Structure of the Scalar Mesons

$f_0(980)$ and $a_0(980)$

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Outline

1. Introductory remarks:
   - The scalars $f_0(980)$ and $a_0(980)$ as molecular states
2. Phenomenological model for molecular states

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   - Strong decays

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2. Phenomenological model for molecular states
   - Electromagnetic $f_0(980)$ and $a_0(980)$ decays
   - Strong decays
3. Results
4. Conclusions and outlook

Based on:
together with Thomas Gutsche and Valery Lyubovitskij
arXiv:0712.0354

Motivation: Hadronic Molecules

Many different interpretations for the $f_0(980)/a_0(980)$ structure:

- $q\bar{q}$, $q^2\bar{q}^2$ [Jaffe], $K\bar{K}$ [Weinstein, Isgur], ...

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

1. Mass degeneracy of f_0 and a_0
2. QCD sum rules[1] & lattice QCD[2]:
   - $m_{q^2\bar{q}^2} < m_{q\bar{q}}$, ([1]Chen (2007), [2]Alford, Jaffe (2004))
3. f_0/a_0-masses slightly below $K\bar{K}$ threshold.

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Further candidates for molecular structure[3]:

$$D^*_{s0}(2317) = KD \qquad B^*_{s0}(5725) = B\,\bar{K}$$
$$D_{s1}(2460) = D^*K \qquad B_{s1}(5778) = B^*\bar{K}$$

(Fässler, Gutsche, Lyubovitskij, Ma (2007/2008))

$\Delta\Delta$ System (Clement *et al.*, Bashkanov *et al.*)

Phenomenological Model for Hadronic Molecules[1]

covariance

full gauge invariance

finite size effects

one size parameter

coupling $g_{SK\bar{K}}$
fixed self-consistently

$\Downarrow$

Consistent evaluation of decay properties

[1] Fässler, Gutsche, Ivanov, Lyubovitskij, Wang, Phys. Rev. D 68 (2003) 014011

The Model - Basics

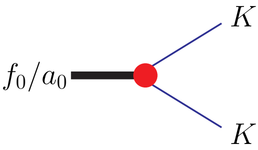
Assume pure molecular structure of $f_0(980)$ and $a_0(980)$

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

The coupling between molecule and constituents

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

$$K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}$$



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

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

$$\Lambda \approx 1\ \text{GeV}$$

Local case (point-like interaction): $\Lambda \rightarrow \infty$

The Model - Coupling $f_0 K \bar{K}$

Compositeness Condition[1]

Field renormalization constant Z_{f_0}: Matrix element between bare and physical field.

f_0 composite object $\Leftrightarrow Z_{f_0} = 0$.

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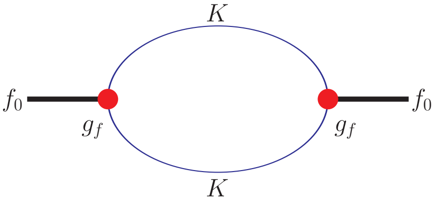
The coupling $g_{f_0 K \bar{K}}$ determined self-consistently by

$$Z_{f_0} = 1 - g_f^2 \tilde{\Pi}'(m_{f_0}^2) = 0 \,.$$

$g_f^2 \tilde{\Pi}(p^2)$: Mass operator



[1] Salam
Weinberg

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$$\begin{aligned} g_{f_0} &= 3.21 - 3.03 \text{ GeV } (\Lambda{=}0.7\text{-}1.3 \text{ GeV}) \\ g_{f_0} &= 2.90 \text{ GeV (local vertex function)} \end{aligned}$$

Electromagnetic Interaction-Local Limit

Electromagnetic fields are included via minimal substitution

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

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

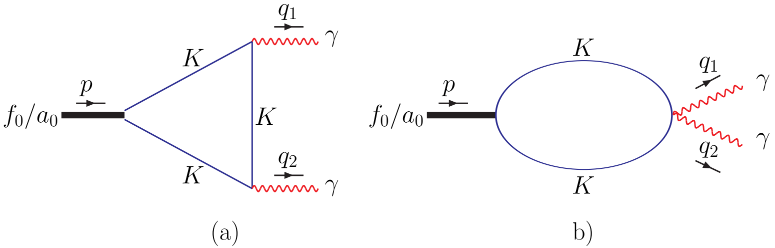


Figure: Diagrams in case of local interaction.

The Model - Gauge Invariance I

Strong interaction Lagrangian is nonlocal.

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

Gauged by applying

$$K^{\pm}(y) \to e^{\mp ieI(y,x)} K^{\pm}(y) , \quad I(y,x) = \int_x^y dz_\mu A^\mu(z)$$ [1]

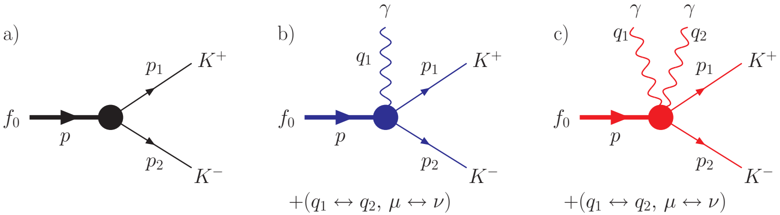
$$\mathcal{L}_{int}^{str+em} = g_{f_0 K \bar{K}} f_0(x) \int dy \Phi(y) \Big[K^{+}\left(x - \frac{y}{2}\right) e^{ieI(x-\frac{y}{2},x)} \times e^{-ieI(x,x+\frac{y}{2})} K^{-}\left(x + \frac{y}{2}\right) + \bar{K}^0\left(x - \frac{y}{2}\right) K^0\left(x + \frac{y}{2}\right)\Big]$$

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

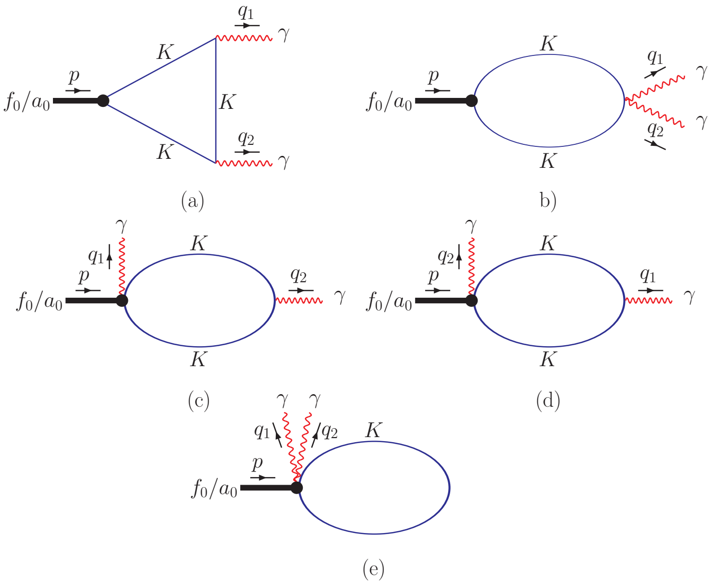
The Model - Gauge Invariance II

Expansion in electromagnetic field yields:

$$1 + ie\left[I(x-\frac{y}{2},x) - I(x+\frac{y}{2},x)\right] - \frac{e^2}{2}\left[I(x-\frac{y}{2},x) - I(x+\frac{y}{2},x)\right]^2$$



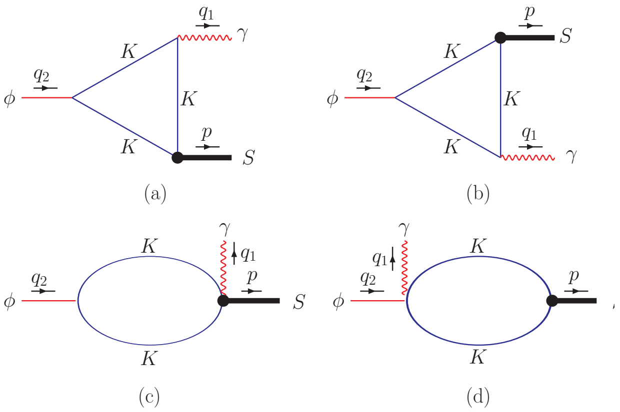
Diagrams contributing to the $f_0/a_0 \to \gamma\gamma$ decay process



Radiative Decays $\phi \to \gamma S$ ($S = a_0,\, f_0$)

$$
\begin{aligned}
\mathcal{L}_{\phi K\bar{K}} &= \frac{g_{\phi K\bar{K}}}{\sqrt{2}}\,\phi^{\mu}\,(\bar{K}i\partial_{\mu}K - Ki\partial_{\mu}\bar{K}) \\
g_{\phi K\bar{K}} &= g_{\rho\pi\pi} = 6 \quad \text{(SU(3) symmetry relations}^{2}\text{)}
\end{aligned}
$$

Diagrams contributing to the $\phi \to \gamma S$ decay process



[2] Zhang et al., Phys. Rev. D 74 (2006) 014013

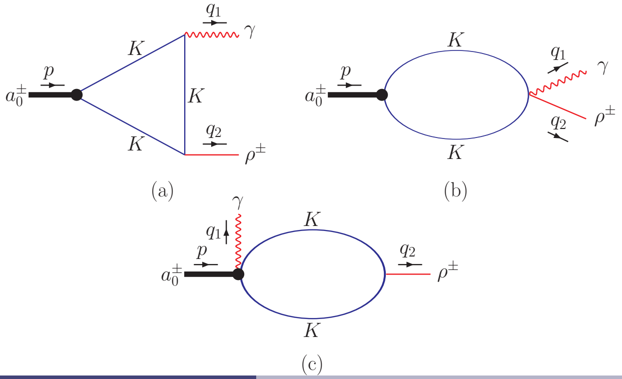
Radiative Decays $f_0/a_0 \to \gamma V$ ($V = \rho, \omega$)

$$\mathcal{L}_{\omega K\bar{K}} = \frac{g_{\omega K\bar{K}}}{\sqrt{2}}\,\omega^\mu\,(\bar{K}i\partial_\mu K - Ki\partial_\mu \bar{K})$$

$$\mathcal{L}_{\rho K\bar{K}} = \frac{g_{\rho K\bar{K}}}{\sqrt{2}}\,\rho^\mu\,(\bar{K}\vec{\tau}i\partial_\mu K - K\vec{\tau}i\partial_\mu \bar{K})\,, \quad \vec{\tau} = (\tau^+, \tau^0, \tau^-)$$

$$g_{\omega K\bar{K}} = g_{\rho K\bar{K}} = \frac{g_{\rho\pi\pi}}{\sqrt{2}} = 4.24$$

Diagrams contributing to the $a_0^\pm \to \gamma\rho^\pm$ decay process



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

Experiment	$\Gamma(f_0 \to \gamma\gamma)$ [keV]
PDG (2007)	$0.29^{+0.07}_{-0.09}$
BELLE (2007)	$0.205^{+0.095\,+0.147}_{-0.083\,-0.117}$
Crystal Ball Collab. (1990)	$0.31 \pm 0.14 \pm 0.09$
SLAC Mark II (1990)	$0.29 \pm 0.07 \pm 0.12$
Our result	0.21-0.26 (Λ=0.7-1.3 GeV) 0.29 (local)

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Experiment	$\Gamma(a_0 \to \gamma\gamma)$ [keV]
Crystal Barrel (1997)	0.3 ± 0.1
Our result	0.20-0.21 (Λ=1.0-1.3 GeV) 0.23 (local)

Useful to determine Meson Structure?

Reference	Meson structure	$\Gamma(f_0 \to \gamma\gamma)$ [keV]
Schumacher (2006)	$(q\bar{q})$	0.33
Scadron et al. (2004)	$(q\bar{q})$	0.31
Achasov et al. (1982)	$(q^2\bar{q}^2)$	0.27
Oller, Oset (1998)	(hadronic)	0.20
Hanhart et al. (2007)	(hadronic)	0.22 ± 0.07
Our result	(hadronic)	0.25 (NL); 0.29 (LC)

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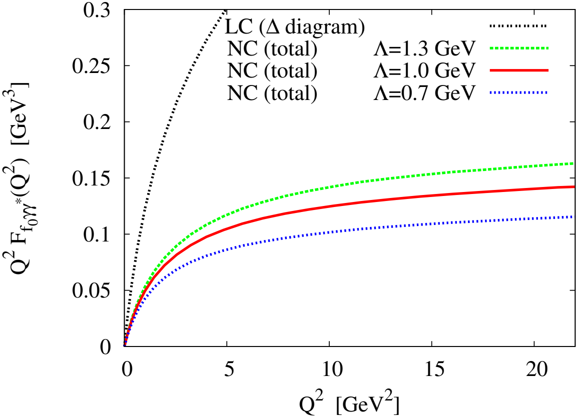
Oller, Oset (1998)	(hadronic)	0.78
Our result	(hadronic)	0.21 (NL); 0.23 (LC)

However... $f_0 \to \gamma\gamma^*$



(NC: Nonlocal case, LC: Local case)

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

Results $\phi \rightarrow \gamma a_0 / f_0$

Results $\phi \rightarrow S\gamma$:

$$\Gamma(\phi \rightarrow a_0\gamma) = 0.34 \text{ keV}$$
$$\Gamma(\phi \rightarrow f_0\gamma) = 0.57 \text{ keV}$$

Data $\phi \rightarrow S\gamma$:

PDG (2007): $\Gamma_{\phi a_0 \gamma} = 0.30 - 0.35 \text{ keV}$

$\Gamma_{\phi f_0 \gamma} = 0.44 - 0.51 \text{ keV}$

CMD2 (1999): $\Gamma_{\phi f_0 \gamma} = 0.426 - 0.924 \text{ keV}$

Results $a_0/f_0 \to \rho\gamma$, $V = \rho, \omega$

Results:

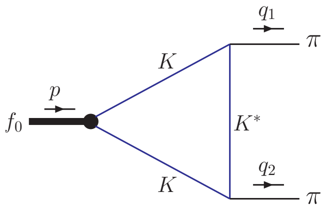
$$\begin{aligned}
\Gamma(a_0 \to \rho\gamma) &= 6.60 \text{ keV } (\Lambda = 1 \text{ GeV}); \quad 7.19 \text{ keV (local)} \\
\Gamma(f_0 \to \rho\gamma) &= 7.59 \text{ keV } (\Lambda = 1 \text{ GeV}); \quad 8.10 \text{ keV (local)} \\
\Gamma(a_0 \to \omega\gamma) &= 6.23 \text{ keV } (\Lambda = 1 \text{ GeV}); \quad 6.77 \text{ keV (local)} \\
\Gamma(f_0 \to \omega\gamma) &= 7.13 \text{ keV } (\Lambda = 1 \text{ GeV}); \quad 7.58 \text{ keV (local)}
\end{aligned}$$

The Strong Two-Pion Decay

Interaction Lagrangian

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

Decay is illustrated by



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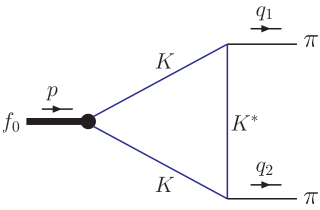

$$\Rightarrow S^T_{K^*\mu\nu}(x-y) = S^V_{K^*\mu\nu}(x-y) + \frac{i}{m^2_{K^*}} g_{\mu\nu}\delta^{(4)}(x-y)$$

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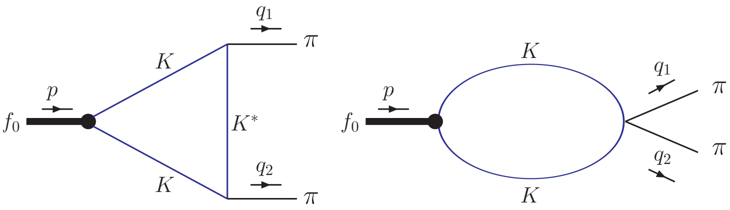

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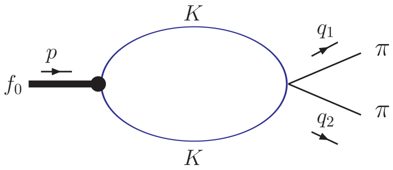

& lowest order ChPT

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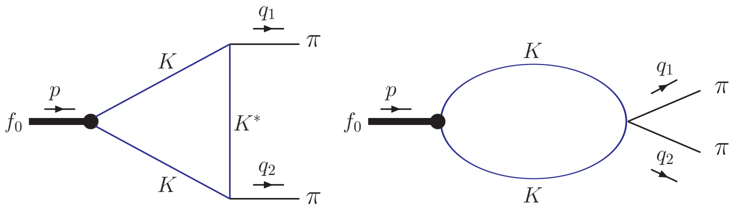

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& lowest order ChPT

Results Strong Decays

Data	$\Gamma(f_0 \to \pi\pi)$ [MeV]
PDG (2007) (total width)	$40 - 100$
BELLE (2007)	$51.3^{+20.8}_{-17.7}{}^{+13.2}_{-3.8}$
Analysis (Anisovich 2002)	64 ± 8
Our result	69 (Λ=1 GeV)

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Data	$\Gamma(a_0 \to \pi\eta)$ [MeV]
PDG (2007) (total width)	$50 - 100$
L3 Collab. (2002)	$50 \pm 13 \pm 4$
WA102 (2000)	61 ± 19
Our result	59 (Λ=1 GeV)

Conclusions and Outlook

- Covariant and full gauge invariant framework to describe the properties of a hadronic molecule.
- Results of the decays

$$\begin{aligned} a_0/f_0 &\rightarrow \gamma\gamma \\ \phi &\rightarrow \gamma a_0/\gamma f_0 \\ a_0/f_0 &\rightarrow \gamma\rho/\gamma\omega \end{aligned} \qquad \begin{aligned} f_0 &\rightarrow \pi\pi \\ a_0 &\rightarrow \pi\eta \end{aligned}$$

  are in good agreement with experimental measurements.
- Additional observable: Form factor $F_{f_0\gamma\gamma^*}$

Outlook

- a_0-f_0 mixing
- Heavy quark meson decays
  e.g. $D^*_{s0}(2317) \rightarrow f_0\rho/f_0\pi$, $D_{s1}(2460) \rightarrow f_0\pi$, $B_{s0}(5725) \rightarrow f_0$...

Thank you for your attention!

Eberhard Karls Universität Tübingen

References I

T. Mori *et al.* [Belle Collaboration], Phys. Rev. D **75**, 051101 (2007) [arXiv:hep-ex/0610038].

T. Barnes, Phys. Lett. B **165**, 434 (1985).

H. Marsiske *et al.* [Crystal Ball Collaboration], Phys. Rev. D **41**, 3324 (1990).

J. Boyer *et al.*, Phys. Rev. D **42**, 1350 (1990).

A. V. Anisovich, V. V. Anisovich and V. A. Nikonov, Eur. Phys. J. A **12**, 103 (2001) [arXiv:hep-ph/0108186].

M. Schumacher, Eur. Phys. J. A **30**, 413 (2006) [Erratum-ibid. A **32**, 121 (2007)] [arXiv:hep-ph/0609040].

N. N. Achasov, S. A. Devyanin and G. N. Shestakov, Phys. Lett. B **108**, 134 (1982) [Erratum-ibid. B **108**, 435 (1982)].

J. A. Oller and E. Oset, Nucl. Phys. A **629**, 739 (1998) [arXiv:hep-ph/9706487].

C. Hanhart, Yu. S. Kalashnikova, A. E. Kudryavtsev and A. V. Nefediev, Phys. Rev. D **75**, 074015 (2007) [arXiv:hep-ph/0701214].

C. Amsler, Rev. Mod. Phys. **70**, 1293 (1998) [arXiv:hep-ex/9708025].

J. A. Oller, E. Oset, F. Guerrero and J. R. Pelaez, Nucl. Phys. A **663**, 991 (2000) [arXiv:hep-ph/9908494].

V. V. Anisovich, V. A. Nikonov and A. V. Sarantsev, Phys. Atom. Nucl. **65**, 1545 (2002) [Yad. Fiz. **65**, 1583 (2002)] [arXiv:hep-ph/0102338].

References II

- M. K. Volkov and V. L. Yudichev, Phys. Atom. Nucl. **64**, 2006 (2001) [Yad. Fiz. **64**, 2091 (2001)] [arXiv:hep-ph/0011326].
- V. V. Anisovich and A. V. Sarantsev, Eur. Phys. J. A **16**, 229 (2003) [arXiv:hep-ph/0204328].
- M. D. Scadron, G. Rupp, F. Kleefeld and E. van Beveren, Phys. Rev. D **69**, 014010 (2004) [Erratum-ibid. D **69**, 059901 (2004)] [arXiv:hep-ph/0309109].
- D. Barberis *et al.* [WA102 Collaboration], Phys. Lett. B **488**, 225 (2000) [arXiv:hep-ex/0007019].
- P. Achard *et al.* [L3 Collaboration], Phys. Lett. B **526**, 269 (2002) [arXiv:hep-ex/0110073].

Results of the strong decays

Reference	Meson structure	$\Gamma(f_0 \to \pi\pi)$ [MeV]
Barnes (1985)	$q\bar{q}$	400
Volkov et al. (2001)	$q\bar{q}$	28
Anisovich et al. (2003)	$q\bar{q}$	52-58
Scadron et al. (2004)	$q\bar{q}$	53
Oller et al. (2000)	hadronic	19.5
Our result	hadronic	69 (Λ=1 GeV)

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Reference	Meson structure	$\Gamma(a_0 \to \pi\eta)$ [MeV]
Barnes (1985)	$q\bar{q}$	225
Scadron et al. (2004)	$q\bar{q}$	138
Oller et al. (2000)	hadronic	20
Our result	hadronic	59 (Λ=1 GeV)