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Centrally Produced  $K_s K_s$  System at 800 GeV**

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# Spin-Parity Analysis of the Centrally produced $K_s K_s$ system at 800 GeV

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Results are presented of the spin-parity analysis on a sample of centrally produced mesons in the reaction  $pp \rightarrow p_{slow}(K_s K_s)p_{fast}$  with 800 GeV protons on liquid hydrogen. The spin-parity analysis in the mass region between threshold and  $1.58 \text{ GeV}/c^2$  shows that the  $K_s K_s$  system is produced mainly in  $S$  wave. The  $f_0(1500)$  is clearly observed in this region. Above  $1.58 \text{ GeV}/c^2$  two solutions are possible, one with mainly  $S$  wave and another with mainly  $D$  wave. This ambiguity prevents a unique determination of the spin of the  $f_J(1710)$  meson.

## 1. INTRODUCTION

The first evidence of the Central Production of  $f_0(1500)$  in the reaction

$$pp \rightarrow p_s(K_s K_s)p_f, \quad K_s \rightarrow \pi^+ \pi^- \quad (1)$$

is presented here. The  $f_0(1500)$  was first observed in  $K^- p$  [1] interactions and beautifully confirmed in low energy  $\bar{p}p$  annihilations by the Crystal Barrel Collaboration [2]. Its properties are of current interest because it is considered a candidate to be the lowest lying glueball state [3].

One of the advantages of the final state selected is that only states with quantum numbers  $J^{PC} = (\text{even})^{++}$  are allowed to decay into  $K_s K_s$ . This not only greatly simplifies the analysis but eliminates confusion coming from all the other states. The results presented here are based on 10% of the  $5 \times 10^9$  events recorded by FNAL E690 during Fermilab's 1991 Fixed Target run.

## 2. DATA SELECTION

### 2.1. The detector

The data was taken at Fermilab with an 800 GeV proton beam on a liquid hydrogen ( $LH_2$ )

target, and the E690 spectrometer. The spectrometer is composed of two parts: a) the Main Spectrometer (MS), and b) the Beam Spectrometer (BS). The MS has an approximately conical geometrical acceptance with an average 700 mrad radius, good momentum resolution from about 0.2 to 15 GeV/c, a Freon 114 threshold Cherenkov counter with a pion threshold of 2.6 GeV/c, a time of flight system (TOF) with  $\pi/p$  separation up to 1.5 GeV/c, and a target veto system. Neither the TOF nor the Cherenkov counter were used in the work presented here.

The BS, used to measure the incoming and outgoing protons, has an approximately conical geometrical acceptance with an average radius of about 1 mrad, a  $p_t$  resolution of 6 MeV/c, and a longitudinal momentum resolution of 425 MeV/c. The longitudinal momentum acceptance of the BS for the interacted beam ranges from approximately 650 to 800 GeV/c.

The trigger required an equal number on incoming and outgoing tracks in the BS and at least one additional track in the MS.

## 2.2. Event selection

Final state (1) was selected by requiring a primary vertex in the  $LH_2$  target with two  $K_s$ , an incoming beam track, and a fast forward proton. No direct measurement was made of the slow proton  $p_s$ . The target veto system was used to reject events with more than a missing proton. The events were accepted when either no veto counter was on, or only one veto counter was on with the missing  $p_i$  pointing to it. About 12% of the selected events were rejected with the veto system. The missing mass squared seen in Figure 1.a shows a clear proton peak with little background; the arrows indicate the cuts used in the event selection.

The MS has essentially no acceptance for  $x_F > 0$ , which insures a gap of at least 3.5 units of rapidity between  $p_f$  and the central products. The average rapidity gap between the  $K_s K_s$  system and  $p_s$  is 2.5 units. Figure 1.b shows the uncorrected  $x_F$  distribution for the  $K_s K_s$  system, the arrows indicate the cuts used in the event selection.

The  $\pi^+ \pi^-$  invariant mass for the  $K_s$ 's has a width of  $\sigma = 2 \text{ MeV}/c^2$ . No direct particle ID (Cherenkov or TOF) was used to identify the  $K_s$  decay products. In about 7% of the events a  $K_s$  is compatible with a  $\Lambda$ ; these events were kept, to avoid any biases in the angular distributions.

The proton mass was assigned to the missing particle in the events that passed the cuts, then the three momenta of  $p_s$  and the longitudinal momentum of  $p_f$  were calculated using energy and momentum conservation.

Figure 1.c shows the  $K_s K_s$  invariant mass for the 11182 events that passed the previous cuts and were used in the analysis. The analysis was not continued beyond  $2 \text{ GeV}/c^2$  because the number of events is very low. But for  $-0.22 < x_F < -0.02$  the  $K_s K_s$  invariant mass beyond  $2 \text{ GeV}/c^2$  is smooth, with no evidence of the  $\xi(2230)$  state seen by the BES Collaboration [4].

## 3. DATA ANALYSIS

### 3.1. Angular distributions

The reaction studied here was analyzed as a two step process: the production step in which

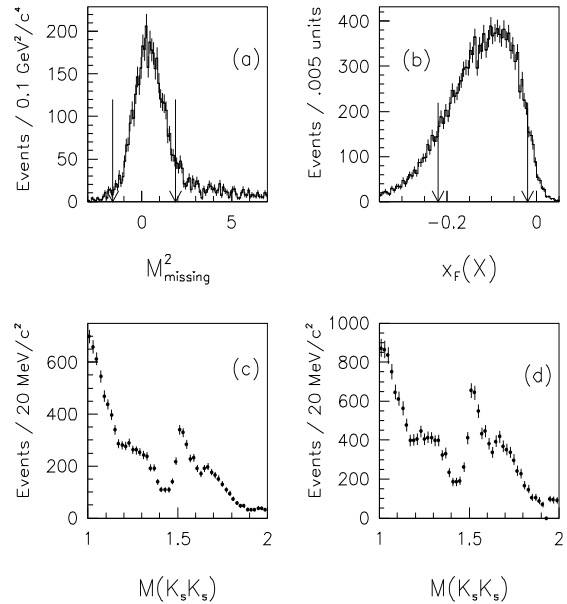


Figure 1. a) Missing mass squared for  $1.4 < M(K_s K_s) < 1.8 \text{ GeV}/c^2$ . b) Uncorrected  $x_F$  distribution. c) Measured  $K_s K_s$  invariant mass. d) Acceptance corrected and background subtracted  $K_s K_s$  invariant mass.

an ( $X$ ) system is formed by the collision of two objects (from now on referred to as “pomeron”) emitted by each of the scattered protons, and the decay step in which the object ( $X$ ) decays into  $K_s K_s$ . The production coordinate system was defined in the CM of the ( $X$ ) system, with the y-axis perpendicular to the plane of the two “pomerons” in the overall CM, and the z-axis in the direction of the “beam pomeron” in the ( $X$ ) CM. The two variables needed to specify the decay process were taken as the polar and azimuthal angles ( $\theta, \phi$ ) of one of the  $K_s$  (taken at random) in the production coordinate system. The acceptance corrected  $\cos \theta$  and  $\phi$  distributions are shown in Figures 2 and 3. The acceptance is flat in  $\phi$ , and dips near  $\cos \theta = \pm 1$ . On average the correction at  $\cos \theta = \pm 1$ , relative to the correction at 0, is 65%.

The five variables used to specify the production process were the transverse momenta of the

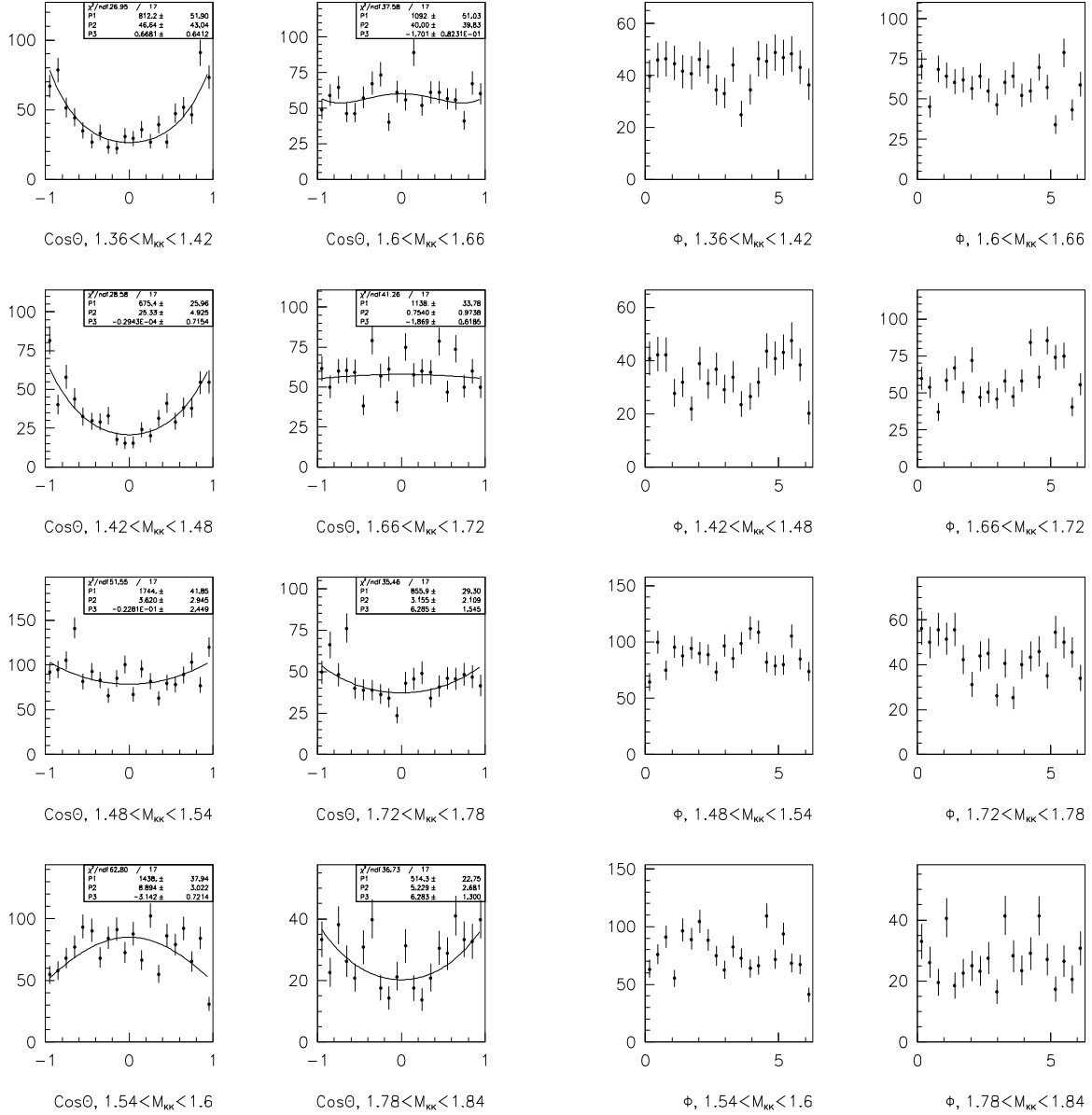


Figure 2. Acceptance corrected  $\cos\theta$  angular distributions in bins of the  $K_s K_s$  invariant mass, starting at  $1.36 \text{ GeV}/c^2$  in steps of  $60 \text{ MeV}/c^2$ .

slow and fast protons ( $p_{i,s}^2, p_{i,f}^2$ ), the  $x_F$  and invariant mass of the  $K_s K_s$  system, and  $\delta$ , the angle between the planes of the scattered protons in the

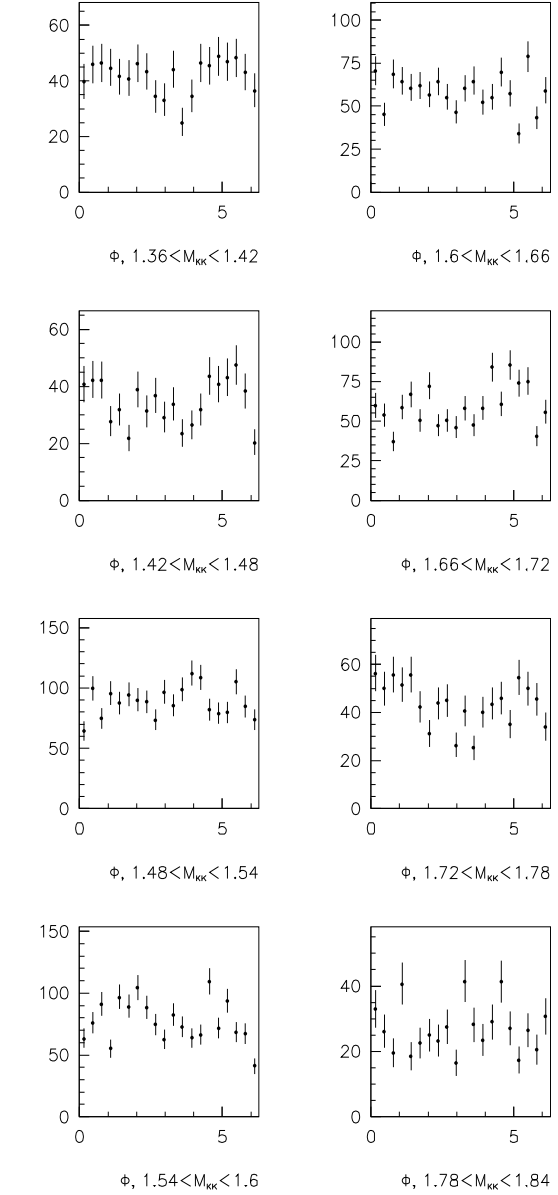


Figure 3. Acceptance corrected  $\phi$  angular distributions in bins of the  $K_s K_s$  invariant mass, starting at  $1.36 \text{ GeV}/c^2$  in steps of  $60 \text{ MeV}/c^2$ .

$K_s K_s$  CM. Although our 11182 events constitute a large sample, it is not large enough to bin the data in all five production variables. The present

analysis was done in bins of the  $K_s K_s$  invariant mass for the  $x_F$  selected region, and integrating over  $p_{i,s}^2$ ,  $p_{i,f}^2$  and  $\delta$ .

### 3.2. Partial wave analysis

The acceptance corrected moments, defined as

$$I(\Omega) = \frac{1}{\sqrt{4\pi}} \left\{ \sum_i t_{i0} Y_i^0 + 2 \sum_{l,m>0} t_{lm} \text{Re}(Y_l^m) \right\} \quad (2)$$

are shown in Figure 4. The odd moments (not shown) are consistent with zero, as expected for a system of two identical bosons. The acceptance corrected mass distribution ( $t_{00}$  moment) is shown in Figure 1.d. The error bars are statistical errors only.

In the two step process considered here the ( $X$ ) system is formed by the interchange of two “pomeron” and it decays afterwards independently of the two final state protons. The two “pomeron” form a plane; parity in the strong interactions implies that reflection in this plane should be a symmetry of the system [5]. Therefore the amplitudes used for the Partial Wave Analysis (PWA) were defined in the reflectivity basis [6]. Since the  $t_{43}$  and  $t_{44}$  moments are consistent with zero (see Fig 4), only spherical harmonics with  $l = 0, 2$  and  $m = 0, \pm 1$  were considered. The waves used were  $L_m^\epsilon$ , with  $L = S, D$ ,  $m \geq 0$  and  $\epsilon = \pm 1$ :

$$S_0^- = Y_0^0 = \frac{1}{\sqrt{4\pi}} \quad (3)$$

$$D_0^- = Y_2^0 = \sqrt{\frac{5}{16\pi}} (3 \cos^2 \theta - 1) \quad (4)$$

$$D_1^- = \frac{Y_2^1 - Y_2^{-1}}{\sqrt{2}} = -\sqrt{\frac{15}{16\pi}} \sin 2\theta \cos \phi \quad (5)$$

$$D_1^+ = \frac{Y_2^1 + Y_2^{-1}}{\sqrt{2}} = -i\sqrt{\frac{15}{16\pi}} \sin 2\theta \sin \phi \quad (6)$$

Waves with different reflectivity  $\epsilon$  do not interfere.

The PWA analysis was done in two different ways. First since the  $\phi$  angular distributions are fairly flat only  $S_0^-$  and  $D_0^-$  waves were used: a) by fitting to the  $\cos \theta$  angular distributions, and b) by using the extended maximum likelihood

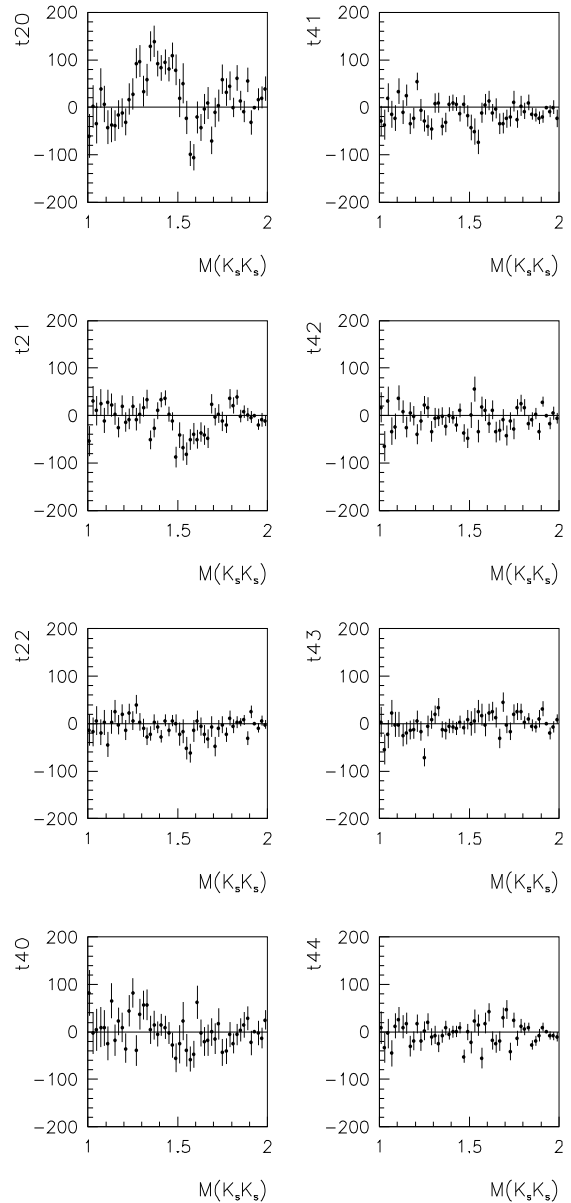


Figure 4. Acceptance corrected moments as a function of the  $K_s K_s$  invariant mass.

method. The results of the fit to the  $\cos \theta$  angular distributions are shown in Figure 2. Within errors the results were the same in both cases, giving a solution that, except for two small  $D$  wave contri-

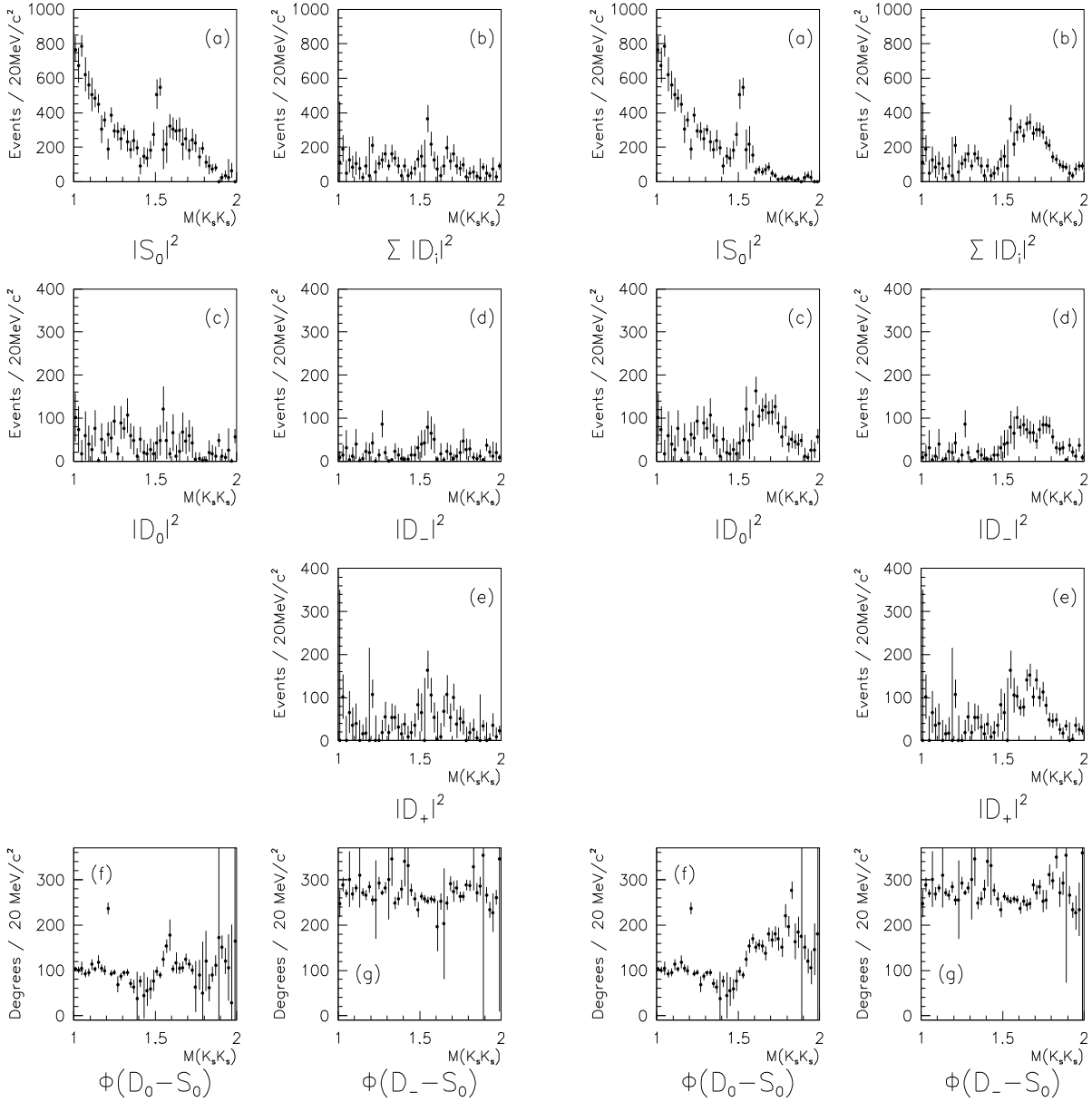


Figure 5. Waves as a function of  $K_s K_s$  invariant mass for solution one. a)  $S$  and b) total  $D$  waves, c) to e) individual  $D$  wave, and f) and g) phases relative to the  $S$  wave.

butions at  $\sim 1.3 \text{ GeV}/c^2$  and  $\sim 1.6 \text{ GeV}/c^2$ , was all  $S$  wave. Second, all four waves (3-6) were used.

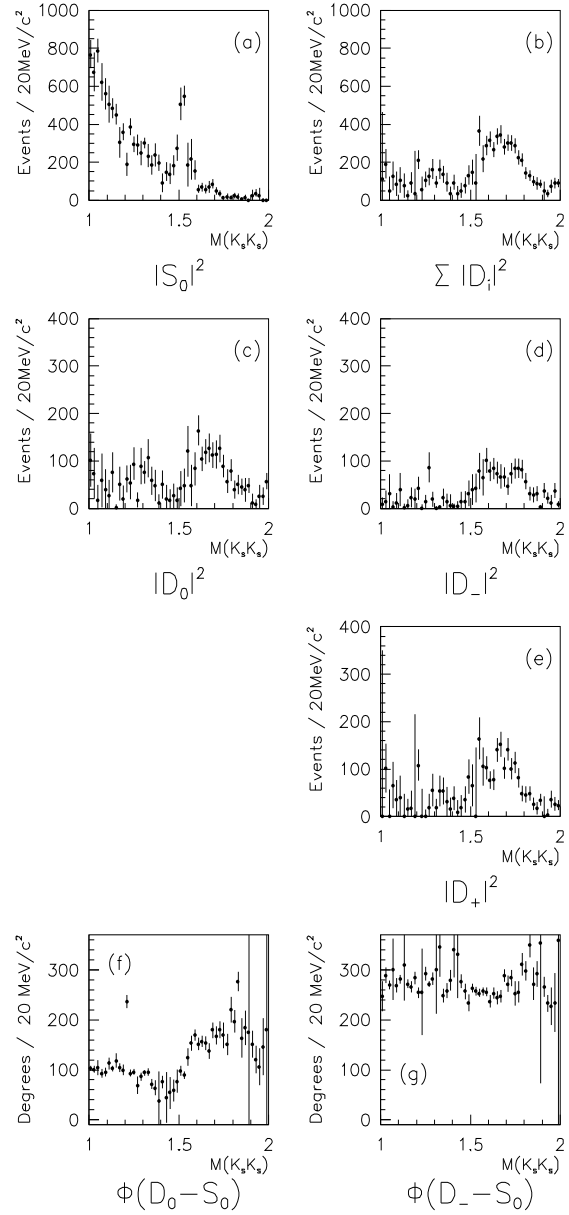


Figure 6. Waves as a function of  $K_s K_s$  invariant mass for solution two. a)  $S$  and b) total  $D$  waves, c) to e) individual  $D$  wave, and f) and g) phases relative to the  $S$  wave.

The amplitudes were extracted both a) from the moments shown in Figure 4, and b) by maxi-

mizing the extended likelihood with respect to the four wave moduli and the two relative phases  $\varphi(D_{0,1}^-) - \varphi(S_0^-)$ . Within errors both analyses gave the same answer.

When using the four waves (3-6) the inherent ambiguities of a two body system are such that there are two solutions for each mass bin [6,7]. Both solutions give identical moments or identical values of the Likelihood. In order to continue the solutions from one mass bin to the next, one follows the Barrelet zeros. In general these zeros are complex and one lies above the real axis and the other lies below it. When the zeros cross the real axis the solutions bifurcate [6,7]. In the analysis presented here, there is a bifurcation point at  $1.58 \text{ GeV}/c^2$ . Before this bifurcation point there are only two solutions, one which is mostly  $S$  wave, and another that is mostly  $D$  wave. Since at threshold the  $K_s K_s$  cross section is dominated by the presence of the  $f_0(980)$  [9] it is possible to eliminate the solution that has a very small  $S$  wave contribution at threshold. The remaining solution bifurcates at  $1.58 \text{ GeV}/c^2$  into a solution that has a large  $S$  wave contribution (solution one), and another that has a large  $D$  wave component (solution two). The solutions obtained using maximum likelihood are shown in Figures 5 and 6. Solution one is shown in Figure 5, and solution two in Figure 6. The errors shown are statistical errors only.

A striking feature of both solutions is the large  $S$  wave peak observed at  $\sim 1.5 \text{ GeV}/c^2$ . This corresponds to the  $f_0(1500)$  observed by the Crystal Barrel collaboration [2]. The mass peaks at  $1.52 \text{ GeV}/c^2$  instead of at  $1.50 \text{ GeV}/c^2$ , but this could be easily due to interference with the  $S$  wave background.

Beyond  $1.58 \text{ GeV}/c^2$  both solution one and two are equally valid, and at the moment there is no way to decide with this data alone which of the two solutions is the correct one. However, given that beyond  $1.58 \text{ GeV}/c^2$  the angular distributions are fairly structureless, and that an analysis in  $\cos \theta$  alone gives very little  $D$  wave, solution one could be favored.

## 4. CONCLUSIONS

A PWA analysis in a sample of 11182 centrally produced  $K_s K_s$  events at 800 GeV has been presented. Two solutions have been found in the analysis. In both of them a clear  $f_0(1500)$  has been observed. The ambiguity above  $1.58 \text{ GeV}/c^2$  prevents a unique determination of the spin of the  $f_J(1710)$  meson. Due to lack of statistics the analysis was not carried out beyond  $2 \text{ GeV}/c^2$ , but the  $K_s K_s$  invariant mass spectrum is smooth beyond that point and shows no sign of the  $\xi(2230)$  meson seen by the BES Collaboration [4].

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