Light scalars in semi-leptonic decays of heavy quarkonia

N.N. Achasov and A.V. Kiselev

Laboratory of Theoretical Physics,

Sobolev Institute for Mathematics,

Academician Koptiug Prospekt, 4,

Novosibirsk, 630090, Russia

Based on Physical Review D 86, 114010 (2012)

ABSTACT

We study the mechanism of production of the light scalar mesons in the $D_s^+ \to \pi^+\pi^-\, e^+\nu$ decays: $D_s^+ \to s\bar{s}\, e^+\nu \to [\sigma(600) + f_0(980)]\, e^+\nu \to \pi^+\pi^-\, e^+\nu$, and compare it with the mechanism of production of the light pseudoscalar mesons in the $D_s^+ \to (\eta/\eta')\, e^+\nu$ decays: $D_s^+ \to s\bar{s}\, e^+\nu \to (\eta/\eta')\, e^+\nu$.

ABSTACT

We show that the $s\bar{s} \to \sigma(600)$ transition is negligibly small in comparison with the $s\bar{s} \to f_0(980)$ one.

As for the the $f_0(980)$ meson, the intensity of the $s\bar{s} \to f_0(980)$ transition makes near thirty percent from the intensity of the $s\bar{s} \to \eta_s$ ($\eta_s = s\bar{s}$) transition.

So, the $D_s^+ \to \pi^+\pi^- e^+\nu$ decay supports the previous conclusions about a dominant role of the four-quark components in the $\sigma(600)$ and $f_0(980)$ mesons.

Introduction

At present the nontrivial nature of the well-established light scalar resonances $f_0(980)$ and $a_0(980)$ is denied by very few people.

As for the nonet as a whole, even a cursory look at PDG Review gives an idea of the four-quark structure of the light scalar meson nonet, $\sigma(600)$, $\kappa(800)$, $f_0(980)$, and $a_0(980)$, inverted in comparison with the classical P wave $q\bar{q}$ tensor meson nonet, $f_2(1270)$, $a_2(1320)$, $K_2^*(1420)$, $\phi_2'(1525)$.

Really, while the scalar nonet cannot be treated as the P wave $q\bar{q}$ nonet in the naive quark model, it can be easy understood as the $q^2\bar{q}^2$ nonet, where $\sigma(600)$ has no strange quarks, $\kappa(800)$ has the s quark, $f_0(980)$ and $a_0(980)$ have the additional $s\bar{s}$ pair.

Similar states were found by Jaffe in 1977 in the MIT bag.

Introduction

By now it is established also that the mechanisms of the $a_0(980)$, $f_0(980)$, and $\sigma(600)$ meson production in the ϕ radiative decays, in the photon-photon collisions, and in the $\pi\pi$ scattering indicate to the four-quark structure of the light scalars.

In particular, the was shown that the ideal $q\bar{q}$ model prediction $g^2_{f_0(980)\gamma\gamma} : g^2_{a^0_0(980)\gamma\gamma} = 25:9$ [a] is excluded by experiment.

---

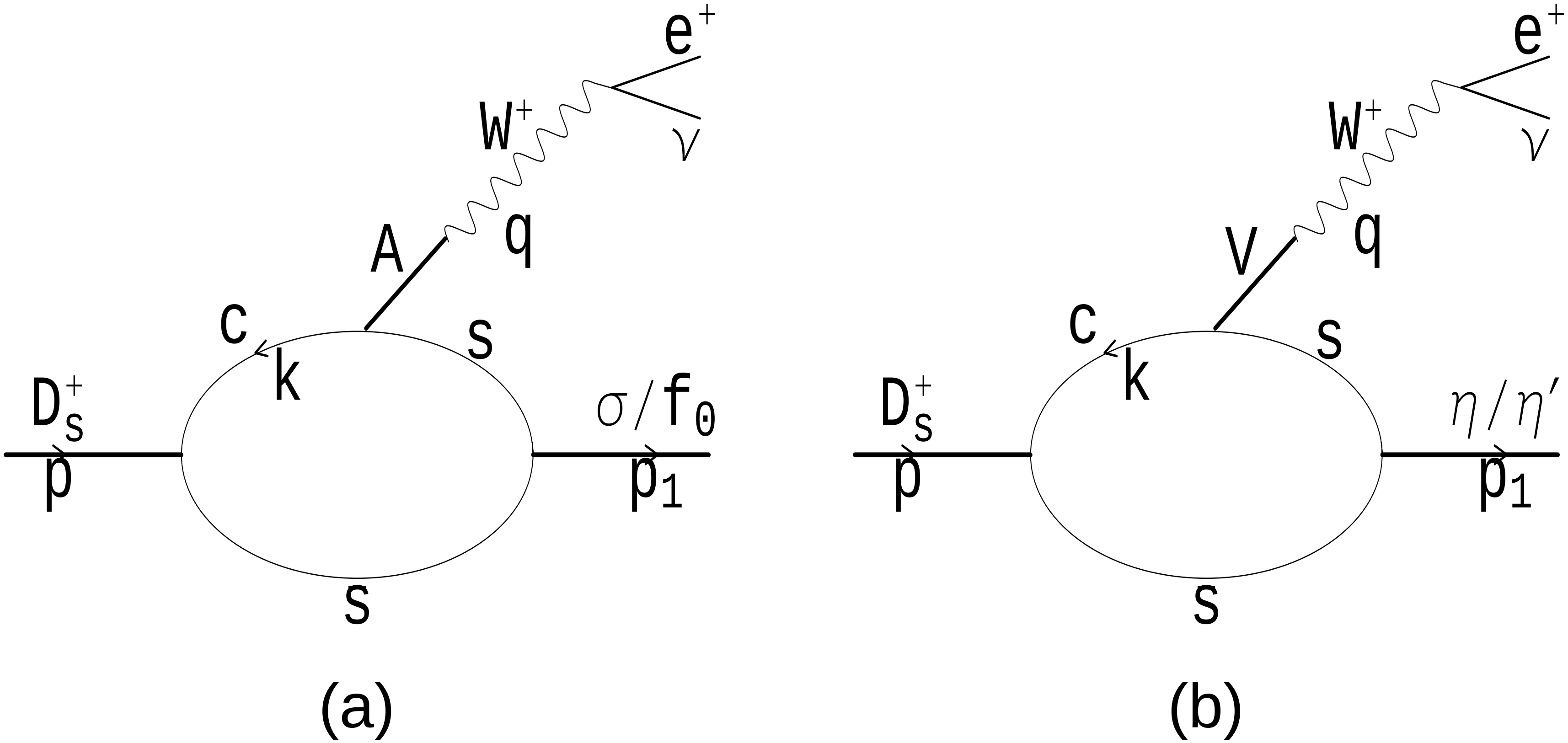
[a] We mean the $f_0(980) = (u\bar{u} + d\bar{d})\sqrt{2}$ and $a^0_0(980) = (u\bar{u} - d\bar{d})\sqrt{2}$ case.

Introduction

In addition, the absence of the $J/\psi \to \gamma f_0(980)$, $a_0(980)\rho$, $f_0(980)\omega$ decays in contrast to the intensive the $J/\psi \to \gamma f_2(1270)$, $\gamma f_2'(1525)$, $a_2(1320)\rho$, $f_2(1270)\omega$ decays argues against the P wave $q\bar{q}$ structure of $a_0(980)$ and $f_0(980)$ also.

It is time to explore the light scalar mesons in the decays of of heavy quarkonia. The semi-leptonic decays are of prime interest because they have the clear mechanisms.

The $D_s^+ \to (\sigma/f_0)\, e^+\nu$ and $D_s^+ \to (\eta/\eta')\, e^+\nu$ decays



Model of the $D_s^+ \to (\sigma/f_0)\, e^+\nu$ and $D_s^+ \to (\eta/\eta')\, e^+\nu$ decays

The $D_s^+ \to (\sigma/f_0)\, e^+\nu$ and $D_s^+ \to (\eta/\eta')\, e^+\nu$ decays

Below we study the mechanism of production of the light scalar mesons in the $D_s^+ \to \pi^+\pi^-\, e^+\nu$ decays:

$D_s^+ \to s\bar{s}\, e^+\nu \to [\sigma(600) + f_0(980)]\, e^+\nu \to \pi^+\pi^-\, e^+\nu$,

and compare it with the mechanism of production of the light pseudoscalar mesons in the $D_s^+ \to (\eta/\eta')\, e^+\nu$ decays:

$D_s^+ \to s\bar{s}\, e^+\nu \to (\eta/\eta')\, e^+\nu$, in a model of the NJL type.

$$M[D_s^+(p) \to P(p_1)W^+(q) \to P(p_1)\, e^+\nu] = \frac{G_F}{\sqrt{2}} V_{cs} V_\alpha L^\alpha\,,$$

$$M[D_s^+(p) \to S(p_1)W^+(q) \to S(p_1)\, e^+\nu] = \frac{G_F}{\sqrt{2}} V_{cs} A_\alpha L^\alpha\,,$$

$$\mathrm{V}_\alpha = \mathrm{f}_+^{\mathrm{P}}(\mathrm{q}^2)(\mathrm{p}+\mathrm{p}_1)_\alpha + \mathrm{f}_-^{\mathrm{P}}(\mathrm{q}^2)(\mathrm{p}-\mathrm{p}_1)_\alpha\,,$$

$$\mathrm{A}_\alpha = \mathrm{f}_+^{\mathrm{S}}(\mathrm{q}^2)(\mathrm{p}+\mathrm{p}_1)_\alpha + \mathrm{f}_-^{\mathrm{S}}(\mathrm{q}^2)(\mathrm{p}-\mathrm{p}_1)_\alpha\,,$$

$$\mathrm{L}_\alpha = \bar{\nu}\gamma_\alpha(1+\gamma_5)\mathrm{e}\,, \qquad \mathrm{q} = (\mathrm{p}-\mathrm{p}_1)\,.$$

The influence of $f_-^P(q^2)$ and $f_-^S(q^2)$ are negligible for m_{e^+}.

The decay rates in the stable P and S states

$$\frac{d\Gamma(D_s^+ \to P\, e^+ \nu)}{dq^2} = \frac{G_F^2 |V_{cs}|^2}{24\pi^3} p_1^3(q^2) |f_+^P(q^2)|^2,$$

$$\frac{d\Gamma(D_s^+ \to S\, e^+ \nu)}{dq^2} = \frac{G_F^2 |V_{cs}|^2}{24\pi^3} p_1^3(q^2) |f_+^S(q^2)|^2.$$

For the $f_+^P(q^2)$ and $f_+^S(q^2)$ form factors we use the vector dominance model

$$f_+^P(q^2) = f_+^P(0) \frac{m_V^2}{m_V^2 - q^2} = f_+^P(0) f_V(q^2)\,,$$

$$f_+^S(q^2) = f_+^S(0) \frac{m_A^2}{m_A^2 - q^2} = f_+^S(0) f_A(q^2)\,,$$

where $V = D_s^*(2112)^{\pm}$, $A = D_{s1}(2460)^{\pm}$.

Definitions

Following the NJL type model we write $f_+^P(0)$ and $f_+^S(0)$ in the form

$$f_+^P(0) = g_{D_s^+ c\bar{s}} F_P g_{s\bar{s}P}\,, \quad f_+^S(0) = g_{D_s^+ c\bar{s}} F_S g_{s\bar{s}S}\,.$$

We know the structure of η and η'

$$\eta = \eta_q \cos\phi - \eta_s \sin\phi\,, \quad \eta' = \eta_q \sin\phi + \eta_s \cos\phi\,,$$

where $\eta_q = (u\bar{u} + d\bar{d})/\sqrt{2}$ and $\eta_s = s\bar{s}$.

The angle $\phi = \theta_i + \theta_P$, where θ_i is the ideal mixing angle with $\cos\theta_i = \sqrt{1/3}$ and $\sin\theta_i = \sqrt{2/3}$, i.e., $\theta_i = 54.7^\circ$, and θ_P is the angle between the flavor-singlet state η_1 and the flavor-octet state η_8.

Definitions

Particle Data Group give the θ_P band $-20^\circ \lesssim \theta_P \lesssim -10^\circ$ that gives us the opportunity to extract information about the $s\bar{s} \to \eta_s$ coupling constant, $g_{s\bar{s}\eta_s}$, from experiment and to compare with the $s\bar{s} \to f_0$ coupling constant, $g_{s\bar{s}f_0}$, extracted from experiment also.

We consider the next set of θ_P.

$$\theta_P = -11^\circ \;:\quad \eta = 0.72\eta_0 - 0.69\eta_s\,,\quad \eta' = 0.69\eta_0 + 0.72\eta_s$$
$$\theta_P = -14^\circ \;:\quad \eta = 0.76\eta_0 - 0.65\eta_s\,,\quad \eta' = 0.65\eta_0 + 0.76\eta_s$$
$$\theta_P = -18^\circ \;:\quad \eta = 0.8\eta_0 - 0.6\eta_s\,,\quad \eta' = 0.6\eta_0 + 0.8\eta_s\,.$$

$$BR(D_s^+ \to s\bar{s}\, e^+\nu \to \eta\, e^+\nu) = (2.67 \pm 0.29)\%,$$

$$BR(D_s^+ \to s\bar{s}\, e^+\nu \to \eta'\, e^+\nu) = (9.9 \pm 2.3) \times 10^{-3}.$$

$D_s^+ \to s\bar{s}\, e^+\nu \to \pi^+\pi^-\, e^+\nu$

$$M(D_s^+ \to s\bar{s}\, e^+\nu \to [\sigma(600) + f_0(980)]\, e^+\nu \to \pi^+\pi^-\, e^+\nu)$$

$$= \frac{G_F}{\sqrt{2}} V_{cs}\, L^{\alpha}\, (p+p_1)_{\alpha}\, g_{D_s^+ c\bar{s}}\, f_A(q^2) \times$$

$$e^{i\delta_B^{\pi\pi}} \frac{1}{\Delta(m)} \Big(F_\sigma g_{s\bar{s}\sigma} D_{f_0}(m) g_{\sigma\pi^+\pi^-} + F_\sigma g_{s\bar{s}\sigma} \Pi_{\sigma f_0}(m) g_{f_0\pi^+\pi^-}$$

$$+ F_{f_0} g_{s\bar{s} f_0} \Pi_{f_0\sigma}(m) g_{\sigma\pi^+\pi^-} + F_{f_0} g_{s\bar{s} f_0} D_\sigma(m) g_{f_0\pi^+\pi^-} \Big)\,,$$

where m is the invariant mass of the $\pi\pi$ system, $\Delta(m) = D_{f_0}(m) D_\sigma(m) - \Pi_{f_0\sigma}(m)\Pi_{\sigma f_0}(m)$, $D_\sigma(m)$ and $D_{f_0}(m)$ are the inverted propagators of the σ and f_0 mesons, $\Pi_{\sigma f_0}(m) = \Pi_{f_0\sigma}(m)$ is the off-diagonal element of the polarization operator, which mixes the σ and f_0 mesons.

$D_s^+ \to \pi^+\pi^- e^+\nu$

$$\frac{d^2\Gamma(D_s^+ \to \pi^+\pi^- e^+\nu)}{dq^2 dm} = \frac{G_F^2\,|V_{cs}|^2}{24\,\pi^3}\, g^2_{D_s^+ c\bar{s}}\, |f_A(q^2)|^2\, p_1^3(q^2, m)$$

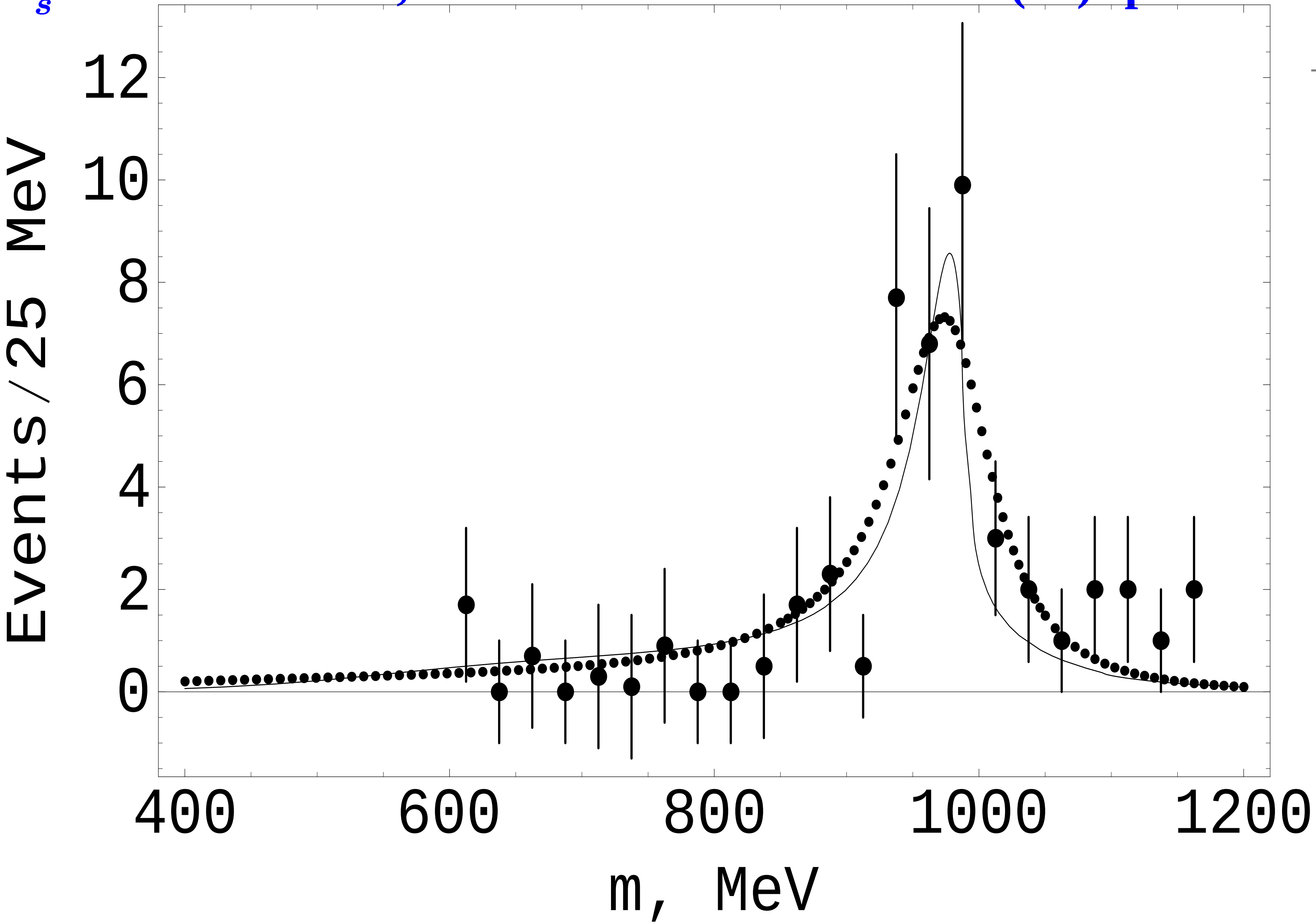
$$\times \frac{1}{8\pi^2}\, m\, \rho_{\pi\pi}(m) \left|\frac{1}{\Delta(m)}\right|^2$$

$$\times \Big| F_\sigma g_{s\bar{s}\sigma} D_{f_0}(m) g_{\sigma\pi^+\pi^-} + F_\sigma g_{s\bar{s}\sigma} \Pi_{\sigma f_0}(m) g_{f_0\pi^+\pi^-}$$

$$+ F_{f_0} g_{s\bar{s}f_0} \Pi_{f_0\sigma}(m) g_{\sigma\pi^+\pi^-} + F_{f_0} g_{s\bar{s}f_0} D_\sigma(m) g_{f_0\pi^+\pi^-} \Big|^2,$$

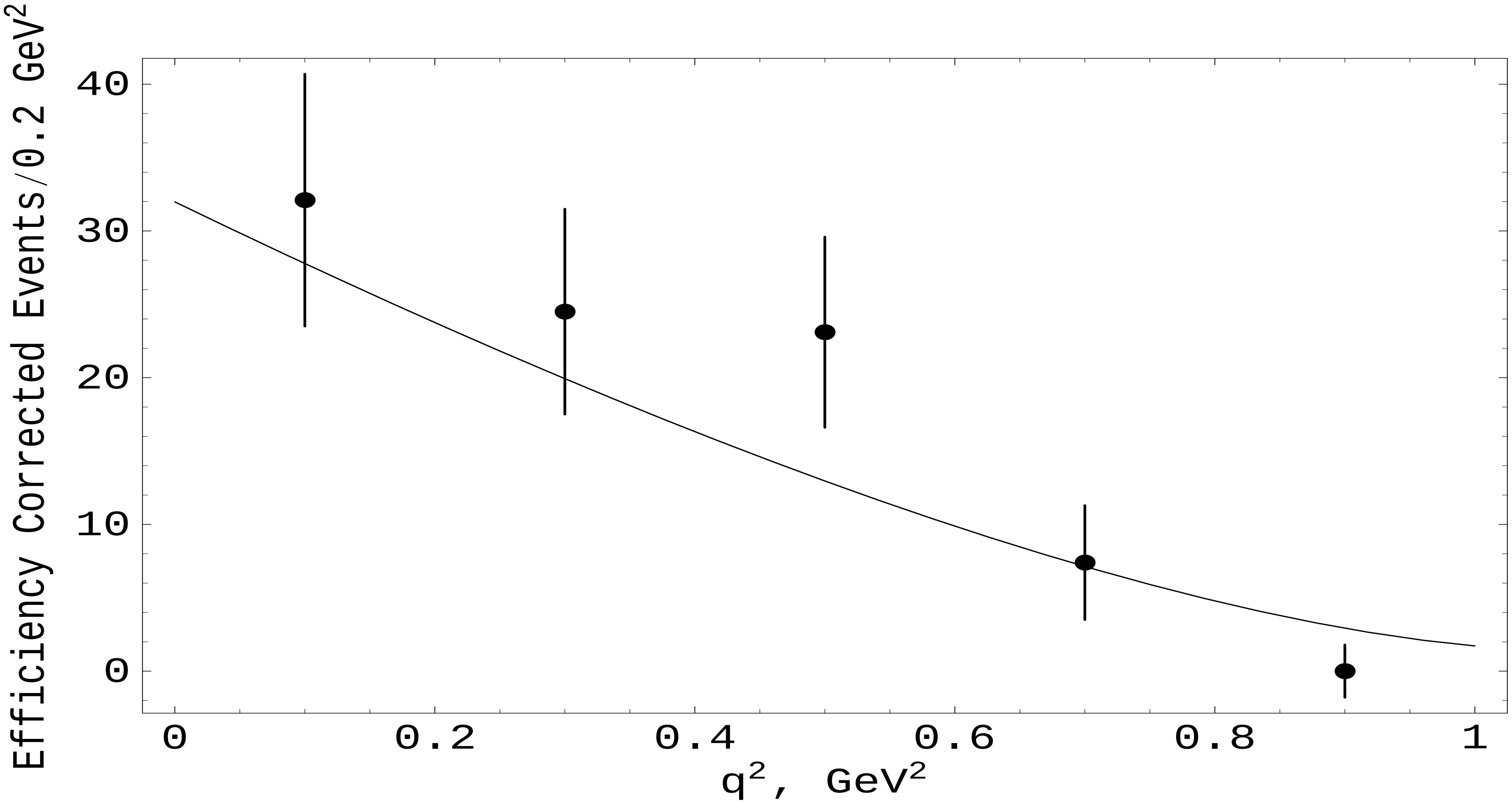
where $\rho_{\pi\pi}(m) = \sqrt{1 - 4m_\pi^2/m^2}$.

$D_s^+ \to \pi^+\pi^- e^+\nu$, CLEO data on $\pi^+\pi^-$ mass (m) spectrum



CLEO dotted line: $BR(D_s^+ \to f_0(980)\, e^+\nu \to \pi+\pi^-\, e^+\nu) = 0.20\%$. Our solid line: 0.17%

The q^2 distribution, the CLEO data



The q^2 distribution for $BR(D_s^+ \to f_0(980)\, e^+\nu)$. The axial-vector dominance model (the theoretical curve) describes the data quite satisfactorily.

Results of the analysis of the CLEO data

$Br(D_s^+ \to f_0 e^+ \nu \to \pi^+\pi^- e^+ \nu) = 0.17\%$			
$\frac{F_\sigma g_{s\bar{s}\sigma}}{F_{f_0} g_{s\bar{s}f_0}}$	$\frac{F_{f_0}^2 g_{s\bar{s}f_0}^2}{F_\eta^2 g_{s\bar{s}\eta}^2}$	$\frac{F_{f_0}^2 g_{s\bar{s}f_0}^2}{F_{\eta'}^2 g_{s\bar{s}\eta'}^2}$	$\frac{F_\eta^2 g_{s\bar{s}\eta}^2}{F_{\eta'}^2 g_{s\bar{s}\eta'}^2}$
0.039	0.67	0.49	0.73
The $\eta - \eta'$ mixing			
θ_P	-11°	-14°	-18°
$\frac{F_{f_0}^2 g_{s\bar{s}f_0}^2}{F_\eta^2 g_{s\bar{s}\eta_s}^2}$	0.32	0.29	0.24
$\frac{F_{f_0}^2 g_{s\bar{s}f_0}^2}{F_{\eta'}^2 g_{s\bar{s}\eta_s}^2}$	0.27	0.28	0.31

Discussion and conclusion

When fitting the CLEO data, we use the parameters of the resonances obtained by us in PRD 85, 094016 (2012) in the analysis of the $\pi\pi$ scattering and the $\phi \to \gamma(\sigma + f_0) \to \gamma\pi^0\pi^0$ decay. So the 44 events in Fig. on page 14 determine only one parameter $f_+^\sigma(0)/f_+^{f_0}(0) = F_\sigma g_{s\bar{s}\sigma}/F_{f_0} g_{s\bar{s}f_0}$.

The Adler zero at m^2 near $(m_\pi^2)/2$ determines

$f_+^\sigma(0)/f_+^{f_0}(0)$=0.039, 0.014, 0.055, 0.058, 0.032, 0.055

for six fits from PRD 85, 094016 (2012).

So the intensity of the $\sigma(600)$ production is much less than the intensity of the $f_0(980)$ production ($(f_+^\sigma(0)/f_+^{f_0}(0))^2 < 0.003$).

Discussion and conclusion

That is we find the direct evidence of decoupling of $\sigma(600)$ with the $s\bar{s}$ pair. As far as we know, this is truly a new result, which agrees well with the decoupling of $\sigma(600)$ with the $K\bar{K}$ states, obtained in PRD 85, 094016 (2012)

$g^2_{\sigma K^+K^-}/g^2_{\sigma\pi^+\pi^-}$ =0.04, 0.001, 0.01, 0.01, 0.003, 0.025 for six fits.

The decoupling of $\sigma(600)$ with the $K\bar{K}$ states means also the decoupling of $\sigma(600)$ with $\sigma_q = (u\bar{u} + d\bar{d})/\sqrt{2}$ because σ_q results in $g^2_{\sigma K^+K^-}/g^2_{\sigma\pi^+\pi^-} = 1/4$.

Fit 1 describes the $\pi^+\pi^-$ spectrum on better than others, $(f_+^\sigma(0)/f_+^{f_0}(0))^2 = (0.039)^2, g^2_{\sigma K^+K^-}/g^2_{\sigma\pi^+\pi^-} = 0.04$.

So,the CLEO experiment gives new support in favour of the four-quark, $ud\bar{u}\bar{d}$, structure of the $\sigma(600)$ meson.

Discussion and conclusion

In the chirally symmetric model of the NJL type the coupling constants of the pseudoscalar and scalar partners with quarks are equal to each other, i.e., $g_{s\bar{s}\eta_s} = g_{s\bar{s}f_{0s}}$, where $f_{0s} = s\bar{s}$. If to neglect the strange quark mass as compared with the charmed quark mass ($m_s/m_c \ll 1$) in the numerators of the integrands for the decay diagrams, then $F_{f_0} = F_{\eta'}$ and we find that $g^2_{s\bar{s}f_0}/g^2_{s\bar{s}\eta_s} \approx 0.3$. So, the $f_{0s} = s\bar{s}$ part in the $f_0(980)$ wave function is near thirty percent.

Taking into account the suppression of the $f_0(980)$ meson coupling with the $\pi\pi$ system, $g^2_{f_0\pi^+\pi^-}/g^2_{f_0K^+K^-} = 0.154$, one can conclude that the $f_{0q} = (u\bar{u} + d\bar{d})/\sqrt{2}$ part in the $f_0(980)$ wave function is suppressed also.

So, the CLEO experiment gives new support in favour of the four-quark, $(sd\bar{s}\bar{d} + sd\bar{s}\bar{d})/\sqrt{2}$, structure of the $f_0(980)$ meson, too.

Outlook

Certainly, there is an extreme need in experiment on the $D_s^+ \to s\bar{s}\, e^+\nu \to \pi^+\pi^-\, e^+\nu$ decay with high statistics.

Of great interest is the experimental search for the decays $D^0 \to d\bar{u}\, e^+\nu \to a_0^-(980)\, e^+\nu \to \pi^-\eta\, e^+\nu$ and $D^+ \to d\bar{d}\, e^+\nu \to a_0^0(980)\, e^+\nu \to \pi^0\eta\, e^+\nu$ (or the charge conjugate ones), which will give the information about the $a_q^- = d\bar{u}$ (or $a_q^+ = u\bar{d}$) component in the $a_0^-(980)$ (or $a_0^+(980)$) wave function and $a_q^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$ component in the a_0^0 wave function.

Now it is known that

$BR(D^0 \to d\bar{u}\, e^+\nu \to \pi^-\, e^+\nu) = (2.89 \pm 0.08) \times 10^{-3}$ and

$BR(D^+ \to d\bar{d}\, e^+\nu \to \pi^0\, e^+\nu) = (4.05 \pm 0.18) \times 10^{-3}$.

Outlook

No less interesting is also search for the decays

$$D^+ \to d\bar{d}\,e^+\nu \to [\sigma(600) + f_0(980)]\,e^+\nu \to \pi^+\pi^-\,e^+\nu$$

(or the charge conjugate ones), which will give the information about the $\sigma_q = (u\bar{u} + d\bar{d})/\sqrt{2}$ and $f_{0q} = (u\bar{u} + d\bar{d})/\sqrt{2}$ components in the $\sigma(600)$ and $f_0(980)$ wave functions respectively.

Now it is known that

$BR(D^+ \to d\bar{d}\,e^+\nu \to \eta\,e^+\nu) = (1.14 \pm 0.10) \times 10^{-3}$ and
$BR(D^+ \to d\bar{d}\,e^+\nu \to \eta'\,e^+\nu) = (2.2 \pm 0.5) \times 10^{-4}$.

Comparative research of light scalar and pseudoscalar mesons in semileptonic decays of B quarkonia at super B-factories is very tempting. Now it is known that

Outlook

$BR(B^0 \to d\bar{u}\, e^+\nu \to \pi^-\, e^+\nu) = (1.44 \pm 0.05) \times 10^{-4}$,
$BR(B^+ \to u\bar{u}\, e^+\nu \to \pi^0\, e^+\nu) = (7.79 \pm 0.26) \times 10^{-5}$,
$BR(B^+ \to u\bar{u}\, e^+\nu \to \eta\, e^+\nu) = (3.8 \pm 0.6) \times 10^{-5}$ and
$BR(B^+ \to u\bar{u}\, e^+\nu \to \eta'\, e^+\nu) = (2.3 \pm 0.8) \times 10^{-5}$.

This work was supported in part by RFBR, Grant No. 13-02-00039, and Interdisciplinary project No. 102 of Siberian division of RAS.

THANK YOU