Inclusive ρ^0 and f^0 production in 100-GeV/c $\bar{p}p$ interactions

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Inclusive and semi-inclusive ρ^0 production in 100-GeV/c $\bar{p}p$ interactions has been studied as a function of c.m. rapidity and transverse momentum. Cross sections are compared with those for $\bar{p}p$ interactions at other energies, as well as pp and $\pi^{\pm}p$ interactions, over the range $\sim 2 < p_{\text{lab}} < 200$ GeV/c. A measurement of the f^0 production cross section has been made. Calculations of the contribution from ρ^0 decay to prompt lepton production are presented.

Very little is known about inclusive meson resonance production in high-energy antiproton-proton collisions; the highest-energy results available are at 12 GeV/c.[1] From correlation studies in high-energy collisions, there is mounting evidence that most of the final-state particles result from the decay of particle clusters and some[2] have interpreted these clusters as being resonances. An experimental determination of resonance production cross sections is therefore of importance. Also, by a comparison of $\bar{p}p$ data with the results obtained in pp interactions, one may investigate the extent of meson resonance production in annihilation events. In view of the fact that little is known about the properties of $\bar{p}p$ annihilation above 12 GeV/c,[1] this is an important first step in understanding this process at high energies. Finally, current studies of direct lepton production in hadronic reactions suggest that meson resonance decay is an obvious source of leptons and, in particular, has not been measured in $\bar{p}p$ interactions above ~ 20 GeV/c.

The data presented here were obtained from a 98 000-picture exposure of the 30-in. bubble-chamber–wide-gap-spark-chamber hybrid system at Fermilab.[3] Data on particle multiplicities, neutral particles, and $\pi^{\pm}$ production have been published elsewhere.[4] The results presented here are based on an inclusive sample of 9364 inelastic events. Figure 1(a) shows the $\pi^+\pi^-$ mass distribution for all inelastic events. All tracks not identified as a proton by ionization ($p_{\text{lab}} > 1.4$ GeV/c) have been included as $\pi^{\pm}$. The $\pi^{\pm}\pi^{\pm}$ mass distribution (not shown) shows no structure and is reasonably well fitted (in the region $0.5 < m_{\pi\pi} < 1.0$ GeV/c) by an exponential function of mass.

The average mass resolution for ρ^0's produced in the central region is estimated to be $\simeq \pm 50$ MeV.

A fit to the inclusive $\pi^+\pi^-$ mass spectrum was performed in the mass region 0.5–1.0 GeV using an exponential background and a p-wave Breit-Wigner formula[5] with the mass and width of the ρ^0 allowed to vary. We find (3050 ± 700) ρ^0's above background with $M(\rho^0) = (734\pm10)$ MeV and $\Gamma(\rho^0) = (175\pm10)$ MeV. On the basis of this fit [shown as the solid line in Fig. 1(a)] we determine that there are (0.33 ± 0.06) ρ^0's per inelastic event, corresponding to an inclusive cross section of (11.4 ± 2.5) mb. This indicates that $\sim 12.5\%$ of the $\pi^{\pm}$'s are the result of ρ^0 decay. We note that the ρ^0 mass given by the fit is substantially lower than its commonly quoted value of (773 ± 3) MeV.[6] A similar shift in the ρ^0 mass has been observed in $\bar{p}p$ reactions previously.[7]

Figure 2 shows the inclusive ρ^0 cross section plotted as a function of beam momentum for pp,[8] $\bar{p}p$,[1,9] and $\pi^{\pm}p$ (Ref. 10) interactions. The data are consistent with a logarithmic rise with p_{lab} with the exception of $\bar{p}p$ at low energies. The rapid fall and then slow rise of the inclusive ρ^0 cross section in $\bar{p}p$ interactions is similar to that observed for inclusive $\pi^{\pm}$ production[4] and is presumably related to the different energy dependences of the non-annihilation and annihilation contributions. A fit to the formula $\sigma = A \ln(p_{\text{lab}}) + B$ gives the value (7.3 ± 0.7) mb for the 100-GeV/c pp inclusive ρ^0 cross section. The difference between ρ^0 cross sections in $\bar{p}p$ and pp interactions at 100 GeV/c is therefore (4.1 ± 2.2) mb and may be interpreted as the annihilation component of $\bar{p}p \to \rho^0 X$. We note that at 12 GeV/c, Gall *et al.*[1] quote a $\bar{p}p \to \rho^0$ inclusive cross section of (6.5 ± 0.5) mb, of which (4.4 ± 0.4) mb is due to annihilations. Subtraction of $\bar{p}p$ and pp ρ^0 cross sections at 12 GeV/c yields (4.7 ± 0.6) mb; hence identifying $\bar{p}p$ and pp differences as the annihilation contribution appears to
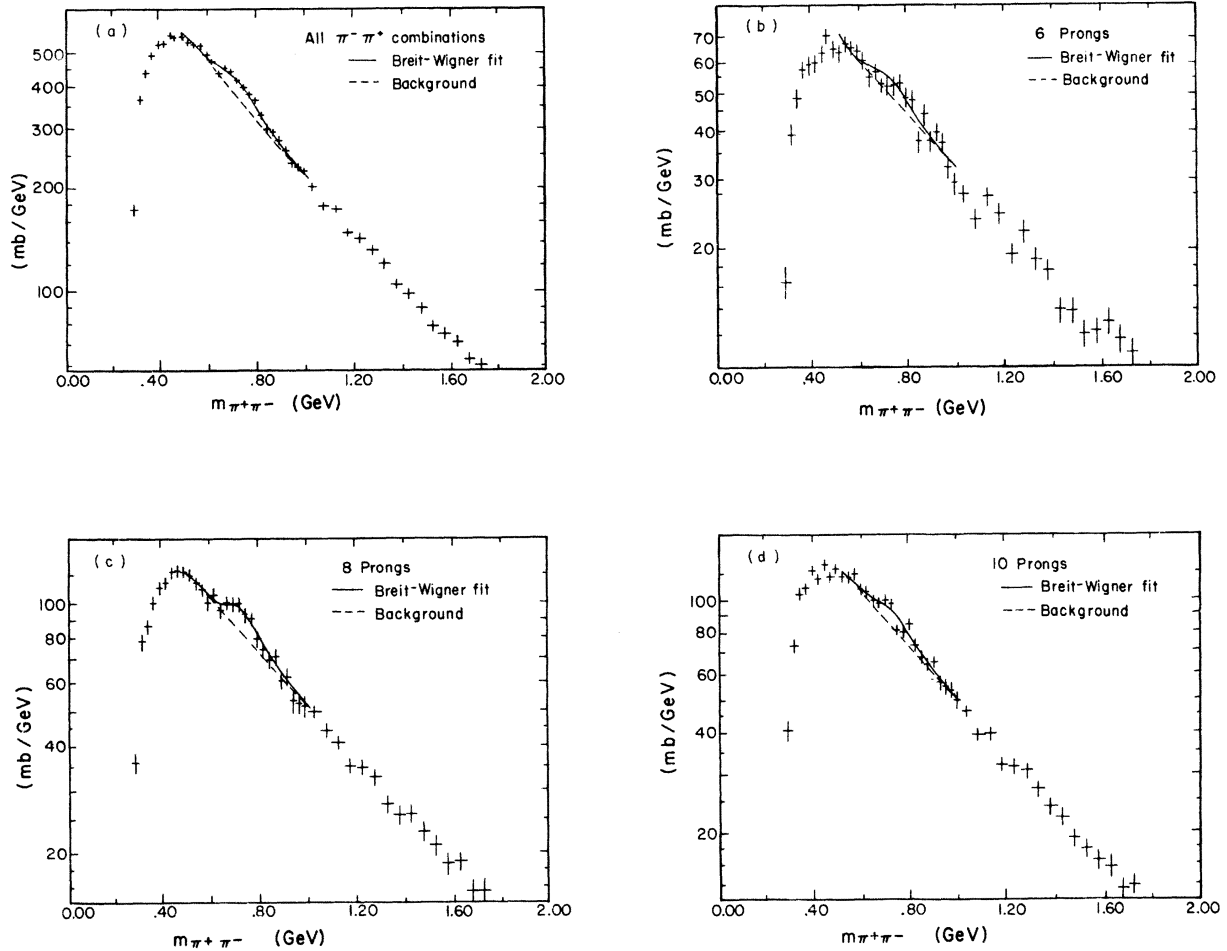
FIG. 1. The $\pi^+\pi^-$ invariant-mass ($m_{\pi^+\pi^-}$) distribution resulting from inelastic events for (a) all, (b) six-prong, (c) eight-prong, and (d) ten-prong events. The curves correspond to fits to a Breit-Wigner form (solid) plus background (dashed).

be a reasonable first approximation. Since the difference between $\bar{p}p$ and pp inelastic cross sections[4] (≥ 4 prongs) at 100 GeV/c is (3.6 ± 0.7) mb, the above discussion suggests that there are (1.2 ± 0.7) ρ^0's per annihilation event. We also note that in a sample of $\bar{p}p$ nonannihilation events with a slow proton ($p_{lab} < 1.4$ GeV/c) there is an average of (0.21 ± 0.04) ρ^0's/event, suggesting that annihilation events are substantially richer in ρ^0's than nonannihilation events.

To obtain semi-inclusive ρ^0 cross sections, the mass and width of the ρ^0 were fixed at 734 and 175 MeV respectively and fits were carried out on the semi-inclusive $\pi^+\pi^-$ mass spectra [see, for example, Figs. 1(b)–1(d)], subject to the condition that the semi-inclusive cross sections add up to the inclusive cross section as determined above. The above value of the width is greater than the
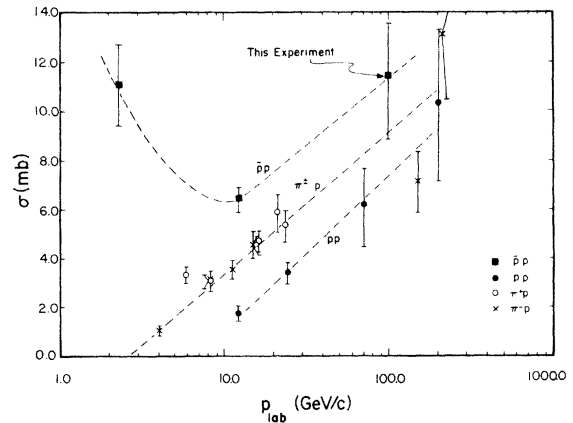

FIG. 2. Inclusive ρ^0 cross sections for $\bar{p}p$, pp, and $\pi^{\pm}p$ interactions versus beam laboratory momentum. The curves are drawn to guide the eye.

standard value[6] in order to allow for the loss in resolution for forward hemisphere tracks. The fitted cross sections are not very sensitive to changes in the width; the cross sections obtained with the standard value for the width of 150 MeV are well within errors of the values quoted in Table I. The data indicate that ρ^0's are associated, on the average, with higher charged multiplicities than, for example, neutral pions.[4]

To investigate the production characteristics of ρ^0's, the data were divided into different ranges of the center-of-mass rapidity of the $\pi^+\pi^-$ combination and fits to the mass distribution were carried out for each rapidity range. It is observed [Fig. 3(a)] that ρ^0 production is dominantly central; the width of the rapidity distribution at half maximum is approximately one unit, similar to that observed for γ's.[4] By comparison with 12-GeV/c data,[1] it is seen that the rise in the ρ^0 cross section between 12 and 100 GeV/c is mainly due to the increase in

TABLE I. Semi-inclusive cross sections.

Charged multiplicity	ρ^0 cross section (mb)	$\langle\rho^0\rangle$
2	...	...
4	0.45 ± 0.31	0.06 ± 0.04
6	1.18 ± 0.56	0.14 ± 0.07
8	3.75 ± 0.91	0.54 ± 0.13
10	2.03 ± 0.90	0.49 ± 0.21
12	2.14 ± 0.92	0.97 ± 0.42
14	$0.66^{+0.87}_{-0.66}$	$0.73^{+0.97}_{-0.73}$
≥ 16	$1.24^{+1.63}_{-1.24}$	$2.3^{+3.1}_{-2.3}$
Total	11.4 ± 2.5	0.33 ± 0.06

the range of available rapidity and not due to an increase in central production.

This is in distinct contrast to the pp case.[11] The different energy dependences of the annihilation and nonannihilation components in $\bar{p}p$ interactions are probably responsible for this feature, rather than scaling. Data at a third energy will help settle this question.

The transverse-momentum distribution of ρ^0's is found to be consistent with an exponential in $p_T{}^2$; the slope $[2.2 \pm 0.8$ $(\text{GeV}/c)^{-2}]$ is smaller than that observed at 12 GeV/c $[4.1 \pm 0.4$ $(\text{GeV}/c)^{-2}]$. The average transverse momentum of ρ^0's is (0.54 ± 0.12) GeV/c, a value substantially larger than that
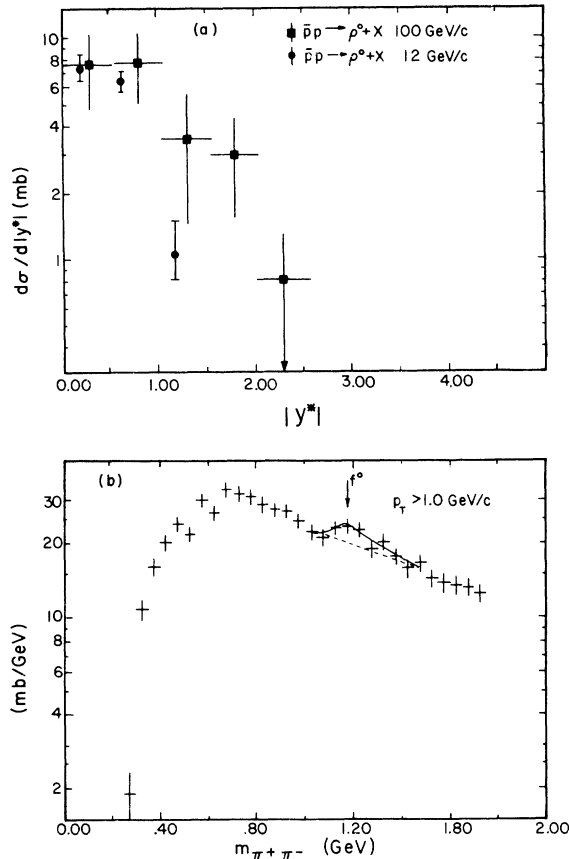

FIG. 3. (a) c.m. ρ^0 rapidity distribution at 12 GeV/c (Ref. 1) and 100 GeV/c and (b) the $\pi^+\pi^-$ invariant-mass ($m_{\pi^+\pi^-}$) distribution for $p_T(\pi^+\pi^-) > 1.0$ GeV/c. The curves correspond to a fit to a Breit-Wigner form (solid) plus background (dashed).
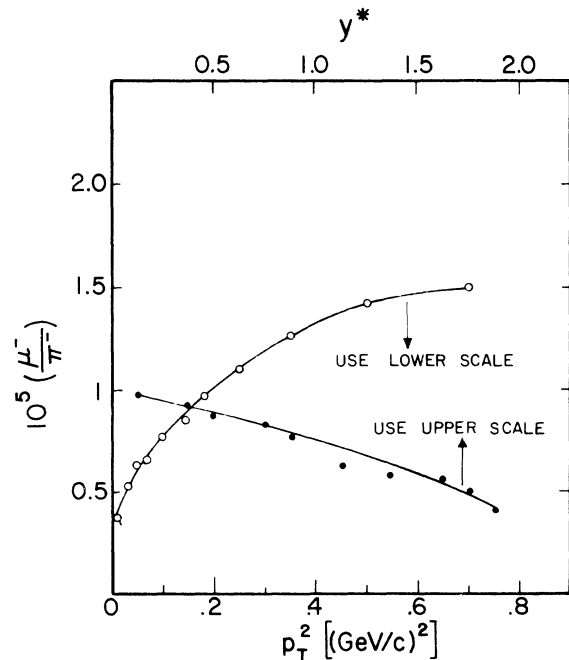

FIG. 4. The ratio μ^-/π^- determined in this experiment as a function of the ρ^0 transverse momentum (p_T) and c.m. rapidity (y^*).

for γ's, K_S^0's, and $\pi^\pm$'s (0.345 ± 0.002 GeV/c) in this experiment.[4] In the higher transverse-momentum region, there is evidence for f^0 production, as illustrated in Fig. 3(b) where we show the $\pi^+\pi^-$ mass distribution of $p_T(\pi^+\pi^-)>1$ GeV/c. In the mass range 1.0 to 1.5 GeV/c, a fit including an exponential background and a d-wave Breit-Wigner contribution, allowing for the branching ratio[6] into $\pi^+\pi^-$, yields an f^0 cross section of (1.2 ± 0.6) mb for $p_T>1$ GeV/c.

Using the rapidity and transverse-momentum distributions of ρ^0's as determined from this experiment, we have calculated the ρ^0 contribution to prompt lepton production assuming[6] a $\mu^+\mu^-$ branching fraction of 6.7×10^{-5}. The results are presented in Fig. 4, which shows the ρ^0 contribution to the ratio μ^-/π^- as a function of p_T and center-of-mass rapidity, y^*. The average ratio μ^-/π^- is found to be (0.8 ± 0.2)$\times10^{-5}$. It will be interesting

to compare this result with a measurement of the inclusive muon production in $\bar{p}p$ interactions at this energy in the future.

In conclusion, we have observed several interesting features in ρ^0 production in high-energy $\bar{p}p$ interactions. This analysis suggests an enrichment of ρ^0's in an annihilation process as compared to a nonannihilation process. We observe that most ρ^0's are produced centrally in a manner similar to pions; however, the central production cross section does not increase in the energy range 12 to 100 GeV/c, in contrast to pp collisions. For higher transverse momenta (>1.0 GeV/c) we find evidence for substantial f^0 production, observed at the level of $\sim30\%$ of $\pi^\pm$ production and $\sim90\%$ of ρ^0 production. Finally, the contribution of ρ^0 decay to a measurement of prompt lepton production in 100-GeV/c $\bar{p}p$ interactions (as yet unmeasured) is expected to be 0.8×10^{-5} of charged pion production.

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