

Conventional mesons below 2 GeV

Francesco Giacosa^{1,*}

¹Institute of Physics, Jan Kochanowski University, ul. Uniwersytecka 7, 25-406, Kielce, Poland

Abstract. We briefly review the status of various conventional quark-antiquark mesons below 2 GeV and outline some open questions: the status of the strange-antistrange orbitally excited vector meson, the status of the nonet of axial-tensor mesons (chiral partners of the well known tensor mesons), and the isoscalar mixing angle in the pseudotensor sector, which can eventually represent a novel manifestation of the chiral anomaly.

1 Introduction

The study of exotic mesons is an important topic in modern hadronic physics, which is in the centre of dedicated theoretical and experimental works, e.g Refs. [1–9] and refs. therein.

Yet, a necessary condition toward such a study is a clear understanding of the conventional mesons and baryons, e.g. Refs. [10, 11]. Namely, only when the standard quark-antiquark and three-quark states are fully under control in a certain energy region, the search for states that do not fit into this conventional picture can be fruitful.

In this work we concentrate on conventional mesonic states below 2 GeV. In particular, we present a mini-review of the achievements of a series of works (by myself and collaborators) based on a quite long time span in which various mesonic nonets with different quantum numbers have been studied in the framework of hadronic effective models that employ either flavor or chiral symmetry. In particular, for any given nonet or chiral multiplet, either a flavor or a chiral invariant and purely mesonic model has been set to study the masses and, most importantly, the decays of the corresponding states. In this way one could test the goodness of the quark-antiquark assignment by comparing theoretical data to experimental decay widths and branching ratios.

2 Quark-antiquark conventional nonets

In the non-relativistic notation, a quark-antiquark ($\bar{q}q$) nonet is classified by $n^{2S+1}L_J$, where n is the radial quantum number, and S , L and J are the spin, spacial, and total angular momenta, respectively. The relativistic notation is denoted as J^{PC} , where $P = (-1)^{L+1}$ is parity and $C = (-1)^{L+S}$ the charge conjugation.

In Table 1 we report various $n = 1$ mesonic nonets together with both notations above. We also refer to the results obtained by our previous works on the subject by using effective flavor/chiral mesonic models that study masses and decays. Here, we concentrate on the main picture and do not write down the Lagrangian(s), for which we refer to the quoted

*francescogiacosa@gmail.com

papers. Moreover, for each nonet we shall also discuss the mixing of the nonstrange and the strange components, since this information may be linked to nonperturbative physics (chiral anomaly).

Table 1: Summary of conventional mesons and related references based on hadronic models.

$n^{2S+1}L_J$	J^{PC}	Current	$I = 1$ $u\bar{d}, \bar{d}u$ $\frac{d\bar{d}-u\bar{u}}{\sqrt{2}}$	$I = 1/2$ $u\bar{s}, d\bar{s}$ $s\bar{d}, s\bar{u}$	$I = 0$ $\approx \frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$I = 0$ $\approx s\bar{s}$	Refs.
1^1S_0	0^{-+}	$\bar{q}i\gamma^5q$	π	K	$\eta(547)$	$\eta'(958)$	[12]
1^3P_0	0^{++}	$\bar{q}q$	$a_0(1450)$	$K_0^*(1430)$	$f_0(1370)$	$f_0(1500)$	[12–15]
1^3S_1	1^{--}	$\bar{q}\gamma^\mu q$	$\rho(770)$	$K^*(892)$	$\omega(782)$	$\phi(1020)$	[12]
1^3P_1	1^{++}	$\bar{q}\gamma^5\gamma^\mu q$	$a_1(1260)$	K_{1A}	$f_1(1285)$	$f_1'(1420)$	[12, 16]
1^1P_1	1^{+-}	$\bar{q}\gamma^5\partial^\mu q$	$b_1(1235)$	K_{1B}	$h_1(1170)$	$h_1(1415)$	[16, 17]
1^3D_1	1^{--}	$\bar{q}\partial^\mu q$	$\rho(1700)$	$K^*(1680)$	$\omega(1650)$	$\phi(???)$	[17, 18]
1^3P_2	2^{++}	$\bar{q}i\gamma^\mu\partial^\nu q$	$a_2(1320)$	$K_2^*(1430)$	$f_2(1270)$	$f_2'(1525)$	[19, 20]
1^3D_2	2^{--}	$\bar{q}i\gamma^5\gamma^\mu\partial^\nu q$	$\rho_2(???)$	$K_2(1820)$	$\omega_2(???)$	$\phi_2(???)$	[20]
1^1D_2	2^{-+}	$\bar{q}i\gamma^5\partial^\mu\partial^\nu q$	$\pi_2(1670)$	$K_2(1770)$	$\eta_2(1645)$	$\eta_2(1870)$	[21, 22]
1^3D_3	3^{--}	$\bar{q}\gamma^\mu\partial^\nu\partial^\rho q$	$\rho_3(1690)$	$K_3^*(1780)$	$\omega_3(1670)$	$\phi_3(1850)$	[23]

It is useful to comment one by one the entries of the Table 1 above:

- The first entry refers to the well-known and established pseudoscalar mesons $\{\pi, K, \eta(547), \eta'(958)\}$ with $J^{PC} = 0^{-+}$. These states are particularly important in low-energy QCD since they correspond to the (quasi-)Goldstone bosons emerging upon spontaneous symmetry breaking of chiral symmetry. In chiral mesonic models, they appear in (extensions of) the Mexican hat potential [24] and are also the starting point of chiral perturbation theory, e.g. Ref. [25]. Due to the axial (or chiral) anomaly [26, 27], the two isoscalar fields are given by the mixing:

$$\begin{pmatrix} \eta(547) \\ \eta' \equiv \eta(958) \end{pmatrix} = \begin{pmatrix} \cos\beta_P & \sin\beta_P \\ -\sin\beta_P & \cos\beta_P \end{pmatrix} \begin{pmatrix} \eta_N \equiv \sqrt{\frac{1}{2}}(\bar{u}u + \bar{d}d) \\ \eta_S \equiv \bar{s}s \end{pmatrix}, \quad (1)$$

with a large mixing angle $\beta_P = -43.4^\circ$ [28]. In other words, the large mixing can be also understood by the fact that pseudoscalar mesons belong to a so-called ‘‘heterochiral’’ multiplet [29], for which a chirally invariant (but axial breaking) term can be easily written down.

- The second entry refers to their chiral partners of the pseudoscalar mesons, the since long time debated $\bar{q}q$ scalar mesons with $J^{PC} = 0^{++}$, see also e.g. Refs. [30–33]. Here, the assignment is not yet conclusive, even if their placement above 1 GeV seems quite natural for P -wave states. In addition, the scalar glueball, to be predominantly identified with $f_0(1710)$ [13, 34, 35] is likely to mix with these states. In turn, the scalar states below 1 GeV need to be interpreted as four-quark objects [2].
- In the third entry, the well-known vector mesons $\{\rho(770), K^*(892), \omega(782), \phi(1020)\}$ with $J^{PC} = 1^{--}$ are listed. Being the second-lightest nonet, an enlargement of chiral perturbation theory that contains these states has been developed, see Ref. [36]. Moreover, the

vector states belong to a homochiral multiplet [29], hence the strange-nonstrange mixing is expected to be small. In fact, one has:

$$\begin{pmatrix} \omega(782) \\ \phi(1020) \end{pmatrix} = \begin{pmatrix} \cos\beta_V & \sin\beta_V \\ -\sin\beta_V & \cos\beta_V \end{pmatrix} \begin{pmatrix} \omega_N \\ \omega_S \end{pmatrix}, \quad (2)$$

where the small isoscalar-vector mixing angle $\beta_V = -3.9^\circ$ implies that $\omega(782)$ is mostly nonstrange and $\phi(1020)$ strange.

- The chiral partners of vector mesons are the axial-vector mesons $\{a_1(1260), K_{1A} \equiv K_1(1270)/K_1(1400), f_1(1285), f'_1(1420)\}$ with $J^{PC} = 1^{++}$. The mass difference w.r.t. vector mesons is another clear manifestation of spontaneous chiral symmetry breaking. The isoscalar mixing angle is, as expected, also small, thus $f_1(1285)$ is predominately nonstrange and $f'_1(1420)$ strange. In the kaonic sector mixing with pseudovector mesons take place, see below.
- The nonet of pseudovector mesons $\{b_1(1235), K_{1B} \equiv K_1(1270)/K_1(1400), h_1(1170), h_1(1415)\}$ with $J^{PC} = 1^{+-}$ is also quite well known. The isoscalar states are again nonstrange and strange, respectively. The kaonic states are not eigenstates of C , thus the state K_{1A} belonging to the $J^{PC} = 1^{++}$ axial-vector nonet and K_{1B} belonging to the $J^{PC} = 1^{+-}$ pseudovector nonet mix:

$$\begin{pmatrix} K_1(1270) \\ K_1(1400) \end{pmatrix} = \begin{pmatrix} \cos\varphi_K & -i\sin\varphi_K \\ -i\sin\varphi_K & \cos\varphi_K \end{pmatrix} \begin{pmatrix} K_{1A} \\ K_{1B} \end{pmatrix}, \quad (3)$$

with the large mixing angle $\varphi_K = (56.4 \pm 4.3)^\circ$ [16, 37]. On the other hand, the isoscalar mixing angle is not yet known. It could be potentially large because the pseudovector mesons belong to a heterochiral multiplet (just as pseudoscalar mesons), see also the discussions concerning pseudotensor mesons below.

- The chiral partners of the pseudovector mesons are the orbitally excited vector mesons, the first ones in our table with $L = 2$. They indeed fit quite well with a regular nonet, but **one state is still not identified yet: the mostly strange state $\phi(???)$** . In Ref. [18] this state was denoted with a putative and yet undiscovered resonance $\phi(1930)$. In the latest version of the PDG, in the review of the quark model the assignment $\phi(2170)$ has been also discussed, yet this interpretation does not fit with our results, both for what concerns the mass and the decays of this state.
- The next entry refers to the tensor states $\{a_2(1320), K_2^*(1430), f_2(1270), f'_2(1525)\}$ with $J^{PC} = 2^{++}$ [30, 38, 39] (for theoretical aspects see [40], yet for different interpretations Refs. [41, 42]). This nonet, together with the pseudoscalar and vector mesons described above, is a very well established nonet of quark-antiquark states that serve as an excellent example for the validity of the quark model. The isoscalar states $f_2(1270)$ and $f'_2(1525)$ are nonstrange and strange respectively, in agreement with the homochiral nature of the underlying chiral multiplet.
- The chiral partners of tensor mesons are the so-called axial axial-tensor mesons $\{\rho_2(???) , K_2(1820), \omega_2(???) , \phi_2(???)\}$ with $J^{PC} = 2^{--}$, see also Refs. [43, 44]. **The natural question is: where are the states $\rho_2, \omega_2, \text{ and } \phi_2$?** It is quite surprising that these states, that represent conventional mesons being chiral partners of well known tensor states, could not be identified yet. In Ref. [20] they turn out to be quite wide, in agreement with lattice [45], the main decay mode being the one into a vector-pseudoscalar mesonic pair.

- Going further, one encounters the quite interesting pseudotensor mesons $\{\pi_2(1670), K_2(1770), \eta_2(1645), \eta_2(1870)\}$ with $J^{PC} = 2^{-+}$. These states fit rather well into the quark-antiquark picture, under the assumption that the mixing angle in the isoscalar sector is large:

$$\begin{pmatrix} \eta_2(1645) \\ \eta_2(1870) \end{pmatrix} = \begin{pmatrix} \cos \beta_{PT} & \sin \beta_{PT} \\ -\sin \beta_{PT} & \cos \beta_{PT} \end{pmatrix} \begin{pmatrix} \eta_{2,N} \equiv \sqrt{\frac{1}{2}}(\bar{u}u + \bar{d}d) \\ \eta_{2,S} \equiv \bar{s}s \end{pmatrix}, \quad (4)$$

with $\beta_{PT} \simeq -42^\circ$, similar to the case of pseudoscalar mesons. The question here is: **is the mixing angle in the pseudotensor really that large? If yes, is the chiral anomaly the reason for that?** This is a relevant question because it would allow to investigate the nonperturbative features of the chiral anomaly in a novel sector. Indeed, the pseudotensor mesons belong to a heterochiral nonet, thus the mixing could be (potentially) large.

- The chiral partners of the pseudotensor mesons are not listed in Table 1, but are expected to be heavier than 2 GeV. At present, they are completely unknown.
- The last entry of Table 1 deals with the quite well established states $\{\rho_3(1690), K_3^*(1780), \omega_3(1670), \phi_3(1850)\}$ with $J^{PC} = 3^{--}$. These states form also an almost ideal nonet, whose isoscalar members $\omega_3(1670)$ and $\phi_3(1850)$ are mostly nonstrange and strange, in agreement with the corresponding homochiral multiplet. The chiral partners of this nonet are also at present unknown.

As next and final point, we have a quick look at some radially excited states with $n = 2$, see Table 2.

Table 2: Some nonets of conventional radially excited mesons.

$n^{2S+1}L_J$	J^{PC}	$I = 1$ $\bar{u}d, d\bar{u}$ $\frac{\bar{d}d - \bar{u}u}{\sqrt{2}}$	$I = 1/2$ $\bar{u}s, d\bar{s}$ $\bar{s}d, s\bar{u}$	$I = 0$ $\approx \frac{\bar{u}u + \bar{d}d}{\sqrt{2}}$	$I = 0$ $\approx s\bar{s}$	Refs.
2^1S_0	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1295)$	$\eta(1440)$	[46]
2^3P_0	0^{++}	$a_0(1950)$	$K_0^*(1950)$	$f_0(1790)$	$f_0(2100)$	[46]
2^3S_1	1^{--}	$\rho(1450)$	$K^*(1410)$	$\omega(1420)$	$\phi(1680)$	[18]
...	

Some comments are in order:

- The pseudoscalar mesons are quite well known. The states $\eta(1405)$ and $\eta(1475)$ can be actually identified with a single state $\eta(1440)$.
- The excited scalar mesons are subject to large uncertainty, yet in Ref. [46] an attempt toward their systematization is put forward.
- The nonet of radially excited vector mesons is quite stable: masses and decays fit well with the basic quark-antiquark assignment.
- In general, it is clear that, besides these examples, the radially excited states are still poorly known, leaving room for improvement.

3 Conclusions

In this work we have briefly reviewed the status of quark-antiquark states as resulting from hadronic flavor/chiral model(s) that we presented in a series of papers listed in Tables 1 and

2. The main outcome is that the states listed in these tables fit quite well with this basic $\bar{q}q$ picture, but some questions (bold in the main text) are still open, in particular:

(i) Which is the ϕ meson of the orbitally excited vector meson multiplet?

(ii) Where are the axial-tensor mesons with $J^{PC} = 2^{--}$?

(iii) Which is the value of the mixing angle in the isoscalar sector of pseudotensor meson?

Finally, what about states that go beyond the $\bar{q}q$? Besides the already mentioned light scalar four-quark states and glueball(s), a special case is the one of hybrid states. Quite recently, evidence toward a nonet of hybrid ($\bar{q}qg$, where g stands for a gluon) states with $J^{PC} = 1^{-+}$ is emerging: besides the well known $\pi_1(1600)$, the resonance $\eta_1(1855)$ has been newly discovered [47]. Then, in Refs. [48, 49] the additional (not yet measured) states $\eta_1(1661)$ and $K_1(1761)$ have been discussed and their decays have been evaluated, thus offering a prediction for future searches. In the near future, a better theoretical and experimental understanding of this hybrid nonet is expected.

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References

- [1] R.L. Workman et al. (Particle Data Group), PTEP **2022**, 083C01 (2022)
- [2] J.R. Pelaez, Phys. Rept. **658**, 1 (2016), 1510.00653
- [3] L. Maiani, A. Pilloni (2022), 2207.05141
- [4] M. Mai, U.G. Meißner, C. Urbach (2022), 2206.01477
- [5] G. Mezzadri, PoS **EPS-HEP2015**, 423 (2015)
- [6] A. Rizzo (CLAS), PoS **CD15**, 060 (2016)
- [7] H. Al Ghouli et al. (GlueX), AIP Conf. Proc. **1735**, 020001 (2016), 1512.03699
- [8] M.F.M. Lutz et al. (PANDA) (2009), 0903.3905
- [9] J. Nys, A.N. Hiller Blin, V. Mathieu, C. Fernández-Ramírez, A. Jackura, A. Pilloni, J. Ryckebusch, A.P. Szczepaniak, G. Fox (JPAC), Phys. Rev. D **98**, 034020 (2018), 1806.01891
- [10] S. Godfrey, N. Isgur, Phys. Rev. D **32**, 189 (1985)
- [11] C.S. Fischer, S. Kubrak, R. Williams, Eur. Phys. J. A **50**, 126 (2014), 1406.4370
- [12] D. Parganlija, P. Kovacs, G. Wolf, F. Giacosa, D.H. Rischke, Phys. Rev. D **87**, 014011 (2013), 1208.0585
- [13] S. Janowski, F. Giacosa, D.H. Rischke, Phys. Rev. D **90**, 114005 (2014), 1408.4921
- [14] F. Giacosa, T. Gutsche, V.E. Lyubovitskij, A. Faessler, Phys. Lett. B **622**, 277 (2005), hep-ph/0504033
- [15] F. Giacosa, T. Gutsche, V.E. Lyubovitskij, A. Faessler, Phys. Rev. D **72**, 094006 (2005), hep-ph/0509247
- [16] F. Divotgey, L. Olbrich, F. Giacosa, Eur. Phys. J. A **49**, 135 (2013), 1306.1193
- [17] F. Giacosa, J. Sammet, S. Janowski, Phys. Rev. D **95**, 114004 (2017), 1607.03640
- [18] M. Piotrowska, C. Reisinger, F. Giacosa, Phys. Rev. D **96**, 054033 (2017), 1708.02593
- [19] F. Giacosa, T. Gutsche, V.E. Lyubovitskij, A. Faessler, Phys. Rev. D **72**, 114021 (2005), hep-ph/0511171

- [20] S. Jafarzade, A. Vereijken, M. Piotrowska, F. Giacosa, *Phys. Rev. D* **106**, 036008 (2022), 2203.16585
- [21] A. Koenigstein, F. Giacosa, *Eur. Phys. J. A* **52**, 356 (2016), 1608.08777
- [22] V. Shastry, E. Trotti, F. Giacosa, *Phys. Rev. D* **105**, 054022 (2022), 2107.13501
- [23] S. Jafarzade, A. Koenigstein, F. Giacosa, *Phys. Rev. D* **103**, 096027 (2021), 2101.03195
- [24] F. Giacosa, *Acta Phys. Polon. B* **47**, 7 (2016), 1511.04605
- [25] J. Gasser, *Lect. Notes Phys.* **629**, 1 (2004), hep-ph/0312367
- [26] T. Feldmann, P. Kroll, B. Stech, *Phys. Rev. D* **58**, 114006 (1998), hep-ph/9802409
- [27] G. 't Hooft, *Phys. Rept.* **142**, 357 (1986)
- [28] G. Amelino-Camelia et al., *Eur. Phys. J. C* **68**, 619 (2010), 1003.3868
- [29] F. Giacosa, A. Koenigstein, R.D. Pisarski, *Phys. Rev. D* **97**, 091901 (2018), 1709.07454
- [30] A. Rodas, A. Pilloni, M. Albaladejo, C. Fernandez-Ramirez, V. Mathieu, A.P. Szczepaniak (Joint Physics Analysis Center), *Eur. Phys. J. C* **82**, 80 (2022), 2110.00027
- [31] E. Klempt, A.V. Sarantsev, *Phys. Lett. B* **826**, 136906 (2022), 2112.04348
- [32] A.V. Sarantsev, I. Denisenko, U. Thoma, E. Klempt, *Phys. Lett. B* **816**, 136227 (2021), 2103.09680
- [33] C. Amsler, F.E. Close, *Phys. Rev. D* **53**, 295 (1996), hep-ph/9507326
- [34] J. Sexton, A. Vaccarino, D. Weingarten, *Phys. Rev. Lett.* **75**, 4563 (1995), hep-lat/9510022
- [35] L.C. Gui, Y. Chen, G. Li, C. Liu, Y.B. Liu, J.P. Ma, Y.B. Yang, J.B. Zhang (CLQCD), *Phys. Rev. Lett.* **110**, 021601 (2013), 1206.0125
- [36] E.E. Jenkins, A.V. Manohar, M.B. Wise, *Phys. Rev. Lett.* **75**, 2272 (1995), hep-ph/9506356
- [37] H. Hatanaka, K.C. Yang, *Phys. Rev. D* **78**, 074007 (2008), 0808.3731
- [38] L. Burakovsky, J.T. Goldman, *Phys. Rev. D* **57**, 2879 (1998), hep-ph/9703271
- [39] L. Bibrzycki, R. Kaminski, *Phys. Rev. D* **87**, 114010 (2013), 1306.4882
- [40] A. Koenigstein, F. Giacosa, D.H. Rischke, *Annals Phys.* **368**, 16 (2016), 1508.00110
- [41] L.S. Geng, F.K. Guo, C. Hanhart, R. Molina, E. Oset, B.S. Zou, *Eur. Phys. J. A* **44**, 305 (2010), 0910.5192
- [42] R. Molina, D. Nicmorus, E. Oset, *Phys. Rev. D* **78**, 114018 (2008), 0809.2233
- [43] L.M. Abreu, F.M. da Costa Júnior, A.G. Favero, *Phys. Rev. D* **101**, 116016 (2020), 2004.10736
- [44] D. Guo, C.Q. Pang, Z.W. Liu, X. Liu, *Phys. Rev. D* **99**, 056001 (2019), 1901.03518
- [45] C.T. Johnson, J.J. Dudek (Hadron Spectrum), *Phys. Rev. D* **103**, 074502 (2021), 2012.00518
- [46] D. Parganlija, F. Giacosa, *Eur. Phys. J. C* **77**, 450 (2017), 1612.09218
- [47] M. Ablikim et al. (BESIII), *Phys. Rev. Lett.* **129**, 192002 (2022), 2202.00621
- [48] W.I. Eshraim, C.S. Fischer, F. Giacosa, D. Parganlija, *Eur. Phys. J. Plus* **135**, 945 (2020), 2001.06106
- [49] V. Shastry, C.S. Fischer, F. Giacosa, *Phys. Lett. B* **834**, 137478 (2022), 2203.04327