

port No. SLAC-PUB-1107, 1972 (unpublished).

⁴C. H. Llewellyn-Smith, CERN Report No. CERN-Th-1621, 1973 (unpublished).

⁵S. S. Gerstein and V. N. Folomeshkin, *Yad. Fiz.* **8**, 768 (1969) [*Sov. J. Nucl. Phys.* **8**, 447 (1969)].

⁶Ph. Heusse *et al.*, in *Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, 1972*, edited by J. D. Jackson and A. Roberts (National Accelerator Laboratory, Batavia, Ill., 1973), paper No. 783.

⁷D. H. Perkins, in *Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, 1972*, edited by J. D. Jackson and A. Roberts (National Accelerator Laboratory, Batavia, Ill., 1973), Vol. 4,

p. 211.

⁸B. C. Barish, J. F. Bartlett, D. Buchholz, T. Humphrey, F. Merritt, Y. Nagashima, F. J. Sciulli, D. Shields, H. Suter, G. Krafczyk, and A. Maschke, Caltech Report No. CALT-68-396, 1973 (to be published).

⁹A. Benvenuti, D. Chang, D. Cline, W. T. Ford, R. Imlay, T. Y. Ling, A. K. Mann, F. Messing, J. Pilcher, D. D. Reeder, C. Rubbia, and L. Sulak, *Phys. Rev. Lett.* **30**, 1084 (1973).

¹⁰A. Bodek, thesis, Massachusetts Institute of Technology Report No. COO-3069-116, 1973 (unpublished).

¹¹B. C. Barish, J. F. Bartlett, D. Buchholz, T. Humphrey, F. Merritt, Y. Nagashima, F. J. Sciulli, D. Shields, H. Suter, G. Krafczyk, and A. Maschke, *Phys. Rev. Lett.* **31**, 180 (1973).

Inclusive π^- Distributions from 205-GeV/c pp Interactions*

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Inclusive π^- distributions from 205-GeV/c pp interactions, covering the full range of longitudinal and transverse momenta, have been obtained using the 30-in. hydrogen bubble chamber at the National Accelerator Laboratory. These data provide new evidence for scaling in the fragmentation region and for a plateau in the central region of rapidity. The 90°-c.m. invariant cross section varies as $\exp[-(10 \pm 2)P_T^2]$ in the range $P_T^2 \leq 0.1$ (GeV/c)².

In this Letter, we report on a measurement of the single-particle inclusive distribution for the reaction $pp \rightarrow \pi^- + \text{anything}$ at 205 GeV/c. This measurement covers the entire range in both the center-of-mass longitudinal (P_L^*) and transverse (P_T) momenta. This is also the highest energy at which a single experiment covering the entire range of these variables has been reported. Similar data^{1,2} have been reported from the CERN intersecting storage rings (ISR). These ISR experiments cover various restricted intervals of P_L^* and P_T , at energies corresponding to laboratory momenta between 225 and 1500 GeV/c.

Our data were obtained from approximately 17 000 pictures taken with the 30-in. hydrogen bubble chamber exposed to a 205-GeV/c proton beam at the National Accelerator Laboratory (NAL). The results reported here are confined to negative-particle production. Ordinarily, the measurement of momenta and angles of secondary

tracks in a bubble chamber is a routine matter. However, for this high beam momentum and for high-multiplicity events, there are practical complications involving track matching in the different stereoscopic views, overlapping track images, and poor momentum determination for fast forward-going secondaries. To determine how these complications might affect our data, we have made two independent sets of measurements, using somewhat different experimental methods.

Following the scan³ of the film, a fiducial volume was selected that yielded a 20-cm minimum track length for outgoing tracks. For the first measurement method, each view was examined at high magnification (6 times life size), and the spatial pattern of the bubbles was used to match all secondary tracks. The event was then measured in two views and spatially reconstructed using TVGP. For the second method, a minimum-sagitta criterion was used to determine which

negatively charged secondary tracks were candidates for production in the backward c.m. hemisphere.⁴ These tracks were then measured in three views and processed through TVGP, using a computer track-matching program. The numbers of events (negative tracks) analyzed by each method were 440 (1250) and 1484 (1854), respectively. The two methods yielded compatible results in a track-by-track test as well as compatible distributions for the entire samples, and the data have been combined.

Typical measurement errors in $y^* = \tanh^{-1}(P_L^*/E^*)$, P_T , and $x = 2P_L^*/\sqrt{s}$ were also determined by repeated measurements of a sample of the events. For 40-GeV/c negative tracks ($x \approx +0.2$; 95% of the negative tracks have lower momenta), typical errors are $\Delta y^* \sim 0.2$, $\Delta P_T \sim 0.1$ GeV/c, and $\Delta x \sim 0.03$. These, as well as the smaller errors associated with backward hemisphere and 90° c.m. tracks, provide ample resolution for the spectra presented here.

Since pp collisions are symmetric in the c.m. system, the backward hemisphere is equivalent,

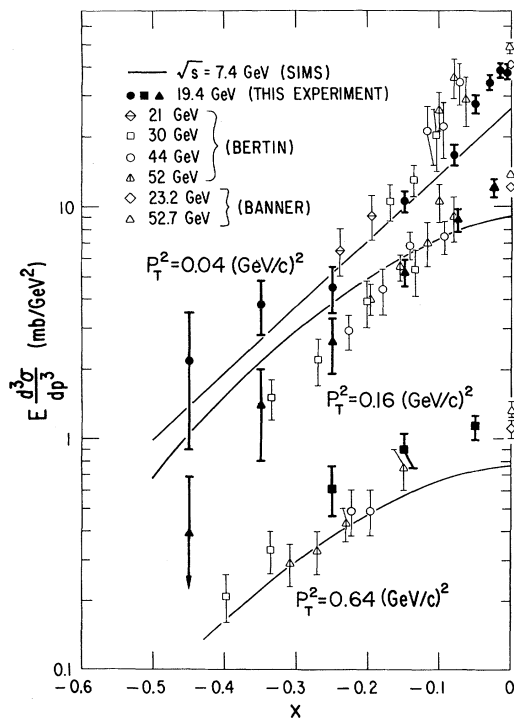


FIG. 1. The inclusive π^- invariant cross section as a function of x for different P_T^2 values. All cross sections given in this paper refer to only one hemisphere, and must be integrated over both hemispheres to obtain total cross sections. Errors given in this paper include estimates of both statistical and systematic uncertainties.

for single-particle spectra, to the entire solid angle. This symmetry may be used to check the track selection and measurements for the above two methods. However, to exploit this symmetry and to calculate kinematic quantities (e.g., rapidity) on an individual track basis requires mass identification, which we do not have.

Since the negative tracks are mostly pions, we have used a simple Monte Carlo technique to estimate the effects of the K^- and \bar{p} contamination. We tried several functional forms for the K^- and \bar{p} spectra with intensities⁵⁻⁷ of 7% K^- 's and 2% \bar{p} 's in the Monte Carlo generation. The resulting corrections⁸ were insensitive to reasonable variations of the shape of the K^- and \bar{p} spectra.

Figure 1 shows the π^- invariant cross section $Ed^3\sigma/dp^3$ as a function of x for different values of P_T^2 .⁹ Also shown are published data at 28.5 GeV/c¹⁰ and at ISR energies.^{1,2} For $|x| \geq 0.1$, the data are equal within errors to the ISR results.

Figure 2 shows $Ed^3\sigma/dp^3$ as a function of P_T^2 for $|x| \leq 0.02$,¹¹ as well as the integral with respect to x of the invariant cross section. The integrated distribution at 205 GeV/c is very similar to the distribution observed¹⁰ at 28.5 GeV/c. Our $|x| \leq 0.02$ ($\sim 90^\circ$ c.m.) data are in good agreement with ISR data² for $x \approx 0$ and $P_T \geq 0.23$ GeV/c.

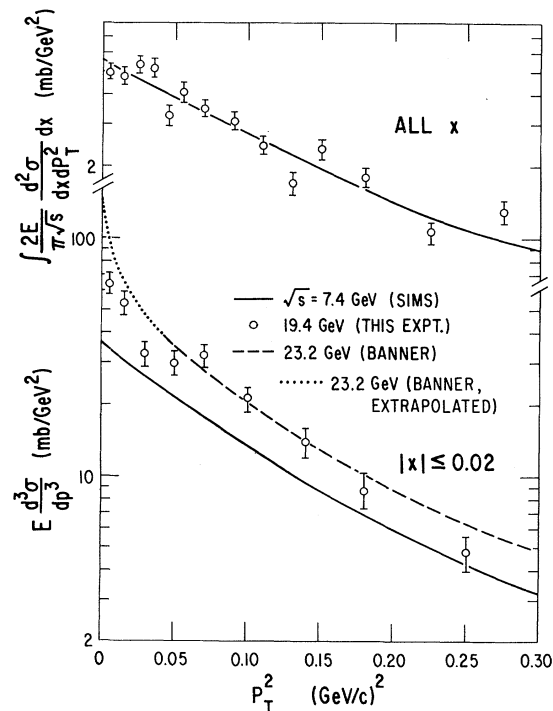


FIG. 2. Inclusive π^- invariant cross section at 90° c.m. as a function of P_T^2 . Also shown is the invariant cross section integrated from $x=0$ to $x=1$.

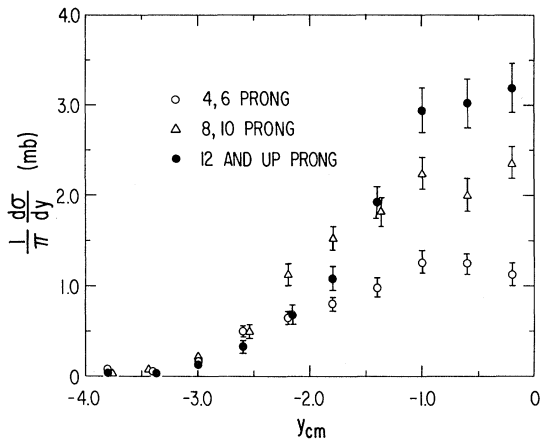


FIG. 3. The π^- rapidity distributions for various charged multiplicities.

The dashed curve is given by $146 \exp(-6.39P_T + 0.36P_T^2)$ and is taken from the fit of Banner *et al.*² to their $\sqrt{s} = 23.2$ -GeV data. The extrapolation of this curve into the region $P_T < 0.23$ GeV/c is also shown. It is clear that the extrapolated curve lies considerably above our data points.

In the range $P_T^2 \leq 0.1$ (GeV/c)², our 90° invariant cross section is well fitted by $(55 \pm 4) \exp[-10 \pm 2)P_T^2]$. A similar Gaussian behavior at small P_T (for $x \approx 0.2$) has previously been observed at 12 GeV/c by Akerlof *et al.*¹² and at 24 GeV/c by Allaby *et al.*¹³ In these low-energy experiments, the data are not consistent with an $\exp(-BP_T)$ variation at small P_T . Our 90° c.m. data also favor a Gaussian variation at small P_T , and are inconsistent with the exponential behavior at small P_T given by the extrapolation of the fit of Banner *et al.*²

The small- P_T region is quite important in determining the behavior of $\pi^- d\sigma/dy$ in the central region as a function of s . The region $P_T^2 \leq 0.05$ (GeV/c)², according to our data, contains $\sim 33\%$ of the 90° cross section.

Integrating our data over P_T^2 , we obtain

$$\pi^{-1}(d\sigma/dy)_{y^*=0} = 6.5 \pm 0.5 \text{ mb.}$$

The fit of Banner *et al.* to their ISR data, when integrated over all P_T , gives $\pi^{-1}(d\sigma/dy)_{y^*=0} = 7.7 \pm 0.5$ mb. However, if the form $A \exp(-BP_T^2) + C \exp(-DP_T^2)$, which is consistent with both our data and low energy data, were used with the data of Banner *et al.*, the 90° cross section would decrease by $\sim 15\%$. Therefore, the absolute value of the integrated 90° cross section at the ISR energies is correspondingly uncertain.

In Fig. 3 we present our rapidity distributions

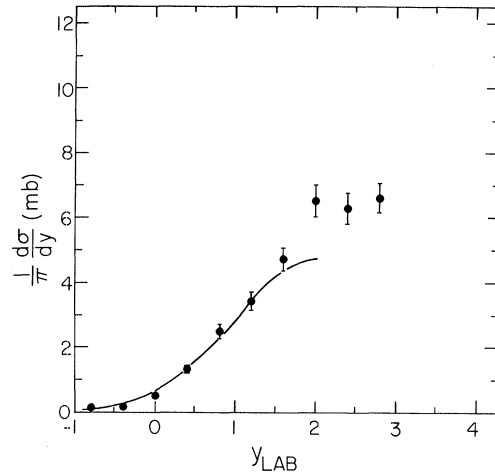


FIG. 4. The inclusive π^- rapidity distribution at 205 GeV/c. The curve represents the 28.5-GeV/c data.

for various multiplicities.¹⁴ There is a definite trend¹⁵ for the width of the distribution to decrease as the multiplicity increases. The rms width of the highest multiplicity data shown in Fig. 3 is a factor of 1.3 ± 0.1 smaller than that of the lowest multiplicity data.

Figure 4 shows the π^- inclusive rapidity distribution (summed over all multiplicities) and a comparison with the 28.5-GeV/c data. Because of the above inconsistency between our results at low P_T and the P_T parametrization used for some of the ISR data, we have not shown integrated ISR results in Fig. 4.

From the rapidity data shown in Fig. 4, we note the following:

(1) The scaling of the invariant cross section $Ed^3\sigma/dp^3$ in the fragmentation region appears as scaling for $\pi^{-1}d\sigma/dy$ for $y_{\text{lab}} \lesssim 1$ and seems to occur at energies less than 30 GeV/c. In this y region, our $d\sigma/dy$ results are equal to those at 28.5 GeV/c within the experimental precision of $\sim \pm 10\%$.

(2) Our data show evidence for a plateau in the central region. The full width of the plateau is of the order of two units of rapidity. In fact, even the separate multiplicity curves in Fig. 3 are individually consistent with such a plateau.

(3) $d\sigma/dy$ for π^- in the central region is increasing with s ; i.e., scaling, if it occurs in this region, is being approached from below.

Finally, it is interesting to point out that Landau's hydrodynamical model¹⁶ is not ruled out by the inclusive distributions shown here. This model predicts a Gaussian distribution in rapidity

ity and provides an adequate description of our data.

We wish to thank the 30-in. bubble chamber crew and the staff of the neutrino laboratory at NAL for their help in obtaining this exposure. We are also extremely grateful to the scanning and measuring personnel at both Argonne National Laboratory and NAL for their conscientious efforts. Finally, it is with pleasure that the NAL authors and R. Engelmann acknowledge most informative discussions with E. L. Berger and M. Jacob in the early stages of this analysis.

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¹A. Bertin *et al.*, Phys. Lett. **38B**, 260 (1972).

²M. Banner *et al.*, Phys. Lett. **41B**, 547 (1972).

³G. R. Charlton *et al.*, Phys. Rev. Lett. **29**, 515 (1972).

⁴For pion production at 90° c.m., the maximum laboratory momentum is 15 GeV/c, assuming a transverse momentum limit of 1.45 GeV/c.

⁵G. R. Charlton *et al.*, Phys. Rev. Lett. **30**, 574 (1973). They find $2\sigma(K_s^0)/\sigma(\pi^-) = 0.17 \pm 0.02$.

⁶M. G. Albrow *et al.*, Phys. Lett. **40B**, 136 (1972).

⁷A. Bertin *et al.*, Phys. Lett. **41B**, 201 (1972).

⁸The resulting π^- fraction as a function of y in the backward c.m. hemisphere ranges from 0.90 to 0.98. In the forward hemisphere, the pion contribution varies from 0.91 at 90° to ~ 0.70 in the beam fragmentation re-

gion. After applying these corrections, our distributions are consistent with forward-backward c.m. symmetry.

⁹For purposes of comparison, we show our data for the following P_T^2 intervals: (0, 0.08), (0.12, 0.20), and (0.4, 0.7) (GeV/c)². The data of W. H. Sims *et al.* [Nucl. Phys. **B41**, 317 (1972)] are integrated over the following P_T^2 intervals: (0.035, 0.045), (0.14, 0.18), and (0.54, 0.74) (GeV/c)².

¹⁰Sims *et al.*, Ref. 9; J. Hanlon, private communication.

¹¹We have also tried using rapidity ($|y^*| \leq 0.8$) rather than x to select a region near 90° c.m. The results were unchanged by this procedure or by narrowing the x or y^* interval.

¹²C. W. Akerlof *et al.*, Phys. Rev. D **3**, 645 (1971).

¹³J. V. Allaby *et al.*, in *Proceedings of the Fourth International Conference on High Energy Collisions, Oxford, England, 1972* (Rutherford High Energy Laboratory, Chilton, Didcot, Berkshire, England, 1972).

¹⁴The results of Ref. 5 indicate that the kaon fraction is roughly independent of multiplicity. We also assume a similar behavior for \bar{p} .

¹⁵Preliminary indications of this trend have been reported by J. Whitmore *et al.* and G. Bellettini *et al.*, in *Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, September 1972*, edited by J. D. Jackson and A. Roberts (National Accelerator Laboratory, Batavia, Ill., 1973), Vol. I.

¹⁶S. Z. Belenkji and L. D. Landau, Nuovo Cimento Suppl. **3**, 15 (1956); P. Carruthers and M. Duong-Van, Phys. Lett. **41B**, 597 (1972); F. Cooper and E. Schonberg, Phys. Rev. Lett. **30**, 880 (1973).