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QCD compositeness as revealed in exclusive vector boson reactions through double-photon annihilation: $e^+e^- \to \gamma\gamma^* \to \gamma V^0$ and $e^+e^- \to \gamma^*\gamma^* \to V^0V^0$

Stanley J. Brodsky [a], Richard F. Lebed [b], Valery E. Lyubovitskij [c,d,e,*]

[a] SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94309, USA
[b] Department of Physics, Arizona State University, Tempe, AZ 85287-1504, USA
[c] Institut für Theoretische Physik, Universität Tübingen, Kepler Center for Astro and Particle Physics, Auf der Morgenstelle 14, D-72076, Tübingen, Germany
[d] Department of Physics, Tomsk State University, 634050 Tomsk, Russia
[e] Laboratory of Particle Physics, Mathematical Physics Department, Tomsk Polytechnic University, Lenin Avenue 30, 634050 Tomsk, Russia

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ABSTRACT

We study the exclusive double-photon annihilation processes, $e^+e^- \to \gamma\gamma^* \to \gamma V^0$ and $e^+e^- \to \gamma^*\gamma^* \to V_a^0 V_b^0$, where the V_i^0 is a neutral vector meson produced in the forward kinematical region: $s \gg -t$ and $-t \gg \Lambda^2_{\rm QCD}$. We show how the differential cross sections $\frac{d\sigma}{dt}$, as predicted by QCD, have additional falloff in the momentum transfer squared t due to the QCD compositeness of the hadrons, consistent with the leading-twist fixed-$\theta_{\rm CM}$ scaling laws, both in terms of conventional Feynman diagrams and by using the AdS/QCD holographic model to obtain the results more transparently. However, even though they are exclusive channels and not associated with the conventional electron–positron annihilation process $e^+e^- \to \gamma^* \to q\bar{q}$, these total cross sections $\sigma(e^+e^- \to \gamma V^0)$ and $\sigma(e^+e^- \to V_a^0 V_b^0)$, integrated over the dominant forward- and backward-$\theta_{\rm CM}$ angular domains, scale as $1/s$, and thus contribute to the leading-twist scaling behavior of the ratio $R_{e^+e^-}$. We generalize these results to exclusive double-electroweak vector-boson annihilation processes accompanied by the forward production of hadrons, such as $e^+e^- \to Z^0 V^0$ and $e^+e^- \to W^-\rho^+$. These results can also be applied to the exclusive production of exotic hadrons such as tetraquarks, where the cross-section scaling behavior can reveal their multiquark nature.

1. Introduction

A surprising result, shown by Davier, Peskin, and Snyder (DPS) [1], is that there are exclusive hadronic contributions to the electron–positron annihilation cross section ratio $R_{e^+e^-} = \sigma(e^+e^- \to X)/\sigma(e^+e^- \to \mu^+\mu^-)$ that are scale invariant, but are not associated with the annihilation process $e^+e^- \to \gamma^* \to q\bar{q}$. These exclusive processes are based on double-photon annihilation subprocesses, such as $e^+e^- \to \gamma\gamma^* \to \gamma V^0$ and $e^+e^- \to \gamma^*\gamma^* \to V_a^0 V_b^0$, where the V_i^0 are vector bosons such as the ρ meson. Since the amplitude involves spin-$\frac{1}{2}$ electron exchange in the t and u channels, it behaves as $s^{\frac{1}{2}}$ for $s \gg -t, -u$. The total cross section (which includes a phase-space factor of $1/s^2$), integrated over the dominant forward and backward regions, thus behaves as $1/s$.

In this paper we show how the QCD compositeness of the vector bosons affects the matrix elements and cross sections for these double-photon processes. The effects of compositeness reflect the fact that the coupling of the virtual photon proceeds through the vertex $\gamma^* \to q\bar{q}$. One may study the scaling behavior solely using conventional Feynman diagram techniques, as we describe below and in Sec. 2. In order to obtain explicit closed-form results that manifest the correct scaling behavior, we start by employing the light-front quantization of QCD (LF-QCD); in those terms, the virtual $q\bar{q}$ then couples to the valence hadronic light-front wave function $\psi_{V^0}(x, \vec{k}_\perp)$. The integration over the light-front momentum fractions $x = k^+/P^+$ and $1-x$, and relative transverse momentum $k_\perp$, of the pair leads to an extra factor of the QCD mass scale $\Lambda_{\rm QCD}$ in the numerator of the amplitude. In order to track both the small- and large-momentum behavior of these processes, we utilize the AdS/QCD (AdS = anti-de Sitter) holographic light-front model [2,3] which is successful in explaining the main features of meson and baryon spectroscopy, as well as the dynami-

* Corresponding author.
E-mail address: lubovit@tphys.physik.uni-tuebingen.de (V.E. Lyubovitskij).

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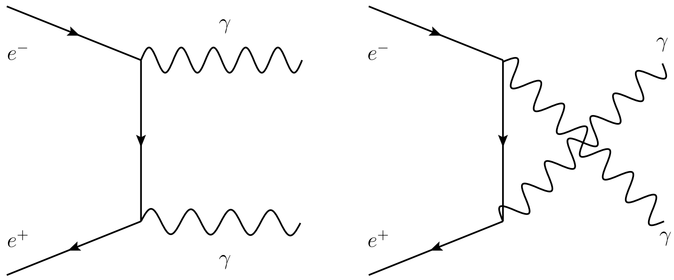

Fig. 1. The double-photon annihilation amplitude in the Born approximation.

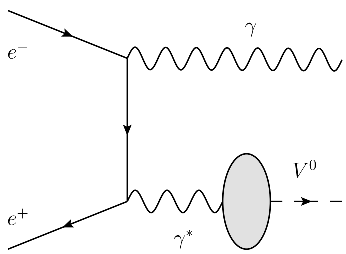

Fig. 2. Exclusive production of a photon and vector boson via double-photon annihilation (the corresponding u-channel diagram is implied). The differential cross section is peaked in the forward and backward directions. Compositeness of the vector boson produces a monopole falloff of the differential cross section $d\sigma/dt$ in $|t|$.

cal properties of hadrons. This nonperturbative approach to hadron physics gives a good overall description of meson and baryon form factors, including consistency with the perturbative QCD (pQCD) power-law scaling of hadronic form factors at large momentum transfer. The AdS/QCD hadronic scale κ can be related to the slope of the Regge trajectories, as well as providing mass relations such as $\kappa = M_\rho/\sqrt{2}$ [2,3]. We also show that the AdS/QCD prediction for f_ρ, the leptonic decay constant of the ρ meson, is in excellent agreement with measurement.

The double-photon $e^+e^- \to \gamma\gamma$ amplitude illustrated in the first inset of Fig. 1 behaves for large energy as

$$\mathcal{M}(s,t) \propto \alpha_{\rm em}\left(\frac{s}{-t}\right)^{\alpha_R} = \alpha_{\rm em}\left(\frac{s}{-t}\right)^{1/2}, \tag{1}$$

for $s \gg -t$, corresponding to spin-$\frac{1}{2}$ exchange in the t channel, where the differential cross section is $d\sigma/dt \propto |\mathcal{M}(s,t)|^2/s^2$. The fermion-exchange amplitudes have both t- and u-channel contributions; however, the interference is suppressed in the dominant forward- and backward-peaked domains. As we shall show, and consistent with dimensional analysis, the differential cross section for the production of a single vector meson $\frac{d\sigma}{dt}(e^+e^- \to \gamma V^0)$ via double-photon annihilation (see Fig. 2) must have the extra falloff $G_V^2(t) \sim \kappa^2/|t|$ at large $-t \gg \kappa^2$; *i.e.*,

$$\frac{d\sigma}{dt}(e^+e^- \to \gamma V^0) \sim \frac{\alpha_{\rm em}^3}{s|t|}\frac{\kappa^2}{|t|}. \tag{2}$$

The mass parameter κ is specifically the scale parameter of AdS/QCD approach; however, the power scaling of AdS/QCD and pQCD for $G_V^2(t)$ at large t are the same, consistent with the twist dimension dictated by QCD compositeness. Physically, the extra falloff in $|t|$ results from the phase-space hadronization of the virtual $q\bar{q}$ in the amplitude $e^+e^- \to \gamma q\bar{q} \to \gamma V^0$, which is represented by the transition form factor $G_V(q^2)$. In the case where two vector bosons are produced with opposite transverse momenta (see Fig. 3), the amplitude is suppressed by two form factors, so the differential cross section at $s \gg -t \gg \kappa^2$ scales as

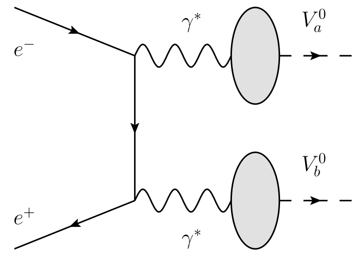

Fig. 3. Exclusive production of two vector bosons via double-virtual photon annihilation (the corresponding u-channel diagram is implied). Compositeness of the vector bosons produces a dipole falloff of the differential cross section $d\sigma/dt$ in $|t|$.

$$\frac{d\sigma}{dt}(e^+e^- \to \gamma^*\gamma^* \to V_a^0 V_b^0) \sim \frac{\alpha_{\rm em}^4}{s|t|}\frac{\kappa^4}{t^2}. \tag{3}$$

The powers of $\alpha_{\rm em}$ correspond to the couplings of the virtual photons to the currents of the annihilating leptons and the vector bosons. In effect, the cross sections are the same as that given by the naive vector-meson dominance (VMD) model [4] but multiplied by the form factors required by QCD compositeness. It is worth noting that such nontrivial form factors also naturally arise in chiral perturbation theory calculations [5,6], but carry a different scaling, as discussed below.

The scaling results for the exclusive cross sections are consistent with the leading-twist quark fixed-angle counting rules [7–9]: $\frac{d\sigma}{dt}(A+B \to C+D) \propto F(\theta_{\rm CM})/s^{N-2}$, where $N = N_A + N_B + N_C + N_D$ is the total twist or number of elementary constituents. In our case, $N-2=3$ for $e^+e^- \to \gamma V^0$ and $N-2=4$ for $e^+e^- \to V_a^0 V_b^0$, which would give the scaling for non-forward angles (where s, $-t$, $-u$ are all of comparable size). In the present case, the integration over the forward peaks in t and u does not modify the $1/s$ scaling of the total cross section; *e.g.*, $\sigma_{e^+e^-\to\gamma V^0}(s) \propto \alpha_{\rm em}^3/s$, up to logarithms in t (or u), which are cut off by the mass scales in the process: m_e^2 from the propagator between the photons and κ^2 from the dominant part of the hadronization integral.

Although compositeness does not affect the leading $1/s$ scaling of the total cross sections of these reactions, it does strongly modify the t and u dependence of the amplitudes in terms of new types of transition form factors. An analysis such as that given in Ref. [10], based on an effective field theory in which the vector mesons are treated as elementary fields, cannot yield the form factors and counting rules predicted by QCD due to meson compositeness.

In addition, QCD also predicts the $\frac{1}{M^2_{V_i^0}}$ falloff of the amplitudes as the mass of each vector boson is increased; this falloff corresponds to the timelike q^2 of the virtual photon. One thus finds new tests of color confinement and the nonperturbative hadronic wave functions of hadrons. We also show that these results can be extended to electroweak exclusive processes involving electron or neutrino exchange, such as $e^+e^- \to Z^0 V^0$, which are accessible at the proposed International Lepton Collider (ILC), and to exotic multi-quark hadrons.

2. Coupling of virtual photons to vector bosons

In this section we demonstrate how the correct momentum dependence (consistent with QCD compositeness) of the $\gamma^* \to V^0$ transition amplitude can be evaluated in the AdS/QCD approach. The full q^2 dependence of the corresponding transition form factor is model dependent, but at large values of q^2, its scaling must be consistent with pQCD.

First, we point out that the full off-shell $\gamma^*(q) \to V^{0*}(q)$ transition is given by the amplitude $G_V(q^2)(g^{\mu\nu}q^2 - q^\mu q^\nu)/q^2$, where the tensor guarantees gauge invariance, the $1/q^2$ comes from the