Study of the process $e^+e^- \to K^+K^-\pi^0$ with the CMD-3 detector

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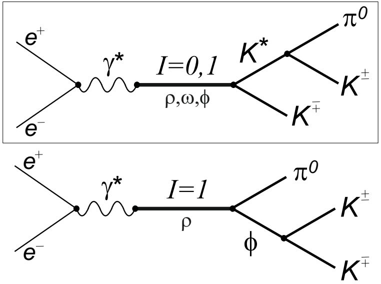
- This process is one of three charge modes of the reaction $e^+e^- \to K\bar{K}\pi$ contributing significantly to the total cross-section of electron-positron annihilation into hadrons (about 12% in neighborhood of $\sqrt{s} = 1.65$ GeV).
- The combined study of the annihilation reactions to the final states $K^+K^-\pi^0$, $K_SK^\pm\pi^\mp$ and $K_SK_L\pi^0$ via the $K^*(892)K$ intermediate state allows testing of isotopic relations.
- The combined study of the τ-lepton decays $\tau^\pm \to K_S\pi^\pm\nu$ and $\tau^\pm \to K^\pm\pi^0K_S\nu$ with Belle II as well as the three annihilation reactions mentioned above could provide additional valuable information about the $K^*(892)^\pm$ mass, namely unveil an impact of the hadronic and electromagnetic interactions in the final state (Denis A. Epifanov report at this conference).

The main mechanisms of the reaction $e^+e^- \to K^+K^-\pi^0$ in the energy range up to 2 GeV: transitions through K^*K (dominant channel) and $\phi\pi^0$ intermediate states. We present here preliminary results of the cross-section measurement of the channel $e^+e^- \to K^*K \to K^+K^-\pi^0$.

- Two main mechanisms in the energy range up to 2 GeV – transitions through $K^*(892)K$ and $\phi(1020)\pi^0$ intermediate states.
- We present here preliminary results of the cross-section measurement of the dominated chanell $e^+e^- \to K^*K \to K^+K^-\pi^0$. To suppress $\phi\pi^0$ contribution, a constraint is imposed on the invariant mass of kaons: $m_{inv}(K^+K^-) > 1045$ MeV.
- The separation of isoscalar and isovector amplitudes is possible by means of joint fitting the cross-sections for the final states $K^+K^-\pi^0$ and $K_SK_L\pi^0$ using isospin symmetry.

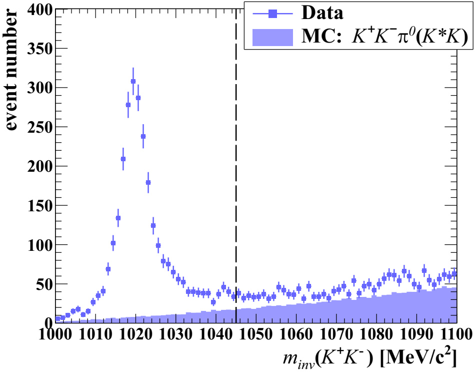


Data set

scan	points	L [1/pb]	$\sqrt{s}$ range [GeV]
2011	33	18.0	1.15–2.00
2012	16	13.3	1.28–1.99
2017	32	46.0	1.28–2.00
2019	40	58.9	1.15–1.98
2020	5	46.6	1.87–1.94
2021	4	47.8	1.94–2.00
2022	33	282.3	1.58–1.90
2023	20	162.6	1.26–1.59

Total:

- luminosity integral: 676 1/pb
- 160 energy points



(4/13) Event selection and the main background

Event preselection

- Two good non-collinear tracks with zero total charge going through the central part of the drift chamber (DC)
- At least two photons, i.e. $N_\gamma > 1$

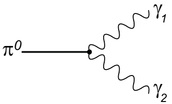
Kinematic reconstruction

- A kinematic 4C-fit (4C-KF) is performed where conservation of energy-momentum is required
- To suppress the background we require $\chi^2/ndf < 35$

The main background processes

Multi-hadron generator[1] (MHG) simulations reveal the following primary sources of background events:

- $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$
- $e^+e^- \to K^+K^-\pi^0\pi^0$
- $e^+e^- \to K_S^0 K^\pm \pi^\mp \to K^\pm\pi^\mp\pi^0\pi^0$



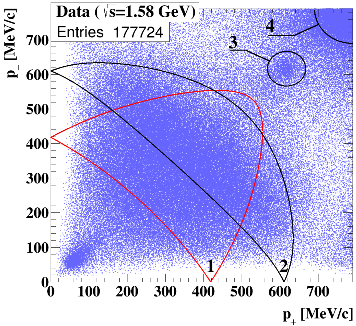
The signal event number is determined by analyzing the spectrum of $m_{inv}(\gamma_1\gamma_2)$ – the invariant mass of the photon pair with minimum KF χ^2/ndf.

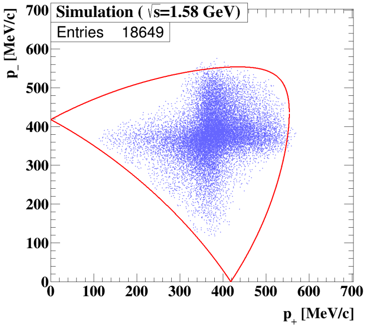
Attention: the presence of a neutral pion in the final state of the main background process drastically increases the uncertainty of the background shape in the $m_{inv}(\gamma_1\gamma_2)$ distribution.

Ref: [1] Korobov, A. A. and Eidelman, S. I., Data-driven Low-energy Generic Generator for CMD-3, J. Phys. Conf. Ser., 1525,1,2020.

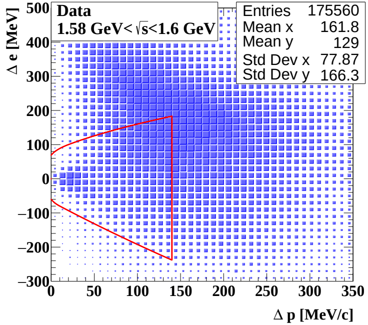
Track momenta absolute values
The absolute values of both measured and reconstructed track momenta must be within the kinematically permissible range.

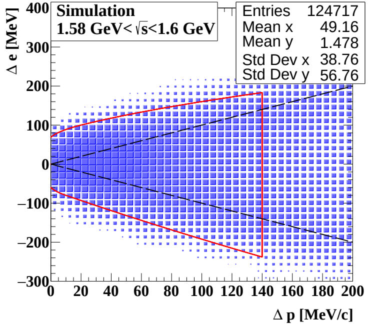
Numerical denotations: 1 – signal range; 2 – $e^+e^- \to \pi^+\pi^-\eta$ range; 3 – the region dominated by events of the process $e^+e^- \to K^+K^-$; 4 – the region dominated by Bhabha events.





Total energy-momentum before KF
We constrain the energy imbalance $\Delta e = \sqrt{s} - e(K^+K^-\gamma_1\gamma_2)$ and the momentum imbalance $\Delta p = |\boldsymbol{p}_+ + \boldsymbol{p}_- + \boldsymbol{p}(\gamma_1\gamma_2)|$ to be in the area marked by continuos curves.





The Boosted Decision Tree (BDT) method is the main tool for background suppression.

- The input arguments of the classifier include 15 both measured and reconstructed quantities. The arguments 1–11 depend essentially on the absolute values of the quantum momenta, while 12–15 are the polar angles of the particles.

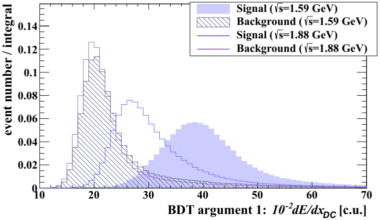
Correlation matrix (signal) — $\sqrt{s}$=1.58 GeV — Linear correlation coefficient [%]

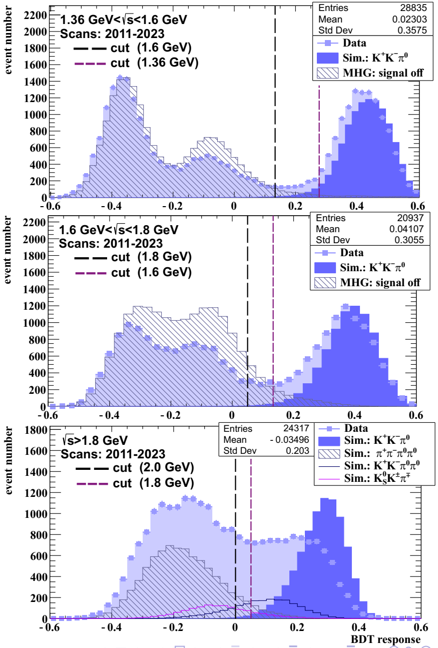
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15	0	0	-1	0	0	0	0	0	1	0	-1	-32	14	16	100
14	0	0	0	0	0	0	0	0	1	0	0	-91	35	100	16
13	-1	0	1	0	0	0	0	-1	-1	1	1	-39	100	35	14
12	-1	0	1	0	0	0	0	1	-1	0	0	100	-39	-91	-32
11	-17	-18	19	11	0	-29	15	-19	-51	37	100	0	1	0	-1
10	-55	-50	72	69	-67	-24	-6	-41	-71	100	37	0	1	0	0
9	38	36	-52	-48	49	17	-2	-9	100	-71	-51	-1	-1	1	1
8	27	25	-33	-31	32	8	49	100	-9	-41	-19	1	-1	0	0
7	6	9	-8	-13	6	7	100	49	-2	-6	15	0	0	0	0
6	13	10	-23	-22	-46	100	7	8	17	-24	-29	0	0	0	0
5	37	34	-52	-54	100	-46	6	32	49	-67	0	0	0	0	0
4	-9	-64	18	100	-54	-22	-13	-31	-48	69	11	0	0	0	0
3	-74	-8	100	18	-52	-23	-8	-33	-52	72	19	1	1	0	-1
2	4	100	-8	-64	34	10	9	25	36	-50	-18	0	0	0	0
1	100	4	-74	-9	37	13	6	27	38	-55	-17	-1	-1	0	0

Correlation matrix (background) — $\sqrt{s}$=1.58 GeV — Linear correlation coefficient [%]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15	0	1	0	0	0	0	0	0	0	0	0	-20	8	-1	100
14	0	0	0	0	0	0	0	0	1	0	0	-72	25	100	-1
13	1	0	-1	-1	1	0	1	0	0	-1	0	-35	100	25	8
12	-1	0	0	0	0	0	0	1	0	0	0	100	-35	-72	-20
11	13	10	-27	-26	18	23	69	12	-40	12	100	0	0	0	0
10	-18	-10	41	46	-51	-17	15	-9	-44	100	12	0	-1	0	0
9	8	2	-21	-16	35	-7	-38	-44	100	-44	-40	0	0	1	0
8	12	9	-11	-10	6	11	34	100	-44	-9	12	1	0	0	0
7	11	12	-15	-19	0	28	100	34	-38	15	69	0	1	0	0
6	15	10	-33	-33	-39	100	28	11	-7	-17	23	0	0	0	0
5	20	12	-44	-40	100	-39	0	6	35	-51	18	0	1	0	0
4	1	-41	0	100	-40	-33	-19	-10	-16	46	-26	0	-1	0	0
3	-54	2	100	0	-44	-33	-15	-11	-21	41	-27	0	-1	0	0
2	1	100	2	-41	12	10	12	9	2	-10	10	0	0	0	1
1	100	1	-54	1	20	15	11	12	8	-18	13	-1	1	0	0

- To train and test the classifier, use was made of the data obtained by simulating the signal process and the main background reactions.
- Each energy point has its own classifier (a forest is formed). The sizes of the signal and background samples coincide and amount to about 10000 events per point.
- The separation quality by dE/dx_{DC} rapidly decreases with increasing energy.

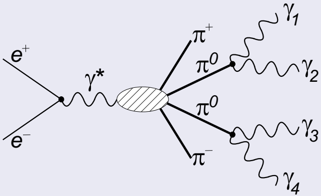


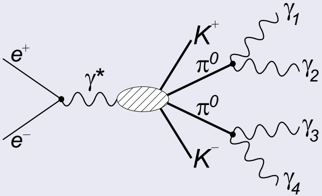


The background $m_{inv}(\gamma_1\gamma_2)$ distribution may have a peak in the m_{π^0} neighborhood if the background pion $\pi^0 \to \gamma_1\gamma_2$. This takes place mainly when the number of photons in an event $N_\gamma > 2$. Kinematic reconstruction of the main background processes with mass constraint $m_{inv}(\gamma_1\gamma_2) = m_{\pi^0}$ for $N_\gamma > 2$ can allow the background shape to be reduced and simplified.

Processes $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ and $e^+e^- \to K^+K^-\pi^0\pi^0$

These annihilation channels are kinematically identical. The kinematic reconstruction requires conservation of energy-momentum and satisfaction of the mass constraint $m_{inv}(\gamma_1\gamma_2) = m_{\pi^0}$. $\Rightarrow$ We have 5C-KF for $N_\gamma > 3$ and 2C-KF with one photon missed for $N_\gamma > 2$.

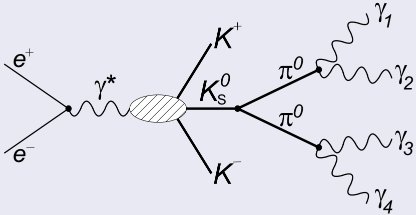




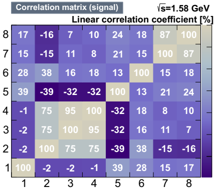
As a result, the 5C-KF gives $m_{inv}(\gamma_3\gamma_4)$ reconstructed. If the photon, for example, γ_4 is missed, the 2C-KF recovers $m_{inv}(\gamma_3\gamma_4)$ and the momentum absolute value of the missed photon $\boldsymbol{p}(\gamma_4)$. These values with the best χ^2 are saved for subsequent analysis (6 quantities).

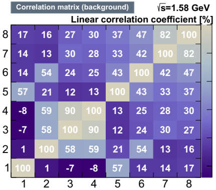
Process $e^+e^- \to K^0_S K^\pm \pi^\mp$

The constraints are supplemented by a mass one $m_{inv}(\gamma_1\gamma_2\gamma_3\gamma_4) = m(K^0_S)$ for both charge-conjugate processes. $\Rightarrow$ We have 6C-KF for $N_\gamma > 3$ and 3C-KF with one photon missed for $N_\gamma > 2$.



The recovered values $m_{inv}(\gamma_3\gamma_4)$ and the momentum absolute values of the missing photon with the best χ^2 are saved for subsequent analysis (6 quantities).



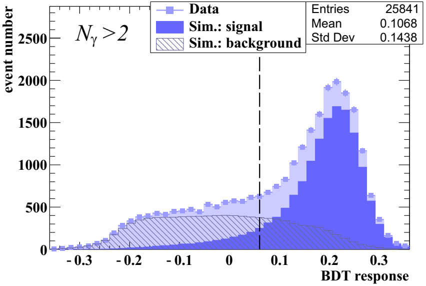


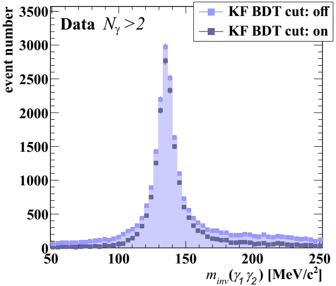
BDT for $N_\gamma > 2$ (one missing photon)

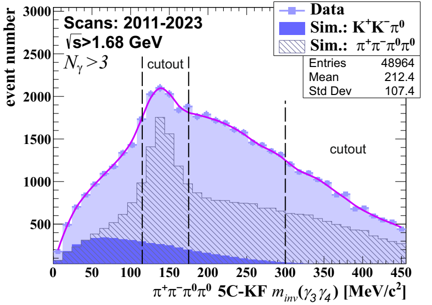
- Input arguments: KF-recovered $m_{inv}(\gamma_3\gamma_4)$ and momenta absolute values of the missing photon for each main background process (8 quantities)
- To train and test the forest, use was made of the data obtained by simulating the signal process and the main background reactions
- Selection by BDT response reduces background by almost three times

Background shape simplification

- The number of signal events with $N_\gamma > 3$ does not exceed 20% of the total number of signal events
- The reaction $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ is the dominant background process
- Exclusion of events with $m_{inv}(\gamma_3\gamma_4)$ in the range from 110 Mev to 160 MeV prevents peak formation



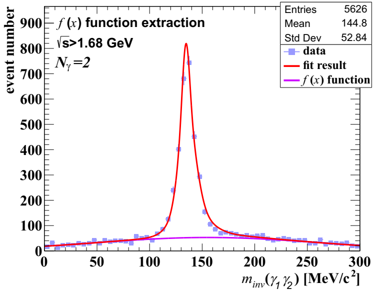




Fit function: $p_1 s(p_2 x - p_3) + p_4 f(x) + p_5 g(x)$. Being determined from simulation the function $s(x)$ describes signal. The superposition of the functions $f(x)$ and $g(x)$ describes background.

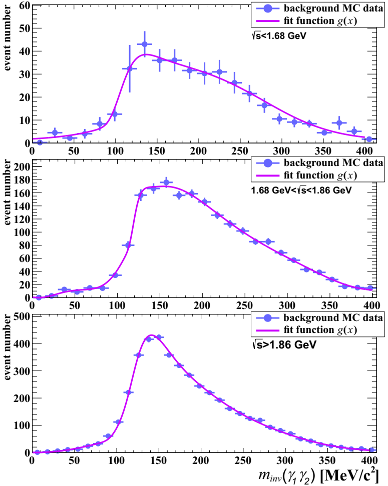
$f(x)$ determination

The class with $N_\gamma = 2$ contains mainly non-physical background. The shape of the latter is extracted from experiment.

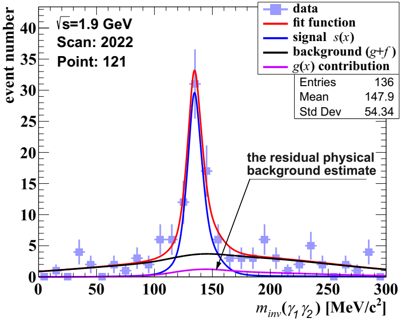


$g(x)$ determination

The physical background shape is determined from modeling all background processes for several energy ranges.



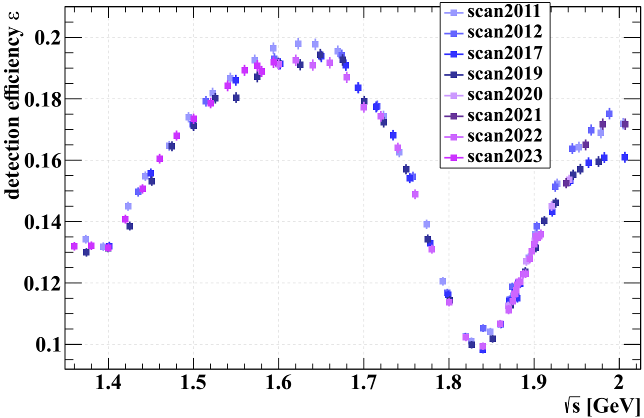
Typical spectrum



- The total number of selected signal events is about 25k events.
- The fitting function at each point defines a PDF, which is used to calculate the error using the MC method.

- The visible cross-section is known to be $\sigma_{vis} = N_{sig}/\varepsilon L$, where N_{sig} is the signal yield, ε – the detection efficiency and L – the luminosity.
- The detection efficiency ε in leading order is determined from simulation: $\varepsilon = N^{MC}_{sel}/N^{MC}_{tot}$, with N^{MC}_{sel} – the number of events selected and N^{MC}_{tot} – the total number of simulated events.

Since the simulation is performed with ISR, the radiation correction introduced into the simulation has a significant impact on the efficiency energy dependence. For now the radiation correction is extracted from BaBar data fit.



Efficiency corrections

- The efficiency correction taking into account the photon reconstruction inefficiency is calculated using the reaction $e^+e^- \to \pi^+\pi^-\pi^0$ and does not exceed 3%.
- It has been proven that no correction of the track reconstruction efficiency is required.

Systematic uncertainties

systematic uncertainty source	estimate
selection cuts (without BDTs)	1.1%
photon reconstruction	0.8%
track reconstruction	1.0%
luminosity measurement	1.5%
total	2.3%

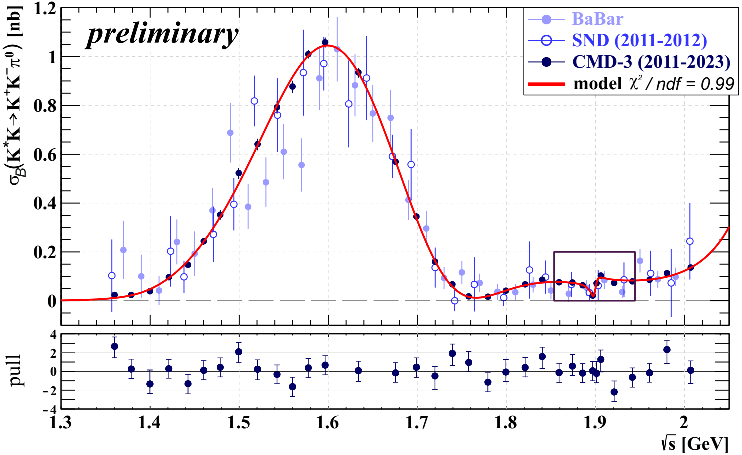
The systematic uncertainty generated by selection on BDT responses remains to be investigated. It appears to be the main source of uncertainty.

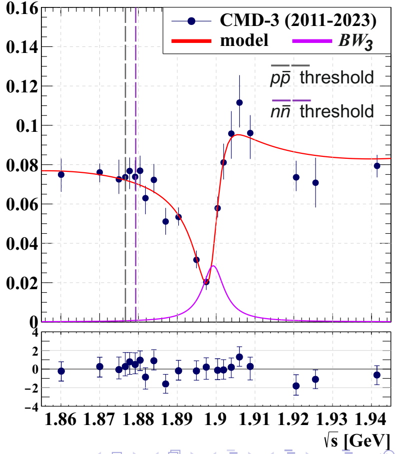
The visible cross-section fit function: $f_V(\sqrt{s}, \boldsymbol{p}) = \int dx f_B(\sqrt{s(1-x)}, \boldsymbol{p}) R_{FK}(x,s)$.
Denotations: f_B is a function of Born cross-section model, $\boldsymbol{p}$ is a vector of model parameters and $R_{FK}(x,s)$ is a well-known Fadin-Kuraev kernel.

$1+\delta_r(\sqrt{s}) = f_B(\sqrt{s})/f_V(\sqrt{s})$ – the radiative correction.
$\Rightarrow$ Born cross-section is calculated as $\sigma_B[\sqrt{s}] = (1+\delta_r(\sqrt{s}))\sigma_V[\sqrt{s}]$.

Preliminary fit: 16 parameters. The phase of the $\rho(1700)$ resonance is fixed by isospin symmetry. Separation of isoscalar and isovector amplitudes does not yet seem possible.

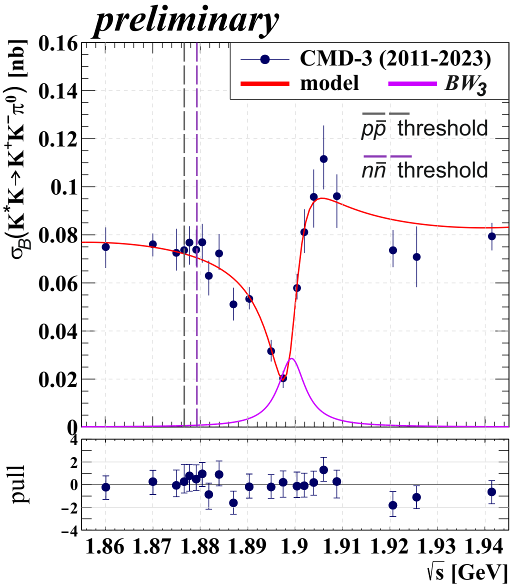
	mass [GeV]	width [GeV]
BW_1	1.752±0.008	0.194±0.01
BW_2	1.598±0.005	0.325±0.015
$\rho(1700)$	1.72 (fixed)	0.25 (fixed)
$\omega(1650)$	1.67 (fixed)	0.315 (fixed)
$\varphi(2170)$	2.175 (fixed)	0.061 (fixed)
BW_3	1.8992±0.0013	0.0069±0.0024





(12/13) $\rho(1900)$?

Parameters of the introduced resonance:
$m = 1.8992 \pm 0.0013$ GeV and $\Gamma = 6.9 \pm 2.4$ MeV.



$\rho(1900)$

$I^G(J^{PC}) = 1^+(1^{--})$

OMITTED FROM SUMMARY TABLE

See the review on "Spectroscopy of Light Meson Resonances."

$\rho(1900)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1880 ± 10		[1] ABLIKIM	22L	BES3	2.0–3.08 $e^+e^- \to K^+K^-\pi^0$
$1909 \pm 17 \pm 25$	54	[2] AUBERT	08S	BABR	10.6 $e^+e^- \to \phi\pi^0\gamma$
1880 ± 30		AUBERT	06D	BABR	10.6 $e^+e^- \to 3\pi^+3\pi^-\gamma$
1860 ± 20		AUBERT	06D	BABR	10.6 $e^+e^- \to 2(\pi^+\pi^-\pi^0)\gamma$
1910 ± 10		[3,4] FRABETTI	04	E687	$\gamma p \to 3\pi^+3\pi^- p$
1870 ± 10		ANTONELLI	96	SPEC	$e^+e^- \to$ hadrons

[1] From a partial wave amplitude analysis at $\sqrt{s} = 2.125$ GeV which includes all the possible intermediate states that match J^{PC} conservation in the subsequent two-body decay. The intermediate states are parameterized with the relativistic Breit-Wigner functions. Statistical error only.
[2] From the fit with two resonances.
[3] From a fit with two resonances with the JACOB 72 continuum.
[4] Supersedes FRABETTI 01.

$\rho(1900)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
69 ± 15		[1] ABLIKIM	22L	BES3	2.0–3.08 $e^+e^- \to K^+K^-\pi^0$
$48 \pm 17 \pm 2$	54	[2] AUBERT	08S	BABR	10.6 $e^+e^- \to \phi\pi^0\gamma$
130 ± 30		AUBERT	06D	BABR	10.6 $e^+e^- \to 3\pi^+3\pi^-\gamma$
160 ± 20		AUBERT	06D	BABR	10.6 $e^+e^- \to 2(\pi^+\pi^-\pi^0)\gamma$
37 ± 13		[3,4] FRABETTI	04	E687	$\gamma p \to 3\pi^+3\pi^- p$
10 ± 5		ANTONELLI	96	SPEC	$e^+e^- \to$ hadrons

[1] From a partial wave amplitude analysis at $\sqrt{s} = 2.125$ GeV which includes all the possible intermediate states that match J^{PC} conservation in the subsequent two-body decay. The intermediate states are parameterized with the relativistic Breit-Wigner functions. Statistical error only.
[2] From the fit with two resonances.
[3] From a fit with two resonances with the JACOB 72 continuum.
[4] Supersedes FRABETTI 01.

- Cross-section of the process $e^+e^- \to K^*(892)K \to K^+K^-\pi^0$ has been preliminary measured with the best statistical accuracy in the energy range up to 2 GeV.
- Evidence for the existence of a narrow resonance near the threshold of the nucleon-antinucleon pair production has been obtained.
- However, we still need to carefully consider several remaining sources of systematics.

Somewhat more distant and global plans include

- a joint fitting of cross-sections of the reaction under study and $K^*(892)K$-mediated reaction $e^+e^- \to K_S K_L \pi^0$ using isotopic relations;
- a dynamics study.

Thank you for attention