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**A MEASUREMENT OF THE DIRECT PHOTON
PRODUCTION CROSS SECTION AT THE CERN $\bar{p}p$
COLLIDER**

The UA2 Collaboration

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ABSTRACT

A measurement of the inclusive cross-section for production of direct photons in $\bar{p}p$ collisions at a centre of mass energy of 630 GeV is presented as a function of the photon transverse momentum. The data correspond to a total integrated luminosity of 7.4 pb^{-1} . The results support predictions from QCD theory.

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1. INTRODUCTION

The direct production of isolated large transverse momentum (p_T) photons in hadron-hadron collisions is a convenient way to study the constituents of hadronic matter and their interactions. A measurement of the direct photon cross-section provides a test of QCD with the advantage that the photon transverse momentum is not affected by fragmentation effects, resulting in experimental uncertainties which are considerably smaller than those obtained for instance in the measurement of a jet cross-section. Next-to-leading order calculations are also available and can be directly compared to the experimental results. The copious production of high transverse momentum hadron jets is, however, a large source of background: hadron jets often contain one or more π^0 (or η) mesons which decay into photon pairs that are not resolved by the calorimeter. This background has a cross-section approximately four orders of magnitude higher than the direct photon signal. The latter, however, results in isolated electromagnetic clusters, whereas the background from hadron jets is accompanied by jet fragments, so that an "isolation requirement" is very effective in reducing the contamination of the signal sample. The residual contamination from large p_T isolated π^0 's (or η 's) is measured and subtracted on a statistical basis, by considering the fraction of photons in the sample that initiate showers in a 1.5 radiation length (r.l.) thick lead converter.

The analysis, based on a sample of data collected during the 1988-1989 running period at the CERN $\bar{p}p$ Collider ($\sqrt{s} = 630$ GeV), corresponding to an integrated luminosity of $7.4 \pm 0.4 \text{ pb}^{-1}$, is performed in a central fiducial region of the UA2 detector covering the pseudorapidity interval $|\eta| < 0.76$.

2. THE UA2 APPARATUS

The UA2 detector was substantially upgraded between 1985 and 1987 to better exploit the increased CERN $\bar{p}p$ Collider luminosity. An extensive description of the apparatus can be found elsewhere [1]. Here we describe only some features relevant to this study.

The detector provides full azimuthal coverage around the interaction region in a pseudorapidity range $-3 < \eta < 3$ and consists of a central tracking detector surrounded by electromagnetic and hadronic calorimeters [2]. The calorimeter is divided into a central part (CC) within $|\eta| < 1$ and two end cap regions (EC) reaching $|\eta| = 3$. The same technique (absorber plates with scintillator and wavelength shifter readout) is used throughout. An electromagnetic compartment with lead absorber plates (17-24.4 r.l. depending on polar angle) is followed by hadronic compartments with iron absorber plates. Granularity is provided by segmentation into 624 cells pointing approximately towards the interaction region. Each of the 240 CC cells subtends 10° in polar angle θ

and 15° in azimuthal angle ϕ . The EC cells have a segmentation $\Delta\phi = 15^\circ$, $\Delta\eta = 0.2$ in the range $1.0 < |\eta| < 2.2$ while the two cells closest to the beam axis ($2.2 < |\eta| < 2.5$ and $2.5 < |\eta| < 3.0$) cover 30° in azimuth.

Clusters are reconstructed in the calorimeter by joining all cells with an energy greater than 400 MeV sharing a common edge. Clusters with a small lateral size and a small energy leakage into the hadronic compartments are marked as electromagnetic clusters and are subsequently examined as potential photon candidates.

In addition to the presence of an electromagnetic calorimeter cluster, photons are characterized by the absence of an associated track. Track information is provided by the central detector, consisting of two arrays of silicon pad counters [3] used for tracking and ionization measurement placed respectively at radii of 2.9 cm and 14.8 cm around the beam. A cylindrical drift chamber with jet geometry (the jet vertex detector JVD) [4] is located between the two silicon arrays. The outer silicon counter is followed by a transition radiation device TRD [5] consisting of two sets of radiators and proportional chambers. The outermost part of the central detector is a scintillating fibre detector SFD [6] which consists of eight stereo triplets of scintillating fibres arranged in cylindrical layers. In the forward regions three stereo triplets of proportional tubes ECPT [7] are placed in front of the end cap calorimeters.

The position of the event vertex is reconstructed using the SFD in conjunction with the two silicon arrays and the JVD.

In both the central region and the end caps the last elements before the calorimeters are preshower detectors used to localize the early development of the electromagnetic shower initiated in a lead converter. In the central region this function is provided by the SFD where a 1.5 r.l. lead cylinder is positioned before the last two stereo triplets of fibres. In the end cap region this is accomplished by a 2 r.l. thick iron-lead converter placed before the last stereo triplet of the ECPT.

Photons which convert in the lead are identified by a large cluster of charge in the preshower detector in front of an electromagnetic cluster in the calorimeter, with no reconstructed track pointing to it.

Calorimeter clusters due to beam halo particles are rejected using two planes of large area scintillation counters (VETO counters) covering the back sides of the end cap calorimeters. Particles which give an early signal with respect to the nominal beam crossing time are rejected in the analysis.

3. PHOTON IDENTIFICATION

The trigger requirements for photon candidates are implemented in a three-level trigger system [8] based mainly on information from the calorimeters. The first level uses analog sums of the signals from the photomultipliers of the calorimeter cell compartments. At the second level, electromagnetic and hadronic clusters are reconstructed in a special-purpose processor using information from a fast digitization of the calorimeter cell signals. A complete calorimeter reconstruction is performed in the third level processors using the final digitization and the full set of calibration constants. Information on the shower radius (transverse size) and the fraction of shower energy detected in hadronic compartments (longitudinal depth) are used to reject the jet background.

The present analysis is performed only in the central region of the UA2 apparatus. Each photon candidate is required to have an electromagnetic cluster in the central calorimeter. To ensure that the cluster is fully contained in the central region it is required that the centroid of the cluster have pseudorapidity $|\eta| < 0.76$ and that the displacement of the event vertex from the centre of the detector along the beam axis be less than 250 mm.

Only events with a single reconstructed $\bar{p}p$ interaction vertex are considered. In addition the events must contain at least one cluster having the characteristics expected for an isolated single photon :

- a. The lateral and longitudinal profiles of the cluster are required to be consistent with that expected for a single isolated electron or photon.
- b. The absence of any charged track in front of the calorimeters as ensured by pulse height requirements imposed on any silicon pad or pad cluster present in either silicon counter within a window of $\Delta\eta < 0.2$ and $\Delta\phi < 15^\circ$ about the cluster axis as defined by the line joining the interaction vertex to the cluster centroid.
- c. At most one preshower signal in a cone $\sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.265$ about the cluster axis.

A total of 26086 photon candidates with $p_T > 15$ GeV are found in the central region satisfying these selection criteria. The global efficiency for detecting a photon candidate is estimated to be $\epsilon_C = 0.443 \pm 0.009$. This value does not include effects associated with photon conversions in the preshower detector.

4. CONVERSION PROBABILITY AND BACKGROUND CALCULATIONS

Isolation criteria reject a large fraction of π^0 's and η 's while retaining direct photons. The residual background originating from π^0 and η decays is measured by considering the fraction α of events in which the photon has begun showering in the converter of the preshower detector.

In order to compute α , all the efficiencies which have a different value for converted and unconverted photon candidates must be taken into account. The definition of a photon candidate as converted or unconverted relies on the detection of charge clusters in the preshower detector. A photon conversion is defined by the observation of a signal in the preshower detector exceeding that expected for 3 minimum ionizing particle (MIP) equivalents associated with the calorimeter cluster. Preshower clusters not related to real photons originate mainly from two sources : "ghost" preshower signals due to SFD pattern recognition ambiguities and real preshower signals generated by the underlying event or by particles from the jet(s) in the event. A fake preshower cluster can move events from the unconverted to the converted class or can cause the rejection of a converted photon by simulating a non-isolated preshower. We define ϵ_1^c to be the probability of having one and only one preshower signal in association with a converted photon; and ϵ_0^u and ϵ_1^u to be the probabilities of finding respectively zero and one preshower signal in the case of an unconverted photon.

Another correction factor to be applied only to the unconverted photons comes from the efficiency of the method used to find a good unconverted photon candidate without knowing its direction precisely (ϵ_s^u).

The efficiencies ϵ_1^c and ϵ_s^u are estimated using a sample of identified electrons from W decays [9], while ϵ_0^u and ϵ_1^u are measured by inspecting the uncorrelated regions at $\pm 90^\circ$ in azimuth with respect to an electromagnetic high energy cluster.

The numbers of observed converted (N_c^{seen}) and unconverted (N_u^{seen}) photons are then related to the true numbers (N_c^{true} , N_u^{true}) of photons by the following relationships :

$$N_c^{\text{seen}} = \epsilon_1^c \cdot N_c^{\text{true}} + \epsilon_1^u \cdot N_u^{\text{true}}$$

$$N_u^{\text{seen}} = \epsilon_0^u \cdot \epsilon_s^u \cdot N_u^{\text{true}}$$

The conversion probability α in the sample of photon candidates is defined as :

$$\alpha = \frac{N_c^{\text{true}}}{N_c^{\text{true}} + N_u^{\text{true}}}$$

The conversion probability ϵ_γ of an incident single photon is evaluated as a function of the photon energy using the EGS shower simulation programme [10]. The simulation has been tuned to describe correctly the response to test beam electrons of 10 and 40 GeV and electrons from W decays in the detector. The total systematic error on ϵ_γ is estimated to range from 2.4% to 2.0% with increasing energy.

The effective conversion probability ϵ_π of the background originating from unresolved multiphotons from π^0 and η decays is calculated using ϵ_γ for each photon. The ratio of the number of η to the number of π^0 has been measured to be 0.6 and is p_T independent [11].

The effect of multi- π^0 states in the background has been estimated by comparing the conversion probability measured for a background data sample selected by requiring a large lateral cluster profile, after subtracting the residual single photon component, with the value of ϵ_π calculated from single π^0 's and η 's. The two values are found to agree. This suggests that despite the fact that the conversion probability of a multi- π^0 system is close to unity, such a background component is highly suppressed by the preshower isolation requirement. The uncertainty in the two-photon angular resolving power (20 ± 7 mrad in the SFD preshower detector) is the main source of systematic error for ϵ_π . This error is slightly energy dependent and ranges from 2.7% to 1.5% with increasing π^0 energy.

The calculated values of ϵ_π and ϵ_γ are shown in Fig. 1 as a function of the photon energy E_γ . The measured conversion probabilities, α , lie between the two theoretical curves and tend towards ϵ_γ as E_γ increases.

The only significant background in this analysis is due to multiphoton contamination. Its fraction in the sample is computed from the values of α , ϵ_γ , ϵ_π :

$$b(p_T) = \frac{\alpha - \epsilon_\gamma}{\epsilon_\pi - \epsilon_\gamma}$$

The fraction of multiphoton background is shown in Fig. 2, where a wider binning than for the cross-section calculation is used for display purposes. As it is seen in the figure it decreases with increasing p_T .

The remaining background caused by beam halo particles has been estimated to be less than 1% of the photon candidate sample and has been neglected.

$W \rightarrow e\nu$ decays are expected to contribute at most 30 events in the p_T interval between 20 and 45 GeV as a result of inefficiencies in the electron track reconstruction. This contribution corresponds to 0.2% of the photon candidate events in the same p_T range.

5. INCLUSIVE CROSS-SECTION

The invariant inclusive cross-section for direct photon production is evaluated from

$$E \frac{d\sigma}{d^3p} = \frac{N_\gamma(p_T) \cdot [1 - b(p_T)]}{2\pi p_T \Delta p_T \mathcal{L} \epsilon_c A(p_T)}$$

where $N_\gamma(p_T)$ is the number of photon candidates in a p_T -bin of width Δp_T , $b(p_T)$ is the background fraction in that bin, $\mathcal{L} = 7.4 \pm 0.4 \text{ pb}^{-1}$ is the integrated luminosity corresponding to the data sample [12], ϵ_c is the efficiency of the selection criteria for detecting direct photon events and $A(p_T)$ is the geometrical acceptance computed by a Monte Carlo simulation.

The results are consistent, within statistical and systematic errors, with similar measurements at the same centre of mass energy [13,14]. The cross-section values together with the statistical and the p_T dependent systematic errors are listed in Table 1.

The systematic uncertainty on the normalization of the cross-section has a component that depends on the p_T of the photon and a component which is independent on it.

The overall p_T independent systematic error is 9%. It includes contributions from a 1% uncertainty on the energy scale (6.4%), a 5.4% error on the luminosity measurement, a 2% uncertainty on the evaluation of the photon identification cut efficiency excluding the preshower isolation efficiency and a 1% error on the acceptance determination.

The p_T dependent part of the systematic error is due to the uncertainties in the preshower isolation efficiency (sys1) and in the Monte Carlo evaluation of ϵ_γ and ϵ_π (sys2). In addition, an uncertainty arises from the difference in the energy reconstruction for converted photons for which the point of impact with the calorimeter

is defined by the preshower location, and for unconverted photon for which it is determined from calorimeter information alone (sys3).

As a cross-check of the estimate of the systematic error, the analysis has been repeated using a different set of isolation criteria based on calorimeter and track information. The two cross-section measurements agree within statistical and systematic errors.

The results are compared to next-to-leading order QCD calculations [15]. Different sets of structure functions [16] and different choices of the Q^2 scale [17] have been used for the comparison. In addition, the isolation cut used in the selection of the data suppresses the contribution of bremsstrahlung from final state quarks so that this effect is not included in the calculation of the QCD expectations. The p_T distribution of the data together with the QCD expectations for various choices of structure functions are shown in Fig. 3. Within uncertainties the data agree well with the QCD predictions but do not distinguish among the different structure function sets.

A comparison between the inclusive cross-sections for direct photons and jets at $\eta = 0$ [18] is shown in Fig. 4.

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p_T (GeV)	$E \frac{d\sigma}{d^3p}$ (pb GeV ⁻²)	$\Delta (E \frac{d\sigma}{d^3p})$ (pb GeV ⁻²)				
		stat.	sys1	sys2	sys3	sys.tot.
15.9	7.26	4.01 10 ⁻¹	1.38 10 ⁻¹	1.34	2.76 10 ⁻¹	1.37
17.9	3.81	2.46 10 ⁻¹	6.10 10 ⁻²	6.25 10 ⁻¹	1.45 10 ⁻¹	6.44 10 ⁻¹
19.9	1.74	1.53 10 ⁻¹	2.61 10 ⁻²	2.59 10 ⁻¹	1.29 10 ⁻¹	2.91 10 ⁻¹
21.9	8.78 10 ⁻¹	1.01 10 ⁻¹	1.32 10 ⁻²	1.18 10 ⁻¹	7.46 10 ⁻²	1.40 10 ⁻¹
23.9	6.04 10 ⁻¹	7.24 10 ⁻²	7.25 10 ⁻³	7.61 10 ⁻²	1.39 10 ⁻²	7.79 10 ⁻²
25.9	3.60 10 ⁻¹	5.23 10 ⁻²	4.32 10 ⁻³	4.28 10 ⁻²	1.01 10 ⁻²	4.43 10 ⁻²
27.9	2.05 10 ⁻¹	3.83 10 ⁻²	2.46 10 ⁻³	2.38 10 ⁻²	7.58 10 ⁻³	2.50 10 ⁻²
29.9	1.72 10 ⁻¹	2.98 10 ⁻²	1.55 10 ⁻³	1.86 10 ⁻²	8.08 10 ⁻³	2.03 10 ⁻²
33.5	6.88 10 ⁻²	1.06 10 ⁻²	6.88 10 ⁻⁴	7.02 10 ⁻³	3.92 10 ⁻³	8.05 10 ⁻³
40.4	1.83 10 ⁻²	4.29 10 ⁻³	1.83 10 ⁻⁴	1.70 10 ⁻³	1.83 10 ⁻⁴	1.72 10 ⁻³
48.8	7.31 10 ⁻³	2.24 10 ⁻³	5.85 10 ⁻⁵	6.51 10 ⁻⁴	4.46 10 ⁻⁴	7.89 10 ⁻⁴
56.1	1.66 10 ⁻³	1.06 10 ⁻³	1.66 10 ⁻⁵	1.41 10 ⁻⁴	2.07 10 ⁻⁴	2.51 10 ⁻⁴
65.7	6.21 10 ⁻⁴	5.33 10 ⁻⁴	4.35 10 ⁻⁶	5.03 10 ⁻⁵	5.40 10 ⁻⁵	7.39 10 ⁻⁵
81.4	1.97 10 ⁻⁴	1.50 10 ⁻⁴	1.58 10 ⁻⁶	1.52 10 ⁻⁵	1.10 10 ⁻⁵	1.87 10 ⁻⁵

Table 1 : Inclusive direct photon cross-section at $|\eta| = 0$.

The quoted errors Δ do not include the overall systematic scale uncertainty of $\pm 9\%$. See text for definition of the systematic errors sys1, sys2, sys3. They have been added in quadrature to give the total p_T dependent systematic error sys. tot.

FIGURE CAPTIONS

- Fig. 1 Conversion fraction for photon candidates. The curves labeled ϵ_γ and ϵ_π are the conversion probabilities for single photons and multiphoton background, respectively.
- Fig. 2 The fractional multiphoton background contamination in the sample of photon candidate events.
- Fig. 3 The invariant differential cross-section for direct photon production is compared with the QCD calculation of Ref. [15] with two different sets of structure functions [16], namely Duke-Owens set 1 (DO1) and Aurenche et al. (ABFOW) with an optimized Q^2 scale (OPT) and $Q^2 = p_T^2$. The errors shown include statistical and p_T dependent systematic errors added in quadrature.
- Fig. 4 The differential cross-sections for direct photon production and jet production [18] are compared at $\eta = 0$.

Figure 1

Figure 2

Figure 3

Figure 4