HIGH- p_T DIRECT PHOTON PRODUCTION AT 11°
IN pp COLLISIONS AT $\sqrt{s} = 63$ GeV

The Axial Field Spectrometer Collaboration

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ABSTRACT

The production of direct photons has been measured relative to π^0 's in the rapidity range $2.00 < y < 2.75$ in pp collisions at $\sqrt{s} = 63$ GeV at the CERN Intersecting Storage Rings. The γ/π^0 ratio increases from $\leq 2\%$ at $p_T = 1.5$ GeV/c to $\sim 8\%$ at $p_T = 4.25$ GeV/c, similar to the value observed near 90° . The results indicate no strong enhancement of single-photon production due to quark bremsstrahlung in this kinematic region.

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The production of direct photons in hadronic interactions has attracted considerable experimental and theoretical interest in recent years since their initial observation at the CERN Intersecting Storage Rings (ISR) near 90° in the centre of mass [1]. Single high- p_T photons emerging from the collision can be interpreted as direct products of hard scatterings between hadron constituents. The dominant mechanism for producing direct single photons in the central region is believed to be the QCD analogue of the Compton process $qg \rightarrow \gamma q$. In addition, QCD predicts that photons should be produced by quark bremsstrahlung $qq(\bar{q}) \rightarrow \gamma qq(\bar{q})$, $qg \rightarrow \gamma qg$, $gg \rightarrow \gamma q\bar{q}$, and quark-antiquark annihilation $q\bar{q} \rightarrow \gamma g$. Bremsstrahlung processes are not expected to be a major source of single photons at 90° in the p_T range 3-9 GeV/c, but lead in some models [2] to a strong enhancement of the γ/π^0 ratio at small centre-of-mass angles. Recent measurements [3] have shown that bremsstrahlung production of single photons in the central region is indeed small. In this paper we present the first measurement of the direct photon signal relative to π^0 's in the forward direction (7.3° - 15.4°) in pp collisions at $\sqrt{s} = 63$ GeV. We find the γ/π^0 ratio to rise to $\sim 8\%$ at $p_T \sim 4.25$ GeV/c, similar to the value measured at 90° in the same p_T range. The results are compared with two theoretical predictions [2,4] for the γ/π^0 ratio in this kinematic region.

A detailed description of the apparatus and trigger can be found elsewhere [5,6]. The photon detector consisted of a uranium/scintillator sandwich calorimeter with good energy and position resolution [$\sigma(E)/E \approx 0.11/\sqrt{E}$ and $\sigma_x \sim 2.3$ mm for single showers, respectively], and was part of the Axial Field Spectrometer (AFS) at the CERN ISR [7]. A hexagonal geometry with three independent readout views allowed π^0 's to be resolved as two showers up to energies of approximately 25 GeV. Each view consisted of a front and back section made up of alternating layers of uranium plates and scintillator strips. The front section was 6.5 radiation lengths (0.47 interaction lengths) in depth, and the back section was 13.0 radiation lengths (0.93 interaction lengths). The strips, 1 cm wide in the front and 3 cm wide at the back, were read out with wavelength shifter bars and photomultiplier tubes (PMs). The anode signals from the PMs were recorded by ADCs and the dynode signals were

used for triggering. A 3.5 cm wide area around the perimeter of the front section served as a "veto" region for detecting additional photons from meson decays when only one photon was in the fiducial region. The centre of the calorimeter was situated at an angle of 11° with respect to the outgoing proton beam and subtended a solid angle of 25 msr. The rapidity range covered was $2.00 < y < 2.75$ and the maximum p_T , limited mainly by the total integrated luminosity was ~ 4.5 GeV/c.

The trigger for the calorimeter was formed by adding the dynode outputs from all PMs for each view separately, and requiring a minimum energy deposition for each of the sums. The calorimeter trigger was put in coincidence with a "minimum bias" trigger from the AFS which was sensitive to $\sim 80\%$ of the total pp inelastic cross-section. The uranium radioactivity was used as a source of ionization to maintain the strip-to-strip and over-all energy calibration during the data taking.

The data sample consisted of 623,000 triggered events corresponding to an integrated luminosity of $7.1 \times 10^{36} \text{ cm}^{-2}$. Pedestals were subtracted from the raw ADC values and a cut of 25 MeV was applied to each channel to suppress the uranium noise. The pulse heights were corrected for a small non-linearity in the PMs due to saturation at very high energies. This effect was measured channel by channel, using a light-flasher system in the calorimeter, and amounted to a 1% correction to the total pulse height for a 20 GeV shower. The conversion from ADC pulse height to energy was determined using π^0 events and is described in Ref. [6]. The procedure demanded that the reconstructed π^0 mass for real events be the same as for π^0 events generated with a Monte Carlo and reconstructed using the same pattern recognition program. The resulting uncertainty in the over-all energy scale obtained using this method was $\pm 3.0\%$.

The p_T of single-photon or π^0 candidates was required to be well above the trigger threshold in order to avoid any possible differences in trigger efficiency between the two classes of events. This resulted in retaining approximately 25% of the data for the final analysis. The reconstructed showers were required to lie within a fiducial area with a boundary 1 cm from the surrounding veto region, and to have a minimum energy deposition of 200 MeV in the front section and 400 MeV in

the whole calorimeter. The low minimal energy requirement allowed the possibility of finding low-energy photons from asymmetric π^0 decays. In addition, a requirement of $E_{\text{front}}/E_{\text{total}} > 0.2$ was made to reduce the background from hadrons. A test was made on the shower radius in the front section of the calorimeter $R < 1$ cm for single-photon candidates in order to suppress the background from π^0 's where the two showers had merged. No radius cut was necessary on showers in the π^0 sample.

We define the "unassigned energy" as the energy in the calorimeter not associated with accepted photons. A cut was made on the maximum unassigned energy of the three views, corresponding to an energy deposition of < 400 MeV in the front, and < 800 MeV total (excluding the veto). Figure 1 gives the unassigned energy distribution in the front section for one and two shower events, and shows that single shower events generally have larger unassigned energy than those containing two showers. This difference is mainly due to soft photons from π^0 decays not found by the reconstruction program. The cut effectively removed a large fraction of the single-photon background from meson decays, where two photons were inside the fiducial region but only one was found passing the cuts. Single-photon events were allowed to have only one accepted γ , and π^0 events were allowed to have only two accepted γ 's with an effective mass $100 < m_{\gamma\gamma} < 170$ MeV. The single-photon background from meson decays, due to one γ found in the fiducial region and the other in the veto region, was minimized by requiring the energy in the veto to be < 400 MeV. The number of background single-photon events surviving these cuts and the geometrical background where only one photon hit the calorimeter and the other was completely outside, were calculated using a Monte Carlo program and subtracted as described below.

The unassigned energy and γ multiplicity cuts necessarily make the single-photon and π^0 measurement non-inclusive. The unassigned energy cut does, however, allow for several accompanying hadrons, given that the average energy deposited in the whole calorimeter by a minimum-ionizing particle was 150 MeV. Events with additional photons near the trigger particle were in general eliminated either by the γ multiplicity cut or the unassigned energy cut, unless the accompanying γ energy was very low. The effect of these cuts could be measured on the π^0 sample

owing to the additional constraint of the π^0 mass, and showed that the cuts resulted in a 25% loss of π^0 's which otherwise would have been accepted. The cuts were necessary for the single γ analysis in order to reduce the background to an acceptable level. The implications of these cuts on the measured γ/π^0 ratio are discussed later.

Figure 2 shows the observed γ/π^0 ratio as a function of p_T after applying all cuts. The calculation of the background, reconstruction efficiency, and geometrical acceptance were made using a Monte Carlo program. The reconstruction efficiency was computed by simulating showers in the calorimeter using the EGS Monte Carlo program [8] and analysing the events with the same pattern recognition program and cuts as were used for the real data. Figure 3 shows the reconstruction efficiency for single γ 's and π^0 's as a function of p_T . The fall-off in the π^0 efficiency at high p_T was mainly due to merging where the two photons were too close together to be resolved. These were often found as one shower by the program, but only contributed to the single-photon background if the shower survived the radius cut. The cut was conservatively chosen at a value of 1 cm so as not to adversely affect the efficiency for finding real single showers, and resulted in a 6% loss of the true single-photon signal. The background due to merged π^0 's surviving after all cuts is given by curve (e) in fig. 2 and was the dominant background at high p_T .

The geometrical background due to π^0 , η , η' , and ω decays was computed assuming the y - p_T distribution of the η , η' , and ω to be the same as that of the π^0 . The π^0 distribution was taken from a measurement at $\sqrt{s} = 53$ GeV [9] scaled to our energy and covered a rapidity range $1.6 < y < 3.0$. This was large enough to include all meson decays contributing to the geometrical background. The production spectrum was varied over limits consistent with our own measurements of the π^0 cross-section over the rapidity range $2.00 < y < 2.75$ in order to determine the sensitivity of the final result to the parametrization used to generate the background. The resulting uncertainty due to the parametrization is included in our systematic errors. We have used our measured value for the ratio $\eta/\pi^0 = 0.46 \pm 0.07$ given in reference [6], whilst the ratio $\eta'/\pi^0 = 0.90 \pm 0.25$ and $\omega/\pi^0 = 0.87 \pm 0.17$,

which make up only a small fraction of the background, were taken from measurements at 90° [10]. Figure 2 shows the geometrical backgrounds as a function of p_T .

The background expected from hadrons faking single photons was estimated using measurements taken with the calorimeter in a test beam. The hadron events were analysed with the standard pattern recognition program to determine the fraction of events reconstructed as single photons passing all the cuts. The misidentification probability was folded with the hadron momentum spectrum to give an upper limit of 1.0% in the observed γ/π^0 , independent of p_T . The contribution to the γ/π^0 ratio, after correcting for relative efficiency and acceptance, was $< 0.5\%$.

The background from beam-gas events was studied using the full event reconstruction of the central drift chamber of the AFS. Events were required to have ≥ 2 reconstructed tracks on a vertex inside the interaction diamond and no out-of-time hits in central scintillation counters. These cuts suppressed background events which triggered the apparatus by themselves, although background events which triggered only the calorimeter and occurred in time with a valid minimum bias event were not rejected. The vertex requirement produced no change in the γ/π^0 ratio within the statistical errors. However, requiring the vertex caused a 30% loss in statistics, mainly due to the fact that a substantial fraction of the events which triggered the forward calorimeter did not have two or more tracks in the rapidity region ($|y| < 1$) covered by the central detector. Selecting events with high multiplicity (≥ 6 tracks) in the central region, which were unlikely to be minimum bias events in time with a background calorimeter trigger, also did not change the γ/π^0 ratio. We conclude that the γ/π^0 ratio is not significantly affected by beam-gas events and we did not make a vertex requirement in the final analysis.

The background from cosmic rays which triggered the calorimeter and satisfied the additional trigger requirement was measured during runs with the ISR off. Events which triggered the calorimeter alone, but occurred in time with a minimum bias event, were measured with the calorimeter trigger in coincidence with a random clock to simulate the minimum bias trigger during normal ISR conditions. Both sources of background were found to be negligible.

The background from other hadron decays producing single photons such as $\Sigma^0 \rightarrow \Lambda^0 \gamma$ and $\eta' \rightarrow \rho \gamma$ is negligible for kinematic reasons in this y - p_T region.

Curve (f) in fig. 2 shows the γ/π^0 ratio due to single photons from all meson decays compared with the observed γ/π^0 ratio. The error bars on the data-points include the systematic as well as statistical errors. The systematic error is mainly due to two effects: i) the uncertainty in determining the absolute energy scale on a run-to-run basis, which contributes $\sim 1\%$ to the error on the γ/π^0 ratio; and ii) the non-linearity correction, which contributes 0.5-1.0% to the ratio for $3 < p_T < 4.5$ GeV/c. The band given for curve (f) indicates the statistical and systematic error on the background calculation. The main contribution to the systematic error comes from the uncertainty in the parametrization used for the production spectrum for the π^0 , η , η' , and ω , and the uncertainty in the particle ratios η/π^0 , η'/π^0 , and ω/π^0 . This contributes $\sim 3\%$ to the over-all error on the background at the lowest p_T values but is negligible at high p_T . The background from hadron showers was not included in curve (f), but is less than 1% for all p_T . Figure 2 indicates that the sum of all known sources of background fails to account for the observed γ/π^0 ratio for $p_T \geq 2$ GeV/c. We interpret this difference as being due to the production of direct single photons.

Figure 4 shows the γ/π^0 ratio after subtracting the background given in fig. 2 and correcting for the relative efficiency and acceptance of single photons and π^0 's. These were computed assuming that the y - p_T distribution of single photons was the same as for π^0 's. The errors reflect the statistical and systematic errors on the background as well as the data. The remaining background due to hadrons cannot exceed 0.5% over the entire p_T range.

An additional source of systematic error comes from the fact that the unsigned energy and γ multiplicity cuts reject, at some level, events with accompanying particles. These could be due to fragments of the beam jet which enter the calorimeter, but should affect the single- γ and π^0 events by the same amount. However, the trigger particles themselves may be either part of a jet, as in the case of a bremsstrahlung photon or π^0 , and hence may be accompanied by other particles, or

unaccompanied as in the case of Compton photons. One would expect the cuts to affect bremsstrahlung photon and π^0 events in a similar way due to the fact that the products of the quark fragmentation associated with the bremsstrahlung photon are similar to the jet accompanying a high- p_T π^0 [3]. If all of the observed direct photon signal was due to bremsstrahlung, then our measured γ/π^0 ratio would be essentially correct. If all of the signal were due to unaccompanied photons, then the true γ/π^0 ratio would be lower by a factor of ~ 1.25 because the cuts produce a 25% loss in the π^0 signal, but would not affect the single photons. No attempt has been made to correct the γ/π^0 ratio for these effects, and this should be considered when comparing the results with theoretical predictions.

Figure 4 shows our data compared with two such calculations. The first [4] is based on a QCD calculation including higher-order corrections to the leading logarithm approximation and finds a bremsstrahlung component at the level $\gamma_{\text{brem}}/\gamma_{\text{prompt}} \sim 30\%$. The predicted γ/π^0 ratio is in approximate agreement with the data. The second calculation [2] finds a much larger bremsstrahlung contribution as well as contributions to photons and π^0 's from the constituent interchange model (CIM) and predicts a ratio which is clearly higher than the observed ratio. Also shown is the γ/π^0 data at 90° in the same p_T range from ref. [11]. The ratio at $\theta \sim 11^\circ$ is similar to the 90° data where the bremsstrahlung component is known to be $< 30\%$ [3]. Since the cross-section for π^0 's is in fact smaller and falling more steeply in the forward direction than the central region [6], this implies that the total rate of direct photon production at these forward angles is smaller than at 90° for the same p_T . We cannot, however, separate the bremsstrahlung and Compton components of the single-photon signal with this analysis.

In summary, we have measured the ratio of single-photon production relative to π^0 's in the forward direction ($2.00 < y < 2.75$) and have found the level comparable to that measured at $y \sim 0$ up to a maximum p_T of 4.5 GeV/c. We found no indication of a strong enhancement in the production of direct photons due to quark bremsstrahlung.

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Figure captions

- Fig. 1 : Unassigned energy in the front section of the calorimeter for single-shower (solid curve) and two-shower (dashed curve) events for $p_T > 3.0 \text{ GeV}/c$.
- Fig. 2 : Data points are the observed γ/π^0 ratio. Errors are statistical with systematic error for uncertainty in the energy scale and non-linearity folded in. Curves (a)-(d) are the geometrical background from π^0 , η , η' , and ω , respectively. Curve (e) is the background from π^0 's reconstructed as single γ 's which survive after cuts. Curve (f) is the sum of (a)-(e) where the band gives the statistical and systematic error on the background calculation.
- Fig. 3 : Single-photon (solid curve) and π^0 (dashed curve) reconstruction efficiency versus p_T for $2.00 < y < 2.75$. Bands indicate the error from the Monte Carlo calculation.
- Fig. 4 : γ/π^0 ratio after background subtraction and correction for relative geometrical acceptance and reconstruction efficiency for single photons and π^0 's. Open circles are data at 90° , $\sqrt{s} = 63 \text{ GeV}$, from ref. [11]. Curve (a) is the QCD prediction for the γ/π^0 ratio given in ref. [4]. Curve (b) is the ratio given in ref. [2] using QCD, including CIM contributions.

Fig. 1

Fig. 2

Fig. 3

Fig. 4