Direct soft photon production in $K^+p$ and $\pi^+p$ interactions at 250 GeV/c

EHS-NA22 Collaboration

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Abstract. Inclusive production of direct soft photons is studied in $K^+p$ and $\pi^+p$ interactions at 250 GeV/c. Total cross sections, Feynman-$x$ and transverse momentum distributions of direct $\gamma$'s are presented. The measured cross sections are several times larger than expected from QED inner bremsstrahlung, indicating the presence of an anomalous soft photon source. The model of Lichard and Van Hove, based on the “cold quark-gluon plasma” picture, agrees with the data.

1 Introduction

Experiments over the past decade have found persisting evidence for anomalous sources of electromagnetic radiation in hadron collisions. Electron production at low $p_T$ is more abundant than expected from known origins, including hadronic bremsstrahlung and charmed particle decays [1–5]. A dilepton ($e^+e^-$ and $\mu^+\mu^-$) continuum of masses well below 600 MeV/c$^2$ is measured, up to two orders of magnitude larger than estimated from the Drell-Yan process [6–17]. The ratio of prompt $e^+$ to $\pi$ production in the rapidity region $|\eta| < 1$ and $p_T < 0.4$ GeV/c rises approximately linearly with $n_{ch}$, the charged particle multiplicity of events, indicating that the production rate is proportional to $n_{ch}$ [18]. A possible explanation is “soft annihilation” [19] where lepton pairs are created through annihilation of quarks and antiquarks created during the collision. Alternative explanations are based on thermodynamic models [20–22].

Sea-quark annihilation into virtual photons, observed as lepton pairs, implies that soft real photons must also be produced in the same collision. The first evidence for a direct soft photon signal comes from $\pi^+p$ experiment at 10.5 GeV/c beam momentum [23]. There, the signal was found to be compatible with hadronic inner bremsstrahlung. However, an excess of direct soft photons, four times larger than expected from this last process, has been measured in $K^+p$ collisions at 70 GeV/c [24].

More recently, the AFS collaboration [25] has also searched for a possible excess of photons. The results are not conclusive, but seem to exclude a strong increase of the $\gamma$ signal beyond that observed in [24]. Preliminary data from the HELIOS Collaboration [26] (see also [27]) show a prompt-$\gamma$ signal in the central rapidity region below $p_T < 30$ MeV/c in $p$ Be and $p$ Al collisions at 450 GeV/c. The signal may, however, be compatible with that expected from known sources. Direct soft photons are now also seen by the EMC Collaboration in $p\overline{p}$ interactions at 200 GeV/c [28]. The anomalous effect is therefore not restricted to hadron collisions. This indicates that a phase transition from hadronic to quark matter is unlikely to be the origin.
The mechanism behind these soft phenomena is at present not understood (see [29] for a critical discussion). In the limit of very small $p_{\gamma}$, the wavelength of the photons is large compared to the hadronic interaction region. Processes confined within this region with a typical size and lifetime of $1 \text{ fermi}$ should not contribute. This was verified in an investigation by Andersson et al. [30] using the space-time structure of the Lund string fragmentation model. Therefore, much larger scales, of the order of several to tens of fermi, seem to be involved.

Recently, several models were proposed to explain the soft photon puzzle by non-standard mechanisms. The model by Shuryak [31] is based on a "pion liquid" picture. Barshay considers soft photon emission from a pion condensate [32]. Lichard and Van Hove [33] suggest that the "ultrasoft" effects may find a common explanation in the formation of dense "globs" of cold partonic matter at the end of a QCD cascade.

In this paper we present new results on a search for prompt soft photon emission in the reactions

\[ K^+ p \rightarrow \gamma + X, \]
\[ \pi^+ p \rightarrow \gamma + X; \]

at 250 GeV/c, the highest beam momentum so far reached for positive meson-protons collisions. The differential $\gamma$ cross section in Feynman-$x$ and transverse momentum $(p_T)$ shows a clear excess above the background from $\pi^0$ decay, electromagnetic (em) decays of other hadrons and from hadronic inner bremsstrahlung. The present analysis confirms the existence of an anomalous prompt photon signal with very similar properties as that seen in $K^+ p$ collisions at 70 GeV/c [24].

In Sect. 2, we describe the data samples and the experimental procedures, and present results on the total inclusive photon cross section in reactions (1)-(2). Section 3 discusses the differential cross section. The method to isolate a prompt $\gamma$ signal, and results on total and differential prompt photon cross sections are described in Sect. 4. The conclusions are summarized in Sect. 5.

2 Experimental procedure

The results presented below are based on the complete statistics of the experiment NA22 performed at the CERN SPS. For this experiment, the European Hybrid Spectrometer (EHS) was equipped with the Rapid Cycling Bubble Chamber (RCBC) as vertex detector, filled with liquid hydrogen, and exposed to a 250 GeV/c tagged, positive, meson-enriched beam. A minimum bias interaction trigger was used during data taking. Two thin aluminium and gold foils, used in other studies, were mounted behind the entrance window of RCBC within the sensitive volume. Besides RCBC, the full experimental set-up of EHS consisted of a two lever-arm spectrometer and several particle identification devices. Further details on the set-up and on the trigger conditions are given in [34].

The present analysis is based on a sample of $\gamma$'s observed as $e^+ e^-$ pair conversions in the sensitive volume of RCBC. The so-called "intermediate" and "forward" gamma detectors of EHS are not used in this analysis. The combined acceptance of the gamma detectors limits a study of $\pi^0$ production to Feynman-$x \geq 0.025$, outside the small-$x$ region of interest in this paper. Results on inclusive $\pi^0$ production derived from these devices, are presented in [35,36]. As discussed further on, these data permit some cross-check on the differential cross section $d\sigma/dx$ of $\pi^0$'s.

The events of the sample are selected in a cylindrical fiducial volume of radius $R = \sqrt{x^2 + y^2} < 20\text{ cm}$ for $X > 0$ and $R < 40\text{ cm}$ for $X < 0$; $|Z| < 18\text{ cm}$ and $|Y| \leq 30\text{ cm}$; $(X, Y, Z)$ are the coordinates of the primary event interaction vertex. The origin is chosen at the center of RCBC, the X-axis directed along the spectrometer, and the Z-axis pointing towards the camera. In addition, we introduce a cut to exclude events with primary vertices located upstream of the Al and Au targets, thus eliminating possible background from $\gamma$-conversions in the foils. The selected events are further required to have a well-tagged beam track and to satisfy charge balance. After these cuts, the sample comprises 26910 $K^+ p$ and 78099 $\pi^+ p$ interactions. The scanning efficiency for $\gamma$'s is close to 97%.

The fiducial volume for vertices from $\gamma$-conversions and $V^0$ decays is defined as above but with a radius $R = 33\text{ cm}$ for $X > 0$.

The secondary $e^\pm$ and hadron tracks, as well as those from the primary vertex are reconstructed from measurements in RCBC and in the spectrometer. The $\gamma$'s and $V^0$'s have been passed through the HYDRA-geometry and HYDRA-kinematics programs and fitted to the hypotheses $K^0_S \rightarrow \pi^+ \pi^-$, $\Lambda \rightarrow p \pi^+$, $\bar{A} \rightarrow \bar{p} \pi^+$ and $\gamma \rightarrow e^+ e^-$. For the latter, the $e^+ e^-$ effective mass is left as a free parameter. Kinematic fits are accepted if the corresponding $\chi^2$-probability is larger than 0.01%. Approximately 16% of the $\gamma$'s are ambiguous with one or more hadron hypotheses. For $\gamma$'s with energy $E_{\gamma} < 0.5\text{ GeV}$, the ambiguity level is 3.8%. For kinematical reasons, and following standard procedure, all ambiguous fits involving $\gamma$'s are accepted as $\gamma$'s. We further require the $e^\pm$-tracks to have $p_T < 0.25\text{ GeV/c}$ and track residuals to be less than 300 $\mu$m in space.

The usual corrections for scanning and measuring losses, Compton scattering, conversions outside the fiducial volume or close to the primary vertex are applied. The minimum distance before conversion is chosen to be 3 cm in the $(X-Y)$ plane. The $\gamma$-losses are most significant at low momenta. To minimize systematic errors due to very soft $\gamma$'s and asymmetric $e^+ e^-$ pairs, we introduce additional cuts requiring $p_{\ell} > m_{\pi^+}/2$ and $p_{\pi^+} > 25\text{ MeV/c}$, were $p_{\ell}$ is the lepton momentum, $p_{\pi^+}$ the photon momentum in the laboratory frame. This last cut is corrected for using a momentum-dependent weight-factor based on the known QED electron momentum distrib-

* For more details on the scanning procedure and corrections see [34].

** Results on $A, \bar{A}$ and $K^0_S$ production in this experiment are given in [37,38].
bution. It has an average value of 1.015. The combined correction factors have an average value of 43.8 and 43.3 for $K^+p$ and $\pi^+p$ interactions, respectively, mainly arising from the $\gamma$-conversion probability in the fiducial volume of the bubble chamber. The ratio of the number of accepted 4C-fit $\gamma$'s to that found at the scanning is equal to 0.72 for both reactions.

After all cuts, we retain for further analysis 2540 and 7646 $\gamma$'s in the $K^+p$ and $\pi^+p$ data samples, respectively. The corresponding inclusive cross section is equal to $(118.4 \pm 3.0)$ mb in reaction (1) and $(147.8 \pm 2.2)$ mb in reaction (2) for $p_\gamma > m_{\pi^0}/2$. The $\gamma$-cross section for $p_\gamma \leq m_{\pi^0}/2$ can be estimated, under the assumption that all $\gamma$'s come from $\pi^0$-decay, by using the symmetry property of the $\gamma$-momentum distribution: $d\sigma/dp_\gamma = d\sigma/dp_{\pi^0}$, with $p_{\pi^0} = m_{\pi^0}/4p_\gamma$. With this correction, we measure a total inclusive $\gamma$ cross section of $(123.2 \pm 3.3)$ mb for $K^+p$ and $(154.5 \pm 2.7)$ mb for $\pi^+p$ collisions. The errors quoted are statistical only.

The total inclusive cross section is plotted in Fig. 1 as a function of beam momentum. Our measurements continue the trend seen at lower energy [37-42]. The cross section increases as $a + b \ln (s/s_0)$ ($s_0 = 1 \text{ GeV}^2$). From the fit shown in Fig. 1 we find $a_{K^p} = (-53 \pm 5)$ mb, $b_{K^p} = (28.9 \pm 1.2)$ mb, $a_{\pi^p} = (-32 \pm 4)$ mb, $b_{\pi^p} = (30.2 \pm 1.0)$ mb.

### 3 Differential cross sections

In view of the very low detection efficiency for low-energy $\gamma$'s all data presented here and in Sect. 4 pertain to $\gamma$'s with $p_\gamma > m_{\pi^0}/2$.

The differential cross section, $d\sigma/d\chi$, for reactions (1)-(2) is shown in Fig. 2 and also given in Table 1. The spectra have a sharp maximum at $\chi = 0$ and are forward-backward asymmetric. The solid curves in Fig. 2 are FRITIOF (version 2) predictions [45,37] subjected to the same $\gamma$-momentum cut. The agreement with the data is quite good for $|\chi| \leq 0.02$ and $p_\gamma > 40 \text{ MeV/c}$.

The data described here indicate the possible presence of a very soft $\gamma$-component in the kinematical regions $|\chi| \leq 0.02$ and $p_\gamma \leq 40 \text{ MeV/c}$, not present in the FRITIOF model. The next section is devoted to a detailed study of this phenomenon.

### 4 Direct soft photons

The photons measured in this experiment originate from various sources:

- indirect photons from the em decay of short-lived had-
Table 1. $d\sigma /dx$-spectra for $\gamma$’s in reactions (1)-(2) at 250 GeV/c

<table>
<thead>
<tr>
<th>$x$-interval</th>
<th>$d\sigma /dx$, mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ p \rightarrow \gamma + X$</td>
<td>$\pi^+ p \rightarrow \gamma + X$</td>
</tr>
<tr>
<td>$-0.00$ to $-0.002$</td>
<td>$27200 \pm 5200$</td>
</tr>
<tr>
<td>$-0.002$ to $-0.006$</td>
<td>$10600 \pm 1470$</td>
</tr>
<tr>
<td>$-0.006$ to $-0.010$</td>
<td>$8700 \pm 1300$</td>
</tr>
<tr>
<td>$-0.010$ to $-0.015$</td>
<td>$6800 \pm 1150$</td>
</tr>
<tr>
<td>$-0.015$ to $-0.020$</td>
<td>$5530 \pm 910$</td>
</tr>
<tr>
<td>$-0.020$ to $-0.025$</td>
<td>$4800 \pm 720$</td>
</tr>
<tr>
<td>$-0.025$ to $-0.030$</td>
<td>$4720 \pm 900$</td>
</tr>
<tr>
<td>$-0.030$ to $-0.035$</td>
<td>$5250 \pm 1050$</td>
</tr>
<tr>
<td>$-0.035$ to $-0.040$</td>
<td>$4050 \pm 690$</td>
</tr>
<tr>
<td>$-0.040$ to $-0.045$</td>
<td>$4130 \pm 740$</td>
</tr>
<tr>
<td>$-0.045$ to $-0.050$</td>
<td>$3780 \pm 710$</td>
</tr>
<tr>
<td>$-0.050$ to $-0.055$</td>
<td>$3220 \pm 440$</td>
</tr>
<tr>
<td>$-0.055$ to $-0.060$</td>
<td>$4560 \pm 740$</td>
</tr>
</tbody>
</table>

Fig. 3. The $d\sigma /d|x$ differential cross section for $\gamma$’s in reaction (1) at 250 GeV/c together with the FRITIOF prediction.
To isolate the direct soft photon contribution(s) we proceed in several steps. The distribution in Feynman-$x$ of $\gamma$'s is determined using, on the one hand, FRITIOF for non-$\pi^0$ decays, and the properties of the $\pi^0 \rightarrow \gamma \gamma$ decay kinematics for the dominant $\pi^0$ contribution, on the other hand. For the $p_T$-distributions we mainly rely on FRITIOF. The method adopted largely follows the one described in [24], which in turn was based on earlier work [23]. We refer to these publications for further details.

We first discuss the differential $\gamma$ cross section as a function of Feynman-$x$. In a first step, we subtract from the experimental sample the contribution from non-$\pi^0$ hadronic EM decays using the FRITIOF model cross sections and $x$-distributions. This component is shown in Fig. 2 (dashed curves). The $\gamma$-spectrum remaining after subtraction is plotted in Fig. 6. It should be noted that the inclusive production cross sections of $\eta$, $\eta'$, $\omega$, $\phi$,
\( \Sigma^0, \Sigma^0 \) are either not measured at all in this experiment
\((\eta^0, \Sigma^0, \Sigma^0)\), or in part of the forward cm hemisphere only
\((\omega, \phi)\). Where possible, we verified that the FRITIOF
predicted cross sections for these hadrons are compatible
with our data. For \( n \) production, preliminary results from
this experiment [36] indicate that FRITIOF overestimates
the cross section by as much as a factor of two in the
x-region covered by the gamma detectors \((x > 0.1)\). The
form of its x-spectrum, however, is compatible with
the data in the measured region. The uncertainty on the
various meson- and baryon cross sections introduces a
systematic error on the prompt photon cross section which
is taken into account in the results quoted below.

In a second step, we estimate the (dominant) contribution
from \( \pi^0 \to \gamma \gamma \) decay using the technique proposed
in [44] (see also [24]). In this method, the differential
cross section \( d\sigma (\gamma) / dx \) is analytically calculated from
the parent \( \pi^0 \) distribution \( d\sigma (\pi^0) / dx \). For the latter, a
suitable parametrization is chosen and subsequently fitted
to the experimental \( d\sigma (\gamma) / dx \) distribution obtained
in the first step. The kinematics of \( \pi^0 \to \gamma \gamma \) decay has
the interesting property that the photon data for
\(|x_\gamma| < 2M_{\pi}/\sqrt{s} = 0.012\) determine the \( \pi^0 \) distribution for
all \( x \). This allows to exclude the very central region of the
y-spectrum in the fit-procedure. In practice, we determine
the \( \pi^0 \) x-spectrum using the y x-spectrum in the intervals
\( -0.4 \leq x_\gamma \leq -0.008 \) and \( 0.008 \leq x_\gamma \leq 0.5 \). The
y-spectrum derived from this fit is shown in Fig. 6 (dashed
lines). It agrees very well with the data in the fitted intervals.
With the \( \pi^0 \) x-spectrum now determined for all \( x \), we are able to calculate the y-spectrum from \( \pi^0 \) decay in the region
\(-0.008 < x_\gamma < 0.008 \). Subtraction of this contribution finally yields the prompt photon distribution.

As a (partial) cross-check on the y-spectrum from \( \pi^0 \)
decays, we compared the experimental distribution \( d\sigma (\pi^0)/dx \), derived in [35] from the EHS gamma detectors,
to the \( \pi^0 \)-spectrum obtained in the fit-procedure, in the interval \( 0.025 < x (\pi^0) < 0.15 \). The two spectra agree with each other within errors (not shown).

The dashed histograms in Fig. 7 are predictions by
Lichard and Van Hove [33] derived in the “cold-quark
 gluon plasma” (CQGP) model. In this model, soft pho-
tons are produced via gluon Compton scattering and
quark-antiquark annihilation in lowest order QED and
QCD. The predictions of this model are entirely compatible
with our data.

The QED hadronic inner bremsstrahlung contribution
to direct soft photons is also shown in Fig. 7. It is calcu-
lated, as explained in [24], from the exact QED formu-
lae in the soft energy limit [46,29] by Monte Carlo

Fig. 7 a, b. The \( d\sigma / dx \) spectrum of y’s after
subtraction of all hadron decays in reaction (1) at
250 GeV/c a and in reaction (2) at
250 GeV/c b. The curves show the hadronic
bremsstrahlung contribution and the CQGP model prediction

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\* We chose this interval to allow comparison with the \( K^+ p \) data
at 70 GeV/c. Note that the experimental resolution in Feynman-x
is \( \sim 2 \times 10^{-4} \) in the interval \(-0.01 < x_\gamma < 0.01 \), and \( \sim 2 \text{ MeV/c} \) in transverse momentum for \( p_\gamma < 100 \text{ MeV/c} \).

** The model predictions of [33] are multiplied by the ratios of total
inelastic cross sections at 250 and 70 GeV/c \((1.10 \pm 0.01)\) and
\((1.30 \pm 0.01)\) for \( K^+ p \) and \( \pi^+ p \), respectively.
sampling over the photon phase space. The QED $x$-spectrum lies systematically below the data, although its shape is quite similar. The total inner bremsstrahlung cross section with the cut $p_T > m_{\pi^0}/2$ and for $-0.001 < x_{\gamma} < 0.008$ is equal to $1.3$ mb for $K^+p$ collisions and $1.6$ mb for $\pi^+p$ collisions.

To extract the prompt photon differential cross section as a function of transverse momentum, we first use FRITIOF to simulate the background sources. As noted in Sect. 3, this model reproduces well the $d\sigma/dp_T^2$ (Figs. 3-4) and $d\sigma/dp_T$ (Fig. 5) distributions, except at very small $p_T$.

From Figs. 3-4 we deduce an excess cross section above the FRITIOF background of $(6.0 \pm 1.4)$ mb (Fig. 3b) and $(7.7 \pm 0.8)$ mb (Fig. 4b) for $p_T \leq 0.0015$ (GeV/c)$^2$. The signal is plotted in Fig. 8 as a function of $p_T$. The cross section of anomalous soft photons, for $p_T \leq 40$ MeV/c, amounts to $(6.0 \pm 1.7)$ mb in $K^+p$ collisions and $(7.6 \pm 1.2)$ mb in $\pi^+p$ collisions. These values are consistent, within statistical and systematic errors, with those derived from the inclusive $x$-distribution. The corresponding cross section for $70$ GeV/c $K^+$ interactions is equal to $(5.5 \pm 0.6)$ mb. The ratio of these cross sections at $250$ and $70$ GeV/c is the same, within errors, as that of the total inelastic cross section.

For an independent check of the background subtraction procedure, we have used the experimental data on $\pi^-s$ to simulate "$\pi^-\rightarrow \gamma \gamma$ decays", with the assumption that the $p_T$ spectra of $\pi^0s$ and $\pi^-s$ are identical in the low-$p_T$ region. The "$\gamma$-spectrum" so obtained was normalized to the measured $\gamma$ $p_T$-spectrum (with non-$\pi^0$ hadron decay background removed) in the interval $0.1 < p_T(\gamma) < 1.5$ GeV/c and extrapolated to $p_T = 0$. This yields a prompt photon cross section of $(6.6 \pm 1.5)$ mb and $(9.4 \pm 1.7)$ mb for $K^+p$ and $\pi^+p$ collisions in the region $p_T \leq 40$ MeV/c. Combining the results of the two methods, we arrive at a final estimate, including systematic errors, of $(6.3 \pm 1.6)$ mb and $(8.2 \pm 1.5)$ mb, respectively, for the cross section of prompt photons with $p_T \leq 40$ MeV/c in reactions (1) and (2).

The dashed histograms in Fig. 8 show the CQGP-model predictions. They agree well with the data. In contrast, the inner bremsstrahlung cross section, also plotted in Fig. 8, is several times smaller than the measured direct photon signal. For $p_T \leq 40$ MeV/c, it is equal to $0.98$ mb and $1.18$ mb for the $K^+p$ and $\pi^+p$ data, respectively.

We have also attempted to extract the prompt photon cross section as a function of cm rapidity. Using the FRITIOF background $p_T$-distribution in a given interval of rapidity, we obtain the cross sections given in Table 3. Despite the large errors, these results show that the signal of prompt photons with $p_T < 40$ MeV/c is concentrated in the forward cm hemisphere ($y > 0.25$). It is much weaker, if at all present, in the central and backward regions.

It should be noted that the experimental data points at the smallest $p_T$-values are slightly overestimated due to resolution smearing. This effect is not included in the FRITIOF background simulation. We have also studied the possible influence on the prompt photon signal of ambiguous $\gamma$-fits (see Sect. 2). No enhancement of the fraction of such $\gamma$’s is seen in the kinematical regions of interest.

5 Summary and conclusions

In this paper a study is presented of inclusive photon production in $K^+p$ and $\pi^+p$ interactions at $250$ GeV/c beam momentum. The results can be summarized as follows:

- Up to $250$ GeV/c, the total inclusive photon cross section increases logarithmically with the square of the cm energy and with the same rate for $K^+p$ and $\pi^+p$ collisions.
- For photon energies larger than $m_{\pi^0}/2$, we find that the model FRITIOF reproduces the inclusive $p_T^2$ and $p_T$ differential cross sections, except for the very small $p_T$-region: $p_T^2 < 0.0015$ (GeV/c)$^2$, $p_T \leq 40$ MeV/c. The model also describes the differential cross section $d\sigma/dx$ for $x < 0$ and for positive $x$-values up to $x \sim 0.1$, but does not explain the large photon cross section in a very narrow interval around $x = 0$.
- After subtraction of the $\gamma$-component due to electromagnetic decays of hadrons, we find evidence for an

| Table 3. Inclusive cross section of prompt photons, with $p_T < 40$ MeV/c, as a function of cm rapidity |
|----------------------------------------|----------------------------------------|
| $y$-interval | Cross section (mb) |
| $K^+p \rightarrow \gamma + X$ | $\pi^+p \rightarrow \gamma + X$ |
| $y > 0.25$ | $4.7 \pm 1.2$ | $5.0 \pm 0.8$ |
| $-0.25 < y < 0.25$ | $1.3 \pm 0.6$ | $1.0 \pm 0.4$ |
| $-0.75 < y < -0.25$ | $1.0 \pm 0.4$ |
| $-2.03 < y < -0.75$ | $0.8 \pm 0.7$ |
"anomalous" direct soft signal with a cross section several times larger than that expected from QED bremsstrahlung.

Our data on direct photon emission at 250 GeV/c agree with the predictions of Lichard and Van Hove based on the existence of "globs" of cold quark-parton matter.

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