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LETTER TO THE EDITOR

HARD EXCLUSIVE BARYON-ANTIBARYON PRODUCTION IN 2-γ COLLISIONS

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We present a perturbative calculation of baryon pair production in two-photon collisions, $\gamma\gamma \to \mathrm{B\bar{B}}$, in which baryons are treated as quark-diquark systems. Our approach accounts for constituent mass effects in a systematic way. Taking the diquark-model parameters from foregoing studies of other electron- and photon-induced baryonic reactions, our results agree well with the most recent large momentum-transfer data for the $\mathrm{p\bar{p}}$, $\Lambda\bar{\Lambda}$, and $\Sigma^0\bar{\Sigma}^0$ channels.

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The present study was stimulated by recent experimental efforts of the OPAL [1], L3 [2, 3], and BELLE [4] groups to measure $\gamma\gamma \to \mathrm{B\bar{B}}$ cross sections at large energies and momentum transfers, where a theoretical description by means of perturbative QCD is supposed to become applicable. It updates and extends previous work [5 − 7] on the perturbative description of two-photon annihilation into baryon-antibaryon pairs within a quark-diquark model of baryons. We have made three improvements compared to these previous studies:

- all octet baryon channels are considered,
- calculations are performed within the full diquark model with scalar and vector diquarks taken into account,

- constituent-mass effects are included.

Our model is a modification of the usual hard-scattering mechanism [8], baryons are described as quark-diquark systems. Diquarks are introduced to parameterize binding effects between two quarks in a baryon. This approach allows us to model higher-order and non-perturbative effects which are undoubtedly present at currently experimentally accessible momentum transfers. Within the hard-scattering picture, the hadronic amplitude $\mathcal{M}_{\{\lambda\}}\left(\hat{s},\hat{t}\right)$ for $\gamma\gamma \to \mathrm{B\bar{B}}$ is expressed as a convolution of a perturbatively calculable hard-scattering amplitude $\hat{T}_{\{\lambda\}}$, with non-perturbative baryon distribution amplitudes Ψ_{B},

$$\mathcal{M}_{\{\lambda\}}\left(\hat{s},\hat{t}\right) = \int_0^1 \mathrm{d}x \int_0^1 \mathrm{d}y\, \Psi_{\mathrm{B}}^{\dagger}(x)\, \Psi_{\mathrm{\bar{B}}}^{\dagger}(y)\, \hat{T}_{\{\lambda\}}\left(x,y;\hat{s},\hat{t}\right) . \qquad (1)$$

Here x and y are the longitudinal momentum fractions carried by the quark and antiquark in the baryon and antibaryon, respectively. $\hat{s}$ and $\hat{t}$ denote massless Mandelstam variables, which we will discuss further below. The subscript $\{\lambda\}$ denotes all possible helicity configurations of photon and baryon helicities. The hard-scattering amplitude consists of a coherent superposition of tree graphs that describe the scattering process on the constituent level. This means that the two incoming photons are attached either to the quark or diquark line and quark and diquark are connected via one-gluon exchange. Form factors at the gauge-boson diquark vertices ensure that the correct asymptotic (fixed angle) scaling behaviour of differential cross sections is recovered for large enough momentum transfers. The parameterization of the diquark form factors and of the quark-diquark distribution amplitudes for the present study has been adopted from previous work [9] in which these parameters have been fitted to electromagnetic nucleon form factors. The analytic form of the quark-diquark distribution amplitudes is flavour dependent such that a heavy strange quark carries on average more of the baryon momentum than a light up or down quark.

Before presenting our results we want to comment on a more technical point, the treatment of constituent masses. In the standard hard-scattering approach, the masses and transverse momenta are neglected when calculating the hard-scattering amplitude. We keep the collinear approximation, but take into account hadron masses. In this approximation, each constituent four-momentum is proportional to the hadron four-momentum. Likewise, the constituent mass is also proportional to the hadron mass where the proportionality constant is the fraction of the hadron momentum which is carried by the constituent. A variable constituent mass may look somewhat peculiar, but one has to keep in mind that the momentum fractions are weighted by the distribution amplitudes so that, e.g., a quark in a proton has, on the average, about 1/3 of the proton mass. Perturbative amplitudes are then calculated with these variable constituent masses and expressed in terms of the hadronic Mandelstam variables s, t and u. As a final step massless Mandelstam variables $\hat{s}$, $\hat{t}$ and $\hat{u}$ are introduced, and the amplitudes are expanded in terms of $(m_{\rm B}/\sqrt{\hat{s}})$, where $m_{\rm B}$ is the baryon mass. Only leading-order and next-to-leading order terms are kept in this expansion. The leading-order terms provide the hadron-helicity conserving amplitudes, the next-to-leading order terms contribute to helicity amplitudes in which the hadronic helicity is flipped by one unit. This treatment of mass effects has the advantage that no additional mass parameters for the constituents are introduced, and it preserves gauge invariance with respect to photon and gluon. Furthermore, it provides also the correct crossing relations on the hadronic level between the s- and t-channel processes, $\gamma{\rm B} \to \gamma{\rm B}$ and $\gamma\gamma \to {\rm B}\bar{\rm B}$, respectively. A more detailed account of the above and other technical questions, including analytical expressions for the dominant amplitudes and the treatment of time-like diquark form factors, can be found in Ref. [10].

Let us now present the results of our calculations. The energy dependence of the integrated cross sections ($|\cos(\theta)| \leq 0.6$) for the p, Λ, and Σ^0 channels is shown in Fig. 1. θ denotes the centre-of-mass scattering angle. The data are taken from the CLEO [11, 12], VENUS [13], OPAL [1] and L3 [2, 3] collaborations. Preliminary data from BELLE, which agree nicely with the previous data, have been reported most recently at the Photon2003 conference in Frascati [4]. The solid lines, which correspond to the full diquark-model calculation with mass effects included, are seen to lie well within the range of the data. The dashed line in the left plot has been obtained by omitting the mass correction terms, that is, with the two hadronic helicity-conserving amplitudes only. It can be seen that mass effects are still sizable in the energy and momentum-transfer range of a few GeV. The contributions from the (mass dependent) hadronic helicity flip amplitudes are of the same order of

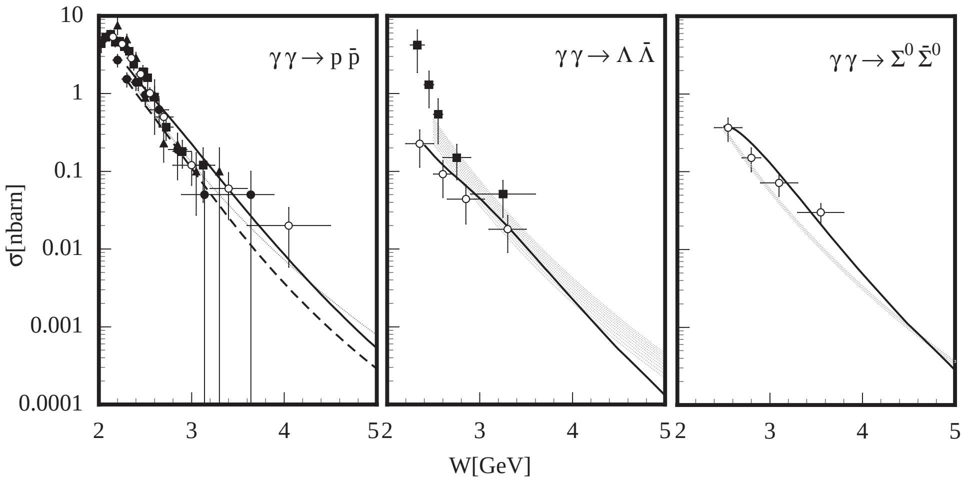

Fig. 1. Integrated $\gamma\gamma \to {\rm p}\bar{\rm p}$, $\Lambda\bar{\Lambda}$, and $\Sigma^0\bar{\Sigma}^0$ cross sections ($|\cos(\theta)| \leq 0.6$) vs. $W = \sqrt{s}$. Solid (dashed) line: predictions obtained with the standard parameterization of the diquark model (cf. Ref. [9]) with (without) mass corrections. The shaded line (band) is the result of the handbag approach [15]. The data are taken from the CLEO [11, 12] (■), VENUS [13] (▲), OPAL [1] (●), and L3 [2, 3] (○) collaborations, respectively.

magnitude as those from the hadronic helicity conserving ones. At this point, it should be mentioned that the predictions for $\gamma\gamma \to \mathrm{B\bar{B}}$ obtained within the pure quark hard-scattering approach are less satisfactory [14] and lie at least one order of magnitude below the data.

There exists an alternative description of hard baryon-antibaryon production in two-photon collisions, the generalized parton picture, which also achieves a good agreement with the experimental data [15]. Within this approach, annihilation is assumed to be dominated by the handbag contribution. This contribution is formally power-suppressed compared to the leading twist one, calculated in the pure quark hard-scattering approach. Nevertheless, as mentioned at the beginning, the regime where leading twist fully dominates seems out of reach for current experiments. The authors of Ref. [15] factorize the handbag amplitude for $\gamma\gamma \to \mathrm{B\bar{B}}$ into a hard $\gamma\gamma \to q\bar{q}$ amplitude and into form factors encoding the soft physics of the transition $q\bar{q} \to \mathrm{B\bar{B}}$. The integrated cross section may then be written as a combination of these form factors,

$$\sigma(\gamma\gamma \to \mathrm{B\bar{B}})|_{|\cos(\theta)|\le 0.6} = 181 \text{ nbarn GeV}^2 \frac{1}{s} \times \left\{ |R^{\mathrm{B}}_{\mathrm{A}}(s) + R^{\mathrm{B}}_{\mathrm{P}}(s)|^2 + \frac{s}{4m^2_{\mathrm{B}}} |R^{\mathrm{B}}_{\mathrm{P}}(s)|^2 + 0.134 |R^{\mathrm{B}}_{\mathrm{V}}(s)|^2 \right\} . \qquad (2)$$

Here, $R^{\mathrm{B}}_{\mathrm{V}}$, $R^{\mathrm{B}}_{\mathrm{A}}$ and $R^{\mathrm{B}}_{\mathrm{P}}$ are vector, axial and pseudoscalar form factors, respectively, related to the generalized parton distribution functions for a baryon B. The numerical prefactors are the result of integrating the hard amplitude over the angular range $|\cos(\theta)| \le 0.6$. The authors of Ref. [15] argue that $R^{\mathrm{B}}_{\mathrm{V}}$ is negligible. They consider the rest as an effective form factor $\left(R^{\mathrm{B}}_{\mathrm{eff}}\right)^2 = |R^{\mathrm{B}}_{\mathrm{A}}(s) + R^{\mathrm{B}}_{\mathrm{P}}(s)|^2 + s/(4m^2_{\mathrm{B}})|R^{\mathrm{B}}_{\mathrm{P}}(s)|^2$ and fix it by means of the integrated $\gamma\gamma \to \mathrm{p\bar{p}}$ cross-section data. Predictions for the other hyperon channels are then obtained by means of isospin and U-spin relations. The down/up ratio $\rho = F^{d,\mathrm{p}}_i / F^{u,\mathrm{p}}_i$, $i =$V,A,P of the various proton form factors remains as a parameter, where $R^{\mathrm{p}}_i = \sum_q e^2_q F^{q,\mathrm{p}}_i$, with e_q the charge of quark q. The shaded bands in Fig. 1 correspond to $0.25 \le \rho \le 0.75$. With this parameterization, the handbag approach provides results comparable with those from the diquark model, as shown in the figure.

Freund et al. [16] have investigated the time reversed-process, $\mathrm{p\bar{p}} \to \gamma\gamma$, within the generalized parton picture. They have tried to model the time-like double distributions for $\mathrm{p\bar{p}} \to q\bar{q}$ directly and obtain a value of 0.25×10^{-9} fm^2 for the integrated cross section ($|\cos(\theta)| \le 0.7$) at $s = 10$ GeV^2. The corresponding prediction from the diquark model is much larger, namely 0.14×10^{-7} fm^2 [10]. This, however, is the order of magnitude one would naively expect from the $\gamma\gamma \to \mathrm{p\bar{p}}$ data and agrees also with the findings of Diehl and collaborators [15]. These considerations could be interesting in the light of plans for a $\mathrm{p\bar{p}}$ storage ring at GSI in Darmstadt [17].

The diquark-model provides, of course, also predictions for octet baryon channels different from p, Λ, or Σ^0 (see Ref. [10]). Those agree roughly with estimates based on $SU(3)$ flavour-symmetry relations. The $\Lambda\bar{\Sigma}^0$ cross section is, for example, small in agreement with the upper limits quoted by the L3 collaboration. $\Sigma^+\bar{\Sigma}^-$, $\Sigma^-\bar{\Sigma}^+$ and $\Xi^-\bar{\Xi}^+$ cross sections are, on the other hand, of the same order of magnitude as the $\Lambda\bar{\Lambda}$ cross section, so that there is a chance for their measurement. There are indeed efforts from the BELLE collaboration to determine $\Sigma^+\bar{\Sigma}^-$ and $\Xi^0\bar{\Xi}^0$ cross sections [4]. A comparison of different octet baryon channels could be useful to gain information on the amount of $SU(3)$-symmetry breaking in the baryon distribution amplitudes.

From the integrated cross sections shown in Fig. 1 it may seem that the perturbative QCD approach works already at relatively low energies ($W = \sqrt{s} \approx 2.5$ GeV) and momentum transfers. Recent differential cross section data, however, reveal that the perturbative predictions for $W \lesssim 3$ GeV have to be taken with some caution. Angular distributions for $\gamma\gamma \to \mathrm{p\bar{p}}$ for different values of the photon centre-of-mass energy W are shown in Fig. 2. The data show an enhancement in the cross sections around $\theta = 90°$ which decreases with increasing energy. Such an enhancement can neither be explained within the diquark model nor within the handbag approach. It is a clear signal for the dominance of low partial waves and is most likely caused by non-perturbative production mechanisms like, e.g., $\mathrm{p\bar{p}}$ production via intermediate-state resonances. As one would expect, the perturbative description of the differential cross section becomes better with increasing W. At $W \approx 3$ GeV, the theoretically predicted angular distribution is already close to the measured one. There are also attempts by the BELLE collaboration to determine the angular distributions for the $\Lambda\bar{\Lambda}$ and the $\Sigma^0\bar{\Sigma}^0$ channels [4]. It will be interesting to see whether these exhibit a similar behaviour as the $\mathrm{p\bar{p}}$ differential cross sections.

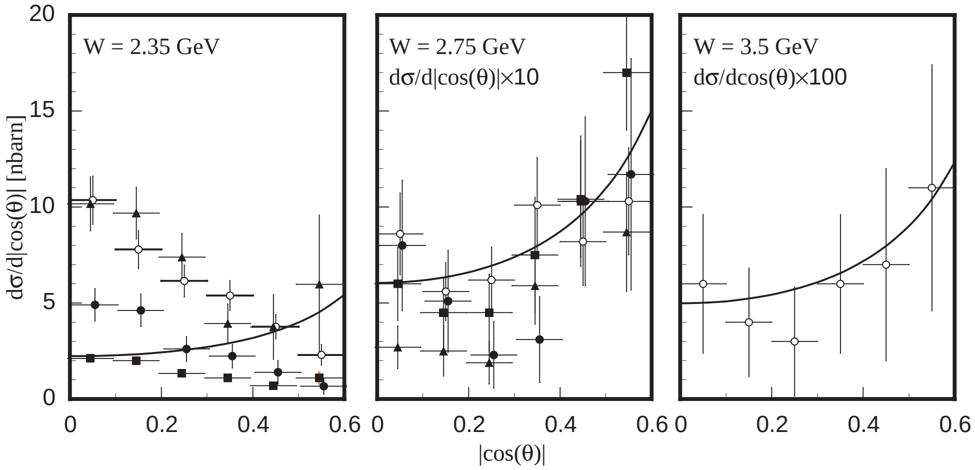

Fig. 2. Differential cross sections $\mathrm{d}\sigma(\gamma\gamma \to \mathrm{p\bar{p}})/\mathrm{d}|\cos(\theta)|)$ *for different values of* $W = \sqrt{s}$*. Solid line and symbols for the data as in Fig. 1.*

Finally, we want to mention that there are efforts from the L3 collaboration to determine the $\gamma\gamma \to \Delta^{++}\bar{\Delta}^{--}$ cross section. This is a particularly interesting process for the diquark-model description, because it involves only vector diquarks and would thus allow to constrain the model parameters for the vector diquarks. Corresponding theoretical investigations are presently in progress [18].

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TVRDA EKSKLUZIVNA TVORBA BARIONA-ANTIBARIONA U SUDARIMA 2-γ

Izlažemo perturbativan račun tvorbe barionskog para, $\gamma\gamma \to \mathrm{B\bar{B}}$, u kojemu se barioni predstavljaju kao sustav kvark-dikvark. Ovaj pristup na sustavan način objašnjava učinke sastavnica (konstituenata) masa. Uzimajući parametre ranijih istraživanja drugih barionskih reakcija izazvanih elektronima i fotonima, postigli smo slaganje ishoda naših računa s najnovijim podacima za kanale $\mathrm{p\bar{p}}$, $\Lambda\bar{\Lambda}$ i $\Sigma^0\bar{\Sigma}^0$ na velikim prijenosima impulsa.