Study of interference effects in the decays of ψ mesons in K^+K^-

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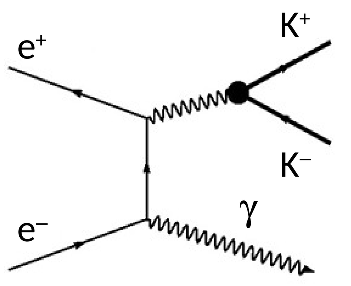
ABSTRACT: Using the ISR technique with an undetected photon, the $e^+e^- \to K^+K^-$ cross section and the charged kaon electromagnetic form factor have been measured in the energy region 2.6-7.5 GeV in the BABAR experiment. The BABAR measurements together with data from other experiments are used to perform a model-independent determination of the relative phases between single-photon and three-gluon amplitudes in J/ψ and ψ(2S) → $K\bar{K}$ decays. The values of the branching fractions measured in the $e^+e^- \to K^+K^-$ reaction are shifted due to interference of resonant and nonresonant amplitudes. We have determined the absolute values of the shifts to be 5% for J/ψ and 15% for ψ(2S) decay. The interference patterns near the ψ(3770) and ψ(4160) resonances have been also studied. For the ψ(3770) the resonant cross section is determined to be $\sigma(e^+e^- \to \psi(3770) \to K^+K^-) = 0.073^{+0.061}_{-0.044}$ pb with 3.2σ statistical significance. For the ψ(3770) the upper limit $\sigma(e^+e^- \to \psi(4160) \to K^+K^-) < 0.062$ pb is set at 90% CL.

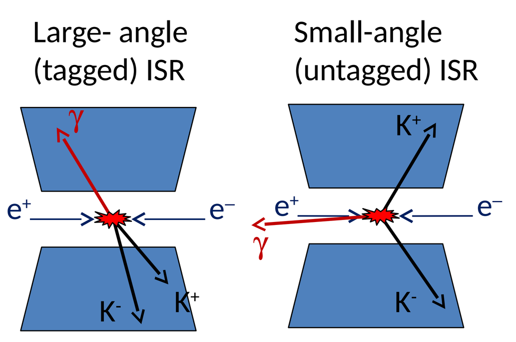
I. Measurement of the $e^+e^- \to K^+K^-$ cross section at BABAR



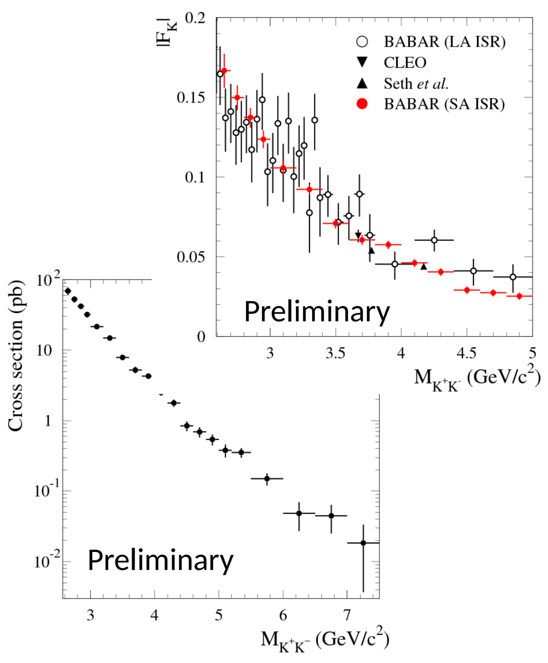
The BABAR detector collected data at center-of-mass energy of 10.6 GeV. The initial-state-radiation (ISR) technique is used to measure exclusive hadronic cross section at lower energies. The mass spectrum of the K^+K^- system produced in the reaction $e^+e^- \to K^+K^-\gamma$ is related to the cross section for the nonradiative process $e^+e^- \to K^+K^-$.

$$\frac{d\sigma_{e^+e^-\to K^+K^-}}{dm} = \frac{2m}{s} W(s,x)\,\sigma_{e^+e^-\to K^+K^-}(m), \quad x = \frac{2E_\gamma}{\sqrt{s}} = 1 - \frac{m^2}{s},$$

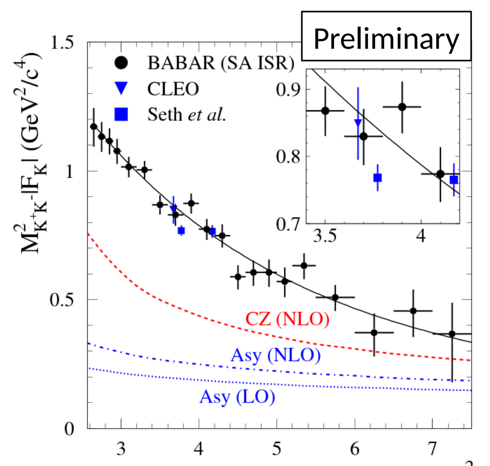
The radiator function W(s,x) is calculated in QED with a high accuracy (better than 0.5%).



The produced hadron system is boosted against the ISR photon. Due to limited detector acceptance the mass region below 2.5 GeV can be studied only with detected photon.
Above 3 GeV statistics may be significantly increased with use of small-angle ISR.



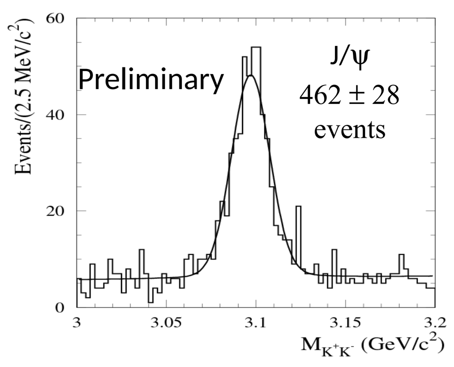
$$\sigma_{K^+K^-}(m) = \frac{\pi\alpha^2\beta^3}{3m^2}|F_K(m)|^2$$



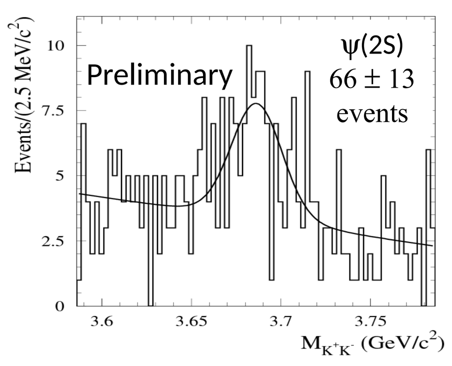
The measured continuum cross section may be used to calculate electromagnetic (single-photon) contribution to $\psi \to K^+K^-$ decay and effect of interference between resonant and nonresonant $e^+e^- \to K^+K^-$ amplitudes.

II. J/ψ and ψ(2S) decays

	B(ψ → K^+K^-)	WA
J/ψ	$(3.36 \pm 0.20 \pm 0.12)\times 10^{-4}$	2.43 ± 0.25
ψ(2S)	$(0.73 \pm 0.15 \pm 0.02)\times 10^{-4}$	0.71 ± 0.05

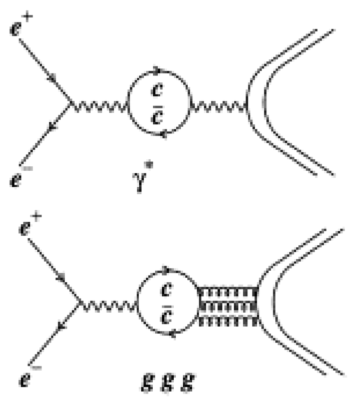


To calculate the world average for the J/ψ, data obtained in the $e^+e^- \to K^+K^-$ reaction are used.



There is also the measurement [4], in which J/ψ's were produced in the ψ(2S) → J/ψπ⁺π⁻ decay:
B(J/ψ → K^+K^-) = $(2.86 \pm 0.21)\times 10^{-4}$

III. Phenomenology of ψ→ $K\bar{K}$



$$\mathcal{B}(\psi \to K^+K^-) = \left|A_\gamma^{K^+K^-} + A_s e^{i\varphi}\right|^2,$$
$$\mathcal{B}(\psi \to K_SK_L) = \left|A_\gamma^{K_SK_L} + A_s e^{i\varphi}\right|^2$$

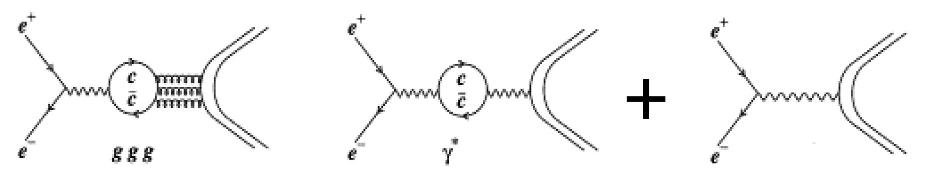
$$|A_\gamma|^2 = \mathcal{B}_{ee}\frac{|F_K(M_\psi)|^2}{4}\beta^3$$

In previous analyses [4,5,6] the single-photon K_SK_L amplitude was assumed to be zero, while the single photon K^+K^- amplitude was assumed to be equal to the same amplitude for $\pi^+\pi^-$, which is determined from the $\psi \to \pi^+\pi^-$ decay.

$$\mathcal{B}(\psi \to K^+K^-) = \left|\underbrace{A_\gamma^{K^+K^-}}_{\approx A_\gamma^{\pi^+\pi^-}} + A_s e^{i\varphi}\right|^2,$$
$$\mathcal{B}(\psi \to K_SK_L) = \left|\underbrace{A_\gamma^{K_SK_L}}_{\approx 0} + A_s e^{i\varphi}\right|^2 \Rightarrow \varphi \approx \pm 90°$$

We perform a model-independent determination of the phase:
✓ A_γ's are calculated from the measured values of kaon form factors.
✓ From data we estimate that the ratio of the neutral and charged form factors (κ) is equal to 0.2±0.1 at J/ψ and 0.15 ± 0.07 at ψ(2S).

IV. Effect of interference



$$\sigma = \sigma_0\left|1 - \sqrt{\frac{\sigma_\psi B(\psi\to f)}{\sigma_0}}\frac{m\Gamma}{m^2 - E^2 - im\Gamma}\right|^2 = \sigma_0\left|1 - \sqrt{\frac{\sigma_\psi}{\sigma_0}}(A_\gamma + A_s e^{i\varphi})\frac{m\Gamma}{m^2 - E^2 - im\Gamma}\right|^2 =$$
$$\sigma_0 + \sigma_\psi B(\psi\to f) + 2\sqrt{\frac{\sigma_0}{\sigma_\psi}}A_s\sin\phi\,\frac{m^2\Gamma^2}{(m^2-E^2)^2 + m^2\Gamma^2} - \cancel{2\sqrt{\sigma_0\sigma_\psi}\frac{m\Gamma(m^2-E^2)}{(m^2-E^2)^2+m^2\Gamma^2}}(A_\gamma + A_s\cos\phi), \quad \sigma_\psi = \frac{12\pi}{m^2}B(\psi\to e^+e^-)$$

For narrow resonances the interference term proportional to (m^2-E^2) integrates to zero due to the beam energy spread in direct e^+e^- experiments and detector resolution in ISR measurements. The remaining interference term has a Breit-Wigner shape and causes a shift of the measured B(ψ → K^+K^-) relative to its true value by

$$\delta B = 2\sqrt{\frac{\sigma_0}{\sigma_\psi}}A_s\sin\phi$$

The values of the branching fraction for J/ψ → K^+K^- measured in the reaction $e^+e^- \to K^+K^-$ and in the decay ψ(2S) → ππ J/ψ → ππ K^+K^- differ by δB.

V. Relative phases and interference shifts

For the J/ψ we perform calculations for two values of B(J/ψ→K_SK_L), $(2.62 \pm 0.21)\times 10^{-4}$ [4] and $(1.82 \pm 0.14)\times 10^{-4}$ [7], and two signs of sinφ.

$J/\psi \to K_SK_L$	φ	$\varphi(\kappa=0)$	$\delta\mathcal{B}(J/\psi\to K^+K^-)\times 10^4$
BES [28]	$(96\pm6)°$	$(97\pm4)°$	0.13 ± 0.01
	$-(96\pm5)°$	$-(95\pm4)°$	-0.13 ± 0.01
NU [20]	$(111\pm5)°$	$(108\pm4)°$	0.15 ± 0.01
	$-(109\pm5)°$	$-(106\pm4)°$	-0.15 ± 0.01

For J/ψ, we confirm the results of the previous works [4,5,6] that the strong amplitude for the ψ→ K^+K^- decay has a large imaginary part.
The φ and δB values depend weakly on $\kappa = (A_\gamma^{KSKL}/A_\gamma^{K+K-})$.

φ	$\varphi(\kappa=0)$	$\delta\mathcal{B}(\psi(2S)\to K^+K^-)\times 10^4$
$(81\pm13)°$	$(91\pm10)°$	0.11 ± 0.01
$-(56\pm15)°$	$-(55\pm13)°$	-0.10 ± 0.01

For ψ(2S), the result on the relative phase strongly depends on the sign of sinφ.

VI. Corrected branching fraction for J/ψ and ψ(2S)→K^+K^-

BABAR results for two signs of sin φ:

$$\mathcal{B}(J/\psi\to K^+K^-) = (3.22\pm0.20\pm0.12)\times 10^{-4},\ \sin\varphi > 0,$$
$$(3.50\pm0.20\pm0.12)\times 10^{-4},\ \sin\varphi < 0,$$

For J/ψ the sinφ sign can be chosen from comparison of the branching fractions measured in the $e^+e^- \to K^+K^-$ reaction and ψ(2S) →J/ψπ⁺π⁻ decay. Comparison our data with the measurement of Ref.[4] $(2.86 \pm 0.21)\times 10^{-4}$ gives an indication that the sign is positive.

$$\mathcal{B}(\psi(2S)\to K^+K^-) = (0.62\pm0.15\pm0.02)\times 10^{-4},\ \sin\varphi > 0,$$
$$(0.83\pm0.15\pm0.02)\times 10^{-4},\ \sin\varphi > 0,$$

For ψ(2S) a theoretical argument can be used. The ratio of the $|A_s|^2$ for ψ(2S) and J/ψ decay is 0.192 ±0.026 for the negative sign and 0.170 ±0.23 for the positive. The latter value is closer to the expectation that this ratio is approximately equal to the ratio B(ψ(2S)→e^+e^-)/ B(J/ψ→e^+e^-) = 0.131.

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VII. ψ(3770) decays to light hadrons

The ψ(3770) meson is the lowest-mass $c\bar{c}$ state above open-charm threshold. It is expected to decay predominantly to $D\bar{D}$ pairs. Assuming that $c\bar{c}$ annihilation into light hadrons is proportional to $|\Psi(0)|^2$ we estimate

$$B(\psi(3770)\to f) \approx B(\psi(2S)\to f)\frac{B(\psi(3770)\to e^+e^-)}{B(\psi(2S)\to e^+e^-)}$$
$$\approx 10^{-3}B(\psi(2S)\to f) \qquad (1)$$

About 90 light-hadron final states were studied, but only two decays, to φη[8] and pp̄[9], were observed. The measured branching fractions are significantly exceed the above prediction. The mechanism explaining relatively large values of branching fractions is production of light hadrons via intermediate DD loops [10,11]. The predicted B(ψ(3770) → K^+K^-) =9×10^{-5} [10] is larger than the above prediction by about three orders of magnitude. The branching fraction for the single-photon mechanism of this decay is calculated to be about 5×10^{-9} and negligible.

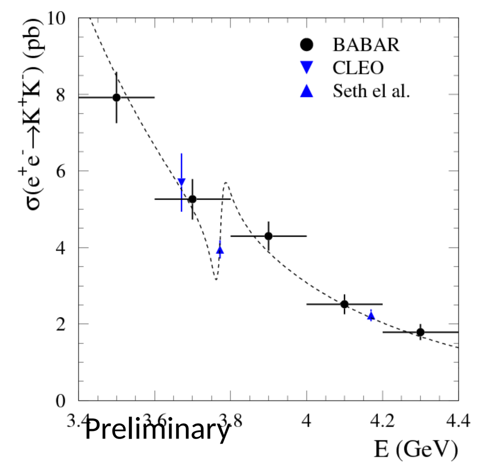
VIII. Interference pattern near the ψ(3770) resonance

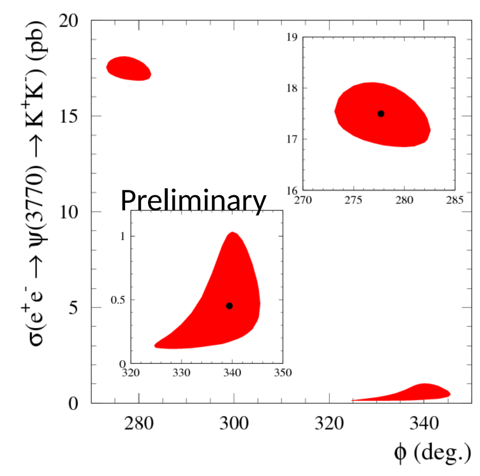
With B(ψ(3770) → K^+K^-) ~10^{-4} [10] the decay reveals itself as an interference pattern in the energy dependence of the $e^+e^- \to K^+K^-$ cross section near the ψ(3770) resonance.

$$\sigma_{K^+K^-}(E) = \left|\sqrt{\sigma_{\rm cont}} - \sqrt{\sigma_\psi e^{i\phi}}\frac{m_\psi\Gamma_\psi}{D}\right|^2 =$$
$$\sigma_{\rm cont} + (\sigma_\psi + 2\sqrt{\sigma_{\rm cont}\sigma_\psi}\sin\phi)\frac{m_\psi^2\Gamma_\psi^2}{|D|^2} -$$
$$2\sqrt{\sigma_{\rm cont}\sigma_\psi}\cos\phi\frac{m_\psi\Gamma_\psi(m_\psi^2 - E^2)}{|D|^2},$$

$$\sigma_{\rm cont}(E) = \frac{\pi\alpha^2\beta^3}{3E^2}|F_K(E)|^2, \qquad |F_K(E)| = \frac{A}{E^2(E^\gamma + B)},$$

where $\sigma_\psi \equiv \sigma_{\psi(3770)}$ is the cross section for the process $e^+e^- \to \psi(3770) \to K^+K^-$ in the resonance maximum, and $D = m_\psi^2 - E^2 - im_\psi\Gamma_\psi$

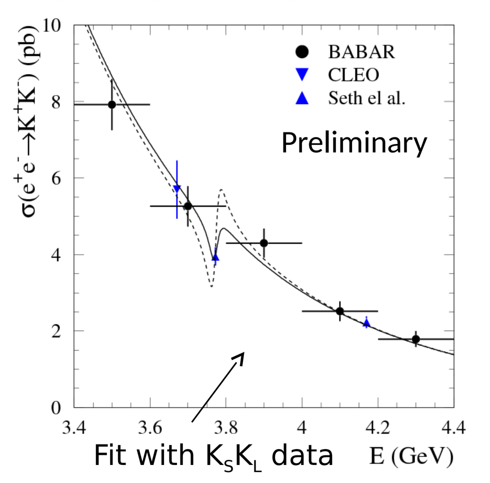


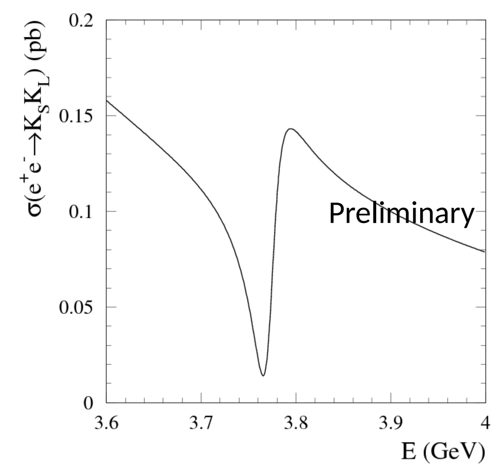


The fit yields two solutions for $\sigma_{\psi(3770)}$ and φ with statistical significance of 3.2σ. They corresponds to branching fractions of about 10^{-4} and 10^{-3}.

IX. Constraints from $e^+e^- \to K_SK_L$

Since the single-photon contribution is small, B(ψ(3770) → K_SK_L) = B(ψ(3770) → K^+K^-), but the nonresonant $e^+e^- \to K_SK_L$ cross section is significantly, at least by an order of magnitude, lower than that for K^+K^-. The interference pictures are strongly different for K_SK_L and K^+K^-.
The data $\sigma(e^+e^- \to K_SK_L)(m_\psi) < 0.07$ pb at 90% CL [12] and $\sigma_{cont}(K_SK_L) / \sigma_{cont}(K^+K^-) = 0.030 \pm 0.015$ at E= m_ψ [13,14,15] are added to the fit.





The fit with K_SK_L data yields a single solution:

$$\boxed{\begin{aligned}\sigma_{\psi(3770)} &= 0.073^{+0.62}_{-0.44}\ \text{pb},\\ \phi &= (308^{+17}_{-34})°.\end{aligned}}$$

The values of $\sigma_{\psi(3770)}$ and φ are shifted from those for the fit without K_SK_L constraints by about 1.5σ. The statistical significance is the same, 3.2σ. The branching fraction B(ψ(3770) → K^+K^-) corresponding to the measured cross section is about 10^{-5}.
The same fitting procedure is used in the energy region of the ψ(4160) resonance. The upper limit on the $e^+e^- \to$ ψ(3770) → K^+K^- cross section is set

$$\boxed{\sigma_{\psi(4160)} < 0.062 \text{ pb at } 90\% \text{ CL.}}$$

The corresponding limit on the branching fraction is B(ψ(4160) → K^+K^-) < 2×10^{-5} at 90% CL.