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# Light and Not So Light Scalar Mesons

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I. Introduction to Scalar Mesons

II. Resonance Spectrum Expansion Model and Applications

III. Light-Weight and Medium-Weight Scalar Mesons

IV. Conclusions and Outlook

# I. Introduction to Scalar Mesons

$\Rightarrow$ Scalar mesons have been very problematic in standard quark models:

- ground-state nonet seems too light for $P$-wave $q\bar{q}$ states, i.e., $f_0(600)$ ($\sigma$), $K_0^*(800)$ ($\kappa$), $f_0(980)$, and $a_0(980)$;
- approximate mass degeneracy of $f_0(980)$ and $a_0(980)$ is puzzling;
- $f_0(600)$ and $K_0^*(800)$ are very broad, while $f_0(980)$ and $a_0(980)$ are much narrower;
- $K_0^*(800)$ still controversial experimentally (in PDG2008, but omitted (?) from summary table);
- disagreement on interpretation of $f_0(1370)$ (existence?) and especially $f_0(1500)$ (glueball?), besides $f_0(1710)$ and tentative $f_0(1770)$.

$\Rightarrow$ Some major theoretical approaches:

- $qq\bar{q}\bar{q}$ states (*Jaffe*, 1977; many followers more recently), explaining light scalars with large colour-hyperfine interaction, and also $f_0(980)/a_0(980)$ degeneracy;
- quark-level Linear $\sigma$ Model (qlLSM) (*Scadron*, 1982; *Delbourgo & Scadron*, 1995, 1998; *Scadron et al.*, 2000 $\longrightarrow$), self-consistent nonperturbative theory of light scalars and pseudoscalars as fundamental fields as well as $q\bar{q}$ states;

- mesonic $t$-channel exchanges produce $a_0(980)$ and $f_0(980)$ as $K\bar{K}$ molecules, and $\sigma$ (too light) as a purely dynamical resonance (*Isgur & Weinstein*, 1982, 1990; *Janssen, Pearce, Holinde, Speth*, 1990, 1995);
- effective-Lagrangian model (*Schechter et al.*, 1995 $\rightarrow$), light scalars are mixtures of $q^2\bar{q}^2$ (dominant) and $q\bar{q}$ states;
- $K$-matrix method to extract "bare" states from the data (*Anisovich, Sarantsev*, 1995 $\rightarrow$), $K$-matrix poles are claimed to be linked to QCD model predictions;
- unitarised Chiral Perturbation Theory (ChPT) (*Oller, Oset, Peláez*, 1998 $\rightarrow$), light scalars are dynamical poles in meson-meson scattering that disappear (?) in the $N_c \rightarrow \infty$ limit;
- Roy-equation approach to the $\pi\pi$ $S$-wave, with input from ChPT, produces dynamical $\sigma$ pole (*Caprini, Colangelo, Leutwyler*, 2006).

$\Rightarrow$ Alternative is unitarisation of bare scalar states, via their strong coupling to $S$-wave two-meson channels:

- Helsinki unitarised quark model of *Törnqvist* (1982, 1995) and *Törnqvist, Roos* (1996); doubling of some scalar states, producing e.g. a light $\sigma$, but **no** light $\kappa$;
- Unitarised quark-meson models of *van Beveren, Dullemond, Rijken, Rupp et al.* (1983, 1986) and *van Beveren, Rupp* (1998 $\rightarrow$); unitarisation gives rise to **two complete** light scalar nonets, starting from only one bare $P$-wave $q\bar{q}$ nonet. Also new charmed scalars $D^*_{s0}(2317)$ and $D^*_{sJ}(2860)$ reproduced (2003) resp. predicted (2006).

⇒ Note:

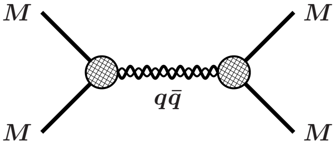
- Original quark-meson model, published in Z. Phys. C **30** (1986) 615 predicted the poles of the light scalar nonet at:

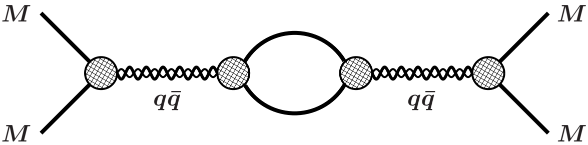
  $\sigma$: 470 − $i$208 MeV; $\kappa$: 727 − $i$263 MeV;

  $f_0(980)$: 994 − $i$20 MeV; $a_0(980)$: 968 − $i$28 MeV.
- These were **not** the result of a fit;
- The few parameters had been fixed previously to charmonium and bottomonium, as well as some light vector and pseudoscalar mesons;
- The employed confining potential for the bare spectrum was a harmonic oscillator (HO) with mass-independent frequency;
- This model predicted a $\rho(1250)$ resonance as the first radially excited $\rho$ meson;
- The $\rho(1250)$ has now been confirmed once again in the analysis of Surovtsev and Bydžovský, Nucl. Phys. A **807** (2008) 145;
- In the recent formulation of the model (see next slide), only the confinement **spectrum** enters the equations, thus allowing much more flexibility;
- Nevertheless, in **all** phenomenological applications, we have been sticking to the HO, simply because it works;
- Anyone who disagrees, may try their favourite confinement spectrum in our expressions, to see whether better results can be obtained!

# II. Resonance Spectrum Expansion Model and Applications

⇒ Building blocks of Resonance Spectrum Expansion (RSE) are:

$V =$ 


$V\Omega V =$ 


- $V$ is the effective two-meson potential;
- $\Omega$ is the two-meson loop function;
- the blobs are the ${}^3P_0$ vertex functions, modelled by a spherical $\delta$ shell in coordinate space, i.e., a spherical Bessel function in momentum space;
- the wiggly lines stand for $s$-channel exchanges of infinite towers of $q\bar{q}$ states, i.e., a kind of Regge propagators (see arXiv:0809.1149 [hep-ph]).

For $N$ meson-meson channels and several $q\bar{q}$ channels:

$$\begin{aligned} V_{ij}^{(L_i,L_j)}(p_i,p_j';E) &= \lambda^2 r_0\, j_{L_i}^i(p_i r_0)\, j_{L_j}^j(p_j' r_0) \sum_{\alpha=1}^{N_{q\bar{q}}} \sum_{n=0}^{\infty} \frac{g_i^{(\alpha)}(n) g_j^{(\alpha)}(n)}{E - E_n^{(\alpha)}} \\ &\equiv \mathcal{R}_{ij}(E)\, j_{L_i}^i(p_i r_0)\, j_{L_j}^j(p_j' r_0)\ , \end{aligned} \qquad (1)$$

where $L_i, L_j$ are the angular momenta of channels $i, j$, and $N_{q\bar{q}}$ is the number of included $q\bar{q}$ channels with the same quantum numbers (e.g. $n\bar{n} + s\bar{s}$ and/or ${}^3S_1 + {}^3D_1$).

$\Rightarrow$ Note:

This effective, energy-dependent meson-meson potential is separable of rank $N$. The corresponding off-energy-shell $T$-matrix can be solved in closed form:

$$T_{ij}^{(L_i,L_j)}(p_i,p_j';E) = -2\lambda^2 r_0\, \rho_{ij}\, j_{L_i}^i(p_i r_0) \sum_{m=1}^{N} \mathcal{R}_{im}(E) \left\{ [\mathbb{1} - \Omega\,\mathcal{R}]^{-1} \right\}_{mj} j_{L_j}^j(p_j' r_0)\ , \qquad (2)$$

where $\rho_{ij} \equiv \sqrt{\mu_i p_i \mu_j' p_j'}$, with relativistically defined reduced masses and momenta, and where the loop function is given by the diagonal $N_{MM} \times N_{MM}$ matrix

$$\Omega = -2i\lambda^2 r_0\, \mathrm{diag}\left( j_{L_k}^k(p_k r_0) h_{L_k}^{(1)k}(p_k' r_0) \right)\ , \qquad (3)$$

with $h^{(1)}$ the spherical Hankel-1 function.

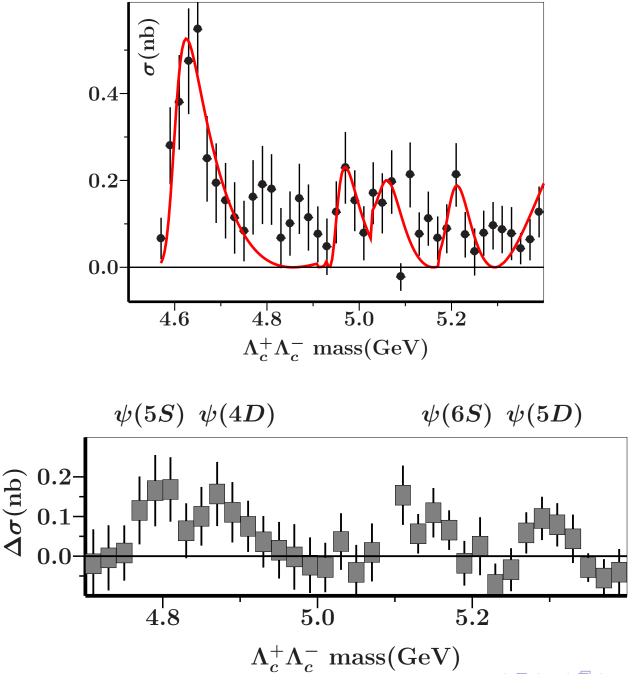
⇒ Note:

- This model does **not** correspond to the exchange of an $s$-channel resonance only, but of a whole spectrum of states;
- From duality arguments, this will effectively also account for some $t$-channel phenomena;
- Concretely, approximating the infinite sum in Eq. (**??**) by one or more $s$-channel states plus a remainder, one obtains the typical $s$-channel seed(s) plus contact term of (unitarised) chiral models. See arXiv:0809.1149 [hep-ph] for details.

⇒ Applications:

- Single-channel description of $K_0^*(800)$, $K_0^*(1430)$ (EPJC **22** (2001) 493), of $D_{s0}(2317)$ (PRL **91** (2003) 012003), and of $D_{s1}(2460)$, $D_1(2400)$ (EPJC **32** (2001) 493);
- Multichannel description of $f_0(600)$, $K_0^*(800)$, $f_0(980)$, and $a_0(980)$ (PLB **641** (2006) 265, see below), and of $D_{sJ}(2860)$ (PRL **97** (2006) 202001);
- RSE formulation of production amplitudes, manifestly satisfying generalised unitarity (AOP **323** (2008) 1215);
- Single-channel application of production formalism to production processes of $K_0^*(800)$ and $f_0(600)$ (JPG **34** (2007) 1789);
- Deriving a **complex** relation between production and scattering amplitudes, while respecting (generalised) unitarity, allows to separate dynamics from kinematics when describing production processes (EPL **81** (2008) 61002);
- Applying the formalism to $\pi\pi$ production processes at very different mass scales allows to deduce the effective string-breaking distance, in agreement with recent lattice calculations (arXiv:0712.1771 [hep-ph]);
- Production amplitudes exhibit zeros in leading order, which are not present in scattering amplitudes. Application to the recent BELLE enhancement at 4.634 GeV in $\Lambda_c^+\Lambda_c^-$ leads to an indication of 5 new charmonium vector states, viz. $\psi(5S, 6S, 3D, 4D, 5D)$ (arXiv:0809.1151 [hep-ph]; also see Fig. 1 on next slide).

Figure 1:

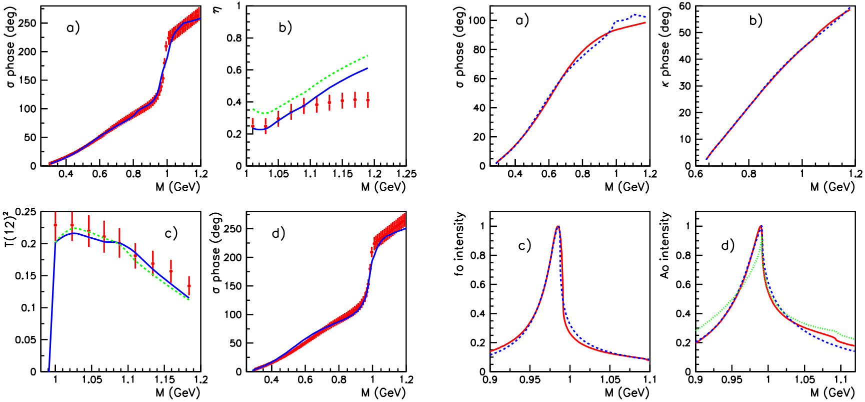


σ(nb)
0.4
0.2
0.0
4.6
4.8
5.0
5.2
$\Lambda_c^+\Lambda_c^-$ mass(GeV)
ψ(5S) ψ(4D)
ψ(6S) ψ(5D)
Δσ(nb)
0.2
0.1
0.0
4.8
5.0
5.2
$\Lambda_c^+\Lambda_c^-$ mass(GeV)

## III. Light-Weight and Medium-Weight Scalar Mesons

⇒ Published work:

- E. van Beveren, D. V. Bugg, F. Kleefeld, and G.R., Phys. Lett. B **641** (2006) 265. Only pseudoscalar-pseudoscalar (PP) channels were included, i.e., $\pi\pi$, $\eta\eta$, $\eta\eta'$, $\eta'\eta'$ for coupled $\sigma$-$f_0(980)$ system; $\eta\pi$, $KK$, $\eta'\pi$, for $a_0(980)$; $K\pi$, $K\eta$, $K\eta'$ for $\kappa$. Results (Fig. 1):




- Pole positions:

  $\sigma$: $530 - i226$ MeV; $\kappa$: $745 - i316$ MeV;

  $f_0(980)$: $1007 - i38$ MeV; $a_0(980)$: $1021 - i47$ MeV.

⇒ Preliminary new results:

- Now we also include all vector-vector (VV) ($L = 0$ and $L = 2$) and scalar-scalar (SS) channels, i.e., $\rho\rho$, $\omega\omega$, $K^*K^*$, $\phi\phi$ and $\sigma\sigma$, $f_0(980)f_0(980)$, $\kappa\kappa$, $a_0(980)a_0(980)$ for the coupled $\sigma$-$f_0(980)$ system, and $\rho\omega$, $K^*K^*$ and $a_0(980)\sigma$, $a_0(980)f_0(980)$, $\kappa\kappa$ for the $a_0(980)$. For the $\kappa$, see below.

- Fit to data compiled by Bugg and Surovtsev carried out in the **isoscalar case**, up to 1.6 GeV. The parameters are $\lambda$, $r_0$, and a subthreshold damping constant, as well as the pseudoscalar and scalar mixing angles. Both $\lambda$ and $r_0$ stabilise close to published values, while the angles also settle at reasonable values. Results: see Fig. 2 on next slide. Clearly, the VV and SS channels have a somewhat too drastic influence on the phase, despite an increased subtreshold damping. Probable reason: too sharp thresholds for final-state resonances (see also conclusions).

  Poles for PP+VV+SS fit:

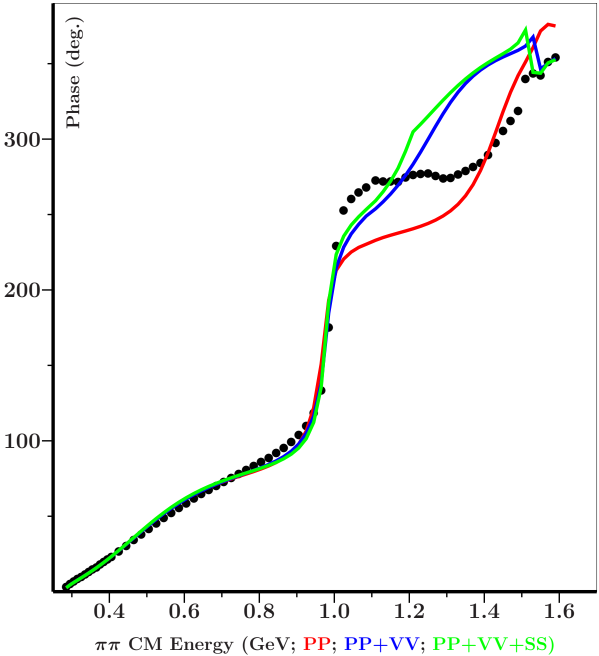
  $\sigma$: $464 - i217$ MeV; $f_0(980)$: $987 - i29$ MeV (second sheet);

  $f_0(1370)$: $1334 - i185$ MeV; $f_0(1500)$(?): $1530 - i14$ MeV.

  $f_0(1500)$(???): $1519 - i219$ MeV.

⇒ Note: The $f_0(1500)$ might be hard to interpret experimentally because of the presence of a relatively narrow confinement (CDD) pole as well as a very broad dynamical pole.

Figure 2:


Phase (deg.)
300
200
100
0.4
0.6
0.8
1.0
1.2
1.4
1.6
$\pi\pi$ CM Energy (GeV; PP; PP+VV; PP+VV+SS)

- In the **isodoublet** case, no stable fit can be obtained with the VV and SS channels. Also,the LASS data are known to violate unitarity above 1.3 GeV. So we fit up to 1.3 GeV, with only PP channels (see the Fig. 3), and parameters very close to the isoscalar case, as well as a reasonable pseudoscalar mixing angle. See further the conclusions.

  Poles for PP fit:

  $\kappa$: $722 - i266$ MeV;

  $K_0^*(1430)$: $1400 - i96$ MeV;

- In the **isotriplet case**, inclusion of the VV and SS channels hardly improves the already good fit to the $a_0(980)$ line shape parametrised by Bugg in a fit to KLOE and Crystal Barrel data (see Fig. 4). However, the pseudoscalar mixing angle improves, as well as the pole position of the $a_0(1450)$.

  Poles for PP+VV+SS fit:

  $a_0(980)$: $1023 - i47$ MeV (second sheet); $a_0(1450)$: $1420 - i185$ MeV.

Figure 3:

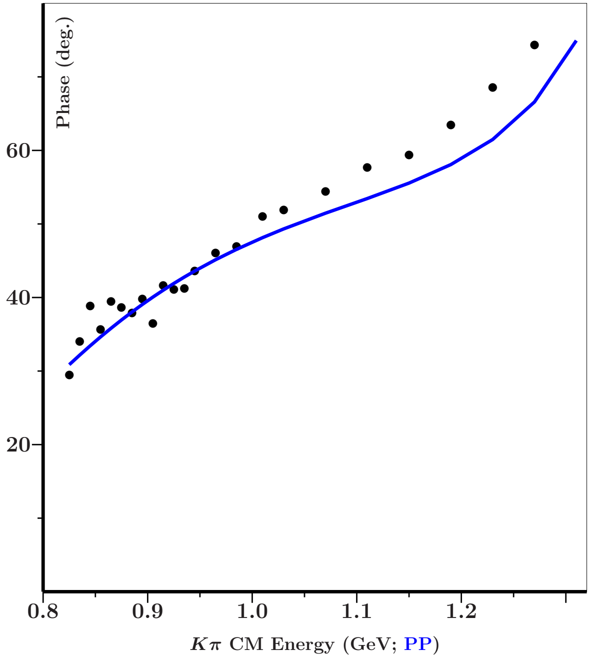
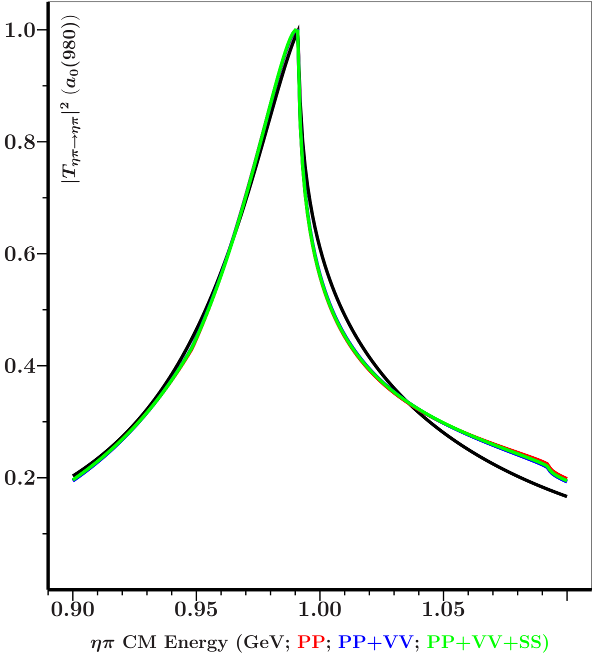


Figure 4:



$|T_{\eta\pi\to\eta\pi}|^2$ ($a_0(980)$)
1.0
0.8
0.6
0.4
0.2
0.90
0.95
1.00
1.05
$\eta\pi$ CM Energy (GeV; PP; PP+VV; PP+VV+SS)

## IV. Conclusions and Outlook

- Inclusion of VV and SS channels has a sizable influence on the $S$-wave phase shifts above 1 GeV, but the effect is too drastic;
- In the isoscalar and isotriplet case, the predictions for the poles of the intermediate scalars improve considerably.
- The situation in the isodoublet case is complicated due to the lack of reliable data above 1.3 GeV. Nevertheless, also here the effect of the VV and SS channels is too crude.
- A possible solution to the very sudden changes in phase shifts due to the opening of VV and SS channels is to use complex masses for them, especially for the broad ones ($\sigma$, $\kappa$, $\rho$). This will make it possible to simulate e.g. the important $4\pi$ decays. A forced unitarisation of the $T$-matrix will then have to be carried out.