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Scalar Glueballs and Friends

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Abstract

The $f_0(1500)$ is identified in three glueball favoured production mechanisms: $p\bar{p}$ annihilation, $\psi \to \gamma f_0$ and Central Production. The production rate for glueballs in $\psi \to \gamma G$ has been quantified and the $f_0(1500)$ is found to be consistent with a glueball - $q\bar{q}$ mixture. We illustrate a remarkable property of central production where kinematic cuts appear to make a systematic separation between glueballs and $q\bar{q}$ of the same J^{PC}. When the cut favouring glueballs is applied, the $f_0(1500)$ and other enigmatic states appear prominently while confirmed $q\bar{q}$ states are empirically suppressed.

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The lightest glueball in lattice QCD is predicted to be a scalar[1, 2] for which there is a trio of suspects

- $f_0(1500)$[3, 4, 5]
- $f_J(1710)$[6] where $J = 0$ or 2[7]
- $f_0(1370)$[7]

Evidence that may help to incriminate one or more of these has emerged in recent months and in this talk I shall report for the first time on what may be the long sought clear dynamical discrimination between $q\bar{q}$ and glueballs[8, 9].

The new developments relate to the classic production mechanisms that are believed to favour glueballs[10]:

1. Glueballs should be produced in proton-antiproton annihilation, where the destruction of quarks creates opportunity for gluons to be manifested. This is the Crystal Barrel [11], and E760 [12] production mechanism, in which detailed decay systematics of $f_0(1500)$ have been studied. The empirical situation with regard to $f_J(1710)$ is currently under investigation.

2. Glueballs should be enhanced compared to ordinary mesons in radiative quarkonium decay. The $f_0(1500)$ and $f_J(1710)$ are produced in radiative J/ψ decay at a level typically of ~ 1 part per thousand.

3. Glueballs are hypothesised to be favoured over ordinary mesons in the central region of high energy scattering processes, away from beam and target quarks. The $f_J(1710)$ and possibly the $f_0(1500)$ have been seen in the central region in pp collisions[13, 14].

In recent months there have been breakthroughs in each of these three areas, in particular that the $f_0(1500)$ is now definitely seen in central production[8, 9]. I shall deal with each in turn.

1 $p\bar{p}$ annihilation

The first clear sightings of the $f_0(1500)$ were in $p\bar{p}$ annihilation and their implications for glueball phenomenology have been analysed in some detail[4]. This is widely regarded as the first potential clear sighting of a glueball mixed in with other scalar $q\bar{q}$ states[15, 16]. The completion of the programme in $p\bar{p}$ annihilation is now governed principally by the closure of LEAR at the end of 1996. Analysis of the data will continue so that during the next three years we may obtain information about the decay channels for this state together with confirmation of other scalar states in this mass region, such as $a_0(1450)$.

This is for the future and I shall not repeat here my recent summary which may be found in ref.[15]. I want instead to concentrate on the new developments in the other two favoured mechanisms.

2 $J/\psi \to \gamma f_J$

There have been significant advances in the quantitative analysis of glueball production in the second of these processes, $J/\psi \to \gamma f_J$ [17, 18].

The production rate for glueballs or $q\bar{q}$ in $J/\psi \to \gamma R$ is quantified in ref[17]; specifically, for scalar mesons

$$10^3 br(J/\psi \to \gamma 0^{++}) = (\frac{m}{1.5 \text{ GeV}})(\frac{\Gamma_{R\to gg}}{96 \text{ MeV}})\frac{x|H_S(x)|^2}{35}. \qquad (1)$$

This is to be compared with the analogous formula for a tensor meson:

$$10^3 br(J/\psi \to \gamma 2^{++}) = (\frac{m}{1.5 \text{ GeV}})(\frac{\Gamma_{R\to gg}}{26 \text{ MeV}})\frac{x|H_T(x)|^2}{34}. \qquad (2)$$

where $x|H_J|(x)|^2$ is a loop integration in pQCD whose magnitude is shown in fig. 1. Having scaled the expressions this way, because $\frac{x|H_J|^2}{30-45} \sim O(1)$ in the x range relevant for production of 1.3 - 2.2 GeV states, we see immediately that the magnitudes of the branching ratios are driven by the denominators 96 and 26 MeV for 0^{++} and 2^{++}. Thus if a state R_J is produced in $J/\psi \to \gamma X$

at $O(10^{-3})$ then $\Gamma(R_J \to gg)$ will typically be of the order 100 MeV for 0^{++}, $O(25$ MeV) for 2^{++}.

This immediately shows why the 2^{++} $q\bar{q}$ states are prominent: A 2^{++} state with a total width of $O(100$ MeV) (typical for 2^{++} $q\bar{q}$'s in this mass range[4, 19]) will be easily visible in $J/\psi \to \gamma 2^{++}$ with branching fraction $O(10^{-3})$, while remaining consistent with

$$br(R[Q\bar{Q}] \to gg) = 0(\alpha_s^2) \simeq 0.1 - 0.2. \tag{3}$$

For a glueball, on the other hand, one expects[17, 18]

$$br(R[G] \to gg) = 0(1). \tag{4}$$

From our relations above, we see that for a 0^{++} to be produced at the 10^{-3} level in J/ψ radiative decay it must either have a large gluonic content and width $O(100)$ MeV or, if it is a $q\bar{q}$ meson, it must have a very large width, $\gtrsim 500$ MeV.

When applied to the data the conclusions are:

(i) The $f_0(1500)$ is probably produced at a rate too high to be a $q\bar{q}$ state. The average of world data suggests it is a glueball-$q\bar{q}$ mixture.

(ii) The $f_J(1710)$ is produced at a rate which is consistent with it being $q\bar{q}$, only if $J = 2$. If $J = 0$, its production rate is too high for it to be a pure $q\bar{q}$ state but is consistent with it being a glueball or mixed $q\bar{q}$-glueball having a large glueball component.

(iii) The $f_0(1370)$ may have some glueball admixture in its wavefunction but contains $q\bar{q}$ dominantly.

These studies were stimulated by the advances in lattice QCD which predict that the lightest "ideal" (i.e., quenched approximation) glueball be 0^{++}, with state-of-the-art mass prediction of $1.61 \pm 0.07 \pm 0.13$ GeV (where the first error is statistical and the second is systematic)[2]. This subsumes the values in the literature of 1.55 ± 0.05 GeV[20] and 1.74 ± 0.07 GeV[6]. That

lattice QCD is now concerned with such fine details represents considerable advance in the field and raises both opportunity and enigmas. It encourages serious consideration of the further lattice predictions that the 2^{++} glueball lie in the 2 GeV region as well as implying that scalar mesons in the $1.5-1.7$ GeV region merit special attention. Amsler and Close[4] initially pointed out that the $f_0(1500)$ shares features expected for a glueball that is mixed with the nearby isoscalar members of the $^3P_0$ $q\bar{q}$ nonet. If the $f_J(1710)$ proves to have $J=2$, then it is not a candidate for the ground state glueball and the $f_0(1500)$ will be essentially unchallenged. On the other hand, if the $f_J(1710)$ has $J=0$ it becomes a potentially interesting glueball candidate. Indeed, Sexton, Vaccarino and Weingarten[21] argue that $f_{J=0}(1710)$ should be identified with the ground state glueball, based on its similarity in mass and decay properties to the state seen in their lattice simulation.

The properties of the $f_J(1710)$, and the production of this state together with $f_0(1500)$ in the three glueball favoured processes, are now the leading questions for experiment.

3 A Glueball-$q\bar{q}$ filter in Central Hadron Production

"Central production" where the produced mesons have no memory of the flavour of the initiating hadrons[10] and are excited via the gluonic fields of the "Pomeron"[22] is the final example in our trinity of glueball production mechanisms. However, although at first sight this is an environment where the production of glueballs may be especially favoured, the reality is more complicated.

First there is the well known problem that non diffractive transfer of flavour (Regge exchange) can contaminate this simple picture and lead to the appearance of $q\bar{q}$ mesons in the central region. Furthermore, even for the diffractive production, momentum transfer between the gluons of the Pomeron and the aligned constituents of the produced meson may lead to

either gg or $q\bar{q}$ states. The former may be favoured relative to $q\bar{q}$ production due to colour factors but unless further cuts are made to enhance the gg signal, the appearance of novel states in central production is not of itself definitive evidence for a glueball. This is clear from the data which show well known $q\bar{q}$ states, such as $f_1(1285)$, alongside potential glue states (as, for example, in the 4π mass spectrum, ref.[23, 24]). Similar mixtures were seen in other channels, for example $\pi\pi$ where there is not only a clear $f_0(980)$ but also the $f_2(1270)$ and even $\rho(770)$. This confusing menagerie of states, with assorted J^{PC} and with established $q\bar{q}$ alongside "interesting" states, has caused central production to be an enigma.

The first clue on how to decode the central production came with the empirical observation earlier in 1996[24] that the structures seen in central production are a function of the topology, and depend on whether events are classified as either LL or LR ("left left" or "left right" in the sense of how the beams scatter into the final state relative to the initial direction). Specifically, when the two beams scatter into opposing hemispheres (LR as defined in ref.[24]) the $f_1(1285)$ $^3P_1$ $q\bar{q}$ is clearly visible (fig 2a) whereas in the same side configuration (LL) it is less prominent relative to the structures in the $1.4-2$ GeV mass range. (fig 2b). Such discrimination has also been seen for the $f_2(1270)$ $^3P_2$ $q\bar{q}$ relative to the enigmatic $f_0(980)$ in the $\pi\pi$ channel[24]. Similar phenomena have recently been noted also in Fermilab data [25] and, in retrospect, at the ISR[26].

This phenomenon led us to reconsider the mechanisms for the production of gg and $q\bar{q}$ in the central region[8]. Our notation is that in the centre of mass frame the initial protons have $p = (P + M^2/2P; p_T = 0, p_L = P)$, $q = (P + M^2/2P; q_T = 0, q_L = -P)$, the outgoing protons having respectively momenta $p' \equiv (p'_L = x_a p;\ p'_T)$ and $q' \equiv (q'_L = x_b q;\ q'_T)$ and $x_F \equiv x_a - x_b$. The data have historically been presented as a function of $M_R^2 \sim (1 - x_a)(1 - x_b)s$ with some separation as a function of $t_a \sim -\frac{(p'_T)^2}{1-x_a}$; $t_b \sim -\frac{(q'_T)^2}{1-x_b}$. The longitudinal momenta, p'_L, q'_L therefore control the M_R distribution. The topological separation into LL and LR was novel and independent of

the magnitudes of $t_{a,b}$[24]. We suggested that it is driven primarily by the variable $dP_T \equiv |\vec{p'_T} - \vec{q'_T}|$ and that gg configurations are enhanced in kinematic configurations where the gluons can flow "directly" into the final state with only small momentum transfer, in particular when $dP_T \to 0$ (driven by fig. 3b rather than 3a). This configuration may also enhance 0^{++}, 2^{++} mesons made from bosons in S-wave relative to their $q\bar{q}$ $^3P_{0,2}$ counterparts.

When the $\vec{p'_T}$ and $\vec{q'_T}$ are co-moving and of equal magnitude such that $dP_T \to 0$, they tend to produce an overall transverse boost of the meson R but with limited relative (internal) momentum: the resulting configuration for R will be strongly coupled to an S-state. By contrast, when the $\vec{p'_T}$ and $\vec{q'_T}$ are equal in magnitude but anti-aligned (so dP_T is large) then there can be significant relative l_T ($\sim dP_T$) within R; excitation of the l_T degree of freedom corresponds to P-wave (and higher orbitals) in the static limit. Thus by making the selection on data that $dP_T \to 0$, there is the possibility that $q\bar{q}$ with $J^{PC} = 0^{++}, 1^{++}, 2^{++}$ (which are all P-wave composites) will be suppressed relative to glueballs (or at least, relative to S-wave bound states of bosons with these J^{PC}).

The above intuitive picture was only a first sketch of the full dynamics at best, designed principally as a starting point that is qualitatively consistent with the pattern of the LL and LR topologies. Nonetheless, when the WA102 collaboration at CERN tested the suggestion that the variable $dP_T \equiv |\vec{p'_T} - \vec{q'_T}|$ controls the dynamics, they found a remarkable picture.

The $dP_T \geq 0.5$ GeV (fig 3a) is similar to the original LR sample as expected. The sample with $0.2\ GeV \leq dP_T \leq 0.5\ GeV$ (fig 3b) shows the $f_1(1285)$ becoming suppressed and a sharpening of the $f_0(1500)$ and $f_2(1900)$ structures. However, the most dramatic effect is seen in the $dP_T \leq 0.2\ GeV$ sample (fig 3c) where the $f_1(1285)$, a $q\bar{q}$ state, has essentially disappeared while the $f_0(1500)$ and $f_2(1900)$ structures have become more clear. These surviving structures have been identified as glueball candidates: the $f_0(1500)$ is motivated by lattice QCD while the $f_2(1900)$ is noted to have the right mass to lie on the Pomeron trajectory[27]. The $f_0(1500)$ is rather clean and

appears at $dP_T \to 0$ with a shape and mass that are not inconsistent with what is seen in $p\bar{p}$ annihilation. This is in contrast to the full data sample of the present experiment where this state interfered with the $f_0(1370)$ and was shifted to a lower mass ($\sim$ 1440 MeV)[23] and with a much narrower width ($\sim$ 60 MeV).

Similar cuts have been applied to the $\pi\pi$, $K\bar{K}$ $\eta\pi\pi$ and $K\bar{K}\pi$ data [9]).

For the $\pi^+\pi^-$ mass spectrum for $dP_T < 0.2$ GeV there is effectively no ρ or $f_2(1270)$ signals. These only become apparent as dP_T increases. However, the $f_0(980)$, which is responsible for the sharp drop in the spectrum around 1 GeV, is clearly visible in the small dP_T sample, (figures 4)

Figures (5) show the effect of the dP_T cut on the K^+K^- spectrum. The $f_2(1525)$ is produced dominantly at high dP_T whereas the $f_J(1710)$ is produced dominantly at low dP_T. In the channels $K\bar{K}\pi$ and $\eta\pi\pi$ the $f_1(1285)$ and $f_1(1420)$ are more prominent when $dP_T > 0.5\ GeV$ and start to disappear at low dP_T.

It would appear that the undisputed $q\bar{q}$ states (i.e. ρ, $f_2(1270)$, $f_1(1285)$, $f_2(1525)$) are suppressed as dP_T goes to zero whereas the glueball candidates $f_J(1710)$, $f_0(1500)$ and $f_2(1930)$ survive. It is also intersting to note that the enigmatic $f_1(1420)$ disappears at low dP_T while the $f_0(980)$, a state that possibly has a strong admixture of $K\bar{K}$ in its wavefunction[28, 29],does not.

Thus we have a tantalising situation in central production of mesons. We have stumbled upon a remarkable empirical feature that does not appear to have been noticed previously. Although its extraction via the dP_T cut was inspired by intuitive arguments following the observation of an $LL - LR$ asymmetry, we have no simple dynamical explanation. Nonetheless, the empirical message is dramatic enough to stand alone and thereby we are suggesting[8] that a systematic study of meson production as a function of $dP_T \equiv |\vec{p_T'} - \vec{q_T'}|$ holds special promise for isolating the systematics of meson production in the central region and in filtering $q\bar{q}$ mesons from those with significant *boson-boson* content. The latter include $K\bar{K}$ molecular bound

states (or $s\bar{s}$ states with significant $K\bar{K}$ component in the wavefunction), *pomeron* - *pomeron* states and *glueballs*. Our selection procedure will need to be tested further in future experiments in order to determine the extent of its empirical validity. In turn we hope thereby that its dynamical foundations may be put on a sounder footing and the filtering of glueballs be made a practical reality.

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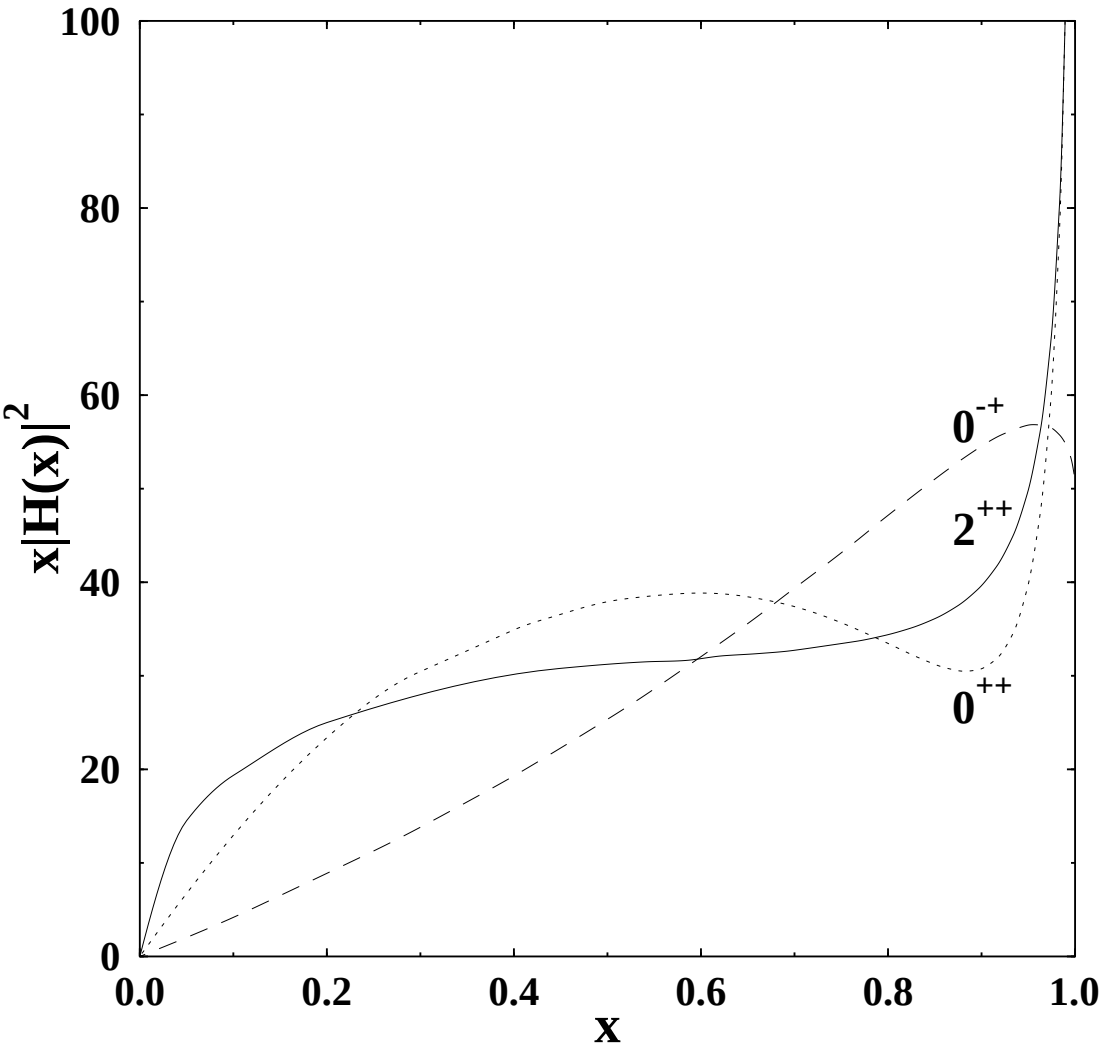

Figure 1: Computation of $\psi \to \gamma gg \to \gamma R$ in pQCD involves a loop integral. The magnitude of this loop integral, $x|H|^2$ is plotted versus x for 0^{++} (dotted), 0^{-+} (dashed) and 2^{++} (solid); $x = 1 - (\frac{m_R}{m_V})^2$.

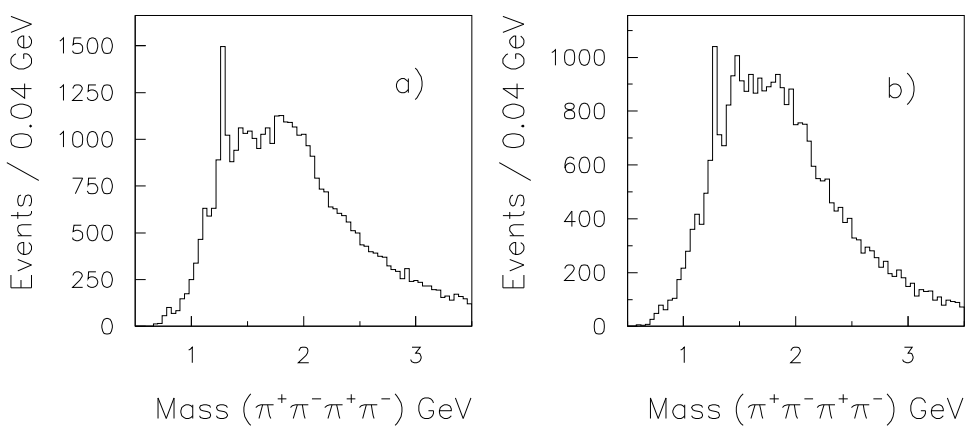

Figure 2: The 4π mass spectra from WA91 for (a) LR and (b) LL topologies.

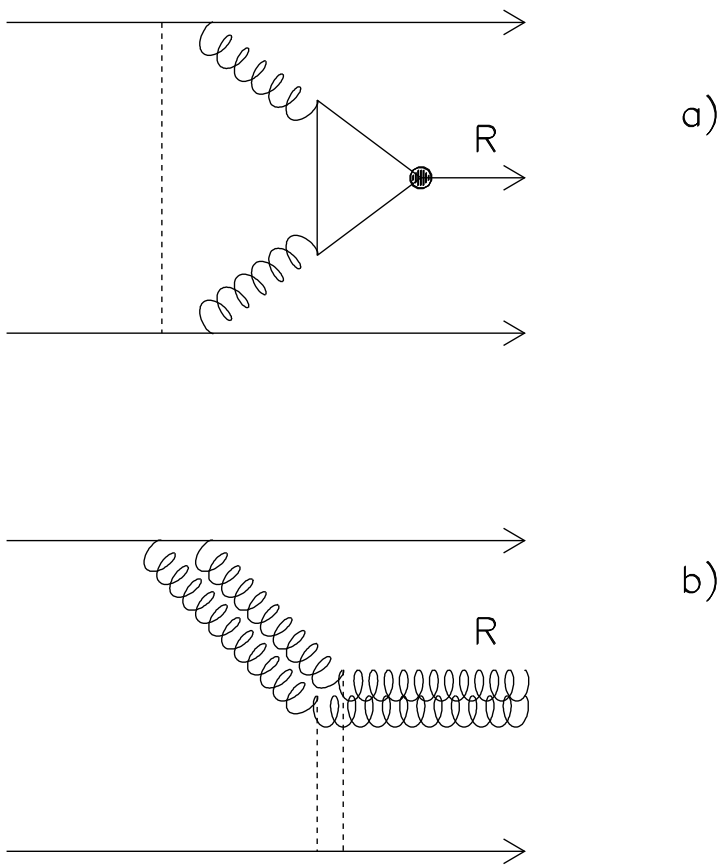

Figure 3: (a) Two gluons with large p_L fuse to make a meson R. This requres considerable rescattering to produce aligned constituents in the exclusive production of a meson R. (b) Diffractive scattering of a gluonic Pomeron to produce a glueball. By analogy with the diffractive photoproduction of ${}^3S_1$ vector mesons, this can be favourable to 0^{++} and 2^{++} "S"-wave glueballs.

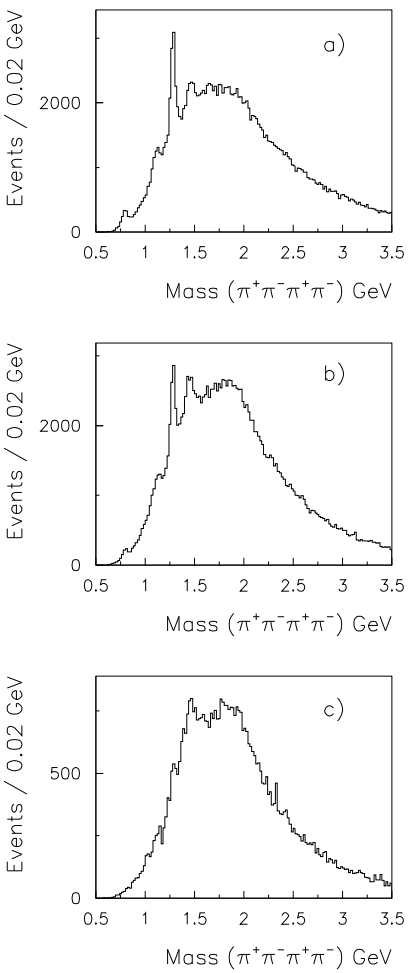

Figure 4: The 4π mass spectra (a) With $dP_T > 0.5$ GeV exhibiting a clear $f_1(1285)$; (b) $0.2 < dP_T < 0.5$ GeV (c) $dP_T < 0.2$ GeV where the $f_1(1285)$ has disappeared while the $f_0(1500)$ is seen more clearly.

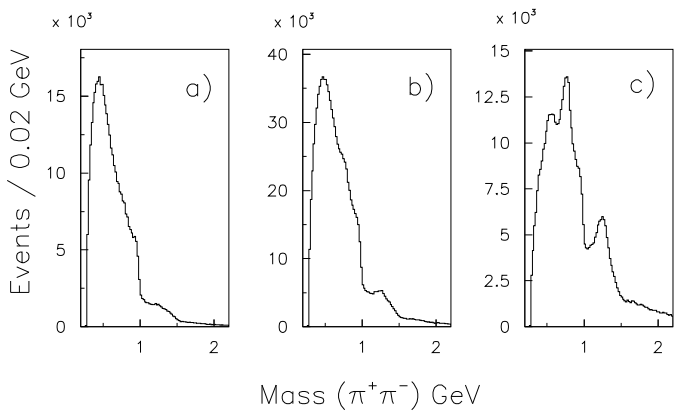

Figure 5: The $\pi\pi$ mass spectrum for a) $dP_T < 0.2$ GeV, b) $0.2 < dP_T < 0.5$ GeV and c) $dP_T > 0.5$ GeV. The $\rho(770)$ and $f_2(1270)$ only become apparent as dP_T increases. The $f_0(980)$ is responsible for the sharp drop in the spectrum round 1 GeV and is clearly visible in the low dP_T sample.

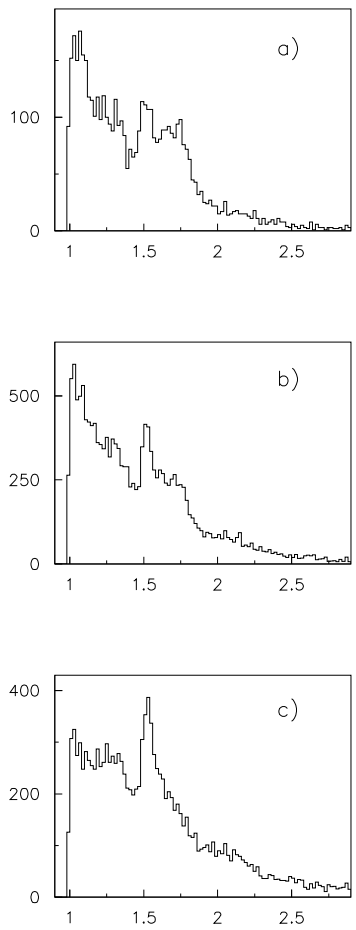

Figure 6: K^+K^- mass spectrum for a) $dP_T < 0.2$ GeV, b) $0.2 < dP_T < 0.5$ GeV and c) $dP_T > 0.5$ GeV.The $f_2(1525)$ is produced dominantly at high dP_T, fig (c), whereas the $f_J(1710)$ is produced dominantly at low dP_T, fig (a).