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DIRECT PHOTON PRODUCTION AT THE CERN $\bar{p}p$ COLLIDER

The UA2 Collaboration

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ABSTRACT

Using the UA2 apparatus we have measured the inclusive cross-section for production of high- p_T direct photons in $\bar{p}p$ collisions at $\sqrt{s} = 546$ GeV and $\sqrt{s} = 630$ GeV. The results are in good agreement with QCD predictions.

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1. INTRODUCTION

The direct production of large transverse momentum (p_T) photons in hadron-hadron collisions is a convenient process for studying the hadronic constituents and their interactions. At the collision energies of the CERN $p\bar{p}$ Collider, $\sqrt{s} = 546$ GeV and $\sqrt{s} = 630$ GeV, a substantial yield of high- p_T photons is expected to result from leading order QCD processes [1]. In previous publications [2,3,4], we have presented measurements of jet production at SPS Collider energies and we have shown that the data are in agreement with perturbative QCD calculations. A measurement of the direct photon production cross-section offers an alternative test of the theory with the advantages that the photon energy measurement is not affected by fragmentation effects, and that QCD calculations have been carried out to the next-to-leading order in the strong coupling constant, α_s [5,6]. However, the production cross-section for direct photons is nearly four orders of magnitude smaller than the production cross-section for hadronic jets. This is a consequence of the low average parton charge, of the small size of the electromagnetic coupling constant as compared with the strong coupling constant, and of the fact that subprocesses such as gluon-gluon collisions are important for jet production but do not contribute to photon production.

The relatively copious production of high- p_T hadronic jets is responsible for the dominant background to the measurement of direct photons. Hadronic jets often contain high- p_T π^0 and η mesons which decay into photon pairs. Since it is usually not possible to resolve both decay photons, the π^0 's and η 's behave as single photons in the UA2 detector. To suppress this background, we exploit the fact that such 'photons' are generally accompanied by other jet fragments whereas direct photons are expected to be well isolated [7].

In a previous publication [2] we presented a measurement of isolated neutral clusters in the central calorimeter of UA2. Although the measured yield was consistent with the expected yield of direct photons, the residual background contamination of the sample was not evaluated. In this letter, we define a sample of well isolated direct photon candidates. We then estimate the residual background from isolated π^0 's and η 's by considering the fraction of the sample for which the photon has begun showering in a converter [8]. Independent measurements are made both in the central region (covering the interval of pseudorapidity $|\eta| < 1.0$) and in the forward regions (covering the pseudorapidity intervals $1.0 < |\eta| < 1.8$) of the UA2 detector. In the latter regions, we repeat at $\sqrt{s} = 630$ GeV the measurement of the inclusive π^0 cross-section which had previously been performed at $\sqrt{s} = 546$ GeV [9].

2. APPARATUS.

Since the UA2 detector has been described in detail elsewhere [10], only a brief summary of its main features is presented here.

The detector provides full azimuthal coverage about the beams in three distinct regions of polar angle: $40^\circ < \theta < 140^\circ$, the central region, and $20^\circ < \theta < 40^\circ$, $140^\circ < \theta < 160^\circ$, the forward regions.

At the center of the detector, a compact system of cylindrical drift and proportional chambers is used to detect charged particles and to measure the position of the event vertex.

An array of 480 calorimeter cells, each cell covering 15° of azimuth and approximately 0.2 units of rapidity [11], is used to measure the energies of electrons and photons with good precision. Each cell is segmented longitudinally to provide electron(photon)-hadron separation. In the central region, the calorimeter has sufficient thickness (4.5 absorption lengths) to contain most of the energy of hadronic showers. Hadrons and hadronic jets are therefore reasonably well measured. In the forward regions, the calorimeter has a thickness of approximately one absorption length. This is not sufficient to contain hadronic showers. However, the forward regions are equipped with magnetic spectrometers to measure the momenta of charged particles.

Both the central and the forward regions are equipped with preshower detectors. For the work presented here, the preshower detectors function as active photon converters which permit the precise measurement of the conversion point. The photon direction is determined from the coordinates of the event vertex and the preshower signal. In the central region, the preshower detector consists of a 1.5 radiation length cylindrical tungsten converter followed by a cylindrical multiwire proportional chamber [12]. The resolution of the conversion point is sufficient to determine the photon direction with a precision of 10 mrad (rms). Adjacent signals can be resolved if they are separated by at least 35 mrad. In each forward region, the preshower detector consists of a 1.4 radiation length lead-iron converter followed by a multi-tube proportional chamber [13]. The photon direction is determined with a precision of 2 mrad (rms).

3. DATA TAKING AND ANALYSIS

The data were recorded with the same trigger as that which was used in the study of the process $p\bar{p} \rightarrow W \rightarrow e\nu$ [14]. The trigger required the deposition of at least 10 GeV of transverse energy into a 2×2 cell matrix of the electromagnetic calorimeter.

During the period from 1981 until 1984, the UA2 detector was exposed to an integrated luminosity of 142 nb^{-1} at a collision energy of $\sqrt{s} = 546 \text{ GeV}$ and to an integrated luminosity of 310 nb^{-1} at a collision energy of $\sqrt{s} = 630 \text{ GeV}$.

Due to the different characteristics of the central and forward detectors, we use two different sets of criteria to select single photon candidates.

Each central candidate is required to have an energy cluster in the central calorimeter. Clusters are constructed from adjacent cells according to a previously described algorithm [2]. To ensure that all clusters are fully contained in the central calorimeter, we require that the centroid of each cluster have pseudorapidity $|\eta| < 0.8$. We consider only those candidates that contain clusters having transverse momenta larger than 15 GeV/c. Each candidate is required to have the characteristics that are expected for an isolated single photon:

- a. the associated cluster must have small longitudinal and lateral size as expected for electron candidates [14],
- b. no charged track and at most one preshower signal may be found in a cone of $\sqrt{(\Delta\phi^2 + \Delta\eta^2)} < 0.35$ about the direction defined by the event vertex and the cluster centroid, and
- c. the associated cluster must be well isolated in the calorimeter. The pattern of photomultiplier signals is required to be consistent with that expected for a single isolated electron or photon [11].

Each forward photon candidate is required to contain an energy cluster in one of the forward calorimeters. Because the forward calorimeter cells have a large transverse size, forward clusters are defined as energy depositions in one cell or in two cells at the same azimuth. We consider only forward candidates with at least one cluster of transverse momentum larger than 12 GeV. All forward candidates are required to satisfy the following criteria:

- a. the associated cluster must have small lateral and longitudinal extent (as for electron candidates [14]),
- b. no charged track is permitted to point to the cluster, and
- c. the total energy of all charged and neutral particles impinging on the cells adjacent to the cluster must not exceed 0.3 GeV.

There are 1350 events in the central region with $p_T > 15$ GeV and 2566 events in the forward regions with $p_T > 12$ GeV which satisfy the selection criteria.

Photons that do not convert in the preshower detector penetrate into the calorimeter before initiating electromagnetic showers. The longitudinal development of such showers is different from those that are initiated by converted photons. In the central region, where the depth of the first longitudinal calorimeter segment is 17 radiation lengths instead of 24 in the forward region, we correct the number of unconverted photon candidates by 14% for the different efficiency of criterion a. In the forward region this correction is negligible. In addition, the energy scale for unconverted photons

differs slightly from that for converted photons and electrons. This results in a -6% correction on the number of unconverted photons in both regions.

The isolation criteria that are applied in both the central and the forward regions are intended to reject a larger fraction of π^0 's and η 's than of direct photons. Evidence for this effect is provided by studying the fraction α of photon candidates that convert in the preshower counters. In Figure 1, α is presented as a function of photon energy for both the central and forward samples. The average value of α is 0.737 ± 0.014 in the central region and 0.646 ± 0.014 in the forward regions (for p_T larger than 15 GeV).

A pure sample of single photons is expected to have $\alpha = \varepsilon_\gamma$, where ε_γ is the photon conversion probability. We calculate ε_γ from Monte Carlo simulations of the preshower detectors using the EGS Program [15]. The simulations correctly describe the response of the preshower detectors to test beam electrons. The result is presented as a function of the photon energy in Figure 1 for both the central and forward detectors. Since different thresholds are used to define preshower signals in the central and forward regions (equivalent to the passage of 2 and 6 minimum ionizing particles, respectively), the behaviour of ε_γ is different in the two regions. In the central region, ε_γ is independent of photon energy in the p_T interval spanned by the data ($p_T > 15$ GeV) and has the value 0.68 ± 0.01 . In the forward regions, ε_γ depends upon photon energy. The average value in the p_T interval spanned by the data ($p_T > 12$ GeV) is 0.50 ± 0.02 . An extrapolation of ε_γ to lower energies agrees well with data containing resolved π^0 decays in the forward regions.

A pure sample of unresolved π^0/η decays is expected to have $\alpha = \varepsilon_\pi$, where ε_π , the two-photon conversion probability, is shown in Figure 1 for both regions (including the effect of the isolation criteria). It is approximately 0.9 in the central region and 0.7 in the forward regions. As the number of photons in each cluster is increased, α asymptotically approaches 1.0. Since the measured values of α are between those expected for single and di-photons in both regions, it is clear that both data samples have a substantial content of single (direct) photon events.

We compare the measured values of α with those obtained from samples of events which fail the isolation criteria. In the central region, we relax the requirement that each event have no more than one preshower signal and require that it fail criterion c. In the forward regions, we require that each event fail criterion c. The results are shown in Fig. 1. In the central region, the average value of α is consistent with those expected for multi-(π^0 or η) states. In the forward regions, the average value of α is close to the value expected for a sample of single π^0 's or η 's. The photon multiplicity per cluster is smaller in the forward regions than in the central region because the forward calorimeters are more distant from the beam crossing point than is the central calorimeter. Since the transverse size of an electromagnetic shower is approximately the same in both detectors, the solid angle subtended by a photon-induced shower is smaller in the forward calorimeters than in the central calorimeter. The forward calorimeters are therefore more efficient at resolving

nearby π^0 's or η 's. Since the average value of α for the forward non-isolated sample is close to the single π^0/η value, the sample must have a substantial content of single π^0 's and η 's. It can therefore be used to perform a measurement of the production cross section for inclusive π^0 's.

We conclude from the above comparison that the isolation cuts do enrich the single photon content of both the central and forward samples.

4. REJECTION OF BACKGROUNDS

In addition to the multi-photon backgrounds discussed above, the direct photon signal is also subject to contamination from sources of fake photons.

Beam halo particles impinging on the calorimeters can simulate unconverted photons. We suppress this background by requiring that particles produced by an actual collision strike the two sets of small angle scintillation hodoscopes located at the ends of the detector. The signals from the hodoscopes are required to occur at the correct time. In the forward regions, the timing of the calorimeter signals is required to be consistent with a genuine $p\bar{p}$ interaction. The residual contamination of the signal in the central region is evaluated using information from a second set of scintillation counters placed at larger polar angles. The overall contamination is measured to be less than 3%. Although this is quite small, it is possible that the high- p_T tail of the photon spectrum is more substantially contaminated. The high- p_T region is also subject to contamination by $W \rightarrow e\nu$ decays for which the charged tracks were not reconstructed. Since the signature of both backgrounds is a large, unbalanced energy deposition in the calorimeters, they are suppressed by requiring that the missing transverse momentum of each event be less than 80% of the photon transverse momentum. Although direct photon events are expected to be well balanced, the recoil system can occasionally escape detection into the uninstrumented regions of polar angle less than 20° or into the magnet coils of the forward regions. The resulting inefficiency of this requirement is evaluated to be less than 5% in the central region and to be 7.5% in the forward regions.

We consider the possibility that high- p_T , 'stable' hadrons satisfy the photon selection criteria. The probability that a hadron passes the longitudinal energy deposition requirements in the calorimeter has been measured to be about 1% in the central region [11] and to be 3 to 5% (depending upon p_T) in the forward regions. Since charged hadrons are likely to fail the track isolation requirement (the efficiency of the tracking system is about 90% in the central region and is 95% in the forward regions), the dominant hadron background is due to neutrons and neutral kaons. Using the measured ratios of the production cross sections K/π and p/π [16], we estimate the total hadron contamination to be less than 1% of the π^0 contamination in the central region and to be 4.5% of the π^0 contamination in the forward regions.

5. CALCULATION OF THE MULTI-PHOTON CONTAMINATION

As was discussed in section 4, the selected sample of direct photon candidates contains a residual contamination of unresolved π^0 and η decays. If we assume that the contamination is due to single π^0 's and η 's only, the fractional contamination of the sample, $b(p_T)$, is related to the converted fraction α by the expression

$$b(p_T) = (\alpha - \varepsilon_\gamma) / (\varepsilon_\pi - \varepsilon_\gamma) \quad (1)$$

where ε_π and ε_γ are the conversion probabilities for two unresolved photons and for a single photon, respectively. The probabilities ε_π and ε_γ are shown in Fig. 1 as functions of energy. The calculation of ε_π assumes that the ratio of the number of η 's to the number of π^0 's is 0.6 [9]. In the central region, the effect of the preshower isolation cut on resolvable photon pairs is also included.

The assumption that all of the contamination is due to single π^0 's and η 's has the effect of underestimating ε_π and of overestimating $b(p_T)$. The contribution of unresolved multi- (π^0/η) states to $b(p_T)$ is evaluated using the ISAJET Monte Carlo program [17]. The inclusion of multi- (π^0/η) states has the effect of reducing $b(p_T)$ by 0.03 ± 0.04 in the central region and by 0.10 ± 0.04 in the forward regions. The quoted errors are the estimated systematic uncertainties associated with the Monte Carlo calculation.

The measured background fractions $b(p_T)$ decrease with p_T and take the average values 0.28 ± 0.09 in the central region and 0.70 ± 0.06 in the forward regions. The quoted uncertainties are dominantly statistical.

6. INCLUSIVE CROSS-SECTIONS

The invariant cross-section for the inclusive production of direct photons is evaluated from

$$E d\sigma/d^3p = N_\gamma(p_T) [1 - b(p_T)] / [p_T \Delta p_T L \varepsilon_c A] \quad (2)$$

where $N_\gamma(p_T)$ is the number of photon candidates in a p_T bin of width Δp_T , L is the integrated luminosity that corresponds to the data sample, ε_c is the efficiency of the experimental selection criteria for retaining direct photon events, and A is the geometrical acceptance in the η, ϕ plane.

Since hadronic collisions produce a number of spectator particles, the isolation criteria induce a loss of real events. We evaluate the efficiency of the isolation criteria from samples of minimum bias events (scaled to the known density of spectator particles in our sample) and $W \rightarrow e\nu$ events. We estimate the total efficiency of all cuts to be $\varepsilon_c = 0.55 \pm 0.06$ in the central region, and to be $\varepsilon_c = 0.79 \pm 0.07$ in the forward regions.

The results of the measurement are listed in Table 1 and are shown in Figs. 2 and 3. Only the p_T -dependent errors are presented and they are dominantly statistical. The total systematic uncertainty on the normalization of the cross section is 20%. It includes contributions from uncertainties on the energy scale (10%), the cut efficiency (10%), the Monte Carlo corrections (10%), and the integrated luminosity (8%).

In an earlier publication [9] we presented a measurement of the inclusive π^0 spectrum at $\sqrt{s} = 546$ GeV and $\langle\eta\rangle = 1.4$. We have repeated the analysis at $\sqrt{s} = 630$ GeV with the exception that we now subtract the single photon contribution. The result is listed in Table 1 and is shown in Fig. 3.

7. DISCUSSION OF THE RESULTS

In Figures 2 and 3, the direct photon cross-section is compared with an $O(\alpha_S^2)$ QCD calculation. The calculation makes use of the matrix elements of Reference 5 and the structure functions of Reference 18 (set 1). The Q^2 scale is chosen according to Reference 19, however, the result depends little on the definition of Q^2 .

The prediction includes contributions from the bremsstrahlung of the final state quarks. The isolation criteria partly suppress such processes in the data. This effect has been studied by excluding from the calculation all bremsstrahlung photons with quark-photon angles smaller than 20° and 45° [6]. The results are shown as the two lower curves in Figs. 2 and 3. The difference between the two curves indicates the range of the uncertainty in the calculation caused by the isolation cuts. Reasonable agreement is observed between the measurements and the calculations.

Data were collected at two collision energies, $\sqrt{s} = 546$ GeV and $\sqrt{s} = 630$ GeV. The ratio of the direct photon cross-sections at the two energies in the central region is

$$\sigma_\gamma(\sqrt{s} = 630 \text{ GeV}) / \sigma_\gamma(\sqrt{s} = 546 \text{ GeV}) = 1.14 \pm 0.07$$

where the cross-sections have been integrated over the interval $p_T > 15$ GeV. Since the systematic errors cancel in the ratio, the quoted error is purely statistical. This value agrees with the expected ratio of 1.14 from a lowest order QCD calculation using the structure functions of Ref. 18. The corresponding ratio for the π^0 cross sections that are measured at $\langle\eta\rangle = 1.4$ is

$$\sigma_{\pi^0}(\sqrt{s} = 630 \text{ GeV}) / \sigma_{\pi^0}(\sqrt{s} = 546 \text{ GeV}) = 1.47 \pm 0.05$$

where we calculate an expected ratio of 1.41 using the structure functions of Ref. 18 and the fragmentation functions of Ref. 20.

As was mentioned in the introduction, it is expected that the ratio of the cross-section for single photon production to that for jet production is of the order 10^{-4} . A complete lowest order calculation using the structure functions of Ref. 18 predicts that $\sigma(\gamma)/\sigma(\text{jet}) = 4.2 \cdot 10^{-4}$ for transverse momenta between 30 GeV and 50 GeV. In this p_T range, the ratio of the measured direct photon cross-section to the measured jet cross-section [4] is

$$\sigma_\gamma / \sigma_{\text{jet}} = 2.9 \pm 0.9(\text{stat.}) \pm 1.2(\text{syst.}) \cdot 10^{-4}$$

where the systematic error is due to the uncertainty of the jet energy scale.

The production of direct photons from $\bar{p}p$ collisions has also been observed at the ISR [21]. The cross-section has been measured at $\sqrt{s} = 53$ GeV in a transverse momentum range $p_T < 6$ GeV. The difficulty of identifying jets in this low p_T range precludes a reliable measurement of the γ/jet ratio. The authors of Ref. 21 present instead a measurement of the γ/π^0 ratio, a quantity which is more accessible to experiment, but which is more difficult to interpret theoretically because it involves a description of the jet fragmentation mechanism. Moreover, in such a p_T range, higher twist effects are expected to contribute significantly to the inclusive pion cross-section [22]. In Figure 4, we compare our measurement of the γ/π^0 ratio (obtained from Figure 3) to that of Reference 21. The data are presented as a function of the scaling variable $x_T = 2p_T/\sqrt{s}$. They exhibit a strong non-scaling behaviour. In most of the x_T region spanned by our data ($0.04 < x_T < 0.16$), the ISR experiment has no evidence of direct photon production. Although non-scaling behaviour is expected to result from higher-order QCD processes, we do not expect that perturbative QCD calculations provide an adequate description of ISR data in this x_T range (corresponding to $p_T < 3$ GeV). The lack of scaling can be characterized by the parameter Δn in the following expression,

$$p_T^{-\Delta n} \cdot \sigma(\gamma)/\sigma(\pi^0) = f(x_T) \quad (3)$$

We find that values of Δn near 1 adequately describe both sets of data. However, the absence of overlap in x_T between the data samples precludes a reliable determination of Δn .

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TABLE 1

Inclusive cross section for $\bar{p}p \rightarrow \gamma + X$ and $\bar{p}p \rightarrow \pi^0 + X$

$E d\sigma/d^3p$ (pb GeV ⁻²) at $\sqrt{s}=630$ GeV			
p_T (GeV)	γ ($\eta=0$)	γ ($\eta=1.4$)	π^0 ($\eta=1.4$)
13		11.8 $\pm$ 2.8	176 $\pm$ 30
15		3.7 $\pm$ 1.6	64.9 $\pm$ 1.7
15.5	6.09 $\pm$ 1.14		
17	4.13 $\pm$ 0.64	2.2 $\pm$ 0.9	26.7 $\pm$ 1.0
19	2.25 $\pm$ 0.45		12.5 $\pm$ 0.6
19.7		0.65 $\pm$ 0.34	
21	1.17 $\pm$ 0.25		5.64 $\pm$ 0.42
23	0.58 $\pm$ 0.13		3.05 $\pm$ 0.31
24.7		0.20 $\pm$ 0.09	
25	0.38 $\pm$ 0.10		2.14 $\pm$ 0.22
27	0.16 $\pm$ 0.05		0.89 $\pm$ 0.14
29	0.19 $\pm$ 0.06		0.57 $\pm$ 0.11
31.8	0.054 $\pm$ 0.018		0.38 $\pm$ 0.07
35.1		0.022 $\pm$ 0.010	
35.9	0.056 $\pm$ 0.018		0.080 $\pm$ 0.030
40			0.075 $\pm$ 0.022
42.8	0.008 $\pm$ 0.003		
47.5			0.015 $\pm$ 0.007

The cross-sections are averaged over the pseudorapidity intervals $|\eta| < 0.8$ ($\eta=0$) and $1.0 < |\eta| < 1.8$ ($\eta=1.4$). The errors do not include the overall p_T -independent systematic error of 20%.

FIGURE CAPTIONS

1. The probability for conversion in the preshower detectors (and for recognition of the signal) as a function of energy. The curve labeled ϵ_γ is an EGS simulation of the conversion probability for single photons and the curve labeled ϵ_π is the same for single π^0 (and η) fulfilling the selection criteria for photon candidates. The dots represent the conversion probability for the selected photon candidates and the triangles represent the conversion probability for candidates that fail certain isolation criteria (see text).
2. The invariant inclusive cross-section for direct photon production at $\sqrt{s} = 630$ GeV and $\eta \approx 0$. Curve I shows a prediction [6] for the total direct photon yield. Curves II and III result from excluding bremsstrahlung photons with quark-photon angles less than 20° and 45° , respectively. The normalization error has not been included in the error bars.
3. The invariant inclusive cross-section for direct photon and π^0 production at $\sqrt{s} = 630$ GeV and $1.0 < |\eta| < 1.8$. The curves have the same meaning as in Fig. 2.
4. The ratio of the inclusive cross-sections for direct photons and π^0 's as a function of x_T . The solid points are the results of this experiment. The results of a similar measurement [21] of inclusive cross-sections in $\bar{p}p$ collisions at $\sqrt{s} = 53$ GeV and $\eta = 0$ are shown as a set of open circles.

Fig. 1

Fig. 2

Fig. 3

Fig. 4