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HADRONIC PRODUCTION OF $J^{PC} = 2^{++}$ GLUEBALLS*

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INTRODUCTION

Color confinement and the running coupling constant make the existence of multi-gluon resonances or glueballs[1a,2] inescapable in QCD. Lattice Gauge calculations[15,16] have quantitatively demonstrated this.

Thus, in spite of the fact that perturbative QCD has had many successes which include quantitative ones to ~ 10-20%, the glueball missing link must be found if the theory is to survive.

BNL/CCNY use an OZI[3-6] suppressed channel with variable mass, namely the reaction $\pi^- p \to \phi\phi n$ as a filter which allows resonating gluons or glueballs to pass, while strongly rejecting conventional quark-built hadronic states.† The breakdown of the OZI suppression signals a glueball.

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† Provided $\phi\phi$ system $J \geq 1$ so that vacuum mixing is neglectable, otherwhise this vacuum mixing could possibly lead to apparent violations of Zweig suppression, since it can lead to large departures from ideal mixing.

THE OZI RULE[7]

In the u,d,s quark system $q\bar{q}$ meson nonets are well established for $J^{PC} = 0^{-+}$, 1^{--}, 2^{++} and 3^{--}. Except for the 0^{-+} nonet, all those with $J \geq 1$ are nearly ideally mixed[8] and representable by Zweig's Quark Line Diagrams.

In disconnected diagrams the $s\bar{s}$ pair in the ϕ or f' has to be annihilated or created by at least two or three hard gluons respectively to conserve all quantum numbers including color. Asymptotic freedom strongly decouples hard glue from quarks at relatively moderate gluon energies* and this is observed to occur at energies as low as those involved in the three-gluon decay of the ϕ, and thus is referred to as "precocious". The resultant relatively weak coupling constants of the hard gluons naturally explains the observed OZI suppression factors ~ 100 for both ϕ and f' decay and production, and the even larger OZI suppression (~ 1,000) in the decay of the J/ψ and Υ.

In $q\bar{q}$ meson states, departures from ideal mixing can only be expected to occur when flavor changing diagrams which convert $s\bar{s}$ quark pairs into $u\bar{u}$ or $d\bar{d}$ quark pairs or vice versa have gluons relatively strongly coupled.

One such flavor mixing mechanism is vacuum effects[9] which are expected to be important for J = 0 (e.g., the $J^{PC} = 0^{-+}$ nonet).

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* $\Lambda_{eff} \lesssim$ 100-200 MeV.

but unimportant for $J \geq 1$ and this is certainly consistent with the experimental results.

In QCD the is only other known basic flavor mixing mechanism, is the presence of glueballs with the same quantum numbers near enough to the nonet singlet masses and with the appropriate width to effectively mix with the singlets.

It is a well-known experimental fact that in all Zweig disconnected diagrams in the ϕ, f', J/ψ and Υ systems the OZI rule appears universal.[6,10] As previously discussed, the OZI rule appears on paper to be defeatable by two-step processes, each of which are OZI allowed. However experimentally there is no evidence for this occurring and reasons why it should probably not occur have been given.[11-12]

Figures 1 through 3 are the Zweig Quark Line Diagrams for the three reactions studied by the BNL/CCNY group in three generations of experiments since 1978.[3,4,13] In Fig. 4 a scatter plot of K^+K^- masses from the BNL/CCNY experiment, we see the general ≈ uniform background from the reaction a) $\pi^-p \rightarrow K^+K^-K^+K^-n$ which is OZI allowed, and the two ϕ bands representing b) $\pi^-p \rightarrow \phi K^+K^-n$ which is also OZI allowed. Where the two ϕ bands cross we have the Zweig forbidden reaction $\pi^-p \rightarrow \phi\phi n$.

The black spot shows an obviously more or less complete breakdown of the Zweig suppression.

The black spot is ≈ 1,000 times the density of reaction (a) and ≈ 50 times the density of reaction (b). If one projects out the ϕ bands, even with rather wide cuts ± 14 MeV, there is a huge $\phi\phi$ signal compared to the ≈ 13 percent background from reaction (b). The recoil neutron signal is also very clean (≈ 97% neutron).

Figure 5 shows the acceptance corrected $\phi\phi$ mass spectrum in the ten mass bins which were used for the final partial wave analysis of the 3652 events.[13]

All waves (i.e. 52) with J = 0 - 4, L = 0 - 3, S = 0 - 2, P = ± and η (exchange naturality) = ± were allowed in the partial wave analysis (PWA). The Gottfried-Jackson frame angles, β(polar) and γ(azimuthal) and the polar angles (θ_1,θ_2) of the K^+ decay in the $\phi_{1,2}$ rest systems relative to the ϕ direction, and the corresponding azimuthal angles α_1 and α_2 were used to specify an event.

In the PWA we find a unique solution (Figs. 6a and 6b) which consists of only three $J^{PC} = 2^{++}$ waves, an S-wave with S = 2, a D-wave with S = 2, and a D-wave with S = 0, which is a good fit. All three waves have $J_Z = 0$ in the Gottfried-Jackson frame and the exchange naturality = (-1), the characteristics of pion exchange. The observed $(d\sigma/dt')_{\phi\phi} = e^{(9.4 \pm 0.7)t'}$ for $t' < 0.3$, the low t'-region which contains most of the data. The only charged particle exchange which will give this is pion exchange. The best two-wave fit is ≈ 30 σ away. Our selected three-wave fit is ≈ 15 σ better than the next best three-wave fit.

The few percent background was estimated to be entirely (within errors) composed of the reaction $\pi^- p \to \phi K^+ K^- n$. A partial wave analysis of this background in the region where the K^+K^- mass was slightly larger than that of the ϕ revealed that ≈ 65% of it was structureless and incoherent like one would expect from the addition of many possible partial waves. Only approximately 7% of the background was 2^{++} which had an ≈ 0 amplitude in the threshold region and peaked at ≈ 2.4 GeV (see Fig. 7). There was ≈ 28% of 1^{--} background which are expected quantum numbers for a ϕK^+K^- system where all particles are in an S-wave with respect to each other and the production is via π-exchange (i.e., a kinematic effect). Thus the ϕK^+K^- background reaction was totally different than the 2^{++} states observed in the $\phi\phi$ system.

The partial wave amplitudes and phase behavior of the $\phi\phi$ system (shown in Figs. 6a and 6b) clearly suggest that these three waves are produced by resonances. A two-pole K-matrix fit which allows all three observed waves to mix in each pole was rejected by ≈ 15σ fit.

A three-pole K-matrix fit gave a good fit. The Argand diagram for this fit is shown in Fig. 8, and exhibits the phase motion characteristics typical of resonance pole behavior. A four-pole K-matrix fit did not lead to any further improvement. The three-pole K-matrix fit was used to fit the data contained in 90 angular variable bins for each of the ten mass bins used, thus yielding a total of 900 data bins. The fit was good to $\lesssim$ one σ. The resonance parameters of this fit are given in Table I.

Due to the small mostly incoherent background, the S-wave which dominates the $g_T(2050)$ must be used as a phase reference. The phase difference of this and the other two D-waves precisely match the

Table 1

Breit-Wigner Resonance parameters of the three-pole K-matrix fit

$M_1 = 2.050^{+.090}_{-.050}$	$\Gamma_1 = .200^{+.160}_{-.050}$	$\approx 50\%^{+10\%}_{-10\%}$	data
S-wave, S = 2		$\approx 98\%^{+02\%}_{-70\%}$	coupling sign (+) defined
D-wave, S = 2		$\approx 0\% + 50\%$	coupling sign (−)
D-wave, S = 0		$\approx 2\%^{+25\%}_{-02\%}$	coupling sign (−)
$M_2 = 2.300^{+.020}_{-.100}$	$\Gamma_2 = .200^{+.060}_{-.050}$	$\approx 20\%^{+20\%}_{-10\%}$	data
S-wave, S = 2		$\approx 30\%^{+20\%}_{-20\%}$	coupling sign (+)
D-wave, S = 2		$\approx 50\%^{+20\%}_{-10\%}$	coupling sign (+)
D-wave, S = 0		$\approx 20\%^{+20\%}_{-20\%}$	coupling sign (+)
$M_3 = 2.350^{+.020}_{-.030}$	$\Gamma_3 = .270^{+.090}_{-.130}$	$30\%^{+10\%}_{-20\%}$	data
S-wave, S = 2		$\approx 40\%^{+10\%}_{-20\%}$	coupling sign (+)
D-wave, S = 2		$\approx 05\%^{+15\%}_{-05\%}$	coupling sign (−)
D-wave, S = 0		$\approx 55\%^{+20\%}_{-15\%}$	coupling sign (+)

Masses and Γ are in GeV. $I^G J^{PC} = 0^+2^{++}$ for all three resonances.

3-pole K-matrix fit, thus clearly demonstrating that all three states have the pole behavior which is the best and only critical definition of a resonance.

Attributing the production of these states to 1-3 primary $J^{PC} = 2^{++}$ glueballs has explained all their features in a clear-cut and simple manner.[5,6,11,12]

GLUEBALL MASSES

The constituent (i.e. gluon has effective mass) gluon models[14] would predict three low lying $J^{PC} = 2^{++}$ glueballs. The mass estimates from the lattice gauge groups cover the range ≈ 1.7 to 2.5 GeV for $J^{PC} = 2^{++}$ glueballs.[15-17] with which we are clearly consistent.

GLUEBALL WIDTH

The hadronization process (i.e., creation of one or more $q\bar{q}$ pairs) must occur near the outer region of confinement involving strongly interacting soft glue, including collective interactions, if we are to have resonances decay with typical hadronic widths ($\Gamma_{hadronic}$ ~ 100 to several hundred MeV) that are more or less independent of the number of particles in the dominant decay mode as observed.

The gluon-gluon coupling is stronger than the quark-gluon coupling and thus it would be expected, via gluon splittings before the final hadronization, to have a similar hadronization process to a $q\bar{q}$ hadron and to have typical hadronic widths for non-exotic J^{PC} states. For exotic J^{PC} states, this arguement may not hold since no one yet knows what suppresses the unobserved exotic sector. Therefore Meshkov's oddballs[14] may be narrow.

One can ask why we have not seen a Meshkov oddball (i.e. exotic J^{PC})? Approximately 90% of our $\phi\phi$ data is characteristic of being produced by pion exchange. Exotic J^{PC} cannot be produced by pion exchange. Our data exhibits great selectivity for $M = 0$. However for

A_1 exchange (for example) one can create an exotic J^{PC}. Estimating the ratio of A_1 exchange to π exchange would lead to a guesstimate of a few percent or less. Thus we need much more statistics, and may eventually find evidence for a 1^{-+} or 3^{-+} oddball.

SUMMARY OF CHARACTERISTICS OF $\pi^-p \to \phi\phi n$

The observed characteristics of the reaction $\pi^-p \to \phi\phi n$ are very unusual and striking in the following respects:

1. The expected OZI suppression is completely broken in a very unusual manner, since virtually all of the $\pi^-p \to \phi\phi n$ cross section is composed of three resonant $\phi\phi$ states, the $g_T(2050)$, the $g_{T'}(2300)$ and the $g_{T''}(2350)$, all with the same quantum numbers $I^GJ^{PC} = 0^+2^{++}$. In contrast, hadronic reactions in other channels (e.g. $\pi^-p \to K^0_sK^0_sn$)[18,19] show no such selective quantum numbers or resonance phenomena.

2. The OZI allowed background reaction $\pi^-p \to \phi K^+K^-n$ which is unexpectedly only a few percent of the OZI forbidden $\pi^-p \to \phi\phi n$ consists mainly of a structureless, incoherent, flat in all angular distributions, background. Approximately twenty-eight percent of the reaction has $J^{PC} = 1^{--}$ which are expected quantum numbers for a ϕK^+K^- system where all particles are in a relative S-wave (i.e., a kinematic effect). Only $\approx$ 7% of the cross section is non-resonant 2^{++} S-wave*. Thus it is entirely different than the $\phi\phi$ 2^{++} amplitudes. This reaction has about the same threshold and simiiar kinematics to the $\pi^-p \to \phi\phi n$ reaction, thus threshold effects would be quite similar

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* The K^+K^- system and the ϕ are in a relative S-wave. The K^+K^- pair are in a relative P-wave.

in the two reactions and it is clear that the striking characteristics of the $\phi\phi$ data cannot be attributed to such a naive mechanism.

The above characteristics of the data can be very well explained naturally within the context of QCD, if one assumes 1-3 primary glueballs with $J^{PC} = 2^{++}$ produce these states.[5,6,11,12]

One or two primary $J^{PC} = 2^{++}$ glueballs could break the OZI suppression and mix with nearby $q\bar{q}$ states with the same quantum numbers and similar masses. However the simplest explanation is that we have a triplet of $J^{PC} = 2^{++}$ glueballs. These would be in the right mass range predicted from Lattice Gauge calculations[15-17] and would fit[12] the prediction of three distinct masses made by T.D. Lee.[20]

ALTERNATIVE EXPLANATIONS AND CRITICISMS

Recent differences[21] regarding the degree of OZI forbiddeness of the reaction $\pi^- p \to \phi\phi n$ observed by BNL/CCNY have been resolved[22] and it was concluded that these resonances would be OZI forbidden if they were of the $q\bar{q}$ type and therefore they constituted strong evidence for glueball(s).

In recent papers[23,12] we have clearly shown that alternative explanations by Gomm,[24] Karl, et al.[25] and Donoghue[26] are incorrect and do not fit the data. Thus the glueball resonance hypothesis is the only published explanationof the data which is viable and it naturally arises in the context of QCD.

WHY HAVE THE g_T's NOT BEEN SEEN IN OTHER CHANNELS?

The MK III results observe $J/\psi \to \gamma\phi\phi$.[27] Their detection efficiency for $\phi\phi$ is very low in the mass region of the $g_T(2050)$,

$g_{T'}(2300)$ and $g_{T''}(2350)$. Thus they find only ~ 10 events in this mass region. However if one corrects their $\phi\phi$ mass spectrum for the detection efficiency it is not inconsistent with the shape of the mass spectrum seen by BNL/CCNY. However one should note we are comparing ≈ 4,000 observed events to ~ 10. It appears that the MK III can only observe strong signal, narrow, high mass $\phi\phi$ states such as the decay of the η_c, and thus is not likely to be able to observe the BNL/CCNY states. D. Hitlin may have some newer results.[27d]

The DM2 group[28] has reported at the Bari Conference ~ 50 $\gamma\phi\phi$ events in the mass region of the BNL/CCNY experiment. At present due to the limited statistics they are unable to say whether this signal is related to the resonant structures (i.e., the g_T, $g_{T'}$, $g_{T''}$) observed by BNL/CCNY.

It should be noted that in a related experiment $\pi^- Be \to \phi\phi$ inclusive[29] the data are found to be consistent with the $g_{T'}$ and $g_{T''}$ and two Breit Wigner resonances are needed to explain the results. The acceptance discriminates against the g_T. This reaction would only be expected to be partially Zweig suppressed. If a $K\bar{K}$ or $K(^{\Lambda}_{\Sigma})$ pair were created, the Zweig suppression would not apply. Booth <u>et al.</u> have recently studied[30] the case of central production of $\phi\phi$ in the exclusive reactions

$$Ap \to AK^+K^-K^+K^-p$$

$$Ap \to A\phi K^+K^-p$$

$$Ap \to A\phi\phi p \quad (\text{where } A = \pi^+ \text{ or } p).$$

Their results demonstrate that the $\phi\phi$ reaction does not exhibit the expected OZI suppression.

The other hadronic production experiments involve OZI-allowed channels therefore one would expect the g_T's to be submerged in the many other hadronic states one could expect. Thus their detection would likely require very large statistics and even then it might be quite difficult to separate them from the other hadronic states.

Figure 9 shows the results of the analysis of a 23 GeV/c $\pi^- p \rightarrow K_s^0 K_s^0 n$ experiment.[18] In the mass region of the g_T's, the $J^{PC} = 2^{++}$ amplitude behavior is smooth and structureless and shows no phase motion. Furthermore, the 0^{++} and 4^{++} states are also populated unlike the selection of only $J^{PC} = 2^{++}$ in $\pi^- p \rightarrow \phi\phi n$. This experiment has had its statistics raised by a factor of ~ 3 recently[19] and the results are the same. This is what I would expect when the effects of the OZI suppression filter action are eliminated as they are in this reaction.

Incidentally in this $\pi^- p \rightarrow K_s^0 K_s^0 n$ experiment there is no evidence for the $\theta(1700)$.[31,27] In the analysis we conclude the coupling of $\theta \rightarrow \pi\pi$ is consistent with the OZI suppression expected if the θ is an $s\bar{s}$ pair.

As to why the g_T's have not yet been seen in the radiative J/ψ decay I would suggest the following:

We argue the Zweig suppression in our channel (with a pure glue intermediate state) should filter out other hadronic states and give a highly enriched sample of glueballs. What we found in the data is certainly consistent, namely, we find three new states with the same quantum numbers and nothing else accompanied by no background (within errors).

In the J/ψ radiative decay ≈ 90% of the observed states are known conventional ones and thus it is an inefficient filter for glueballs.

As I discussed in Ref. 12, if glueballs were strongly coupled in the radiative decay of the J/ψ then the perturbatively calculated decay ratio $J/\psi \to \gamma gg/ggg$ would be expected to be much larger than the observed rate[34] whereas they agree. Furthermore the width of the J/ψ would be expected to be broadened.

The evidence for the glueball candidates iota(1420) and θ(1700) are reviewed here by Hitlin[27d] and Meshkov,[28] and the reader is referred to their papers.

In regard to the g_T's, it is also worth noting that Chanowitz and Sharpe[33] have concluded that strange quarks may well be favored in glueball decay and in particular in the $\phi\phi$ S-wave.*

Furthermore I would like to point out that except for color, the quantum numbers of a gluon and a ϕ are the same. Thus one can imagine that gluons would like to go into ϕ mesons just like photons like to go into vector mesons (i.e. similar to VDM). Of course the color must

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* They also have meikton states breaking the OZI suppression and possibly being associated with our states as well as glueballs. However this arguement depends on bag calculations and the dynamical mechanisms are not clear.

be changed to a singlet but such color rearrangements might perhaps be accomplished by soft gluon exchanges in the final hadronization. Thus this may also be another reason why the g_T's if they are glueballs are only seen in the $\phi\phi$ decay mode. If sufficient statistics are gathered in $J/\psi \to \gamma\phi\phi$ some evidence for the g_T, $g_{T'}$, and $g_{T''}$ states may be seen.

CONCLUSIONS ON THE STATUS OF THE g_T's AS GLUEBALL STATES

One can prove the g_T, $g_{T'}$, and $g_{T''}$ are glueballs with the appropriate input axioms. Then as we concluded previously the $g_T(2050)$, $g_{T'}(2300)$ and $g_{T''}(2350)$ are produced by 1-3 primary $J^{PC} = 2^{++}$ glueballs, if you assume as input axioms:

1. QCD is correct.

2. The OZI rule is universal for weakly coupled glue in disconnected Zweig diagrams where the disconnection is due to the creation or annihilation of new flavor(s) of quark(s), and $J \geq 1$ for the disconnected system (to avoid possible vacuum mixing effects).

We have previously stated that the BNL/CCNY $g_T(2050)$, $g_{T'}(2300)$ and $g_{T''}(2350)$ are naturally explained within the context of QCD by concluding they are produced by 1-3 primary glueballs. One or two broad primary glueballs could in principle break down the OZI suppression and mix with one or two quark states which accidentally have the same quantum numbers and close to the same mass. However the simplest explanation of the rather unusual characteristics of our data is that we have found a triplet of $J^{PC} = 2^{++}$ glueball states.

Alternatives to the Glueball resonance explanation have been discussed earlier and found to be incorrect or do not fit the data or both.[23,12]

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FIGURE CAPTIONS

Fig. 1 The Zweig quark line diagram for the reaction $\pi^- p \rightarrow K^+K^-K^+K^- n$, which is connected and OZI allowed.

Fig. 2 The Zweig quark line diagram for the reaction $\pi^- p \rightarrow \phi K^+K^- n$, which is connected and OZI allowed.

Fig. 3a The Zweig quark line diagram for the reaction $\pi^- p \rightarrow \phi\phi n$ which is disconnected (i.e. a double hairpin diagram) and is OZI forbidden. Two or three gluons are shown connecting the disconnected parts of the diagram depending upon the quantum numbers of the $\phi\phi$ system. For the g_T's, $J^{PC} = 2^{++}$, and only two gluons are required. From the data analysis they come from the annihilation of the incident π^- and a π^+ exchanged between the lower and the upper parts of the diagram.

Fig. 3b The $J^{PC} = 2^{++}$ glueball intermediate state in $\pi^- p \rightarrow \phi\phi n$. The dash-dot lines with crosshatch lines region indicates that we don't know details of the glueball hadronization into $\phi\phi$.

Fig. 4 Scatter plot of K^+K^- effective mass for each pair of K^+K^- masses. Clear bands of $\phi(1020)$ are seen with enormous enhancement (black spot) where they overlap (i.e. $\phi\phi$) showing essentially complete breakdown of OZI suppression.

Fig. 5 The $\phi\phi$ mass spectrum corrected for acceptance. The solid line is the fit to the data with the three resonant states to be described later. The points at the bottom of the diagram are the acceptance for each mass bin to be read with the scale at the right.

Fig. 6a The three $J^{PC} = 2^{++}$ partial waves at production in 50 MeV mass bins (except at ends). $J_Z = 0$ in the Gottfried-Jackson frame and the exchange naturality is (-) corresponding to pion exchange for all three waves. The smooth curves are derived from a three-pole K-matrix Fit.

Fig. 6b D-S phase difference from the partial wave analysis vs. $\phi\phi$ mass. The smooth curves are derived from a three-pole K-matrix fit.

Fig. 7 The partial wave intensities in the background reaction $\pi^- p \rightarrow \phi K^+K^- n$.

Fig. 8 Argand plot from K-matrix fit.

Fig. 9 The square of the moduli of the S_0, D_0, and G_0 amplitudes together with their absolute phases from the best fit as functions of $K^0_S K^0_S$ effective mass for $t' < 0.1\ (\mathrm{GeV}/c)^2$. The solid curves are the results of our preferred mass-dependent fit in the same t' interval (Ref. 31).

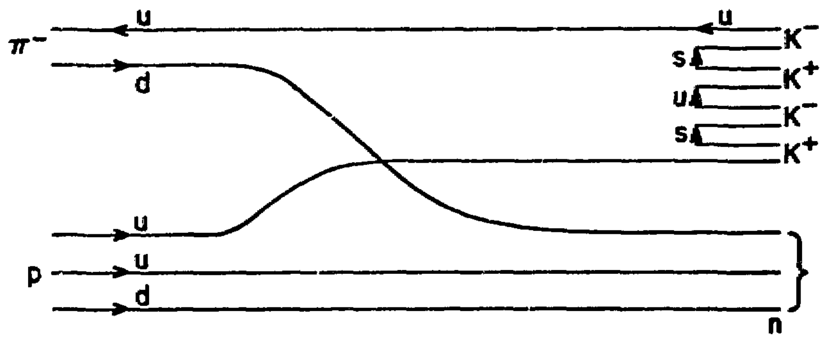


Figure 1

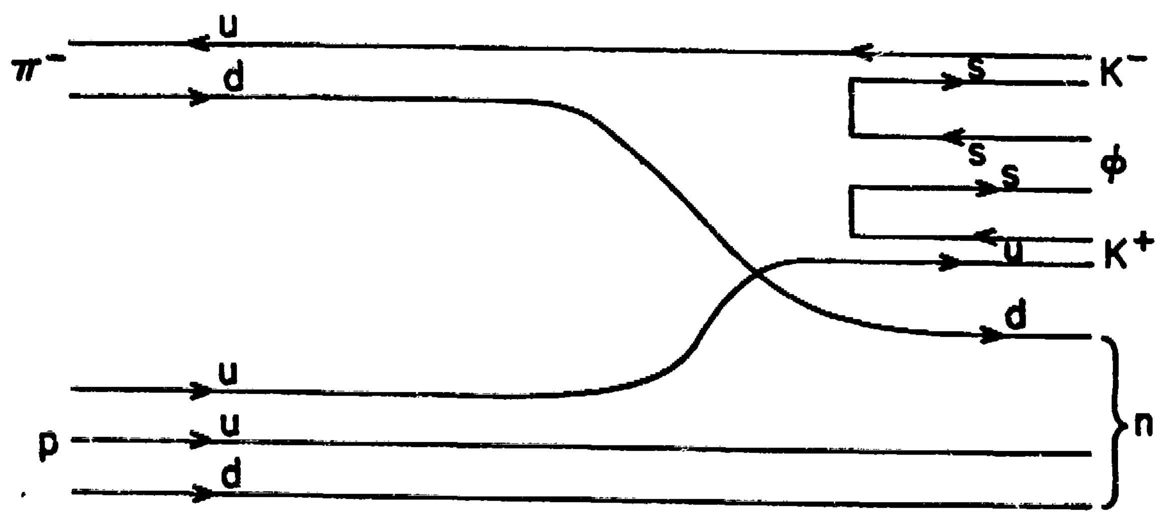
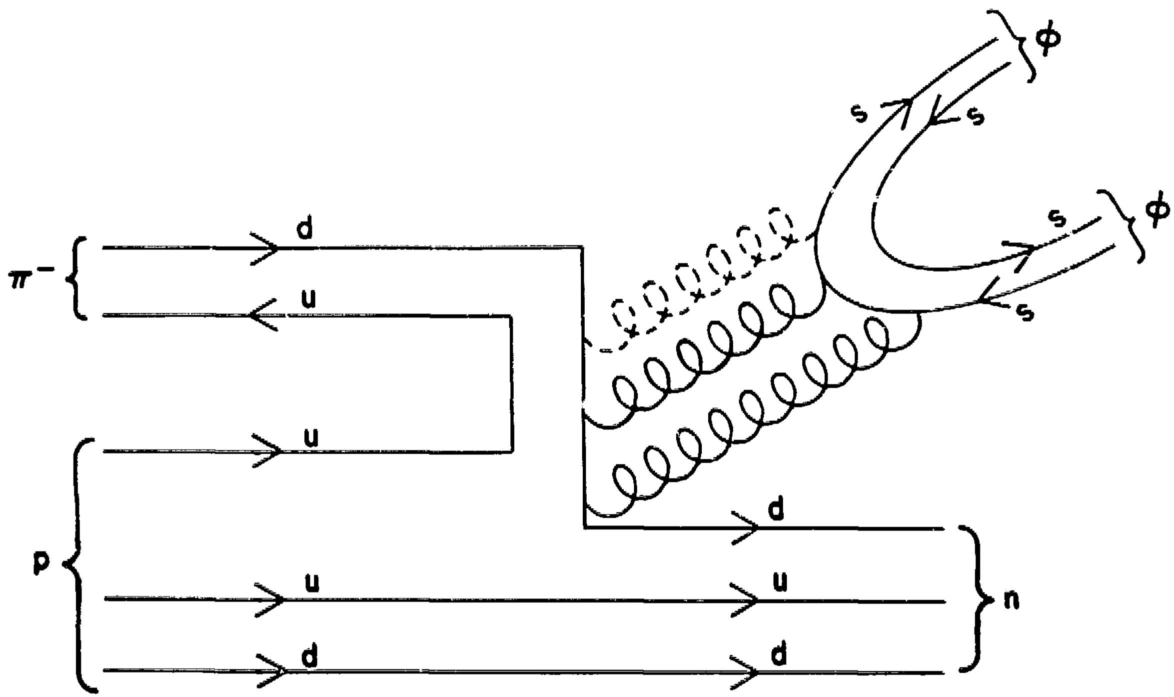


Figure 2



$\pi^- p \longrightarrow \phi\phi n$

Figure 3a

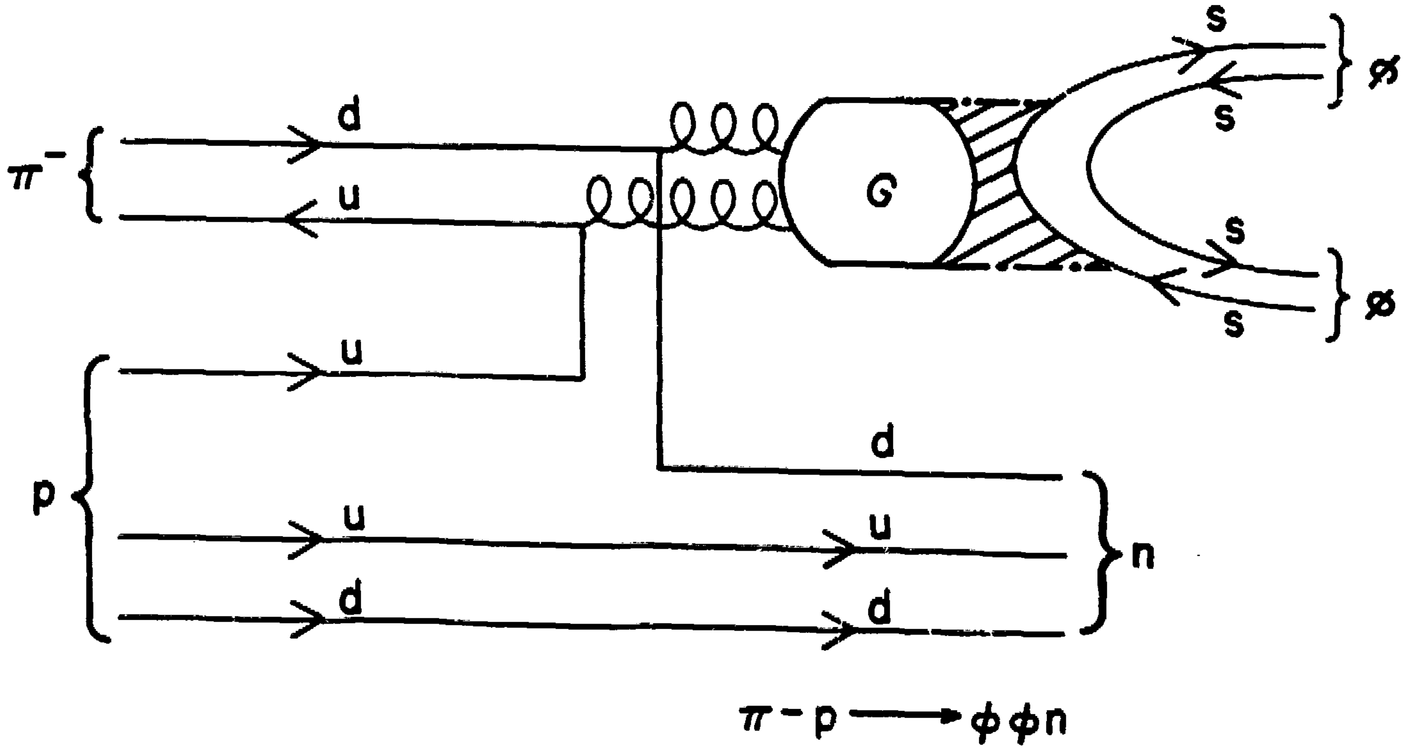


Figure 3b

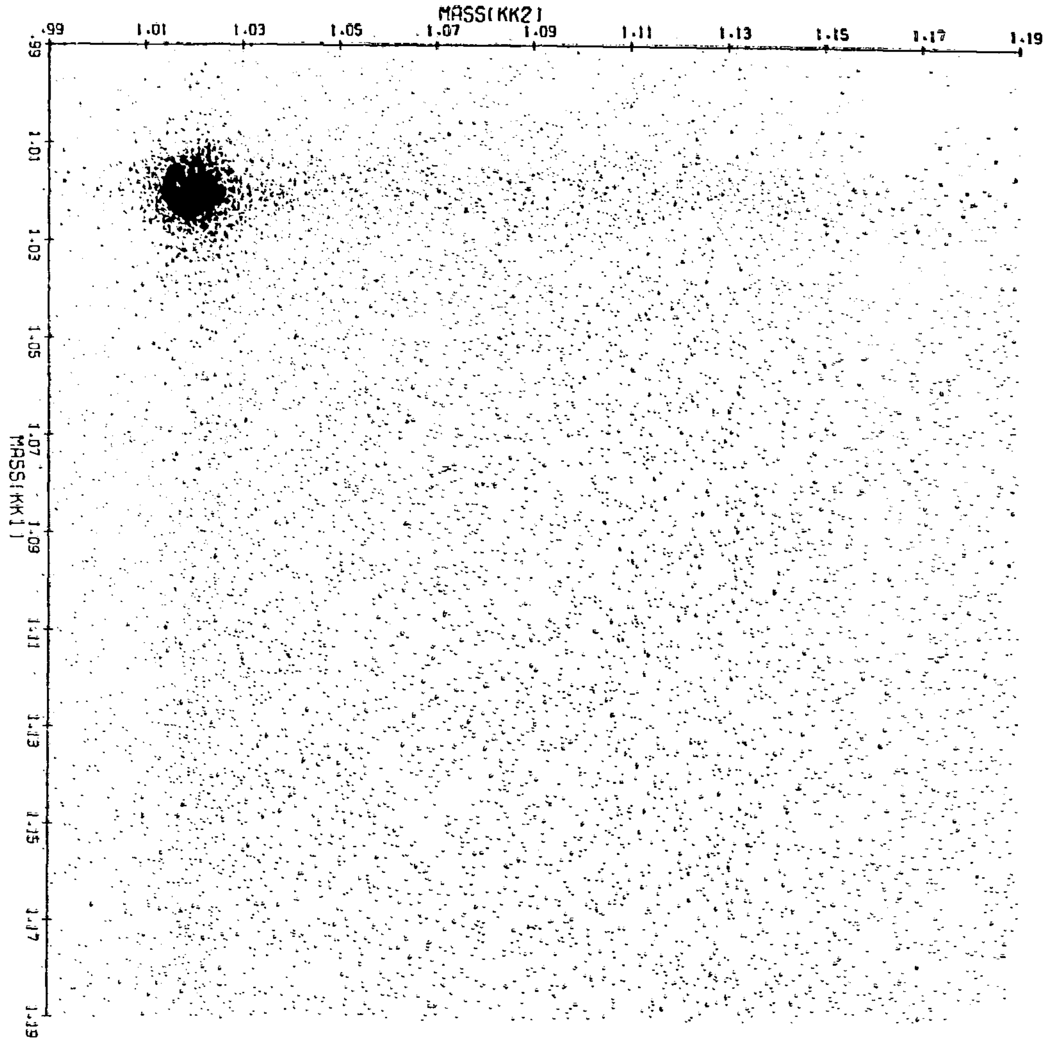
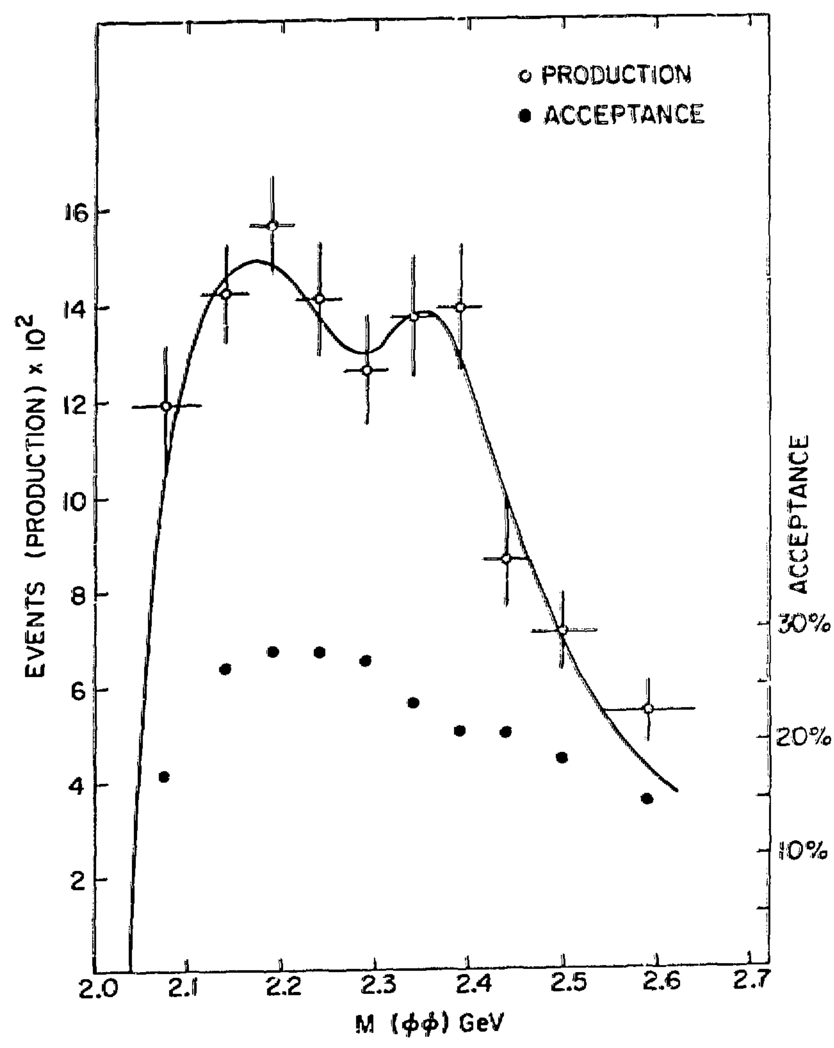
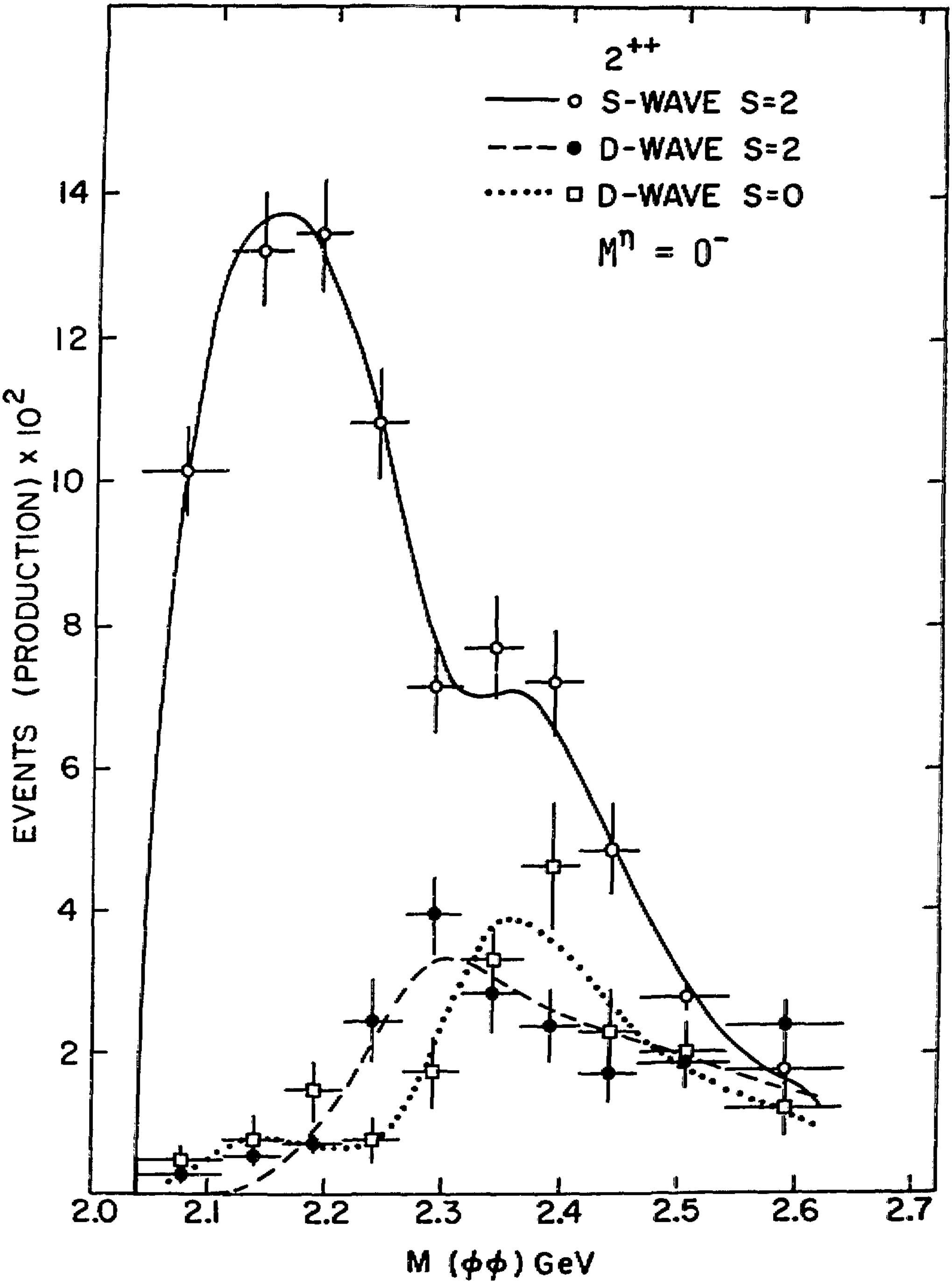


Figure 4



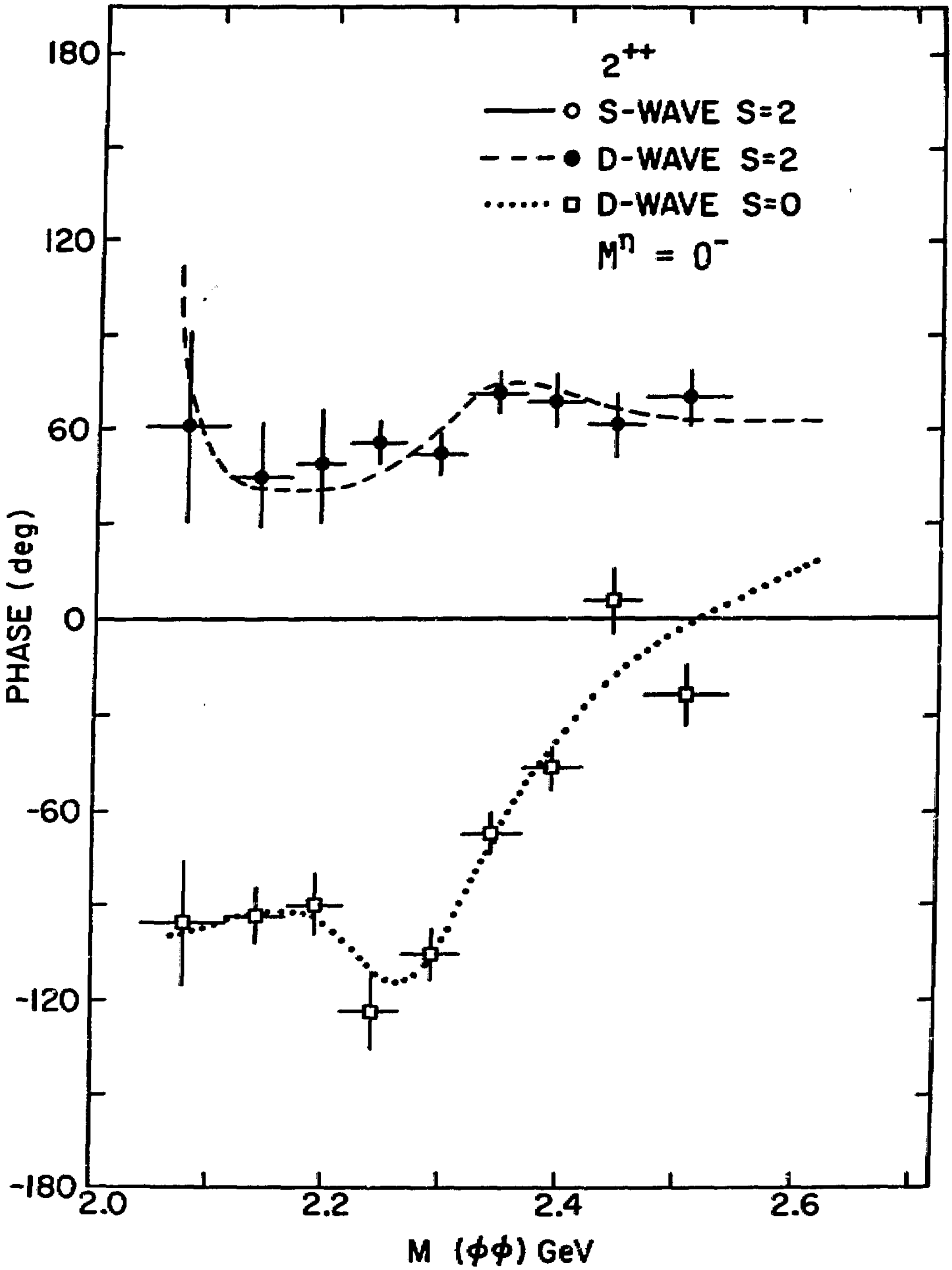
○ PRODUCTION
● ACCEPTANCE
EVENTS (PRODUCTION) x 10^2
ACCEPTANCE
16
14
12
10
8
6
4
2
30%
20%
10%
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
M ($\phi\phi$) GeV

Figure 5



2++
S-WAVE S=2
D-WAVE S=2
D-WAVE S=0
Mη = 0−
EVENTS (PRODUCTION) x 10²
14
12
10
8
6
4
2
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
M (φφ) GeV

Figure 6a



180
120
60
0
-60
-120
-180
PHASE (deg)
2⁺⁺
S-WAVE S=2
D-WAVE S=2
D-WAVE S=0
Mⁿ = 0⁻
2.0
2.2
2.4
2.6
M (φφ) GeV

Figure 6b

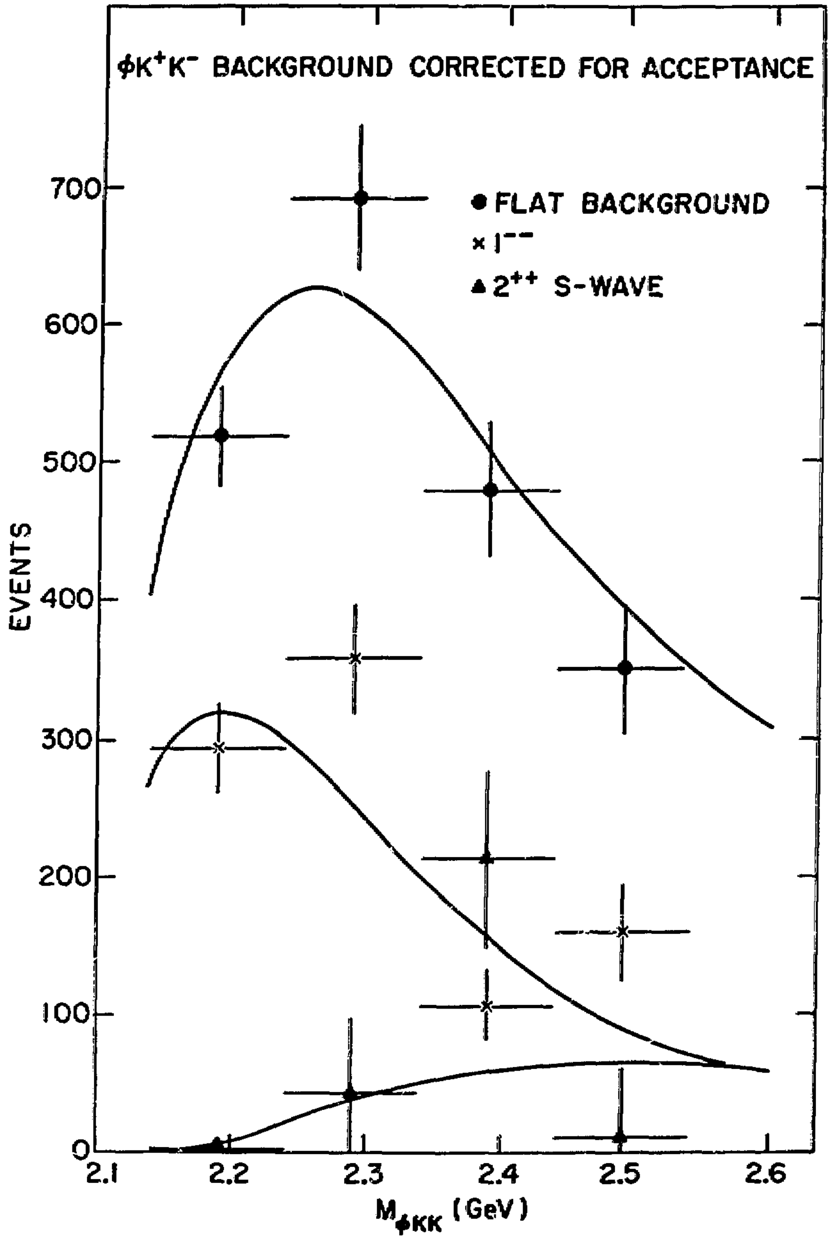

φK+K− BACKGROUND CORRECTED FOR ACCEPTANCE
● FLAT BACKGROUND
× 1−−
▲ 2++ S-WAVE
EVENTS
700
600
500
400
300
200
100
0
2.1
2.2
2.3
2.4
2.5
2.6
MφKK (GeV)

Figure 7

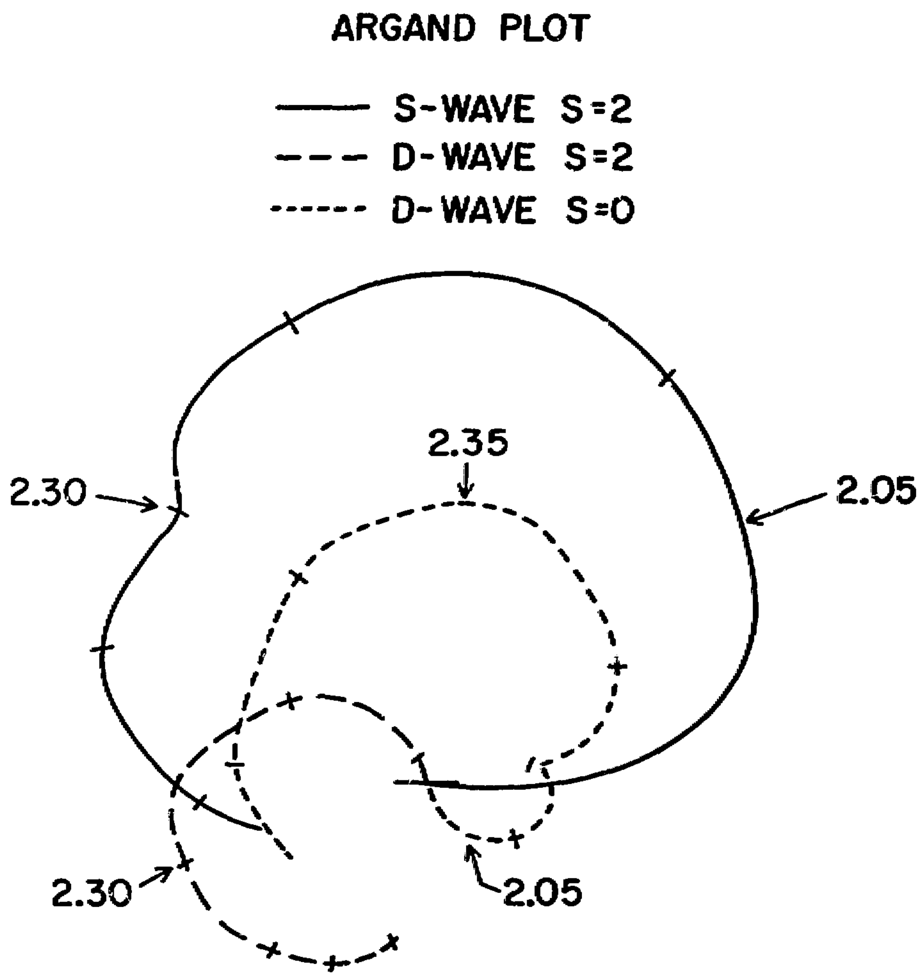
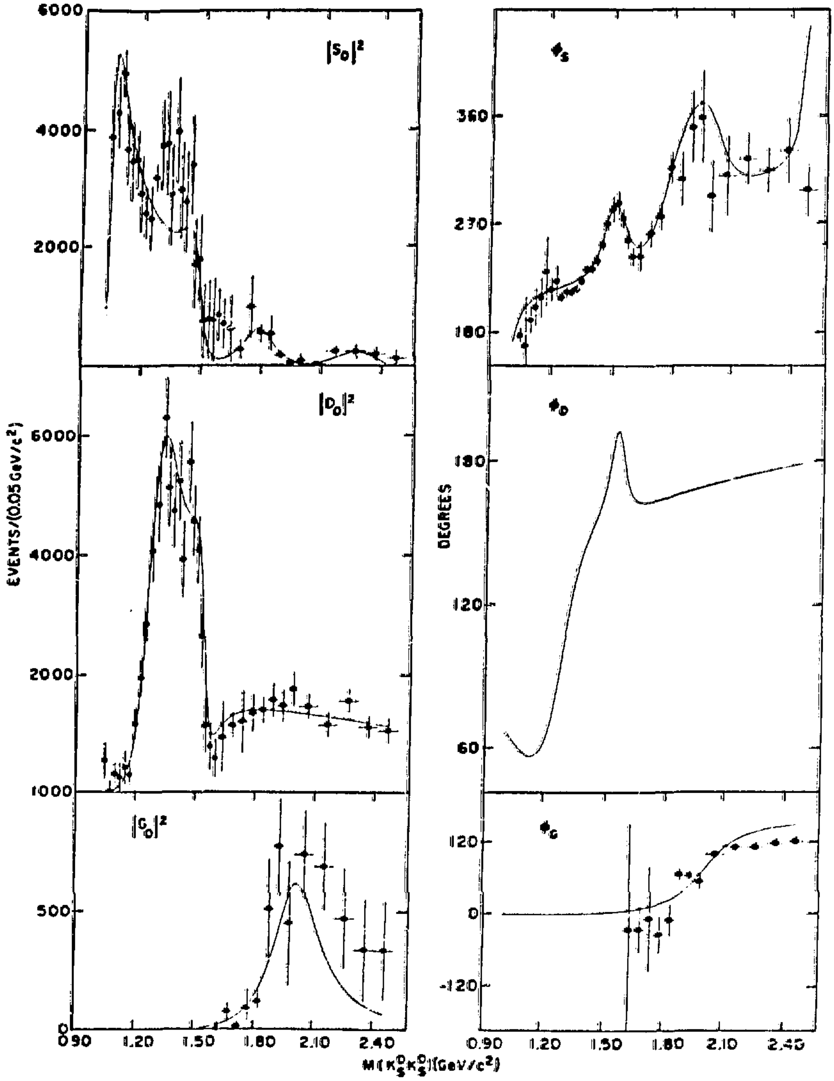


Figure 8



$|S_0|^2$
$|D_0|^2$
$|G_0|^2$
ϕ_S
ϕ_D
ϕ_G
EVENTS/(0.05 GeV/c^2)
DEGREES
6000
4000
2000
1000
500
0
360
270
180
120
60
-120
0.90
1.20
1.50
1.80
2.10
2.40
M($K^0_S K^0_S$)(GeV/c^2)

Figure 9