The exclusive production of baryon-antibaryon (B B) pairs in the collision of two quasi-real photons has been studied using different detectors at \(e^+e^-\) colliders. Results are presented for \(\gamma\gamma \rightarrow pp\), \(\gamma\gamma \rightarrow \Lambda \bar{\Lambda}\), and \(\gamma\gamma \rightarrow \Sigma^0 \bar{\Sigma}^0\) final states. The cross-section measurements are compared with all the existing experimental data and with the analytic calculations based on the three-quark model, on the quark-diquark model, and on the handbag model.

1. Introduction

The exclusive production of baryon-antibaryon (B B) pairs in the collision of two quasi-real photons can be used to test predictions of QCD. At \(e^+e^-\) colliders the photons are emitted by the beam electrons and the B B pairs are produced in the process \(e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^- B B\).

The application of QCD to exclusive photon-photon reactions is based on the work of Brodsky and Lepage. According to their formalism the process is factorized into a non-perturbative part, which is the hadronic wave function of the final state, and a perturbative part. Calculations based on this ansatz yields e.g. \(e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^- p\bar{p}\) cross-sections about one order of magnitude smaller than the existing experimental results, for \(p\bar{p}\) centre-of-mass energies \(W\) greater than 2.5 GeV.

Recent studies have extended the systematic investigation of hard exclusive reactions within the quark-diquark model to photon-photon processes. In addition, the handbag contribution has been recently proposed to describe the photon-photon annihilation into baryon-antibaryon pairs at large momentum transfer.

\(^{a}\)In this paper positrons are also referred to as electrons.
In this paper, all the existing measurements of the cross-sections for the exclusive $e^+e^- \rightarrow e^+e^- \overline{B}\overline{B}$ processes are presented. In particular, results for $\gamma\gamma \rightarrow p\overline{p}$, $\gamma\gamma \rightarrow \Lambda\overline{\Lambda}$, and $\gamma\gamma \rightarrow \Sigma^0\overline{\Sigma}^0$ final states are reported. These cross-section measurements are compared with the analytic calculations based on the three-quark model, on the quark-diquark model, and on the handbag model.

2. The $\gamma\gamma \rightarrow p\overline{p}$ cross-section measurements

The differential cross-section for the process $e^+e^- \rightarrow e^+e^- p\overline{p}$ is given by

$$\frac{d^2\sigma(e^+e^- \rightarrow e^+e^- p\overline{p})}{dW \, d|\cos\theta^*|} = \frac{N_{ev}(W, |\cos\theta^*|)}{\mathcal{L}_{e^+e^-} \varepsilon_{\text{TRIG}} \Delta W \Delta |\cos\theta^*|}$$

where $N_{ev}$ is the number of events selected in each $(W, |\cos\theta^*|)$ bin, $\varepsilon_{\text{TRIG}}$ is the trigger efficiency, $\varepsilon_{\text{DET}}$ is the detection efficiency, $\mathcal{L}_{e^+e^-}$ is the measured integrated luminosity, and $\Delta W$ and $\Delta |\cos\theta^*|$ are the bin widths in $W$ and in $|\cos\theta^*|$.

The total cross-section $\sigma(\gamma\gamma \rightarrow p\overline{p})$ for a given value of $\sqrt{s_{ee}}$ is derived from the differential cross-section $d\sigma(e^+e^- \rightarrow e^+e^- p\overline{p})/dW$ by using the luminosity function $d\mathcal{L}_{\gamma\gamma}/dW$.

The resulting differential cross-sections for the process $\gamma\gamma \rightarrow p\overline{p}$ in bins of $W$ and $|\cos\theta^*|$ are then summed over $|\cos\theta^*|$ to obtain the total cross-section as a function of $W$ for $|\cos\theta^*| < 0.6$.

Fig. 1a) shows the cross-section $\sigma(\gamma\gamma \rightarrow p\overline{p})$ measurements as a function of $W$ for $|\cos\theta^*| < 0.6$ obtained by ARGUS, CLEO, VENUS, OPAL, L3, and BELLE. Some predictions based on the quark-diquark model and the three-quark model are also shown in this figure. There is good agreement between the different experiments results for $W > 2.3\text{GeV}$. At $W < 2.3\text{GeV}$ the OPAL measurements agree with the ARGUS results, but both these measurements lie below the results obtained by CLEO, VENUS, L3, and BELLE.

Within the estimated theoretical uncertainties and for $W > 2.2\text{GeV}$ there is a good agreement between the L3 and OPAL results and the quark-diquark model predictions. The three-quark model is excluded. At low $W$ the BELLE results are above the quark-diquark model predictions. This measurement agrees with the quark-diquark model for $2.5 \text{GeV} < W < 3.0 \text{GeV}$, while at higher $W$ a steeper fall of the BELLE cross-section is observed.

An important consequence of the pure quark hard scattering picture is the power law which follows from the dimensional counting rules. We expect that for asymptotically large $W$ and fixed $|\cos\theta^*|$, 

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Figure 1. Cross-sections $\sigma(\gamma\gamma \rightarrow p\bar{p})$ as a function of $W$. The data and the theoretical predictions cover a range of $|\cos(\theta^*)| < 0.6$. a) (Left plot) The experimental data are compared to the quark-diquark model prediction. The error bars include statistical and systematic uncertainties. b) (Right plot) The data are compared to the quark-diquark model predictions of $n=7.5$ (dash-dotted line), and of $n=8$ (solid line), using the standard distribution amplitude (DA) with and without neglecting the mass $m_p$ of the proton, and with the predictions of the power law with fixed and with fitted exponent $n$. The inner error bars are the statistical uncertainties and the outer error bars are the total uncertainties.

The measured differential cross-sections $d\sigma(\gamma\gamma \rightarrow p\bar{p})/dW$ where $n = 8$ is the number of elementary fields and $t = -W^2/2(1-|\cos(\theta^*)|)$. The introduction of diquarks modifies the power law by decreasing $n$ to $n = 6$. This power law is compared to the OPAL data in Fig. 1b) with $\sigma(\gamma\gamma \rightarrow p\bar{p}) \sim W^{-2(\text{fixed})}$ using three values of the exponent $n$: fixed values $n = 8$, $n = 6$, and the fitted value $n = 7.5 \pm 0.8$ obtained by taking into account statistical uncertainties only. More data covering a wider range of $W$ would be required to determine the exponent $n$ more precisely.

The measured differential cross-sections $d\sigma(\gamma\gamma \rightarrow p\bar{p})/d|\cos(\theta^*)|$ in different $W$ ranges and for $|\cos(\theta^*)| < 0.6$ are shown in Fig. 2.

In the range $2.15 < W < 2.55$ GeV the OPAL differential cross-section lies below the results reported by CLEO, VENUS, L3, and BELLE (Fig. 2a)). Since the CLEO measurements are given for the lower $W$ range $2.0 < W < 2.5$ GeV, their results have been rescaled by a factor 0.635 which is the ratio of the two CLEO total cross-section measurements integrated over the $W$ ranges $2.0 < W < 2.5$ GeV and $2.15 < W < 2.55$ GeV. This leads to a better agreement between the OPAL and CLEO measurements but the OPAL results are still consistently lower. The shapes of the $|\cos(\theta^*)|$ dependence of all measurements are consistent.

Fig. 2b) shows the differential cross-sections $d\sigma(\gamma\gamma \rightarrow p\bar{p})/d|\cos(\theta^*)|$ in the $W$ range $2.5 < W < 3.0$ GeV obtained by CLEO, OPAL, L3, and
Belles in similar W ranges, these differential cross-section have been normalized to the that averaged within $|\cos \theta^*| < 0.3$. The measurements are consistent within the uncertainties.

The comparison of the differential cross-section as a function of $|\cos \theta^*|$ for $2.55 < W < 2.95$ GeV with the calculation of at $W = 2.8$ GeV for different distribution amplitudes (DA) is also shown in this figure together with pure quark model and the handbag model prediction. The shapes of the curves are consistent with those of the data. Fig. 2 shows that the differential cross-section at low W decreases at large $|\cos \theta^*|$, while the opposite trend is observed in the higher W region. The transition point seems to occur at $W \approx 2.5$ GeV.

Another important consequence of the hard scattering picture is the hadron helicity conservation rule. For each exclusive reaction like $\gamma \gamma \to pp$ the sum of the two initial helicities equals the sum of the two final ones. According to the simplification used in, neglecting quark masses, quark and antiquark and hence proton and antiproton have to be in opposite helicity states. If the (anti) proton is considered as a point-like particle, simple QED rules determine the angular dependence of the unpolarized $\gamma \gamma \to pp$ differential cross-section:

$$\frac{d\sigma(\gamma \gamma \to pp)}{d|\cos \theta^*|} \propto \frac{(1 + \cos^2 \theta^*)}{(1 - \cos^2 \theta^*)}.$$  (1)

This expression is compared to the OPAL data in two W ranges, $2.55 < W < 2.95$ GeV (Fig. 3a) and $2.15 < W < 2.55$ GeV (Fig. 3b). The normalisation in each case is determined by the best fit to the data.
In the higher $W$ range, the prediction (1) is in agreement with the data within the experimental uncertainties. In the lower $W$ range this simple model does not describe the data. At low $W$ soft processes such as meson exchange are expected to introduce other partial waves, so that the approximations leading to (1) become invalid.

Figure 3. Measured differential cross-section, $d\sigma(\gamma\gamma \rightarrow p\bar{p})/d |\cos(\theta^*)|$, with statistical (inner bars) and total uncertainties (outer bars) for a) $2.55 < W < 2.95$ GeV and b) $2.15 < W < 2.55$ GeV. The data are compared with the point-like approximation for the proton (1) scaled to fit the data. The other curves show the pure quark model \(^2\), the diquark model of \(^{11}\) with the Dziembowski distribution amplitudes (DZ-DA), and the diquark model of \(^{10}\) using standard and asymptotic distribution amplitudes.

3. The $\gamma\gamma \rightarrow \Lambda\bar{\Lambda}$ and $\gamma\gamma \rightarrow \Sigma^0\Sigma^0$ cross-section measurements

The cross-sections $\sigma(\gamma\gamma \rightarrow \Lambda\bar{\Lambda})$ and $\sigma(\gamma\gamma \rightarrow \Sigma^0\Sigma^0)$ in real photon collisions as a function of $W$ and for $|\cos(\theta^*)| < 0.6$ can be extracted by deconvoluting the two-photon luminosity function and the form factor \(^{14}\).

Fig. 4 compares the L3 \(^{18}\) $\sigma(\gamma\gamma \rightarrow \Lambda\bar{\Lambda})$ measurement with that obtained by CLEO \(^{19}\). For $W > 2.5$ GeV the two results are compatible inside the large experimental errors. The cross-section measurement obtained by CLEO at lower $W$ values is steeper that the one obtained by L3. The L3 \(^{18}\) data, fitted with a function of the form $\sigma \approx W^{-n}$, gives a value $n = 7.6 \pm 3.9$. In Fig. 4 the $\sigma(\gamma\gamma \rightarrow \Lambda\bar{\Lambda})$ and $\sigma(\gamma\gamma \rightarrow \Sigma^0\Sigma^0)$ cross-section measurements are compared to the predictions of the quark-diquark model calculation \(^{20}\). The absolute predictions using the standard distribution amplitude \(^{20}\) (Standard DA) reproduce well the L3 data, the asymptotic DA and the DZ-DA models \(^{20}\) are excluded. The CLEO \(^{19}\) and L3 \(^{18}\) $\sigma(\gamma\gamma \rightarrow \Lambda\bar{\Lambda})$ cross-section measurements and L3 $\sigma(\gamma\gamma \rightarrow \Sigma^0\Sigma^0)$ cross-section measurements for $W > 2.5$ GeV are satisfactory described also by the handbag model, see Ref. \(^{13}\).
Figure 4. Measurements of the $\sigma(\gamma\gamma \rightarrow \Lambda\bar{\Lambda})$ and $\sigma(\gamma\gamma \rightarrow \Sigma^0\Sigma^0)$ cross-sections as a function of $W$. In a) the $\sigma(\gamma\gamma \rightarrow \Lambda\bar{\Lambda})$ cross-section is compared to the one obtained by CLEO $^{19}$. The dashed line shows the power law fit as described in the text. In b) and c) the $\sigma(\gamma\gamma \rightarrow \Lambda\bar{\Lambda})$ and $\sigma(\gamma\gamma \rightarrow \Sigma^0\Sigma^0)$ measurements are compared to the quark-diquark model predictions $^{20}$.

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