Study of Light Scalars in Photon-Photon collisions, the learned Lessons

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ABSTACT

After short review of the nature of the light scalar mesons, we dwell on the investigation of the high-statistics Belle data on the two-photon production of the light scalar mesons and ascertain that these data allow us to establish their production mechanisms.

ABSTACT

We show that the light scalars are produced in the two photon collisions via four-quark transitions in contrast to the classic P wave tensor $q\bar{q}$ mesons which are produced via two-quark transitions $\gamma\gamma \to q\bar{q}$. In particular, we show that the ideal $q\bar{q}$ model prediction $g^2_{f_0\gamma\gamma} : g^2_{a_0\gamma\gamma} = 25 : 9$ is excluded by experiment. Thus we get new strong evidence of the four-quark nature of these states.

A programme of further investigations is laid down.

OUTLINE

1. Introduction.
2. The lessons of the linear sigma model.
3. The $\pi\pi \to \pi\pi$ scattering on the light scalar resonances.
4. The ϕ meson radiative decays on the light scalar resonances.
5. Light scalars in $\gamma\gamma$ collisions:
   i) in $\gamma\gamma \to \pi^+\pi^-$,
   ii) in $\gamma\gamma \to \pi^0\pi^0$,
   iii) in $\gamma\gamma \to \pi^0\eta^0$.
6. Summary.
7. Outlook.

Introduction

Emerged 50 years ago from the linear sigma model (LSM), 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

In **chiral limit** is realized $U_L(3) \times U_R(3)$ symmetry.

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

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 supposed 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

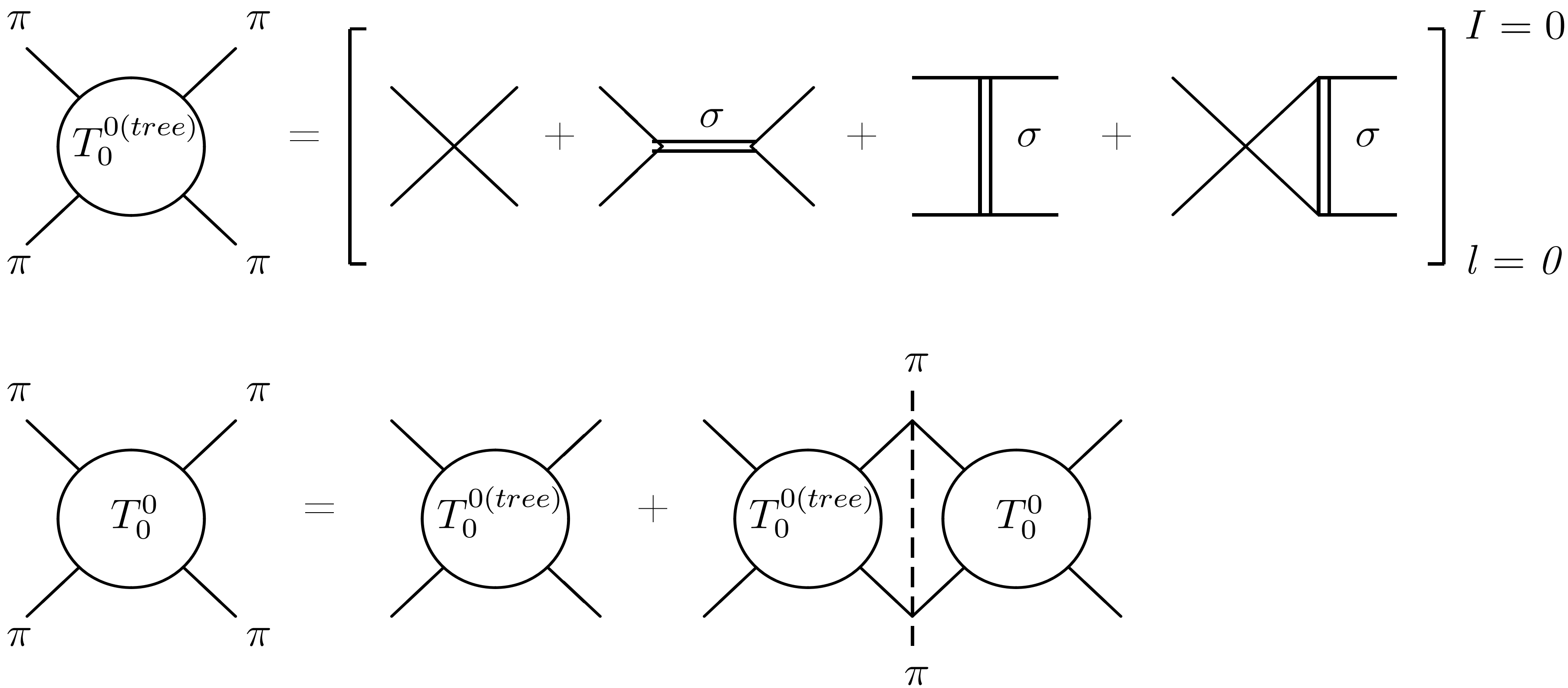
Situation changes when we showed that in the linear σ-model

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

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

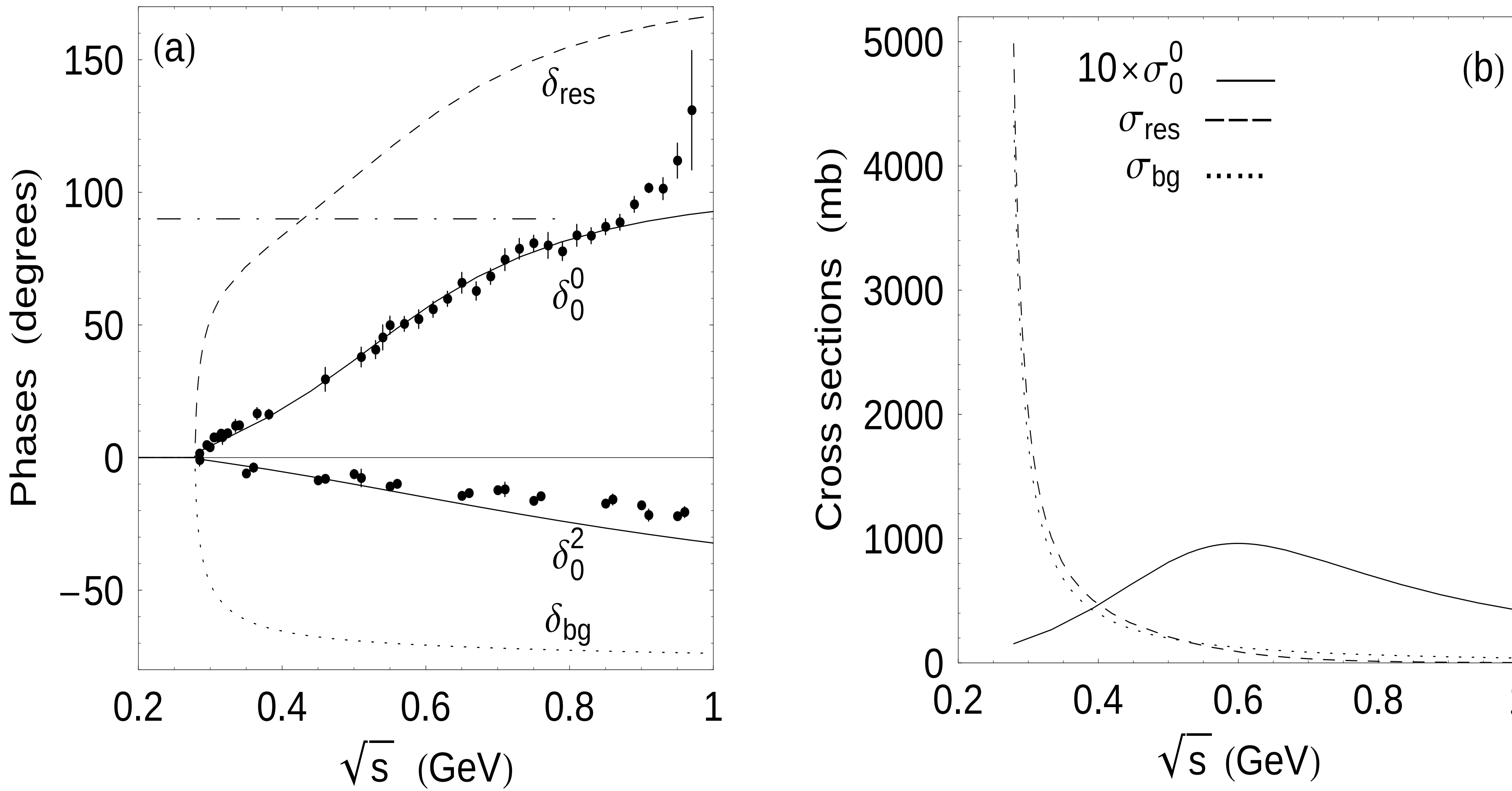
there is a negative background phase which hides the σ meson (1993, 1994). It has been made clear that shielding wide lightest scalar mesons in chiral dynamics is very natural. This idea was picked up and triggered new wave of theoretical and experimental searches for the σ and κ mesons.

Our approximation



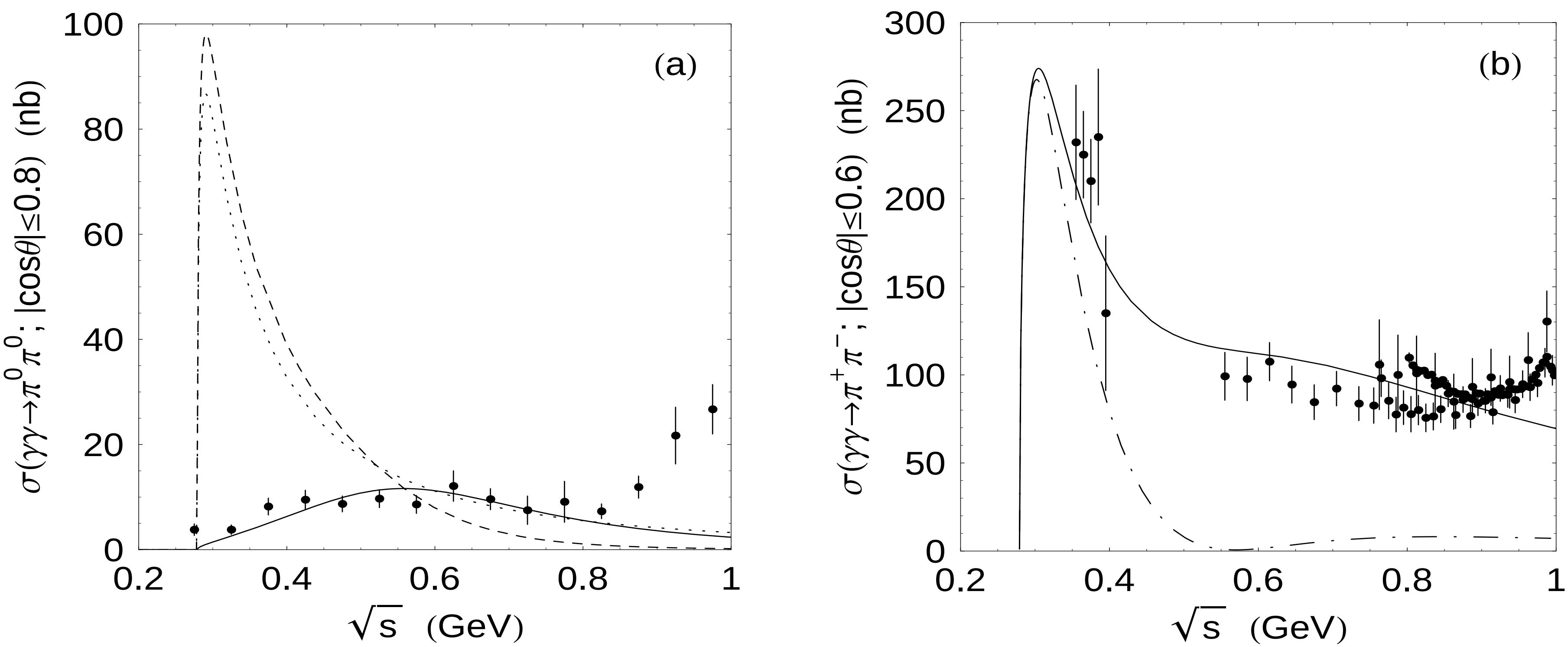
Chiral Shielding in $\pi\pi \to \pi\pi$

$m_\sigma = 0.93\,$GeV, $M_{res} = 0.43\,$GeV, $\Gamma_{res}^{phys}(M_{res}) = 0.53\,$GeV



The σ model. Our approximation. $\delta = \delta_{res} + \delta_{bg}$.

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 $T^{Born}(\gamma\gamma \to \pi^+\pi^-)$.

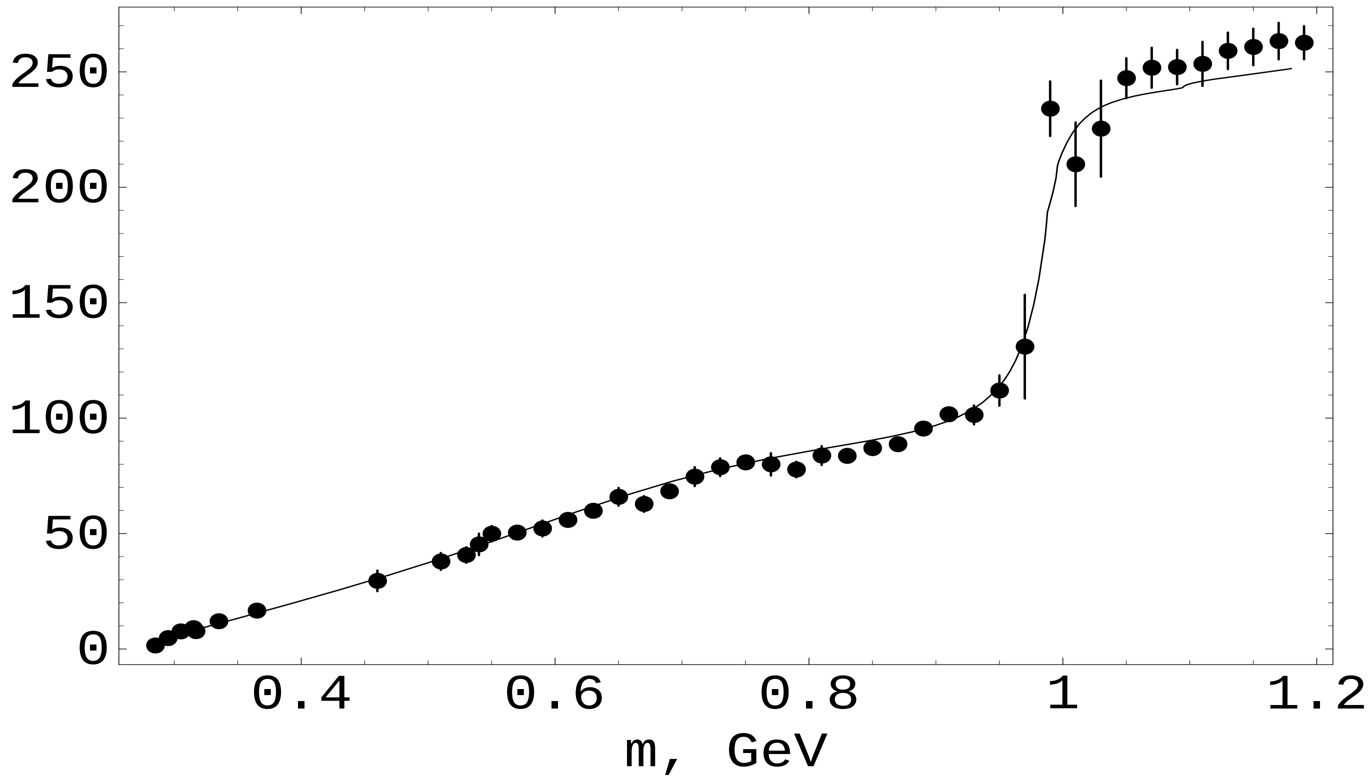
The four-quark transition: $\gamma\gamma \to \pi^+\pi^- \to \sigma$.

Troubles and Expectancies

In theory the principal problem is impossibility to use the linear σ-model in the tree level approximation.

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, and Adler's conditions.

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



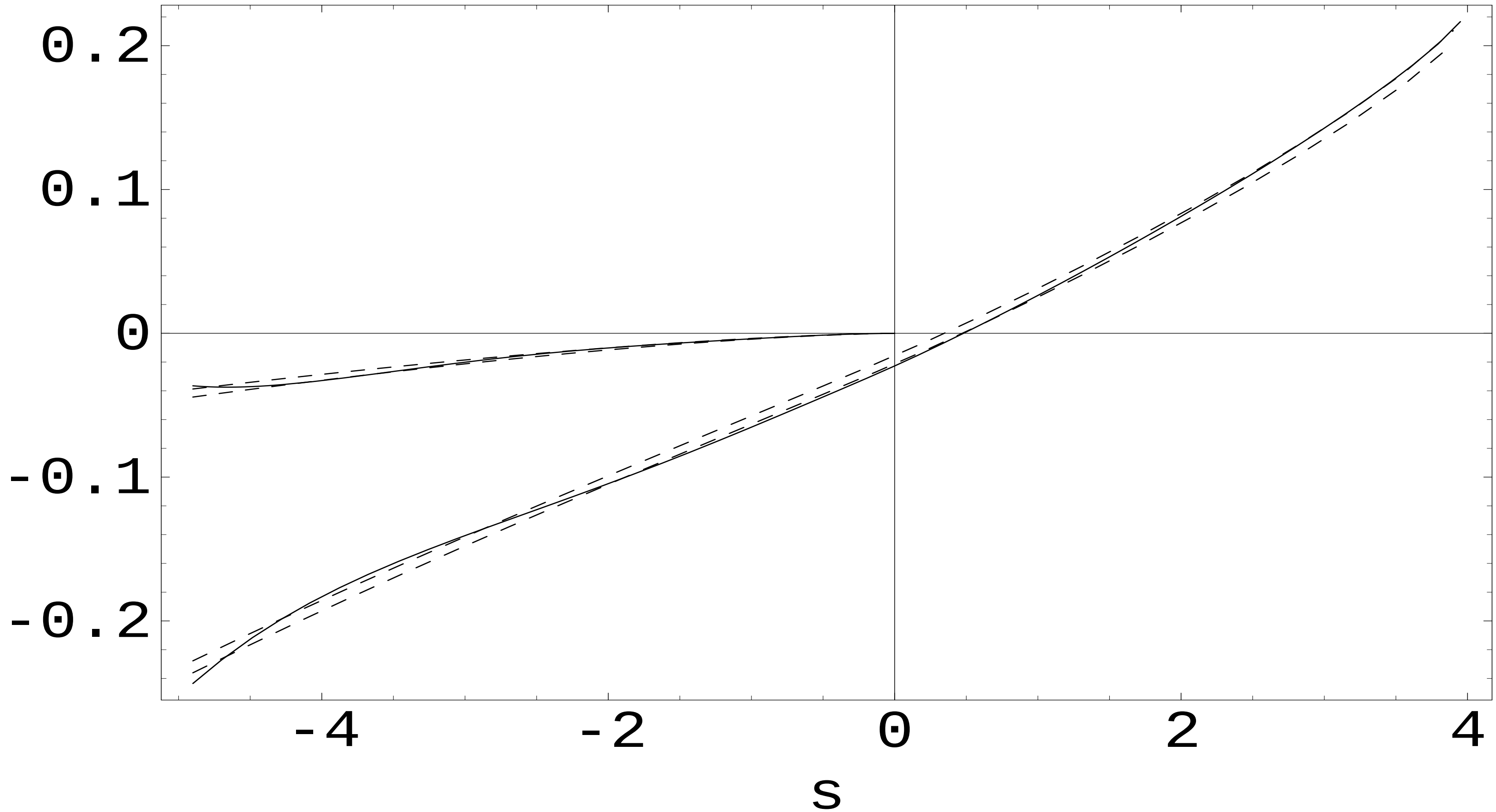
$g^2_{\sigma\pi^+\pi^-}/4\pi = 0.57\,\text{GeV}^2, \quad g^2_{\sigma K^+K^-}/4\pi = 0.048\,\text{GeV}^2$

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

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

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

T_0^0, comparison with CCL results under the threshold,



s in units of m_π^2 ;

the real part under the threshold: $-5 < s < 4$;

the imaginary part on the left cut: $-5 < s < 0$

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 found by Jaffe in 1977 in the MIT bag.

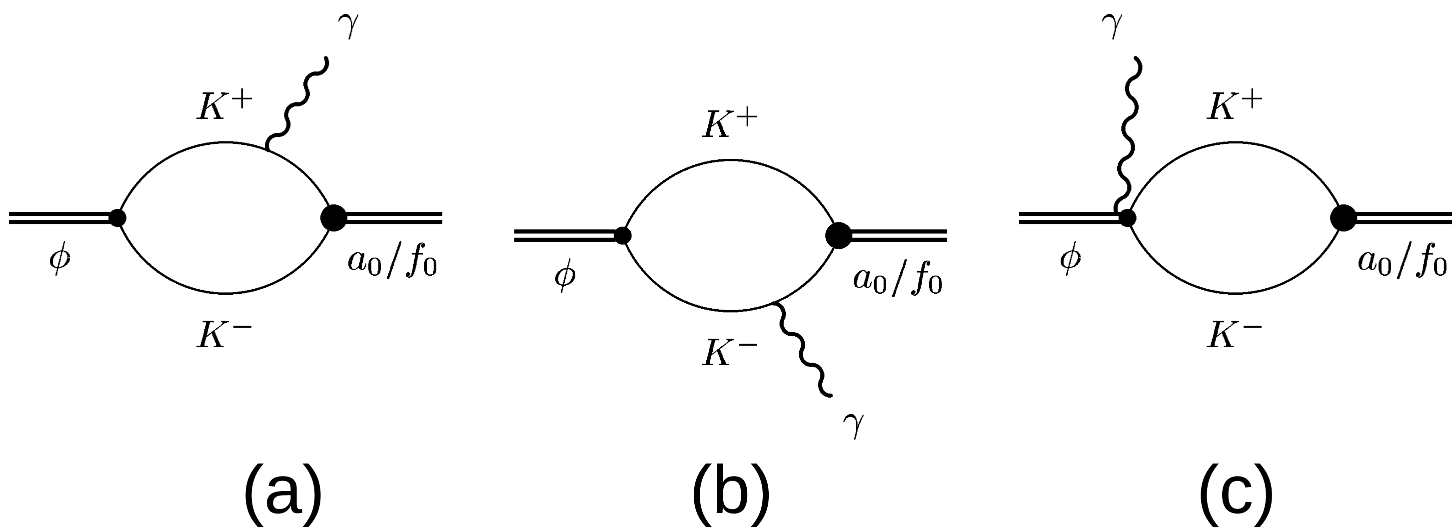
Radiative Decays of ϕ-Meson

Ten years later (1987,1989) 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.

Now these decays are studied not only theoretically but also experimentally. 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.

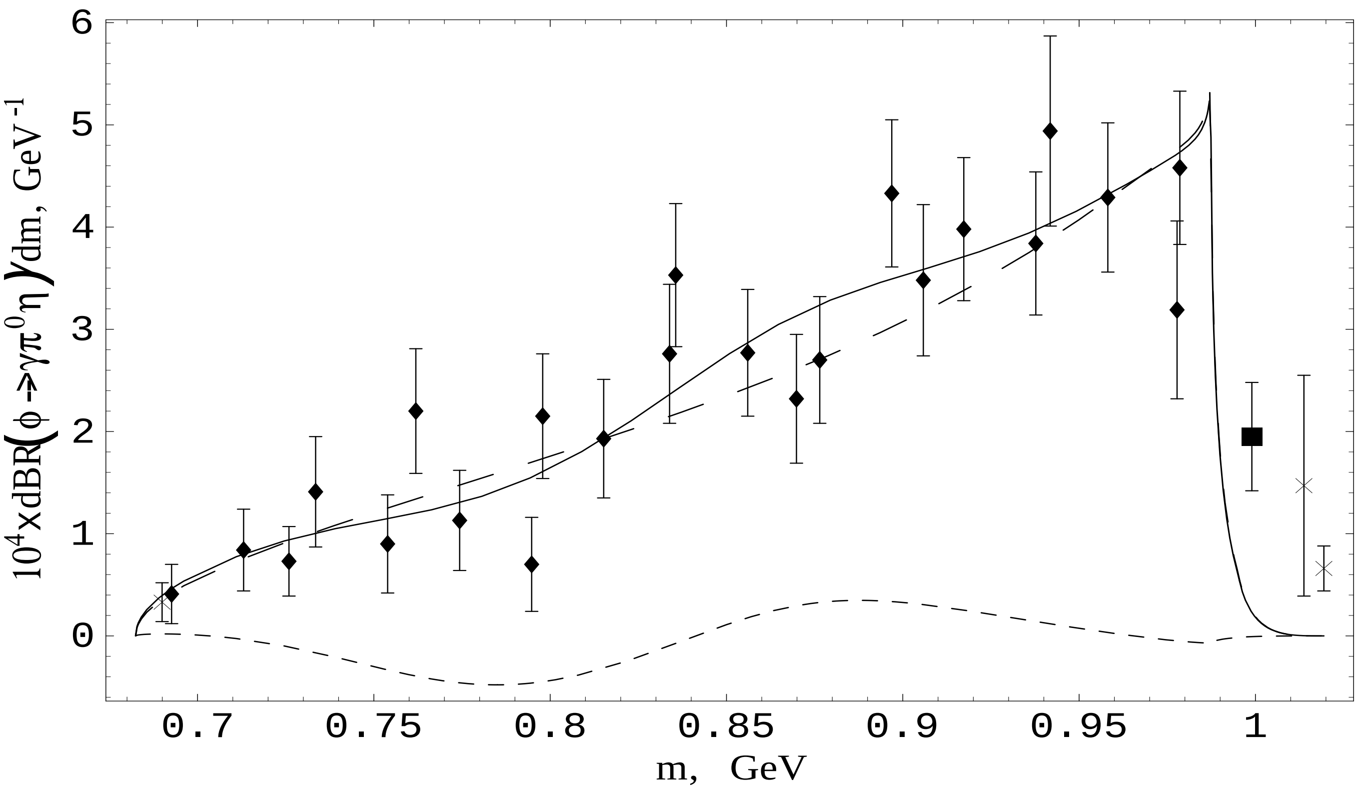
K^+K^--Loop Model



When basing the experimental investigations, we suggested one-loop model $\phi \to K^+K^- \to \gamma a_0/f_0$. 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.

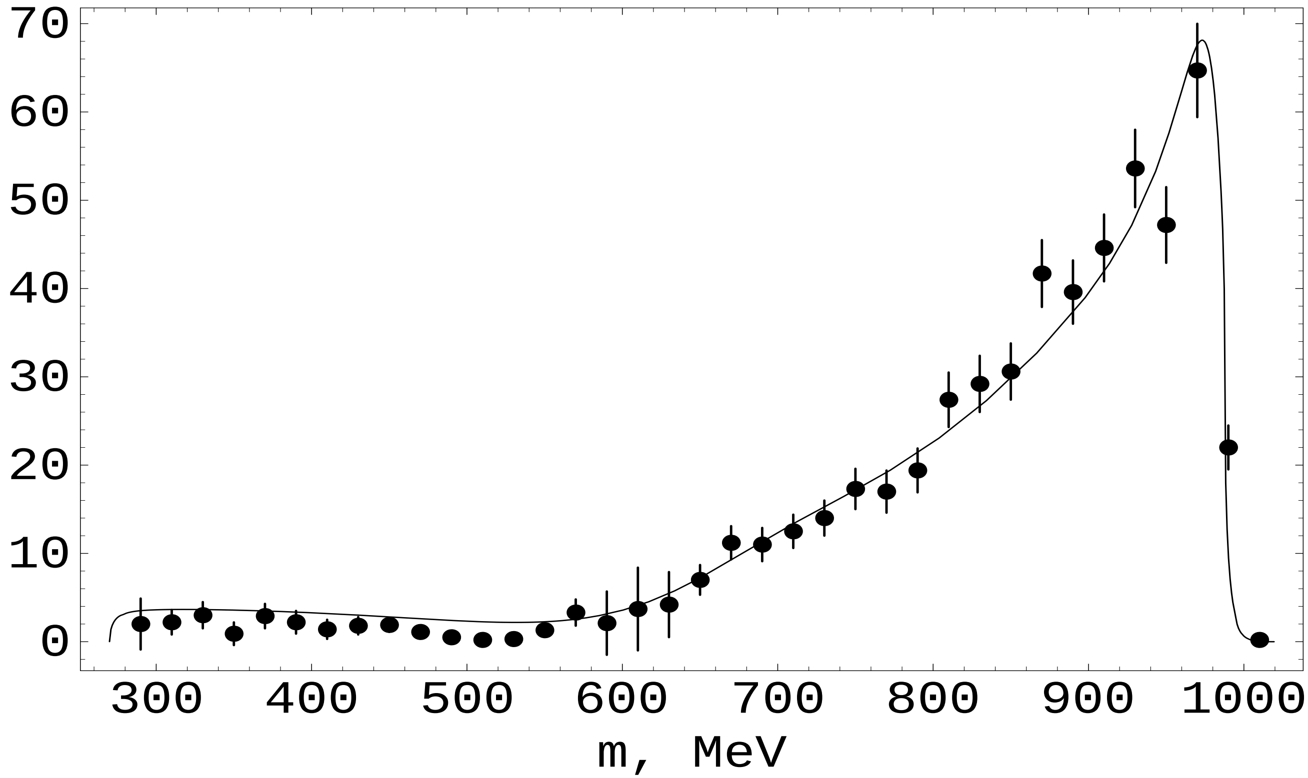
$\phi \to \gamma\pi^0\eta$, KLOE



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

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

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



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

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

The K^+K^--Loop Mechanism is established

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.

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

Twenty nine years ago (1982) 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.

Experiment supported this predicton

$\Gamma(a_0 \to \gamma\gamma) = (0.19 \pm 0.07^{+0.1}_{-0.07})/B(a_0 \to \pi\eta)$ keV, Crystal Ball

$\Gamma(a_0 \to \gamma\gamma) = (0.28 \pm 0.04 \pm 0.1)/B(a_0 \to \pi\eta)$ keV, JADE.

$\Gamma(\mathrm{f}_0 \to \gamma\gamma) = (0.31 \pm 0.14 \pm 0.09)$ keV, Crystal Ball,

$\Gamma(\mathrm{f}_0 \to \gamma\gamma) = (0.24 \pm 0.06 \pm 0.15)$ keV, MARK II.

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

$$\Gamma(\mathrm{a}_0 \to \gamma\gamma) = (1.5 - 5.9)\Gamma(\mathrm{a}_2 \to \gamma\gamma)$$

$$= (1.5 - 5.9)(1.04 \pm 0.09) \text{ keV.}$$

$$\Gamma(f_0 \to \gamma\gamma) = (1.7 - 5.5)\Gamma(f_2 \to \gamma\gamma)$$

$$= (1.7 - 5.5)(2.8 \pm 0.4) \text{ keV.}$$

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. 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

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

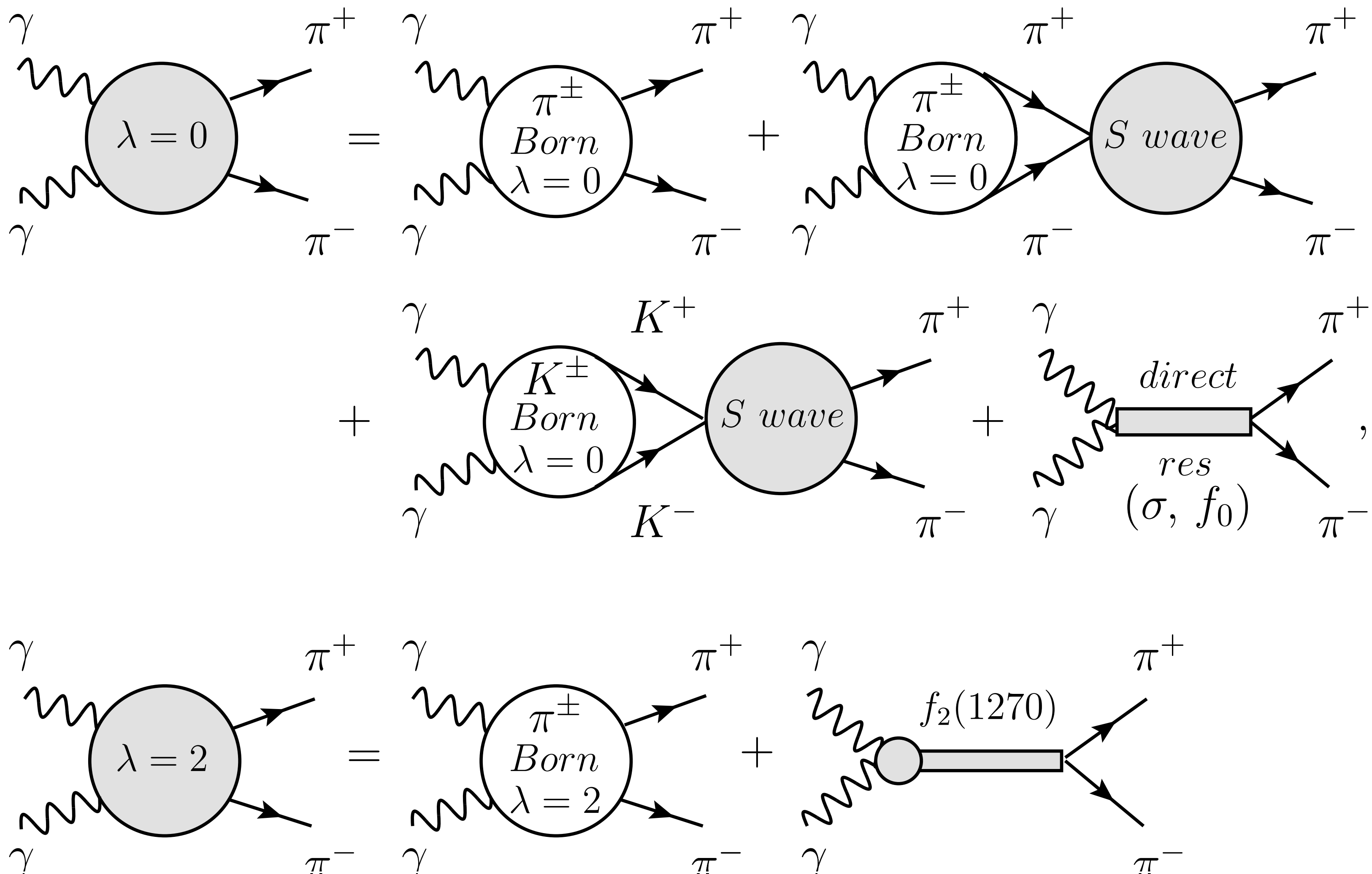
the four-quark transitions caused by the rescatterings:
$\sigma \to \pi^+\pi^- \to \gamma\gamma$, $f_0(980) \to K^+K^- \to \gamma\gamma$, and
$a_0^0(980) \to K^+K^- + \pi^0\eta \to \gamma\gamma$,

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.

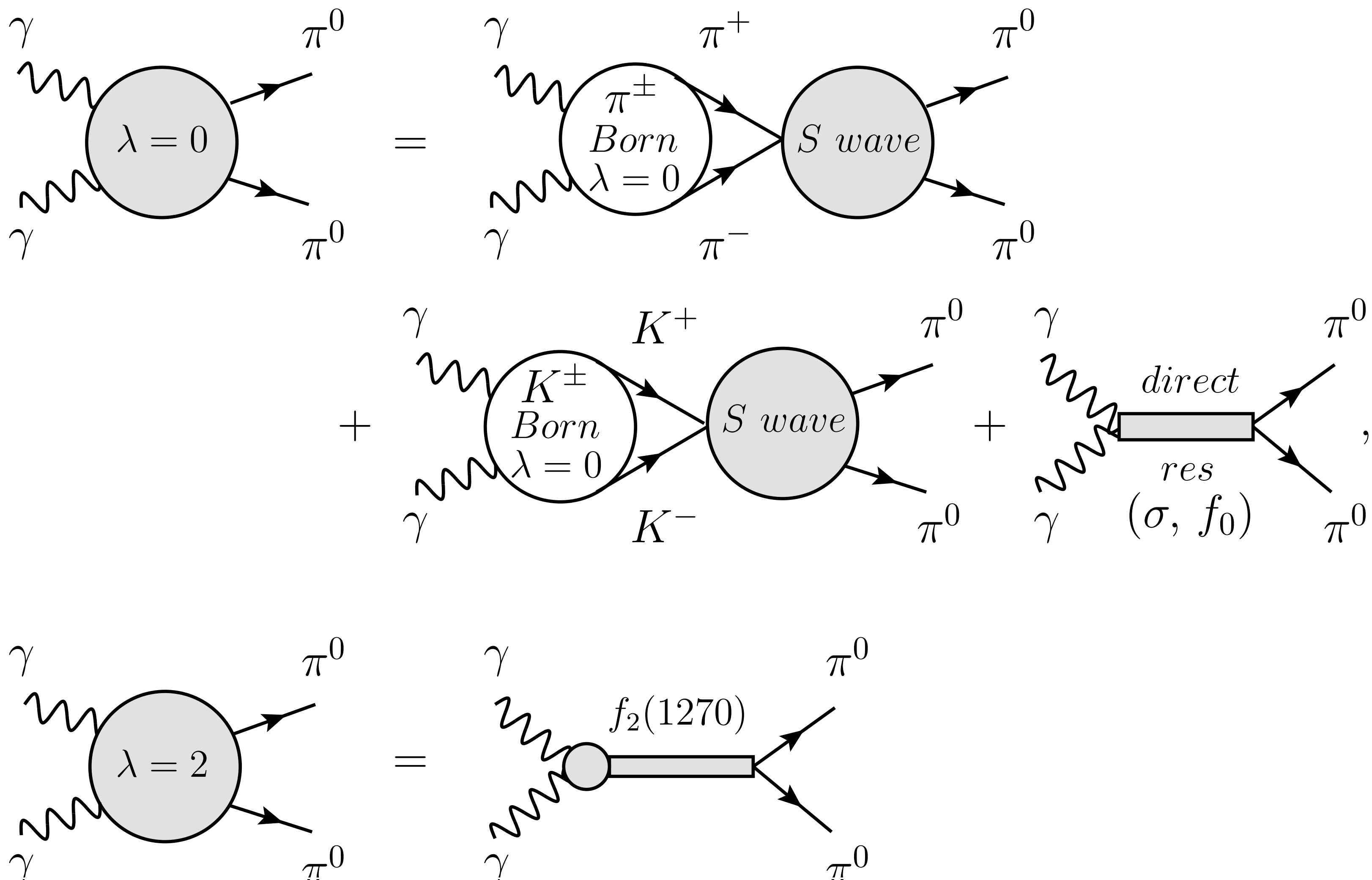
The two-photon light scalar widths averaged over resonance mass distributions $\langle\Gamma_{f_0\to\gamma\gamma}\rangle_{\pi\pi} \approx$ 0.19 keV, $\langle\Gamma_{a_0\to\gamma\gamma}\rangle_{\pi\eta} \approx$ 0.3 keV and $\langle\Gamma_{\sigma\to\gamma\gamma}\rangle_{\pi\pi} \approx$ 0.45 keV.

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.

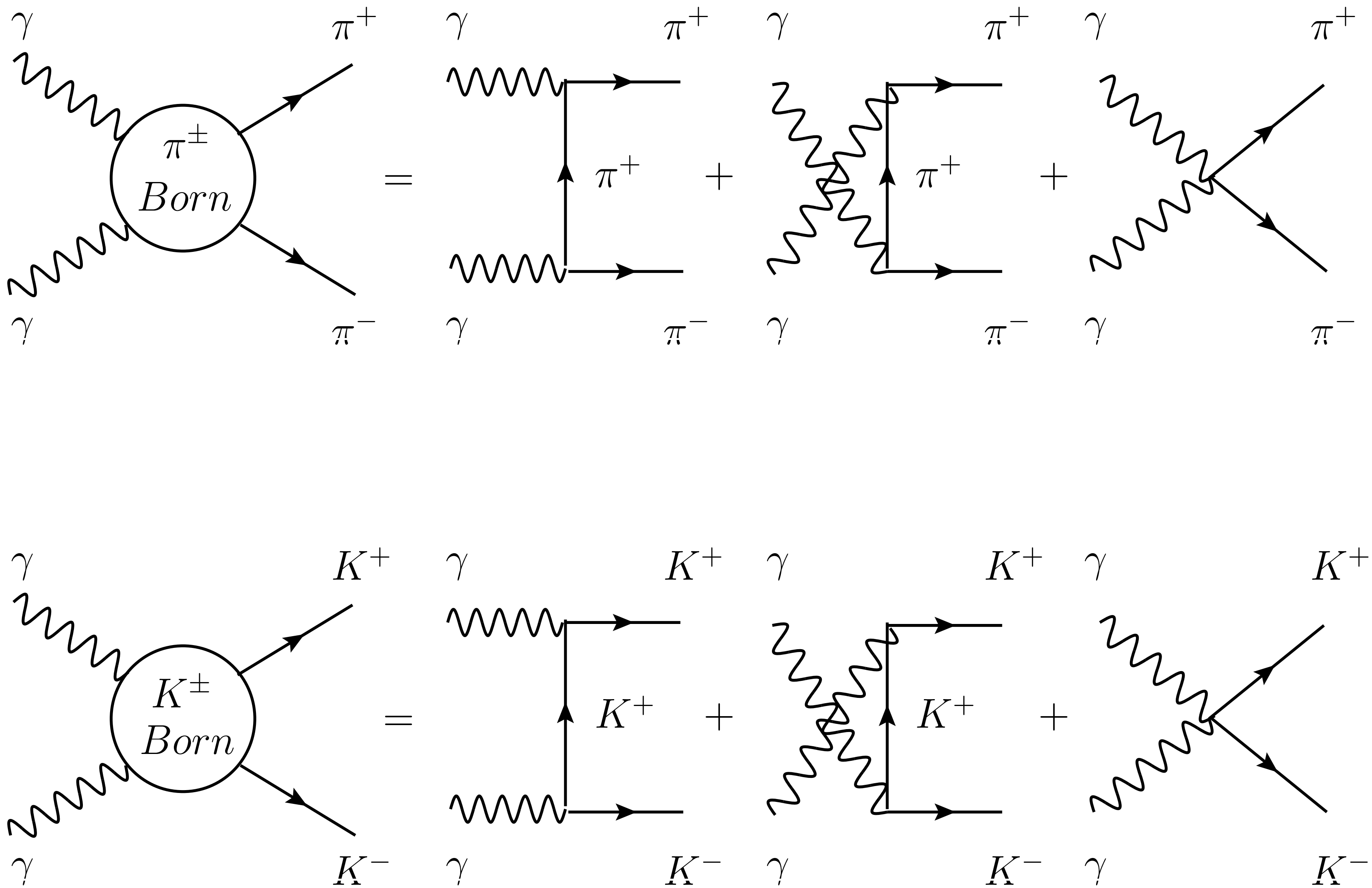
Dynamics of $\gamma\gamma \to \pi^+\pi^-$



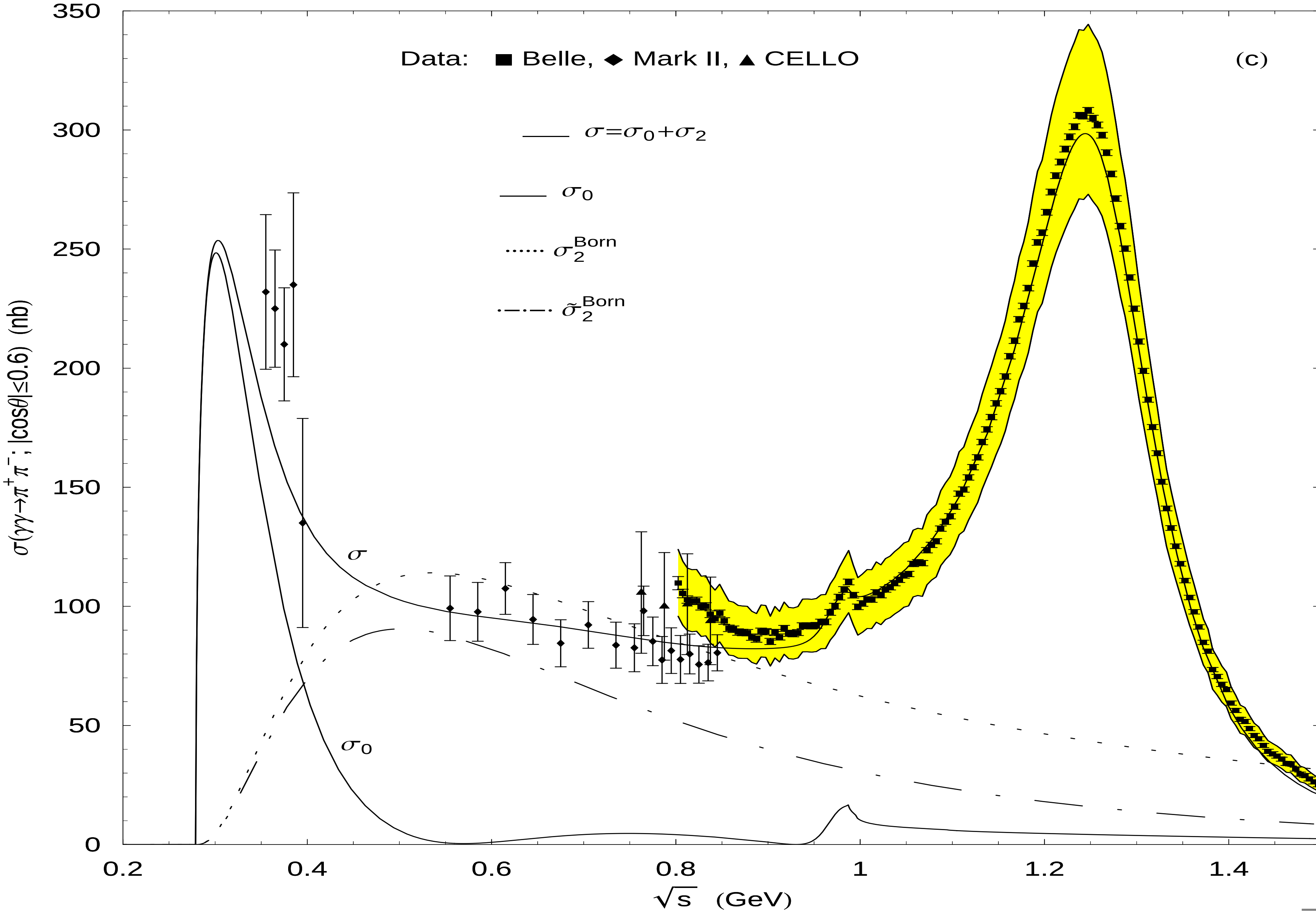
Dynamics of $\gamma\gamma \to \pi^0\pi^0$



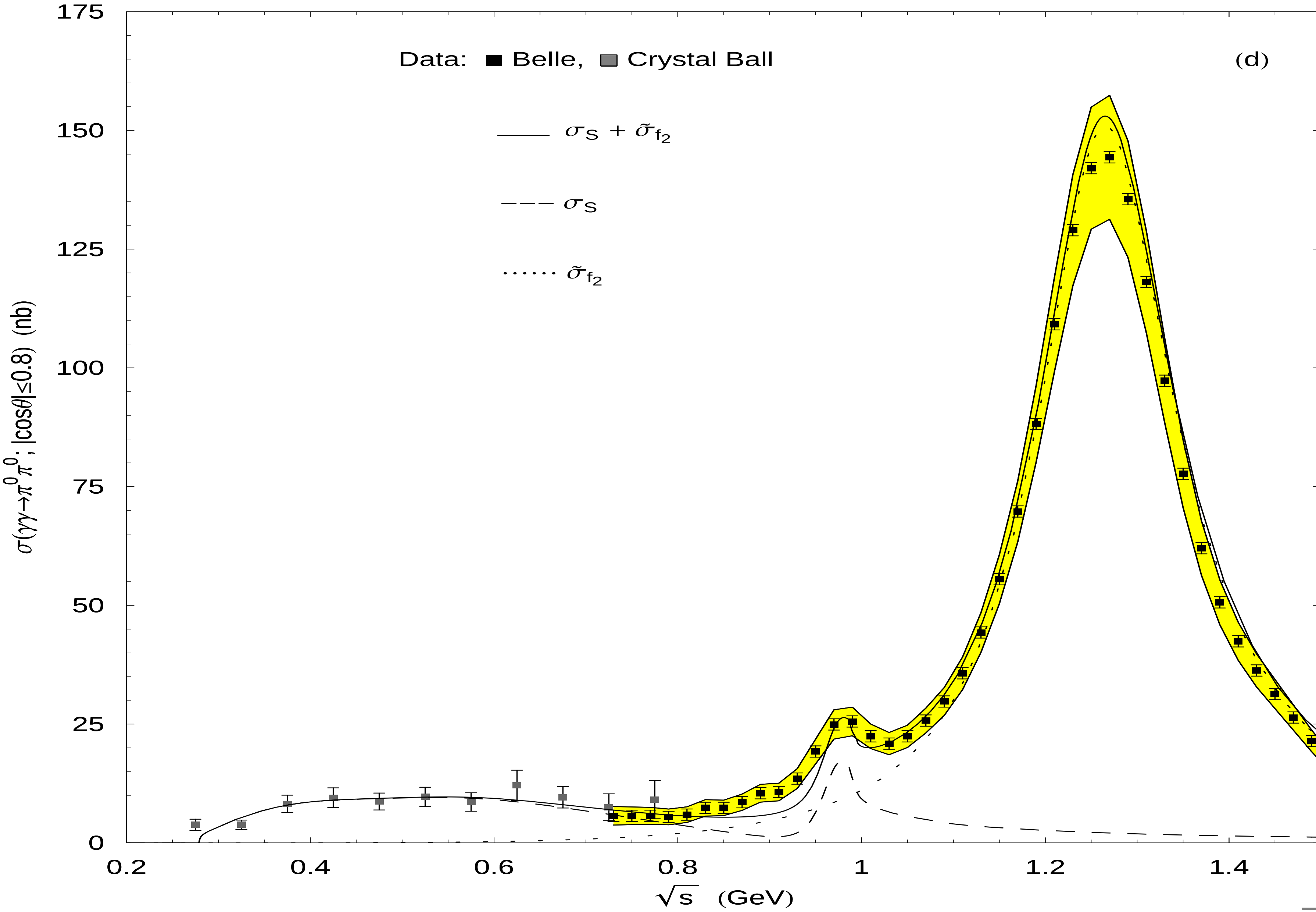
The $\pi^\pm$ and $K^\pm$ Born contributions



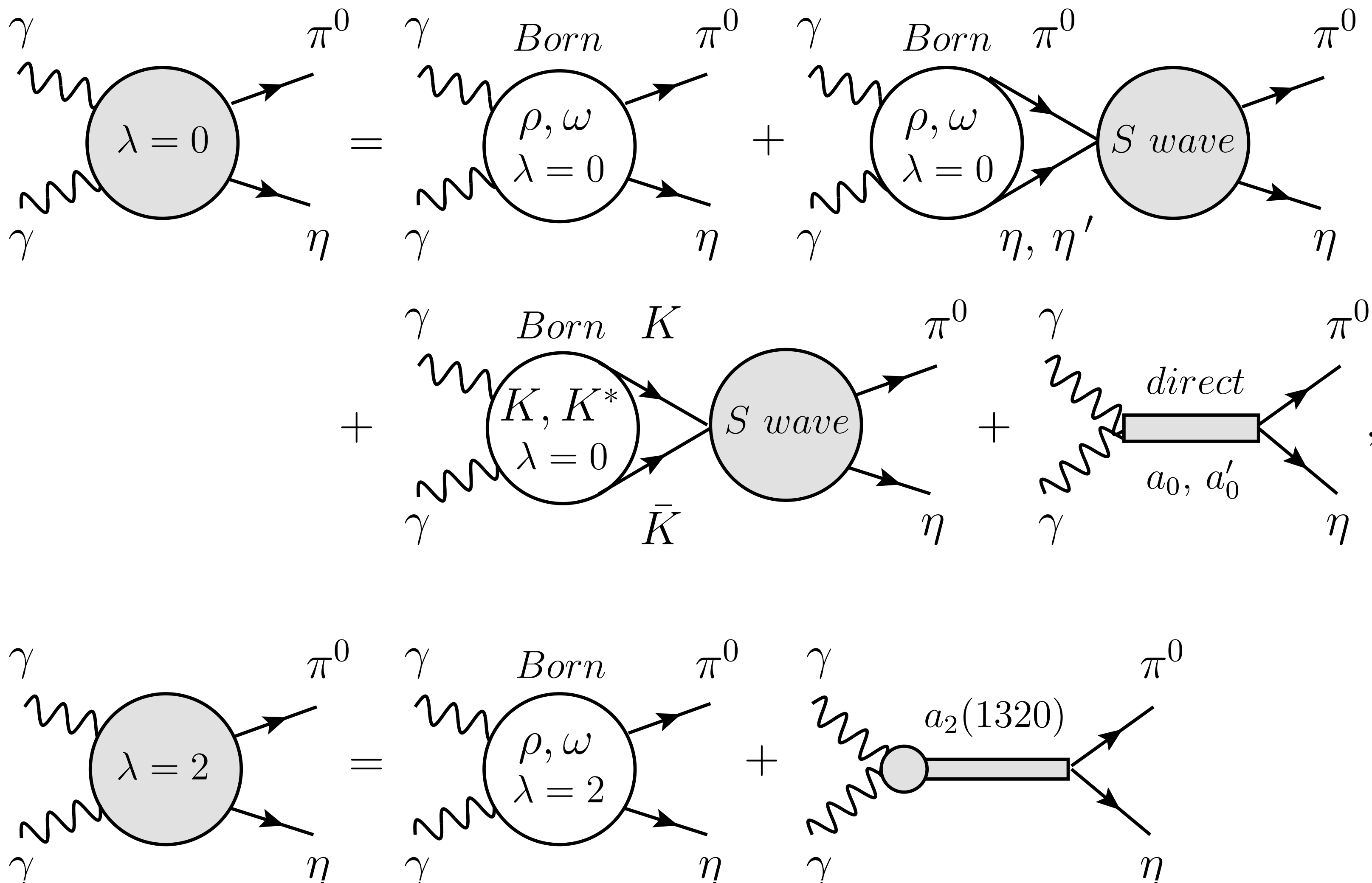
The Belle data on $\gamma\gamma \to \pi^+\pi^-$



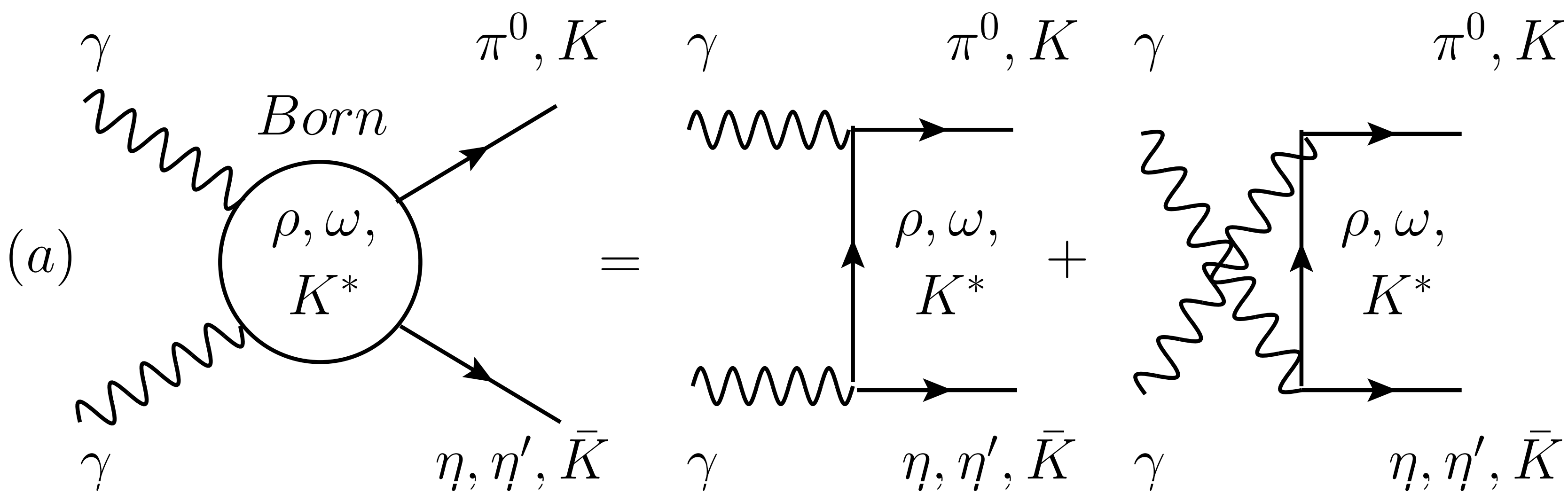
The Belle data on $\gamma\gamma \to \pi^0\pi^0$



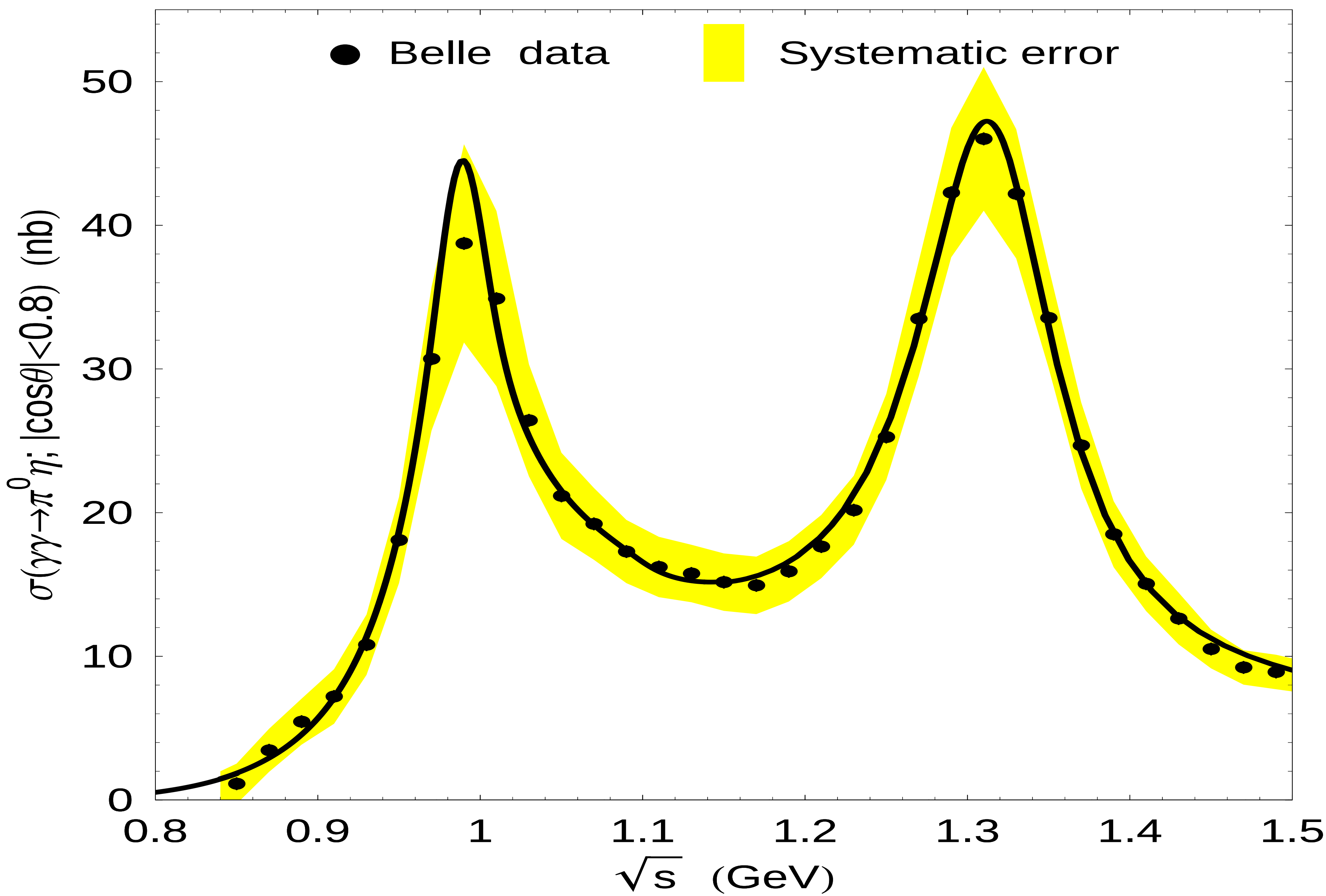
Dynamics of $\gamma\gamma \to \pi^0\eta$



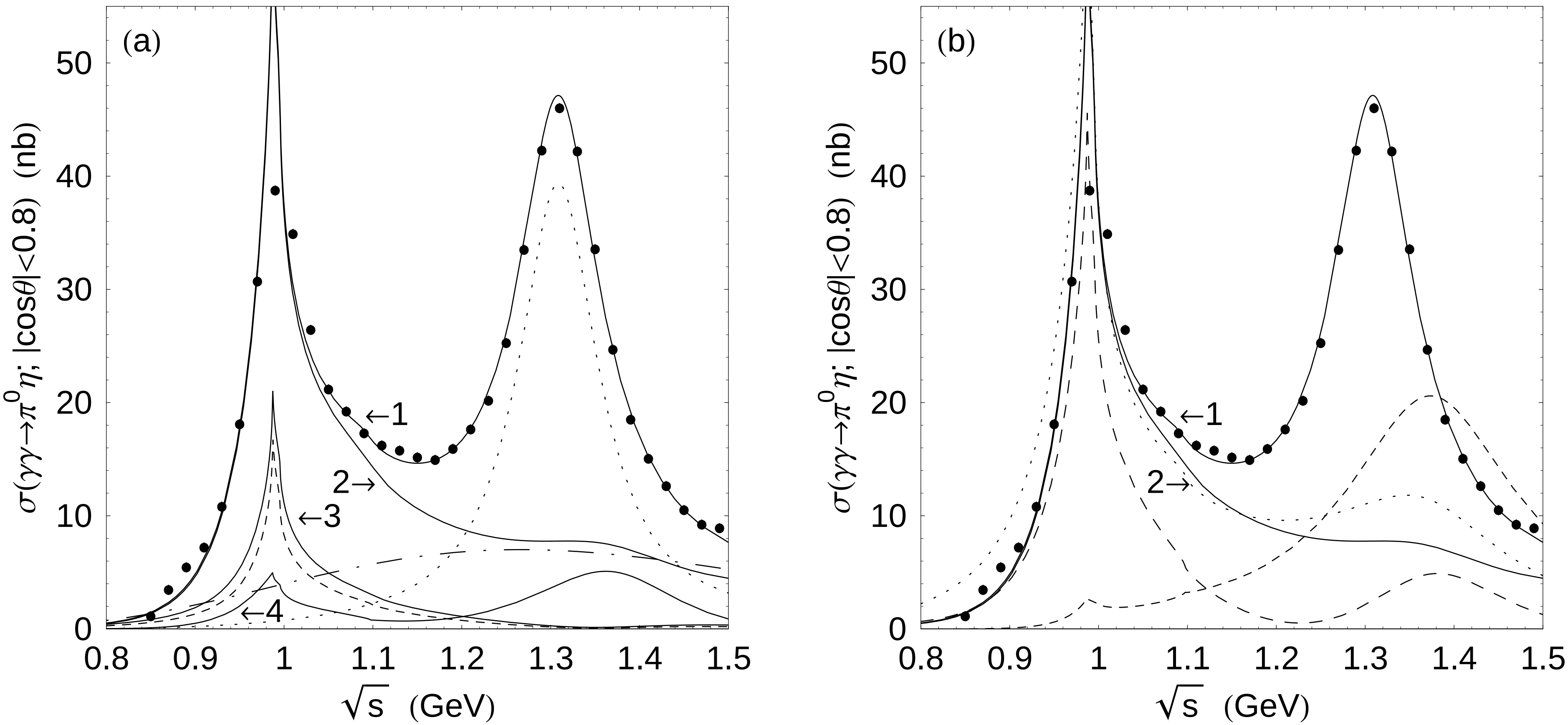
The V Born contributions



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



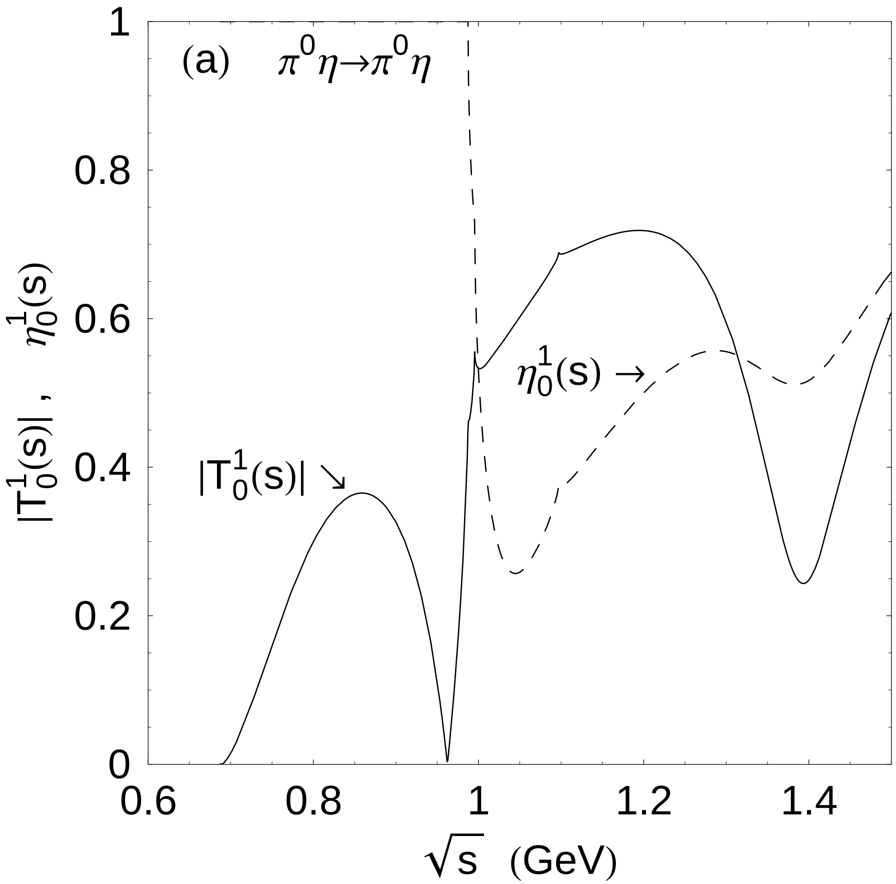
Main constituents of $\gamma\gamma \to \pi^0\eta$ reaction mechanism

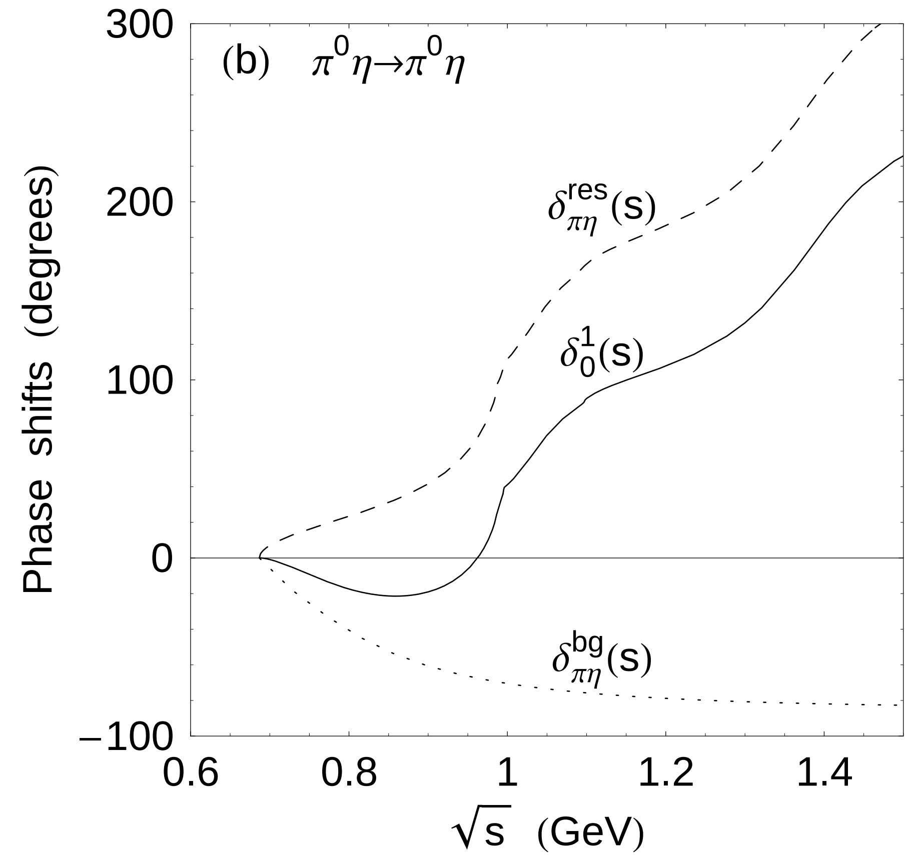


The experimentally observed pattern is the result of the combination of many dynamical factors.

The rescattering contributions are the most essential ones.

Preliminary S wave of $\pi^0\eta \to \pi^0\eta$





The $\pi\eta$ scattering length a_0^1 consists with the chiral theory expectations $(0.005 - 0.01)m_\pi^{-1}$.

Lessons

The mass spectrum of the light scalars, $\sigma(600)$, $\kappa(800)$, $f_0(980)$, $a_0(980)$, gives an idea of their $q^2\bar{q}^2$ structure.

Both intensity and mechanism of the $a_0(980)/f_0(980)$ production in the radiative decays of $\phi(1020)$, the $q^2\bar{q}^2$ transitions $\phi \to K^+K^- \to \gamma[a_0(980)/f_0(980)]$, indicate their $q^2\bar{q}^2$ nature.

Both intensity and mechanism of the scalar meson decays into $\gamma\gamma$, basically the $q^2\bar{q}^2$ transitions, $\sigma(600) \to \pi^+\pi^- \to \gamma\gamma$, $f_0(980) \to K^+K^- \to \gamma\gamma$, $a_0^0(980) \to K^+K^- + \pi^0\eta \to \gamma\gamma$ indicate their $q^2\bar{q}^2$ nature.

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

Outlook

1. $\gamma\gamma \to K^+K^-$, $K^0\overline{K^0}$ near the thresholds, it is expected a drastic suppression of the Born contribution in the K^+K^- channel.
2. $\gamma\gamma^*(\mathbf{Q^2}) \to \pi^0\pi^0$, $\pi^0\eta$, it is expected a drastic decrease of the $\sigma(600)$, $f_0(980)$ and $a_0(980)$ contributions with increasing Q^2 as opposed to a decrease of the $f_2(1270)$ and $a_2(1320)$ ones.
3. Search for $J/\psi \to f_0(980)\omega$ and $J/\psi \to a_0(980)\rho$.
4. Search for the $a_0(980) - f_0(980)$ mixing in
   i) $J/\psi \to f_0(980)\phi \to a_0(980)\phi \to \pi^0\eta\phi$ and
   ii) $\pi^-p \to f_0(980)n \to a_0(980)n \to \pi^0\eta n$,
   it is expected a strong jump in the spin asymmetry that could give an exclusive information on $(g_{a_0K^+K^-} \cdot g_{f_0K^+K^-})/4\pi$.

Outlook

5. The new precise experiment on $\pi\pi \to K\bar{K}$ would give the crucial information about the inelasticity η_0^0 and about the phase $\delta_B^{K\bar{K}}(m)$ near the $K\bar{K}$ threshold. The precise measurement of the inelasticity η_0^0 near 1 GeV in $\pi\pi \to \pi\pi$ would also be very important.

A lot of thanks