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A STUDY OF THE PRODUCTION OF HIGH- p_T π^0 's
AT THE CERN INTERSECTING STORAGE RINGS

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ABSTRACT

The inclusive cross-section for π^0 production near 90° in pp collisions at the CERN Intersecting Storage Rings has been studied for the p_T range $3 < p_T < 16$ GeV/c at four different centre-of-mass energies ($\sqrt{s} = 30.6, 44.8, 52.7$, and 62.8 GeV). In this experiment the two photons from the $\pi^0 \rightarrow \gamma\gamma$ decay were resolved and measured separately for p_T values up to 10 GeV/c. Results indicate an agreement with the p_T^{-8} behaviour for the lower values of p_T and a slower decrease of the cross-section for the higher values of p_T . The high- p_T data deviate from the scaling expression $p_T^{-n} F(x_T)$, which holds for the lower p_T values ($p_T < 8$ GeV/c).

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We have measured the π^0 inclusive cross-section for values of $3 < p_T < 16$ GeV/c in pp collisions in the CERN Intersecting Storage Rings (ISR) at 90° centre of mass. A part of the present data was reported in previous publications [1,2]. In the present paper we extend up to 10 GeV/c the p_T region in which the two photons from the π^0 decay are detected separately. At the higher p_T region the two showers were measured as a merged unresolved shower. Data were taken at four c.m. energies: $\sqrt{s} = 30.6, 44.8, 52.7, \text{ and } 62.8$ GeV.

1. EXPERIMENTAL APPARATUS

Liquid-argon/lead calorimeters of high spatial resolution and large solid-angle acceptance were used for the detection of the photons from the π^0 decay, $\pi^0 \rightarrow \gamma\gamma$. Three different geometrical arrangements of the detector were used in order to cover the full p_T range efficiently, and are shown in fig. 1.

The first geometrical arrangement of the apparatus, the so-called "retracted geometry", consisted of two identical liquid-argon/lead calorimeters, located at 1.6 m from the interaction point, at the side towards the motion of the c.m. of the intersecting beams. With this arrangement, each calorimeter module covered a solid angle of approximately 0.26 sr corresponding to 70° to 110° in polar angle and 20° in azimuth. The minimum opening angle between showers detected separately as two resolved showers, was 1.5° ; consequently, the two photons from the π^0 decay were resolved for p_T values up to 6 GeV/c.

In order to be able to resolve π^0 's at higher p_T values, the two calorimeters were further retracted to a distance of 2.1 m from the interaction point. In this second configuration of the apparatus, the "super-retracted geometry", each calorimeter covered a solid angle of approximately 0.12 sr. Furthermore, in this arrangement the calorimeters were placed away from the direction of the c.m. motion of the ISR beams, and their effective acceptance in the c.m. frame was therefore somewhat smaller than their acceptance in the laboratory system, and the $\pi^0 \rightarrow \gamma\gamma$ angles larger. In this configuration the calorimeters were exposed to less beam-gas background, and π^0 's were detected as resolved showers up to p_T 's of 10 GeV/c.

For higher values of p_T 's the large solid angle (4 sr total fiducial area) of the "normal geometry" was required (see fig. 1c). In this configuration four calorimeters were used and placed at a distance of 0.86 m from the interaction point, each calorimeter covering 45° in azimuth and 45° to 135° in polar angle. With this configuration the minimum opening angle for two-shower separation was 3° , and most of the $\pi^0 \rightarrow \gamma\gamma$ decays for p_T 's > 7 GeV/c (90% of the π^0 's for $p_T > 8$ GeV/c) were detected as a single merged shower consisting of two coalesced electromagnetic showers.

The calorimeters (described in more detail elsewhere [3-5]) were about 17 radiation lengths deep and subdivided longitudinally (along the direction of the shower development) into three sections (see fig. 2):

- i) the ϕ section, 2.5 radiation lengths, 14 gaps of liquid argon (LA);
- ii) the UV section, 2.5 radiation lengths, 14 gaps of LA;
- iii) the θ section, 12 radiation lengths, 44 gaps. The energy deposited in each section was recorded separately, allowing the identification of electromagnetic showers by taking into account their characteristic longitudinal development.

Transversely, the calorimeters were subdivided into strips oriented in four different directions. The layout of the strips, which is shown in fig. 2, provided measurement of the transverse size of e.m. showers. In addition, the four different projections of each shower allowed accurate spatial localization of the shower. A spatial resolution of $\sigma_x = 5$ mm was achieved with an electron test beam at the CERN Proton Synchrotron (PS). This was obtained by comparing the reconstructed shower position with the electron position as measured by a scintillator hodoscope.

The calorimeter energy resolution was measured at the PS, and can be described by the following expression:

$$\frac{\sigma(E)}{E} = (0.10 \pm 0.02)/\sqrt{E} \quad \text{with } E \text{ in GeV}.$$

The observed π^0 and η^0 mass resolution during the operation of the calorimeters at the ISR was consistent with the above expression. The linearity of the energy response was investigated by beam tests and particle masses, as discussed elsewhere [6].

2. TRIGGER REQUIREMENTS

The trigger occurred at two levels, the first being the pre-trigger and the second the calorimeter trigger.

The pre-trigger was a minimum bias trigger which only required the occurrence of an inelastic proton-proton collision in the ISR. For this purpose a coincidence between two sets of scintillator hodoscopes at small angles to the beams -- the so-called "beam-beam" counters -- or a coincidence between the scintillator counters SC1 and SC2 placed at 90° with respect to the beams was required.

The calorimeter trigger imposed the additional requirement of some minimum energy deposit in the LA calorimeters, introducing a selective trigger for events of interest.

With the test beams the longitudinal and radial developments of electron- and pion-induced showers were studied [3]. The difference in the longitudinal development was used in order to define a trigger which would efficiently select electromagnetic showers and reject hadronic ones. For this purpose, the energy deposited in localized regions in the first two sections (ϕ and UV sections) of a calorimeter was required to exceed certain thresholds. To further enhance the sample of high- p_T π^0 's, a minimum total energy was required. This total energy threshold varied according to the p_T region studied, and corresponded to 3 GeV for the retracted and super-retracted geometries and to 5 GeV for the normal geometry.

The requirement in the first ϕ floor was changed for the case of the super-retracted geometry since it gave a different trigger efficiency for separated π^0 's and single photons, because a photon, 12% of the time, converts late or does not convert at all in the ϕ section. For the other two geometries the inefficiency introduced by the ϕ requirement was taken into account in the data analysis stage.

3. DATA ANALYSIS

For the runs with the first two geometries, the "retracted" and the "super-retracted" ones, the π^0 's were identified as resolved pairs of photon showers. For this purpose, each event was required to have at least two reconstructed showers of energy above 400 MeV each, inside a certain fiducial volume. The fiducial volume was defined to be $|x| \leq 280$ mm, $|y| \leq 700$ mm in order to avoid inefficiencies at the edges of the calorimeters. In addition, in the "retracted" geometry a few strips close to the beam plane were excluded from the fiducial area, since they were exposed to too much background. Since the proportional chambers used in the normal geometry electron-pair search were removed for both the retracted and the super-retracted geometry runs, no track reconstruction was possible, and the effective mass $M_{\gamma\gamma}$ of the photon pairs was computed by assuming that the interaction point was at the centre of the 40 cm long interaction diamond. The effect due to the uncertainty in the vertex position was found to be small but has been taken into account in the acceptance calculations.

To avoid losses due to asymmetric decays of the π^0 's the asymmetry of the photon pair $\alpha \equiv |E_2 - E_1|/E_{\text{tot}}$ was restricted to values smaller than 0.4 for the retracted runs, and smaller than 0.7 for the super-retracted ones.

To improve the background rejection, stringent cuts were imposed on the longitudinal and lateral shower development, as will be discussed in the next section.

An additional requirement for the resolved shower pairs was to restrict their invariant mass to be consistent with that of a π^0 . Given the experimental mass resolution $\sigma_M \approx 15$ MeV, it was demanded that the invariant mass should be in the range $90 < M_{\gamma\gamma} < 180$ MeV.

For p_T 's above 10 GeV/c the photon opening angle became small enough so that the two showers started merging into one, but the rates were so low that the large solid angle of the normal geometry was needed. For this geometry most of the π^0 decays consisted of single showers representing two overlapping e.m. showers, or

less often as a resolved pair of nearly coincident photons. In order to include these resolved pairs in our data sample, the π^0 momentum was defined as the sum of the momenta of all showers situated inside a cone with a half-angle of 5° around the shower carrying the largest p_T .

Contributions to the counting rate from other final-state particles such as unresolved $2\pi^0$ systems, η 's, and direct photons, were taken into consideration. The data sample was corrected for the first two contributions. Specifically, the accidental overlap of photon showers from two different π^0 's were subtracted by extrapolating a plot of counting rate versus angular size of the deposited energy to zero angular size. The η production made a small contribution ($< 4\%$) to the counting rate, as shown by our measured η cross-section [7]. The η 's always appeared as resolved shower pairs because of their large opening angle. The single-photon subtraction, however, was not possible since the angular resolution in this arrangement of the apparatus was insufficient to allow a distinction between overlapping $\pi^0 \rightarrow \gamma\gamma$ showers and genuine single-photon showers. Single-photon production has been measured with the retracted geometries of the apparatus [6,8] and found to be of the order of $\gamma/\pi^0 \lesssim 30\%$ for $p_T < 9$ GeV/c. However, the results in this paper, using unresolved π^0 decays, have not been corrected for direct photon events.

4. BACKGROUND SUBTRACTION

The background to the π^0 events from beam-beam interactions was quite small and mainly due to hadronic events misidentified by electromagnetic showers. Most of these were rejected at the trigger level, as mentioned in the trigger section, by requiring a shower development characteristic of that of an electromagnetic shower. The rejection power of the calorimeter was measured during exposures of a detector module to pion and electron beams at the CERN PS, and was found to be $1/250$ after imposing selection criteria and integrating over the p_T spectrum.

There was substantial background due to beam-gas events, i.e. those events due to upstream interactions of beam particles with residual gas in the vacuum

pipe or with ISR components such as vacuum pipe walls or magnet pole tips. These particles entered the calorimeter from the side and could therefore be rejected since they were characterized by broad transverse shower size and abnormal longitudinal development. In particular, these particles left little or no energy in the θ section of the calorimeters since they traversed them essentially parallel to the beam direction. A cut was thus imposed on the fractions of energy deposited in the first two sections of the calorimeter, i.e. on E_ϕ/E_{tot} and $E_{\text{UV}}/E_{\text{tot}}$, requiring that sufficient energy was deposited in the θ section, as expected from a normal e.m. shower development. A further cut was imposed on the radius of the showers in order to reject the very wide showers ($R_\phi \leq 16$ mm and $R_{\text{UV}} \leq 18$ mm, where R_ϕ , R_{UV} are the shower radius in the ϕ and UV sections, respectively). The above cuts, which were found to have a high rejection power for hadrons (according to the PS test results), were at the same time highly efficient for e.m. showers. Their efficiency was investigated by using both the PS electron shower data and the EGS shower simulation code [9] (described in the next section) and found to be about 92-95% efficient.

These cuts were equally efficient for removing background corresponding to single merged showers or shower pairs reconstructing in the π^0 mass. The latter were due to wide showers which were split by the shower-finding program into two barely resolved showers, which gave a low mass enhancement peaking under the π^0 peak.

A special type of background which applied to the unresolved π^0 's was that originating from cosmic rays. Those events were identified as cosmic rays because they were more in the two calorimeters Q2 and Q3, which were facing upward and which counted downward-moving showering particles, than in Q1 and Q4 (facing downward). This asymmetry could be removed by requiring the event to contain at least one charged track originating in the interaction diamond in any one of the other three octants. It was checked (by using the high statistical accuracy of the data, ~ 2300 counts in the 9-10 GeV/c bin at $\sqrt{s} = 62.4$ GeV) that the above cut removed the up-down asymmetry in the data but did not introduce a p_T -dependent bias.

In addition, the cosmic-ray background was directly measured by special cosmic-ray runs. The results showed that the observed up-down asymmetry was indeed due to cosmic rays, and also that the above charged track cut removed $\sim 90\%$ of the cosmic-ray associated background events. The data from these special cosmic-ray runs were used for a final cosmic-ray background subtraction.

Figure 3 shows for both the retracted and super-retracted geometries the distribution in invariant mass $M_{\gamma\gamma}$ for the events which satisfied all the above-mentioned selection criteria. A clear η peak is also observed [7]. There is still a small residual background left under the π^0 peak which is due to uncorrelated showers. The size of this residual background was estimated either by studying events of the right-hand side and left-hand side of the peaks, or by parametrizing the π^0 mass spectrum as a Gaussian on top of a background curve, and fitting. Both methods indicated that the background was approximately 6% independent of the p_T value and c.m. energy.

5. EFFICIENCY AND ACCEPTANCE CORRECTION

The solid angle acceptance for the $\pi^0 \rightarrow \gamma\gamma$ events was calculated by means of a Monte Carlo program. The efficiency of the trigger conditions was determined either by studying special runs where a minimum bias trigger was used together with a condition on the total energy deposited in the whole calorimeter -- in order to select events of sufficiently high energy -- or by studying showers produced in untriggered octants. For the case of the normal geometry, which covered a larger polar angle, an additional correction was made for the variation of the trigger threshold with the angle of incidence.

As mentioned before, the data where the ϕ threshold was required were further corrected for the inefficiency of this requirement, i.e. for the late- or non-conversion probability of the shower within the ϕ section. This probability was found to be essentially independent of the total energy of the shower.

The efficiency of the event reconstruction procedure was estimated by two methods. The first method consisted in varying the minimum energy cut and observing

its effect on the pattern recognition and by inspection of event displays. The second, more sophisticated, method made use of the EGS shower code. The EGS program [9] is a system of subroutines intended for detailed simulation of e.m. cascades in a variety of situations. The EGS simulation was checked and found to give a good description of e.m. showers of energies higher than 500 MeV since it successfully reproduced features of the data collected with the test beams in the PS. In particular the EGS described very well the distributions of the fractional energy deposited in the ϕ and UV sections for electron showers when checked with the electron events of the PS test. To obtain the reconstruction efficiencies, π^0 's were generated and their shower development was given by the EGS program. The generated π^0 's were then used as input to the standard pattern recognition program. The reconstruction efficiencies were calculated as a function of p_T , and the results given by the two different methods agreed very well. The result was found to be independent of p_T and had a value equal to 68% for resolved π^0 's and 88% for the merged ones. The inefficiencies are primarily due to two causes: asymmetric decays where one photon has too low an energy to be reconstructed; and cases where a photon converts late in the ϕ section or not at all, and thereby fails to be reconstructed.

For the resolved π^0 geometries, special care was taken to determine merging corrections for the highest p_T values, since for these p_T values the two-photon showers started overlapping as the π^0 opening angle decreased. The merging correction was estimated either by using the EGS program or by direct simulation of high p_T π^0 's from the data at lower p_T 's without resorting to Monte Carlo methods. In both cases the simulated data were reconstructed by the normal reconstruction program, thereby determining the number of π^0 's which were reconstructed as resolved showers. Both methods gave very small merging corrections, of the order of a few percent, for the highest p_T 's involved i.e. 6 GeV/c for the retracted geometry and 10 GeV/c for the super-retracted one.

For the normal geometry data, additional corrections were made to take into account π^0 decays with large $\gamma\gamma$ opening angles, for finite energy resolution, and

for non-linearity in the energy scale caused by energy leakage through the finite depth of the calorimeters. The energy leakage correction was studied by either the EGS code or by using shower data tables, and was found to be small (at most a 10% cross-section correction for the highest p_T 's). We have corrected the normal geometry data for accidental overlap of showers from two different π^0 's by extrapolating a plot of the counting rate versus the angular size of the deposited energy to zero angular size. This correction does not apply to data with resolved π^0 decays because these events show up as background in the $\gamma\gamma$ mass plot. These corrections are not very p_T dependent. Typical values are shown in Table 1.

A final correction was applied for the inefficiency of the pre-trigger, namely for these events where the produced charged particles were not within the acceptance of the beam-beam counters or the SC1-SC2 hodoscopes. The beam-beam counters covered a limited solid angle which corresponded to 66% of the total inelastic proton-proton cross-section at $\sqrt{s} = 30.6$ GeV, increasing to 84% for $\sqrt{s} = 62.8$ GeV. Since the pre-trigger could also be produced by another scintillator counter coincidence (SC1-SC2 or the similar barrel scintillators used with the super-retracted configuration), the pre-trigger efficiency was calculated as a combination of the above-mentioned beam-beam coverage and the scintillator counter coverage. The resulting pre-trigger geometric efficiencies were 78% for $\sqrt{s} = 30.6$, 90% for $\sqrt{s} = 52.7$, and 91% for $\sqrt{s} = 62.8$ GeV. The barrel scintillator had a larger solid angle coverage (98%); therefore, for the super-retracted geometry, the pre-trigger was almost 100% efficient for all inelastic events, with no bias towards a particular class of events.

6. DETERMINATION OF THE PHOTON ENERGY SCALE

The absolute energy scale was determined by monitoring the π^0 mass peak. This method, however, presupposes that the distance from the interaction point to the shower position is accurately known, since the π^0 mass calculation involves knowledge of the opening angle between the two decay photons. For a shower detector the localization of the shower position is not simple since it requires knowledge

of the exact depth at which the conversion took place. It is more convenient, for the definition of the shower position, to refer to some effective plane in which one specifies the shower centre of gravity. Since the calorimeter position in space is known from survey measurements, all one needs is to define the position of the effective plane relative to the calorimeter front face.

The method employed in this paper used the plane obtained using showers generated with the EGS and reconstructed with the normal reconstruction program. The effective plane position was obtained from the reconstructed position of the generated showers. Our earlier results used charged particle tracks in the proportional chambers and calorimeter to survey the effective position of the latter. The charged tracks do not, however, have the same longitudinal distributions as showers, and we find that this method gave an effective plane about 30 mm shallower than the true value. This change in distance leads to a change in angles, and therefore in mass and energy scales, as well as in solid angle. The resulting changes in cross-section are rather small for the retracted configurations, but are significant in the normal configuration, where the total distance to the interaction point is relatively small; it leads to a 5% change in the energy scale, and a corresponding change in the cross-section. We estimate the uncertainty in the effective plane as 15 mm.

An additional correction had to be applied to the method of calibration on the π^0 mass. This correction corresponds to the result of the combination of two different effects: the steepness of the π^0 spectrum, and the finite detector resolution. The net result is a shift of the π^0 average observed mass to higher values. The magnitude of this shift was calculated by a Monte Carlo program and found to be 1-2% depending on the p_T of the π^0 's which were used for the calibration.

For the retracted and super-retracted geometries the energy scale was thus calibrated to yield a mass of 138 MeV for π^0 's of $p_T \sim 3-4$ GeV/c (2% mass shift). The mass calibration so determined gave the η mass at its correct shifted value.

For the normal geometry where the π^0 's appeared as single merged showers, the energy scale was determined using the resolved $\eta \rightarrow \gamma\gamma$ decays with p_T of 6-7 GeV/c.

The energy scale determined with the above calibration procedure was accurate to about 2%. The error in the distance of the effective plane adds an error which depends on the configuration. This leads to a total error in energy scale, which is 4% for the normal configuration, 3% for the retracted configuration, and 2.5% for the super-retracted configuration.

Luminosities were monitored by beam-beam counters which effectively recorded the interactions at small forward angles. For each geometrical arrangement, table 2 shows the integrated luminosities corresponding to each c.m. energy.

7. RESULTS

The π^0 inclusive cross-section at 90° c.m. is shown in figs. 4 to 7 for the four c.m. energies. The cross-sections measured with different geometrical arrangements of the apparatus are plotted together. The over-all uncertainty in absolute normalization varied from 27% to 42% for the different geometries. The various contributions to this uncertainty are listed in table 3. The main source is the uncertainty in the energy scale, which was discussed in detail in the previous section. Tables 4 to 6 give the cross-sections separately for each different geometrical arrangement.

The data from the two retracted geometries where the π^0 's were recognized as resolved showers are in good agreement with each other, despite the fact that the data come from two essentially independent experiments. These results are also in remarkable agreement with those of Clark et al. [10] up to the largest p_T value of their resolved data ($p_T = 4.5$ GeV/c) and are also compatible with the unresolved π^0 data of the CCOR collaboration [11] for p_T 's up to 6 GeV/c.

Our cross-section based on unresolved pions obtained with the normal geometry seems to be higher than those from the resolved showers for p_T 's > 6.5 GeV/c. Part of this discrepancy may be due to single photons, since the unresolved π^0

cross-section measurement includes the contribution from single photons as explained before. However, the single-photon production as measured by our group [6,8] is not large enough to explain fully the discrepancy between resolved and unresolved data, which is of the order of 25% at $p_T \sim 7$ GeV/c rising to 40% at $p_T \sim 9.5$ GeV/c. Therefore, this remaining part of the discrepancy should probably be attributed to the photon energy scale uncertainty. Our unresolved data are lower than those of the CCOR and CERN-Saclay-Zurich Collaborations. In a previous publication [2] where part of these data were reported, the disagreement between our data and those of the above collaborations was even larger (a factor of 4 at the largest values of p_T). The shift in the effective plane led to an increase in the cross-sections for the normal configuration, which reduces this discrepancy.

8. DISCUSSION

Previous measurements [1,12] for the inclusive pion production up to transverse momenta $p_T \sim 8$ GeV/c, for various values of the c.m. energies, have shown that the invariant cross-section around 90° could be well described by the parametrization:

$$E \frac{d^3\sigma}{dp^3} = A p_T^{-n} (1 - x_T)^m, \quad \text{where } x_T = 2p_T/\sqrt{s}, \quad (1)$$

with $n \approx 8$ [13].

For larger p_T 's, theories [14,15] predict that the invariant cross-section should approach a p_T^{-4} law as p_T is increased at a fixed value of x_T . In order to determine the value of n , we have not attempted to fit the data to the form given by eq. (1), since in the above parametrization the parameters n and m are strongly coupled. Rather, assuming that eq. (1) is valid, we have solved for n at fixed x_T . The effective power n is then described by the following expression:

$$n = - \log \left[E \frac{d^3\sigma}{dp^3} \Big|_1 \Big/ E \frac{d^3\sigma}{dp^3} \Big|_2 \right] / \log \left[\sqrt{s_1}/\sqrt{s_2} \right], \quad (2)$$

where

$$p_T^1 = \frac{x_T \sqrt{s_1}}{2} \quad \text{and} \quad p_T^2 = \frac{x_T \sqrt{s_2}}{2}.$$

We used the above expression and divided pairs of experimental data at different c.m. energies but at the same x_T (interpolating the highest accuracy data). The result is shown in fig. 8.

The sizes of many of the error bars in fig. 8 are dominated by our lower level of accuracy [2] at $\sqrt{s} = 52.7$ GeV (20-30% at the largest values of x_T). In addition, the relative normalization error in cross-sections for two different $\sqrt{s}$ values, but for the same geometry, has to be considered, estimated to be about 10%. This corresponds to an uncertainty of 0.7 in the value of n , and would result, for example, from a 1% relative shift of photon energy scales between the interspersed runs at the two $\sqrt{s}$ values. However, one should note that this method for the determination of n is independent of the absolute energy scale uncertainty, which shifts by the same percentage the value of x_T but does not affect the n value.

From fig. 8 it can be observed that when using the data at $\sqrt{s} = 52.7$ and 62.8 GeV, as well as the data at $\sqrt{s} = 44.8$ and $\sqrt{s} = 62.8$ GeV, for values of x_T up to 0.25 n is consistent with the value of 8, but for $x_T > 0.30$ n decreases toward a value of 6. This behaviour is similar to that reported in our previous publication [2], as well as in refs. 10 and 11, but the fall in n is less pronounced.

We note that the points which show the decrease in n come from the data with unresolved showers, induced by both π^0 's and direct photons. Since our measurements of single photons do not extend to the region of p_T where this effect is observed, no corrections can be made for the unknown fraction of single photons. It may however account for some fraction, perhaps important, of the drop in n , if the single photon cross-section does not follow the scaling law. For this reason, and for the greater reliability of the technique, we stress the importance of the data reported here on resolved pion decays.

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Table 1

Typical correction factors for normal geometry

Correction for	Equivalent counting rate effect
Shower transverse size requirement	0.90 ± 0.02
Reconstruction efficiency	0.88 ± 0.02
Beam-beam or SC requirement	0.91 ± 0.02
Associated track requirement	0.75 ± 0.05
Threshold and efficiency effects	0.75 ± 0.05
Conversion probability	0.97 ± 0.02
Large opening angle π^0 decay	0.97 ± 0.02
Two opening angle π^0 decay	1.15 ± 0.05
Contribution from η	1.04 ± 0.02
Non-linearity in energy scale	0.90 ± 0.04

Table 2

$\int L \cdot dt$ = integrated luminosity (cm^{-2})

$\sqrt{s}$ (GeV)	Retracted geometry	Super-retracted geometry	Normal geometry
30.6	0.65×10^{36}	1.41×10^{36}	-
44.8	-	12.45×10^{36}	-
52.7	1.00×10^{36}	-	4.48×10^{36}
62.8	0.98×10^{36}	8.95×10^{36}	81.80×10^{36}

Table 3

Uncertainties in the absolute normalization of the π^0 inclusive cross-sections

Luminosity measurement	$\pm 7\%$		
Reconstruction efficiency	$\pm 5\%$		
Trigger efficiency plus acceptance calculation	$\pm 5\%$		
Other normalization uncertainty	$\pm 5\%$		
Absolute energy calibration	(Normal)	(Retracted)	(Super-retracted)
	40%	30%	25%
Total	42%	32%	27%

Table 4
Invariant cross-section for the reaction $p + p \rightarrow \pi^0 + \text{anything}$,
obtained with the retracted geometry

P_T range (GeV/c)	$\langle P_T \rangle$ (GeV/c)	$E(d^3\sigma/dp^3) \quad (\text{cm}^2/\text{GeV}^2 \text{ c}^{-3})$		
		$\sqrt{s} = 30.6 \text{ GeV}$	$\sqrt{s} = 52.7 \text{ GeV}$	$\sqrt{s} = 62.8 \text{ GeV}$
3.0-3.1	3.05	$(6.46 \pm 0.92) \times 10^{-32}$	$(2.93 \pm 0.40) \times 10^{-31}$	$(3.19 \pm 0.44) \times 10^{-31}$
3.1-3.2	3.15	$(5.02 \pm 0.73) \times 10^{-32}$	$(2.27 \pm 0.31) \times 10^{-31}$	$(2.55 \pm 0.35) \times 10^{-31}$
3.2-3.3	3.25	$(3.67 \pm 0.53) \times 10^{-32}$	$(1.66 \pm 0.23) \times 10^{-31}$	$(1.94 \pm 0.27) \times 10^{-31}$
3.3-3.4	3.35	$(2.69 \pm 0.41) \times 10^{-32}$	$(1.24 \pm 0.17) \times 10^{-31}$	$(1.52 \pm 0.21) \times 10^{-31}$
3.4-3.5	3.45	$(1.90 \pm 0.30) \times 10^{-32}$	$(9.52 \pm 1.31) \times 10^{-32}$	$(1.12 \pm 0.15) \times 10^{-31}$
3.5-3.6	3.55	$(1.29 \pm 0.21) \times 10^{-32}$	$(7.07 \pm 0.98) \times 10^{-32}$	$(8.53 \pm 1.18) \times 10^{-32}$
3.6-3.7	3.65	$(1.02 \pm 0.17) \times 10^{-32}$	$(5.40 \pm 0.75) \times 10^{-32}$	$(6.53 \pm 0.91) \times 10^{-32}$
3.7-3.8	3.75	$(7.01 \pm 0.13) \times 10^{-33}$	$(4.09 \pm 0.57) \times 10^{-32}$	$(5.17 \pm 0.72) \times 10^{-32}$
3.8-3.9	3.85	$(4.84 \pm 0.92) \times 10^{-33}$	$(3.13 \pm 0.44) \times 10^{-32}$	$(3.71 \pm 0.52) \times 10^{-32}$
3.9-4.0	3.95	$(3.52 \pm 0.72) \times 10^{-33}$	$(2.40 \pm 0.35) \times 10^{-32}$	$(3.02 \pm 0.43) \times 10^{-32}$
4.0-4.2	4.10	$(2.09 \pm 0.43) \times 10^{-33}$	$(1.48 \pm 0.21) \times 10^{-32}$	$(2.05 \pm 0.29) \times 10^{-32}$
4.2-4.4	4.30	$(1.06 \pm 0.24) \times 10^{-33}$	$(9.63 \pm 1.38) \times 10^{-33}$	$(1.25 \pm 0.18) \times 10^{-32}$
4.4-4.6	4.50	$(6.76 \pm 1.86) \times 10^{-34}$	$(6.18 \pm 0.91) \times 10^{-33}$	$(7.64 \pm 1.10) \times 10^{-33}$
4.6-4.8	4.70	$(3.43 \pm 1.22) \times 10^{-34}$	$(3.84 \pm 0.59) \times 10^{-33}$	$(5.19 \pm 0.78) \times 10^{-33}$
4.8-5.0	4.89	$(1.73 \pm 1.03) \times 10^{-34}$	$(2.46 \pm 0.40) \times 10^{-33}$	$(3.19 \pm 0.50) \times 10^{-33}$
5.0-5.4	5.18	$(7.65 \pm 3.07) \times 10^{-35}$	$(1.41 \pm 0.22) \times 10^{-33}$	$(1.97 \pm 0.30) \times 10^{-33}$
5.4-5.8	5.58	$(7.04 \pm 3.00) \times 10^{-35}$	$(6.10 \pm 1.22) \times 10^{-34}$	$(9.87 \pm 1.65) \times 10^{-34}$
5.8-6.2	5.97		$(2.74 \pm 0.59) \times 10^{-34}$	$(4.27 \pm 0.83) \times 10^{-34}$

Table 5

Invariant cross-section for the reaction $p + p \rightarrow \pi^0 + \text{anything}$,
obtained with the super-retracted geometry

p_T range (GeV/c)	$\langle p_T \rangle$ (GeV/c)	$E(d^3\sigma/dp^3)$ ($\text{cm}^2/\text{GeV}^2 \text{ c}^{-3}$) $\sqrt{s} = 30.6 \text{ GeV}$
4.0-4.5	4.20	$(2.28 \pm 0.25) \times 10^{-33}$
4.5-5.0	4.70	$(6.35 \pm 0.79) \times 10^{-34}$
5.0-5.5	5.20	$(1.86 \pm 0.30) \times 10^{-34}$
5.5-6.0	5.71	$(5.66 \pm 1.26) \times 10^{-35}$

p_T range (GeV/c)	$\langle p_T \rangle$ (GeV/c)	$E(d^3\sigma/dp^3)$ ($\text{cm}^2/\text{GeV}^2 \text{ c}^{-3}$)	
		$\sqrt{s} = 44.8 \text{ GeV}$	$\sqrt{s} = 62.8 \text{ GeV}$
4.0- 4.2	4.10	$(1.03 \pm 0.11) \times 10^{-32}$	$(2.29 \pm 0.23) \times 10^{-32}$
4.2- 4.4	4.30	$(6.44 \pm 0.66) \times 10^{-33}$	$(1.43 \pm 0.15) \times 10^{-32}$
4.4- 4.6	4.50	$(3.92 \pm 0.40) \times 10^{-33}$	$(8.96 \pm 0.92) \times 10^{-33}$
4.6- 4.8	4.70	$(2.46 \pm 0.25) \times 10^{-33}$	$(5.86 \pm 0.60) \times 10^{-33}$
4.8- 5.0	4.89	$(1.56 \pm 0.16) \times 10^{-33}$	$(3.84 \pm 0.40) \times 10^{-33}$
5.0- 5.4	5.18	$(8.00 \pm 0.83) \times 10^{-34}$	$(2.15 \pm 0.22) \times 10^{-33}$
5.4- 5.8	5.58	$(3.49 \pm 0.37) \times 10^{-34}$	$(9.52 \pm 0.99) \times 10^{-34}$
5.8- 6.2	5.97	$(1.53 \pm 0.17) \times 10^{-34}$	$(4.17 \pm 0.45) \times 10^{-34}$
6.2- 6.6	6.37	$(6.83 \pm 0.84) \times 10^{-35}$	$(2.33 \pm 0.26) \times 10^{-34}$
6.6- 7.0	6.80	$(3.67 \pm 0.49) \times 10^{-35}$	$(1.25 \pm 0.15) \times 10^{-34}$
7.0- 7.5	7.24	$(1.49 \pm 0.23) \times 10^{-35}$	$(5.78 \pm 0.73) \times 10^{-35}$
7.5- 8.0	7.70	$(5.99 \pm 1.25) \times 10^{-36}$	$(2.80 \pm 0.40) \times 10^{-35}$
8.0- 9.0	8.32	$(2.56 \pm 0.55) \times 10^{-36}$	$(1.14 \pm 0.17) \times 10^{-35}$
9.0-10.0	9.40	$(2.84 \pm 1.23) \times 10^{-37}$	$(2.28 \pm 0.52) \times 10^{-36}$

Table 6

Invariant cross-section for the reaction $p + p \rightarrow \pi^0 + \text{anything}$,
obtained with the normal geometry^{*)}

p_T range (GeV/c)	$\langle p_T \rangle$ (GeV/c)	$E(d^3\sigma/dp^3)$ (cm ² /GeV ² c ⁻³)	
		$\sqrt{s} = 52.7$ GeV	$\sqrt{s} = 62.8$ GeV
6.0- 7.0	6.50	$(1.57 \pm 0.37) \times 10^{-34}$	$(2.58 \pm 0.54) \times 10^{-34}$
7.0- 8.0	7.50	$(2.55 \pm 0.28) \times 10^{-35}$	$(4.89 \pm 0.52) \times 10^{-35}$
8.0- 9.0	8.50	$(5.63 \pm 0.74) \times 10^{-36}$	$(1.27 \pm 0.14) \times 10^{-35}$
9.0-10.0	9.50	$(1.47 \pm 0.27) \times 10^{-36}$	$(3.69 \pm 0.39) \times 10^{-36}$
10.0-12.0	11.00	$(1.80 \pm 0.57) \times 10^{-37}$	-
10.0-11.0	10.50	-	$(1.20 \pm 0.13) \times 10^{-36}$
11.0-12.0	11.50	-	$(4.28 \pm 0.51) \times 10^{-37}$
12.0-13.0	12.50	-	$(1.46 \pm 0.21) \times 10^{-37}$
13.0-14.0	13.50	-	$(4.50 \pm 1.00) \times 10^{-38}$
14.0-16.0	15.00	-	$(1.19 \pm 0.27) \times 10^{-38}$

*) In the earlier version of this preprint, the interpolation to the centre of the bin was not sufficiently accurate.

Figure captions

- Fig. 1 : Geometrical arrangement of the apparatus:
- a) Retracted geometry,
 - b) Super-retracted geometry,
 - c) Normal geometry.
- Fig. 2 : Internal layout of a calorimeter module.
- Fig. 3 : $M_{\gamma\gamma}$ invariant mass spectrum for $\sqrt{s} = 62.8$ GeV for:
- a) Retracted geometry,
 - b) Super-retracted geometry.
- Fig. 4 : π^0 invariant cross-section versus p_T at $\sqrt{s} = 30.6$ GeV (error bars include point-to-point systematic uncertainty).
- Fig. 5 : π^0 invariant cross-section versus p_T at $\sqrt{s} = 44.8$ GeV.
- Fig. 6 : π^0 invariant cross-section versus p_T at $\sqrt{s} = 52.7$ GeV.
- Fig. 7 : π^0 invariant cross-section versus p_T at $\sqrt{s} = 62.8$ GeV.
- Fig. 8 : The value of n evaluated as discussed in the text as a function of x_T (the error bars are statistical only). There is an additional common systematic error of ± 0.7 in n , as described in the text.

Fig. 1

Calorimeter sections
(16 channels)

"U" STRIPS

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

- $\sqrt{s_1} = 52.7, \sqrt{s_2} = 62.8$ NORMAL GEOMETRY
- $\sqrt{s_1} = 52.7, \sqrt{s_2} = 62.8$ RETRACTED GEOMETRY
- ◻ $\sqrt{s_1} = 30.6, \sqrt{s_2} = 52.7$ RETRACTED GEOMETRY
- △ $\sqrt{s_1} = 30.6, \sqrt{s_2} = 44.8$ SUPER-RETRACTED GEOMETRY
- × $\sqrt{s_1} = 44.8, \sqrt{s_2} = 62.8$ SUPER-RETRACTED GEOMETRY

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Fig. 8