Nature of Light Scalar Mesons in Bright Light of Photon-Photon Collisions

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ABSTRACT

The surprising thing is that the light scalar meson problem, arising 50 years ago from the linear sigma model (LSM) with spontaneously broken chiral symmetry, has become central in the nonperturbative quantum chromodynamics (QCD), because it has been made clear that LSM could be the low energy realization of QCD.

First, we review briefly signs of four-quark nature of light scalars.

Then 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 that are produced via two-quark transitions $\gamma\gamma \to q\bar{q}$. Thus we get new evidence of the four-quark nature of the lower scalar states.

OUTLINE

1. Introduction
2. Evidence for the four-quark nature of the light scalar mesons
   - i) Normal ($q\bar{q}$) and inverted ($q^2\bar{q}^2$) mass spectra
   - ii) The ϕ meson radiative decays about light scalars
   - iii) Chiral shielding of the $\sigma(600)$ meson in $\pi\pi \to \pi\pi$ and other evidence
3. Light scalar manifestations in $\gamma\gamma$ collisions
   - i) Prediction of the four-quark model. New stage of high statistics measurements, the Belle data
   - ii) Dynamics of the $\sigma(600)$ and $f_0(980)$ production in $\gamma\gamma \to \pi\pi$
   - iii) Dynamics of the $a_0(980)$ production in $\gamma\gamma \to \pi^0\eta$
4. Future trends: the $\sigma(600)$, $f_0(980)$ and $a_0(980)$ investigations in $\gamma\gamma \to K\bar{K}$ and in $\gamma\gamma^*$ collisions

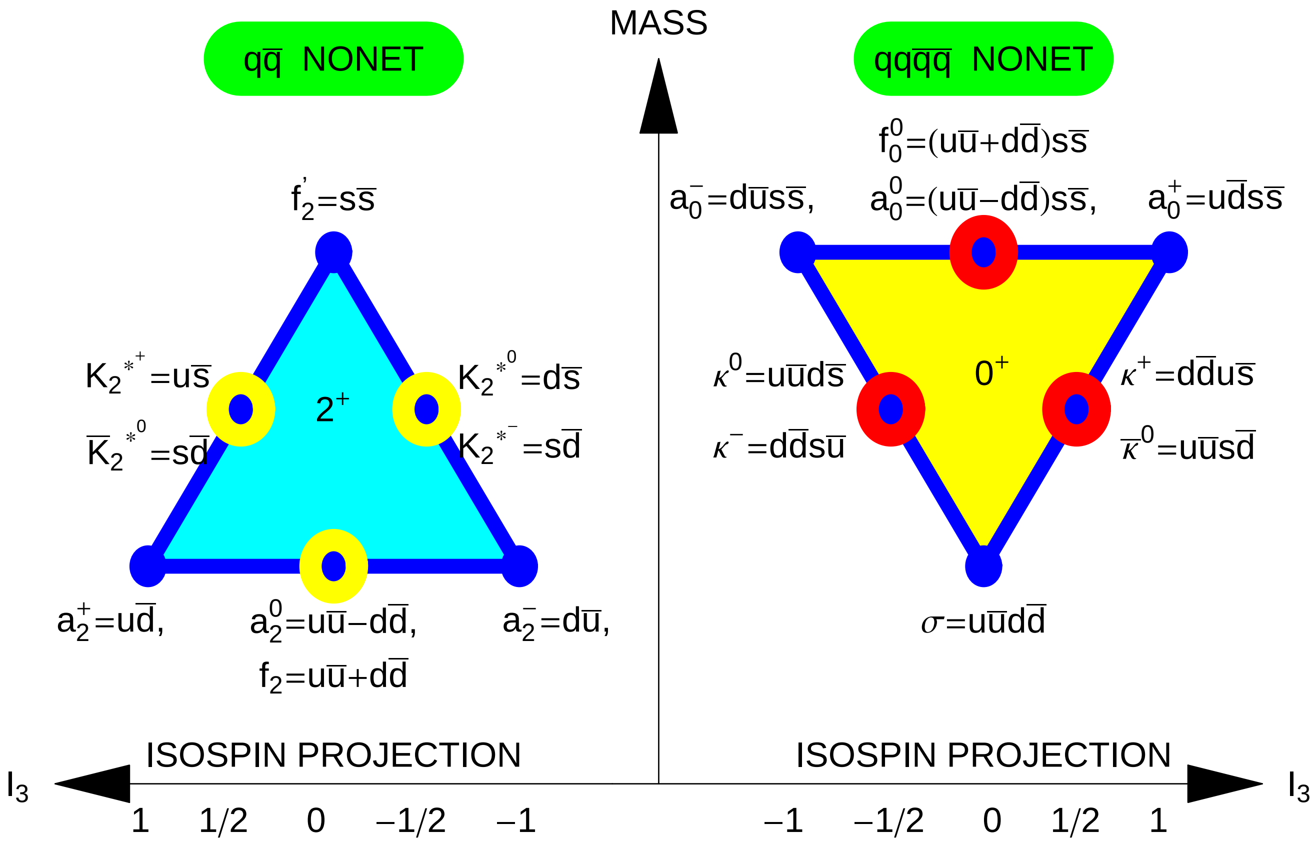
1. INTRODUCTION

The scalar channels in the region up to 1 GeV became a stumbling block of QCD. The point is that both perturbation theory and sum rules do not work in these channels because there are not solitary resonances in this region.

At the same time the question on the nature of the light scalar mesons is major for understanding the mechanism of the chiral symmetry realization, arising from the confinement, and hence for understanding the confinement itself.

2. FOUR-QUARK NATURE OF THE LIGHT SCALARS

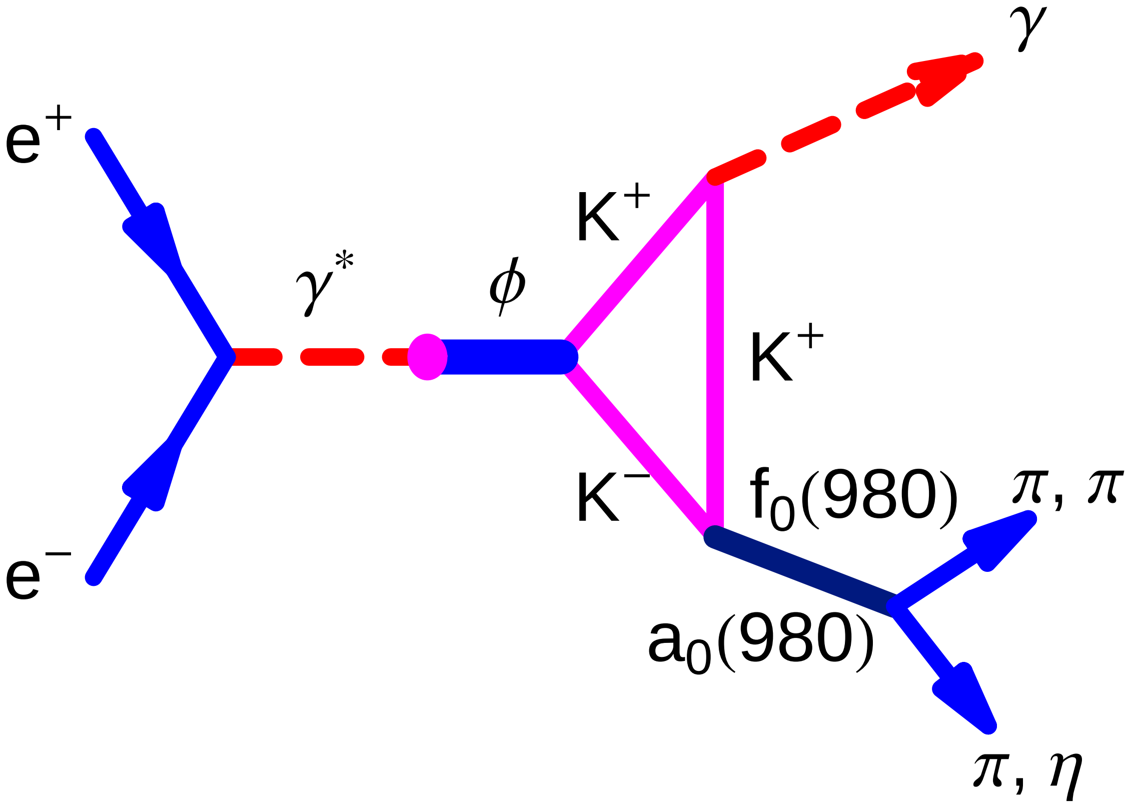
i) Normal $\mathbf{2}^{++}$ and inverted $\mathbf{0}^{++}$ mass spectra



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

2. FOUR-QUARK NATURE OF THE LIGHT SCALARS

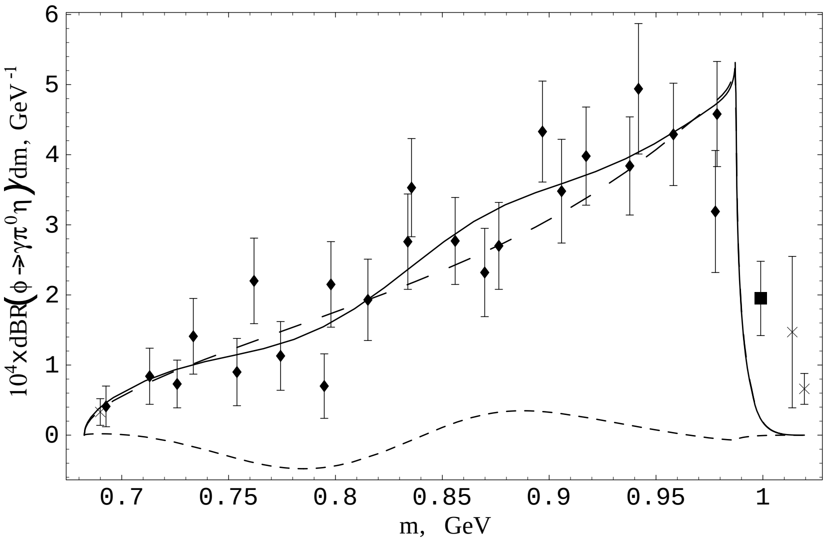
ii) The ϕ meson radiative decays about light scalars

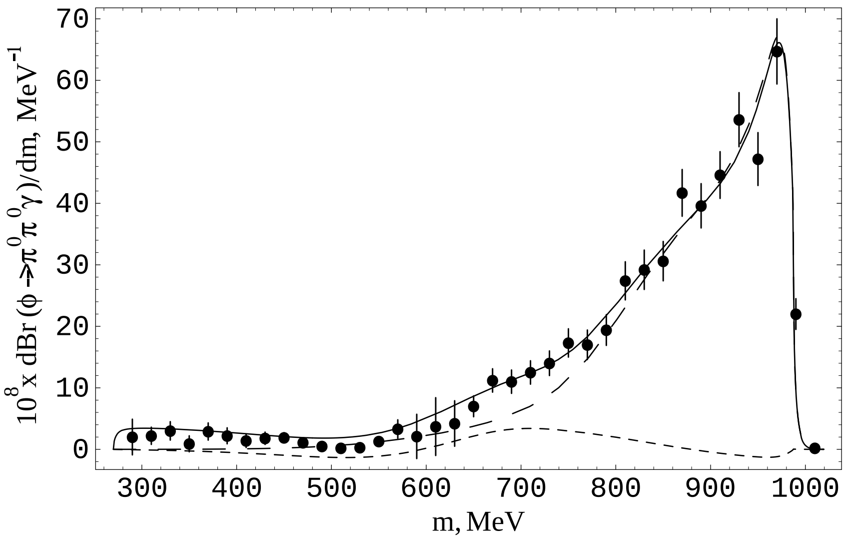


Both intensity and mechanism of the $f_0(980)$ and $a_0(980)$ production in the radiative decays of the $\phi(1020)$, via the $q^2\bar{q}^2$ transitions $\phi \to K^+K^- \to \gamma[f_0(980)/a_0(980)]$, testify to their $q^2\bar{q}^2$ nature.

2. FOUR-QUARK NATURE OF THE LIGHT SCALARS

ii) The ϕ meson radiative decays about light scalars





The left (right) plot shows the fit to the KLOE data for the $\pi^0\eta$ ($\pi^0\pi^0$) mass spectrum in the $\phi\longrightarrow\gamma\pi^0\eta$ ($\phi\longrightarrow\gamma\pi^0\pi^0$) decay caused by the $a_0(980)$ ($\sigma(600)+f_0(980)$) production via the K^+K^- loop mechanism.

2. FOUR-QUARK NATURE OF THE LIGHT SCALARS

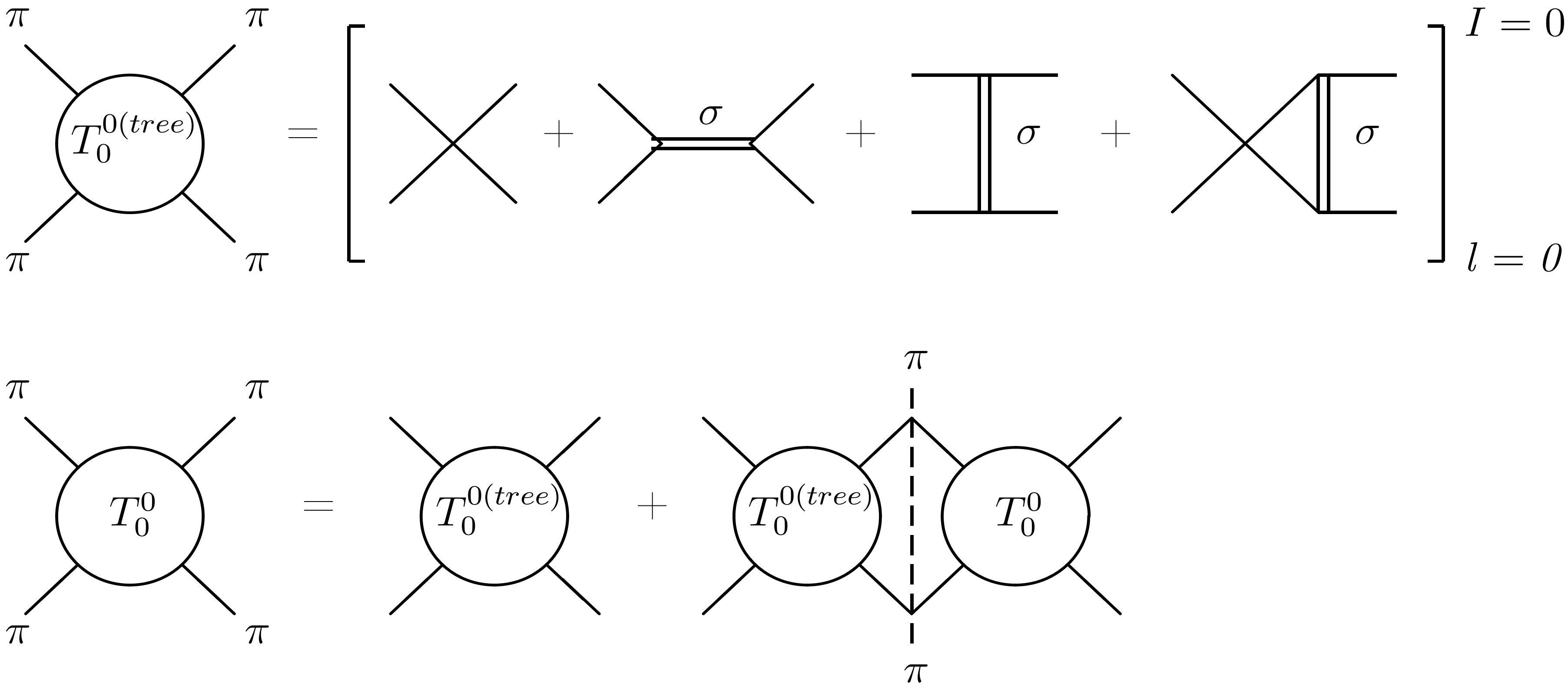
iii) Chiral shielding of the $\sigma(600)$ in $\pi\pi \longrightarrow \pi\pi$

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 an information on these states disappeared from 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.

Situation has changed when we showed that in the $SU(2) \times SU(2)$ linear σ model there is a negative background phase which hides the σ meson. 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.

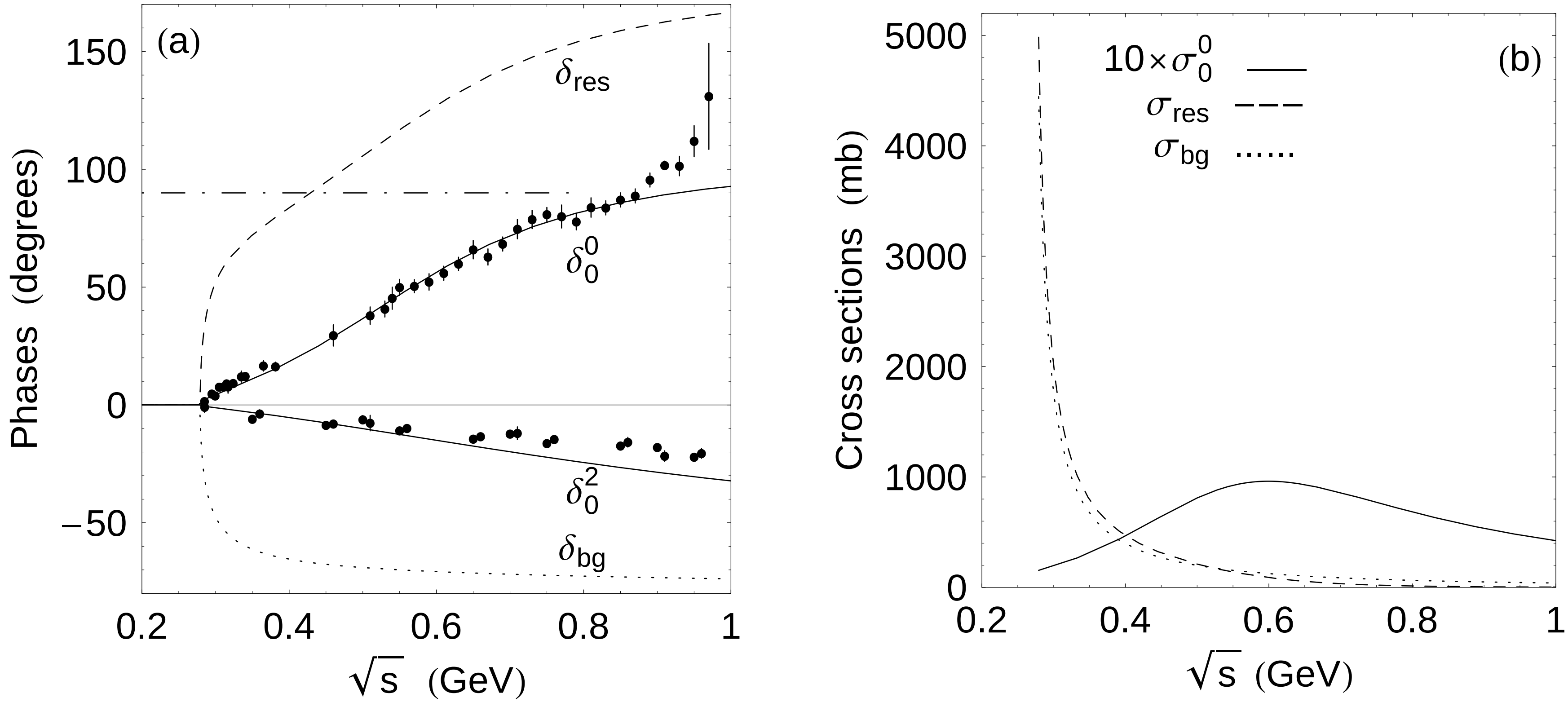
Chiral shielding of the $\sigma(600)$

can be easily revealed with the use of the S wave $I=0\ \pi\pi$ scattering amplitude T_0^0 satisfying the simplest Dyson equation with the real π mesons in the intermediate state



2. FOUR-QUARK NATURE OF THE LIGHT SCALARS

iii) Chiral shielding of the $\sigma(600)$ in $\pi\pi \to \pi\pi$



The σ model. Our approximation is illustrated (a) with the help of the $\pi\pi$ phase shifts $\delta_{res},\ \delta_{bg},\ \delta_0^0 = \delta_{res} + \delta_{bg}$ and (b) with the help of the corresponding cross sections.

2. FOUR-QUARK NATURE OF THE LIGHT SCALARS

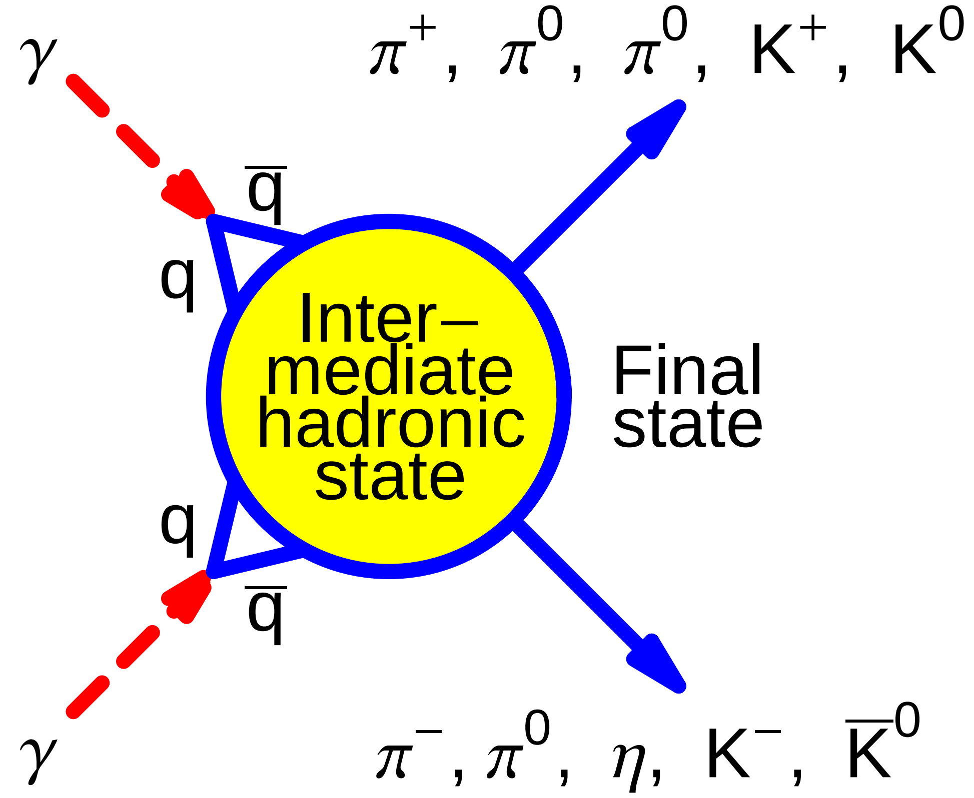
iii) . . . other evidence

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

- **It seems undisputed**
  that in all respect the $a_0(980)$ and $f_0(980)$ mesons are strangers in the company of the $b_1(1235)$, $h_1(1170)$, $a_1(1260)$, $f_1(1285)$, $a_2(1320)$, and $f_2(1270)$ mesons which are the members of the lower P wave $q\bar{q}$ multiplet.

3. LIGHT SCALARS IN $\gamma\gamma$ COLLISIONS

Photons are probes of the quark structure of hadrons



Investigations of the mechanisms of these reactions are an important constituent of the light scalar meson physics.

3. LIGHT SCALARS IN $\gamma\gamma$ COLLISIONS

Twenty eight years ago we predicted that if the $a_0(980)$ and $f_0(980)$ are the $q^2\bar{q}^2$ MIT bag states, then their $\gamma\gamma$ widths,

$$\Gamma(a_0(980)\to\gamma\gamma)\sim\Gamma(f_0(980)\to\gamma\gamma)\sim 0.27\ \text{keV},$$

are an order of magnitude smaller than those of the $q\bar{q}$ mesons η', $f_2(1270)$, and the theoretical predictions in the $q\bar{q}$ model.

Experiment supported this prediction:

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

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

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

$\Gamma(\mathrm{f}_0\to\gamma\gamma)=(0.29\pm 0.07\pm 0.12)$ keV, MARK II.

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

$\Gamma(a_0\to\gamma\gamma)\approx(1.5-5.9)\Gamma(a_2\to\gamma\gamma)\approx(1.5-6)$ keV,

$\Gamma(f_0\to\gamma\gamma)\approx(1.7-5.5)\Gamma(f_2\to\gamma\gamma)\approx(4.5-14)$ keV.

Nature of Light Scalars 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 and their decays into photons are the four-quark transitions caused by the rescattering mechanisms $\sigma\to\pi^+\pi^-\to\gamma\gamma$, $f_0(980)\to K^+K^-\to\gamma\gamma$ and $a_0(980)\to K^+K^-+\pi\eta\to\gamma\gamma$, 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.

Nature of Light Scalars and Production Mechanisms in $\gamma\gamma$ Collisions

As a result the practically model-independent prediction of the $q\bar{q}$ model for the $2^{++}\gamma\gamma$ coupling constants $g^2_{f_2\gamma\gamma} : g^2_{a_2\gamma\gamma} = 25 : 9$ agrees with experiment rather well; $\Gamma_{f_2\to\gamma\gamma} \approx 2.8$ keV, $\Gamma_{a_2\to\gamma\gamma} \approx 1$ keV.

The two-photon light scalar widths averaged over resonance mass distributions are: $\langle\Gamma_{f_0\to\gamma\gamma}\rangle_{\pi\pi} \approx$ 0.19 keV, $\langle\Gamma_{a_0\to\gamma\gamma}\rangle_{\pi\eta} \approx$ 0.4 keV and $\langle\Gamma_{\sigma\to\gamma\gamma}\rangle_{\pi\pi} \approx$ 0.45 keV.

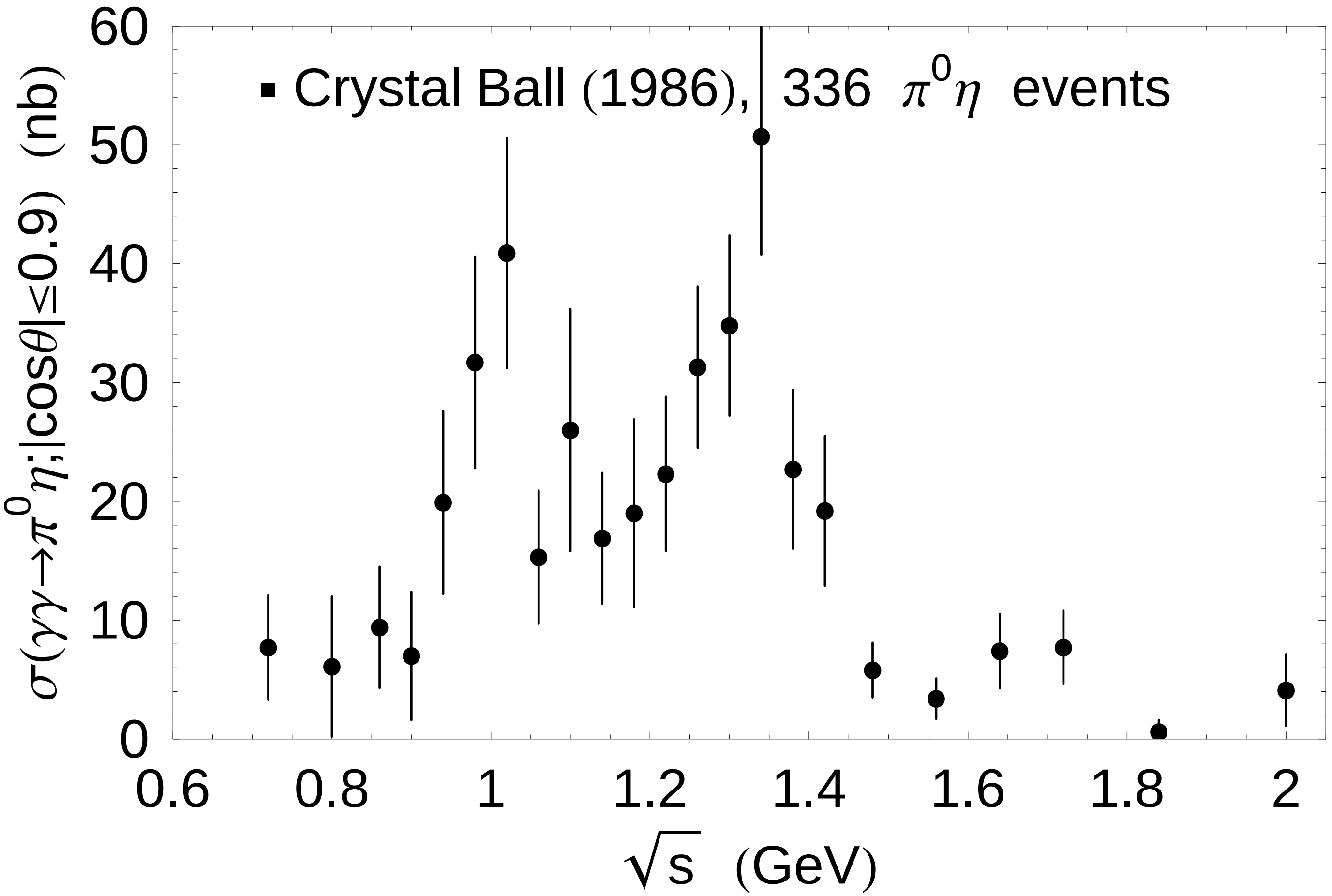
As to the ideal $q\bar{q}$ model prediction for the $0^{++}\gamma\gamma$ coupling constants $g^2_{f_0\gamma\gamma} : g^2_{a_0\gamma\gamma} = 25 : 9,$ it is excluded by experiment.

3. LIGHT SCALARS IN $\gamma\gamma$ COLLISIONS

Our statements for the $\sigma(600)$ $f_0(980)$ and $a_0(980)$ resonances are based on the detailed analysis of the new Belle Collaboration data on the $\gamma\gamma\to\pi^+\pi^-$, $\gamma\gamma\to\pi^0\pi^0$, and $\gamma\gamma\to\pi^0\eta$ reaction cross sections for energies up to 1.5 GeV. Owing to huge statistics and high resolution in the invariant mass of the $\pi\pi$ and $\pi^0\eta$ systems in the Belle experiments, clear signals from the $f_0(980)$ and $a_0(980)$ resonances were detected.

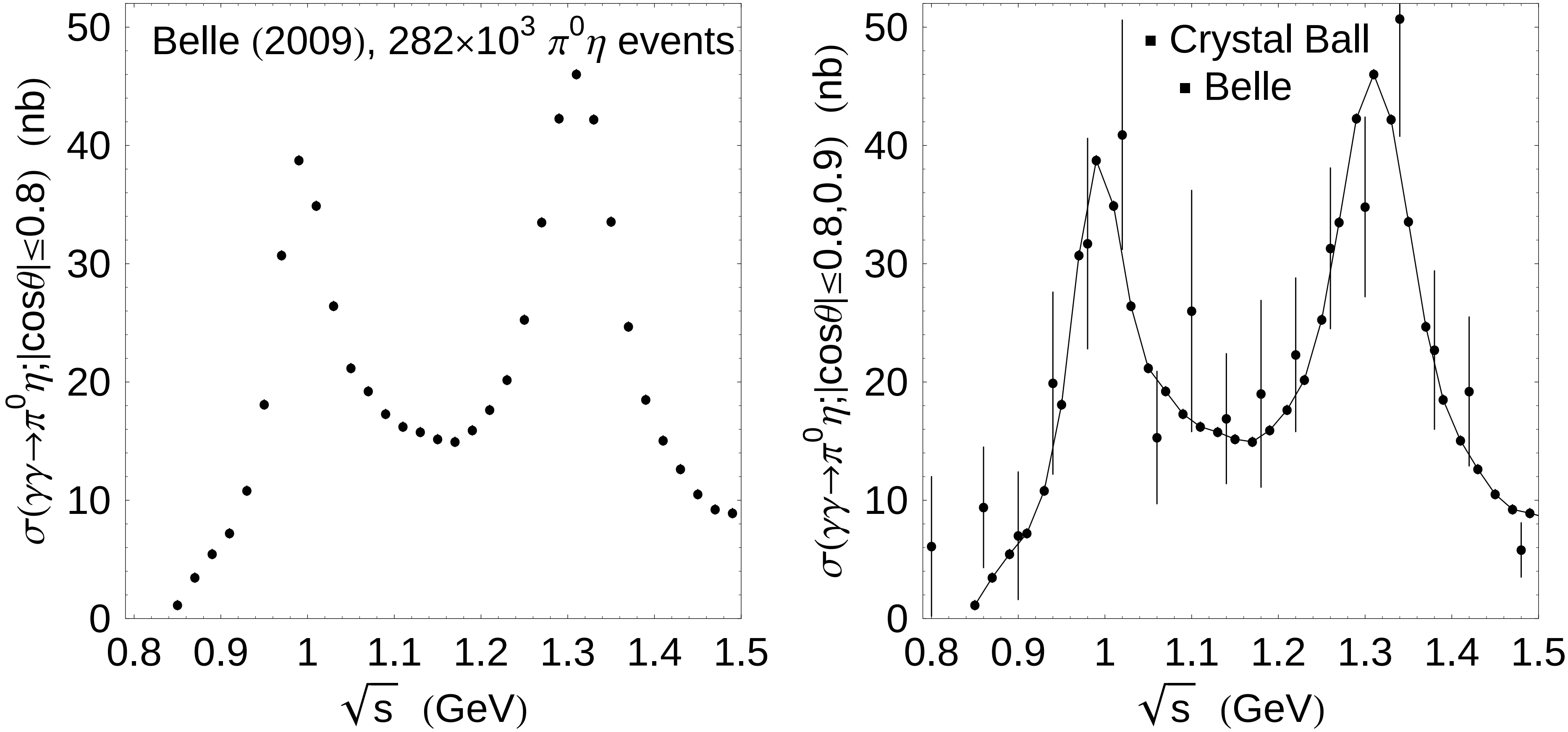
The experimental situation developed as follows.

The first Crystal Ball data on the $a_0(980)$ in $\gamma\gamma \to \pi^0\eta$



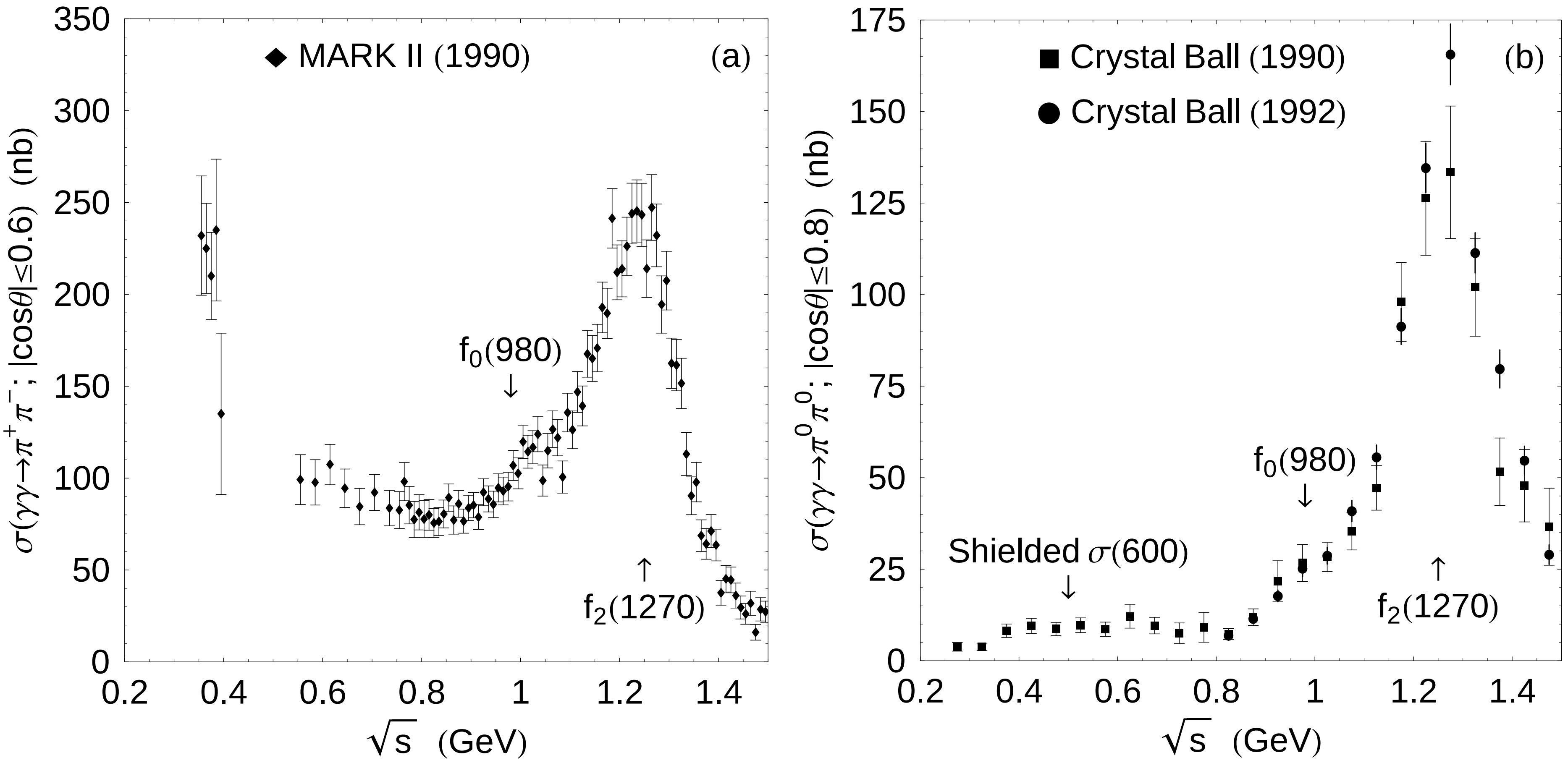
The $a_0(980)$ and $a_2(1320)$ signals.

The data of unprecedented precision from Belle (2009)



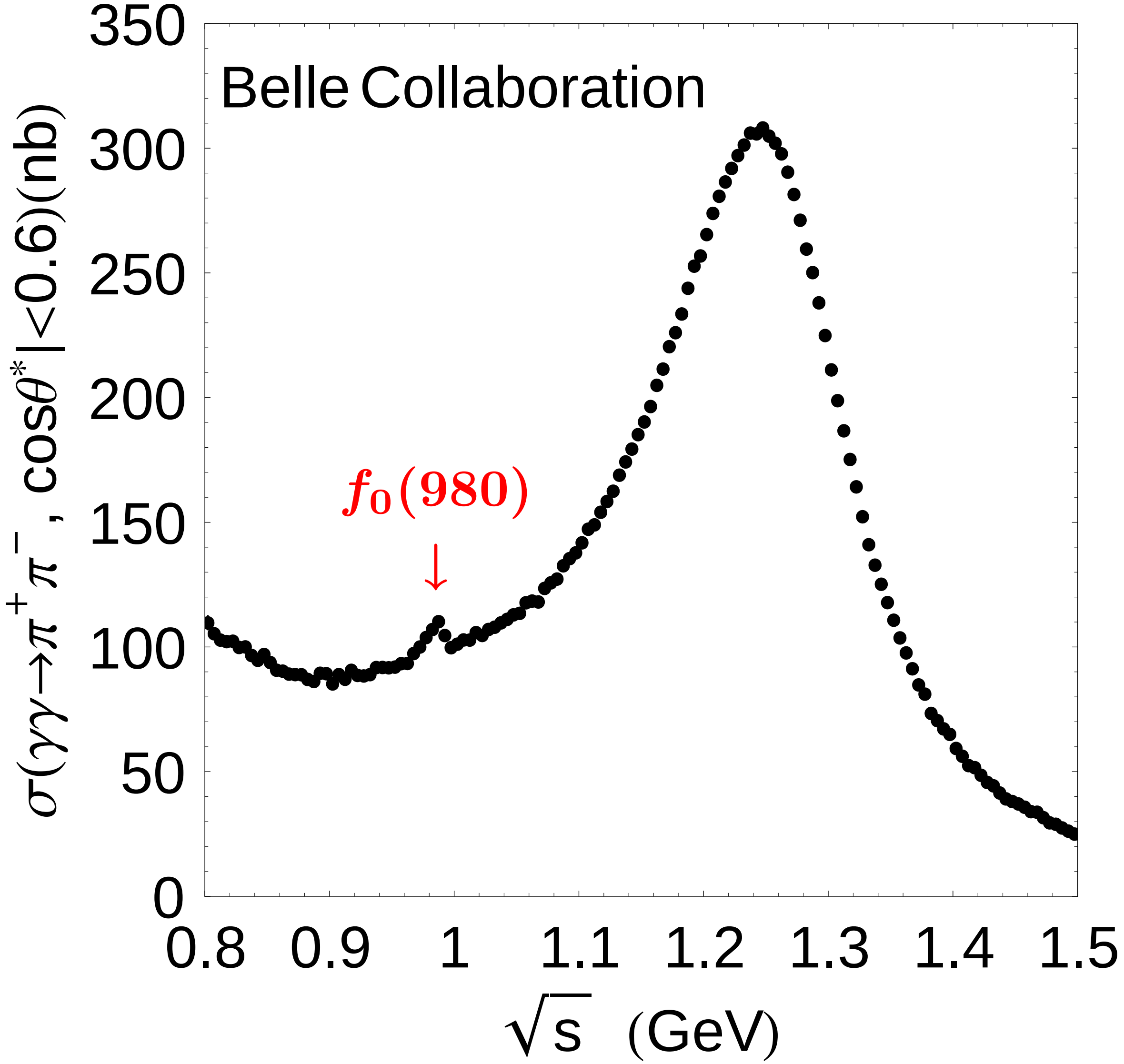
After 23 years, the statistics for $\gamma\gamma \to \pi^0\eta$ has been raised by three order of magnitude and a clear signal from $a_0(980)$ has been detected in the recent Belle experiment.

MARK II $\gamma\gamma \to \pi^+\pi^-$ and Crystal Ball $\gamma\gamma \to \pi^0\pi^0$ data



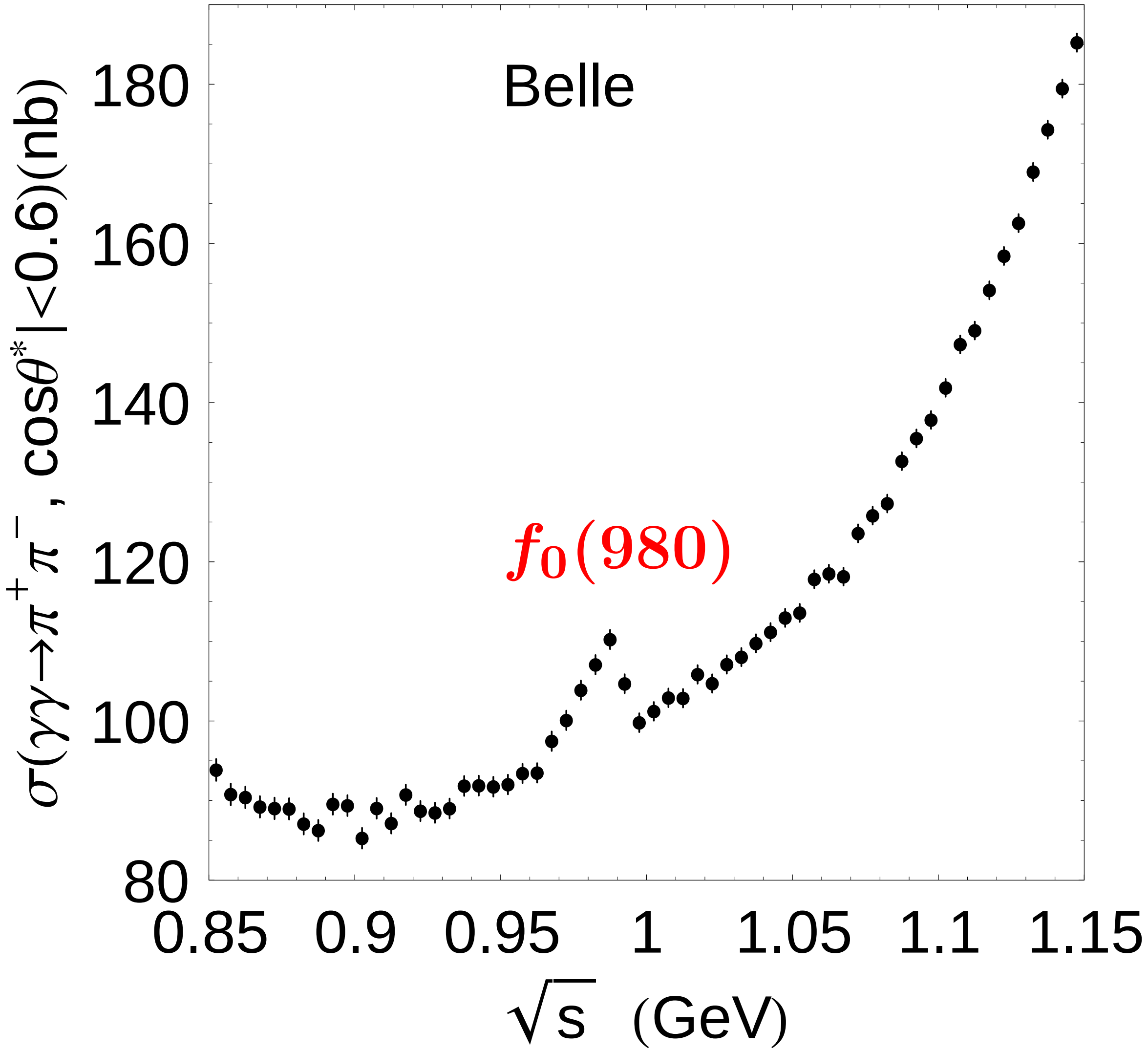
Only weak hints at the $f_0(980)$ production were obtained in these experiments.

The high-statistics Belle data on $\gamma\gamma \to \pi^+\pi^-$ (2007)



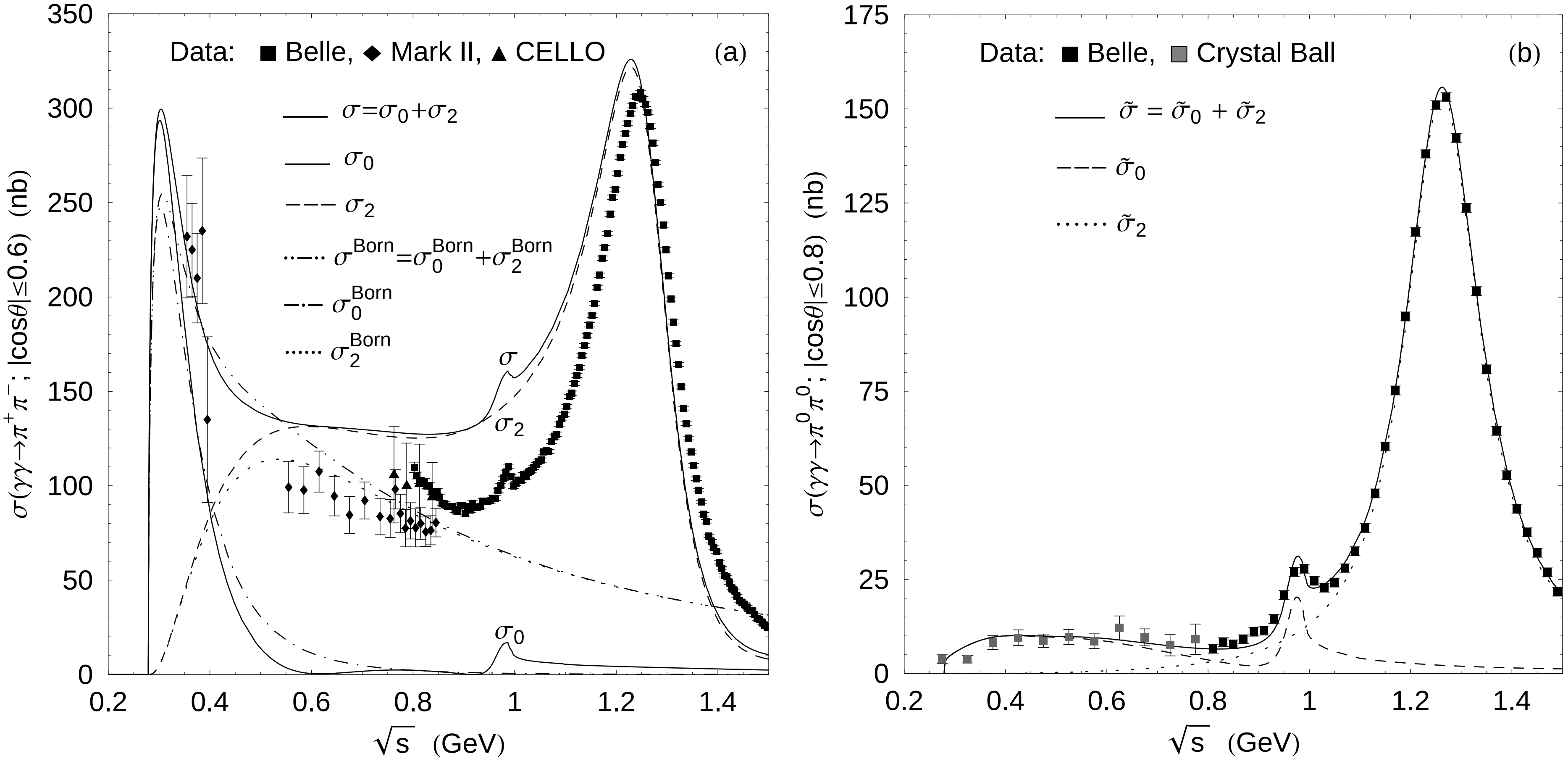
A clear signal from the $f_0(980)$ has been observed for the first time.

The high-statistics Belle data on $\gamma\gamma \to \pi^+\pi^-$ (2007)



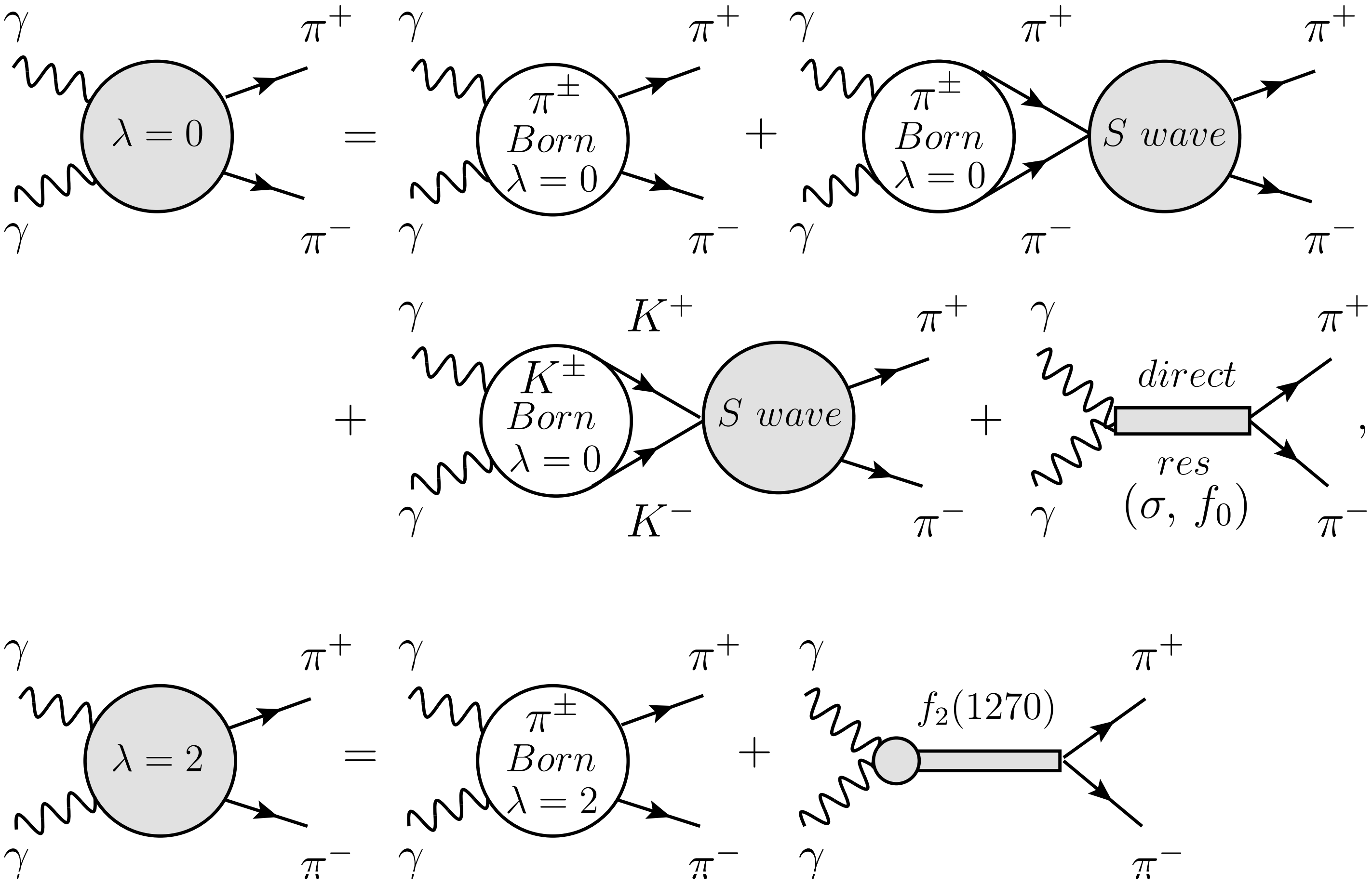
The same $f_0(980)$ signal with the threefold magnification.

The Belle data on $\gamma\gamma \to \pi^+\pi^-$ (2007) and $\gamma\gamma \to \pi^0\pi^0$ (2008)



The $f_0(980)$ in $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to \pi^0\pi^0$.

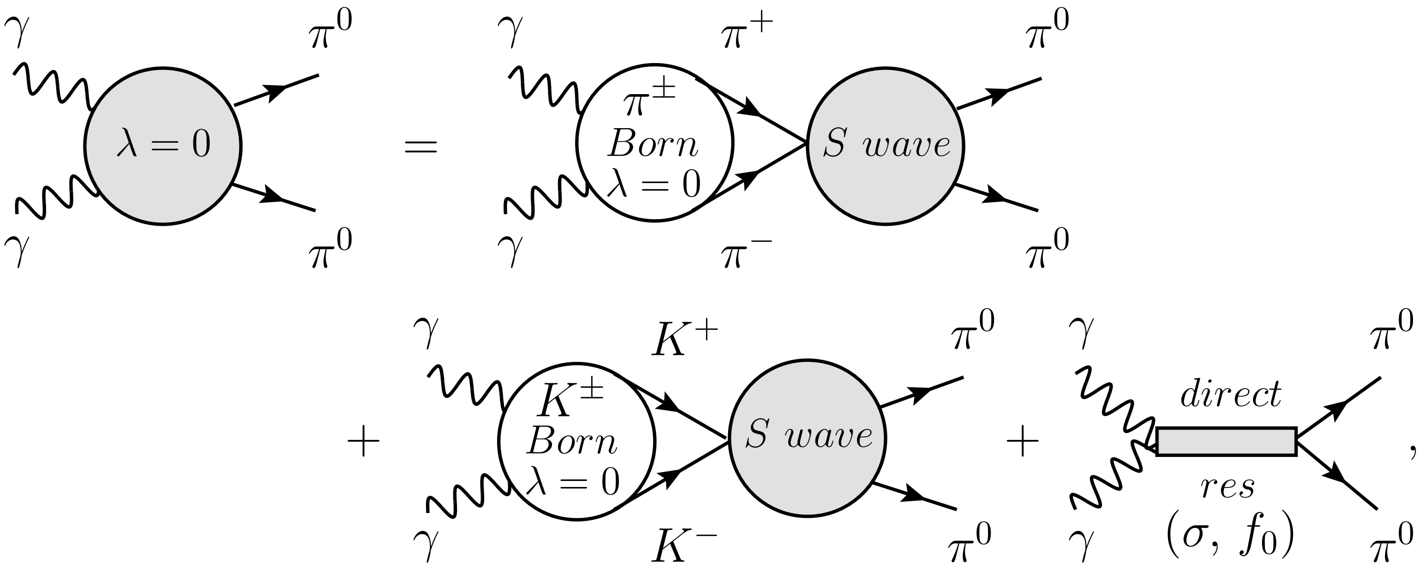
Dynamical model for the helicity amplitudes $\gamma\gamma \to \pi^+\pi^-$

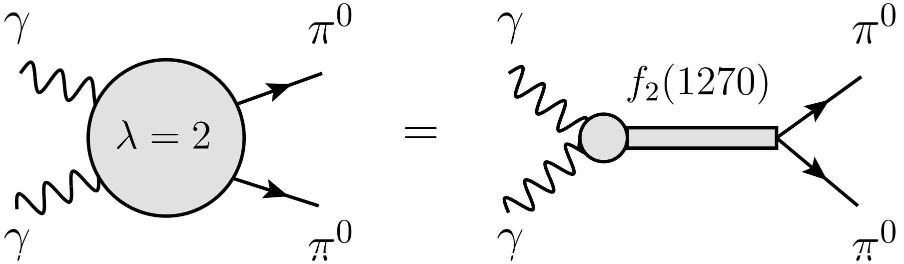


$$\text{Amplitude} = \text{Born} + \sum \text{Born} \times \text{Strong FSI} + \text{Direct}$$

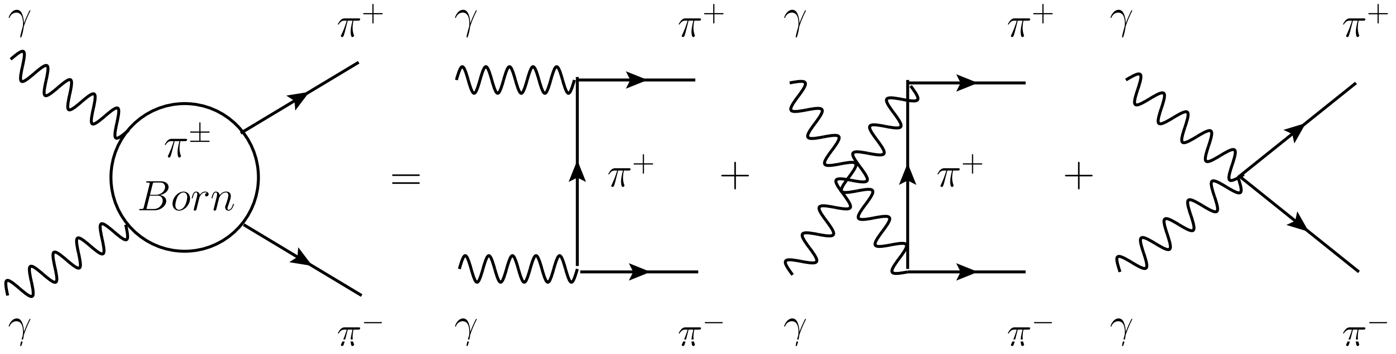
The amplitude satisfies the Watson theorem in the elastic region.

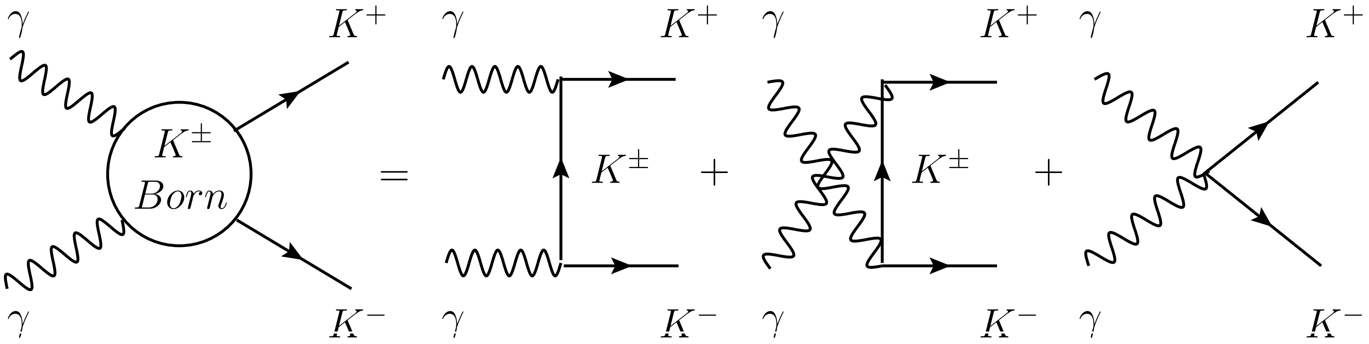
Dynamical model for the helicity amplitudes $\gamma\gamma \to \pi^0\pi^0$





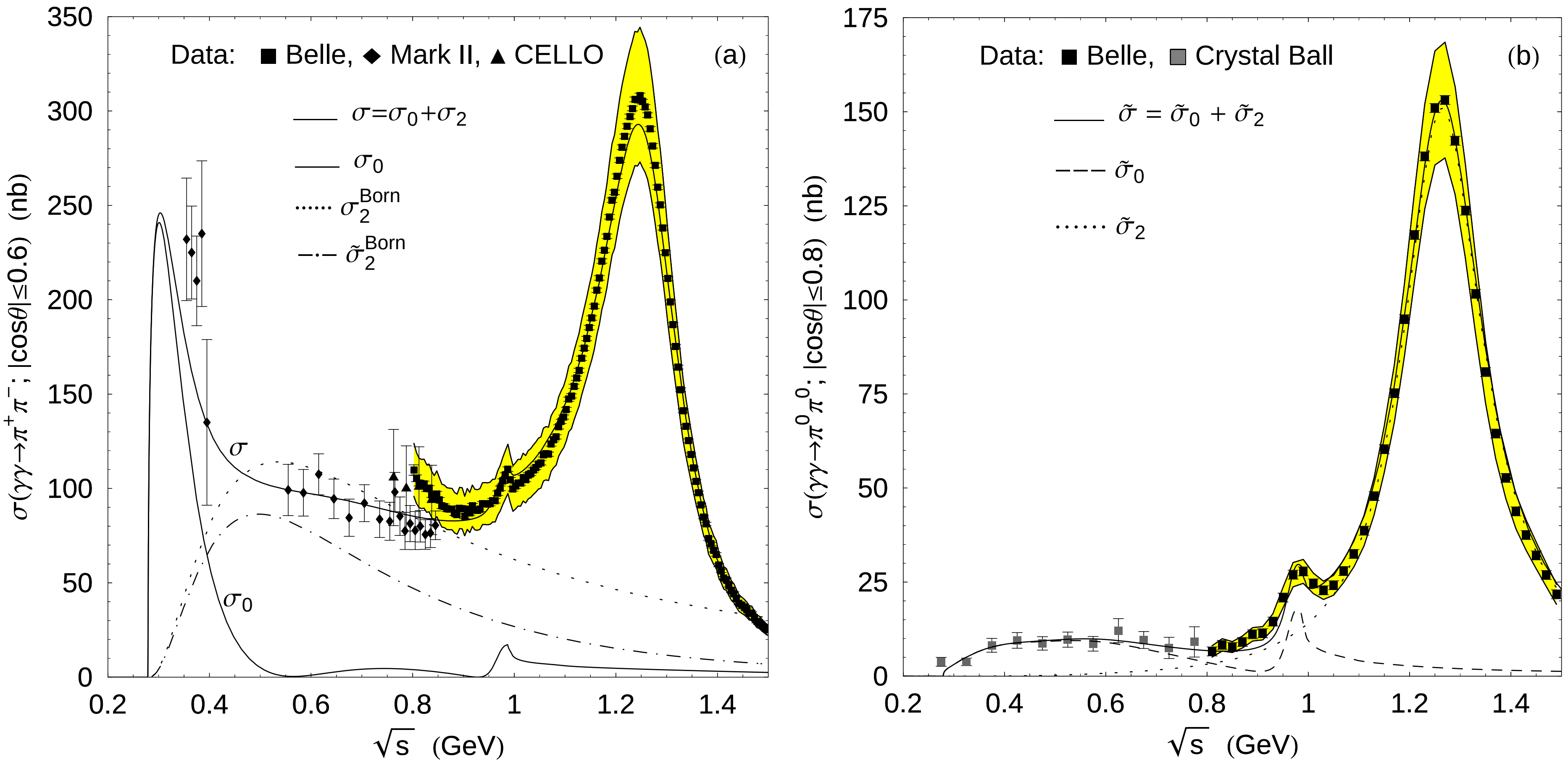
The $\pi^{\pm}$ and $K^{\pm}$ Born contributions





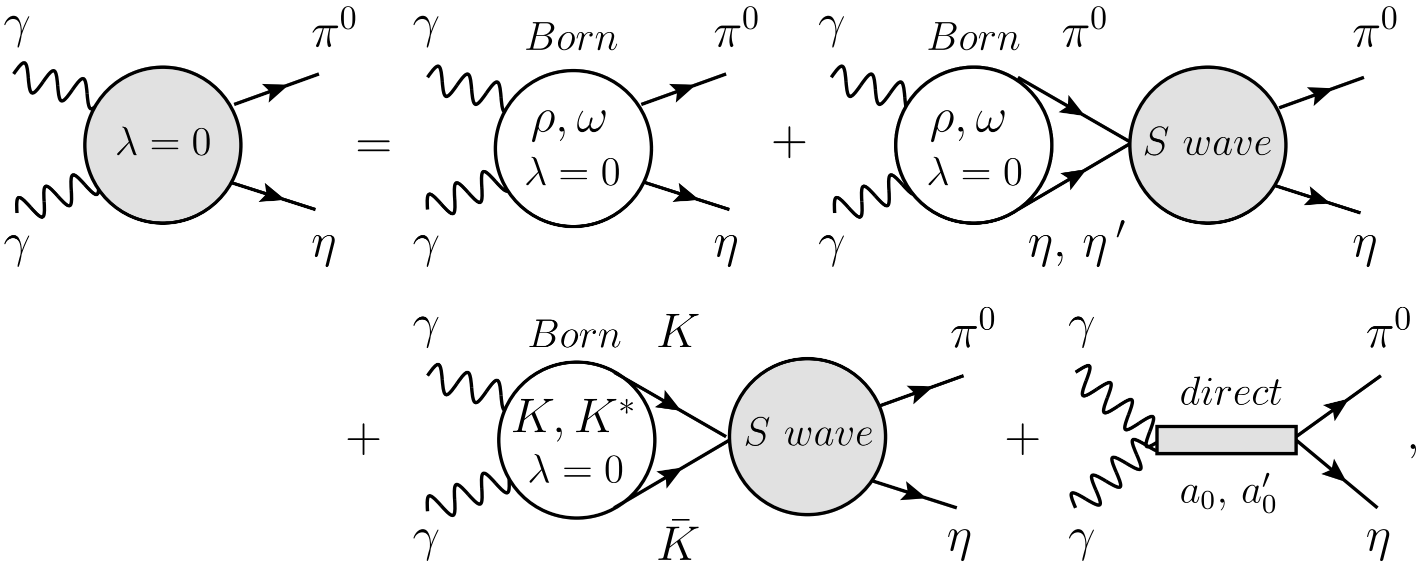
The elementary Born exchanges are modified by form factors.

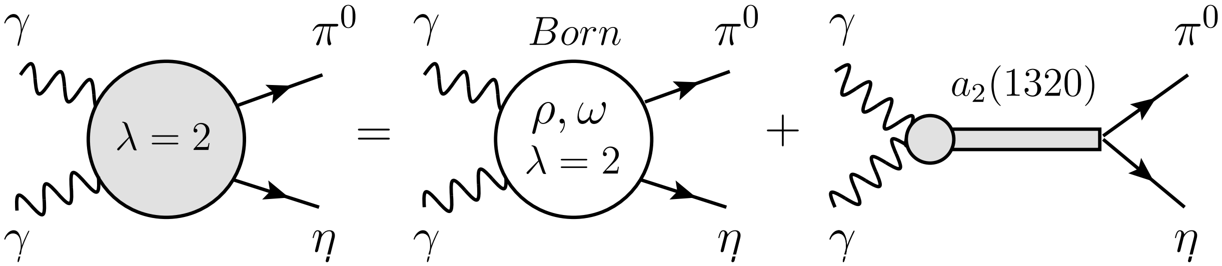
The simultaneous description of the Belle data on $\gamma\gamma \to \pi\pi$



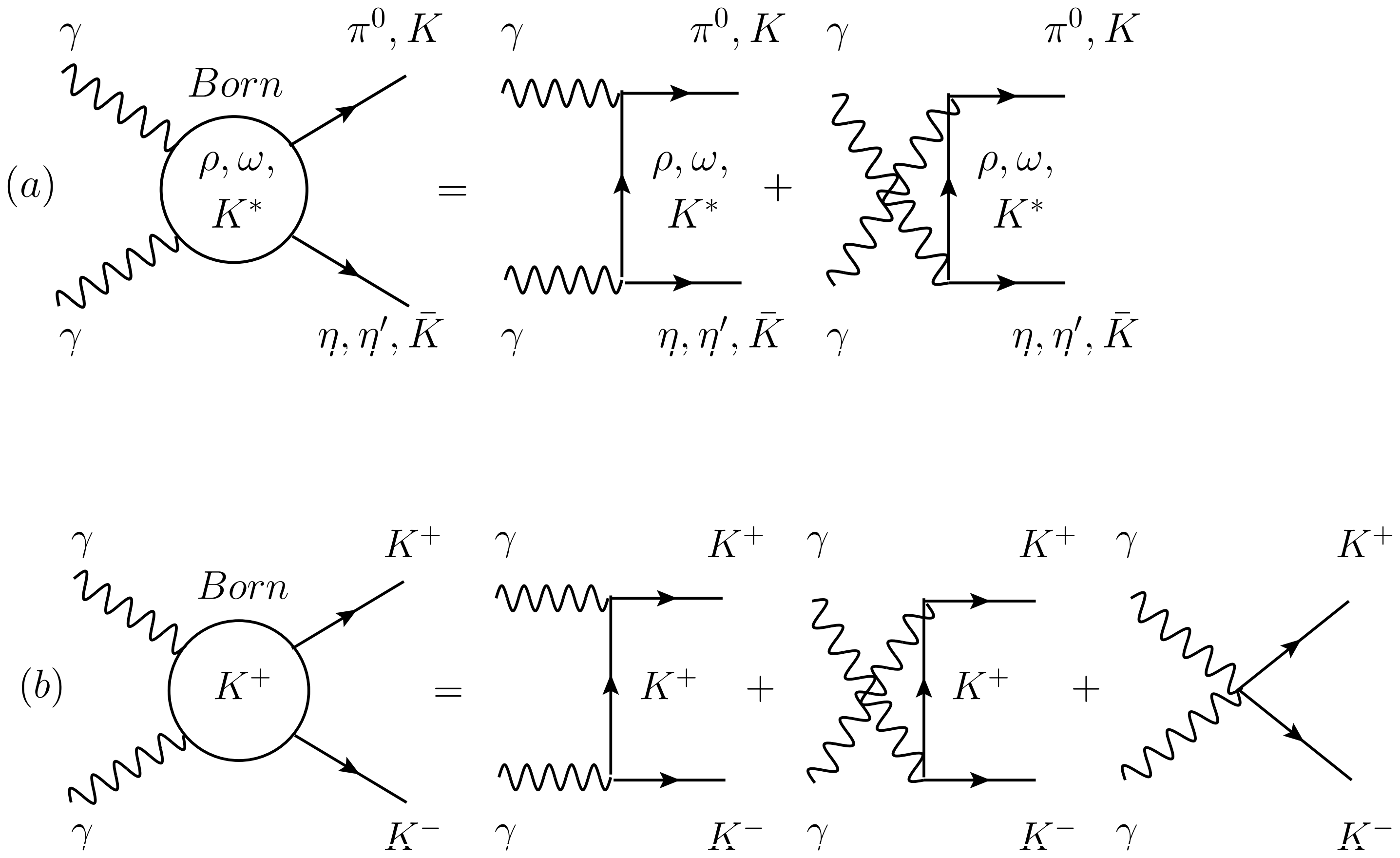
The yellow bands show the size of the systematic errors of the Belle data.

Dynamical model for the helicity amplitudes $\gamma\gamma \to \pi^0\eta$



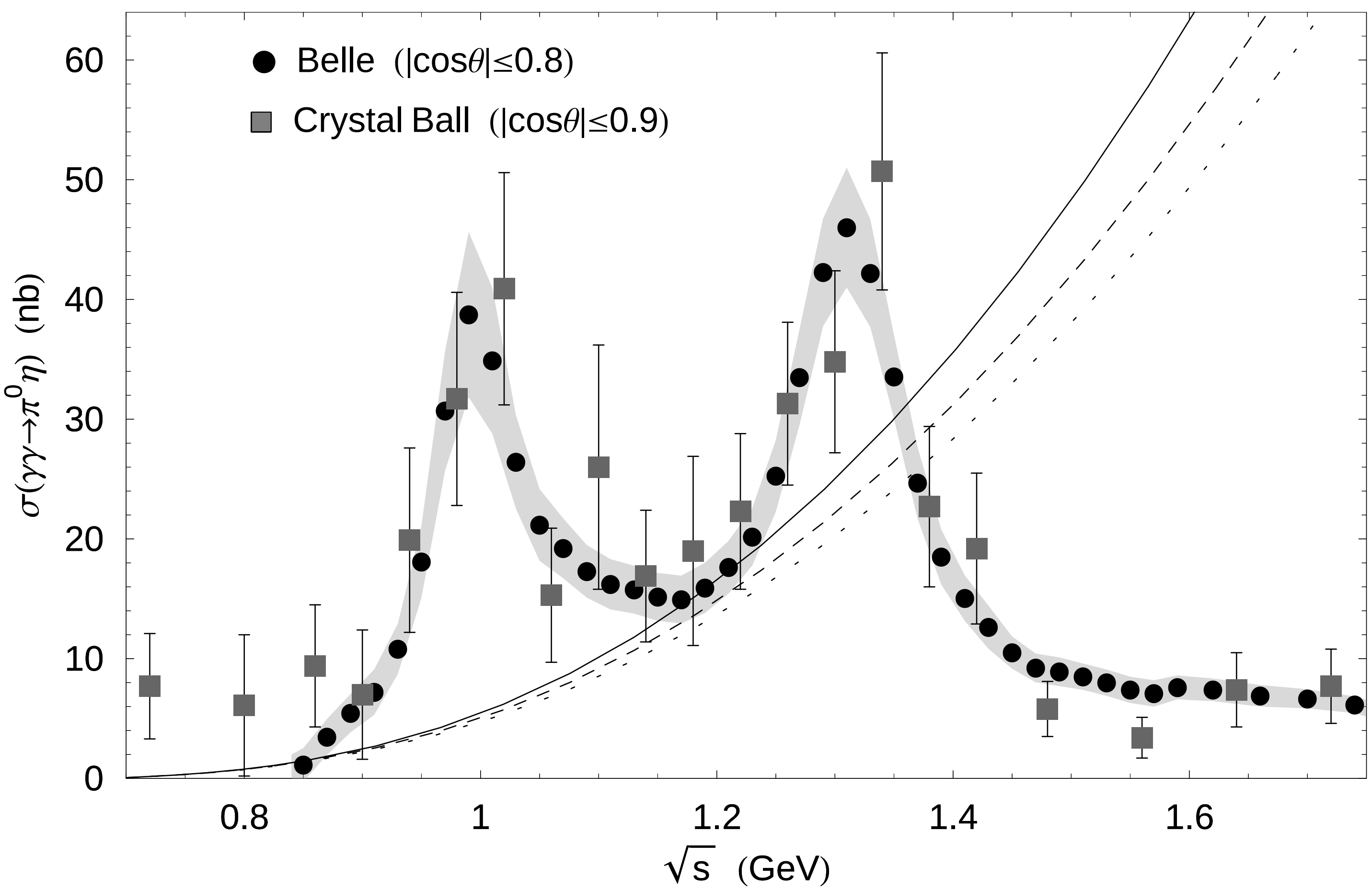


The ρ, ω, K^*, and K Born exchanges



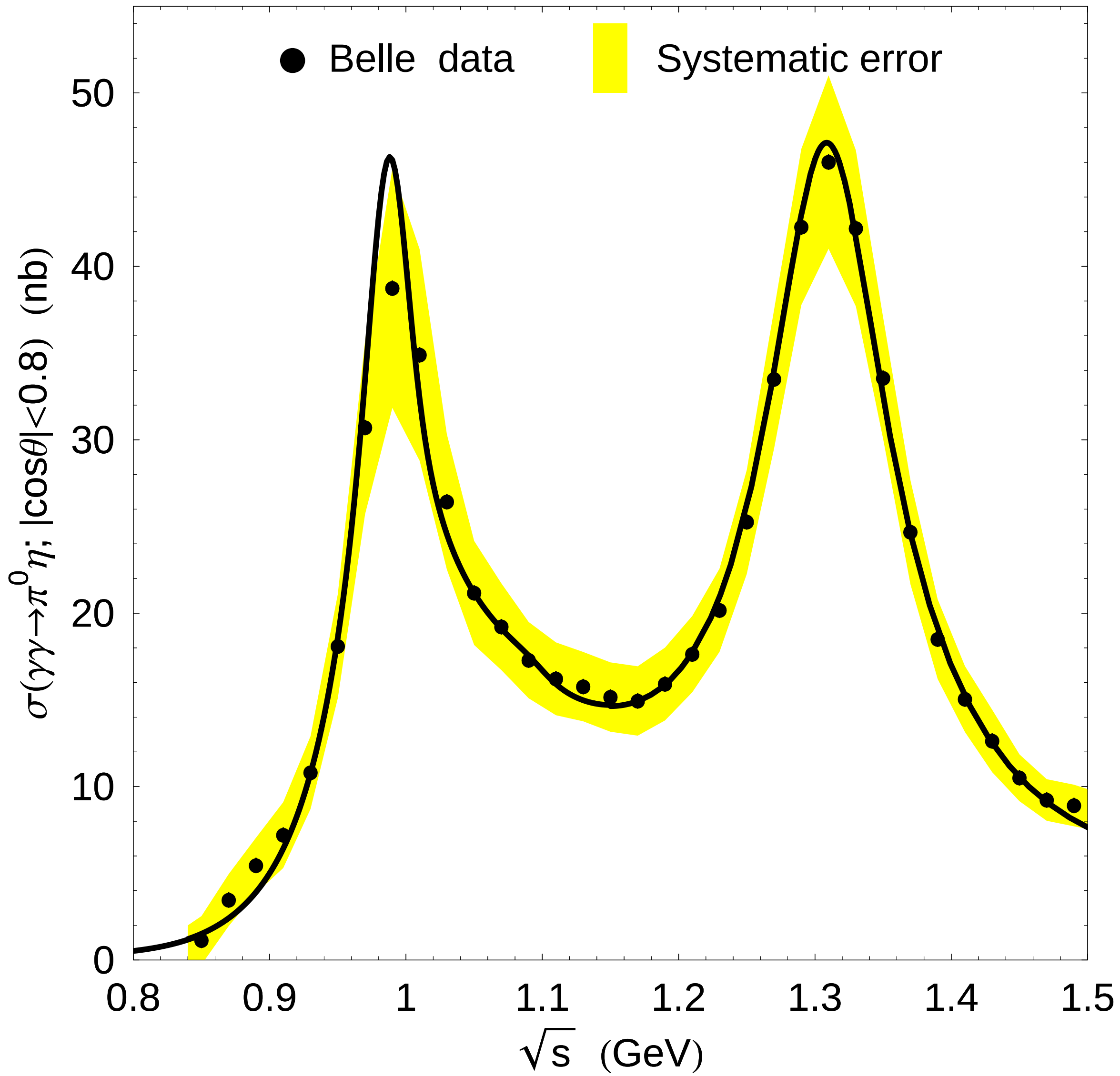
The elementary Born exchanges are modified by form factors.

The Belle and Crystal Ball data for the $\gamma\gamma \to \pi^0\eta$ cross section



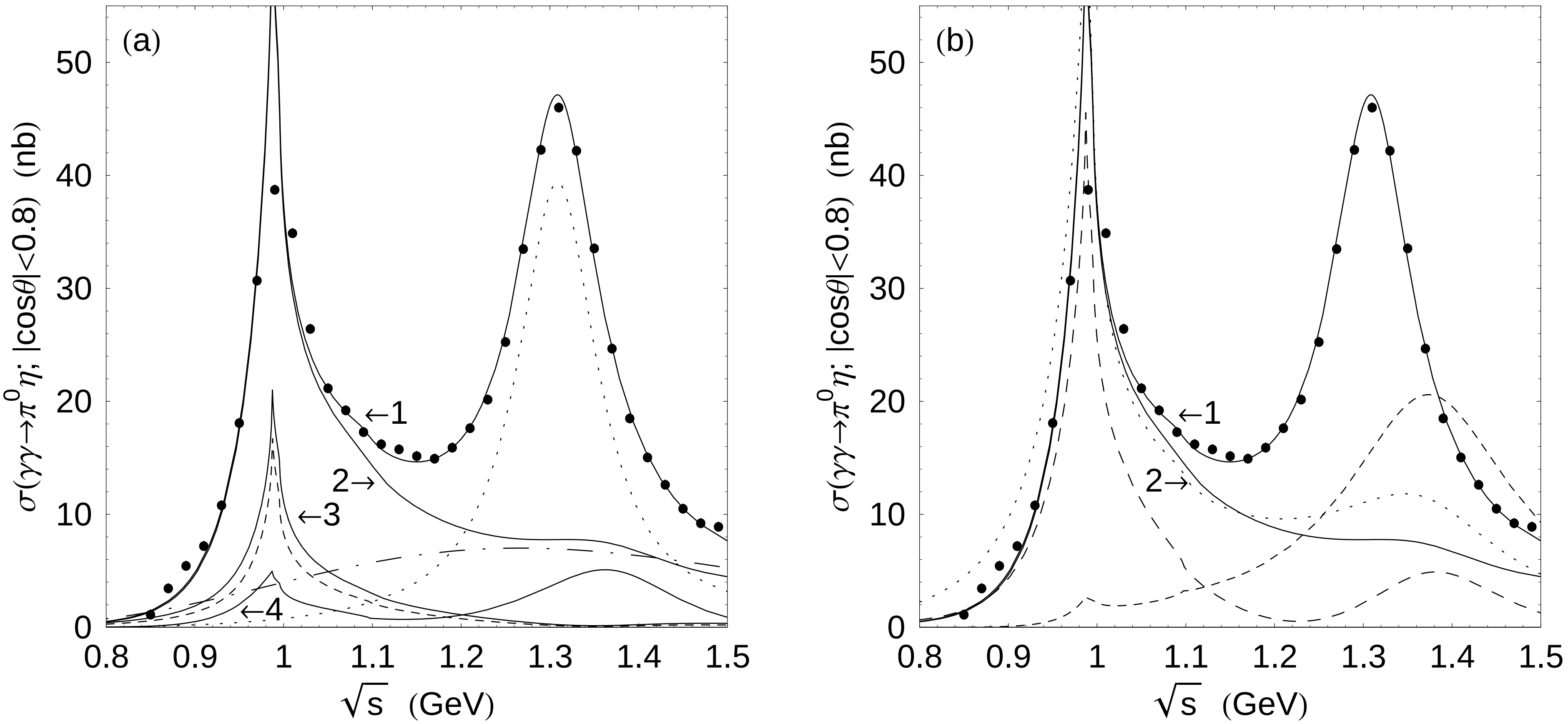
The solid, dashed, and dotted lines correspond to the total, helicity-0, and S wave $\gamma\gamma \to \pi^0\eta$ cross sections caused by the elementary ρ and ω exchanges for $|\cos\theta| \leq 0.8$.

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



The average statistical error of the Belle data is of about ± 0.4 nb.

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.

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

The inelastic rescattering $\gamma\gamma \to K^+K^- \to \pi^0\eta$ with K^+K^- produced via the charged one-kaon exchange mechanism This mechanism predicts the natural scale for the $a_0(980)$ production cross section in $\gamma\gamma \to \pi^0\eta$. The maximum of the cross section $\gamma\gamma \to K^+K^- \to a_0(980) \to \pi^0\eta$ is basically controlled by the product of the parameter $R_{a_0} = g^2_{a_0K^+K^-}/g^2_{a_0\pi\eta}$ and the value $|\widetilde{I}^{K^+}_{K^+K^-}(4m^2_{K^+})|^2$. Its estimate gives $\sigma(\gamma\gamma \to K^+K^- \to a_0(980) \to \pi^0\eta; |\cos\theta| \leq 0.8) \approx 0.8 \cdot 1.4\alpha^2 R_{a_0}/m^2_{a_0} \approx 24\,\text{nb} \cdot R_{a_0}$.

There is the noticeable additional narrowing of the $a_0(980)$ peak due to this mechanism in the $\gamma\gamma \to \pi^0\eta$ channel.

The K^* exchange narrows slightly the $a_0(980)$ peak.

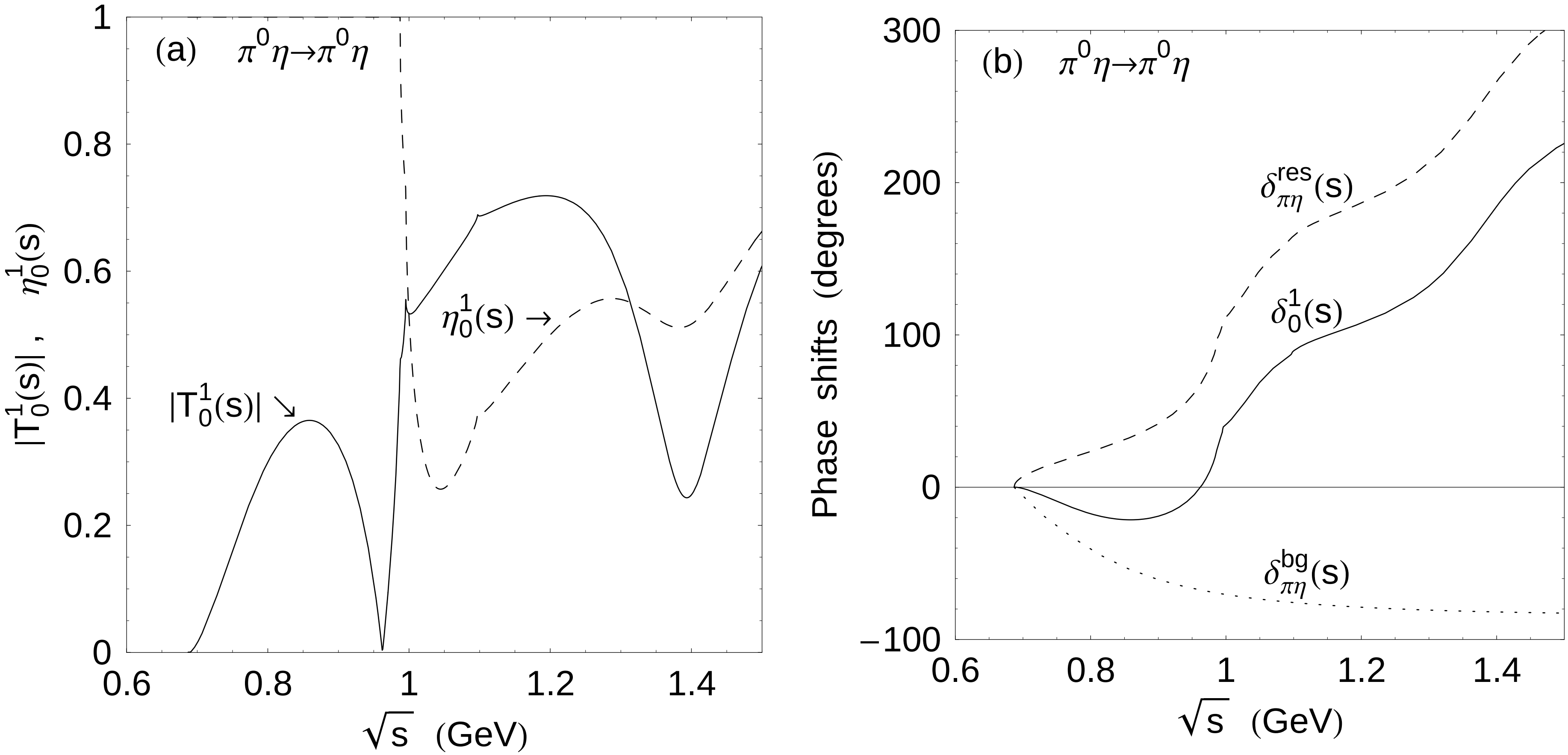
Main constituents of the $\gamma\gamma \to \pi^0\eta$ reaction mechanism

The $\gamma\gamma \to K\bar{K} \to \pi^0\eta$ rescattering mechanism alone cannot describe the data in the $a_0(980)$ resonance region.

The observed cross section can be obtain by adding the Born ρ and ω exchange contribution, modified by the S wave rescattering $\gamma\gamma \to (\pi^0\eta + \pi^0\eta') \to \pi^0\eta$, and the amplitude caused by the direct transitions of the a_0 and a_0' resonances into photons.

Each of the contributions of these two mechanisms are not too large in the $a_0(980)$ region. But the main thing is that their coherent sum with the contribution of the inelastic rescattering $\gamma\gamma \to K\bar{K} \to \pi^0\eta$ leads to the considerable enhancement of the $a_0(980)$ resonance manifestation.

Preliminary information on the S wave amplitude $\pi^0\eta \to \pi^0\eta$



One of the results of our analysis consists in the model information obtained for the first time on the S wave amplitude of the reaction $\pi^0\eta \longrightarrow \pi^0\eta$. The $\pi\eta$ scattering length a_0^1 consists with the chiral theory expectations $(0.005 - 0.01)m_\pi^{-1}$.

4. FUTURE TRENDS

1) The $f_0(980)$ and $a_0(980)$ in $\gamma\gamma \to K^+K^-$, $K^0\bar{K}^0$

- The Belle Collaboration has investigated the $\gamma\gamma \to \pi^+\pi^-$, $\gamma\gamma \to \pi^0\pi^0$, and $\gamma\gamma \to \pi^0\eta$ reactions with the highest statistics. However, similar information is still lacking for the processes $\gamma\gamma \to K^+K^-$ and $\gamma\gamma \to K^0\bar{K}^0$. The S wave contributions from the K^+K^- Born term, $f_0(980)$, and $a_0(980)$ resonances near thresholds of these two channels are not clearly understood. They can be measured with the Belle, L3, CLEO, and KLOE-2 detectors.

4. FUTURE TRENDS

2) The $\sigma(600)$, $f_0(980)$, and $a_0(980)$ in $\gamma\gamma^*$ collisions

- There are the promising possibility of investigating the nature of the light scalars in $\gamma\gamma^*$ collisions. If the $\sigma(600)$, $f_0(980)$, and $a_0(980)$ are $q^2\bar{q}^2$ states, their contributions to the $\gamma\gamma^* \to \pi\pi$ and $\gamma\gamma^* \to \pi^0\eta$ cross sections should decrease with increasing Q^2 more rapidly than the contributions from the classical tensor mesons $f_2(1270)$ and $a_2(1320)$. Recently, a similar behavior of the contribution from the $q^2\bar{q}^2$ exotic resonance state with $I^G = 2^+$ and $J^{PC} = 2^{++}$ to the $\gamma\gamma^* \to \rho^0\rho^0$ and $\gamma\gamma^* \to \rho^+\rho^-$ cross sections was observed by the L3 Collaboration.

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 $\gamma\gamma$, namely, the $q^2\bar{q}^2$ transitions $\sigma(600) \to \pi^+\pi^- \to \gamma\gamma$ and $f_0(980)/a_0(980) \to K^+K^- \to \gamma\gamma$, indicate their $q^2\bar{q}^2$ nature also.
- In addition, the absence of $J/\psi \to \gamma f_0(980)$, $\rho a_0(980)$, $\omega f_0(980)$ in contrast to the intensive $J/\psi \to \gamma f_2(1270)$, $\gamma f_2'(1525)$, $\rho a_2(1320)$, $\omega f_2(1270)$ decays intrigues against the P wave $q\bar{q}$ structure of the $a_0(980)$ and $f_0(980)$.

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Thank you !