Der Wissenschaftsfonds.

Excited Scalar and Pseudoscalar Mesons in the Extended Linear Sigma Model

Denis Parganlija

[Based on D. Parganlija and F. Giacosa, arXiv:1612.09218]

In collaboration with
F. Giacosa (Kielce)

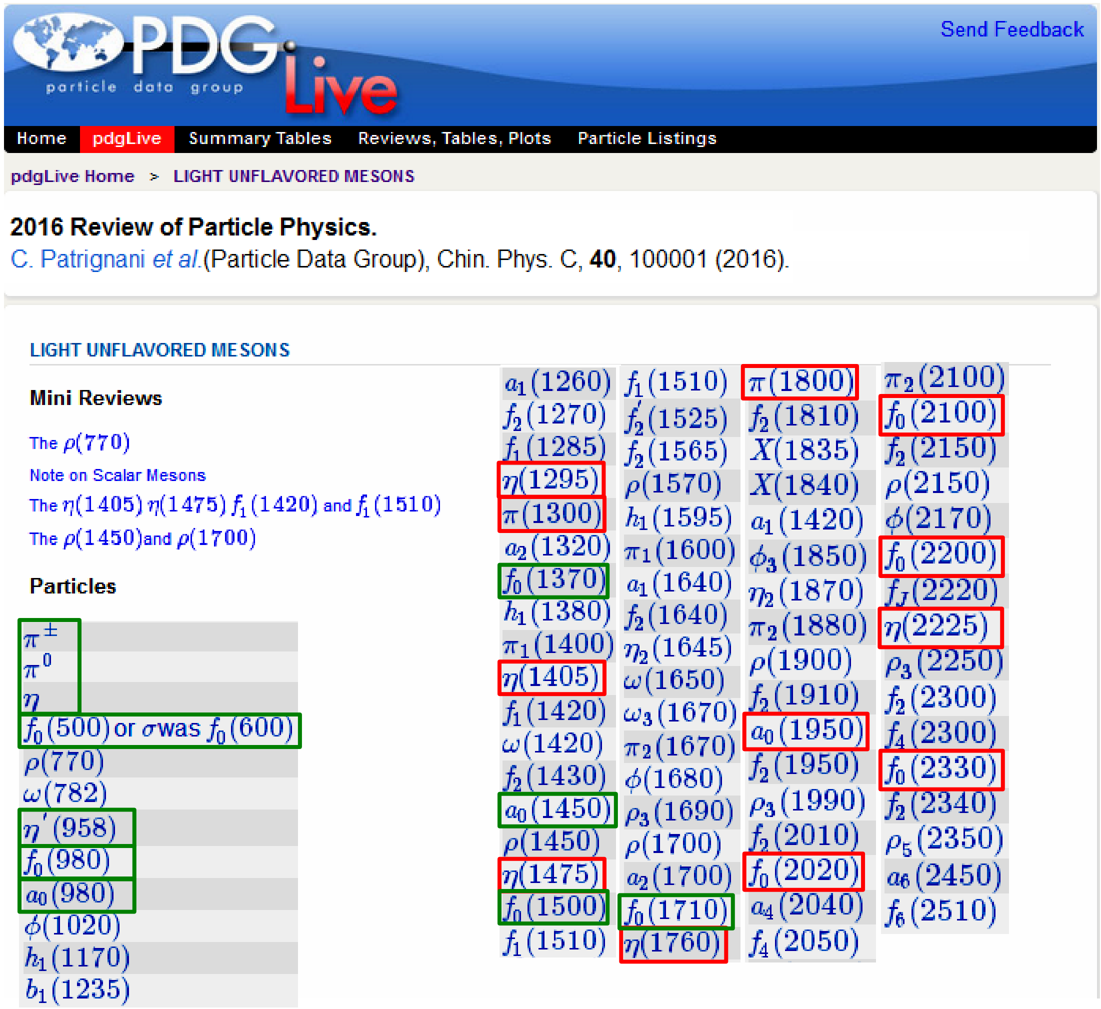
Mesons: Definitions and Experimental Data

- **Mesons: hadrons with integer spin**
- **Quantum numbers: J^{PC}**

Total Spin **Parity** **Charge Conjugation**

- **Scalar mesons: $J^{PC} = 0^{++}$ [σ or $f_0(500)$, $a_0(980)$, $a_0(1450)$…]**
- **Pseudoscalar mesons: $J^{PC} = 0^{-+}$ [π, K, η, η'…]**
- **Vector mesons: $J^{PC} = 1^{--}$ [ρ, K^*, ω, $\varphi(1020)$…]**
- **Axial-Vector mesons: $J^{PC} = 1^{++}$ [$a_1(1260)$, $f_1(1285)$, $K_1(1270)$, $K_1(1400)$…]**

The Need for Excited States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C. Patrignani *et al.*(Particle Data Group), Chin. Phys. C, **40**, 100001 (2016).

LIGHT UNFLAVORED MESONS

Mini Reviews

The $\rho(770)$
Note on Scalar Mesons
The $\eta(1405)$ $\eta(1475)$ $f_1(1420)$ and $f_1(1510)$
The $\rho(1450)$ and $\rho(1700)$

Particles

$\pi^\pm$, π^0, η, $f_0(500)$ or σ was $f_0(600)$, $\rho(770)$, $\omega(782)$, $\eta'(958)$, $f_0(980)$, $a_0(980)$, $\phi(1020)$, $h_1(1170)$, $b_1(1235)$

$a_1(1260)$, $f_2(1270)$, $f_1(1285)$, $\eta(1295)$, $\pi(1300)$, $a_2(1320)$, $f_0(1370)$, $h_1(1380)$, $\pi_1(1400)$, $\eta(1405)$, $f_1(1420)$, $\omega(1420)$, $f_2(1430)$, $a_0(1450)$, $\rho(1450)$, $\eta(1475)$, $f_0(1500)$, $f_1(1510)$

$f_1(1510)$, $f_2'(1525)$, $f_2(1565)$, $\rho(1570)$, $h_1(1595)$, $\pi_1(1600)$, $a_1(1640)$, $f_2(1640)$, $\eta_2(1645)$, $\omega(1650)$, $\omega_3(1670)$, $\pi_2(1670)$, $\phi(1680)$, $\rho_3(1690)$, $\rho(1700)$, $a_2(1700)$, $f_0(1710)$, $\eta(1760)$

$\pi(1800)$, $f_2(1810)$, $X(1835)$, $X(1840)$, $a_1(1420)$, $\phi_3(1850)$, $\eta_2(1870)$, $\pi_2(1880)$, $\rho(1900)$, $f_2(1910)$, $a_0(1950)$, $f_2(1950)$, $\rho_3(1990)$, $f_2(2010)$, $f_0(2020)$, $a_4(2040)$, $f_4(2050)$

$\pi_2(2100)$, $f_0(2100)$, $f_2(2150)$, $\rho(2150)$, $\phi(2170)$, $f_0(2200)$, $f_J(2220)$, $\eta(2225)$, $\rho_3(2250)$, $f_2(2300)$, $f_4(2300)$, $f_0(2330)$, $f_2(2340)$, $\rho_5(2350)$, $a_6(2450)$, $f_6(2510)$

$J^P = 0^-$ $\qquad$ $J^P = 0^+$

Note:

1) we assume that $\eta(1405)$ and $\eta(1475)$ are one state: $\eta(1440)$

2) $f_0(1790)$ reported by BES (2004) and LHCb (2014)

3) $a_0(1950)$ reported by BABAR (2015).

Are there excited quarkonia here?

The Need for Excited States

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STRANGE MESONS ($S = \pm1$, $C = B = 0$)

Mini Reviews

- The Charged Kaon Mass
- Rare Kaon Decays (rev.)
- Dalitz Plot Parameters for $K \to 3\pi$ Decays
- $K^{+-}_{\ell 3}$ and $K^{0}_{\ell 3}$ Form Factors

Particles

$K^\pm$
K^0
K^0_S
K^0_L
$K^*_0(800)$ or κ
$K^*(892)$
$K_1(1270)$
$K_1(1400)$
$K^*(1410)$
$K^*_0(1430)$
$K^*_2(1430)$
$K(1460)$
$K_2(1580)$
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$K^*_5(2380)$
$K_4(2500)$
$K(3100)$

$J^P = 0^-$

$J^P = 0^+$

Are there excited quarkonia here?

Quantum Chromodynamics

- **QCD Lagrangian:**

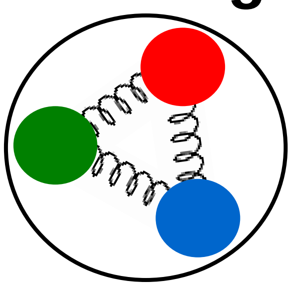
$$\mathcal{L} = \bar{q}_f \left(i\gamma^\mu \boxed{D_\mu} - m_f \right) q_f - \frac{1}{4} \boxed{G^a_{\mu\nu}} G^{\mu\nu}_a$$

$$D_\mu = \partial_\mu - i g A^a_\mu t^a$$

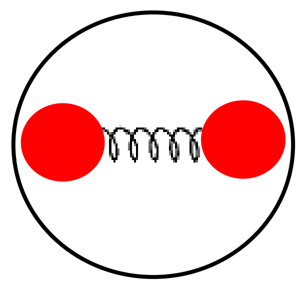
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

Strong Coupling is Energy-Dependent

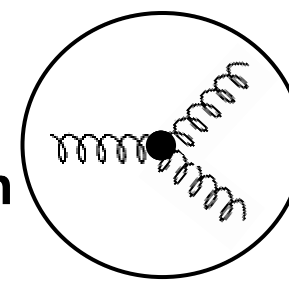
- **Large coupling and confinement lead to the emergence of hadrons**



Baryons
(Half-Integer Spin)



Mesons
Integer Spin



- **But: perturbative expansion does not work**

Two approaches to Low-Energy QCD

QCD

Quarks/gluons as degrees of freedom:

Lattice

[Wilson; Alexandrou, Bicudo, Cardoiso, Dürr, Fodor, Gregory, Irving, Katz, Lang, Prelovsek, Silva, Suganuma…]

Light-front wave functions

[Brodsky, Pauli, Pinsky, Teramond, …]

Bethe-Salpeter Equations

[Eichmann, Fischer, Nicmorus, Roberts, Williams, Windisch,…]

Hadrons as degrees of freedom:

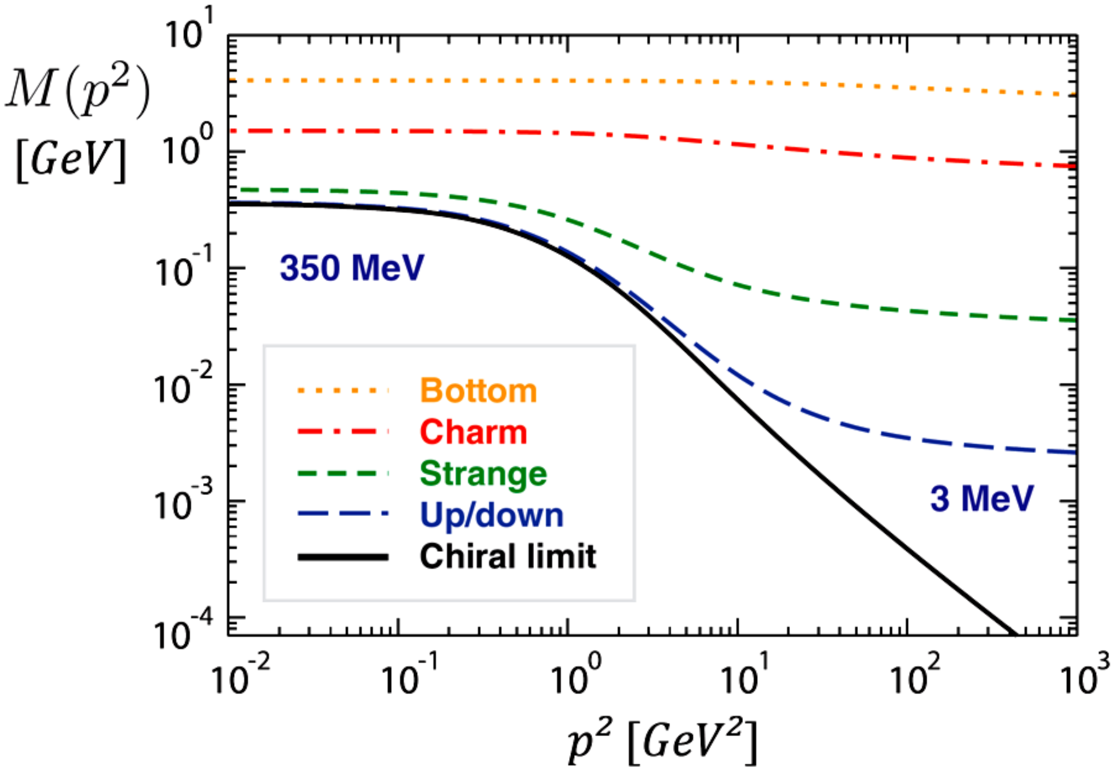
Chiral Perturbation Theory

Linear Sigma Model

Can a Model Ever Describe QCD?

- **Symmetries of the QCD Lagrangian:** Poincare; Local $SU(3)_c$ Colour; Global Chiral $U(N_f)$x $U(N_f)$; Dilatational; CPT; Z_n ($n = 0, \ldots, N_c - 1$) **can all be implemented**
- **Degrees of freedom:** quantum numbers I, J, P, C are contained – as observed by experiment and calculated in first-principles approaches
- Suitable for dynamics → can **test structure of observed particles**
- **Historical success:** a simple chiral model predicted the sigma meson a decade before first experimental hints

Connection to QCD Degrees of Freedom



The diagram contains typical DSE solutions for the quark mass function from realistic truncations.

[G. Eichmann, H. Sanchis-Alepuz, R. Williams, R. Alkofer and C. S. Fischer, Prog. Part. Nucl. Phys. 91, 1 (2016); arXiv:1606.09602 [hep-ph]]

Mesons

$$\sqrt{2}\bar{q}_{j,R}q_{i,L} = \sqrt{2}\bar{q}_j\mathcal{P}_L\mathcal{P}_L q_i$$

$$\mathcal{P}_L = \frac{1-\gamma_5}{2}$$

$$= \frac{1}{\sqrt{2}}\left(\bar{q}_j q_i - \bar{q}_j\gamma^5 q_i\right) = \frac{1}{\sqrt{2}}\left(\bar{q}_j q_i + i\bar{q}_j i\gamma^5 q_i\right)$$

scalar pseudoscalar

$$P = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\eta_N + \pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta_N - \pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & \eta_S \end{pmatrix}$$

$u\bar{d}$

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

Linear Sigma Model

- $\Phi = S + iP \qquad L_\mu = V_\mu + A_\mu \qquad R_\mu = V_\mu - A_\mu$

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

$$D_\mu\Phi = \partial_\mu\Phi + ig_1(\Phi R_\mu - L_\mu\Phi)$$

$$L_{\mu\nu} = \partial_\mu L_\nu - \partial_\nu L_\mu$$

$$R_{\mu\nu} = \partial_\mu R_\nu - \partial_\nu R_\mu$$

Explicit Symmetry Breaking

Chiral Anomaly

Ground states!

The Point of Our Study

- **Consider two hypotheses:**
  ***i*) f_0(1790) and a_0(1950) are excited scalar quarkonia**
  ***ii*) pseudoscalars above 1 GeV are excited scalar quarkonia**
- **The study is performed by adding a scalar and a pseudoscalar nonet of excited states to the ground-state model**

Content of Excited States

$f_0(1790)$ → $\frac{(\sigma_N^E + a_0^{0E})}{\sqrt{2}}$

$\eta(1295)$ → $\frac{i(\eta_N^E + \pi^{0E})}{\sqrt{2}}$

$a_0(1950)$ → a_0^{+E}

$$\Phi_E = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{(\sigma_N^E + a_0^{0E}) + i(\eta_N^E + \pi^{0E})}{\sqrt{2}} & a_0^{+E} + i\pi^{+E} & K_0^{\star +E} + iK^{+E} \\ a_0^{-E} + i\pi^{-E} & \frac{(\sigma_N^E - a_0^{0E}) + i(\eta_N^E - \pi^{0E})}{\sqrt{2}} & K_0^{\star 0E} + iK^{0E} \\ K_0^{\star -E} + iK^{-E} & \bar{K}_0^{\star 0E} + i\bar{K}^{0E} & \sigma_S^E + i\eta_S^E \end{pmatrix}$$

η_S^E → $\eta(1440)$

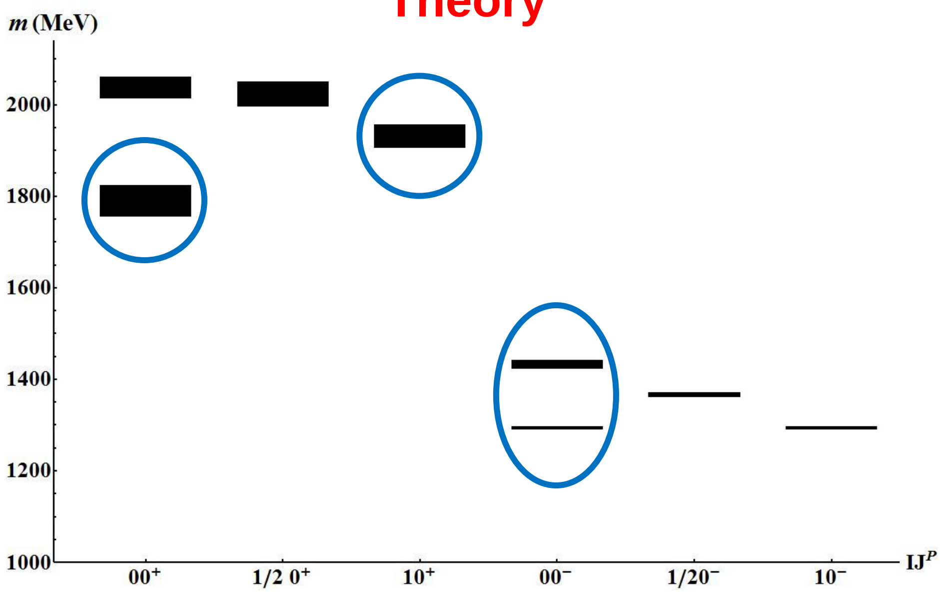
The Model for the Excited States

$$\mathcal{L}_E = \mathrm{Tr}[(D_\mu\Phi_E)^\dagger(D_\mu\Phi_E)] + \alpha\,\mathrm{Tr}[(D_\mu\Phi_E)^\dagger(D_\mu\Phi) + (D_\mu\Phi)^\dagger(D_\mu\Phi_E)] - (m_0^*)^2\left(\frac{G}{G_0}\right)^2 \mathrm{Tr}(\Phi_E^\dagger\Phi_E)$$
$$-\lambda_0\left(\frac{G}{G_0}\right)^2 \mathrm{Tr}(\Phi_E^\dagger\Phi + \Phi^\dagger\Phi_E) - \lambda_1^*\,\mathrm{Tr}(\Phi_E^\dagger\Phi_E)\,\mathrm{Tr}(\Phi^\dagger\Phi) - \lambda_2^*\,\mathrm{Tr}(\Phi_E^\dagger\Phi_E\Phi^\dagger\Phi + \Phi_E\Phi_E^\dagger\Phi\Phi^\dagger)$$
$$-\kappa_1\,\mathrm{Tr}(\Phi_E^\dagger\Phi + \Phi^\dagger\Phi_E)\,\mathrm{Tr}(\Phi^\dagger\Phi) - \kappa_2[\mathrm{Tr}(\Phi_E^\dagger\Phi + \Phi^\dagger\Phi_E)]^2 - \kappa_3\,\mathrm{Tr}(\Phi_E^\dagger\Phi + \Phi^\dagger\Phi_E)\,\mathrm{Tr}(\Phi_E^\dagger\Phi_E) - \kappa_4[\mathrm{Tr}(\Phi_E^\dagger\Phi_E)]^2$$
$$-\xi_1\,\mathrm{Tr}(\Phi_E^\dagger\Phi\Phi^\dagger\Phi + \Phi_E\Phi^\dagger\Phi\Phi^\dagger) - \xi_2\,\mathrm{Tr}(\Phi_E^\dagger\Phi\Phi_E^\dagger\Phi + \Phi^\dagger\Phi_E\Phi^\dagger\Phi_E) - \xi_3\,\mathrm{Tr}(\Phi^\dagger\Phi_E\Phi_E^\dagger\Phi_E + \Phi\Phi_E^\dagger\Phi_E\Phi_E^\dagger) - \xi_4\,\mathrm{Tr}(\Phi_E^\dagger\Phi_E)^2$$
$$+\mathrm{Tr}(\Phi_E^\dagger\Phi_E E_1 + \Phi_E\Phi_E^\dagger E_1) + c_1^*[(\det\Phi - \det\Phi_E^\dagger)^2 + (\det\Phi^\dagger - \det\Phi_E)^2] + c_{1E}^*(\det\Phi_E - \det\Phi_E^\dagger)^2$$
$$+\frac{h_1^*}{2}\mathrm{Tr}(\Phi_E^\dagger\Phi + \Phi^\dagger\Phi_E)\,\mathrm{Tr}(L_\mu^2 + R_\mu^2) + \frac{h_{1E}^*}{2}\mathrm{Tr}(\Phi_E^\dagger\Phi_E)\,\mathrm{Tr}(L_\mu^2 + R_\mu^2)$$
$$+h_2^*\,\mathrm{Tr}(\Phi_E^\dagger L_\mu L^\mu\Phi + \Phi^\dagger L_\mu L^\mu\Phi_E + R_\mu\Phi_E^\dagger\Phi R^\mu + R_\mu\Phi^\dagger\Phi_E R^\mu) + h_{2E}^*\,\mathrm{Tr}[|L_\mu\Phi_E|^2 + |\Phi_E R_\mu|^2]$$
$$+2h_3^*\,\mathrm{Tr}(L_\mu\Phi_E R^\mu\Phi^\dagger + L_\mu\Phi R^\mu\Phi_E^\dagger) + 2h_{3E}^*\,\mathrm{Tr}(L_\mu\Phi_E R^\mu\Phi_E^\dagger)\;.$$

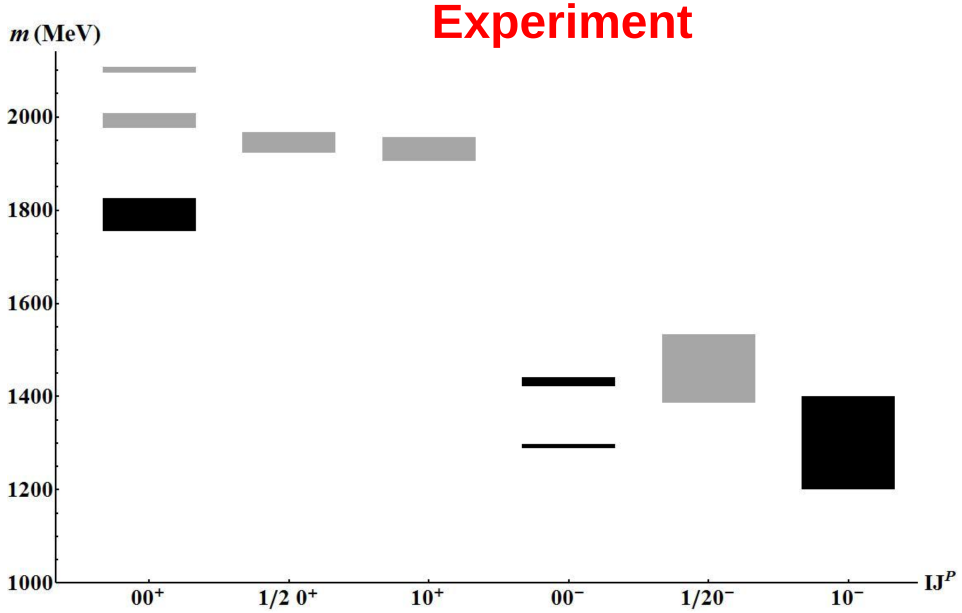
- **No mixing among excited states**
- **No mixing of excited states with ground states**
- **Discard large-N_c suppressed terms**
- **Then masses are determined by 4 parameters and more than 35 decays by 2 parameters**

Masses

Theory



Experiment



Encircled blue: input masses

Shaded areas: unconfirmed states

Results

Model state	IJ^P	Mass (MeV)	Decay	Width (MeV)	Note
σ_N^E	00^+	1790 ± 35*	$\sigma_N^E \to \pi\pi$	270 ± 45*	Assigned to $f_0(1790)$; mass, $\pi\pi$ and KK decay widths fixed to BES II data [127]. Other decays not (yet) measured.
			$\sigma_N^E \to KK$	70 ± 40*	
			$\sigma_N^E \to a_1(1260)\pi$	47 ± 8	
			$\sigma_N^E \to \eta\eta'$	10 ± 2	
			$\sigma_N^E \to \eta\eta$	7 ± 1	
			$\sigma_N^E \to f_1(1285)\eta$	1 ± 0	
			$\sigma_N^E \to K_1 K$	0	
			$\sigma_N^E \to \sigma_N \pi\pi$	0	
			Total	405 ± 96	
a_0^E	10^+	1931 ± 26*	$a_0^E \to \eta\pi$	94 ± 16	Candidate state: $a_0(1950)$ recently measured by BABAR; $m_{a_0(1950)} = (1931 \pm 26)$ MeV and $\Gamma_{a_0(1950)} = (271 \pm 40)$ MeV [183]. Requires confirmation [5].
			$a_0^E \to KK$	94 ± 54	
			$a_0^E \to \eta'\pi$	48 ± 8	
			$a_0^E \to f_1(1285)\pi$	28 ± 5	
			$a_0^E \to K_1 K$	9 ± 5	
			$a_0^E \to a_1(1260)\eta$	6 ± 1	
			$a_0^E \to a_0(1450)\pi\pi$	1 ± 1	
			Total	280 ± 90	
η_N^E	00^-	1294 ± 4*	$\eta_N^E \to \eta\pi\pi + \eta'\pi\pi + \pi KK$	7 ± 3	Assigned to $\eta(1295)$; PDG mass [5].
η_S^E	00^-	1432 ± 10*	$\eta_S^E \to K^\star K$	128^{+204}_{-128}	Assigned to $\eta(1440)$; mass from BES data [191, 192]. Full width ~ 100 MeV at this mass [192]. $\Gamma_{\eta(1440)\to\eta\pi\pi}$ suppressed [192].
			$\eta_S^E \to KK\pi$	28^{+41}_{-28}	
			$\eta_S^E \to \eta\pi\pi$ and $\eta'\pi\pi$	suppressed	
			Total	156^{+245}_{-156}	

[See 1612.09218 for more details]

Results

σ_S^E	00^+	2038 ± 24	$\sigma_S^E \to KK$	24^{+46}_{-24}	Candidate states: $f_0(2020)$; $m_{f_0(2020)} = (1992 \pm 16)$ MeV and $\Gamma_{f_0(2020)} = (442 \pm 60)$ MeV
			$\sigma_S^E \to \eta\eta'$	16 ± 3	
			$\sigma_S^E \to \eta\eta$	7 ± 1	
			$\sigma_S^E \to K_1 K$	4^{+8}_{-4}	and
			$\sigma_S^E \to \eta'\eta'$	1 ± 0	
			$\sigma_S^E \to \pi\pi$, $\rho\rho$ and $\omega\omega$	suppressed	$f_0(2100)$;
			$\sigma_S^E \to a_1(1260)\pi$ and $f_1(1285)\eta$	suppressed	$m_{f_0(2100)} = (2101 \pm 7)$ MeV and
			$\sigma_S^E \to \pi^E \pi$ and $\eta_N^E \eta$	suppressed	$\Gamma_{f_0(2101)} = 224^{+23}_{-21}$ MeV.
			$\sigma_S^E \to \sigma_S \pi\pi$	suppressed	
			Total	52^{+58}_{-32}	Both require confirmation [5].
$K_0^{\star E}$	$\frac{1}{2}0^+$	2023 ± 27	$K_0^{\star E} \to \eta' K$	72 ± 12	
			$K_0^{\star E} \to K\pi$	66 ± 46	
			$K_0^{\star E} \to K_1 \pi$	10 ± 7	Candidate state: $K_0^\star(1950)$;
			$K_0^{\star E} \to a_1(1260) K$	6 ± 4	$m_{K_0^\star(1950)} = (1945 \pm 22)$ MeV and
			$K_0^{\star E} \to \eta K$	6^{+9}_{-6}	$\Gamma_{K_0^\star(1950)} = (201 \pm 90)$ MeV.
			$K_0^{\star E} \to f_1(1285) K$	2 ± 1	
			$K_0^{\star E} \to K_1 \eta$	0	Requires confirmation [5].
			$K_0^{\star E} \to K_0^\star(1430)\pi\pi$	0	
			Total	162^{+79}_{-76}	
π^E	10^-	1294 ± 4	-	-	Width badly defined due to large errors of the experimental input data.
K^E	$\frac{1}{2}0^-$	1366 ± 6	-	-	Width badly defined due to large errors of the experimental input data.

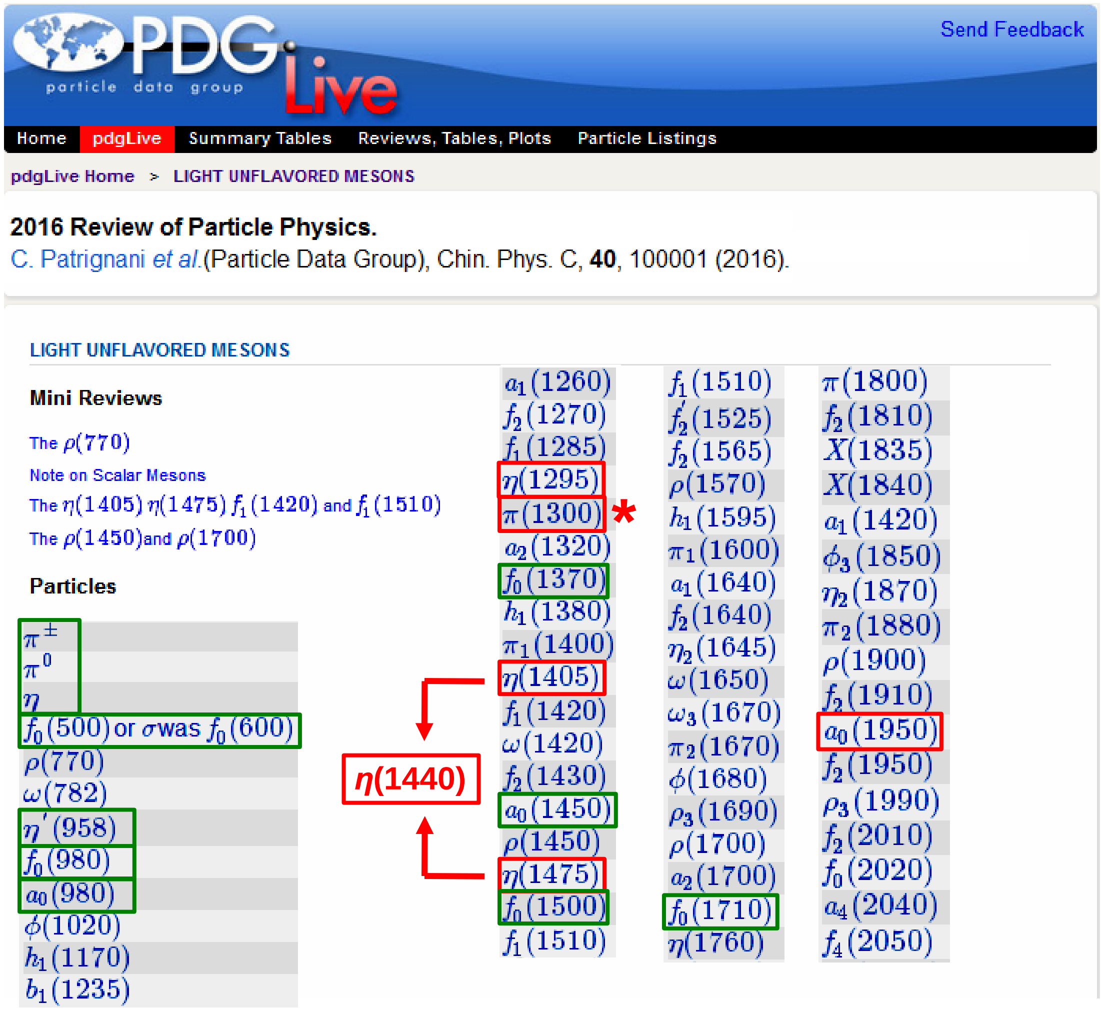
[See 1612.09218 for more details]

Enforcing Excited Pseudoscalars as Quarkonia

Model state	IJ^P	Mass (MeV)	Decay	Width (MeV)	Note
η_N^E	00^-	1294 ± 4	$\eta_N^E \to \eta\pi\pi + \eta'\pi\pi + \pi K K$	55 ± 5*	Assigned to $\eta(1295)$; PDG mass [5].
η_S^E	00^-	1432 ± 10	$\eta_S^E \to K^\star K$ $\eta_S^E \to K K \pi$ $\eta_S^E \to \eta\pi\pi$ and $\eta'\pi\pi$ Total	26 ± 3* 3 ± 0 suppressed 29 ± 3	Assigned to $\eta(1440)$; mass and $K^\star K$ width from Refs. [191, 192]. Our estimate for $\Delta\Gamma_{\eta(1440)\to K^\star K}$.
π^E	10^-	1294 ± 4	$\pi^E \to \rho\pi$ $\pi^E \to 3\pi$ $\pi^E \to K K \pi$ Total	368 ± 37 204 ± 15 2 ± 0 574 ± 52	Assigned to $\pi(1300)$; degenerate in mass with $\eta(1295)$ according to Eq. (32). Compares well with $\Gamma_{\pi(1300)} = (200 - 600)$ MeV [5].
K^E	$\frac{1}{2}0^-$	1366 ± 6	$K^E \to K^\star\pi$ $K^E \to K\pi\pi$ $K^E \to \rho K$ $K^E \to \omega K$ $K^E \to K\pi\eta$ Total	112 ± 11 35 ± 4 20 ± 2 7 ± 1 0 174 ± 18	Assigned to $K(1460)$; $m_{K(1460)} \sim 1460$ Me $\Gamma_{K(1460)} \sim 260$ MeV [5].
All scalars	-			Calculated via Eqs. (39), (41), (43), (45) and Eq. (53).	Unobservable due to extremely large decays into vectors [$\mathcal{O}$(1 GeV)].

[See 1612.09218 for more details]

The Need for Excited States



Green: ground state (not necessarily quarkonium)

Red: excited state

one state: $\eta(1440)$

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Particles

- $K^\pm$
- K^0
- K^0_S
- K^0_L
- $K^*_0(800)$ or κ
- $K^*(892)$
- $K_1(1270)$
- $K_1(1400)$
- $K^*(1410)$
- $K^*_0(1430)$
- $K^*_2(1430)$
- $K(1460)$ *
- $K_2(1580)$
- $K(1630)$
- $K_1(1650)$
- $K^*(1680)$
- $K_2(1770)$
- $K^*_3(1780)$
- $K_2(1820)$
- $K(1830)$
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- $K_3(2320)$
- $K^*_5(2380)$
- $K_4(2500)$
- $K(3100)$

Green: ground state (not necessarily quarkonium)

Red: excited state

one state: $\eta(1440)$

Conclusion

- **Excited scalar and pseudoscalar mesons have been investigated in the Extended Linear Sigma Model**
- **The model also contains ground-state (pseudo)scalars and (axial-)vectors**
- **The main goal was to test whether f_0(1790) and the recently observed a_0(1950) can be interpreted as excited scalar mesons**
- **The answer is positive but there appears to be tension with the simultaneous interpretation of pseudoscalars above 1 GeV as excited states**
- **The study has predicted more than 35 decays – all of them measurable by BABAR, BES, LHCb and PANDA**