

# (PDG) Review of Scalar Mesons Below 2 GeV

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## Outline

1. The  $I = 1/2$  states
2. The  $I = 1$  states
3. The  $I = 0$  states
4. Conclusions

## Introduction

- Scalars are difficult to resolve because large decay widths cause a strong overlap between resonances and background
- Several decay channels can open up within a short mass range (e.g., at the  $K\bar{K}$  and  $\eta\eta$  thresholds) producing cusps
- One expects non- $q\bar{q}$  objects like glueballs and multiquark states
- Special sophisticated analyses like PWA and Dalitz plot needed
- We briefly discuss  $I = 1/2$ ,  $I = 1$  and  $I = 0$  states since the  $(I = 2)$   $\pi\pi$  and  $(I = 3/2)$   $K\pi$  phase shifts do not exhibit any resonant behavior

## The $I = 1/2$ States – I

- The whole story began from the LASS experiment, which gave rise to numerous  $K^*$  states by studying  $K^- p \rightarrow \bar{K}^0 \pi^+ \pi^- n$  and  $K^- p \rightarrow K^- \pi^+ n$  at 11 GeV
- High-statistics measurements of  $D$  decays with CLEO, FOCUS and E791 under favorable conditions of small combinatorial background
- Experiments at the  $B$  factories (BaBar and Belle) have to account for  $K^*$ 's although under rather ambiguous conditions
- $\tau$  decays into  $K\pi$  and  $K\pi\pi$  are a clean laboratory without background and final state interactions

## The $I = 1/2$ States – II

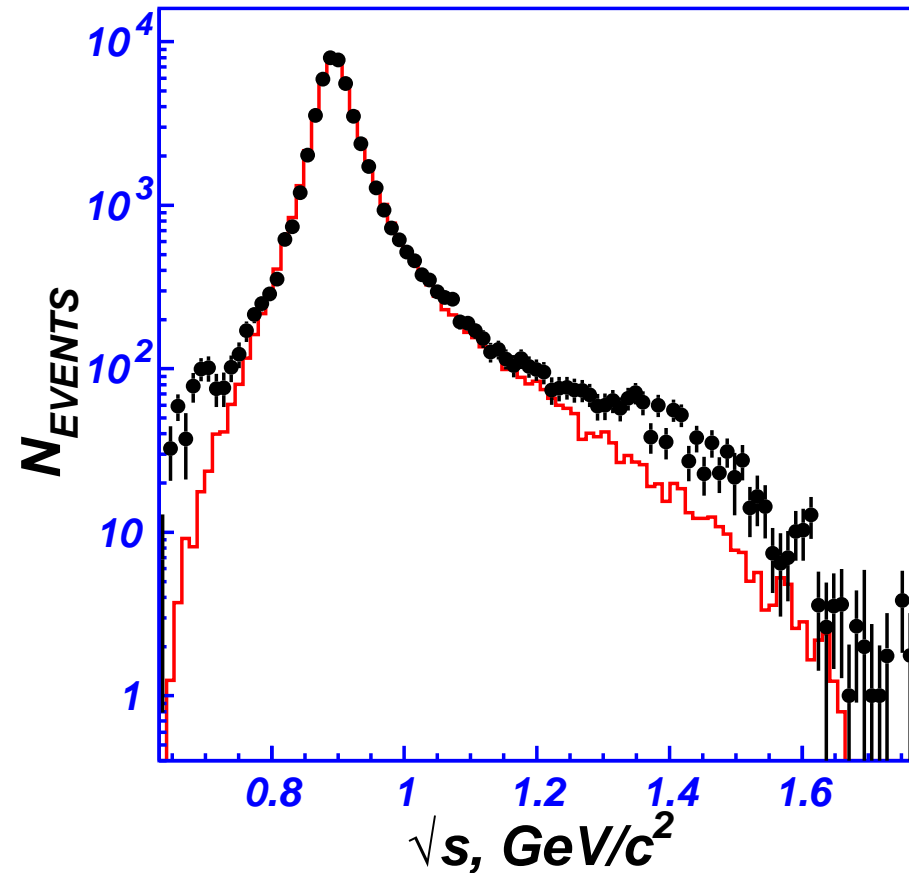
State	$K_0^*(800)$	$K_0^*(1430)$	$K_0^*(1950)$
Mass, MeV	$682 \pm 29$	$1425 \pm 50$	$1945 \pm 10 \pm 20$
Width, MeV	$547 \pm 24$	$270 \pm 80$	$201 \pm 34 \pm 79$

### Some comments:

- $K_0^*(1430)$  is a difficult state to study  
with  $K^*(1410)$  ( $J^P = 1^-$ ) and  $K_2^*(1430)$  ( $J^P = 2^+$ ) nearby
- $\mathcal{B}(K\pi) = (93 \pm 10)\%$  is based on a single LASS measurement:  
D. Aston et al., Nucl. Phys. 296 (1988) 493;  $K^-p \rightarrow K^- \pi^+ n$  at 11 GeV
- $K_0^*(1950)$  is solely based on the same LASS analysis,  $\mathcal{B}(K\pi) = (52 \pm 14)\%$ ,  
confirmed by reanalysis of A. Anisovich (1997) and Z.Y. Zhou (2006)

### The $I = 1/2$ States – III

- The  $K^*(800)$  or  $\kappa$  is still very controversial
- BES sees it in  $J/\psi \rightarrow \bar{K}^* K \pi$ , but at higher mass  $\sim 850$  MeV
- J.R. Pelaez, Mod. Phys. Lett. A19 (2004) 2879, obtains  
 $M = 753 \pm 52$  MeV,  $\Gamma = 470 \pm 66$  MeV from  $K\pi \rightarrow K\pi$  and S-matrix pole
- S. Descotes-Genon, B. Moussallam, Eur. Phys. J. C 48 (2006) 553 obtain  
 $M = 753 \pm 52$  MeV,  $\Gamma = 557 \pm 24$  MeV from  $K\pi \rightarrow K\pi$ , S-matrix pole  
and applying Roy-Steiner equations
- D. Bugg, Phys. Rev. D 81 (2010) 014002 obtains  
 $M = 663 \pm 35$  MeV,  $\Gamma = 658 \pm 45$  MeV accounting for  $s$ -dependent width,  
couplings to  $K\pi$  and  $K\eta'(958)$  and Adler zero

Evidence for the  $\kappa$  from  $\tau$  decays

D. Epifanov et al. (Belle), Phys. Lett. B 648 (2007) 341

### The $I = 1$ States – I

- Two isovector states are established:  $a_0(980)$  and  $a_0(1450)$
- $a_0(980)$  decays into  $\eta\pi$  and  $K\bar{K}$ . The  $K\bar{K}$  component is large, but the resonance is just below the threshold generating a cusp. Mass and width of the  $a_0(980)$  can be strongly distorted, the results are strongly model-dependent
- $a_0(1450)$  is well above thresholds with various decays reported:  
 $\eta\pi$ ,  $K\bar{K}$ ,  $\eta'(958)\pi$ ,  $\omega\pi\pi$ ,  $a_0(980)\pi\pi$

### The $I = 1$ States – II

State	$a_0(980)$	$a_0(1450)$
Mass, MeV	$980 \pm 20$	$1474 \pm 19$
Width, MeV	50 – 100	$265 \pm 13$

- Large spread of values for the  $a_0(980)$ , strong model dependence; data for the  $K\bar{K}$  are scarce, might be different from the  $\eta\pi$ ?
- The  $a_0(1450)$  parameters are based on Crystal Barrel  $p\bar{p}$  data at rest, other analyses: a big spread from 1290 to 1565 MeV for mass, 80 to 270 MeV for width



## The $I = 0$ States – I (General)

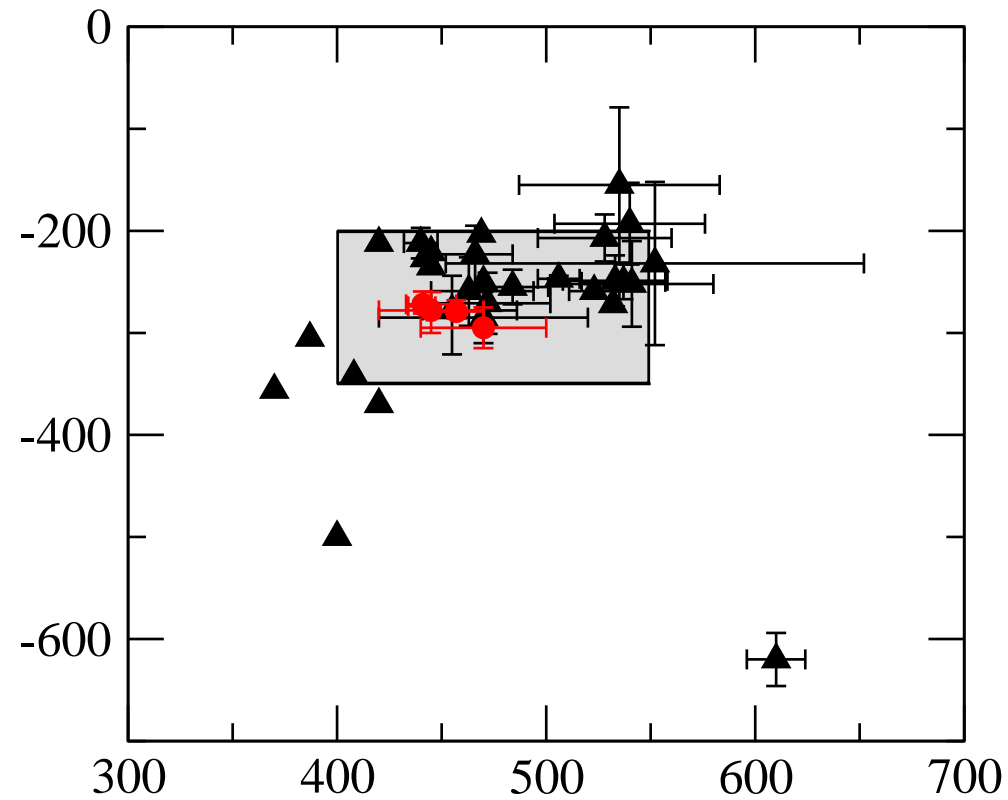
- The  $I = 0$ ,  $J^{PC} = 0^{++}$  sector is the most complex
- Data exist in the  $\pi\pi$ ,  $K\bar{K}$ ,  $\eta\eta$ ,  $4\pi$ ,  $\omega\omega$ , and  $\eta\eta'(958)$  in  $S$ -wave
- Various production processes:  $\pi N$ ,  $p\bar{p}$ ,  $J/\psi$ ,  $D$ ,  $B$  decays
- Five poles are needed:  $f_0(500)$  or  $\sigma$ ,  $f_0(980)$ ,  $f_0(1370)$ ,  $f_0(1500)$ , and  $f_0(1710)$

## The $I = 0$ States – II ( $\sigma$ )

- Long and controversial history
- $\pi\pi$   $S$ -wave phase shifts  $\delta_J^I = \delta_0^0$ : old information from  $\pi N$  scattering and new data near threshold from  $K_{e4}$  decay
- An enhancement in  $M(\pi^+\pi^-)$  is observed in  $D^+ \rightarrow \pi^+\pi^-\pi^+$ ,  $J/\psi \rightarrow \omega\pi^+\pi^-$  and  $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$
- The  $\pi\pi$  scattering amplitude has unusual energy dependence due to crossed channel exchanges and  $f_0(1370)$
- Analyses of  $\pi\pi$  data that include unitarity, threshold behavior, constraints from Adler zeroes, scattering lengths and  $K_{e4}$  data find a light scalar with a pole near  $(500 - i250)$  MeV

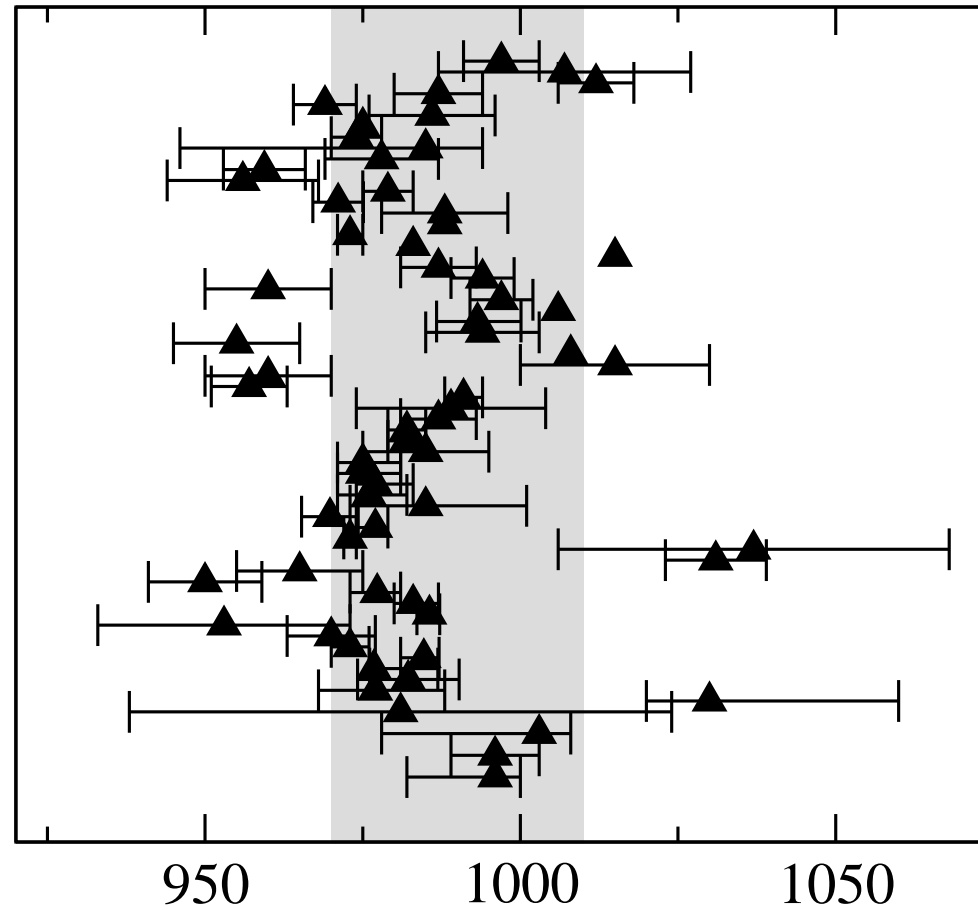
### The $I = 0$ States – III ( $\sigma$ )

- Precise pole positions with uncertainties below 20 MeV were extracted using Roy equations and minimal data by the Bern group, B. Moussalam and R. Garcia-Martin et al.
- $\sqrt{s_{\text{Pole}}^{\sigma}} = (400 - 550) - i(200 - 350)$  MeV
- A more radical approach is to average the advanced dispersion analyses:  
 $\sqrt{s_{\text{Pole}}^{\sigma}} = (446 \pm 6) - i(276 \pm 5)$  MeV
- The  $\gamma\gamma$  data are inconclusive due to its large width
- There are theoretical indications that the  $f_0(500)$  is not a  $q\bar{q}$

The  $I = 0$  States – IV ( $\sigma$  pole position)

## The $I = 0$ States – V ( $f_0(980)$ )

- Seen very clearly as a narrow signal in many processes
- Overlaps strongly with the background from  $f_0(500)$  and  $f_0(1370)$ , that can result in a dip in the  $M(\pi\pi)$  spectrum at the  $K\bar{K}$  threshold
- A dip changes to the  $M(\pi^0\pi^0)$  peak in  $\pi^-p \rightarrow \pi^0\pi^0n$
- Seen in  $\phi \rightarrow \pi^+\pi^-\gamma$ ,  $\pi^0\pi^0\gamma$  by KLOE, SND and CMD-2
- Also seen in various charmonium and  $B$  meson decays
- A recent dispersive analysis of B. Moussallam and R. Garcia-Martin et al.!
- $M(f_0(980)) = 990 \pm 20$  MeV

The  $I = 0$  States – VI ( $f_0(980)$  mass)

## The $I = 0$ States – VII (Above 1 GeV)

- $f_0(1500)$  is well established and seen by Crystal Barrel in  $p\bar{p}$  in five decay modes:  $\pi\pi$ ,  $K\bar{K}$ ,  $\eta\eta$ ,  $\eta\eta'(958)$ ,  $4\pi$ ; also seen in central production
- $p\bar{p}$ ,  $p\bar{n}/n\bar{p}$  show a single enhancement at 1400 MeV in  $M(4\pi)$  resolved in  $f_0(1370)$  and  $f_0(1500)$ , the  $4\pi$  mode is about half of the  $f_0(1500)$  and dominant for the  $f_0(1370)$ , other branchings rather uncertain
- Both Belle and BaBar observe scalars in  $B$  and  $D$  decays reporting broad or narrow structures between 1 and 1.6 GeV in  $\pi^+\pi^-$  and  $K^+K^-$
- $f_0(1710)$  seen in  $J/\psi$  radiative decays and central production mostly decays into  $K\bar{K}$  and  $\eta\eta$ ;  $\pi\pi$  and  $\omega\omega$  possibly seen
- Belle studied  $\gamma\gamma \rightarrow \pi^0\pi^0$ ,  $(\eta\eta)$  and found an  $S$ -wave state with mass 1470 (1262) MeV and width 90 (484) MeV and huge errors

### The $I = 0$ States – VIII (Summary)

State	$\sqrt{s_{\text{pole}}}$ , MeV	$M_{\text{BW}}$ , MeV	$\Gamma_{\text{BW}}$ , MeV
$f_0(500)$	(400-550)-i(200-350)	400-1200	600-1000
$f_0(980)$	–	$990 \pm 20$	40-100
$f_0(1370)$	(1200-1500)-i(150-250)	1200-1500	200-500
$f_0(1500)$	–	$1505 \pm 6$	$109 \pm 7$
$f_0(1710)$	–	$1720 \pm 6$	$135 \pm 8$

The  $\langle\langle \text{BW} \rangle\rangle$  values are a mixture of Breit-Wigner and  $S$ -matrix poles  
 Averaging hardly makes sense!



## Interpretation of the $I = 0$ States – I (Below 1 GeV)

- $f_0(980)$  and  $a_0(980)$  are 4-quark states or molecules:  
 $\gamma\gamma$  is inconclusive,  $f_0(980)$  has a large  $s\bar{s}$  from  $J/\psi$  and  $D_s$  decays,  
 $\phi \rightarrow f_0(980)\gamma$  and  $\phi \rightarrow a_0(980)\gamma$  show a role of kaon loops
- $f_0(980)$ ,  $a_0(980)$ ,  $f_0(500)$  and  $K_0^*(800)$  form a low-mass scalar nonet of predominantly four-quark states
- Models with chiral Lagrangians predict  $f_0(500)$  and a nonet with  $f_0(500)$ ,  $f_0(980)$ ,  $a_0(980)$  and  $K_0^*(800)$  (or  $K_0^*(1430)$ )
- The unitarized quark model with coupled  $q\bar{q}$  and meson-meson channels, light scalars are bare  $q\bar{q}$  confinement states strongly shifted from 1.3-1.5 GeV due to strong coupling to  $S$ -wave two-meson decays.  
 $f_0(500)$ ,  $f_0(980)$ ,  $K_0^*(800)$  and  $a_0(980)$  as well as  
 $f_0(1370)$ ,  $f_0(1500)$  (or  $f_0(1710)$ ),  $K_0^*(1430)$  and  $a_0(1450)$  form two nonets - manifestations of the same bare input states

## Interpretation of the $I = 0$ States – II (Above 1 GeV)

- The  $f_0(1370)$  and  $f_0(1500)$  decay mostly into  $2\pi$  and  $4\pi$ , while  $f_0(1710)$  into  $K\bar{K}$
- In the naive quark model  $f_0(1370)$ ,  $a_0(1450)$  and  $K_0^*(1430)$  – the same SU(3) flavor nonet as  $(u\bar{u} + d\bar{d})$ ,  $u\bar{d}$  and  $u\bar{s}$  states, mixing with the light scalars (?), the  $f_0(1710)$  is an  $s\bar{s}$  state:  $f_0(1710)$  ( $f_2'(1525)$ ) are produced in  $p\bar{p}$ , but suppressed compared to  $f_0(1500)$  ( $f_2(1270)$ ), and  $f_0(1500)$  is also a  $(u\bar{u} + d\bar{d})$ , but very narrow and too light
- But in  $\gamma\gamma$  the  $f_0(1500)$  is not observed while the  $f_0(1710)$  is, so it is mainly glue (?). The  $f_0(1500)$ 's small width and enhanced production at small  $p_t$  in central collisions favor its non- $q\bar{q}$ . In a mixing scheme of F. Close glue is shared between  $f_0(1370)$ ,  $f_0(1500)$  and  $f_0(1710)$  (mainly  $n\bar{n}$ , glue and  $s\bar{s}$ )
- In other schemes two-gluon coupling to  $n\bar{n}$  is suppressed by chiral symmetry and  $K\bar{K}$  is enhanced  $\Rightarrow f_0(1710)$  is an unmixed glueball
- Broad  $KK\bar{K}$  signal of Belle as a  $f_0(1500)$  glueball, in conflict with BaBar
- $f_0(1370)$  and  $f_0(1710)$  are bound states of two vectors

## Conclusions

- $f_0(500)$  ( $\sigma$ ) definitely and  $K_0^*(800)$  ( $\kappa$ ) most probably exist
- Many other scalars observed, probably too many for normal  $q\bar{q}$
- $\gamma\gamma$  collisions can help (?) with much larger data samples, KLOE-2 with taggers, CMD-3/SND, BES-III, SuperB-factories
- Many interesting observations from the  $J/\psi$  and  $\psi(2S)$  decays (BES), results from Belle and BaBar suffer from low data hadronic samples, but their  $\tau$  decay data are very rich and potentially helpful
- Theoretical interpretation is very far from final and new experimental observations badly needed
- Strong model dependence, variety of approaches
- A nightmare for experiment and paradise for theory!

Back-up