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# EVIDENCE FOR A $J^{PC} = 4^{++}$ $K\overline{K}$ STATE AT $\sim 2.2$ GeV/c$^2$ FROM $K^-p$ INTERACTIONS AT 11 GeV/c*

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## ABSTRACT

Data from the reaction $K^-p \to K^-K^+\Lambda$ at 11 GeV/c have been obtained in the LASS spectrometer at SLAC. A spherical harmonic moments analysis of the $K^-K^+$ system provides evidence for a rather narrow $J^{PC} = 4^{++}$ state at $\sim$2.2 GeV/c$^2$. Relevant data from the reaction $K^-p \to K^0_SK^0_S\Lambda$ in the present experiment are shown also, and comparisons made to results from MARK III and GAMS in this mass region.

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In recent years there has been great interest in $\overline{K}K$ systems in the 2.2 GeV/c$^2$ mass region. The MARK III group, investigating $J/\psi$ radiative decay, observed a narrow structure in this vicinity in both the $K^-K^+$ and $K^0_SK^0_S$ modes [1]. This state, now known as the X(2220) [2], has average mass and width values of 2231 $\pm$ 8 and 21 $\pm$ 17 MeV/c$^2$, respectively. The DM2 collaboration, also studying radiative $J/\psi$ decay, claims to observe no narrow signal at ~2.2 GeV/c$^2$ [3]. The interest in the X(2220) stems from the possibility that it may be a new kind of object, such as a glueball or meikton [4], rather than a conventional $q\overline{q}$ state. In this regard, it is of importance to establish the quantum numbers of the state, and whether or not it is produced in hadronic interactions. If it is so produced, and can be readily accommodated within the level structure of the quark model, it is unlikely to be an exotic state. Preliminary results from the present experiment [5, 6, 7] have provided evidence for a narrow $\overline{K}K$ state at ~2.2 GeV/c$^2$. In addition, a narrow signal has been observed in this region by the GAMS collaboration for the $\eta\eta'$ system produced in $\pi^-p$ interactions at 38 and 100 GeV/c [8]. However, attempts at detecting the direct formation of the X(2220) in $p\overline{p}$ interactions have succeeded only in establishing upper limits for this process [9, 10].

In this paper, the results of an analysis of the $K^-K^+$ system in the 2.2 GeV/c$^2$ region are presented. This system is produced in the reaction

$$K^-p \rightarrow K^-K^+\Lambda_{seen}, \qquad (1)$$

at 11 GeV/c. Relevant data on the $K^0_SK^0_S$ system produced in the reaction

$$K^-p \rightarrow K^0_SK^0_S\Lambda_{seen} \qquad (2)$$

in the same experiment [11] are also used for comparison purposes. All final state particles, including those from the decay of the recoil $\Lambda$, are measured in the spectrometer, so that the data samples are very clean.

The data were obtained with the Large Aperture Superconducting Solenoid (LASS) spectrometer at SLAC, the details of which are described elsewhere [11, 12]. The $K^-$ beam exposure corresponds to a sensitivity of 4.1 events/nb, and the acceptance is approximately isotropic over almost the full $4\pi$ solid angle. After event reconstruction, events from reaction (1) which have $t' \leq 1.0$ (GeV/c)$^2$ ($t' \equiv |t| - |t|_{min}$, where $t$ is the momentum transfer squared from target proton to $\Lambda$) are selected to enhance the dominant hypercharge exchange processes. Contamination in this sample from the final states $\pi^+\pi^-\Lambda$ and $p\bar{p}\Lambda$ is negligibly small, while the $\Sigma^0$ background is estimated at $\sim 8\%$. The final data sample contains 12,294 events.

The Dalitz plot, shown in fig. 1a, exhibits clear $K^-K^+$ bands due to the well-known $\phi(1020)$ and $f_2'(1525)$ resonances. At higher mass, the faint band of events at $\sim 1.8$ GeV/c$^2$ is associated with the production of $\phi_3(1850)$ [13]. Substantial diffractive production of the low mass $K^+\Lambda$ system is observed. This becomes significant for $K^-K^+$ mass above $\sim 1.7$ GeV/c$^2$, and dominates the region above 2.0 GeV/c$^2$.

The data sample for reaction (2), which is discussed in detail in ref. [11], contains 441 events. The only prominent feature of the Dalitz plot (fig. 1b) is the $f_2'(1525)$ band; odd angular momentum $\overline{K}K$ states are suppressed because of Bose-Einstein statistics. No low mass enhancement is present in the $K^0_S\Lambda$ system, confirming the diffractive nature of the $K^+\Lambda$ enhancement observed in fig. 1a.

In order to investigate the $K^-K^+$ helicity amplitude structure in the 2.2 GeV/c$^2$ region for reaction (1), it is necessary to examine the mass dependence of the $K^-K^+$ angular distribution in the $t$-channel helicity frame. To this end, the data in the mass interval 2.00 - 2.44 GeV/c$^2$ are divided into low $t'$ ($t' \leq 0.2$ (GeV/c)$^2$; 747 events) and high $t'$ ($0.2 \leq t' \leq 1.0$ (GeV/c)$^2$; 822 events) samples, which are analysed separately. The low $t'$ region is expected to be dominated by helicity zero amplitudes produced by unnatural parity exchange, whereas in the high $t'$ region the main contributions should be due to helicity one amplitudes produced by natural parity exchange.

For the low $t'$ region, the acceptance corrected spherical harmonic moments ($t_{LM} = \sqrt{4\pi}N\langle Y_{LM}\rangle; L \leq 8, M = 0$) in the $t$-channel helicity frame are shown in fig. 2. No structure is observed in the mass spectrum, $t_{00}$; however, the other moments show a small peak at $\sim$ 2.2 GeV/c$^2$, while moments with $L \geq 9$ (not shown) are within $1\sigma$ of zero throughout this range. In particular, for the peak region 2.16-2.28 GeV/c$^2$, $t_{70}$ and $t_{80}$ differ from zero by 3.3 and 2.3 standard deviations, respectively. Since amplitudes with spin $J$ can contribute to moments with $L$ up to $2J$, it follows that, if the signals observed in fig. 2 are associated with the production of a resonance, then it is probable that the state has $J^P = 4^+$.

The high $t'$ moments show no indication of structure at $\sim$ 2.2 GeV/c$^2$, but this is not unexpected. Natural parity production for the $\phi(1020)$, the $f_2'(1525)$ and the $\phi_3(1850)$ in reaction (1) is observed to decrease more rapidly with mass than does its unnatural parity counterpart. The moments of fig. 2 indicate that any resonance production via unnatural parity exchange has decreased substantially with respect to that observed in the $\phi_3(1850)$ region [13]. It follows that it is quite reasonable that the high $t'$ effects observed at the $\phi_3(1850)$ should be absent at 2.2 GeV/c$^2$, both in the moments of the angular distribution, and in the region of the Dalitz plot outside the diffractive overlap (fig. 1a). For these reasons the high $t'$ region will be discussed no further in this paper.

The open dots of fig. 2a represent the acceptance corrected mass distribution for reaction (2) at low $t'$ (21 observed events); corrections have been made for $K_S^0$ branching ratio [2], and for the undetected $K_L^0 K_L^0$ mode, so that the distributions of fig. 2a are directly comparable. Ignoring possible small odd-$J$ contributions to reaction (1) in this region, the comparison shows that $\sim$ 80% of the cross section is due to diffractive overlap. The remaining acceptance corrected moments for reaction

(2) (not shown) are consistent with zero at the $2\sigma$ level. This indicates clearly that most of the angular structure observed for the $\overline{K}K$ system from reaction (1) in the 2.2 GeV/c$^2$ region results from the kinematic overlap between the low-mass $K^+\Lambda$ diffractive enhancement and the forward region of $t$-channel helicity cosine (cf. fig. 1a).

In order to interpret the structure observed in the low $t'$ moments, it is necessary to consider how they relate to the underlying helicity amplitudes. The spherical harmonic moments can be expressed as bilinear products of production amplitudes $L_{\lambda\pm}$ of the $K^-K^+$ system with spin $L$ and $t$-channel helicity $\lambda$, via natural (+) or unnatural (−) parity exchange [14]. Since the measured moments with $M > 2$ are consistent with zero, amplitudes with $\lambda > 1$ can be neglected and all moments up to $L = 8$, $M = 2$ expressed in terms of the amplitudes $S_0$, $P_0$, $P_\pm$, $D_0$, $D_\pm$, $F_0$, $F_\pm$, $G_0$ and $G_\pm$, where the simplified notation, $L_0 \equiv L_{0-}$, and $L_\pm \equiv L_{1\pm}$ has been adopted.

All low $t'$ moments, from $t_{10}$ up to $t_{80}$, exhibit a peak in the 2.2 GeV/c$^2$ region. This behavior is very similar to that already observed in the $\phi_3(1850)$ region [13], where all low $t'$ moments up to $t_{60}$ show a clear signal in the vicinity of the resonance mass. It is in marked contrast to that observed in the $\phi(1020)$ and $f_2'(1525)$ regions for reaction (1), where only $t_{00}$ and $t_{20}$ show clear peaks; $t_{10}$ and $t_{30}$ exhibit the oscillatory behavior characteristic of interference between a Breit-Wigner (B-W) amplitude and an approximately real background amplitude, and $t_{40}$ is suppressed because the $D_0$ and $D_+$ amplitudes are of similar size at low $t'$ in the $f_2'(1525)$ region.

The analysis of the $\phi_3(1850)$ region [13] has shown that this change in the nature of the measured moments is due to interference between the resonant $F$ wave and the approximately imaginary amplitude describing the diffractive production of the low mass $K^+\Lambda$ system. Indeed, such a simple explanation is even able to account for the observed difference in behavior of the low and high $t'$ moments in this range. Since the low mass $K^+\Lambda$ region overlaps even more with the 2.2 GeV/c$^2$ region (fig. 1a), it is reasonable to attribute the peaks observed for all moments with L $\geq$ 1 in fig. 2 to a similar interference effect. This, in turn, implies the existence at this mass of a small, resonant $4^+$ amplitude which interferes with the large, imaginary, diffractive background, just as for the $\phi_3(1850)$, to yield a small B-W shaped contribution to all of the low $t'$ moments. It should be noted, however, that the apparent absence of background in the $t_{80}$ distribution (fig. 2i) indicates that this moment may result from the square of the resonant amplitude, rather than from an interference effect.

In order to further investigate the nature of the leading (i.e. largest $J$) $G_0$ amplitude, linear combinations of the low $t'$ moments are created such that the resulting amplitude products contain only an interference term involving $G_0$, the additional terms depending on $S$, $P$, $D$ and $F$ amplitudes only. This is exactly analogous to the procedure followed in ref. [13] in studying the $F_0$ amplitude in the $\phi_3(1850)$ region; it should be emphasized that it provides information only on the amplitude deemed to be the leading one on the basis of the moments. The results, labelled according to $G_0$ term, are shown in figs. 3a-d, and indeed a small peak is observed at $\sim$ 2.2 GeV/c$^2$ in all four distributions. Since the line-shape due to the imaginary part of a narrow B-W amplitude is very similar to that due to the modulus squared, each of the small peaks observed in the distributions of fig. 3 is consistent with the conjecture that it results from interference between a $G_0$ B-W amplitude and an approximately imaginary background amplitude.

As discussed previously, the background in this region results predominantly from kinematic overlap with the diffractively-produced $K^+\Lambda$ system. It follows that the $S_0$, $P_0$, $D_0$ and $F_0$ wave $\overline{K}K$ amplitudes at $\sim$ 2.2 GeV/c$^2$ are due mainly to this overlap. The distributions of fig. 3 indicate that each of these amplitudes is approximately imaginary with respect to $G_0$, and hence that their sum, $A_{\text{diff}}$, shares this property. As indicated by the subscript, this is precisely what would be expected for the amplitude describing diffractive $K^+\Lambda$ production.

The distribution shown in fig. 4 is the sum of those shown in fig. 3. The equivalent linear combination of moments corresponds to the interference term between $G_0$ and $A_{\text{diff}}$, plus other terms independent of $G$ wave amplitudes. The observed signal, which has significance $\sim 3\sigma$ in the range 2.16-2.28 GeV/c$^2$, is quite consistent with that which would result from the interference between a resonant $G_0$ amplitude and an approximately imaginary background. Indeed, a fit to the data of fig. 4 using a B-W line-shape and a coherent linear background term yields a relative phase measurement of $73^{+51}_{-57}$ degs., and mass and width values $2220^{+46}_{-37}$ and $69^{+109}_{-69}$ MeV/c$^2$, respectively. Although the phase uncertainty is large (due mainly to a strong mass-phase correlation), the result is consistent with the simple diffractive overlap picture discussed above, and in ref. [13]. Similar fits to the more precise low $t'$ $F_0$ wave interference data in the $\phi_3(1850)$ region (figs. 3a-3c of ref. [13]) with mass and width fixed at the values obtained from the amplitude analysis (viz. 1855 and 74 MeV/c$^2$) yield a relative phase value of $98 \pm 9$ degs., in excellent agreement with the model. Consequently, the phase is fixed at 90°, and the curve in fig. 4 represents the result of a fit to the data of the imaginary part of a relativistic $G$-wave B-W amplitude plus a linear background term. This yields the following estimates of the mass and width parameter values:

$$M = 2209^{+17}_{-15} \text{ MeV/c}^2,$$

$$\Gamma = 60^{+107}_{-57} \text{ MeV/c}^2.$$

The width estimate is essentially the same as that obtained with the phase unconstrained. However, the error on the mass is smaller, and the value has changed. This indicates that an additional systematic uncertainty ~10 MeV/c$^2$ should be associated with the mass value obtained under the assumption of a pure imaginary coherent background amplitude.

Finally, if the $t_{80}$ moment of fig. 2i is considered to be free of background (as mentioned previously), it may be fit using a $G$ wave relativistic B-W line-shape only. This yields mass and width values

$$M = 2194^{+29}_{-29}\ \mathrm{MeV/c^2},$$

$$\Gamma = \quad 78^{+182}_{-73}\ \mathrm{MeV/c^2},$$

in good agreement with those obtained from the data of fig. 4 on rather different grounds.

In the context of the quark model, it is natural to interpret this $G$ wave $\overline{K}K$ state as the $f_4'(2210)$, the mostly $s\bar{s}$ member of the $^3\mathrm{F}_4$ ground state nonet; this nonet would also include the $f_4(2030)$ [2], the $a_4(2040)$ [15], and the $K_4^*(2060)$ [16]. The mass formula [17] yields an octet-singlet mixing angle of $64 \pm 30°$, but the value is particularly sensitive to the mass of the $K_4^*(2060)$. For example, a $1\sigma$ increase in this mass results in a new mixing angle value of 42°. This indicates that the multiplet could be almost ideally mixed, and that the $f_4'(2210)$ has large $s\bar{s}$ content, in accord with its production characteristics.

The mass and width values of the $f_4'(2210)$ are consistent with those obtained by MARK III for the X(2220) [1], and with the signal in the $\eta\eta'$ mass spectrum observed by the GAMS collaboration [8]. In addition, the $K^0_S K^0_S$ mass distribution for $t' \leq 2.0$ GeV/c$^2$ from reaction (2) in this mass region has been shown [11] to be very similar to that observed for radiative $J/\psi$ decay (fig. 5). Furthermore, the angular distributions observed for the GAMS data [8] and for reaction (2) [11] indicate clearly that amplitudes having $J \geq 2$ are present. Finally, a recent spherical harmonic moments analysis of the MARK III data has revealed the presence of significant $t_{80}$ and $t_{82}$ signals for the $K^0_S K^0_S$ system at $\sim$2.2 GeV/c$^2$ [18]. All of this suggests that the X(2220), which has been conjectured to be a glueball state, may simply be the mostly $s\bar{s}$ member of a quark model $^3F$ ground state nonet [19]. In particular, it is simplest to conclude that the same state, namely the $^3F_4$ discussed above, has been observed by GAMS, MARK III, and in the present experiment. However, it should be noted that both the $^3F_2$ and $^3F_4$ $s\bar{s}$ states are expected in this mass region, and that it is predicted in ref. [19] that the $^3F_2$ state is more likely to be produced in radiative $J/\psi$ decay.

In conclusion, data from reaction (1) have been analyzed in the context of a simple diffractive overlap model to provide evidence for the existence of the $f_4'(2210)$. It should be emphasized that the analysis neither excludes nor requires the presence of any underlying state, in particular one having $J^{PC} = 2^{++}$. If the $f_4'(2210)$ is presumed to be an isoscalar, its quantum numbers are $I^G(J^{PC}) = 0^+(4^{++})$, and it is a good candidate to be the mainly $s\bar{s}$ member of the ground state $4^{++}$ nonet predicted by the quark model. Furthermore, it seems possible that this state and the X(2220) observed in radiative $J/\psi$ decay, are one and the same.

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# FIGURE CAPTIONS

1. The Dalitz plot (a) for reaction (1), and (b) for reaction (2), in the present experiment. In (b) the points correspond to the lower $K^0_S\Lambda$ mass value.

2. The acceptance corrected unnormalized $K^-K^+$ spherical harmonic moments with $M = 0$ for $t' \leq 0.2$ (GeV/c)$^2$ (solid dots) in the 2.2 GeV/c$^2$ mass region; the open dots in fig. 2a indicate the corresponding distribution for reaction (2).

3. (a)-(d) The mass dependence of particular $G_0$ wave interference contributions to the $K^-K^+$ angular distribution projected as described in the text.

4. The mass dependence of the interference between the $G_0$ and diffractive background amplitudes projected as described in the text. The curve corresponds to the fit using the imaginary part of a Breit-Wigner amplitude plus a linear background.

5. The comparison of the acceptance corrected $K^0_SK^0_S$ mass distribution from reaction (2) with that from radiative $J/\psi$ decay [1]; the integrated LASS distribution has been normalized to the number of MARK III events in the mass range 1.8-2.7 GeV/c$^2$.

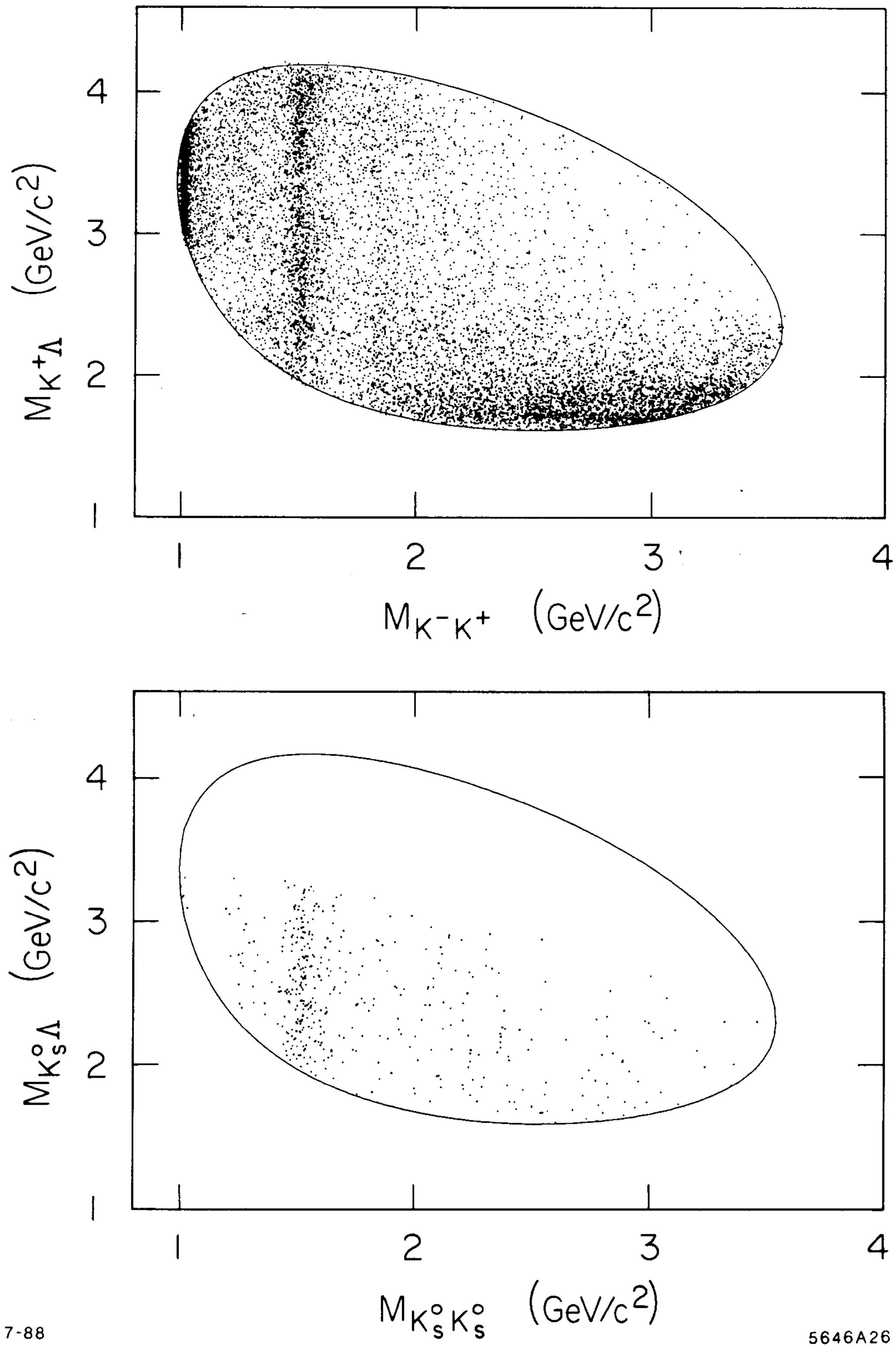
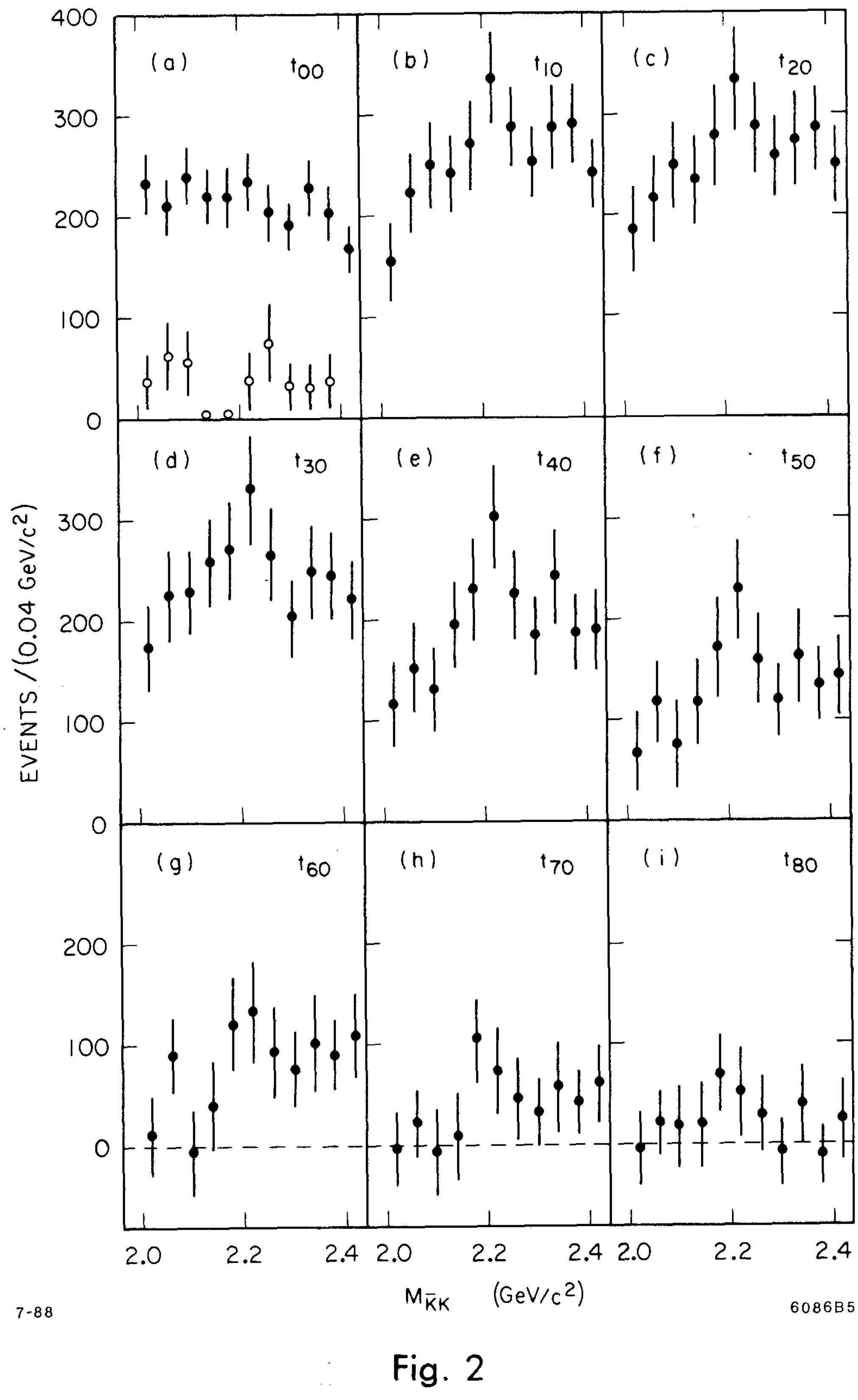

4
3
2
1
$M_{K^+\Lambda}$ (GeV/c$^2$)
1
2
3
4
$M_{K^-K^+}$ (GeV/c$^2$)
4
3
2
1
$M_{K^0_s\Lambda}$ (GeV/c$^2$)
1
2
3
4
$M_{K^0_s K^0_s}$ (GeV/c$^2$)
7-88
5646A26

Fig. 1



(a) $t_{00}$
(b) $t_{10}$
(c) $t_{20}$
(d) $t_{30}$
(e) $t_{40}$
(f) $t_{50}$
(g) $t_{60}$
(h) $t_{70}$
(i) $t_{80}$
400
300
200
100
0
EVENTS /(0.04 GeV/c$^2$)
2.0
2.2
2.4
$M_{\bar{K}K}$ (GeV/c$^2$)
7-88
6086B5


Fig. 2

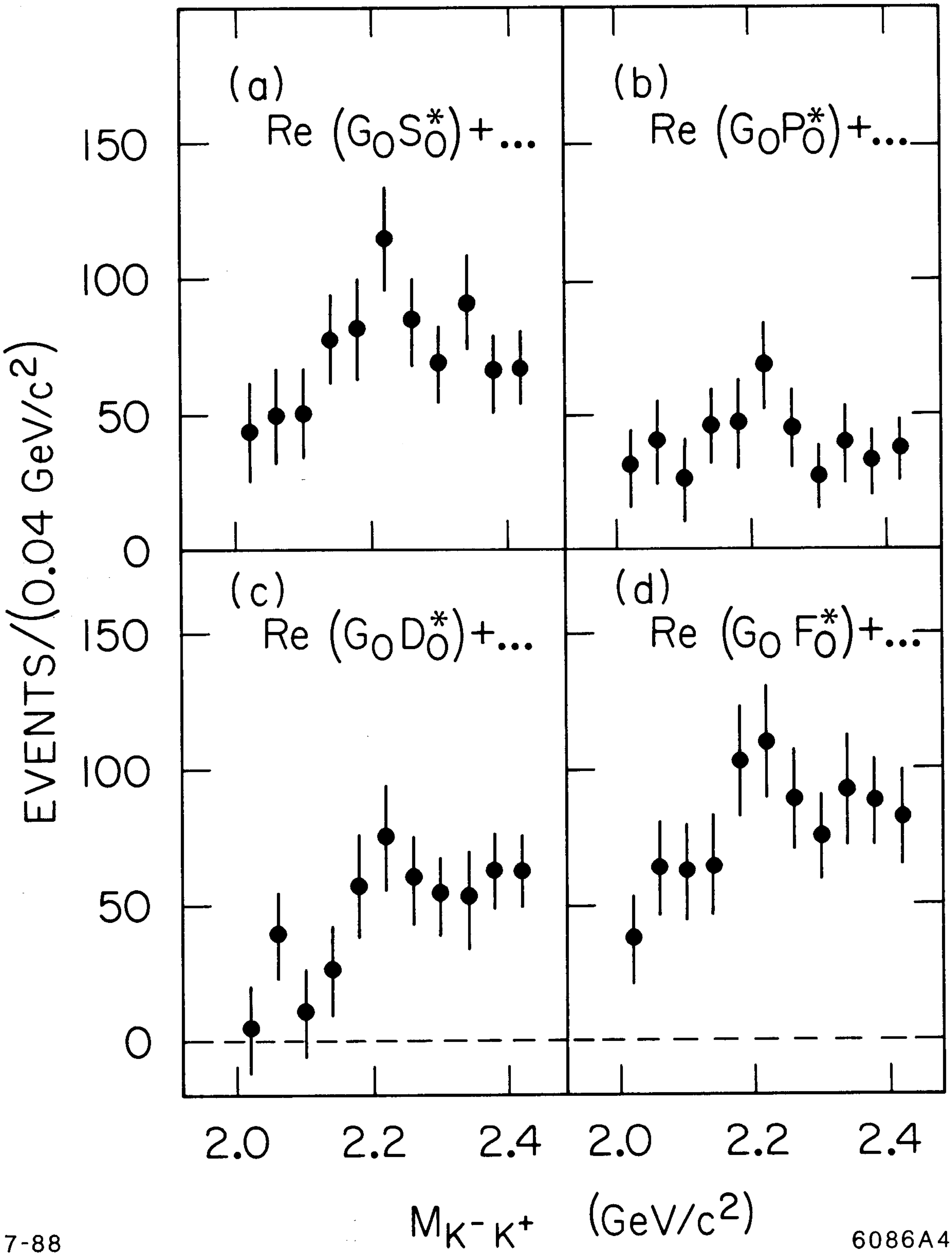
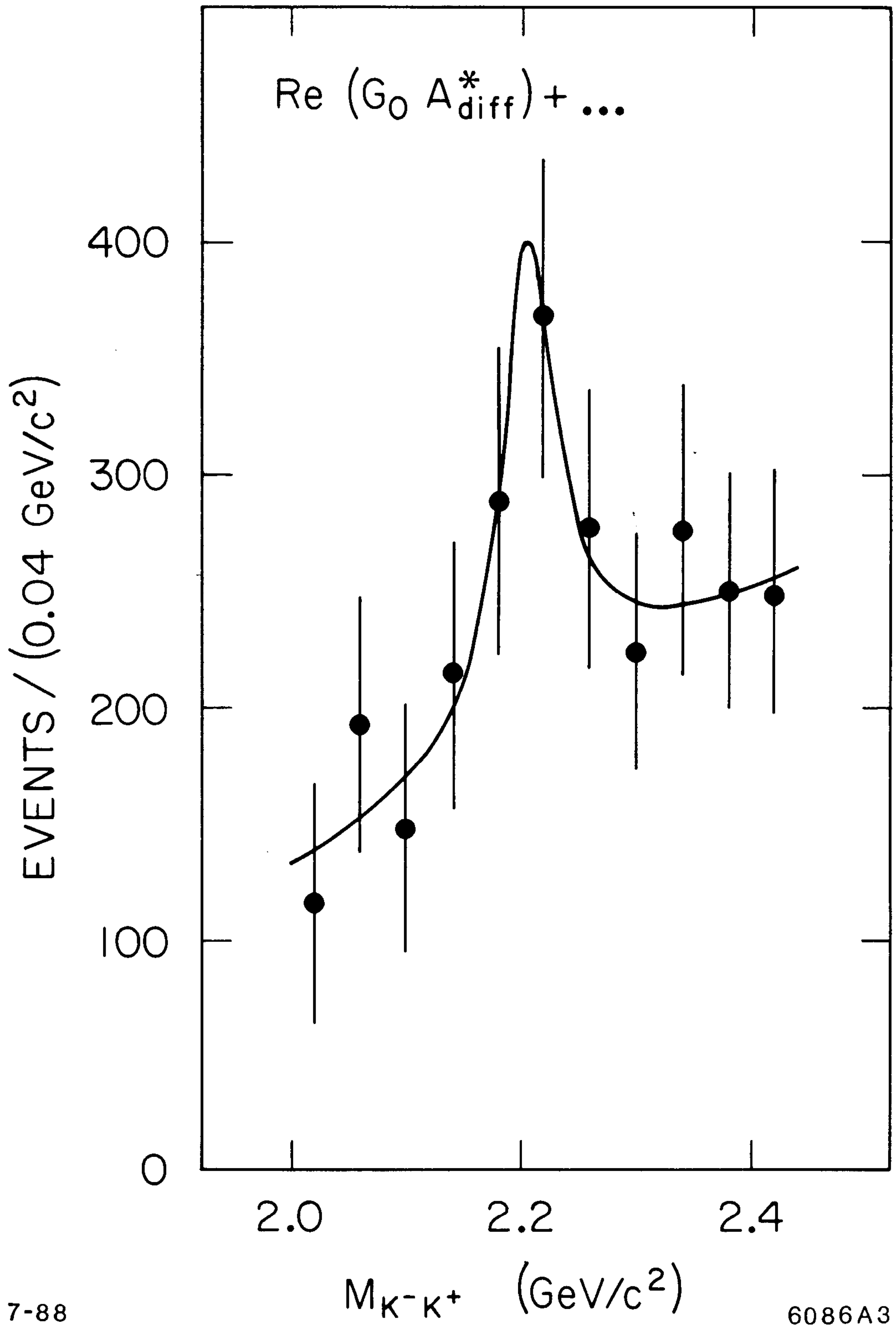
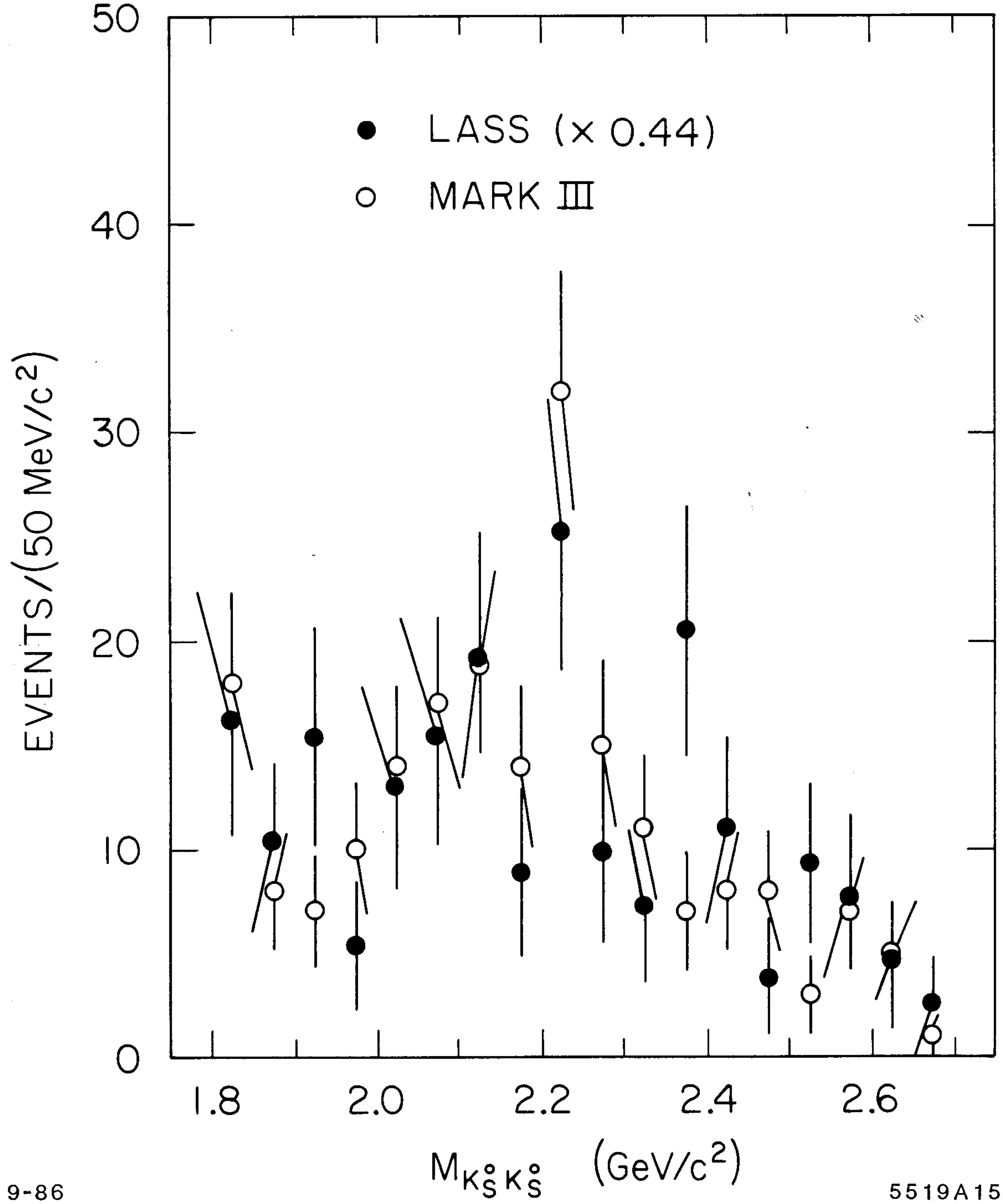

(a)
Re $(G_0 S_0^*)+\ldots$
(b)
Re $(G_0 P_0^*)+\ldots$
(c)
Re $(G_0 D_0^*)+\ldots$
(d)
Re $(G_0 F_0^*)+\ldots$
150
100
50
0
EVENTS/(0.04 GeV/c$^2$)
2.0
2.2
2.4
$M_{K^-K^+}$ (GeV/c$^2$)
7-88
6086A4

Fig. 3



Re $(G_0 A^*_{diff}) + \ldots$
400
300
200
100
0
EVENTS / (0.04 GeV/c$^2$)
2.0
2.2
2.4
$M_{K^-K^+}$ (GeV/c$^2$)
7-88
6086A3


Fig. 4



50
40
30
20
10
0
LASS (x 0.44)
MARK III
EVENTS/(50 MeV/c$^2$)
1.8
2.0
2.2
2.4
2.6
$M_{K^0_S K^0_S}$ (GeV/c$^2$)
9-86
5519A15


Fig. 5