ON THE $\sigma_L/\sigma_T$ RATIO IN POLARIZED VECTOR MESON PHOTOPRODUCTION

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Abstract

We study the spin-dependent cross-sections of vector meson photoproduction for longitudinally and transversely polarized photons within a QCD-model. The dependence of the $\sigma_T/\sigma_L$ ratio on the photon virtuality and on the meson wave function is analysed.

Key-words: diffraction, meson, photoproduction, parton, distribution, polarization, wave function

Investigation of diffractive vector meson photoproduction is a problem of considerable interest now. The factorization of diffractive vector meson production with longitudinally polarized photons into the hard part and parton distribution was proved in [1]. Thus, on the one hand, such processes, can provide an excellent tool to study the parton distribution in a hadron at small $x$. On the other hand, they should give an important information on the vector meson wave function. One of the observables which was investigated experimentally at HERA [2] is the ratio of the cross sections with transversely and longitudinally polarized photons $R = \sigma_L/\sigma_T$ for nonzero photon virtuality. To calculate $R$, the amplitudes with transverse vector meson polarization within some model approach should be analysed. The nonrelativistic wave function gives the ratio $R \sim Q^2/M_V^2$ [3] which is not supported by the experiment. More realistic wave functions which include the transverse quark motion can improve the situation [4, 5].

In this report, we focus our attention on dependences of the $R$ ratio on the form of the meson wave function. We consider the following matrix structure of the vector meson wave function

$$\hat{\psi}_V = g \frac{E_V (k_1 + m_q) E_V (k_2 + m_q)}{M_V z (1 - z)} \phi_V (z, k_1^2).$$

(1)

Here $k_1$ and $k_2$ are the quark momenta, $E_V$ is the vector meson polarization and $\phi_V (z, k_1^2)$ is the distribution amplitude. The momentum $k_1$ carries the fraction $z$ of the vector meson momentum and can be written in the form

$$k_1 = -z V + \Delta - K,$$

(2)

where $K = [0, 0, k_\perp]$ is the quark transverse momentum and the vector $\Delta$ puts the quark momentum on the mass shell $k_1^2 = m_q^2$ in calculating the imaginary part of the amplitude. The wave function (1) can be decomposed into the following structures

$$\psi_V = g \left[ \hat{E}_V \left( M_V + \frac{m_q^2}{M_V z (1 - z)} \right) + \frac{m_q}{M_V z (1 - z)} \hat{V} - \frac{K \cdot K}{M_V z (1 - z)} - 2 (1 - z) \Delta \cdot V \right].$$
of the skewed gluon distribution amplitude. The gluon distribution in the case of vector meson production depends on \(|F_{2}\) 2-dimensional integrals over \(A\) transverse for the transverse one we have this case one should calculate only two amplitudes with longitudinal.

We find that for small \(m_q^2/M_V^2\) and \(K^2/M_V^2\) the function \((3)\) reduces to the standard form of the vector meson wave function \(gE_V(M_V + \hat{V})\). The same is true in the nonrelativistic limit.

The leading term of the amplitude of diffractive vector meson production is mainly imaginary. The imaginary part of the amplitude can be written as an integral over \(z\) and 2-dimensional integrals over \(k_\perp\) and \(l_\perp\). The integral over \(l_\perp\) can be represented in terms of the skewed gluon distribution \(F^g\) and has the form \([3]\)

\[
\sum T_i \propto \frac{1}{(k_\perp^2 + |t| + \tilde{Q}^2)^2} \int \frac{d^2l_\perp (l_\perp^2 + \tilde{l}_\perp \tilde{r}_\perp - \tilde{l}_\perp \tilde{k}_\perp)G(l_\perp^2, x, ...)}{(l_\perp^2 + \lambda^2)((\tilde{l}_\perp + \tilde{r}_\perp)^2 + \lambda^2)((\tilde{l}_\perp - \tilde{k}_\perp)^2 + |t| + \tilde{Q}^2)}
\]

\[
\approx \frac{1}{(k_\perp^2 + |t| + \tilde{Q}^2)^2} \int_0^{l_\perp < k_\perp^2 + \tilde{Q}^2 + |t|} \frac{d^2l_\perp (l_\perp^2 + \tilde{l}_\perp \tilde{r}_\perp)}{(l_\perp^2 + \lambda^2)((\tilde{l}_\perp + \tilde{r}_\perp)^2 + \lambda^2)} G(l_\perp^2, x, ...)
\]

\[
= \frac{1}{(k_\perp^2 + |t| + \tilde{Q}^2)^2} F^g_x(x, t, k_\perp^2 + \tilde{Q}^2 + |t|),
\]

where \(\tilde{Q}^2 = m_q^2 + z(1-z)Q^2\), \(G\) is the nonintegrated gluon distribution, and \(r_\perp\) is the transverse part of the momentum carried by the two-gluon system. The distribution \(F^g_0(x, 0, q_0^2)\) is normalized to \((xg(x, q_0^2))\).

We use the helicity conservation hypothesis in diffractive vector meson production. In this case one should calculate only two amplitudes with longitudinal \(A_L = A_{\gamma L \rightarrow V L}\) and transverse \(A_T = A_{\gamma T \rightarrow V T}\) photon polarization. Other amplitudes which do not conserve helicity vanish as \(|t| \rightarrow 0\). The following approximation for the skewed gluon distribution

\[
F^g_x(x, t, q_0^2) \simeq F(t)(xg(x, q_0^2)),
\]

is used for simplicity, where \(F(t)\) is a hadron form factor. The longitudinal amplitude is found to be as follows

\[
A_L = 4N \int dz \int dk_\perp^2 (xg(x, k_\perp^2 + Q^2 + |t|)) \phi_V(z, k_\perp^2) \quad \frac{\sqrt{Q^2} \left(k_\perp^2 + m_q^2 + M_V^2z(1-z)\right) \left(k_\perp^2 - \tilde{Q}^2\right)}{M_V^2 \left(k_\perp^2 + \tilde{Q}^2\right) \left(k_\perp^2 + |t| + \tilde{Q}^2\right)^2}.
\]

For the transverse one we have

\[
A_T = 2N \left(E_V^T \cdot E_T^\gamma\right) \int dz \int dk_\perp^2 (xg(x, k_\perp^2 + Q^2 + |t|)) \phi_V(z, k_\perp^2) \quad \frac{k_\perp^2 m_q^2 - 2k_\perp^2z(1-z) + 2k_\perp^2 z(1-z) \tilde{Q}^2 - \tilde{Q}^2 m_q^2 - 2k_\perp^2 \tilde{Q}^2}{M_V z(1-z) \left(k_\perp^2 + \tilde{Q}^2\right) \left(k_\perp^2 + |t| + \tilde{Q}^2\right)^2}.
\]

Here \(N\) is some normalization factor which is the same for longitudinal and transverse amplitude. The gluon distribution in the case of vector meson production depends on \(x\)
which is fixed by \( x = x_p = (Q^2 + |t| + M_V^2)/W^2 \). In (6,7) we leave a small \( t \) variable in the denominator and in the scale of the gluon structure function. Note that at HERA energies, we can consider only the gluon contribution to the amplitudes (6,7).

The cross sections with longitudinal and transverse photon polarization are \( \sigma_{L(T)} \propto A_{L(T)}^2 \). In our analyses we use the same wave function \( \phi_V \) for longitudinal and transverse vector meson polarization which vanishes as \( z(1-z) \) for \( z \to 0 \) or \( z \to 1 \). In this case it can be found that for \( t = 0 \) we have divergence in \( \sigma_T \). This problem can be solved in two separate ways. The first one was proposed in [4] for \( |t| = 0 \) by considering the scale dependence in the gluon distribution \( xg(x, k^2_{\perp} + \bar{Q}^2) \propto (k^2_{\perp} + \bar{Q}^2)^\lambda \) with \( \lambda \sim 0.3 \) for small \( x \). The additional factor \( (k^2_{\perp} + \bar{Q}^2)^\lambda \) reduces the divergence of the integral, and one can found that [4]

\[
\sigma_L \propto \frac{1}{(1 + \lambda)^2} \quad \text{and} \quad \sigma_T \propto \frac{1}{\lambda^2}.
\]

(8)

![Figure 1](image.png)

Fig.1 Regularization functions at \( Q^2 = 5\text{GeV}^2 \), normalized to unity at \( z = 0.5 \): \( F^H \) -dashed line; \( F^S \) -solid curve.

We call this method the "hard regularization". Some problem appears here with the factorization of the amplitude to the hard and soft part - gluon distribution becomes dependent on the momentum \( k^2_{\perp} \) of the hard contribution.

The other possibility is based on the fact that, in the fixed target experiments it is usually impossible to determine \( t \), and the cross section integrated over momentum transfer

\[
\sigma = \int dt \frac{d\sigma}{dt}
\]

is measured. The average momentum transfer can be estimated from (8) to be about \( |t| \sim 0.1\text{GeV}^2 \) for (6,7). Thus, one can use the "soft scale regularization" which includes the nonzero momentum transfer \( t \) in the denominator of (6,7) and in the gluon distribution. In this case the integrals become convergent too. As a result, we can write two different regularization functions for integrals (6,7) at small \( k^2_{\perp} \) and \( m_q = 0 \)

\[
F^H = \left( z(1-z)Q^2 \right)^\lambda \quad \text{with} \quad \lambda = 0.3
\]
\[ F^S = \left( \frac{z(1-z)Q^2}{z(1-z)Q^2 + |\bar{t}|} \right)^2 \] with \(|\bar{t}| = 0.1\text{GeV}^2. \] (10)

The regularization functions normalized to unity are shown in Fig.1. We see that \( F^H \) practically coincides with \( F^S \) at \( Q^2 = 5\text{GeV}^2. \) For larger \( Q^2 \) the difference between these functions will be a little bit larger.

In what follows, we use the ”soft regularization”. The corresponding cross sections \( \sigma^{L,T} \propto (A_{L,T})^2 \) were calculated for different forms of the wave function \( \phi_V(z, k^2_\perp) \) with the exponential \( k^2_\perp \) dependence there \[ \phi_1^V = N_1 z(1-z) \exp(-k^2_\perp b g(z)), \quad b = 4.0[\text{GeV}^{-2}]; \] \[ \phi_2^V = N_2 z(1-z) g(z) \exp(-k^2_\perp b g(z)), \]
\[ g(z) = 1/(z(1-z)), \quad b = .88[\text{GeV}^{-2}]. \] (11)

Here \( N_i \) is a wave-function normalization factor which is cancelled in the ratio of cross sections.

In addition, for \( \rho \) production, the wave function that has a two-maximum form in the \( z \)-distribution was tested

\[ \phi_3^\rho = N_3 z(1-z) V(z) g(z) \exp(-k^2_\perp b g(z)), \]
\[ V(z) = 1 + .077 C_2^{3/2}(1 - 2z) - .077 C_4^{3/2}(1 - 2z), \]
\[ g(z) = 1/(z(1-z)), \quad b = .88[\text{GeV}^{-2}]. \] (13)

This form of \( V(z) \) was found from the QCD sum rules for the \( \rho \) meson in [8].

Calculations for \( R = \sigma^L/\sigma^T \) were made for \( \rho, \phi \) and \( J/\Psi \) meson production for different \( Q^2 \) by using the same parameters \( b \) in (11).
Results for $\rho$ are shown in Fig. 2 together with known experimental data. We find that the wave function $\phi_1^\rho$ gives the $R$ ratio which is essentially smaller than experimental data. Results for the wave function $\phi_2^\rho$ are compatible with data. At the same time, $R$ for the wave function $\phi_3^\rho$ is similar to that found for $\phi_2^\rho$. So, different forms of $z$-dependences of the wave function give similar results for the $R$-ratio. However, this ratio is sensitive to the form of the $k_2^T$ distribution of the wave function.

Results for $\phi$ meson production are shown in Fig. 3. They are compatible with the data for $\phi_2^\phi$ as in the case of $\rho$ production. For $J/\Psi$ production, the wave functions $\phi_1^\phi$ and $\phi_2^\phi$
are not far from available experimental data (Fig.4). This is caused by the nonzero quark mass \( m_Q \sim M_{J/\Psi}/2 \) which regularizes integral for the \( A_T \) amplitude. Similar calculations were performed for the "hard regularization". It was found that within 5-10 % there is no difference between the "hard" and "soft" regularization up to \( Q^2 \simeq 50 - 100 \text{GeV}^2 \). Thus, we cannot determine now what physical mechanism is more relevant to experiment.

To conclude, we would like to note that the effects of the gluon distribution should be cancelled especially in the ratio of cross sections with different photon polarizations and the \( R \) ratio is expected to be dependent mainly on the vector meson wave function structure. We find that the \( R \) ratio is weakly dependent on the \( z \)-distribution of the wave function. Really, results for the asymptotic form \( \propto z(1-z) \) practically coincide (Fig.1) with the wave function found from the QCD sum rules \( \propto z(1-z)V(z) \) which has two maxima in the \( z \)-distribution (\( \phi_3^V \)). At the same time, the \( R \) ratio is strongly sensitive to the transverse component of the wave function. Really, for light quark production, the simple exponential form \( \exp(-b k^2_\perp) \) in the wave function gives a result which is much smaller than experimental data. For the \( z \)-dependent transverse component \( \exp(-b k^2_\perp/(z(1-z))) \) the \( R \) ratio is consistent with experiment. For heavy quark production, the results of calculation for both wave functions (11) are not far from experiment (Fig.4).

Note that, generally, the form of the vector meson wave function for longitudinal and transverse polarization might be different [9]. This requires an additional investigation of the \( R \) ratio in that case.

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References

[1] J.C. Collins, L. Frankfurt, M. Strikman, Phys. Rev. D56, 2982 (1997).

[2] H1 Collaboration, C. Adloff et al., Eur.Phys.J. C13, 371 (2000; S. Aid et al., Z. Phys. C75, 607-618 (1997);
ZEUS Collaboration; J.Breitweg et al., Eur.Phys.J. C6, 603 (1999); M. Derrick et al., Eur. Phys. J. C2, 247 (1998).

[3] M.G. Ryskin, R.G. Roberts, A.D. Martin, E.M. Levin, Z. Phys. C76, 231 (1997).

[4] A.D. Martin, M.G. Ryskin, T.Teubner, Phys. Rev. D55, 4329 (1997);

[5] J.L. Cudell, I. Royen, Nucl. Phys. B545, 505 (1999);

[6] S.V. Goloskokov, [hep-ph/0011341], to appear in Proc. of 14th Int. Spin Physics Symposium, SPIN2000, Osaka, Japan, 2000.

[7] R. Jakob, P. Kroll, Phys.Lett. B315, 463 (1993);

[8] A.P. Bakulev, S.V. Mikhailov, Phys. Lett. B436, 351 (1998).

[9] P. Ball, V.M. Braun, Phys. Rev. D54, 2182 (1996);