Exotics at Our Home

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Light Scalars as Four-quark states

1. Introduction.
2. Confinement, chiral dynamics and light scalar mesons.
3. The lessons of the linear sigma model.
4. The $\sigma(600)$ and $f_0(980)$ mesons, the chiral shielding of $\sigma(600)$, the $\sigma(600)$ – $f_0(980)$ mixing, the chiral expansion, and the Roy equations in the $\pi\pi \to \pi\pi$ scattering.
5. The ϕ-meson radiative decays on light scalar resonances.
6. Light scalars in $\gamma\gamma$ collisions.
7. To learn light scalars in semi-leptonic decays of heavy quarkonia.
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Introduction

Emerged 58 years ago from the linear sigma model (LSM) (M. Gell-Mann and M. Levy, Nuovo Cimento 16, 705 (1960)), the problem of the light scalar mesons became central in the nonperturbative QCD for LSM could be its low energy realization.

The scalar channels in the region up to 1 GeV is a stumbling block of QCD. The point is that not only perturbation theory fails here, but sum rules as well in view of the fact that isolated resonances are absent in this region.

QCD, Chiral Limit, Confinement, σ-models

$$L = -(1/2)Tr\,(G_{\mu\nu}(x)G^{\mu\nu}(x)) + \bar{q}(x)(i\hat{D} - M)q(x).$$

M mixes Left and Right Spaces $q_L(x)$ and $q_R(x)$. But in chiral limit $M \to 0$ these spaces separate realizing $U_L(3) \times U_R(3)$ symmetry accurate within violation through gluonic anomaly.

As Experiment suggests, Confinement forms colourless observable hadronic fields and spontaneous breaking of chiral symmetry with massless pseudoscalar fields.

There are two possible scenarios for QCD at low energy.

1. $U_L(3) \times U_R(3)$ non-linear σ-model.
2. $U_L(3) \times U_R(3)$ linear σ-model.

The experimental nonet of the light scalar mesons suggests $U_L(3) \times U_R(3)$ linear σ-model.

History of Light Scalar Mesons

Hunting the light σ and κ mesons had begun in the sixties already. But long-standing unsuccessful attempts to prove their existence in a conclusive way entailed general disappointment and a preliminary information on these states disappeared from Particle Data Group (PDG) Reviews. One of principal reasons against the σ and κ mesons was the fact that both $\pi\pi$ and πK scattering phase shifts do not pass over 90^0 at putative resonance masses. [a]

[a] Meanwhile, there were discovered the narrow light scalar resonances, the isovector $a_0(980)$ and isoscalar $f_0(980)$.

$SU_L(2) \times SU_R(2)$ linear σ model

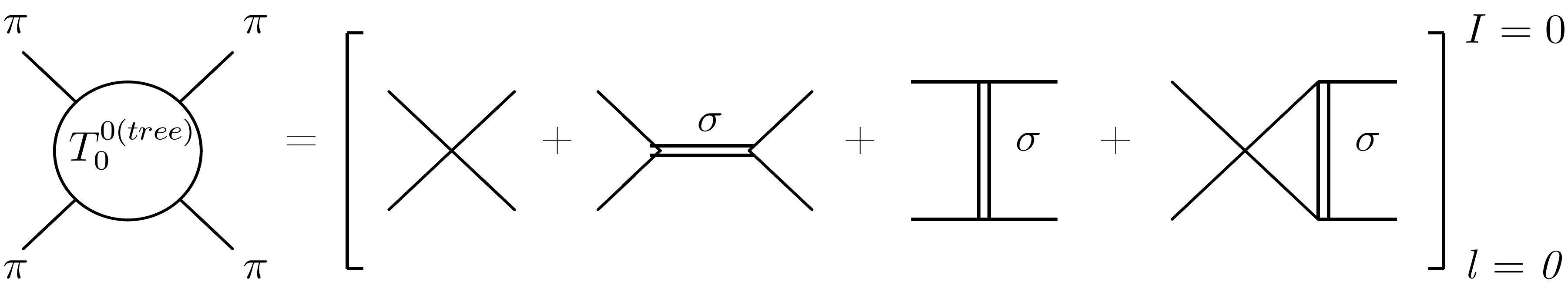
Situation changes when we showed that in the linear σ-model

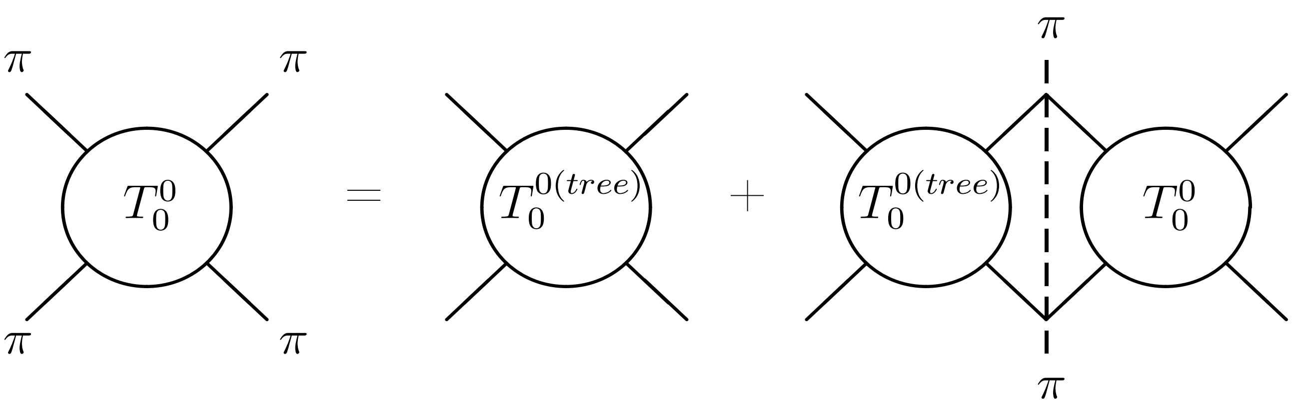
$$\mathrm{L} = \frac{1}{2}\left[(\partial_\mu \sigma)^2 + (\partial_\mu \vec{\pi})^2\right] - \frac{m_\sigma^2}{2}\sigma^2 - \frac{m_\pi^2}{2}\vec{\pi}^2$$

$$-\frac{m_\sigma^2 - m_\pi^2}{8f_\pi^2}\left[\left(\sigma^2 + \vec{\pi}^2\right)^2 + 4f_\pi \sigma\left(\sigma^2 + \vec{\pi}^2\right)\right]^2$$

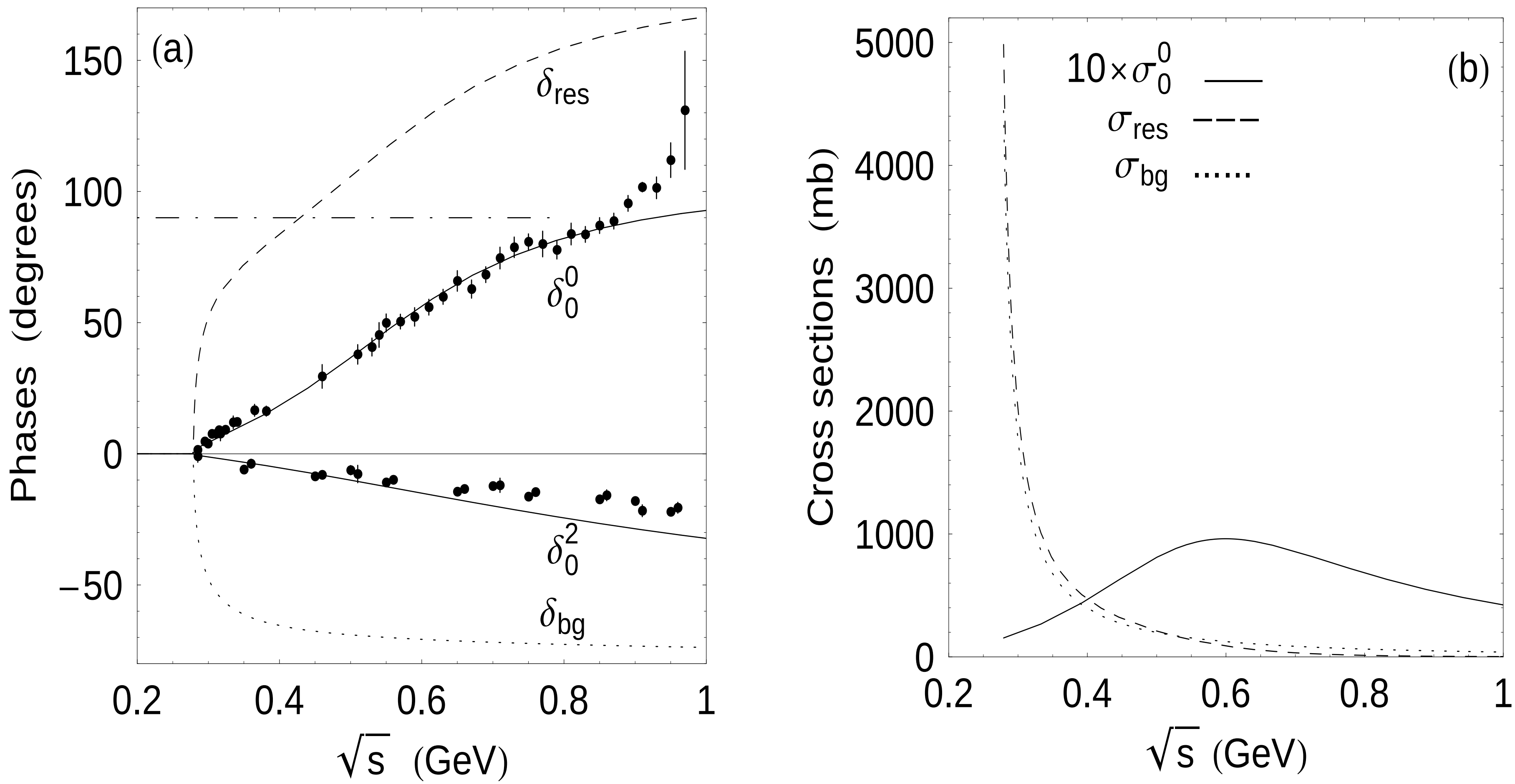
there is a negative background phase which hides the σ meson (N.N. Achasov and G.N. Shestakov, Phys. Rev. D 49, 5779 (1994)). It has been made clear that shielding wide lightest scalar mesons in chiral dynamics is very natural. This idea was picked up and triggered new wave of theoretical and experimental searches for the σ and κ mesons.

Our approximation





Chiral Shielding in $\pi\pi \to \pi\pi$



The σ model. Our approximation. $\delta_0^0 = \delta_{res} + \delta_{bg}$.

Chiral shielding in $\gamma\gamma \to \pi^+\pi^-$

N.N. Achasov and G.N. Shestakov, Phys. Rev. Lett. 99, 072001 (2007)

$$T_S(\gamma\gamma \to \pi^+\pi^-) = T_S^{Born}(\gamma\gamma \to \pi^+\pi^-)$$

$$+8\alpha I_{\pi^+\pi^-}\, T_S(\pi^+\pi^- \to \pi^+\pi^-)$$

$$= T_S^{Born}(\gamma\gamma \to \pi^+\pi^-) + 8\alpha I_{\pi^+\pi^-}\left(\frac{2}{3}T_0^0 + \frac{1}{3}T_0^2\right)$$

in elastic region

$$= \frac{2}{3}e^{i\delta_0^0}\left\{T_S^{Born}(\gamma\gamma \to \pi^+\pi^-)\cos\delta_0^0 + 8\frac{\alpha}{\rho_{\pi\pi}}\mathrm{ReI}_{\pi^+\pi^-}\sin\delta_0^0\right\}$$

$$+\frac{1}{3}e^{i\delta_0^2}\left\{T_S^{Born}(\gamma\gamma \to \pi^+\pi^-)\cos\delta_0^2 + 8\frac{\alpha}{\rho_{\pi\pi}}\mathrm{ReI}_{\pi^+\pi^-}\sin\delta_0^2\right\}$$

Chiral shielding in $\gamma\gamma \to \pi^0\pi^0$

$$T_S(\gamma\gamma \to \pi^0\pi^0) = 8\alpha I_{\pi^+\pi^-}\, T_S(\pi^+\pi^- \to \pi^0\pi^0)$$

$$= 8\alpha I_{\pi^+\pi^-} \left(\frac{2}{3} T_0^0 - \frac{2}{3} T_0^2\right)$$

in elastic region

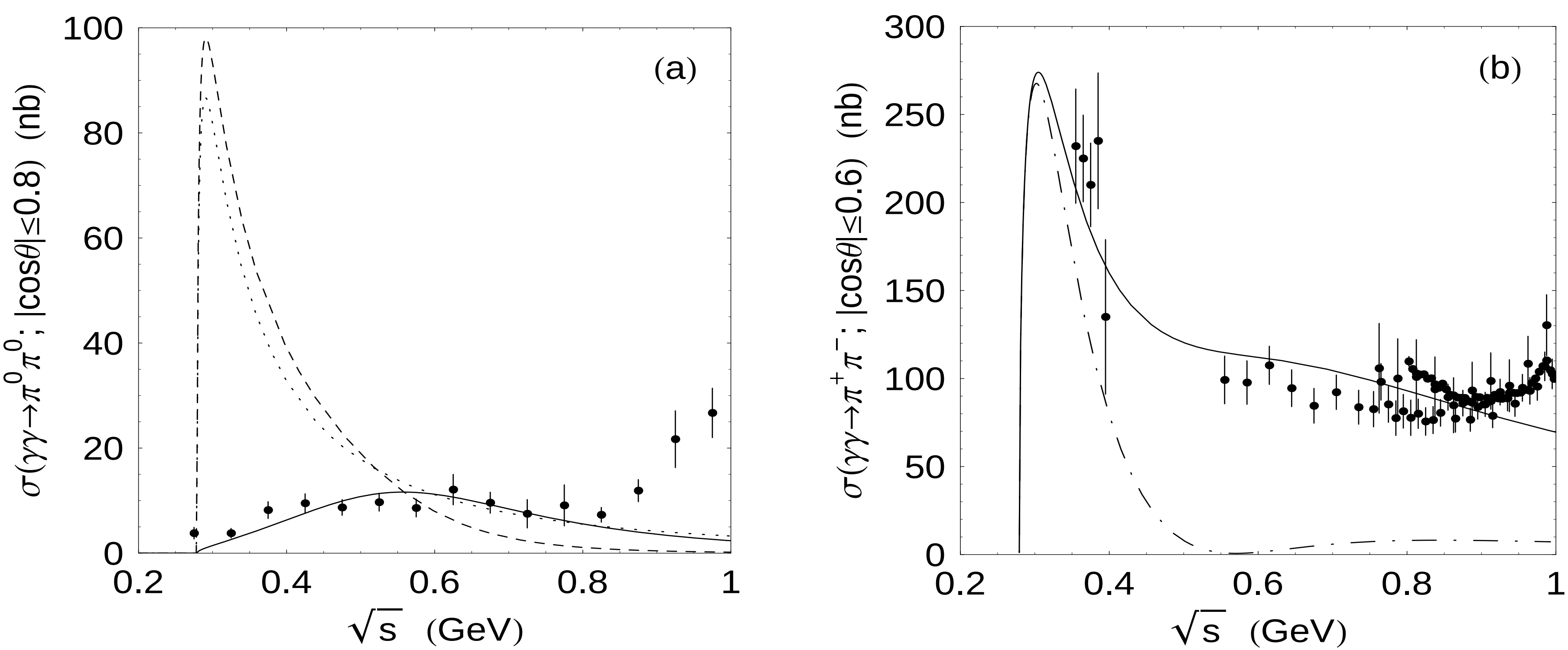
$$= \frac{2}{3} e^{i\delta_0^0} \left\{ T_S^{Born}(\gamma\gamma \to \pi^+\pi^-) \cos\delta_0^0 + 8\frac{\alpha}{\rho_{\pi\pi}} \mathrm{Re} I_{\pi^+\pi^-} \sin\delta_0^0 \right\}$$

$$- \frac{2}{3} e^{i\delta_0^2} \left\{ T_S^{Born}(\gamma\gamma \to \pi^+\pi^-) \cos\delta_0^2 + 8\frac{\alpha}{\rho_{\pi\pi}} \mathrm{Re} I_{\pi^+\pi^-} \sin\delta_0^2 \right\}$$

$$I_{\pi^+\pi^-} = \frac{m_\pi^2}{s}\left(\pi + i\ln\frac{1+\rho_{\pi\pi}}{1-\rho_{\pi\pi}}\right)^2 - 1\,, \quad s \geq 4m_\pi^2\,,$$

$$T_S^{Born}(\gamma\gamma \to \pi^+\pi^-) = \frac{8\alpha}{\rho_{\pi^+\pi^-}} \mathrm{Im} I_{\pi^+\pi^-}\,.$$

Chiral Shielding in $\gamma\gamma \to \pi\pi$



(a) The solid, dashed, and dotted lines are $\sigma_S(\gamma\gamma \to \pi^0\pi^0)$, $\sigma_{res}(\gamma\gamma \to \pi^0\pi^0)$, and $\sigma_{bg}(\gamma\gamma \to \pi^0\pi^0)$.

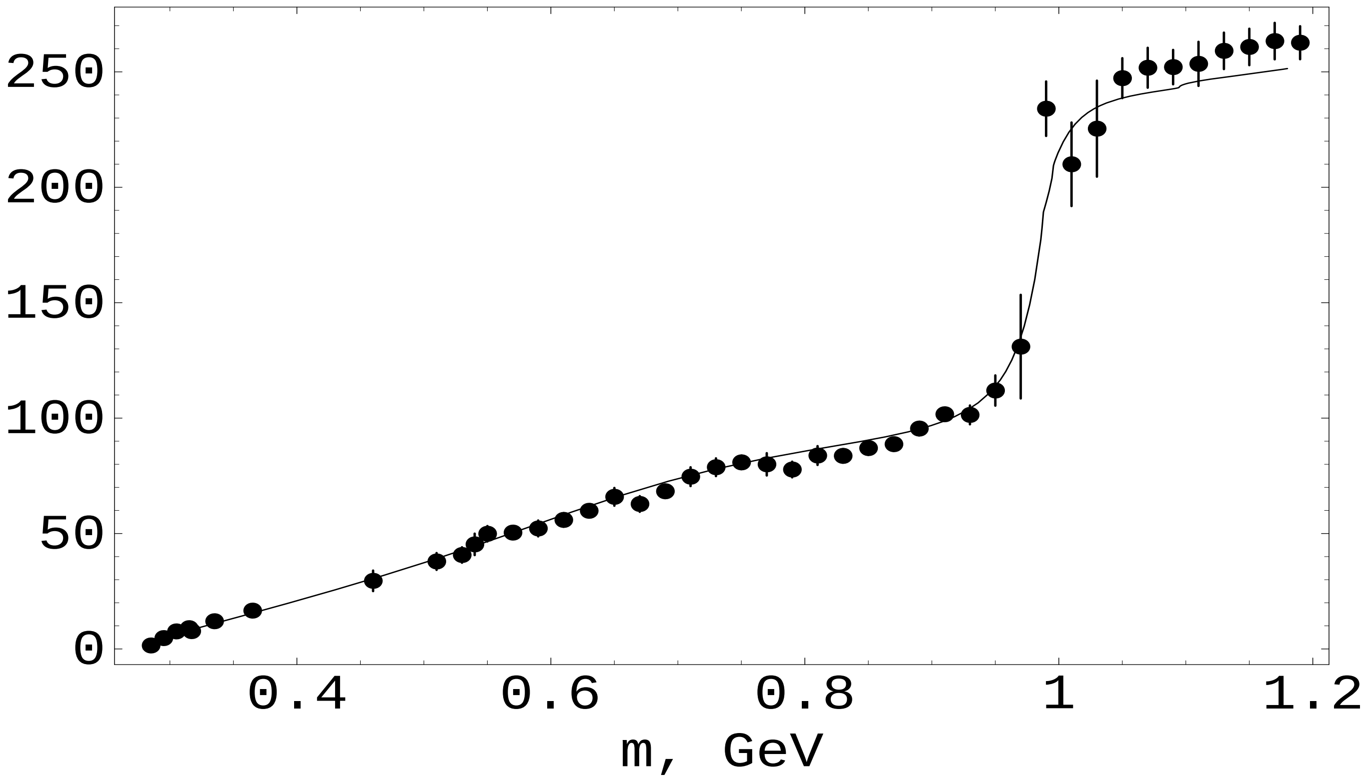
(b) The dashed-dotted line is $\sigma_S(\gamma\gamma \to \pi^+\pi^-)$. The solid line includes the higher waves from $T^{Born}(\gamma\gamma \to \pi^+\pi^-)$.

Troubles and Expectancies

In theory the principal problem is impossibility to use the linear σ-model in the tree level approximation inserting widths into σ meson propagators because such an approach breaks the both unitarity and Adler self-consistency conditions. The comparison with the experiment requires the non-perturbative calculation of the process amplitudes. Nevertheless, now there are the possibilities to estimate odds of the $U_L(3) \times U_R(3)$ linear σ-model to underlie physics of light scalar mesons in phenomenology, taking into account the idea of chiral shielding, our treatment of $\sigma(600)$-$f_0(980)$ mixing based on quantum field theory ideas, and Adler's conditions

(N.N. Achasov and A.V. Kiselev, Phys. Rev. D 83, 054008 (2011); Phys. Rev. D 85, 094016 (2012)) .

Phenomenological Treatment, $\delta_0^0 = \delta_B^{\pi\pi} + \delta_{res}$



$$g^2_{\sigma\pi^+\pi^-}/4\pi = 0.57\,\text{GeV}^2, \quad g^2_{\sigma K^+K^-}/4\pi = 0.048\,\text{GeV}^2$$

$$g^2_{f_0\pi^+\pi^-}/4\pi = 0.36\,\text{GeV}^2, \quad g^2_{f_0 K^+K^-}/4\pi = 2\,\text{GeV}^2$$

$$m_\sigma = 507\,\text{MeV}\,,\ \Gamma_\sigma(m_\sigma) = 353\,\text{MeV}\,,\ m_{f_0} = 987\,\text{MeV}\,,$$

$$\Gamma_{f_0}(m_{f_0}) = 130\,\text{MeV}\,, \quad a_0^0 = 0.226\,m_{\pi^+}^{-1}$$

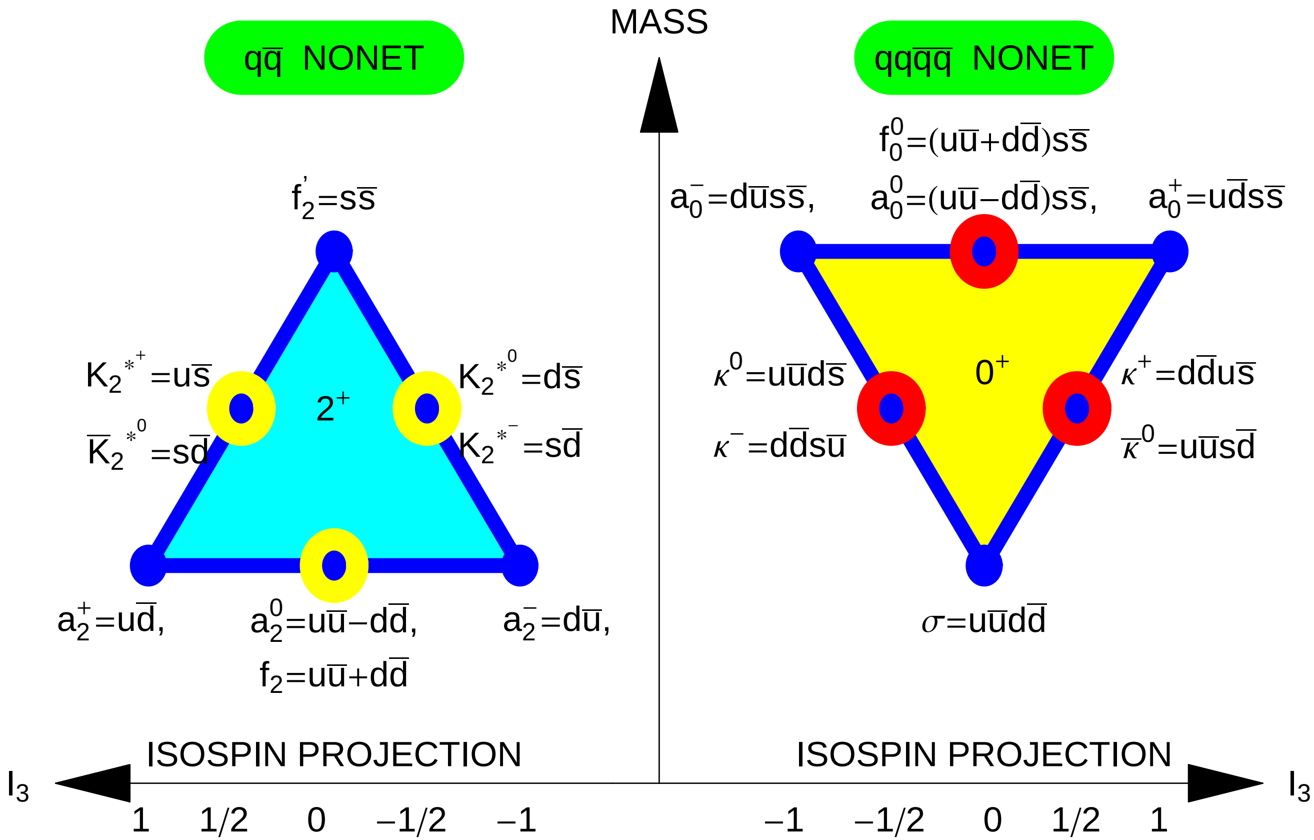
Four-quark Model

The nontrivial nature of the well-established light scalar resonances $f_0(980)$ and $a_0(980)$ is no longer denied practically anybody. 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 σ has no strange quarks, κ has the s quark, f_0 and a_0 have the $s\bar{s}$-pair.

Similar states were predicted by Jaffe in 1977 in the MIT bag (R.L. Jaffe, Phys. Rev. D 15, 267, 281 (1977)).

Four-quark Model

i) Normal 2^{++} and inverted 0^{++} mass spectra



The mass spectrum of the light scalars

$\sigma\,(600),\ \kappa\,(800),\ a_0\,(980),\ f_0\,(980)$

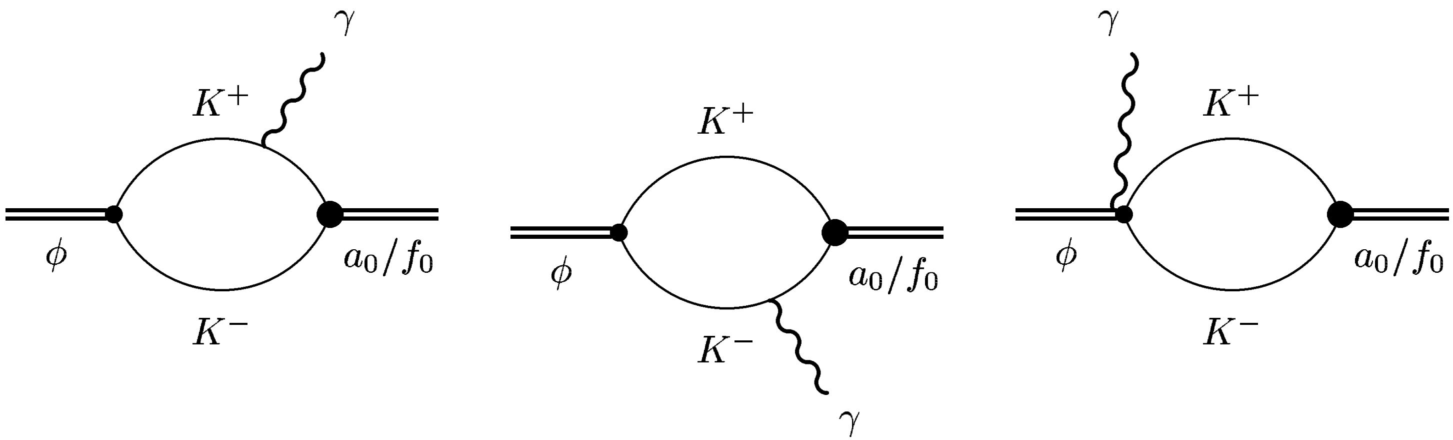
gives an idea of their $q^2\bar{q}^2$ structure.

Radiative Decays of ϕ-Meson

Ten years later we showed that $\phi \to \gamma a_0 \to \gamma\pi\eta$ and $\phi \to \gamma f_0 \to \gamma\pi\pi$ can shed light on the problem of $a_0(980)$ and $f_0(980)$ mesons
(N.N. Achasov and V.N. Ivanchenko, Nucl. Phys. B 315, 465 (1989)).

The first measurements (1998, 2000) were reported by SND and CMD-2. After (2002) they were studied by KLOE in agreement with the Novosibirsk data but with a considerably smaller error.
Note that $a_0(980)$ is produced in the radiative ϕ meson decay as intensively as $\eta'(958)$ containing $\approx 66\%$ of $s\bar{s}$, responsible for $\phi \approx s\bar{s} \to \gamma s\bar{s} \to \gamma\eta'(958)$. It is a clear qualitative argument for the presence of the $s\bar{s}$ pair in the isovector $a_0(980)$ state, i.e., for its four-quark nature.

K^+K^--Loop Model



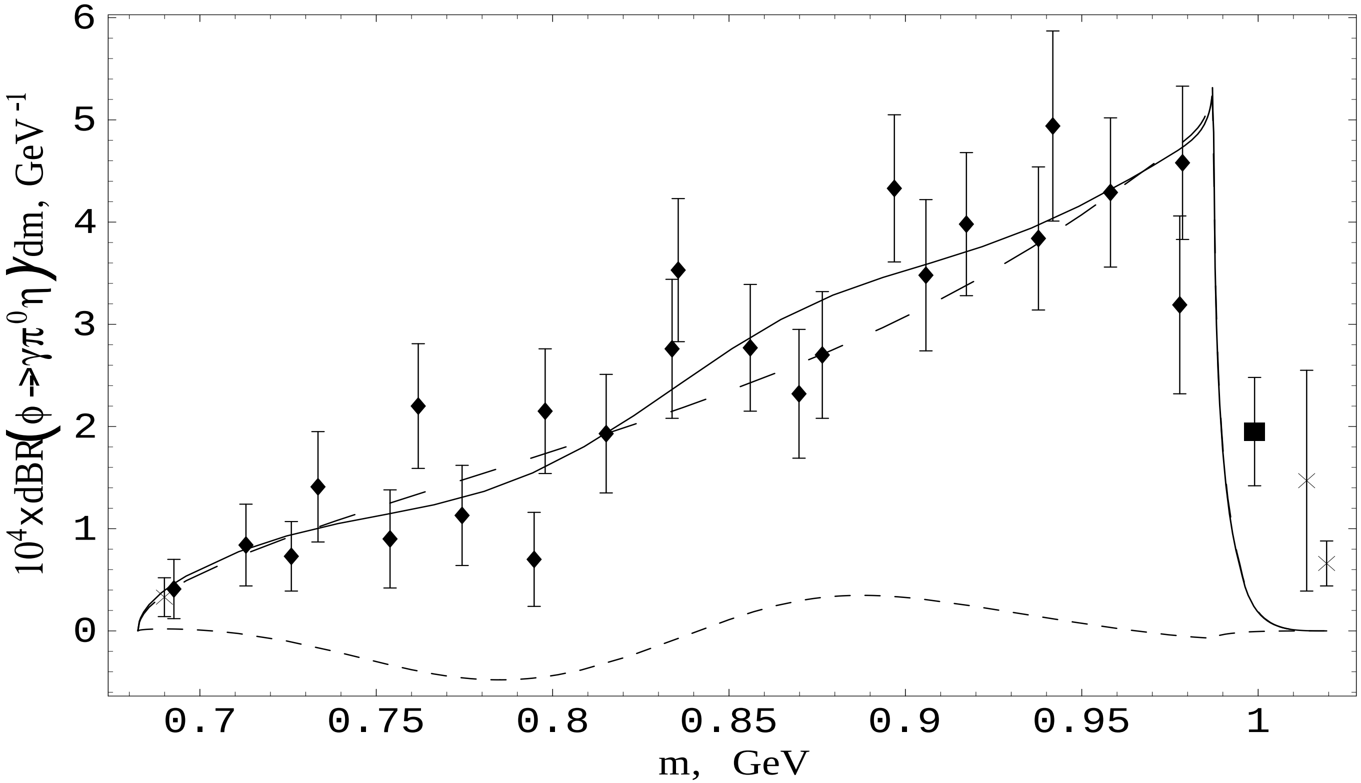
(a) (b) (c)

When basing the experimental investigations, we suggested one-loop model $\phi \to K^+K^- \to \gamma a_0/f_0$ (N.N. Achasov and V.N. Ivanchenko, Nucl. Phys. B 315, 465 (1989); N.N. Achasov and V.V. Gubin, Phys. Rev. D 56, 4084 (1997)).

This model is used in the data treatment and is ratified by experiment.

Gauge invariance gives the conclusive arguments in favor of the K^+K^- - loop transition as the principal mechanism of $a_0(980)$ and $f_0(980)$ meson production in the ϕ radiative decays.

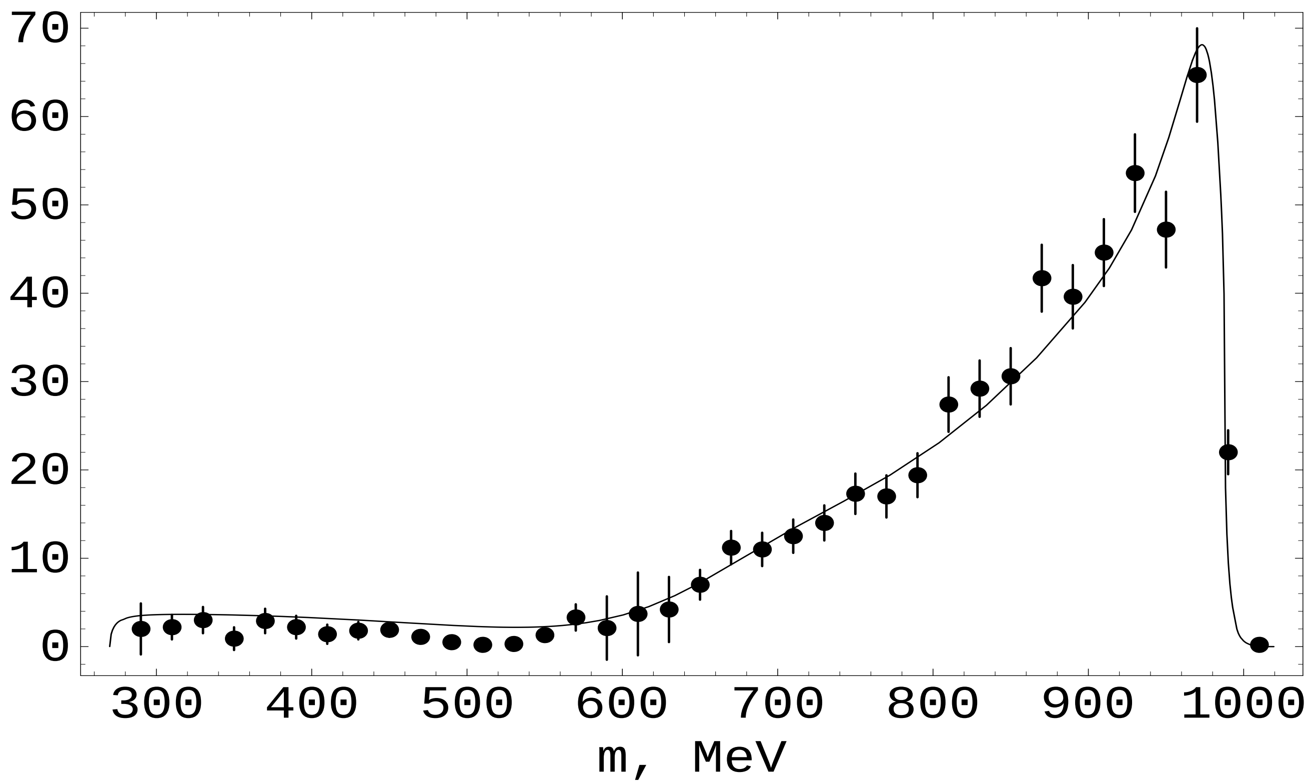
$\phi \to \gamma\pi^0\eta$, KLOE



$$\frac{dBR(\phi \to K^+K^- \to \gamma a_0 \to \gamma\pi^0\eta\,,\, m)}{dm} =$$

$$= \frac{4|g(m)|^2\omega(m)p_{\pi\eta}(m)}{\Gamma_\phi\, 3(4\pi)^3 m_\phi^2}\left|\frac{g_{a_0K^+K^-}g_{a_0\pi\eta}}{D_{a_0}(m)}\right|^2$$

$\phi \to \gamma\pi^0\pi^0$, KLOE



$$\frac{dBR(\phi \to K^+K^- \to \gamma(\sigma + f_0) \to \gamma\pi^0\pi^0\,,\ m)}{dm} =$$

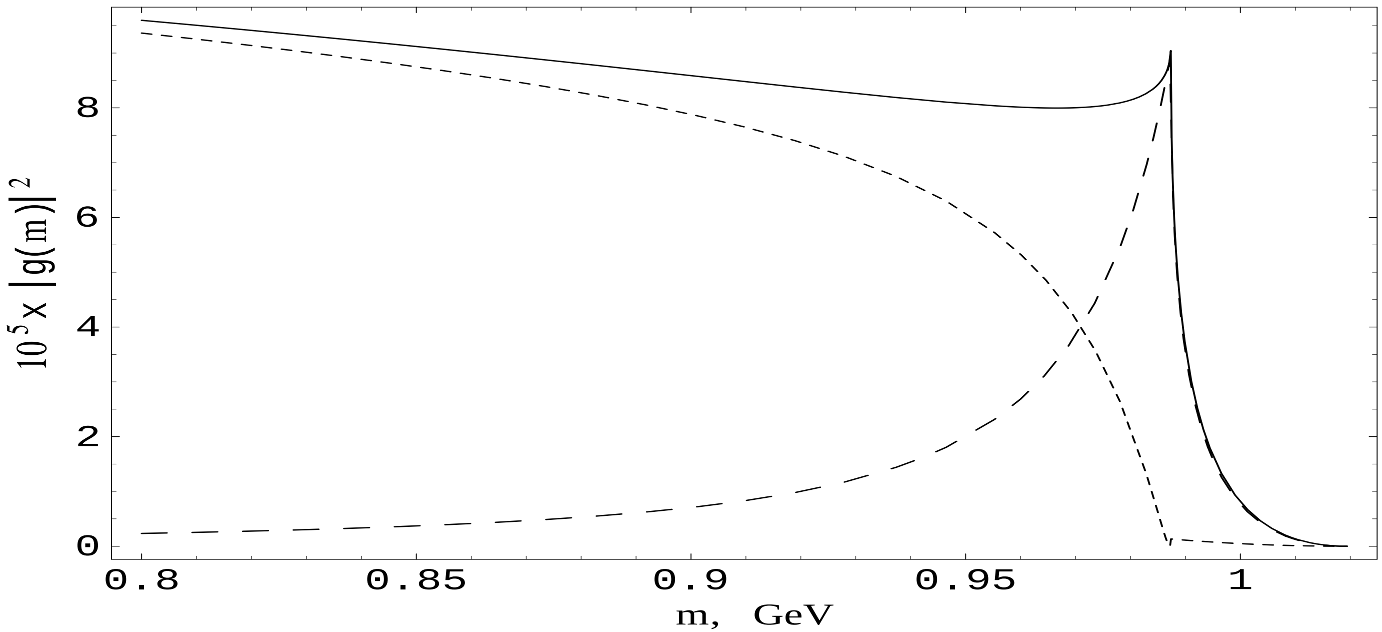
$$= \frac{16|g(m)|^2\omega(m)p_{\pi\eta}(m)}{\Gamma_\phi\, 3\pi m_\phi^2}\left|T_0^0(K^+K^- \to \pi^0\pi^0)\right|^2$$

Spectra and Gauge Invariance

To describe the experimental spectra $|g_R(m)|^2\omega(m)$ should be smooth at $m \leq 0.99$ GeV (the photon energy $\omega(m) \geq 29$ MeV). But gauge invariance requires $g(m) \sim \omega(m)$.

So stopping the impetuous increase of the $\omega(m)^3$ function at $\omega(990\,\text{MeV}) = 29$ MeV is the crucial point in understanding the mechanism of the production of $a_0(980)$ and $f_0(980)$ resonances in the ϕ radiative decays. The K^+K^--loop model $\phi \to K^+K^- \to \gamma R$ solves this problem in the elegant way with the help of the nontrivial threshold phenomenon.

Threshold Phenomenon



The universal in K^+K^--loop model function $|g(m)|^2 = |g_R(m)/g_{RK^+K^-}|^2$ is drawn with the solid line. The contribution of the imaginary part is drawn with the dashed line. The contribution of the real part is drawn with the dotted line.

K^+K^--Loop Mechanism is established

In truth this means that $a_0(980)$ and $f_0(980)$ are seen in the radiative decays of ϕ meson owing to K^+K^- intermediate state.

So, the mechanism of production of $a_0(980)$ and $f_0(980)$ mesons in the ϕ radiative decays is established at a physical level of proof.

WE ARE DEALING WITH THE FOUR-QUARK TRANSITION.

A radiative four-quark transition between two $q\bar{q}$ states requires creation and annihilation of an additional $q\bar{q}$ pair, i.e., such a transition is forbidden according to the OZI rule, while a radiative four-quark transition between $q\bar{q}$ and $q^2\bar{q}^2$ states requires only creation of an additional $q\bar{q}$ pair, i.e., such a transition is allowed according to the OZI rule.

The large N_C expansion supports this conclusion (N.N. Achasov, Nucl. Phys. A 728, 425 (2003)).

About the $K\bar{K}$ molecular model

We (N.N. Achasov, V.V. Gubin, and V.I. Shevchenko, Phys. Rev. D 56, 203 (1997); N.N. Achasov and A.V. Kiselev, Phys. Rev. D 76, 077501 (2007) and Phys. Rev. D 78, 058502 (2008)) showed that the description of the $\phi \to K^+K^- \to \gamma a_0(980)/f_0(980)$ decays requires the virtual momenta of the $K(\bar{K})$ more than 2 GeV. While in the case of the loose molecules with the bounding energy about 20 MeV, they would have to be equal about 100 MeV.

Besides, it should be noted that the production of scalar mesons in the pion-nucleon collisions with large momentum transfers also points to their compactness (N.N. Achasov and G.N. Shestakov, Phys. Rev. D 58, 054011 (1998)).

So, there are no physical signals that confirm the molecule model !

$a_0(980)\,/\,f_0(980) \to \gamma\gamma$ & $q^2\bar{q}^2$-Model

Thirty six years ago we predicted the suppression of $a_0(980) \to \gamma\gamma$ and $f_0(980) \to \gamma\gamma$ in the $q^2\bar{q}^2$ MIT model,

$\Gamma(a_0(980) \to \gamma\gamma) \sim \Gamma(f_0(980) \to \gamma\gamma) \sim 0.27$ keV

(N.N. Achasov, S.A. Devyanin, and G.N. Shestakov, Phys. Lett. 108B, 34 (1982); Z. Phys. C 16, 55 (1982)).

Experiment supported this prediction

$\Gamma(f_0(980) \to \gamma\gamma) \approx 0.31$ keV and $\Gamma(a_0(980) \to \gamma\gamma) \approx 0.3$ keV

C. Patrignani et al.(Particle Data Group), Chin. Phys. C 40, 100001 (2016) and 2017 update.

When in the $q\bar{q}$ model it was anticipated

$\Gamma(\mathrm{a}_0 \to \gamma\gamma) \approx (1.5 - 5.9)\Gamma(\mathrm{a}_2 \to \gamma\gamma) \approx (1.5 - 5.9) \cdot 1$ keV.

$\Gamma(f_0 \to \gamma\gamma) \approx (1.7 - 5.5)\Gamma(f_2 \to \gamma\gamma) \approx (1.7 - 5.5) \cdot 2.8$ keV.

Scalar Nature and Production Mechanisms in $\gamma\gamma$ collisions

Recently the experimental investigations have made great qualitative advance. The Belle Collaboration published data on $\gamma\gamma \to \pi^+\pi^-$ (2007), $\gamma\gamma \to \pi^0\pi^0$ (2008), and $\gamma\gamma \to \pi^0\eta$ (2009), whose statistics are huge. They not only proved the theoretical expectations based on the four-quark nature of the light scalar mesons, but also have allowed to elucidate the principal mechanisms of these processes.

(N.N. Achasov and G.N. Shestakov, Phys. Rev. D 77, 074020 (2008); Phys. Rev. D 81, 094029 (2010); Usp. Fiz. Nauk 181, 827 (2011)).

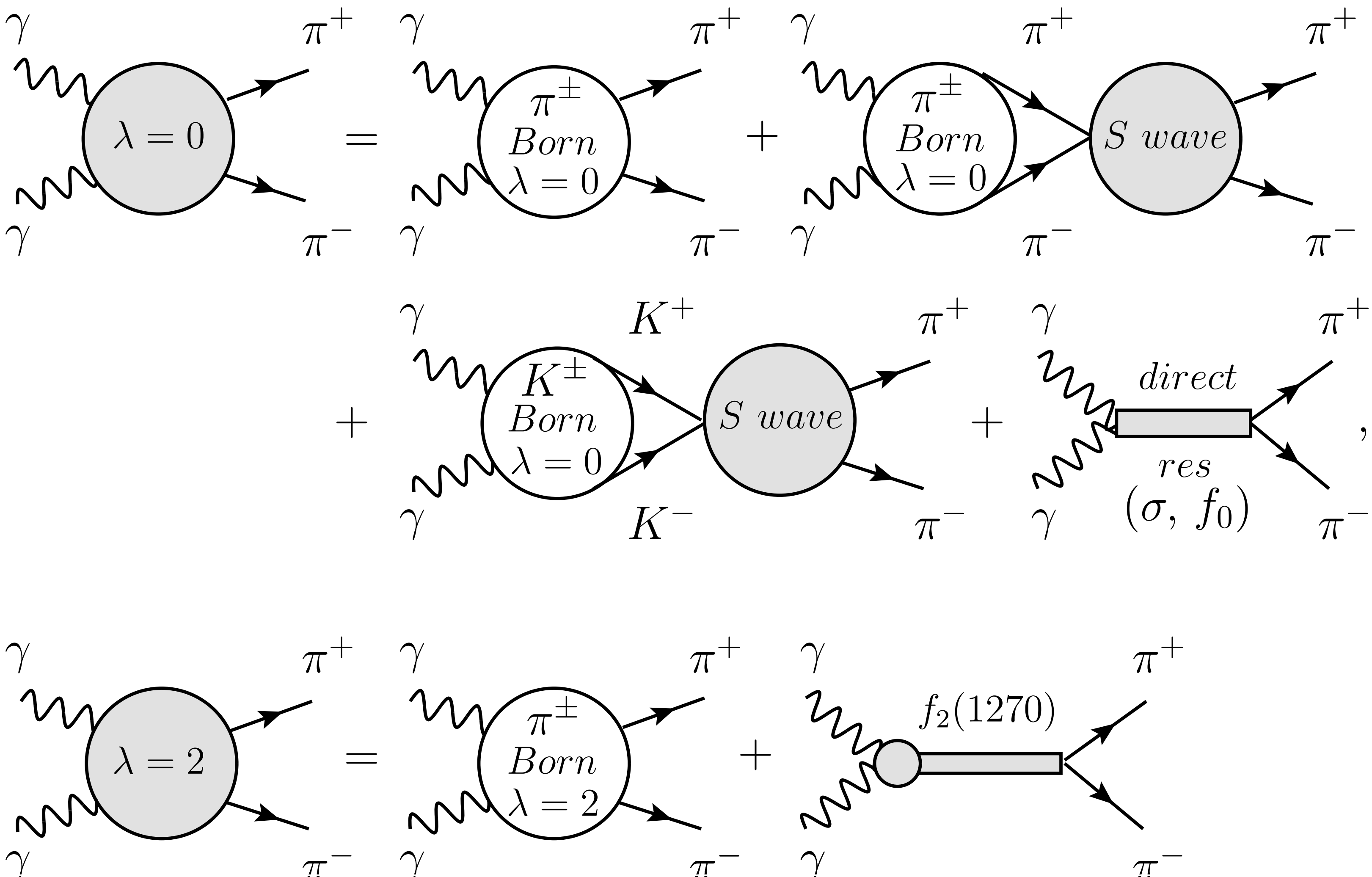
Specifically, the direct coupling constants of the $\sigma(600)$, $f_0(980)$, and $a_0(980)$resonances with the $\gamma\gamma$ system are small with the result that their decays in the two photon are the four-quark transitions caused by the rescatterings $\sigma \to \pi^+\pi^- \to \gamma\gamma$,

Scalar Nature and Production Mechanisms in $\gamma\gamma$ collisions

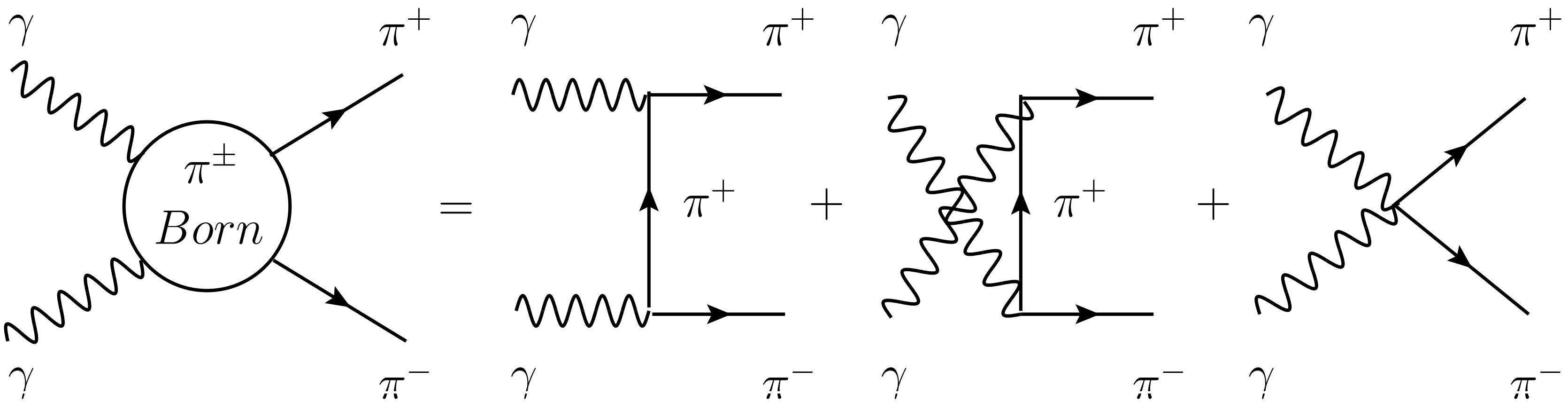
$f_0(980)\to K^+K^-\to\gamma\gamma$, and $a_0(980)\to K^+K^-\to\gamma\gamma$ in contrast to the two-photon decays of the classic P wave tensor $q\bar q$ mesons $a_2(1320)$, $f_2(1270)$ and $f_2'(1525)$, which are caused by the direct two-quark transitions $q\bar q\to\gamma\gamma$ in the main.
As a result the practically model-independent prediction of the $q\bar q$ model $g^2_{f_2\gamma\gamma}:g^2_{a_2\gamma\gamma}=25:9$ agrees with experiment rather well.

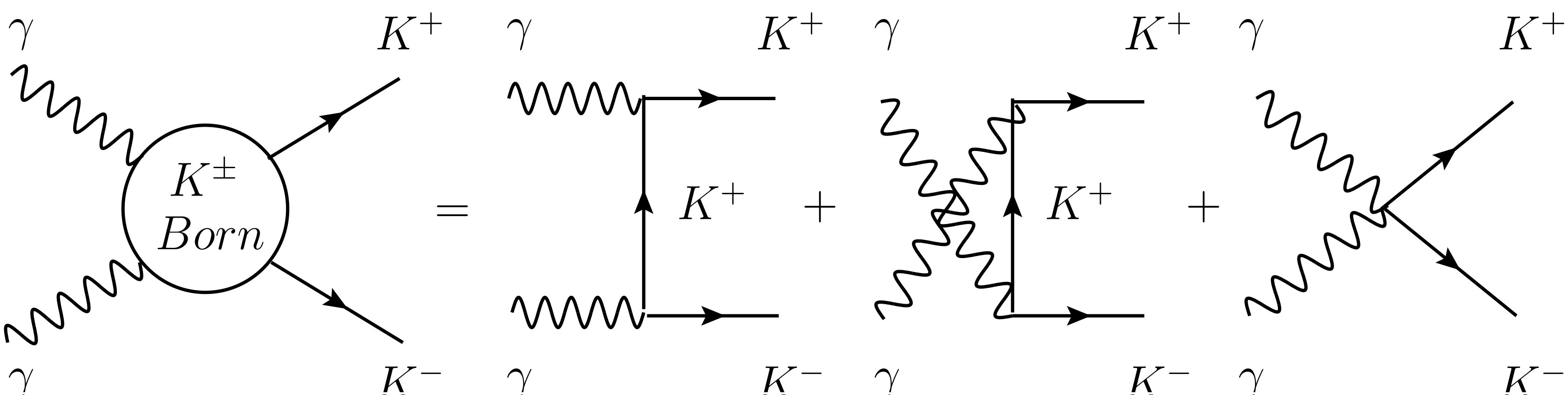
The two-photon light scalar widths averaged over resonance mass distributions $\langle\Gamma_{f_0\to\gamma\gamma}\rangle_{\pi\pi}\approx$ 0.19 keV, $\langle\Gamma_{a_0\to\gamma\gamma}\rangle_{\pi\eta}\approx$ 0.3 keV and $\langle\Gamma_{\sigma\to\gamma\gamma}\rangle_{\pi\pi}\approx$ 0.45 keV.
As to the ideal $q\bar q$ model prediction $g^2_{f_0\gamma\gamma}:g^2_{a_0\gamma\gamma}=25:9$, it is excluded by experiment.

Dynamics of $\gamma\gamma \to \pi^+\pi^-$

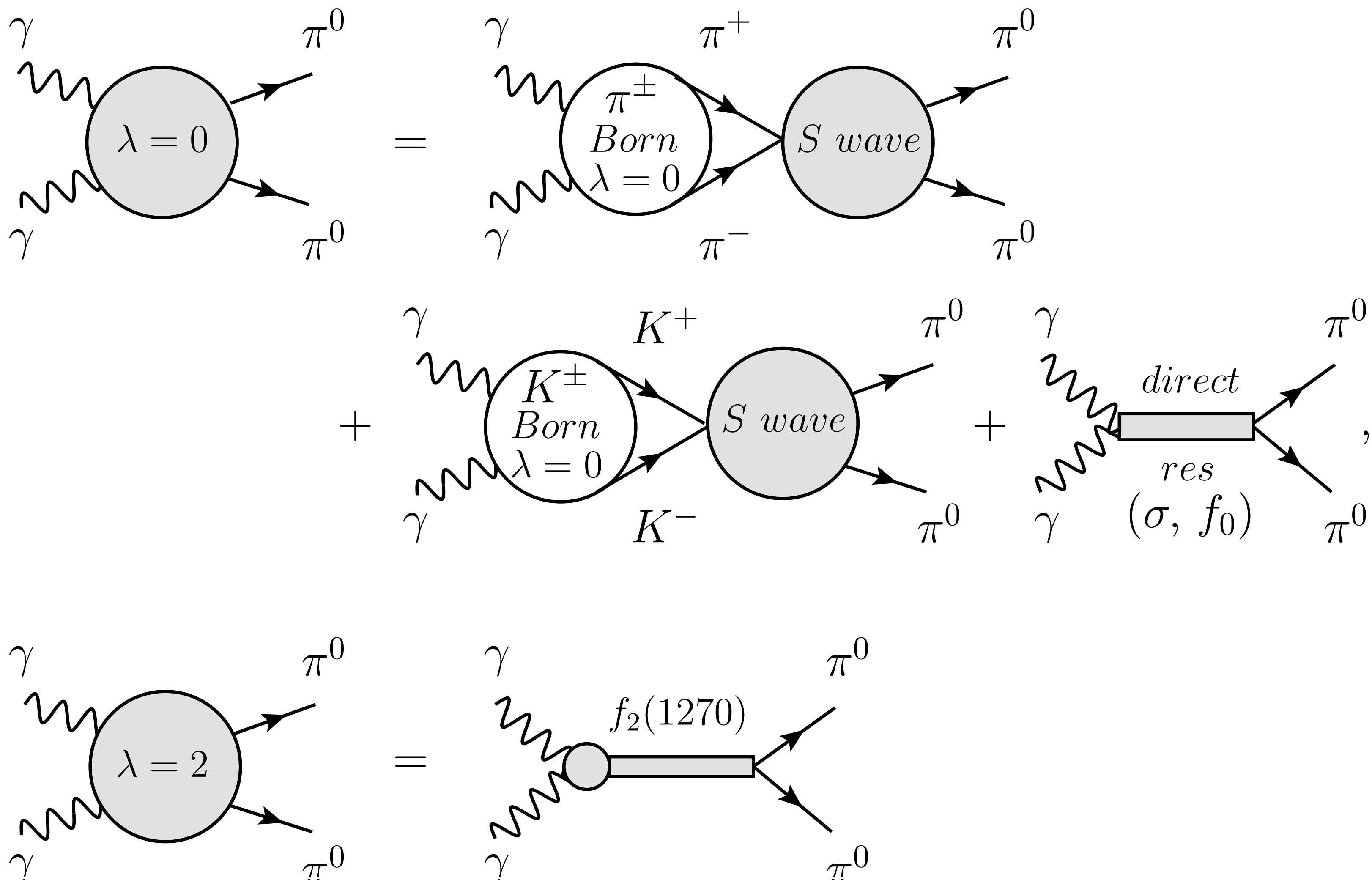


The $\pi^{\pm}$ and $K^{\pm}$ Born contributions

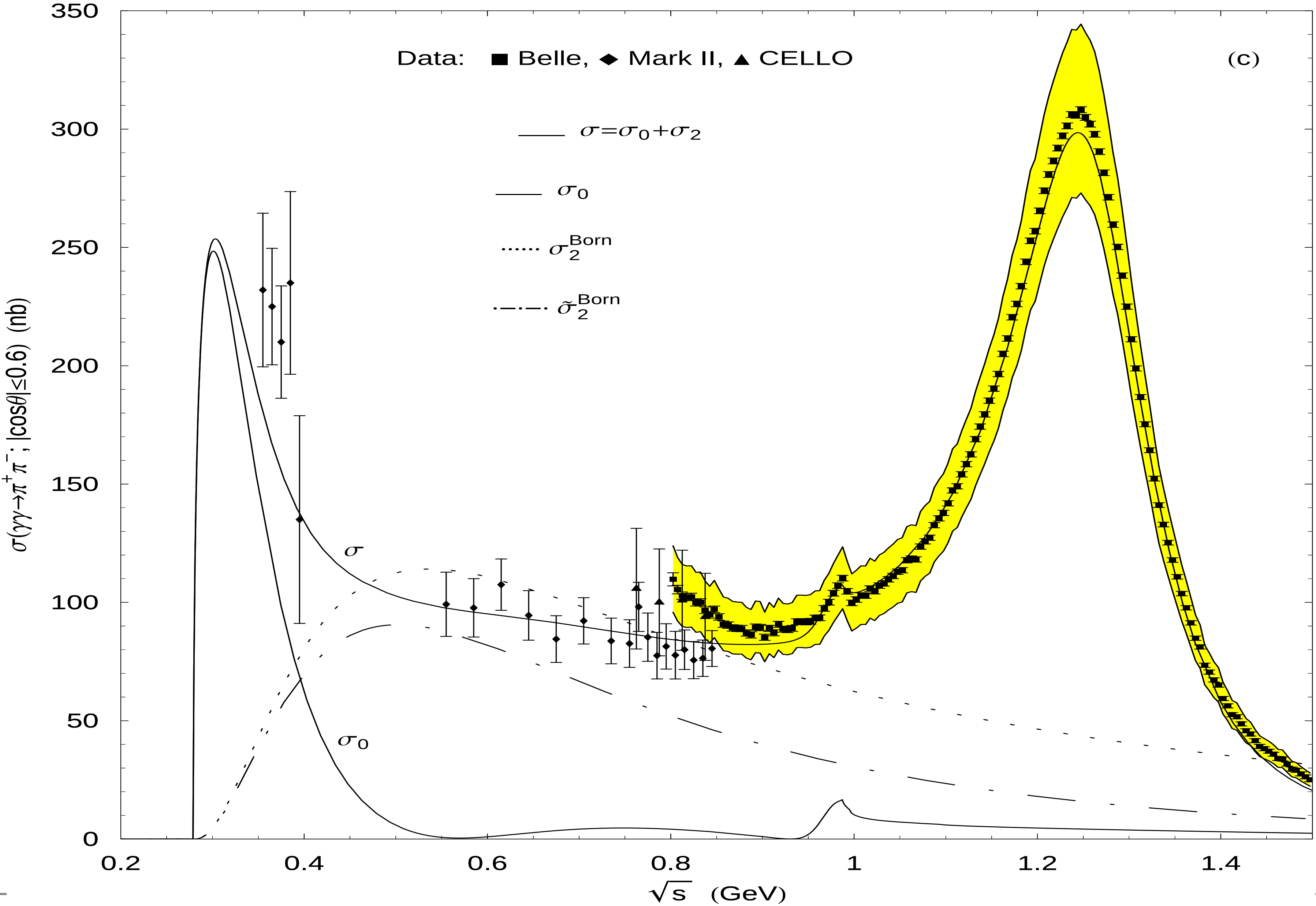




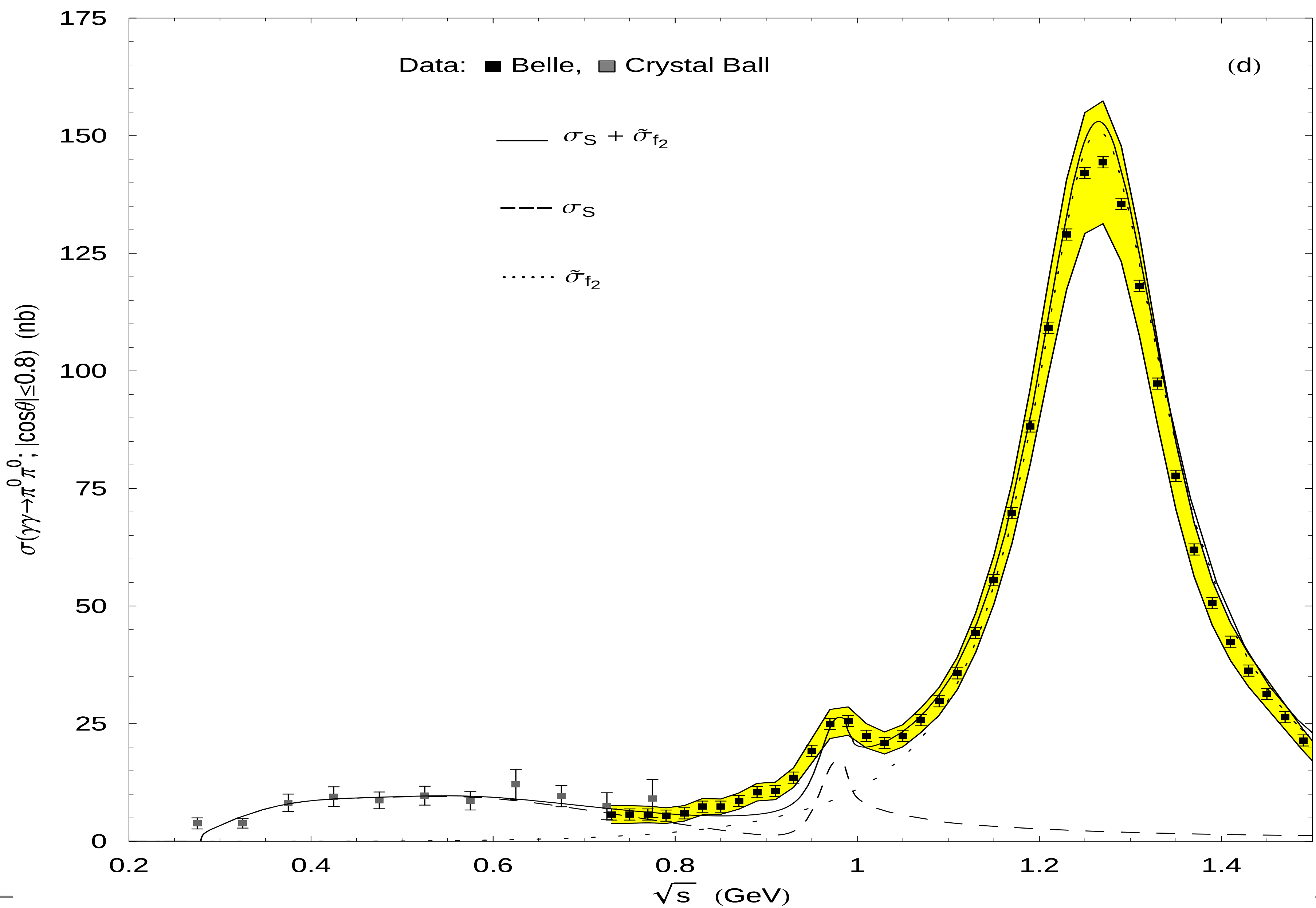
Dynamics of $\gamma\gamma \to \pi^0\pi^0$



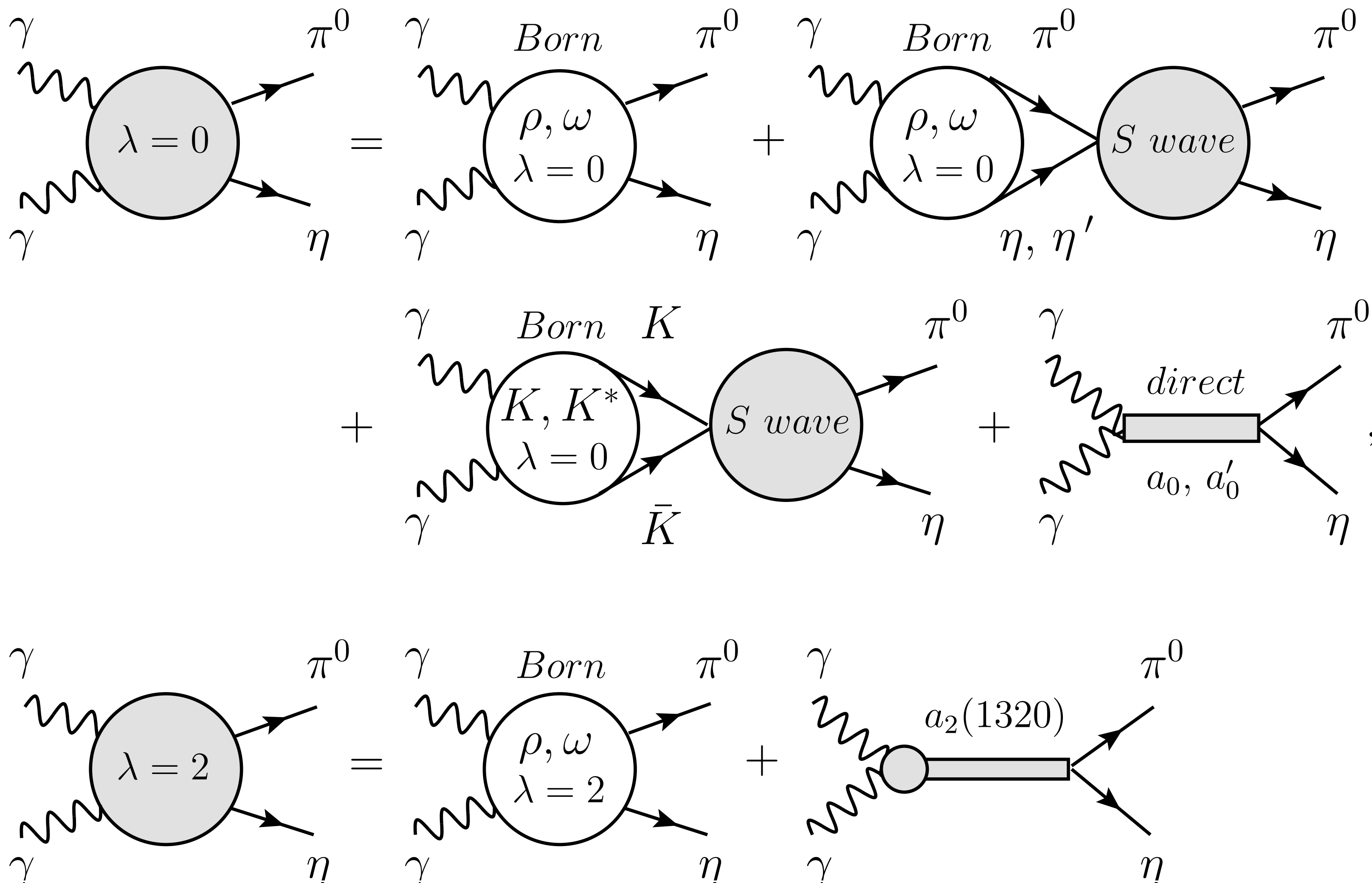
The Belle data on $\gamma\gamma \to \pi^+\pi^-$



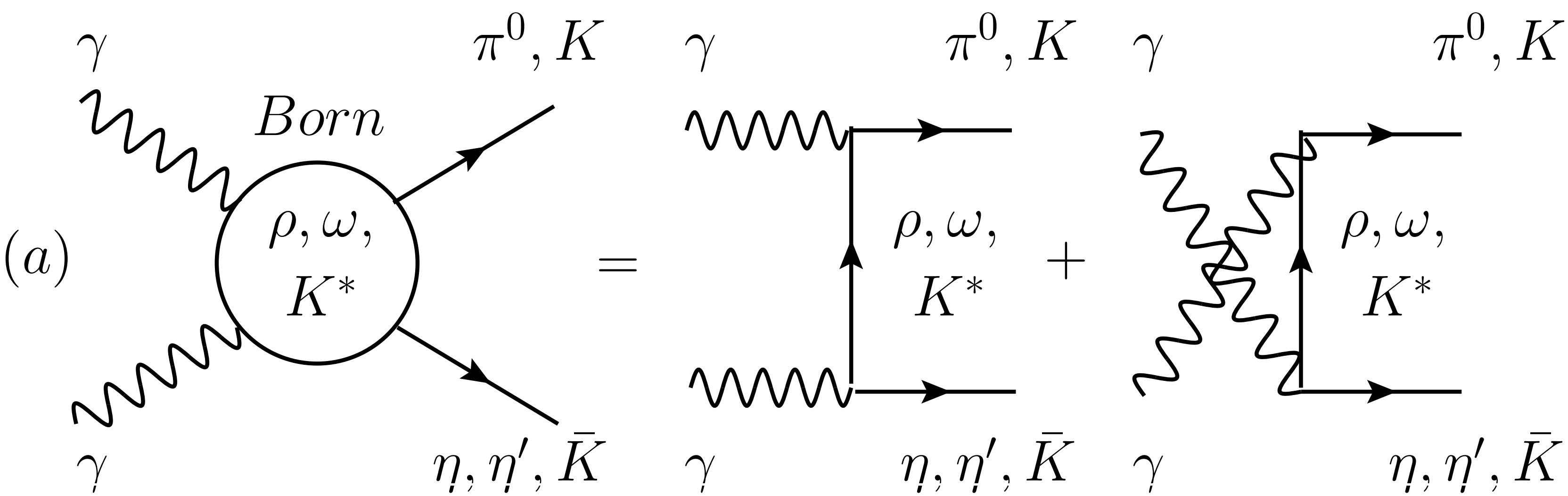
The Belle data on $\gamma\gamma \to \pi^0\pi^0$



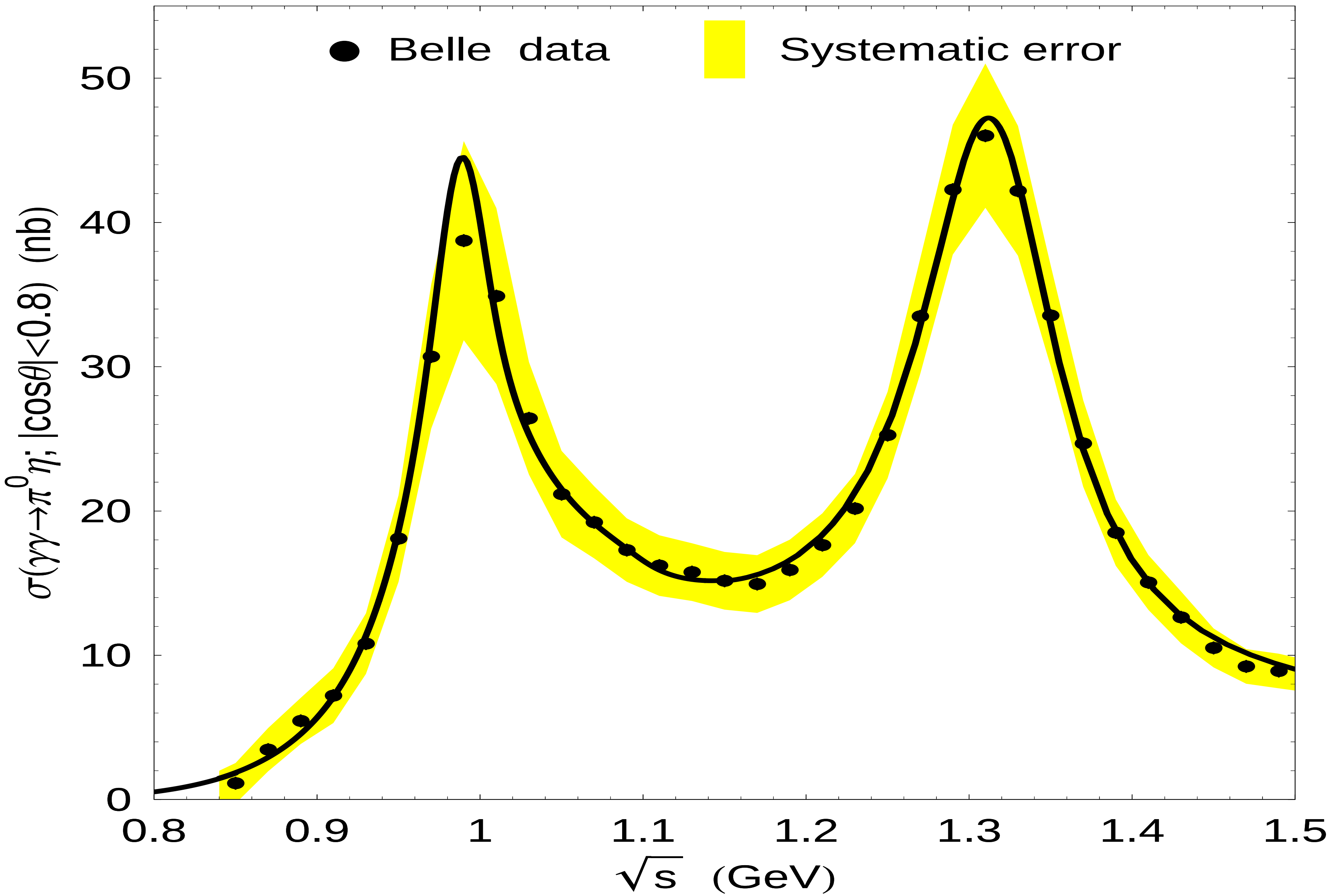
Dynamics of $\gamma\gamma \to \pi^0\eta$



The V Born contributions

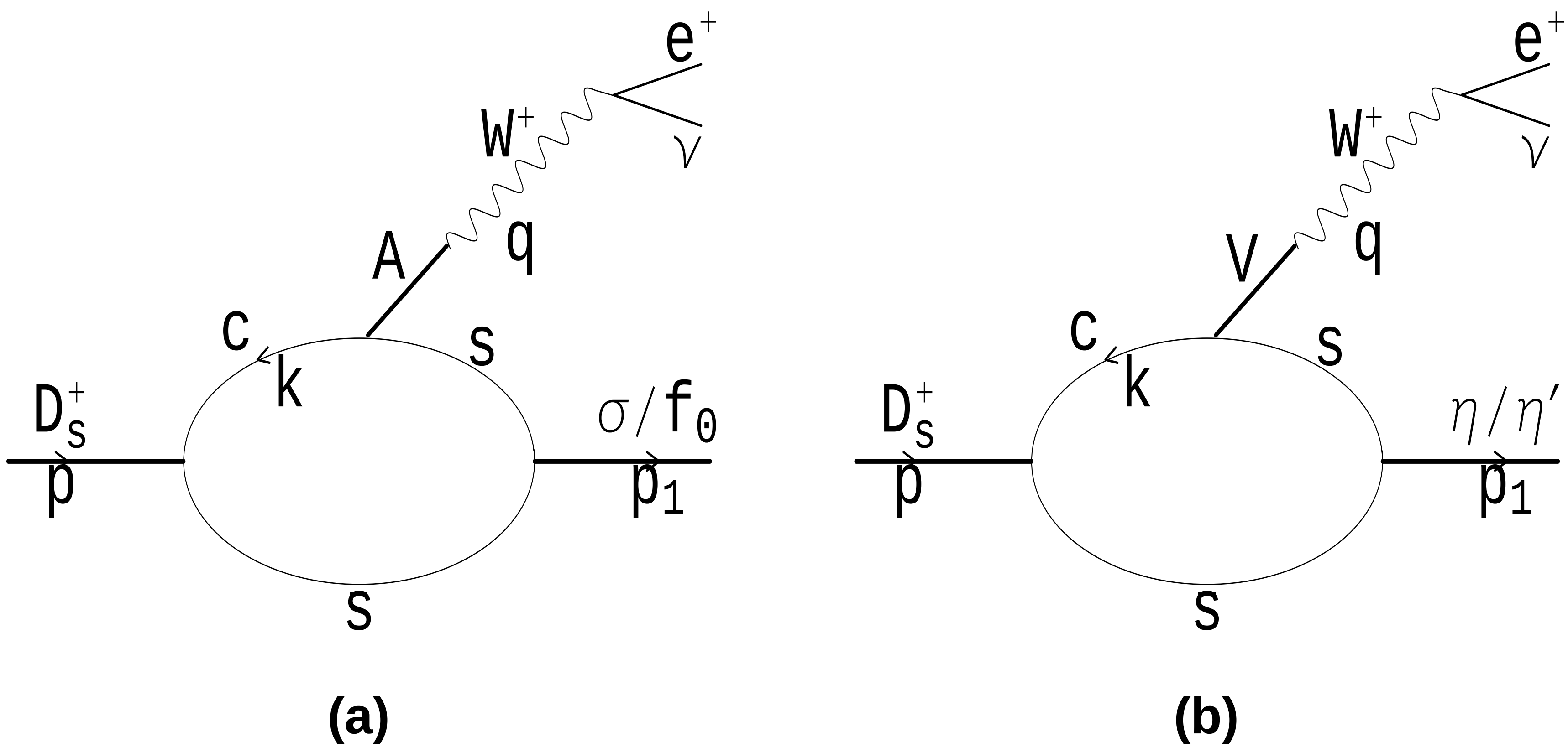


The Belle data on $\gamma\gamma \to \pi^0\eta$



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

The semi-leptonic decays are of prime interest because they have the clear mechanisms (N.N. Achasov and A.V. Kiselev, Phys. Rev. D 86, 114010 (2012); Int. J. Mod. Phys. A 35, 1460447 (2014)).



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

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 the chirally symmetric model of the Nambu-Jona-Lasinio type.

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, that we obtained in N.N. Achasov and A.V. Kiselev, PRD 85, 094016 (2012)
$g^2_{\sigma K^+K^-}/g^2_{\sigma\pi^+\pi^-} \lesssim 0.04$.

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

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 $g^2_{\sigma K^+K^-}/g^2_{\sigma\pi^+\pi^-} = 1/4$.

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

Besides, we find that the $f_{0s} = s\bar{s}$ and $f_{0q} = (u\bar{u} + d\bar{d})/\sqrt{2}$ parts 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
$BR(D^+ \to d\bar{d}\, e^+\nu \to \eta\, e^+\nu) = (1.14 \pm 0.10) \times 10^{-3}$,
$BR(D^+ \to d\bar{d}\, e^+\nu \to \eta'\, e^+\nu) = (2.2 \pm 0.5) \times 10^{-4}$.

Outlook

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

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

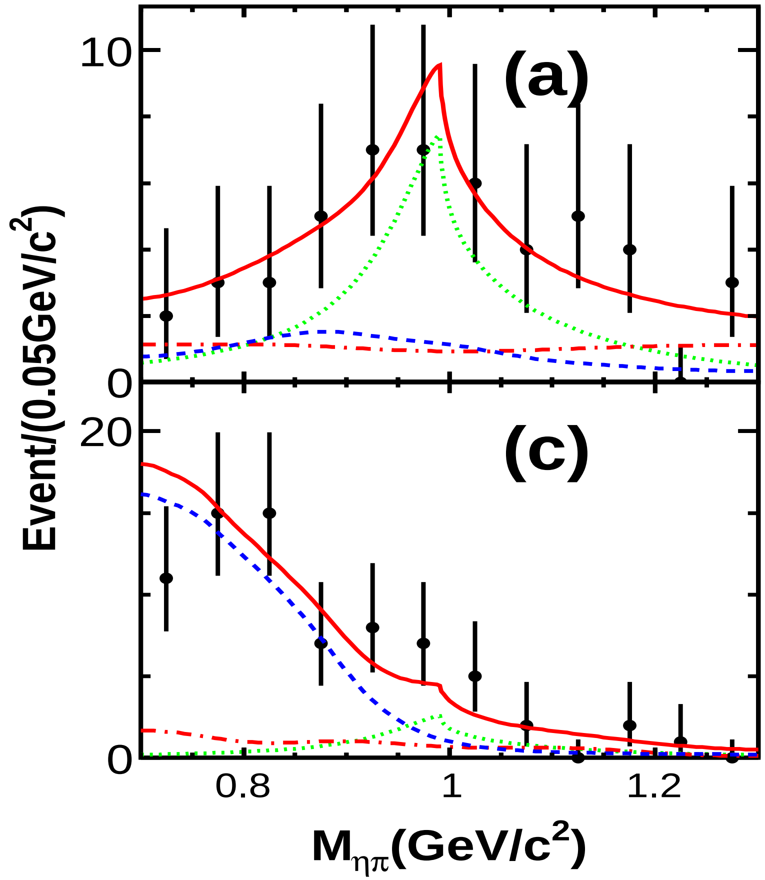
NEW

We just have analyzed the new experiment from BESIII, "Observation of Semileptonic Decay $D^0 \to a_0^-(980)\, e^+\nu_e \to \pi^-\eta\, e^+\nu_e$ and Evidence for $D^+ \to a_0^0(980)\, e^+\nu_e \to \pi^0\eta\, e^+\nu_e$", M. Ablikim *et. al.*, arXiv: 1803.02166v1 [hep-ex].

The BESIII experiment is the first step in experimental study of these decays. We present a possible variant of the $\eta\pi$ invariant mass distribution when
a_0 has no constituent $q\bar{q}$ pair at all,
N.N. Achasov and A.V. Kiselev, arXiv: 1805......v1 [hep-ph].

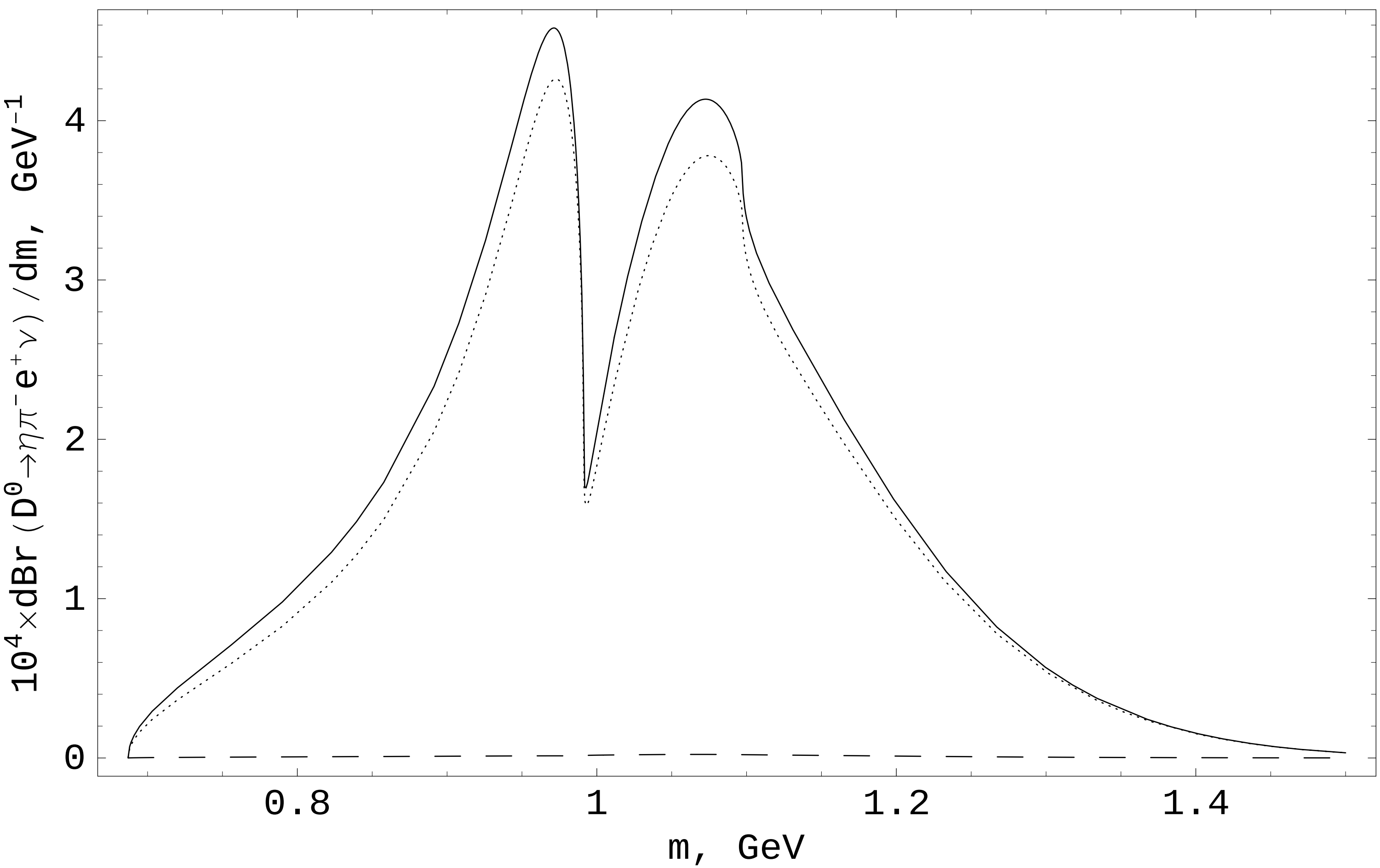
The higher statistics could check this prediction.

NEW



(a) $D^0 \to (a_0^-, a_0'^-)\, e^+\nu \to \eta\pi^- e^+\nu$ **and**
(c) $D^+ \to (a_0^0, a_0'^0)\, e^+\nu \to \eta\pi^0 e^+\nu$ **decays. Green curves are signal, red ones represent total contribution, other ones represent backgrounds.**

NEW



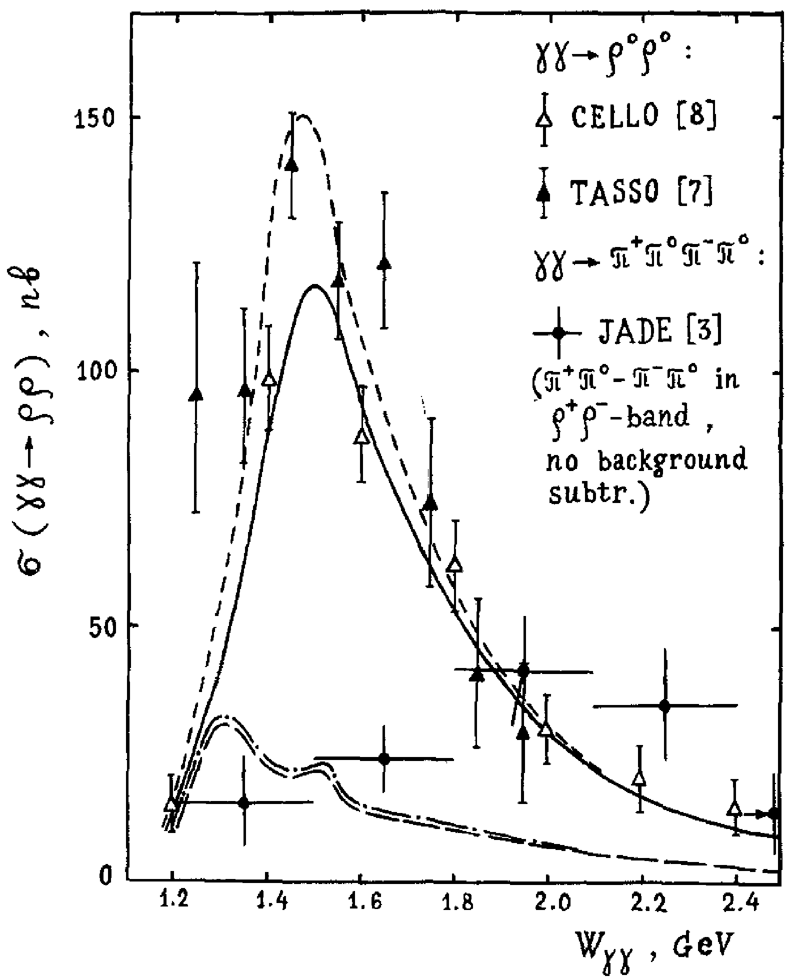
The $D^0 \to (a_0^-, a_0'^-)\, e^+\nu \to \eta\pi^- e^+\nu$ **spectrum with** $g_{d\bar{u}a_0^-} = 0$.

Isotensor Tensor $E(1500-1600)$ state

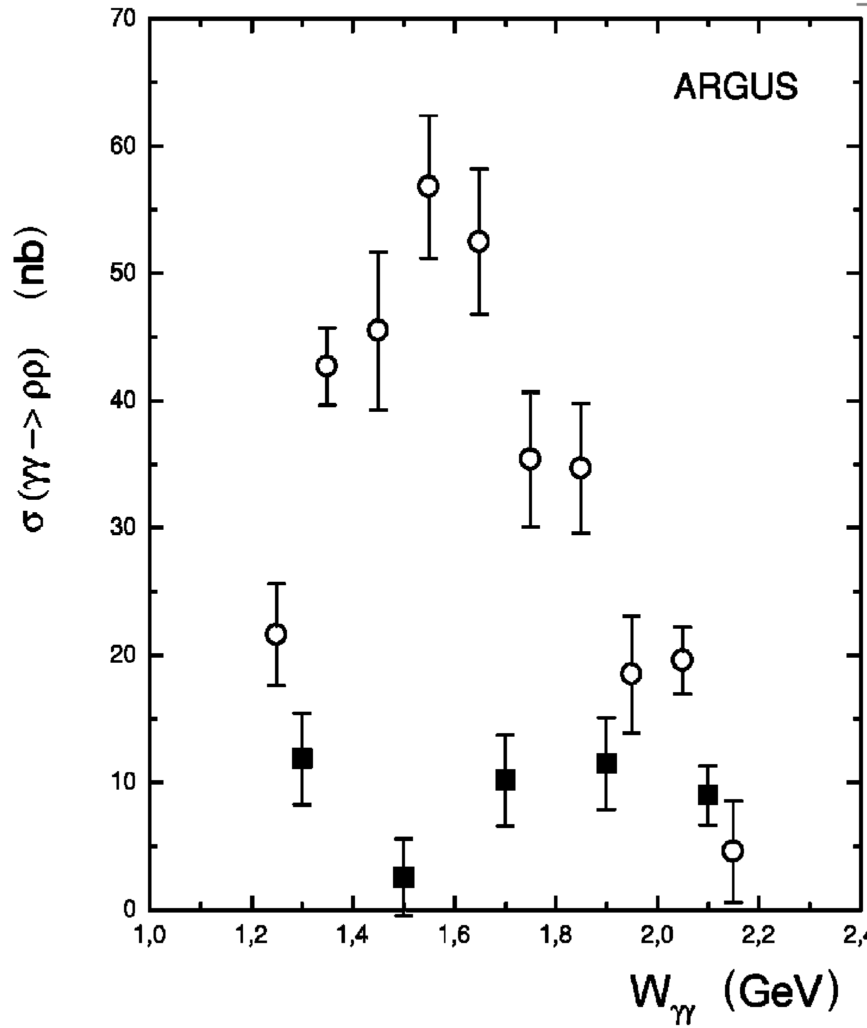
Thirty six years ago we predicted the striking interference picture in the $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$ reactions in the $q^2\bar{q}^2$ MIT model,
N.N. Achasov, S.A. Devyanin, and G.N. Shestakov,
Phys. Lett. 108B, 34 (1982); Z. Phys. C 16, 55 (1982).
We explained the stong boost near the threshold in the $\gamma\gamma\to\rho^0\rho^0$ reaction by the production of the isotensor tensor and isoscalar tensor resonances, then the destructive interference of their contributions follows from isotopic symmetry!

Experiment backed up this prediction, JADE 1983, ARGUS 1991, see,
N.N. Achasov and G.N. Shestakov, Z. Phys. C 27, 99 (1985); Sov. Phys. Usp. 34 (6), 471 (1991).

$\gamma\gamma \to \rho^0\rho^0$ and $\gamma\gamma \to \rho^+\rho^-$



(a)



(b)

a) TASSO 1982, JADE 1983, CELLO 1984 b) ARGUS 1991

$\gamma\gamma \to \rho^0\rho^0$ and $\gamma\gamma \to \rho^+\rho^-$

We believe that the Belle data will support the above picture, but the urgent task is the search for the charged components of the isotensor state:

$E^{\pm}$ in the mass spectra of the $\rho^{\pm}\rho^{0}$ states in the reactions $\gamma N \to \rho^{\pm}\rho^{0} N(\Delta)$ in JEFLAB,

N.N. Achasov and G.N. Shestakov, Phys. Rev. D 60, 114021 (1999),

$E^{\pm\pm}$ in the mass spectra of the $\rho^{\pm}\rho^{\pm}$ states in the reactions $\pi N \to \pi\rho^{\pm}\rho^{\pm} N(\Delta)$ and $NN \to N(\Delta)\rho^{\pm}\rho^{\pm} N(\Delta)$ in Protvino in IHEP,

N.N. Achasov and G.N. Shestakov, Sov. Phys. Usp. 34 (6), 471 (1991); International Journ al of Modern Physics A, Vol. 7, No. 18 (1992) 4313-4333.

X(3872) State as Charmonium $\chi_{c1}(2P)$

The two dramatic discoveries have generated a stream of the $D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}$ molecular interpretations of the $X(3872)$ resonance.

The mass of the $X(3872)$ resonance is 50 MeV lower than predictions of the most lucky naive potential models for the mass of the $\chi_{c1}(2P)$ resonance,

$$m_X - m_{\chi_{c1}(2P)} = -\Delta \approx -50\,\text{MeV},$$

and the relation between the branching ratios

$$BR(X \to \pi^+\pi^-\pi^0 J/\psi(1S)) \sim BR(X \to \pi^+\pi^- J/\psi(1S)),$$

that is interpreted as a strong violation of isotopic symmetry.

X(3872) State as Charmonium $\chi_{c1}(2P)$

But, the bounding energy is small, $\epsilon_B \lesssim 1$ MeV. That is, the radius of the molecule is large,
$r_{X(3872)} \gtrsim 5$ fermi$= 5 \cdot 10^{-13}$ cm. As for the charmonium, its radius is less one fermi,
$r_{\chi_{c1}(2P)} \lesssim$ fermi $= 10^{-13}$ cm.
That is, the molecule volume is $125 \div 1000$ times as large as the charmonium volume, $V_{X(3872)}/V_{\chi_{c1}(2P)} \gtrsim 125 \div 1000$.

This means a probability of production of a giant molecule in hard processes, at small distances, is suppressed in comparison with a probability of production of heavy a charmomium by a factor $\sim V_{\chi_{c1}(2P)}/V_{X(3872)}$.

X(3872) State as Charmonium $\chi_{c1}(2P)$

But, in reality

$$0.74 < \frac{\sigma(\mathrm{pp} \to \mathrm{X(3872)} + \mathrm{anything})}{\sigma(\mathrm{pp} \to \psi(\mathrm{2S}) + \mathrm{anything})} < 2.1.$$

with rapidity in the range 2,5 - 4,5 and transverse momentum in the range 5-20 GeV.

In addition,

$$0.2 < \frac{\mathrm{BR}(\mathrm{B}^0 \to \mathrm{X(3872)K}^+\pi^-)}{\mathrm{BR}(\mathrm{B}^0 \to \psi(\mathrm{2S})\mathrm{K}^+\pi^-)} < 0.6.$$

The extended molecule is produced in hard processes as intensively as the compact charmonium. It's miracle!

X(3872) State as Charmonium $\chi_{c1}(2P)$

We explain the shift of the mass of the $X(3872)$ resonance with respect to the prediction of a potential model for the mass of the $\chi_{c1}(2P)$ charmonium by the contribution of the virtual $D^*\bar{D} + c.c.$ intermediate states into the self energy of the $X(3872)$ resonance.

This allows us to estimate the coupling constant of the $X(7872)$ resonance with the $D^{*0}\bar{D}^0$ channel, the branching ratio of the $X(3872) \to D^{*0}\bar{D}^0 + c.c.$ decay, and the branching ratio of the $X(3872)$ decay into all non-$D^{*0}\bar{D}^0 + c.c.$ states.

X(3872) State as Charmonium $\chi_{c1}(2P)$

We predict that the hadron channels of the decays of $\chi_{c1}(2P)$ via two gluon ($X(3872) \to gluon\, gluon \to hadrons$) should be the same as in the $\chi_{c1}(1P)$ case, that is, there should be a few tens of such channels.

As for the $\rho J/\psi$ state, it is produced both via the one photon, $X \to c\bar{c} \to \gamma^* c\bar{c} \to \rho J/\psi$, and via the three gluons (via the contribution $\sim m_u - m_d$), $X \to c\bar{c} \to ggg\, c\bar{c} \to \rho J/\psi$. Close to our scenario is an example of the $J/\psi \to \rho\eta'$ and $J/\psi \to \omega\eta'$ decays.

$BR(J/\psi \to \rho\eta') = (1.05 \pm 0.18) \cdot 10^{-4}$ and

$BR(J/\psi \to \omega\eta') = (1.82 \pm 0.21) \cdot 10^{-4}$.

Note that in the $X(3872)$ case the ω meson is produced on its tail, while the ρ meson is produced on a half. $m_X - m_{J/\psi} = 775$ MeV

X(3872) State as Charmonium $\chi_{c1}(2P)$

We predict:

1. If the one-photon mechanism dominates in the $X(3872) \to \rho J/\psi$ decay then one should expect $BR(\chi_{b1}(2P) \to \rho\Upsilon(1S)) \sim (e_b/e_c)^2 \cdot 1.6\%$

$= (1/4) \cdot 1.6\% \approx 0.4\%$!!!

Where e_c and e_b are the charges of the c and b quarks, respectively.

2. If the three-gluon mechanism via the contribution $\sim m_u - m_d$ dominates in the $X(3872) \to \rho J/\psi$ decay then one should expect $BR(\chi_{b1}(2P) \to \rho\Upsilon(1S)) \sim 1.6\%$!!!

The direct indication that $X(3872) \equiv \chi_{c1}(2P)$

The LHCb Collaboration published a landmark result

R. Aaij et al. (LHCb Collaboration), Nucl. Phys. B 886, 665 (2014).

$$\frac{BR(X \to \gamma\psi(2S))}{BR(X \to \gamma J/\psi)} = C_X \left(\frac{\omega_{\psi(2S)}}{\omega_{J/\psi}}\right)^3 = 2.46 \pm 0.7$$

On the other hand

$$\frac{BR(\chi_{b1}(2P) \to \gamma\Upsilon(2S))}{BR(\chi_{b1}(2P) \to \gamma\Upsilon(1S))} = C_{\chi_{b1}(2P)} \left(\frac{\omega_{\Upsilon(2S)}}{\omega_{\Upsilon(1S)}}\right)^3 = 2.16 \pm 0.28$$

$$C_X = C_{\chi_{c1}(2P)} = 136.78 \pm 38.89$$

$$C_{\chi_{b1}(2P)} = 80 \pm 10.37$$

Note that all versions of the potential model predict
$C_{\chi_{c1}(2P)} \gg 1$ **and** $C_{\chi_{b1}(2P)} \gg 1$.

X(3872) State as Charmonium $\chi_{c1}(2P)$

Once more, we discuss the scenario where the $\chi_{c1}(2P)$ charmonium sits on the $D^{*0}\bar{D}^0$ threshold but not a mixing of the giant $D^*\bar{D}$ molecule and the compact $\chi_{c1}(2P)$ charmonium. The point is such a mixing $\sim \sqrt{V_{\chi_{c1}(2P)}/V_{X(3872)}}$ and a branching ratio of a decay via such a mixing $\sim V_{\chi_{c1}(2P)}/V_{X(3872)}$

N.N. Achasov and E.V. Rogozina, JETP Lettrs. 2014. V. 100. P. 227; Mod. Phys. Lett. A. 2015. V. 30. P. 1550181; Journal of University of Science and Technology of China, 2016,Vol. 46, No 7, PP. 574-579.
Nikolay Achasov, EPJ Web of Conference 125 (2016) 04002- 1-9.
N.N. Achasov, Physics of Particles and Nuclei, 2017, Vol. 48, No. 6, pp.839-840.

Two-gluon Annihilation of Charmonium $\chi_{c2}(2P)$

We (N.N. Achasov and Kang Xian-Wei, Chinese Physics C, Vol. 41, No. 12 (2017)123102) expect that

$$BR(\chi_{c2}(2P) \to gluon\, gluon) \gtrsim 2\%$$

if the Particle Data Group as well as the BaBar and Belle collaborations have correctly identified the state.

In reality, this branching ratio corresponds to the one for $\chi_{c2}(2P)$ decaying into light hadrons. The hadron channels of the two-gluon decays of $\chi_{c2}(2P)$ should be the same as in the $\chi_{c2}(1P)$ case, that is, there should be a few tens of such channels.

Two-gluon Annihilation of Charmonium $\chi_{c2}(2P)$

The ratio of the two-photon and two-gluon widths of the charmonium decays does not depend on the wave function in the nonrelativistic potential model of charmonium. It allows to find the low limit of $BR(\chi_{c2}(2P) \to gluon\, gluon)$. The comparison with the well-known data about $\chi_{c2}(1P)$ allows us to conclude that

$$BR(\chi_{c2}(2P) \to 2g) \approx (6.5 \pm 2.0)\%$$

is very likely.

The confirmation of the $\chi_{c2}(2P)$ state can be tested by BESIII, for example, through the process $e^+e^- \to \psi(4040) \to \gamma\chi_{c2}(2P)$. The search for two-gluon decays of the $\chi_{c2}(2P)$ state is feasible for BESIII as well as other super factories such as BaBar and Belle.

A lot of thanks

I am grateful Organizers for the kind Invitation.

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