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Final-State Interactions in the $\pi^- + p \to K + \bar{K} + N$ REACTION*

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In this Letter we report results of a study of the reaction $\pi^- + p \to K + \bar{K} + N$ at incident momenta less than 2.3 BeV/c. We find that the distribution in momentum transfer to the recoil nucleon is consistent with the assumption that most $K\bar{K}$-pairs are produced in peripheral $\pi^- + p$ collisions, as suggested by the data of Erwin et al.[1] However, the effective-mass distributions for the $\bar{K}N$ system indicate that an additional contribution to the $K\bar{K}N$ final state arises from production of the isotopic spin $I = 0$ resonant state Y_0^* (1520 MeV),[2] with the subsequent decay $Y_0^* \to \bar{K} + N$. We have also examined the $K\bar{K}$ effective-mass distributions for possible effects due to final-state interactions. Although the K^0K^- effective-mass distribution is consistent with the phase-space estimate, an enhancement is observed for the neutral $K\bar{K}$-system (K_1K_1n final states) in the region $M^2(K_1K_1) \approx (1.02\ \text{BeV})^2$. A satisfactory fit to the data is obtained if the enhancement is attributed to strong scattering in the $I = 0$, S-wave $K\bar{K}$ state. In a study of the reaction $K^- + p \to \Lambda + K + \bar{K}$ at 2.24 and 2.5 BeV/c, Bertanza et al. have observed a similar enhancement at approximately the same mass; however, only final states of the type ΛK_1K_2 were found.[3] The relation of the two results is discussed.

The data were obtained during an extensive exposure of the Lawrence Radiation Laboratory's 72-in. hydrogen bubble chamber to a secondary π^- beam at six momentum settings ranging from 1.51 to 2.25 BeV/c. A total of 225,000 pictures with 10 to 20 π^- mesons each were taken and scanned for visible production of strange particles. Of the 12,000 events measured, 158 were unambiguously identified via the kinematical constraint program PACKAGE as belonging to one of the following hypotheses:

a. $\pi^- + p \rightarrow K^0 + K^- + p$, with $K^0 \rightarrow \pi^+ + \pi^-$,

b. $\pi^- + p \rightarrow K^0 + \overline{K^0} + n$, with $K^0 \rightarrow \pi^+ + \pi^-$, and $\overline{K^0} \rightarrow \pi^+ + \pi^-$.

The number of observed events together with the approximate path length examined is summarized in Table I.

The Dalitz plot for the reaction $\pi^- + p \rightarrow K^0 + K^- + p$, together with its projections on the $M^2(K^0K^-)$ and $M^2(K^-p)$ axes, is shown in Fig. 1. Since the effects of two-body interactions may be obscured in events occurring too close to the kinematic threshold, all events for which the laboratory momentum of the incident pion p_π is less than 1.95 BeV/c have been plotted separately and are not used in the analysis of effective-mass distributions. The phase-space curves represent weighted averages for the data appearing in the plots. A strong enhancement appears in the $M^2(K^-p)$ distribution at $M^2 \simeq (1520\ \text{MeV})^2$, with estimated full-width $\Gamma \simeq 25$ MeV. Since the resonant state, $Y_0^*(1520\ \text{MeV})$ is readily produced in the π^- momentum interval studied here,[4] we attribute the peak to the reaction $\pi^- + p \rightarrow Y_0^* + K^0$ followed by $Y_0^* \rightarrow K^- + p$. No significant deviation from the phase-space curve is observed for either the $M^2(K^0K^-)$ or the $M^2(K^0p)$ distributions.

The Dalitz plot for the reaction $\pi^- + p \rightarrow K^0 + \overline{K^0} + n$ is shown in Fig. 2. In the present experiment we can fit only those events for which both the K^0 and $\overline{K^0}$ decay via the $K_1 \rightarrow \pi^+ + \pi^-$ mode; interactions leading to the K_1K_2n final states are kinematically underdetermined, since neither the neutron nor the K_2 is observed.[5] In addition, the K^0 cannot be distinguished from the $\overline{K^0}$, so that each event must be represented by two points on the Dalitz plot. The distribution for $M^2(K^0\overline{K^0})$ is still unique and may be compared directly with the $M^2(K^0K^-)$ distribution; in the other projection we are constrained to study the sum of the distributions for $M^2(K^0n)$ and $M^2(\overline{K^0}n)$. It must be noted that if the product CP is conserved in production and decay, the observed K_1K_1 events result only from those states in which the relative angular momentum, L, of the neutral $K\overline{K}$ system is even. Consequently, the K_1K_1n events serve as a detector for only a restricted portion of the $K^0\overline{K^0}n$ final state.

A comparison of the $M^2(K_1K_1)$ distribution with the phase-space curve indicates a systematic tendency for the K_1K_1 system to be produced with low effective mass, a peak occurring in the region $M^2(K_1K_1) \sim (1.02\text{ BeV})^2$. Since no corresponding deviation is observed in the K^0K^-p events, we ascribe the effect to a strong interaction in the $I = 0$ $K\overline{K}$ system.[6] Possible assignments for the enhanced state are 0^{++}, 2^{++}, etc. (spatial parity is designated by the first superscript and G-parity by the second). This result may be compared to the similar enhancement reported by Bertanza et al., in which no K_1K_1 final states were observed. With CP conservation, the difference in decay states is sufficient to conclude that the observed enhancements must arise from strong interactions occurring in two states of the neutral $K\overline{K}$ system with opposite parity.

The combined $M^2(K^0n)$ and $M^2(\overline{K^0}n)$ distributions have been examined for evidence of the decay $Y_0^* \rightarrow \overline{K^0} + n$. Taking into account $\Gamma(Y_0^* \rightarrow K^- + p)/\Gamma(Y_0^* \rightarrow \overline{K^0} + n) = 1$, and the relative detection efficiencies, 3:1, for K^0K^-p and $K^0\overline{K^0}n$ final states due to K^0 decay, the ~20 Y_0^*(1520 MeV) decays observed in the K^0K^-p channel lead to the expectation that ~7±1.5 $K^0\overline{K^0}n$ events will be associated with Y_0^* decay. Although we observe no enhancement in the M^2 interval centered about 1520 MeV, a peak of about 12 counts is present in the next higher interval. Although this M^2 distribution may arise from a series of statistical fluctuations, the shift in the position of the Y_0^*(1520 MeV) resonance may be due to interference with the strong $K^0\overline{K^0}$ interaction.

The distributions for the cosine of the nucleon recoil angle in the $\pi^- + p$ c.m. system, and the invariant momentum transfer to the nucleon, Δ^2, are given in Fig. 3. Chew and Low have shown that if one-pion exchange (OPE) contributes to reactions (a) and (b), the double-differential cross section is dominated in the limit $\Delta^2 \rightarrow -m_\pi^2$ by the term[7]

$$\frac{d^2\sigma}{d\Delta^2 dM^2} = \frac{f^2}{2\pi} \cdot \frac{Mk_\pi}{M_\pi^2 p_\pi} \cdot \frac{\Delta^2}{(\Delta^2+M_\pi^2)^2} \cdot \sigma(\pi\,\pi \rightarrow K\overline{K}), \qquad (1)$$

where M is the effective mass of the $K\overline{K}$-system, f is the π-N coupling constant ($\times\, 2^{1/2}$ for π^+ exchange), k_π(or k_K) is the momentum of either pion (or either kaon) in the $\pi\pi$ c.m. system, and $\sigma(\pi\pi \rightarrow K\overline{K})$ is the $K\overline{K}$ production cross section at energy M for the appropriate initial and final charge states. The solid curves in Figs. 3a and 3b were obtained by suitable integrations over $M^2(K\overline{K})$, where we have taken $\sigma(\pi\pi \rightarrow K\overline{K}) \propto k_K/k_\pi$ and Eq. (1) to be valid for physical values of Δ^2. Agreement with the data is satisfactory. In addition, Treiman and Yang have pointed out that for reactions occurring peripherally, there can be no correlation between directions defined in the rest frame of the incident pion by $\overline{p}_0 \times \overline{p}_f$ (initial and final nucleon momentum) and $\overline{p}_K \times \overline{p}_{\overline{K}}$.[8] After subtraction of events associated with Y_0^*(1520 MeV) decay, the distribution in the angle $\psi = \cos^{-1}(\bar{p}_0 \times \bar{p}_f \cdot \bar{p}_K \times \bar{p}_{\bar{K}})$ for all remaining events is uniform within statistics.

If the adequacy of the OPE mechanism is accepted for $K\bar{K}$ productions not associated with Y_0^* decay, Eq. (1) may be used to estimate the cross sections for $\pi + \pi \to K + \bar{K}$.[9] In particular, we shall consider the strongly interacting $I = 0$ state. Since the enhancement in $M^2(K_1K_1)$ occurs close to the $K^0\overline{K^0}$ threshold,[10] it is possible that it may arise from strong S-wave scattering in the $K\bar{K}$-system.[11] For simplicity we take into account only the two channels $K\bar{K} \leftrightarrow K\bar{K}$, and $K\bar{K} \leftrightarrow \pi\pi$. Using the zero-effective-range approximation[12] and detailed balancing, we can write the S-wave $K\bar{K}$ production cross section for pure $I = 0$ initial and final states:

$$\sigma_0(\pi\pi \to K\bar{K}) = \frac{4\pi k_K}{k_\pi^2} \cdot \frac{2b_0}{(1+b_0k_K)^2+(a_0k_K)^2}, \qquad (2)$$

where $A_0 = a_0 + i\,b_0$ is the $I = 0$, S-wave, $K\bar{K}$ scattering length. The additional factor of two arises from symmetrization of the initial and final states. Since we assume that the $K\bar{K}$ system is produced in the S-wave, one-fourth of the events will lead to the K_1K_1 final state.[13] Taking into account the isotopic composition of the initial $\pi^-\pi^+$ state, we obtain

$$\sigma(\pi^-\pi^+ \to K_1K_1) = (1/3)\,(1/4)\,\sigma_0(\pi\pi \to K\bar{K}) . \qquad (3)$$

Using Eqs. (1), (2), and (3), we have evaluated $d\sigma/dM^2$ for several combinations of a_0 and b_0. For normalization, it was assumed that all events with $M^2(K_1K_1)$ less than 1.3 BeV^2 were associated with the enhanced 0^{++} state. We find that $A_0 \simeq \pm(4 \text{ to } 6) + i0.3$ fermis provides an adequate fit to both the observed cross section[14] (determined predominantly by b_0) and the shape of the $M^2(K_1K_1)$ distribution.

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FOOTNOTES AND REFERENCES

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†On leave of absence from the Israel Atomic Energy Commission Laboratories, Rehovoth.

1. A. R. Erwin, G. A. Hoyer, R. H. March, W. D. Walker, and T. P. Wangler, Phys. Rev. Letters 9, 34 (1962).

2. M. Ferro-Luzzi, R. D. Tripp, and Mason B. Watson, Phys. Rev. Letters 8, 28 (1962).

3. L. Bertanza, V. Brisson, P. L. Connolly, E. L. Hart, I. S. Mittra, G. C. Monetti, R. R. Rau, N. P. Samios, I. O. Skillicorn, S. S. Yamamoto, M. Goldberg, L. Gray, J. Leitner, S. Lichtman, and J. Westgard, Phys. Rev. Letters 9, 180 (1962), and private communication.

4. G. Alexander, G. R. Kalbfleisch, D. H. Miller, and G. A. Smith, Phys. Rev. Letters 8, 447 (1962).

5. Some fraction of the $K_2 \to \pi + \mu + \nu$ decays may fit as $K_1 \to \pi^+ + \pi^-$. As a check for any serious contamination due to K_2 decays, the lifetime has been calculated for events used in the present analysis. We find $\tau = 0.86 \pm 0.08 (10^{-10})$sec, consistent with a pure sample of K_1 decays (see for example G. Alexander, S. P. Almeida, and F. S. Crawford, Phys. Rev. Letters 9, 69 (1962), footnote 11).

6. The $I = 1$ $K\bar{K}$ system can be produced from either the $I = 1/2$ or $I = 3/2$ component of the initial $\pi^- + p$ state; consequently destructive interference is possible in the K^0K^- channel. Because the data were obtained over a range of incident momenta, we consider such a complete accidental cancellation unlikely.

7. G. F. Chew and F. E. Low, Phys. Rev. **113**, 1640 (1959).

8. S. B. Treiman and C. N. Yang, Phys. Rev. Letters **8**, 140 (1962).

9. These cross sections were estimated in Ref. 1. It may be noted that the cross sections of Erwin et al. are overestimated because k_K rather than k_π is used in the numerator of Eq. (1).

10. In the absence of a strong $K\bar{K}$ interaction, explicit evaluation of Eq. 1 yields results for the expected $M^2(K\bar{K})$ distribution quite similar to the phase-space estimate. Consequently, conclusions based upon a comparison with the phase-space curves remain unchanged.

11. The possibility that the enhancement arises from the decay of a zero strangeness $J = 2^{++}$, resonant state cannot be ruled out. However, such a state may be expected to decay much more rapidly into two or four pions. Since no well-established peak has been observed in the neutral $\pi\pi$ system in the corresponding mass region, the hypothesis is not required by existing experimental data. It may be noted that to the extent that $K\bar{K}$-pair production occurs peripherally, the lowest relative angular momentum allowed to the K^0K^- system is $L = 1$. The centrifugal barrier in this state may contribute to the tendency for the Dalitz plot (Fig. 1) to be depopulated as $M^2(K^0K^-) \to (M_{K^0} + M_{K^-})^2$.

12. See for example R. H. Dalitz, Strong Interaction Physics and the Strange Particles, Enrico Fermi Institute for Nuclear Studies Report EFINS-61-69.

13. In addition to having $I = 0$, the initial S-wave $\pi\pi$ state is even under charge conjugation, C. Since I and C are conserved in the peripheral

collision, the final charge state must be (1/2) $(K^0\overline{K^0} + \overline{K^0}K^0)$ - (1/2) $(K^+K^- + K^-K^+)$ =(1/2) $(K_1K_1 + K_2K_2)$ - (1/2) $(K^+K^- + K^-K^+)$ [see for example, M. Goldhaber, T. D. Lee, and C. N. Yang, Phys. Rev. 112, 1796 (1958)].

14. Using the path length given in Table I, for $p_\pi > 1.95$ BeV/c, and correcting for the 10% electron and muon beam contamination, we estimate the contribution to the cross section to be 0.1μb per event.

Table I

Beam momentum (BeV/c)	Number of observed events		Path length
	K^0K^-p	$K^0\overline{K^0}n$	(10^5 meters)
1.51	0	0	5.1
1.69	2	7	6.4
1.89	16	10	10.1
2.05	13	8	3.4
2.17	24	18	12.2
2.25	37	23	15.2
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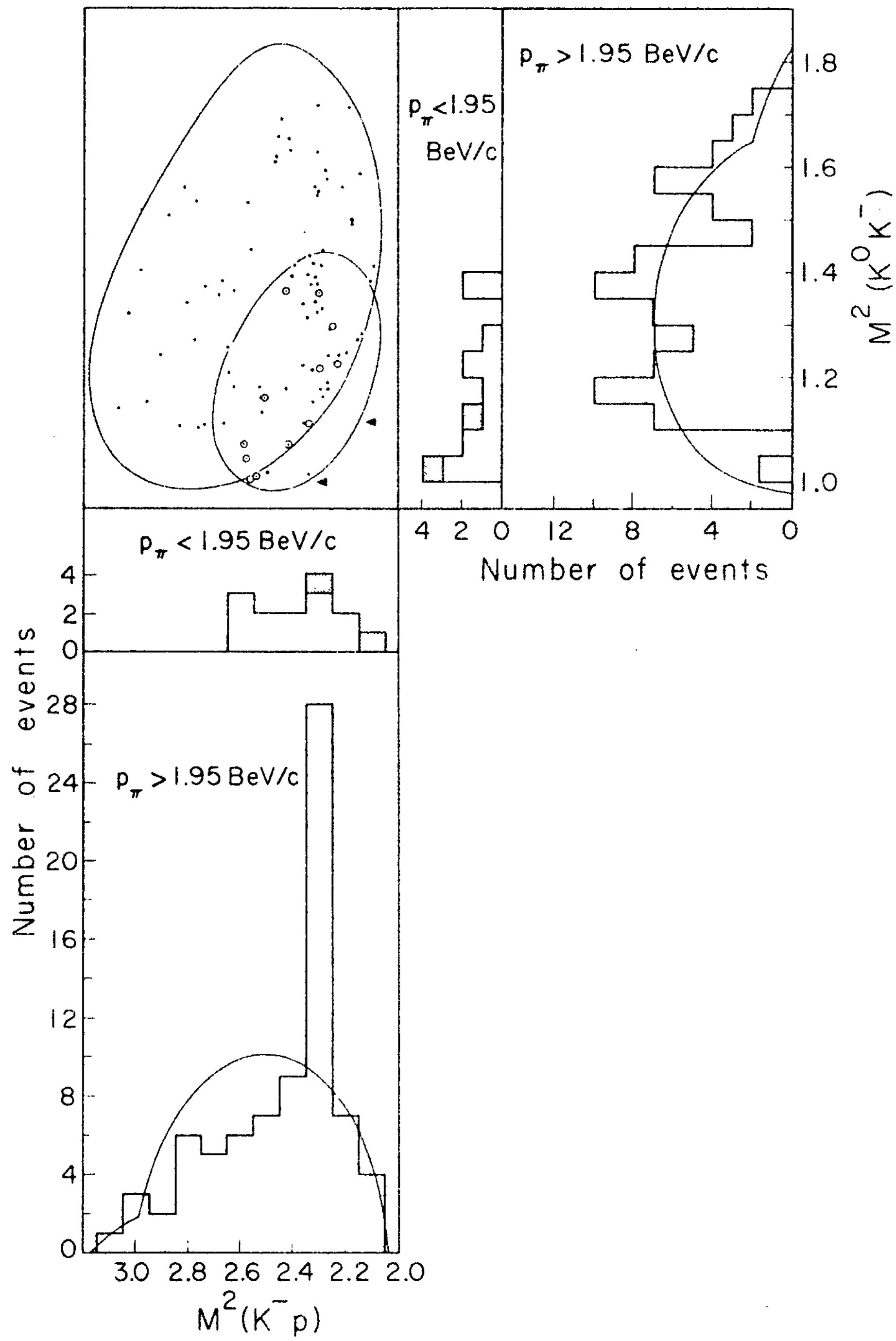
Total	92	66	

FIGURE LEGENDS

Fig. 1. Dalitz plot for $\pi^- + p \rightarrow K^0 + K^- + p$. Phase-space curves are normalized to the total number of events. Events for incident pion momenta, p_π, less than 1.95 BeV/c are projected separately. The shaded areas correspond to $p_\pi < 1.78$ BeV/c. See text for details.

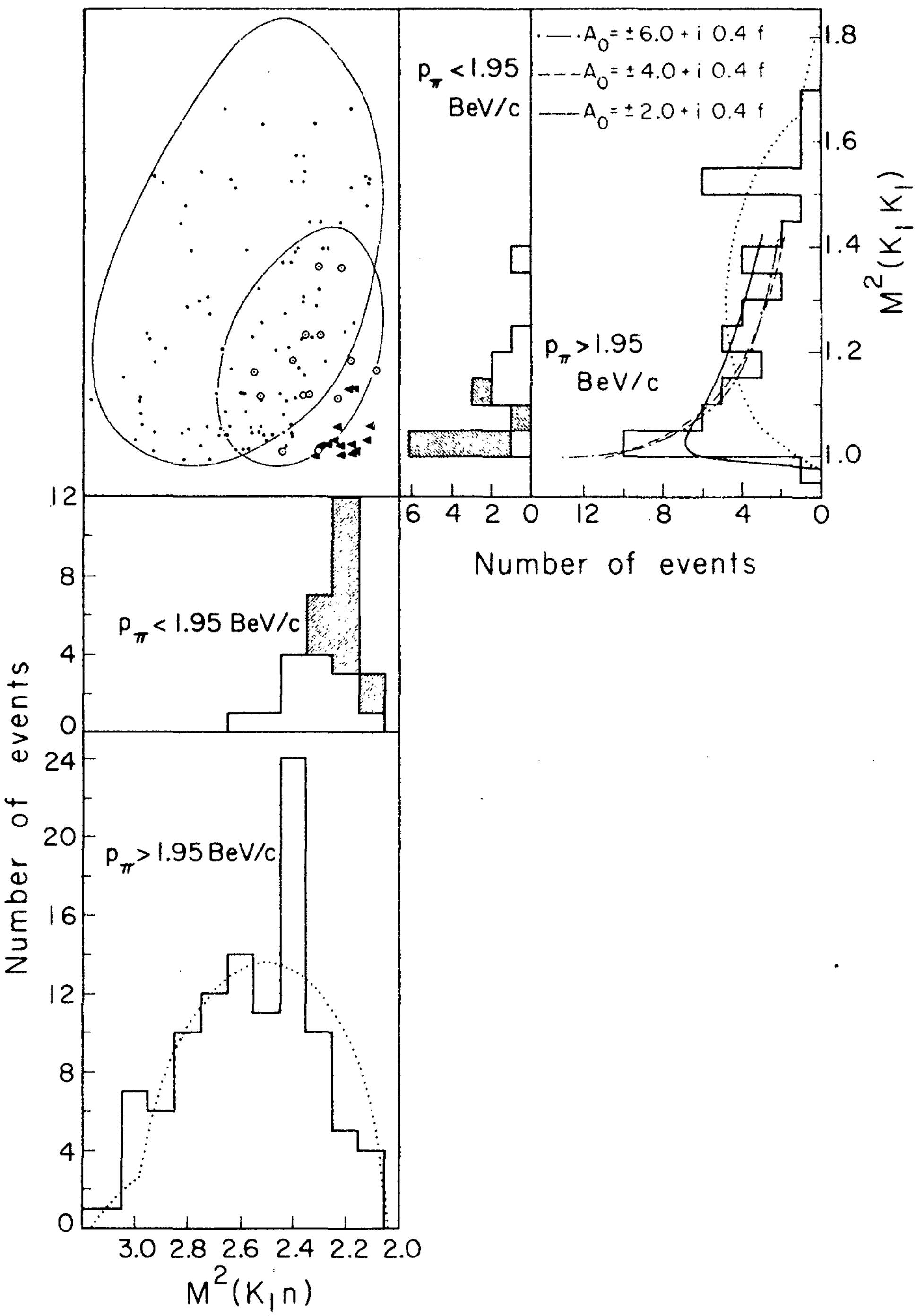
Fig. 2. Dalitz plot for $\pi^- + p \rightarrow K_1 + K_1 + n$. Each event yields two points on the plot. Phase-space curves (dotted) are normalized to the total number of events with $p_\pi > 1.95$ BeV/c. The effect of strong $I = 0$, S-wave $K\bar{K}$ scattering is indicated for several values of the complex scattering length $A_0 = a_0 + i\, b_0$. See text for details.

Fig. 3. Production c.m. angular distribution and invariant momentum transfer, Δ^2, for the recoil nucleon. The solid curves were calculated assuming that $K\bar{K}$-pair production occurs in peripheral collisions. Data are for $p_\pi > 1.95$ BeV/c. Elimination of events possibly associated with Y_0^* decay results in no significant change in the distributions.



MUB 1393

Fig 1



$A_0 = \pm 6.0 + i\ 0.4$ f
$A_0 = \pm 4.0 + i\ 0.4$ f
$A_0 = \pm 2.0 + i\ 0.4$ f
$p_\pi < 1.95$ BeV/c
$p_\pi > 1.95$ BeV/c
$M^2(K_1 K_1)$
Number of events
$p_\pi < 1.95$ BeV/c
$p_\pi > 1.95$ BeV/c
Number of events
$M^2(K_1 n)$
MUB 1394

Fig. 2

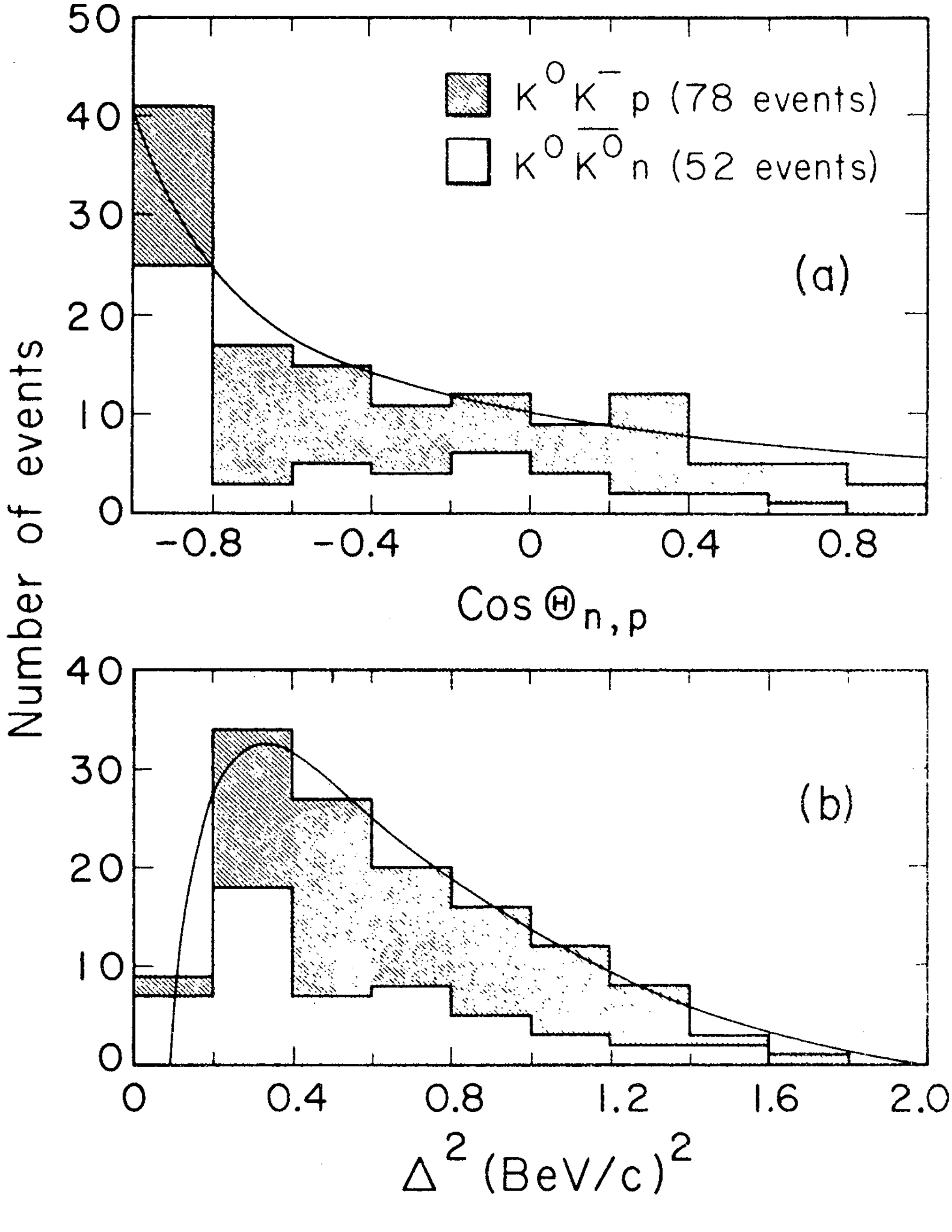


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Fig. 3