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REMARKS ON DOING STRONG-INTERACTION PHYSICS INVOLVING MULTIPARTICLE FINAL STATES IN THE 100-BeV REGION

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Introduction

Strong-interaction physics in the many BeV region involves many inelastic channels. Experiments can be roughly divided into three groups:

(i) Elastic scattering and single-particle yield experiments give information on the overall structure of the particles and interaction involved.

(ii) Observation of many-particle systems are used to identify new and/or unstable particles produced in the interactions.

(iii) Measurement of the energy dependence and angular distribution of particular channels is needed to understand detailed dynamical models.

No mixture of hard facts, mild prejudice and taste presently permits me to make a decision on which group will prove the most important. Experiments involving the detection of many-particle systems have been mainly carried out with bubble chambers; spectrometer systems have been found useful primarily where a single channel involving two decay particles dominated (i. e. photoproduction of ρ mesons) or where narrow-mass particles were produced in two-body reactions (i. e. CERN proton-recoil experiments).

As the incident particle energies reach the 100-BeV region, it would be wonderful if new narrow particles or resonances are found or dominating channels are observed. Life would be both exciting and simplified for the experimenter. However, it is important to also make sure that interesting "bread and butter" physics can be done. The best way I know of determining this is to use available high-energy work and to try to extrapolate it to the new-energy region. This suggests that at 100 BeV many channels will be involved in inelastic scattering and that no single one will dominate. If this is indeed the case, can one still separate individual channels and determine their properties? Is the bubble chamber still a useful tool near 100 BeV for multichannel physics, and how does it compare to alternate tools involving spark and streamer-chamber systems?

This note is an attempt to use the results of the study of the π-p inelastic interaction at 13 and 20 BeV by the Harvard Bubble Chamber group[1,2] to try to answer this question. It will be concluded that the large bubble chambers under construction should still be able to do very useful survey experiments, but that detailed studies of particular channels require the much higher rate of useful event collection of spark-chamber systems. A large streamer chamber, in particular, should, in addition, be able to perform the survey experiments in a time short compared to that required for the bubble chamber, with no particular bias problems. To make detailed comparisons of various devices, or in order to make optimum choices of dimensions, it is necessary to know beforehand the detailed experimental errors of each device. Factors of two are very important here. Since fullscale prototypes of none of the large devices exist at the present time, errors used are estimates probably no better than a factor of two. This must be kept in mind when considering the discussion below which perforce has to be based on some performance specifications.

The results of the Harvard work on 13 and 20-BeV π^- interactions in the BNL 80 in. chamber is used because I am familiar with it--the remarks in this note are my own and not necessarily those of the members of the group.

Some Useful Results of the 13 and 20 BeV/c Work with $\pi^- + p$

(i) **Topological cross section (mb)**

Number of Prongs	13 BeV/c	20 BeV/c
0 (no V^o)		0.2 ± 0.01 mb
2 (no V^o)	10.2 ± 0.6 mb	7.9 ± 0.3
4 (no V^o)	9.3 ± 0.6	8.4 ± 0.3
6 (no V^o)	4.2 ± 0.2	5.1 ± 0.2
8 (no V^o)	1.0 ± 0.1	1.8 ± 0.1
> 8		0.40 ± 0.02
n + V^o	1.4 ± 0.3	1.3 ± 0.2
		25.1 mb

No. of Prongs	20 BeV/c
2p + V^o	0.4 mb
4p + V^o	0.5
6p + V^o	0.3
8p + V^o	0.08
> 8 p + V^o	0.01

(ii) Events Analyzed: 4-prong (no V^o) with proton visually identifiable by larger than minimum ionization.

Reaction	σ 20 BeV (mb)	σ 13 BeV (mb)	% contamination	% loss by proton requirement
$\pi^- p \rightarrow \pi^- p \pi^+ \pi^-$	0.89 ± 0.06	1.14 ± 0.15	~ 3%	1%
$\rightarrow \pi^- p \pi^+ \pi^- \pi^o$	0.7 ± 0.1		~ 20%	20%

50% of 4-prong events have proton identifiable by bubble density--thus the cross-section of measured events (selected on basis of prong number and proton ionization) is 5.0 mb.

(iii) Cross-sections of Identified Channels. These are listed in Table I.

(iv) Measurement, Momentum, Mass Accuracies. The following parameters permitted a clean separation of 4c from 1c events (~ 3% contamination) and a fair separation of 1c from 0c events (~ 20% contamination): <u>nominal point accuracy</u> in xy plane in real space = 90μ. (This value gives reasonable χ^2 distributions.); <u>transverse momentum</u> of unfitted 4c events ≈ 40 MeV/c (see Fig. 1); <u>longitudinal momentum</u> of unfitted 4c events ≈ 400 MeV/c (see Fig. 1). Mass width of ω^o (1c events) ≃ 100 MeV (full width at half height).

(v) Justification for Selection of 4-Prong Events. There are no present plans for the analysis of events with ≥ 6 prongs. This is based on the experience by some groups (particularly Warsaw) at somewhat lower energy that because so many different combinations are possible for a given multiparticle state (i.e. ρ^o) that it becomes very difficult to separate various production channels.

Some Conclusions and Extrapolations from the 13 and 20 BeV/c $\pi^- p$ Experiments

(i) No single inelastic channel dominates. One result of this fact is that some resonances (i.e. ρ) sit on a sizable nonresonant background. The detector requires a mass acceptance very much wider than the resonance width.

(ii) The available accuracy permitted the identification of quite a few particles and channels (see Table I) and the study of relevant angular distributions.[1,2] Interesting "bread and butter" physics can be done at 20 BeV without excessive difficulty in the 80 in. bubble chamber

(iii) Final states with ≥ 6 particles are difficult to analyze because of the multiplicity of combinations involved. There is some hope that as the energy is increased, a cleaner separation of "projectile fireball" and "target fireball" will ease this problem.

(iv) Strange-particle production appears to also occur in many channels. To study individual channels with bubble chambers even at 20 BeV requires several million pictures.

(v) An excellent "selective criterion" for useful events is the number of prongs at the interaction vertex. Selecting "4-prong events" reduces the number of events requiring analysis by a factor of three at 20 BeV. At 100 BeV this factor should be higher.

(vi) The additional requirement of low-momentum proton increased the selectivity of the "criterion" from a factor of three to five. I know of no obvious reason why this improvement by 1.7 should increase at higher energy. It must be remembered that this factor was obtained after selection for prong number had been made--it might be somewhat higher if the low-momentum proton requirement had been used by itself. But five would be an upper limit for this case.

(vii) Systems in which transverse and longitudinal momenta are determined less accurately than in the quoted experiment will probably not be able to separate 0c and 1c events. How much relaxation is permitted before separation difficulties between 4c and 1c events occur can only be determined with more detailed Monte Carlo calculations.

Measurement Accuracy

To compare various devices and parameters, simple two and three point-fit formulas for angles and curvature are used. A track in the xy plane perpendicular to the magnetic field is taken as an example, with a momentum p of 50 BeV/c, 1/2 the desired incident momentum. Following Plano,[3] the following relations are used:

$$\delta p^{meas} = \frac{32.6\,\epsilon}{B}\left(\frac{p}{L}\right)^2 \qquad (1)$$

$$\delta p^{m.s.} = \frac{0.057\,p}{B\sqrt{X_o}\;\beta\sqrt{L}} \qquad (2)$$

$$\delta\lambda = \frac{1.4\,\epsilon\,S}{L} \qquad (3)$$

$$\delta p = \left\{ (\delta p^{meas})^2 + (\delta p^{m.s.})^2 \right\}^{1/2} \quad (4)$$

$$\delta p_{\perp} \approx \left\{ 2(p\,\delta\lambda)^2 + (\alpha \delta p)^2 \right\}^{1/2} \quad (5)$$

$$\delta p_{\parallel} \approx \delta p \quad (6)$$

$$\alpha = \frac{0.5}{p} \quad (7)$$

where

p (BeV/c)	=	momentum
L (meter)	=	track length
B (Webers/m^2 = 10^4 gauss)	=	magnetic field
ϵ (meter)	=	effective uncertainty of a point in real space xy plane
X_o (meter)	=	radiation length (10 m for liquid H_2, 300 m for Ne gas)
S	=	stereo factor
α	=	Cocconi "typical" emission angle
λ	=	dip angle between track and xy plane

Note that ϵ should include all sources of error such as setting accuracy, turbulence, magnetic field uncertainty; it is best obtained by fitting events and requiring reasonable χ^2 distributions. In this fashion $\epsilon = 90 \times 10^{-6}$m has been obtained for the 80 in. BNL chamber,[1] and

$\epsilon = 500 \times 10^{-6}$ m for the SLAC streamer chamber.[4] $\epsilon = 250\mu$ is used as an estimate for the 12-ft ANL and 25-ft BNL chambers.[5] The factor of two in front of the first term on the right side of Eq. (5) is used to include approximately the azimuthal angle error which depends on the measured momentum.[6]

Table II lists typical values for the ANL 12-ft bubble chamber (3m track) and the proposed 25-ft chamber (5 m limit arbitrarily set by nuclear absorption factor of 0.54). For purposes of comparison, the first column lists values for a 1 m track at 10 BeV/c typical of the 20 BeV π^- work.[1,2] Table III lists typical values for streamer chambers.

General Conclusions Based on Accuracy Estimates

(i) The values of $\epsilon = 250\mu$ and $\epsilon = 500\mu$ are those quoted by the bubble and streamer chamber experts respectively. They are based on extrapolation of smaller operating systems. It is hard to do better, but one might also do worse. Thus, the maximum useful energy region of any particular device depends critically upon the effective value of ϵ which can be obtained. At the present time, all one can hope to estimate are dimensions below which it is not wise to go in order to be reasonably sure that a significantly new energy region will be accessible at NAL. Based on the accuracy obtained at 20 BeV, estimates of Tables II and III and their dependence on p, my own minimum choice is the 12-ft chamber in 40kG, or a 8 m streamer chamber in 20 kG. Both devices should be useful at 50 BeV and could well be useful at higher energies.

(ii) If similar accuracies can be obtained in the 12-ft and 25-ft bubble chamber, the latter should be useful up to an energy 1.7 higher than the 12-ft chamber. In addition, the higher photon conversion efficiency of the larger chamber also makes it preferable to the 12-ft chamber for strong-interaction physics.

(iii) Any measures that reduce the value of ϵ (better knowledge of magnetic field, decreased turbulence, more uniform electric field, etc.) rapidly pay off linearly in increased useful energy.

Event Rate

(i) For the purpose of the survey experiments with pions and protons, the greatest advantage of the streamer chamber over a bubble chamber (effective accuracies assumed similar) is the streamer chamber's much larger rate of data-collection ability. This is illustrated in Table IV which is based on the use of the simplest possible trigger for the streamer chamber, i.e., a particle has stopped in the target. In addition, a permissible trigger rate of 10/sec and a sensitive time of 10 μsec has been taken.[4]

(ii) The low event rates and the multiplicity of channels are likely to limit the use of bubble chambers to survey experiments where high statistics are not required.

(iii) A streamer chamber with similar accuracy to that of the bubble chamber should be able to do the survey just about as well (except for very low recoil momentum events). In addition, it has much wider uses as is discussed in Ref. 4 although I am somewhat pessimistic about the development and the usefulness of highly selective triggers for very many different channels. However, even taking the most pessimistic approach, a brute force approach of taking many pictures and using postmortem visual selection can be used. In 20 days, 10^6 strong interactions can be obtained. With automatic measuring devices, these should yield much interesting physics.

General Conclusions

(i) Interesting "bread and butter" physics in strong interactions involving the detection of multiparticle final states in a bubble chamber is being carried out, and successfully, at various laboratories up to 28 BeV. Separation of many individual reaction channels has proven quite feasible (Table I) with individual cross sections small but not unreasonable. These cross sections will probably decrease with energy but they are unlikely to vanish suddenly. NAL will, thus, be able to extend this "bread and butter" physics to a new energy region, the energy limit depending on physics and the accuracy of the detection systems. The hope is, of course, that in addition, new and exciting phenomena are discovered.

(ii) Coherent production appears to be a promising method of selectively enhancing some of the reaction channels.

(iii) Survey experiments on strong interactions involving multiparticle final states can be carried out in either the 12-ft or 25-ft bubble chamber. The problem of nuclear absorption will reduce the efficiency of data collection, but not to an unreasonable level.

(iv) The 25-ft chamber potentially can do this survey better than the 12-ft chamber. Its rate of data collection will be higher, and it should be able to extend the separation of individual channels to higher energies. NAL should plan to use the 25-ft chamber for strong-interaction physics.

(v) The exact energy, up to which a given device (bubble chamber, spark-streamer chamber systems) can still do the separation of individual reaction channels, depends so strongly on the point accuracy obtainable (which can only be guessed) that I know of no way of distinguishing between potential advantages of bubble chamber and spark-streamer chamber systems on that basis alone at the present time.

(vi) The high rate of data collection of spark-streamer chamber systems obviously makes them the most promising tool for the detailed study of the physics under discussion. They are also the best tools for the study of coherent production and for the use of selective triggers. Systems required to extend these studies to the new energy region are likely to be too complex to await completion of bubble-chamber survey experiments before the start of construction.

(vii) Experience with both the streamer chamber and large wire spark-chamber systems is just being accumulated. This experience will be most helpful in evaluating various combinations of narrow gap, wide gap, and streamer chambers. In the final analysis, the choice will probably depend not only on the particular reaction of most interest, but on the experience and taste of the people who are actually doing the work of construction, and who will analyze the events. Very detailed Monte Carlo calculations are required for the design of hybrid systems to prevent systematic bias.

Acknowledgments

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Table I. Cross Sections for Meson Resonance Production In $\pi^- - p \rightarrow p\pi^+\pi^-\pi^-$.

Reaction	σ (mb) 13 BeV/c	20 BeV/c
$\pi^- p \rightarrow p\pi^- \rho^o$ [a]	0.72 ± 0.11	0.54 ± 0.05
$\pi^- p \rightarrow p\pi^- f^o$ [b]	0.12 ± 0.04	0.16 ± 0.04
$\pi^- p \rightarrow p$"A" ($\rightarrow \pi^- \rho^o$)	0.14 ± 0.04	0.16 ± 0.04
$\pi^- p \rightarrow pA^-(1640)$ ($\rightarrow \pi^+\pi^-\pi^-$)	0.043 ± 0.009	0.030 ± 0.005
$\pi^- p \rightarrow pA^-(1640)$ ($\rightarrow \pi^- f^o$)	0.018 ± 0.005	0.014 ± 0.003

[a] Includes ρ^o's from "A" decay. [b] Includes f^o's from A^-(1640) decay.

Table I. Cross Sections for Baryon Resonance Production In $\pi^- p \rightarrow p\pi^+\pi^-\pi^-$.

Reaction	σ (mb) 13 BeV/c	20 BeV/c
$\pi^- p \rightarrow N^{*++}(1236)\pi^-\pi^-$ ($\rightarrow \pi^+ p$)	0.23 ± 0.05	0.08 ± 0.02
$\pi^- p \rightarrow N^{*o}(1236)\pi^+\pi^-$ ($\rightarrow \pi^- p$)	0.050 ± 0.010	0.052 ± 0.007
$\pi^- p \rightarrow N^{*o}(1350\text{-}1500)\pi^+\pi^-$ ($\rightarrow \pi^- p$)	0.083 0.015	0.039 ± 0.006
$\pi^- p \rightarrow N^{*o}(1668)\pi^+\pi^-$ ($\rightarrow \pi^- p$)	0.057 ± 0.011	0.041 ± 0.006

Table II. Typical Parameters for One Track In Bubble Chambers.

Chamber Size	6 ft	12 ft			25 ft		
p (BeV/c)	10	50	50	50	50	50	50
L (m)	1	3	3	3	5	5	5
B (kG)	18	20	20	40	20	20	40
ϵ (μ)	90	100	250	250	100	250	250
δp^{meas} (MeV/c)	160	450	1120	560	160	400	200
$\delta p^{m.s.}$ (MeV/c)	90	260	260	130	210	210	100
$\delta p \simeq \delta p_{\parallel}$ (MeV/c)	180	500	1120	560	260	460	220
S	4	4	4	4	4	4	4
$\delta\lambda$ (mrad)	0.56	0.19	0.48	0.48	0.11	0.28	0.28
$p\delta\lambda$ (MeV/c)	5.6	9.5	25	25	5.5	14	14
$\alpha\delta p$ (MeV/c)	9	5	11	6	3	5	2
$\delta p_{\perp}$ (MeV/c)	12	14	35	35*	8	20	20*

*Improvement in angle accuracy due to better knowledge of p not included--possible reduction by a factor of 0.7-1.0.

Table III. Typical Parameters for One Track In Streamer Chambers.

p (BeV/c)	50	50	50	50	50	50
L (m)	4 m	4 m	6 m	6 m	10	10
B (kG)	20	40	20	40	20	40
ϵ (μ)	500	500	500	500	500	500
$\delta p = \delta p_{\parallel} = \delta p^{meas}$ (MeV/c)	1300	650	570	290	210	110
S	4	4	4	4	4	4
$\delta\lambda$(mrad)	0.70	0.70	0.47	0.47	0.28	0.28
$p d\lambda$ (MeV/c)	35	35	24	24	14	14
$\alpha \delta p$ (MeV/c)	13	7	6	3	2	1
$\delta p_{\perp}$ (MeV/c)	50	50*	34	34*	20	20*

*Improvement in angle accuracy due to better knowledge of p not included--possible reduction by factor of 0.7-1.0.

Table IV. Comparison of Bubble and Streamer Chambers.

	Bubble Chambers		Streamer Chambers	
Production length (in of liquid H_2)	1	3	1.3×10^{-2}	5.3×10^{-2}
10 atm gas target length (m)	-	-	1	4
Triggers/beam pulse (Max)	1	1	10	10
Pions/beam pulse	5	5	5.5×10^{3}	1.4×10^{3}
Pions/sensitive time	5	5	5.5×10^{-2}	1.4×10^{-2}
Inelastic events/beam pulse	0.5	1.3	8	8
Effective track length (m)	3	5	8	8
Nuclear absorption factor for 2 tracks	0.48	0.29	1.0	1.0
Useful inelastic events/beam pulse	0.24	0.38	8	8
Beam pulses for 10^3 events at 500 μb	2×10^{5}	1.3×10^{5}	6×10^{3}	6×10^{3}
No. of days (10^4 pulses/day)	20	13	0.6	0.6
No. of inelastic events (σ = 25mb)	5×10^{4}	5×10^{4}	5×10^{4}	5×10^{4}

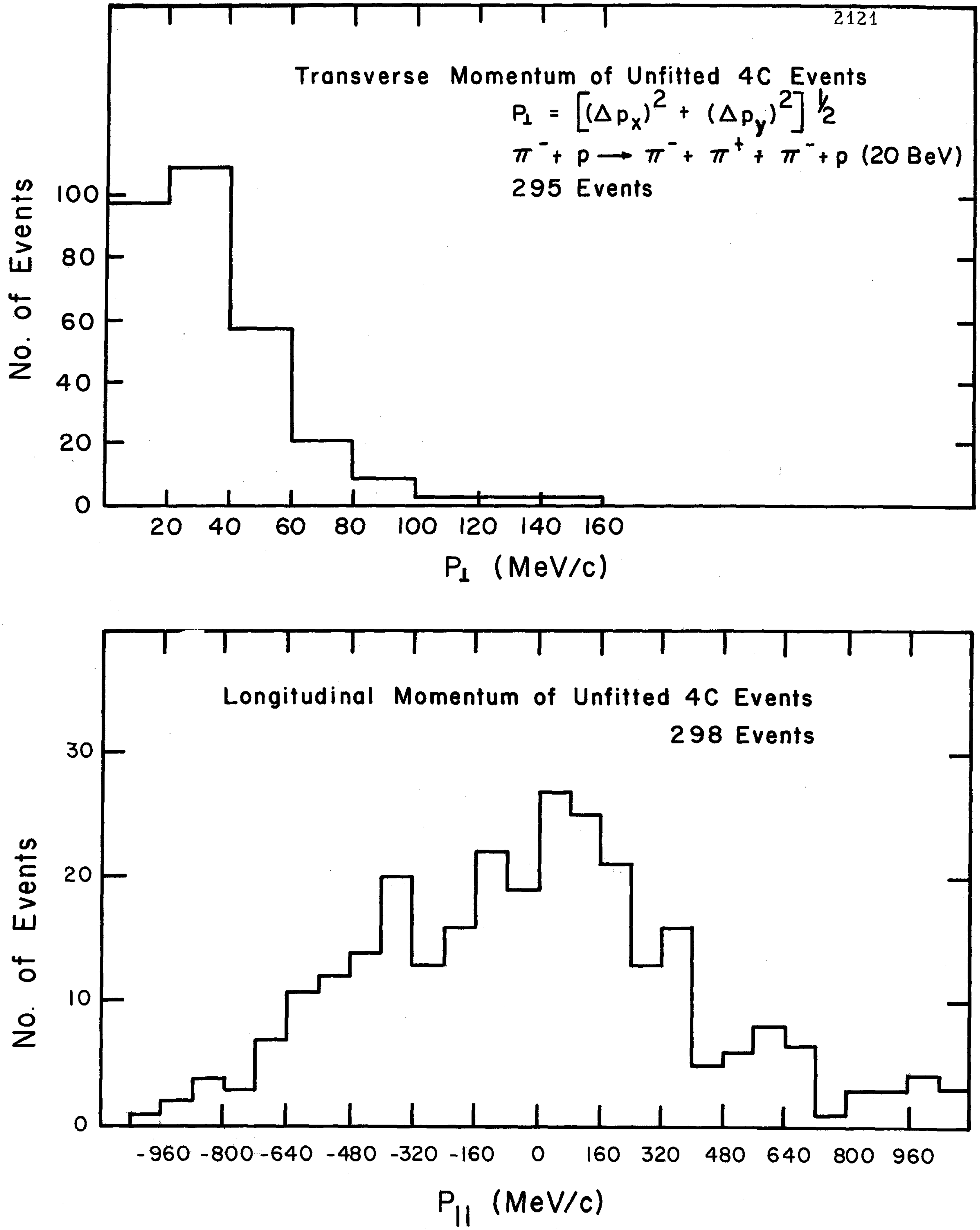

Fig. 1. Results for unfitted 4c events in π^- + p at 20 GeV/c.