Four-Quark Nature of Light Scalar Mesons

N. N. Achasov, [a] A. V. Kiselev, [b] and G. N. Shestakov [c]

[a]achasov@math.nsc.ru
[b]kiselev@math.nsc.ru
[c]shestako@math.nsc.ru

OVERTURE

Laboratory of Theoretical Physics,
S. L. Sobolev Institute for Mathematics,
630090, Novosibirsk, Russia

ABSTACT

It is shown that all predictions for the light scalars which are based on their four-quark nature are supported by experiment.

OUTLINE

The $a_0(980)$ and $f_0(980)$ mesons are well-established parts of the proposed light scalar meson nonet,

R. L. Workman *et al.* (Particle Data Group), Review of particle physics, Prog. Theor. Exp. Phys. 2022, 083C01 (2022).

From the beginning, the $a_0(980)$ and $f_0(980)$ mesons became one of the central problems of nonperturbative QCD, as they are important for understanding the way chiral symmetry is realized in the low-energy region and, consequently, for understanding confinement. Many experimental and theoretical papers have been devoted to this subject.

There is much evidence that supports the four-quark model of light scalar mesons,

R.L. Jaffe, Phys. Rev. D 15, 267 (1977), Phys. Rev. D 15, 281 (1977), S. Weinberg, Phys. Rev. Lett. 110, 261601 (2013).

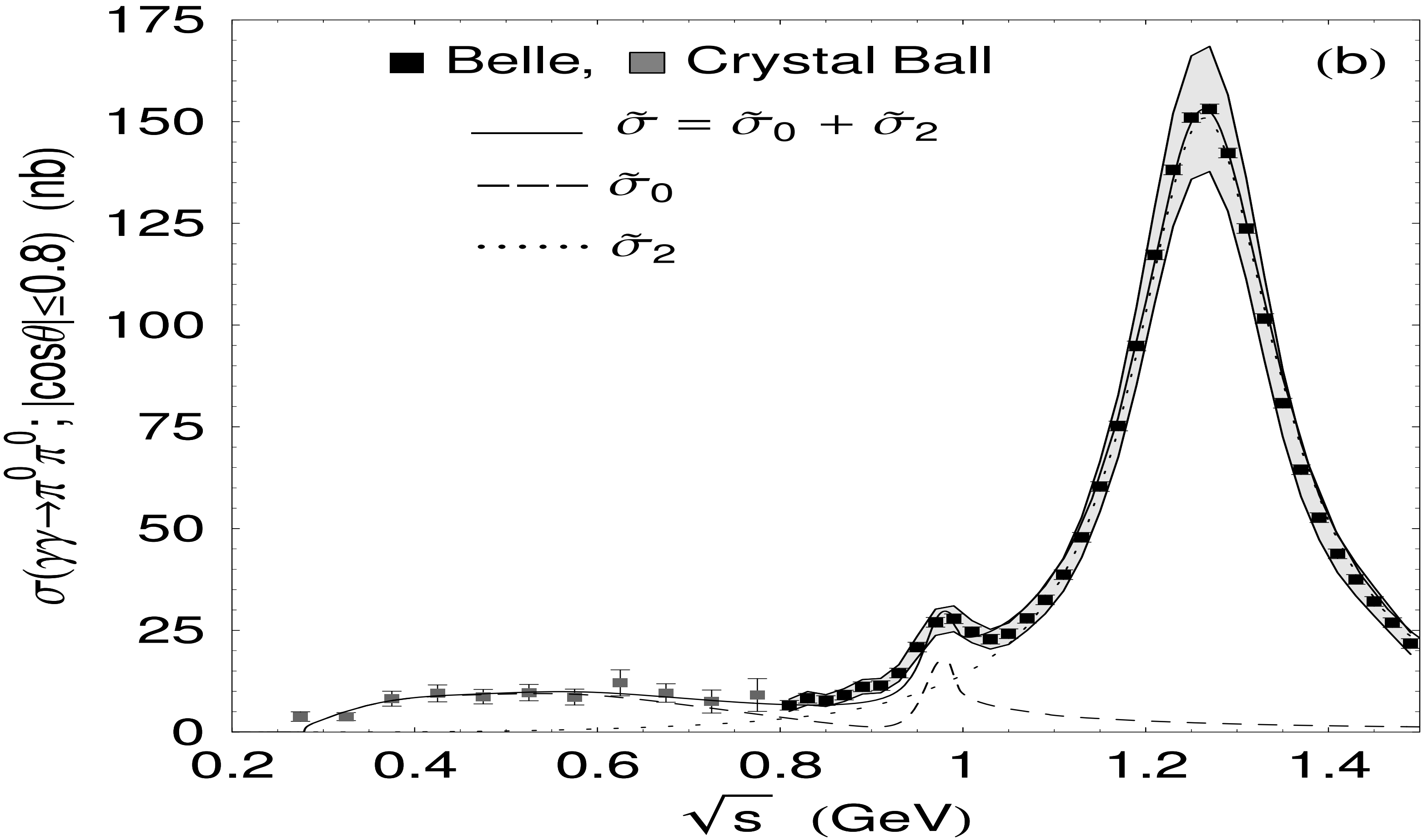
OUTLINE

The suppression of the $a_0^0(980)$ and $f_0(980)$ resonances in the $\gamma\gamma \to \eta\pi^0$ and $\gamma\gamma \to \pi\pi$ reactions, respectively, was predicted in 1982,N.N. Achasov, S.A. Devyanin, and G.N. Shestakov, Phys. Lett. B 108, 134 (1982), Z. Phys. C 16, 55 (1982),
$\Gamma_{a_0^0\gamma\gamma} \approx \Gamma_{f_0\gamma\gamma} \approx 0.27$ keV,
and confirmed by experiment,
M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).
The high quality Belle data,
Uehara et al. (Belle Collaboration), Phys. Rev. D 78, 052004 (2008), Phys. Rev. D 80, 032001 (2009),
allowed to elucidate the mechanisms of the $\sigma(600)$, $f_0(980)$, and $a_0^0(980)$ resonance production in $\gamma\gamma$ collisions confirmed their four-quark structure.

OUTLINE

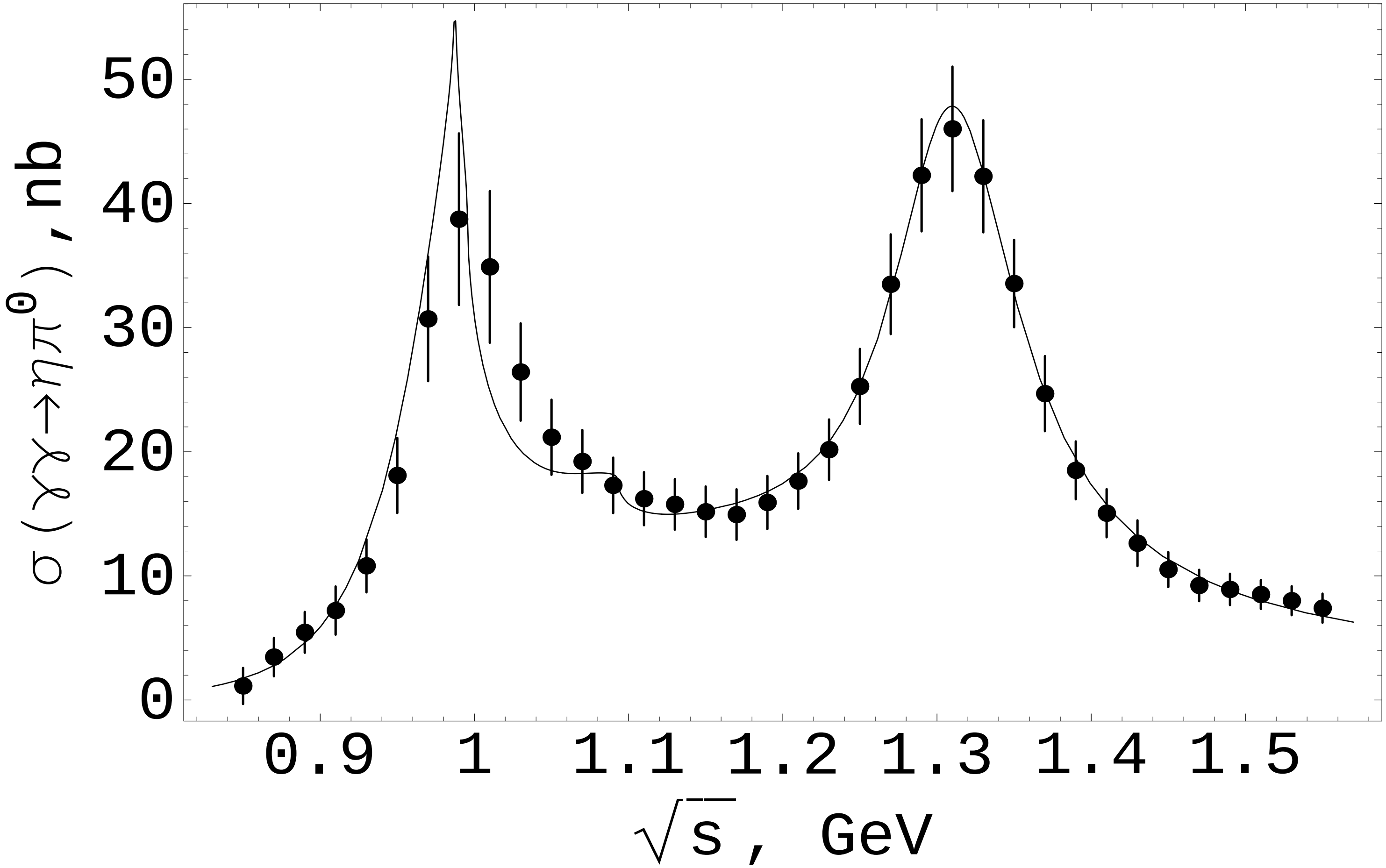
Light scalar mesons are produced in $\gamma\gamma$ collisions mainly via rescatterings, that is, via the four-quark transitions. As for $a_2(1320)$ and $f_2(1270)$ (the well-known $q\bar{q}$ states), they are produced mainly via the two-quark transitions (direct couplings with $\gamma\gamma$),
N.N. Achasov and G.N. Shestakov, Z. Phys. C 41, 309 (1908), Phys. Rev. D 77, 074020 (2008), Phys. Rev. D 81, 094029 (2010), Usp. Fiz. Nauk 54, 799 (2011),
N.N. Achasov and A.V. Kiselev, Phys. Rev. D 98, 096009 (2018).
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. 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.

OUTLINE



N.N. Achasov and G.N. Shestakov, Phys. Rev. D 77, 074020 (2008), Usp. Fiz. Nauk 54, 799 (2011).

OUTLINE



N.N. Achasov and A.V. Kiselev, Phys. Rev. D 98, 096009 (2018).

OUTLINE

Note also that the absence of $J/\psi \to \gamma f_0(980),\ \rho a_0(980),\ \omega f_0(980)$ decays in the presence of the intense $J/\psi \to \gamma f_2(1270),\ \gamma f_2'(1525),\ \rho a_2(1320),\ \omega f_2(1270)$ decays is at variance with the P-wave two-quark, $q\bar{q}$, structure of $a_0(980)$ and $f_0(980)$ resonances,

N.N. Achasov, Phys. Usp. 41, 1149 (1998), Phys. At. Nucl. 65, 546 (2002).

OUTLINE

The argument in favor of the four-quark nature of $a_0(980)$ and $f_0(980)$ is the fact that the $\phi(1020) \to a_0^0\gamma$ and $\phi(1020) \to f_0\gamma$ decays go through the kaon loop: $\phi \to K^+K^- \to a_0^0\gamma$, $\phi \to K^+K^- \to f_0\gamma$, i.e., via the four-quark transition,

N.N. Achasov and V.N. Ivanchenko, Nucl. Phys. B 315, 465 (1989),
N.N. Achasov, Nucl. Phys. A 728, 425 (2003),
N.N. Achasov and V.V. Gubin, Phys. Rev. D 63, 094007 (2001),
Phys. Rev. D 56, 4084 (1997),
N.N. Achasov and A.V. Kiselev, Phys. Rev. D 73, 054029 (2006),
Phys. Rev. D 68, 014006 (2003).

OUTLINE

The kaon-loop model was suggested in Ref.
N.N. Achasov and V.N. Ivanchenko, Nucl. Phys. B 315, 465 (1989)
and confirmed by experiment ten years later,
M.N. Achasov $et\ al.$ (SND Collaboration), Phys. Lett. B 438, 441 (1998), Phys. Lett. B 479, 53 (2000), Phys. Lett. B 440, 442 (1998), Phys. Lett. B 485, 349 (2000),
R.R. Akhmetshin $et\ al.$ (CMD-2 Collaboration) Phys. Lett. B 462, 380 (1999),
A.Aloisio $et\ al.$ (KLOE Collaboration), Phys. Lett. B 536, 209 (2002), Phys. Lett. B 537, 21 (2002),
F. Ambrosino $et\ al.$ (KLOE Collaboration), Phys. Lett. B 681, 5 (2009).

OUTLINE

It was shown in Ref.

N.N. Achasov, Nucl. Phys. A 728, 425 (2003)

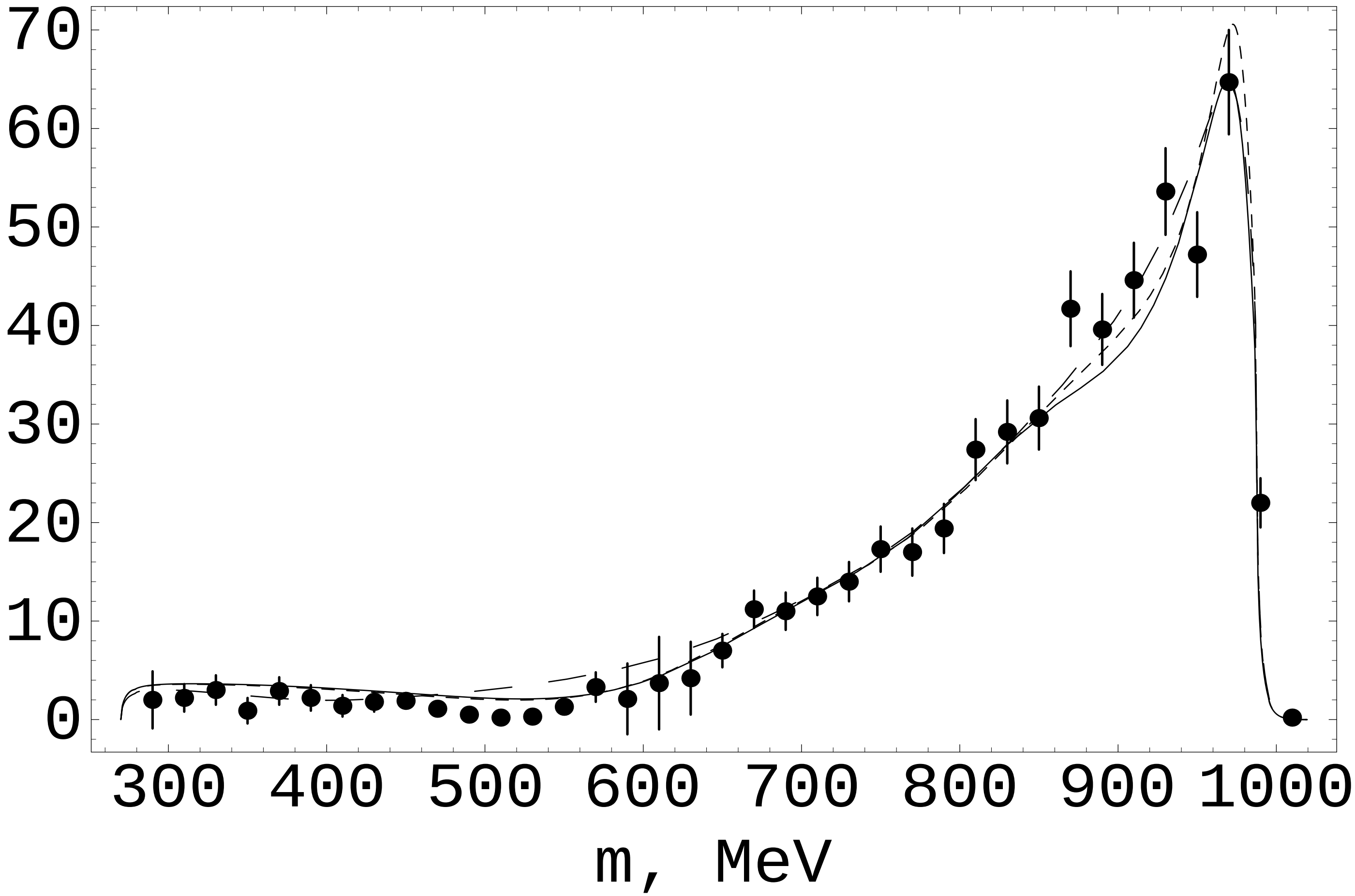
that the production of $a_0^0(980)$ and $f_0(980)$ in $\phi\to a_0^0\gamma\to\eta\pi^0\gamma$ and $\phi\to f_0\gamma\to\pi^0\pi^0\gamma$ decays is caused by the four-quark transitions, resulting in strong restrictions on the large-N_C expansion of the decay amplitudes. The analysis showed that these constraints give new evidence in favor of the four-quark nature of the $a_0(980)$ and $f_0(980)$ mesons.

OUTLINE

In Refs.
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), Phys. Rev. D 78, 058502 (2008)
it was shown that the description of the $\phi \to K^+K^- \to \gamma a_0^0(980)/f_0(980)$ decays requires virtual momenta of $K(\bar{K})$ greater than 2 GeV, while in the case of loose molecules with a binding energy about 20 MeV, they would have to be 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).

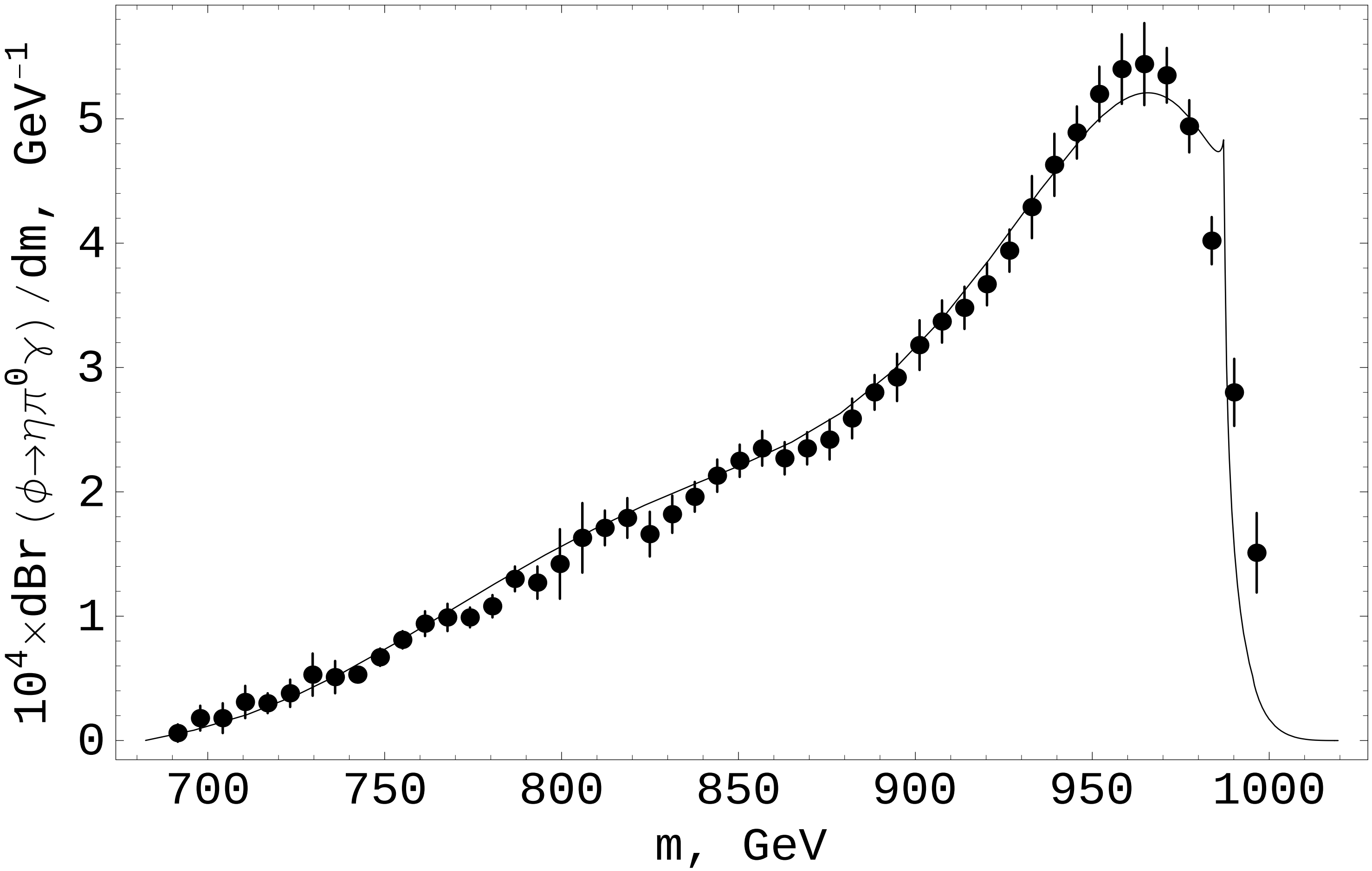
OUTLINE

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



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

OUTLINE



N.N. Achasov and A.V. Kiselev, Phys. Rev. D 98, 096009 (2018).

OUTLINE

It was also shown in Refs.

N.N. Achasov and G.N. Shestakov, Phys. Rev. D 49, 5779 (1994), Phys. Rev. Lett. 99, 072001 (2007)

that the linear $S_L(2) \times S_R(2)$ σ model,

M. Gell-Mann and M. Levy, Nuovo Cimento 16, 705 (1960),

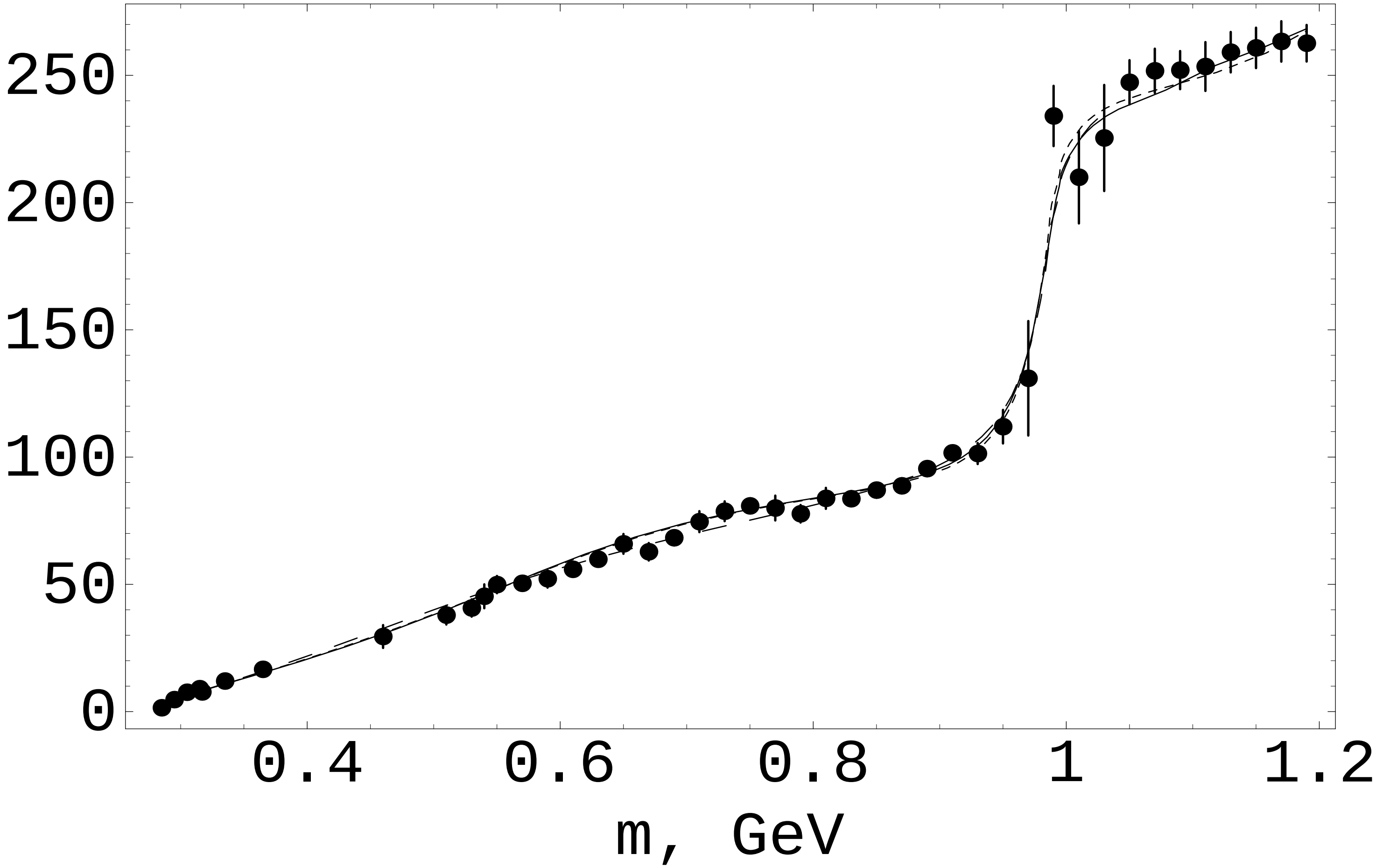
contains a chiral shielding of the σ meson and reflects all of the main features of low-energy $\pi\pi \to \pi\pi$ and $\gamma\gamma \to \pi\pi$ reactions up to energy 0.8 GeV and agrees with the four-quark nature of the σ meson.

OUTLINE

This allowed for the development of a phenomenological model with the right analytical properties in the complex s plane that took into account the linear σ model, the $\sigma(600) - f_0(980)$ mixing and the background,
N.N. Achasov and A.V. Kiselev, Phys. Rev. D 83, 054008 (2011), Phys. Rev. D 85, 094016 (2012).
This background has a left cut inspired by crossing symmetry, and the resulting amplitude agrees with results obtained using the chiral expansion, dispersion relations, and the Roy equation,
I. Caprini, G. Colangelo and H. Leutwyler, Phys. Rev. Lett. 96, 132001 (2006),
and with the four-quark nature of the $\sigma(600)$ and $f_0(980)$ mesons as well. This model well describes the experimental data on $\pi\pi \to \pi\pi$ scattering up to 1.2 GeV.

OUTLINE

The phase δ_0^0 of the $\pi\pi$ scattering (degrees) is shown.



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

OUTLINE

It is shown in Refs.

N.N. Achasov and A.V. Kiselev, Phys. Rev. D 97, 036015 (2018), Phys. Rev. D 98, 096009 (2018)

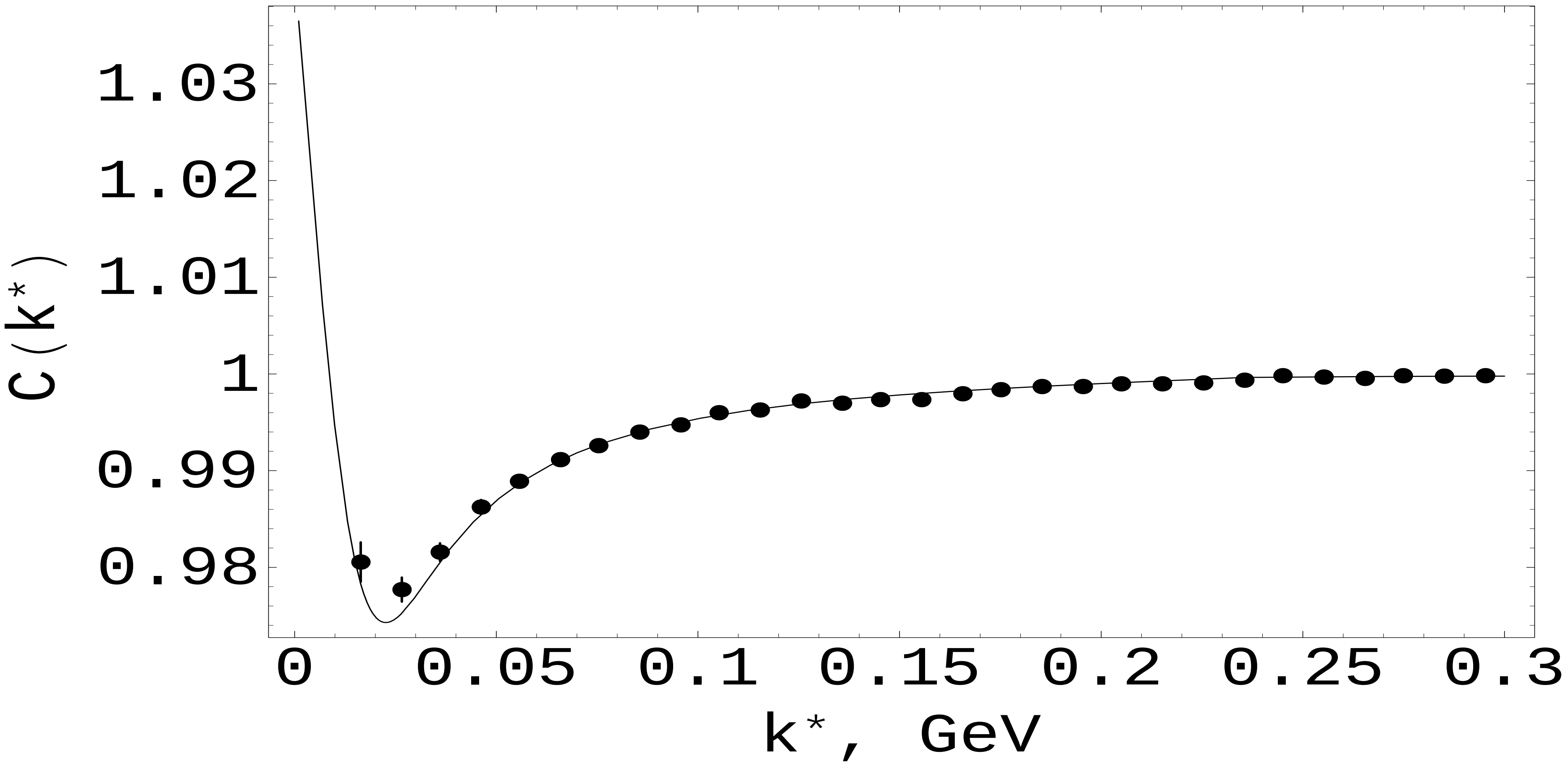
that the recent data on the $K_S^0 K^+$ correlation in Pb-Pb interactions Ref.

S. Acharya $et\ al.$ (ALICE Collaboration), Phys. Lett. B 774, 64 (2017)

agree with the data on the $\gamma\gamma \to \eta\pi^0$ and $\phi \to \eta\pi^0\gamma$ reactions and support the four-quark model of the $a_0(980)$ meson. It is shown that the data does not contradict the validity of the Gaussian assumption.

OUTLINE

The $K_S^0 K^+$ correlation



N.N. Achasov and A.V. Kiselev, Phys. Rev. D 98, 096009 (2018).

OUTLOOK

In Refs.

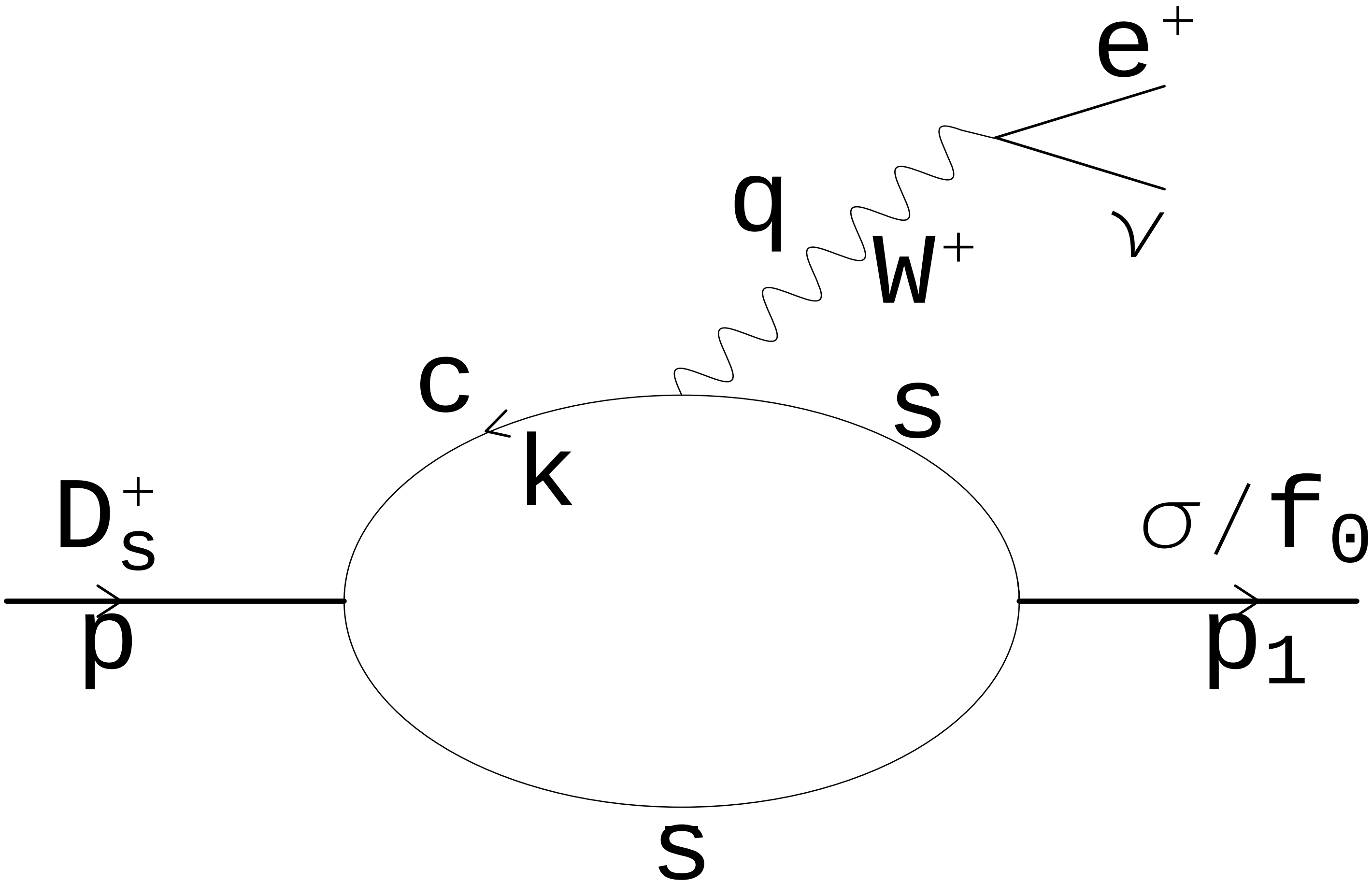
N.N. Achasov and A.V. Kiselev, Phys. Rev. D 86, 114010 (2012), Int. J. Mod. Phys. Conf. Ser. 35, 1460447 (2014)

it was suggested the program of studying light scalars in semileptonic D and B decays, which are the unique probe of the $q\bar{q}$ constituent pair in the light scalars. We studied the CLEO data about production of scalars $\sigma(600)$ and $f_0(980)$ in the $D_s^+ \to s\bar{s}\, e^+\nu_e \to \pi^+\pi^-\, e^+\nu$ decays, the conclusion was that the fraction of the $s\bar{s}$ constituent components in $\sigma(600)$ and $f_0(980)$ is small. Unfortunately, the CLEO statistics

K.M Ecklund $et\ al$. (CLEO Collaboration), Phys. Rev. D 80, 052009 (2009)

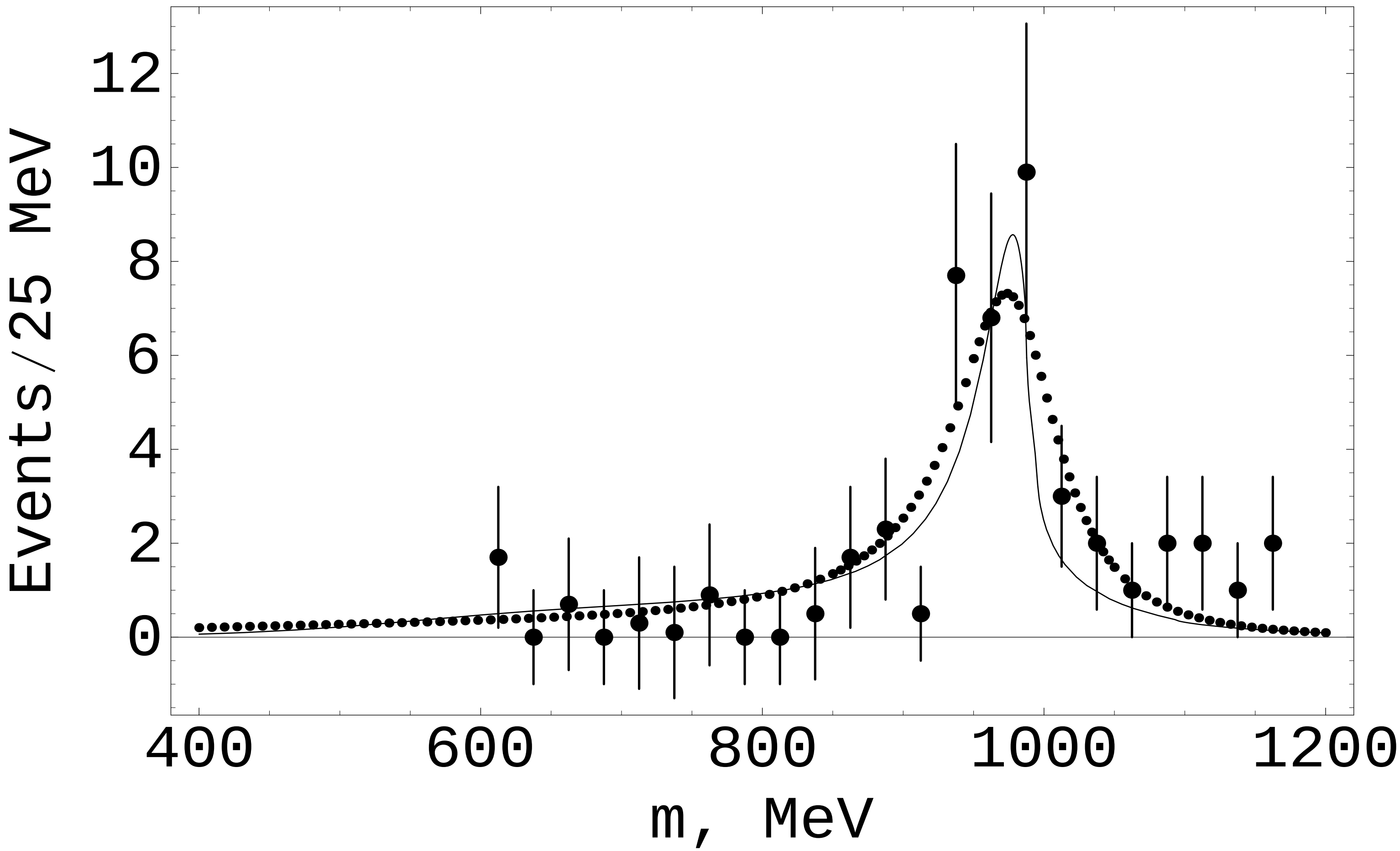
is rather poor, and thus new high-statistics data are highly desirable.

OUTLOOK



OUTLOOK

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



N.N. Achasov and A.V. Kiselev, Phys. Rev. D 86, 114010 (2012)

OUTLOOK

It was noted in Refs.

N.N. Achasov and A.V. Kiselev, Phys. Rev. D 86, 114010 (2012), Int. J. Mod. Phys. Conf. Ser. 35, 1460447 (2014)

that no less interesting is the study of semileptonic decays of D^0 and D^+ mesons:

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

$$D^0 \to d\bar{u}\, e^+\nu_e \to a_0^- e^+\nu_e \to \pi^-\eta e^+\nu_e \text{ and}$$

$$D^+ \to d\bar{d}\, e^+\nu_e \to a_0^0 e^+\nu_e \to \pi^0\eta e^+\nu_e$$

or the charged-conjugated ones which had not been investigated.

OUTLOOK

It is very tempting to study light scalar mesons in semileptonic decays of B mesons

N.N. Achasov and A.V. Kiselev, Int. J. Mod. Phys. Conf. Ser. 35, 1460447 (2014):

$$B^0 \to d\bar{u}\, e^+\nu_e \to a_0^- e^+\nu_e \to \pi^-\eta e^+\nu_e,$$

$$B^+ \to u\bar{u}\, e^+\nu_e \to a_0^0 e^+\nu_e \to \pi^0\eta e^+\nu_e,$$

$$B^+ \to u\bar{u}\, e^+\nu_e \to [\sigma(600) + f_0(980)]e^+\nu_e \to \pi^+\pi^- e^+\nu_e$$

or the charged-conjugated ones.

OUTLOOK

Recently BESIII Collaboration measured the decays

$D^0 \to d\bar{u}\, e^+\nu \to a_0^- e^+\nu \to \pi^-\eta e^+\nu$ and

$D^+ \to d\bar{d}\, e^+\nu \to a_0^0 e^+\nu \to \pi^0\eta e^+\nu$ for the first time

M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. 121, 081802 (2018).

In Ref.

N.N. Achasov and A.V. Kiselev, Phys. Rev. D 98, 096009 (2018)

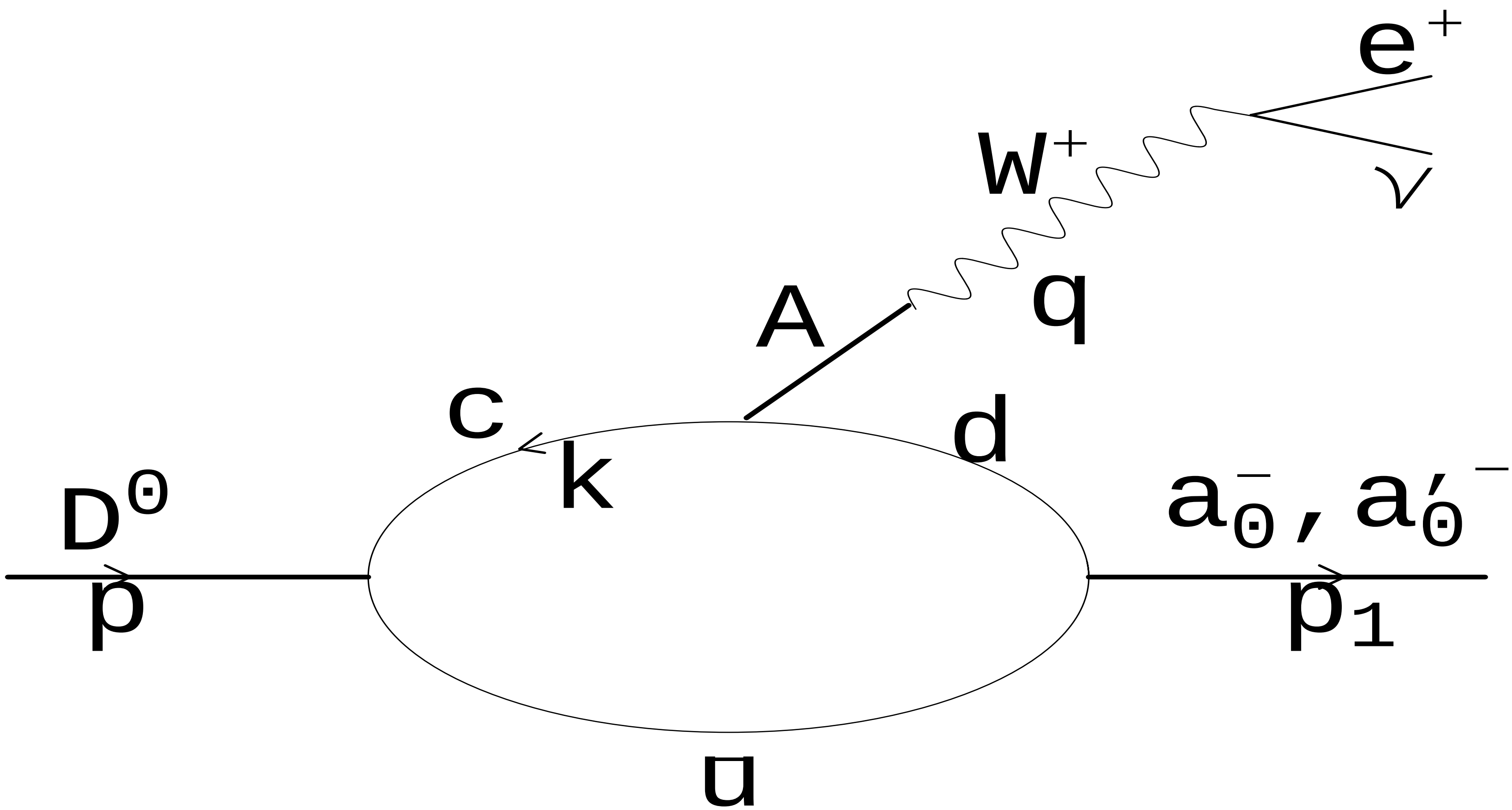
we discuss these measurements taking into account also contribution of a_0' meson with mass about 1400 MeV.

OUTLOOK

Below is presented a variant when $a_0^-(980)$ has no $q\bar{q}$ constituent component at all, that is, $a_0^-(980)$ is produced as a result of mixing $a_0'^-(1400) \to a_0^-(980)$,

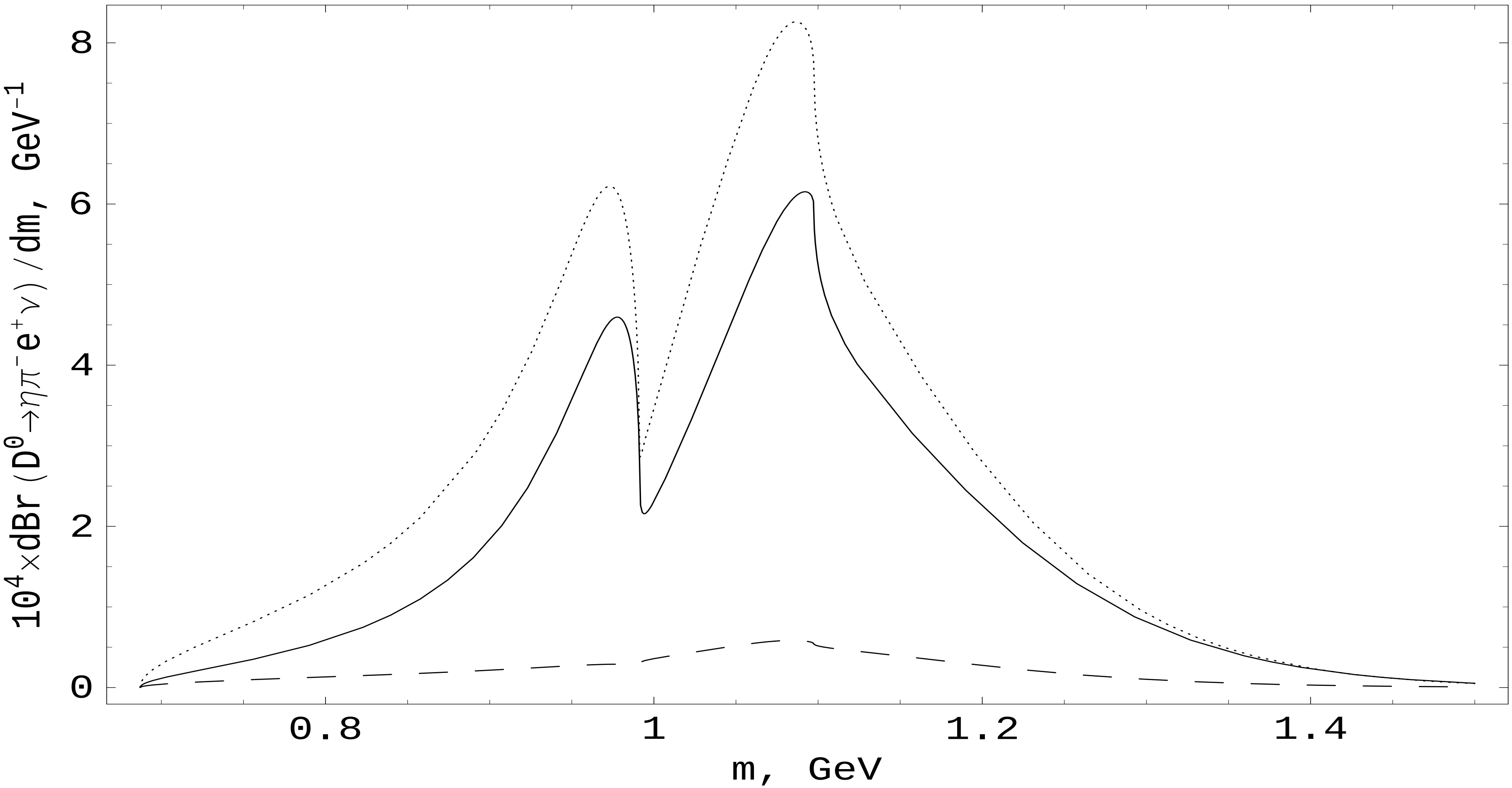
$D^0 \to d\bar{u}\, e^+\nu_e \to a_0'^- e^+\nu_e \to a_0^- e^+\nu_e \to \pi^-\eta e^+\nu_e$.

OUTLOOK



N.N. Achasov and A.V. Kiselev, Phys. Rev. D 98, 096009 (2018).

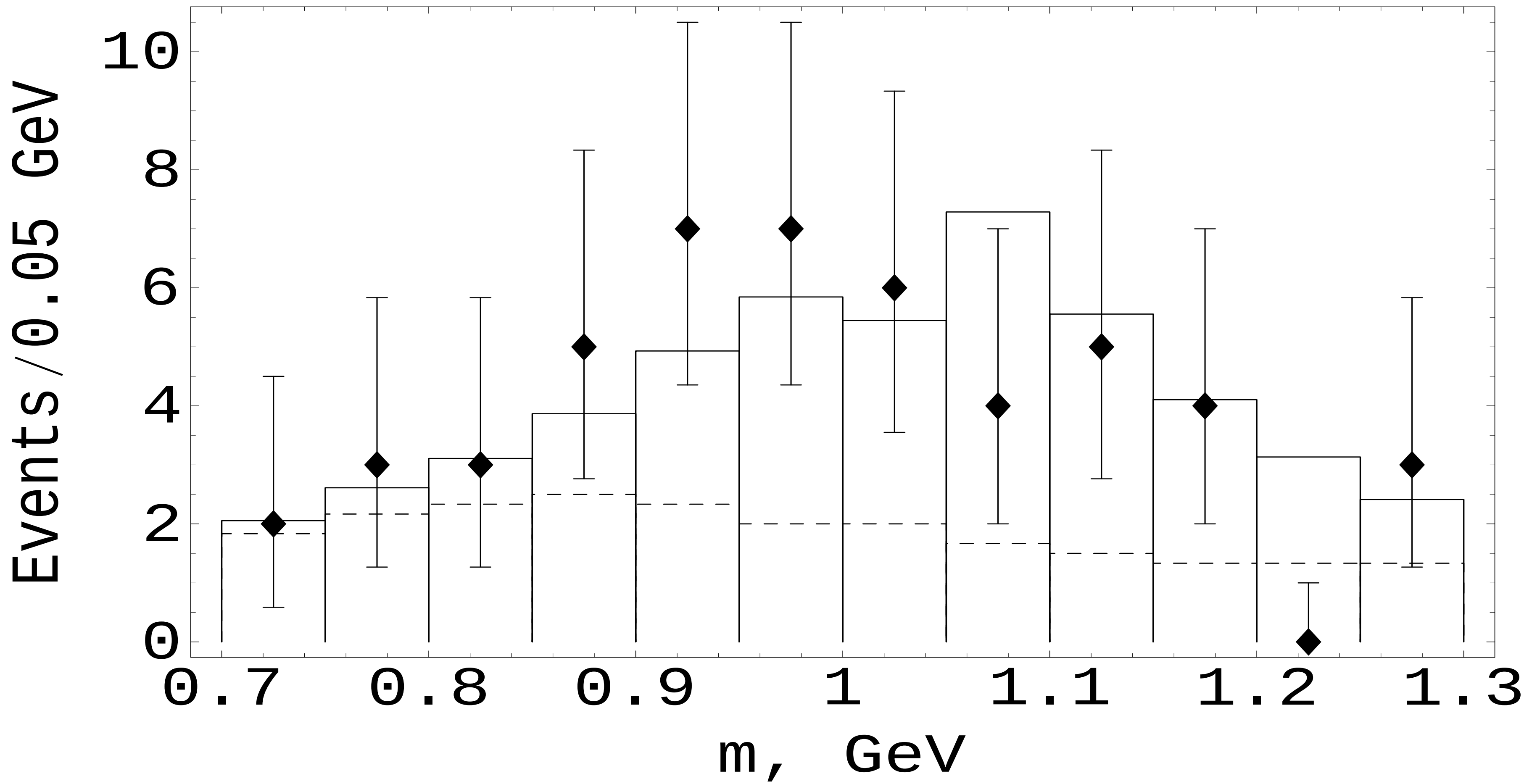
OUTLINE



N.N. Achasov and A.V. Kiselev, Phys. Rev. D 98, 096009 (2018).

OUTLOOK

$D^0 \to a_0'^- \to a_0^- \to \eta\pi^- e^+\nu_e$



N.N. Achasov and A.V. Kiselev, Phys. Rev. D 98, 096009 (2018).

OUTLOOK

The first measurements of BESIII is the important step for the investigation of light scalar mesons nature, but for the present the statistics is not adequate for the conclusions.
A more refined review of semileptonic decays of D and D_s mesons was carried out in our articles N.N. Achasov, A.V. Kiselev, and G.N. Shestakov Phys.Rev. D102 (2020) no.1, 016022 –1-7 and Phys.Rev. D104 (2021) no.1, 016034 –1-9.

And finally we analyzed the BESIII data on the decay $J/\psi \to \gamma\pi^0\pi^0$ and showed that the results of this high-statistics experiment can be interpreted in favor of the four-quark nature of light scalar mesons $f_0(980)$ and $f_0(500)$. N.N. Achasov, J.V. Bennett, A.V. Kiselev, E.A. Kozyrev, and G.N. Shestakov. Phys.Rev. D103 (2021) no.1, 016022 –1-5.

A LOT OF THANKS

We are grateful Organizers for the kind Invitation.

The work was carried out within the framework of the state contract of the Sobolev Institute of Mathematics, Project No. FWNF-2022-0021.