}_{\pm u}|^2 \equiv |T^{++}_{\pm +}|^2 + |T^{++}_{\pm 0}|^2 + |T^{++}_{\pm -}|^2 + |T^{+-}_{\pm +}|^2 + +|T^{+-}_{\pm 0}|^2 + |T^{+-}_{\pm -}|^2. \tag{51}$$

Again, we have

$$\begin{aligned} |T^{+u}_{+u}|^2 - |T^{+u}_{-u}|^2 &= -2(T^{uud}_0)^2\{1 - 2d_1^2(1 + \cos^2\theta_\phi)\} \\ &\quad -4(T^V_0)(T^{s\bar{s}}_0)\cos\theta_{p'} + 4(T^V_0)(T^{uud}_0)d_1\cos\theta_\phi \\ &\quad -2(T^{s\bar{s}}_0)(T^{uud}_0)\{2d_1\cos\theta_{p'}\cos\theta_\phi - d_2\sin\theta_{p'}\sin\theta_\phi\}, \\ |T^{+u}_{+u}|^2 + |T^{+u}_{-u}|^2 &= 2\{(T^V_0)^2 + (T^{s\bar{s}}_0)^2 + (T^{uud}_0)^2\} + 4(T^V_0)(T^{uud}_0)d_1\cos\theta_\phi \\ &\quad -2(T^{s\bar{s}}_0)(T^{uud}_0)\{2d_1\cos\theta_{p'}\cos\theta_\phi + d_2\sin\theta_{p'}\sin\theta_\phi\}. \end{aligned} \tag{52}$$

Target–Vector-meson Asymmetry $\mathcal{L}_{TV}$

The target–vector-meson asymmetry $\mathcal{L}_{TV}$ is defined as

$$\mathcal{L}_{TV} \equiv \frac{|T^{+u}_{u+}|^2 - |T^{+u}_{u-}|^2}{|T^{+u}_{u+}|^2 + |T^{+u}_{u-}|^2}, \tag{53}$$

where

$$|T^{+u}_{u\pm}|^2 \equiv |T^{++}_{+\pm}|^2 + |T^{+-}_{+\pm}|^2 + |T^{++}_{-\pm}|^2 + |T^{+-}_{-\pm}|^2. \tag{54}$$

And we get

$$\begin{aligned} |T^{+u}_{u+}|^2 - |T^{+u}_{u-}|^2 &= 4(T^{uud}_0)^2 d_1(d_1\cos\theta_\phi\cos 2\theta_\phi - d_4\sin\theta_\phi\sin 2\theta_\phi) \\ &\quad -4(T^V_0)(T^{s\bar{s}}_0)\cos\theta_{p'}\cos\theta_\phi \\ &\quad +2(T^V_0)(T^{uud}_0)(\cos^2\theta_\phi + \cos 2\theta_\phi) \\ &\quad -2(T^{s\bar{s}}_0)(T^{uud}_0)\{d_1\cos\theta_{p'}(\cos^2\theta_\phi + \cos 2\theta_\phi) \\ &\quad - \sin\theta_{p'}(d_1\cos\theta_\phi\sin\theta_\phi + d_4\sin 2\theta_\phi)\}, \end{aligned} \tag{55}$$

$$\begin{aligned} |T^{+u}_{u+}|^2 + |T^{+u}_{u-}|^2 &= \{(T^V_0)^2 + (T^{s\bar{s}}_0)^2\}(1 + \cos^2\theta_\phi) \\ &\quad +2(T^{uud}_0)^2\{d_1^2(\cos^2\theta_\phi + \cos^2 2\theta_\phi) + d_1^2\sin^2\theta_\phi + d_4^2\sin^2 2\theta_\phi\} \\ &\quad +2(T^V_0)(T^{uud}_0)d_1\cos\theta_\phi(1 + \cos 2\theta_\phi) \\ &\quad -2(T^{s\bar{s}}_0)(T^{uud}_0)\{d_1\cos\theta_{p'}\cos\theta_\phi(1 + \cos 2\theta_\phi) \\ &\quad + \sin\theta_{p'}(d_1\sin\theta_\phi + d_4\cos\theta_\phi\sin 2\theta_\phi)\}. \end{aligned} \tag{56}$$

Target–Recoil Asymmetry $\mathcal{L}_{TR}$

The target–recoil asymmetry $\mathcal{L}_{TR}$ is defined as

$$\mathcal{L}_{TR} \equiv \frac{|T^{++}_{uu}|^2 - |T^{+-}_{uu}|^2}{|T^{++}_{uu}|^2 + |T^{+-}_{uu}|^2}, \tag{57}$$

where

$$|T^{+\pm}_{uu}|^2 \equiv |T^{+\pm}_{++}|^2 + |T^{+\pm}_{+0}|^2 + |T^{+\pm}_{+-}|^2 + |T^{+\pm}_{-+}|^2 + +|T^{+\pm}_{-0}|^2 + |T^{+\pm}_{--}|^2. \tag{58}$$

Therefore, we get

$$\begin{aligned}|T^{++}_{uu}|^2 - |T^{+-}_{uu}|^2 &= -2(T^{uud}_0)^2 \cos\theta_{p'}\{(1-2d_1^2) - 2d_1^2\cos^2\theta_\phi\} \\ &+(T^V_0)(T^{uud}_0)2\{2d_1\cos\theta_{p'}\cos\theta_\phi + d_2\sin\theta_{p'}\sin\theta_\phi\} \\ &-2(T^{s\bar{s}}_0)(T^{uud}_0)\{2d_1\cos 2\theta_{p'}\cos\theta_\phi - d_2\sin 2\theta_{p'}\sin\theta_\phi\}, \qquad (59)\\ |T^{++}_{uu}|^2 + |T^{+-}_{uu}|^2 &= 2\{(T^V_0)^2 + (T^{s\bar{s}}_0)^2 + (T^{uud}_0)^2\} + 4(T^V_0)(T^{uud}_0)d_1\cos\theta_\phi \\ &-2(T^{s\bar{s}}_0)(T^{uud}_0)\{2d_1\cos\theta_{p'}\cos\theta_\phi - d_2\sin\theta_{p'}\sin\theta_\phi\}. \qquad (60)\end{aligned}$$

The beam–target and target–vector meson asymmeties are of the most interest because at small $|t|$ they are proportional to the interference $T^V_0 T^{s\bar{s}}_0$ and can bring information on the amplitude a_0. Figs.3,4 show the result of calculation of the beam–target asymmetry at different signs of a: $a_0 = a_1 < 0$ in Fig.3 and $a_0 = a_1 > 0$ in Fig.4. We choose $B^2 = 0, 0.0025, 0.01$. The result for all the other posiible combinations a_0, a_1 can be reproduced strightforward by making use of the above expressions. Our calculation shows that at small $|t| \sim |t_{max}|$ the asymmetry may be as much as 30% when the proposed strangeness probability in the proton is only 0.25%.

As a summary, we analyzed polarization observables based on the RHOM that takes into account the Lorentz contraction effects of the composite particle wave function. We find that even with a less than 1% admixture of strange quarks, the deviations of the asymmetries from those of the pure diffractive VDM photoproduction are as much as $10 \sim 50\%$ depending on the value of t when we take the knockout amplitudes into account. The strong t-dependence of the asymmetries could be crucial for testing experimentally the $s\bar{s}$–uud cluster model for the strangeness content of the proton. Current experimental data [17] on the asymmetries are not sufficiently accurate to extract the knockout contribution

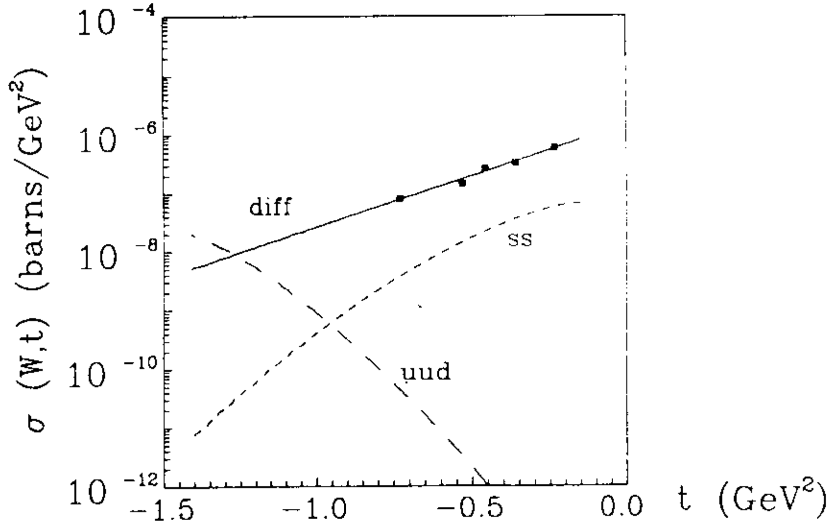

FIG. 1. The t-dependence of the unpolarized photoproduction cross section $d\sigma/dt$ with W=2.1 GeV and Q^2 = 0.02 GeV^2. The solid line corresponds to the diffractive cross section, the dashed line to the $s\bar{s}$ knockout cross section, and the dashed-dotted line to the uud knockout cross section. Experimental data [12] are given by dark circles for comparison.

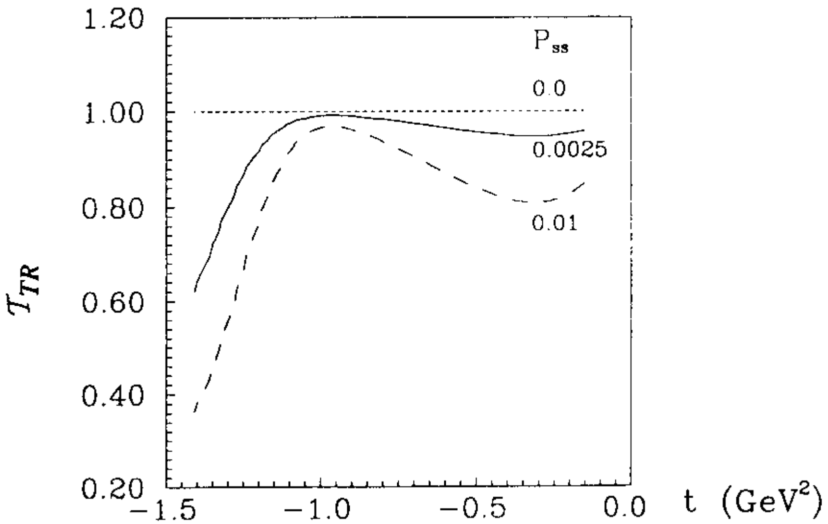

FIG. 2. The t-dependence of the transverse asymmetry $\mathcal{T}_{TR}$ with B^2=0 (solid line), 0.25% (dotted line), and 1% (dash-dotted line).

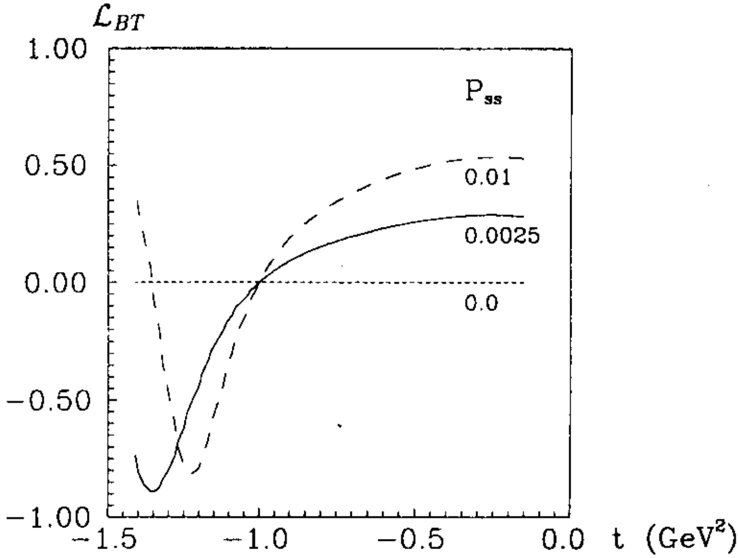

FIG. 3. The t-dependence of the longitudinal asymmetry $\mathcal{L}_{BT}$ with $a_0 = a_1 < 0$ and B^2=0 (solid line), 0.25% (dotted line), and 1% (dash-dotted line).

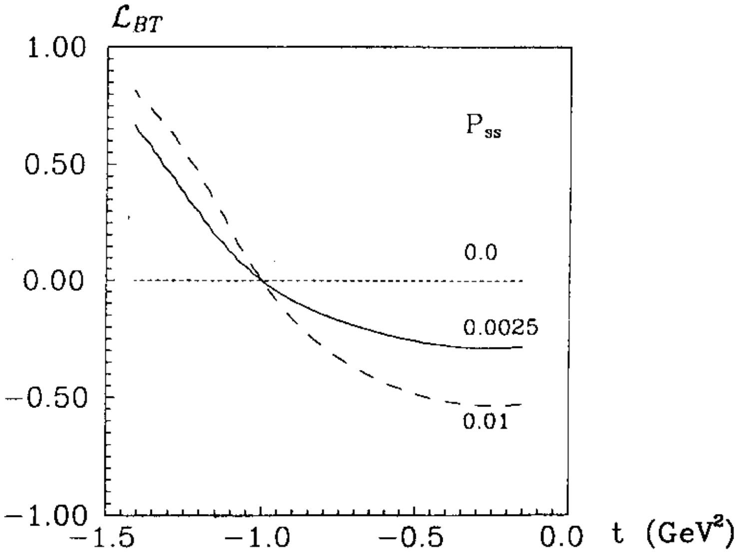

FIG. 4. The t-dependence of the longitudinal asymmetry $\mathcal{L}_{BT}$. Notation is the same as in Fig.3 but $a_0 = a_1 > 0$.

from the diffractive process. However, the similar effect should be seen in ϕ - electroproduction and it may be checked in future experiments at CEBAF.

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