EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

HIGH ENERGY PHOTOPRODUCTION OF LARGE TRANSVERSE MOMENTUM
 π^0 MESONS : A QUANTITATIVE TEST OF QCD

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Abstract:

The first results on inclusive photoproduction of π^0 at transverse momenta up to 4 GeV/c, using incident γ energies between 50 and 150 GeV are presented. A comparison is made with inclusive π^0 production obtained, in the same experiment, with incident π^- . Using the π^- data to parameterize the hadronic behaviour of the photon, significant differences are observed in quantitative agreement with QCD Compton scattering and corrections thereof.

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1. Introduction

Most features of photoproduction of hadrons are similar to those observed in hadroproduction. This is simply interpreted by the vector dominance model (VDM) which describes the photon as a superposition of vector mesons [1]. However, in high transverse momentum processes, the photon exhibits a point-like coupling to quarks [2]. This has, for instance, been clearly shown for photoproduction of prompt γ [3]. In the case presented here, photoproduction of high p_T π^0 , the basic processes involved (Born terms) are photon gluon fusion, $\gamma g \rightarrow q\bar{q}$ and QCD Compton scattering $\gamma q \rightarrow gq$. So far, evidence for the corresponding time reversed processes has been looked for in hadroproduction of prompt γ at large p_T . A study of these processes using initial state photons avoids the experimental difficulties associated with final state prompt γ identification required in hadroproduction experiments.

Detailed calculations for the process $\gamma N \rightarrow \pi^0 + X$, which involve QCD corrections next to the leading log approximation, have been recently completed. They show that higher order terms are under control [4]. Smearing corrections, often referred to as "intrinsic p_T effects", are predicted to be small [5]. In order to test these QCD predictions the magnitude of the VDM contribution must be known. This contribution has been determined from measurements with a π^- beam in the same apparatus.

As will be discussed in the interpretation of the results, the wide range of p_T and energy covered by the π^0 detectors allows measurement of the increasing QCD contribution to photoproduction.

2. Experimental Details

The experiment was performed in the E12 e- γ beam at the CERN SPS using the NA14 spectrometer. A bremsstrahlung photon beam is derived from a broadband electron beam of 140 GeV mean energy and intensity of 10^8 e $^-$ /SPS pulse crossing a 10 % X_0 radiator. Photons above ~ 50 GeV are tagged, yielding a beam of 80 GeV mean energy, but extending up to ~ 150 GeV. The experimental target is isoscalar (Li^6) having a thickness corresponding to 10 % X_0 .

A description of the spectrometer can be found in ref. [3]. The data presented here come from a trigger which required, in addition to a minimum bias pretrigger, a local deposit of energy in a calorimeter corresponding to a transverse momentum greater than 900 MeV/c. These data correspond to a sensitivity of ~ 1.7 evts/pb above $E_\gamma = 50$ GeV.

The forward ($\theta_{cm} < 50^\circ$) and backward ($\theta_{cm} > 90^\circ$) regions in the centre of mass are covered by calorimeters labelled FC and BC respectively and consist of lead glass blocks. The intermediate region is covered by a lead scintillator sandwich labelled IC. All three calorimeters are equipped with fine grained position detectors. The salient parameters are listed in Table 1.

3. The π^0 Identification

The π^0 candidates can, in principle, be selected by combining two photon candidates. The two photons are simply defined as neutral clusters giving the correct shower topology. In most cases the two photon clusters overlap at the calorimeter level whilst, up to the highest useful energies, the two impacts can be distinguished in at least one projection of the position detector.

For FC and BC a simple algorithm [6] was developed to partition the two photon energies and thus reconstruct the π^0 mass when only one cluster is seen in the lead glass mosaic. One assumes a universal, energy independent, shape for the radial energy distribution of the showers. This shape is taken from isolated photon candidates and from electron data. Knowing the position of the two impacts, it is then possible to find a unique solution for the two energies. This method works well up to 35 GeV in BC and 100 GeV in FC.

For IC the presence of two impacts in at least one of the projections of the position detector is required. In the case where the two photons fall in the same calorimeter module, the energy is shared out according to the signals in the position detector. Losses due to merging in both projections only occur at the highest energies, corresponding to p_T above 4 GeV/c, and are smaller than the statistical uncertainties.

Further details on the analyses presented here can be found in ref. [6,7].

The energy calibration of the calorimeters was carried out using two separated photon clusters leading to the π^0 mass. The resulting uncertainty is small and only limited by statistics. The reconstruction technique can introduce some biases for energetic π^0 s where the clusters merge. Such π^0 s were not used for calibration. Independent checks were made using the η mass for which the two photon showers are well separated and from the measured ratio of energy over momentum for electron tracks. From these results the systematic uncertainty at the mean energy is estimated to be better than 1.5% whilst the error due to non linearity is estimated to be better than 2%.

Figure 1 displays the experimental mass distributions obtained for the three calorimeters. Backgrounds arise primarily from isolated photons having a satellite cluster in the position detector or from wrong energy shar-

ing for energetic π^0 's. Proper cuts have been made to remove the major part of these backgrounds which are concentrated in the π^0 decay distribution at $|\cos\theta^*|=0$ and 1. The remaining $|\cos\theta^*|$ distribution ranging from 0.1 to 0.8 is perfectly flat showing no systematic loss.

Muon induced backgrounds, significant only at very high p_T , are rejected using the efficient methods described in [3].

The selection criteria induce losses which have, in most cases, been directly measured using the data. Losses due to γ conversions, backscattering from electromagnetic showers into the charged particle veto counters and random vetoes are measured using reconstructed π^0 and η candidates where the appropriate veto counter has fired. Losses due to late conversion in the converter were estimated using reconstructed π^0 and η 's where only one photon is seen in the position detector.

To estimate the merging probability in the position detector, use is made of the azimuthal (ϕ) distribution of γ 's from reconstructed π^0 's where the γ 's are separated in both projections. Knowing that the ϕ distribution should be flat, the probability for separating two clusters versus the projected distance of the two impacts is derived. Finally, knowing the number of π^0 's with impacts separated in only one projection, it is verified that the level of complete merging is indeed very small up to the highest energies.

4. Results

Transverse momentum distributions are shown in Fig. 2a and b for incident π^- and γ , respectively, for the three calorimeters. For FC (BC) a p_L cut of 40 (10) GeV/c was imposed. These cuts ensure that both the energy range and the mean energy of the π^0 candidate vary weakly with p_T .

The π^- data are well described by the parameterization obtained in a previous experiment [8] on inclusive π^0 production by incident π^- and π^+ . Since those data were obtained using a hydrogen target, a shadowing correction ($A^{\alpha-1}$) with a p_T dependence of α taken from ref [9], is introduced. For a Li^6 target this correction for the cross-section/nucleon does not exceed 20% in the relevant p_T domain.

The Monte Carlo simulation of the geometrical acceptance of the apparatus and of the various losses previously described also includes the smearing effects due to energy and angular resolution. Owing to the rapid variation of the cross-section in p_T the smearing effects give, on average, a correction of order 20%.

The data from the three calorimeters agree with [8] to better than 10%. Since the π^- data do not have high statistics over the full kinematical range covered by the photon induced data, it is assumed that the parameterization of [8] provides a valid extrapolation. More recent results [10] have confirmed the validity of their parameterization to within the quoted systematic uncertainty of 15%.

The VDM contribution to the photon cross-section was computed by assuming that it is simply the average of the π^- and π^+ induced inclusive π^0 cross-sections scaled by the ratio of the γ to $\pi^\pm$ inelastic cross-sections $\sim 1/205$ at 90 GeV. Data on inclusive pion photoproduction at low p_T justifies the above assumption. The π^- data were taken at 70, 90 and 120 GeV. It was verified that for these three energies the parameterization of ref[8] was good. The VDM contribution is then evaluated using this parameterization with the photon energy spectrum folded in.

The γ data in Fig. 2b show significant deviations from VDM predictions in the central region (BC and IC). In the forward region the FC data show very clearly an excess which increases with p_T . With the p_L cut of 40 GeV/c applied to the latter data, the observed cross-section is, on average, more than twice that predicted by VDM. Systematic errors on the difference are below 15% and cannot explain the excess.

The data of the three calorimeters have been combined to produce the p_L dependence of the cross-section for three p_T intervals (Fig. 3). The excess over VDM increases from 30% at low p_T and low p_L to more than a factor 3 for the largest measured values.

The full curves drawn on Fig. 2b and 3 are obtained by adding VDM to the predictions of [4] which are discussed in the next section. There is good agreement over the full kinematic range despite large variation in the ratio of QCD/VDM contributions. The overall uncertainty on the normalization and reconstruction efficiency is estimated to be around 20%.

5. Interpretation

The most recent and complete analysis of Aurenche et al. [4] and their computer code have been used to generate π^0 from QCD Born, leading log and next to leading order terms. Whilst at the parton level, there is little ambiguity in the choice of the structure functions, there is a wide range of parameterizations for the fragmentation functions. Due to the trigger bias, one is only sensitive to the region $z > 0.5$. The choice made here for the quark fragmentation function is based on experimental data from EMC [11] and agrees with the one made by Baier et al. [12] for $z > 0.5$.

Two rather distinct cases were assumed for the gluon fragmentation function : either the gluon fragments like a quark or it has a softer fragmentation function as given by [12]. A global fit, using only the overall normalization N as a free parameter, with 94 degrees of freedom, gives $\chi^2 = 156$ and $N = 0.97$ in the first case, while ref. [12] gives $\chi^2 = 147$ and $N = 0.91$. With the present uncertainty on the overall normalization the data cannot clearly discriminate between the two hypotheses.

At large (p_T, p_L) the QCD terms involving the direct coupling of photons dominate the others and thus no double counting is expected when adding the QCD and VDM contributions. Such an effect would occur

through the anomalous structure function terms which lead to a (p_T, p_L) shape that is similar to the one from VDM. The latter dominates the QCD part only at low (p_T, p_L) . From Fig. 3 it can be deduced that the double counting cannot exceed the uncertainty on VDM itself, which is of the order 15%. Within this limit the correction in the region of large p_T and p_L is negligible.

In Fig. 4 the QCD cross-section, with the photon energy spectrum [7a] folded in, is compared to the observed cross-section in excess of VDM in the forward region (FC with $p_L > 40$ GeV). As expected, the QCD Compton term clearly dominates at large p_T , while the photon gluon fusion process diminishes. On average, the leading logarithm (anomalous photon structure function) contribution is found to be 30% lower than the fusion term with a similar shape. Next to leading order corrections, with the present choice of scale breaking ($Q^2 = p_T^2$, $\Lambda_{\overline{MS}} = 200$ MeV) are found to be of the order of the QCD Compton term with approximately the same slope. The choice of scales, ambiguous in perturbative calculations, can be optimized as explained in ref. [13]. Although the total QCD cross-section turns out to be insensitive to these changes [14] the relative contribution of the various terms changes significantly.

Since at high p_T the Born term contributions represent about half of the total cross-section, very distinct features are expected at the exclusive level induced by the two jet topology (in the laboratory system) of these events. Experimentally, striking differences have already been observed in an exclusive study of our π^- and γ induced data [15].

6. Conclusions

The first measurement of photoproduction of inclusive π^0 at large transverse momentum in a kinematical domain allowing a meaningful comparison with QCD has been presented. The inclusive cross-section observed deviates both in shape and size from what could be expected from a purely hadron-like behaviour of the photon.

A very satisfactory agreement between the data and the QCD Compton scattering, including corrections, is observed over the large kinematical domain covered by this experiment. This agreement does not depend critically on the choice of the gluon fragmentation function. Furthermore, QCD terms account for most of the inclusive π^0 production at large p_T and p_L . These results constitute a test of the validity of QCD perturbative calculations.

In summary, this paper presents, for the first time, evidence for the QCD Compton process and corrections thereof and complements the one which presented evidence for deep-inelastic QED Compton scattering [3].

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8. References

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9. Figure Captions

Fig. 1. Experimental $\gamma - \gamma$ mass distributions obtained from the three calorimeters at various energies ; the relevant low energy domain corresponds to 1a, the high energy one to 1b. The mass cut used to identify pizeros is indicated by arrows.

Fig. 2. The inclusive π^0 data compared with theoretical predictions. The π^- induced data is shown in Fig. 2a. The curves are obtained by using the parameterization of ref. [8]. These data were taken with two transverse momentum thresholds, namely 900 and 1400 Mev/c. The two sets of data have been appropriately combined. Fig. 2b shows the photon induced data : the dotted curves (VDM) use the parameters from ref. [8], the solid curves show the sum of VDM and the prediction of Aurenche et. al. [4]. A cut of $p_L > 40$ Gev/c (10 Gev/c) is imposed on the FC (BC) data respectively.

Fig. 3 The measured cross-section for inclusive π^0 photoproduction versus longitudinal momentum for three p_T intervals : $1.7 < p_T < 2.1$, $2.1 < p_T < 2.5$, and $p_T > 2.5$ Gev/c. The dotted curves show the VDM prediction, the solid curves show the sum of VDM and the prediction of Aurenche et. al. [4].

Fig. 4. The measured cross-section for inclusive π^0 photoproduction versus p_T after subtraction of the VDM component, for $p_L > 40$ Gev/c. The three curves are derived using the computer code of ref. [4]. The dashed and dashed-dotted curves correspond to Compton and fusion terms respectively, the full curve is the total contribution. The gluon is assumed to fragment as a quark. Also shown are systematic errors due to normalization and reconstruction efficiency.

Region covered		CALORIMETER		
		Forward FC	Intermediate IC	Backward BC
Dist. from Tgt	cm.	1550	1350	240
Coverage θ_{LAB}	mrad.	6.5 - 80	80 - 150	$0_H, 80_V - 275$
$\theta_{\text{cm}} \gamma N \rightarrow \pi^0 X$ (100GeV)	deg	5 - 60	60 - 95	$0_H, 60_V - 125$
Rapidity domain		0.5 to 2	0 to 0.5	-0.7 to 0.5
Converter before position detector		Active $3X_0$ Pb Glass	Active $4.5X_0$ Pb Scint.	Passive $4.5X_0$ Lead
Position Detector		y . z crossed scintillator fingers		
Finger width	cm.	1.5	1.5	0.8
Material for total absorption		Pb Glass	Pb Scintillator	Pb Glass
Cell size	cm ²	14 x 14	25 cm in projn.	9.3 x 9.3
Charged Veto		Scintillator matched to cell size		MWPC's
Expected energy range for π^0	GeV	≤ 100	≤ 45	≤ 35
Two shower separation for 50% prob of resolu. per projection	cm.	4	5	1.9
Width of π^0 (σ)	MeV	8.5	12.7	.16
Mass cut applied (Mev)		100 - 170	100 - 170	100 - 170
Signal/background (average)		9	8	2.1
η mass (error is statistical)	MeV	546 ± 0.5		552 ± 0.5
E/p for electrons (raw)		0.980	0.975	1.05 ± 0.03

TABLE 1 Relevant Parameters for the NA14 Calorimeters.

Fig. 1

Fig. 2a

Fig. 2b

Fig. 3

Fig. 4