We study baryon pair production in two-photon collisions, $\gamma\gamma \rightarrow BB$, within perturbative quantum chromodynamics, treating baryons as quark-diquark systems. We extend previous work within the same approach by treating constituent-mass effects systematically by means of an expansion in the small parameter (mass/photon energy). Our approach enables us to give a consistent description of the cross sections for all octet baryon channels. Adopting the model parameters from foregoing work, we are able to reproduce the most recent large-momentum-transfer data from LEP for the $p\bar{p}$, $\Lambda\bar{\Lambda}$, and $\Sigma^0\bar{\Sigma}^0$ channels in a quite satisfactory way. We also briefly address the crossed process for the proton channel, $\gamma p \rightarrow \gamma p$.

Introduction sec:intro

Theoretical analyses of exclusive reactions in quantum chromodynamics (QCD), where intact hadrons appear in the initial and final states, are of great importance for a better understanding of the mechanism of confinement and of the dynamics of hadronic bound states. Although much progress has been made in the theoretical understanding within frameworks based on perturbation theory blrev,pire,stefanis, there still remain many open problems. It is a matter of ongoing discussion whether the currently experimentally accessible energies are high enough such that the perturbative treatment becomes applicable contro. As a possible way to model non-perturbative effects which do not seem to be fully separated from perturbatively calculable contributions at intermediately large momentum transfers, the introduction of diquarks has been proposed in anskrollpire. In a series of papers this effective model has been developed further and successfully applied to a variety of exclusive reactions gamgammp,Compton,fixed,time,Ja94,KSG96,KSPS97,fizb,CW,mass. In this work we continue the investigations within the diquark model and consider exclusive two-photon reactions.

The theoretical description of exclusive reactions within perturbation theory is based on the ideas of Brodsky and Lepage blrev,blpaper, and Efremov and Radyushkin efrad. Within this so-called hard scattering picture (HSP), an exclusive reaction amplitude can be written as a convolution of process-dependent, perturbatively calculable, hard-scattering amplitudes with process-independent probability amplitudes for finding the pertinent valence Fock states in the scattering hadrons. The latter are non-perturbative quantities, but their dependence on the momentum-transfer $Q^2$ can be determined perturbatively. Their extraction from experimental observations is challenged by the fact that they enter only integrated quantities, such as form factors. However, their shape can be constrained with the help of QCD sum rules, lattice QCD and other non-perturbative methods. These studies seem to indicate that the distribution of longitudinal momentum fractions among the valence quarks in a nucleon is quite asymmetric for finite momentum transfers. This can be interpreted as evidence for binding effects between two quarks in a nucleon and motivates the introduction of diquarks stefanis,anselmino. Comprehensive reviews of the HSP are given, for example, in blrev,pire,stefanis.

The HSP as presented above is exactly valid only for asymptotically large momentum transfers, $Q^2 \rightarrow \infty$, where long- and short-distance effects are completely incoherent. However, as already mentioned above, experimental observations seem to indicate that this separation is not yet achieved at presently accessible momentum transfers of a few GeV. Thus a perturbative calculation of the short distance contributions may not be completely self-consistent.

Inspired by the aforementioned correlations observed in hadronic wave functions, a quark-diquark model was developed in anskrollpire to parameterize possible non-perturbative effects within a perturbative framework. Within this model which is based on the HSP, baryons are treated as quark-diquark systems. The composite nature of the diquarks is taken into account by diquark form factors which are parameterized such that asymptotically the scaling behavior of the pure quark HSP emerges. The possibility of the reformulation of the pure quark HSP in terms of quark and diquark degrees of freedom has been demonstrated in bernd,marc. In earlier studies of two-photon annihilation into baryons, $\gamma\gamma \rightarrow BB$ gamgampp, and of Compton scattering off baryons, $\gamma B \rightarrow \gamma B$ Compton,KSG96, all quark masses have been neglected, while masses for diquarks were introduced as additional parameters. In recent studies within the diquark model fizb,CW,mass a different strategy was adopted to treat mass effects more consistently without introducing new mass parameters for the hadronic constituents. In the following we will reconsider the two-photon
reactions with this improved treatment of mass effects.

We start by introducing the necessary ingredients of the quark-diquark model for the reaction $\gamma \gamma \rightarrow BB$. While we try to keep the present discussion as self-contained as possible, we omit certain details of the model which can be found, for example, in CW. We explain our choice of quark and diquark distribution amplitudes (DAs), and our treatment of constituent masses in Sections sec:amp.qD and sec:mass, respectively. Having collected all ingredients of the model, we list our analytical results for the hard scattering amplitudes for the two-photon annihilation process in Section sec:ampres. In Section sec:results we present the numerical results for this reaction, compare to existing data for the proton-antiproton, $\Lambda \bar{\Lambda}$, and $\Sigma^0\Sigma^0$ channels, and give predictions for other final states. We then go on and briefly comment on the crossed reaction, specifically Compton scattering off protons. Section sec:final ends the discussion with a summary and some concluding remarks.

The $\gamma \gamma \rightarrow BB$ amplitude sec:amp

As stated in the introduction, within the HSP an exclusive scattering amplitude can be written as a convolution integral of a hard-scattering amplitude with distribution amplitudes, describing the longitudinal momentum distribution of valence quarks in the participating hadrons. In the diquark model a baryon is considered as consisting of a quark and a diquark. The diquark is treated as a quasi-elementary constituent which may survive medium hard collisions.

Within this framework, we obtain the following convolution integral for the $\gamma \gamma \rightarrow BB$ amplitude:

$$M_{(\lambda)} (s, t) = \frac{1}{\lambda} \int_{M_B} \int_{M_B} \Psi^B_B (x_1) \Psi^B_B (y_1)$$

For the process $\gamma \gamma \rightarrow BB$, there are six independent complex helicity amplitudes $M_{\lambda_B, \lambda_B; \lambda_i, \lambda_i}$, where the $\lambda_i, i = 1, 2$ label the helicities of the incoming photons, and $\lambda_B, \bar{\lambda}_B$ are the helicities of the baryon and antibaryon, respectively. Following the conventions in rosti76, we express our observables in terms of the following amplitudes: eqnarray $\varphi_i = M_{-12, 12, 1, -1}$.

The complete set of parameters of the quark-diquark model is listed in Table params. We emphasize

within the diquark form factors, and the anomalous magnetic moment of the vector diquark $\kappa_V$.

The SU(3) quark-diquark flavor wave functions $\chi^D_S$ for the lowest-lying baryon octet are listed in Table flav. table SU(3) quark-diquark flavor wave functions for the lowest lying baryon octet flav arrayl@*2mml

$$\chi^D_S = u_S[u,d] \chi^D_L = \sqrt{3} [uV_{u,d} - \sqrt{2} d V_{u,s}]$$

The hard-scattering amplitudes are calculated perturbatively with point-like constituents. For sake of completeness, we list the Feynman rules within the diquark model in the Appendix. Vector diquarks are allowed to possess an anomalous (chromo)magnetic moment $\kappa_V$, corresponding to the most general form of the coupling of a spin-1 gauge boson to a spin-1 particle. The composite nature of diquarks is taken into account by diquark form factors. These phenomenological vertex functions multiply each n-point contribution, that is, those Feynman graphs where $(n-2)$ gauge bosons couple to the diquark. The particular choice for space-like $Q^2$ eqnarray $F_s^{(3)}(Q^2) = \delta_s Q^2 Q_S^2 + Q^2$.

The parameterizations (form3) and (form4) are only valid for space-like $Q^2$. For time-like arguments $s$ we have chosen the following prescription: eqnarray $F_s^{(3)}(s) = \delta_s Q^2 Q_S^2 - s$, $F^{(3)}_s(s) = a_S F_s^{(3)}(s), n > 3$.

The complete set of parameters of the quark-diquark model is listed in Table params. We emphasize that the only a priori free parameters of the model are the constants $f_D, c_i$ in the wave function (huangy), the values of $Q_D^2, a_D$ in the diquark form factors, and the anomalous magnetic moment of the vector diquark $\kappa_V$. 2
The remaining constants \(m_q, m_D\), and \(b^2\) which appear in the DA are fixed by the physical considerations explained above. The initially free parameters were fixed in fixed by fitting elastic electron-nucleon scattering data, and all subsequent calculations within the model have used this set of parameters with success.

Table Parameters of the diquark model

\[
\begin{array}{l}
m_q = 330 \text{ MeV} & m_D = 580 \text{ MeV}, \text{ for light quarks} \\
\end{array}
\]

Treatment of constituent masses

Above, we assumed that every baryonic constituent has a four-momentum proportional to the four-momentum of its parent hadron ansa. Therefore, every constituent of a baryon \(B\) carrying momentum fraction \(x_pB\) acquires an effective mass \(x m_B\), where \(m_B\) is the baryon mass. Since the momentum fractions are weighted by the hadron DA (huangv) in the convolution integral, Eq. (HSP), the quark and diquark constituents carry average masses

\[
\langle m_{av}^{\alpha} \rangle = \langle x \rangle m_B \approx 13 m_B, m_{\text{quark}}
\]

We emphasize that this treatment of constituent masses in the hard-scattering amplitude does not require the introduction of new mass parameters, contrary to the prescription used in gamgampp,Compton. Our mass treatment is consistent in the sense, that it preserves \(U(1)\) gauge invariance with respect to the photon and \(SU(3)\) gauge invariance with respect to the gluons. As we will see below, it also provides the correct crossing relations between the (hadronic) amplitudes for two-photon annihilation into baryons, Eqs. (cmsampscr), and those for Compton scattering off baryons. Moreover, by including mass corrections up to \(O(m_B/\sqrt{s})\), not only vector diquarks but also quarks can change their helicity. Thus also the quark-scalar diquark state is able to contribute to helicity-flip amplitudes. Such contributions have been neglected throughout in previous work gamgampp,Compton,Ja94,KSG96,KSPS97. The inclusion of helicity-flip contributions from the quark-scalar diquark system naturally leads to more pronounced polarization effects for observables which require baryonic helicity flips.

The elementary \(\gamma\gamma \rightarrow qD\bar{q}\bar{D}\) amplitudes

There are altogether 60 Feynman graphs (30 containing \(S\) diquarks, 30 with \(V\) diquarks) which contribute to the elementary hard scattering amplitudes \(\hat{T}\) for \(\gamma\gamma \rightarrow qD\bar{q}\bar{D}\). \(\hat{T}\) has the general structure equation

\[
\hat{T}_{\{\lambda\}}^{\{\lambda\}} = e_2 \hat{T}_{\{\lambda\}}^{(3,D)} + e_q e_D \hat{T}_{\{\lambda\}}^{(4,D)} + e_D^2 \hat{T}_{\{\lambda\}}^{(5,D)},
\]