# The resonances in $e^+e^-$ annihilation near $\sqrt{s} = 2.25$ GeV

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ICHEP 2020, Prague

# $e^+e^- \to K^+K^-$ near 2.2 GeV



Phys. Rev. D88 (2013), 032013
Phys. Rev. D99 (2019), 032001

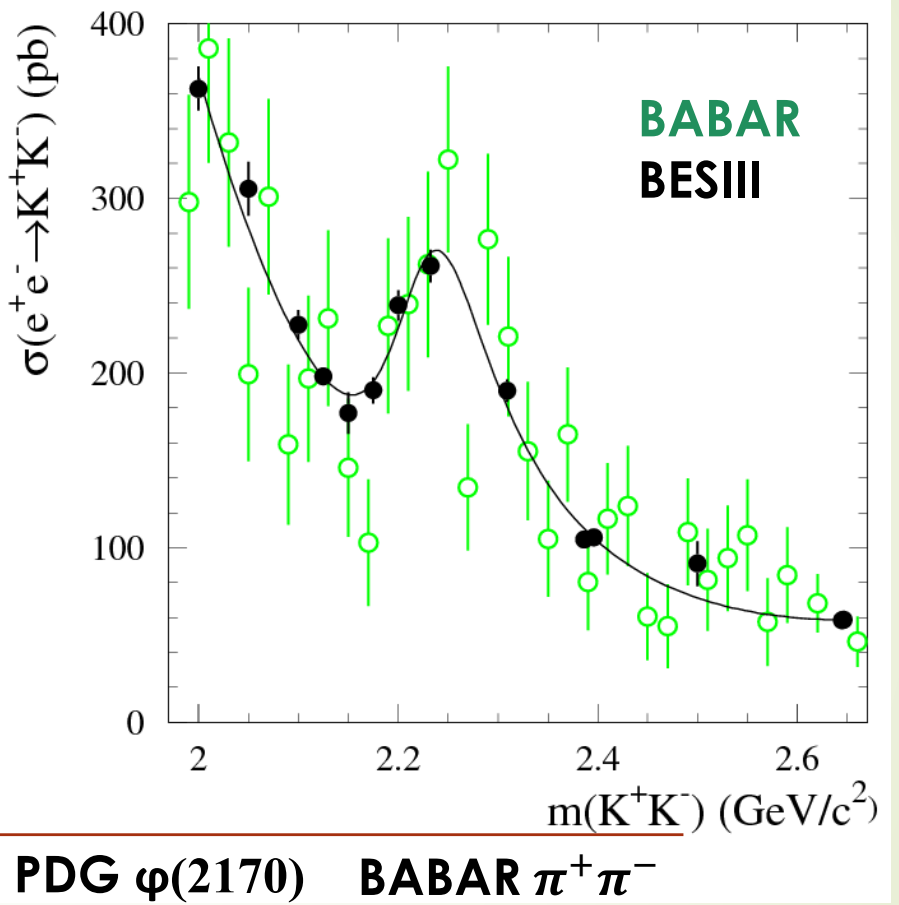
- Recently the very precise measurement of the $e^+e^- \to K^+K^-$ cross section has been carried out in the BESIII experiment
- A resonance structure was observed near 2250 MeV.
- The BESIII data are fitted together with the BABAR $K^+K^-$ data, in which this structure is also seen with a 3.5σ significance.

$$\sigma(e^+e^- \to K^+K^-) = \frac{\pi\alpha^2\beta^3}{3s}|F_{K^+}|^2,$$

$$F_{K^+} = BW(s) + e^{i\varphi}P(s),$$

where $P(s)$ is a second order polynomial.

$$\sigma_{res} = 39 \pm 6 \text{ pb}$$




| | $K^+K^-$ | PDG φ(2170) | BABAR $\pi^+\pi^-$ |
|---|---|---|---|
| Mass (MeV) | 2227 ± 9 | 2188 ± 10 | 2254 ± 22 |
| Width (MeV) | 127 ± 14 | 83 ± 12 | 109 ± 76 |

# $\phi(2170)$ properties



- Observed in three processes,
- but in the only decay mode $\phi(2170) \to \phi f_0(980)$
- Relatively narrow $\Gamma \approx 100$ MeV
- M≈2170 MeV, almost definitely less than 2.2 GeV

| **Process** | **Mass (MeV)** | **Width (MeV)** |
|---|---|---|
| $e^+e^- \to \phi f_0$ (BABAR[1], Belle) | 2180 ± 8 ± 8 | 77 ± 15 ± 10 |
| $J/\psi \to \eta\phi f_0$ (BESII,BESIII[2])<br>interference with $A_{non\text{-}res}$ | 2200 ± 6 ± 5<br>2170 ± 10 ± 5 | 104 ± 15 ± 15<br>128 ± 26 ± 10 |
| $e^+e^- \to \eta\phi f_0$ (BESIII[3]) | 2135 ± 8 ± 9 | 104 ± 24 ± 12 |


1. BABAR, Phys. Rev. D86, 012008 (2012)
2. BESIII, Phys. Rev. D91, 052017 (2015)
3. BESIII, Phys. Rev. D99, 012014 (2019)


BESIII concludes that the parameter of the resonance in the $K^+K^-$ cross section differ from the $\phi(2170)$ PDG parameters by more than $3\sigma$ in mass and more than $2\sigma$ in width.

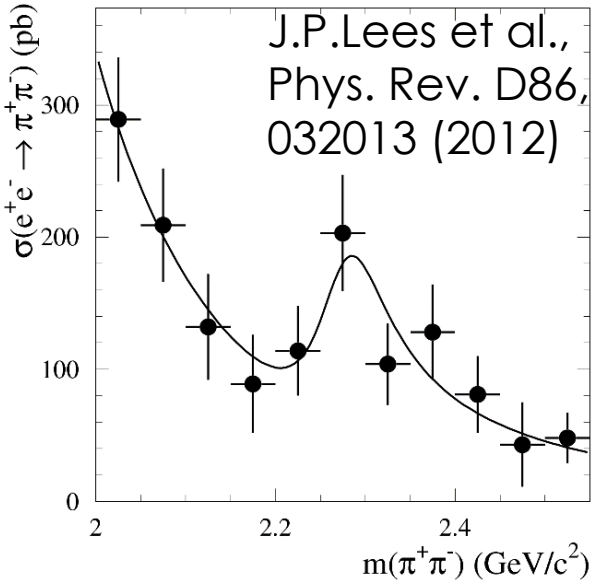
# Isovector resonance near 2250 MeV

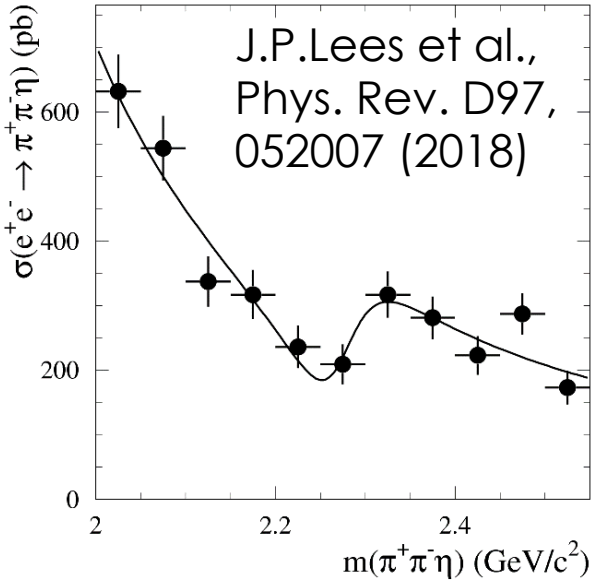


In $e^+e^-$ collisions, the isovector resonance structure in this energy region is seen in several processes

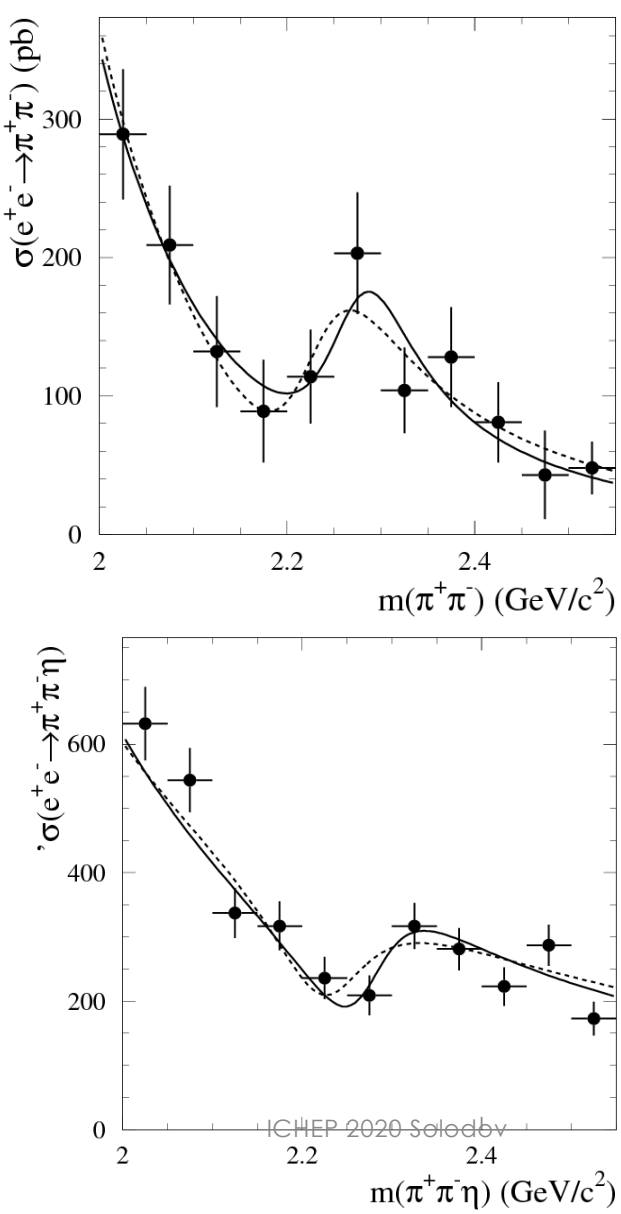
| | M, MeV | Γ, MeV |
|---|---|---|
| $e^+e^- \to \eta'\pi^+\pi^-$ | 1990±80 | 310±140 |
| $e^+e^- \to f_1\pi^+\pi^-$ | 2150±60 | 350±60 |
| $e^+e^- \to \pi^+\pi^-$ | 2254±22 | 109±76 |
| $e^+e^- \to \eta\pi^+\pi^-$ | ~2250 | ~80 |

- In the $\eta'\rho$ and $f_1\rho$ modes the resonance-like structure are seen near the reaction thresholds (see back up slide).
- A relatively narrow interference patterns are observed in the $\pi^+\pi^-$ and $\eta\pi^+\pi^-$ final states.
- A simultaneous fit to these two cross sections gives 4.6σ significance for the resonance with M = 2270 ± 20 MeV and $\Gamma = 116^{+90}_{-60}$ MeV.



# A simultaneous fit to the $K^+K^-$, $\pi^+\pi^-$ and $\eta\pi^+\pi^-$ cross sections




| | $\pi^+\pi^-$ and $\pi^+\pi^-\eta$ | $K^+K^-$, $\pi^+\pi^-$ and $\pi^+\pi^-\eta$ |
|---|---|---|
| $M_R$ (MeV/$c^2$) | 2270 ± 20 | 2232 ± 8 |
| $\Gamma_R$ (MeV) | $116^{+90}_{-60}$ | 133 ± 14 |
| $\sigma(e^+e^- \to R \to K^+K^-)$ (pb) | | 41 ± 6 |
| $\sigma(e^+e^- \to R \to \pi^+\pi^-)$ (pb) | $34^{+26}_{-19}$ | $34^{+27}_{-20}$ |
| $\sigma(e^+e^- \to R \to \pi^+\pi^-\eta)$ (pb) | $33^{+34}_{-13}$ | $27^{+14}_{-11}$ |
| $\chi^2/v$ | 13.96/12 | 17.2/14 |

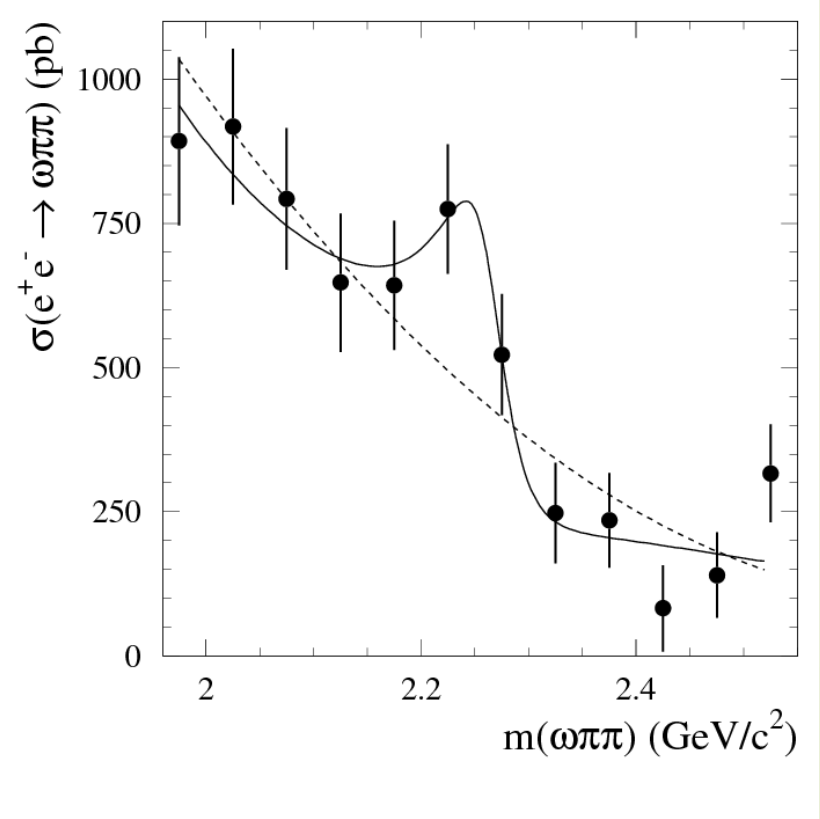
- ✓ The dashed curves are the results of the simultaneous fit.
- ✓ It is very likely that the interference patterns observed in all three cross sections are manifestations of the same isovector resonance, ρ(2240) .
- ✓ The decay rates of the ρ(2240) to $K^+K^-$, $\pi^+\pi^-$ and $\eta\pi^+\pi^-$ are close to each other.

# ω-like resonance near 2250 MeV



The indication of ω-like resonance near 2250 MeV is seen in the BABAR data on the reactions $e^+e^- \to \omega\pi^+\pi^-$ and $\omega\pi^0\pi^0$. B.Aubert et al., Phys. Rev. D76, 092005 (2007), J.P.Lees et al., Phys. Rev. D98, 112015 (2018)

- The fit results are
  $M = 2265 \pm 20$ MeV
  $\Gamma = 75^{+125}_{-27}$ MeV
- The obtained values of the resonance mass and width are close to those for the isovector resonance.
- The dashed curve represents the fit without resonance by a second-order polynomial.
- The significance of the resonance estimated from the difference of $\chi^2$ for the two hypotheses is 2.6σ.

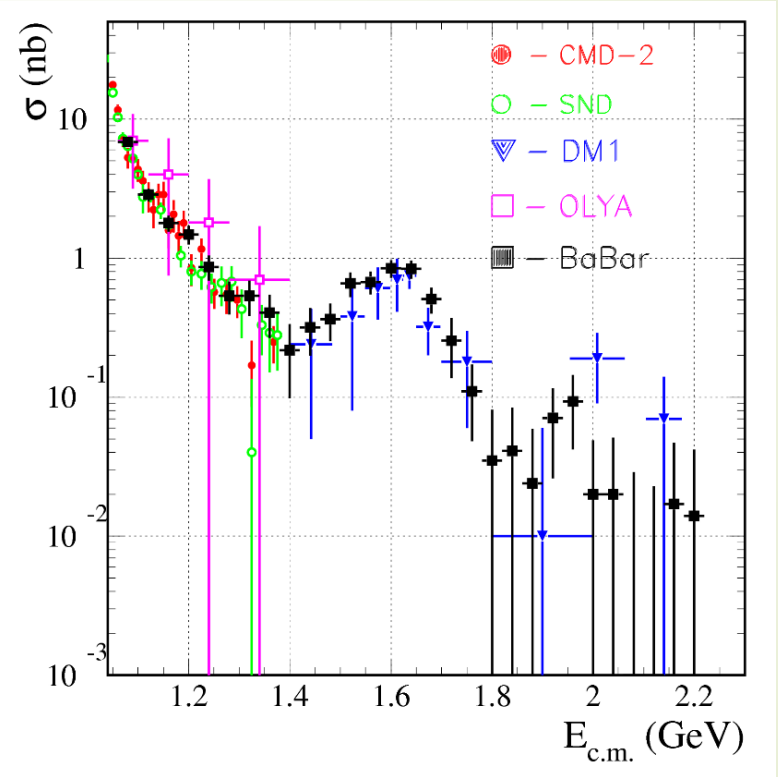


# $e^+e^- \to K_S K_L$ data



Phys. Rev. D89 (2014), 092002

- A resonance seen in the $e^+e^- \to K^+K^-$ cross section should manifest itself in the $e^+e^- \to K_S K_L$ cross section
- For the most precise $e^+e^- \to K_S K_L$ data, obtained at BABAR, the maximum presented energy is 2.2 GeV.
- Above 2 GeV the $e^+e^- \to K_S K_L$ cross section is consistent with zero within statistical errors of about 20 pb.
- Therefore, BABAR data in the range 2.0-2.5 GeV should be sensitive to the resonance observed in the $e^+e^- \to K^+K^-$ cross section.




In this work we expand the energy region of the BABAR measurement up to 2.5 GeV.

# Selection criteria for $e^+e^- \to K_S K_L \gamma$ events

The ISR technique is used to measure the $e^+e^- \to K_S K_L$ cross section. All the same as in Phys. Rev. D89 (2014), 092002
We select events containing

- ✓ A high energy photon (ISR photon) with $E_{cm} > 3$ GeV
- ✓ A $K_S \to \pi^+\pi^-$ candidate
  - The decay length in the xy plane is larger than 0.2 cm
  - The cosine between the KS momentum and flight direction is larger than 0.9992
  - The $\pi^+\pi^-$ invariant mass is in the range 0.482-0.512 GeV. The sidebands (0.472,0.482) and (0.512,0.522) GeV are used to estimate non-KS background
- ✓ A $K_L$ candidate (cluster in the calorimeter with the energy deposition larger than 0.2 GeV)
- ✓ No other tracks originating from the interaction region
- ✓ No other photon candidates with energy greater than 0.5 GeV

# Selection criteria for $e^+e^- \to K_S K_L \gamma$ events

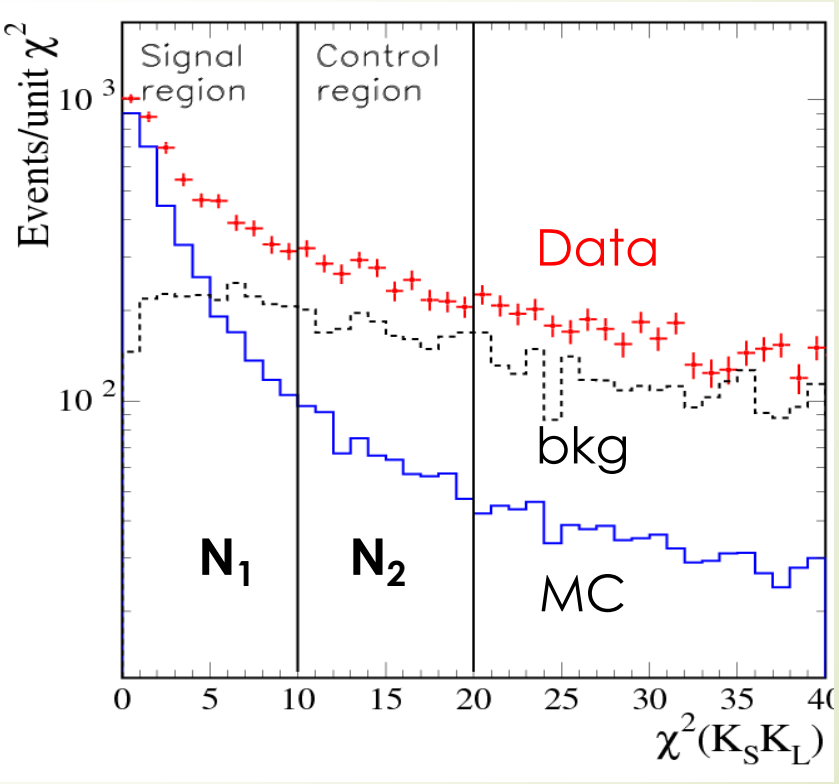
The ISR photon, $K_S$ and $K_L$ candidates are subjected to a kinematic fit to the $e^+e^- \to K_S K_L \gamma$ hypothesis with four constrains of total energy-momentum balance. Only angular information is used in the fit for the $K_L$ candidate. From the fit we determine the $\chi^2$ and the $K_S K_L$ invariant mass.

- Events with $\chi^2 < 10$ are selected.
- The sideband ($10 < \chi^2 < 20$) is used to estimate background

$$N_b = (N_2 - aN_s)/b,$$
$$N_s = N_1 - N_b,$$

where a ≈ 0.2 and b=0.87 ± 0.09 are the $N_2/N_1$ ratios for signal and background. They are determined using simulation.

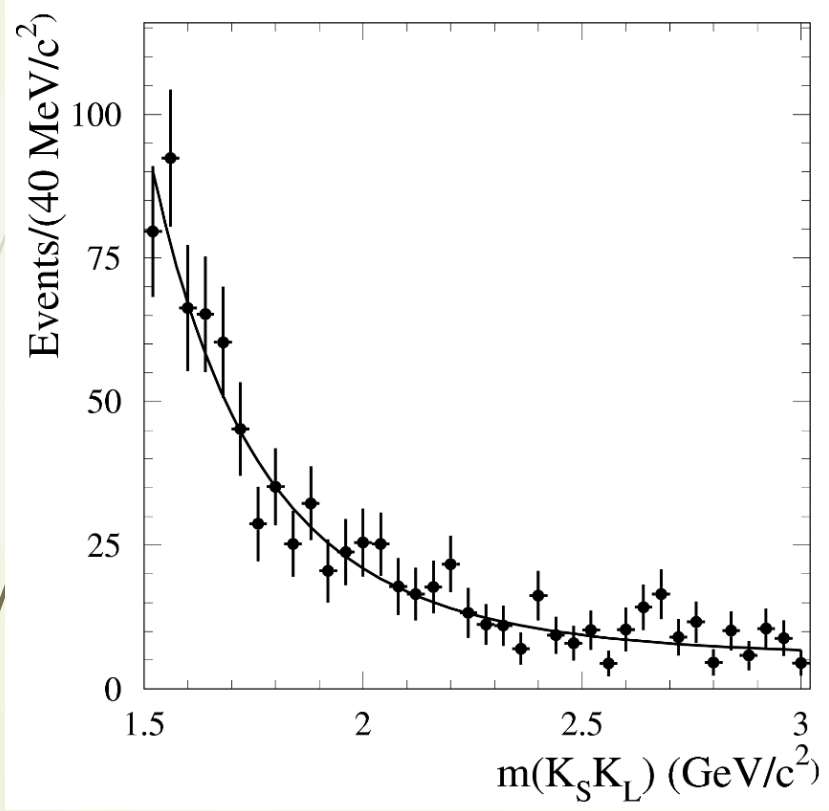
- The $K_S K_L$ mass resolution near 2.25 GeV is about 10 MeV.



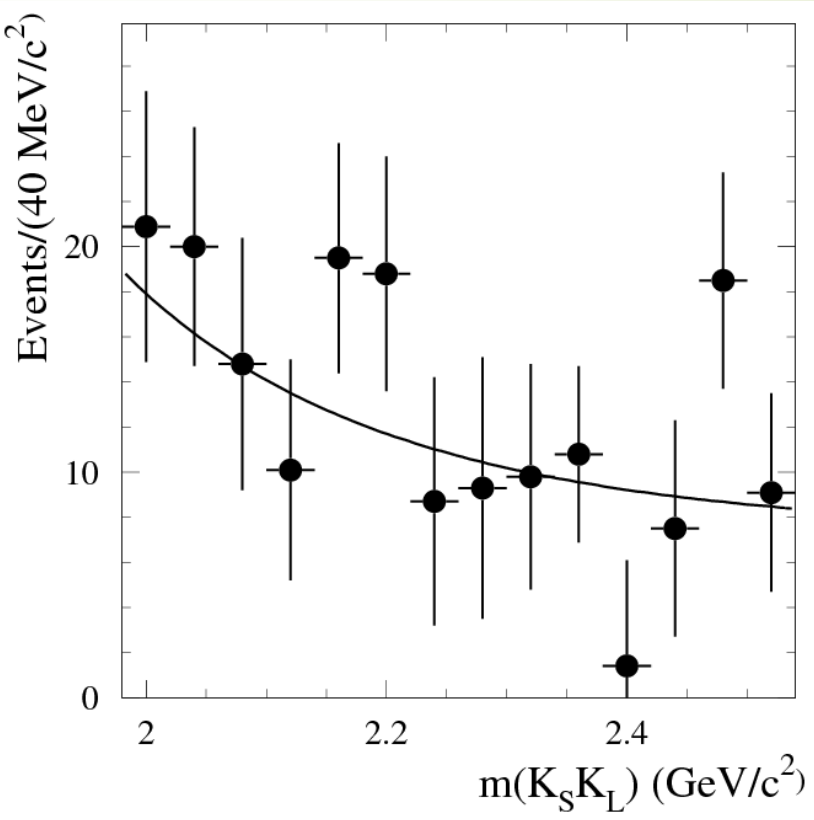
# Background subtraction



The background mass distribution estimated from the $\chi^2$ sideband




The mass distribution in the signal $\chi^2$ region and fitted background

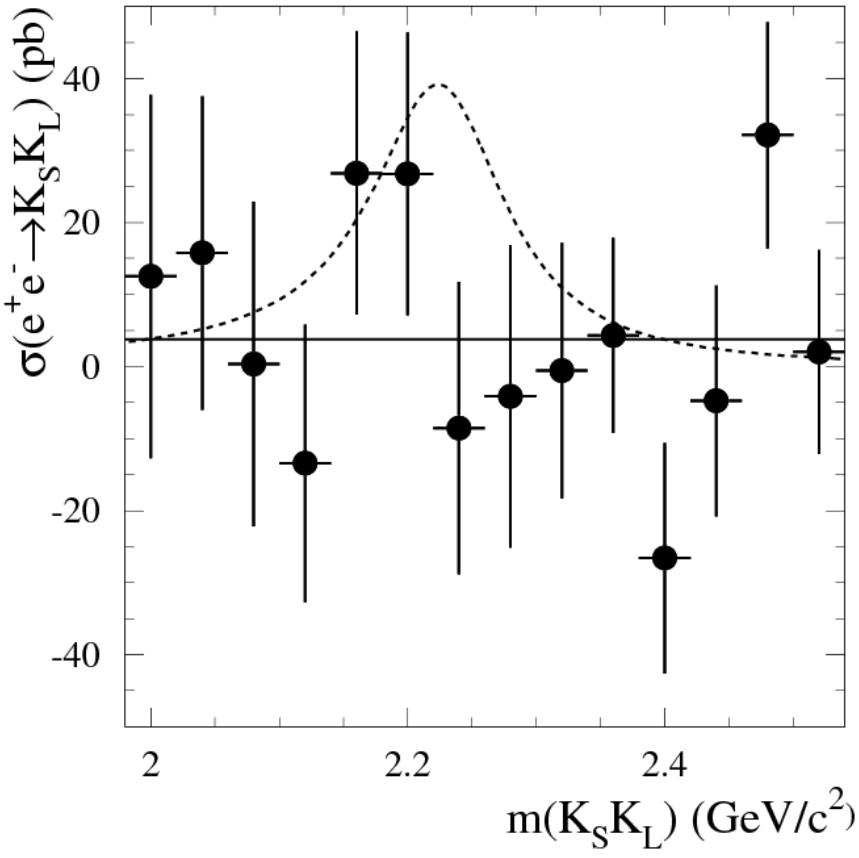



The systematic uncertainty of fitted background above 2 GeV is 12%

# The $e^+e^- \to K_S K_L$ cross section



- The measured $e^+e^- \to K_S K_L$ cross section is consistent with zero.
- The statistical uncertainty is about 20 pb. The correlated systematic uncertainty is about 6 pb.
- The dashed curve represents the cross section for the resonance observed in $K^+K^-$.
- Formally, from the $\chi^2$ difference between the resonance and non-resonance hypotheses the resonance interpretation can be excluded at 2.3σ.



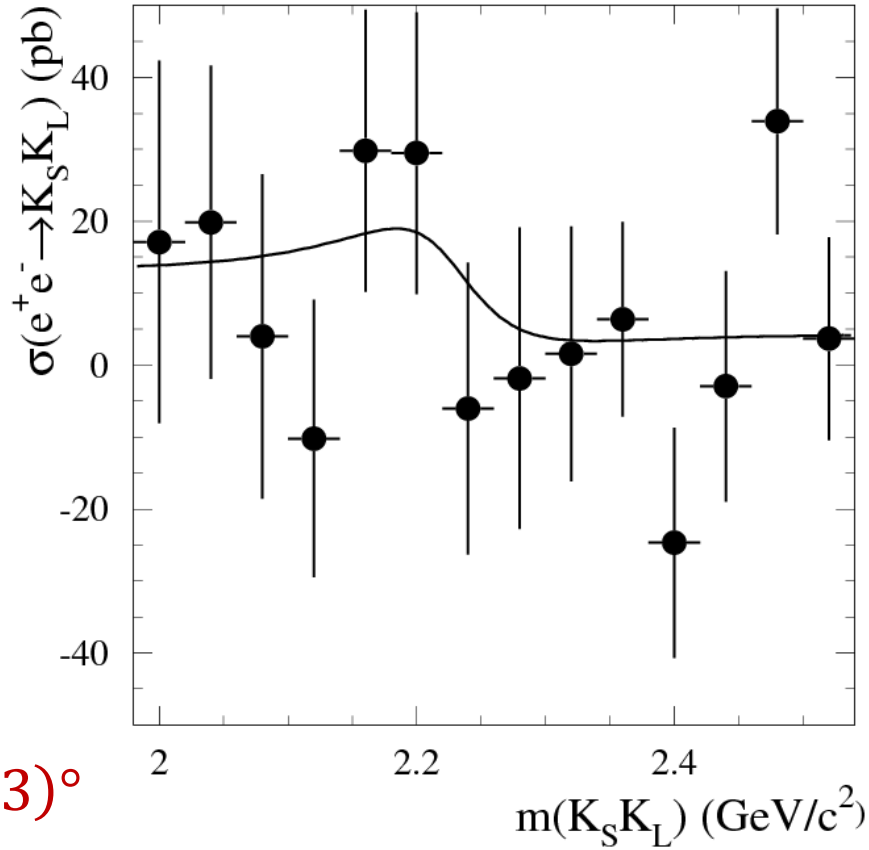

- Possible destructive interference between the resonant and nonresonant $e^+e^- \to K_S K_L$ amplitudes may significantly weaken this constraint

# The $e^+e^- \to K_S K_L$ cross section



- The measured $e^+e^- \to K_S K_L$ cross section is fitted by a coherent sum of resonant and nonresonant amplitudes - see slide 2.
- We also take into account the uncertainty in background subtraction and the statistical error of the resonance cross section obtained from the fit to the $e^+e^- \to K^+K^-$ data.
- The fit yields $\chi^2$/nd = 11.0/12 and the following values of parameters:

$$\sigma_{NR} = 7.3^{+7.4}_{-5.3}\ \text{pb},\quad \varphi = (-69 \pm 23)^\circ$$




We conclude that the BABAR $e^+e^- \to K_S K_L$ data do not exclude the resonance observed in $K^+K^-$, but restrict the possible range of allowed values of the relative phase between the resonant and nonresonant amplitudes. The picture can be even more complicated!

# Two-resonance fit for $K_S K_L$



The isovector and isoscalar amplitudes enter to the $e^+e^- \to K_S K_L$ amplitude (in contrast to the $e^+e^- \to K^+K^-$ case) with opposite signs [1]

$$A(e^+e^- \to K^+K^-) = A_{I=0} + A_{I=1},$$
$$A(e^+e^- \to K_S K_L) = A_{I=0} - A_{I=1}$$

The quark model predicts that $A_{I=0} = 1/3\ A_{I=1}$. So, the resonance amplitude in the $e^+e^- \to K_S K_L$ reaction is about two times smaller than that in the $e^+e^- \to K^+K^-$ reaction. This weakens the constraints on the nonresonant $e^+e^- \to K_S K_L$ cross section and the interference phase. The two-resonance fit to the $e^+e^- \to K_S K_L$ cross section yields $\chi^2/nd = 10.6/12$ and the values of parameters:

$$\sigma_{NR} = 5.0^{+8.2}_{-4.8}\ \text{pb},\ \ \varphi = (-51 \pm 55)^\circ$$

The fit with zero nonresonant cross section also have the acceptable $\chi^2/nd = 12.1/14$.

The two-resonance fit allows to simultaneously describe the $e^+e^- \to K^+K^-$ and $e^+e^- \to K_S K_L$ data without strong constraints on the interference parameters.

1. C.Bruch, A.Khodjamirian and J.H.Kuhn, Eur. Phys. J. C 39, 41 (2005)

# Fit with ρ(2240) and $\phi(2170)$



$\phi(2170)$ also can contribute to all these modes. The $e^+e^- \to K^+K^-$, $\pi^+\pi^-$ and $\eta\pi^+\pi^-$ cross sections are fitted simultaneously.

$$\sigma(e^+e^- \to K^+K^-) = \frac{m_\phi^2 \beta(s)^3}{s\beta(m_\phi^2)^3}\left|\sqrt{\sigma_\phi}BW_\phi + \sqrt{\sigma_\rho}BW_\rho + e^{i\varphi}P(s)\right|^2$$

The inclusion of the ϕ(2170) (PDG parameters are taken and fixed) improves the fit quality insignificantly. The fitted value of the ϕ(2170) peak cross section is found to be consistent with zero, $0.8^{+2.9}_{-0.8}$ pb.

# Summary (1)

- The $e^+e^- \to K_S K_L$ cross section has been measured in the energy region 2.0-2.5 GeV.
- The measured cross section is consistent with zero within the statistical uncertainties of about 20 pb. The correlated systematic uncertainty is about 6 pb.
- The interference patterns seen in the $e^+e^- \to \pi^+\pi^-$ and $e^+e^- \to \eta\pi^+\pi^-$ data near 2.25 GeV provide 4.6 evidence for the existence of the isovector resonance ρ(2240). Its mass and width are consistent with the parameters of the resonance observed in the $e^+e^- \to K^+K^-$ channel.
- All three cross sections are well described by the model with the isovector resonance ρ(2240) with M = 2236 ± 8 MeV/$c^2$ and Γ = 137 ± 14 MeV. (We`d suggest to replace in PDG the name of ρ(2150) )

# Summary (2)

- The BABAR $e^+e^- \to K_S K_L$ data do not exclude the existence of the ρ(2240) resonance, but strongly restrict the possible range of allowed values of the relative phase between the resonant and nonresonant $e^+e^- \to K_S K_L$ amplitudes. This restriction may be significantly weakened by inclusion in the fit an additional isoscalar resonance with close mass.
- The 2.6σ indication of such a ω-like resonance is seen in the $e^+e^- \to \omega\pi\pi$ reaction.
- The $e^+e^- \to K^+K^-$, $\pi^+\pi^-$ and $\eta\pi^+\pi^-$ cross sections have been fitted using a model with an additional contribution of the ϕ(2170) resonance. The inclusion of ϕ(2170) improves the fit quality insignificantly. The fitted value of the ϕ(2170) contribution is consistent with zero – still only ϕ(1020)$f_0$ observed !
- *Phys.Rev.D* 101 (2020) 1, 012011 - Published

# $e^+e^- \to \eta'\pi^+\pi^-$ and $e^+e^- \to f_1\pi^+\pi^-$

B.Aubert et al., Phys. Rev. D 76, 092005 (2007).