Structure of the Scalar Mesons $f_0(980)$ and $a_0(980)$

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Outline

1. Introductory remarks
2. Phenomenological model for hadronic molecules
3. Electromagnetic $f_0(980)$ and $a_0(980)$ decays
4. Strong decays
5. Conclusions and outlook

Together with:
Thomas Gutsche and Valery Lyubovitskij
arXiv:0808.0705, arXiv:0712.0354 to appear in EPJ A

Meson Structure - The Quark Model and beyond

QCD soft limit ⇒ Hadronic world

Constituent Quark Model

Basic model for hadronic structure: Mesons ($q\bar{q}$) and Baryons (qqq states)

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$\swarrow$

Success

q$\bar{\text{q}}$-nonets:

e.g.

Pseudoscalars,

Vector Mesons, ...

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↙ ↘

Success

q$\bar{\text{q}}$-nonets:

e.g.

Pseudoscalars,

Vector Mesons, ...

Failures

Meson spectrum much richer than expected by quark model!

e.g.

Scalar Mesons

Meson Structure - The Quark Model and beyond

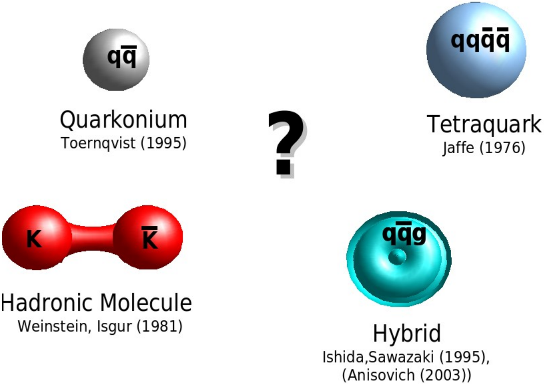
Overview

J^{PC}	I=1	I=$\frac{1}{2}$	I=0		
0^{-+}	π	K	η	η'	
1^{--}	$\rho(770)$	$K^*(892)$	$\Phi(1020)$	$\omega(782)$	
0^{++}	**$a_0(980)$**	$\kappa(800)$	$\sigma(400-1200)$	**$f_0(980)$**	
	$a_0(1450)$	$K_0^*(1430)$	$f_0(1370)$	$f_0(1500)$	$f_0(1710)$

Scalars below 1 GeV, possibly non-quarkonium states.

Possible Candidates for f_0- and a_0-Structure

Most discussed interpretations for the f_0/a_0-substructure:



Motivation: f_0 and a_0 - Hadronic Molecules

Evidence supporting the $K\bar{K}$-molecule picture

1. **Mass spectrum:** $q\bar{q}$: $m_\sigma \approx m_{a_0} < m_\kappa < m_{f_0}$
   $q^2\bar{q}^2$: $m_\sigma < m_\kappa < m_{a_0,f_0}$

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5. Dynamically generated resonances
   meson exchange [3] and unitarized coupled channel models [4]

Further candidates for molecular structure[5]:

$$D^*_{s0}(2317) = DK \qquad X(3872) = D^0\ \bar{D}^{*0} + c.c.$$
$$D_{s1}(2460) = D^*K \qquad Y(4260) = D\bar{D}_1(2420) - c.c.$$

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Outline

The Model - Basics I

Molecular structure of f_0/a_0 : $|f_0/a_0\rangle = \frac{1}{\sqrt{2}}\Big(\big|K^+K^-\big\rangle \pm \big|K^0\bar{K}^0\big\rangle\Big)$

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$K\bar{K}$-model

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Able to reproduce experimental data?

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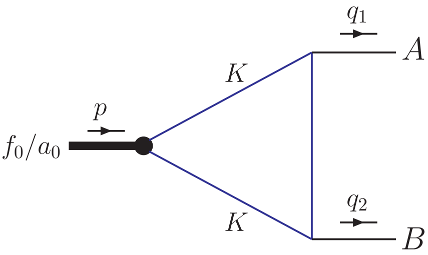

Two-body decays:

$a_0/f_0 \to AB$

Decays proceed via kaon-loops!

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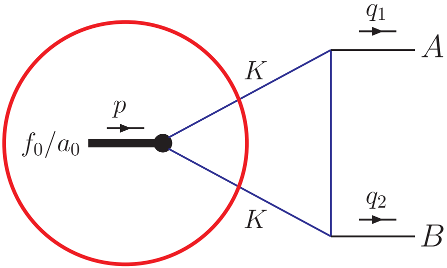


Two-body decays:

$a_0/f_0 \to AB$

Decays proceed via kaon-loops!

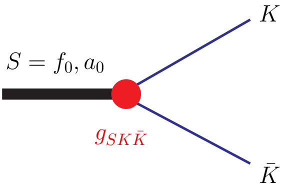
Coupling between molecule and constituent kaons.

The Model - Basics II

Interaction Lagrangian:

$$\mathcal{L}_{f_0 K \bar{K}}(x) = g_{f_0 K \bar{K}} f_0(x) \int dy\, \Phi(y^2) \bar{K}\left(x - \frac{y}{2}\right) K\left(x + \frac{y}{2}\right)$$

$$\bar{K} = \begin{pmatrix} K^- \\ \bar{K}^0 \end{pmatrix}, \quad K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}$$



1. $\Phi(y^2)$: Finite size effects due to extended structure of hadronic molecule.
2. $g_{SK\bar{K}}$: Coupling constant between molecule and constituents.

The Model - Basics III

1. **Gaussian form factor** allows for finite size of the hadr. molecule

$$\Phi(y^2) = \int \frac{d^4k}{(2\pi)^4} e^{-iky} \widetilde{\Phi}(-k^2), \quad \widetilde{\Phi}(k_E^2) = \exp(-k_E^2/\Lambda^2)$$

$$\Lambda = 0.7 - 1.3 \text{ GeV}; \quad \text{Local limit: } \Lambda \rightarrow \infty$$

2. The coupling $g_{SK\bar{K}}$ fixed **self-consistently** by the compositeness condition[1]:

$$Z_{S=f_0,a_0} = 1 - g^2_{SK\bar{K}} \tilde{\Pi}'(p^2)\Big|_{p^2=m_S^2} = 0 \, .$$

[1] Salam, Weinberg

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$$Z_{f_0} = \left| \left\langle f_0^{bare} \middle| f_0^{dressed} \right\rangle \right| = 0$$

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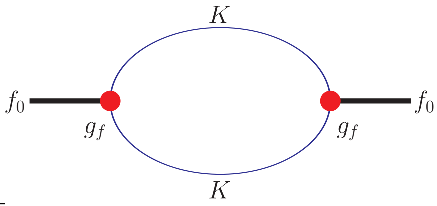
$g^2_{SK\bar{K}} \tilde{\Pi}(p^2)$ Mass operator:



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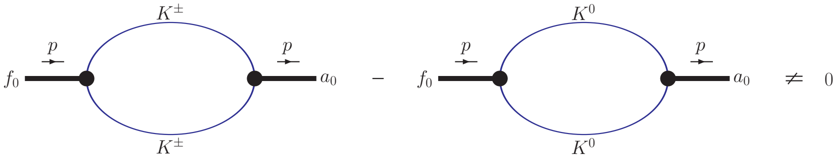
$\mathbf{f_0 - a_0}$ mixing contributions

$f_0 - a_0$ mixing due to mass difference between K^+ and K^0:

$(g_{f_0 K\bar{K}} \equiv g_{f_0 K^+ K^-} = g_{f_0 K^0 \bar{K}^0}; \quad g_{a_0 K\bar{K}} \equiv g_{a_0 K^+ K^-} = -g_{a_0 K^0 \bar{K}^0})$

Charged and neutral kaon loops do not cancel!



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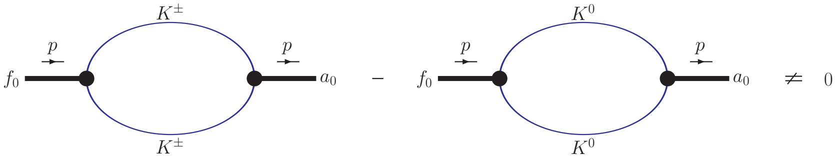
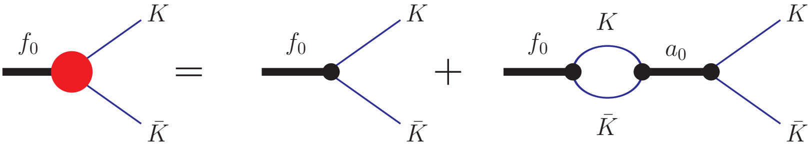


$\Rightarrow$ transition between f_0 and a_0 modifies $g_{SK\bar{K}}$ $\Rightarrow$ effective coupling.



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Electromagnetic Interaction-Local Limit

Electromagnetic fields are included via minimal substitution

$$\partial^\mu K^\pm \to (\partial^\mu \mp ieA^\mu)K^\pm$$

$$\mathcal{L}_{int}^{em} = ieA^\mu \left(K^- \partial_\mu K^+ - K^+ \partial_\mu K^-\right) + e^2 A^2 K^+ K^-$$

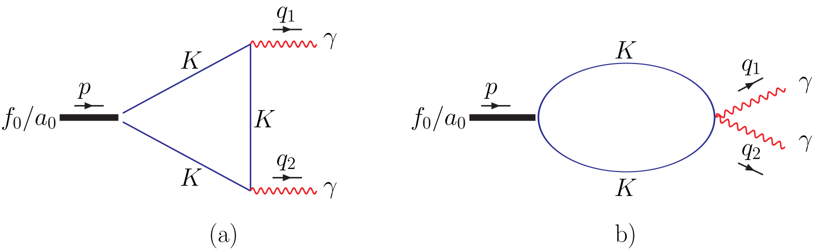


Figure: Diagrams in case of local interaction.

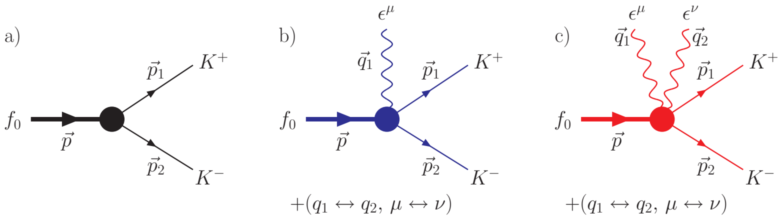
The Model - Gauge Invariance

Strong interaction Lagrangian nonlocal:

$$\mathcal{L}_{int}^{str} = g_{f_0 K\bar{K}} f_0(x) \int dy \Phi(y) \bar{K}\left(x - \frac{y}{2}\right) K\left(x + \frac{y}{2}\right)$$

also gauged with $K^{\pm}(y) \to e^{\mp ieI(y,x)} K^{\pm}(y)\,, \quad I(y,x) = \int\limits_x^y dz_\mu A^\mu(z)$)*

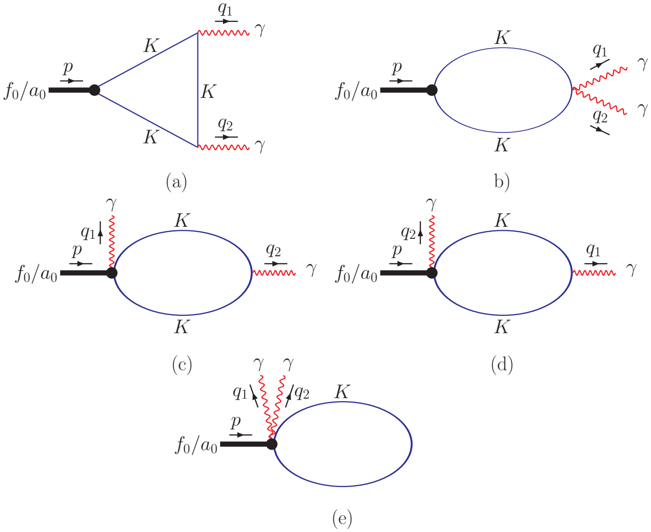
⇒ Additional contact vertices



)* J. Terning, Phys. Rev. D**44**, 887 (1991)

Radiative Decay

Diagrams contributing to the $f_0/a_0 \to \gamma\gamma$ decay processes



Results $f_0/a_0 \to \gamma\gamma$

Experiment	$\Gamma(f_0 \to \gamma\gamma)$ [keV]
PDG (2008)	$0.29^{+0.07}_{-0.09}$
BELLE (2006)	$0.205^{+0.095\,+0.147}_{-0.083\,-0.117}$
Crystal Ball Collab. (1990)	$0.31 \pm 0.14 \pm 0.09$
Mark II Detector (1990)	$0.29 \pm 0.07 \pm 0.12$
Our result	**0.24** (0.25) (Λ=1.0 GeV); **0.29** (0.29) (LC) finite size effects: 0.21-0.26 (Λ=0.7-1.3 GeV)

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Experiment	$\Gamma(a_0 \to \gamma\gamma)$ [keV]
Crystal Barrel (1997)	0.3 ± 0.1
Our result	**0.21** (0.19) (Λ=1.0 GeV); **0.26** (0.23) (LC) finite size effects: 0.16-0.21 (Λ=0.7-1.3 GeV)

Useful to determine meson structure?

Reference	Meson structure	$\Gamma(f_0 \to \gamma\gamma)$ [keV]
Barnes (1985)	$(q\bar{q})$	4.5
Anisovich (2001)	$(q\bar{q})$	$0.28^{+0.09}_{-0.13}$
Oller (1997)	(hadronic)	0.20
Hanhart (2007)	(hadronic)	0.22 ± 0.07
Our result	(hadronic)	**0.24** (NL); **0.29** (LC)

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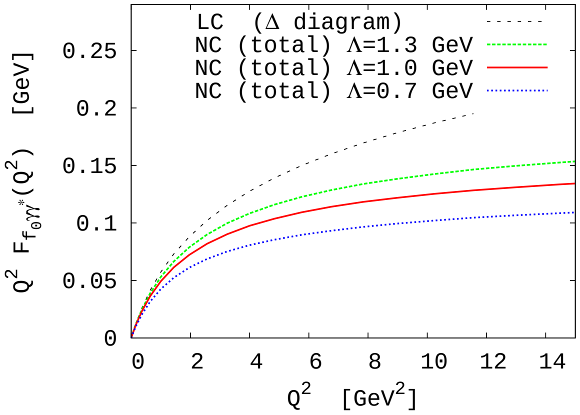
Reference	Meson structure	$\Gamma(a_0 \to \gamma\gamma)$ [keV]
Barnes (1985)	$q\bar{q}$	1.5
Anisovich (2001)	$q\bar{q}$	$0.3^{+0.11}_{-0.10}$
Oller (1997)	(hadronic)	0.78
Our result	(hadronic)	**0.21** (NL); **0.26** (LC)

Form factor for different size parameters Λ.

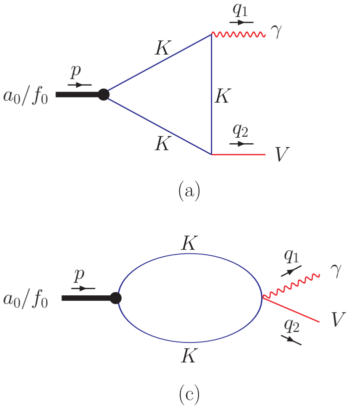


(NC: Nonlocal case, LC: Local case)

$F_{f_0\gamma\gamma^*}$ (one off-shell photon) is sensitive to the size parameter Λ
⇒ provides an opportunity to deduce the f_0 structure.

Radiative Decays

Diagrams contributing to the $f_0/a_0 \to \gamma V$ decay process (V=ρ, ω)



$$\mathcal{L}_{VK\bar{K}} = g_{\rho K\bar{K}} \vec{\rho}^{\,\mu} (\bar{K} \vec{\tau}\, i\partial_\mu K - K \vec{\tau}\, i\partial_\mu \bar{K}) + \sum_{V=\phi,\omega} g_{VK\bar{K}} V^\mu (\bar{K}\, i\partial_\mu K - K\, i\partial_\mu \bar{K})$$

$$g_{\rho K\bar{K}} = g_{\omega K\bar{K}} = \frac{g_{\phi K\bar{K}}}{\sqrt{2}} = \frac{g_{\rho\pi\pi}}{2} = 3 \quad (SU(3) \text{ symmetry relations}).$$

Results Electromagnetic Decays

Results $\Gamma(\phi \to a_0\gamma)$ and $\Gamma(\phi \to f_0\gamma)$ in [keV]:

Our res.:	$\Gamma_{\phi\to a_0\gamma} = 0.41\ (0.37)$		$\Gamma_{\phi\to f_0\gamma} = 0.63\ (0.64)$
PDG (07):	$\Gamma_{\phi\to a_0\gamma} = 0.30 - 0.35$		$\Gamma_{\phi\to f_0\gamma} = 0.44 - 0.51$
PDG (08):	$\Gamma_{\phi\to a_0\gamma} = 0.30 - 0.35$		$\Gamma_{\phi\to f_0\gamma} = 1.28 - 1.47$
SND (00):	$\Gamma_{\phi\to a_0\gamma} = 0.30 - 0.45$	CMD2 (99):	$\Gamma_{\phi\to f_0\gamma} = 0.48 - 2.00$

Results:

$$\begin{aligned}
\Gamma(a_0 \to \rho\gamma) &= 7.29 \text{ keV } (\Lambda = 1 \text{ GeV}); \quad 7.94 \text{ keV (local)} \\
\Gamma(f_0 \to \rho\gamma) &= 7.44 \text{ keV } (\Lambda = 1 \text{ GeV}); \quad 7.93 \text{ keV (local)} \\
\Gamma(a_0 \to \omega\gamma) &= 6.88 \text{ keV } (\Lambda = 1 \text{ GeV}); \quad 7.47 \text{ keV (local)} \\
\Gamma(f_0 \to \omega\gamma) &= 6.99 \text{ keV } (\Lambda = 1 \text{ GeV}); \quad 7.43 \text{ keV (local)}
\end{aligned}$$

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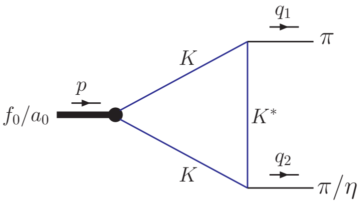
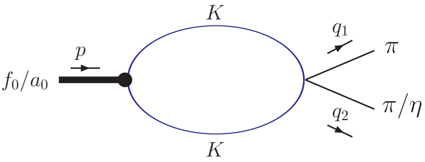
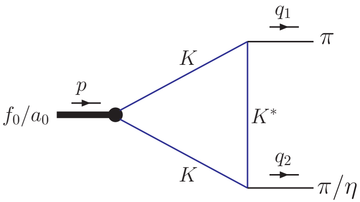
Strong Decays

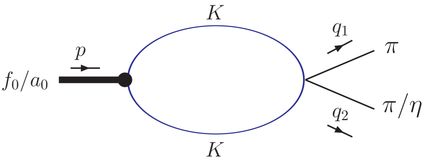




$$\mathcal{L}_{K^*K\pi} = \frac{g_{K^*K\pi}}{\sqrt{2}} K_\mu^{*\dagger} \vec{\pi}\vec{\tau}\, i\overset{\leftrightarrow}{\partial}{}^\mu K + h.c\,, \quad \mathcal{L}_{K^*K\eta} = \frac{g_{K^*K\eta}}{\sqrt{2}} K_\mu^{*\dagger} \eta\, i\overset{\leftrightarrow}{\partial}{}^\mu K + h.c.$$

Strong Decays





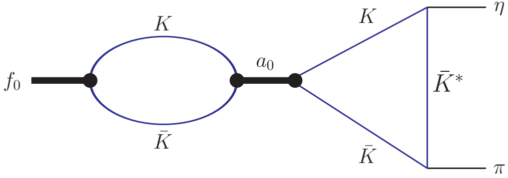
$$\mathcal{L}_{K^*K\pi} = \frac{g_{K^*K\pi}}{\sqrt{2}} K_\mu^{*\dagger} \vec{\pi}\vec{\tau}\, i\overleftrightarrow{\partial}^{\mu} K + h.c\,, \quad \mathcal{L}_{K^*K\eta} = \frac{g_{K^*K\eta}}{\sqrt{2}} K_\mu^{*\dagger} \eta\, i\overleftrightarrow{\partial}^{\mu} K + h.c.$$

$\Gamma(f_0 \to \pi\pi)$	PDG (08)	BELLE (06)	Our result
[MeV]	40-100	$51.3^{+20.8\,+13.2}_{-17.7\,-3.8}$	57.4 (Λ=1 GeV)

$\Gamma(a_0 \to \pi\eta)$	PDG (08)	L3 (01)	WA102 (00)	Our result
[MeV]	50-100	$50 \pm 13 \pm 4$	61 ± 19	61.0 (Λ=1 GeV)

Isospin Violating Decays

$a_0 - f_0$ mixing generates the isospin violating decays
$f_0 \to \pi\eta$ and $a_0 \to \pi\pi$. :



Strongly suppressed compared to the dominant strong decays:

$$\Gamma(f_0 \to \pi\eta) = 0.57 \text{ MeV}$$
$$\Gamma(a_0 \to \pi\pi) = 1.59 \text{ MeV}$$

Conclusions and Outlook

Conclusions

- Covariant and gauge invariant quantum field approach.
- Only one free size parameter but finite size and mixing effects.
- Predictions for strong/em decay processes in good agreement with experimental measurements
- $\Rightarrow K\bar{K}$-model sufficient to describe em/strong decays
- Further observables to test the molecular structure:
  Form factor $F_{f_0\gamma\gamma^*}$ and $f_0 - a_0$ mixing strength.

Outlook

- Weak processes
- Transitions between molecular states
  e.g. $D_{s0}^{*+}(2317) \rightarrow f_0\pi^+$, ...

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Gauge Invariance

Most general expression for the decay amplitude

$$
\begin{aligned}
T &= \epsilon_\mu \epsilon_\nu T^{\mu\nu} \\
T^{\mu\nu} &= A g^{\mu\nu} + B q_1^\mu q_1^\nu + C q_1^\mu q_2^\nu + D q_2^\mu q_1^\nu + E q_2^\mu q_2^\nu \,,
\end{aligned}
$$

q_1, q_2 photon momenta; ϵ polarization vectors.

Lorentz condition implies: $\epsilon_{i\mu} q_i^\mu = 0,\ i = 1, 2$
Gauge invariance implies: $T^{\mu\nu} q_{1,\mu} q_{2,\nu} = 0.$

Therefore: Terms A and B should be left and $A = -D(q_1 q_2)$:

$$T^{\mu\nu} = D(-g^{\mu\nu}(q_1 q_2) + q_2^\mu q_1^\nu)$$

$\Rightarrow$ Structure also diagrammatically reproduced!

Evaluation of the diagrams

$$\mathcal{M}^{\mu\nu}(q_1, q_2) = e^2 \left(F_{f_0\gamma\gamma}(p^2,\, q_1^2,\, q_2^2)b^{\mu\nu} + G_{f_0\gamma\gamma}(p^2,\, q_1^2,\, q_2^2)c^{\mu\nu}\right)$$
$$= e^2 2\frac{g_{f_0 K\bar{K}}}{(4\pi)^2} I^{\mu\nu}$$
$$b^{\mu\nu} = g^{\mu\nu}(q_1 q_2) - q_1^\nu q_2^\mu$$
$$c^{\mu\nu} = g^{\mu\nu} q_1^2 q_2^2 + q_1^\mu q_2^\nu (q_1 q_2) - q_1^\mu q_1^\nu q_2^2 - q_2^\mu q_2^\nu q_1^2$$

The calculation of the matrix elements can be simplified by splitting each diagram into a gauge invariant part and a reminder term

$$I^{\mu\nu} = I_\perp^{\mu\nu} + \delta I^{\mu\nu}, \qquad I_\perp^{\mu\nu}(q_1,\, q_2) = F_\perp b^{\mu\nu} + G_\perp c^{\mu\nu}.$$

The sum of all reminder terms cancels $\sum \delta I^{\mu\nu} = 0$.

$$F_{f_0\gamma\gamma}(p^2, q_1^2, q_2^2)$$
$$= 2\frac{g_{f_0\gamma\gamma}}{(4\pi)^2}\left[F_{\perp_\Delta}(p^2, q_1^2, q_2^2) + F_{\perp_{c)}}(p^2, q_1^2, q_2^2) + F_{\perp_{d)}}(p^2, q_1^2, q_2^2)\right]$$

Results Electromagnetic Decays

Electromagnetic decay properties for $f_0(980) \to \gamma\gamma$ in dependence on Λ.

Λ [GeV]	$g_{f_0 K\bar{K}}$ [GeV]	$\Gamma_{\gamma\gamma}$ [keV]
0.7	3.21	0.21
0.8	3.16	0.23
0.9	3.12	0.24
1.0	3.09	0.25
1.1	3.06	0.25
1.2	3.04	0.25
1.3	3.03	0.26
local	2.90	0.29

The values depend only weakly on Λ.

$\Rightarrow$ The Coupling constant and consequently the width are not very sensitive on the size of the $f_0(980)$.

$q\bar{q}$ Models

Uncertainties concerning diquark models.

1. The quark loop result for $\Gamma_{\gamma\gamma}$ is very sensitive to a $\bar{n}n$ admixture due to an enhancement factor of 25 of the $\bar{n}n$ component with respect to $\bar{s}s$. This factor comes from the el. charge of the quarks.[2]

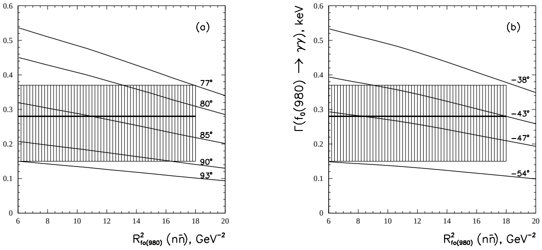

Figure 5: Partial width $\Gamma_{f_0(980)\to\gamma\gamma}$; experimental data are from [15] (shaded area). a) Curves are calculated for positive mixing angles $\varphi = 77°, 80°, 85°, 90°, 93°$ and b) negative angles $\varphi = -38°, -43°, -47°, -54°$.

[A.V. Anisovich (2001)]

2. Model dependent quark coupling and const. quark masses.
3. $\Gamma \propto R_{f_0}^4$

[A.V. Anisovich et. al., Eur. Phys. J. A 12, 103 (2001)]

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[2] [F. Kleefeld et. al., Phys. Rev. D 66, 034007, (2002)]

Dependence on substructure[1]

$$\Gamma(\phi \to \gamma f_0(s\bar{s})) = 0.18 \text{ keV}$$
$$\Gamma(\phi \to \gamma f_0(n\bar{n})) = 0.04 \text{ keV} \times \sin^2\Theta \quad *$$
$$\Gamma(\phi \to \gamma f_0(K\bar{K})) = 0.6 \text{ keV}$$

[1] Kalashnikova (2006); * $\omega - \phi$ mixing angle

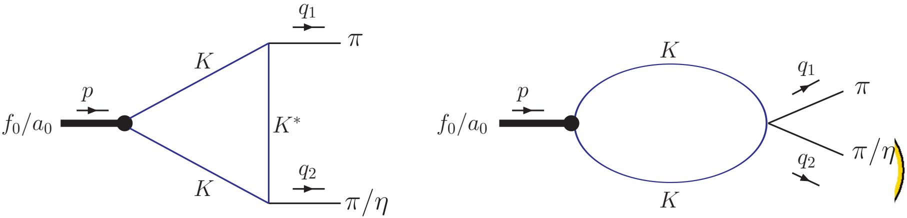
The Strong Two-Pion Decay

Interaction Lagrangian $\mathcal{L}_{K^*K\pi} = \frac{g_{K^*K\pi}}{\sqrt{2}} \left((K^*_{m\mu})^\dagger \vec{\pi}\vec{\tau}_{mn} i\overleftrightarrow{\partial^\mu} K_n\right) + h.c.$

massive vector meson described by tensor field

$$\Rightarrow S^T_{K^*\mu\nu}(x-y) = S^V_{K^*\mu\nu}(x-y) + \frac{i}{m^2_{K^*}} g_{\mu\nu}\delta^{(4)}(x-y)$$

& lowest order ChPT generates $\pi\pi K\bar{K}$ interaction



Results Strong Decays

Data	$\Gamma(f_0 \to \pi\pi)$ [MeV]
PDG (2008)	$40 - 100$
BELLE (2006)	$51.3^{+20.8}_{-17.7}{}^{+13.2}_{-3.8}$
Our result	57.4 (Λ=1 GeV)

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Our result	57.4 (Λ=1 GeV)

Data	$\Gamma(a_0 \to \pi\eta)$ [MeV]
PDG (2008)	$50 - 100$
L3 Collab. (2001)	$50 \pm 13 \pm 4$
WA102 (2000)	61 ± 19
Our result	61.0 (Λ=1 GeV)

Results of the strong decays

Reference	Meson structure	$\Gamma(f_0 \to \pi\pi)$ [MeV]
Barnes (1985)	$q\bar{q}$	400
Anisovich (2002)	$q\bar{q}$	52-58
Scadron (2003)	$q\bar{q}$	53
Oller (1999)	hadronic	19.5
Our result	hadronic	57.4 (Λ=1 GeV)

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Scadron (2003)	$q\bar{q}$	53
Oller (1999)	hadronic	19.5
Our result	hadronic	57.4 (Λ=1 GeV)

Reference	Meson structure	$\Gamma(a_0 \to \pi\eta)$ [MeV]
Barnes (1985)	$q\bar{q}$	225
Scadron (2003)	$q\bar{q}$	138
Oller (1999)	hadronic	20
Our result	hadronic	61.0 (Λ=1 GeV)