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ABSTRACT

A mass dependent asymmetry was observed in decay angular distribution of a photoproduced K^+K^- system near the K^+K^- threshold. The corresponding moments $<Y_1^0>$ have been evaluated. Interpreting the asymmetry as an S-P wave interference due to the states $S^*_{993}(0^+)$ and $\phi_{1019}(1^-)$ one can compute the moments $<Y_1^0>$ through an amplitude analysis. The theoretical calculation reproduces the experimental results well, if one assumes a real S wave amplitude for the S^*_{993}. The data can not be explained by a nonresonant real S wave. Ohter possibilities have been discussed. An estimate of the photoproduction cross section of the $S^* \rightarrow K^+K^-$ can be given on the basis of the above hypothesis.

I. INTRODUCTION

In an experiment carried out at the 7 GeV Synchrotron DESY using a tagged photonbeam and a magnetic track chamber spectrometer the reaction

$$\gamma p \rightarrow K^+K^-p \qquad (1)$$

has been investigated in the energy region 4.6 to 6.7 GeV. A short description of the experiment and a number of results have been published[1]. A more detailed paper is in preparation[2].

In studying the KK angular distribution it was observed that the distribution of the K^+ helicity angle θ^H, measured in the K^+K^- restsystem with respect to the helicity axis, changes its shape near threshold in a characteristic way, when plotted as a function of the invariant KK mass (fig. 1).

In the mass region around the ϕ_{1019} meson the dominant feature of the polar angular distribution is the $\sin^2\theta^H$ shape representing the S channel helicity conservation in ϕ photoproduction; in passing however through a KK mass region which extends from threshold to the ϕ mass region an asymmetry occurs in the angular distribution which decreases as one approaches the ϕ region and changes sign at the ϕ mass. This is exhibited by a fit of the angular distribution with a superposition of Legendre polynomials (solid line, fig. 1).

It has been investigated whether the asymmetry in the K^+K^- decay angular distribution was caused by an inherent asymmetry of the experimental set up, such as a misalignement. For this purpose we have computed with Monte Carlo techniques trajectories of particles of the event type (1). Subjecting them to simulated experimental conditions such as the trigger and acceptance-constraints we investigated the distribution of the helicity angle. Introducing then a misalignement into the geometric acceptance with respect to the beam axis, no significant changes or asymmetry of the angular distribution occurred which was comparable to the experimental effect.

A plausible explanation of the asymmetry is an interference effect of a resonant spin 1 state with a resonant or nonresonant spin 0 state, both amplitudes being produced coherently.

The spin 1 state is represented by the diffractively produced ϕ_{1020}. (fig. 3b). Although there is no direct evidence for an additional signal other than the ϕ in our K^+K^- mass distribution (fig. 2), the observed asymmetry in the angular distribution is a strong indication of the presence of a-possibly-resonant S-wave.

The observed asymmetry can be expressed quantitatively by computing moments $\langle Y_L^M \rangle$, in particular $\langle Y_1^0 \rangle$, of the experimental angular distribution as a function of the invariant KK mass. Fig. 4 shows that $\langle Y_1^0 \rangle$, which is the moment representing the S-P-wave interference. It is negative near threshold and crosses the zeroline about at the ϕ mass.

A candidate for a resonant spin 0 state is the $S^*_{993}(0^+)$ meson which is known to couple strongly to the $K\bar{K}$ channel. Experimentally the S^* has been observed in hadron induced reactions[3], and as a sharp rise o the isospin even S wave phase shift in $\pi\pi$ scattering[4]. As a member of a scalar nonett the S^*_{993} has drawn considerable theoretical interest[5] being considered e.g. a candidate for a quarkless gluon state.

Alternatively the K^+K^- final state near KK threshold can be produced through a nonresonant diffractive amplitude of the Drell-Söding[6] type (fig. 3c). This reaction channel has been used in the photoproduction of pion pairs as an explanation for the observed skewing of the ρ^0 mass distribution[7]. Although asymptotically the $K\bar{K}$ system has for reasons of charge conjugation in this channel only odd angular momentum states, an S wave contribution may occur due to the difference of K^+p and K^-p scattering at our energies. A quantitative computation however is involved since the K propagator is far from the mass shell.

In addition the possibility can not be excluded, that a nonresonant K^+K^- final state is produced by a real amplitude, (an example being electromagnetic K^+K^- pair production via Bethe Heitler diagrams).

In this paper our main interest is to investigate the possibility that the interference is due to the S^*_{993}, (discussing however also the other possibilities), which might be produced by a diagram such as shown in fig. 3a.

On the basis of this assumption we can also theoretically calculate the moment $\langle Y^0_1 \rangle$ by introducing a parametrization for the contributing production and decay amplitudes. Using the established values for the width and the resonance mass we can fit the experimentally observed mass dependence of the interference. For a special choice the relative production phase of ϕ and S^*, the fit yields estimates of the corresponding S^* photoproduction cross sections.

II. ANALYSIS PROCEDURE

The analysis is based on 3500 events of reaction (1) which have been selected by requiring energy momentum conservation using a one constraint fit[2].

Evaluating the K^+ angular distribution in the helicity frame of the K^+K^- restsystem experimental moments $\langle Y^M_L \rangle$ have been obtained from our data for mass bins ΔM^2_{KK} using the relation

$$\langle Y^M_L \rangle_{\Delta M^2_{KK}} = \sum_i n_i \, (\theta^H_i, \phi^H_i, M^2_{KK}) \; Y^M_L(\theta^H_i, \phi^H_i) \qquad . \tag{2}$$

The sum is taken over individual events, which were acceptence-corrected by weights n_i, and over the entire range in θ^H and ϕ^H in each mass bin ΔM^2_{KK}.

Assuming that two amplitudes A_ϕ and A_{S^*} for production and decay contributing to the observed rate, we can compute theoretical moments $\langle Y^M_L \rangle$ from the relation

$$\langle Y^M_L \rangle = \int d\Omega^H dM^2_{KK} \, |A_{S^*} + A_\phi|^2 \; Y^M_L \, (\theta^H, \phi^H) \cdot f \tag{3}$$

where

f = flux · No. of target nucleons

$\Delta\Omega$ = element of the K^+ decay angle in the helicity system.

The amplitudes include a Breit Wigner mass dependence for the production, the decay is described using standard angular momentum wave functions so that the total amplitudes can be written:

$$\begin{aligned} A_{S^*} &= a_{S^*} \cdot Y^0_0 \\ A_\phi &= \Sigma \, a^M_\phi \, Y^M_L \, (\theta^H, \phi^H) \qquad . \end{aligned} \tag{4}$$

We write the relativistic Breit Wigner production amplitude in the form

$$a_r = c^M_r \varepsilon_r \, \frac{1 + i\varepsilon_r}{1 + \varepsilon^2_r} \, e^{i\delta_r} \qquad \varepsilon_r = \frac{M_r \Gamma_r}{M^2_{KK} - M^2_r} \tag{5}$$

r stands for ϕ, S^*;

M_r = central mass of ϕ, S^*; Γ_r = energy dependent width[9]

δ_r is a production phase, hence

$\Delta\delta = \delta_{\phi_{1019}} - \delta_{S^*_{993}}$ is the relative production phase between the ϕ_{1019} and the S^*_{993}.

The amplitudes are being normalized by a constant c^M_r, when $M = \pm 1, 0$ refers to the spin orientation with respect to the helicity axis in case of a spin 1 meson.

$$c^M_r = \sqrt{\frac{\sigma^M_r}{\alpha_r M_r \Gamma_r}} \tag{5a}$$

The normalization is chosen such that[6]

$$\int |a_\phi^M|^2 \, dM_{KK}^2 = \sigma_\phi^M \qquad M = +1.0 \quad . \tag{5b}$$

σ_ϕ^M represents the total cross section fo the reaction (1) when the $K\bar{K}$ system forms a ϕ meson; M refers to the helicity conserving respectively nonconserving part of the cross section. σ_{S^*} is defined analogously.
α_r is a correction factor in the normalization for the resonant amplitude near K^+K^- threshold.

Introducing (4) into (3) it can be seen that the S-P-wave interference appears only in the moment $\langle Y_1^o \rangle$. This moment represents the interference of a spin 0 state with the helicity flip part of the ϕ production. After normalizing the moments by dividing through the rate in each mass bin M_{KK}^2, one obtains the relation

$$\frac{\langle Y_1^o \rangle}{\langle Y_o^o \rangle} = 2 \, \frac{\mathrm{Re}\,(a_{S^*} a_\phi^{o*})}{N(\Delta M_{KK}^2)} \quad , \tag{6}$$

where $N(\Delta M_{KK}^2) = \int d\Omega^H \, |(A_{S^*} + A_\phi)|^2$ is proportional to the rate in the mass bin ΔM_{KK}^2.

In order to compare (6) with the experimental result special choices of δ_r have been made. Taking the ϕ production to be essentially a diffractive process that is $\delta_{\phi 1019} = \frac{\pi}{2}$ (even in the helicity flip part) we consider two different choices for the phase of the S-meson: $\delta = \frac{\pi}{2}$ and $\delta = 0$ which corresponds to $\Delta\delta = 0, \frac{\pi}{2}$.

a) $\Delta\delta = 0$ both amplitudes are diffractive.

From (6) one obtains

$$\frac{\langle Y_1^o \rangle}{\langle Y_o^o \rangle} = 2 \cdot \frac{U}{N} \, (1 - \varepsilon_\phi \varepsilon_{S^*}) \quad . \tag{7}$$

b) $\Delta\delta = \frac{\pi}{2}$ the S^* amplitude is real and the ϕ amplitude diffractive

$$\frac{\langle Y_1^o \rangle}{\langle Y_o^o \rangle} = -2 \cdot \frac{U}{N} \, (\varepsilon_r + \varepsilon_\phi) \quad , \tag{8}$$

where

$$U = c_\phi^o \cdot c_{S^*} \cdot \frac{\varepsilon_\phi \cdot \varepsilon_{S^*}}{(1+\varepsilon_\phi^2)(1+\varepsilon_{S^*}^2)} \quad .$$

The helicity flip cross section σ_ϕ^o can be expressed using the spin density matrix element ρ_{oo} of the ϕ decay

$$\sigma_\phi^o = \rho_{oo} \, \sigma(\gamma p \to p\phi) \quad . \tag{9}$$

III. RESULTS

We used for the total widths Γ_ϕ and Γ_{S^*} experimental values[9]. For ρ_{oo} we evaluated a number from the data of this experiment[2], which represents an average over the KK mass region from $M_{KK} = 1.00$ to $M_{KK} = 1.024$ GeV $\sigma(\gamma p \to K^+K^-)$ was obtained from an integration of the differentical cross section $\frac{d\sigma}{dt}(\gamma p \to p\phi)$.[2]

Hence in (9) it was used

$$\rho_{oo} = 0.03 \pm 0.015$$

$$\sigma_{tot}(\gamma p \to \phi p \to K^+K^-p) = 0.25 \pm 0.02 \ \mu b \quad .$$

The expressions (7) and (8) were fitted to the experimental moments (2) adjusting the only free parameter σ_{S^*}, thus rendering an estimate for the total cross section of the photoproduction of the S^*.

This analysis is for reason of low statistics near threshold clearly little sensitive to the K^+K^- mass dependence of the amplitudes, (since there the mass districution shows no distinct signal) but it is sensitive to the relative production phase of the two assumed amplitudes and whether they are of a resonant or nonresonant type (which again introduces a phase). Therefore in order to investigate the effect of a nonresonant amplitude it seems sufficient to consider here only a simple minded $1/M^2_{K^+K^-}$ mass-dependence. The results obtained are then as follows (fig. 4):
Assuming that the interference is due to a real and resonant S^*_{993}-amplitude that is $\Delta\delta = \pi/2$, in a one parameter fit a very good agreement with the data was obtained, yielding

$$\sigma_{tot}(\gamma p \to S^*_{993} p \to K^+K^- p) = (2.7 \pm 1.5 \times 10^{-3})\ \mu b \qquad (10)$$

$$\chi^2 = 12.5 \quad (6 \text{ degrees of freedom}) \quad .$$

No acceptable fits could be obtained assuming a real and nonresonant K^+K^- production amplitude.

This makes it unlikely the the interference is for example due to a pure electromagnetic production of K^+K^- pairs. (It is on the other hand interesting to note that Coulomb corrections at the K^+K^- threshold introduce an imaginary part to this amplitude[10] (fig. 3d).

Also the assumption of an imaginary and resonant (S^*_{993}) amplitude renders no acceptable fit, which excludes the possibility that the photoproduction of the S^* is predominantly diffractive.

Assuming however an imaginary and nonresonant amplitude one obtains also a fair agreement with the experimental data within the errors[11]. Thus the presence of an S-wave part of a Drell-Söding amplitude can not be discarded on the basis of our data.

Therefore in summarizing the results:
The hypothesis that the observed interference is due to the photoproduction of a scalar meson with an invariant mass very close to the K^+K^- threshold (for which the S^*_{993} is the most likely candidate) is in very good agreement with the data. The fitted value for the total photoproduction cross section (10) of this reaction channel being about 1% of the total ϕ photoproduction cross section has to be taken as an upper limit estimate, in view of the fact that also a nonresonant imaginary amplitude would provide a satisfacting explanation of the experimental data. This estimate depends of cause on the assumed total width of the S^*_{993}. If one takes a width of 300 MeV as it was recently suggested[12], instead of the width given in the dates compilation tables, one can fit the data equally well but obtains a fitted value for σ_{tot} which is about 10 times larger than the one given in (10).

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8. The t dependence (t = four momentum transver to the proton in (1)) was absorbed by using cross sections σ_t which are integrated over t (for the normalization factor c_r).

9. For Γ we used the energy dependent width of a resonance of the mass M_r and the spin S decaying into two K's (M_K) of invariant mass M_{KK}:

$$\Gamma_r = \Gamma_r^o * \frac{M_r}{M_{KK}} * \left|\frac{M_{KK}^2 - 4\cdot M_K^2}{M_r^2 - 4\cdot M_K^2}\right|^{2S+1}$$

$\Gamma_{S^*}^o$ was taken from the N. Barash-Schmidt et al. tables of particle properties: Rev. of Mod. Phys. 48, No. 2, Part II, (1976).
For Γ_ϕ^o we used the experimental width of this experiment (8 MeV).

10. In the K^+K^- mass range considered here the effect is small compared to the errors, and can be ignored.
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11. Within our statistics a purely imaginary amplitude with one free parameter can always be fitted to the data, almost independent of what mass dependence one assumes for the S-wave. Different mass assumptions based on the paper of Pumplin (8) rendered comparable fits.

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FIGURE CAPTIONS

Fig. 1: Decay angular distribution of acceptance corrected events of the K^+ helicity angle Θ^H, measured in the K^+K^- restsystem with respect to the helicity axis, for consecutive $M_{K^+K^-}$-bins. The solid line represents a fit of the angular distribution with a super position of Legendre polynomials $\Sigma\, a_L\, P_L\, (\cos \Theta^H)$.

Fig. 2: Distribution of the invariant K^+K^- mass of acceptance corrected events.

Fig. 3: Diagrams for the photoproduction of K^+K^- pairs, a) S^* productions in t channel exchange, b) diffractive ϕ photoproduction, c) Drell/Söding diagrams, d) Coulomb corrections at K^+K^- threshold.

Fig. 4: Moments $\langle Y_1^o\rangle/\langle Y_o^o\rangle$ as a function of $M_{K^+K^-}$ from experimental data. Solid and dotted lines: Result of a fit of the moments $\langle Y_1^o\rangle/\langle Y_o^o\rangle$ calculated from (6) for two different relative production phases δ between the ϕ and a resonant or nonresonant K^+K^- amplitude.

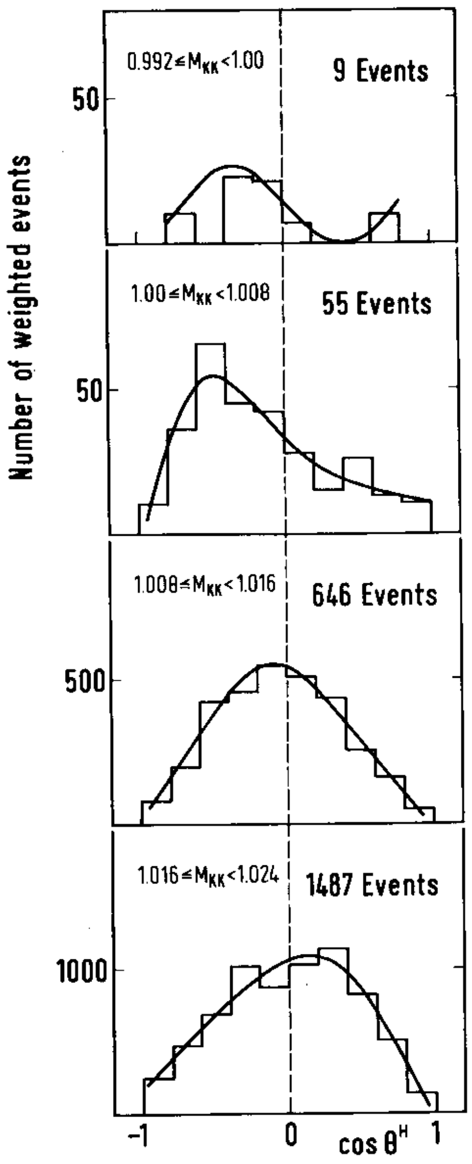
Number of weighted events
50
50
500
1000
$0.992 \leq M_{KK} < 1.00$
9 Events
$1.00 \leq M_{KK} < 1.008$
55 Events
$1.008 \leq M_{KK} < 1.016$
646 Events
$1.016 \leq M_{KK} < 1.024$
1487 Events
-1
0
$\cos \theta^H$
1

Fig. 1

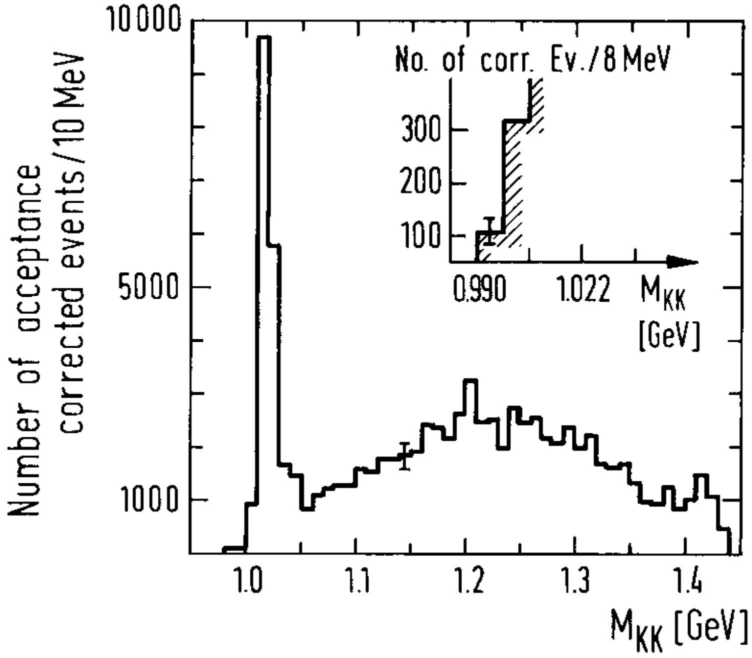
Number of acceptance corrected events/10 MeV
10000
5000
1000
1.0
1.1
1.2
1.3
1.4
M_{KK} [GeV]
No. of corr. Ev./8 MeV
300
200
100
0.990
1.022
M_{KK}
[GeV]

Fig. 2

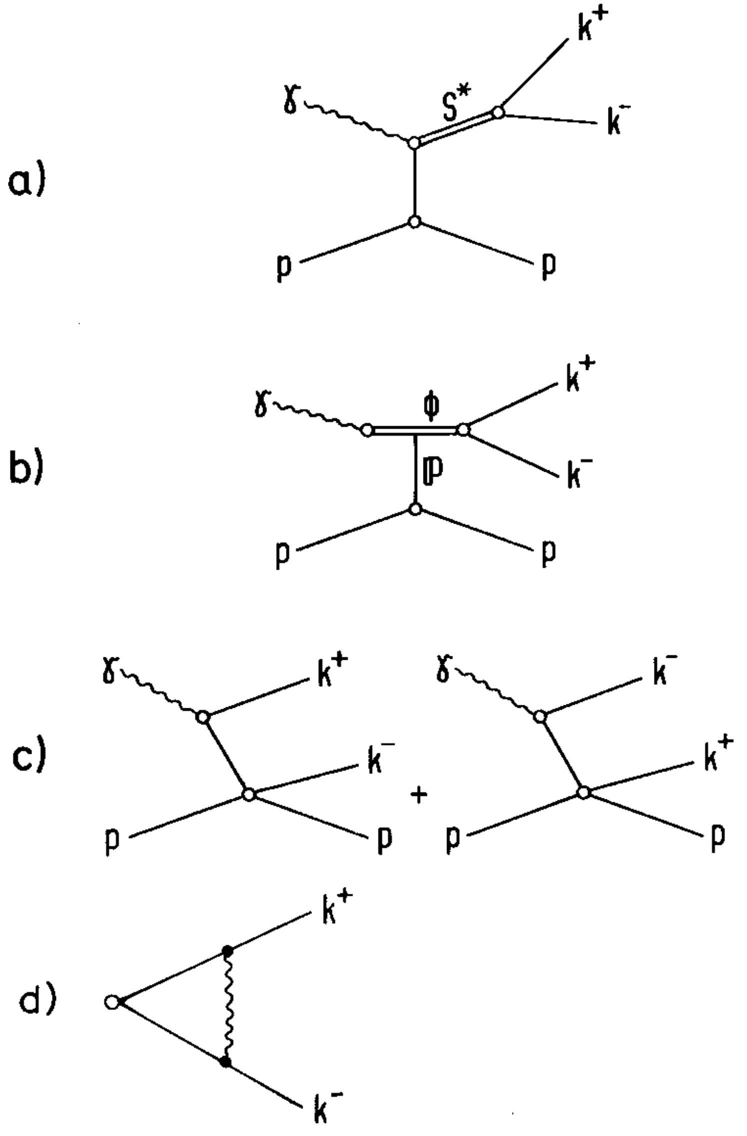
a)
γ
S*
k+
k−
p
p
b)
γ
ϕ
ℙ
k+
k−
p
p
c)
γ
k+
k−
p
p
+
γ
k−
k+
p
p
d)
k+
k−

Fig. 3

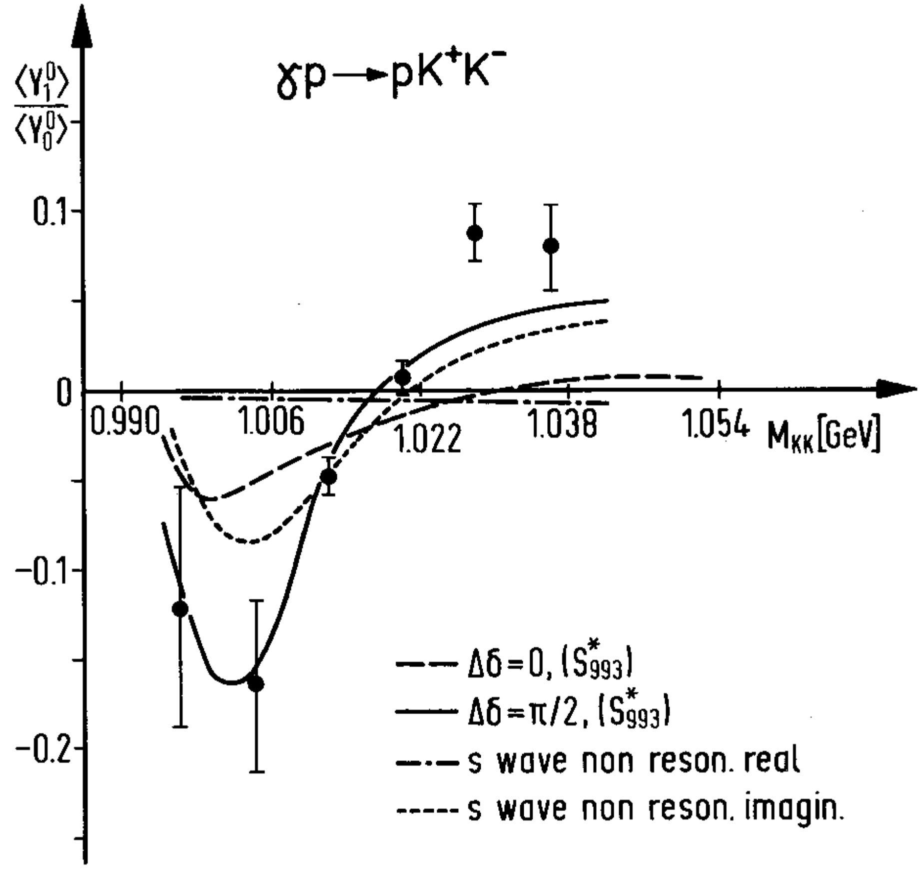
γp ⟶ pK+K−
⟨Y₁⁰⟩/⟨Y₀⁰⟩
0.1
0
−0.1
−0.2
0.990
1.006
1.022
1.038
1.054
M_KK [GeV]
Δδ = 0, (S*993)
Δδ = π/2, (S*993)
s wave non reson. real
s wave non reson. imagin.

Fig. 4