The mixing of the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ and the search for the scalar glueball using data from the CERN WA102 experiment

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1. An introduction to the WA102 experiment
2. The observation and properties of the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$.
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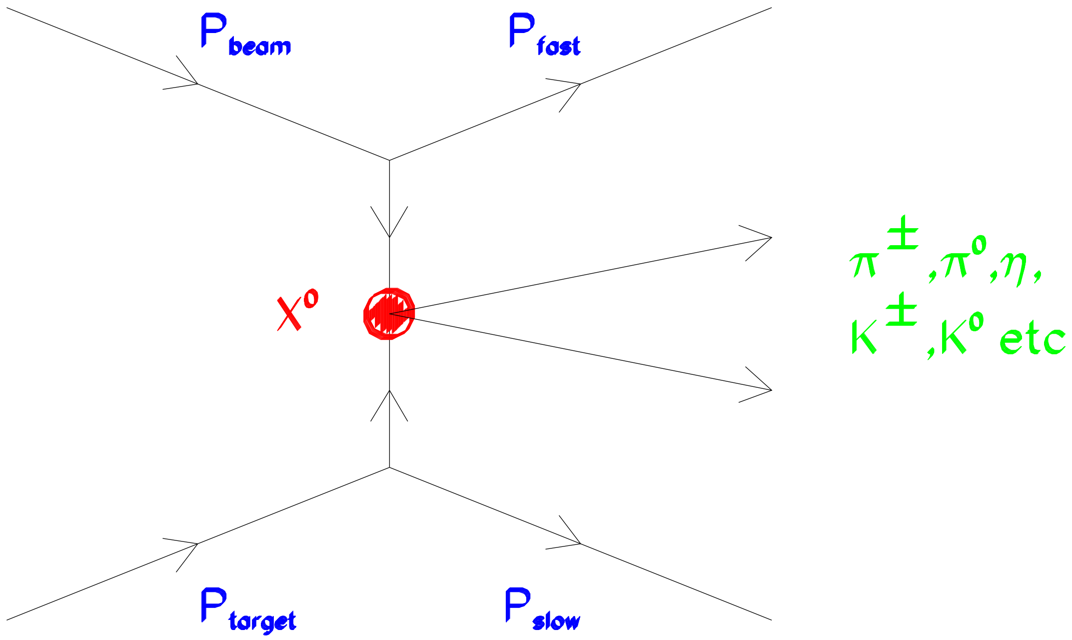
Experiment WA102 has studied exclusive final states in the reaction

$$pp \to p_f p_s (X^0)$$

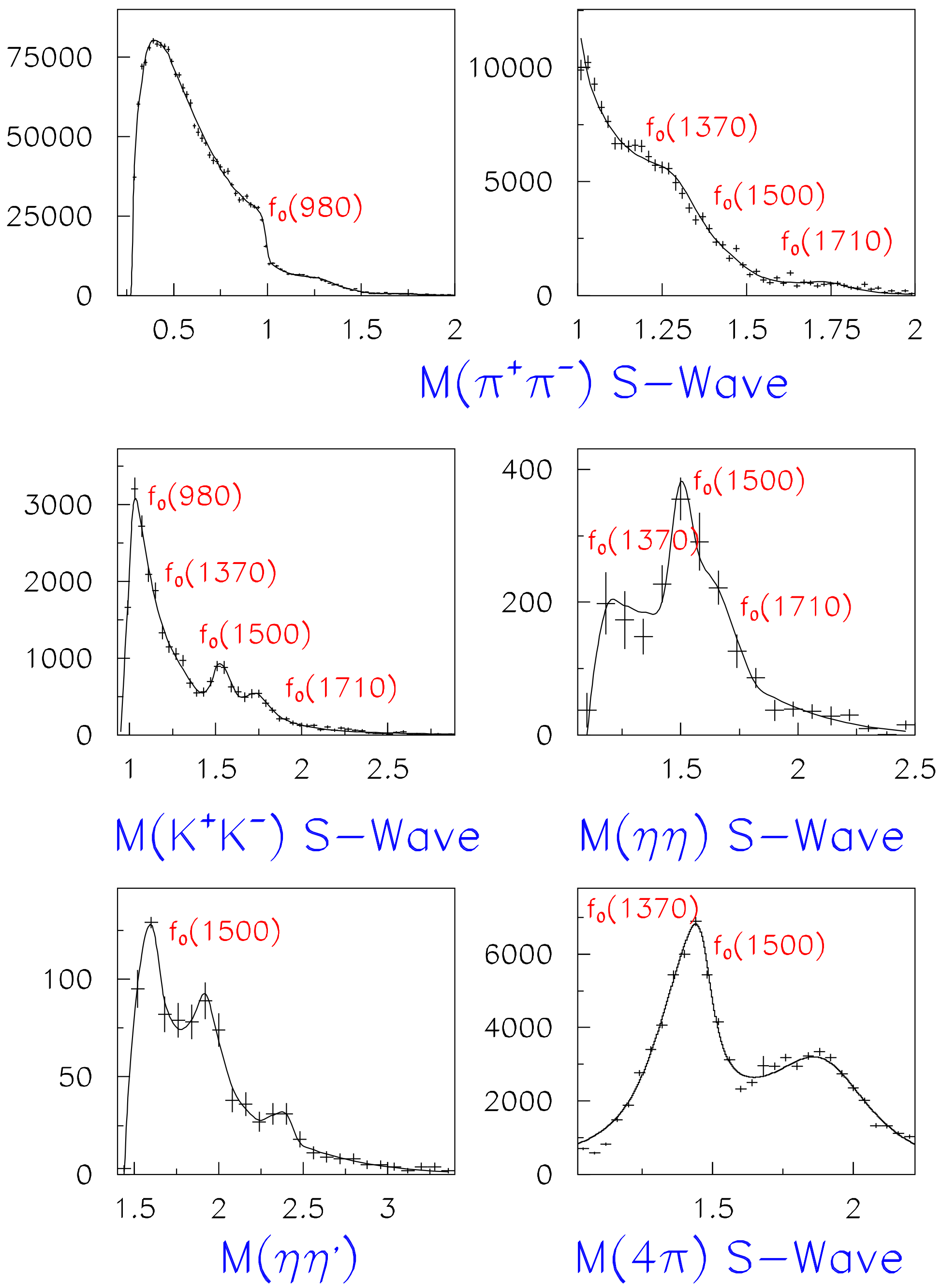
at 450 GeV/c

Centre of mass view



which is predicted to be a source of gluonic final states via double Pomeron exchange.

The observation of the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ in the WA102 experiment



The parameters of the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ in the WA102 experiment

The sheet II pole positions are

$$
\begin{array}{llllll}
f_0(1370) & \mathrm{M} & = (1310 \pm 19 \pm 10) & -i\,(136 \pm 20 \pm 15) & \mathrm{MeV} \\
f_0(1500) & \mathrm{M} & = (1508 \pm 8 \pm 8) & -i\,(\;54 \pm \;7 \pm \;6) & \mathrm{MeV} \\
f_0(1710) & \mathrm{M} & = (1712 \pm 10 \pm 11) & -i\,(\;62 \pm \;8 \pm \;9) & \mathrm{MeV}
\end{array}
$$

The relative decay rates

$$\pi\pi : K\overline{K} : \eta\eta : \eta\eta' : 4\pi$$

$$f_0(1370)$$

$$1 : 0.46 \pm 0.19 : 0.16 \pm 0.07 : 0.0 : 34.0^{+22}_{-9}$$

$$f_0(1500)$$

$$1 \;:\; 0.33 \pm 0.07 \;:\; 0.18 \pm 0.03 \;:\; 0.096 \pm 0.026 \;:\; 1.36 \pm 0.15$$

$$f_0(1710)$$

$$1 : 5.0 \pm 0.7 : 2.4 \pm 0.6 :< \; 0.18 \; (90 \; \% \;\; CL) :< \; 5.4 \; (90 \; \% \;\; CL)$$

The established $J^{PC} = 0^{++}$ I $= 0$ states in the glueball region

$f_0(1370)$ $f_0(1500)$ $f_0(1710)$

There are many scenarios of which state has the largest 'glue' content

We assume the mixing is strongest between the glueball and nearest $q\overline{q}$ neighbours.

The three physical states can be read as

$$\begin{pmatrix} |f_0(1710)\rangle \\ |f_0(1500)\rangle \\ |f_0(1370)\rangle \end{pmatrix} = \begin{pmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{pmatrix} \begin{pmatrix} |G\rangle \\ |S\rangle \\ |N\rangle \end{pmatrix},$$

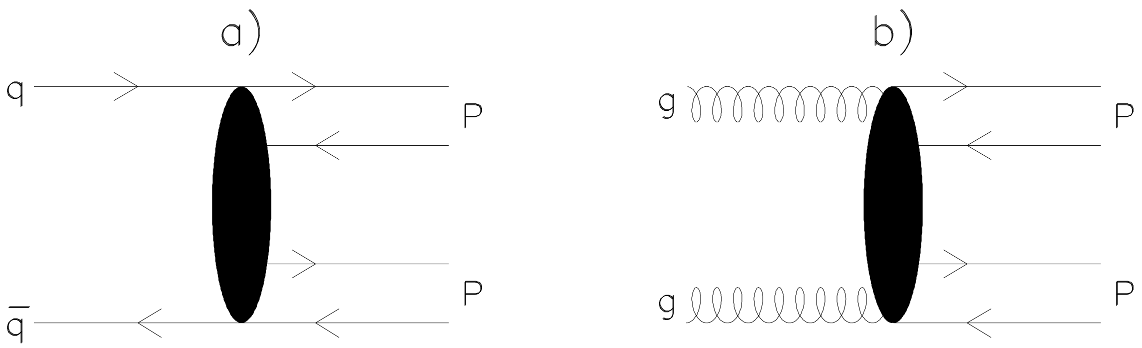
where $|G\rangle$, $|S\rangle$ and $|N\rangle$, represent the bare states.

The element x_i, y_i and z_i can be determined from

a) knowing the masses of the states and the mixing strength i.e Close and Amsler, Weingarten

b) studying the two body pseudoscalar decays of the resonances.

The two decay diagrams considered are the following



(a) the direct coupling of the quarkonia component of the three states to the final pseudoscalar mesons (PP) (fig. a).

(b) the coupling of $gg \to qq\overline{qq}$ as in fig. b. r_2 is the ratio of diagram b) to a)

The three physical states can be read as

$$\begin{pmatrix} |f_0(1710)\rangle \\ |f_0(1500)\rangle \\ |f_0(1370)\rangle \end{pmatrix} = \begin{pmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{pmatrix} \begin{pmatrix} |G\rangle \\ |S\rangle \\ |N\rangle \end{pmatrix}$$

where x_i, y_i and z_i are determined from the reduced partial widths given by

$$\gamma^2(f_i \to \eta\eta') \qquad 2[2\alpha\beta(z_i - \sqrt{2}y_i)]^2$$

$$\gamma^2(f_i \to \eta\eta) \qquad [2\alpha^2 z_i + 2\sqrt{2}\beta^2 y_i + r_2 x_i]^2$$

$$\gamma^2(f_i \to \pi\pi) \qquad 3[z_i + r_2 x_i]^2$$

$$\gamma^2(f_i \to K\bar{K}) \qquad 4[\tfrac{1}{2}(z_i + \sqrt{2}y_i) + r_2 x_i]^2$$

where

$\alpha = (\cos\phi - \sqrt{2}\sin\phi)/\sqrt{6}$,

$\beta = (\sin\phi + \sqrt{2}\cos\phi)/\sqrt{6}$, and

ϕ is the mixing angle of η and $\eta\prime$.

Results of the fit

A χ^2 fit has been performed to the branching ratios.

	Measured Branching ratio	All free Fitted	χ^2
$\frac{f_0(1370)\to\pi\pi}{f_0(1370)\to K\overline{K}}$	2.17 ± 0.9	2.29	0.01
$\frac{f_0(1370)\to\eta\eta}{f_0(1370)\to K\overline{K}}$	0.35 ± 0.21	0.02	2.5
$\frac{f_0(1500)\to\pi\pi}{f_0(1500)\to\eta\eta}$	5.5 ± 0.84	6.33	0.99
$\frac{f_0(1500)\to K\overline{K}}{f_0(1500)\to\pi\pi}$	0.32 ± 0.07	0.29	0.13
$\frac{f_0(1500)\to\eta\eta'}{f_0(1500)\to\eta\eta}$	0.52 ± 0.16	0.24	2.9
$\frac{f_0(1710)\to\pi\pi}{f_0(1710)\to K\overline{K}}$	0.20 ± 0.03	0.21	0.04
$\frac{f_0(1710)\to\eta\eta}{f_0(1710)\to K\overline{K}}$	0.48 ± 0.13	0.13	6.2
$\frac{f_0(1710)\to\eta\eta'}{f_0(1710)\to\eta\eta}$	$< 0.05 (90\% cl)$	0.06	0.08

The parameters determined from the fit are

M_G (MeV)	1446 ± 16
M_S (MeV)	1664 ± 9
M_N (MeV)	1374 ± 28
M_3 (MeV)	1248 ± 31
f (MeV)	90 ± 11
ϕ (Deg)	-25 ± 4
r_2	1.25 ± 0.14

Note that the pseudoscalar mixing angle (ϕ) agrees with the accepted value of ≈ -20 Degrees. Hence the physical states can be read as

$$|f_0(1710)\rangle = (0.42{\pm}0.14)|G\rangle+(0.89{\pm}0.12)|S\rangle+(0.17{\pm}0.08)|N\rangle,$$

$$|f_0(1500)\rangle = -(0.61{\pm}0.07)|G\rangle+(0.37{\pm}0.06)|S\rangle-(0.69{\pm}0.08)|N\rangle,$$

$$|f_0(1370)\rangle = (0.65{\pm}0.08)|G\rangle-(0.15{\pm}0.04)|S\rangle-(0.73{\pm}0.09)|N\rangle.$$

although the relative amounts of glue vary between the different mixing methods they all tend to agree that the $f_0(1370)$ and $f_0(1710)$ have the $s\bar{s}$ and $n\bar{n}$ in phase while in the $f_0(1500)$ they are out of phase.

Comparison with the production mechanisms of these states

$\gamma\gamma$ production

The most sensitive probe of the flavours and phases comes from $\gamma\gamma$ couplings. Ignoring mass-dependent effects, the calculated mixings imply

$$\Gamma(f_1(1710) \to \gamma\gamma) : \Gamma(f_1(1500) \to \gamma\gamma) : \Gamma(f_1(1370) \to \gamma\gamma) =$$

$$(5z_1 + \sqrt{2}y_1)^2 : (5z_2 + \sqrt{2}y_2)^2 : (5z_3 + \sqrt{2}y_3)^2$$

$$= 4.6 \pm 0.9 : 8.6 \pm 0.8 : 15.3 \pm 0.9.$$

Measurements of the $\gamma\gamma$ couplings of these states would pin down their quark and glue content

$p\bar{p}$ production

If production dominantly through $n\bar{n}$ then the mixing would imply

$$\sigma(p\overline{p} \to \pi + f_0(1710)) < \sigma(p\overline{p} \to \pi + f_0(1370)) \sim \sigma(p\overline{p} \to \pi + f_0(1500))$$

Experimentally

$$p\overline{p} \to \pi + f_0(1370) : \pi + f_0(1500)) \sim 1 : 1.$$

and there is no evidence for the production of the $f_0(1710)$.

Radiative J/ψ decays

Based on the mixing could predict

$$\sigma(J/\psi \to \gamma f_0(1370)) < \sigma(J/\psi \to \gamma f_0(1500)) \sim \sigma(J/\psi \to \gamma f_0(1710))$$

Experimentally

$$J/\psi \to f_0(1500) : J/\psi \to f_0(1710) = 1.0 : 1.1 \pm 0.4$$

Central pp collisions

The cross sections of well established quarkonia in WA102 suggest that the production of $s\bar{s}$ is strongly suppressed relative to $n\bar{n}$.

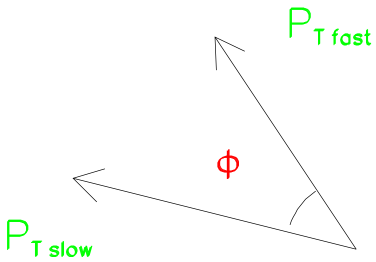
Experimentally observe

$$pp \to pp + (f_0(1710) : f_0(1500) : f_0(1370)) \sim 0.14 : 1.7 : 1.$$

This would be natural if the production were via the $n\bar{n}$ and gg components.

Additional information from central pp collisions

The azimuthal angle ϕ between the outgoing protons



A model to describe double Pomeron exchange

- for Pomerons acting as non-conserved vector currents

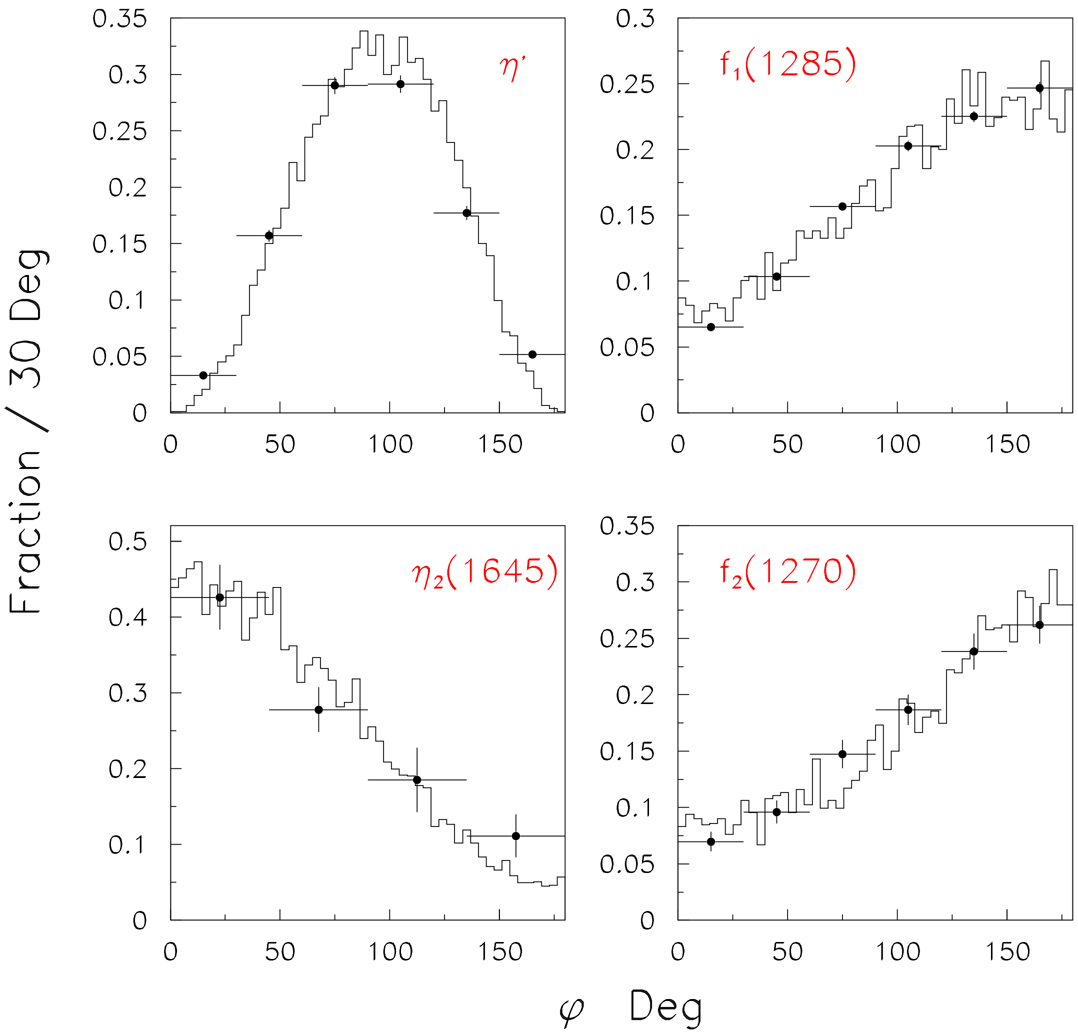
$$\frac{d\sigma}{dt_1 dt_2 d\phi'} \sim {G_E^p}^2(t_1){G_E^p}^2(t_2)F^2(t_1,t_2,M^2)A(t_1,t_2,\phi')$$

where $G_E(t)$ is the proton- $I\!P$ form factor

$A(t_1,t_2,\phi')$ is the prediction for the interaction of two Pomerons acting like non-conserved vector currents

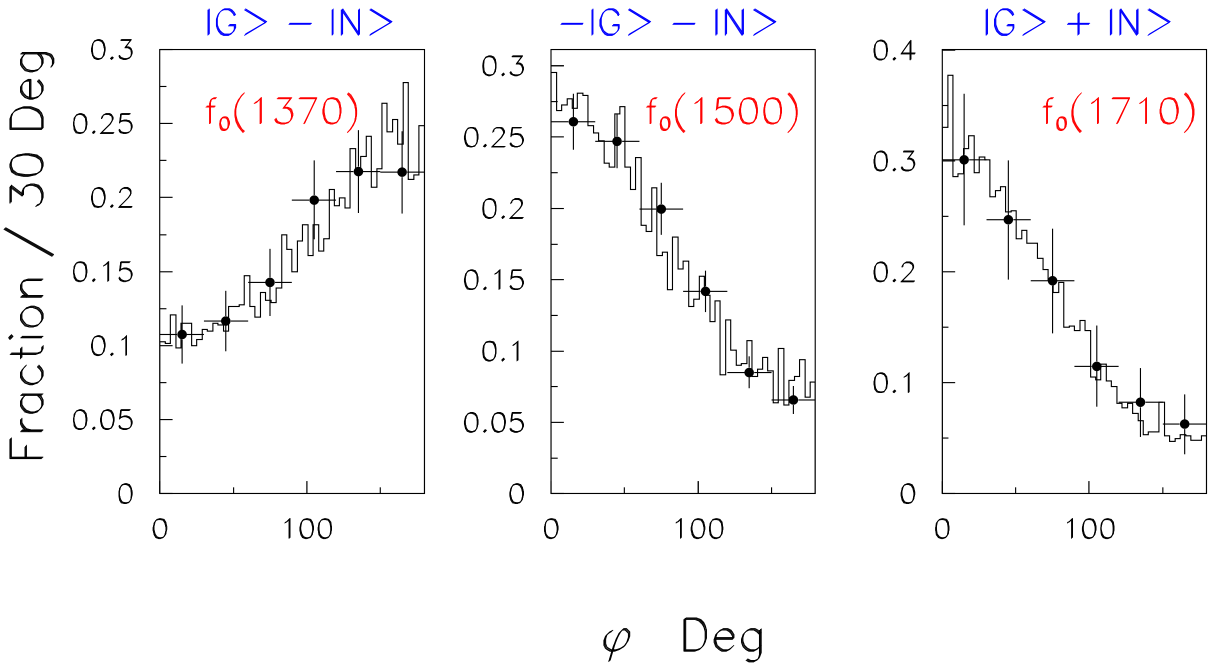
and $F^2(t_1,t_2,M^2)$ is the $I\!P$- $I\!P$ -Meson form factor

Data and Model predictions



All the effects are consistent with a vector like behaviour of Pomeron exchange

The scalar sector



$F^2(t_1, t_2, M^2)A(t_1, t_2, \phi')$ is

$$t_1 t_2 [e^{-b_L(t_1+t_2)/2} + \frac{\sqrt{t_1 t_2}}{\mu^2} e^{-b_T(t_1+t_2)/2} \cos(\phi')]^2$$

b_T and b_L are fixed and μ^2 is the only free variable

	$f_0(1370)$	$f_0(1500)$	$f_0(1710)$
μ^2/GeV^2	-0.5	$+0.7$	$+0.8$

Does the sign of μ^2 measure the phase between the Glue and the $n\overline{n}$ components of the state

$\pi^- p$ and $K^- p$ production

The $f_0(1500)$ and $f_0(1710)$ are found to have $n\bar{n}$ and $s\bar{s}$ components. Therefore both should be produced in $\pi^- p$ and $K^- p$.

$f_0(1500)$

Clearly observed in $\pi^- p$.

Also evidence in $K^- p \to K^0_S K^0_S \Lambda$. The signal is weak compared to the $f_2'(1525)$, as expected from the $s\bar{s}$ content found for the $f_0(1500)$.

$f_0(1710)$

Evidence in $\pi^- p \to K^0_S K^0_S n$, originally called the $S^{*\prime}(1720)$.

One of the longstanding problems of the $f_0(1710)$ is that inspite of its dominant $K\bar{K}$ decay mode it was not observed in $K^- p$ experiments.

Some fits by Lindenbaum and Longacre show that the data are not incompatible with the $f_0(1710)$. This needs to be re-investigated.

Summary

The hypothesis that the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ are due to the mixing between the scalar nonet states and the scalar glueball has been tested using data on the pseudoscalar decay modes of these mesons.

A mixing solution is found that is consistent with the observed decay modes. Namely:

$$|f_0(1710)\rangle = 0.42|G\rangle + 0.89|S\rangle + 0.17|N\rangle,$$

$$|f_0(1500)\rangle = -0.61|G\rangle + 0.37|S\rangle - 0.69|N\rangle,$$

$$|f_0(1370)\rangle = 0.65|G\rangle - 0.15|S\rangle - 0.73|N\rangle.$$

This solution has consequences for the production mechanisms of these states which has also been discussed.

Several areas of work could give improvements (i.e. $\gamma\gamma$ and K^-p) but the general conclusion is that all the data are consistent with the proposed mixing hypothesis.