Open issues in the realm of mesons up to 2 GeV

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Seminar

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Outline

Symmetries of QCD

Conventional mesons

The state $a_1(1260)$

Pseudotensor mesons and large isoscalar mixing

Excited vectors and the missing strange-antistrange $\varphi(1930?)$

Conclusions

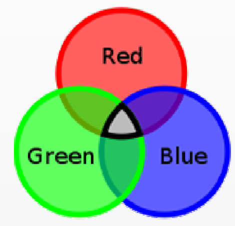
Symmetries of QCD

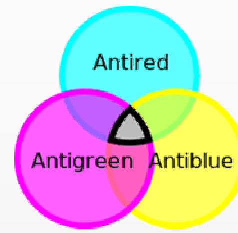
Born	Giuseppe Lodovico Lagrangia 25 January 1736 Turin
Died	10 April 1813 (aged 77) Paris

Francesco Giacosa

The QCD Lagrangian

Quark: u,d,s and c,b,t R,G,B



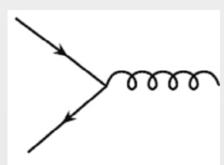


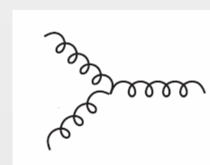
$$q_i = \begin{pmatrix} q_i^R \\ q_i^G \\ q_i^B \end{pmatrix}; \; i = u,d,s ,...$$

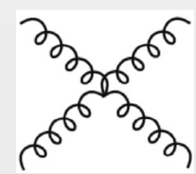
8 type of gluons ($R\bar{G}$,$B\bar{G}$,…)

$$A_\mu^a \; ; \; a = 1,...,8$$

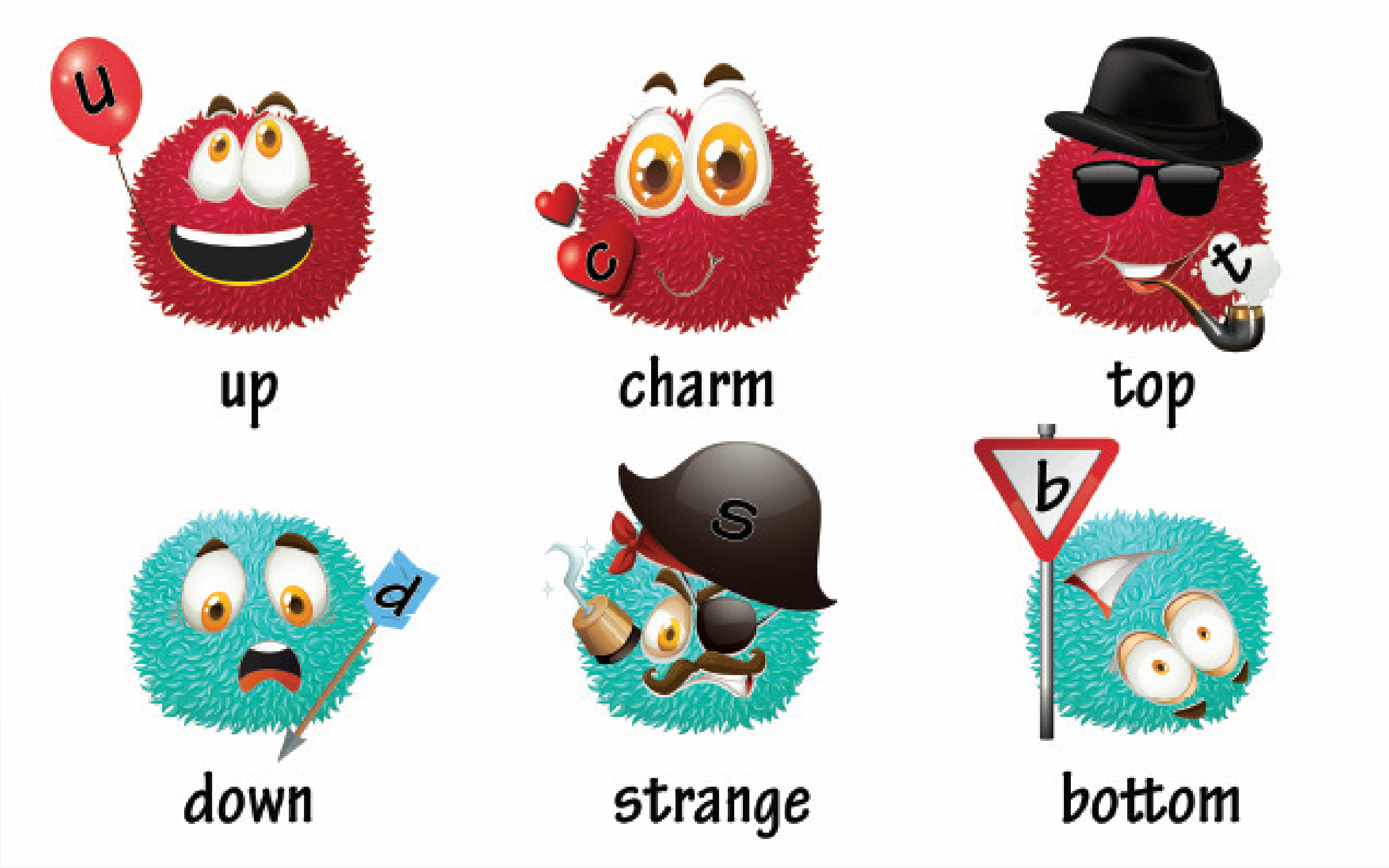
$$\mathcal{L}_{QCD} = \sum_{i=1}^{N_f} \bar{q}_i (i\gamma^\mu D_\mu - m_i) q_i - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu}$$







Confinement: quarks never ‘seen’ directly. How they might look like ☺



Picture by Pawel Piotrowski

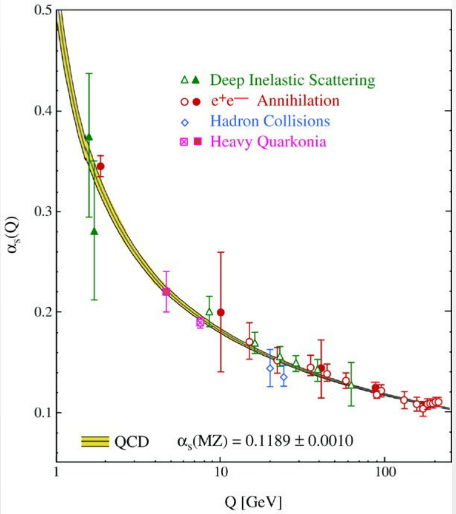
Trace anomaly:
the emergence of a dimension

Chiral limit: $m_i = 0$

$x^\mu \rightarrow x'^\mu = \lambda^{-1} x^\mu$ is a classical symmetry broken by quantum fluctuations (trace anomaly)

Dimensional transmutation $\Lambda_{YM} \approx 250 \text{ MeV}$

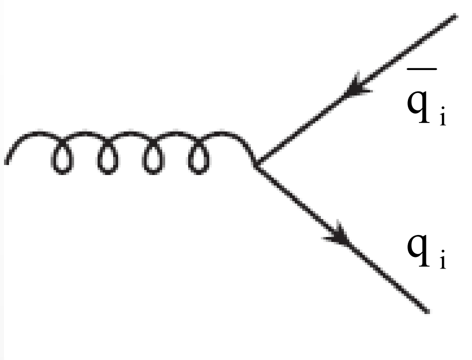
$$\alpha_S(\mu = Q) = \frac{g^2(Q)}{4\pi}$$



Effective gluon mass: $m_{gluon} = 0 \rightarrow m^*_{gluon} \approx 500 - 800 \text{ MeV}$

Gluon condensate: $\left\langle G^a_{\mu\nu} G^{a,\mu\nu} \right\rangle \neq 0$

Flavor symmetry



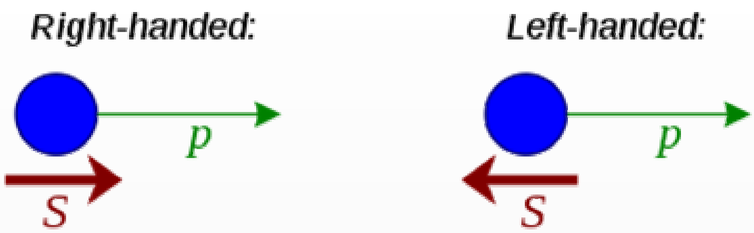
Gluon-quark-antiquark vertex

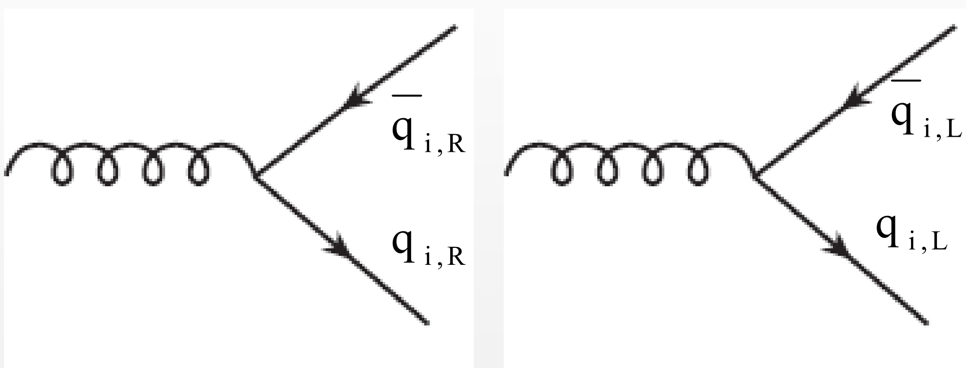
It is democratic! The gluon couples to each flavor with the same strength

$$q_i \to U_{ij} q_j$$

$$U \in U(3)_V \to U^+ U = 1$$

Chiral symmetry





$$q_i = q_{i,R} + q_{i,L}$$

$$q_{i,R} = \frac{1}{2}(1+\gamma^5)q_i$$

$$q_{i,L} = \frac{1}{2}(1-\gamma^5)q_i$$

$$q_i = q_{i,R} + q_{i,L} \rightarrow U^R_{ij} q_{j,R} + U^L_{ij} q_{j,L}$$

$$U(3)_R \times U(3)_L = U(1)_{R+L} \times U(1)_{R-L} \times SU(3)_R \times SU(3)_L$$

baryon number **anomaly U(1)A** **SSB into SU(3)V**

Chiral (or axial) anomaly: explicitely broken by quantum fluctuations

$$\partial^\mu (\bar{q}^i \gamma_\mu \gamma_5 q^i) = \frac{3g^2}{16\pi^2} \varepsilon^{\mu\nu\rho\sigma} \mathrm{tr}(G_{\mu\nu} G_{\rho\sigma})$$

In the chiral limit (mi=0) chiral symmetry is exact, but is **spontaneously broken** by the QCD vacuum

Symmetries of QCD and breakings

$SU(3)_{color}$: exact. Confinement: you never see color, but only white states.

Dilatation invariance: holds only at a classical level and in the chiral limit. Broken by quantum fluctuations (**scale anomaly**) and by quark masses.

$SU(3)_R \times SU(3)_L$: holds in the chiral limit, but is broken by nonzero quark masses. Moreover, it is **spontaneously** broken to $U(3)_{V=R+L}$

$U(1)_{A=R-L}$: holds at a classical level, but is also broken by quantum fluctuations (**chiral anomaly**)

Conventional mesons: quark-antiquark fields

Hadrons

The QCD Lagrangian contains ‘colored’ quarks and gluons. However, no ‚colored‘ state has been seen.

Confinement: physical states are “white” and are called hadrons.

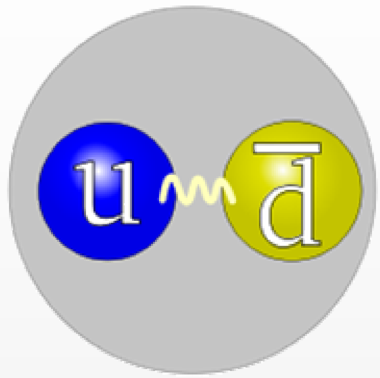
Hadrons can be:

Mesons: bosonic hadrons

Baryons: fermionic hadrons

A meson is **not necessarily** a quark-antiquark state.
A quark-antiquark state is a conventional meson.

Example of conventional quark-antiquark states: the ρ and the π mesons



$$|\rho^+\rangle \propto |u\bar{d}\rangle + \frac{1}{N_c}\left(|\pi^+\pi^0\rangle + \ldots\right)$$

where

$$|u\bar{d}\rangle = |\text{valence } u + \text{valence } \bar{d} + \text{gluons}\rangle$$

Rho-meson $m_{\rho^+} = 775 \ \text{MeV}$

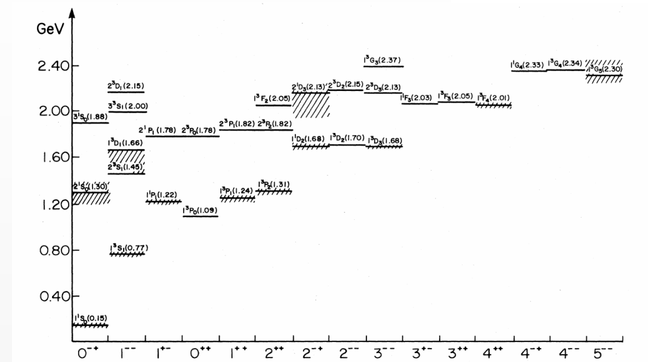
Pion $m_{\pi^+} = 139 \ \text{MeV}$

$$m_u + m_d \approx 7 \ \text{MeV}$$

Mass generation in QCD is a nonpert. penomenon based on SSB (mentioned previusly).

Quark model(s) and their QFT extensions

Mesons in a Relativized Quark Model with Chromodynamics
S. Godfrey, N. Isgur
Phys.Rev. D32 (1985) **189-231**



QCD phenomenology based on a chiral effective Lagrangian
T. Hatsuda, T. Kunihiro
Phys.Rept. **247** (1994) 221-367

NJL: quark-based model with
chiral symmetry and SSB
chiral condensate
Effective quark mass
Mesons as quarkonia (pion: ok)

The Infrared behavior of QCD Green's functions: Confinement dynamical symmetry breaking, and hadrons as relativistic bound states
R. Alkofer, L. von Smekal
Phys.Rept. **353** (2001) 281

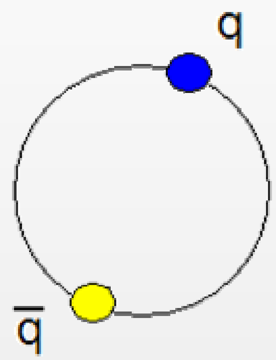
DS:
quarks and gluons propagators from QCD
Condensates
Effective quark and gluon masses
Spectra of mesons as quarkonia (pion: ok) and baryons as qqq states

Baryons as relativistic three-quark bound states
G. Eichmann et al.
Progr. Part. Nucl. Phys. **91** (2016) 1

Conventional mesons

Quark: u,d,s,… R,G,B

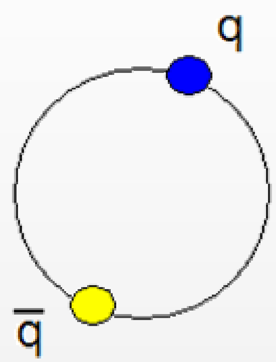
Quark-antiquark bound states: conventional mesons



$$|color\rangle = \sqrt{1/3}\,(\bar{R}R + \bar{B}B + \bar{G}G)$$

Conventional mesons/2

Surely, with quark-antiquark states we can understand a lot of QCD, but definitely not everything.

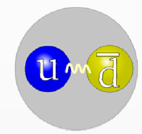


$$P = -(-1)^{L} \qquad C = (-1)^{L+S}$$

L , S → J = L+ S $\qquad J^{PC}$

$$L = S = 0 \rightarrow J^{PC} = 0^{-+}$$ pseudoscalar mesons

$$\left|\pi^{+}\right\rangle = \left|u\bar{d}\right\rangle \left|space : L = 0\right\rangle \left|spin : S = 0\right\rangle \left|\bar{R}R + \bar{B}B + \bar{G}G\right\rangle$$



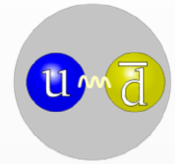
$$\left|K^{+}\right\rangle = \left|u\bar{s}\right\rangle \left|space : L = 0\right\rangle \left|spin : S = 0\right\rangle \left|\bar{R}R + \bar{B}B + \bar{G}G\right\rangle$$

...

$$\left|D^{0}\right\rangle = \left|u\bar{c}\right\rangle \left|space : L = 0\right\rangle \left|spin : S = 0\right\rangle \left|\bar{R}R + \bar{B}B + \bar{G}G\right\rangle$$

...

$$L=0\,,\ S=1 \rightarrow J^{PC}=1^{--}$$ vector mesons



$$\left|\rho^{+}\right\rangle = \left|u\bar{d}\right\rangle \left|space: L=0\right\rangle \left|spin: S=1\right\rangle \left|\bar{R}R+\bar{B}B+\bar{G}G\right\rangle$$

...

$$\left|K^{*}(892)^{+}\right\rangle = \left|u\bar{s}\right\rangle \left|space: L=0\right\rangle \left|spin: S=1\right\rangle \left|\bar{R}R+\bar{B}B+\bar{G}G\right\rangle$$

...

$$\left|D^{*0}\right\rangle = \left|u\bar{c}\right\rangle \left|space: L=0\right\rangle \left|spin: S=1\right\rangle \left|\bar{R}R+\bar{B}B+\bar{G}G\right\rangle$$

...

$$\left|j/\Psi\right\rangle = \left|c\bar{c}\right\rangle \left|space: L=0\right\rangle \left|spin: S=1\right\rangle \left|\bar{R}R+\bar{B}B+\bar{G}G\right\rangle$$

$$L = S = 1 \rightarrow J^{PC} = 0^{++}$$ scalar mesons

$$|\sigma\rangle = |u\bar{u} + d\bar{d}\rangle |space: L = 1\rangle |spin: S = 1\rangle |\bar{R}R + \bar{B}B + \bar{G}G\rangle$$

corresponds to the resonance $f_0(1370)$.

...

...

$$|\chi_{c0}(1S)\rangle = |c\bar{c}\rangle |space: L = 1\rangle |spin: S = 1\rangle |\bar{R}R + \bar{B}B + \bar{G}G\rangle$$

PDG quark-antiquark listing

$n\,^{2s+1}\ell_J$	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
$1\,^1S_0$	0^{-+}	π	K	η	$\eta'(958)$
$1\,^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1380)$	$h_1(1170)$
$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$
$1\,^3P_1$	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$	$f_1(1420)$	$f_1(1285)$
$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$
$1\,^3D_1$	1^{--}	$\rho(1700)$	$K^*(1680)$		$\omega(1650)$
$1\,^3D_2$	2^{--}		$K_2(1820)$		

Spontaneous symmetry breaking at the meson level

$$\pi = \pi^0 \equiv \sqrt{1/2}(\bar{u}u - \bar{d}d) \quad \text{neutral pion}$$

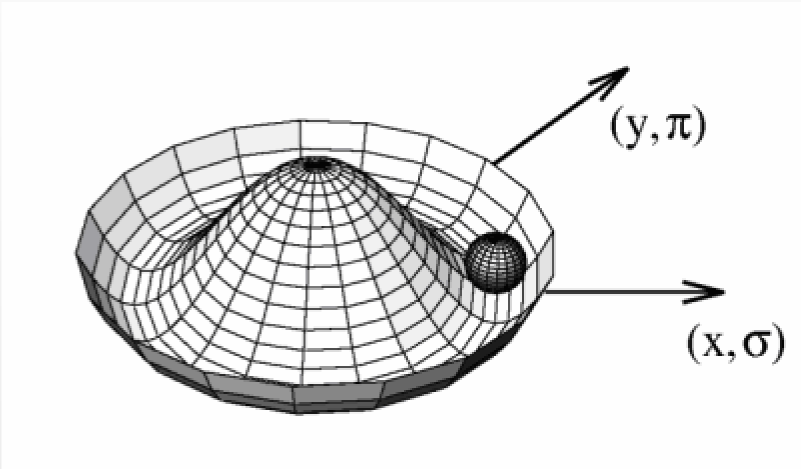
$$\sigma \equiv \sqrt{1/2}(\bar{u}u + \bar{d}d) \equiv f_0(1370)$$

Chiral transformation: $\sigma \leftrightarrow \pi$

$$V = \frac{m_0^2}{2}\left(\sigma^2 + \pi^2\right) + \frac{\lambda}{4}\left(\sigma^2 + \pi^2\right)^2$$

$$m_0^2 < 0 \quad \rightarrow \text{Mexican hat}$$

$$\text{SSB: } \langle\sigma\rangle \propto \langle u\bar{u} + d\bar{d}\rangle \neq 0$$

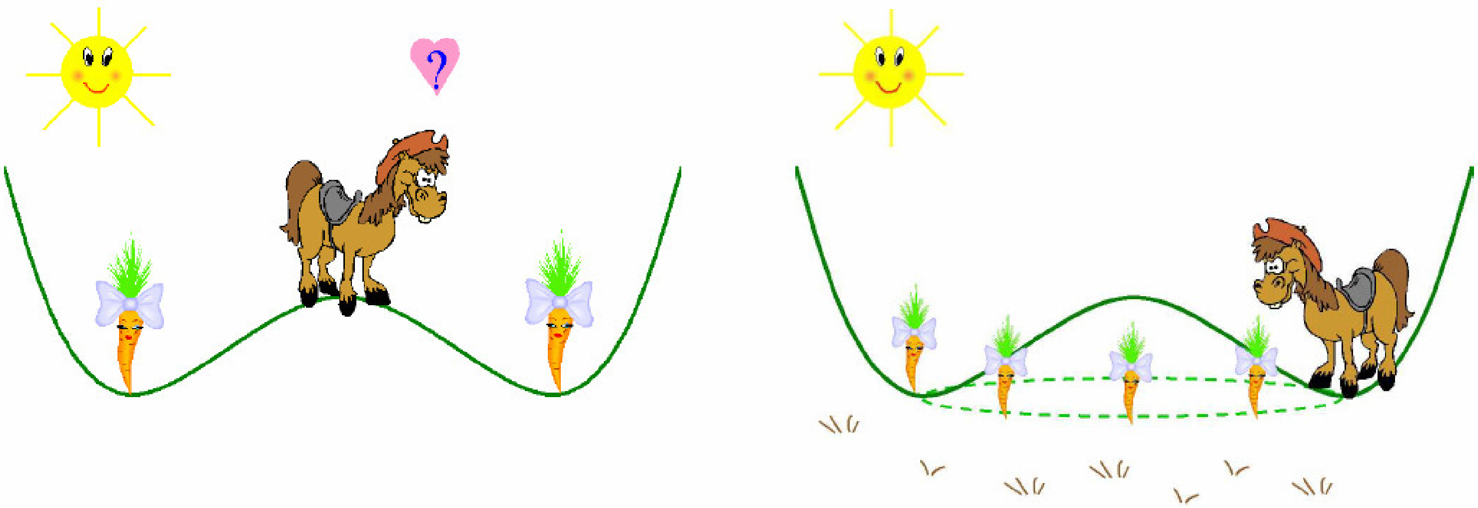


The mass of the pion vanishes, the mass of the sigma is large.

The donkey of Buridan

Jean Buridan (in Latin, *Johannes Buridanus*) (ca. 1300 – after 1358)

Spontaneous Symmetry Breaking



Although Nicolás likes the symmetric food configuration, he must break the symmetry deciding which carrot is more appealing. In three dimensions, there is a continuous valley where Nicolás can move from one carrot to the next without effort.

Picture taken from A. Pich, arXiv:0705.4264 [hep-ph],
Cern-Claf Lecture on 'The Standard model of electroweak interactions '

Chiral anomaly and η η' mesons

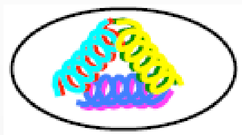
Pseudoscalar fields (L=S=0)

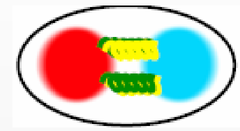
$$\begin{pmatrix} \eta \equiv \eta(547) \\ \eta' \equiv \eta(958) \end{pmatrix} = \begin{pmatrix} \cos\theta_P & \sin\theta_P \\ -\sin\theta_P & \cos\theta_P \end{pmatrix} \begin{pmatrix} \eta_N = \sqrt{1/2}(\bar{u}u + \bar{d}d) \\ \eta_S = \bar{s}s \end{pmatrix}$$

$$\theta_P \simeq -42^\circ$$

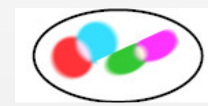
Mixing angle large (due to the anomaly, driven e.g. by instantons); non-perturbative phenomenon of QCD

Non-conventional mesons: theoretical expectations

1) Glueballs 

2) Hybrids 

3) Four-quark states

Compact diquark-antidiquark states 

Molecular states (a type of dynamical generation) 

Companion poles (another type of dynamical generation)

Today: I shall not speak of those fields, but to detect them we need to understand q-antiq

The state $a_1(1260)$

The meson a1(1260)

- L=1, S= 1 coupled to J=1
- Chiral partner of the rho meson (hence a quark-antiquark state)
- …but different interpretations exist (as rho-pion molecular state)
- Important to understand both for spectroscopy but also for chiral symmetry and its breaking

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

$a_1(1260)$ $I^G(J^{PC}) = 1^-(1^{++})$

See also our review under the $a_1(1260)$ in PDG 06, Journal of Physics **G33** 1 (2006).

$a_1(1260)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1230±40 OUR ESTIMATE				
1245^{+10}_{-16} OUR AVERAGE Error includes scale factor of 1.1.				

$a_1(1260)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*C*
250 to 600 OUR ESTIMATE				
389± 29 OUR AVERAGE Error includes scale factor of 1.3.				

Axial-vector mesons

$n\,^{2s+1}\ell_J$	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
$1\,^1S_0$	0^{-+}	π	K	η	$\eta'(958)$
$1\,^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$
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$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$
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$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$
$1\,^3D_1$	1^{--}	$\rho(1700)$	$K^*(1680)$		$\omega(1650)$
$1\,^3D_2$	2^{--}		$K_2(1820)$		

The eLSM: a chiram model of QCD

PHYSICAL REVIEW D **87,** 014011 (2013)

Meson vacuum phenomenology in a three-flavor linear sigma model with (axial-)vector mesons

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[2]*Institute for Theoretical Physics, Johann Wolfgang Goethe University, Max-von-Laue-Strasse 1, D-60438 Frankfurt am Main, Germany*
[3]*Institute for Particle and Nuclear Physics, Wigner Research Center for Physics, Hungarian Academy of Sciences, H-1525 Budapest, Hungary*
[4]*Frankfurt Institute for Advanced Studies, Ruth-Moufang-Strasse 1, D-60438 Frankfurt am Main, Germany*
(Received 7 August 2012; published 8 January 2013)

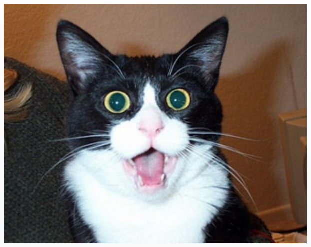
PHYSICAL REVIEW D **90,** 114005 (2014)

Is $f_0(1710)$ a glueball?

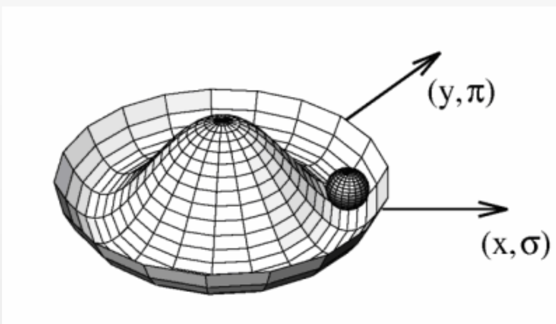
Stanislaus Janowski,[1] Francesco Giacosa,[1,2] and Dirk H. Rischke[1]

[1]*Institute for Theoretical Physics, Goethe University, Max-von-Laue-Straße 1, 60438 Frankfurt am Main, Germany*
[2]*Institute of Physics, Jan Kochanowski University, 25-406 Kielce, Poland*
(Received 26 August 2014; published 2 December 2014)

Model of QCD – eLSM with scalar Glueball



$$
\begin{aligned}
\mathcal{L} \;=\; & \frac{1}{2}(\partial_\mu G)^2 - \frac{1}{4}\frac{m_G^2}{\Lambda^2}\left(G^4 \ln\left|\frac{G}{\Lambda}\right| - \frac{G^4}{4}\right) + \mathrm{Tr}\left[(D^\mu\Phi)^\dagger(D_\mu\Phi)\right] \\
& - m_0^2\left(\frac{G}{G_0}\right)^2 \mathrm{Tr}\left[\Phi^\dagger\Phi\right] - \lambda_1(\mathrm{Tr}\left[\Phi^\dagger\Phi\right])^2 - \lambda_2 \mathrm{Tr}\left[(\Phi^\dagger\Phi)^2\right] \\
& + \left(\frac{G}{G_0}\right)^2 \mathrm{Tr}\left[\left(\frac{m_1^2}{2} + \Delta\right)\left((L^\mu)^2 + (R^\mu)^2\right)\right] \\
& - \frac{1}{4}\mathrm{Tr}\left[(L^{\mu\nu})^2 + (R^{\mu\nu})^2\right] + \mathrm{Tr}\left[H\left(\Phi^\dagger + \Phi\right)\right] \\
& + c_1[\det(\Phi) - \det(\Phi^\dagger)]^2 + \frac{h_1}{2}\mathrm{Tr}[\Phi^\dagger\Phi]\mathrm{Tr}[L_\mu L^\mu + R_\mu R^\mu] \\
& + h_2 \mathrm{Tr}[\Phi^\dagger L_\mu L^\mu \Phi + \Phi R_\mu R^\mu \Phi^\dagger] + 2h_3 \mathrm{Tr}[\Phi R_\mu \Phi^\dagger L^\mu]
\end{aligned}
$$

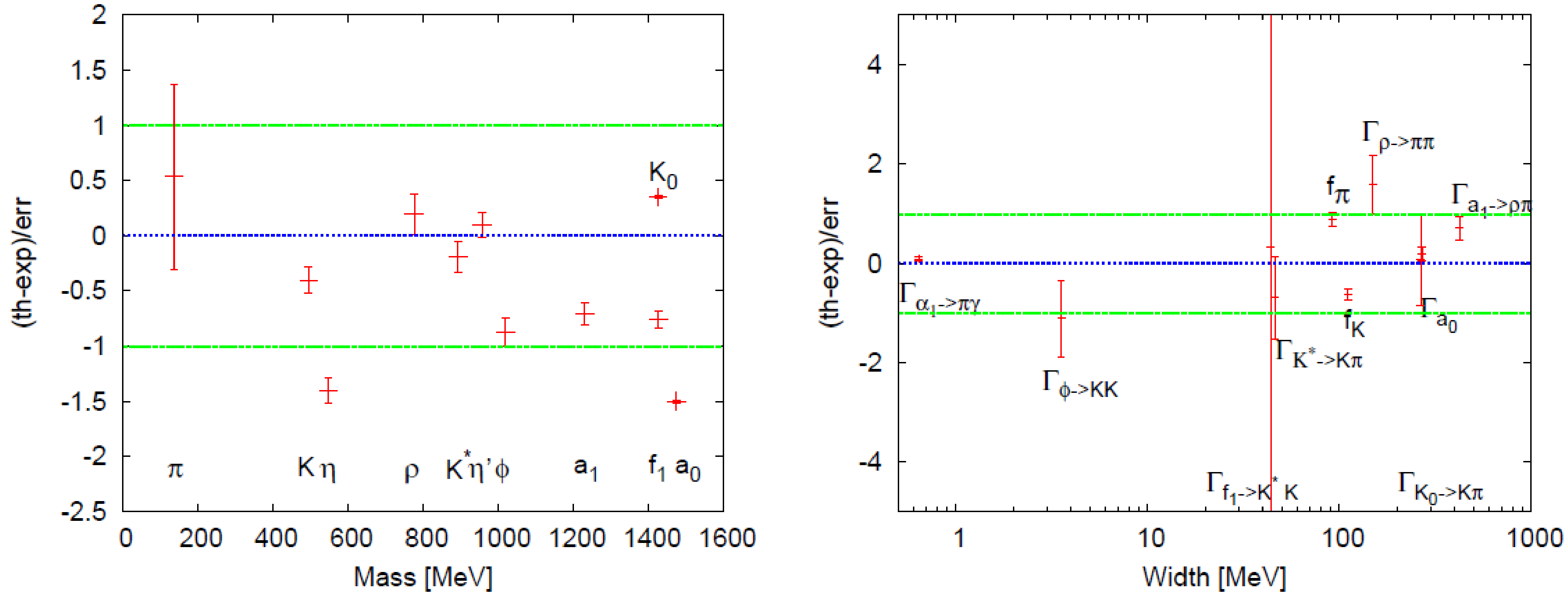


$$
\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}
\frac{(\sigma_N + a_0^0) + i(\eta_N + \pi^0)}{\sqrt{2}} & a_0^+ + i\pi^+ & K_0^{\star +} + iK^+ \\
a_0^- + i\pi^- & \frac{(\sigma_N - a_0^0) + i(\eta_N - \pi^0)}{\sqrt{2}} & K_0^{\star 0} + iK^0 \\
K_0^{\star -} + iK^- & \bar{K}_0^{\star 0} + i\bar{K}^0 & \sigma_S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

$$
L^\mu, R^\mu = \frac{1}{\sqrt{2}}\begin{pmatrix}
\frac{\omega_N \pm \rho^0}{\sqrt{2}} \pm \frac{f_{1N} \pm a_1^0}{\sqrt{2}} & \rho^+ \pm a_1^+ & K^{\star +} \pm K_1^+ \\
\rho^- \pm a_1^- & \frac{\omega_N \mp \rho^0}{\sqrt{2}} \pm \frac{f_{1N} \mp a_1^0}{\sqrt{2}} & K^{\star 0} \pm K_1^0 \\
K^{\star -} \pm K_1^- & \bar{K}^{\star 0} \pm i\bar{K}_1^0 & \omega_S \pm f_{1S}
\end{pmatrix}
$$

S. Janowski, D. Parganlija, F. Giacosa, D. H. Rischke, **Phys. Rev. D84, 054007 (2011**)
D. Parganlija, P. Kovacs, G. Wolf , F. Giacosa, D. H. Rischke, **Phys.Rev. D87 (2013) 014011**

Results of the eLSM (11 parameters, 21 exp. quantities)



arXiv:1208.0585

Overall phenomenology is good (many more quantities can be calculated)

Scalar mesons $a_0(1450)$ and $K_0(1430)$ above 1 GeV and are quark-antiquark states.

Importance of the (axial-)vector mesons on the phenomenology

Glueball: f0(1710)

a1 -> $\rho\pi$

The decay of a1 into $\rho\pi$ is poorly known experimentally (200-600 MeV quoted by the PDG).

The ρ further decays into two pions, finally one has a 3-pion decay.

Can one measure it better? (Presently, we have tau-decays. However, there is a strong mixing with non resonant background).

a1 -> γπ

This is a very peculiar channel and crucial for chiral symmetry and the chiral condensate.

Namely, before the Mexican hat forces the formation of the chiral condensate, one has:

$$L_{\text{int}} = -g_1 \sigma_N \vec{a}_1^{\mu} \partial_{\mu} \vec{\pi}$$

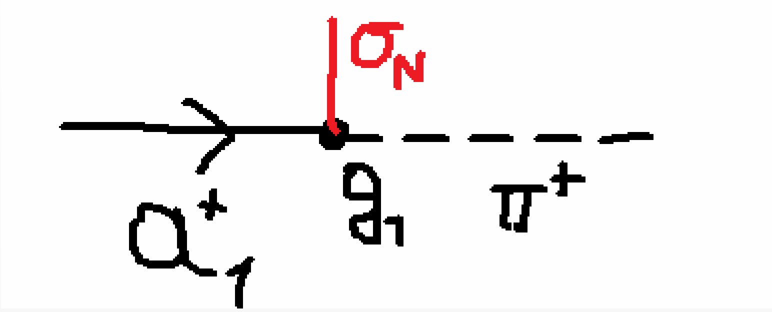
But upon condensation of the chiral condensate:

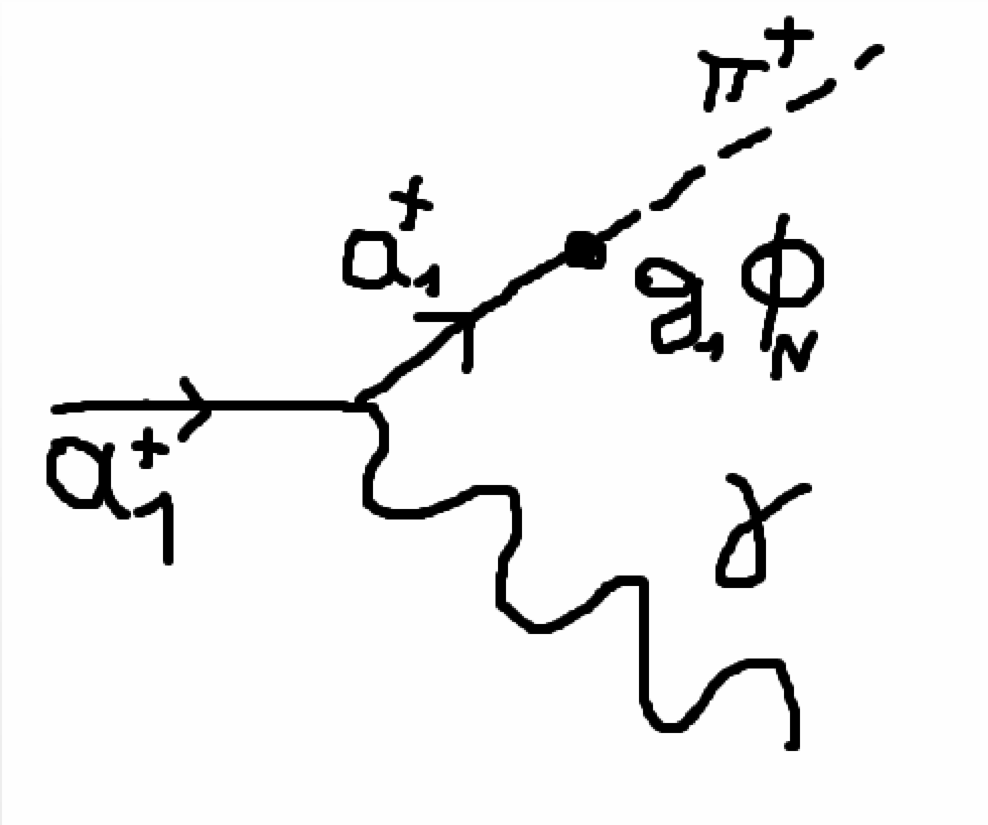
$$\sigma_N \to \sigma_N + \phi_N$$

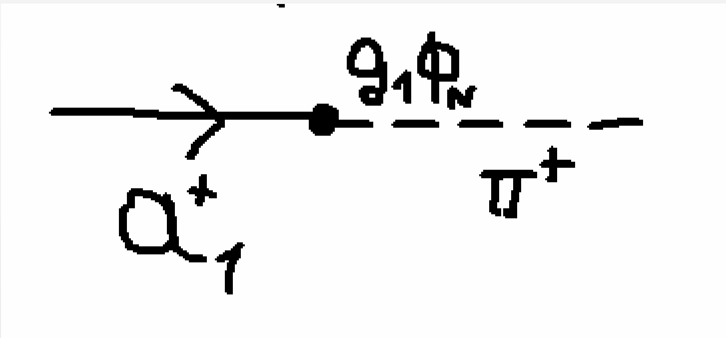
$$L_{\text{int}} = -g_{1N} \phi_N \vec{a}_1^{\mu} \partial_{\mu} \vec{\pi} + \ldots$$

Mixing proportional to the chiral condensate

a1 -> γπ: intuitive origin







Present experimental information

$\Gamma(\pi\gamma)$ Γ_{12}

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
640±246	ZIELINSKI	84C	SPEC	200 $\pi^+ Z \rightarrow Z 3\pi$

Need for more precise value for both the strong and the radiative decay of this state

Pseudotensor mesons

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DOI 10.1140/epja/i2016-16356-x

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Theoretical Physics

Phenomenology of pseudotensor mesons and the pseudotensor glueball

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Abstract. We study the decays of the pseudotensor mesons ($\pi_2(1670), K_2(1770), \eta_2(1645), \eta_2(1870)$) interpreted as the ground-state nonet of 1^1D_2 $\bar{q}q$ states using interaction Lagrangians which couple them to pseudoscalar, vector, and tensor mesons. While the decays of $\pi_2(1670)$ and $K_2(1770)$ can be well described, the decays of the isoscalar states $\eta_2(1645)$ and $\eta_2(1870)$ can be brought in agreement with the present experimental data only if the mixing angle between nonstrange and strange states is surprisingly large (about $-42°$, similar to the mixing in the pseudoscalar sector, in which the chiral anomaly is active). Such a large mixing angle is however at odd with all other conventional quark-antiquark nonets: if confirmed, a deeper study of its origin will be needed in the future. Moreover, the $\bar{q}q$ assignment of pseudotensor states predicts that the ratio $[\eta_2(1870) \to a_2(1320)\,\pi]/[\eta_2(1870) \to f_2(1270)\,\eta]$ is about 23.5. This value is in agreement with Barberis *et al.*, (20.4 ± 6.6), but disagrees with the recent reanalysis of Anisovich *et al.*, (1.7 ± 0.4). Future experimental studies are necessary to understand this puzzle. If Anisovich's value is confirmed, a simple nonet of pseudoscalar mesons cannot be able to describe data (different assignments and/or additional states, such as an hybrid state, will be needed). In the end, we also evaluate the decays of a pseudoscalar glueball into the aforementioned conventional $\bar{q}q$ states: a sizable decay into $K_2^*(1430)\,K$ and $a_2(1230)\,\pi$ together with a vanishing decay into pseudoscalar-vector pairs (such as $\rho(770)\,\pi$ and $K^*(892)\,K$) are expected. This information can be helpful in future studies of glueballs at the ongoing BESIII and at the future PANDA experiments.

ArXiv: 1608.08777

Pseudotensor mesons

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $u\overline{d}$, $\overline{u}d$, $\frac{1}{\sqrt{2}}(d\overline{d}-u\overline{u})$	I = $\frac{1}{2}$ $u\overline{s}$, $d\overline{s}$; $\overline{d}s$, $-\overline{u}s$	I = 0 f'	I = 0 f
$1\,^1S_0$	0^{-+}	π	K	η	$\eta'(958)$
$1\,^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1380)$	$h_1(1170)$
$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$
$1\,^3P_1$	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$	$f_1(1420)$	$f_1(1285)$
$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$
$1\,^3D_1$	1^{--}	$\rho(1700)$	$K^*(1680)$		$\omega(1650)$
$1\,^3D_2$	2^{--}		$K_2(1820)$		

L=2, S =0, out of which J =2

Lagrangians and decays

Pseudotensor mesons: {π2(1670), K2(1770),η2(1645),η2(1870)}
Lagrangians based on flavour symmetry

$$\mathcal{L}_{TVP} = c_{TVP}\,\mathrm{Tr}\{\,T_{\mu\nu}\,[V^{\mu},\,(\partial^{\nu}P)]_{-}\,\}\,,$$

$$P = \begin{pmatrix} \frac{\eta_N+\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta_N-\pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & \eta_S \end{pmatrix}, \quad V^{\mu} = \begin{pmatrix} \frac{\omega_N^{\mu}+\rho^{0\mu}}{\sqrt{2}} & \rho^{+\mu} & K^{*+\mu} \\ \rho^{-\mu} & \frac{\omega_N^{\mu}-\rho^{0\mu}}{\sqrt{2}} & K^{*0\mu} \\ K^{*-\mu} & \bar{K}^{*0\mu} & \omega_S^{\mu} \end{pmatrix},$$

$$T^{\mu\nu} = \begin{pmatrix} \frac{\eta_{2,N}^{\mu\nu}+\pi_2^{0\mu\nu}}{\sqrt{2}} & \pi_2^{+\mu\nu} & K_2^{+\mu\nu} \\ \pi_2^{-\mu\nu} & \frac{\eta_{2,N}^{\mu\nu}-\pi_2^{0\mu\nu}}{\sqrt{2}} & K_2^{0\mu\nu} \\ K_2^{-\mu\nu} & \bar{K}_2^{0\mu\nu} & \eta_{2,S}^{\mu\nu} \end{pmatrix}.$$

$$\mathcal{L}_{TXP} = c_{TXP}\,\mathrm{Tr}(\,T_{\mu\nu}\,\{X^{\mu\nu},\,P\}_{+})$$

$$P = \begin{pmatrix} \frac{\eta_N+\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta_N-\pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & \eta_S \end{pmatrix}, \quad X^{\mu\nu} = \begin{pmatrix} \frac{f_{2,N}^{\mu\nu}+a_2^{0\mu\nu}}{\sqrt{2}} & a_2^{+\mu\nu} & K_2^{*+\mu\nu} \\ a_2^{-\mu\nu} & \frac{f_{2,N}^{\mu\nu}-a_2^{0\mu\nu}}{\sqrt{2}} & K_2^{*0\mu\nu} \\ K_2^{*-\mu\nu} & \bar{K}_2^{*0\mu\nu} & f_{2,S}^{\mu\nu} \end{pmatrix},$$

$$T^{\mu\nu} = \begin{pmatrix} \frac{\eta_{2,N}^{\mu\nu}+\pi_2^{0\mu\nu}}{\sqrt{2}} & \pi_2^{+\mu\nu} & K_2^{+\mu\nu} \\ \pi_2^{-\mu\nu} & \frac{\eta_{2,N}^{\mu\nu}-\pi_2^{0\mu\nu}}{\sqrt{2}} & K_2^{0\mu\nu} \\ K_2^{-\mu\nu} & \bar{K}_2^{0\mu\nu} & \eta_{2,S}^{\mu\nu} \end{pmatrix}.$$

Tree-level decay widths:

$$\Gamma^{tl}_{T\to VP} = \frac{k_f}{8\pi\, m_T}\,\frac{g^2_{TVP}}{15}\left(2\,\frac{k_f^4}{m_V^2} + 5\,k_f^2\right)\Theta(m_T - m_V - m_P)\,,$$

and

$$\Gamma^{tl}_{T\to XP} = \frac{k_f}{8\pi\, m_T}\,\frac{g^2_{TXP}}{45}\left(4\,\frac{k_f^4}{m_X^4} + 30\,\frac{k_f^2}{m_X^2} + 45\right)\Theta(m_T - m_X - m_P)\,.$$

Results for I = 1 and I = 1/2

Decay process	Theory (MeV)	Experiment (MeV)
$\pi_2(1670) \to \rho(770)\,\pi$	80.6 ± 10.8	80.6 ± 10.8
$\pi_2(1670) \to f_2(1270)\,\pi$	146.4 ± 9.7	146.4 ± 9.7
$\pi_2(1670) \to \bar{K}^*(892)\,K + c.c.$	11.7 ± 1.6	10.9 ± 3.7
$\pi_2(1670) \to \bar{K}_2^*(1430)\,K + c.c.$	0	
$\pi_2(1670) \to f_2'(1525)\,\pi$	0.1 ± 0.1	
$\pi_2(1670) \to a_2(1320)\,\pi$	0	not seen
$\pi_2(1670) \to a_2(1320)\,\eta$	0	
$\pi_2(1670) \to a_2(1320)\,\eta'(958)$	0	
$K_2(1770) \to \rho(770)\,K$	22.2 ± 3.0	
$K_2(1770) \to \bar{K}^*(892)\,\pi$	25.5 ± 3.4	seen
$K_2(1770) \to \bar{K}^*(892)\,\eta$	10.5 ± 1.4	
$K_2(1770) \to \bar{K}^*(892)\,\eta'(958)$	0	
$K_2(1770) \to \omega(782)\,K$	8.3 ± 1.1	seen
$K_2(1770) \to \phi(1020)\,K$	4.2 ± 0.6	seen
$K_2(1770) \to a_2(1320)\,K$	0	
$K_2(1770) \to \bar{K}_2^*(1430)\,\pi$	84.5 ± 5.6	dominant
$K_2(1770) \to \bar{K}_2^*(1430)\,\eta$	0	
$K_2(1770) \to \bar{K}_2^*(1430)\,\eta'(958)$	0	
$K_2(1770) \to f_2(1270)\,K$	5.8 ± 0.4	seen
$K_2(1770) \to f_2'(1525)\,K$	0	

Table 4: Decays of $I = 1$ and $I = 1/2$ pseudotensor states. The first two entries were used to determine the coupling constants of the model, see Eq. (3.2). The total decay widths are $\Gamma^{tot}_{\pi_2(1670)} = (260 \pm 9)$ MeV and $\Gamma^{tot}_{K_2(1770)} = (186 \pm 14)$ MeV.

ArXiv: 1608.08777

Comments

The prediction for the decay channel $\pi_2(1670) \to K^*(892)\, K$ is in agreement with the present value quoted by the PDG.

In our model $\pi_2(1670)$ does not couple to the $a_2(1320)\,\pi$ channel, see Eq. (A.2). Experimentally this decay could also be excluded to a good accuracy

The experimental total decay width of $\pi_2(1670)$ reads $\Gamma^{\text{exp,tot}}_{\pi_2(1670)} = (260 \pm 9)$ MeV. The value in our model is ≈ 238.8 MeV. The reason why the sum of the theoretical and experimental decay modes in our model is slightly smaller than the experimental total width is due to the fact that the model does not include the decay $\pi_2(1670) \to f_0(500)\,\pi$, which is ≈ 26 MeV.

Experimentally, the decay channel $K_2(1770) \to \bar{K}_2^*(1430)\,\pi$ is dominant. The total decay width of $K_2(1770)$ is $\Gamma^{\text{exp,tot}}_{K_2(1770)} = (186 \pm 14)$ MeV. Theoretically, the $K_2(1770) \to \bar{K}_2^*(1430)\,\pi$ decay mode is the dominant one $(84.5 \pm 5.6$ MeV$)$.

The full theoretical decay width of $K_2(1770)$ amounts to (162.0 ± 15.4) MeV which is compatible with the experimental value.

Comments/2

Most of the decays which are predicted by our model to vanish were consistently not seen in experiments. Yet, the decays $\pi_2(1670) \to a_2(1230)\,\eta$ and $K_2(1270) \to K^*(892)\,\eta$ are expected to be small but not zero. They were not yet measured, hence they represent a test of our approach as soon as new experimental data will be available.

Various branching ratios of $K_2(1770)$ can be calculated from Tab. At present, experimental results are missing (no average or fit is quoted by PDG). In this respect, our approach makes predictions for new future experimental measurements. In this context, it will also be possible to determine the mixing angle of the bare 1^1D_2 and 1^3D_2 configurations into the physical $K_2(1770)$ and $K_2(1820)$ states [so far, $K_2(1770)$ is dominated by 1^1D_2].

Isoscalar sector: mixing

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

Let us allow for a large mixing angle!

Isoscalar sector: naive results

Decay process	Theory (MeV) ($\beta_{pt} = 14.8°$)	Theory (MeV) ($\beta_{pt} = 0.0°$)	Experiment (MeV)
$\eta_2(1645) \to \bar{K}^*(892)\, K + c.c.$	3.2 ± 0.4	8.6 ± 1.1	seen
$\eta_2(1645) \to a_2(1320)\, \pi$	315.6 ± 21.2	337.8 ± 22.6	
$\eta_2(1645) \to \bar{K}_2^*(1430)\, K + c.c.$	0	0	
$\eta_2(1645) \to f_2(1270)\, \eta$	0	0	not seen
$\eta_2(1645) \to f_2(1270)\, \eta'(958)$	0	0	
$\eta_2(1645) \to f_2'(1525)\, \eta$	0	0	
$\eta_2(1645) \to f_2'(1525)\, \eta'(958)$	0	0	
$\eta_2(1870) \to \bar{K}^*(892)\, K + c.c.$	60.1 ± 8.0	45.6 ± 6.1	
$\eta_2(1870) \to a_2(1320)\, \pi$	32.2 ± 2.1	0	
$\eta_2(1870) \to \bar{K}_2^*(1430)\, K + c.c.$	0	0	
$\eta_2(1870) \to f_2(1270)\, \eta$	2.5 ± 0.2	0.1 ± 0.1	
$\eta_2(1870) \to f_2(1270)\, \eta'(958)$	0	0	
$\eta_2(1870) \to f_2'(1525)\, \eta$	0	0	
$\eta_2(1870) \to f_2'(1525)\, \eta'(958)$	0	0	

Table 5: Decays of $I = 0$ pseudo-tensor states. The total decay widths are $\Gamma^{tot}_{\eta_2(1645)} = (181 \pm 11)$ MeV and $\Gamma^{tot}_{\eta_2(1870)} = (225 \pm 14)$ MeV.

ArXiv: 1608.08777

Only a large and negative mixing angle works

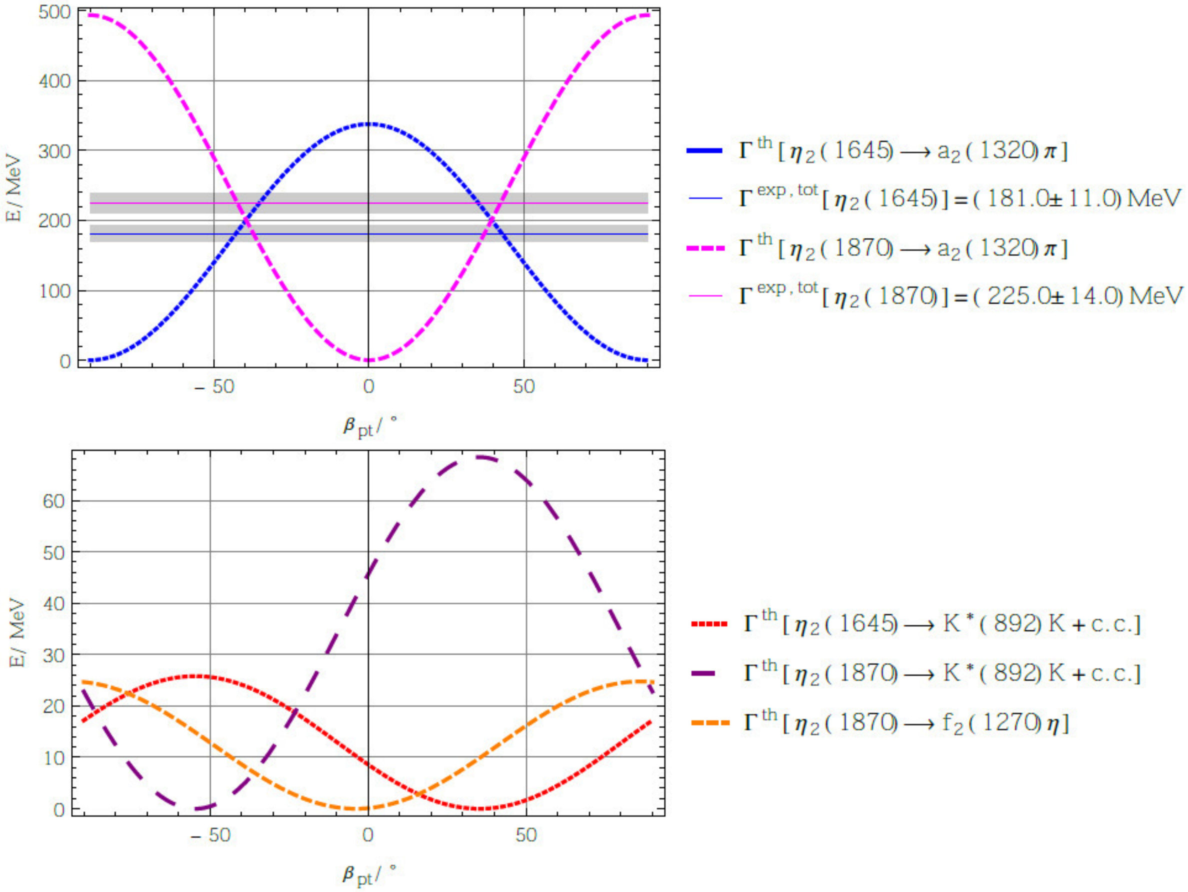

Figure 1: Upper panel: $\eta_2(1645) \to a_2(1320)\,\pi$ and $\eta_2(1870) \to a_2(1320)\,\pi$ as function of β_{pt}. The bands correspond to the total decay widths of $\eta_2(1645)$ and $\eta_2(1870)$. Lower panel: $\eta_2(1645) \to K^*(892)\,K$, $\eta_2(1870) \to K^*(892)\,K$, and $\eta_2(1870) \to f_2(1270)\,\eta$ as function of β_{pt}. Only for $\beta_{pt} \approx -40°$ the decay $\eta_2(1870) \to K^*(892)\,K$ is suppressed. For further details, see discussion in the main text.

ArXiv: 1608.08777

Results in the isoscalar sector for a large mixing

Decay process	Theory (MeV) ($\beta_{pt} = -42°$)	Experiment (MeV)
$\eta_2(1645) \to \bar{K}^*(892)\, K + c.c.$	24.7	seen
$\eta_2(1645) \to a_2(1320)\, \pi$	186.5	
$\eta_2(1645) \to \bar{K}_2^*(1430)\, K + c.c.$	0	
$\eta_2(1645) \to f_2(1270)\, \eta$	0	not seen
$\eta_2(1645) \to f_2(1270)\, \eta'(958)$	0	
$\eta_2(1645) \to f_2'(1525)\, \eta$	0	
$\eta_2(1645) \to f_2'(1525)\, \eta'(958)$	0	
$\eta_2(1870) \to \bar{K}^*(892)\, K + c.c.$	3.3	
$\eta_2(1870) \to a_2(1320)\, \pi$	221.0	
$\eta_2(1870) \to \bar{K}_2^*(1430)\, K + c.c.$	0	
$\eta_2(1870) \to f_2(1270)\, \eta$	9.4	
$\eta_2(1870) \to f_2(1270)\, \eta'(958)$	0	
$\eta_2(1870) \to f_2'(1525)\, \eta$	0	
$\eta_2(1870) \to f_2'(1525)\, \eta'(958)$	0	

Table 6: Decays of $I = 0$ pseudotensor states. The total decay widths are $\Gamma^{tot}_{\eta_2(1645)} = (181 \pm 11)$ MeV and $\Gamma^{tot}_{\eta_2(1870)} = (225 \pm 14)$ MeV.

ArXiv: 1608.08777

Comments

The experimental total width of $\eta_2(1645)$ is (181 ± 11) MeV, while the the theoretical result for $\beta_{pt} = -42°$ reads 211 MeV

The experimental total width of $\eta_2(1870)$ is (225 ± 14) MeV; the corresponding theoretical width for $\beta_{pt} = -42°$ reads 233.7 MeV.

The suppressed decay of $\eta_2(1870)$ into $K^*(892)\,K$ is the result of a destructive interference due to a large and negative strange-nonstrange mixing angle (similar to the one in the pseudoscalar sector).

In conclusion, it is possible to interpret the resonances $[\pi_2(1670), K_2(1770), \eta_2(1645), \eta_2(1870)]$ as the ground-state $\bar{q}q$ pseudotensor mesons nonet if a large and negative mixing angle of about $-42°$ is considered. In this respect, there is – at the stage of the present experimental knowledge – no need to include further additional fields, such as an hybrid pseudotensor state, in the model.

Branching ratios of $\eta_2(1870)$ /1

$\eta_2(1870)$			
Branching ratio	Theory	Experiment	Collaboration
$\Gamma^{\exp}(a_2(1320)\,\pi)/\Gamma^{\exp}(f_2(1270)\,\eta)$	≈ 23.5	$\mathbf{1.7 \pm 0.4}$	average by [1]
		1.60 ± 0.4	Anisovich et al. [32]
		20.4 ± 6.6	Barberis et al. [33]
		4.1 ± 2.3	Adomeit [34]
$\Gamma^{\exp}(a_2(1320)\,\pi)/\Gamma^{\exp}(a_0(980)\,\pi)$		$\mathbf{32.6 \pm 12.6}$	Barberis et al. [33]
$\Gamma^{\exp}(a_0(980)\,\pi)/\Gamma^{\exp}(f_2(1270)\,\eta)$		$\mathbf{0.48 \pm 0.45}$	Barberis et al. [33]

Table 7: Theoretical and experimental branching ratios for $\eta_2(1870)$. The mixing angle $\beta_{pt} \approx -42°$ is used for theoretical predictions. Bold numbers are also bold in PDG [1].

Large conflict for the first entry! Which experiment is right? Can we get new data?

Branching ratios of η2(1870) /2

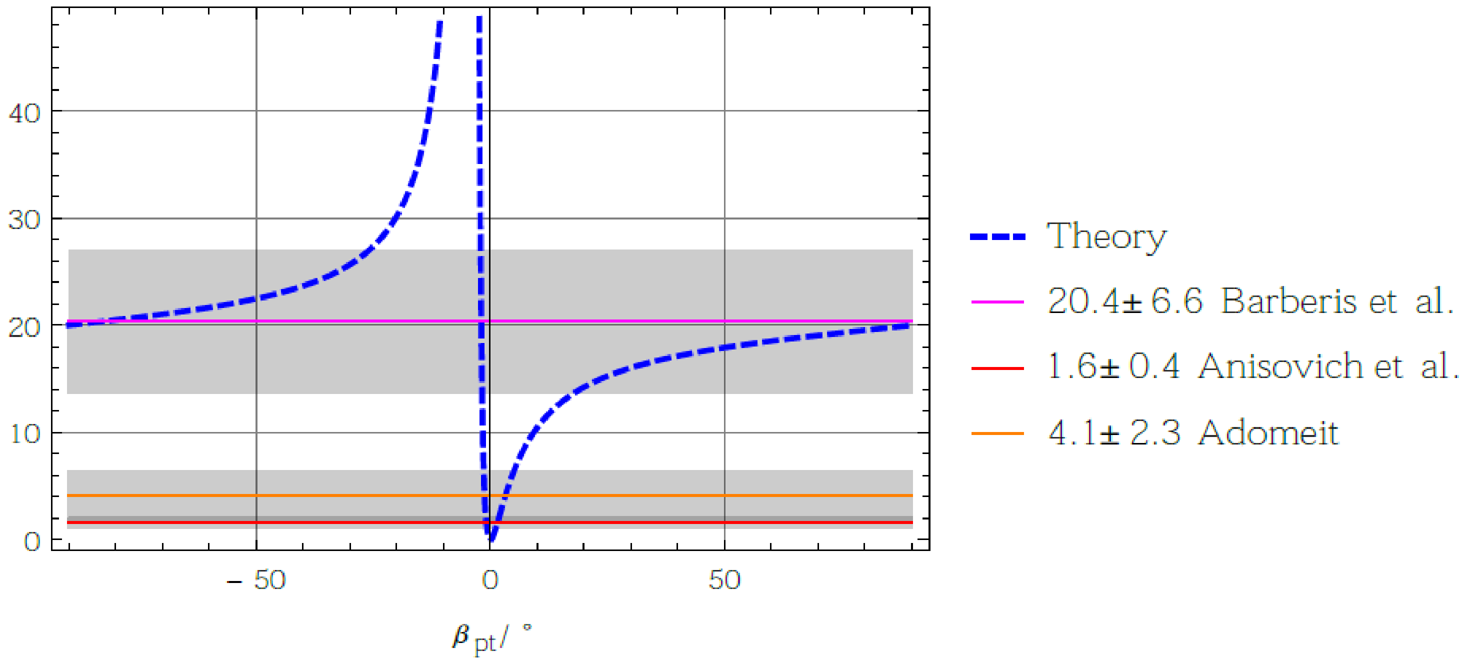

Figure 2: β_{pt}-dependency of the branching ratio $\Gamma(a_2(1320)\,\pi)/\Gamma(f_2(1270)\,\eta)$ of $\eta_2(1870)$. The bands correspond to the experimental values, see Tab. (7).

ArXiv: 1608.08777

Considerations

If new experimental data confirms our results,

- we have good candidates for a ground-state pseudotensor meson nonet.
- the large mixing angle $\beta_{pt} \approx -40^{\circ}$ would be a mystery which deserves a detailed study.
- the current phenomenological study should be redone, including higher order corrections.

If new experimental data is at odd with our results,

- an understanding of the lowlying pseudotensor states as a standard quark-antiquark nonet would be hard.
- $\eta_2(1870)$ could be wrongly assigned as a $\bar{q}q$-state.
- possible further mixings with (hybrid) states could be included in the model.

Large mixing angle: where does it come from?

Uniwersytet
Jana Kochanowskiego w Kielcach

PHYSICAL REVIEW D **97**, 091901(R) (2018)

Rapid Communications

How the axial anomaly controls flavor mixing among mesons

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

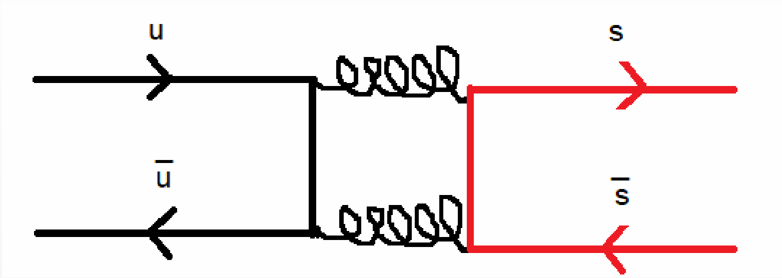
$$\theta_P \simeq -42^\circ$$

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

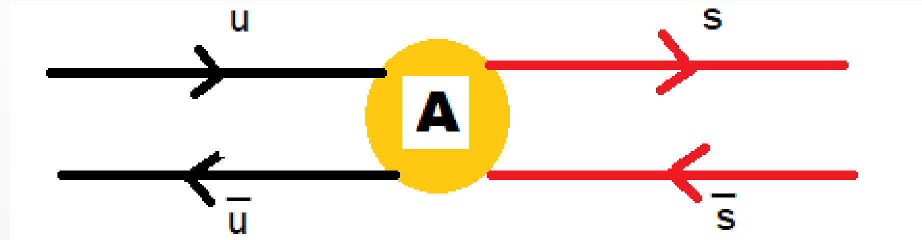
$$\beta_{pt} = -42^\circ$$

Large mixing angle: where does it come from? /2

Such a mixing is suppressed...



But this can be large



- For pseudoscalar mesons: η(547) and η'(958). Θmix = -42° Large mixing caused by the axal anomaly.
- For vector mesons: ω(782) and φ(1020). Θmix = -3° Very small mixing.
- For tensor mesons: f2(1270) and f'2(1525). Θmix = 3° Also very small mixing. Why?
- Pseudotensor mesons: also large, but confirmation is needed.

Details in: **1709.07454**

Excited vector mesons

Strong and radiative decays of excited vector mesons and predictions for a new $\phi(1930)$ resonance

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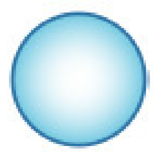
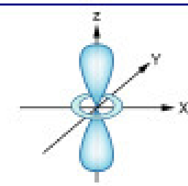
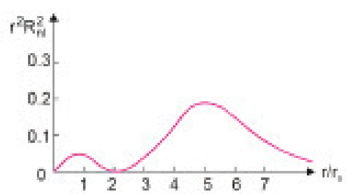
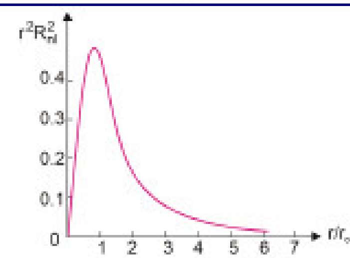
Excited vector mesons

$n\,^{2s+1}\ell_J$	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	$\theta_{\rm quad}$ [°]	$\theta_{\rm lin}$ [°]
$1\,^1S_0$	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^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1380)$	$h_1(1170)$		
$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$		
$1\,^3P_1$	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$	$f_1(1420)$	$f_1(1285)$		
$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$	32.1	30.5
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$		
$1\,^3D_1$	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^{--}	$\rho(1450)$	$K^*(1410)$	$\phi(1680)$	$\omega(1420)$		

L=2, S =1 coupled to: J =1
L=0, S =1 (but n = 2): J =1

Excited vector mesons: properties

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	$\rho(1450), K^*(1410), \phi(1680), \omega(1420)$	$\rho(1700), K^*(1680), \phi_P, \omega(1650)$
Decay types	$V_E \to PP$ $V_E \to VP$ $V_E \to \gamma P$	$V_D \to PP$ $V_D \to VP$ $V_D \to \gamma P$

Matrices of fields

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

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

$$V_E^\mu = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\omega_E^\mu+\rho_E^{\mu 0}}{\sqrt{2}} & \rho_E^{\mu+} & K_E^{\mu\star+} \\ \rho_E^{\mu-} & \frac{\omega_E^\mu-\rho_E^{\mu 0}}{\sqrt{2}} & K_E^{\mu\star 0} \\ K_E^{\mu\star-} & \bar{K}_E^{\mu\star 0} & \phi_E^\mu \end{pmatrix}$$

$$V_D^\mu = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\omega_D^\mu+\rho_D^{\mu 0}}{\sqrt{2}} & \rho_D^{\mu+} & K_D^{\mu\star+} \\ \rho_D^{\mu-} & \frac{\omega_D^\mu-\rho_D^{\mu 0}}{\sqrt{2}} & K_D^{\mu\star 0} \\ K_D^{\mu\star-} & \bar{K}_D^{\mu\star 0} & \phi_D^\mu \end{pmatrix}$$

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

Lagrangians

The Lagrangian of the model is:

$$\mathcal{L} = \mathcal{L}_{1,E} + \mathcal{L}_{1,D} + \mathcal{L}_{2,E} + \mathcal{L}_{2,D},$$

where:

$$\mathcal{L}_{1,E} = ia_E Tr[\partial^\mu P, V_{E,\mu}]P \qquad \mathcal{L}_{1,D} = ia_D Tr[\partial^\mu P, V_{D,\mu}]P$$

$$\mathcal{L}_{2,E} = b_E Tr[\tilde{V}_E^{\mu\nu}\{V_{\mu\nu}, P\}] \qquad \mathcal{L}_{2,D} = b_D Tr[\tilde{V}_D^{\mu\nu}\{V_{\mu\nu}, P\}]$$

$a_E, a_D, b_E, b_D -$ 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
$e_0 = \sqrt{4\pi\alpha} \qquad \alpha \approx 1/137 \qquad g_\rho \approx 5.5 \pm 0.5 \qquad Q = diag(\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3})$

Strong and radiative decay widths

TYPE OF DECAY

- $R \to PP$

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

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

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

EXAMPLES

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

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

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

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

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;
a_i, b_i- coupling constants ($i = E, D$);
m_a, m_b- masses of decay products;
$S-$ symmetry factor;

Results: radially excited vector mesons/1

TABLE VII. Decays widths of (predominantly) radially excited vector mesons into a pseudoscalar meson and a ground-state vector meson ($V_E \to VP$).

Decay process $V_E \to VP$	Theory (MeV)	Experiment (MeV)
$\rho(1450) \to \omega\pi$	74.7 ± 31.0	~84 ± 13 seen by Clegg 94 [47]
$\rho(1450) \to K^*(892)K$	6.7 ± 2.8	Possibly seen by Coan 04 [62]
$\rho(1450) \to \rho(770)\eta$	9.3 ± 3.9	$<16.0 \pm 2.4$ by Donnachie 91 [49]
$\rho(1450) \to \rho(770)\eta'$	≈ 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
$\omega(1420) \to \rho\pi$	196 ± 81	Dominant, $\Gamma_{\text{tot}} = (180 - 250)$ 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
$\phi(1680) \to K\bar{K}^*$	110 ± 46	Dominant, $\Gamma_{\text{tot}} = 150 \pm 50$ by PDG
$\phi(1680) \to \phi(1020)\eta$	12.2 ± 5.1	Seen by Achasov 14 [63]
$\phi(1680) \to \phi(1020)\eta'$	≈ 0	Not listed in PDG

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Results: radially excited vector mesons/2

TABLE VI. Decays widths of (predominantly) radially excited vector mesons into two pseudoscalar 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	$< 6.7 \pm 1.0$ by Donnachie 91 [49]
$\rho(1450) \to \pi\pi$	30.8 ± 6.7	$\sim 27 \pm 4$, seen by Clegg 94 [47]
$K^*(1410) \to K\pi$	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
$\omega(1420) \to \bar{K}K$	5.9 ± 1.3	Not listed in PDG
$\phi(1680) \to \bar{K}K$	19.8 ± 4.3	Seen by Buon 82 [54]

TABLE VIII. Decay widths of (predominantly) radially excited vector mesons into a photon and a pseudoscalar meson ($V_E \to \gamma P$).

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	~0.2–1.5 (see text)
$\rho(1450) \to \gamma\eta'$	0.056 ± 0.033	Not listed
$K^*(1410) \to \gamma K$	0.18 ± 0.11	< 0.0529 MeV seen by PDG and Alavi-Harati 02B [64]
$\omega(1420) \to \gamma\pi$	0.60 ± 0.36	1.90 ± 0.75 (see text)
$\omega(1420) \to \gamma\eta$	0.023 ± 0.014	Not listed
$\omega(1420) \to \gamma\eta'$	0.0050 ± 0.0030	Not listed
$\phi(1680) \to \gamma\eta$	0.14 ± 0.09	Seen
$\phi(1680) \to \gamma\eta'$	0.076 ± 0.045	Not listed

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Which mass for the missing state?

TABLE I. Mass differences between the members of the two nonets of excited vector mesons.

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

Hence, we can estimate the mass of $\phi(???)$ as

$$m_{\phi(???)} \simeq (m_{\phi(1680)} + 250 \pm 20)\ \text{MeV} = 1930 \pm 20\ \text{MeV}.$$

From now on we shall call this hypothetical state

$$\phi(???) \equiv \phi(1930).$$

Orbitally excited/1

TABLE X. Decays widths of (predominantly) orbitally excited vector mesons into a pseudoscalar meson and a ground-state vector meson ($V_D \to VP$).

Decay process $V_D \to VP$	Theory (MeV)	Experiment (MeV)
$\rho(1700) \to \omega\pi$	140 ± 59	Seen (see text)
$\rho(1700) \to K^*(892)K$	56 ± 23	83 ± 66 MeV (see text)
$\rho(1700) \to \rho\eta$	41 ± 17	68 ± 42 MeV (see text)
$\rho(1700) \to \rho\eta'$	≈ 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
$\omega(1650) \to \rho\pi$	370 ± 156	~ 205, 154 ± 44, ~ 273, 120 ± 18 (see text)
$\omega(1650) \to K^*(892)K$	42 ± 18	Not listed in PDG
$\omega(1650) \to \omega(782)\eta$	32 ± 13	~ 100, 56 ± 30 (see text)
$\omega(1650) \to \omega(782)\eta'$	≈ 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

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Orbitally excited/2

TABLE IX. Decays widths of (predominantly) orbitally excited vector mesons into two pseudoscalar mesons ($V_D \to PP$).

Decay process $V_D \to PP$	Theory (MeV)	Experiment (MeV)
$\rho(1700) \to \bar{K}K$	40 ± 11	$8.3^{+10}_{-8.3}$ MeV (see text)
$\rho(1700) \to \pi\pi$	140 ± 37	75 ± 30 by Becker 79 [65]
$K^*(1680) \to K\pi$	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
$\omega(1650) \to \bar{K}K$	37 ± 10	Not listed in PDG
$\phi(1930) \to \bar{K}K$	104 ± 28	Resonance not yet known

TABLE XI. Decay widths of (predominantly) orbitally excited vector mesons into a photon and a pseudoscalar meson ($V_D \to \gamma P$).

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
$\omega(1650) \to \gamma\pi$	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
$\phi(1930) \to \gamma\eta$	0.19 ± 0.12	Resonance not yet known
$\phi(1930) \to \gamma\eta'$	0.13 ± 0.08	Resonance not yet known

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Prediction for φ(1930)

Can one find this state?

TABLE XII. Summary table for the putative state $\phi(1930)$.

Meson $\phi(1930)$	
Quark composition	$\approx s\bar{s}$
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

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Conclusions

- There are open issues in the realm of conventional mesons below 2 GeV
- a1(1260): decay into ρπ and γπ
- Pseudotesnor mesons: decays of $\eta_2(1870)$
- Excited vector mesons: search for φ(1930)

Thanks

Back-up slides

Results of the eLSM (11 parameters, 21 exp. quantities)

Observable	Fit [MeV]	Experiment [MeV]
f_π	96.3 ± 0.7	92.2 ± 4.6
f_K	106.9 ± 0.6	110.4 ± 5.5
m_π	141.0 ± 5.8	137.3 ± 6.9
m_K	485.6 ± 3.0	495.6 ± 24.8
m_η	509.4 ± 3.0	547.9 ± 27.4
$m_{\eta'}$	962.5 ± 5.6	957.8 ± 47.9
m_ρ	783.1 ± 7.0	775.5 ± 38.8
$m_{K^\star}$	885.1 ± 6.3	893.8 ± 44.7
m_ϕ	975.1 ± 6.4	1019.5 ± 51.0
m_{a_1}	1186 ± 6	1230 ± 62
$m_{f_1(1420)}$	1372.5 ± 5.3	1426.4 ± 71.3
m_{a_0}	1363 ± 1	1474 ± 74
$m_{K_0^\star}$	1450 ± 1	1425 ± 71
$\Gamma_{\rho\to\pi\pi}$	160.9 ± 4.4	149.1 ± 7.4
$\Gamma_{K^\star\to K\pi}$	44.6 ± 1.9	46.2 ± 2.3
$\Gamma_{\phi\to\bar{K}K}$	3.34 ± 0.14	3.54 ± 0.18
$\Gamma_{a_1\to\rho\pi}$	549 ± 43	425 ± 175
$\Gamma_{a_1\to\pi\gamma}$	0.66 ± 0.01	0.64 ± 0.25
$\Gamma_{f_1(1420)\to K^\star K}$	44.6 ± 39.9	43.9 ± 2.2
Γ_{a_0}	266 ± 12	265 ± 13
$\Gamma_{K_0^\star\to K\pi}$	285 ± 12	270 ± 80

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Error from PDG or 5% of exp.
Scalar-isoscalar sector not included.

$$\chi^2_{red} = 1.2$$

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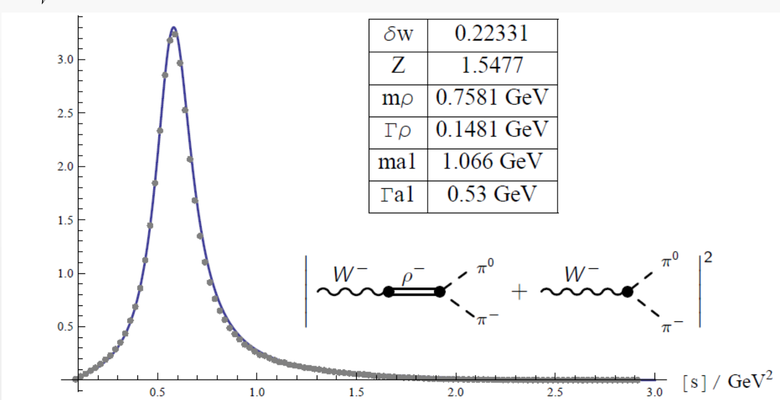
The weak tau-decay into mesons

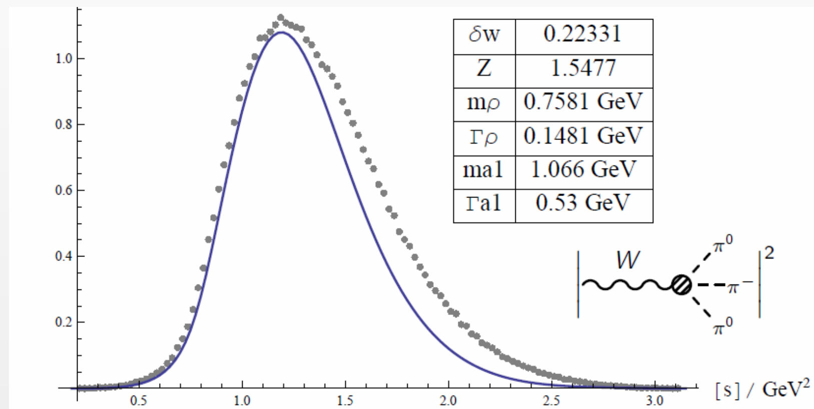
$$\tau \to W^- \nu_\tau \to \pi\pi\nu_\tau$$

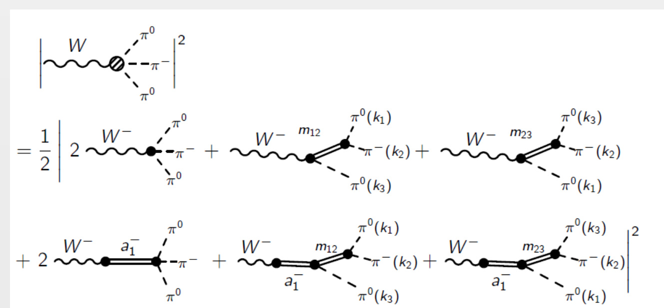
$$\tau \to W^- \nu_\tau \to \pi\pi\pi\nu_\tau$$

$$\frac{1}{N_V}\frac{dN_V}{ds}$$



$$\frac{1}{N_A}\frac{dN_A}{ds}$$





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Quark-antiquark currents

Meson	$n^{2S+1}L_J$	J^{PC}	S	L	Hermitian quark current operators
pseudoscalar	1^1S_0	0^{-+}	0	0	$P_{ij} = \bar{q}_j \, i\gamma^5 \, q_i$
vector	1^3S_1	1^{--}	1		$V_{ij}^{\mu} = \bar{q}_j \, \gamma^\mu \, q_i$
pseudovector	1^1P_1	1^{+-}	0	1	$P_{ij}^{\mu} = \bar{q}_j \, \gamma^5 \overleftrightarrow{\partial}^\mu \, q_i$
scalar	1^3P_0	0^{++}	1		$S_{ij} = \bar{q}_j \, q_i$
axial vector	1^3P_1	1^{++}	1		$A_{ij}^{\mu} = \bar{q}_j \, \gamma^5\gamma^\mu \, q_i$
tensor	1^3P_2	2^{++}	1		$X_{ij}^{\mu\nu} = \bar{q}_j \, i\left[\gamma^\mu \overleftrightarrow{\partial}^\nu + \gamma^\nu \overleftrightarrow{\partial}^\mu - \frac{2}{3}\tilde{G}^{\mu\nu}\overleftrightarrow{\not{\partial}}\right] q_i$
pseudotensor	1^1D_2	2^{-+}	0	2	$T_{ij}^{\mu\nu} = \bar{q}_j \, i\left[\gamma^5 \overleftrightarrow{\partial}^\mu \overleftrightarrow{\partial}^\nu - \frac{2}{3}\tilde{G}^{\mu\nu}\overleftrightarrow{\partial}_\alpha \overleftrightarrow{\partial}^\alpha\right] q_i$
excited vector	1^3D_1	1^{--}	1		$S_{ij}^{\mu} = \bar{q}_j \, \overleftrightarrow{\partial}^\mu \, q_i$
axial tensor	1^3D_2	2^{--}	1		$B_{ij}^{\mu\nu} = \bar{q}_j \, i\left[\gamma^5\gamma^\mu \overleftrightarrow{\partial}^\nu + \gamma^5\gamma^\nu \overleftrightarrow{\partial}^\mu - \frac{2}{3}\tilde{G}^{\mu\nu}\gamma^5\overleftrightarrow{\not{\partial}}\right] q_i$
spin-3 tensor	1^3D_3	3^{--}	1		...

Pseudotensor glueball: predicitons

"$G_2(3040)$"	
Branching ratio	Theory
$\Gamma^{\rm th}(a_2(1320)\,\pi)/\Gamma^{\rm th}(K_2^*(1430)\,K+c.c.)$	0.9
$\Gamma^{\rm th}(a_2(1320)\,\pi)/\Gamma^{\rm th}(f_2(1270)\,\eta)$	6.0
$\Gamma^{\rm th}(a_2(1320)\,\pi)/\Gamma^{\rm th}(f_2(1270)\,\eta'(958))$	8.5
$\Gamma^{\rm th}(a_2(1320)\,\pi)/\Gamma^{\rm th}(f_2'(1525)\,\eta)$	9.0
$\Gamma^{\rm th}(a_2(1320)\,\pi)/\Gamma^{\rm th}(f_2'(1525)\,\eta'(958))$	11.0

Other considerations on pseudotensor mesons

Our model

- couples pseudotensor mesons to pseudoscalar, vector and tensor mesons.
- reproduces present experimental data for $\pi_2(1670)$ and $K_2(1770)$.
- identifies $\eta_2(1870)$ and $\eta_2(1645)$ with the $\bar{q}q$ pseudotensor meson nonet, if non-strange-strange mixing is large.
- predicts a large non-strange-strange mixing angle $\beta_{pt} \approx -40°$ in the isoscalar sector.
- contributes to the discussion on conflicting experimental results for the branching ratios of $\eta_2(1870)$.

Useful ratios from PDG

Branching ratios from PDG for $\eta_2(1645)$:

$$\Gamma^{\mathrm{exp}}(\bar{K}\,K\,\pi)/\Gamma^{\mathrm{exp}}(a_2(1320)\,\pi) = 0.07 \pm 0.03\,,$$

$$\Gamma^{\mathrm{exp}}(a_2(1320)\,\pi)/\Gamma^{\mathrm{exp}}(a_0(980)\,\pi) = 13.1 \pm 2.3\,.$$

Branching ratio from PDG for $\eta_2(1870)$:

$$\Gamma^{\mathrm{exp}}(a_2(1320)\,\pi)/\Gamma^{\mathrm{exp}}(f_2(1270)\,\eta) \neq 0\,.$$