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PERIPHERAL NUCLEON-ANTINUCLEON PRODUCTION BY 13 GeV/c PIONS*

R. S. Dulude[†] and J. A. Gaidos

Physics Department, Purdue University,
 Lafayette, Indiana 47907

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ABSTRACT

A measurement of the cross sections for $\pi^+ p \rightarrow (\bar{p}n)p$ and $\pi^- p \rightarrow (\bar{p}n)p$ within the range $-t(pp) < 0.5 \text{ (GeV/c)}^2$ corresponding to identifiable recoil protons and with mass $m(N\bar{N}) < 2.7 \text{ GeV}$ for unambiguous one-constraint fits yields values of $25.9 \pm 1.6 \text{ } \mu\text{b}$ at 13.1 GeV/c and $29.1 \pm 2.4 \text{ } \mu\text{b}$ at 13.2 GeV/c , respectively. The angular distributions of $N\bar{N}$ vary strongly with $m(N\bar{N})$ and suggest high spins. The cross section for $\pi^+ p \rightarrow (p\bar{p})\Delta^{++}$ with $t'(p\Delta) < 0.75 \text{ (GeV/c)}^2$ is $3.7 \pm 0.4 \text{ } \mu\text{b}$ and may be mediated by M1 p-exchange.

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Introduction:

We present data on the reactions

$$\pi^+ p \rightarrow (p\bar{n})p \quad (1)$$

$$\pi^- p \rightarrow (\bar{p}n)p \quad (2)$$

$$\pi^+ p \rightarrow (p\bar{p})\Delta^{++} \quad (3)$$

at 13.1 GeV/c and 13.2 GeV/c incident π^+ and π^- momenta. These data were obtained from 34.3 and 9.7 events per microbarn exposures of the SLAC 82-inch hydrogen bubble chamber. This paper is a continuation of our work on peripherally produced nucleon-antinucleon pairs previously reported for reaction (1) [1].

To insure reliable isolation of the one-constraint class of reactions (1) and (2), a restriction to clearly identifiable recoil protons was enforced, corresponding to a laboratory momentum of less than 0.75 GeV/c; however, inasmuch as the reaction is highly peripheral, few events are lost through this selection criterion. Similar observations have been made in studies of the reaction $\pi^- p \rightarrow (\bar{p}p)n$ at 18.8 and 9.8 GeV/c in a wire chamber spectrometer at CERN [2] and in the preliminary report on reaction (2) at 12 GeV/c from the OMEGA Spectrometer at CERN [3].

Reactions (1) and (2) are particularly interesting because the $N\bar{N}$ pair is produced in a pure $I = 1$ state and reaction (3) has the feature that additional information is available through the measurable polarization of the Δ^{++} .

Secondary interactions of the antinucleons were sufficiently copious to serve as a check on the production cross sections.

Data:

Event samples of reaction (1) and (2) were culled respectively from 215,000 and 89,000 measured two-prong interactions by selections on

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missing mass, chi-squared probability and identifiable recoil protons. Each candidate was examined by a physicist for ionization consistency, secondary interactions and possible associated gamma conversions or vees.

Because of the tendency of the peripherally produced nucleon-anti-nucleon pairs to accumulate at low $m(N\bar{N})$ mass values and hence within a very restrictive kinematical configuration corresponding to the low Q-value, successful fits to alternative reaction hypotheses were rare in this region and initially no events with ambiguous fits were accepted. However, for large values of $m(N\bar{N})$ the number of ambiguous fits increases because of an inability to resolve events when the outgoing charged track exceeds ~ 9 GeV/c in the laboratory. These ambiguous events occur in a very narrow kinematical region and corrections are easily made for 88% of the data for which $m(N\bar{N}) < 2.7$ GeV/c, based upon smooth interpolation from adjacent kinematical regions and consistent with cross section ratios of the ambiguous channels as well as compatible with observed annihilation rates. Data of reactions (1) and (2) for $m(N\bar{N}) < 2.7$ GeV were corrected by $\sim 3\%$, from 1017 to 1046 events, whereas for $m(N\bar{N}) > 2.7$ GeV the correction is $\sim 37\%$, from 124 to 170 events. For this latter high mass region, the charged peripheral baryon is usually produced parallel to the beam and those in the forward direction are nearly always unresolvable. For quantitative considerations, we will confine our discussion to $m(N\bar{N}) < 2.7$ GeV and $|t_{(pp)}| < 0.5$ (GeV/c)² for reactions (1) and (2).

The four-constraint reaction (3) presented no ambiguity problems for $|t'(p\Delta)| < 0.75$ (GeV/c)², where $m(\Delta^{++}) = m(\pi^+p) < 1.4$ GeV is satisfied by only one π^+p combination for each event. A conspicuous Δ^{++} is

shown clearly in fig. 1, where the pi-plus in $\pi^+ p \rightarrow \pi^+ p p \bar{p}$ is combined with the proton of lesser center-of-mass longitudinal momentum.

Indicating the number of events after corrections for ambiguous fits by parentheses, the data samples and cross sections for $m(N\bar{N}) < 2.7$ GeV and $-t(pp) < 0.5$ (GeV/c)² are 762 (779) events and 25.9 ± 1.6 μ b for reaction (1), and 255 (267) events and 29.1 ± 2.4 μ b for reaction (2). For $m(N\bar{N}) > 2.7$ GeV and $-t(pp) < 0.5$ (GeV/c)² there are respectively 90 (112) and 34 (58) events in our samples of reactions (1) and (2). By including the entire $m(N\bar{N})$ mass range and an extrapolating over t , the cross sections for channels (1) and (2) are 34 ± 3 and 38 ± 5 μ b.

There are 141 events in reaction (3) for $|t'(p\Delta)| < 0.75$ (GeV/c)² corresponding to a cross section of $3.7 \pm .4$ μ b, in which a Breit-Wigner function and smooth polynomial background were used to describe the low-mass $\pi^+ p$ system.

Cross Sections:

The cross sections of reactions (1) and (2) given above can be checked approximately from the secondary $\bar{N}p$ interactions by using these values to specify the $\bar{N}$ flux and from the known $\bar{N}p$ topological cross sections to predict the number of secondary interactions within our fiducial volume. The cross sections for $\bar{p}p \rightarrow 4, 6, 8$ prongs are reasonably constant for the $\bar{N}$ laboratory momentum in this experiment, which averages at ~ 6 GeV/c; the cross sections are $\sim 17, 7$ and 1.5 mb for 4, 6 and 8 prongs respectively, for a sum of ~ 25 mb [4]. These values should also be applicable for $\bar{n}p \rightarrow 3, 5, 7$ prongs corresponding to the same number of positive charges produced in the reaction. Accordingly, for $m(p\bar{n}) < 2.7$ GeV, we should have observed ~ 72 reactions of $\bar{n}p \rightarrow 3, 5, 7$ prongs and did find 68; similarly, we expected ~ 24 events of

$\bar{p}p \rightarrow 4, 6, 8$ prongs from reaction (2) and found 18. Topological distributions are also in good agreement with predictions. Expected fractional partition into 3, 5, 7 or 4, 6, 8 prongs is 0.67, 0.27, 0.06 compared with the observed values of 0.56 ± 0.08 , 0.30 ± 0.06 , 0.15 ± 0.04 and 0.72 ± 0.20 , 0.28 ± 0.12 , $0 \pm .05$ for the $\bar{p}p$ and $\bar{p}p$ secondaries respectively from reactions (1) and (2).

This same procedure was applied to reaction (3) where the number of 4, 6, 8 prong secondaries was expected to be 23.8, 8.8, 1.3 and found to be 24, 7, 1, also in excellent agreement.

Results from the study of $\pi^-p \rightarrow (p\bar{p})n$ in comparable $m(N\bar{N})$ and $t(pp)$ regions yield a cross section of $\sim 6 \mu b$ [2], some five times smaller than reactions (1) or (2). Furthermore, a convincing argument based upon the angular distribution of the $(p\bar{p})$ system and the $t(pn)$ behavior strongly suggests that this reaction is mediated by one-pion-exchange. Assuming that these peripheral reactions can be described in terms of an isospin exchange amplitude $A(I_{N\bar{N}}, I_e)$, where $I_{N\bar{N}}$ is the isospin of the $(N\bar{N})$ pair and I_e the isospin of the exchanged meson, the channels $\pi^+p \rightarrow (p\bar{n})p$, $\pi^-p \rightarrow (\bar{p}n)p$ and $\pi^-p \rightarrow (p\bar{p})n$ have the respective rates of $|A(1,0) - A(1,1)/\sqrt{6}|^2$, $|A(1,0) + A(1,1)/\sqrt{6}|^2$ and $|A(0,1)/3 - A(1,1)/\sqrt{6}|^2$. The disparity in cross sections may be attributed to a substantial amount of isoscalar exchange in reactions (1) and (2).

In the 12 GeV/c OMEGA experiment [3] the ratio of $\pi^-p \rightarrow (\bar{p}n)p/\pi^-p \rightarrow (K^-K^0)p$ in terms of events observed was ~ 3.5 , which, for a cross section of $\geq 10 \mu b$ in the $\pi^-p \rightarrow K^-K^0p$ channel implies a cross section of $\sim 35 \mu b$ for reaction (2) in agreement with our values quoted above. This very approximate estimate presumes nearly equal acceptance for the $(\bar{p}n)p$ and $(K^-K^0)p$ final states, a reasonable assumption for the OMEGA trigger.

Distributions:

Mass spectra of the peripherally produced nucleon-antinucleon pairs are shown in fig. 2, where the dotted additions to the histograms 2-a and 2-b represent corrections due to the inclusion of ambiguous events. The dashed curves in fig. 2-a, -b, -c were obtained from an interpolation of the mass distributions observed in $\pi^-p \rightarrow (p\bar{p})n$ at 9.8 and 18.8 GeV/c [2] to represent the expected shape at ~ 13 GeV/c for $m(N\bar{N}) < 2.7$ GeV. It is evident in the interpolation, as well as the original data at both energies, that for low-momentum transfer the $p\bar{p}$ mass spectrum peaks below both the $p\bar{n}$ and $\bar{p}n$ distributions. This is unlikely to be an experimental bias in that for both spectrometer and bubble chamber experiments the low-mass region is the least biased. Possibly there is some small but significant $I = 0$ structure appearing in $m(p\bar{p}) \sim 2.05$ GeV.

The t -distributions for reactions (1) and (2) are shown respectively in fig. 2-d and 2-e for $m(N\bar{N}) < 2.7$ GeV. A one-pion-exchange propagator modified by the Dürr-Pilkahn form-factor [5] yields the dashed curves. Apparently the peripheral nature of reactions (1) and (2) is well described by such a t -channel approximation.

For reaction (3), the effects of $t_{\min}$ are appreciable so the distribution in $t' = t - t_{\min}$ is given in fig. 2-f, where it is clear that although a simple exchange amplitude will approximately describe the data, some modification is necessary to reproduce the dip at $|t'| \sim 0.1$ (GeV/c)².

Histograms of the Jackson and Treiman-Yang angles for reaction (1) are given in fig. 3, where the data have been subdivided into four regions of $m(p\bar{n})$. The shaded portions of the Jackson angle plots indicate events added from the ambiguous fit sample. No shaded area is shown in the Treiman-Yang spectra because the ambiguous events were uniformly distributed.

Except possibly for $m(p\bar{n}) < 2.1$ GeV, the distributions are isotropic in the Treiman-Yang angle and suggestive of one-pion-exchange. Moreover, in this case G-parity forces the $(p\bar{n})$ system to have $s = 1$, l even and j odd; consequently, the odd harmonics must vanish and the Jackson angle spectra are necessarily symmetric. From fig. 3, it is apparent that the data are nearly symmetric in $\cos \theta_J^{p\bar{n}}$.

The corresponding angular distributions for the charge conjugate $(\bar{p}n)$ system are displayed in fig. 4, where the shaded area again indicates the inclusion of ambiguous events. Although the spectra are reasonably symmetric and similar to the $(p\bar{n})$ system, the paucity of events precludes a detailed comparison.

Angular distributions of the $(p\bar{p})$ system in reaction (3) are shown in fig. 5-a, where the data have been divided into only two mass bins, by $m(p\bar{p}) \gtrless 2.3$ GeV. These data are defined by $m(\Delta^{++}) = m(\pi^+ p) < 1.4$ GeV with appropriate background subtractions. Clearly the Treiman-Yang angle is not isotropic and therefore not consistent with a single-pion-exchange production mechanism. Additional evidence against pion exchange derives from the Δ^{++} decay angles given in fig. 5-b. Here, especially for $m(p\bar{p}) < 2.3$ GeV, the Jackson angle of the proton follows a distribution oppositely peaked from the $1 + 3 \cos^2 \theta$ shape characteristic of one-pion-exchange. Investigations of $\pi^+ p \rightarrow X^0 \Delta^{++}$, with X^0 various combinations of K and π states, for $m(X^0) \approx 2-3$ GeV revealed no angular dispositions similar to those in fig. 5. There were no significant differences in the angular distributions for $|t'(p\Delta)| \lesssim 0.1$ (GeV/c)², a division suggested by the dip shown in fig. 2-f.

Discussion:

Notwithstanding the disparity in cross sections, mass distributions of the peripherally produced charged $N\bar{N}$ pairs in reactions (1) and (2) are remarkably similar to that observed in the neutral $p\bar{p}$ system, except possibly for peaking some 100 MeV higher. In both the charge exchange and non-charge exchange channels, the differential cross section exhibits a dependence on momentum transfer consonant with one-pion-exchange and a distribution in Treiman-Yang angle which is essentially isotropic.

The distributions in Jackson angle of reactions (1) and (2) at 13 GeV/c and of reaction (2) at 12 GeV/c [3] are in close agreement throughout the $m(N\bar{N})$ range, but differ substantially from the $p\bar{p}$ data at 9.8 and 18.8 GeV/c [2]. Whereas the $p\bar{n}$ and $\bar{p}n$ spectra are nearly symmetric for $m(N\bar{N}) < 2.1$ GeV, with pronounced enhancements at $\cos \theta \approx \pm 1$ and a strong but broader structure at $\cos \theta \approx 0$, the $p\bar{p}$ distribution shows marked backward peaking and considerably less of an accumulation near $\cos \theta \approx 0$. In the central mass region, $m(N\bar{N}) \sim 2.3$ GeV, the $p\bar{n}$ and $\bar{p}n$ data exhibit a flat shape with modest wings at $\cos \theta \approx \pm 1$, where, in contrast, the $p\bar{p}$ events are more uniform near $\cos \theta \approx \pm 1$ and cluster strongly around $\cos \theta \approx 0$. For larger masses, $m(N\bar{N}) \geq 2.5$ GeV, the $\bar{p}n$ and $p\bar{n}$ systems tend to decay nearly symmetrically fore and aft, whereas the $p\bar{p}$ decay is strongly asymmetrical towards the forward direction. These qualitative observations are reflected in the moments of the $N\bar{N}$ decay angular distributions given in fig. 6, for reactions (1) and (2) as well as the $p\bar{p}$ data [2].

A rapid variation with $m(N\bar{N})$ of the angular distribution in the $N\bar{N}$ system is manifested in all of the above channels, albeit differently for the charged and neutral $N\bar{N}$ pairs. Comparison of the Legendre

coefficients for $p\bar{p}$ decay with $p\bar{p} \rightarrow \pi^+\pi^-$ data reveals the same energy dependence and provides a strong argument for one-pion-exchange, but suggests no definitive explanation for the angular correlation with $M(N\bar{N})$ [2]. No corresponding data from the reactions $\pi p \rightarrow \pi^+\pi^0$ or $\bar{p}n \rightarrow \pi^-\pi^0$ exist with which a similar comparison to $(\bar{n}p)$ and $(\bar{p}n)$ decays can be effected. However, investigations of $\bar{p}p$ and $\bar{p}n$ total cross sections [6], two body [7] and general annihilation channels [8] reveal the existence of significant structures at $m(N\bar{N}) \sim 1.932, 2.19$ and 2.36 GeV. Although no definite association with G-parity or spin has been satisfactory, it is generally inferred that these enhancements have $I = 1$. Regardless of how formed, the $N\bar{N}$ interaction for $m(N\bar{N}) < 3$ GeV is complicated and presently not understood.

For reaction (3), because of large $t_{\min}$ effects, $\sim 75\%$ of the events have $|t| > 0.3$ (GeV/c)² and do not strongly overlap dynamically with the $(\bar{p}p)n$ data, as well as recoiling from a higher spin system. The angular spectra of the Δ^{++} decay shown in fig. 5-b are suggestive of ρ -exchange with dipole (M1) coupling [9], especially for $m(p\bar{p}) < 2.3$ GeV. A curve representing the Jackson angle distribution, $(5-3 \cos^2\theta)/8$, in fig. 5-b corresponding to ρ -exchange is in reasonable agreement with the data. For dipole coupling, reaction (3) can be described in terms of two helicity amplitudes, $f \equiv f_{3/2 \ 1/2}^1$ and $g \equiv f_{3/2 \ 1/2}^0$, where the superscript refers to the helicity of the $(p\bar{p})$ system and the subscripts refer to the Δ^{++} and target proton; if the $(p\bar{p})$ state is natural spin-parity, $g \equiv 0$. Letting ξ represent the cosine of the t -channel scattering angle, the Δ^{++} density matrices for M1 ρ -exchange are given by

$$\rho_{33} = 3/8, \quad \rho_{31} = 0, \quad \rho_{3-1} = \frac{\sqrt{3}}{8} \left[\frac{2(\xi^2-1)|f|^2}{2(\xi^2+1)|f|^2 + (\xi+1)^2|g|^2} + \frac{(\xi+1)^2|g|^2}{2(\xi^2+1)|f|^2 + (\xi+1)^2|g|^2} \right]$$

where $\rho_{3-1} \approx \sqrt{3}/8$ for $\xi \rightarrow -\infty$, a fair approximation since $\xi \leq -1$ and grows rapidly with t . With $\rho_{3-1} \approx \sqrt{3}/8$, the Treiman-Yang angle should follow $(1 + 2 \sin^2 \varphi)/4\pi$ as illustrated in fig. 5-b; again this is a reasonable representation of the data for $m(p\bar{p}) < 2.3$ GeV.

Without knowledge of the spin-parity, isospin composition of the $(p\bar{p})$ system, only a few simple observations can be made. Assuming that reaction (3) can be described by a t -channel exchange whereby a $(p\bar{p})$ system of spin j is formed by ρ exchange which subsequently decays into a p and $\bar{p}$ of helicities λ and $\bar{\lambda}$, this amplitude can be written

$$A_m^j(\lambda\bar{\lambda}) = \sqrt{\frac{2j+1}{4\pi}} T_{\lambda\bar{\lambda}} D_{m,\lambda-\bar{\lambda}}^{j*}(\theta, \varphi)$$

where $T_{\lambda\bar{\lambda}}$ is a helicity amplitude. The angular distribution of the $(p\bar{p})$ system is then given by

$$W(\theta, \varphi) = \sum A_m^j \rho_{mm}^{jj'} A_m^{j'}$$

with $\rho_{mm}^{jj'}$, the density matrix for $p\bar{p}$ production, where the specification of ρ -exchange restricts m, m' to 0, ± 1 . In order to describe the peculiar Treiman-Yang angle distribution in fig. 5-a, a large contribution is required in $W(\theta, \varphi)$ by the terms containing

$$\text{Re } \rho_{10}^{jj'} \text{ Re } Y_L^1(\theta, \varphi), \quad \begin{array}{l} j+j' \text{ odd, } L \text{ odd} \\ |j-j'| \leq L \leq |j+j'| \end{array}$$

Apparently it is necessary to have substantial interference between $(p\bar{p})$ states of even and odd spin as well as a significant unnatural parity component ($g \neq 0$) to describe reaction (3).

Interpretations:

A recent conjecture is that a high density of resonances (actually levels) occurs just above threshold for $N\bar{N}$ production due to long-range pion exchange between the N and $\bar{N}$ for low relative velocity [10].

Isolation of Breit-Wigner type resonances are essentially unrealizable in this scheme and the $\bar{N}\bar{N}$ system would exhibit some complicated structure.

Although reactions (1) and (2) can proceed by diffractive dissociation, a model based upon an extension of dual quark diagrams to include self-energy corrections to the bare hadron predicts this mode to be suppressed [11]. The similarity in mass structure $m(\bar{N}\bar{N})$ of charge exchange and non-charge exchange $\bar{N}\bar{N}$ production tends to support the case for lack of diffractive dissociation dominance.

Somewhat intermediate between the above considerations are analyses of $\bar{p}p \rightarrow \pi^+\pi^-$ in terms of a finite number of resonant states. The most recent fitting of $\bar{p}p \rightarrow \pi^+\pi^-$ finds resonances of $J = 3, 4, 5$ at 2.11, 2.3, and 2.48 GeV and perhaps $J = 2$ at threshold, with no isospin decomposition [12]. Inversely, the $\pi^-\pi^+ \rightarrow \bar{p}p$ analysis fits a resonance into each spin state from $J = 1$ to 5, with and without a complicated background, and finds mass positions and widths similar to the $\bar{p}p \rightarrow \pi^+\pi^-$ case, but with poor chi-square coincidence levels [2]. Careful studies of very low energy $\bar{p}d$ interactions reveal evidence for several narrow resonant states near threshold [13].

Presumably, detailed studies of various quasi-two body interactions, $\bar{N}\bar{N} \rightarrow \rho\pi, f\pi, \omega\pi, pp, \dots$, which from formation studies have cross sections comparable to $\bar{p}p \rightarrow \pi^+\pi^-$ [14], should lead to a better understanding of the $\bar{N}\bar{N}$ system for $m(\bar{N}\bar{N}) < 4$ GeV, produced in peripheral reactions.

Conclusion:

We have presented cross sections and differential distributions for the reactions $\pi^+p \rightarrow (\bar{p}n)p$ and $\pi^-p \rightarrow (\bar{p}n)p$ at 13 GeV/c for $m(\bar{N}\bar{N}) < 2.7$ GeV and $t < 0.5$ (GeV/c)². Although these reactions exhibit a t -dependence

characteristic of one-pion-exchange, their cross sections are not consistent with this approximation when compared to the rate for $\pi^- p \rightarrow (p\bar{p})n$. The mass distribution $m(N\bar{N})$ shows a strong peaking near 2.1 GeV in all channels and a description of the angular decay of the $N\bar{N}$ system requires several spin states. Data for the reaction $\pi^+ p \rightarrow (p\bar{p})\Delta^{++}$ with $-t' < 0.75 \text{ (GeV/c)}^2$ (but large t) have been presented which suggests the necessity of vector exchange for an interpretation.

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Figure Captions

- Fig. 1. Mass distribution of $\pi^+ p_s$ in $\pi^+ p \rightarrow \bar{p} p_s \pi^+$ at 13 GeV/c, with p_s the slower proton when ordered by center of mass longitudinal momentum.
- Fig. 2. Mass distributions of the $(N\bar{N})$ system from (a) $\pi^+ p \rightarrow (p\bar{n})p$, (b) $\pi^- p \rightarrow (\bar{p}n)p$ and (c) $\pi^+ p \rightarrow (p\bar{p})\Delta^{++}$ at 13 GeV/c; (d), (e) and (f) are the corresponding distributions in four-momentum transfer.
- Fig. 3. Distribution of the Jackson and Treiman-Yang angles of the proton in the $(p\bar{n})$ system for $\pi^+ p \rightarrow (p\bar{n})p$ at 13 GeV/c in various $m(p\bar{n})$ regions.
- Fig. 4. Distribution of the Jackson and Treiman-Yang angles of the antiproton in the $(\bar{p}n)$ system for $\pi^- p \rightarrow (\bar{p}n)p$ at 13 GeV/c in various $m(\bar{p}n)$ regions.
- Fig. 5. (a) Histograms of the Jackson and Treiman-Yang angles of the proton in the $(p\bar{p})$ system for $\pi^+ p \rightarrow (p\bar{p})\Delta^{++}$ at 13 GeV/c for $m(p\bar{p}) \geq 2.3$ GeV. (b) Histograms of the Jackson and Treiman-Yang angles of the Δ^{++} decay for $m(p\bar{p}) \leq 2.3$ GeV. The curves represent M1- ρ exchange.
- Fig. 6. Moments of $(N\bar{N})$ decay. $\odot\odot$ $p\bar{n}$ data from reaction 1, $\ominus$ $\bar{p}n$ data from reaction 2, $\bullet$ $p\bar{p}$ data from $\pi^- p \rightarrow (p\bar{p})n$ at 9.8 and 18.8 GeV/c.

Events / 0.1 Cos ($\theta_{j}^{p\bar{n}}$)

Events / 20° $\phi_{T-y}^{p\bar{n}}$