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A STUDY OF STRANGE AND STRANGEONIUM STATES PRODUCED IN LASS*

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Results are presented from the analysis of several final states from a high-sensitivity (4 ev/nb) study of inelastic K^-p interactions at 11 GeV/c carried out in the LASS Spectrometer at SLAC. New information is reported on leading and underlying K^* states, and the strangeonium states produced by hypercharge exchange are compared and contrasted with those observed in radiative decays of the J/ψ.

1. Overview of the Experiment

The spectroscopy of light-quark mesons continues to play a significant role in High Energy Physics. Much is now known, but our understanding of higher excitations and non-leading states is still far from complete. In order to make a useful contribution, an experiment must have both high sensitivity and good acceptance, criteria fulfilled by the experiment whose results are described below.

The Large Aperture Superconducting Solenoid (LASS) Spectrometer[1] is shown in Fig. 1. Situated in an RF separated beam, it features a solenoidal vertex detector and downstream dipole spectrometer giving good acceptance over 4π sr and good momentum resolution. Two threshold Čerenkov counters, Time-of-Flight counters and dE/dx measurement in the cylindrical chambers surrounding the liquid hydrogen target provide good particle identification. The trigger for the experiment was two or more charged particles in the "box" of proportional chambers surrounding the target—essentially σ_{tot} except for the all-neutral final states.

The results presented below come from studies of K^* production in the channels $K^-\pi^+n$, $\bar{K}^\circ\pi^+\pi^-n$, and $K^-\eta p$ and of "strangeonium" production by hypercharge exchange in $K^\circ_sK^\pm\pi^\mp\Lambda$, $K^-K^+\Lambda$, and $K^\circ_sK^\circ_s\Lambda$.

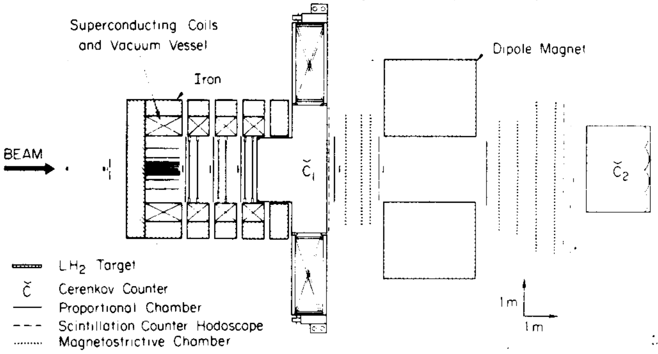

Fig. 1. The LASS Spectrometer

2. New K^* Results

The large cross section $K^-\pi^+n$ channel is ideal for studying natural J^PK^* states. The internal angular structure of the $K^-\pi^+$ system shows complex structure, and is analysed[2] in terms of moments of spherical harmonic functions in the Gottfried-Jackson (t-channel helicity) frame. In general, states of spin J will appear in moments up to $L=2J$. After demanding $|t'| < 0.2$ (GeV/c)^2 and removing events with π^+n mass below 1.7 GeV/c^2 (N^* cut) there remain 151 000 events with $K^-\pi^+$ masses below 2.6 GeV/c^2. Figure 2 clearly shows the well-known leading states, with Breit-Wigner fits giving masses (widths) in agreement with the world averages:[3] $K^*(892)$ 897.0 ± 1.4 (49.9 ± 2.5); $K^*(1430)$ 1433.0 ± 2.1 (115.8 ± 4.3); and $K^*(1780)$ 1778.1 ± 7.7 (186 ± 36). All values are in MeV/c^2 and systematic errors are included.

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The higher moments shown in Fig. 3 confirm the $J^P=4^+$ $K^*(2060)$ and require a new 5^- state. The curves shown are the result of a simple model fit to the 21 moments with $L \leq 10$ and $M \leq 1$, higher moments being consistent with zero. The F, G, and H-waves are parametrised as Breit-Wigners with a background term while the S, P and D-waves are assumed to be coherent amplitudes, with linear mass dependence in both magnitude and phase. The $M=1$ moments are related to those with $M=0$ using the parametrisation of Estabrooks et al.[4] The resulting masses (widths) in MeV/c^2 are 2062 ± 27 (221 ± 75) and 2382 ± 33 (178 ± 69) for $J^P=4^+$ and 5^- respectively. The significance of the 5^- structure compared with a background term alone is $\sim 5\sigma$.

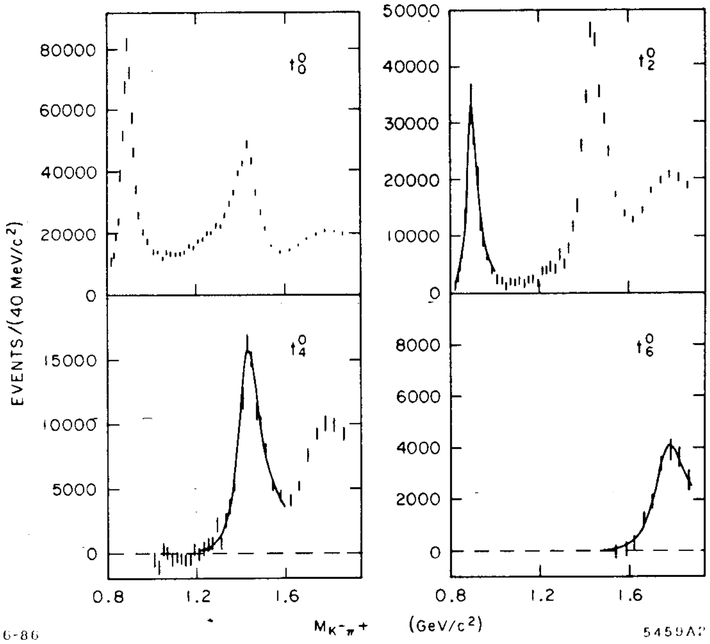

Fig. 2. The unnormalised L-even, $M=0$ $K^-\pi^+$ moments for the mass region below 1.88 GeV/c^2 extracted from the reaction $K^-p \to K^-\pi^+n$. The curves are described in the text.

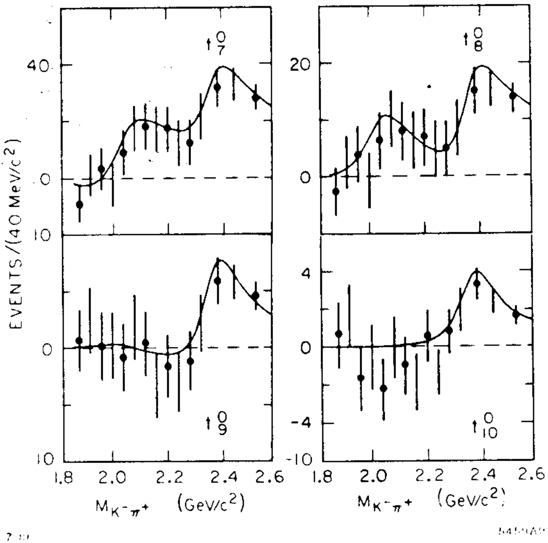

Fig. 3. The unnormalised $L > 6$, $M=0$ $K^-\pi^+$ moments for the mass region above 1.88 GeV/c^2 extracted from the reaction $K^-p \to K^-\pi^+n$. The moments are plotted in overlapping bins; black dots indicate the independent mass bins used for the fit described in the text.

We turn now to the related $\bar{K}^\circ\pi^+\pi^-n$ channel which can be viewed as exploring inelastic $K\pi$ interactions, while $K^-\pi^+n$ tells us only about $K\pi$ elastic scattering. Figure 4 shows the observed $\bar{K}^\circ\pi^+\pi^-$ mass spectrum after applying an N^* cut; there are 34 000 events in the final Partial Wave Analysis (PWA) sample below 2.3 GeV/c^2. A three-body PWA using the SLAC-LBL program reveals, surprisingly, that most of the $\bar{K}^\circ\pi^+\pi^-$ production is resonant.[5] I will concentrate on the natural J^P production, which dominates all the important features.

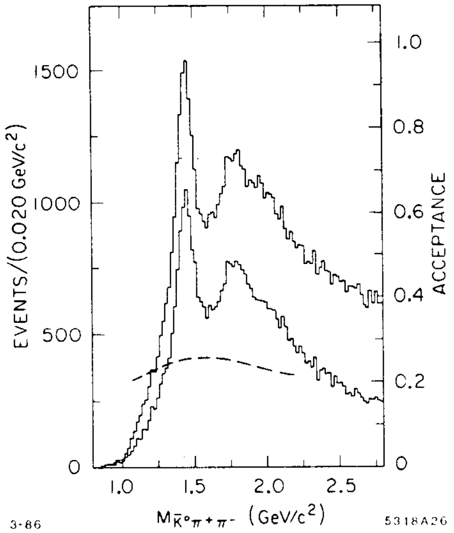

Fig. 4. The $\bar{K}^\circ\pi^+\pi^-$ mass spectrum from the reaction $K^-p \to \bar{K}^\circ\pi^+\pi^-n$. The inner histogram is the PWA sample with $|t'| < 0.3$ (GeV/c)^2; the dashed line shows the mass dependence of the acceptance function.

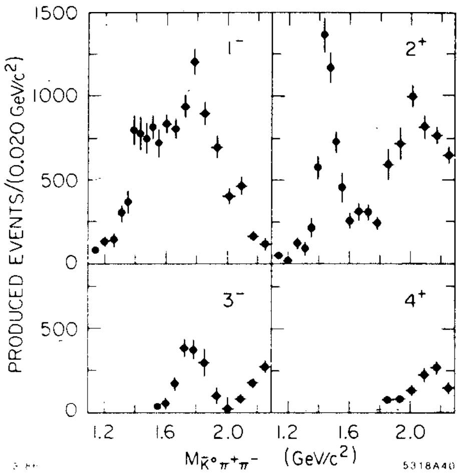

Fig. 5. The $\bar{K}^\circ\pi^+\pi^-$ natural spin-parity wave intensities. Partial waves of the same J^P are summed coherently.

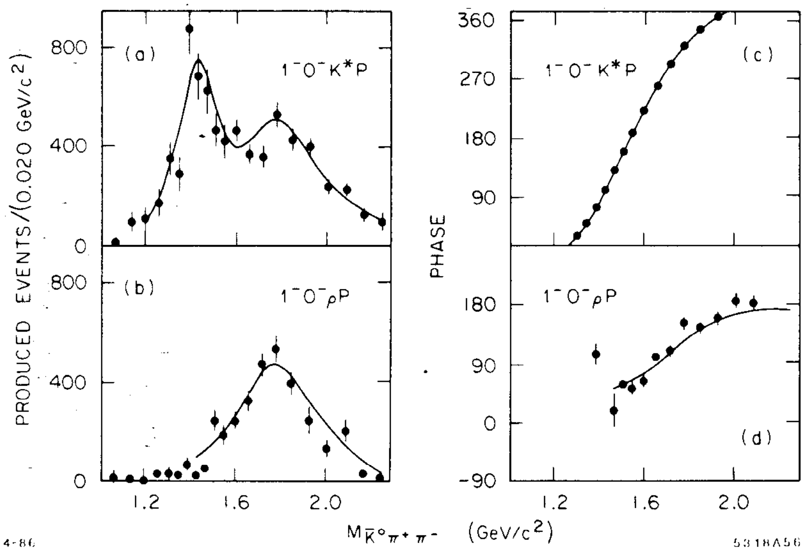

Fig. 6. The $\bar{K}^\circ\pi^+\pi^-$ 1^- waves compared with the predictions of the five-wave model described in the text.

Figure 5 shows the natural parity J^P decomposition. The leading 2^+, 3^- and 4^+ K^* states are clear, and there are also interesting structures in the 1^- at 1.4 and 1.8 GeV/c^2 and in the 2^+ at about 2 GeV/c^2. Figures 6(a) and (b) show the 1^- intensity broken down into $K^*\pi$ and $K\rho$ components, indicating states at ~1.4 GeV/c^2 coupling only to $K^*\pi$ and ~1.75 GeV/c^2 coupling to both $K^*\pi$ and $K\rho$. We have made a simultaneous fit to these waves and the leading $2^+K^*\pi$, $3^-K^*\pi$ and $3^-\rho K$ waves, thus tightly constraining the relative phase behaviour of the 1^- waves. The result of this fit is shown in Fig. 6; a coherent background was allowed in the $1^-K^*\pi$ amplitude, though this is not essential for a good fit. The masses (widths) of the two 1^- states are: 1420 ± 17 (240 ± 30) and 1735 ± 30 (423 ± 48) MeV/c^2; systematic errors are included. This analysis confirms previous observations.[5,6] The lower state is presumably the first radial excitation of the $K^*(890)$.

Figures 7(a) and (b) show the intensities of the $2^+K^*\pi$ and $2^+\rho K$ waves. Apart from the leading 2^+ $K^*(1430)$, a large enhancement is evident in both waves at ~2.0 GeV/c^2. We have fit the intensities and relative phases of these two waves above 1.69 GeV/c^2 to a Breit-Wigner and a coherent linear background; the overall phase is set using the fit to the $1^-K^*\pi$ wave described above. The result of the fit, shown in Fig. 7, is satisfactory, although the size of background required means that the single resonance interpretation is not unique.

There are almost no data on decays of K^* states into $K\eta$. We have searched for these in the $K^-\pi^+\pi^-\pi^\circ p$ final state. Figure 8 shows the $\pi^+\pi^-\pi^\circ$ spectrum of events satisfying a 1C kinematic fit to this channel. Consistency of particle identification has been demanded and events satisfying the 4C fit to $K^-\pi^+\pi^-p$ have been excluded. We see a strong η signal; the shaded areas are control regions used for background estimation. In Fig. 9 is shown the $K\eta$ mass spectrum after applying N^* and Y^* cuts and subtracting the control regions. The spectrum is dominated by a single resonance which is consistent with the 3^- $K^*(1780)$; this interpretation is confirmed by a preliminary moments analysis. The observed events correspond to a $K\eta$ branching ratio of ~2.5%. In contrast, there is no evidence of the $K^*(1430)$ whatever; the shaded area shows the expectation if its $K\eta$ branching ratio were 0.5%. These observations disagree strongly with SU(3) predictions.

3. Analysis of Strangeonium Channels

We expect channels involving hypercharge exchange (*e.g.*, those with a slow Λ) to be a fruitful source of $s\bar{s}$ states. In all the cases described

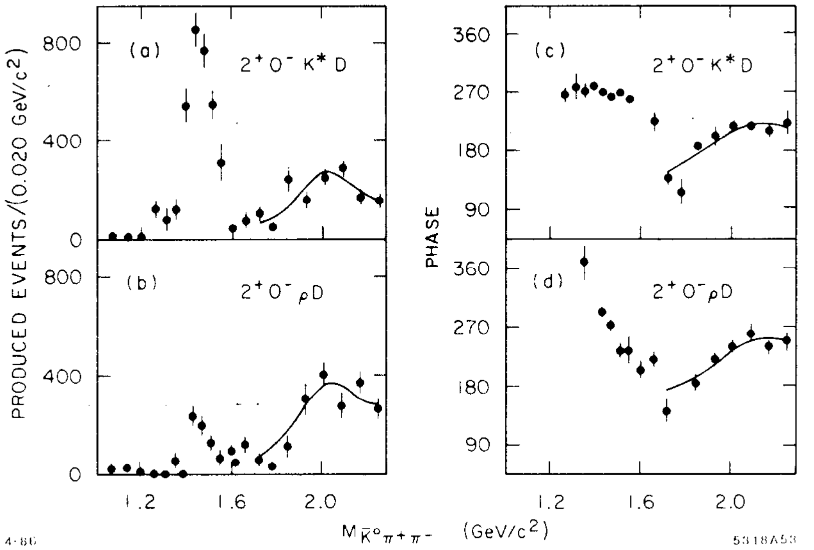

Fig. 7. The $\bar{K}^\circ\pi^+\pi^-$ 2+ waves; the fit at high mass is described in the text.

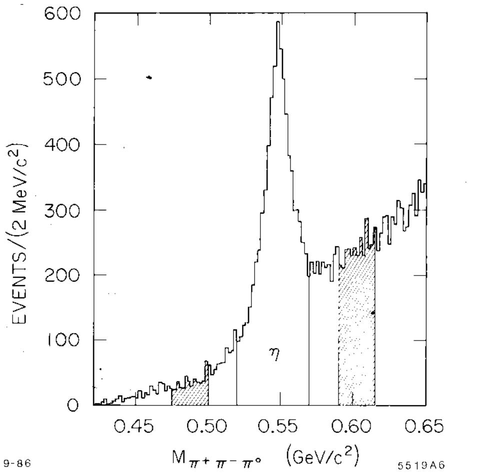

Fig. 8. The $\pi^+\pi^-\pi^\circ$ mass spectrum from the reaction $K^-p \to K^-\pi^+\pi^-\pi^\circ p$. The shaded control regions are used to estimate non-η background under the η signal.

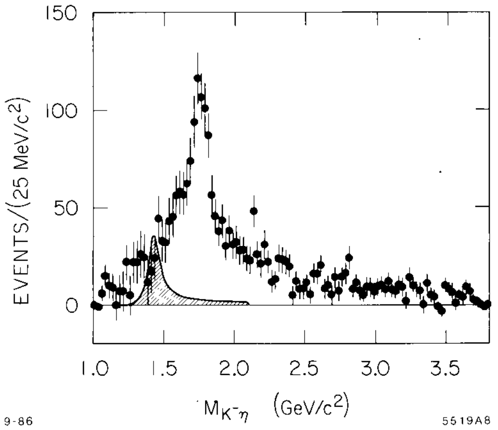

Fig. 9. The background-subtracted $K\eta$ mass spectrum from the $K^-p \to K^-\eta p$ reaction after N^* and Y^* cuts. The shaded curve shows the signal expected for a $K^*(1430) \to K\eta$ branching ratio of 0.5%.

below, the Λ is reconstructed in the LASS Spectrometer, and particle identification performs only a supporting role in event selection. The resultant acceptance is extremely uniform with no "holes."

The $K\bar{K}\pi$ mass spectrum for the combined $K^0_sK^\mp\pi^\pm\Lambda$ channels, shown in Fig. 10, is somewhat disappointing! There is some evidence of production of $f_1(1285)$ and $f_1(1420)$, but the cross section is small and statistics are limited. The spectrum is similar to that observed in the analogous π^-p reaction, indicating that these states do not have dominant $s\bar{s}$ content. Apart from these states and a sharp rise in the spectrum at K^*K threshold, the gross features are very similar to $\bar{K}^\circ\pi^+\pi^-$. A preliminary PWA, in contrast, shows that production of unnatural J^P states is predominant and that the 1.4-1.6 GeV/c² mass region consists almost entirely of 1^+K^*K. The broad bump at ~1.52 GeV/c² could, therefore, be the $f_1(1530)$, claimed as an $s\bar{s}$ resonance by Gavillet et al.,[7] though we find that $\bar{K}^*$ production exceeds K^* in both channels. We find no evidence for $0^-\delta\pi$ but

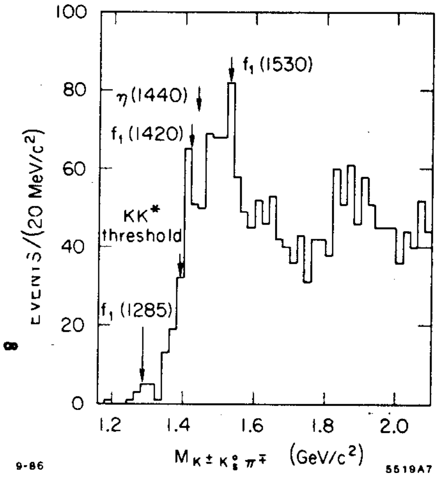

Fig. 10. The summed $K_s^\circ K\pi$ mass spectrum from the $K^-p \rightarrow K_s^\circ K^+\pi^-\Lambda$ and $K_s^\circ K^-\pi^+\Lambda$ channels.

cannot completely exclude it in the 1.42 GeV/c^2 region.

Finally, we turn to the $K^-K^+\Lambda$ and $K_s^\circ K_s^\circ\Lambda$ channels. These provide new information on hypercharge exchange production mechanisms and also permit interesting comparisons with $K\bar{K}$ spectra found in radiative J/ψ decay, thought to be "glue"-enriched.

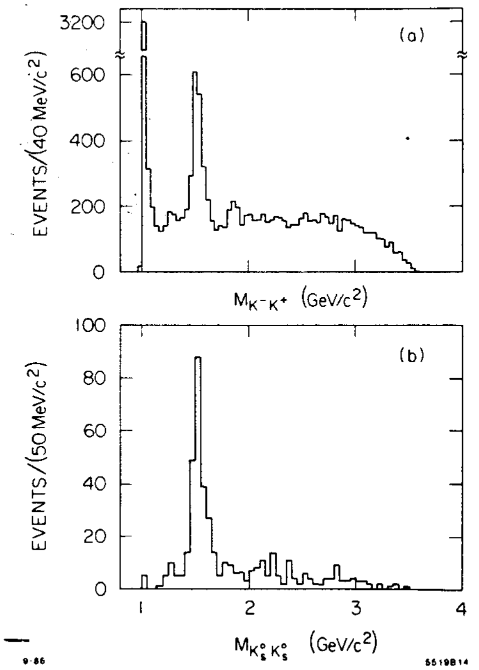

Fig. 11. The $K\bar{K}$ mass spectra (a) from the $K^-K^+\Lambda$; and (b) from the $K_s^\circ K_s^\circ\Lambda$ final states, demanding $|t'| < 2$ (GeV/c)^2.

Figure 11 shows the $K\bar{K}$ mass spectra from these channels. The $K_s^\circ K_s^\circ$ spectrum is dominated by the $f_2(1525)$; since the CP restriction of even spin does not apply to K^-K^+, this spectrum also shows a clear $\phi(1020)$ and evidence of the $\phi_3(1860)$. The cross section for production of $f_2(1525)$ in the two channels is consistent at ~1.5 μbarns and in agreement with interpolations of measurements at other beam momenta.

The other major difference between the spectra —the continuum in K^-K^+—is a result of diffractive production of N^*, as is clear from the Dalitz plot shown in Fig. 12.

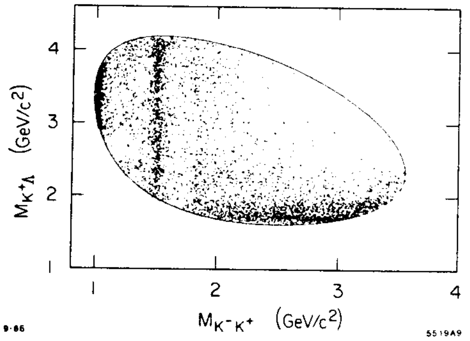

Fig. 12. The Dalitz plot of the $K^-p \rightarrow K^-K^+\Lambda$ reaction, corresponding to Fig. 11(a).

In order to better understand the structures in the K^-K^+ data, we have performed a moments analysis similar to that in the $K\pi$ channel but without an N^* cut. The moments above 1.68 GeV/c^2 are shown in Fig. 13. The structure at 1.86 GeV/c^2 is seen in moments up to t_6^0 and is verified as $J^P = 3^-$; curves corresponding to Breit-Wigner fits of t_0^0 and t_6^0 are shown (a linear background is included in the former). The masses (widths) determined from the fits average to 1857 ± 9 (69 ± 18) MeV/c^2. There is also structure in the moments around 2.2 GeV/c^2, which is discussed below.

Figure 14 shows comparisons of the $K_s^\circ K_s^\circ$ mass spectrum with that seen by the Mark III group[8] in radiative decay of the J/ψ. Figure 14(a) shows that there is no evidence whatever for hadronic production of the $f_2(1720)$ or "θ;" however, Fig. 14(b) demonstrates that the data from the two experiments are statistically compatible in the region of the $X(2220)$ or "ξ."

We can try and combine evidence from the two $K\bar{K}$ channels to speculate further on what might be happening in the "ξ" region. The K^-K^+ moments (Fig. 13) up to t_8^0 show structure in the

2.2 GeV/c^2 region which, while not statistically compelling, is compatible with a spin-4 state of width < 100 MeV/c^2. The large diffractive N^* production in this channel leads to substantial moments up to t^0_6, though they should be smooth and not have structure as a function of K^-K^+ mass.

Although statistics in the $K^\circ_sK^\circ_s$ channel are poor at 2.2 GeV/c^2, it is clear that the events are not distributed isotropically in the Gottfried-Jackson frame. Figure 15 shows the $K^\circ_sK^\circ_s$ spectrum for events in the forward direction only ($\cos\theta_J > 0.85$); the cut enhances the 2.2 GeV/c^2 region. Inset are the L=2 and 4 moments which show some effects, which are significant when integrated from 2.1-2.3 GeV/c^2.

Synthesising the evidence, it is clear that the 2.2 GeV/c^2 region has $J^P \geq 2^+$ and there is some indication of a rather narrow state with $J^P = 4^+$.

4. Conclusions

Light quark spectroscopy is alive and well! We are still gleaning valuable information on the existenceand decay modes of both leading and underlying K^* states.The systematics of mass-splittings of both radial and spin- orbit excitations is still not well understood and we still encounter surprises ($K^*(1410)$ and $K\eta$).

In the "strange"-onium world, hadronic production provides valuable comparisons with e^+e^- collisions in our attempts to understand meson structure. In $K\bar{K}\pi$, we see evidence for production of $f_1(1285)$, $f_1(1420)$ and $f_1(1530)$, and no evidence for $\eta(1440)$ ("ι"). Many issues remain unresolved here; experiments are difficult and the position of K^*K threshold is a great complication. In $K\bar{K}$, we confirm the $\phi_3(1860)$ and find the "ξ" region consistent with Mark III data and with quark model expectations. The total absence of the $f_2(1720)$ ("θ") in hadronic production is extremely interesting.

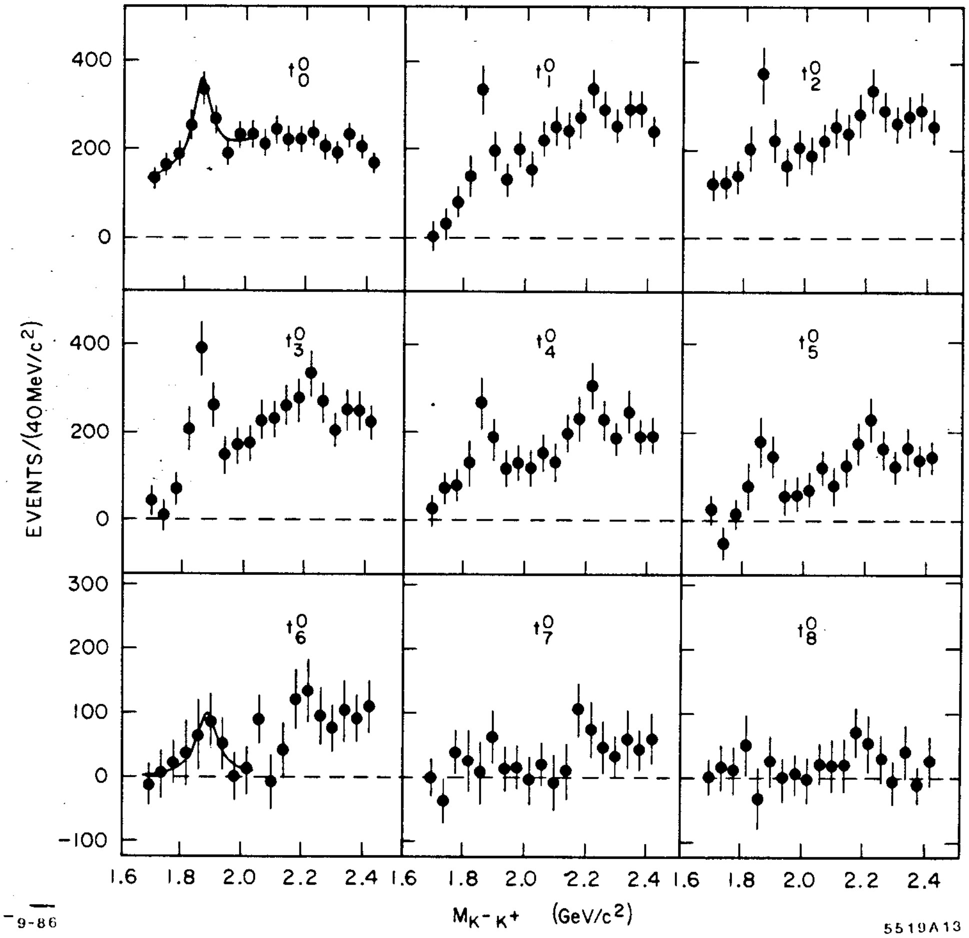

Fig. 13. The unnormalised M=0 K^-K^+ moments extracted from the $K^-p \to K^-K^+\Lambda$ reaction with $|t'| < 0.2$ (GeV/c)^2 required.

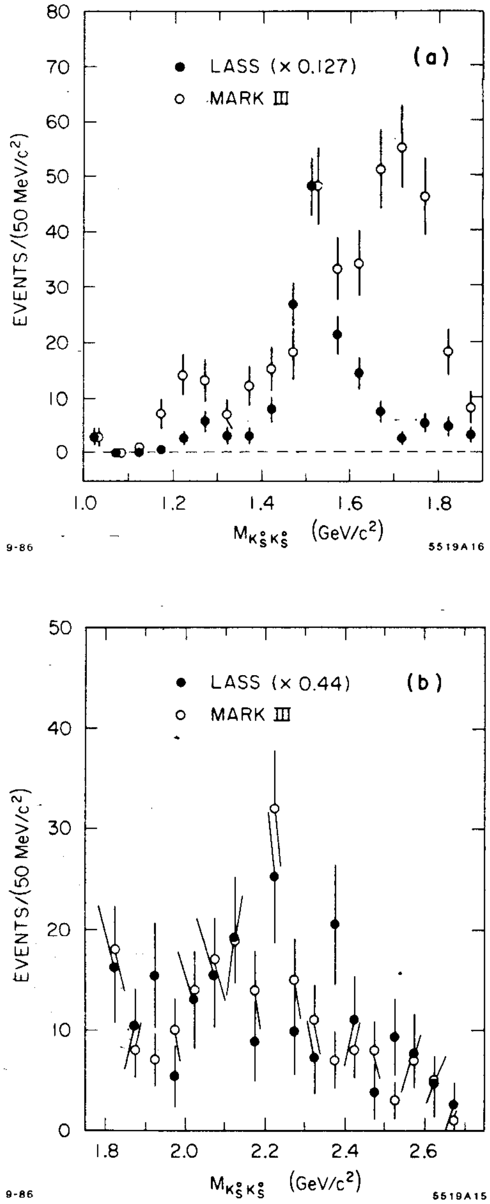

Fig. 14. The acceptance corrected $K_s^\circ K_s^\circ$ mass spectrum from $K^- p \to K_s^\circ K_s^\circ \Lambda$ in LASS compared with Mark III data from $\psi \to \gamma K_s^\circ K_s^\circ$: (a) below 1.9 GeV/c^2 normalised at the $f_2(1525)$ peak and; (b) above 1.8 GeV/c^2 normalised to total events in the 1.8–2.7 GeV/c^2 mass interval.

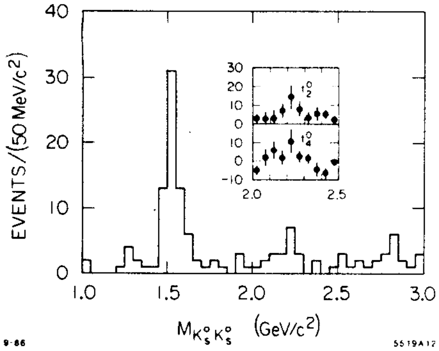

Fig. 15. The $K_s^\circ K_s^\circ$ mass spectrum with $\cos\theta_J > 0.85$; inset are the L=2 and 4, M=0 unnormalised moments.

References

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