The Quest for Light Scalar Quarkonia from eLSM

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Questions

Scalar mesons have been studied for decades but we still do not understand them completely:

i) The PDG cites five $IJ^{PC}=00^{++}$ states in the energy region under 1 GeV: $f_0(600)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$. Suppose you had a theory containing the following states: scalar quark-antiquark (2 states if we consider *u*, *d*, *s* quarks), scalar tetraquark (again, with three flavours → 2 states) and a scalar glueball state. **How do we assign them to the measured states?** Thus: **What is the structure of scalar mesons?**

ii) An order parameter for the chiral phase transition (restoration of the chiral symmetry) is the degeneration of the pion and its chiral partner, a scalar meson. This scalar meson has to be a quark-antiquark state (just as the pion). But **there are five scalars** – and thus five potential chiral partners of the pion. Thus: **Which scalar is a non-strange quark-antiquark state?**

Our Approach

A comprehensive study of scalars should include other mesons they can interact with: pseudoscalars, vectors and axial-vectors [1]. We present an **Extended Linear Sigma Model with vector and axial-vector mesons (eLSM)** not only in the **non-strange** but in the **strange sector** as well – the first time such a study has been performed with **all** the mentioned states.

The Fields

The following four matrices contain the scalar (S), pseudoscalar (P), vector (V) and axial-vector (A) mesons from our model.

$$S=\frac{1}{\sqrt{2}}\begin{pmatrix}\frac{\sigma_N+a_0^0}{\sqrt{2}} & a_0^+ & K_S^+\\ a_0^- & \frac{\sigma_N-a_0^0}{\sqrt{2}} & K_S^0\\ K_S^- & \bar{K}_S^0 & \sigma_S\end{pmatrix}\quad P=\frac{1}{\sqrt{2}}\begin{pmatrix}\frac{\eta_N+\pi^0}{\sqrt{2}} & \pi^+ & K^+\\ \pi^- & \frac{\eta_N-\pi^0}{\sqrt{2}} & K^0\\ K^- & \bar{K}^0 & \eta_S\end{pmatrix}$$

$$V^\mu=\frac{1}{\sqrt{2}}\begin{pmatrix}\frac{\omega_N+\rho}{\sqrt{2}} & \rho^+ & K^{*+}\\ \rho^- & \frac{\omega_{N\mu}-\rho_\mu^0}{\sqrt{2}} & K^{*0}\\ K^{*-} & \bar{K}^{*0} & \omega_S\end{pmatrix}^\mu\quad A^\mu=\frac{1}{\sqrt{2}}\begin{pmatrix}\frac{f_{1N}+a_1^0}{\sqrt{2}} & a_1^+ & K_1^+\\ a_1^- & \frac{f_{1N}-a_1^0}{\sqrt{2}} & K_1^0\\ K_1^- & \bar{K}_1^0 & f_{1S}\end{pmatrix}^\mu$$

The Lagrangian

Let us define $\Phi := S+iP$, $L^\mu := V^\mu+A^\mu$ and $R^\mu := V^\mu-A^\mu$. Then the Lagrangian with the $U(3)_L\times U(3)_R$ Chiral Symmetry reads:

$$\begin{aligned}\mathcal{L}=&\,\mathrm{Tr}\,[(D^\mu\Phi)^\dagger(D^\mu\Phi)]-m_0^2\,\mathrm{Tr}\,(\Phi^\dagger\Phi)-\lambda_1[\mathrm{Tr}\,(\Phi^\dagger\Phi)]^2-\lambda_2\mathrm{Tr}\,(\Phi^\dagger\Phi)^2\\&+\mathrm{Tr}\,[H(\Phi+\Phi^\dagger)]+c[(\det\Phi+\det\Phi^\dagger)^2-4\det(\Phi\Phi^\dagger)]\\&-\frac{1}{4}\mathrm{Tr}\,(L_{\mu\nu}^2+R_{\mu\nu}^2)+\mathrm{Tr}\left[\left(\frac{m_1^2}{2}+\Delta\right)(L_\mu^2+R_\mu^2)\right]\\&-2ig_2(\mathrm{Tr}\,\{L_{\mu\nu}[L^\mu,L^\nu]\}+\mathrm{Tr}\{R_{\mu\nu}[R^\mu,R^\nu]\})\\&+\frac{h_1}{2}\mathrm{Tr}\,(\Phi^\dagger\Phi)\,\mathrm{Tr}\,(L_\mu^2+R_\mu^2)+h_2\mathrm{Tr}[(L_\mu\Phi)^2+(\Phi R_\mu)^2]\\&+2h_3\,\mathrm{Tr}\,(\Phi R_\mu\Phi^\dagger L^\mu)\end{aligned}$$

We implement the **explicit breaking** of the Chiral Symmetry (via the *H* and Δ terms), the **chiral anomaly** (via the *c* term) and the **spontaneous breaking** of the Chiral Symmetry (shifting the scalars by the non-strange and strange condensates ϕ_N and ϕ_S, i.e., $\sigma_{N/S}\to\sigma_{N/S}+\phi_{N/S}$).

Note: $D_\mu\Phi = \partial_\mu\Phi - ig_1(L_\mu\Phi - \Phi R_\mu)$.

The Global Fit of Masses

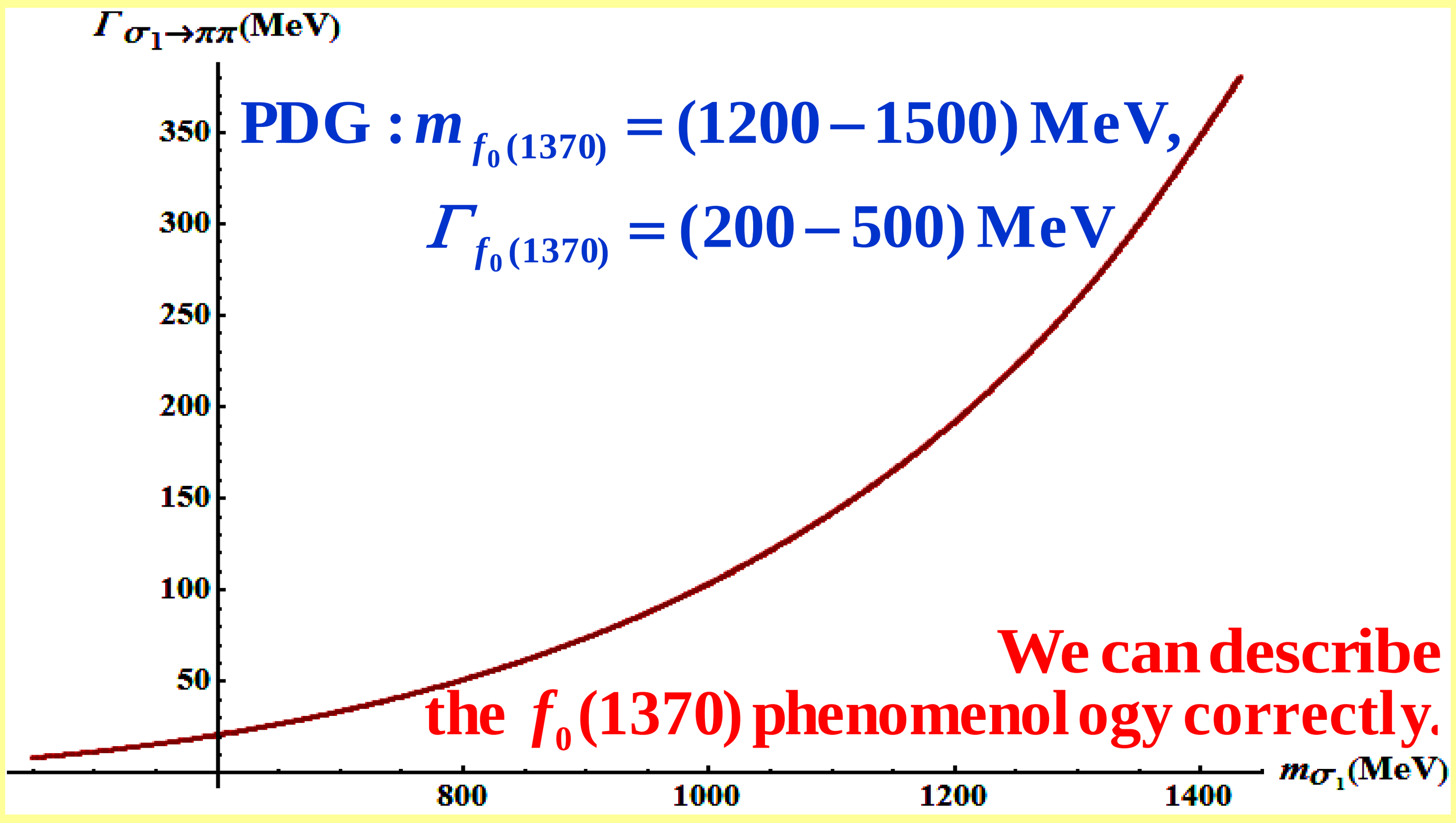
The model parameters are fixed using a global fit of all meson masses (except the sigmas). The results are shown in the following table.

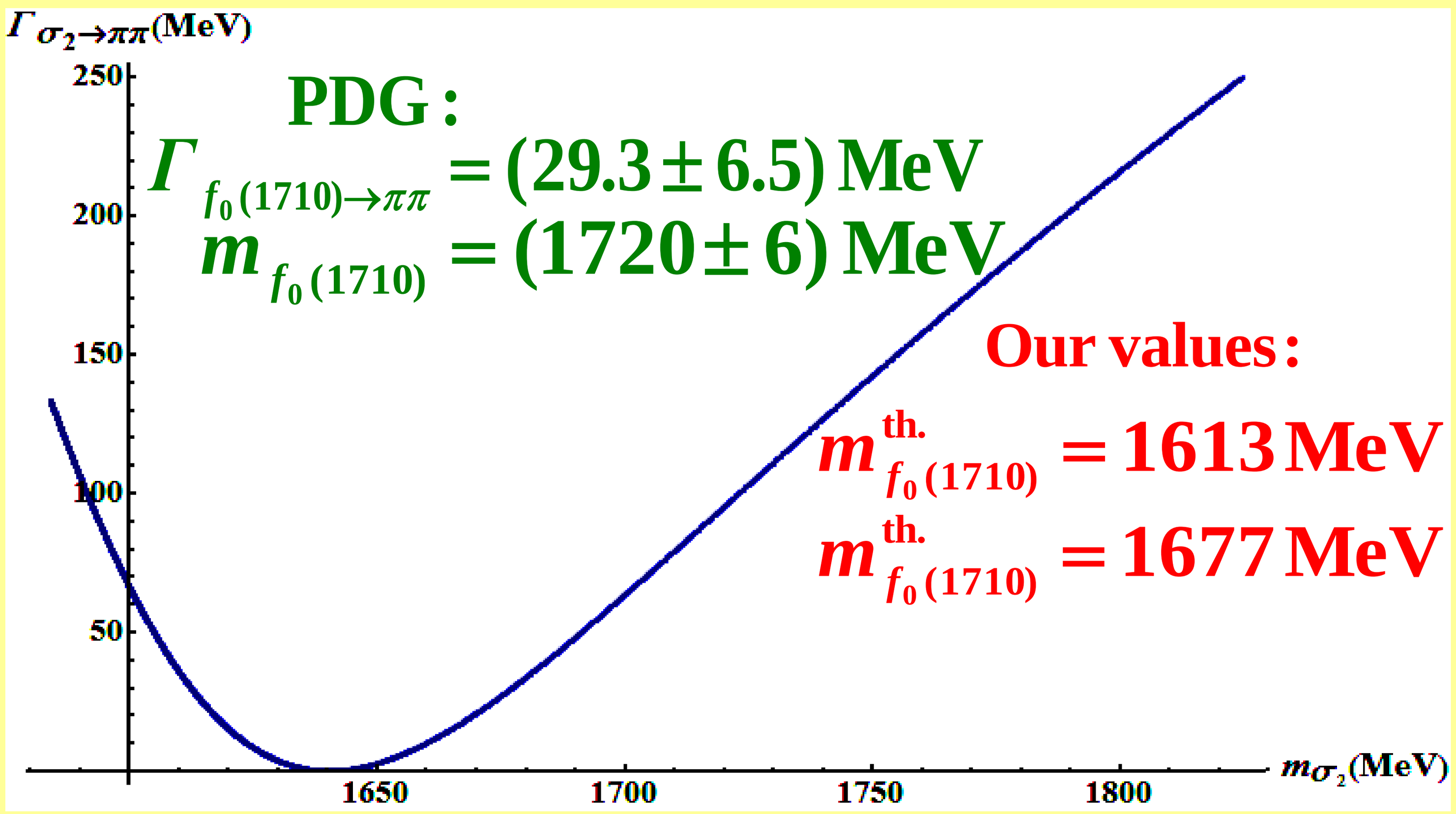
Mass	Our value (MeV)	PDG Value (MeV)	Mass	Our value (MeV)	PDG Value (MeV)
m_π	138.65	139.57	$m_{\varphi(1020)}$	1036.9	1019.5
m_K	497.96	493.68	$m_{f_1(1420)}$	1457	1426.4
m_η	523.20	547.85	$m_{a_1(1260)}$	1219	1230
$m_{\eta'}$	957.79	957.78	m_{K_1}	1343	1272
m_ρ	775.49	775.49	$m_{K_0^*(1430)}$	1452	1474
m_{K^*}	916.52	891.66	$m_{a_0(1450)}$	1550	1425

The correspondence to the PDG data is very good. All the states in our model are quarkonia [1] – thus, all of the above resonances are favoured to be quark-antiquark states.

What about the σ states?

The pure non-strange state σ_N and the pure strange state σ_S mix producing the states σ_1 (95% non-strange) and σ_2 (95% strange); decays below.





Summary and Outlook

We thus see scalar quarkonia above 1 GeV: $f_0(1370)$ as a predominantly non-strange and $f_0(1710)$ as a predominantly strange quark-antiquark state. However: we still need to include a glueball and tetraquark states.

References

[1] D. Parganlija, F. Giacosa and D. H. Rischke, Phys. Rev. D 82, 054024 (2010) [arXiv: 1003.4934 [hep-ph].]

[2] D. Parganlija, arXiv: 1105.3647 [hep-ph].