Institut für Theoretische Physik
Technische Universität Wien

Mysteries of Light and Not-So-Light Scalar Mesons

[D. Parganlija et al., arXiv: 1208.0585 – to appear in PR D]

[PhD Thesis of D. Parganlija, arXiv: 1208.0204]

Denis Parganlija

Thanks to:
F. Giacosa, S. Janowski and D. H. Rischke (Frankfurt)
Gy. Wolf and P. Kovács (Budapest)
D. Bugg (London)

Mesons: Definitions and Experimental Data

Mesons: hadrons with integer spin, usually quark-antiquark states

Quantum numbers: *JPC*

Total Spin **Parity** **Charge Conjugation**

Scalar mesons: *JPC* = 0++ [σ or f0(500), a0(980), a0(1450)…]

Pseudoscalar mesons: *JPC* = 0-+ [*π*, *η*, *η´*…]

Vector mesons: *JPC* = 1-- [*ρ*, *ω*, *φ*(1020)…]

Axial-Vector mesons: *JPC* = 1++ [a1(1260), f1(1285), …]

Motivation:
Data on *IJPC* = 00++ Mesons

Six states up to 1.8 GeV (isoscalars)

State	Mass [MeV]	Width [MeV]
f0(500)	400 - 550	400 - 700
f0(980)	990 ± 20	40 - 100
f0(1370)	1200 - 1500	200 - 500
f0(1500)	1505 ± 6	109 ± 7
f0(1710)	1720 ± 6	135 ± 8
f0(1790)	1790^{+40}_{-30}	270^{+60}_{-30}

What Are They?

A toy model with *u*, *d*, *s* quarks

Mi $f_0^N \equiv (\bar{u}u+\bar{d}d)/\sqrt{2}$ **qu** $f_0^S \equiv \bar{s}s$

At most two physical states can be described (but no vectors/axial-vectors)

Thus the mysteries are:

Which scalars of the six are quarkonia?

What is the structure of the remaining ones?

Additional States I

Masses of salars vs. masses of vectors

Tetraquarks!

Reverse Mass Ordering

Additional States I: Tetraquarks

Original idea was by Jaffe (1977):

PHYSICAL REVIEW D VOLUME 15, NUMBER 1 1 JANUARY 1977

Multiquark hadrons. I. Phenomenology of $Q^2\bar{Q}^2$ mesons*

R. J. Jaffe†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 15 July 1976)

The spectra and dominant decay couplings of $Q^2\bar{Q}^2$ mesons are presented as calculated in the quark-bag model. Certain known 0^+ mesons [$\epsilon(700), S^*, \delta, \kappa$] are assigned to the lightest cryptoexotic $Q^2\bar{Q}^2$ nonet. The usual quark-model 0^+ nonet ($Q\bar{Q}$ $L = 1$) must lie higher in mass. All other $Q^2\bar{Q}^2$ mesons are predicted to be broad, heavy, and usually inelastic in formation processes. Other $Q^2\bar{Q}^2$ states which may be experimentally prominent are discussed.

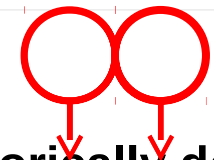
This is the first of two papers on multiquark states in the quark-bag model. This paper is concerned primarily with phenomenology— the spectrum of $Q^2\bar{Q}^2$ mesons, their important couplings, and the possibility that certain known mesons are actually made of two quarks and two antiquarks. The second paper[1] (known hereafter as II) summarizes the calculational methods developed to handle multiquark hadron states with particular reference to $Q^2\bar{Q}^2$ mesons. Here we shall defer all detailed calculations and instead quote liberally from the results of II. A The mass of a hadron should increase roughly linearly with the number of quarks. With (nonstrange) $Q\bar{Q}$ mesons at 700 MeV and Q^3 baryons at 1100 MeV one expects $Q^2\bar{Q}^2$ mesons at around 1500 MeV. Given the splittings within SU(6) multiplets, the lightest $Q^2\bar{Q}^2$ mesons might be expected at masses less than 1 GeV. Certainly there is no evidence of mesons with exotic quantum numbers in this range.

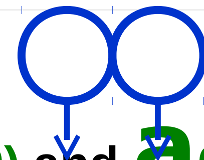
In this paper we examine the S-wave $Q^2\bar{Q}^2$ sector of a colored-quark-gluon model[5] based on a semiclassical approximation[6] to the MIT bag theory.[7]

(Did not call them 'tetraquarks')

Additional States II: Meson Molecules

Note: as a matter of principle, tetraquarks ≠ meson molecules





Historically developed for $f_{0(980)}$ and $a_{0(980)}$ since

i)

ii) they have large *KK* coupling

iii) they do not decay into pions as strongly as expected from the quarkonium picture

Tetraquarks vs. bound states

Additional States II: Meson Molecules

Weinstein and Isgur (1982):

VOLUME 48, NUMBER 10 PHYSICAL REVIEW LETTERS 8 MARCH 1982

Do Multiquark Hadrons Exist?

John Weinstein and Nathan Isgur
Department of Physics, University of Toronto, Toronto, Canada M5S 1A7
(Received 30 November 1981)

The $qq\bar{q}\bar{q}$ system has been examined by solving the four-particle Schrödinger equation variationally. The main findings are that (1) $qq\bar{q}\bar{q}$ bound states normally do not exist, (2) the cryptoexotic 0^{++} sector of this system with $K\bar{K}$ quantum numbers is probably the only exception to (1) and its bound states can be identified with the S^* and δ just below $K\bar{K}$ threshold, (3) $qq\bar{q}\bar{q}$ bound states provide a model for the weak binding and color-singlet clustering observed in nuclei, and (4) there is no indication that this system has strong resonances.

PACS numbers: 12.35.Ht, 12.40.Qq, 14.40.Cs

When supplemented with ingredients from chromodynamics, nonrelativistic quark-potential models enjoy considerable success in describing mesons and baryons.[1] It is natural to try to extend these models to multiquark sectors, both in the hope of uncovering interesting new phenomena and out of a desire to understand nuclei, the only known multiquark systems. One of the principle conclusions of the work on which we report here[2] like that of the deuteron: It is essentially a weakly bound state of two color-singlet mesons ($q\bar{q}$–$q\bar{q}$) in a wave function with an extension much greater than the mesonic radius.

Even if mesonic nuclei do not exist in nature, we believe that they are an interesting quark-based model for ordinary nuclei. However, we present a series of arguments below in favor of interpreting the $J^{PC}=0^{++}$ $S^*(980)$ and $\delta(980)$ just

Additional States III: Glueball

Glueball motivated by QCD Lagrangian

$$\mathcal{L}_{QCD} = \bar{q}_f (i\not{D} - m_f) q_f - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

$$\not{D} = \gamma^\mu D_\mu = \gamma^\mu (\partial_\mu - igA^a_\mu t^a)$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

Symmetries of the QCD Lagrangian

Poincare Symmetry

Local *SU*(3)*c* Colour Symmetry

CPT Symmetry

Global Chiral *U*(*N*f)x *U*(*N*f) Symmetry

Z3 Symmetry

Dilatation Symmetry

Strong Coupling g ~ 1

↓

Strongly Nonperturbative

↕

Hadrons Emerge

Additional States III: Glueball

$$L_{QCD} = \bar{q}_f (i\not{D} - m_f) q_f - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Dilatation symmetry of QCD Lagrangian if mf = 0

$$x^\mu \to x'^\mu = \lambda^{-1} x^\mu \quad G^a_{\mu\nu} \to G'^a_{\mu\nu} = \lambda^2 G^a_{\mu\nu} \quad q \to q' = \lambda^{3/2} q$$

Introduce dilaton potential in sigma-model Lagrangian

Dilaton field and its condensate

↔ **Glueball field and its condensate**

Dilaton affects meson phenomenology

$$\langle GG \rangle = [(699 \pm 40)\,\text{MeV}]^4$$

[S. Janowski, D. Parganlija, F. Giacosa and D. H. Rischke, PR D 84 (2011) 054007]

Chiral Symmetry of QCD

Left-handed and right-handed quarks:

$$q_f = q_{fL} + q_{fR}; \; q_{fL,R} = P_{L,R} q_f$$

Chirality Projection Operators

$$P_{L,R} = \frac{1 \pm \gamma_5}{2}$$

Transform quark fields

$$q_{fL} \to q'_{fL} = U_L q_{fL} = e^{-i\alpha_L^j t^j} q_{fL}, \; j = 0,\ldots,N_f^2 - 1$$

$$q_{fR} \to q'_{fR} = U_R q_{fR} = e^{-i\alpha_R^j t^j} q_{fR}$$

Quark part of the QCD Lagrangian:

invariant
Chiral Symmetry

Explicit Breaking of
Chiral Symmetry

Chiral Currents

Noether Theorem: $U(N_f)_R \longmapsto R^\mu$

$U(N_f)_L \longmapsto L^\mu$

Vector current $V\mu = (L\mu + R\mu)/2$

Axial-vector current $A\mu = (L\mu - R\mu)/2$

Vector transformation of $\mathcal{L}_{QCD}\big|_{\text{quarks}}$

$$q_f \to q_f' = U_V q_f = e^{-i\sum_{j=1}^{N_f^2-1} \alpha_V^j t^j} q_f \xrightarrow{\text{cons. current}} V^{\mu j} \equiv \rho^{\mu j} = \bar{q}_f \gamma^\mu t^j q_f$$

$j = \{1,2,3\}$

ρ(770)-like

Axial-vector Transformation of $\mathcal{L}_{QCD}\big|_{\text{quarks}}$

$$q_f \to q_f' = U_A q_f = e^{-i\sum_{j=1}^{N_f^2-1} \alpha_A^j \gamma^5 t^j} q_f \xrightarrow{\text{cons. current}} A^{\mu j} \equiv a_1^{\mu j} = \bar{q}_f \gamma^\mu \gamma^5 t^j q_f$$

a1(1260)-like

Spontaneous Breaking of Chiral Symmetry

Transform the (axial-)vector fields

Theory:

ρ and a1 should be degenerate

Experiment:

$$m_{a_1} \cong \sqrt{2} m_\rho$$

Spontaneous Breaking of Chiral Symmetry (SSB) via
→ Goldstone Bosons (pions, kaons…)

Ways to Enlightenment

QCD is strongly non-perturbative in the low-energy region

First-principles:

lattice (scalars very broad, extrapolation problems)

light-front wave functions (holography input, no calculation of decays)

Bethe-Salpeter Equations (non-truncated)

Other approaches:

Chiral Perturbation Theory

Linear Sigma Model…

Ways to Enlightenment I: Chiral Perturbation Theory

Effective low-energy theory of QCD
Contains only Goldstone bosons of QCD as degrees of freedom
Perturbation is in momenta, not in coupling
Extremely useful for example in the case of the σ meson

Ways to Enlightenment I: Chiral Perturbation Theory

Chiral Perturbation Theory and the Question of Sigma

ELSEVIER

Nuclear Physics B

Volume 75, Issue 2, 18 June 1974, Pages 189–245

High statistics study of the reaction $\pi^- p \to \pi^- \pi^+ n$: Apparatus, method of analysis, and general features of results at 17 GeV/*c*

G. Grayer*, B. Hyams, C. Jones, P. Schlein**, P. Weilhammer

CERN, Geneva, Switzerland

W. Blum, H. Dietl, W. Koch***, E. Lorenz, G. Lütjens, W. Männer, J. Meissburger, W. Ochs, U. Stierlin

Max-Planck-Institute für Physik und Astrophysik, Munich, Germany

http://dx.doi.org/10.1016/0550-3213(74)90545-8, How to Cite or Link Using DOI

Permissions & Reprints

View full text

Abstract

A detailed account is given of a high statistics experiment measuring the reaction $\pi^- p \to \pi^- \pi^+ n$ at 17.2 GeV/*c*. The spark chamber and counter triggering system are desribed. The methods of data analysis are described, in particular the determination of angular distributions from apparatus with limited acceptance. Experimental data and their interpretation are presented.

Pions on liquid hydrogen and butanol

Broad enhancement in $\pi\pi$ S-wave from 300000 events

Ways to Enlightenment I: Chiral Perturbation Theory

PDG Removed sigma from the Listings in 1976
Reinstated in 1996
Many works from ChPT on Pion-Pion Scattering (Caprini, Colangelo, Ecker, Esposito-Farese, Garcia-Martin, Gasser, Hanhart, Kambor, Kaminski, Leutwyler, Missimer, Pelaez, Rios, Wyler; Meißner, Weise, …)
Unitarise pion-pion scattering by including loops
Find poles ↔ assign to physical resonances

[Leutwyler *et al.* Phys. Rev. Lett. 96, 132001 (2006)]

No statement of structure!

[Yndurain *et al.*, Phys. Rev. D 76, 074034 (2007)]

[F. Giacosa, Phys. Rev. D 80, 074028 (2009)]

Ways to Enlightenment II

Mesons as composites of constituent quarks

Likewise for strange mesons → *j* = 1 to 8

For example in the isoscalar sector:

Build matrices containing mesons

Ways to Enlightenment II: Resonances

Scalars

$$S = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\sigma_N + a_0^0}{\sqrt{2}} & a_0^+ & K_S^+ \\ a_0^- & \frac{\sigma_N - a_0^0}{\sqrt{2}} & K_S^0 \\ K_S^- & \bar{K}_S^0 & \sigma_S \end{pmatrix}$$

Pseudoscalars

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

Ways to Enlightenment II: Resonances

Vectors

$$V_\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\omega_{N\mu} + \rho^0_\mu}{\sqrt{2}} & \rho^+_\mu & K^{*+}_\mu \\ \rho^-_\mu & \frac{\omega_{N\mu} - \rho^0_\mu}{\sqrt{2}} & K^{*0}_\mu \\ K^{*-}_\mu & \bar{K}^{*0}_\mu & \omega_{S\mu} \end{pmatrix}$$

Axial-Vectors

$$A_\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{f_{1N\mu} + a^0_{1\mu}}{\sqrt{2}} & a^+_{1\mu} & K^+_{1\mu} \\ a^-_{1\mu} & \frac{f_{1N\mu} - a^0_{1\mu}}{\sqrt{2}} & K^0_{1\mu} \\ K^-_{1\mu} & \bar{K}^0_{1\mu} & f_{1S\mu} \end{pmatrix}$$

Ways to Enlightenment II: From Matrices to Interactions

Linear Sigma Model

$$\Phi = S + iP \qquad L_\mu = V_\mu + A_\mu \qquad R_\mu = V_\mu - A_\mu$$

$$\mathcal{L} = \mathrm{Tr}[(D^\mu\Phi)^\dagger(D^\mu\Phi)] - m_0^2\,\mathrm{Tr}(\Phi^\dagger\Phi) - \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 - \lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)^2$$

$$+\,\mathrm{Tr}[H(\Phi+\Phi^\dagger)] + c[(\det\Phi + \det\Phi^\dagger)^2 - 4\det(\Phi\Phi^\dagger)]$$

$$-\frac{1}{4}\mathrm{Tr}(L_{\mu\nu}^2 + R_{\mu\nu}^2) + \mathrm{Tr}\left[\left(\frac{m_1^2}{2} + \Delta\right)(L_\mu^2 + R_\mu^2)\right]$$

$$-\,2ig_2(\mathrm{Tr}\{L_{\mu\nu}[L^\mu, L^\nu]\} + \mathrm{Tr}\{R_{\mu\nu}[R^\mu, R^\nu]\})$$

$$+\,\frac{h_1}{2}\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(L_\mu^2 + R_\mu^2) + h_2\,\mathrm{Tr}[(L_\mu\Phi)^2 + (\Phi R_\mu)^2]$$

$$+\,2h_3\,\mathrm{Tr}(\Phi R_\mu \Phi^\dagger L^\mu)$$

$$\Delta \;\hat{=}\; \begin{pmatrix} \delta_n(m_{u,d}^2) & & \\ & \delta_n(m_{u,d}^2) & \\ & & \delta_s(m_s^2) \end{pmatrix}$$

$$D_\mu\Phi = \partial_\mu\Phi + ig_1(\Phi R_\mu - L_\mu\Phi)$$

$$L_{\mu\nu} = \partial_\mu L_\nu - \partial_\nu L_\mu$$

$$R_{\mu\nu} = \partial_\mu R_\nu - \partial_\nu R_\mu$$

Explicit Symmetry Breaking

Chiral Anomaly

Linear Sigma Model

Different class of mesons have to be considered within **one** theoretical frame

Implements features of QCD:

- $SU(N_f)_L \times SU(N_f)_R$ Chiral Symmetry

- Explicit and Spontaneous Chiral Symmetry Breaking; Chiral $U(1)_A$ Anomaly

Vacuum calculations → calculations at $T \neq 0$

Chiral partners degenerate above T_C → order parameter for restoration of chiral symmetry

The model contains: $N_f = 3$ (mesons with *u*, *d*, *s* quarks) in scalar, pseudoscalar, vector and axial-vector channels

→ extended Linear Sigma Model – eLSM

Best Fit of Resonances from eLSM

Observable	Fit [MeV]	Experiment [MeV]
f_π	92.5	92.4 ± 0.9
f_K	109.6	$155.5/\sqrt{2} \pm 1.1$
m_π	139.0	138 ± 1.4
m_K	503.9	495.6 ± 5.0
m_η	526.5	547.9 ± 5.5
$m_{\eta'}$	967.7	957.8 ± 9.6
m_ρ	767.2	775.5 ± 7.8
$m_{K^\star}$	899.9	893.8 ± 8.9
m_φ	1014.0	1019.5 ± 1.02
m_{a_1}	1178.9	1230 ± 40
m_{K_1}	1296.4	1272 ± 12.7
$m_{f_1(1420)}$	1405.1	1426.4 ± 14.3
m_{a_0}	1441.7	1474 ± 74
$m_{K_0^\star}$	1536.5	1425 ± 71
$m_{f_0^L}$	1214.1	1350 ± 150
$m_{f_0^H}$	1584.1	1720 ± 86

Observable	Fit [MeV]	Experiment [MeV]
$\Gamma_{\rho \to \pi\pi}$	166.5	149.1 ± 7.4
$\Gamma_{K^\star \to K\pi}$	44.3	46.2 ± 2.3
$\Gamma_{a_1 \to \rho\pi}$	737	425 ± 175
$\Gamma_{a_1 \to \pi\gamma}$	0.650	0.640 ± 0.250
$\Gamma_{f_1(1420) \to K^\star K}$	43.3	43.9 ± 2.2
$\Gamma_{f_0^L \to \pi\pi}$	122.3	250 ± 100
$\Gamma_{f_0^L \to KK}$	125.7	150 ± 100
$\Gamma_{f_0^H \to \pi\pi}$	31.3	29.3 ± 6.5
$\Gamma_{f_0^H \to KK}$	141.6	71.4 ± 29.1

[D. Parganlija et al., arXiv: 1208.0585 – to appear in PR D]

[S. Janowski, D. Parganlija, F. Giacosa and D. H. Rischke, PR D 84 (2011) 054007]

Scalar Ambiguities I

Can they represent the same resonance?

Scalar Ambiguities II

Assume that they are the same resonance

[M. Ablikim *et al.* (BES II Collaboration), Phys. Lett. B 603, 138 (2004) and Phys. Lett. B 607, 243 (2005)]

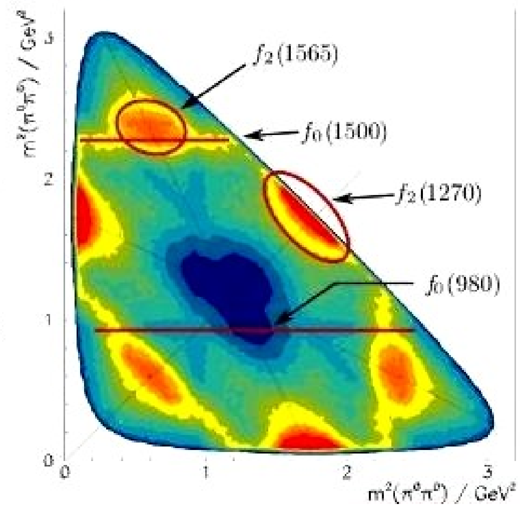
PANDA Experiment at FAIR

Physics - Hadron Spectroscopy

Search for Gluonic Excitations

One of the main challenges of hadron physics is the search for gluonic excitations, i.e. hadrons in which the gluons can act as principal components. These gluonic hadrons fall into two main categories: glueballs, i.e. states where only gluons contribute to the overall quantum numbers, and hybrids, which consist of valence quarks and antiquarks as hadrons plus one or more excited gluons which contribute to the overall quantum numbers.

The additional degrees of freedom carried by gluons allow these hybrids and glueballs to have J^{PC} exotic quantum numbers. In this case mixing effects with nearby $q\bar{q}$ states are excluded and this makes their experimental identification easier. The properties of glueballs and hybrids are determined by the long-distance features of QCD and their study will yield fundamental insight into the structure of the QCD vacuum. Antiproton-proton annihilations provide a very favourable environment to search for gluonic hadrons.



- **It is impossible to consider glueball only: $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ too close**
- **Additional complication: $f_0(1790)$ would interfere… if it exists**
- **Look for $f_0(1790)$!**

A New Statement on Sigma

Heupel, Eichmann, Fischer, Phys. Lett. B 718, 545 (2012)

Physics Letters B 718 (2012) 545–549

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Tetraquark bound states in a Bethe–Salpeter approach

Walter Heupel [a], Gernot Eichmann [a], Christian S. Fischer [a,b,*]

[a] *Institut für Theoretische Physik, Justus-Liebig-Universität Giessen, D-35392 Giessen, Germany*
[b] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, D-64291 Darmstadt, Germany*

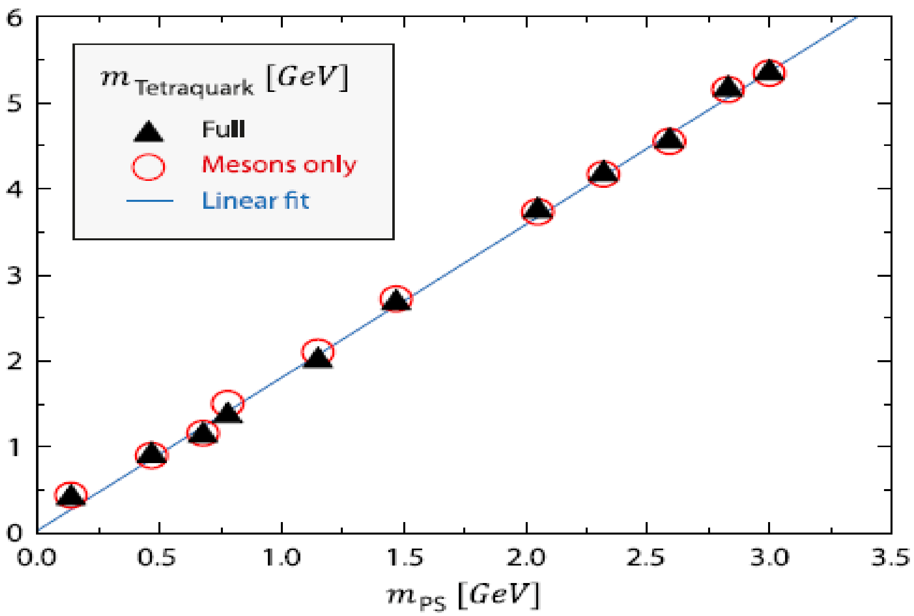
A R T I C L E I N F O

Article history:
Received 17 October 2012
Accepted 2 November 2012
Available online 6 November 2012
Editor: A. Ringwald

A B S T R A C T

We determine the mass of tetraquark bound states from a coupled system of covariant Bethe–Salpeter equations. Similar in spirit to the quark–diquark model of the nucleon, we approximate the full four-body equation for the tetraquark by a coupled set of two-body equations with meson and diquark constituents. These are calculated from their quark and gluon substructure using a phenomenologically well-established quark–gluon interaction. For the lightest scalar tetraquark we find a mass of the order of 400 MeV and a wave function dominated by the pion–pion constituents. Both results are in agreement with a meson molecule picture for the $f_0(600)$. Our results furthermore suggest the presence of a potentially narrow all-charm tetraquark in the mass region 5–6 GeV.

A New Statement on Sigma



Pion-pion component dominant in σ

All-strange tetraquark at ~ 1.2 GeV

osa, Rischke (2012, hep-

ischke, Phys. Rev. D 84, 054007 (2011):

Summary and Outlook

More scalar states than expected by the antiquark-quark picture: f0(500), f0(980), f0(1370), f0(1500), f0(1710), f0(1790)
Where is the quark-antiquark state?
What is the structure of other states?
Relevance for nucleon interaction and chiral restoration
Need one comprehensive approach containing
1) mixing of scalar states
2) interactions of scalars with other meson classes

Summary: Possible Scalar Structures

State	Mass [MeV]	Width [MeV]
$f_0(500)$	400 - 550	400 - 700
$f_0(980)$	980 ± 10	40 - 100
$f_0(1370)$ predominantly $\bar{n}n$	1200 - 1500	200 - 500
$f_0(1500)$ predominantly glueball	1505 ± 6	109 ± 7
$f_0(1710)$ predominantly $\bar{s}s$	1720 ± 6	135 ± 8
$f_0(1790)$	1790^{+40}_{-30}	270^{+60}_{-30}

Spare Slides

Motivation: Reasons to Consider Mesons

More scalar mesons than predicted by quark-antiquark picture → Classification needed

Look for tetraquarks, glueballs… → not all mesons are antiquark-quark states

Nucleon-nucleon interaction modelled via exchange of a scalar isosinglet meson

Restoration of chiral invariance and decofinement ↔ Degeneration of chiral partners π and σ → σ has to be a quarkonium

Identify the scalar quarkonia → Need a formalism with scalar and other states

Summary and Outlook

Explore QCD in non-perturbative and perturbative regions by means of effective models
Essential to understand meson properties already in vacuum
Suggestion for PANDA: inevitable to measure all scalars in order to search for glueballs
CBM experiments accompanied by vector/axial-vector order parameters

Introducing Baryons

Nucleon *N* and its chiral partner *N*(1535)
Mirror assignment
Data for *N*(1535) → *N*π, a1 → πγ and axial coupling of the chiral partner
Only ~50% of the nucleon mass originates from the chiral condensate
Nucleon-nucleon scattering sensitive to the nature of the scalar state

Vectors at Finite *T* and *μ*

Rho meson mass has two contributions:

$$m_\rho^2 = m_1^2 + \frac{\phi_N^2}{2}[h_1 + h_2 + h_3] + \frac{h_1}{2}\phi_S^2$$

~ Gluon Condensate

Quark Condensates

We obtain 640 MeV ≤ m1 ≤ m*ρ*

→ Rho mass decreases by ~(10-15)%

→ Mass of *φ*(1020) also decreases by ~(10-15)%

(in the region where only the chiral condensate decreases)

Resonances become broader

CBM Experiment at FAIR

The energy range up to 15 GeV/u was pioneered at the AGS in Brookhaven. In a second generation experiment the energy range from 10 to 40 GeV/u should be scanned searching for:

- in-medium modifications of hadrons in dense matter.
- indications of the deconfinement phase transition at high baryon densities.
- the critical point providing direct evidence for a phase boundary.
- exotic states of matter such as condensates of strange particles.

- **Statements about spectral functions rather than masses necessary**
- **What about axial-vectors? → Order parameter together with vectors**
- **Note: theoretical description has to include scalars ↔ interaction with axial-vectors**

Otherwise: danger of smearing

What We Did Not Find

Possible Assignments

- **Isospin 1**
- **Isospin ½**
- **Isospin 0 (Isoscalars)**

Check all possibilities

Two K_1 Fields

$$A_\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{f_{1N,A}+a_1^0}{\sqrt{2}} & a_1^+ & K_{1,A}^+ \\ a_1^- & \frac{f_{1N,A}-a_1^0}{\sqrt{2}} & K_{1,A}^0 \\ K_{1,A}^- & \bar{K}_{1,A}^0 & f_{1S,A} \end{pmatrix}_\mu \qquad B_\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{f_{1N,B}+b_1^0}{\sqrt{2}} & b_1^+ & K_{1,B}^+ \\ b_1^- & \frac{f_{1N,B}-b_1^0}{\sqrt{2}} & K_{1,B}^0 \\ K_{1,B}^- & \bar{K}_{1,B}^0 & f_{1S,B} \end{pmatrix}_\mu$$

Induce $K_{1,A}$ - $K_{1,B}$ mixing via Tr(Δ[A_μ, B_μ])

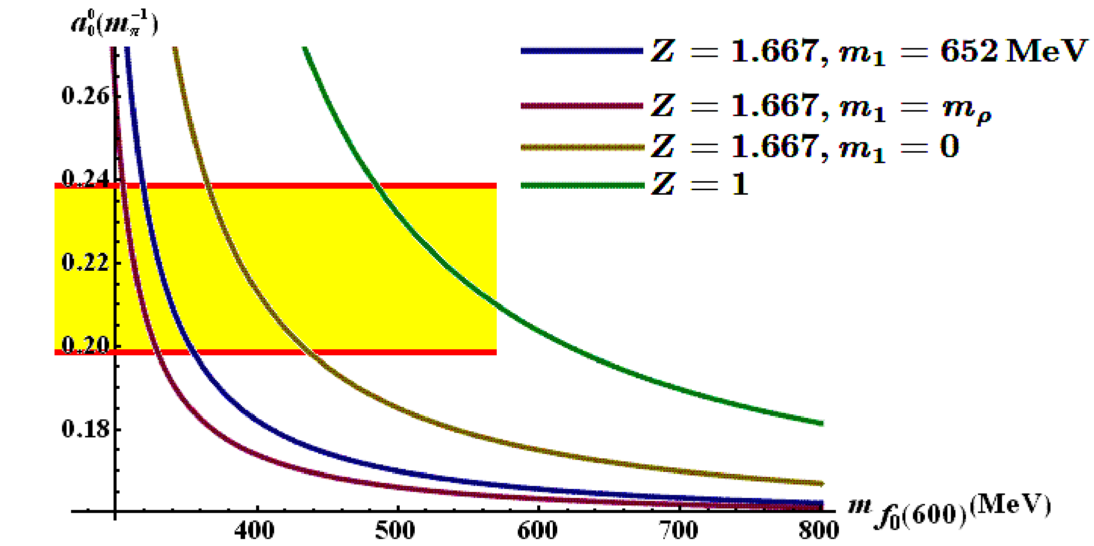
$$\Delta \triangleq \begin{pmatrix} \delta_n(m_{u,d}^2) & & \\ & \delta_n(m_{u,d}^2) & \\ & & \delta_s(m_s^2) \end{pmatrix}$$

Burakovsky, Goldman (1998):

$\varphi_{K_1} \sim 37°$ $\quad m_{K_{1,A}} = 1322\,\text{MeV}$ $\quad m_{K_{1,B}} = 1356\,\text{MeV}$

$m_{K_{1(1270)}} = 1273\,\text{MeV}$ $\quad m_{K_{1(1400)}} = 1402\,\text{MeV}$

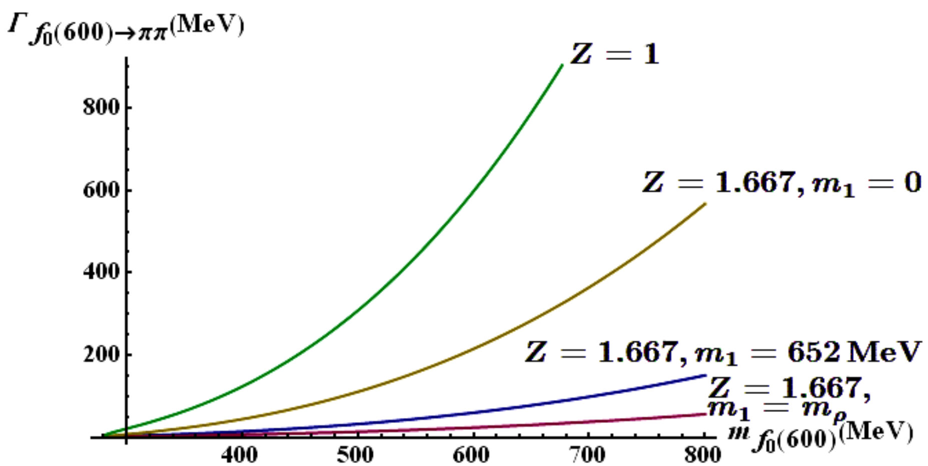
Comparison: the Model with and without Vectors and Axial-Vectors (*Nf*=2)



Include vectors

↓

values decrease



Note: other observables ($\pi\pi$ scattering lengths, *a0*(980)→$\eta\pi$ decay amplitude, phenomonology of *a1*, and others) are fine

[Parganlija, Giacosa, Rischke, Phys. Rev. D 82: 054024, 2010]

Calculating the Parameters

Shift the (axial-)vector fields:

$$f_{1S}^{\mu} \rightarrow f_{1S}^{\mu} + w_{f_{1S}} \partial^{\mu} \eta_S \qquad K^{*\mu} \rightarrow K^{*\mu} + w_{K^*} \partial^{\mu} K_S$$

$$a_1^{\mu} \rightarrow a_1^{\mu} + w_{a_1} \partial^{\mu} \pi \qquad K_1^{\mu} \rightarrow K_1^{\mu} + w_{K_1} \partial^{\mu} K$$

Canonically normalise pseudoscalars and *KS*:

$$\eta_{N,S} \rightarrow Z_{\eta_{N,S}} \eta_{N,S} \qquad \pi \rightarrow Z_{\pi} \pi \qquad K \rightarrow Z_K K \qquad K_S \rightarrow Z_{K_S} K_S$$

Perform a fit of all parameters except *g*2 (fixed via $\rho \rightarrow \pi\pi$)

9 parameters, none free → fixed via masses

$$m_{\pi}, m_K$$

$$m_{a_1} \equiv m_{a_1(1260)}, m_{K_1} \equiv m_{K_1(1270)}$$

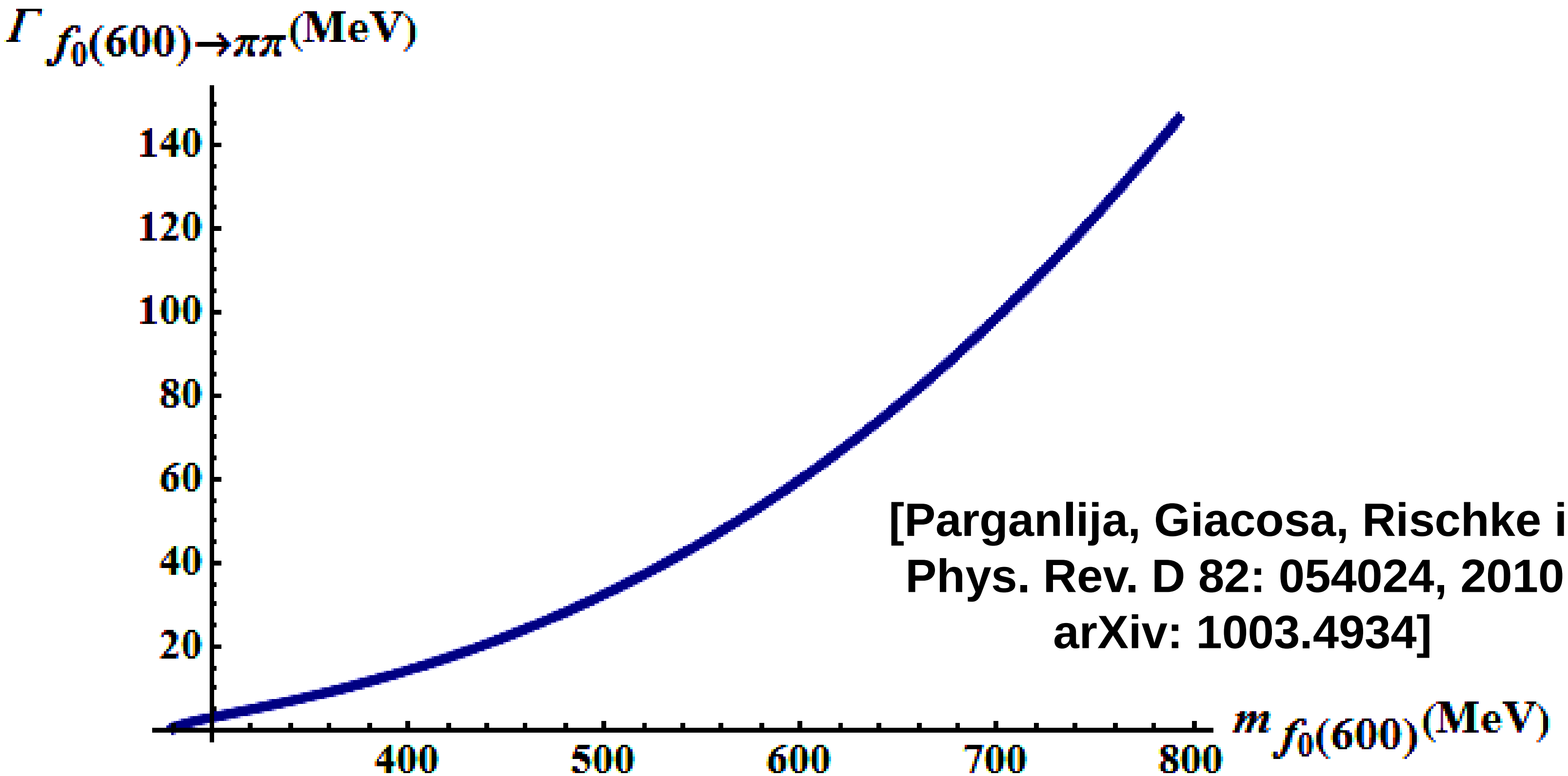
$$m_{a_0} \equiv m_{a_0(1450)}, m_{K_S} \equiv m_{K_0^*(1430)}$$

[Parganlija, Giacosa, Rischke in Phys. Rev. D 82: 054024, 2010; arXiv: 1003.4934]

$$\textbf{Preliminary: no fit with } m_{a_0} < 1\,\text{GeV}, m_{K_S} < 1\,\text{GeV}$$

Note: *Nf* = 2 Limit

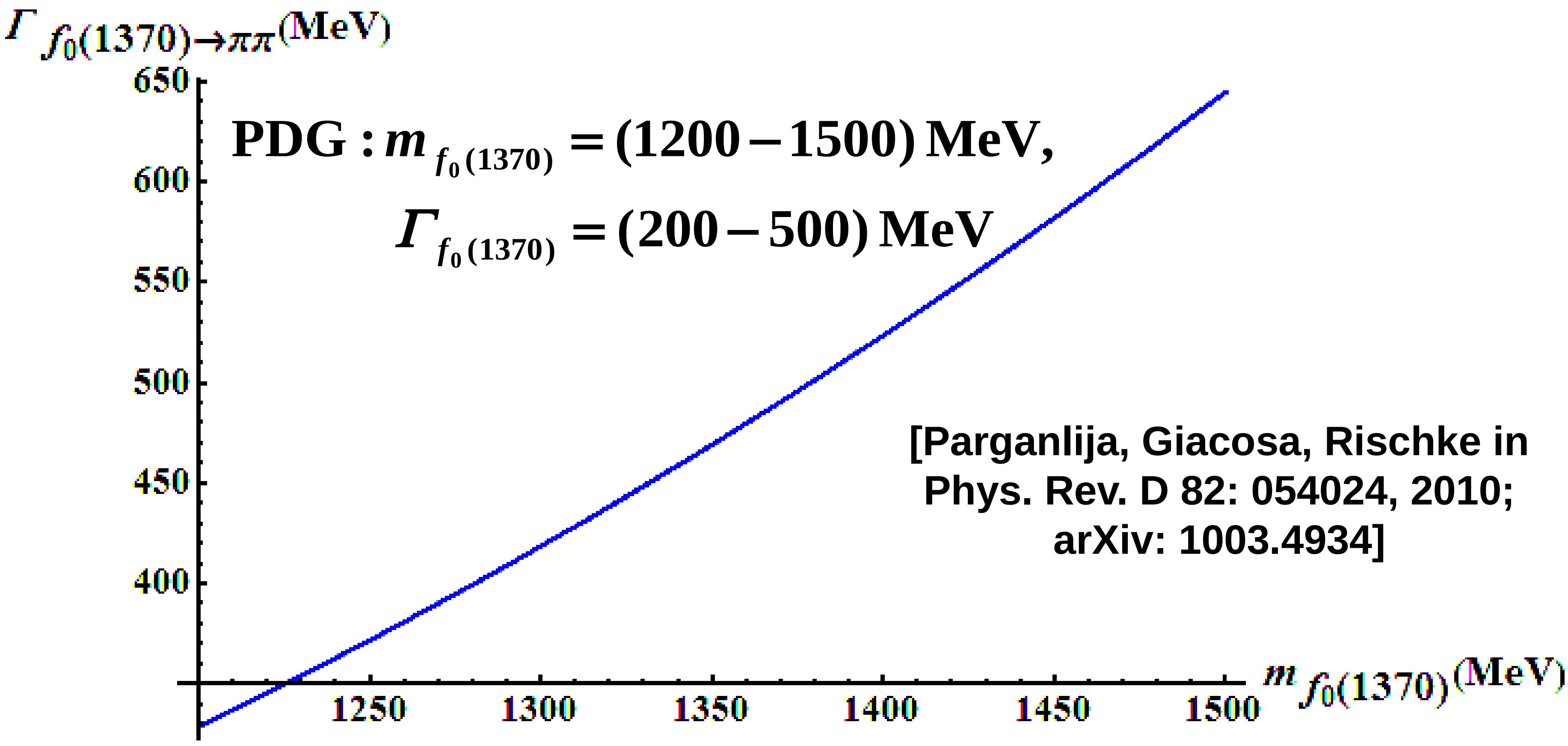
The *f*0(600) state not preferred to be quarkonium



[Parganlija, Giacosa, Rischke in Phys. Rev. D 82: 054024, 2010; arXiv: 1003.4934]

Note: *Nf* = 2 Limit

Experimental data favours $f_0(1370)$ as predominantly $\bar{q}q$



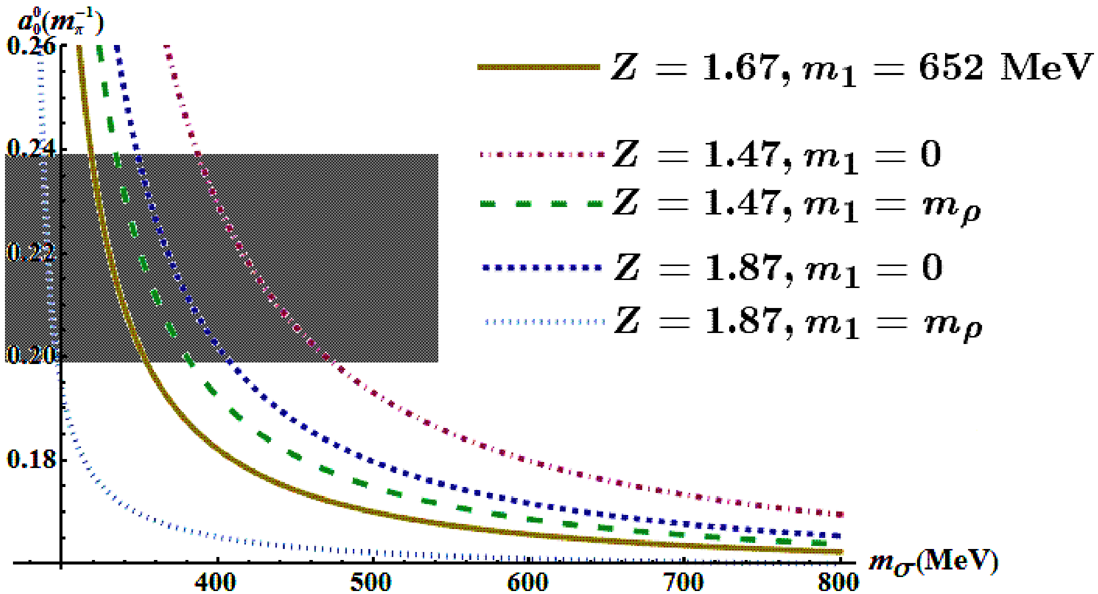
$$\text{PDG}: m_{f_0(1370)} = (1200 - 1500)\ \text{MeV},$$

$$\Gamma_{f_0(1370)} = (200 - 500)\ \text{MeV}$$

[Parganlija, Giacosa, Rischke in Phys. Rev. D 82: 054024, 2010; arXiv: 1003.4934]

Scenario II (N_f =2): Scattering Lengths

Scattering lengths saturated



A ... si-molecular states

Glueball

Scenario II (*Nf* =2): Parameter Determination

Masses: $m_\pi, m_\eta, m_{a_0}, m_\rho, m_{a_1}$

Pion Decay Constant $f_\pi = \frac{\phi}{Z}$

Five Parameters: ***Z*, *h1*, *h2*, *g2*, *mσ***

$$\Gamma_{\rho\to\pi\pi} = (149.4 \pm 1.0)\,\text{MeV} \Rightarrow g_2 = g_2(Z)$$

$$\Gamma_{a_0(1450)} = (265 \pm 13)\,\text{MeV} \Rightarrow h_2 = h_2(Z)$$

$$h_1 \equiv 0\,(h_{2,3}\ \text{small})$$

$$\Gamma_{a_1\to\pi\gamma}[Z] = (0.640 \pm 0.246)\,\text{MeV} \to Z$$

$$m_\sigma \equiv m_{f_0(1370)}\ \text{free}$$

Scenario I (N_f =2): Other Results

$$\Gamma_{\rho\to\pi\pi}[Z, g_2], \Gamma_{f_1\to a_0\pi}[Z, h_2] \text{ exact}$$

Our Result

$$\Gamma_{a_1\to\pi\gamma} = 0.640 \text{ MeV}$$
$$a_0^0 = 0.218$$
$$a_0^2 = -0.0454$$
$$A_{a_0\to\eta\pi} = 3330 \text{ MeV}$$
$$\Updownarrow$$
$$\eta-\eta' \text{ mixing angle}: 41.8^{+0.5}_{-0.2} \text{ deg}$$

[KLOE Collaboration, hep-ex/0612029v3]:

$$\eta-\eta' \text{ mixing angle}: 41.4 \pm 0.5 \text{ deg}$$

Experimental Value

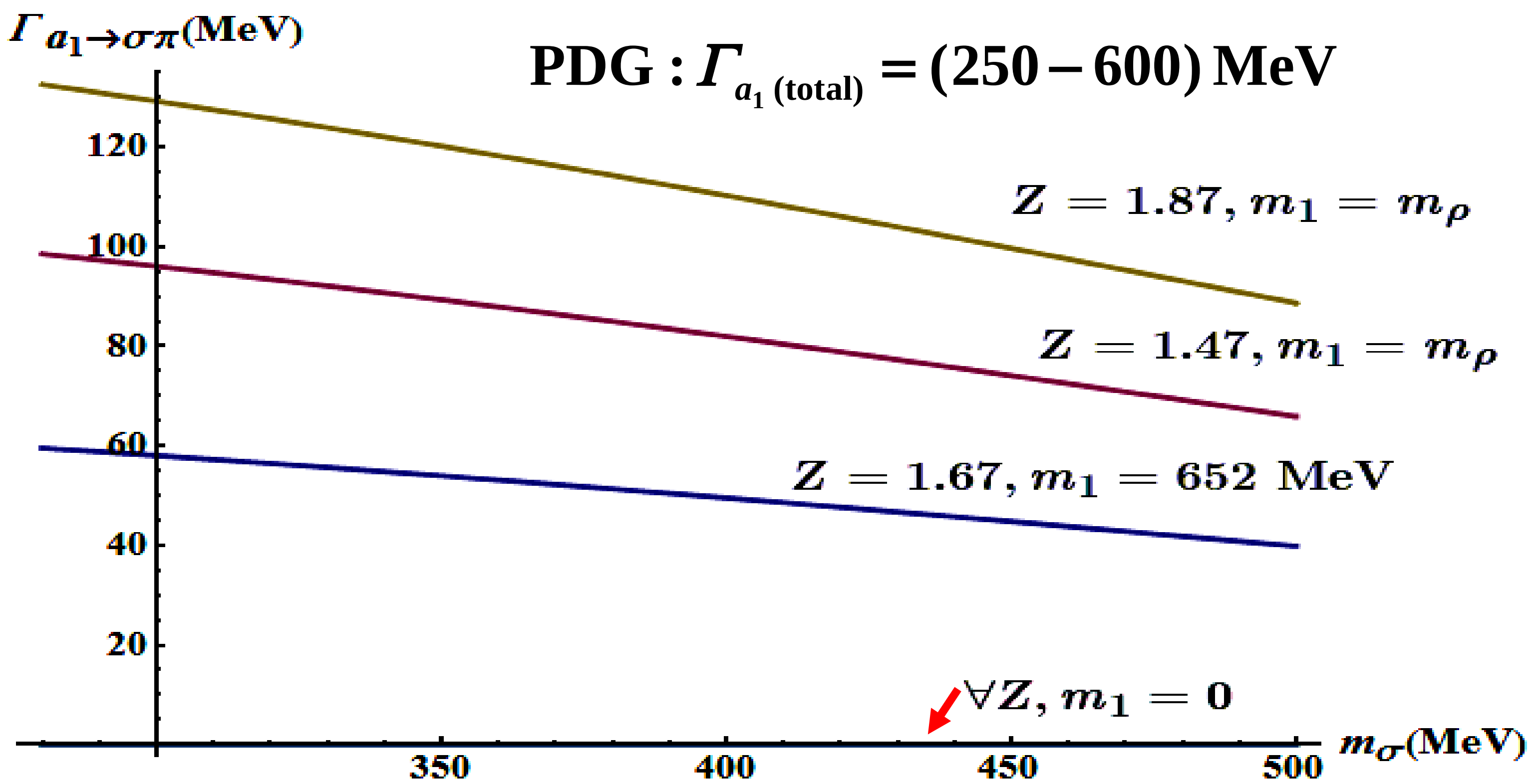
$$\Gamma_{a_1\to\pi\gamma} = 0.640 \text{ MeV}$$
$$a_0^0 = 0.218 \text{ (NA48/2)}$$
$$a_0^2 = -0.0457 \text{ (NA48/2)}$$

$$A_{a_0\to\eta\pi} = 3330 \text{ MeV}$$

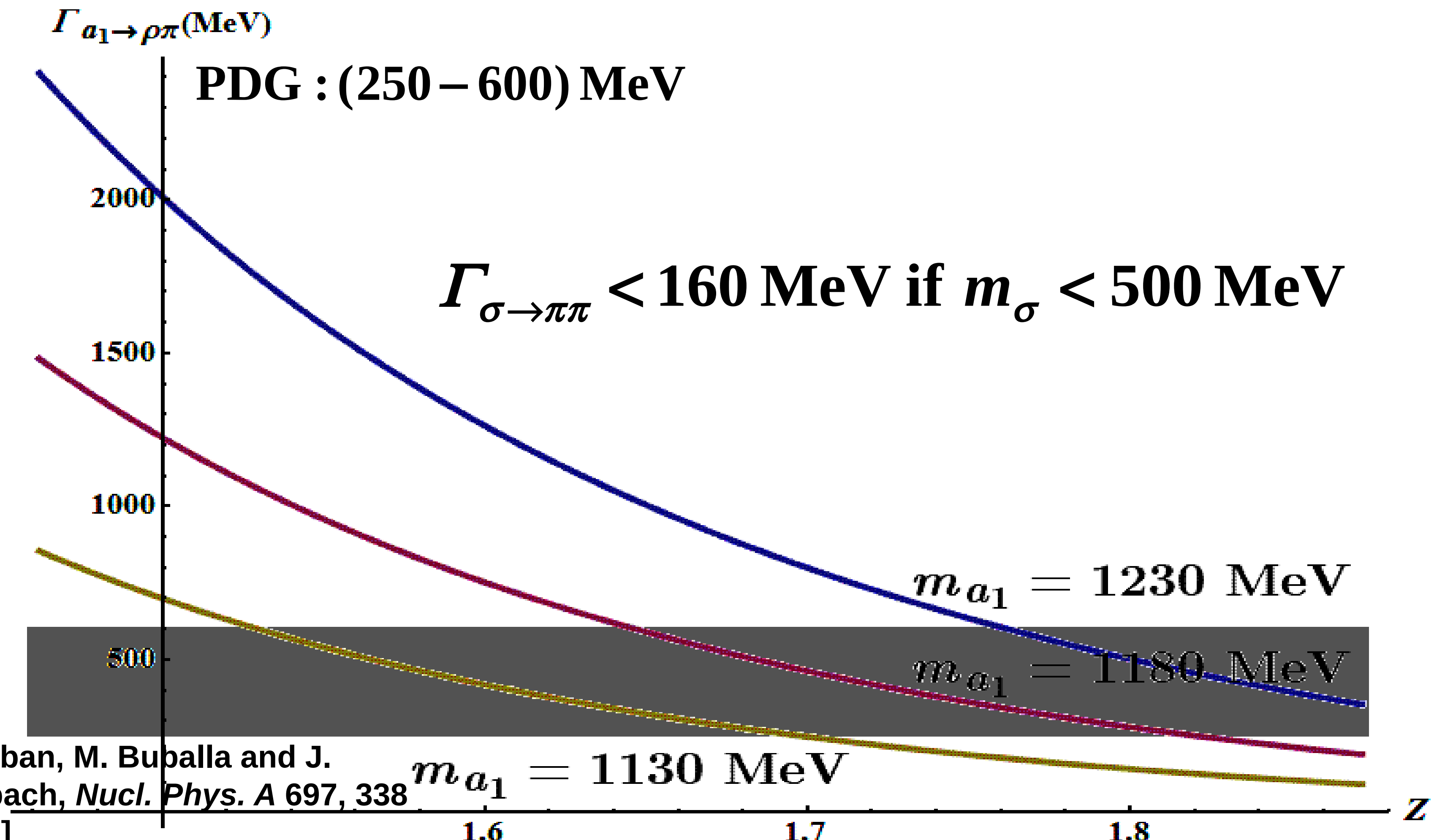
[D. V. Bugg *et al*.,
Phys. Rev. D 50, 4412 (1994)]

Scenario I ($N_f = 2$): $a1 \rightarrow \sigma\pi$ Decay

***m1* = 0** → ***mρ* generated from the quark condensate only;**
our result: *m1* = 652 MeV
a1 → σπ



Scenario I (Nf =2): $a1 \rightarrow \rho\pi$ Decay



[M. Urban, M. Buballa and J. Wambach, *Nucl. Phys. A* 697, 338 (2002)]

Scenario I (N_f =2) : Parameter Determination

Three Independent Parameters: *Z*, *m1*, *mσ*

$$\Gamma_{a_1 \to \pi\gamma}[Z] = (0.640 \pm 0.246)\,\text{MeV} \to Z = 1.67 \pm 0.20$$

$$m_\rho^2 = m_1^2 + \frac{\phi^2}{2}[h_1 + h_2(Z) + h_3(Z)] \quad m_1 = 652^{+123}_{-652}\,\text{MeV}$$

~ Gluon Condensate

Quark Condensate

[S. Janowski (Frankfurt U.), Diploma Thesis, 2010]

Isospin

$$m_\sigma \in [288, 477]\,\text{MeV}$$

$$a_0^0[Z, m_1, m_\sigma] = 0.218 \pm 0.020\,[m_\pi^{-1}]$$

[NA48/2 Collaboration, 2009]

Angular Momentum (*s* wave)

Lagrangian of a Linear Sigma Model with Vector and Axial-Vector Mesons (*Nf* =2)

Vectors and Axial-Vectors

$$\mathcal{L}_{VA} = -\frac{1}{4}\mathrm{Tr}[(L^{\mu\nu})^2 + (R^{\mu\nu})^2] + \left(\frac{m_1^2}{2} + \Delta\right)\mathrm{Tr}[(L^{\mu})^2 + (R^{\mu})^2]$$
$$- 2ig_2(\mathrm{Tr}\{L_{\mu\nu}[L^{\mu}, L^{\nu}]\} + \mathrm{Tr}\{R_{\mu\nu}[R^{\mu}, R^{\nu}]\})$$
$$- 2g_3\{\mathrm{Tr}[(\partial_{\mu}L_{\nu} - ieA_{\mu}[t^3, L_{\nu}] + \partial_{\nu}L_{\mu} - ieA_{\nu}[t^3, L_{\mu}])\{L^{\mu}, L^{\nu}\}]$$
$$+ \mathrm{Tr}[(\partial_{\mu}R_{\nu} - ieA_{\mu}[t^3, R_{\nu}] + \partial_{\nu}R_{\mu} - ieA_{\nu}[t^3, R_{\mu}])\{R^{\mu}, R^{\nu}\}]\}$$

$$L^{\mu\nu} = \partial^{\mu}L^{\nu} - \partial^{\nu}L^{\mu} - (ieA^{\mu}[t^3, L^{\nu}] - ieA^{\nu}[t^3, L^{\mu}])$$
$$R^{\mu\nu} = \partial^{\mu}R^{\nu} - \partial^{\nu}R^{\mu} - (ieA^{\mu}[t^3, R^{\nu}] - ieA^{\nu}[t^3, R^{\mu}])$$

$$\Delta \;\hat{=}\; \begin{pmatrix} \delta_n(m_{u,d}^2) & & \\ & \delta_n(m_{u,d}^2) & \\ & & \delta_s(m_s^2) \end{pmatrix}$$

vectors

$$L^{\mu} = (\omega^{\mu} + f_1^{\mu})\,t^0 + (\vec{\rho}^{\,\mu} + \vec{a}_1^{\,\mu})\cdot\vec{t}$$
$$R^{\mu} = (\omega^{\mu} - f_1^{\mu})\,t^0 + (\vec{\rho}^{\,\mu} - \vec{a}_1^{\,\mu})\cdot\vec{t}$$

axialvectors

Lagrangian of a Linear Sigma Model with Vector and Axial-Vector Mesons (*Nf* =2)

Scalars and Pseudoscalars

$$\mathcal{L}_{SP} = \mathrm{Tr}[(D^\mu\Phi)^\dagger(D^\mu\Phi)] - m_0^2\,\mathrm{Tr}(\Phi^\dagger\Phi) - \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 - \lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)^2$$
$$+\,\mathrm{Tr}[H(\Phi+\Phi^\dagger)] + c[(\det\Phi + \det\Phi^\dagger)^2 - 4\det(\Phi\Phi^\dagger)]$$

Explicit Symmetry Breaking — **Chiral Anomaly**

scalars

$$\Phi = (\sigma + i\eta)\,t^0 + (\vec{a}_0 + i\vec{\pi})\cdot\vec{t}$$

pseudoscalars

$$D^\mu\Phi = \partial^\mu\Phi + ig_1(\Phi R^\mu - L^\mu\Phi) - ieA^\mu[t^3,\Phi]$$

photon

$$\{\sigma, a_0\} \to \{f_0(600), a_0(980)\}\ \text{or}\ \{f_0(1370), a_0(1450)\}$$

Where is the scalar $\bar{q}q$ state?