Study of Light Scalars, the learned Lessons

N.N. Achasov

(in Deutsch N.N. Atschasov)

Laboratory of Theoretical Physics,

Sobolev Institute for Mathematics,

Academician Koptiug Prospekt, 4,

Novosibirsk, 630090, Russia

Electronic Address: achasov@math.nsc.ru

ABSTACT

Attention is paid to the production mechanisms of light scalars that reveal their nature.

In the linear sigma model it is revealed the chiral shielding of the $\sigma(600)$ meson and shown that the σ field is described by its four-quark component.

The $\pi\pi$ scattering amplitude is constructed taking into account the $\sigma(600)$ and $f_0(980)$ mesons, the chiral shielding of $\sigma(600)$, the $\sigma(600)$-$f_0(980)$ mixing, and results, obtained on the base of the chiral expansion and the Roy equations. The data agree with the four-quark nature of $\sigma(600)$ and $f_0(980)$.

ABSTACT

It is shown that the kaon loop mechanism of the ϕ radiative decays, ratified by experiment, is the four-quark transition and points to the four-quark nature of light scalars, produced in these decays.

It is shown also, 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, produced via two-quark transitions $\gamma\gamma \to q\bar{q}$, that points to their four-quark nature, too.

A programme of further investigations is laid down.

OUTLINE

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. Summary.
8. The urgent investigations.

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

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

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

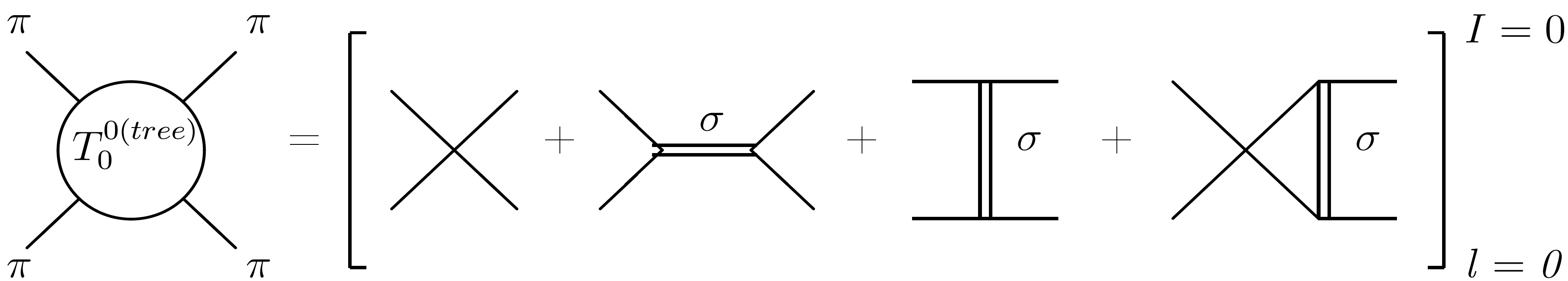
Situation changes when we showed that in the linear σ-model

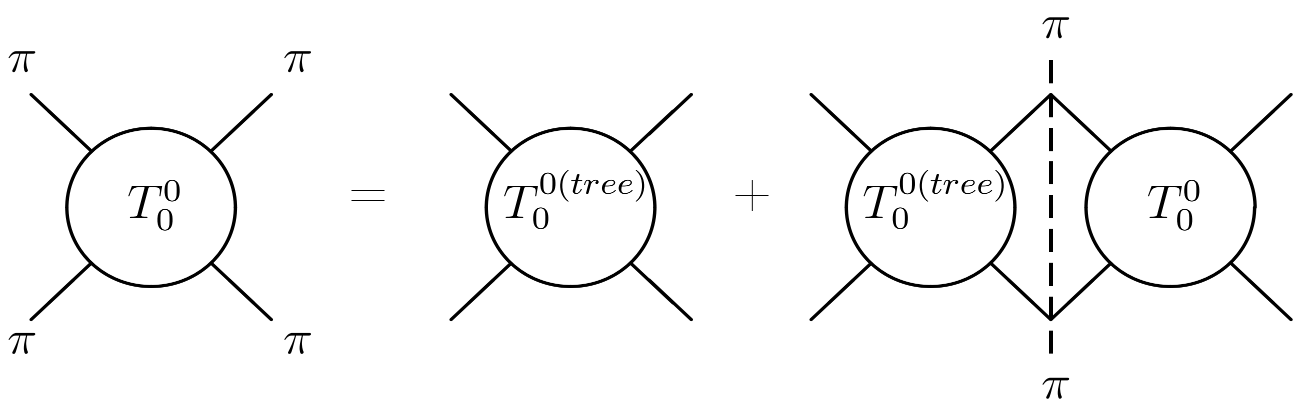
$$\mathbf{L} = \frac{1}{2}\left[(\partial_\mu \sigma)^2 + (\partial_\mu \vec{\pi})^2\right] - \frac{m_\sigma^2}{2}\sigma^2 - \frac{m_\pi^2}{2}\vec{\pi}^2$$

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

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





Our approximation

$$T_0^{0(tree)} = \frac{m_\pi^2 - m_\sigma^2}{32\pi f_\pi^2}\left[5 - 3\frac{m_\sigma^2 - m_\pi^2}{m_\sigma^2 - s}\right.$$

$$\left. -2\frac{m_\sigma^2 - m_\pi^2}{s - 4m_\pi^2}\ln\left(1 + \frac{s - 4m_\pi^2}{m_\sigma^2}\right)\right],$$

$$\mathrm{T}_0^0 = \frac{\mathrm{T}_0^{0(\mathrm{tree})}}{1 - \mathrm{i}\rho_{\pi\pi}\mathrm{T}_0^{0(\mathrm{tree})}} = \frac{\mathrm{e}^{2\mathrm{i}(\delta_{\mathrm{bg}}+\delta_{\mathrm{res}})} - 1}{2\mathrm{i}\rho_{\pi\pi}}$$

$$= \frac{1}{\rho_{\pi\pi}}\left(\frac{\mathrm{e}^{2\mathrm{i}\delta_{\mathrm{bg}}} - 1}{2\mathrm{i}}\right) + \mathrm{e}^{2\mathrm{i}\delta_{\mathrm{bg}}}\mathrm{T}_{\mathrm{res}},$$

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

Our approximation

$$T_{res} = \frac{1}{\rho_{\pi\pi}} \cdot \frac{\sqrt{s}\Gamma_{res}(s)}{M_{res}^2 - s + \mathrm{Re}\Pi_{res}(M_{res}^2) - \Pi_{res}(s)} = \frac{e^{2i\delta_{res}} - 1}{2i\rho_{\pi\pi}}$$

$$T_{bg} = \frac{e^{2i\delta_{bg}} - 1}{2i\rho_{\pi\pi}} = \frac{\lambda(s)}{1 - i\rho_{\pi\pi}\lambda(s)}, \quad \lambda(s) = \frac{m_\pi^2 - m_\sigma^2}{32\pi f_\pi^2}\left[5 - 2\frac{m_\sigma^2 - m_\pi^2}{s - 4m_\pi^2}\ln\left(1 + \frac{s - 4m_\pi^2}{m_\sigma^2}\right)\right], \quad g_{\sigma\pi^+\pi^-} = -\frac{m_\sigma^2 - m_\pi^2}{f_\pi}$$

$$\mathrm{Im}\Pi_{res}(s) = \frac{g_{res}^2(s)}{16\pi}\rho_{\pi\pi}, \quad \mathrm{Re}\Pi_{res}(s) = -\frac{g_{res}^2(s)}{16\pi}\lambda(s)\rho_{\pi\pi}^2,$$

$$g_{res}(s) = \frac{g_{\sigma\pi\pi}}{|1 - i\rho_{\pi\pi}\lambda(s)|}, \quad M_{res}^2 = m_\sigma^2 - \mathrm{Re}\Pi_{res}(M_{res}^2).$$

Results in our approximation

$$T_0^2 = \frac{T_0^{2(tree)}}{1 - \imath\rho_{\pi\pi} T_2^{0(tree)}} = \frac{e^{2i\delta_0^2} - 1}{2i\rho_{\pi\pi}}, \quad g_{\sigma\pi\pi} = \sqrt{\frac{3}{2}}\, g_{\sigma\pi^+\pi^-},$$

$$T_0^{2(tree)} = \frac{m_\pi^2 - m_\sigma^2}{32\pi f_\pi^2}\left[2 - 2\frac{m_\sigma^2 - m_\pi^2}{s - 4m_\pi^2}\ln\left(1 + \frac{s - 4m_\pi^2}{m_\sigma^2}\right)\right].$$

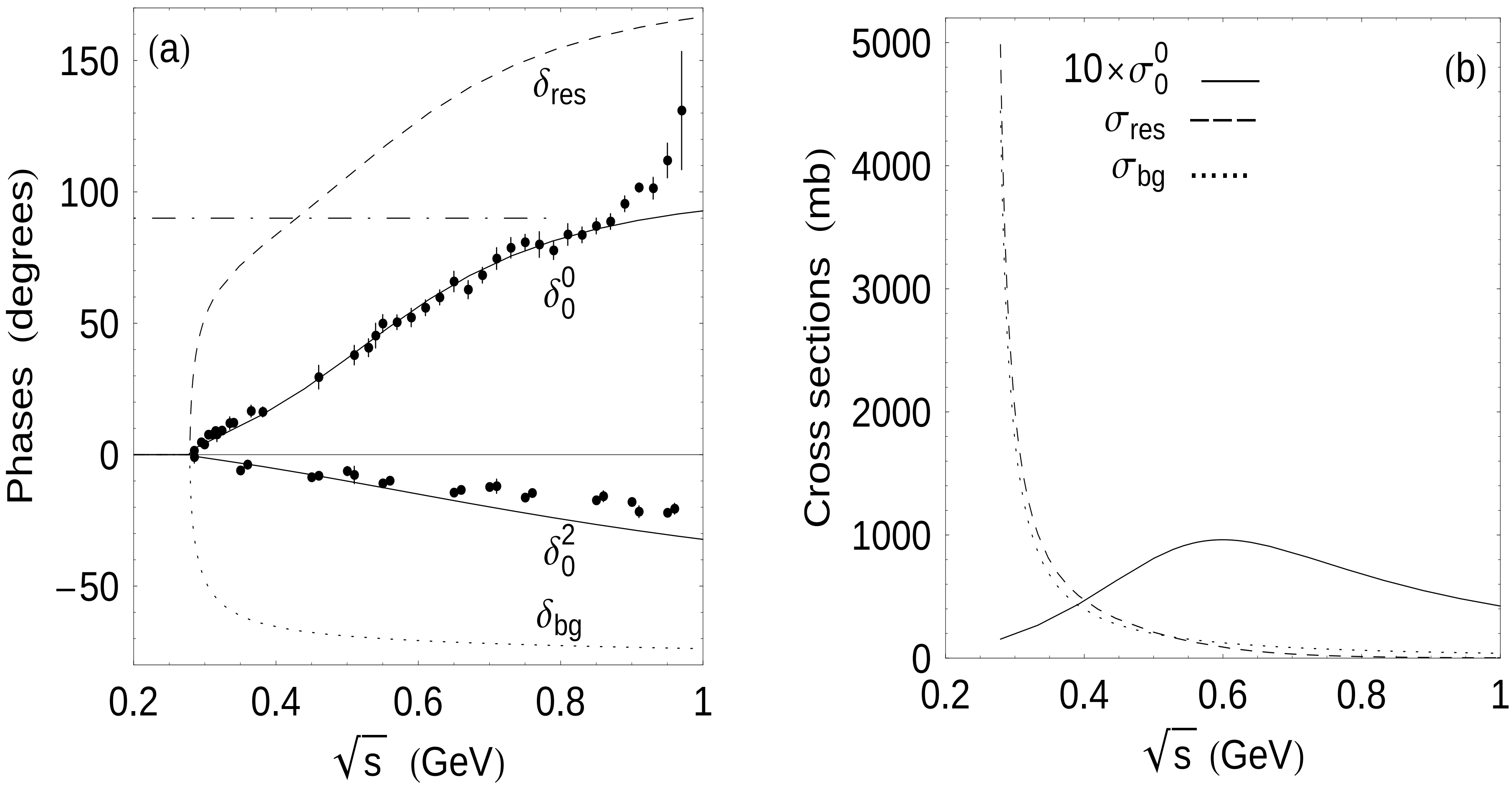
$$\mathrm{M_{res}} = 0.43\,\mathrm{GeV},\ \Gamma_{\mathrm{res}}(\mathrm{M}^2_{\mathrm{res}}) = 0.67\,\mathrm{GeV},\ \mathrm{m}_\sigma = 0.93\,\mathrm{GeV},$$

$$\Gamma^{\mathrm{renorm}}_{\mathrm{res}}(\mathrm{M}^2_{\mathrm{res}}) = \frac{\Gamma_{\mathrm{res}}(\mathrm{M}^2_{\mathrm{res}})}{\left(1 + \mathrm{dRe}\Pi_{\mathrm{res}}(\mathrm{s})/\mathrm{ds}|_{\mathrm{s=M^2_{res}}}\right)} = 0.53\,\mathrm{GeV},$$

$$\Gamma_{\mathrm{res}}(\mathrm{s}) = \frac{\mathrm{g}^2_{\mathrm{res}}(\mathrm{s})}{16\pi\sqrt{\mathrm{s}}}\rho_{\pi\pi}, \quad a_0^0 = 0.18\, m_\pi^{-1}, \quad a_0^2 = -0.04\, m_\pi^{-1},$$

$$g_{res}(M^2_{res})/g_{\sigma\pi\pi} = 0.33,\ (\mathrm{s_A})_0^0 = 0.45\,\mathrm{m}_\pi^2,\ (\mathrm{s_A})_0^2 = 2.02\,\mathrm{m}_\pi^2.$$

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



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

The σ pole in $\pi\pi \to \pi\pi$

$$T_0^0 \to \frac{g_\pi^2}{s - s_\sigma}\,,$$

$$\mathrm{g}_\pi^2 = (0.12 + \mathrm{i}0.21)\,\text{GeV}^2\,,$$

$$s_\sigma = (0.21 - i0.26)\,\text{GeV}^2\,,$$

$$\sqrt{\mathrm{s}_\sigma} = \mathrm{M}_\sigma - \mathrm{i}\frac{\Gamma_\sigma}{2} = (0.52 - \mathrm{i}0.25)\,\text{GeV}.$$

Considering the residue of the σ pole in T_0^0 as the square of its coupling constant to the $\pi\pi$ channel is not a clear guide to understand the σ meson nature for its great obscure imaginary part.

The σ propagator

$$\frac{1}{D_\sigma(s)} = \frac{1}{M_{res}^2 - s + \text{Re}\Pi_{res}(M_{res}^2) - \Pi_{res}(s)}\,.$$

The σ meson self-energy $\Pi_{res}(s)$ is caused by the intermediate $\pi\pi$ states, that is, by the four-quark intermediate states. This contribution shifts the Breit-Wigner (BW) mass greatly $m_\sigma - M_{res} = 0.50$ GeV. So, half the BW mass is determined by the four-quark contribution at least. The imaginary part dominates the propagator modulus in the region 300 MeV $< \sqrt{s} <$ 600 MeV. So, the σ field is described by its four-quark component at least in this energy (virtuality) region.

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

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

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

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

in elastic region

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

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

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

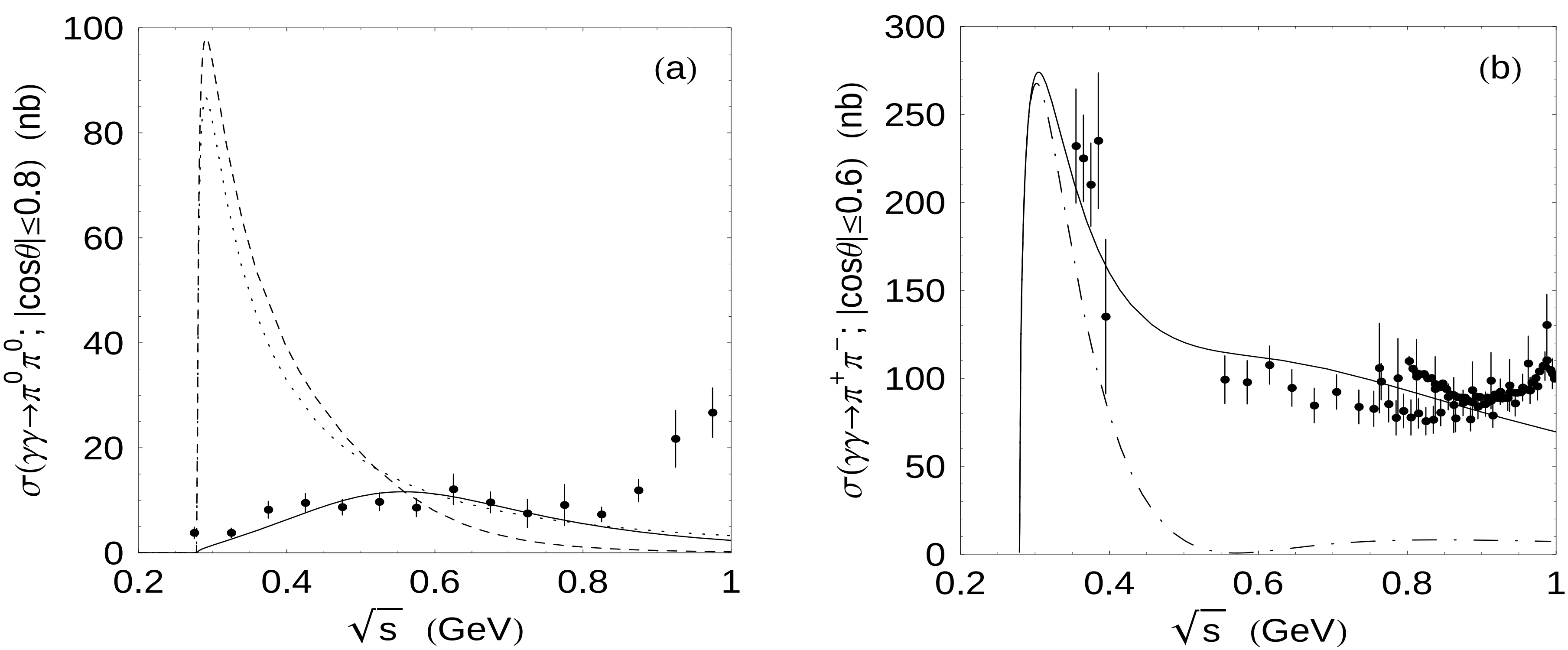
$$= \frac{2}{3}e^{i\delta_0^0}\left\{T_S^{Born}(\gamma\gamma \to \pi^+\pi^-)\cos\delta_0^0 + 8\frac{\alpha}{\rho_{\pi\pi}}\text{Re}I_{\pi^+\pi^-}\sin\delta_0^0\right\}$$

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

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

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

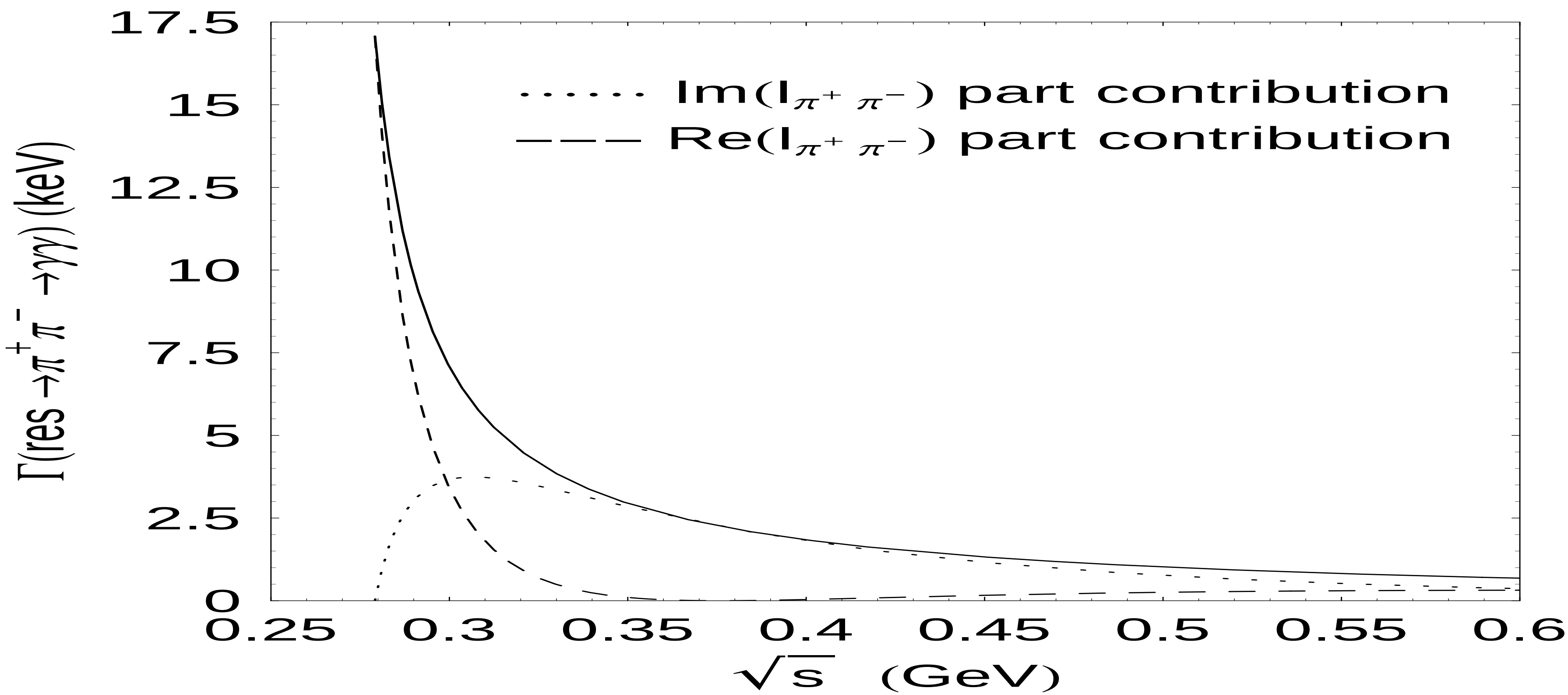
Chiral Shielding in $\gamma\gamma \to \pi\pi$



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

The $\sigma \to \gamma\gamma$ decay.



$$\mathbf{g}(\sigma \to \pi^+\pi^- \to \gamma\gamma,\, \mathrm{s}) = (\alpha/2\pi)\mathbf{I}_{\pi^+\pi^-} \times \mathbf{g}_{\mathrm{res}\,\pi^+\pi^-}(\mathrm{s}),$$

$$\Gamma(\sigma \to \pi^+\pi^- \to \gamma\gamma, \mathrm{s}) = \frac{1}{16\pi\sqrt{\mathrm{s}}}\left|\mathbf{g}(\sigma \to \pi^+\pi^- \to \gamma\gamma, \mathrm{s})\right|^2$$

Four-quark transition $\sigma \to \gamma\gamma$

So, the the $\sigma \to \gamma\gamma$ decay is described by the triangle $\pi^+\pi^-$-loop diagram $res \to \pi^+\pi^- \to \gamma\gamma$ ($I_{\pi^+\pi^-}$). Consequently, it is due to the four-quark transition because we imply a low energy realization of the two-flavour QCD by means of the the $SU_L(2) \times SU_R(2)$ linear σ model. As the previous Fig. suggests, the real intermediate $\pi^+\pi^-$ state dominates in $g(res \to \pi^+\pi^- \to \gamma\gamma)$ in the σ region $\sqrt{s} < 0.6$ GeV.

Thus the picture in the physical region is clear and informative. But, what about the pole in the complex s-plane? Does the pole residue reveal the σ indeed?

The σ pole in $\gamma\gamma \to \pi\pi$

$$\frac{1}{16\pi}\sqrt{\frac{3}{2}}\,T_S(\gamma\gamma \to \pi^0\pi^0) \to \frac{g_\gamma g_\pi}{s - s_\sigma},$$

$$\mathrm{g}_\gamma \mathrm{g}_\pi = (-0.45 - i0.19) \times 10^{-3}\,\mathrm{GeV}^2,$$

$$\mathrm{g}_\gamma / \mathrm{g}_\pi = (-1.61 + i1.21) \times 10^{-3},$$

$$\Gamma(\sigma \to \gamma\gamma) = |\mathrm{g}_\gamma|^2 / \mathrm{M}_\sigma \approx 2\,\mathrm{keV}.$$

It is hard to believe that anybody could learn the complex but physically clear dynamics of the $\sigma \to \gamma\gamma$ decay described above from the residues of the σ pole.

Once more Lesson

Heiri Leutwyler and collaborators obtained

$$\sqrt{\mathbf{s_R}} = \mathbf{M}_\sigma - \mathbf{i}\Gamma_\sigma/2 = \left(441^{+16}_{-8} - \mathbf{i}272^{+9}_{-12.5}\right) \times \text{MeV}$$

with the help of the Roy equation.

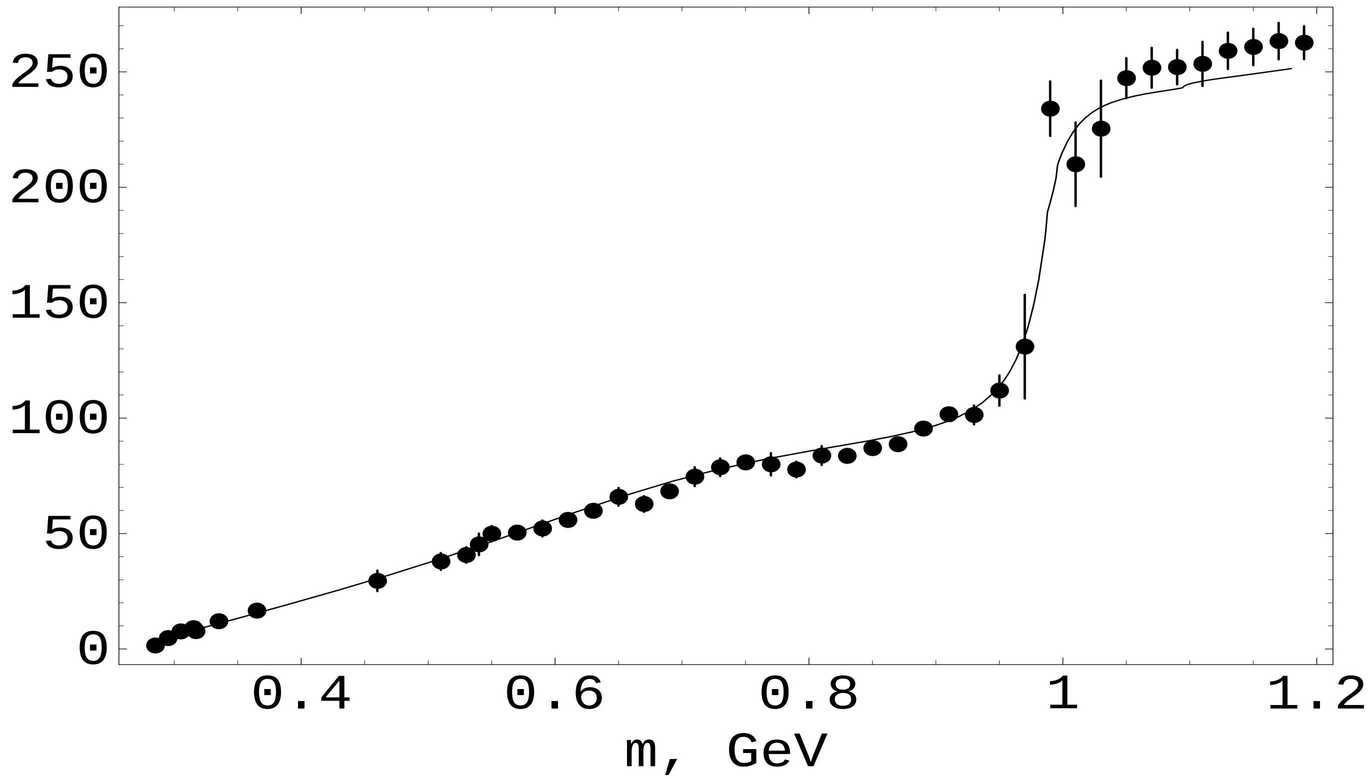
Our result agrees with the above only qualitatively.

$$\sqrt{s_\sigma} = M_\sigma - i\Gamma_\sigma/2 = (518 - i250) \times \text{MeV.}$$

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.

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



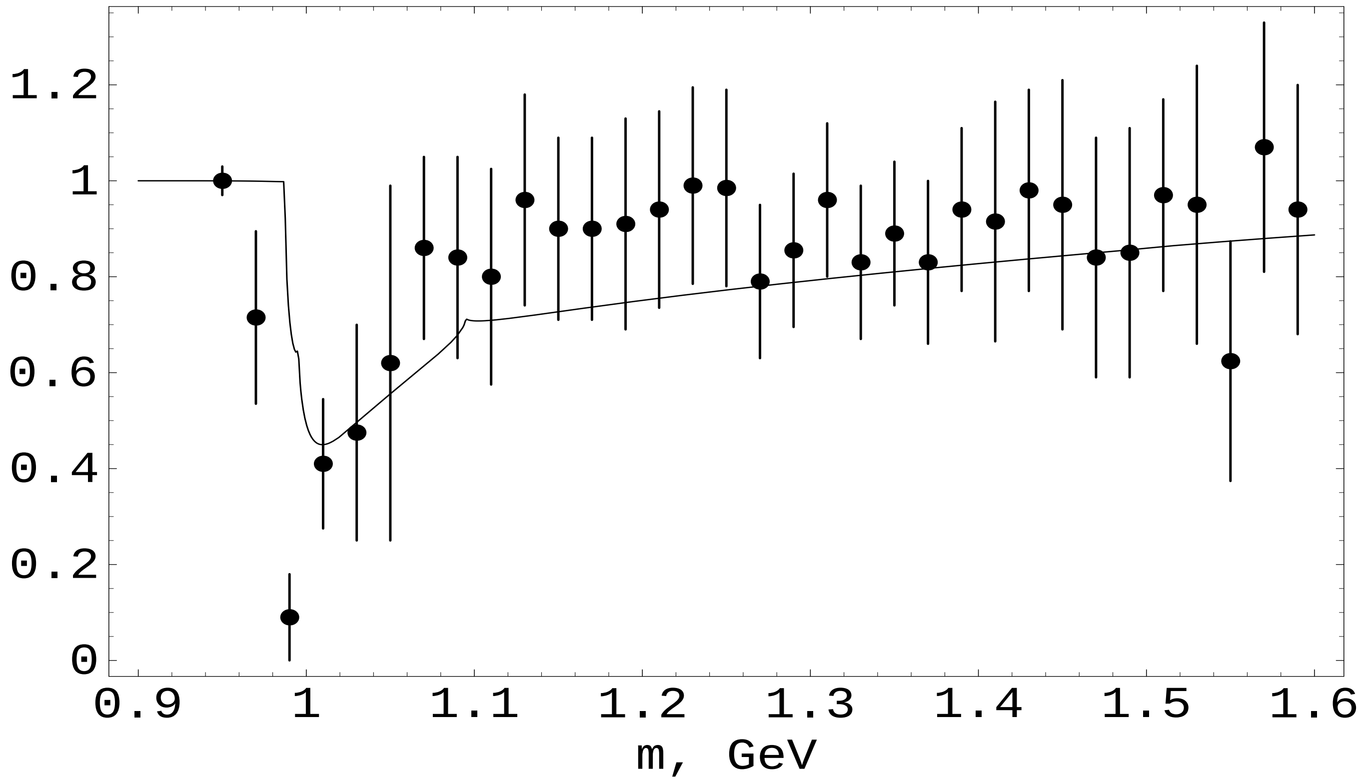
$$g^2_{\sigma\pi^+\pi^-}/4\pi = 0.57\,\text{GeV}^2, \quad g^2_{\sigma K^+K^-}/4\pi = 0.048\,\text{GeV}^2$$

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

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

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

Inelasticity, η_0^0

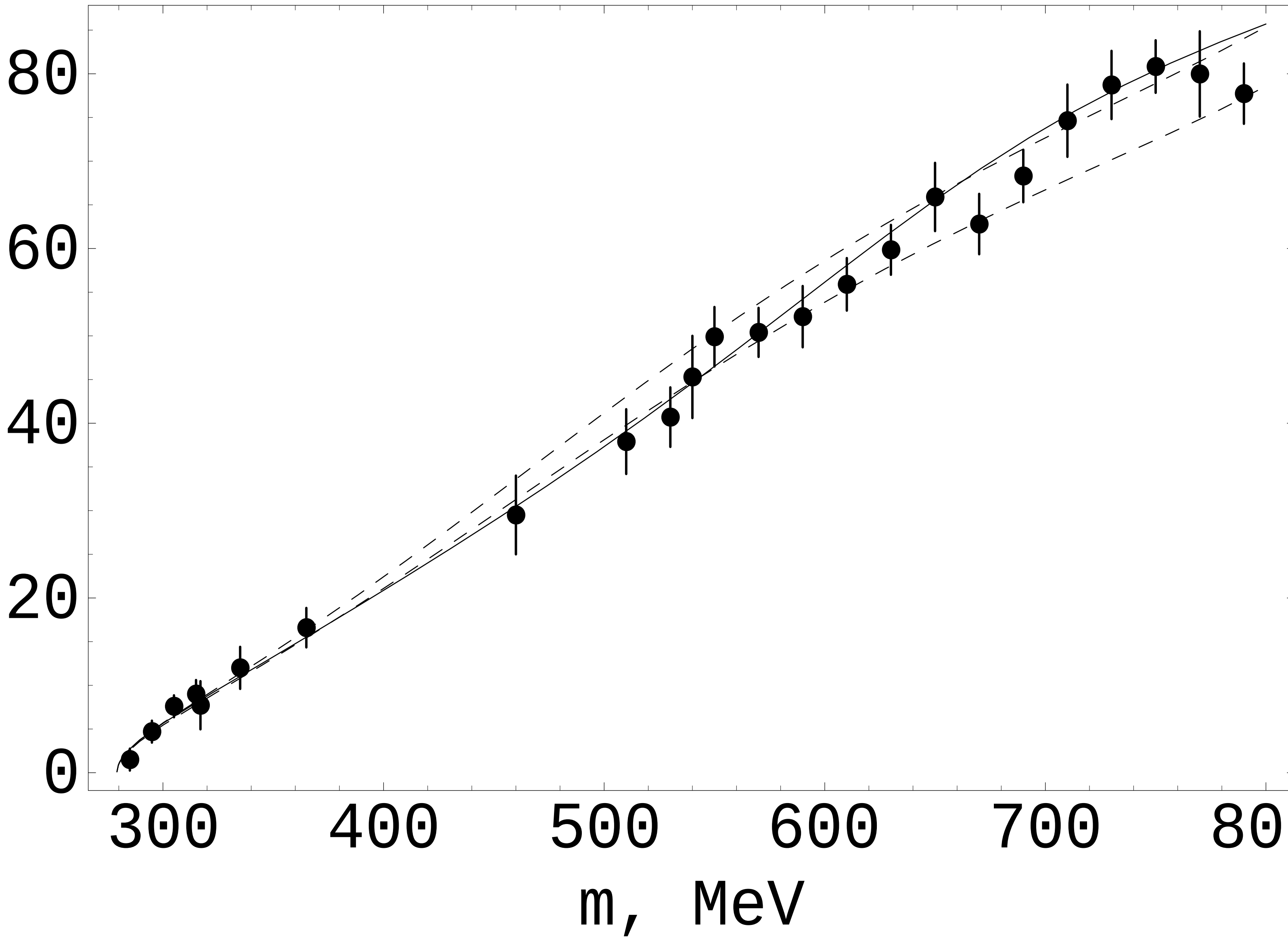


$$\eta_0^0 =$$

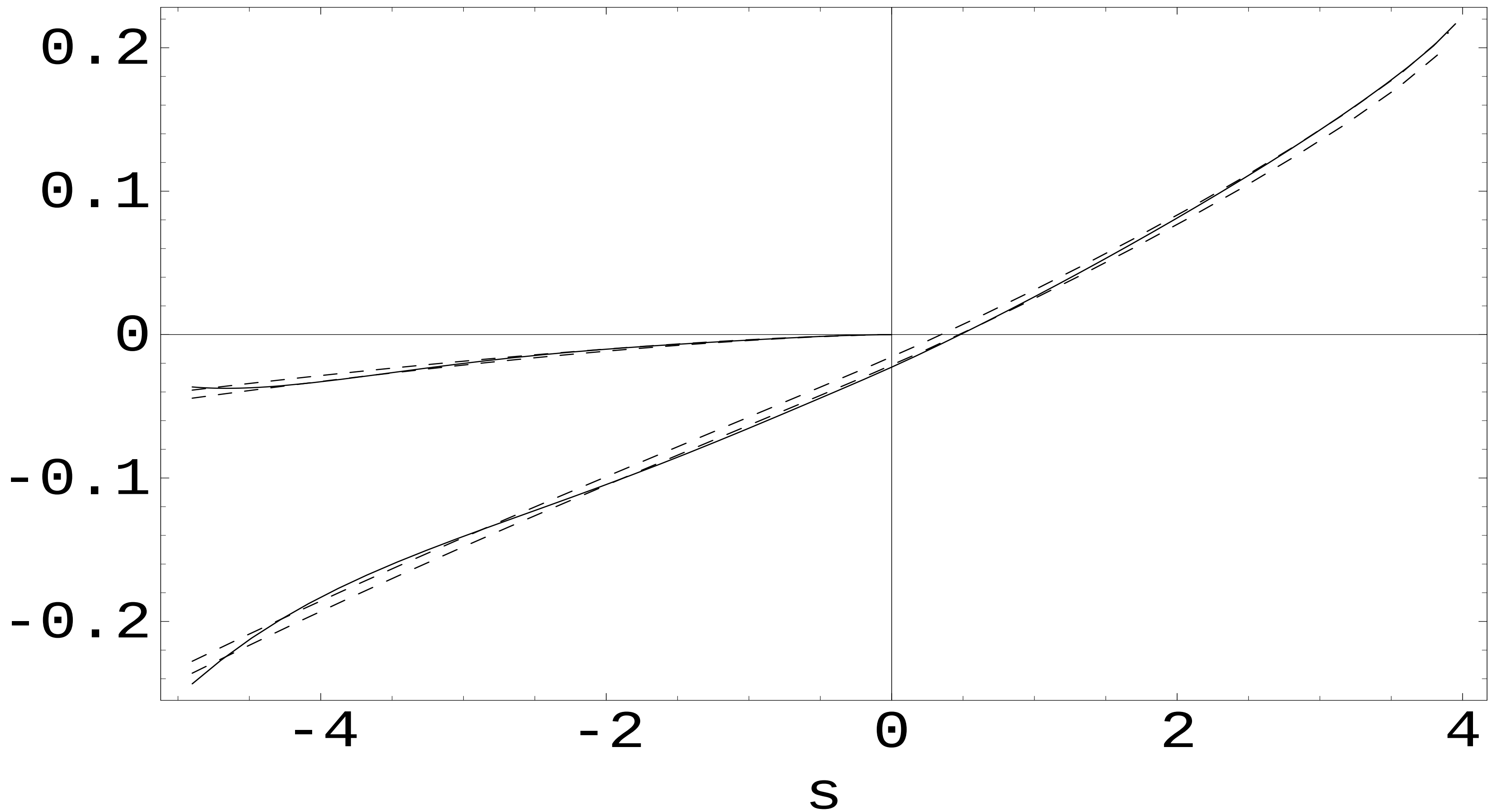
$$\sqrt{1 - 4\rho_{K^+}|T_0^0(\pi\pi \to K^+K^-)|^2 - 4\rho_{K^0}|T_0^0(\pi\pi \to K^0\bar{K}^0)|^2}$$

$$\rho_{K^+} \equiv \rho_{K^+K^-} \equiv \rho_{K^+K^-}(m) = \sqrt{1 - 4m_{K^+}^2/m^2}$$

δ_0^0, comparison with CGL band



T_0^0, comparison with CGL results under the threshold



s in units of m_π^2 ;

the real part under the threshold: $-4.5 < s < 4$;

the imaginary part on the left cut: $-4.5 < s < 0$

$\sigma(600)$ poles

Table I. $\sigma(600)$ poles (MeV) on different sheets of the complex s plane depending on lists of polarization operators $\Pi^{ab}(s) \equiv \Pi^{ab}$.

$\Pi^{\pi\pi}$	$\Pi^{K\bar{K}}$	$\Pi^{\eta\eta}$	$\Pi^{\eta\eta'}$	$\Pi^{\eta'\eta'}$	Fit
II	I	I	I	I	$613.8 - 221.4\,i$
II	II	I	I	I	$609.8 - 291.6\,i$
II	II	II	I	I	$559.4 - 346.6\,i$
II	II	II	II	I	$569.7 - 410.7\,i$
II	II	II	II	II	$581.6 - 411.0\,i$

CGL: $\sqrt{s_\sigma} = M_\sigma - i\Gamma_\sigma/2 = (441^{+16}_{-8} - i272^{+9}_{-12.5})\times$ MeV.

But the Roy equations are approximate, they take into account only the $\pi\pi$ channel, but the true $\pi\pi$ scattering amplitude has the multi (infinity) -list Riemannian surface, that can effect the analytical continuation considerably, especially in the case wide resonance.

$f_0(980)$ poles

Table II. $f_0(980)$ poles (MeV) on different sheets of the complex s plane depending on lists of polarization operators $\Pi^{ab}(s) \equiv \Pi^{ab}$.

$\Pi^{\pi\pi}$	$\Pi^{K\bar{K}}$	$\Pi^{\eta\eta}$	$\Pi^{\eta\eta'}$	$\Pi^{\eta'\eta'}$	Fit
II	I	I	I	I	$990.5 - 19.4\,i$
II	II	I	I	I	$1183.2 - 518.6\,i$
II	II	II	I	I	$1366.0 - 756.5\,i$
II	II	II	II	I	$1390.7 - 813.0\,i$
II	II	II	II	II	$1495.6 - 1057.7\,i$

The futility of the approach that is based on the poles treatment may be additionally illustrated by Fit. As seen on line 1 of Table II, the real part of the $f_0(980)$ pole ReM_{f_0} on the II sheet of the T_0^0 exceeds the K^+K^- threshold (987.4 MeV), it means that ImM_{f_0} equals to $-(\Gamma(f_0 \to \pi\pi) - \Gamma(f_0 \to K^+K^-))/2$, which is physically meaningless.

$f_0(980)$ poles

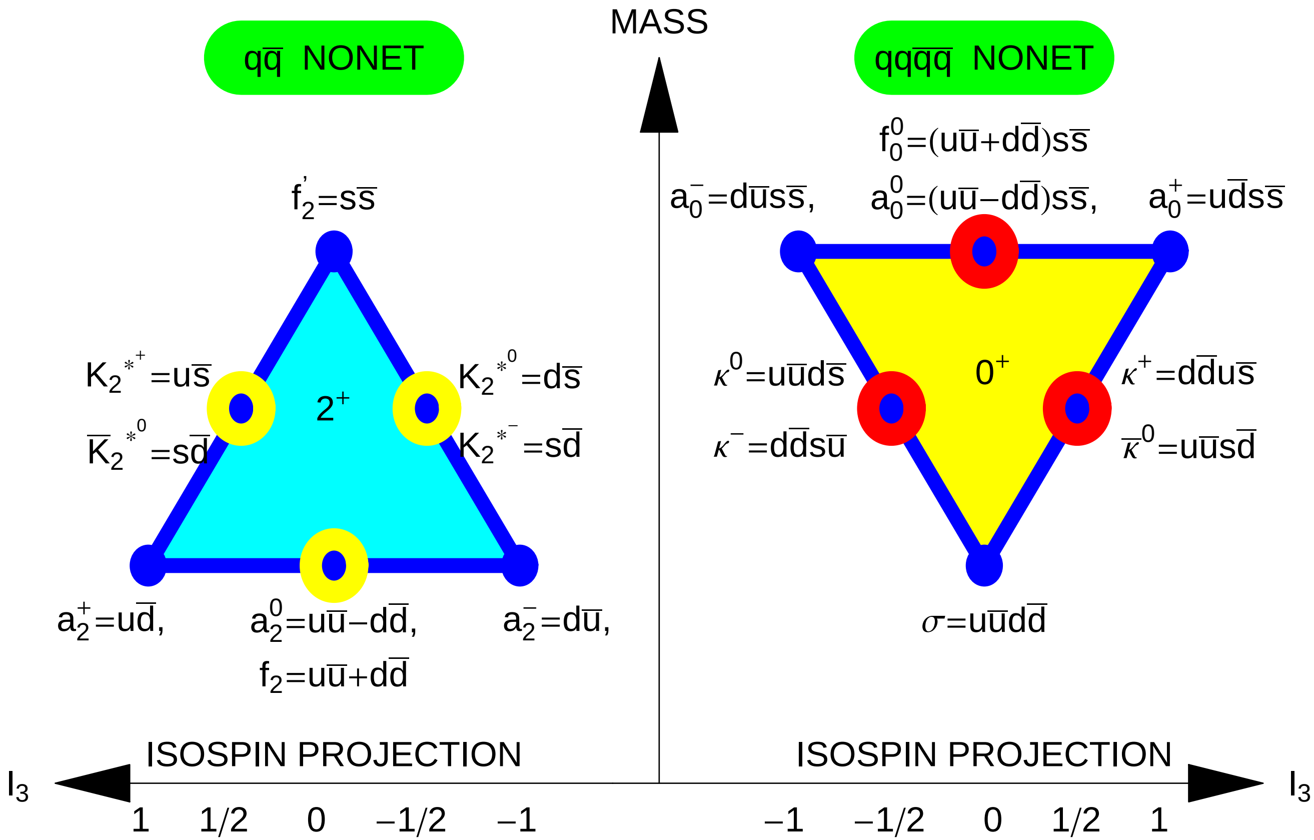
In this case we should take $\Pi^{K^+K^-}$ on the second sheet, this gives the pole at $M_{f_0} = (989.6 - 168.7i)$ MeV, with ReM_{f_0} between the K^+K^- and $K^0\bar{K}^0$ thresholds again. But, the analytical properties are specified on the s plane, and we must consider not M_{f_0}, but $M^2_{f_0} = (0.951 - 0.334\,i)$ GeV^2. So, we have the pole with a real part below the K^+K^- (0.975 GeV^2) and $K^0\bar{K}^0$ thresholds, and an imaginary part dictated by analytical continuation of the kaon polarization operators.

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.

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.

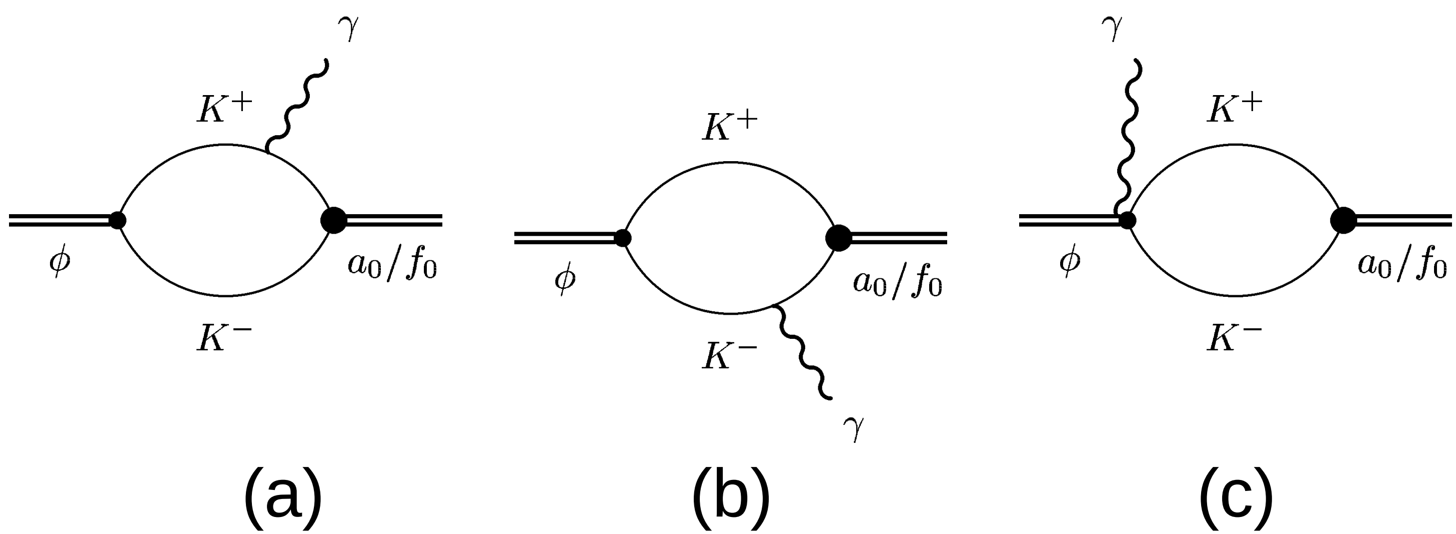
Radiative Decays of ϕ-Meson

Ten years later (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.

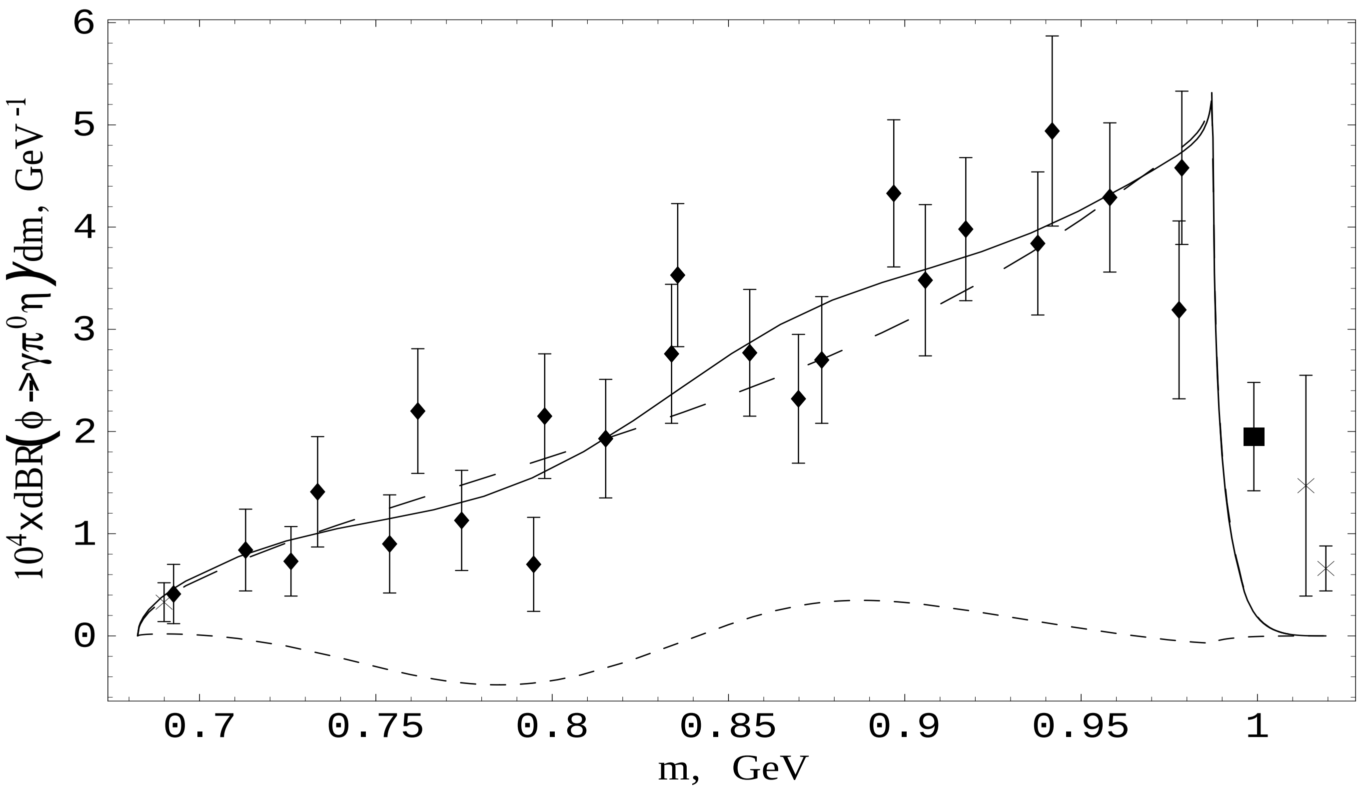
K^+K^--Loop Model



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.

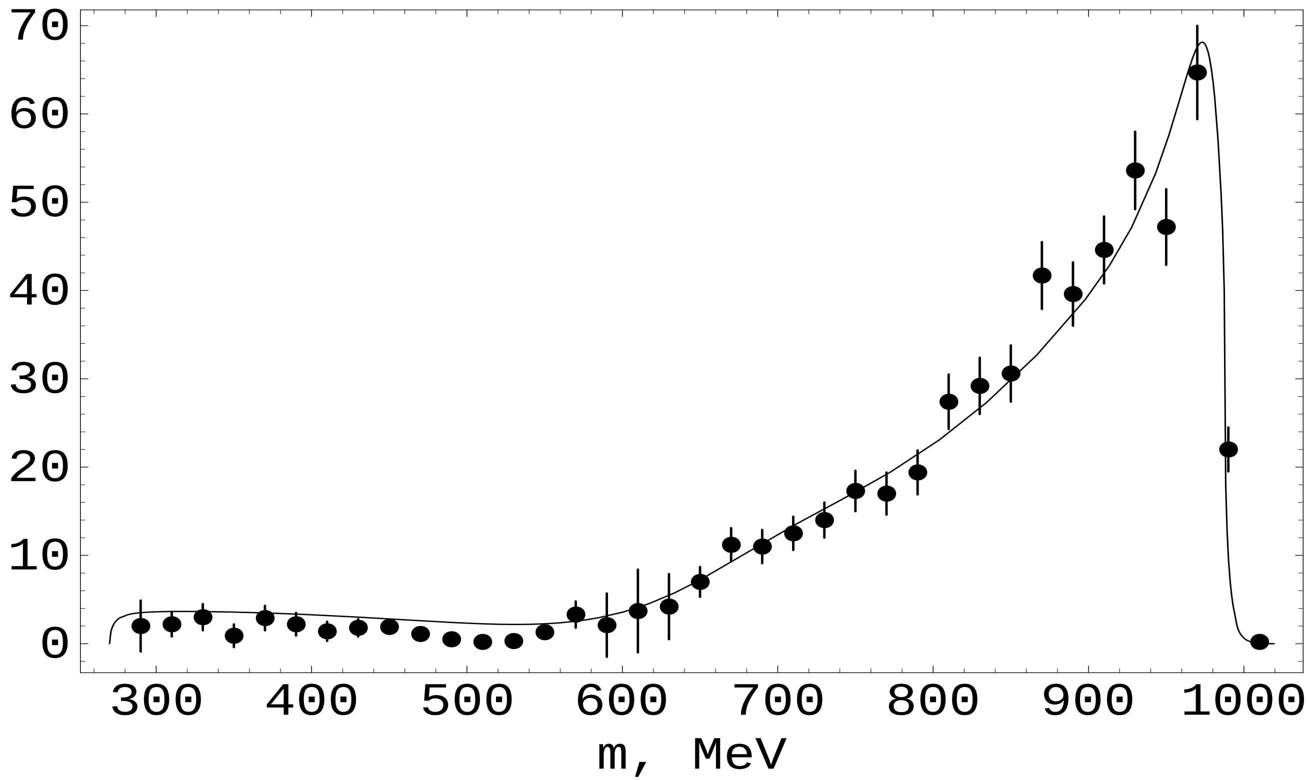
$\phi \to \gamma\pi^0\eta$, KLOE



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

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

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



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

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

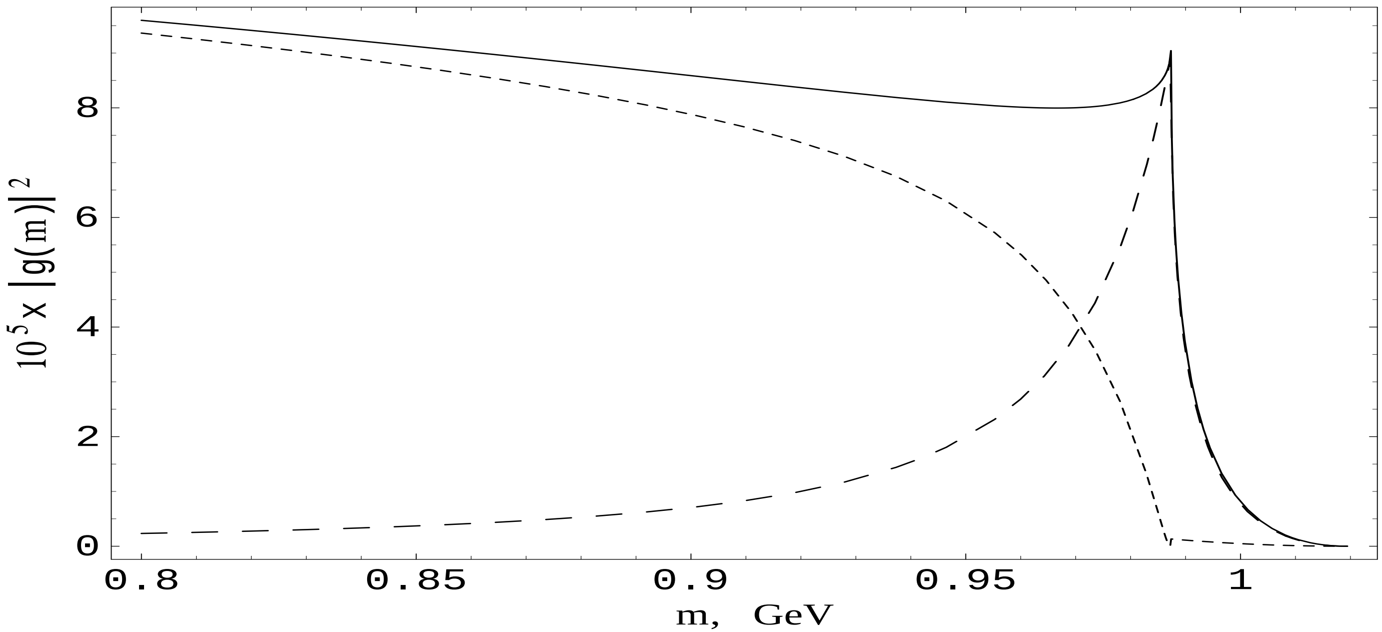
Spectra and Gauge Invariance

To describe the experimental spectra $|g_R(m)|^2\omega(m)$ should be smooth at $m \le 0.99$ GeV (the photon energy $\omega(m) \ge 29$ 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.

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

Twenty nine 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.

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.

$\Gamma(f_0 \to \gamma\gamma) = (0.31 \pm 0.14 \pm 0.09)$ keV, Crystal Ball,

$\Gamma(f_0 \to \gamma\gamma) = (0.24 \pm 0.06 \pm 0.15)$ keV, MARK II.

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

$\Gamma(a_0 \to \gamma\gamma) = (1.5 - 5.9)\Gamma(a_2 \to \gamma\gamma)$

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

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

$= (1.7 - 5.5)(2.8 \pm 0.4)$ 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 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 $a_0(980) \to K^+K^- \to \gamma\gamma$

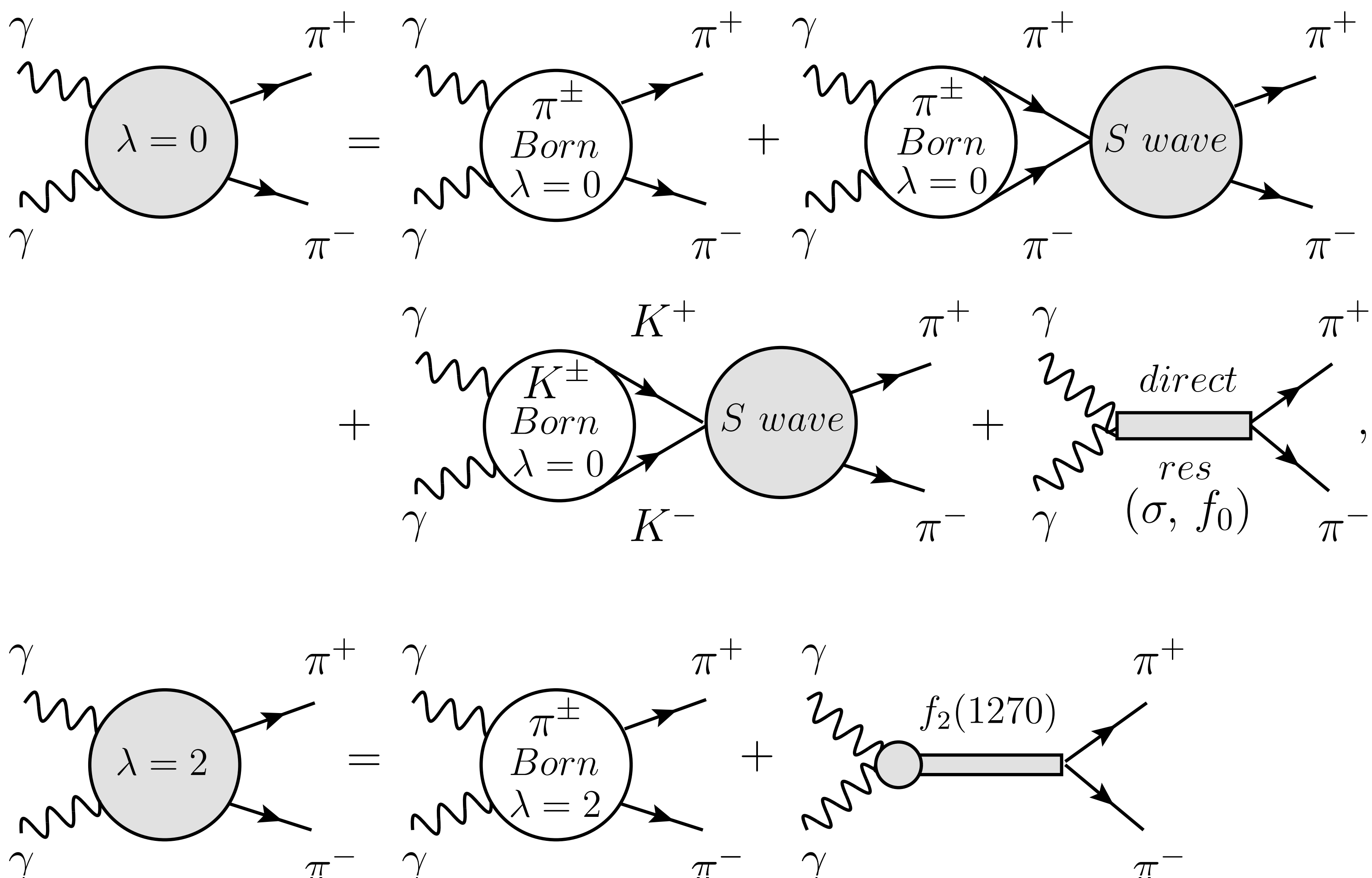
Scalar Nature and Production Mechanisms in $\gamma\gamma$ collisions

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.

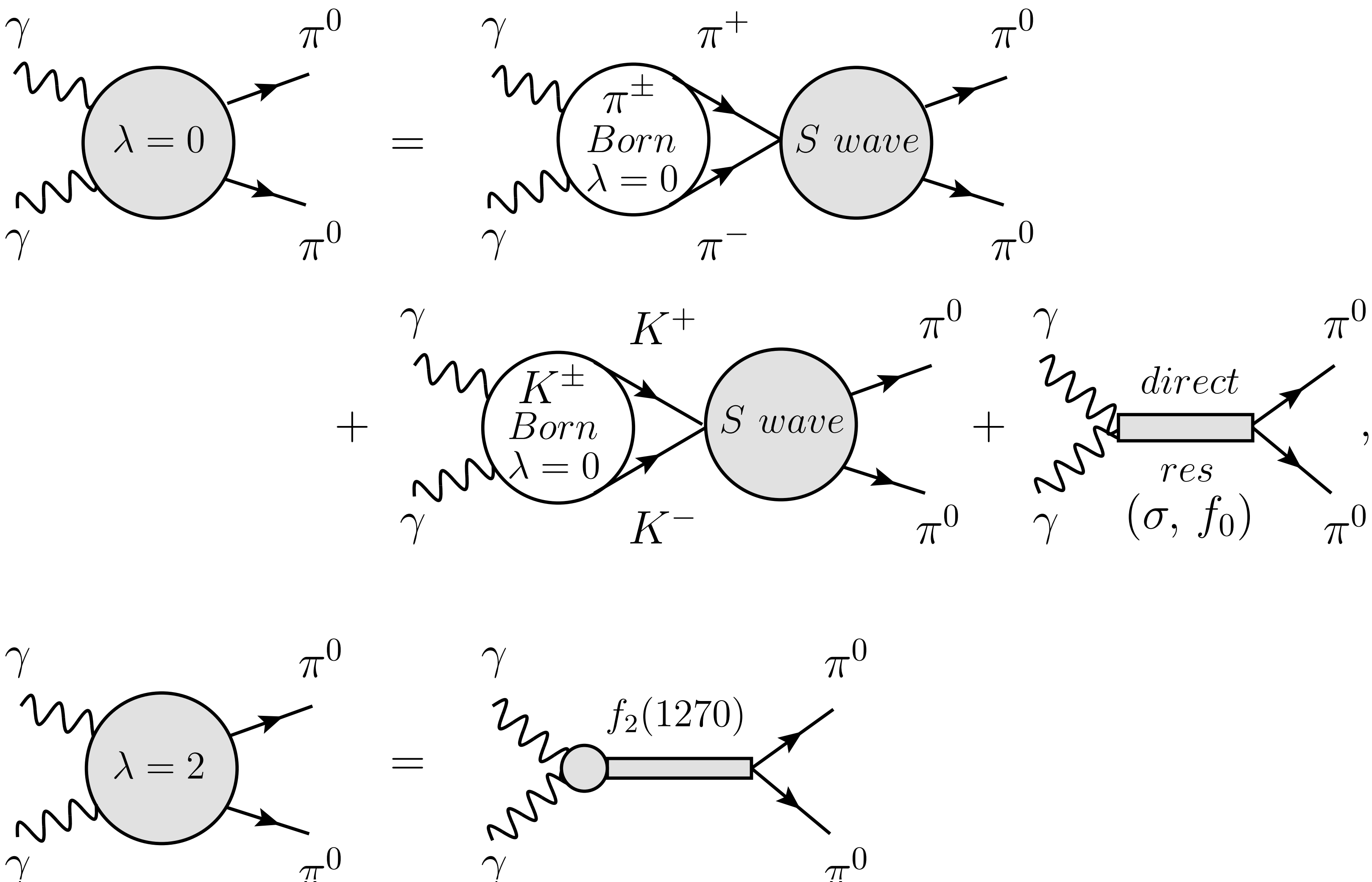
The two-photon light scalar widths averaged over resonance mass distributions $\langle\Gamma_{f_0\to\gamma\gamma}\rangle_{\pi\pi} \approx$ 0.19 keV, $\langle\Gamma_{a_0\to\gamma\gamma}\rangle_{\pi\eta} \approx$ 0.3 keV and $\langle\Gamma_{\sigma\to\gamma\gamma}\rangle_{\pi\pi} \approx$ 0.45 keV.

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.

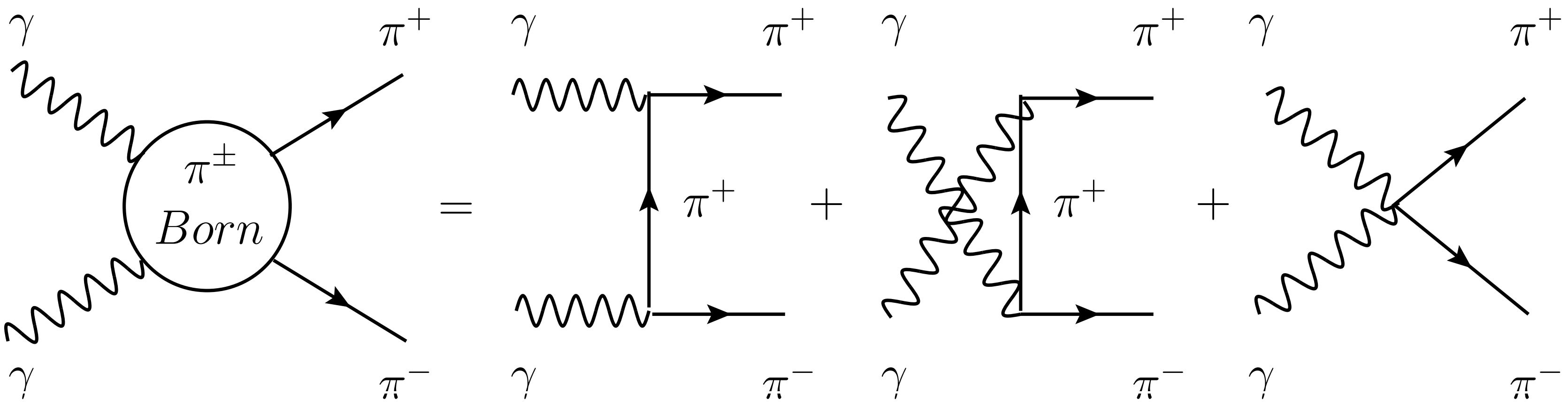
Dynamics of $\gamma\gamma \to \pi^+\pi^-$

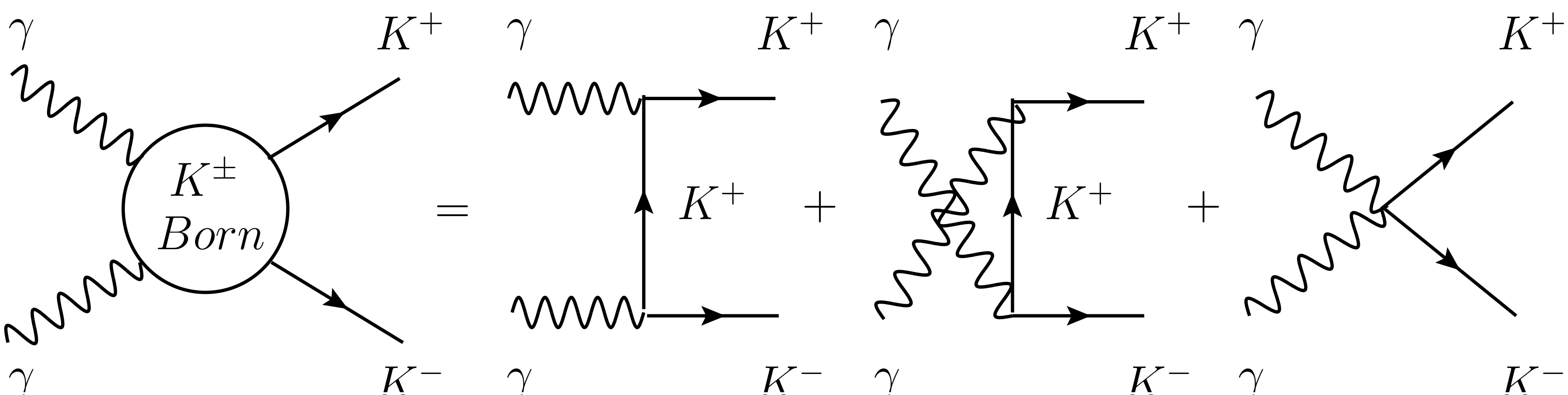


Dynamics of $\gamma\gamma \to \pi^0\pi^0$

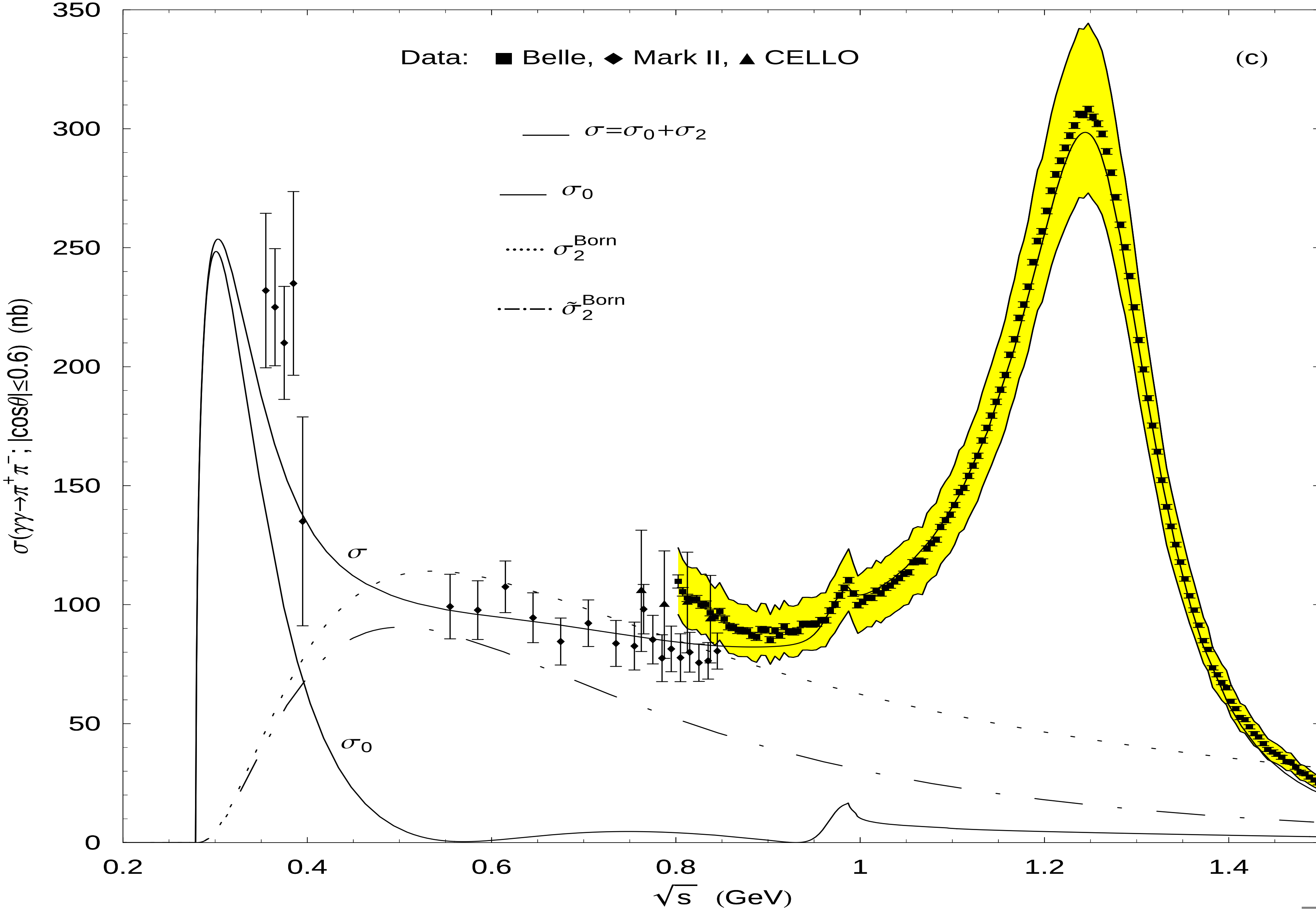


The $\pi^\pm$ and $K^\pm$ Born contributions

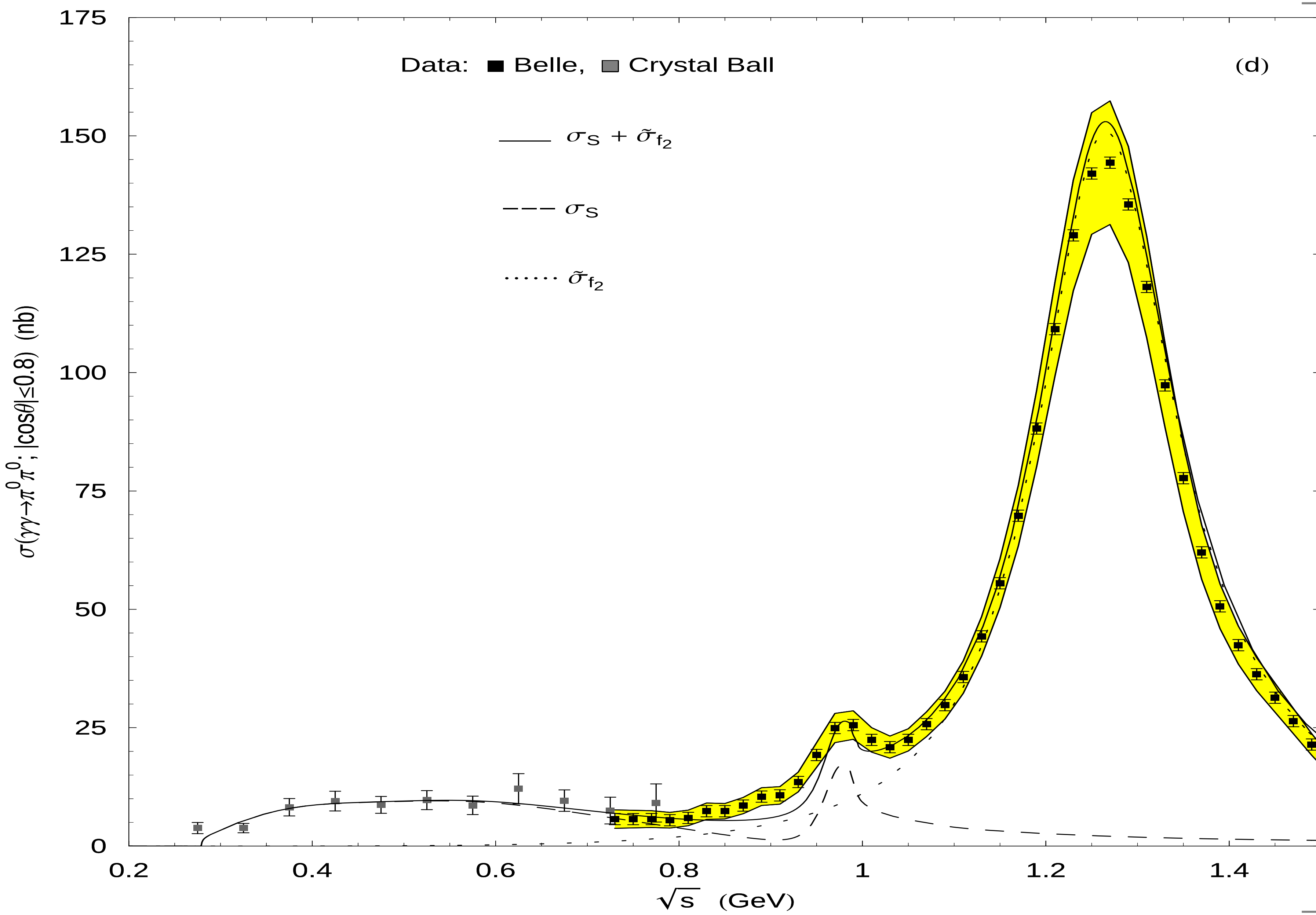




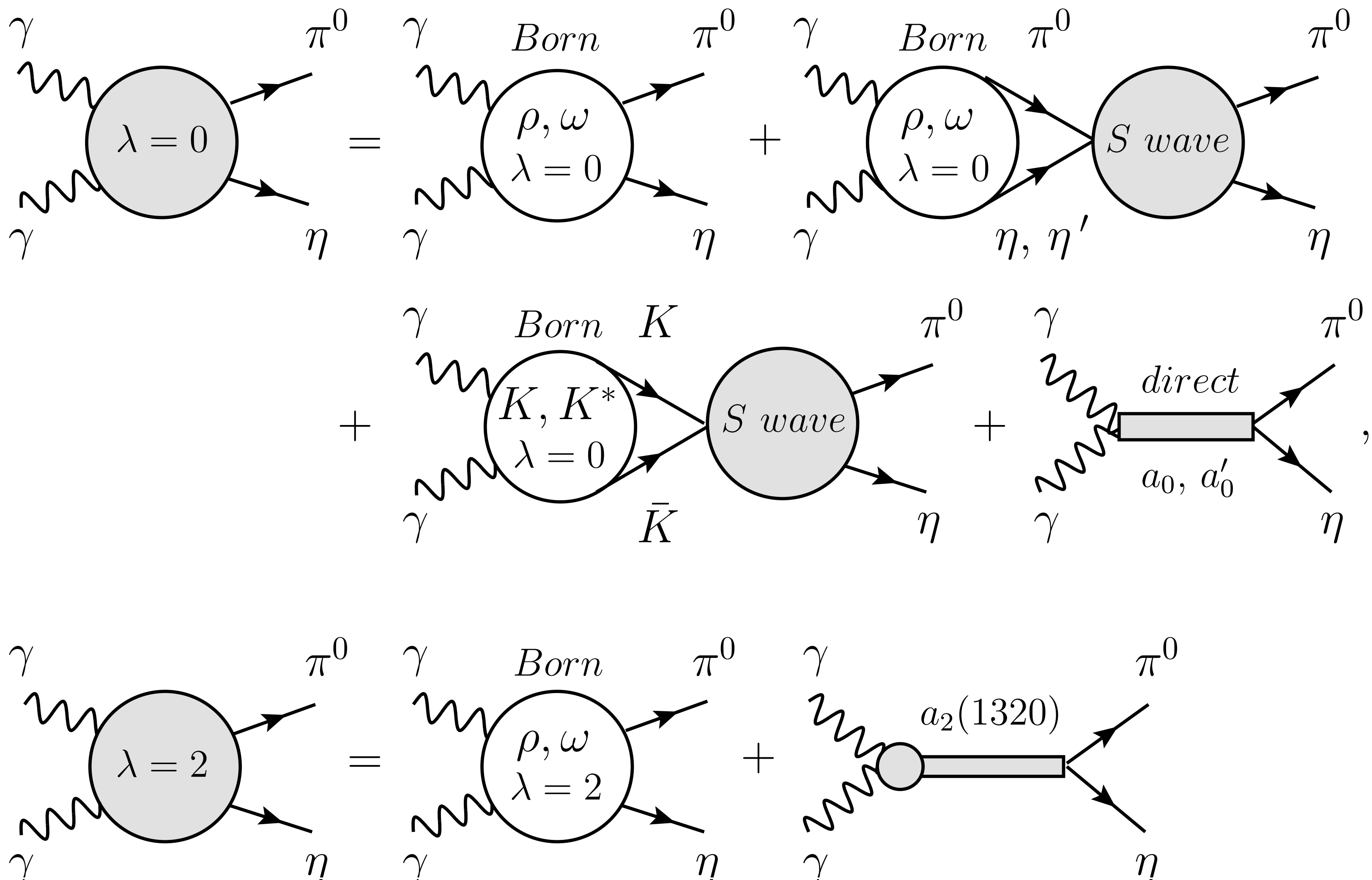
The Belle data on $\gamma\gamma \to \pi^+\pi^-$



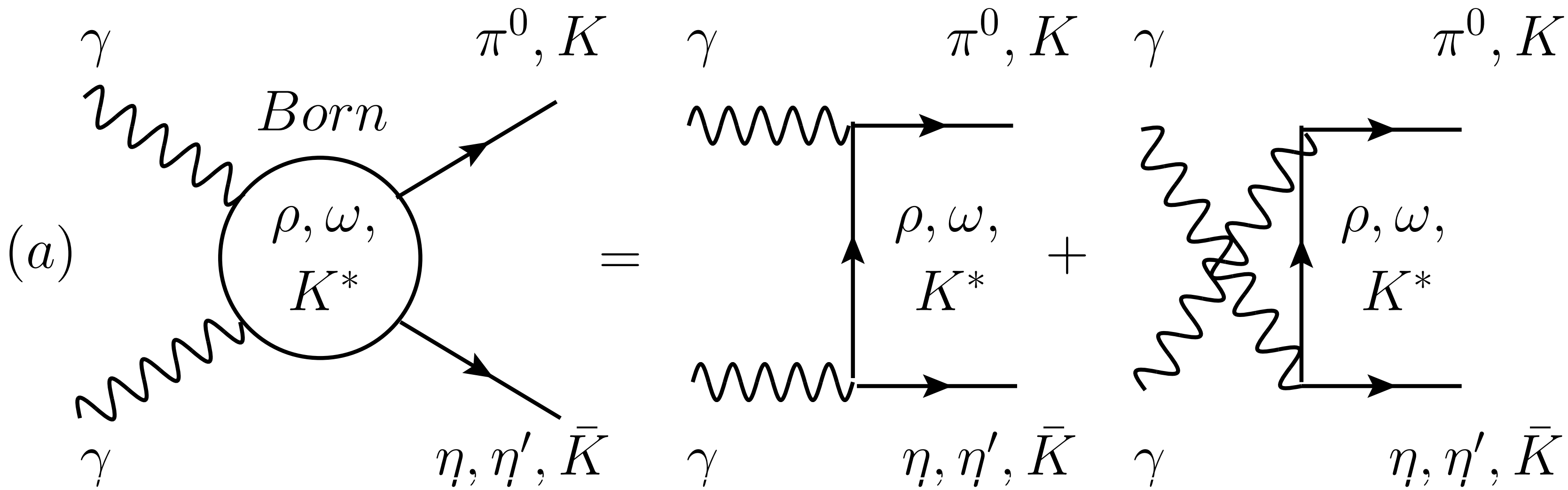
The Belle data on $\gamma\gamma \to \pi^0\pi^0$



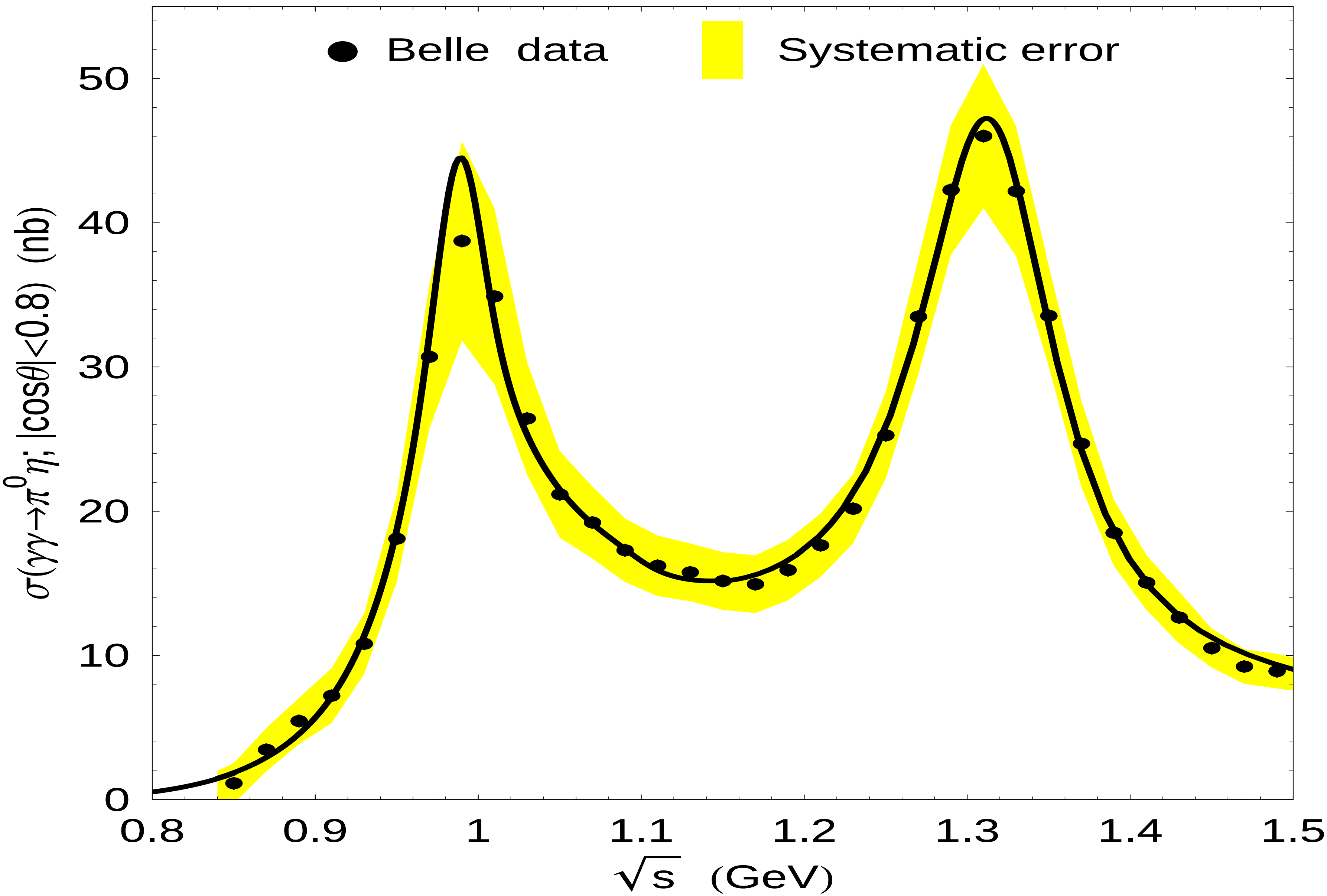
Dynamics of $\gamma\gamma \to \pi^0\eta$



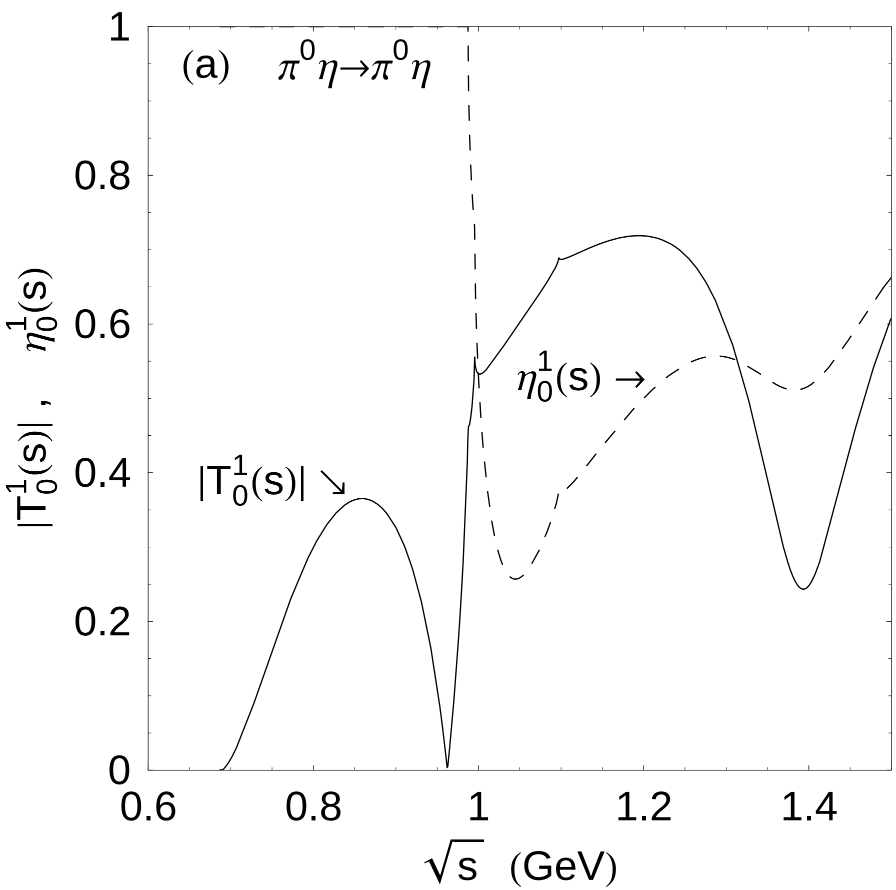
The V Born contributions

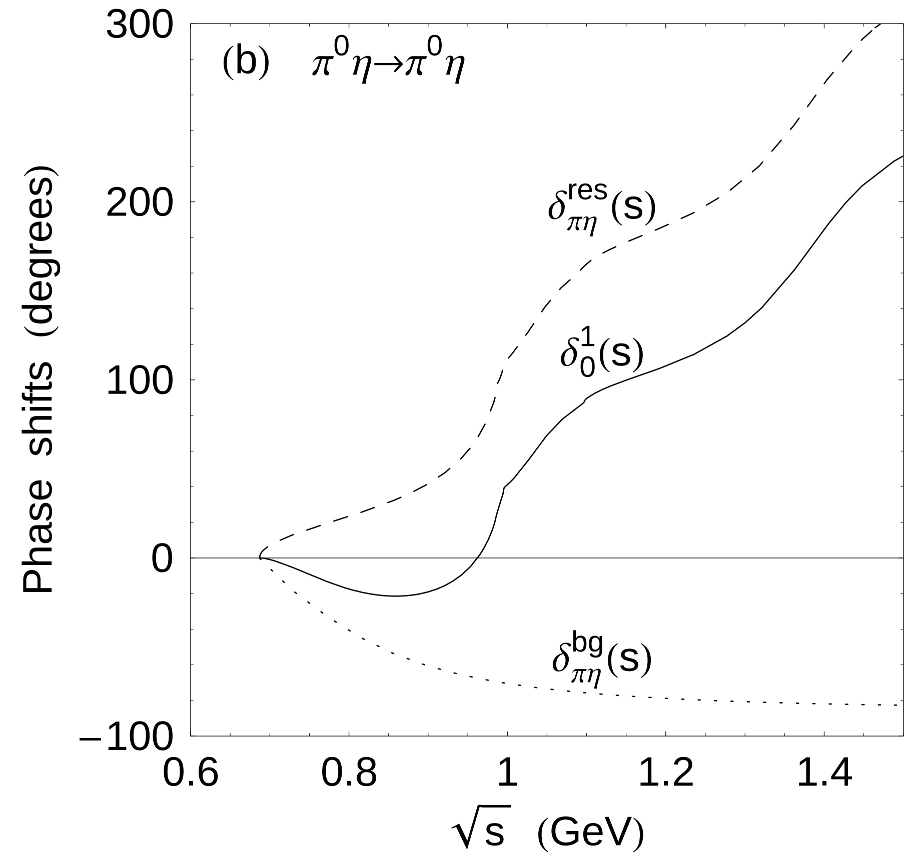


The Belle data on $\gamma\gamma \to \pi^0\eta$



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 $(0.005 - 0.01)m_\pi^{-1}$.

Summary

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 $\gamma\gamma$, the $q^2\bar{q}^2$ transitions, $\sigma(600) \to \pi^+\pi^- \to \gamma\gamma$, $f_0(980)/a_0(980)$ – $\to K^+K^- \to \gamma\gamma$, 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.

The urgent investigations

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. $\gamma\gamma^*(\mathrm{Q}^2) \to \pi^0\pi^0$, $\pi^0\eta$,
   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) $\pi^- p \to f_0(980)n \to a_0(980)n \to \pi^0\eta n$, here
   it is expected a strong jump in the spin asymmetry that could give an exclusive information on $(g_{a_0K^+K^-} \cdot g_{f_0K^+K^-})/4\pi$.

A lot of thanks