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Distinguishing Hybrids from Radial Quarkonia

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Abstract

We present arguments that reinforce the hybrid interpretation of $\pi(1800)$ and we establish that the $\rho(1450)$ and the $\omega(1420)$ can be interpreted as radial–hybrid mixtures. Some questions for future experiments are raised.

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Evidence for the excitation of gluonic degrees of freedom in strong QCD has recently emerged with the possible discovery of a hybrid with $J^{PC} = 0^{-+}$ [1, 2, 3, 4, 5] in the 1.8 GeV mass region. Both its mass and unusual decay patterns are as expected for such gluonic excitations [6, 7]. Idiosyncratic decay patterns have also been noted for 1^{--} in the $1.4 - 1.7$ GeV region [8, 9]. These are in line with the predictions of the extensive study of ref. [10] for hybrids with non–exotic overall $J^{PC} = 0^{-+}, 1^{--}$.

If these states are not hybrids then radially excited quarkonia are the only conservative alternative. In ref. [11] the point of departure was to perform a "control" test by attempting to assign these states to be radial excitations of conventional quarkonia, compute the expected branching ratios for these radial states following the standard prescriptions of refs. [12, 13] and then compare the data against these as well as the gluonic hypothesis. The analysis concluded that hybrid excitations appear to be manifested in the data.

This is a radical result if true and merits critical examination. Here we test its robustness by seeking to relax some implicit assumptions. In ref. [11] the results were all in the special case where the wave function parameter β_A of the incoming state is the same as β of the outgoing states. In the present paper we relax[1] this by allowing β_A to be different from β, i.e. to be "off the iso–β axis". For this purpose, we use a "standard parameter region" where $\beta_A = 0.25 - 0.45$ GeV and $\beta = 0.3 - 0.5$ GeV.

The mass of $1^{--}\rho(1450)$ [8, 14] suggests a natural assignment as $2\,^3S_1\ q\bar{q}$ [15] whereas its decays favour a hybrid interpretation [8, 9, 10]. By relying on the data analysis of ref. [9] we are able to make stonger statements than ref. [10] about mixing in the 1^{--} sector. In ref. [11] we argued that a pure 2^3S_1 interpretation of $\rho(1450)$ is untenable since its πa_1 and πh_1 modes cannot be simultaneously accommodated. In the present paper we show that this conclusion remains true even off the iso–β axis. Moreover, we shall present arguments that $^3D_1$ components in $\rho(1450)$, $\omega(1420)$ and $\omega(1600)$ are insignificant, leaving us with a picture of hybrid–$2S$ mixing. The constitution of the $\rho(1700)$ is presently undetermined. We highlight some channels where study at DAΦNE may illuminate these questions further. These are discussed in section 1.

In section 2 we provide further arguments supporting the hybrid interpretation of 0^{-+} $\pi(1800)$, as proposed in Refs. [10, 11, 16].

[1] All calculations have been done in the conventions of refs. [10, 13], which differ in phase space vconvention and overall normalizing constant from ref. [11]. The normalizing constant is fixed.

1 $2S$ Radialogy: $2\,{}^3S_1$ ρ and ω

Given the masses of the $2\,{}^1S_0$ states around 1.3 GeV and that the hyperfine splitting in S–states tends to elevate the masses of the $2\,{}^3S_1$ members of the supermultiplet, it is natural on mass alone to assign the $\rho(1450)$ [8, 14] and the $\omega(1420)$ to the $2\,{}^3S_1$ levels of the spectrum [15]. Furthermore, they are some 300 MeV below the predicted ${}^3D_1$ states which in absence of mixing are expected around 1.7 GeV, and also lighter than unmixed hybrids which are predicted at $1.8 - 1.9$ GeV [6, 7]. However, it is possibile that spin dependent forces may lower the mass of the hybrid ρ and ω (which are spin $S = 0$ in contrast to the conventional $q\bar{q}$ components which are $S = 1$) and cause mixing between hybrid and conventional quarkonia. Thus one should *a priori* allow in this region for the possibility of a triplication of states

$$|V\rangle \equiv cos\phi(cos\theta|2\,{}^3S_1\rangle + sin\theta|{}^3D_1\rangle) + sin\phi|V_H\rangle \qquad (1)$$

A well known problem for the radial assignment of $\rho(1450)$, $(\phi, \theta \to 0)$, is that the relative partial widths of the state appear idiosyncratic [8, 9, 10]. The signals appear to be in remarkable agreement with those predicted for a hybrid $(\phi \to \frac{\pi}{2})$ [10, 11]. These are very different from the historical predictions of radial or ${}^3D_1$ decays of quarkonia [11, 12, 13]. In particular the the experimentally observed suppression [8] of πh_1 relative to πa_1 is, within the flux–tube model, a crucial test of the hybrid initial state. This empirical result contrasts with the behaviour expected of a ${}^3D_1$ for which both πh_1 and πa_1 are predicted to be large [11, 12, 13] and also with the case of the $2\,{}^3S_1$ where both of these channels are predicted to be small. Some partial widths for a $2\,{}^3S_1$ initial state are shown in Table 1. The reason for the suppression of πh_1 in hybrid 1^{--} decays is because in the hybrid the $q\bar{q}$ has $S = 0$, whereas for the "conventional quarkonium" 1^{--} the $q\bar{q}$ have $S = 1$; the ${}^3P_0$ decay is forbidden by spin orthogonality in the former example for final states where the mesons' $q\bar{q}$ have $S = 0$, as in the πh_1 case. It is therefore interesting that the detailed analyses of refs. [8, 9] commented on the apparently anomalous decays that they found for the 1^{--} state $\rho(1450)$, in particular the suppression of πh_1 relative to a prominent πa_1; specifically

$$\begin{array}{cccccc} \pi a_1 + \rho(\pi\pi)_S & \pi h_1 + \rho\rho + \rho(\pi\pi)_S & \omega\pi & \pi\pi & \eta\pi\pi & \\ 190 & 0 - 39 & 50 - 80 & 17 - 25 & 4 - 19 & MeV \end{array} \qquad (2)$$

There is no $2\,{}^3S_1$ solution consistent with the above data [8]. The noticeable feature in the data is the strong coupling to πa_1 relative to πh_1 which is greater than $\frac{190}{40}$. Ref. [11] noted

Table 1: Widths of selected decay modes of radial $2\,^3S_1$. A range of widths in MeV is indicated on the iso–β axis from β_A, $\beta = 0.3$ to β_A, $\beta = 0.45$, and in a band of thickness 0.15 GeV around the iso–β axis. The direction in which the width increases is indicated along the iso–β axis and perpendicular to the iso–β axis (under "band") , using the axis conventions of Fig. 3. The number of nodal lines crossing the standard parameter region is also indicated.

State	Mode	Iso-β	Band	Nodal Lines
$\rho(1450)$	$\pi\pi$	10 - 90 $\nearrow$	5 - 110 $\nwarrow$	1
	$\omega\pi$	90 - 120 $\nearrow$	50 - 160 $\nwarrow$	1
	$\rho\eta$	20 - 30 $\swarrow$	20 - 40 $\nwarrow$	1
	$K\bar{K}$	60	30 - 90 $\nwarrow$	1
	$K^*\bar{K}$	20 - 40 $\swarrow$	20 - 40 $\nwarrow$	1
	πa_1	5 - 10 $\nearrow$	5 - 80	0
	πh_1	5 $\nearrow$	5 - 30	0
$\rho(1730)$	$\pi\pi$	1 - 80 $\nearrow$	1 - 100 $\nwarrow$	1
	$\omega\pi$	40 - 170 $\nearrow$	20 - 220 $\searrow$	1
	πa_1	20 - 50 $\swarrow$	20 - 110	0
	πh_1	30 - 70 $\swarrow$	30 - 70	0
$\omega(1420)$	$\rho\pi$	270 - 350 $\nearrow$	160 - 450 $\searrow$	0
	πb_1	5 $\nearrow$	5 - 40	0
$\omega(1600)$	$\rho\pi$	190 - 480 $\nearrow$	110 - 620 $\searrow$	1
	πb_1	20 - 40 $\swarrow$	20 - 100	0

that this is outside any sensible solution for a radial and so $\rho(1450)$ cannot be pure $2\,^3S_1$.

The stability of these conclusions with respect to independent variations in β_A, β has not hitherto been assessed. This is the point of departure for the present paper. To test the robustness of this conclusion we have studied what happens if we depart form the "iso-β" contour in β space and allow the initial and final values to differ. Fig. 1 shows that the πa_1 and πh_1 widths form a valley in β space. We can climb the valley walls to elevate the πa_1 rate but this elevates πh_1 too, contrary to experiment where $\pi h_1 < 40$ MeV $\approx \frac{1}{5}\pi a_1$.

Thus the conclusions are robust if present data are reliable. If the experimental rate of πa_1 were reduced by 50% then it could be possible to describe the state as $2\,^3S_1$ with $\beta_A = 0.35$ GeV, $\beta = 0.4$ GeV for which

$$\pi a_1 : \pi h_1 : \omega\pi : \pi\pi = 75 : 25 : 75 : 25 \; MeV \tag{3}$$

though there is no experimental indication of reduced πa_1. If instead one accepts the πa_1, $\omega\pi$ and $\pi\pi$ data, but ignores πh_1, there is the following possibility for $2\,^3S_1$ with $\beta_A = 0.4$ GeV, $\beta = 0.5$ GeV

$$\pi a_1 : \pi h_1 : \omega\pi : \pi\pi = 165 : 50 : 45 : 25 \; MeV \tag{4}$$

This highlights the importance of quantifying the πh_1 channel with new data, in particular in dedicated e^+e^- experiments.

Now we turn to the $\omega(1420)$ and $\omega(1600)$ pair. The first inference is that neither can have a significant $^3D_1$ component. The $\omega(1420)$ data have $\pi b_1 \sim 0$ MeV [8]. The $\omega(1600) \to \pi b_1$ also is small ($\sim$ 30 MeV) [8]. If these data are confirmed it would rule out $^3D_1$ ($\theta \sim \frac{\pi}{2}$) for the $\omega(1420)$ and also for the $\omega(1600)$ as πb_1 is predicted to dominate the $^3D_1$ decays in the iso–β case [11]. The effect of relaxing the iso–β constraint is illustrated in Fig. 2 for the $\omega(1600)$ (results for $\omega(1420)$ are similar). For most of the parameter space the width exceeds 100 MeV and nowhere falls below 30 MeV which reinforces the conclusion that $^3D_1$ is incompatible for these states.

Having eliminated $^3D_1$, then within the three state mixing hypothesis of Eq. 1 this leaves $2\,^3S_1$ and hybrid as possible configurations. Either of these is consistent with the πb_1 channel being small: (i) for the hybrid, the spin selection predicts πb_1 to vanish; (ii) the $2\,^3S_1$ ($\theta \sim 0$) has $\pi b_1 \sim 5$ MeV for $\omega(1420)$ and ~ 30 MeV for $\omega(1600)$ on the iso–β axis. In addition, for radials, $\Gamma(\omega(1600) \to b_1\pi) \geq 2\;\Gamma(\omega(1420) \to b_1\pi)$ in the standard parameter region, consistent with the data [8].

Within the $2\,^3S_1$–hybrid space, data are incompatible with $2\,^3S_1$ alone. If $\omega(1420)$ were pure $2\,^3S_1$, this small value for πb_1 would imply that its $2\,^3S_1$ ρ partner would also have a

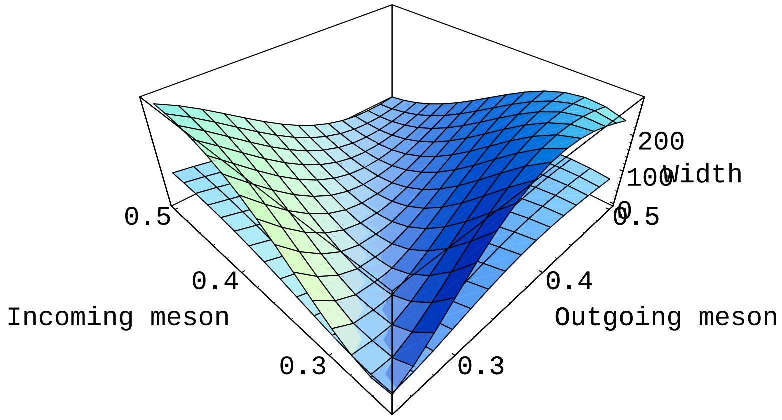

Figure 1: Total widths in MeV of $2\,^3S_1$ $\rho(1450) \to a_1\pi,\ h_1\pi$ ($a_1\pi$ is the larger channel, i.e. the upper of the two sheets), as a function of β_A of the incoming and β of the outgoing mesons in GeV.

small πa_1 width for the same β's. Thus if the $\rho(1450)$ and $\omega(1420)$ have similar internal structure then $\omega(1420)$ cannot be pure $2\,^3S_1$. The e^+e^- widths of $\omega(1420)$ and $\omega(1600)$ are almost the same [8], which suggests strong $2\,^3S_1 - V_H$ mixing. Thus

$$\omega(1420;1600) = cos\phi|2\,^3S_1\rangle + sin\phi|\omega_H\rangle \tag{5}$$

Note also that departure from the iso–β valley would destroy the $\Gamma(\omega \to \pi b_1) \sim 0$ MeV result. This implies that one cannot fit the small πb_1 width for both $\omega(1420)$ and $\omega(1600)$ within a $2\,^3S_1 -^3 D_1$ basis alone even off the iso–β valley, and reinforces the need for a hybrid component.

The $\rho\pi$ decays are also consistent with $2\,^3S_1 - V_H$ mixing. For $\theta, \phi \to 0$, the channel $\rho\pi$ dominates with a predicted $2\,^3S_1$ width ~ 350 MeV for $\omega(1420)$ and ~ 450 MeV for $\omega(1600)$, which can become smaller away from the iso–β axis. Experimentally $\Gamma(\omega(1420) \to \rho\pi) \sim 240$ MeV and for the $\omega(1600)$ the $\rho\pi$ channel is 85 MeV [8]; these results suggest a possible mixing with a component that is "inert" in the channel $\rho\pi$ such as the hybrid [10].

This scenario of $2^3S_1 - V_H$ mixing is also favoured by the $\rho(1450)$. A 2^3S_1 produces the $\omega\pi$ as dominant mode (Table 1) and $\frac{\omega\pi}{\pi\pi} \sim 2-3$ for $\beta_A,\ \beta = 0.35 - 0.4$ GeV, results which are in accord with data (Eq. 2). For a hybrid the $\omega\pi$ is suppressed and the $\pi\pi$ is zero. The presence of the $\pi\pi$ and $\omega\pi$ channels hence calls for a $2\,^3S_1$ component. However, $\rho\eta$ appears to favour hybrid, since the experimental signal is very small (see Eq. 2 and E852 data [17]) and 2^3S_1 should have $\rho\eta$ at a strength of ~ 30 MeV. Hence a $2^3S_1 - V_H$ mixture

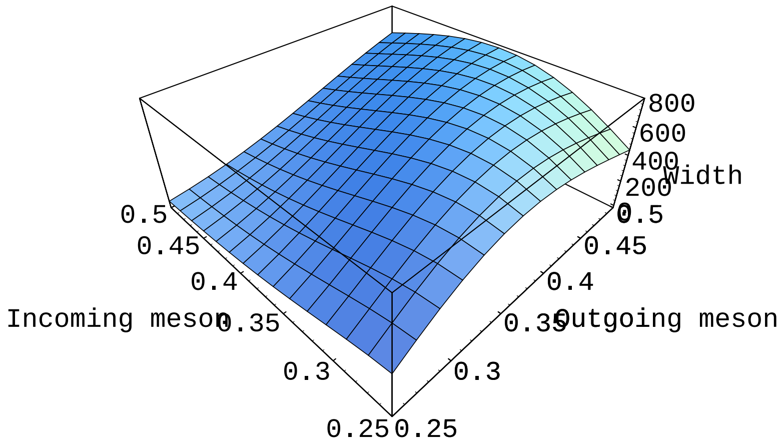

Figure 2: Total widths in MeV of $^3D_1$ $\omega(1600) \to b_1\pi$, as a function of β_A of the incoming and β of the outgoing mesons in GeV.

is a solution. Thus, as in the case of ω, one has

$$\rho(1450) = cos\phi^{'}|2\,^3S_1\rangle + sin\phi^{'}|\rho_H\rangle \tag{6}$$

and the data can be driven by $\rho_H \to \pi a_1$ and $2\,^3S_1$ $\rho \to \pi\pi$.

For $\rho(1700)$ the data indicate a very small $\omega\pi$ mode [8], pointing to hybrid admixture, since $2\,^3S_1$ and $^3D_1$ do not vanish, at least along the iso–β axis [11]. In order to force vanishing one would need to move far off the iso–β axis (see Table 1). However, the experimental $\pi\pi$ coupling of ~ 100 MeV is substantial. This is too large even for pure $2\,^3S_1$ and $^3D_1$ at least in the iso–β limit, and certainly out of line with pure hybrid for which this mode would vanish. If the experimental data survive there would be a conundrum in that the small $\omega\pi$ and large $\pi\pi$ widths point in mutually incompatible directions, namely the $\omega\pi$ favours hybrid while the $\pi\pi$ prefers radial $q\bar{q}$. Errors in the experimental analysis can reduce the $\pi\pi$ coupling by up to 50% [18]. Furthermore, a recent re–analysis of CERN–Munich data found a $\pi\pi$ width of only 39 ± 4 MeV [19]. The true strength of the $\pi\pi$ coupling needs to be established.

The $\rho(1700)$ overall does not provide a strong constraint on our analysis. Within the large uncertainties the above are consistent with it being a $2\,^3S_1 - V_H$ mixture but do not demand it. Improved data in this region, such as at the e^+e^- facility DAΦNE, could be most useful: Specific channels that should be studied include $e^+e^- \to 4\pi$ in order to separate πh_1 and πa_1 in the 4π state. New data in $\pi^+\pi^-\pi^+\pi^-$ have come from H1 at HERA [20], and a coupled channel analysis is in progress at Crystal Barrel [21]. Good data on $\omega\pi$

Table 2: Widths of selected decay modes of radial $3\,^1S_0$ $\pi(1800)$. Conventions are as in Table 1. For the mode $K_0^*(1430)\bar{K}$ widths are indicated for a state at 2 GeV.

Mode	Iso-β	Band	Nodal Lines
$\rho\pi$	0 - 30	0 - 70	2
$K^*\bar{K}$	30 - 50 $\nearrow$	5 - 110 $\searrow$	2
$\rho\omega$	20 - 50 $\nearrow$	5 - 90 $\searrow$	2
$K^*\bar{K}^*$	5 $\swarrow$	1 - 10 $\nwarrow$	2
$\pi f_0(1300)$	0 - 5 $\swarrow$	0 - 5	2
$\pi f_2(1270)$	10 - 20 $\swarrow$	10 - 30 $\nwarrow$	1
$K_0^*(1430)\bar{K}$	5 - 10 $\nearrow$	0 - 10	2

and $\pi\pi$ are also needed.

Note that our scenario requires three ρ (and three ω) states which should be allowed for in future data analyses.

2 $3S$ Radialogy: $3\,^1S_0\,\pi$

There is a resonance $\pi(1800)$ in $\pi f_0(980)$, $\pi f_0(1300)$ and also $(K\bar{K}\pi)_S$. It is a common feature that $\pi(1800)$ is absent in $\rho\pi$ and $K^*\bar{K}$. The presence of clear signals in both $\pi f_0(1300)$ and $\pi f_0(980)$ is remarkable and was commented upon with some surprise [1]. A substantial branching ratio to $\pi f_0(1500)$ has also been reported [4, 22].

In refs. [10, 11, 16] $\pi(1800)$ has been argued to be a hybrid meson. The overall expectations for hybrid 0^{-+} are in line with the data of refs. [1, 3, 4, 5], except that the signal seen in $\rho\omega$ and πf_2 might be a manifestation of $3\,^1S_0$. In order to settle this question, it is imperative to compare the data to the predictions for radial $3S$. Since $\rho\pi$ and K^*K are experimentally [1] found to be suppressed, it is of significant interest whether this can also happen for radial. This was discussed in the iso–β case in ref. [11]; here in Fig. 3 we show the result of allowing $\beta_A \neq \beta$. We clearly see that there are "nodal lines in the amplitude" for each of $\rho\pi$ and K^*K, by which we mean that the amplitude as a function of β_A and β displays lines along which the amplitude vanishes. Moreover, the same happens for $\rho\omega$ and K^*K^*. For $\rho\pi$ the amplitude can vanish even on the iso–β axis. We conclude that radial decays to pairs of S–wave mesons can be forced to vanish, although only in the case of the $\rho\pi$ channel does this happen near to the iso-β axis.

The $\pi f_0(1300)$ is very much suppressed throughout the entire parameter space (see Table 2), relative to the prediction for hybrid of 170 MeV. The same is true of $K_0^*(1430)\bar{K}$ which is small for a $3\,^1S_0\; q\bar{q}$, but large in the data (manifested as $(K\bar{K}\pi)_S$) and the largest channel for a hybrid π_H. This is most easily seen for states at 2 GeV, so that enough phase space for the decay to $K_0^*(1430)\bar{K}$ is available. For radial we have small widths due to nodal lines in the amplitude (see Table 2), while in contrast for hybrid the width is predicted to be 200 MeV.

Nonetheless, in this mass region we also expect the $3\,^1S_0\;\pi$ to appear and we now seek possible signatures. For a $3\,^1S_0$ the $\rho\omega$ channel is expected to be prominent [11]. Fig. 3 shows that the regions in β space where $\rho\omega$ modes could be suppressed by nodes are far from the physically favoured region and so we expect that $3\,^1S_0 \rightarrow \rho\omega$ is indeed a prominent mode. Note that this channel vanishes for hybrid and so the $\rho\omega$ channel promises to be a sharp discriminant between hybrid π and $3\,^1S_0$ initial states. The $\rho\omega$ signal builds up significantly below 1800 MeV and also shows a high mass continuum which looks somewhat different to the $\pi_H(1800)$. A resonant signal however has not yet been established, although a "resonance–like structure" with mass $1742 \pm 12 \pm 10$ MeV and width $226 \pm 14 \pm 20$ MeV has been reported [5]. The πf_2 channel also may discriminate π_H from $3\,^1S_0$. For π_H this is predicted to be a minor mode whereas for $3\,^1S_0$ it is predicted to be a more significant signal. Fig. 4d in ref. [4] shows a clear πf_2 peak at 1700 MeV, certainly below the 1800 MeV region of the $\pi(1800)$ as already noted in ref. [11]. Further analysis and data are now required to establish this. For hybrid πf_2 is 6 MeV [11] while for radial it is possibly larger (see Table 2). It is tempting to suggest that the $3\,^1S_0$ favoured $\rho\omega$ and πf_2 channels peak at ~ 1700 MeV in contrast to the π_H channel πf_0 at ~ 1800 MeV. If two 0^{-+} states were to be isolated in this region this would be strong evidence for hybrid and $3S$ excitation. Categorisation of $5\pi/3\pi$ may further clarify this possibility.

3 Summary and Experimental Strategy

The $\rho(1450)$ and $\omega(1420)$ have masses that are consistent with radial $2S$ but their decays have a strong hybrid character, as already noted [8, 10]. We find that both of these states and the heavier counterpart $\omega(1600)$ can be interpreted as $2S$–hybrid mixtures. Present data on the $\rho(1700)$ are consistent with it being a $2S$–hybrid mixture but do not demand it. We note that three ρ (and three ω) states should be allowed for between $1300 - 1800$ MeV in future data analyses.

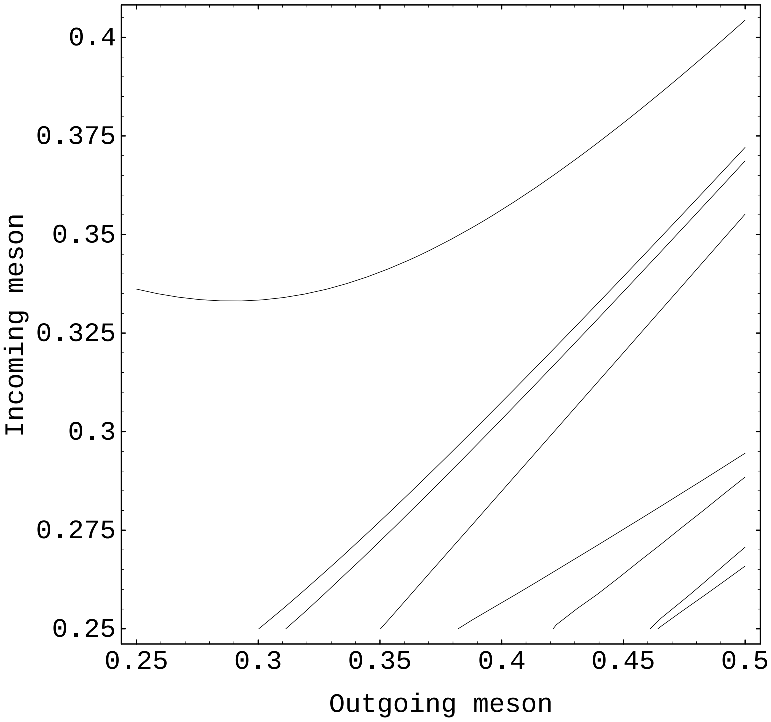

Figure 3: Nodal lines of $3\ ^1S_0$ $\pi(1800) \rightarrow \rho\pi$, $\rho\omega$, K^*K, K^*K^* as a function of the incoming and outgoing meson β_A and β in GeV. For each channel there are two lines of nodes. From top to bottom the nodal lines correspond to the $\rho\pi$, $\rho\omega$, K^*K, K^*K^*, $\rho\pi$, K^*K, $\rho\omega$, K^*K^* channels.

The $3\,^1S_0\ \pi$ is expected in the 1800 MeV mass region as is the hybrid. We find that the decay patterns of these are very different. The low total width state with strong πf_0 (hybrid) and the large total width state with strong $\rho\omega$ ($3S$) is the sharpest discriminant. The established VES state $\pi(1800)$ clearly exhibits the former hybrid character. We also urge data analysts to allow for the possibility of two isovector 0^{-+} resonances in the region $1700-1900$ MeV, one of which is expected to couple strongly to $\rho\omega$.

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