Measurement of $e^+e^- \to$ hadrons in Novosibirsk

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Abstract. We discuss various experiments on $e^+e^- \to$ hadrons performed at the VEPP-2000 (the CMD-3 and SND detectors) and VEPP-4M (the KEDR detector) colliders in Novosibirsk.

1 Introduction

Precise measurement of $R = \sigma(e^+e^- \to$ hadrons$)/\sigma(e^+e^- \to \mu^+\mu^-)$ allows us a study of interactions of light quarks (u, d, s, c) with numerous applications. These include a spectroscopy of light vectors (ρ, ω, ϕ) and their excitations below 3 GeV, a search for and studies of regular and exotic mesons with various quantum numbers in $e^+e^- \to$ hadrons $(n(\pi^+\pi^-)m\pi^0, \ n(K\bar{K})m\pi, \ \ldots)$, calculations of the hadronic vacuum polarization for the muon anomalous magnetic moment $(g_\mu - 2)/2$ and running fine structure constant, $\alpha(0) \to \alpha(M_Z^2)$, determination of various QCD parameters $(\alpha_s$, quark masses, gluon condensates) and tests of QCD sum rules, tests of CVC (Conserved Vector Current)-based relations between $\sigma_{I=1}(e^+e^- \to$ hadrons$)$ and corresponding τ lepton decays. These problems are addressed in experiments with the CMD-3 and SND detectors at the VEPP-2000 collider in the energy range $2m_\pi < \sqrt{s} < 2$ GeV.

One more series of experiments are performed with the KEDR detector at the VEPP-4M collider in the energy range $3 < \sqrt{s} < 4$ GeV. Here the goal is to study interactions of the c quark by precise measurements of the ψ family properties. c quarks are heavy enough to apply perturbative QCD, there are also potential "QCD inspired" models. Basic properties of the vector charmonia $(J/\psi, \ \psi(2S))$ and their excitations (mass M, total width Γ, lepton width Γ_{ll}) provide an input base for such models. Masses of the J/ψ and $\psi(2S)$ resonances provide a mass scale for τ and other charmed particles $(D^\pm, \ D^0, \ D_s, \ X(3872), \ \ldots)$, lepton widths $\Gamma_{ll} \sim |\psi(0)|^2$. In this energy range one can also study production of $\tau^+\tau^-$ pairs near threshold and perform a high-precision measurement of the τ lepton mass M_τ. Precise measurements of the quantity R are important for the determination of the charm quark mass.
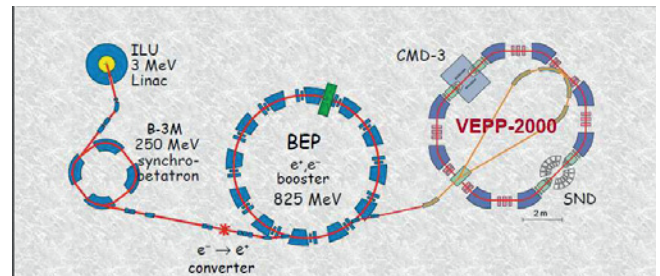

Figure 1. VEPP-2000 accelerator complex

2 Experiments at VEPP-2000

2.1 VEPP-2000 and CMD-3 and SND detectors

The VEPP-2000 e^+e^- collider [1] was designed as an upgrade of the VEPP-2M collider that was successfully operated in Budker Institute for a quarter of a century. The general layout of the VEPP-2000 accelerator complex is shown in Fig. 1. It is designed to cover a larger center-of-mass energy range and a novel concept of round beams should provide much larger luminosity. Comparison of the main parameters of VEPP-2M and VEPP-2000 is given in Table 1.

Table 1. Comparison of VEPP-2M and VEPP-2000

Collider	Operation	$\sqrt{s}$, MeV	$\mathcal{L}$, 10^{30}cm^{-2}s^{-1}
VEPP-2M	1975-2000	[360,1400]	3
VEPP-2000	2010-	[$2m_\pi$, 2000]	100

Currently the maximum achieved luminosity is $2 \cdot 10^{31}$cm^{-2}s^{-1}, still a factor of 5 smaller compared to the designed value. However, the experience of the first three seasons of VEPP-2000 operation was very positive: the regime of round beams is very stable and luminosity at low energies (below 1 GeV) is not falling with energy decrease as rapidly as before. Both detectors currently installed at VEPP-2000 (CMD-3 and SND) collected about 60 pb^{-1}

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each in the $\sqrt{s}$ energy range from 320 MeV (the lowest energy ever achieved at e^+e^- machines) to 2 GeV.

In 2015 commissioning of the new injection complex will start allowing the positron current to be increased. In addition, the booster now running at 825 MeV maximum will be upgraded to allow operation at the maximum energy needed of 1 GeV per beam with the obvious result of continuous injection possible, finally providing average luminosity close to the maximum one. The current plan of the machine is to run as long as possible to reach an integrated luminosity of ~ 1 fb^{-1} by 2020.

The CMD-3 and SND detectors are installed in the straight sections of the collider. The general-purpose magnetic detector CMD-3 is shown in Fig. 2. Its tracking system consists of a drift chamber and two layers of a proportional Z-chamber inside a thin superconducting solenoid with 1.35 T magnetic field, both also used for the trigger. The calorimetry in the detector is based on three subsystems: closest to the beam pipe the barrel liquid xenon calorimeter (LXe), outer barrel calorimeter based on the CsI scintillation crystals and endcap calorimeter made of BGO scintillation crystals. The detector is also equipped with a barrel-like arrangement of time-of-flight scintillation counters, located between LXe and CsI calorimeters, and muon-range system. A more detailed description is given elsewhere [2].

The Spherical Neutral Detector (SND) is shown in Fig. 3. It is a general purpose non-magnetic detector. Parameters of charged tracks are measured using the drift and proportional chambers placed in a common cylindrical gas volume. Particle identification is performed using energy deposition in the drift chamber at particle momenta $p < 300\text{MeV}/c$ and aerogel Cherenkov threshold counters at $p > 300\text{MeV}/c$. Photon energies are measured a using 3-layer spherical electromagnetic calorimeter based on NaI crystals. Muons are detected by the muon system based on proportional tubes and plastic scintillator counters. A more detailed description is given elsewhere [3].

2.2 Measurement of hadronic cross sections

The process $e^+e^- \rightarrow \pi^+\pi^-$ is known to give the dominating contribution to the hadronic vacuum polarization for muon $g - 2$. Therefore, a measurement of its cross section with the highest possible accuracy is of great importance. In
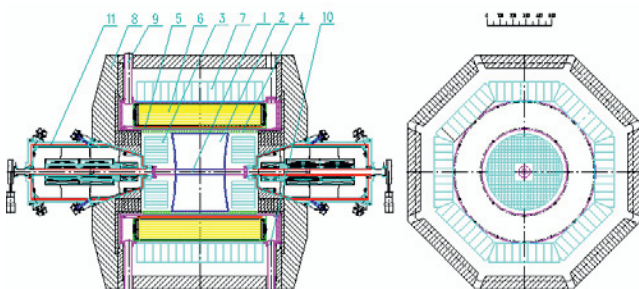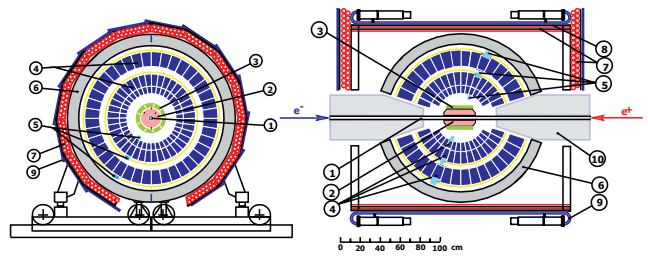

Figure 3. SND detector

Fig. 4 we show preliminary results for the pion form factor (upper) and the estimated statistical accuracy (lower). From the upper figure it can be seen that at low energies there is a region of overlap where results obtained by separating pions and muons in the drift chamber and by energy deposition in the calorimeters can be cross checked. The lower one shows that the statistical precision of the CMD-3 is competitive or better than those of BaBar [4] and KLOE [5].
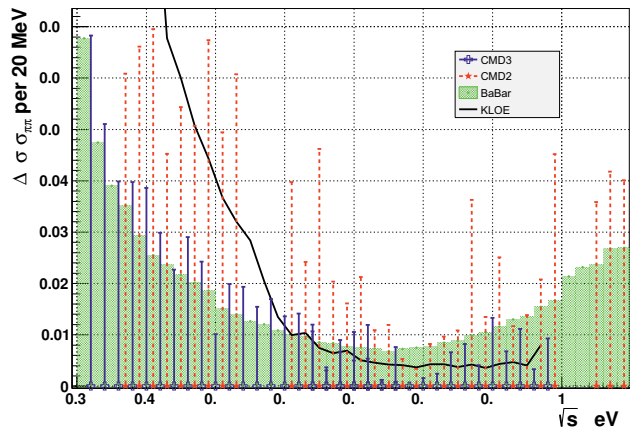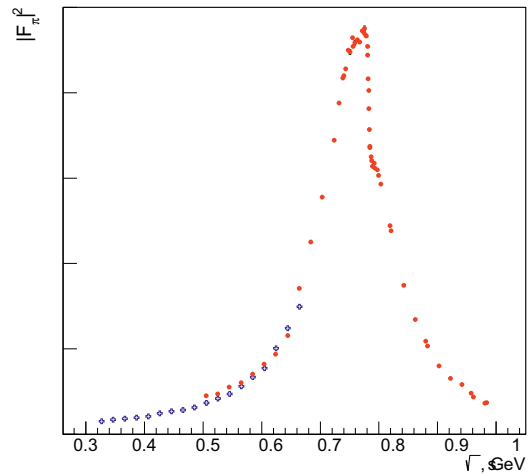

Figure 4. $e^+e^- \rightarrow \pi^+\pi^-$ at CMD-3: $|F_\pi(s)|^2$ and expected accuracy
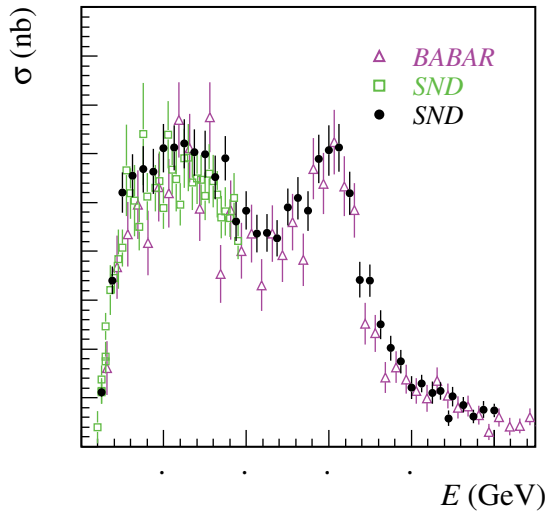

Figure 2. CMD-3 detector

Figure 5. $e^+e^- \to \pi^+\pi^-\pi^0$ at SND

Figure 7. $e^+e^- \to \pi^0\pi^0\gamma$ at SND (upper) and $e^+e^- \to 3\pi^+3\pi^-$ at CMD-3 (lower)

In Fig. 5 we show the cross section of the process $e^+e^- \to \pi^+\pi^-\pi^0$ measured by SND. The cross section is consistent with that by BaBar [6] and is significantly higher than that measured by DM2 [7]. It also shows clearly the two excitations of the $\omega - \omega(1420)$ and $\omega(1650)$.

Figures 6 present the cross section of the process $e^+e^- \to 2\pi^+2\pi^-$ measured by CMD-3 (upper) and SND (lower). While the CMD-3 measurement is in fair con-
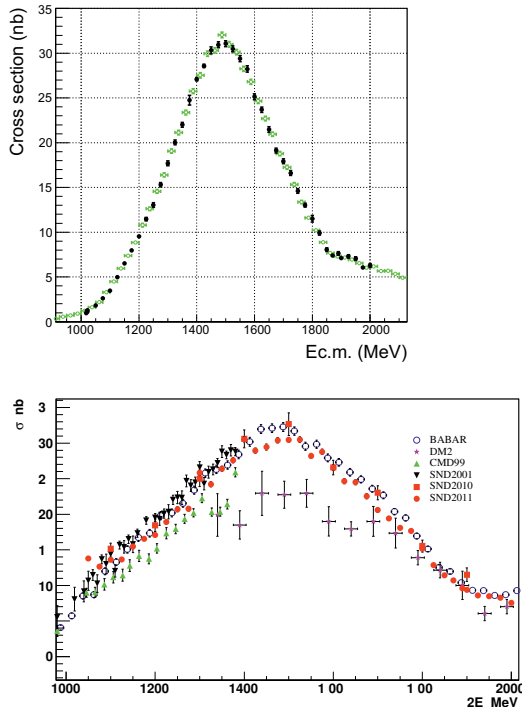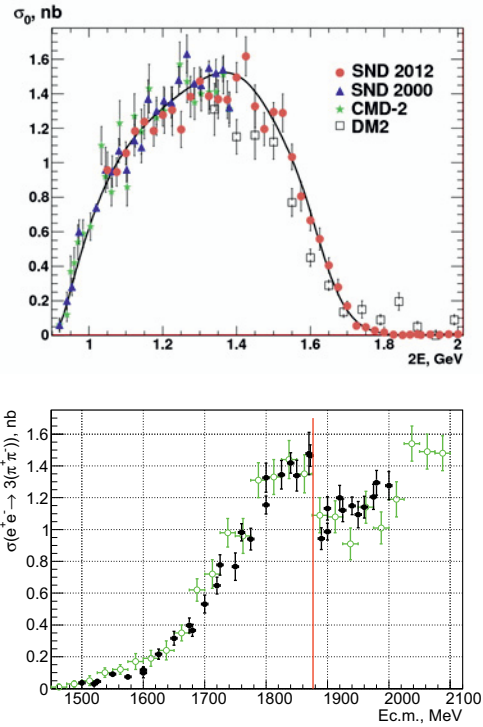

Figure 6. $e^+e^- \to 2\pi^+2\pi^-$ at CMD-3 and SND

sistence with BaBar, preliminary data of SND are slightly lower at higher energies.

Figure 7 (upper) shows the cross section of the process $e^+e^- \to \pi^0\pi^0\gamma$ measured by SND [8]. The process is dominated by the $\omega\pi^0$ intermediate mechanism. It is the first observation of this final state above 1.4 GeV. The lower figure depicts the cross section of production of six charged pions studied by CMD-3 [9]. The cross section is in good agreement with BaBar and in particular confirms the dip structure near $N\bar{N}$ threshold earlier observed by BaBar [10].

The cross section of $p\bar{p}$ production studied by CMD-3 (upper) and SND (lower) is shown in Figs. 8. Both groups report consistent cross sections, also agreeing with the BaBar data [11].

Analysis of many other final states is in progress and both groups plan to present their results in 2014. The goal is a measurement of various multi-body cross sections with a systematic accuracy of 3%. The cross section of the process $e^+e^- \to \pi^+\pi^-$ should be known to better than 0.5%.

3 Experiments at VEPP-4M

3.1 Measurement of J/ψ and $\psi(2S)$ Masses

Precise values of the J/ψ and $\psi(2S)$ masses provide a mass scale for all charm and charmonium particles. High-precision mass measurements are one of the traditional experiments performed at the VEPP-4M collider [12] with the KEDR detector [13] (see Fig. 9) based on the very

accurate absolute beam energy determination using resonance depolarization [14] and laser Compton backscattering [15].

We performed a new measurement based on the combined analysis of all scans of the charmonium energy range in 2002-2008: six at the J/ψ – 2002 (4), 2005 (1) and 2008 (1) and seven at the $\psi(2S)$ – 2002 (3), 2004 (2), 2006 (1), 2008 (1), in total 7×10^5 J/ψ and 2×10^5 $\psi(2S)$ multihadronic events with more than 1000 resonant depolarization energy calibrations [16]. Analysis took into account possible correlations as well as interference with multihadronic continuum characterized by the parameter $\lambda = \sqrt{\frac{R\mathcal{B}_{\mu\mu}}{\mathcal{B}_h}}$ estimated to be 0.38 at the J/ψ and 0.13 at the $\psi(2S)$.
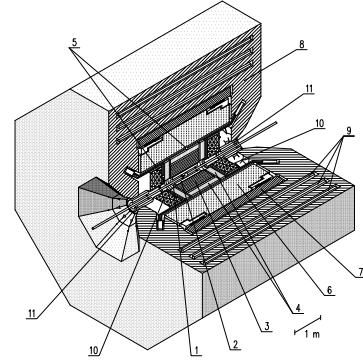
Table 2. Final KEDR results for mass and λ averaged over all scans

| State	Mass, MeV	λ
J/ψ	$3096.900 \pm 0.002 \pm 0.006$	$0.43 \pm 0.07 \pm 0.08$
$\psi(2S)$	$3686.100 \pm 0.004 \pm 0.009$	$0.18 \pm 0.06 \pm 0.08$

Results obtained in various scans are consistent with each other and can be averaged to give the values listed
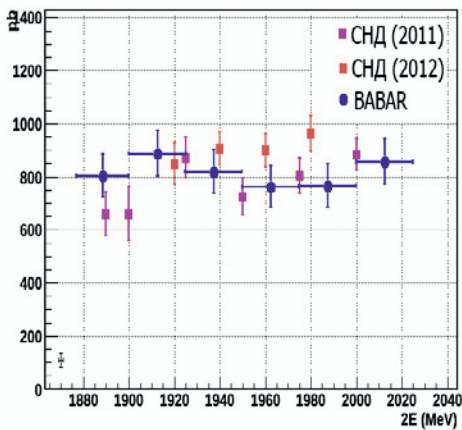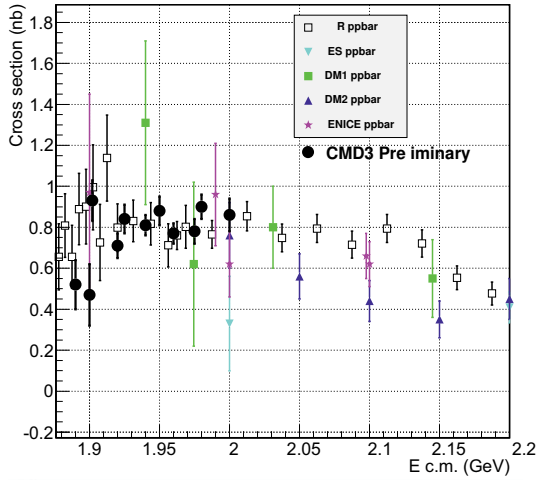
Figure 8. Cross section of $e^+e^- \to p\bar{p}$ at CMD-3 (upper) and SND (lower)

Figure 9. 1 – Vacuum chamber, 2 – Vertex detector, 3 – Drift chamber, 4 – Threshold aerogel counters, 5 – ToF-counters, 6 – Liquid krypton calorimeter, 7 – Superconducting solenoid, 8 – Magnet yoke, 9 – Muon tubes, 10 – CsI calorimeter, 11 – Compensating superconducting coils
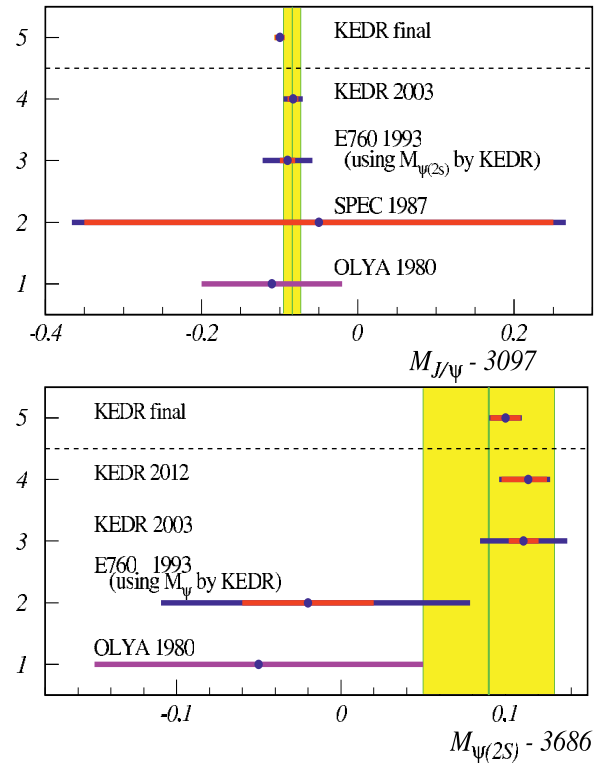
Figure 10. Comparison of the KEDR results on J/ψ and $\psi(2S)$ masses with the previous measurements

in Table 2. These averages also agree with the previous measurements [17–22] and are more precise, see Fig. 10.

3.2 Study of $J/\psi \to e^+e^-$ and $\mu^+\mu^-$

The leptonic width of quarkonium provides important information on its wave function in the origin. For an improvement of our previous measurement [23] and a study of possible systematic effects we determined the ratio of the leptonic widths of the J/ψ based on a data sample of 6.5×10^6 events. Our result $\Gamma(e^+e^-)/\Gamma(\mu^+\mu^-) = 1.0022 \pm 0.0044 \pm 0.0048$ is consistent with unity as expected [24].

Its precision is better than that of CLEO [25] and is comparable to that of BES3 [26]. Figure 11 shows its comparison with all the previous measurements [27–30].

3.3 Study of $\psi(2S) \to \mu^+\mu^-$

Information about basic properties of the $\psi(2S)$ other than mass and total width is scarce: there are only a few measurements of $\Gamma_{e^+e^-}$ [31–34] with an average of 2.37 ± 0.04 keV [35] and indirect estimates of the leptonic branching fractions $\mathcal{B}(e^+e^-) = (78.2 \pm 1.7) \cdot 10^{-4}$ and $\mathcal{B}(\mu^+\mu^-) = (78 \pm 9) \cdot 10^{-4}$ [35] based on the values of $\Gamma_{e^+e^-}$ and total width [36, 37].

KEDR used a data sample of ~ 7 pb^{-1} collected in nine experiments with $3.5 \cdot 10^6$ $\psi(2S)$ mesons produced to measure $\Gamma_{e^+e^-} \mathcal{B}(\mu^+\mu^-)$. Results of different experiments shown in Fig. 12 are consistent with each other and their average gives $\Gamma_{e^+e^-} \mathcal{B}(\mu^+\mu^-) = (19.4 \pm 0.4 \pm 1.1)$ eV, in agreement with and two times more precise than the "world average" constructed of various fits $\Gamma_{e^+e^-} \mathcal{B}(l^+l^-) = (18.5 \pm 2.1)$ eV.

3.4 Decay $J/\psi \to \eta_c(1S)\gamma$

The $J/\psi \to \eta_c(1S)\gamma$ decay is a magnetic dipole transition between two $c\bar{c}$ ground states. Until recently there was a single measurement of Crystal Ball only with the branching fraction of $(1.27 \pm 0.36)\%$ [38], much smaller than the non-relativistic prediction of 3.05%, see [39]. The CLEO measurement gave a somewhat larger value of $(1.98 \pm 0.09 \pm 0.30)\%$ [40] resulting in the average of $(1.7 \pm 0.4)\%$ with a scale factor of 1.6.

The KEDR study based on $\sim 6 \cdot 10^6$ J/ψ decays used the inclusive spectrum of photons similarly to Crystal Ball gave an even larger value of $(3.58 \pm 0.23 \pm 0.45)\%$. In Fig. 13 we present a summary of various results on $\mathcal{B}(J/\psi \to \eta_c(1S)\gamma)$ [41–47]. The preliminary result of KEDR is consistent with the most recent theoretical prediction from the lattice calculations [47].

4 Summary

After three successful seasons of VEPP-2000 operation with two detectors, CMD-3 and SND, a lot of new results on the hadronic cross sections were produced. In close future many precise measurements will be reported improving our knowledge of hadronic vacuum polarization.
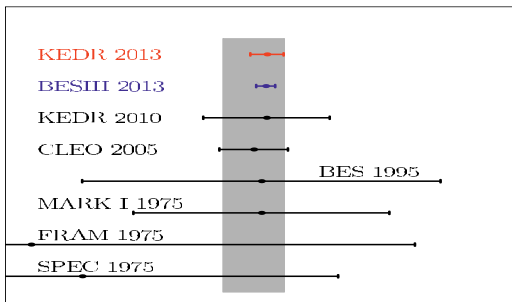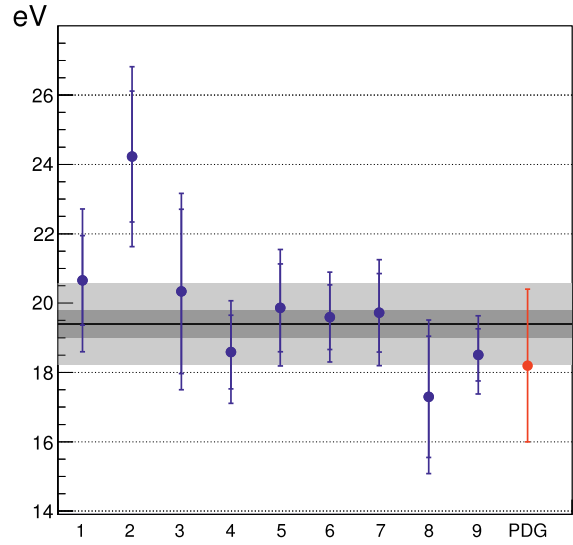

Figure 12. KEDR measurement of $\Gamma_{e^+e^-} \mathcal{B}(\mu^+\mu^-)$ at the $\psi(2S)$

The detailed scans of the charmonium energy range brought various high-precision results: measurement of the J/ψ and $\psi(2S)$ masses, determination of the ratio of the leptonic widths $\Gamma(e^+e^-)/\Gamma(\mu^+\mu^-)$ for the J/ψ, measurement of $\Gamma_{e^+e^-} \mathcal{B}(\mu^+\mu^-)$ for the $\psi(2S)$, study of the $J/\psi \to \eta_c(1S)\gamma)$ decay. Most of these results are still preliminary, analysis is in progress.

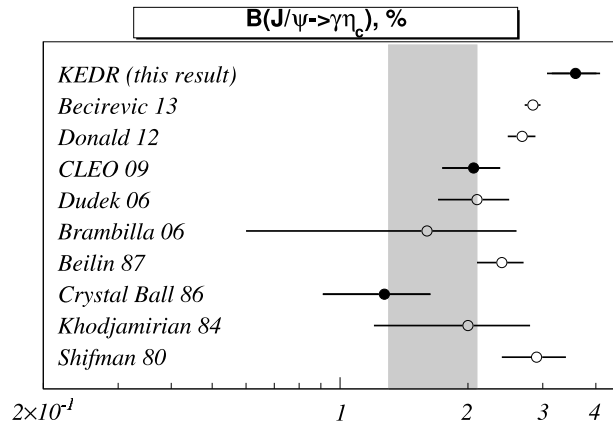**Figure 11.** Measurements of $\Gamma(e^+e^-)/\Gamma(\mu^+\mu^-)$ at the J/ψ

Figure 13. Summary of results on $\mathcal{B}(J/\psi \to \eta_c(1S)\gamma)$

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