Global properties of pion production in the reaction $\gamma\gamma \to 3\pi^+ 3\pi^-$

CELLO Collaboration

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We have studied the properties of pion production in the reaction $\gamma \to 3\pi^+ 3\pi^-$ in the energy range $1.6 \leqslant W_{\gamma\gamma} \leqslant 7.5$ GeV with the CELLO detector at PETRA. We present the topological cross section both for $Q^2 \approx 0$ (anti-tag) and $Q^2 > 0$ (single-tag). The Q^2 dependence of the cross section is flatter than the GVDM prediction. The distribution of the production angle of the pions in the CMS peaks at small angles, indicating a peripheral process. In accordance with the VDM picture the p_T distribution of the pions manifests an exponential fall-off. Like sign pion pairs were found to be Bose–Einstein correlated. We use this correlation to estimate the spatial dimensions of the interaction region.

Photon–photon reactions are generally described by a superposition of a hadronic VDM process plus a point-like QCD contribution. Although there is no clear cut Q^2 ($Q^2 = -m_{\gamma^*}^2$) boundary between the point-like and the hadronic domains, the hadronic sector is believed to dominate at $Q^2 \leqslant 1.0$ GeV^2. Despite the difficulties that VDM faces in formulating a comprehensive model for photon–photon physics, it still serves as a phenomenological framework for the understanding of $\gamma\gamma$ processes. Inclusive $\gamma\gamma$ collisions are found to agree qualitatively with the VDM picture, meeting the model's basic predictions, namely, peripheral hadron production and a pole form factor in the Q^2 dependence of the total cross section. However, some experimental results concerning exclusive hadronic final states, in particular vector meson pair production cannot be accounted for by a VDM model alone [1].

So far, the study of exclusive $\gamma\gamma$ reactions has mainly been confined to low multiplicity final states. The extension to higher multiplicities is expected to shed further light on the applicability of the VDM models as well as on the characteristics of multipion production in $\gamma\gamma$ collisions.

The Bose statistics obeyed by pions give rise to correlations between like-sign pion pairs. For a chaotic (thermal) boson source, the averaged probability to observe two identical bosons divided by the probability to observe two distinguishable ones, defines the *Bose–Einstein correlation function*. So-called Bose–Einstein correlations, also known as the GGLP effect [2], result in an enhancement of the production of like-sign pions at small angles to each other. Analysis of this effect is normally carried out by comparing the ratio R of the numbers of like-sign pairs and uncorrelated pairs, as a function of $q^2 = |k_i - k_j|^2$, the squared four-momenta difference of these pairs. The like-sign pairs must come from the same event, while the uncorrelated pairs can be opposite-sign pairs from the same event or random pairs from different events. Since the correlation function contains information on the average distance between the pions, the GGLP effect can serve as an estimate for the spatial dimension of the interaction region. It is of interest to extend a former study of the GGLP effect in inclusive $\gamma\gamma$ reactions [3], to a multipion exclusive $\gamma\gamma$ final state.

In this letter we present a study of the global properties of pion production in the exclusive reaction

$$\gamma\gamma \to 3\pi^+ 3\pi^- .$$

The data show a high rate of inclusive ρ^0 production (on average 1.5 ρ^0 per event), the detailed features of which will be the subject of a forthcoming paper.

The reaction was measured with the CELLO detector at the e^+e^- storage ring PETRA at a centre of mass energy of 35 GeV. The data correspond to an integrated luminosity of 86 pb^{-1}. A detailed description of the CELLO detector can be found elsewhere [4]. Here we briefly mention the main components related to the present analysis.

Charged particles are measured in the central detector, which consists of a system of cylindrical drift and proportional chambers. The central detector is surrounded by a thin superconducting coil providing a solenoidal magnetic field of 1.3 T. The angular acceptance is 91% of 4π and a momentum resolution of $\sigma(p)/p = 0.02p$ (p in GeV/c) without beam constraint is achieved. The tracking system is completed

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by two planes of proportional chambers perpendicular to the beam in the forward and backward regions which allow charged particle measurement within $|\cos\theta| \leqslant 0.98$.

A 20 radiation lengths deep lead liquid argon calorimeter with fine lateral and longitudinal segmentation is subdivided into two main parts, the barrel and the end caps. Hermetic calorimetry down to 50 mrad is completed by forward shower counters consisting of lead glass arrays. Both the end caps and the forward shower counters were used in this analysis for tagging purposes.

For triggering of charged particle final states a hard wired logic was used as a fast track finder in the $r\phi$ and rz plane of the central detector [5]. In the untagged analysis we accepted only events with charged triggers because their efficiences can be cross checked and they can reliably be simulated by applying the same track finding algorithm as used in the trigger to the hit pattern of Monte Carlo events. The basic trigger requirements were at least two charged particles with p_T above 650 MeV/c or two tracks above 250 MeV/c with an opening angle larger than 45° (135° in part of the experiment). For tagged events one track with p_T above 250 MeV/c and 2 GeV in the forward calorimeter or in the end cap was sufficient to pass the trigger logic.

In order to select the final state $3\pi^+3\pi^-$ an event is accepted if its fulfils the following criteria:

– three positively and three negatively charged particles,

– no neutral showers (not linked to charged particles) in the liquid argon calorimeter and no energy measured in the forward lead glass arrays for untagged events ($Q^2 \approx 0$),

– for single-tag events ($Q^2 > 0$) a minimal shower energy of 5 GeV was required in the forward detector or end cap calorimeter,

– a cut requiring the total invariant mass, $W_{\gamma\gamma}$, to be less than 10 GeV was introduced in order to remove annihilation events,

– in the untagged sample, the missing transverse momentum squared is restricted to be less than 0.05 GeV^2 in order to suppress additional γ induced non-exclusive background,

– to reduce beam–gas interaction background, a cut of a maximum of 2.5 cm was imposed on the distance between the interaction point and the event vertex along the beam line.

Estimation of non-exclusive background is done by fitting the missing transverse momentum squared $|\Sigma p_T|^2$ spectrum of the data, to the same spectrum of the Monte Carlo plus a constant (referred here as flat background). The fit yields a level of $(18 \pm 7)\%$ such a background. A direct estimate of the background coming from $\gamma\gamma \to 3\pi^+3\pi^-\pi^0$ is deduced from the ARGUS preliminary results [6] on this channel giving a contribution of 11% out of the total 18%.

The data are further subjected to a secondary vertex search in order to remove events with K^0_S and converted photons [7]. Extrapolating the decay length of the K^0_S found in our sample to 0, we estimate the kaon contamination to be 2% for the background of $\gamma\gamma \to K^0_S K^\pm \pi^\mp \pi^+ \pi^-$, $K^0_S \to \pi^+\pi^-$. Assuming that the cross section for the reaction $\gamma\gamma \to K^+K^-2\pi^+2\pi^-$ is of the same order as that of the previous one, we estimate the contamination due to the latter background to be 3%. Background from the reaction $\gamma\gamma \to K^{*+}K^{*-}$ with the subsequent decays $K^{*\pm} \to K^0_S \pi^\mp$, $K^0_S \to \pi^+\pi^-$ is found to be negligible. Adding these backgrounds together we estimate the maximal percentage of background events to be 23%.

469 untagged events survive all the above cuts and are the basis of the analysis for the $Q^2 \approx 0$ sample, and 42 are left in the single-tag sample. In order to suppress non-exclusive background in the single-tag sample we require that the azimuthal angle between the tagged electron and the $\gamma\gamma$ system be more than 2.85 rad in the forward detector or more than 2.95 rad in the end cap. Imposing a kinematical fit on $Q^2 > 0$ events, we improve the Q^2 resolution from 10% to 7% in the forward detector and down to 6% in the end cap. 15 events pass these cuts in the $W_{\gamma\gamma}$ range 2.1–3.0 GeV and seven events are left in the range 4.0–6.3 GeV.

To correct for acceptance effects we used through all our analysis a phase space generator. The influence of an intermediate state of one and two ρ^0's (the data contains an average of 1.5 ρ^0's per event) on the acceptance is found to give a maximal effect of 10%.

The topological cross section for the reaction as a function of $W_{\gamma\gamma}$, determined by the invariant mass of the six pion system, is shown in fig. 1. Flat background is subtracted and only statistical errors are plotted. The systematical error is estimated to be

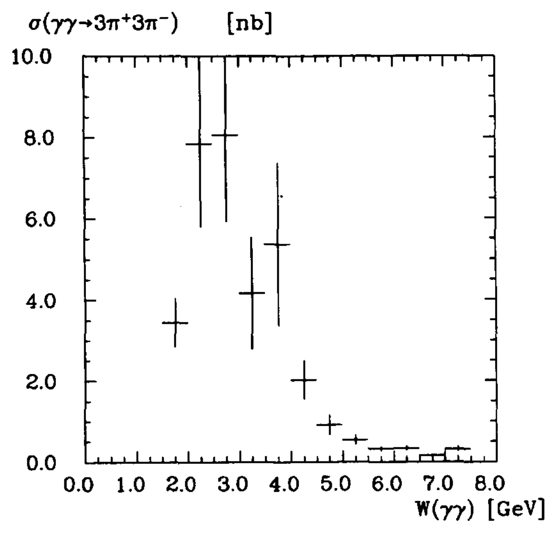


Fig. 1. Topological cross section for the reaction $\gamma \to 3\pi^+3\pi^-$.

around 13% and arises from pion misidentification (7.5%), determination of the flat background (7.0%), track finding efficiency (6.5%), trigger efficiency (3.0%), luminosity calculation (2.0%) and Q^2 dependence of the Monte Carlo generator (2.0%) [8].

The cross section is seen to rise sharply to a value of about 8 nb in the region 2.0–3.0 GeV followed by a decrease to the level of 0.3 nb at 7.0 GeV. Note that the threshold of six pions is far below the enhancement seen around 2.5 GeV.

In figs. 2a, 2b we plot the Q^2 dependence of the topological cross section. Our measurements of $\sigma_{\gamma\gamma^*}(Q^2>0)$ together with the value of $\sigma_{\gamma\gamma}(Q^2\approx 0)$ are compared in fig. 2a ($W_{\gamma\gamma}$: 2.1–3.0 GeV) and fig. 2b ($W_{\gamma\gamma}$: 4.0–6.3 GeV) with the predictions of generalised VDM (GVDM) [9], normalized to the measured cross section at $Q^2\approx 0$. Despite the large errors our data is systematically higher than the GVDM prediction in both $W_{\gamma\gamma}$ ranges. Following a VDM like fall-off in the Q^2 range 0–3.5 GeV^2, the Q^2 dependence of the cross section in both ranges of $W_{\gamma\gamma}$ turns out to be flat over the higher Q^2 bins, lying considerably above the GVDM curve.

To estimate a possible point-like contribution in this channel we have generated a sample of events of the $\gamma\gamma\to$jets. For this purpose we made use of the Berends–Daverveldt–Kleiss generator [10], where instead of a lepton pair a $q\bar{q}$ pair is created which is

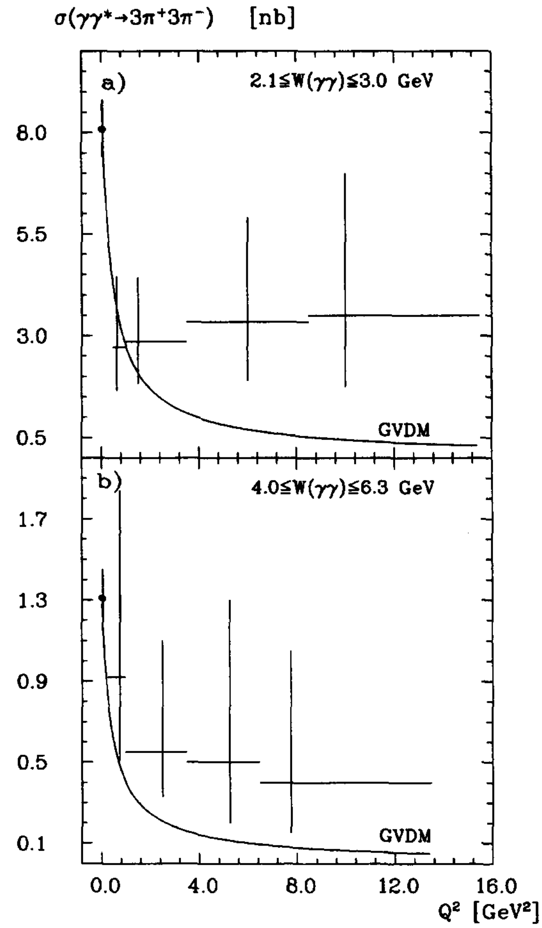


Fig. 2. Q^2 dependence of the topological cross section (a) for $W_{\gamma\gamma}$ between 2.1 to 3.0 GeV and (b) for $W_{\gamma\gamma}$ in the range 4.0–6.3 GeV, in both figures only statistical errors are plotted.

then fragmented with the LUND7.2 program. We found that the point-like cross section in this channel is less than 0.15 nb for the relevant $W_{\gamma\gamma}$ range and can thus be neglected.

In the VDM picture the p_T distribution of the final state hadrons emerging from two photons collisions falls-off exponentially, due to the peripheral character of the reaction. it is further argued that a tail in the p_T distribution seen in inclusive single-tag $\gamma\gamma$ reactions [11], cannot be due to the hadronic part of the photon but corresponds to the point-like coupling of the photons to quarks. The hadronic interaction between the colliding photons gives rise to a limited momentum transfer which manifests itself in small angle production of the final state hadrons.

In figs. 3a–3c we plot the corrected angular distribution of the pions in the $\gamma\gamma$ system at different $W_{\gamma\gamma}$ ranges. In the lower range of $2.0 < W_{\gamma\gamma} < 3.0$ GeV the angular distribution is rather flat. This is not surprising due to the limited available energy. However, the distribution starts to peak at the forward–backward direction for $W_{\gamma\gamma} > 3.0$ GeV. At energies above 4.0 GeV the pions show a clear pattern of a peripheral (forward–backward) production.

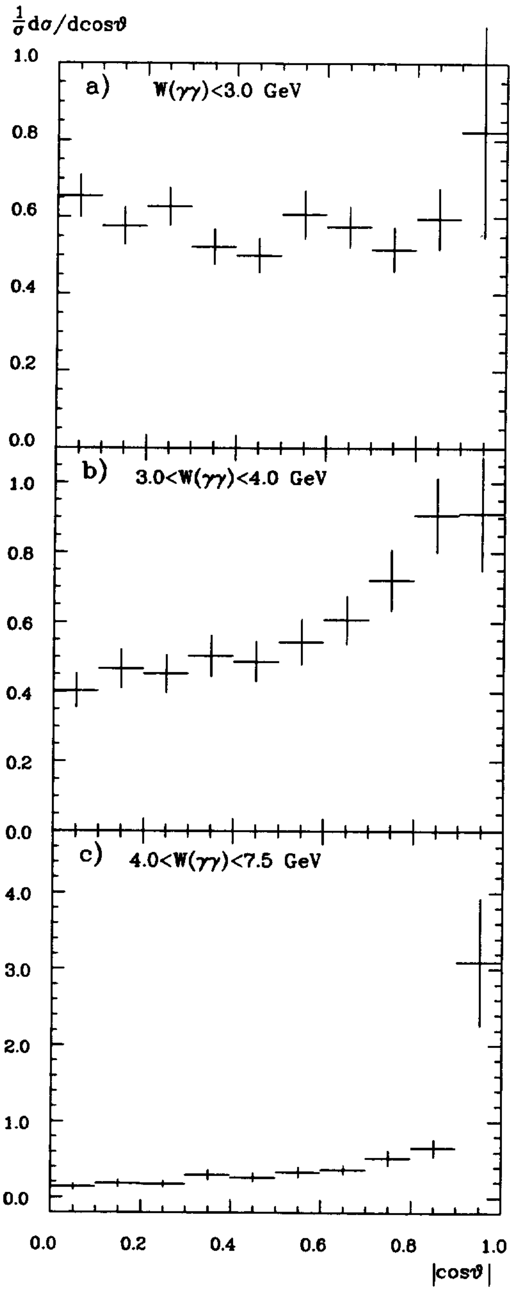


Fig. 3. Corrected angular distribution, $(1/\sigma)\, d\sigma/d\cos\theta$ of the pions in the untagged sample.

In fig. 4 we show the corrected $(1/\sigma)\, d\sigma/dp_T^2$ distribution for single pions as a function of p_T in the $W_{\gamma\gamma}$ range, $4.0 < W_{\gamma\gamma} < 7.5$ GeV. The data are well described by an exponential fall-off $\exp(-ap_T)$ (solid line) with $a=5$. In a previous study of inclusive single-tag $\gamma\gamma$ hadron production [11], having an averaged $W_{\gamma\gamma}$ of 6.1 GeV, a is found to be 6.6 which is not too far away from our value for the six pion exclusive untagged data with an averaged $W_{\gamma\gamma}$ value of 5.6 GeV.

Next we turn to the analysis of the Bose–Einstein correlation. The standard expression for R is given by

$$R = N[1 + \lambda \exp(-r^2 q^2)]\,,$$

where N is a normalization factor, λ is the enhancement factor and r is the effective radius of the interaction region. In fig. 5a we show the ratio R, as a function of q^2, of like-sign pairs of the same event to a sample of pion pairs mixed from different events. In fig. 5b we show the same ratio but this time with a reference sample of opposite-sign pairs from the same event. In this reference sample the presence of ρ^0 me-

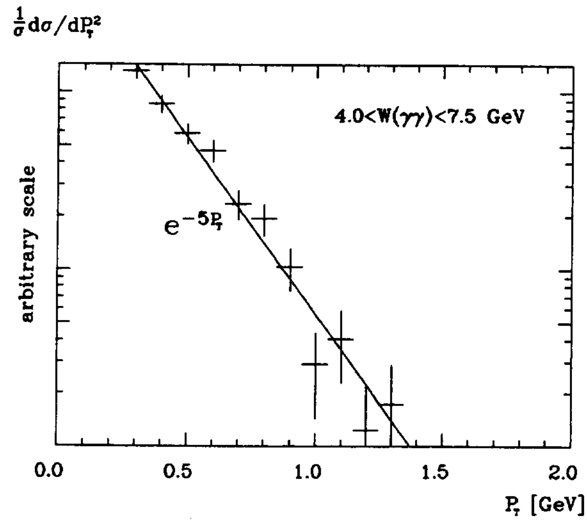
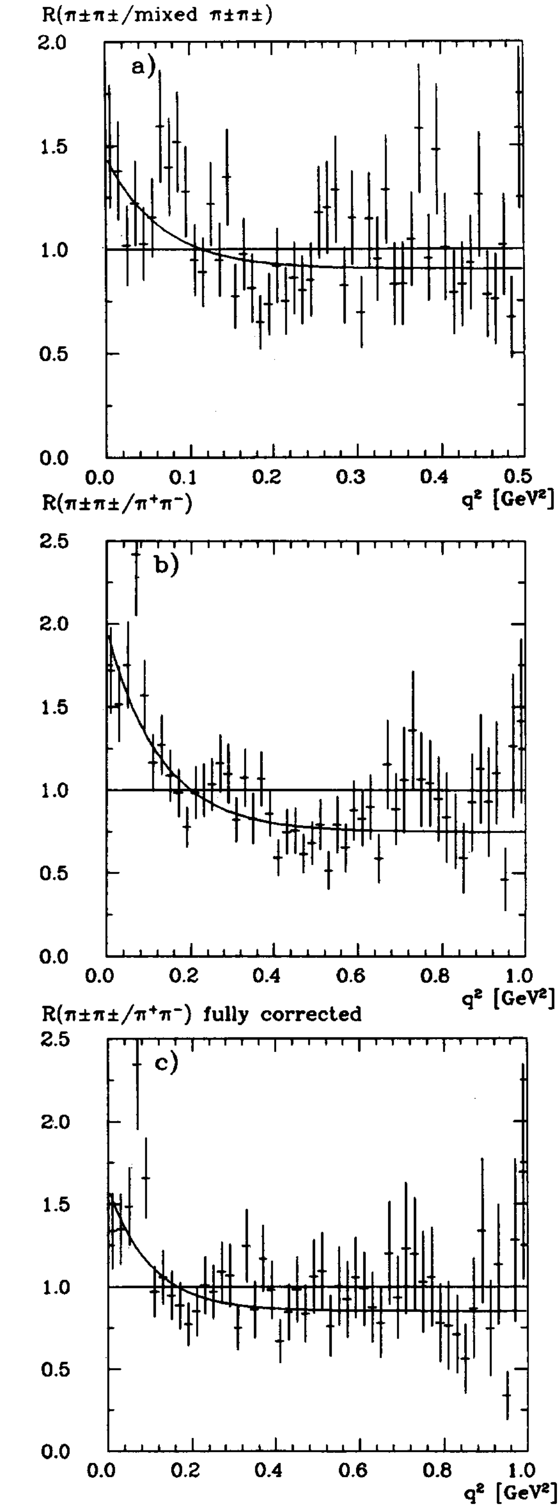


Fig. 4. Corrected transverse momentum distribution, $(1/\sigma)\, d\sigma/dp_T^2$, of the pions in the untagged sample.



◀ Fig. 5. The ratio R between like-sign pions and (a) a mixed $\pi^{\pm}\pi^{\pm}$ sample, (b) a sample of opposite-sign pions from the same event $\pi^+\pi^-$ and (c) the corrected ratio of (b) taking into account the presence of 1.5 ρ^0 per event.

sons (found to be about 1.5 ρ^0 per event) leads to a stronger enhancement (bigger λ), due to the dip in q^2 values that lie near the ρ^0 mass range, i.e. $q^2 = m^2_{\pi^+\pi^-} - 4m^2_\pi \approx 0.5$ GeV ^{2}. One way to correct for the presence of the ρ resonance is to factor out the q^2 dependence of $\pi^+\pi^-$ pairs coming from a π^0 Breit–Wigner (compare with ref. [12]). We corrected the ratio using an appropriate Monte Carlo simulation that includes the above average ρ yield. The result is plotted in fig. 5c. For Coulomb force effects we correct R with a generalized Gamow factor [13] which increases the fitted value of λ by some 6–10%. Since there are uncertainties involved in the correction for strong-interaction effects, we do not correct for this effect in our analysis. As can be seen, the data is significantly different from a constant R value. The results of the least square fits of R to our data is given in table 1, and is shown by the solid lines in figs. 5a–5c. Our values of λ and r are similar to those obtained for $\gamma\gamma$ inclusive pion production [3] namely, $\lambda \approx 0.9$ and $r \approx 0.8$. Interpreting our value for r as the average space–time dimension of the interaction region we obtain an approximate value of 0.6 fm.

In summary we have measured the cross section of the reaction $\gamma\gamma \to 3\pi^+3\pi^-$ in the $W_{\gamma\gamma}$ range between 1.6 and 7.5 GeV and a $Q^2 \approx 0$. The cross section rises sharply from threshold to about 8 nb around 2.5 GeV, followed by a steep fall-off. Preliminary results for this reaction obtained by the ARGUS Collaboration [6], quote somewhat higher values than ours. However, these preliminary results were not corrected for background from other channels. Recent preliminary results obtained by the JADE Collaboration [14], are lower in comparison to ours, although such corrections were implemented in their analysis. The inclusive p_T and angular distributions of the outgoing pions manifest the characteristic behaviour of a diffractive pattern which is also expected by a predominantly VDM process. Although our cross section measurements as a function of Q^2 have relatively large statistical errors, they are seen to disagree with the VDM picture. In particular we call attention to the inconsistency with the expected behaviour of GVDM in

Table 1
GGLP parameters.

q^2 [GeV^2]	λ	r [fm]	Reference sample	Fit probability [%]	NDF
0.0–1.0	1.62 ± 0.25	0.55 ± 0.06	$\pi^+\pi^-$	15	47
0.0–1.0	0.87 ± 0.24	0.62 ± 0.12	corrected-$\pi^+\pi^-$	16	47
0.0–0.5	0.59 ± 0.20	0.54 ± 0.22	mixed-$\pi^\pm\pi^\pm$	22	48

the $W_{\gamma\gamma}$ range 4.0–6.3 GeV, where the pions are seen to be produced in the backward–forward direction. However, a Monte Carlo study of the point-like process $\gamma\gamma \to q\bar{q} \to 3\pi^+3\pi^-$ shows a negligible contribution of such a process in our data. In view of this small point-like contribution, our results suggest that the description of the hadronic part by GVDM in this channel is not appropriate. Finally, pairs of like-sign pions exhibit Bose–Einstein correlations with parameter values consistent with those obtained previously in inclusive $\gamma\gamma$ reactions. Preliminary results of JADE on the GGLP effect in this channel [14] are very similar to ours.

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