MEASUREMENT OF $\gamma^*\gamma^*$ CROSS-SECTION*

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Double-tagged interactions of photons with virtualities Q^2 between 10 GeV^2 and 200 GeV^2 are studied. The cross-section of the reaction $\gamma^*\gamma^* \to$ hadrons is measured and compared to the LO and NLO BFKL calculations.

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1. Introduction

This paper presents the study of double-tagged two-photon interactions $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-$hadrons with the DELPHI detector [1] at the CERN LEPII collider. Both scattered electron and positron are detected by the Small angle TIle Calorimeter (STIC). The kinematics of the interaction is well defined by the measurement of the energies and scattering angles of the tagged particles. If the virtualities of the photons are large enough, the LO process like the Born-box $\gamma^*\gamma^* \to q\bar{q}$ is expected to be comparable to the

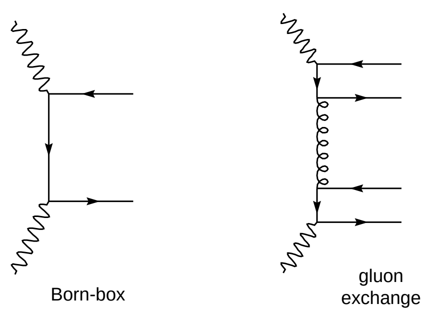

Fig. 1. Main diagrams corresponding to the $\gamma^*\gamma^* \to$ hadrons process.

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processes with (multi)gluon exchange between $q\bar{q}$ dipoles (figure 1), which is described by the BFKL equation [2]. Two-photon interactions are therefore a suitable process to investigate BFKL dynamics.

The kinematics of the process is illustrated in figure 2. We use the following notations: p_i ($i = 1, 2$) are the four-momenta of the beam electrons, $\sqrt{s}$ is the e^+e^- centre-of-mass energy, $E_{\rm beam}$ is the beam energy; the four-momenta of the scattered electrons, their polar angles and their energies are p'_i, θ_i and E_i, respectively.

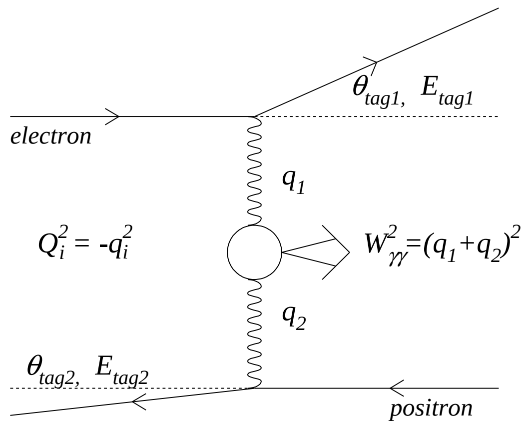

Fig. 2. The kinematics of $\gamma^*\gamma^*$ interactions.

The variables relevant to this study are the virtualities of the photons, Q_i^2, their invariant mass $W_{\gamma^*\gamma^*}$ and a dimensionless variable Y:

$$
\begin{aligned}
Q_i^2 &= -q_i^2 = -(p_i - p_i^{'})^2 = 4E_i E_{\rm beam} \sin^2\left(\frac{\theta_i}{2}\right) , \\
W^2_{\gamma^*\gamma^*} &= -(q_1 + q_2)^2 \simeq s y_1 y_2 \quad \text{with} \quad y_i = 1 - (E_i/E_{\rm beam}) \cos^2\left(\frac{\theta_i}{2}\right) , \\
Y &= \ln(W^2_{\gamma^*\gamma^*}/\sqrt{Q_1^2 Q_2^2}) .
\end{aligned}
$$

2. Detector and data sample

A detailed description of the DELPHI detector and of its performance is presented in Ref. [1]. The study is done with the DELPHI data taken during 1998–2000 runs at e^+e^- centre-of-mass energies from 189 GeV to 209 GeV, corresponding to an integrated luminosity of 550 pb^{-1}.

3. Study of $e^+e^- \to e^+e^- + \text{hadrons}$ interactions

The $\gamma^*\gamma^* \to$ hadrons sample is selected by the following criteria:

- There are two clusters with energy deposition E_i greater than 30 GeV, one in each arm of the STIC and the polar angle θ_i exceeds 2.2°.
- Q_i^2 is between 10 GeV^2 and 200 GeV^2 for both tagged particles.
- Each event contains at least 3 charged particles with the invariant mass calculated from the particles' 4-momenta, W_{had}, larger than 2 GeV/c^2.
- The acollinearity of the clusters is above 0.2 degrees (to remove interference between Bhabha events and untagged $\gamma\gamma \to \mu^+\mu^-$ events).
- If the energy of one cluster, normalised to the beam energy, is larger than 0.85 then the energy of another cluster has to be below 0.5 (to suppress the contamination coming from $e^+e^- \to$ hadrons events).
- The thrust value of the charged particles is less than 0.98 for the events with charged multiplicity below 5 (to remove most of the $\gamma^*\gamma^* \to \tau^+\tau^-$ events).

After these requirements 434 events have been selected. Trigger efficiency is estimated to be larger than 99%.

The event generators used to simulate the $\gamma^*\gamma^*$ events and the non-negligible background processes are listed below together with the respective expected contributions. TWOGAM (version 2.02) [3] and PYTHIA (version 6.205) [4] event generators are used to simulate $\gamma^*\gamma^*$ interactions. The expectations are (331 ± 8) and (330 ± 8) events, respectively. The Monte Carlo generators include the quark–parton model (QPM) part and also the leading-order predictions for the resolved photon contribution:

The process $e^+e^- \to$ hadrons is simulated with the KK2f generator (version 4.14) [6] and its contribution is estimated to be (27 ± 3) events.

The contamination of τ pairs produced in the two-photon interactions is evaluated as (26 ± 3) events by using the TWOGAM program.

The coincidence of an off-momentum electron with a $\gamma^*\gamma \to$ hadrons single-tagged event is evaluated as (5 ± 2) events.

The background subtracted data are corrected for detector effects. The total cross-section, σ_{ee}, of the $e^+e^- \to e^+e^- + \text{hadrons}$ interactions, within the phase space limited by the criteria Q_i^2 between 10 GeV^2 and 200 GeV^2, and W_{had} above 2 GeV/c^2, is measured to be (2.09 ± 0.17) pb using the corrections for detector effects based on TWOGAM and (1.86 ± 0.14) pb for the corrections based on PYTHIA. The statistical and systematic uncertainties are added in quadrature. The expectation of the quark–parton model is (1.81 ± 0.02) pb as obtained with TWOGAM.

The $\gamma^*\gamma^* \to$ hadrons interactions are expected to be sensitive to multiple gluon exchange (Fig. 1). The multigluon ladder is described by the BFKL equation [2], which predicts a growth of the cross-section at large Y. Note that the BFKL calculations are valid within the approximations $W^2_{\gamma^*\gamma^*} \gg Q^2_i$ (the variable Y should be larger than 2) and $|\ln(Q^2_1/Q^2_2)| < 1$ (to maintain the photon virtualities approximately equal). The application of this latter condition has the effect of reducing the data sample by about 37%.

The experimental conditions of the present study ($Q^2_i \gg m^2_e$ and the symmetry requirement for tagged particle detection) permit the relation between $\sigma_{ee}$and $\sigma_{\gamma^*\gamma^*}$to be simplified to a relation involving an effective cross-section $\sigma_{\gamma^*\gamma^*}$,

$$\sigma_{ee} = L_{\mathrm{TT}}\sigma_{\gamma^*\gamma^*} \quad \text{with} \quad \sigma_{\gamma^*\gamma^*} = \sigma_{\mathrm{TT}} + 2\epsilon\sigma_{\mathrm{LT}} + \epsilon^2\sigma_{\mathrm{LL}}\,,$$

where L_{TT} is the flux of the transversely polarised photons calculable in QED, ϵ is around 0.94, $\sigma_{\mathrm{LT}} \simeq 0.2\sigma_{\mathrm{TT}}$ and $\sigma_{\mathrm{LL}} \simeq 0.05\sigma_{\mathrm{TT}}$ [7]. The TWOGAM event generator including QED radiative corrections has been used to calculate L_{TT}.

The measured differential cross-section $d\sigma_{\gamma^*\gamma^*}/dY$ is shown in figure 3. The systematic uncertainties are dominated by the difference between the results obtained with TWOGAM and PYTHIA Monte Carlo generators. The predictions of the QPM and of BFKL calculations, both in LO [8] and NLO [9], are also shown in the figure 3. Note that the BFKL calculations are weighted over a number of Q^2 bins and that therefore the running of α_{s} is also included. The data lie in any case much lower than the BFKL cross-sections calculated in leading-order. On the other hand, the agreement with the NLO predictions is rather good, since the expected growth of the gluon exchange contribution (BFKL) is much weaker and appears mainly for Y values larger than 4. Below this value the cross-section is dominated by the decrease of the QPM contribution. Unfortunately the LEP energy and the present statistics are not sufficient to scan in detail the region at large Y, where BFKL is expected to dominate.

The table contains the cross-section $\sigma_{\gamma^*\gamma^*}$binned over Q^2 of interacting photons. Statistic and systematic uncertainties are added in quadrature.

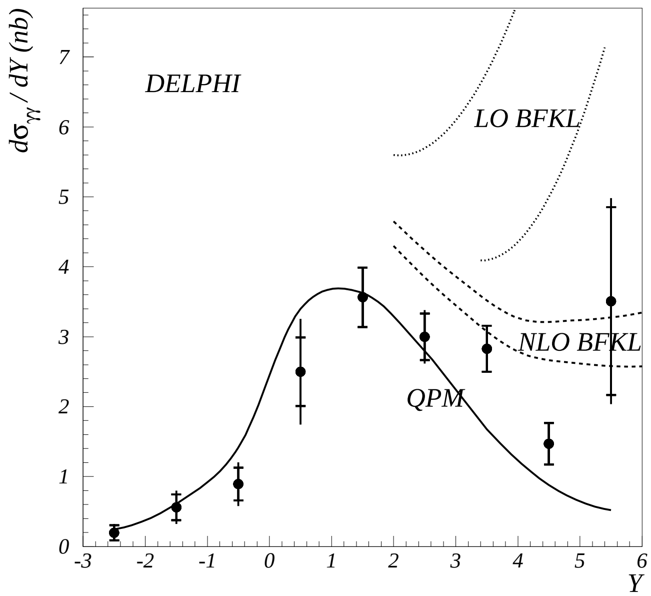

Fig. 3. The differential cross-section for the reaction $\gamma^*\gamma^* \to$ hadrons . The data are shown with error bars: the total error bars indicate the sum in quadrature of the statistical (inner error bars) and of the systematic uncertainties. The solid curve corresponds to the expectation of the quark–parton model (QPM, quark-box diagram, figure 1). The two dotted lines represent the LO BFKL calculations [8]. NLO calculations [9] are shown by the two dashed curves in the middle. The two curves for the BFKL calculations correspond to the Regge scale parameter changing between Q^2 (upper line) and $4Q^2$ (lower one). The QPM contribution is added to both the LO and the NLO BFKL expectations.

Q_i^2 (GeV^2)	(10.0–48.0)	(48.0–86.0)	(86.0–124.0)	(124.0–162.0)	(162.0–200.0)
(10.0–48.0)	3.72±0.34	1.63±0.24	2.25±0.39	1.71±0.30	2.60±0.63
(48.0–86.0)		0.95±0.24	0.70±0.18	1.27±0.34	1.06±0.41
(86.0–124.0)			0.19±0.17	0.92±0.33	0.01±0.29
(124.0–162.0)				0.13±0.16	0.42±0.33
(162.0–200.0)					4.93±6.13

4. Conclusion

Double-tagged $\gamma^*\gamma^*$ interactions have been studied using the DELPHI data taken at the e^+e^- centre-of-mass energies from 189 GeV to 209 GeV and corresponding to an integrated luminosity of 550 pb^{-1}. For virtualities, Q^2, of both photons between 10 GeV^2 and 200 GeV^2 and final state invariant mass W above 2 GeV$/c^2$ the cross-section σ_{ee} of the $e^+e^- \to e^+e^- +$hadrons interactions is measured to be $(2.09 \pm 0.09(\mathrm{stat}) \pm 0.19(\mathrm{syst}))$ pb with the corrections for detector effects based on the TWOGAM event generator [3]. The differential cross-section $d\sigma_{\gamma^*\gamma^*}/dY$ of the $\gamma^*\gamma^* \to$ hadrons interactions is measured and is compared with the predictions based on LO and NLO BFKL calculations. The leading order calculations clearly disagree with the data while the next-to-leading order predictions are found to be more consistent with the data, although the LEP energy is not sufficient to see a sizable effect due to the BFKL type contribution.

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