Excited vector mesons: phenomenology and predictions for a yet unknown vector $s\bar{s}$ state with a mass of about 1.93 GeV

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Based on arXiv:1708.02593

Kolymbari, August 21, 2017

Outline

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Motivation

- Understanding of hadronic resonances.
- Study the decays of two nonets of excited vector mesons predominantly corresponding to 1^3D_1 and 2^3S_1.
- Making predictions for $\bar{s}s$ state in 1^3D_1 nonet.

J^{PC} classification

State	S	L	J	P	C	J^{PC}	Mesons	Name
$^1S_0$	0	0	0	-	+	0^{-+}	π η η' K	pseudoscalar
$^3S_1$	1	0	0	-	-	1^{--}	ρ ω ϕ K^*	vector
$^1P_1$	0	1	1	+	-	1^{+-}	b_1 h_1 h'_1 K_1	pseudo-vector
$^3P_0$	1	1	0	+	+	0^{++}	a_0 f_0 f'_0 K^*_0	scalar
$^3P_1$	1	1	1	+	+	1^{++}	a_1 f_1 f'_1 K_1	axial vector
$^3P_2$	1	1	2	+	+	2^{++}	a_2 f_2 f'_2 K^*_2	tensor

- Not all quantum numbers are permitted for a quark - antiquark states.

$$J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, \cdots$$

are exotic quantum numbers.

PDG quark-antiquark listing/1

Table 15.2: Suggested $q\bar{q}$ quark-model assignments for some of the observed light mesons. Mesons in bold face are included in the Meson Summary Table. The wave functions f and f' are given in the text. The singlet-octet mixing angles from the quadratic and linear mass formulae are also given for the well established nonets. The classification of the 0^{++} mesons is tentative: the light scalars $a_0(980)$, $f_0(980)$, $f_0(500)$ and $K_0^*(800)$ are often considered to be meson-meson resonances or four-quark states, and are omitted from the table. The isoscalar 0^{++} mesons are expected to mix. In particular, the $f_0(1710)$ mixes with the $f_0(1500)$ and the $f_0(1370)$. The $a_0(1450)$ is not firmly established. See the "Note on Non-$q\bar{q}$ mesons" and the "Note on Scalar Mesons" in the Meson Listings for details and alternative schemes. In the 1^{++} nonet the isoscalar slot is disputed by the $f_1(1510)$. The isoscalar assignments in the 2^1S_0 (0^{++}) nonet are also tentative. See the "Note on The Pseudoscalar and Pseudovector Mesons in the 1400 MeV Region" in the Meson Listings.

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $u\bar{d}$, $\bar{u}d$, $\frac{1}{\sqrt{2}}(d\bar{d}-u\bar{u})$	I = $\frac{1}{2}$ $u\bar{s}$, $d\bar{s}$; $\bar{d}s$, $-\bar{u}s$	I = 0 f'	I = 0 f	θ_{quad} [°]	θ_{lin} [°]
$1\,^1S_0$	0^{-+}	**π**	**K**	**η**	**$\eta'(958)$**	−11.4	−24.5
$1\,^3S_1$	1^{--}	**$\rho(770)$**	**$K^*(892)$**	**$\phi(1020)$**	**$\omega(782)$**	39.1	36.4
$1\,^1P_1$	1^{+-}	**$b_1(1235)$**	**K_{1B}**†	$h_1(1380)$	**$h_1(1170)$**		
$1\,^3P_0$	0^{++}	**$a_0(1450)$**	**$K_0^*(1430)$**	**$f_0(1710)$**	**$f_0(1370)$**		
$1\,^3P_1$	1^{++}	**$a_1(1260)$**	**K_{1A}**†	**$f_1(1420)$**	**$f_1(1285)$**		
$1\,^3P_2$	2^{++}	**$a_2(1320)$**	**$K_2^*(1430)$**	**$f_2'(1525)$**	**$f_2(1270)$**	32.1	30.5
$1\,^1D_2$	2^{-+}	**$\pi_2(1670)$**	**$K_2(1770)$**†	$\eta_2(1870)$	**$\eta_2(1645)$**		
$1\,^3D_1$	1^{--}	**$\rho(1700)$**	**$K^*(1680)$**		**$\omega(1650)$**		
$1\,^3D_2$	2^{--}		**$K_2(1820)$**				
$1\,^3D_3$	3^{--}	**$\rho_3(1690)$**	**$K_3^*(1780)$**	**$\phi_3(1850)$**	**$\omega_3(1670)$**	31.8	30.8
$1\,^3F_4$	4^{++}	**$a_4(2040)$**	**$K_4^*(2045)$**		**$f_4(2050)$**		
$1\,^3G_5$	5^{--}	$\rho_5(2350)$	$K_5^*(2380)$				
$1\,^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$		
$2\,^1S_0$	0^{-+}	**$\pi(1300)$**	$K(1460)$	**$\eta(1475)$**	**$\eta(1295)$**		
$2\,^3S_1$	1^{--}	**$\rho(1450)$**	**$K^*(1410)$**	**$\phi(1680)$**	**$\omega(1420)$**		

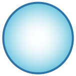
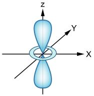
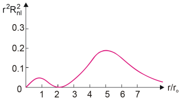
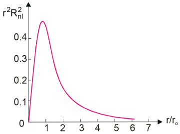
PDG quark-antiquark listing/2

Table 15.3: $q\overline{q}$ quark-model assignments for the observed heavy mesons with established J^{PC}. Mesons in bold face are included in the Meson Summary Table.

$n\,^{2s+1}\ell_J$	J^{PC}	I = 0 $c\overline{c}$	I = 0 $b\overline{b}$	I = $\frac{1}{2}$ $c\overline{u}$, $c\overline{d}$; $\overline{c}u$, $\overline{c}d$	I = 0 $c\overline{s}$; $\overline{c}s$	I = $\frac{1}{2}$ $b\overline{u}$, $b\overline{d}$; $\overline{b}u$, $\overline{b}d$	I = 0 $b\overline{s}$; $\overline{b}s$	I = 0 $b\overline{c}$; $\overline{b}c$
$1\,^1S_0$	0^{-+}	$\eta_c(1S)$	$\eta_b(1S)$	D	$D_s^\pm$	B	B_s^0	$B_c^\pm$
$1\,^3S_1$	1^{--}	$J/\psi(1S)$	$\Upsilon(1S)$	D^*	$D_s^{*\pm}$	B^*	B_s^*	
$1\,^1P_1$	1^{+-}	$h_c(1P)$	$h_b(1P)$	$D_1(2420)$	$D_{s1}(2536)^\pm$	$B_1(5721)$	$B_{s1}(5830)^0$	
$1\,^3P_0$	0^{++}	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$D_0^*(2400)$	$D_{s0}^*(2317)^{\pm\dagger}$			
$1\,^3P_1$	1^{++}	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	$D_1(2430)$	$D_{s1}(2460)^{\pm\dagger}$			
$1\,^3P_2$	2^{++}	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$D_2^*(2460)$	$D_{s2}^*(2573)^\pm$	$B_2^*(5747)$	$B_{s2}^*(5840)^0$	
$1\,^3D_1$	1^{--}	$\psi(3770)$			$D_{s1}^*(2860)^{\pm\ddagger}$			
$1\,^3D_3$	3^{--}				$D_{s3}^*(2860)^\pm$			
$2\,^1S_0$	0^{-+}	$\eta_c(2S)$	$\eta_b(2S)$	$D(2550)$				
$2\,^3S_1$	1^{--}	$\psi(2S)$	$\Upsilon(2S)$		$D_{s1}^*(2700)^{\pm\ddagger}$			
$2\,^1P_1$	1^{+-}		$h_b(2P)$					
$2\,^3P_{0,1,2}$	$0^{++},1^{++},2^{++}$	$\chi_{c0,2}(2P)$	$\chi_{b0,1,2}(2P)$					
$3\,^3P_{0,1,2}$	$0^{++},1^{++},2^{++}$		$\chi_b(3P)$					

† The masses of these states are considerably smaller than most theoretical predictions. They have also been considered as four-quark states.
‡ These states are mixtures of the $1\,^3D_1$ and $2\,^3S_1$ states.
The open flavor states in the 1^{+-} and 1^{++} rows are mixtures of the $1^{+\pm}$ states.

Decays of excited vector mesons

Type of excitation	Radially excited vector mesons	Angular momentum excited vector mesons
Quantum numbers	n $^{2S+1}L_J = 2^3S_1$	n $^{2S+1}L_J = 1^3D_1$
Notation	V_E	V_D
S	1 $\uparrow\uparrow$	1 $\uparrow\uparrow$
n	2	1
L	0	2
orbital		
Radial function		
Associated states	$\rho(1450), K^*(1410), \phi(1680), \omega(1420)$	$\rho(1700), K^*(1680), \phi(1930), \omega(1650)$
Decay types	$V_E \to PP$ $V_E \to VP$ $V_E \to \gamma P$	$V_D \to PP$ $V_D \to VP$ $V_D \to \gamma P$

Nonets of mesons

$$P = \begin{pmatrix} \frac{1}{\sqrt{2}}\frac{\eta_N+\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta_N-\pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & \eta_S \end{pmatrix} \qquad V^\mu = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\omega^\mu+\rho^{\mu 0}}{\sqrt{2}} & \rho^{\mu +} & K_i^{\mu\star +} \\ \rho^{\mu -} & \frac{\omega^\mu-\rho^{\mu 0}}{\sqrt{2}} & K^{\mu\star 0} \\ K^{\mu\star -} & \bar{K}^{\mu\star 0} & \phi^\mu \end{pmatrix}$$

$$V_E^\mu = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\omega_E^\mu+\rho_E^{\mu 0}}{\sqrt{2}} & \rho_E^{\mu +} & K_E^{\mu\star +} \\ \rho_E^{\mu -} & \frac{\omega_E^\mu-\rho_E^{\mu 0}}{\sqrt{2}} & K_E^{\mu\star 0} \\ K_E^{\mu\star -} & \bar{K}_E^{\mu\star 0} & \phi_E^\mu \end{pmatrix} \qquad V_D^\mu = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\omega_D^\mu+\rho_D^{\mu 0}}{\sqrt{2}} & \rho_D^{\mu +} & K_D^{\mu\star +} \\ \rho_D^{\mu -} & \frac{\omega_D^\mu-\rho_D^{\mu 0}}{\sqrt{2}} & K_D^{\mu\star 0} \\ K_D^{\mu\star -} & \bar{K}_D^{\mu\star 0} & \phi_D^\mu \end{pmatrix}$$

- $P = \{\pi, K, \eta, \eta'\}$
- $V = \{\rho(770), K^*(892), \phi(1020), \omega(782)\}$
- $V_E = \{\rho(1450), K^*(1410), \phi(1680), \omega(1420)\}$
- $V_D = \{\rho(1700), K^*(1680), \phi(1930), \omega(1650)\}$

The Lagrangian

The Lagrangian of the model is:

$$\mathcal{L} = \mathcal{L}_{EPP} + \mathcal{L}_{DPP} + \mathcal{L}_{EVP} + \mathcal{L}_{DVP},$$

where:

$$\mathcal{L}_{EPP} = ig_{EPP} Tr[\partial^{\mu} P, V_{E,\mu}]P \qquad \mathcal{L}_{DPP} = ig_{DPP} Tr[\partial^{\mu} P, V_{D,\mu}]P$$

$$\mathcal{L}_{EVP} = g_{EVP} Tr[\tilde{V}_{E}^{\mu\nu}\{V_{\mu\nu}, P\}] \qquad \mathcal{L}_{DVP} = g_{DVP} Tr[\tilde{V}_{D}^{\mu\nu}\{V_{\mu\nu}, P\}]$$

$g_{EPP}, g_{DPP}, g_{EVP}, g_{DVP}-$ coupling constants of the different decay types.

- $R \to \gamma P$ through „vector meson dominance"

$$V_{\mu\nu} \to V_{\mu\nu} + \frac{e_0}{g_\rho} Q F_{\mu\nu}$$

$F_{\mu\nu}-$ field strength tensor for photons
$e_0 = \sqrt{4\pi\alpha} \quad \alpha \approx 1/137 \quad g_\rho \approx 5.5 \pm 0.5 \quad Q = diag(\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3})$

=

$$\mathcal{L}_1 = ia\,\mathrm{Tr}\big[[\partial^\mu P, V_\mu]P\big] =$$

$$\frac{ia}{4}\Big\{K^{*0}_\mu\Big((\partial^\mu \overline{K}^0)\pi^0 - \overline{K}^0(\partial^\mu\pi^0) - \sqrt{2}(\partial^\mu K^-)\pi^+ + \sqrt{2}K^-(\partial^\mu\pi^+)$$
$$+ (\partial^\mu\eta_N)\overline{K}^0 - \eta_N(\partial^\mu\overline{K}^0) + \sqrt{2}\eta_S(\partial^\mu\overline{K}^0) - \sqrt{2}(\partial^\mu\eta_S)\overline{K}^0\Big)$$
$$+ \overline{K}^{*0}_\mu\Big(K^0(\partial^\mu\pi^0) - (\partial^\mu K^0)\pi^0 - \sqrt{2}K^+(\partial^\mu\pi^-) + \sqrt{2}(\partial^\mu K^+)\pi^-$$
$$+ \eta_N(\partial^\mu K^0) - (\partial^\mu\eta_N)K^0 - \sqrt{2}\eta_S(\partial^\mu K^0) + \sqrt{2}(\partial^\mu\eta_S)K^0\Big)$$
$$+ \mathrm{K}^{*-}_\mu\Big((\partial^\mu K^+)\pi^0 - K^+(\partial^\mu\pi^0) - \sqrt{2}K^0(\partial^\mu\pi^+) + \sqrt{2}(\partial^\mu K^0)\pi^+$$
$$+ \eta_N(\partial^\mu K^+) - (\partial^\mu\eta_N)K^+ - \sqrt{2}\eta_S(\partial^\mu K^+) + \sqrt{2}(\partial^\mu\eta_S)K^+\Big)$$
$$+ \mathrm{K}^{*+}_\mu\Big(K^-(\partial^\mu\pi^0) - (\partial^\mu K^-)\pi^0 - \sqrt{2}(\partial^\mu\overline{K}^0)\pi^- + \sqrt{2\overline{K}^0}(\partial^\mu\pi^-)$$
$$+ (\partial^\mu\eta_N)K^- - \eta_N(\partial^\mu K^-) + \sqrt{2}\eta_S(\partial^\mu K^-) - \sqrt{2}(\partial^\mu\eta_S)K^-\Big)$$
$$+ \rho^0_\mu\Big(\overline{K}^0(\partial^\mu K^0) - (\partial^\mu\overline{K}^0)K^0 + K^+(\partial^\mu K^-) - (\partial^\mu K^+)K^- + 2\pi^+(\partial^\mu\pi^-) - 2(\partial^\mu\pi^+)\pi^-\Big)$$
$$+ \rho^-_\mu\Big(\sqrt{2}K^+(\partial^\mu\overline{K}^0) - \sqrt{2}(\partial^\mu K^+)\overline{K}^0 + 2\pi^0(\partial^\mu\pi^+) - 2(\partial^\mu\pi^0)\pi^+\Big)$$
$$+ \rho^+_\mu\Big(\sqrt{2}K^0(\partial^\mu K^-) - \sqrt{2}(\partial^\mu K^0)K^- + 2(\partial^\mu\pi^0)\pi^- - 2\pi^0(\partial^\mu\pi^-)\Big)$$
$$+ \omega\Big(K^0(\partial^\mu\overline{K}^0) - (\partial^\mu K^0)\overline{K}^0 + K^+(\partial^\mu K^-) - (\partial^\mu K^+)K^-\Big)$$
$$+ \sqrt{2}\phi\Big((\partial^\mu K^0)\overline{K}^0 - K^0(\partial^\mu\overline{K}^0) - K^+(\partial^\mu K^-) + (\partial^\mu K^+)K^-\Big)\Big\}.$$

$$\mathcal{L}_2 = b\,\mathrm{Tr}\big[\tilde{E}^{\mu\nu}\{V_{S,\mu\nu},P\}\big] = 2b\,\epsilon^{\mu\nu\alpha\beta}\,\mathrm{Tr}\big[(\partial_\alpha E_\beta)\{(\partial_\mu V_{S,\nu}),P\}\big]$$

$$= \frac{b}{2}\epsilon^{\mu\nu\alpha\beta}\Big\{(\partial_\alpha \rho^0_{E,\beta})\Big(2\pi^0(\partial_\mu\omega_\nu) + 2\eta_N(\partial_\mu\rho^0_\nu) - \overline{K}^0(\partial_\mu K^{*0}_\nu) - K^0(\partial_\mu \overline{K}^{*0}_\nu) + K^+(\partial_\mu K^{*-}_\nu) + K^-(\partial_\mu$$

$$+ \sqrt{2}(\partial_\alpha\rho^-_{E,\beta})\Big(\sqrt{2}\pi^+(\partial_\mu\omega_\nu) + \sqrt{2}\eta_N(\partial_\mu\rho^+_\nu) + K^+(\partial_\mu\overline{K}^{*0}_\nu) + \overline{K}^0(\partial_\mu K^{*+}_\nu)\Big)$$

$$+ \sqrt{2}(\partial_\alpha\rho^+_{E,\beta})\Big(\sqrt{2}\pi^-(\partial_\mu\omega_\nu) + \sqrt{2}\eta_N(\partial_\mu\rho^-_\nu) + K^-(\partial_\mu K^{*0}_\nu) + K^0(\partial_\mu K^{*-}_\nu)\Big)$$

$$+ \sqrt{2}(\partial_\alpha\phi_{E,\beta})\Big(2\eta_S(\partial_\mu\phi_\nu) + K^0(\partial_\mu\overline{K}^{*0}_\nu) + \overline{K}^0(\partial_\mu K^{*0}_\nu) + K^+(\partial_\mu K^{*-}_\nu) + K^-(\partial_\mu K^{*+}_\nu)\Big)$$

$$+ (\partial_\alpha\omega_{E,\beta})\Big(2\pi^0(\partial_\mu\rho^0_\nu) + 2\pi^+(\partial_\mu\rho^-_\nu) + 2\pi^-(\partial_\mu\rho^+_\nu) + 2\eta_N(\partial_\mu\omega_\nu)$$

$$+ K^0(\partial_\mu\overline{K}^{*0}_\nu) + \overline{K}^0(\partial_\mu K^{*0}_\nu) + K^+(\partial_\mu K^{*-}_\nu) + K^-(\partial_\mu K^{*+}_\nu)\Big)$$

$$+ (\partial_\alpha K^{*0}_{E,\beta})\Big(\overline{K}^0(\partial_\mu\omega_\nu) - \pi^0(\partial_\mu\overline{K}^{*0}_\nu) + \sqrt{2}\pi^+(\partial_\mu K^{*-}_\nu) - \overline{K}^0(\partial_\mu\rho^0_\nu) + \sqrt{2}K^-(\partial_\mu\rho^+_\nu)$$

$$+ \eta_N(\partial_\mu\overline{K}^{*0}_\nu) + \sqrt{2}\eta_S(\partial_\mu\overline{K}^{*0}_\nu) + \sqrt{2}\overline{K}^0(\partial_\mu\phi_\nu)\Big)$$

$$+ (\partial_\alpha\overline{K}^{*0}_{E,\beta})\Big(K^0(\partial_\mu\omega_\nu) - \pi^0(\partial_\mu K^{*0}_\nu) + \sqrt{2}\pi^-(\partial_\mu K^{*+}_\nu) - K^0(\partial_\mu\rho^0_\nu) + \sqrt{2}K^+(\partial_\mu\rho^-_\nu)$$

$$+ \eta_N(\partial_\mu K^{*0}_\nu) + \sqrt{2}\eta_S(\partial_\mu K^{*0}_\nu) + \sqrt{2}K^0(\partial_\mu\phi_\nu)\Big)$$

$$+ (\partial_\alpha K^{*-}_{E,\beta})\Big(K^+(\partial_\mu\omega_\nu) + \pi^0(\partial_\mu K^{*+}_\nu) + \sqrt{2}\pi^+(\partial_\mu K^{*0}_\nu) + K^+(\partial_\mu\rho^0_\nu) + \sqrt{2}K^0(\partial_\mu\rho^+_\nu)$$

$$+ \eta_N(\partial_\mu K^{*+}_\nu) + \sqrt{2}\eta_S(\partial_\mu K^{*+}_\nu) + \sqrt{2}K^+(\partial_\mu\phi_\nu)\Big)$$

$$+ (\partial_\alpha K^{*+}_{E,\beta})\Big(K^-(\partial_\mu\omega_\nu) + \pi^0(\partial_\mu K^{*-}_\nu) + \sqrt{2}\pi^-(\partial_\mu\overline{K}^{*0}_\nu) + K^-(\partial_\mu\rho^0_\nu) + \sqrt{2}\overline{K}^0(\partial_\mu\rho^-_\nu)$$

$$+ \eta_N(\partial_\mu K^{*-}_\nu) + \sqrt{2}\eta_S(\partial_\mu K^{*-}_\nu) + \sqrt{2}K^-(\partial_\mu\phi_\nu)\Big)\Big\}$$

Decay widths

TYPE OF DECAY

- $R \to PP$

$$\Gamma_{R\to PP} = S\frac{|\vec{k}|^3}{6\pi m_R^2}[\frac{g_{iPP}}{2}\lambda_{RPP}]^2$$

- $R \to VP, R \to \gamma P$

$$\Gamma_{R\to VP} = S\frac{|\vec{k}|^3}{12\pi}[\frac{g_{iVP}}{2}\lambda_{RVP}]^2$$

EXAMPLES

- $K^*(1410) \to K\eta$

$$\Gamma_{K^*(1410)\to K\eta} = \frac{|\vec{k}|^3}{6\pi m_{K^*(1410)}^2}[\frac{g_{EPP}}{2}\frac{1}{2}(cos\theta_p - \sqrt{2}sin\theta_p)]^2$$

- $\phi(1680) \to \phi(1020)\eta$

$$\Gamma_{\phi(1680)\to\phi(1020)\eta} = \frac{|\vec{k}|^3}{12\pi}[\frac{g_{EVP}}{2}\frac{sin\theta_p}{\sqrt{2}}]^2$$

where:

$|\vec{k}| = \frac{\sqrt{m_R^2+(m_a^2-m_b^2)^2-2(m_a^2+m_b^2)m_R^2}}{2m_R}$;

m_R- mass of the decaying resonance; m_a, m_b- masses of decay products;

$g_{iPP}, g_{iVP}-$ coupling constants ($i = E, D$); $S-$ symmetry factor;

$\theta-$ mixing angle ($\theta = 42^{\circ}$); $\lambda-$ amplitude factor.

Preditions for ϕ_p state

- $s\bar{s}$ state in 1^3D_1 nonet - resonance not yet known.
- Mass of $\phi(???)$

V_E	$\rho(1450)$	$K^*(1410)$	$\phi(1680)$	$\omega(1420)$
V_D	$\rho(1700)$	$K^*(1680)$	ϕ_p	$\omega(1650)$
Difference	250 MeV	270 MeV	?	230 MeV

$$m_{\phi_p} \simeq m_{\phi(1680)} + 250MeV \simeq 1930MeV$$

Coupling constants g_{EPP}, g_{EVP}

- $\Gamma^{exp}_{K^*(1410)\to K\pi} = 15.3 \pm 3.3$ MeV

– $\Gamma^{theory}_{K^*(1410)\to K\pi} = 3\frac{|\vec{k}(m_{K^*(1410)}, m_K, m_\pi)|^3}{6\pi m^2_{K^*(1410)}}(\frac{g_{EPP}}{2}\frac{1}{2})^2$

- $\Gamma^{tot,exp}_{\phi(1680)} = 150 \pm 50$ MeV

– $\Gamma^{theory}_{\phi(1680)\to K^*(892)K} = 4\frac{|\vec{k}(m_{\phi(1680)}, m_K, m_{K^*(892)})|^3}{12\pi}(\frac{g_{EVP}}{2}\frac{1}{2\sqrt{2}})^2$

– $\Gamma^{theory}_{\phi(1680)\to \phi(1020)\eta} = \frac{|\vec{k}(m_{\phi(1680)}, m_{\phi(1020)}, m_\eta)|^3}{12\pi}(\frac{g_{EVP}}{2}\frac{sin\theta_p}{\sqrt{2}})^2$

– $\Gamma^{theory}_{\phi(1680)\to \bar{K}K} = 2\frac{|\vec{k}(m_{\phi(1680)}, m_K, m_K)|^3}{6\pi m^2_{\phi(1680)}}(\frac{g_{EPP}}{2}\frac{1}{\sqrt{2}})^2$

- $F(g_{EPP}, g_{EVP}) = \left(\frac{\Gamma^{theory}_{K^*(1410\to K\pi)} - \Gamma^{exp}_{K^*(1410)\to K\pi}}{\delta\Gamma^{exp}_{K^*(1410)\to K\pi}}\right)^2 + \left(\frac{\Gamma^{theory}_{\phi(1680)\to K^*(892)K} + \Gamma^{theory}_{\phi(1680)\to\phi(1020)\eta} + \Gamma^{theory}_{\phi(1680)\to\bar{K}K} - \Gamma^{tot,exp}_{\phi(1680)}}{\delta\Gamma^{tot,exp}_{\phi(1680)}}\right)^2$

- $g_{EPP} \to 3.66 \pm 0.4$ $\quad g_{EVP} \to 18.4 \pm 3.8$

Coupling constants g_{DPP}, g_{DVP}

- $K^*(1680)$

  $\left.\frac{\Gamma_{K^*(1680)\to K\rho}}{\Gamma_{K^*(1680)\to K\pi}}\right|_{\rm exp} = 1.2 \pm 0.4$

  - $\Gamma^{theory}_{K^*(1680)\to K\rho} = 3\frac{|\vec{k}(m_{K^*(1680)}, m_K, m_\rho)|^3}{12\pi}(\frac{g_{DVP}}{2}\frac{1}{4})^2$
  - $\Gamma^{theory}_{K^*(1680)\to K\pi} = 3\frac{|\vec{k}(m_{K^*(1680)}, m_K, m_\pi)|^3}{6\pi m^2_{K^*(1680)}}(\frac{g_{DPP}}{2}\frac{1}{2})^2$

- Determination of $\Gamma_{K^*(1680)\to K\pi}$

  $$\left.\begin{array}{l} -\left.\frac{\Gamma_{K^*(1680)\to K\pi}}{\Gamma^{tot,exp}_{K^*(1680)}}\right|_{\rm exp} = 0.387 \pm 0.036 \\ -\Gamma^{tot,exp}_{K^*(1680)} = 205 \pm 50 MeV \end{array}\right\} \Rightarrow \Gamma^{exp}_{K^*(1680)\to K\pi} = 79 \pm 21 MeV$$

- $F(g_{DPP}, g_{DVP}) =$

$$\left(\frac{\Gamma^{theory}_{K^*(1680)\to K\pi} - \Gamma^{exp}_{K^*(1680)\to K\pi}}{\delta\Gamma^{exp}_{K^*(1680\to K\pi)}}\right)^2 + \left(\frac{\frac{\Gamma^{theory}_{K^*(1680)\to K\rho}}{\Gamma^{theory}_{K^*(1680)\to K\pi}} - \left.\frac{\Gamma_{K^*(1680)\to K\rho}}{\Gamma_{K^*(1680)\to K\pi}}\right|_{\rm exp}}{\delta\left.\frac{\Gamma_{K^*(1680)\to K\rho}}{\Gamma_{K^*(1680)\to K\pi}}\right|_{\rm exp}}\right)^2$$

- $g_{DPP} = 7.15 \pm 0.94$ $\quad$ $g_{DVP} = 16.5 \pm 3.5$

Decay widths $R \to PP$

Decay channel $V_E \to PP$	Decay channel $V_D \to PP$	Symmetry factor	Amplitude
$\rho(1450) \to \bar{K}K$	$\rho(1700) \to \bar{K}K$	2	$\frac{1}{2}$
$\rho(1450) \to \pi\pi$	$\rho(1700) \to \pi\pi$	1	1
$K^*(1410) \to K\pi$	$K^*(1680) \to K\pi$	3	$\frac{1}{2}$
$K^*(1410) \to K\eta$	$K^*(1680) \to K\eta$	1	$\frac{1}{2}(Cos\theta_p - \sqrt{2}Sin\theta_p)$
$K^*(1410) \to K\eta'$	$K^*(1680) \to K\eta'$	1	$\frac{1}{2}(\sqrt{2}Cos\theta_p + Sin\theta_p)$
$\phi(1680) \to \bar{K}K$	$\phi(1930) \to \bar{K}K$	2	$\frac{1}{\sqrt{2}}$
$\omega(1420) \to \bar{K}K$	$\omega(1650) \to \bar{K}K$	2	$\frac{1}{2}$

Decay widths $R \to VP$

Decay channel $V_E \to VP$	Decay channel $V_D \to VP$	Symmetry factor	Amplitude
$\rho(1450) \to \omega\pi$	$\rho(1700) \to \omega\pi$	1	$\frac{1}{2}$
$\rho(1450) \to K^*(892)K$	$\rho(1700) \to K^*(892)K$	4	$\frac{1}{4}$
$\rho(1450) \to \rho(770)\eta$	$\rho(1700) \to \rho(770)\eta$	1	$\frac{1}{2}Cos\theta_p$
$\rho(1450) \to \rho(770)\eta'$	$\rho(1700) \to \rho(770)\eta'$	1	$\frac{1}{2}Sin\theta_p$
$K^*(1410) \to K\rho$	$K^*(1680) \to K\rho$	3	$\frac{1}{4}$
$K^*(1410) \to K\phi$	$K^*(1680) \to K\phi$	1	$\frac{1}{2\sqrt{2}}$
$K^*(1410) \to K\omega$	$K^*(1680) \to K\omega$	1	$\frac{1}{4}$
$K^*(1410) \to K^*(892)\pi$	$K^*(1680) \to K^*(892)\pi$	3	$\frac{1}{4}$
$K^*(1410) \to K^*(892)\eta$	$K^*(1680) \to K^*(892)\eta$	1	$\frac{1}{4}(Cos\theta_p + \sqrt{2}Sin\theta_p)$
$K^*(1410) \to K^*(892)\eta'$	$K^*(1680) \to K^*(892)\eta'$	2	$\frac{1}{4}(\sqrt{2}Cos\theta_p - Sin\theta_p)$
$\phi(1680) \to K\bar{K}^*$	$\phi(1930) \to K\bar{K}^*$	4	$\frac{1}{2\sqrt{2}}$
$\phi(1680) \to \phi(1020)\eta$	$\phi(1930) \to \phi(1020)\eta$	1	$\frac{1}{\sqrt{2}}Sin\theta_p$
$\phi(1680) \to \phi(1020)\eta'$	$\phi(1930) \to \phi(1020)\eta'$	1	$\frac{1}{\sqrt{2}}Cos\theta_p$
$\omega(1420) \to \rho\pi$	$\omega(1650) \to \rho\pi$	3	$\frac{1}{2}$
$\omega(1420) \to K^*(892)K$	$\omega(1650) \to K^*(892)K$	4	$\frac{1}{4}$
$\omega(1420) \to \omega(782)\eta$	$\omega(1650) \to \omega(782)\eta$	1	$\frac{1}{2}Cos\theta_p$

Decay widths $R \to \gamma P$

Decay channel		Symmetry factor	Amplitude
$V_E \to \gamma P$	$V_D \to \gamma P$		
$\rho(1450) \to \gamma\pi$	$\rho(1700) \to \gamma\pi$	1	$\frac{1}{6}$
$\rho(1450) \to \gamma\eta$	$\rho(1700) \to \gamma\eta$	1	$\frac{1}{2} Cos\theta_p$
$\rho(1450) \to \gamma\eta'$	$\rho(1700) \to \gamma\eta'$	1	$\frac{1}{2} Sin\theta_p$
$K^*(1410) \to \gamma K$	$K^*(1680) \to \gamma K$	1	$\frac{1}{3}$
$\phi(1680) \to \gamma\eta$	$\phi(1930) \to \gamma\eta$	1	$\frac{1}{3} Sin\theta_p$
$\phi(1680) \to \gamma\eta'$	$\phi(1930) \to \gamma\eta'$	1	$\frac{1}{3} Cos\theta_p$
$\omega(1420) \to \gamma\pi$	$\omega(1650) \to \gamma\pi$	1	$\frac{1}{2}$
$\omega(1420) \to \gamma\eta$	$\omega(1650) \to \gamma\eta$	1	$\frac{1}{6} Cos\theta_p$
$\omega(1420) \to \gamma\eta'$	$\omega(1650) \to \gamma\eta'$	1	$\frac{1}{6} Cos\theta_p$

Results

Radially excited vector mesons: $V_E \to VP$

Decay process $V_E \to VP$	Theory [MeV]	Experiment [MeV]
$\rho(1450) \to \omega\pi$	74.7 ± 31.0	$\sim 84 \pm 13$ seen by CLEGG
$\rho(1450) \to K^*(892)K$	6.7 ± 2.8	possibly seen by COAN
$\rho(1450) \to \rho(770)\eta$	9.3 ± 3.9	$< 16.0 \pm 2.4$ seen by DONNACHIE
$\rho(1450) \to \rho(770)\eta'$	≈ 0	not listed in PDG
$K^*(1410) \to K\rho$	12.0 ± 5.0	$< 16.2 \pm 1.5$ by PDG
$K^*(1410) \to K\phi$	≈ 0	not listed in PDG
$K^*(1410) \to K\omega$	3.7 ± 1.5	not listed in PDG
$K^*(1410) \to K^*(892)\pi$	28.8 ± 12.0	$> 93 \pm 8$ by PDG
$K^*(1410) \to K^*(892)\eta$	≈ 0	not listed in PDG
$K^*(1410) \to K^*(892)\eta'$	≈ 0	not listed in PDG
$\phi(1680) \to K\bar{K}^*$	110 ± 46	dominant, $\Gamma_{tot} = 150 \pm 50$ by PDG
$\phi(1680) \to \phi(1020)\eta$	12.2 ± 5.1	seen by ACHASOV
$\phi(1680) \to \phi(1020)\eta'$	≈ 0	not listed in PDG
$\omega(1420) \to \rho\pi$	196 ± 81	dominant, $\Gamma_{tot} = (180 - 250)$ by PDG
$\omega(1420) \to K^*(892)K$	2.3 ± 1.0	not listed in PDG
$\omega(1420) \to \omega(782)\eta$	4.9 ± 2.0	not listed in PDG
$\omega(1420) \to \omega(782)\eta'$	≈ 0	not listed in PDG

- $\Gamma_{R\to VP} = S\frac{|\vec{k}|^3}{12\pi}[\frac{g_{iVP}}{2}\lambda_{RVP}]^2$

Results

Radially excited vector mesons: $V_E \to PP$

Decay process $V_E \to PP$	Theory [MeV]	Experiment [MeV]
$\rho(1450) \to \bar{K}K$	6.6 ± 1.4	$< 6.7 \pm 1.0$ seen by DONNACHE
$\rho(1450) \to \pi\pi$	30.8 ± 6.7	$\sim 27 \pm 4$, seen by CLEGG
$K^*(1410) \to K\pi$	15.3 ± 3.3	15.3 ± 3.3 by PDG
$K^*(1410) \to K\eta$	6.9 ± 1.5	not listed in PDG
$K^*(1410) \to K\eta'$	≈ 0	not listed in PDG
$\phi(1680) \to \bar{K}K$	19.8 ± 4.3	seen by BUON
$\omega(1420) \to \bar{K}K$	5.9 ± 1.3	not listed in PDG

- $\Gamma_{R \to PP} = S \frac{|\vec{k}|^3}{6\pi m_R^2} [\frac{g_{iPP}}{2} \lambda_{RPP}]^2$

Results

Radially excited vector mesons: $V_E \to \gamma P$

Decay process $V_E \to \gamma P$	Theory [MeV]	Experiment [MeV]
$\rho(1450) \to \gamma\pi$	0.072 ± 0.042	not listed
$\rho(1450) \to \gamma\eta$	0.23 ± 0.14	0.09 ± 0.045
$\rho(1450) \to \gamma\eta'$	0.056 ± 0.033	not listed
$K^*(1410) \to \gamma K$	0.18 ± 0.11	seen
$\phi(1680) \to \gamma\eta$	0.14 ± 0.09	seen
$\phi(1680) \to \gamma\eta'$	0.076 ± 0.045	not listed
$\omega(1420) \to \gamma\pi$	0.60 ± 0.36	2 ± 1
$\omega(1420) \to \gamma\eta$	0.023 ± 0.014	not listed
$\omega(1420) \to \gamma\eta'$	0.0050 ± 0.0030	not listed

- $\Gamma_{R\to\gamma P} = S\frac{|\vec{k}|^3}{12\pi}[\frac{g_{iVP}}{2}\lambda_{RVP}]^2$

Results

Angular momentum excited vector mesons: $V_D \to PP$

Decay process $V_D \to PP$	Theory [MeV]	Experiment [MeV]
$\rho(1700) \to \bar{K}K$	40 ± 11	8.3 ± 3.3 seen by DELCOURT
$\rho(1700) \to \pi\pi$	140 ± 37	75 ± 30 seen by BECKER
$K^*(1680) \to K\pi$	82 ± 22	125 ± 43 by PDG
$K^*(1680) \to K\eta$	52 ± 14	not listed in PDG
$K^*(1680) \to K\eta'$	0.72 ± 0.02	not listed in PDG
$\phi(1930) \to \bar{K}K$	104 ± 28	resonance not yet known
$\omega(1650) \to \bar{K}K$	37 ± 10	not listed in PDG

Results

Angular momentum excited vector mesons: $V_D \to VP$

Decay process $V_D \to VP$	Theory [MeV]	Experiment [MeV]
$\rho(1700) \to \omega\pi$	140 ± 59	seen by ACHASOV
$\rho(1700) \to K^*(892)K$	56 ± 23	possibly seen by COAN
$\rho(1700) \to \rho\eta$	41 ± 17	$< 10 \pm 4$ seen by DONNACHIE
$\rho(1700) \to \rho\eta'$	≈ 0	not listed in PDG
$K^*(1680) \to K\rho$	64 ± 27	101 ± 35 by PDG
$K^*(1680) \to K\phi$	13 ± 6	not listed in PDG
$K^*(1680) \to K\omega$	21 ± 9	not listed in PDG
$K^*(1680) \to K^*(892)\pi$	81 ± 34	96 ± 33 by PDG
$K^*(1680) \to K^*(892)\eta$	0.5 ± 0.2	not listed in PDG
$K^*(1680) \to K^*(892)\eta'$	≈ 0	not listed in PDG
$\phi(1930) \to K\bar{K}^*$	260 ± 109	resonance not yet known
$\phi(1930) \to \phi(1020)\eta$	67 ± 28	resonance not yet known
$\phi(1930) \to \phi(1020)\eta'$	≈ 0	resonance not yet known
$\omega(1650) \to \rho\pi$	370 ± 156	205 ± 23 seen by ACHASOV
$\omega(1650) \to K^*(892)K$	42 ± 18	not listed in PDG
$\omega(1650) \to \omega(782)\eta$	32 ± 13	listed in PDG
$\omega(1650) \to \omega(782)\eta'$	≈ 0	not listed in PDG

Results

Angular momentum excited vector mesons: $V_D \to \gamma P$

Decay process $V_D \to \gamma P$	Theory [MeV]	Experiment [MeV]
$\rho(1700) \to \gamma\pi$	0.095 ± 0.058	not listed
$\rho(1700) \to \gamma\eta$	0.35 ± 0.21	not listed
$\rho(1700) \to \gamma\eta'$	0.13 ± 0.08	not listed
$K^*(1680) \to \gamma K$	0.30 ± 0.18	not listed
$\phi(1930) \to \gamma\eta$	0.19 ± 0.12	resonance not yet known
$\phi(1930) \to \gamma\eta'$	0.13 ± 0.08	resonance not yet known
$\omega(1650) \to \gamma\pi$	0.78 ± 0.47	not listed
$\omega(1650) \to \gamma\eta$	0.035 ± 0.021	not listed
$\omega(1650) \to \gamma\eta'$	0.012 ± 0.007	not listed

Predictions for $\phi(1930)$

MESON $\phi(1930)$	
Quark composition	$s\bar{s}$
Old spectroscopy notation	(predom.) n $^{2S+1}L_J = 1^3D_1$
n	(predom.) 1
S	(predom.) 1 $\uparrow\uparrow$
L	(predom.) 2
J^{PC}	1^{--}
Mass	$\approx 1930 \pm 40$ MeV

DECAYS	
Decay channel	Decay width [MeV]
$\phi(1930) \to \bar{K}K$	104 ± 28
$\phi(1930) \to K\bar{K}^*$	260 ± 109
$\phi(1930) \to \Phi(1020)\eta$	67 ± 28
$\phi(1930) \to \Phi(1020)\eta'$	≈ 0
$\phi(1930) \to \gamma\eta$	0.19 ± 0.12
$\phi(1930) \to \gamma\eta'$	0.13 ± 0.08

Ratios

Ratio	PDG result	Our result
$\left.\frac{\Gamma_{\rho(1450)\to\pi\pi}}{\Gamma_{\rho(1450)\to\omega\pi}}\right\|_{exp}$	~ 0.32 by CLEGG 94	0.41 ± 0.20
$\left.\frac{\Gamma_{\rho(1450)\to KK}}{\Gamma_{\rho(1450)\to\omega\pi}}\right\|_{exp}$	< 0.08 DONNACHIE 91	0.088 ± 0.043
$\left.\frac{\Gamma_{\rho(1450)\to\eta\rho}}{\Gamma_{\rho(1450)\to\omega\pi}}\right\|_{exp}$	0.081 ± 0.020 ALUCHENKO 15 ~ 0.21 DONNACHIE 91 > 2 FUKUI 91	≈ 0.12
$\left.\frac{\Gamma_{K^*(1410)\to\rho K}}{\Gamma_{\rho(1450)\to K^*(892)\pi}}\right\|_{exp}$	< 0.17 ASTON 84	≈ 0.42
$\left.\frac{\Gamma_{\phi(1680)\to K\bar{K}}}{\Gamma_{\phi(1680)\to K^*(892)K}}\right\|_{exp}$	0.07 ± 0.01 BUON 82	0.18 ± 0.09
$\left.\frac{\Gamma_{\phi(1680)\to\eta\phi}}{\Gamma_{\phi(1680)\to K^*(892)K}}\right\|_{exp}$	0.07 ± 0.01 AUBERT 08	≈ 0.11
$\frac{\Gamma_{\rho(1700)\to\pi\pi}}{\Gamma_{\rho(1700)\to KK}}$	~ 3.7 DIEKMAN 88 + BIZOT 80 0.83 ± 0.82 KURDADZE 83+ BIZOT 80 8.7 ± 6.7 ASTON 80 + DELCOURT 81B	≈ 3.5
$\left.\frac{\Gamma_{\rho(1700)\to K^*(892)K}}{\Gamma_{\rho(1700)\to\eta\rho}}\right\|_{exp}$	43 ± 21 BIZOT 80 + ANTONELLI 88 1.22 ± 0.27 DELCOURT 81B + DELCOURT 82	≈ 1.37

Conclusions

- Overall agreement of theory with data:
  - theoretically large decays are clearly seen in experiments,
  - theoretically small decays were generally not seen.
- The results for the not−yet discovered resonance ϕ_P are prediction. This resonance, even if broad, is measurable.
- There are some open issues: some theoretical and experimental errors are too large. $K^*(1410)$ is well established, but $K^*(1410) \to K^*(892)\pi$ is too small when compared to data.
- We have just one radially excited ρ but there is evidence that another one $\rho(1250)$ exists.
  S. Coito, G. Rupp and E. van Beveren, Unquenched quark-model calculation of excited ρ resonances and P-wave $\pi\pi$ phase shifts, Bled Workshops Phys. **16** (2015) no.1.
- Radiative decays were determined via VMD. The radiative decays of V_E are still experimentally poorly determined. For the d−vave vector mesons the results are only predictions.
- New experimental results for excited vector states are expected at the GlueX experiment at Jefferson lab.

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Thank you for your attention