**Intrinsic transverse momentum
in the $\pi^- p \rightarrow \gamma\gamma X$ reaction at 280 GeV/c.**

WA-70 collaboration

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Abstract

The correlation between the two high transverse momentum ($p_t > 2.75$ GeV/c) photons of the reaction $\pi^- p \rightarrow \gamma\gamma X$ is studied at the beam momentum of 280 GeV/c. QCD calculations beyond leading logarithms are not sufficient to explain the width of the distributions and the effects due to intrinsic transverse momentum of the incident partons are discussed.

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In a previous paper [1] the WA70 experiment at CERN presented evidence for the high p_t production of double prompt photons in the reaction $\pi^- p \rightarrow \gamma\gamma X$ at 280 GeV/c incident momentum. The measured cross-sections were found to agree, within statistical uncertainties, with QCD calculations beyond leading order (BLL) [2]. In the present paper the correlations of the two photons are analysed. The annihilation $q\bar{q} \rightarrow \gamma\gamma$ is responsible for this reaction at leading order. In the absence of an intrinsic transverse momentum k_t of the initial quarks, the two outgoing photons define a reaction plane with the incident beam and their transverse momenta are equal and opposite. However this kinematical situation does not apply if the initial partons have an intrinsic transverse momentum k_t or if higher order effects are significant. Examples of the latter are soft gluon emission and the process $qg \rightarrow q\gamma\gamma$, where the first photon comes from a bremsstrahlung of the outgoing q and the second arises directly from the primary interaction. The higher order diagrams are expected to be significant since the measured values of the $\pi^- p \rightarrow \gamma\gamma X$ cross-sections in the WA70 experiment are too high to be explained by the leading term alone [1]. The distributions of four different variables, which at leading order should show a δ -function distribution widened only by the experimental resolution, are described in this paper.

The WA70 experiment and its trigger requirement for the observation of two high p_t photons have been described elsewhere [1] together with the general analysis of the data and the selection criteria used. The data amount to 282 $\gamma\gamma$ events with an asymmetric cut of 3.0 and 2.75 GeV/c for the higher and the lower transverse momenta of the two photons. The background in this sample has been estimated to be about 50% [1], based on the analysis of 1997 $\pi^0\pi^0$ and 1161 $\gamma\pi^0$ events.

The correlations between the two high p_t photons are studied from the distributions of the variables $\Delta\phi$, P_{out} , $P_t(\gamma\gamma)$ and z

- $\Delta\phi = |\pi - \phi|$, where $\phi = \arccos(\mathbf{p}_{t1} \cdot \mathbf{p}_{t2} / p_{t1} p_{t2})$ is the angle between the transverse momenta $\mathbf{p}_{t1}$ and $\mathbf{p}_{t2}$ of the two photons and $\Delta\phi$ should be zero for a two body reaction $q\bar{q} \rightarrow \gamma\gamma$ or $gg \rightarrow \gamma\gamma$ with $k_t = 0$.
- P_{out} is the absolute value of the momentum component of one of the two photons out of the reaction plane, defined by the beam and the other photon. Due to the symmetry between the two photons, each event contributes twice to the P_{out} distribution.
- The p_t of the $\gamma\gamma$ pair is defined by $|\mathbf{p}_t(\gamma\gamma)| = |\mathbf{p}_{t1} + \mathbf{p}_{t2}|$. The mean value of this distribution would give, in the absence of higher order effects, a direct measurement of the primordial k_t of interacting partons. Assuming [3] that the transverse momentum of the partons inside the beam and the target hadrons follow the same gaussian distribution $f(k_t^2) = A \exp(-Ak_t^2)$, the p_t of the $\gamma\gamma$ pair arises from the convolution of the two distributions and the relation $\langle p_t(\gamma\gamma) \rangle = \sqrt{2} \langle k_t \rangle$ holds,¹ the average k_t being $\langle k_t \rangle = \sqrt{\pi/4A}$.
- The variable z , defined as $z = -\mathbf{p}_{t1} \cdot \mathbf{p}_{t2} / p_{t1}^2 = -(p_{t2}/p_{t1})\cos(\phi)$, is also symmetrized for an exchange of the two photons, thus each event appears twice in the z distribution. For a two body interaction this distribution is expected to be $\delta(1-z)$; an asymmetry, however, is introduced by the analysis cut of 3.0 and 2.75 GeV/c in the transverse momenta of the photons.

Only two of these four variables are linearly independent, the analysis of all four giving a consistency check. The effect of the intrinsic k_t is obtained by measuring the deviations from a δ -function estimated by the width of a gaussian distribution centred at zero and fitted to the $\Delta\phi$ and P_{out} data and directly by the mean value of the p_t of the $\gamma\gamma$ pair. For the z distribution a more detailed study by a comparison with the QCD calculations beyond leading logarithms is possible.

For each distribution the $\gamma\gamma$ signal, $S(\gamma\gamma)$, is obtained from the distribution of the $\gamma\gamma$ candidates $D(\gamma\gamma)$ by subtracting the background $B(\gamma\gamma)$. The background arises mainly from the decay of high p_t mesons: $\pi^0 \rightarrow \gamma\gamma$; $\eta \rightarrow \gamma\gamma$; $\eta' \rightarrow \gamma\gamma$; $\omega \rightarrow \pi^0\gamma$, which are abundantly produced in $\pi^- p$ hard scattering. This contamination has been evaluated by a Monte Carlo generating QCD leading order diagrams with the

¹ In the Lund Monte Carlo used in this analysis the gaussian width $\sqrt{\langle k_t^2 \rangle} = \sqrt{1/A}$ is the parameter which characterizes the k_t distribution.

LUND fragmentation model [5]. In order to reproduce the $\pi^0\pi^0$ and the $\gamma\pi^0$ data, two Monte Carlos are necessary [1]: the first (MC1) simulates all parton-parton leading order diagrams with outgoing partons fragmenting into a high p_t π^0 or η or any other hadron decaying to a high p_t photon, while the second (MC2) generates single prompt photon events. All particles have been traced to the calorimeter through a full detector simulation including materialization of photons, secondary interactions and trigger effects. The longitudinal and transverse development of electromagnetic and hadronic showers have been parametrized using experimental data. The Monte Carlo events were processed using the same chain of programs as for real data. With these simulated events, the background ratios are calculated: $R_1 = \gamma\gamma/\pi^0\pi^0$ and $R_2 = \gamma\pi^0/\pi^0\pi^0$ from MC1 generation, $R_3 = \gamma\gamma/\gamma\pi^0$ from MC2 generation. The denominators $\pi^0\pi^0$ in R_1 and R_2 and $\gamma\pi^0$ in R_3 are the correctly identified events and the numerators contain the events where a hadron is misidentified as a direct γ . Within the limited statistical accuracy of the Monte Carlos, the values of these ratios are found to be constant over the range of each variable under study ($R_1 = 0.041 \pm 0.007$, $R_2 = 0.153 \pm 0.014$, $R_3 = 0.272 \pm 0.009$) and they are considered to be independent of the $\langle k_t \rangle$ of the generated events. Therefore the background B to the $\gamma\gamma$ candidates is estimated from the corresponding distributions of the $\pi^0\pi^0$ and $\gamma\pi^0$ data:

$$B(\gamma\gamma) = R_1 S(\pi^0\pi^0) + R_3 S(\gamma\pi^0)$$

The signal $S(\pi^0\pi^0)$ has been obtained from the $\pi^0\pi^0$ distribution and $S(\gamma\pi^0)$ is the background subtracted $\gamma\pi^0$ distribution:

$$S(\gamma\pi^0) = D(\gamma\pi^0) - R_2 S(\pi^0\pi^0).$$

The analysis is performed on the background subtracted events:

$$S(\gamma\gamma) = D(\gamma\gamma) - B(\gamma\gamma)$$

corrected for the acceptance and efficiency effects using a Monte Carlo which generates $\gamma\gamma$ events with the processes $q\bar{q} \rightarrow \gamma\gamma$ and $g\bar{g} \rightarrow \gamma\gamma$ and $\langle k_t \rangle = 1.0$ GeV/c [6].

In order to evaluate the widening of the distributions due to intrinsic k_t four samples of Monte Carlo $\gamma\gamma$ events were generated with a gaussian width $\sqrt{\langle k_t^2 \rangle}$ of 0.0, 0.44, 0.8 and 1.2 GeV/c. All the distributions were found to evolve linearly with the gaussian width. The data, after background subtraction, are therefore compared to the corresponding Monte Carlo distributions.

At present the predictions of QCD beyond leading logarithms [2] are available in the form of an analytical calculation in p_{tj} and z without intrinsic transverse momentum. Among the four correlation variables only the z distribution can therefore be compared with the calculation. The p_{tj} distribution, which is less sensitive to k_t , has been found [1] to be in good agreement ($\chi^2 = 4.7/6$ d.o.f) with the BLL predictions. For the other variables a comparison with the leading order Monte Carlo gives an estimate of an effective k_t , which could reproduce the data in the absence of any higher order QCD effect. The results for the three variables for which no higher order calculations are available are presented first and are then compared with those of the z variable using the BLL QCD calculation.

The differential cross-sections in the variables $\Delta\phi$ and P_{out} are presented in fig. 1; they are well reproduced by a gaussian centred at zero. The widths σ of these gaussian fits are given in table 1, and cannot be explained by the experimental resolution alone. The comparison of the widths with those obtained by generating the leading order processes at different $\langle k_t \rangle$ gives the values of $\langle k_t \rangle$ indicated in the table. The quoted errors take into account the statistical uncertainties of the data and of the Monte Carlo. In addition a systematic error of about 0.2 GeV/c in the determination of $\langle k_t \rangle$ arises from the uncertainty in the background subtraction procedure.

The differential cross-section as a function of $p_t(\gamma\gamma)$ is presented in fig. 2a. The mean value of the distribution is also listed in table 1. The measured value of 1.29 ± 0.10 GeV leads to a value of 0.91 ± 0.07 for the average parton transverse momentum, in agreement with the estimates from the other variables. Other experiments have found similar values. For instance the $p_t(\gamma\gamma)$ may be compared with the p_t of the dilepton pair observed in the Drell-Yan process $q\bar{q} \rightarrow l^+l^-$ [7]. In these experiments (fig 2b) there is evidence that the mean p_t of the lepton pair increases as a function of the centre of mass energy : $\langle p_t \rangle = (0.48 \pm 0.05) + (0.034 \pm 0.003) \sqrt{s}$ [7], thus indicating that the primordial k_t has a value of $\langle k_t \rangle \approx 0.48/\sqrt{2} = 0.34$ GeV/c and the experimentally observed higher values are due to dynamical effects. The value obtained in the present experiment is consistent with the Drell-Yan results at a similar energy (fig. 2b).

Fig. 3 shows the differential cross-section $d\sigma/dz$. In order to compare with the analytical QCD program, a binning wider than twice the experimental resolution ($\sigma_z = 0.037$) was chosen and a cut $z > 2.75/p_{Ti}$ was applied for each photon entering the histogram. The BLL predictions [2], without folding in the experimental resolution and intrinsic k_t effects, are shown in the fig. 3a. The distribution $d\sigma/dz \sim \delta(1-z)$, characteristic of the leading order calculation (broken line in fig. 3a), is widened by the presence of BLL QCD diagrams (shaded histogram), which also produce destructive interference at $z \approx 1$ [2]. The data show a distribution wider than expected with a central value $z = 0.98 \pm 0.02$. A statistical comparison between the 10 data points and the theory gives a χ^2 of 62. In fig. 3b the BLL theory has been widened by a gaussian distribution of intrinsic transverse momentum $\langle k_t \rangle = 0.34$ GeV/c (broken line) and $\langle k_t \rangle = 0.9$ GeV/c (continuous line), as suggested by the analysis of the $p_{T}(\gamma\gamma)$. The comparison with the 10 data points gives a χ^2 of 28 and 14 respectively for these two curves, thus favouring a high value of k_t although, with the introduction of BLL calculations, a residual k_t of 0.34 GeV/c would have been expected. It should be noted that these conclusions are insensitive to the normalization of the background subtraction, but are dependent on the shape of the background which is determined from the data with limited statistics.

In conclusion all the variables of the present analysis point toward a higher value of the intrinsic transverse momentum than expected for quarks confined inside a hadron. The BLL QCD calculations alone are not sufficient to reproduce the z distribution, even including a $\langle k_t \rangle$ of 0.340 GeV/c. This may indicate that still higher order QCD diagrams or contributions from multiple soft gluons must be taken into account as in the case of Drell-Yan reactions [8].

Table 1: Effective intrinsic k_t from various $\gamma\gamma$ distributions.

	Experimental resolution	$S(\gamma\gamma)$	$\langle k_t \rangle$ (GeV/c)
	width (σ)	width (σ)	
$\Delta\phi$	0.016 rad	0.295 $\pm$ 0.050 rad	0.98 $\pm$ 0.18
P_{out}	0.190 GeV/c	1.03 $\pm$ 0.12 GeV/c	0.94 $\pm$ 0.13
	mean	mean	
$p_{T}(\gamma\gamma)$	0.147 GeV/c	1.29 $\pm$ 0.10 GeV/c	0.91 $\pm$ 0.07

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Figure captions

Fig.1: The differential cross-section of the reaction $\pi^- p \rightarrow \gamma\gamma X$ as a function of (a) the $\Delta\phi$ variable and (b) the P_{out} variable. The data are integrated over p_{ti} from $p_{t1}=3.0$ GeV/c and $p_{t2}=2.75$ GeV/c and over the full rapidity range. Each event contributes twice to the P_{out} distribution. The error bars include the statistical uncertainties of the data and of the Monte Carlos. Superimposed on the data is the result of the fit of a gaussian centred at zero.

Fig.2: a) The differential cross-section of the reaction $\pi^- p \rightarrow \gamma\gamma X$ as a function of the p_t of the $\gamma\gamma$ pair. The data are integrated over p_{ti} from $p_{t1}=3.0$ GeV/c and $p_{t2}=2.75$ GeV/c and over the full rapidity range. The error bars include the statistical uncertainties of the data and of the Monte Carlos. b) The mean p_t of the $\gamma\gamma$ pair compared to the mean p_t of the lepton pair measured in the reaction $\pi^- N \rightarrow \mu^+ \mu^- X$ by various Drell-Yan experiments. The line is the fit from [7] described in the text.

Fig.3: The differential cross-section of the reaction $\pi^- p \rightarrow \gamma\gamma X$ as function of the z variable. The data are integrated over the full rapidity range, and over p_{ti} from $p_{ti}=3.0$ GeV/c. For each γ entering the histogram a cut $z > 2.75/p_{ti}$ is applied. The error bars are the statistical uncertainties of the data and of the Monte Carlos. a) The leading order $q\bar{q} \rightarrow \gamma\gamma$ prediction (broken line) and the BLL QCD calculations [2] (shaded area) are indicated. b) The BLL calculations widened by an intrinsic transverse momentum $\langle k_t \rangle = 0.34$ GeV/c (broken line) and by $\langle k_t \rangle = 0.9$ GeV/c (continuous line) are superimposed on the data.

FIG.1

FIG. 2

FIG.3