Multiplicity distributions and rescattering effects in *pd* interactions at 200 GeV/*c*

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This study determines topological cross sections and rescattering effects for 200-GeV/*c* *pd* interactions observed in a 60000-picture exposure of the Fermilab 30-inch deuterium bubble chamber. We measure the *pd* inelastic cross section for $n_{ch} \geq 3$ to be 55.0 ± 0.8 mb and find that $(17.4 \pm 1.8)\%$ of the *pn* events have a secondary interaction with the spectator proton. The rescattering is adequately described by a model which assumes the rescattering probability to be independent of the primary collision multiplicity. The multiplicity distribution for nonrescattered *pn* interactions has $\langle n \rangle = 7.3 \pm 0.1$ and $f_2^{cc} = 8.4 \pm 0.5$.

This report presents properties of the multiplicity distribution of charged particles from proton-deuterium interactions at 200 GeV/*c*. The analysis includes a study of rescattering effects and the extraction of proton-neutron cross sections, making use of previously published proton-proton data.[1-3] The data for this experiment are based upon a 60 000-picture exposure of the Fermilab 30-inch deuterium-filled bubble chamber to a 200-GeV/*c* proton beam. Film was divided among the three countries and subjected to two complete scans as well as a high-magnification edit. The information recorded included a beam count and a careful prong count for interactions, noting the presence of neutral-strange-particle decays, γ conversions, Dalitz pairs, and slow protons. The slow protons, recognized either as a stopping positive track or by the use of an ionization-curvature template, were reliably recorded up to 1.4 GeV/*c*. One- and two-prong events, predominantly elastic scatters, were not analyzed in detail. An examination of scanning results on film exchanged between institutions revealed no significant differences.

By using a Čerenkov counter, the beam contamination, consisting primarily of π^+, was measured to be $(6.5 \pm 0.5)\%$. A correction is applied in a bulk fashion, amounting to an increase of ~2.4% in the events-to-beam ratio in the microbarn-equivalent calculation. A total of 173 315 beam tracks and 14 046 events with three or more prongs were recorded in a fiducial volume of 36.5 ± 0.1-cm length. The deuterium density was determined to be 0.138 ± 0.001 g/cm^3 from a measurement of the muon range in $\pi^+ \to \mu^+ + \nu_\mu$ decays at rest. The scanning efficiency of events recorded in two scans was 0.995 ± 0.005, independent of multiplicity.

The slow-proton tracks recorded in scanning were measured and reconstructed. The proton hypothesis was checked by ionization. Short proton stubs were reliably recorded down to a length of approximately 1 mm, with a loss of short stubs in the forward direction (obscured by other outgoing tracks). Even-prong events with spectator proton, whose projected length is less than 1.5 mm, are assigned to the next-lower odd-prong topology.

In column 2 of Table 1, we present the distribution of scanned *pd* events before the proton minimum projected length selection was applied. The minimum length cut on slow protons was applied and small topologically-dependent corrections (≳1%) were made to account for unidentified Dalitz pairs using the distribution of scanned e^+e^- pairs from γ rays, resulting in the corrected number of events and the topological cross-sections shown in columns 3 and 4, respectively, of Table 1. A plot of the *pd* cross sections, $\sigma_i(pd)$, where *i* de-

TABLE I. The *pd* and *pn* topological cross sections at 200 GeV.

Charged prongs	Scanned events	Corrected events (see text)	σ (*pd*) (mb)	σ_j'' (*pn*) (no rescatter) (mb)	σ (*pn*) (mb)
3	588	711	2.79 ± 0.11	4.18 ± 0.17	5.33 ± 0.25
4	1871	1747	6.85 ± 0.21		
5	676	796	3.12 ± 0.12	4.72 ± 0.18	6.02 ± 0.27
6	2137	2012	7.89 ± 0.23		
7	665	782	3.07 ± 0.12	4.74 ± 0.18	6.04 ± 0.27
8	2162	2050	8.04 ± 0.23		
9	564	652	2.56 ± 0.11	3.90 ± 0.16	4.97 ± 0.24
10	1749	1656	6.49 ± 0.20		
11	391	445	1.74 ± 0.09	2.56 ± 0.13	3.26 ± 0.18
12	1173	1125	4.41 ± 0.16		
13	249	287	1.12 ± 0.07	1.66 ± 0.09	2.12 ± 0.14
14	767	723	2.84 ± 0.12		
15	121	139	0.544 ± 0.047	0.811 ± 0.067	1.03 ± 0.09
16	416	399	1.57 ± 0.09		
17	66	72	0.282 ± 0.034	0.375 ± 0.044	0.480 ± 0.058
18	223	216	0.847 ± 0.061		
19	21	21	0.082 ± 0.018	0.134 ± 0.028	0.172 ± 0.036
20	110	110	0.432 ± 0.042		
21	16	18	0.070 ± 0.016	0.070 ± 0.017	0.090 ± 0.021
22	50	48	0.189 ± 0.029		
23	6	6	0.024 ± 0.009	0.024 ± 0.010	0.030 ± 0.012
24	15	15	0.060 ± 0.015		
25	0	1	0.005 ± 0.004	0.004 ± 0.004	0.005 ± 0.005
26	5	6	0.024 ± 0.010		
27	2	1	0.004 ± 0.004	0.004 ± 0.004	0.005 ± 0.005
28	1	1	0.004 ± 0.004		
30	1	1	0.004 ± 0.004		
Totals	14045	14040	55.05 ± 0.78	23.19 ± 0.39	29.55 ± 0.57

notes the number of outgoing prongs, is shown in Fig. 1. As a result of the high magnification used in editing the data, corrections for secondary interactions and neutral decays occurring close to the primary vertex were negligible. The total *pd* cross section for events with three or more charged prongs is found to be 55.05 ± 0.78 mb.[4]

The distribution of odd-prong events is assumed to arise exclusively from nonrescattered *pn* interactions in which the proton spectator is too short to be seen. The level of contamination by coherent deuteron events is negligible.[5] The remaining nonrescattered *pn* events with a seen spectator (evenprongs) were moved to the next lowest odd-prong topology by using the observed number of backward spectators, corrected for the Møller flux factor. The flux-factor calculation indicates that there are 1.19 forward spectators for each backward spectator whose length is longer than the projected length cut. In this manner, we obtain column 5 of Table 1, which gives the partial cross section, $\sigma_j''(pn)$, for *pn* events which have not rescattered.[6] The angular distribution of observed backward protons (not shown) is found to be consistent with isotropy. The usual interpretation[7] given for this effect is that the influence of the flux factor is compensated by a falling energy dependence of the cross section. However, near 200 GeV, the total nucleon-nucleon cross sections have little s dependence.[3] Further, by concentrating on high multiplicities for which the partial cross sections are rising with s, one would not expect a flat spectator distribution. Comparing the data with a Monte Carlo calculation, which incorporates the s dependence of the partial cross sections,[8] using Koba-Nielsen-Olesen scaling for the multiplicities,[9,10] and a Hulthén wave function to describe the nucleons in the deuteron,[7] we find only a 12% probability of agreement with the data for events with eight or more prongs. However, in a low-energy, high-statistics K^+d experiment,[11] clear evidence for the expected flux factor effect is observed. Therefore, we have included the conventional flux factor in our analysis.

To obtain an estimate of the total rescattering

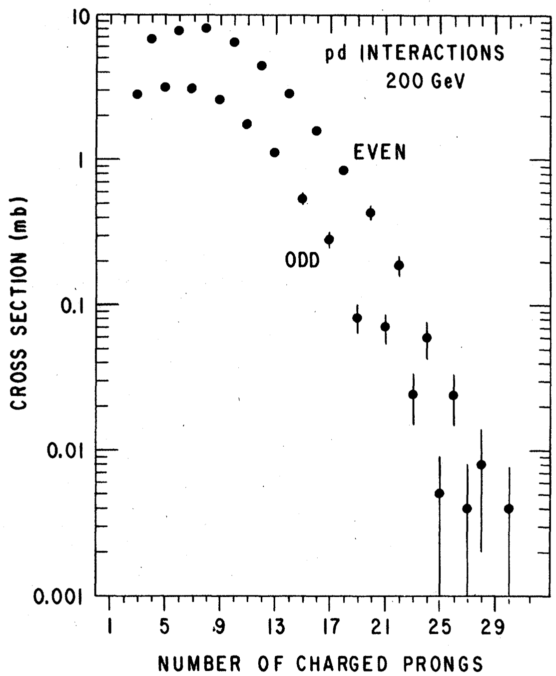

FIG. 1. Measured *pd* partial cross sections. Even-pronged events with a spectator proton shorter than 1.5 mm are counted as odd prongs.

probability P_s, we use the results of the counter experiments[3] which have measured $\sigma_T(pn)$ and $\sigma_T(pp)$. Assuming that $\sigma_{el}(pn)=\sigma_{el}(pp)$ and that $\sigma_1(pn)=2/3\sigma_2(pp)$,[4] we estimate that $\sigma_{\geq 4}(pp) = 29.13\pm 0.45$ mb and $\sigma_{\geq 3}(pn)\approx 30.36\pm 0.76$ mb, which gives the fraction of the *pd* events which occur off the neutron as

$$f_n \equiv \frac{\sigma_{\geq 3}(pn)}{\sigma_{\geq 3}(pn)+\sigma_{\geq 4}(pp)} = 0.510\pm 0.007.$$

[Our measurement of $\sigma_{\geq 3}(pn)$ is given below.] We then estimate P_s as

$$P_s = 1-\frac{\sigma''_{\geq 3}(pn)}{f_n\sigma_{\geq 3}(pd)} = 0.174\pm 0.018.$$

This result is consistent with similar analyses at other Fermilab energies.[12-15]

To study the effects of rescattering on the multiplicity distribution of charged particles, we examine the subsample of the *pd* events which have an even-prong count and no identified slow proton. These events are dominated by proton-proton interactions, but include those *pp* and *pn* events which have been rescattered without producing a slow proton. Thus, making a comparison of these events with the corresponding no-slow-proton sample in proton-proton interactions,[16] one can observe the effects of rescattering. In Fig. 2, we have plotted the ratio of these two cross sections as a function of multiplicity. The evident increase of the ratio at high multiplicity is attributed to rescattering effects in lower multiplicity primary interactions.

The dependence of rescattering upon multiplicity in *pn* interactions can also be seen in a direct comparison with the proton-proton multiplicity distribution.[1] The *pp* partial cross sections at 200 GeV/c are well described (χ^2/DF = 15/10) by the following KNO form[9]

$$\sigma_{KNO}(N) = (11.53Z + 227.8Z^3 - 20.29Z^5)e^{-3.54Z}$$

with

$$Z \equiv \frac{N}{\langle N\rangle} + \frac{N}{7.68}.$$

Since the total *pp* and *pn* cross sections are about equal,[3] it is reasonable to expect that the *pp* and *pn* partial cross sections will interleave, especially for higher multiplicities ($N \gtrsim 6$ prongs) where diffractive effects are small.[2] Thus we assume that the above expression is also approximately valid for odd prongs. The ratio of this expression to the unrescattered *pn* cross section column 5 of Table 1 is shown in Fig. 3; also shown are the values of this ratio for the remaining even-pronged *pd* events. As is evident in the figure, the ratio for unrescattered *pn* events re-

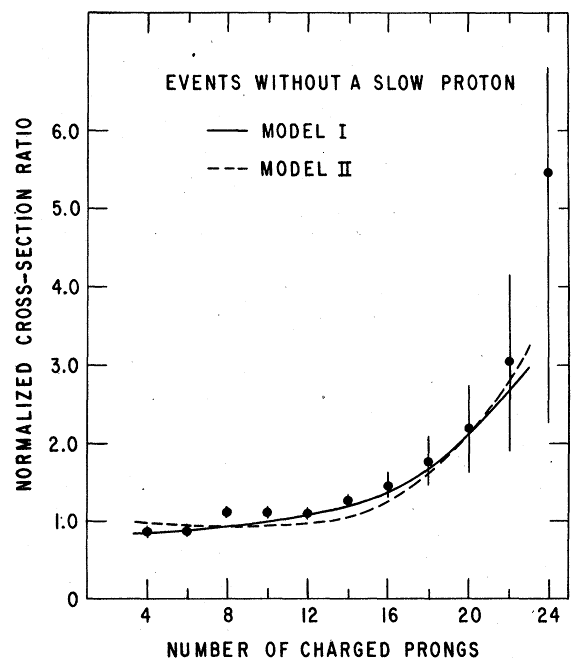

FIG. 2. The normalized ratio of events with no identified slow proton, $[\sigma_i(pd)/\sum_{i=2}\sigma_i(pd)]/[\sigma_i(pp)/\sum_{i=2}\sigma_i(pp)]$. The curves represent the fits to the models described in the text.

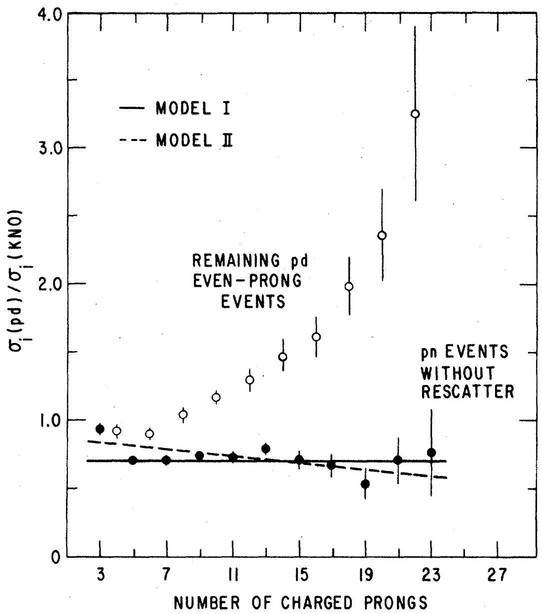

FIG. 3. The ratio of the unrescattered *pn* cross sections to the result of the *pp* KNO fit (see text) evaluated at odd-prong count. Also shown is the ratio of the spectator-subtracted *pd* even-prong cross sections to the KNO fit. The smooth curves follow from the models described in the text and assuming $\sigma_i(pn)$ is given by $\sigma_{\rm KNO}$.

mains relatively flat, while the ratio rapidly increases for even prongs due to the rescattering from lower topologies.

In order to remove the effects of rescattering and to obtain the *pn* partial cross sections $\sigma(pn)$, we have considered two simple, limiting-case rescattering models. In the first model, each event has the probability of rescatter constrained to $P_s = 0.17$, independent of primary multiplicity. And in the second, the rescattering is proportional to the primary multiplicity, in such a way that each outgoing charged and neutral particle[17] is given the same probability of scattering off the spectator, while the total event rescattering is constrained to $P_s = 0.17$. Each model takes as input the multiplicity distribution of unrescattered *pp* events with no slow proton.[16] In fitting these models to the data of Fig. 2, it was assumed that the multiplicity of negatives produced in the secondary collision follows a Poisson distribution, the mean value of which is the only adjustable parameter. An implicit assumption is made that rescattering off of a spectator proton predominately leads to a slow proton in the final state, while rescattering off of a spectator neutron does not; however, the possible systematic errors thus introduced would not substantially change the conclusions of the analysis. Either model gives a satisfactory description of the data and fits are displayed in Fig. 2. In the first model, the mean multiplicity of negative tracks per second scatter is 1.9 ± 0.2. In the second model, a rescatter probility of 1.7% per primary track is obtained, and the corresponding multiplicity is found to be 1.5 ± 0.2.

Using the parameter values thus obtained from the no-slow-proton data, an attempt may be made to discriminate between the two simple models. Each model was used to estimate the nonrescattered portion of the *pn* partial cross sections by subtracting the model-rescattered *pp* data[11] from the measured *pd* cross sections (column 4 of Table 1) yielding the rescattered *pn* cross sections. Then the model equations were again used to obtain the unrescattered *pn* cross sections. Finally, a χ^2 comparison of the model predictions with the measurements, column 5 of Table 1, yields a χ^2 per degree of freedom of 1.5 for model 1 and 2.9 for model II.[18] In Fig. 3, a display of the results of this procedure for the two models

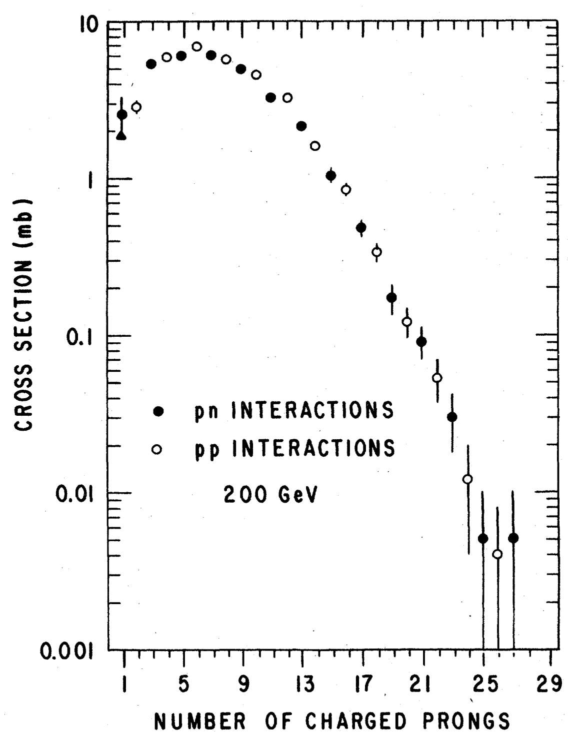

FIG. 4. The charged multiplicity distribution for 200-GeV/*c* *pn* and 205-GeV/*c* *pp* interactions (Ref. 1). $\sigma_1(pn)$ is determined from the measured total cross section $\sigma_T(pn)$ (Refs. 3 and 4) and $\sigma_{\geq 3}(pn)$ measured in this experiment. The (▲) shows the value for $\sigma_1(pn)$ obtained as $\frac{2}{3}\sigma_2(pp)$ (Ref. 4).

TABLE II. Moments of the *pd* and *pn* topological cross sections at 200 GeV. The 200-GeV *pp* moments from Ref. 1 are shown for comparison.

Moments	All prongs pd^a	All prongs pn^b	All prongs pp^c	Negative prongs pd^a	Negative prongs pn	Negative prongs pp
$\langle n \rangle$	8.32 ± 0.10	7.26 ± 0.10	7.68 ± 0.07	3.16 ± 0.05	3.13 ± 0.04	2.84 ± 0.04
$D = (\langle n^2 \rangle - \langle n \rangle^2)^{1/2}$	4.18 ± 0.05	3.95 ± 0.06	3.82 ± 0.05	2.09 ± 0.03	1.98 ± 0.03	1.91 ± 0.03
$\langle n \rangle / D$	1.99 ± 0.04	1.84 ± 0.04	2.01 ± 0.03	1.51 ± 0.04	1.58 ± 0.03	1.49 ± 0.03
$f_2 = \langle n(n-1) \rangle - \langle n \rangle^2$	9.2 ± 0.5	8.37 ± 0.49	6.89 ± 0.35	1.2 ± 0.2	0.78 ± 0.11	0.80 ± 0.09
$f_3 = \langle n(n-1)(n-2) \rangle - 3\langle n(n-1) \rangle \langle n \rangle + 2\langle n \rangle^3$	16 ± 3	8.1 ± 2.7	8.6 ± 2.1	−0.3 ± 0.4	−0.4 ± 0.3	−0.63 ± 0.26

[a] In the *pd* moment calculations, scanned odd-prong events were shifted up by one charge to account for the unscanned proton spectator. The combined one- and two-prong inelastic cross section used was obtained as a sum of the *pn* and *pp* estimates adjusted for nuclear effects; $\sigma_2\,(pd) = 4.5 \pm 0.9$ mb.

[b] An additional systematic error of ±15% has been introduced into the one-prong estimate.

[c] See Ref. 2.

is shown under the assumption that both the *pp* and *pn* multiplicities have the KNO form. The curves are merely illustrative and the departure of the three- and four-prong data points from the general trend of the data is due to the inadequacy of the KNO parametrization at low multiplicity.

Further, the rescatter probability per primary track obtained in the second model is smaller than that expected from the Glauber picture[7] where $(1/4\pi)\langle r^{-2}\rangle \sigma_{tot}(\pi p) \sim 5.0\%$ is a measure of the probability that a pion produced in the primary collision encounters the spectator. Finally, we note that multiplicity data from heavy nuclei also disfavor this second model.[19,20] We therefore favor model I and take the odd-prong events and events with a backward spectator to be an unbiased estimate of the *pn* topological distribution. An analysis of *pd* data at 300 GeV by Sheng *et al.*[13] finds excellent agreement with a model similar to our model II. However, while they did not consider the case with rescattering independent of multiplicity, we note that their odd-prong multiplicity distribution is similar to ours, implying that our model I would give a satisfactory fit to their data.

The topological cross sections for nonrescattered *pn* events given in column 5 of Table I are corrected for rescattering using the constant rescatter probability per event and the Glauber correction, yielding the partial cross sections for proton collisions on free neutrons shown in column 6 of Table I. The *pn* and *pp* multiplicity distributions are compared in Fig. 4. The *pn* one-prong cross section is obtained by subtracting our measured cross section $\sigma_{\geq 3}(pn)$ and the elastic cross section $\sigma_{el}(pn) \approx \sigma_{el}(pp)$ from the total *pn* cross section $\sigma_T(pn) = 39.2 \pm 0.6$ mb.[3] It is evident that our value for $\sigma_1(pn)$ is consistent with the estimate in Ref. 4.

Table II lists some moments of these charged multiplicity distributions. The value estimated in Ref. 4 is used for the unobserved one-prong cross section with an estimated systematic error of ±15% included. The mean number of negatives in *pn* collisions is (0.29 ± 0.06) larger than the value (2.84 ± 0.04) found in *pp* collisions at the same energy. Also, the width, e.g., f_2, of the *pn* distribution is somewhat larger than the *pp* value. These differences are probably due to diffraction contributions in low multiplicities. The values of the moments determined here are in agreement with those of Eisenberg *et al.*[14] with our analysis yielding substantially reduced errors.

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[1]S. J. Barish *et al.*, Phys. Rev. D 9, 2689 (1974).
[2]S. J. Barish *et al.*, Phys. Rev. Lett. 31, 1080 (1973).
[3]A. S. Carroll *et al.*, Phys. Rev. Lett. 33, 928 (1974).
[4]An estimate of this cross section is made using cross sections measured in Refs. 2 and 3, $\sigma_{total}(pd)=73.84\pm0.11$ mb, $\sigma_{elastic}(pp)=6.92\pm0.44$ mb, $\sigma_2(pp)=2.85\pm0.26$ mb, and assuming that $\sigma_{el}(pn)$ and $\sigma_1(pp)\approx\frac{2}{3}\sigma_2(pp)$ (estimated to be at least 80% diffractive in Ref. 2), and applying a 5% Glauber correction. Neglecting rescatter effects from one- and two-pronged events, one finds $\sigma_{\geqslant 3}(pd)=56.2\pm0.7$ mb, which agrees quite well with our direct measurement.
[5]Y. Akimov *et al.*, Phys. Rev. Lett. 35, 763 (1975). The cross section for coherent production $p+d\rightarrow d+X$ is approximately 1.2 mb near our energy, dominated by peaks at the $N^*(1470)$ and $N^*(1688)$. These resonances decay into $N\pi\pi$ final states only about 40% of the time [see Particle Data Group compilation (unpublished)]. These multibody decays are dominated by the $\Delta\pi$ decay mode, which yields three charged particles ~ 50% of the time. Thus approximately 0.25 mb of coherent production contributes to our event sample with $N\geqslant 3$. Further, with our minimum length cut, these events roughly divide evenly between the three-prong and four-prong events, thus introducing negligible bias into the determination of the pn cross sections.
[6]The backward-spectator events bias the center-of-mass energy towards lower values, the odd-prong events remaining near the nominal value. The average beam momentum for our events is thus reduced to approximately 195 GeV/c.
[7]See, for example, the review by A. Fridman, Fortschr. Phys. 23, 243 (1975).
[8]J. Whitmore, Phys. Rep. 10C, 274 (1974).
[9]Z. Koba, H. B. Nielsen, and P. Olesen, Nucl. Phys. B40, 317 (1972).
[10]P. Slattery, Phys. Rev. Lett. 29, 1624 (1972).
[11]A. A. Hirata, thesis, UCRL Report No. UCRL-20248 (unpublished).
[12]S. Dado *et al.*, Phys. Lett. 60B, 397 (1976).
[13]A. Sheng *et al.*, Phys. Rev. D 12, 1219 (1975).
[14]Y. Eisenberg *et al.*, Phys. Lett. 60B, 305 (1976). With reduced statistics, this reference also discusses the pn multiplicity at our energy.
[15]K. Dziuni-kowska *et al.*, Phys. Lett. 61B, 316 (1976).
[16]J. Whitmore *et al.*, Phys. Rev. D 11, 3124 (1975). The same definition of a slow proton was used in both experiments.
[17]We assume the same π^0 to π^- ratio as measured in pp interactions. F. T. Dao and J. Whitmore, Phys. Lett. 46B, 252 (1973).
[18]Elastic scatter events are not included in the calculation of the rescattering contribution of the one prongs to higher topologies, since these events are expected to have a rescatter probability of only about 5% in the Glauber picture, whereas our overall rescatter probability is 17%. The effects of rescattered inelastic one prongs are negligible.
[19]J. R. Elliot *et al.*, Phys. Rev. Lett. 34, 607 (1975).
[20]W. Busza *et al.*, Phys. Rev. Lett. 34, 836 (1975).