Lowest I=0 scalar meson state in the scalar meson nonet - A case study

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Outline:

- Motivation
- Formalism
- Result & Summary

Chiral Symmetry and it's breaking

Chiral symmetry via QCD dynamics:

QCD vacuum is unstable w.r.t the formation of a condensate of tightly bound $q\bar{q}$ pairs.

$$< \bar{\psi}\psi > \equiv < 0 \mid \bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \mid 0 > \neq 0.$$

$< \bar{\psi}\psi > \simeq (250 MeV)^3$: no of $q\bar{q}$ pairs per unit volume.

Quarks flip its helicity proportional to $< \bar{\psi}\psi > \longrightarrow$ just like mass

(constituent quark mass)

Chiral symmetry breaking responsible for mass generation (~90%) of nucleons

$f_0(600)$ **or** σ $\rightarrow$ Mass (400 -1200) MeV
Full Width $\rightarrow$ (600 -1000) MeV

Iso-Scalar meson

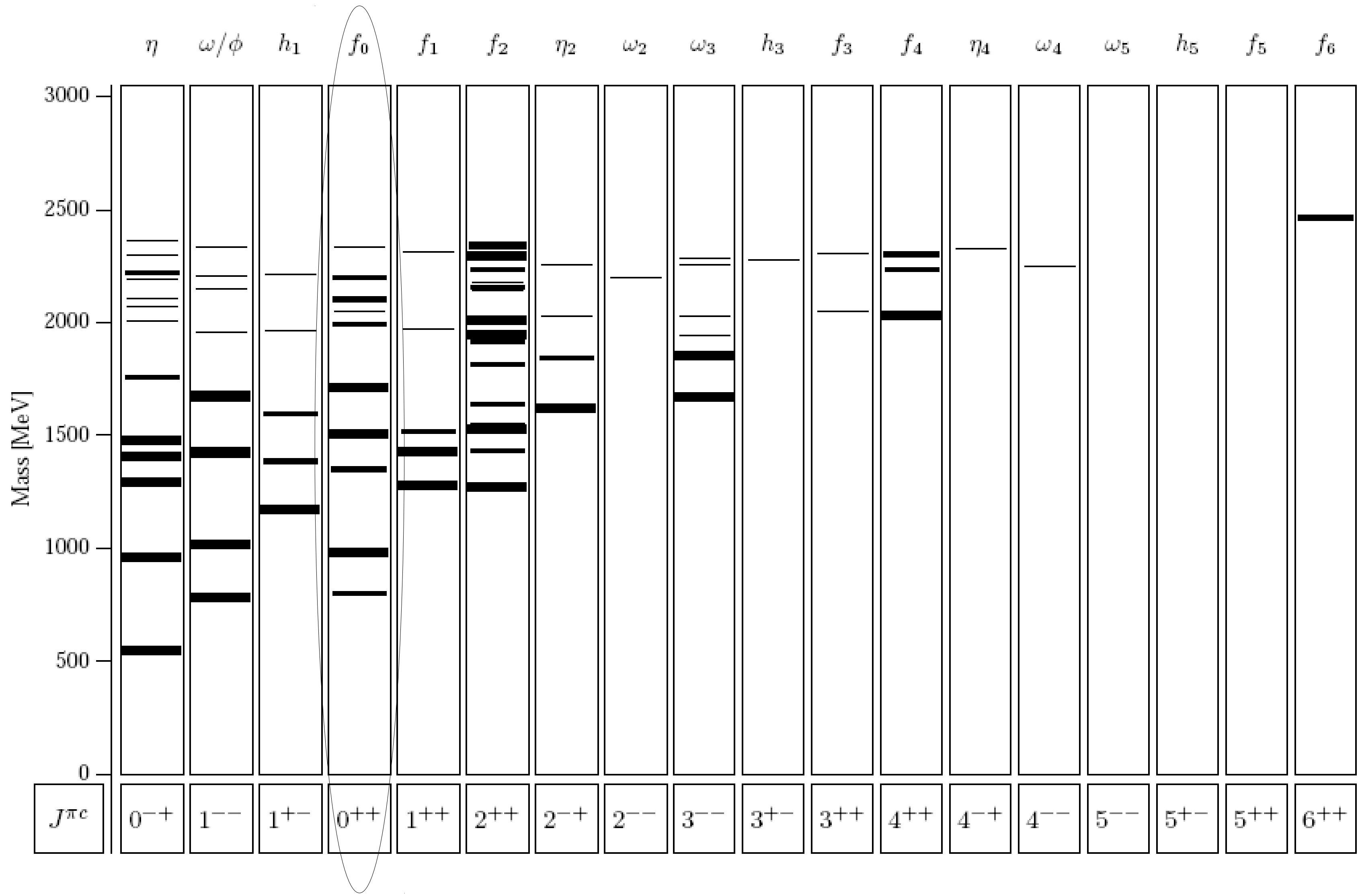


Fig. 7. Experimental light flavoured isoscalar meson spectrum. Data are from [1]. Mean values of resonance positions are indicated by thick lines, less established resonances are represented by medium thick lines, 'further states' by very thin lines.

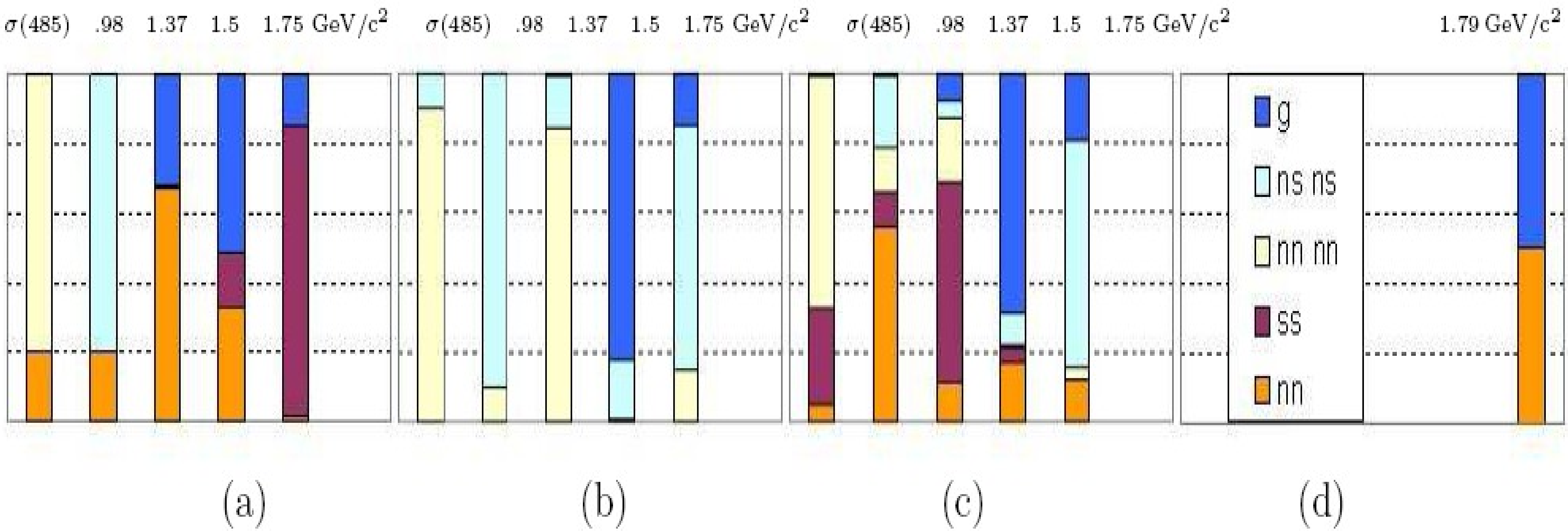
Unusual spectroscopy

$I=0:$	$m[f_0(600)] \approx$	$500 MeV$	$\sqrt{\frac{1}{2}}(\bar{u}u + \bar{d}d)$	$I=1: m[\rho(776)]$	$\approx$	776 MeV	$n\bar{n}$
$I=\frac{1}{2}:$	$m[\kappa] \approx$	$800 MeV$	$\bar{u}s, \bar{s}u, \bar{d}s, \bar{s}d$	$I=0: m[\omega(783)]$	$\approx$	783 MeV	$n\bar{n}$
$I=0:$	$m[f_0(980)] \approx$	$980 MeV$	$\bar{s}s$	$I=1/2: m[K^*(892)]$	$\approx$	892 MeV	$n\bar{s}$
$I=1:$	$m[a_0(980)] \approx$	$980 MeV$	$\bar{u}d, \bar{d}u, \sqrt{\frac{1}{2}}(\bar{u}u - \bar{d}d)$	$I=0: m[\phi(1020)]$	$\approx$	1020 MeV	$s\bar{s}$

- Light scalars are tetraquark state: Jaffe (Phys. Rev. D 15 (1977)) the states above consecutively can be interepreted as $nn\bar{n}\bar{n}$, $nn\bar{n}\bar{s}$, $ns\bar{n}\bar{s}$, $ns\bar{n}\bar{s}$

- Light scalar meson → Two quark stare or four quark state

Model Prediction



Decomposition of scalar isoscalar states into different components

Eur. Phys. J. C21, 531, 2001, Eur. Phys. J. C21, 531, 2001, Phys. Rev. D74, 054030, hep-ph/0603018

Figure taken from: Phys. Rept. 454:1-202,2007.

Formalism: Model

- Consideration:

  Scalar condensates are allowed by the QCD vaccum.

  Mesons having identical external quantum numbers can mix even if they have different internal flavour structures.

- Three types of fields:

  Two chiral effective nonet fields describing the two quark and four quark states.

  Spurion field (Y) representing pure ground gluon-bound state.

Formalism: Model

- Tetraquark field:

a) molecular type $M_a^b = (q_{bA})^\dagger \gamma_4 \frac{1+\gamma_5}{2} q_{aA}$ $M_a^{(2)b} = \epsilon_{acd}\epsilon^{bef}(M^\dagger)_e^c (M^\dagger)_f^d.$

b) scalar di-quark + anti-diquark $\varphi_i = \sqrt{\frac{1}{2}}\varepsilon_{ijk} q_j^t C \gamma^5 q_k$, $\mathcal{S}_{ij}^{[4q]} = \varphi_i^\dagger \varphi_j$

At the symmetry level we are working: we are not interested in the underlying quark structure.

- Transformation properties:

$SU(3)_L \times SU(3)_R$ $M \to U_L M U^\dagger{}_R$ $M' \to U_L M' U^\dagger{}_R$

$U(1)_A$: $M \to e^{2i\nu} M$ $M' \to e^{-4i\nu} M'$

M and M' fields can be distinguished from their $U(1)_A$ transformation properties.

Formalism: Model

- Glueball field:

We interpret the spurion field as effective glueball field.

To accommodate realistic glueball field it is widely used practice to introduce a flavor singlet complex field to the linear/non-linear sigma model. [Phys Rev. D 21, 3393 (1980), Nucl. Phys. B175, 477 (1980), Prog. Theor. Phys. 66, 1789 (1981), Phys. Rev. D 80, 014014 (2009)]

- Basic Lagrangian:

$$\mathcal{L} = \mathrm{Tr}(\partial_\mu \Phi \partial^\mu \Phi^\dagger) + \mathrm{Tr}(\partial_\mu \Phi' \partial^\mu \Phi'^\dagger) + \partial_\mu Y \partial^\mu Y^* - V_0 - V_{SB}$$

Formalism: Model

- Lagrangian:

$$\mathcal{L} = Tr(\partial_\mu\Phi\partial^\mu\Phi^\dagger) + Tr(\partial_\mu\Phi'\partial^\mu\Phi^{\dagger\prime}) + \partial_\mu Y\partial^\mu Y^\star - m_Y{}^2 YY^\star - m_\Phi{}^2 Tr(\Phi^\dagger\Phi) - m_{\Phi'}{}^2 Tr(\Phi^{\dagger\prime}\Phi') - \lambda_1 Tr(\Phi^\dagger\Phi\Phi^\dagger\Phi)$$
$$- \lambda_1{}' Tr(\Phi^{\dagger\prime}\Phi'\Phi^{\dagger\prime}\Phi') - \lambda_2 Tr(\Phi^\dagger\Phi\Phi^{\dagger\prime}\Phi') - \lambda_3(\epsilon_{abc}\epsilon^{def}\Phi_d{}^a\Phi_e{}^b\Phi_f{}'^c + h.c.) - \lambda_Y(YY^\star)^2 + K(YDet(\Phi) + h.c.)$$
$$-\frac{\lambda_m}{2}(Tr[\Phi\Phi^{\dagger\prime}] + Tr[\Phi^\dagger\Phi']) + [Tr(B.\Phi) + h.c.] + [Tr(B'.\Phi') + h.c.] + (D.Y + h.c.)$$

External Symmetry breaking parameters: $B(B') = T_a B_a(T_a B_a{}')$

We consider only two dominant one '0' and '8' components.

Expanding around vev:

$M = T_a(\sigma_a + <\sigma_a> + i\pi_a);$ $\quad$ $\mathrm{M} = \mathrm{T}_a(\sigma_a{}' + <\sigma_a{}'> + i\pi_a{}');$

$$\mathrm{Y} = \sqrt{\tfrac{1}{2}}(y_1 + <y_1> + iy_2);$$

Formalism: Model

- Mixing:

  For I = 1/2, 1 states: Two and four quarks states mixed with each other ---> doublet sector

  For I = 0 scalar and pseudo-scalar states two, four quarks as well as glueball states mixed with each other ---> 5 states each for scalar and Pseudo-scalar.

- Particle content in each sector:
  Pseudo-Scalars: $\{\pi, \pi'\}, \{K, K'\}, \{\eta_1, \eta_2, \eta_3, \eta_4, \eta_5\}$
  Scalars: $\{a, a'\}, \{\kappa, \kappa'\}, \{f_1, f_2, f_3, f_4, f_5\}$

Parameter Fixing

- 20 Parameters:

  Vacuum stability conditions: $\frac{\partial V}{\partial \phi} = 0, \quad \phi = \{< \sigma_i >, < \sigma_i{}' >, < y_1 >\}$

  Physical Input Mass: $(R^{-1}) M^2{}_{bare}(R) = M^2{}_{phys}$

- Input Parameters:
  Mixing angles for the scalar 'a' and pseudoscalar pion doublet fields within the range $\{-\frac{\pi}{2}, \frac{\pi}{2}\}$.
  vacuum condensates for the quarkonia and tetraquark fields. (we assume their values lie below 1 GeV).

- Symmetry breaking parameters: $\frac{B_8}{B_0} = \frac{m_s}{m_{u,d}} = \frac{B'_8}{B'_0}$

Parameter Fixing

- From the mass matrix of pions and 'a' fields we solve all the parameters relevant to doublet sectors.
- Mixing in the doublet sector are only between 2 and 4 quark states ---> parameters related to glueball remain undetermined.
- However the doublet sector put a constraint on the product of vacuum scalar condensates of the glueball field and the coupling constant 'k' of the instanton term.

Parameter Fixing

Parameter fixing @ glueball sector:

- From I = 0 Pseudo-scalar

$$\mathbf{Tr}[M_\eta{}^2] = \mathbf{Tr}[M_\eta{}^2]_{exp}$$
$$\mathbf{Det}[M_\eta{}^2] = \mathbf{Det}[M_\eta{}^2]_{exp}$$

- vacuum scalar condensate of the glueball field.

- instanton coupling constant 'k'

- a constraint in the form of sum between $m_Y{}^2$ and λ'_Y (scanning parameter)

Result

PREDICTION:

From our model we can predict:

1. In the doublet sector the Kaons and the kapp mass spectrum and mixzing angles

2. I=0 scalar meson mass spectrum and mixing angles

3. The mass spectrum and mixing angles for the I=0 pesudoscalars are also can be considered as a prediction (As we have put only two broad constraints the trace and determinant of the physical particles which is far less than the five mass values and 10 mixing angles involved).

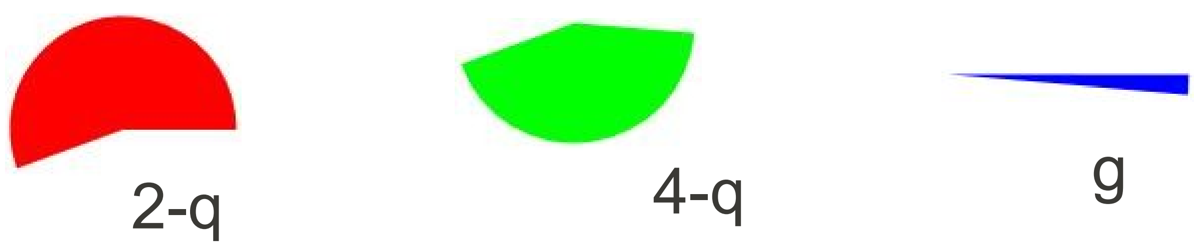
Result

π' mass = 1.2 GeV

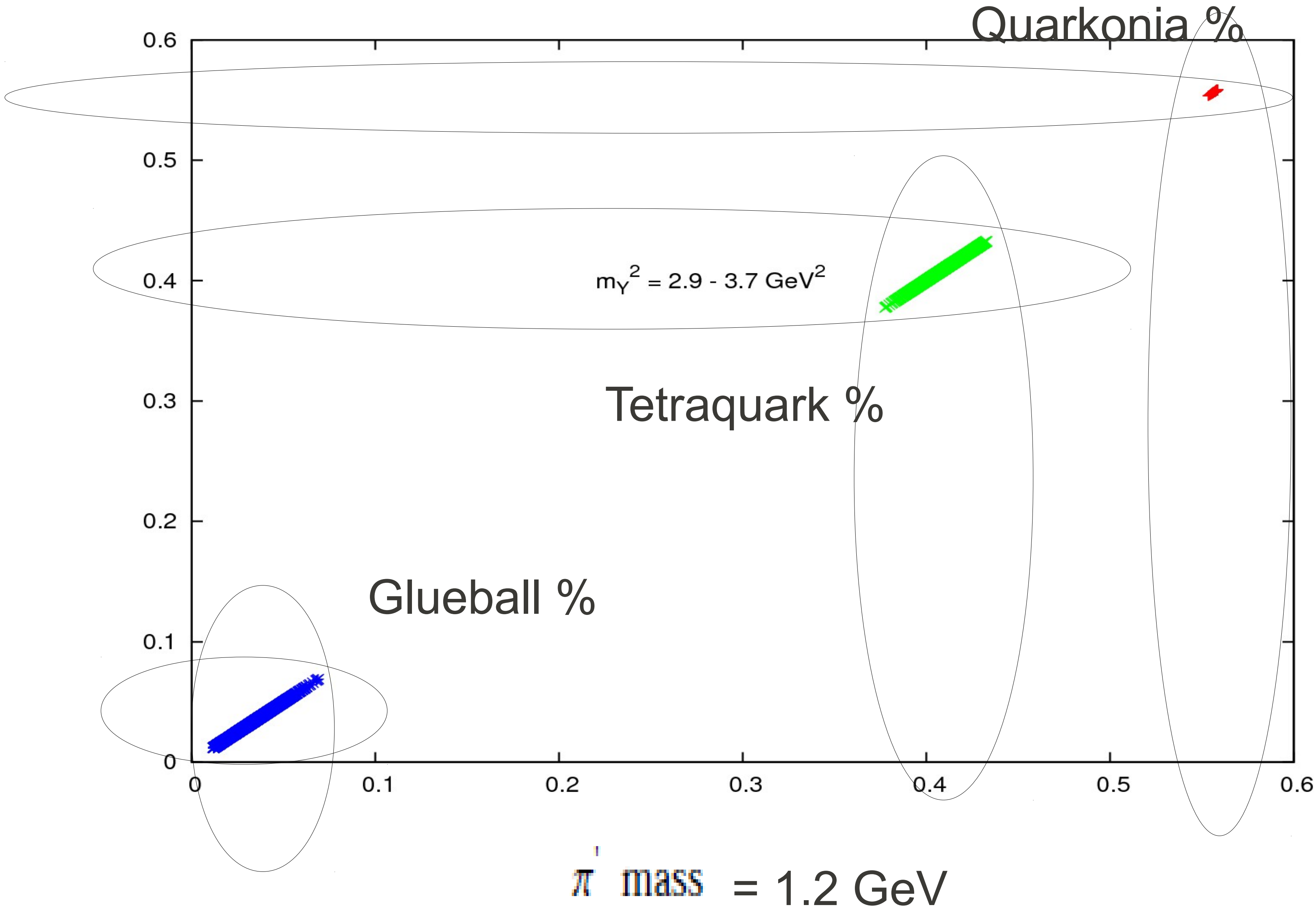
$J^{PC} = 0^{-+}$	Our Value (GeV)	From Experiment (GeV)
η_1	1.757	1.76
η_2	1.424	1.475
η_3	1.363	1.295
η_4	0.947	0.958
η_5	0.545	0.547

$J^{PC} = 0^{++}$	Our Value (GeV)	From Experiment (GeV)
$f_0(1710)$	1.7104	1.72 ± 0.06
$f_0(1500)$	1.365	1.505 ± 0.06
$f_0(1370)$	1.151	1.2-1.5
$f_0(980)$	0.970	0.980 ± 0.010
$f_0(600)$**or**σ	0.591	0.4-1.2

% composition
Lowest I=0 scalars:



Result



Quarkonia %
0.6
0.5
0.4
0.3
0.2
0.1
0
m_Y^2 = 2.9 - 3.7 GeV^2
Tetraquark %
Glueball %
0
0.1
0.2
0.3
0.4
0.5
0.6
π' mass = 1.2 GeV

Result

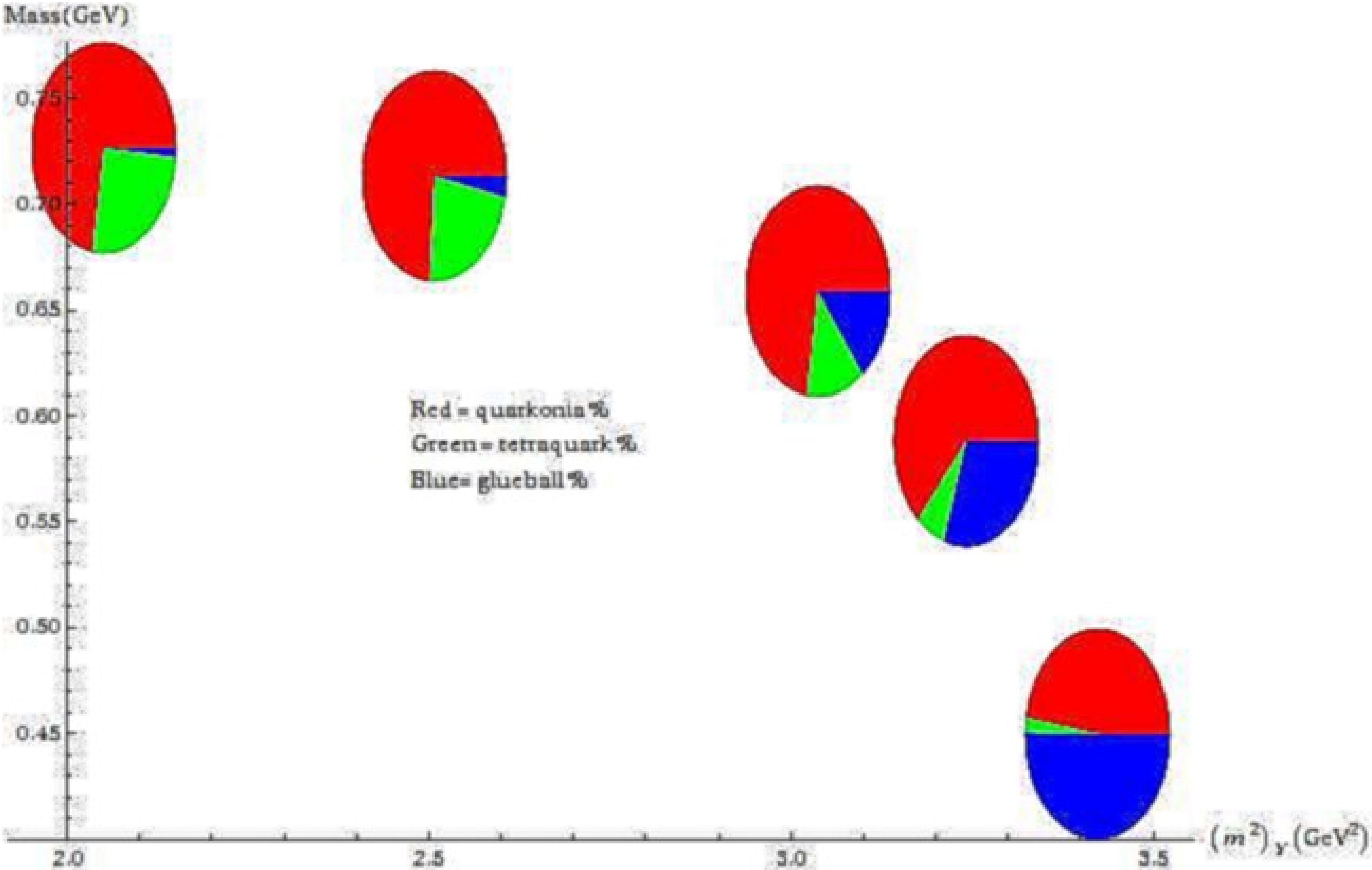
π' mass = 1.4 GeV

$J^{PC} = 0^{-+}$	Our Value (GeV)	From Experiment (GeV)
η_1	1.726	1.76
η_2	1.489	1.475
η_3	1.292	1.295
η_4	1.01	0.958
η_5	0.524	0.547

$J^{PC} = 0^{++}$	Our Value (GeV)	From Experiment (GeV)
$f_0(1710)$	1.710	1.72 ± 0.06
$f_0(1500)$	1.499	1.505 ± 0.06
$f_0(1370)$	1.191	1.2-1.5
$f_0(980)$	0.984	0.980 ± 0.010
$f_0(600)$**or**σ	0.713	0.4-1.2

% composition
Lowest I=0 scalars:

Result



π' mass = 1.4 GeV

Summary & Outlook

- The lowest iso-scalar is predominantly quarkonia, tetra-quark mixed state.
- The above situation may change depending on the mass of the bare glueball field.
- Necessary: Futher study to investigate the decay widths and verify Whether above scenario holds.
- Understanding of the vacuum phenomenology → medium behaviors
- Implication for chiral symmetry restoration

Thank You!

BACK UP SLIDES

Result

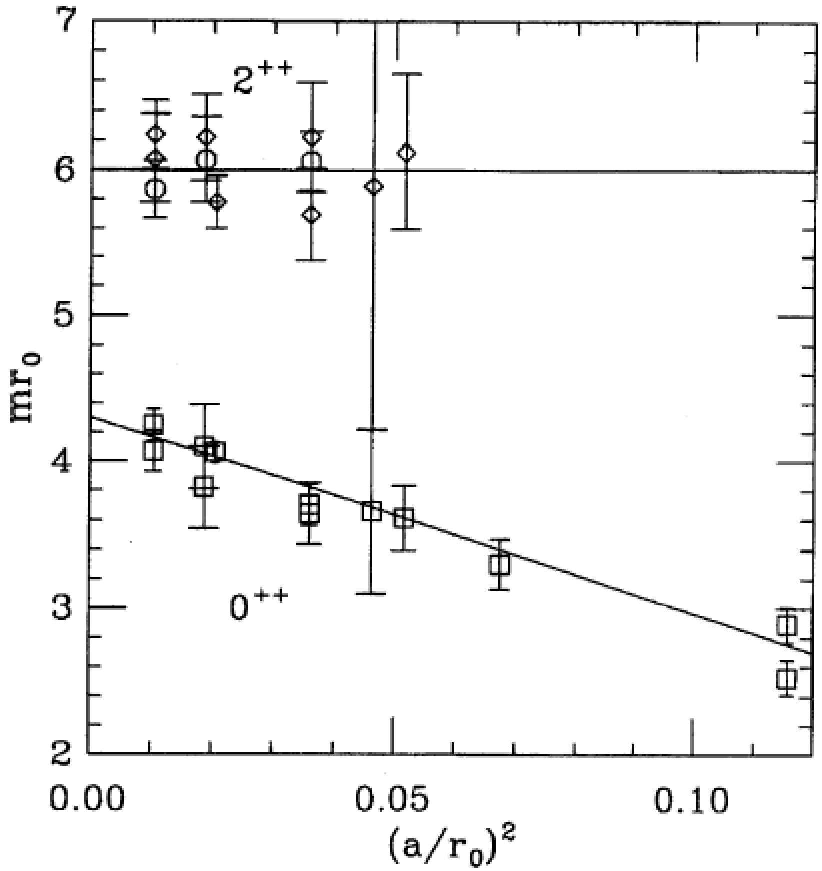
DIFFERENT POSSIBLE SCENARIOS:

1. The ratio of B8/B0 is the ratio of the strange quark mass to u,d quark mass. In our present calculation we have taken the value of this ratio to be 30. We can change this ratio, for e.g., 25 or 20 to see how the different quantites change.

2. I have taken the mass values of the I=0 Pseudoscalar mesons as : 1.76, 1.475, 1.295, 0.958, 0.547. Keeping the last two lightest mesons same we can use differenet meson mass valuea also.

3. There is a huge uncertainity in the π' mass values from 1.2−1.4 Gev. We change the mass value for π' meson and see how different quantites respond to this scenario.

Glueball



$r_0 = 0.5$ fm

extrapolation to a= 0 gives:

m : $1611 \pm 30 \pm 160$ MeV

- Gluons flavour bind Coupling t $s\bar{s}$ and $u\bar{u} + d\bar{d}$ mesons with similar strength.
- Decay rates can be used to distinguished from ordinary mesons.