Frascati Physics Series (1999)
Workshop on Hadron Spectroscopy - Frascati, 8 - 12 March, 1999

SCALAR MESONS IN THE 1500 MeV MASS REGION
(Summary of session 2)

Claude Amsler
Physik-Institut der Universität Zürich, CH-8057 Zürich, Switzerland

ABSTRACT

New data from central production, $\gamma\gamma$ collisions and proton-antiproton annihilation suggest that the $f_0(1500)$ meson has a small $s\bar{s}$ content and a small $\gamma\gamma$ coupling. The $f_J(1710)$ appears to have spin zero and to be dominantly $s\bar{s}$. These results strengthen the hypothesis that $f_0(1500)$ is mostly glue.

1 The $f_0(1500)$ meson

The $f_0(1500)$ was probably observed first in the 2π mass distribution of $\bar{p}p$ and $\bar{p}n$ annihilation into $3\pi^0$ and $2\pi^-\pi^+$ [1]. The claim for a spin 0 isoscalar meson at this mass did not attract much attention at the time due to a confusion with the nearby spin 2 mesons, $f_2'(1525)$ and $f_2(1565)$. The spin 0 assignment was, however, "cautiously suggested" in ref. [1] and the new state did not appear to decay strongly to $K\bar{K}$, in contrast to the $f_2'(1525)$. But a 2^{++} isoscalar meson, $f_2(1565)$, decaying to $\pi\pi$ was discovered at LEAR in $\bar{p}p$ annihilation at rest [2], suggesting that the state observed in ref. [1] might have spin 2. In fact, a spin 2 meson decaying to 4π had been reported earlier in $\bar{p}n \to 3\pi^-2\pi^+$ [3]. However, the spin assignment in ref. [3] was disputed later in favour of 0^{++} in a reanalysis of the same data [4].

A scalar state decaying to $\eta\eta$ and $\eta\eta'$ was reported at 1590 MeV by the GAMS collaboration in high energy $\pi^- p$ reactions, though not decaying to $\pi\pi$ [5]. With the advent of very high statistics data from Crystal Barrel at LEAR [6] and the development of new analysis tools employing the K-matrix formalism [7] it became clear that all observations were consistent with the existence of at least two spin 0 isoscalar mesons in the 1500 MeV region: $f_0(1370)$ and $f_0(1500)$.

The $f_0(1500)$ meson was established by Crystal Barrel, first in its $\eta\eta$ decay mode [8]. A sample of about 100,000 decays into $\pi^0\pi^0$ confirmed its scalar nature [9] and established its relatively narrow width of about 100 MeV. The somewhat higher mass (1590 MeV) and width ($\sim$ 250 MeV) reported earlier by GAMS in $\eta\eta$ was presumably due to the difference between the Breit-Wigner parameters quoted in ref. [5] and the T-matrix pole parameters quoted in ref. [9]. We have heard at this conference from Kondashov [10] that a reanalysis of the GAMS data confirmed both its $\eta\eta$ and $\pi^0\pi^0$ decay modes, see also ref. [11].

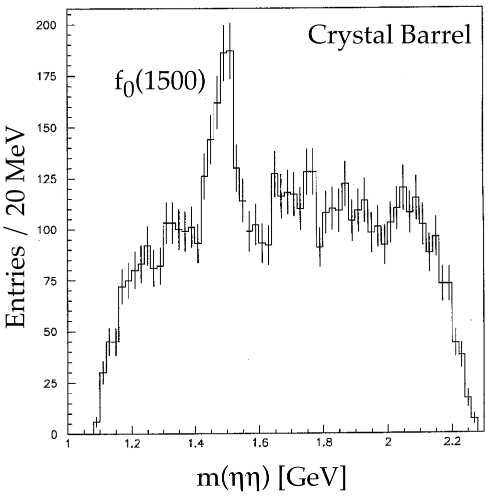

Figure 1: $\eta\eta$ mass distribution in $\bar{p}p \to \eta\eta\pi^0$ at 1940 MeV/c, from ref. [12].

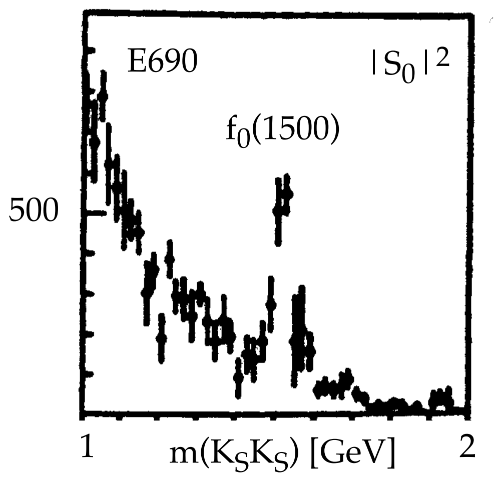

Figure 2: $K_S K_S$ S-wave intensity in pp central production at 800 GeV for solution b of ref. [14].

The $f_0(1500)$ was also observed by Crystal Barrel in its $\eta\eta'$, $K\bar{K}$ and $4\pi^0$ decay modes [6]. It was confirmed in $\bar{p}p$ annihilation in flight and in other reactions, for example:

1. Peters [10] presented the $f_0(1500)$ from Crystal Barrel in $\bar{p}p \to 3\pi^0$ at 600 MeV/c, in $\bar{p}p \to 3\eta$ at 1940 MeV/c and in $\bar{p}p \to \eta\eta\pi^0$ at different $\bar{p}$ momenta

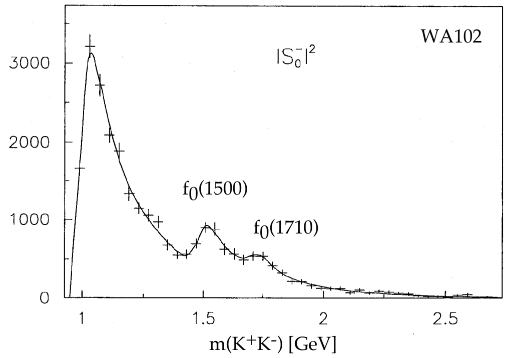

Figure 3: K^+K^- S-wave intensity in pp central production at 450 GeV. The line is the fit, from Kirk [10].

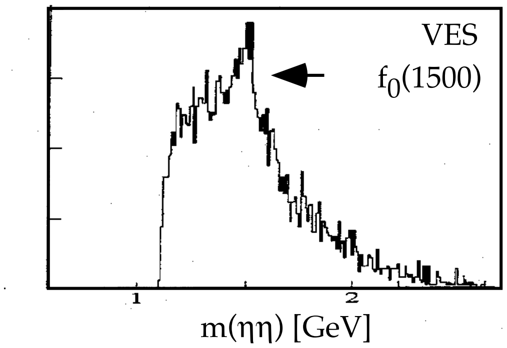

Figure 4: $\eta\eta$ mass distribution in $\pi^- A \rightarrow \pi^-\eta\eta$, from ref. [16].

between 1350 and 1940 MeV/c. Figure 1 shows the $\eta\eta$ mass distribution in $\eta\eta\pi^0$ at 1940 MeV/c.

2. The E687 and the FOCUS collaborations at Fermilab (contribution by Dini [10]), observe $f_0(1500) \rightarrow \pi^+\pi^-$ in $D_s^\pm \rightarrow \pi^-\pi^+\pi^\pm$ decay with a mass of about 1475 MeV and a width of about 100 MeV [13]. Since $c \rightarrow s$ is Cabibbo favoured, this means that $f_0(1500)$ must have a non-vanishing $s\bar{s}$ component in its wave function and should therefore also decay to $K\bar{K}$.

3. The $f_0(1500)$ (and $f_2'(1525)$) are observed in central production $pp \rightarrow ppK_SK_S$ at 800 GeV [14]. Above 1550 MeV there is a twofold ambiguity between 0^{++} and 2^{++}. The K_SK_S S-wave intensity for one of the two solutions is shown in Fig. 2.

4. Kirk showed us the $f_0(1500)$ from WA102 in pp central production at 450 GeV [10]. It decays into K^+K^-, K_SK_S, $\pi^+\pi^-$ and $\pi^0\pi^0$. For instance, its mass and width in K^+K^- are found to be 1497 ± 10 MeV and 104 ± 25 MeV, respectively (Fig.3). No quantitative statements on the decay branching ratios are available yet, but the $\pi\pi$ mode is favoured over $K\bar{K}$ [15]. Also, the $f_0(1370)$ is needed in $\pi\pi$, but not in $K\bar{K}$. This indicates that both $f_0(1370)$ and $f_0(1500)$ do not have large $s\bar{s}$ components, in agreement with Crystal Barrel results. I shall return to the WA102 data below.

5. The VES collaboration studied the production of $\pi^-\eta\eta$ [16] and $\pi^-\eta\eta'$ [17] in pion induced reactions on beryllium at 36 GeV. The data show the production

of $\pi(1800)$ decaying to $\pi^- f_0(1500)$, with $f_0(1500) \to \eta\eta$ or $\eta\eta'$. Figure 4 shows the $\eta\eta$ mass distribution.

6. The Obelix collaboration at LEAR studied $\bar{p}p$ annihilation at rest into $\pi^+\pi^-\pi^0$ in low pressure gas, gas at NTP and in liquid (talk by Villa [10], see also ref. [18]). A combined fit allows the inclusion of both initial S and P atomic states. They observe both the $f_0(1500)$ and the $f_2(1565)$. Note that the previous data on $\pi^+\pi^-\pi^0$ [2] did not include a contribution from $f_0(1500)$.

New data from Crystal Barrel for the 4π decay mode of $f_0(1370)$ and $f_0(1500)$ have been presented by Thoma [10]. The $5\pi^0$ and $\pi^-\pi^+3\pi^0$ annihilation channels published earlier were reanalyzed together with data on deuterium: $\bar{p}n \to \pi^-4\pi^0$ and $\pi^+2\pi^-2\pi^0$. Both $f_0(1370)$ and $f_0(1500)$ decaying to 4π are required. The $5\pi^0$ data have been renalyzed by fixing the $f_0(1500)$ mass and width from the $\pi^-4\pi^0$ analysis. The main result is that $f_0(1500)$ does not appear to decay into $\rho\rho$, in accord with a reanalysis of Mark III data on $J/\psi \to \gamma 2\pi^+2\pi^-$ [19]. It decays mainly to two S-wave dipions ($\sigma\sigma$) with branching fraction relative to 2π

$$\frac{\Gamma[f_0(1500) \to \sigma\sigma \to 4\pi]}{\Gamma[f_0(1500) \to 2\pi]} = 0.66 \pm 0.39, \tag{1}$$

using the 2π data from ref. [20]. This strong coupling to two isoscalar mesons is good news for a state presumed to be mostly glue [21]. The $f_0(1370)$ appears to decay to $\rho\rho$ and $\sigma\sigma$ with a relative rate of 2.0 ± 0.4, confirming the previous analysis [22]. The corresponding ratio (1) for $f_0(1370)$ is hard to obtain due do the difficulty in disentangling $f_0(1370) \to 2\pi$ from $\sigma \to 2\pi$. However, the 4π mode dominates.

Table 1: *Decay branching ratios for $f_0(1500)$ (in %) from Crystal Barrel data, see ref.* [6].

$\pi\pi$	$\eta\eta$	$\eta\eta'$	$K\bar{K}$	4π
29.0 ± 7.5	4.6 ± 1.3	1.2 ± 0.3	3.5 ± 0.3	61.7 ± 9.6

Thus, all data are consistent with the existence of two scalar isoscalar mesons, the broad (300 - 500 MeV) $f_0(1370)$ and the narrow (100 MeV) $f_0(1500)$, none of which appears to have a large $s\bar{s}$ content. The $f_0(1500)$ is now one of the best known unstable mesons. The latest issue of the Review of Particle Physics quotes for its mass and width [23]:

$$M = 1500 \pm 10 \ \text{ MeV}, \quad \Gamma = 112 \pm 10 \ \text{ MeV}. \tag{2}$$

Its decay branching ratios are given in Table 1.

2 The $a_0(1450)$ meson

The isovector scalar state $a_0(1450)$ that was originally discovered in its $\eta\pi$ decay mode in the annihilation channel $\pi^0\pi^0\eta$ [24] was also observed by Crystal Barrel to decay into $\eta'\pi$, $K^0\bar{K}^0$ and $K^0K^{\pm}$. Its mass (1474 $\pm$ 19 MeV) and width (265 $\pm$ 13 MeV) are consistent for all decay modes [6]. Furthermore, its decay branching ratios agree with SU(3) predictions for a $q\bar{q}$ scalar state (Table 2). The evidence for $a_0(1450)$ confirms the theoretical predictions - e.g. from ref. [25] - that the mass scale for the ground state scalar $q\bar{q}$ mesons is 1300 - 1400 MeV, and strengthens the interpretation of $a_0(980)$ as a non-$q\bar{q}$ state.

Table 2: *Predicted and measured decay ratios for $a_0(1450)$, see ref.* [6].

	SU(3)	Data
$\frac{\Gamma(a_0^{\pm}(1450)\rightarrow K^{\pm}K^0)}{\Gamma(a_0^0(1450)\rightarrow\eta\pi^0)}$	0.72 $\pm$ 0.03	0.88 $\pm$ 0.23
$\frac{\Gamma(a_0^0(1450)\rightarrow\eta'\pi^0)}{\Gamma(a_0^0(1450)\rightarrow\eta\pi^0)}$	0.43 $\pm$ 0.06	0.35 $\pm$ 0.16

However, Obelix analyzing $K^{\pm}K_S\pi^{\mp}$ at three hydrogen densities reports this state at a much lower mass of 1290 MeV, with a very small width of 80 MeV [26]. They also report a second solution at 1480 MeV with a width of 200 MeV which agrees with Crystal Barrel but which is not favoured by their likelihood ratio. However, a contribution from the annihilation channel $\bar{p}p \rightarrow K_2^*(1430)\bar{K}$ from atomic P-states - which was ignored in both Crystal Barrel and Obelix analyses - could lead to a preference for the high mass solution. This was demonstrated by Peters [10] with Crystal Barrel data, but should really be settled with Obelix data, since P-wave annihilation is particularly relevant for annihilation in gas.

Let me open a parenthesis here: it was pointed out by Peters [10] that the channel $K_2^*(1430)\bar{K} \rightarrow K\bar{K}\pi$ could mimic the channel $a_0(980)\pi \rightarrow K\bar{K}\pi$ in $\bar{p}p$ annihilation at rest through the interference between the two possible $K_2^* \rightarrow K\pi$ combinations. By the same token this would reduce the measured $a_0(980) \rightarrow K\bar{K}$ coupling, perhaps even leading to the conclusion that $a_0(980)$ does not couple to $K\bar{K}$! This is in my opinion not plausible: $K_2^*(1430)\bar{K}$ must be suppressed in $\bar{p}p$ at rest since the total average mass lies above threshold and furthermore two units of relative angular momentum between $K_2^*(1430)$ and $\bar{K}$ are required from S-states in liquid. From P-states in gas, however, the suppression might be less pronounced. That the observed $K\bar{K}$ threshold enhancement in liquid is mainly due to $a_0(980) \rightarrow K\bar{K}$ can be seen by checking that the $K\bar{K}$ coupling does not vary with total c.m.

energy: from $\bar{p}p$ annihilation at rest one finds that $B(a_0 \to K\bar{K})/B(a_0 \to \eta\pi) = 0.23 \pm 0.05$ [27]; from a_0 decay in $f_1(1285) \to \eta\pi\pi$ and $f_1(1285) \to K\bar{K}\pi$, for which $K_2^*(1430)\bar{K}$ is even farther above threshold, one finds a corresponding consistent ratio of 0.25 ± 0.08 [28]. A more recent measurement leads to 0.17 ± 0.02 [29].

3 The $f_0(1710)$ meson

The spin of the $f_J(1710)$ meson has been controversial ($J = 0$ or 2), some experiments even reporting both a $J^{PC} = 0^{++}$ and a 2^{++} state around 1700 MeV [23]. A recent reanalysis of Mark III data [30] concluded to a scalar state. The issue has now hopefully been settled in favour of 0^{++} by the new data from WA102 presented by Kirk at this workshop [10]: a scalar state with a width of 160 ± 30 MeV and decaying into $\pi^+\pi^-$ is reported at a mass of 1750 ± 20 MeV. It is also observed to decay into K^+K^- with compatible mass and width. The K^+K^- mass distribution is shown above in Fig. 3. The former 2^{++} assignment in central production, e.g. in ref. [31], was apparently due to ambiguities in the partial wave analysis, solved under the assumption that the state observed around 1500 MeV was $f_2'(1525)$, as $f_0(1500)$ had not been established at the time.

A model was proposed in ref. [21] to explain the proliferation of scalar isoscalar states: the data from Crystal Barrel were consistent with a mainly $n\bar{n} \equiv 1/\sqrt{2}(u\bar{u} + d\bar{d})$ state, $f_0(1370)$, with a small admixture of glue, while $f_0(1500)$ was mainly gluonic with a small contribution from $n\bar{n}$ and $s\bar{s}$. The mainly $s\bar{s}$ (with a small admixture of glue) was predicted above 1600 MeV. Such a scalar state would decay mostly to kaonic channels, e.g. $K\bar{K}$ and $K\bar{K}2\pi$. The branching fraction for $f_0(1710) \to K\bar{K}$ has not been reported yet by WA102 but $K\bar{K}$ appears to be large compared to $\pi\pi$ [15]. Hence $f_0(1710)$ could be the awaited (mainly $s\bar{s}$) scalar meson.

Two-photon processes are useful to probe the charge content of mesons through their electromagnetic couplings. Glueballs do not couple directly to photons and their production should therefore be suppressed in $\gamma\gamma$ processes. Apart from phase space factors one expects for the f' and f mesons the ratio of $\gamma\gamma$ widths

$$\frac{\Gamma_{\gamma\gamma}(f')}{\Gamma_{\gamma\gamma}(f)} = \left(\frac{\cos\theta - 2\sqrt{2}\sin\theta}{\sin\theta + 2\sqrt{2}\cos\theta}\right)^2 = \frac{2}{25} \tag{3}$$

for ideal mixing ($f' = s\bar{s}$ and $f = n\bar{n}$, nonet mixing angle $\theta = 35.3°$).

New data in $\gamma\gamma$ collisions have been presented by the LEP collaborations. L3 (see the talk by Braccini [10]) using untagged photons observes three peaks below 2 GeV in the K_SK_S mass distribution (Fig. 5). The lowest peak corresponds to

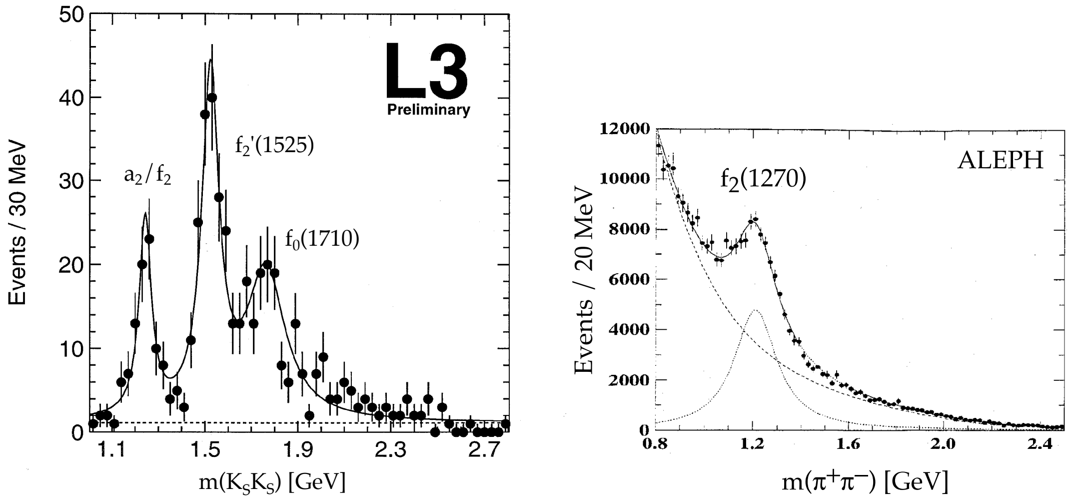

Figure 5: Left: K_SK_S mass distribution in $\gamma\gamma$ collisions at LEP/L3, adapted from Braccini [10]. Right: $\pi^+\pi^-$ mass distribution from LEP/ALEPH, from ref. [32].

$f_2(1270)$ and $a_2(1320)$, interfering destructively. The amplitude analysis leads to a tensor meson at 1525 MeV, $f_2'(1525)$, and favours spin 0 over spin 2 for the third peak, with mass 1765 $\pm$ 22 MeV and width 200 $\pm$ 50 MeV.

Since $f_0(1500)$ does not couple strongly to $K\bar{K}$ (Table 1) its absence in Fig. 5 is not surprising. However, the ALEPH collaboration studying the reaction $\gamma\gamma \to \pi^+\pi^-$ does not observe $f_0(1500)$ either (see Fig.5). Since $f_0(1500)$ has a large coupling to $\pi\pi$ (Table 1) this indicates that $f_0(1500)$ is not produced in $\gamma\gamma$ processes and ALEPH quotes an upper limit for the $\gamma\gamma$ coupling of 0.17 keV [32]. This was to be expected if $f_0(1500)$ is mostly gluonic.

The state at 1765 MeV in Fig.5 is consistent with the $f_0(1710)$ observed by WA102. As an $n\bar{n}$ state it would generate a large $\pi\pi$ signal which ALEPH does not observe in $\gamma\gamma$. Hence the K_SK_S signal in Fig. 5 points to a large $s\bar{s}$ component for $f_0(1710)$, in accord with the WA102 data. The typical $\gamma\gamma$ width of a scalar $n\bar{n}$ mesons like $f_0(1370)$ is 4 keV [33]. From Eq. 3 one then expects a width of roughly 0.3 keV for a mostly $s\bar{s}$ state, ignoring phase space and assuming that the $K\bar{K}$ decay mode is dominant. Braccini reports a $\gamma\gamma$ width of 0.09 keV for $f_2'(1525)$ [10]. From Fig.5 one can then estimate the $\gamma\gamma$ width of $f_0(1710)$ to be given by the ratio of measured event numbers ($\sim$ 1) $\times$ ($2J$+1) (= 5) $\times$ 0.09 $\sim$ 0.4 keV!

Note that in the limit of ideal mixing (and assuming no valence s-quarks in the proton) the OZI rule forbids the production of $s\bar{s}$ states in $p\bar{p}$ annihilations. The Crystal Barrel collaboration has, indeed, not reported any signal from $f_0(1710)$ so far. Thus the current data suggest that $f_0(1710)$ cannot have a large $n\bar{n}$ component.

However, we have of course to wait for the acceptance corrected data and the final branching fractions before drawing definitive conclusions. On the other hand, the $f_0(1710)$ was not observed in $K^-p \rightarrow K_S K_S \Lambda$ interactions [34]. This was surprising for an $s\bar{s}$ state, especially since $f_2'(1525)$ was copiously produced in this reaction. However, at that time $f_0(1710)$ was believed to be 2^{++}. The suppression of scalar states is perhaps of dynamical origin in peripheral K^-p interactions and, in fact, the scalar contribution remains weak through the whole mass range, with no striking signal for any $s\bar{s}$ state up to 1.9 GeV [34].

4 Conclusions

The summary of session 2 may be as follows:

1. The $f_0(1500)$ meson has been confirmed in many processes.
2. From $\bar{p}p$ annihilation and central production one concludes that $f_0(1500)$ is not the $s\bar{s}$ member of the scalar nonet.
3. WA102 data show that $f_J(1710)$ is a scalar and, together with L3 and ALEPH data, suggest a large $s\bar{s}$ component. The production of an $s\bar{s}$ state in $\bar{p}p$ annihilation is suppressed by the OZI rule and, so far, no prominent signal is observed.
4. The absence of $f_0(1500)$ in $\gamma\gamma$ collisions is compatible with a large gluonic admixture in its wave function.

The structure of the scalar meson nonet is therefore suggestive: it consists of the broad isovector $a_0(1450)$, the broad $K_0^*(1430)$, the broad (mostly $n\bar{n}$) $f_0(1370)$ - which may or may not be different from the σ - and the (mostly $s\bar{s}$) $f_0(1710)$. The narrow $f_0(1500)$ is an additional state composed mostly of glue. We are eagerly waiting for the final branching ratios to reach more definitive conclusions, but

se non è vero, è ben trovato!

I wish to thank the speakers of session 2 and also the conference organizers for the pleasant and enlightening workshop.

References

1. L. Gray *et al.*, Phys. Rev. D27 (1983) 307
2. B. May *et al.*, Phys. Lett. B 225 (1989) 450
3. D. Bridges *et al.*, Phys. Rev. Lett. 57 (1983) 1534
4. M. Gaspero, Nucl. Phys. A 562 (1993) 407
5. F. Binon *et al.*, Nuovo Cimento A 78 (1983) 313; Nuovo Cimento A 80 (1984) 363
6. For a review see C. Amsler, Rev. Mod. Phys. 70 (1998) 1293
7. S.U. Chung *et al.*, Ann. Phys. (Leipzig) 4 (1995) 404
8. C. Amsler *et al.*, Phys. Lett. B 291 (1992) 347
9. C. Amsler *et al.*, Phys. Lett. B 342 (1995) 433
10. See the proceedings of this workshop
11. D. Alde *et al.*, Eur. Phys. J. A3 (1998) 361
12. A. Abele *et al.*, Eur. Phys. J. C8 (1999) 67
13. P.L. Frabetti *et al.*, Phys. Lett. B 407 (1997) 79
14. M.A. Reyes *et al.*, Phys. Rev. Lett. 81 (1998) 4079
15. A. Kirk, private communication
16. D.V. Amelin *et al.*, Phys. Atomic Nucl. 59 (1996) 976
17. G.M. Beladidze *et al.*, Sov. J. Nucl. Phys. 55 (1992) 1535
18. A. Bertin *et al.*, Phys. Lett. B 408 (1997) 476
19. D .V. Bugg *et al.*, Phys. Lett. B 353 (1995) 378
20. C. Amsler *et al.*, Phys. Lett. B 355 (1995) 425
21. C. Amsler and F.E. Close, Phys. Rev. D 53 (1996) 295
22. C. Amsler *et al.*, Phys. Lett. B 322 (1994) 431

23. Review of Particle Physics, Eur. Phys. J. C 3 (1998) 1

24. C. Amsler *et al.*, Phys. Lett. B 333 (1994) 277

25. S. Godfrey and N. Isgur, Phys. Rev. D 32 (1985) 189

26. A. Bertin *et al.*, Phys. Lett. B 434 (1998) 180

27. A. Abele *et al.*, Phys. Rev. D 57 (1998) 3860

28. C. Defoix *et al.*, Nucl. Phys. B 44 (1972) 125

29. D. Barberis *et al.*, Phys. Lett. B 440 (1998) 225

30. W. Dunwoodie, Proc. Hadron 97 Conf., Brookhaven, AIP Proc. 432 (S.U. Chung and H. Willutzki, Ed.), 1998, p. 753

31. T.A. Armstrong *et al.*, Phys. Lett. B 227 (1989) 186

32. A. Wright, Proc. Int. Eur. Phys. Conf., Jerusalem, Springer (D. Lellouch, G. Mikenberg and E. Rabinovici, Ed.), 1999, p. 343

33. M. Pennington, these proceedings; see also D. Morgan and M. Pennington, Z. Phys. C48 (1990) 623

34. D. Aston *et al.*, Nucl. Phys. B 301 (1988) 525