OBSERVATION OF π^0 MESONS WITH LARGE TRANSVERSE MOMENTUM
IN HIGH-ENERGY PROTON-PROTON COLLISIONS

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Received 10 August 1973

Invariant cross-sections are presented for the inclusive reaction p + p → π^0 + anything. Measurements of large transverse momentum π^0's (2.5 GeV/c < p_⊥ < 9 GeV/c) were made near 90° at the CERN ISR at five centre-of-mass energies (√s = 23.5, 30.6, 44.8, 52.7 and 62.4 GeV). At large p_⊥, the invariant cross-sections are seen to vary with s and p_⊥, in good agreement with a fit of the form A_π^0 p_⊥^N F(p_⊥/√s), with N ≈ 8 and F(p_⊥/√s) ≈ exp(-26p_⊥/√s).

A well-known aspect of high-energy collisions has been the failure to observe the production of particles with large transverse momentum. Extensive measurements at accelerators and with cosmic rays had shown a steep exponential decline in the probability for hadronically induced transverse momenta [e.g. 1]. The observations presented here demonstrate an energy-dependent flattening of this behaviour, such that the cross-section at p_⊥ = 6 GeV/c and √s = 52.7 GeV is seven orders of magnitude higher than an extrapolation of the well-known exponential [2].

Inclusive π^0 production at large transverse momenta was studied at the CERN Intersecting Storage Rings. Neutral pions that emerged near 90° in the centre-of-mass were identified by electromagnetic showers in either of two spectrometers, each with a useful laboratory solid angle of 0.59 sr. The spectrometers are the same ones that were used to search for high-energy electrons and large mass e^+e^− pairs [3].

Fig. 1 shows a schematic representation of the apparatus, which consisted of two identical spectrometers on the inner and outer sides of the colliding proton beams. Each spectrometer consisted of: i) ten planes of wire spark chamber modules; ii) four sets of scintillation counter hodoscopes: A, B, Z and ST; iii) an array of sixteen lead-glass counters, 3.1 radiation lengths thick; and iv) an array of sixty lead-glass shower counters, 14.8 radiation lengths thick. The A and B hodoscopes were used for triggering and for track verification. The Z counters were used to measure ionization loss; and the ST counters, which were placed after the lead-glass counters, were used during calibration runs to detect particles passing straight through all of the shower detectors. The first array of lead-glass, whose thickness to hadrons was only 0.15 interaction lengths, was employed to select events containing electrons or

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*8 Research supported in part by the US Atomic Energy Commission under contract AT (11-1) 2232A.
or photons [4]. A light source that consisted of a small NaI(Tl) crystal diffused with $^{241}$Am was glued to each of the 152 lead-glass counters to provide continual monitoring of the response of the detectors [5]. For the data at $\sqrt{s} = 44.8$ and 52.7 GeV, there was a 0.17 cm thick sheet of Pb immediately preceding the Z counters of the inside spectrometer. Further details on the assembly and operation of the spectrometers, and on the calibration and monitoring of the shower counters, are given elsewhere [6].

In addition, two 1 m$^2$ scintillation counters, $\Sigma_1$ and $\Sigma_2$, were each centred around a downstream ISR vacuum pipe 5.65 m from the crossing point. The coincidence $\Sigma_1 \Sigma_2$ was timed to select an almost pure sample of beam-beam collisions.

Two sets of logical coincidences were used to sense a $\pi^0$ and trigger the detectors. For the data taken without the Pb sheet, each set of logic required the presence of either a $\Sigma_1 \Sigma_2$ coincidence or a coincidence between an A counter and a B counter on the same side. When the Pb sheet was in place on the inside spectrometer, with $(\Sigma_1 \Sigma_2$ or AB) requirement was changed to $\Sigma_1 \Sigma_2$ only. An additional requirement in each trigger was that one of the two spectrometers should contain a shower which deposited at least 0.5 GeV in the first array of lead-glass counters, and which exceeded a given energy threshold in the second array. This threshold energy was 0.8 GeV for the first trigger, and 1.5 GeV for the second trigger. The rate of the first trigger was electronically suppressed by a carefully monitored factor of about 100, so that less frequent, high $p_1$ events in the second trigger would not be blocked by dead-time. A lower energy bound of 2.5 GeV was set for the presentation of these data because of the combined effects of energy resolution, energy sharing in the different sets of blocks, and thresholds.

The data presented in this paper were taken during the four-month period from September to December 1972. Runs were made at five values of the total centre-of-mass energy: $\sqrt{s} = 23.5$, 30.6, 44.8, 52.7 and 62.4 GeV. The ISR luminosity was measured at each energy by means of the Van der Meer method [7]. The running time spent at the five energies corresponded to the following numbers of proton-proton collisions: $8.1 \times 10^7$, $9.7 \times 10^8$, $3.4 \times 10^9$, $1.8 \times 10^{10}$ and $1.2 \times 10^7$, respectively.

Two methods were used to analyse the inside spectrometer data that were taken with the Pb sheet in place. In the first approach only those events were selected where at least one photon converted in the Pb sheet. The selection criteria demanded: i) that the wire spark chambers after the Pb sheet contain a sufficient number of sparks; ii) that the Z counters indicate an ionization loss greater than 1.6 times minimum; and, iii) that the energy distribution in each of the lead-glass arrays be consistent with electromagnetic showering. The second method of analysis, which was applied to all of the data, used only the energy distribution in the lead-glass.

The background of accidental coincidences was studied from data taken with a special trigger in which some of the coincidence inputs had been delayed. Single beam data were taken to check for beam-gas and beam-wall backgrounds. The total background was negligible for those events that converted in the Pb sheet. For the analysis that did not require conversion, the background was below 5% for $p_1 < 6$ GeV/c, although
it did rise to approximately 20% at $p_{\perp} = 7$ GeV/c.

The solid angle and $\pi^0$ detection efficiency for the two methods were obtained from a Monte Carlo program that calculated the shower development in the Pb sheet and in the lead-glass. The Monte Carlo program was checked by comparing its predictions with the calibration data taken at the CERN Proton Synchrotron and at the Daresbury Electron Synchrotron, using incident electrons and photons of known energy.

Knowledge of the luminosity, background-subtracted rates, and acceptance was insufficient to determine the inclusive cross-section from our data. It was also necessary to know the triggering bias that resulted from the requirement of either the $\Sigma_1 \Sigma_2$ coincidence, or the detection of at least one track coming from the intersection region. This bias was deduced by dividing the data into three categories: i) events with $\Sigma_1 \Sigma_2$ and a track; ii) events with $\Sigma_1 \Sigma_2$ and no track; iii) events with no $\Sigma_1 \Sigma_2$ and a track. It was assumed that the observation of a track at large angles was independent of the presence of the $\Sigma_1 \Sigma_2$ coincidence. This assumption allowed an estimate to be made of the size of the undetected class of high $p_{\perp}$ events, those having no $\Sigma_1 \Sigma_2$ and no track. Inclusive cross-sections were then obtained for each centre-of-mass energy by adding in the estimate of this fourth category. The correction to the ($\Sigma_1 \Sigma_2$ or $AB$) data was found to be independent of $p_{\perp}$. It amounted to a multiplicative factor of 1.49 at 23.5 GeV, 1.37 at 30.6 GeV, 1.21 at 44.8 GeV, 1.14 at 52.7 GeV and

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**Fig. 2.** A comparison of invariant cross-sections for inclusive $\pi^0$ production obtained from the two methods described in the text. These data come from those runs where the inside detector had a lead sheet to convert $\gamma$ rays.
1.10 at 62.4 GeV. The systematic uncertainty in this correction is estimated as ranging from 5% to 10%.

For the $\Sigma$ only data, which are presented at $\sqrt{s} = 44.8$ and 52.8 GeV, the corrections were found to be slightly larger and $p_t$-dependent. Use of the same assumption given above resulted in a typical correction of $1.27 \pm 0.05$ at $p_t = 5$ GeV/c and $\sqrt{s} = 52.7$ GeV.

Fig. 2 compares the results from the two methods of analysis. The comparison was intended to verify the two-photon nature of the events. Since the conversion efficiency is a known function of the number of photons, the agreement of these spectra is consistent with the hypothesis that all of our electromagnetic showers originated from two photons. For example, if the detection efficiency were calculated by assuming the detected events to be either single $\gamma$'s, or $2\pi^0$'s from $K_S^0$ decay, then the results of the two methods of analysis would differ by 35%.

Fig. 3 shows the spectra for all five centre-of-mass energies. A list of cross-sections is given in table 1. The sources of uncertainty in these data can be enumerated as follows: i) the statistical errors, which are plotted in the figure; ii) a calibration uncertainty of $\pm 6\%$ in the energy scale. During the course of the experiment, a change was observed in the relative calibration of the lead-glass detectors. This was traced to a darkening of the lead-glass that was produced by radiation damage. Correction factors to the data were derived.
from three sets of information: the measurements of a final calibration run at the CERN PS done immediately after the end of the experiment, the day-to-day measurements of the relative calibration, and the measurements done with straight-through particles at the ISR. The ±6% energy uncertainty results in a normalization uncertainty of approximately ±45% at $p_L = 3$ GeV/c, and approximately ±55% at $p_L = 5$ GeV/c. This error is independent of $s$ and will not substantially change the smooth fall-off in $p_L$. iii) An $s$-dependent but $p_L$-independent error of ±5% in normalization at each ISR energy, which comes from the luminosity determination using the Van der Meer method. iv) A $p_L$-dependent and $s$-dependent systematic uncertainty that comes from the determination of the trigger bias and detection efficiency. This is 15% near $p_L = 2.5$ GeV/c, and 5% above $p_L = 3$ GeV/c.

This invariant cross-sections which are given for $\sqrt{s} = 44.8$ and 52.7 GeV are slightly higher than those which have been presented at the same energies for inclusive charged pion production near 90° [8, 9]. The uncertainty in our calibration, however, prevents us from attaching much significance to this difference.

An acceptable fit to the data for all energies can be made with the form $E(d^3\sigma/dp^3) = A_0 x_0^n F(p_L/x_0)$.

Choosing $F(p_L/x_0) = \exp(-b p_L/x_0)$ gave $n = (8.24 ± 0.05)$, $A = (1.54 ± 0.10) \times 10^{-26}$, and $b = (26.10 ± 0.50)$. The errors for this fit are statistical only. The $\chi^2$ was 140.7 for 88 degrees of freedom. Because of the systematic uncertainties mentioned above, a total error of ±0.70 must be ascribed to the value of $n$. A plot of the function $F$ is shown in fig. 4.

A large number of theoretical models have recently been proposed to attempt to account for the flattening of the $p_L$-distribution at 90°. Most of these make use of some form of local structure inside the proton to provide the high $p_L$ in the final state. Indeed, the possibility of a break in the steep exponential slope observed at low $p_L$ was anticipated by Bjorn, Bjorken and Kogut [10]. However, the electromagnetic form they predict, $p_L^4 F(p_L/x_0)$, is not observed in our experiment. On the other hand, a constituent exchange model proposed by Blankenbecler, Brodsky and Gunion [11], and extended by others [12], does give an excellent account of the data.

We wish to thank R. Bouhot, G. Siger, B. Smith, J. Lindsay and F. Doughty for technical assistance; J.S. Beale for help with on-line programming; and
A SCALING OF THE INCLUSIVE $\pi^0$ CROSS SECTION AT LARGE TRANSVERSE MOMENTA

Fig. 4. The function $F(p_T/\sqrt{s}) = p_T^n E(d^3\sigma/dp^3)$, as deduced from our measurements, using the best fit value $n = 8.24$. The errors are statistical only.

M.A. Huber, W. Swiatek and W. Duinker for aid in the laboratory. The Columbia and Rockefeller University collaborators wish especially to express their appreciation for the generous hospitality of CERN. We are all indebted to the ISR staff for the outstanding success the operation of this machine represents.

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[2] Preliminary data on the production of large transverse-momentum $\pi^0$'s were presented by this collaboration about one year ago. See Proc. 16th Int. Conf. on High-energy physics, Batavia, eds. J.D. Jackson and A. Roberts (NAL, Batavia, 1972), Vol. 3, p. 317.