Unifying aspects of polarization of vector mesons from hard production in DIS and at Tevatron

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Virtual photons have both the transverse and longitudinal polarization. In the inclusive DIS the impact of longitudinal photons, quantified by \( R = \sigma_L/\sigma_T \sim 0.2 \), is marginal, but in diffractive DIS with excitation of small mass hadronic states or exclusive diffraction into vector mesons, QCD predicts \( R \gg 1 \) in agreement with the experiment. After a brief review of the modern status of QCD theory of diffractive vector meson production I argue that longitudinally polarized gluons give rise to a large longitudinal polarization of the prompt \( J/\Psi \) and \( \Psi' \) observed at the Tevatron.

1. Introduction

In DIS incident leptons serve as a source of virtual photons and experimentally one studies a virtual photoproduction of various hadronic states. By virtue of the optical theorem, the inclusive DIS structure functions are related to the imaginary part of an amplitude of diagonal, \( Q_f^2 = Q_{in}^2 = Q^2 \), forward virtual Compton scattering (CS) \( \gamma^*_\mu(Q_{in}^2)p \rightarrow \gamma^*_\nu(Q_f^2)p' \), which for the reason of vanishing \( (\gamma^*,\gamma^*) \) momentum transfer happens to be diagonal in the photon helicities, \( \nu = \mu \). While real photons are transverse ones, i.e., have only circular polarizations, \( \mu = \pm 1 \), virtual photons radiated by leptons have also the longitudinal polarization, which in the scaling limit equals

\[
\epsilon_L = \frac{2(1-y)}{2(1-y) + y^2},
\]

where \( y \) is a fraction of the beam lepton energy taken away by the photon, so that the photoabsorption cross section measured in the inclusive DIS equals \( \sigma = \sigma_T + \epsilon_L \sigma_L \). The effect of longitudinal photons, quantified by \( R_{DIS} = \sigma_L/\sigma_T \sim 0.2 \), is marginal, though.

Keep the virtuality of the initial photon, \( Q^2 = Q_{in}^2 \), fixed. By analytic continuation to \( Q_f^2 = 0 \) one obtains DVCS, the still further continuation to \( Q_f^2 = -m_V^2 \) transforms CS into the diffractive vector meson (VM) production \( \gamma_\mu(Q^2)p \rightarrow V_\nu(\Delta)p'(-\Delta) \), which is accessible experimentally also at finite \( (\gamma^*V) \) momentum transfer \( \Delta \). Vector mesons have
the three polarization states, $\nu = \pm 1, 0$. The decays of VM's are self-analyzing which allows to reconstruct the full set of helicity amplitudes $A_{\nu\mu}$ and probe the production mechanism in full complexity. The crucial point about diffractive excitation of VM and small mass continuum is that they are entirely dominated by $\sigma_L$.

In this report I review first the spin phenomena in diffractive exclusive vector meson production. The new numerical results reported here were obtained in collaboration with Igor Ivanov. Then I turn to the rôle of longitudinally polarized gluons in inclusive production of vector mesons in hadronic production and shall argue that they are a natural source of large longitudinal polarization of the $J/\Psi$ and $\Psi'$ mesons as discovered at Tevatron. This observation is from an ongoing collaboration work with Pauchy Hwang, Igor Ivanov and Wolfgang Schäfer.

2. Color dipole factorization, $(Q^2 + m_V^2)$ scaling and spin dependence of vector meson production

CS and diffractive VM production at small-$x$ are best described in color dipole (CD) factorization, in which $A_{\nu\mu} = \Psi^*_{\nu,\lambda\bar{\lambda}} \otimes A_{q\bar{q}} \otimes \Psi_{\mu,\lambda\bar{\lambda}}$ where $\lambda, \bar{\lambda}$ stands for $q, \bar{q}$ helicities, $\Psi_{\mu,\lambda\bar{\lambda}}$ is the wave function (WF) of the $q\bar{q}$ Fock state of the photon or VM. The $q\bar{q}$-proton scattering kernel $A_{q\bar{q}}$ is proportional to color dipole cross section, does not depend on, and conserves exactly, the $q, \bar{q}$ helicities. For small dipoles, the CD cross section described by the two-gluon QCD pomeron exchange is manifestly related to the gluon SF of the target ($A \approx 10$ follows from properties of Bessel functions),

$$\sigma(x, r) \approx \frac{\pi^2}{3} r^2 a_S(A) G(x, \frac{A}{r^2}). \quad (2)$$

In exclusive production of the VM one swaps in the final state the pointlike photon, whose $q\bar{q}$ WF is singular at $r \to 0$, for the finite-size VM with WF which is smooth at $r \to 0$. As a result, while DIS probes $\sigma(x, r)$ CD in a broad range of $\frac{1}{Aq^2} \approx r^2 \approx 1 \text{ fm}^2$, the diffractive VM production probes $\sigma(x, r)$, and the VM WF, at a scanning radius $r_S$

$$r \sim r_S = \frac{6}{\sqrt{Q^2 + m_V^2}}. \quad (3)$$

Regarding the spin dependence of diffractive VM, the fundamental point is that the sum of quark and antiquark helicities equals helicity of neither the photon nor vector meson. If for the nonrelativistic massive quarks, $m_f^2 \gg Q^2$ the only allowed transition is $\gamma^*_{\mu} \to q_{\lambda} + \bar{q}_{\bar{\lambda}}$ with $\lambda + \bar{\lambda} = \mu$. In the relativistic case transitions of transverse photons $\gamma^*_\pm$ into the $q\bar{q}$ state with $\lambda + \bar{\lambda} = 0$, in which the helicity of the photon is transferred to the $q\bar{q}$ orbital momentum, are equally allowed. Consequently, in QCD the $s$-channel helicity non-conserving (SCHNC) transitions $\gamma^*_\pm \to (q\bar{q})_{\lambda+\bar{\lambda}=0} \to \gamma^*_L$ and $\gamma^*_{\pm} \to (q\bar{q})_{\lambda+\bar{\lambda}=0} \to \gamma^*_{\pm}$ are allowed and SCHNC persists at small $x$ despite the exact conservation of the helicity of quarks in $q\bar{q}$-target scattering. This argument for SCHNC does not require the applicability of pQCD. Furthermore, the leading contribution to the proton structure function comes entirely from SCHNC transitions of transverse photons - the fact never mentioned in textbooks.
Figure 1. The test of the \((Q^2 + m_V^2)\) scaling. The divergence of the solid and dashed curves indicates the sensitivity to the WF of the VM. The experimental data are from HERA [13].

Still another fundamental point is that the vertex of the SCHC transition \(\gamma^*_L \rightarrow (q\bar{q})_{\lambda+\lambda=0}\) is proportional to \(Q\), which entails [1]

\[
R = \frac{\sigma_L(\gamma^*_L \rightarrow V_{L}p)}{\sigma_T(\gamma^*_T \rightarrow V_{T}p)} \sim \frac{Q^2}{m_V^2} >> 1
\]  

(4)

for diffractive VM’s. As was first noticed in [1], a numerical analysis with realistic soft WF gives values of \(R\) substantially smaller than a crude estimate (4).

The three fundamental consequences of (2), (3) and (4) are:

- the VM production probes [1] the gluon SF of the target at the hard scale \(\overline{Q}^2 \approx (0.1\text{-}0.25)*(Q^2 + m_V^2)\) and \(x = 0.5(Q^2 + m_V^2)/(Q^2 + W^2)\),

- after factoring out the charge-isospin factors all VM production cross section follow a universal function of \(\overline{Q}^2\), i.e. there is \((Q^2 + m_V^2)\) scaling [1], see fig. 1, the same scaling holds also for the effective intercept \(\alpha_{IP}(0) - 1\) of the energy dependence of the production amplitude, see fig. 2,

- the contribution to the diffraction slope \(B\) from the \(\gamma^* \rightarrow V\) transition vertex decreases \(\propto \alpha^2\) exhibiting again the \((Q^2 + m_V^2)\) scaling [12], see fig. 2.
The agreement between theory and experiment [13] is good, although there remains certain sensitivity to not so well known WF of VM's which can not be eliminated at the moment, see also below. The theoretical calculations are based on the differential glue in the proton found in [14].

We emphasize that SCHNC helicity flip only is possible due to the transverse and/or longitudinal Fermi motion of quarks and is extremely sensitive to spin-orbit coupling in the vector meson, I refer for details to [11,15]. The consistent analysis of production of $S$-wave and $D$-wave vector mesons is presented only in [15]. The dominant SCHNC effect in vector meson production is the interference of SCHC $\gamma^*_L \rightarrow V_L$ and SCHNC $\gamma^*_T \rightarrow V_L$ production, i.e., the element $r_{00}$ of the vector meson spin density matrix. The overall agreement between our theoretical estimates [3] of the spin density matrix for diffractive $\rho^0$ assuming pure $S$-wave in the $\rho^0$-meson and the ZEUS [16] and H1 [17] experimental data is very good, there is a clear evidence for $r_{00} \neq 0$, see fig. 3.

The theoretical calculations [3] seem to overpredict $R = \sigma_L/\sigma_T$ at large $Q^2$, see fig. 4, for the compilation of the experimental data see [18]. On the one hand, the admissible $S-D$ mixing brings the theory to a better agreement with the data. on the other hand, as the recent data from ZEUS [18] do indicate, the experimental value of $R$ tends to rise with the time. Here I would like to raise the issue of sensitivity of $R$ to the short distance properties of vector mesons [19].

Consider $R_{el} = \sigma_L/\sigma_T$ for elastic CS $\gamma^*p \rightarrow \gamma^*p$, which is quadratic in the ratio of CS amplitudes. By optical theorem one finds

$$R_{el} = \frac{\sigma_L(\gamma^*_Lp \rightarrow \gamma^*_Lp)}{\sigma_T(\gamma^*_Tp \rightarrow \gamma^*_Tp)} = \left| \frac{A(\gamma^*_Lp \rightarrow \gamma^*_Lp)}{A(\gamma^*_Tp \rightarrow \gamma^*_Tp)} \right|^2 = \left( \frac{\sigma_L}{\sigma_T} \right)_{DIS}^2 \approx 4 \cdot 10^{-2} \quad (5)$$

Here I used the prediction [8] for inclusive DIS $R_{DIS} = \sigma_L/\sigma_T|_{DIS} \approx 0.2$, which is consistent with the indirect experimental evaluations of $R_{DIS}$ at HERA. Such a dramatic
change from $R_{el}$ to $R$ of (4) suggests that predictions of $R$ for diffractive VM production are extremely sensitive to the poorly known admixture of quasi-pointlike $q\bar{q}$ components in VM.

3. Longitudinal gluons and polarization of a direct $J/\Psi$ and $\Psi'$ at Tevatron

There is a long standing mystery of the predominant longitudinal polarization of prompt $J/\Psi$ and $\Psi'$ produced at large transverse momentum $p_\perp$ as observed by the CDF collaboration in inclusive $p\bar{p}$ interactions at Tevatron [4], see fig. 5, in which the polarization parameter

$$\alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + \sigma_L}$$

is shown (the observed $\Psi'$ are arguably the direct ones, the prompt $J/\Psi$'s include the $J/\Psi$'s both from the direct production and decays of higher charmonium states) . Specifically, the color-octet model [20] is able to parameterize the observed reaction cross section (for a criticism of the standard formulation of the color-octet model see [21]), but fails badly in its predictions [22,23] for the polarization parameter $\alpha$. 

![Figure 3](image-url)
Figure 4. The sensitivity of $R = \sigma_L/\sigma_T$ for the $\rho$ production to the S-D-mixing [3], for the compilation of the experimental data see [18].

Figure 5. Predictions [22,23] from the color-octet model for the polarization parameter $\alpha$ vs. $p_\perp$ for direct $\Psi$ and prompt $J/\Psi$ compared to CDF data [4].

Arguably, production of charmonium states at mid-rapidity is controlled by gluon-gluon collisions. Now recall that in the standard collinear factorization the colliding gluons are regarded as on-mass shell, and transversely polarized, ones. Which is the principal reason, why one predicts the predominantly transverse polarization of the produced $J/\Psi$ and $\Psi'$. The QCD subprocesses for direct production of $C = -1$ vector states of charmonium are shown in fig. 6. In order to emphasize an impact of their virtuality of the colliding gluons, I indicate explicitly the origin of the gluon $g^*$. One can readily show that, in close
similarity to virtual photons, the highly virtual gluons have both the familiar transverse and so far ignored longitudinal polarization [3].

Figure 6. The diffractive QCD subprocesses for the production of prompt vector states of charmonium in hadronic reactions.

In order to illustrate our principal point let me focus on the "diffractive" mechanism of fig. 6a. It dominates at large invariant masses \( \hat{w} \) of the \( Vg' \) system, \( \hat{w}^2 \gg M_{\Psi}^2 \). The virtuality of the gluon \( g^* \) is controlled by the transverse momentum \( k_\perp \) of the gluon \( g^* \), so that \( Q^2 \approx k_\perp^2 \). The sub-process \( g^* + g \rightarrow J/\Psi g' \) proceeds predominantly in the forward direction, which implies that the transverse momentum of the \( g^* \) is transferred to the \( J/\Psi \), so that \( p_\perp \approx k_\perp \). The difference between color octet two-gluon state in the \( t \)-channel of fig. 6a and color-singlet two gluon state in the diffractive pomeron exchange is completely irrelevant for spin properties of the \( J/\Psi \) production, and for the diffractive mechanism of fig. 6a we unequivocally predict \( R = \sigma_L/\sigma_T \sim p_\perp^2/m_{\psi'}^2 \), i.e., \( \alpha \rightarrow -1 \) for very large \( p_\perp \). After some color algebra, one can readily relate the total cross section of the "diffractive" mechanism to the cross section of photoproduction of \( J/\Psi \) on nucleons. We found that "diffractive" mechanism is short of strength and could explain only \( \sim 10 \) per cent of the observed yield of the direct \( J/\Psi \).

The diagrams of fig. 6b dominate for \( \hat{w} \sim m_{\psi'} \). Arguably, the above estimate for the \( p_\perp \) dependence of \( R \) applied to this mechanism too. Crude estimates show that the contribution from this mechanism is commensurate to the "diffractive" production.

Besides the predominantly "forward" production when the transverse momentum of the \( g^* \) is transferred predominantly to the direct \( J/\Psi \), one must also consider the large angle reaction \( g^*g \rightarrow J/\Psi + g \), which could affect the polarization parameter \( \alpha \). The full numerical analysis has not been completed yet, still we believe that the so far neglected longitudinal gluons resolve a riddle of the longitudinal polarization of direct \( J/\Psi \) and \( \Psi' \).

4. Conclusions

QCD theory of diffractive production of vector mesons is in a good shape and offers a solid basis for the quantitative interpretation of the experimental data. So far neglected longitudinal gluons are predicted to dominate production of direct vector mesons at large transverse momentum in hadronic collisions and resolve the long-standing riddle of the dominant longitudinal polarization of the \( J/\Psi \) and \( \Psi' \) discovered by CDF.
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