Main results in the charmonium region from KEDR

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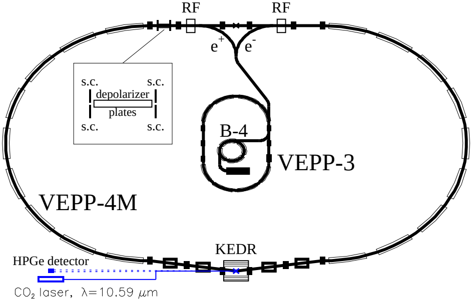
Outline: Main KEDR results in the charmonium region

1. VEPP-4M collider and KEDR detector
2. Cross section of e^+e^- annihilation nearby a narrow resonance
3. Measurement of J/ψ and $\psi(2S)$ masses
4. Study of $J/\psi \to \Gamma_{ee} \times \Gamma_{ll}/\Gamma$
5. Study of $J/\psi \to \gamma\,\eta_c$
6. $\Gamma_{ee} \times \Gamma_{\mu\mu}/\,\Gamma$ determination for $\psi(2S)$
7. $\Gamma_{ee} \times \Gamma_{h}/\,\Gamma$ determination for $\psi(2S)$
8. Determination of main $\psi(3770)$ parameters
   - KEDR results
   - Analysis of BABAR, BELLE, BES, CLEO and KEDR data

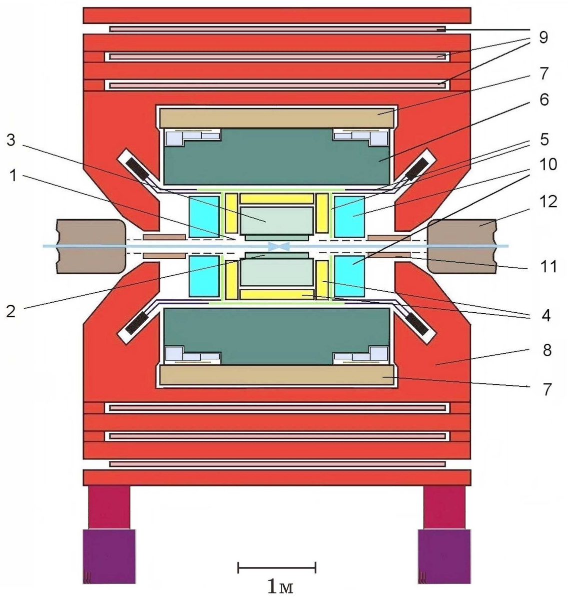
VEPP–4M collider



Circumference	366 m
Beam energy	$1 \div 5$ GeV
Number of bunches	2×2
Beam current at $E = 1.8$ GeV	2.5 mA
Luminosity at $E = 1.8$ GeV	$1.8 \cdot 10^{30} \frac{1}{cm^2 \cdot s}$

- Resonant depolarization technique:
  Instant measurement accuracy $\simeq 1 \times 10^{-6}$
  Energy interpolation accuracy $(5 \div 15) \times 10^{-6}$ $(10 \div 30$ keV)
- Infra-red light Compton backscattering (2005):
  Statistical accuracy $\simeq 5 \times 10^{-5}$ / 30 minutes
  Systematic uncertainty $\simeq 3 \times 10^{-5}$ $(50 \div 70$ keV)

KEDR detector



1. Vacuum chamber
2. Vertex detector
3. Drift chamber
4. Aerogel threshold counters
5. ToF–counters
6. Liquid krypton calorimeter
7. Superconducting coil (0.6 T)
8. Magnet yoke
9. Muon tubes
10. CsI-calorimeter
11. Compensation solenoid
12. VEPP–4M quadrupole

- Luminosity monitoring by single Bremsstrahlung in e^+ and e^- directions
- Scattering electron tagging system for two-photon studies

- Analytical expression for the annihilation cross section nearby a narrow resonance in the soft photon approximation was first obtained in
  Ya.I. Azimov *et al.* JETP Lett. 21 (1975) 172
- With up-today modifications one has

$$\sigma^{e^+e^-\to hadr}(W) = \sigma^{e^+e^-\to hadr}_{continuum}(W) + \frac{12\pi}{W^2}\Big(1+\delta\Big)\times$$
$$\left\{\frac{\Gamma_{ee}\tilde{\Gamma}_h}{\Gamma M}\,\mathrm{Im}\, f(W) - \frac{2\alpha\sqrt{R\,\Gamma_{ee}\Gamma_h}}{3W}\,\lambda\,\mathrm{Re}\,\frac{f^*(W)}{1-\Pi_0}\right\},$$

$$\delta = \frac{3}{4}\beta + \frac{\alpha}{\pi}\left(\frac{\pi^2}{3}-\frac{1}{2}\right) + \beta^2\left(\frac{37}{96}-\frac{\pi^2}{12}-\frac{L}{72}\right), \quad L = \ln\left(W^2/m_e^2\right),$$

$$\beta = \frac{4\alpha}{\pi}\left(\ln\frac{W}{m_e}-\frac{1}{2}\right), \qquad f(W) = \frac{\pi\beta}{\sin\pi\beta}\left(\frac{W^2}{M^2-W^2-iM\Gamma}\right)^{1-\beta}$$

Γ_{ee}, Γ, M – 'dressed' parameters including corrections to the vacuum polarization, $\Gamma_{ee} = \Gamma^{(0)}_{ee}/|1-\Pi_0|^2$

λ–parameter controls the resonance–continuum interference, $\tilde{\Gamma}_h \neq \Gamma_h$

Interference effects in the inclusive hadronic cross section

If strong and electromagnetic decays of the resonance do not interfere

$$\lambda = \sqrt{R\mathcal{B}_{ee}/\mathcal{B}_h}$$

otherwise for an exclusive mode m contributing R_m to the R ratio the partial width is

$$\Gamma_m = R_m\Gamma_{ee} + \Gamma_m^{(s)} + 2\sqrt{R_m\Gamma_{ee}\Gamma_m^{(s)}}\,\langle\cos\phi_m\rangle_\Theta\,,$$

The brackets $\langle\rangle_\Theta$ denote averaging over the phase space.

$$\lambda = \sqrt{\frac{R\mathcal{B}_{ee}}{\mathcal{B}_h}} + \sqrt{\frac{1}{\mathcal{B}_h}}\sum_m\sqrt{b_m\mathcal{B}_m^{(s)}}\,\langle\cos\phi_m\rangle_\Theta$$

where $b_m = R_m/R$ is the branching fraction for the continuum, $\mathcal{B}_m^{(s)} = \Gamma_m^{(s)}/\Gamma$.

$$\tilde{\Gamma}_h = \Gamma_h \times \left(1 + \frac{2\alpha}{3(1-\mathrm{Re}\,\Pi_0)\mathcal{B}_h}\sqrt{\frac{R}{\mathcal{B}_{ee}}}\sum_m\sqrt{b_m\mathcal{B}_m^{(s)}}\,\langle\sin\phi_m\rangle_\Theta\right)$$

Γ_m ambiguity: fit gives $\tilde{\Gamma}_m$ and $\cos\phi_m$, the sign of $\sin\phi_m$ required for Γ_m determination is not known.

Hypotheses on ϕ:

- Phases ϕ_m for different decay modes are not correlated?
- $\phi = 90$ degrees universally?

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

PL B573(2003 63: measurement of J/ψ and $\psi(2S)$ masses with accuracy of 12 and 27 keV, respectively.

Since that time

- Several high precision scans of J/ψ and $\psi(2S)$ regions
- Progress in the beam energy determination technique
- Better understanding of accelerator related effects
- Technical mistake in accounting of interference effects in 2003 analysis was discovered (shift by about 0.6 of quoted errors)

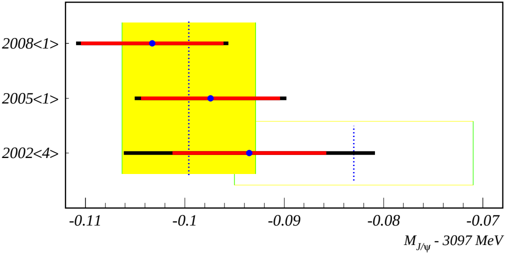
Combined analysis of all scans has been performed taking into account correlations of systematic uncertainties.

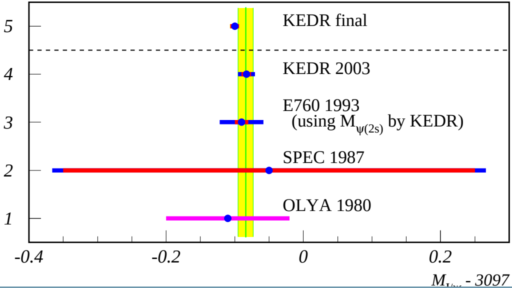
Values of interference parameters $\lambda_{J/\psi}$ and $\lambda_{\psi(2S)}$ were obtained by data fit

J/ψ mass and interference parameter

$$M_{J/\psi}^{KEDR} = 3096.900 \pm 0.002 \pm 0.006 \quad \text{MeV}$$

$$\lambda_{J/\psi} = 0.45 \pm 0.07 \pm 0.04 \quad \text{(0.39 is expected)}$$

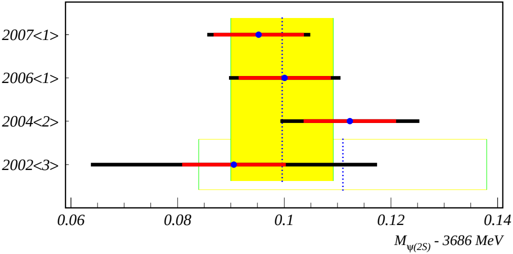


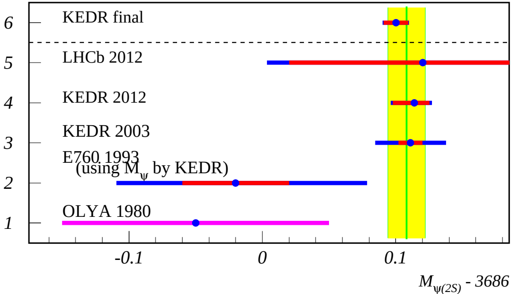


$\psi(2S)$ mass and interference parameter

$$M_{\psi(2S)}^{KEDR} = 3686.100 \pm 0.004 \pm 0.009 \quad \text{MeV}$$

$$\lambda_{\psi(2S)} = 0.17 \pm 0.05 \pm 0.05 \quad (0.13 \text{ is expected})$$



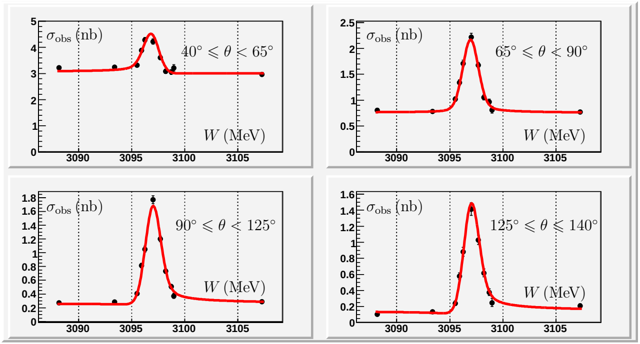


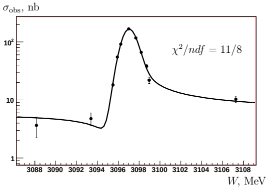
Study of $J/\psi \to \Gamma_{ee} \times \Gamma_{ll}/\Gamma$

J/ψ scan 2005, 220 nb^{-1}, PL B685(2010)134

Joint fit of e^+e^- cross section in a few plora angle bin

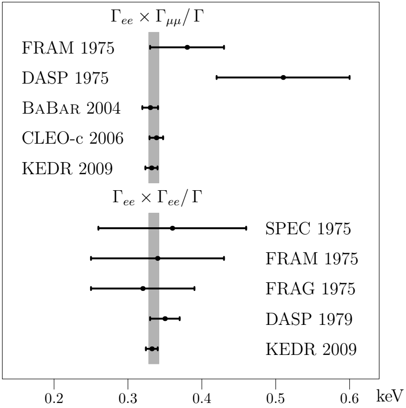
Fit of $\mu^+\mu^-$ cross section with the cosmic background subtraction





$$\Gamma_{ee} \times \Gamma_{ee}/\Gamma = 0.3323 \pm 0.0064 \pm 0.0048 \text{ keV}$$
$$\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma = 0.3318 \pm 0.0052 \pm 0.0063 \text{ keV}$$

Study of $J/\psi \to \Gamma_{ee} \times \Gamma_{ll} / \Gamma$



Gray strip for $\Gamma_{ee} \times \Gamma_{\mu\mu} / \Gamma$ world average values excluding KEDR results.

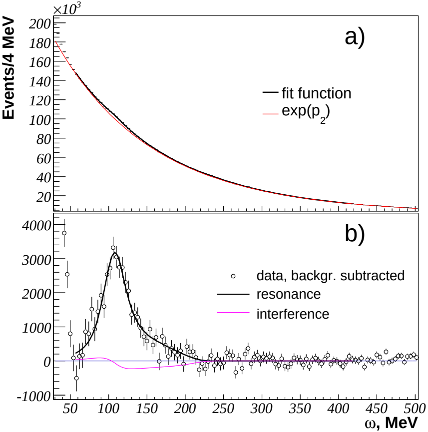
Direct comparison of partial width, PL B731(2014)227:
2007 scan plus peak/continuum data, 2.1 pb^{-1}

$$\Gamma_{e^+e^-}(J/\psi)/\Gamma_{\mu^+\mu^-}(J/\psi) = 1.0022 \pm 0.0044 \pm 0.0048 \ (0.65\%)$$

Study of $J/\psi \to \gamma\, \eta_c$, PL B738(2014)391

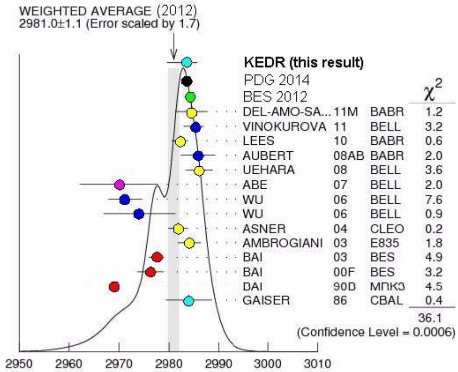
About 2 pb^{-1} in J/ψ–peak, 6.5 millions J/ψ's.

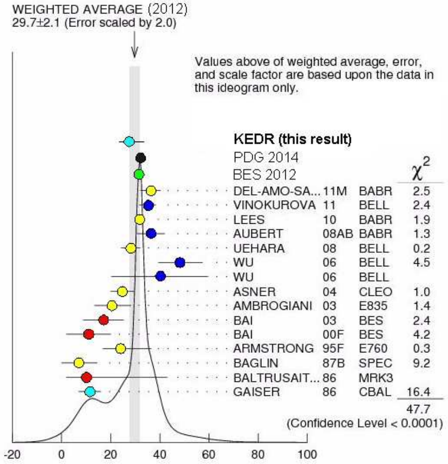
- M1 transition between 1S states of charmonium $\to$ rate can be easily calculated in the limit of the narrow resonance. In this decay $\Gamma_{\eta_c}/\omega_\gamma \sim 1/4$ thus the photon line shape deviates from Breit-Wigner one
- η_c mass, width and the effective partial width $\Gamma^0(J/\psi \to \gamma\, \eta_c)$ have been determined using the inclusive photon spectrum in multihadron J/ψ decays
- ω^3 factor near the η_c peak and interference effects were taken into account



$\Gamma^0(J/\psi \to \gamma\, \eta_c)$ is proportional to the signal height. It is less model dependent than $\Gamma(J/\psi \to \gamma\, \eta_c)$ and better corresponds to theoretical predictions.

η_c mass and width, PL B738(2014)391





J/ψ decays J/ψ decays (ω^3) B decays $\gamma\gamma$ or $pp \to \eta_c$ $J/\psi + X$ $\psi(2S)$ decays

	KEDR		PDG 2014	
$M_{\eta_c} =$	$2983.5 \pm 1.4^{+1.6}_{-3.6}$	MeV	2983.6 ± 0.7	MeV
$\Gamma_{\eta_c} =$	$27.2 \pm 3.1^{+5.4}_{-2.6}$	MeV	32.2 ± 0.9	MeV

$\Gamma^0(J/\psi \to \gamma\,\eta_c)$, PL B738(2014)391

KEDR: $\Gamma^0_{J/\psi\to\gamma\,\eta_c} = 2.98 \pm 0.18^{+0.15}_{-0.33}$ keV

Modified Fig. 9 of A.Pineda, J.Segovia, PRD 87(2013)074024:

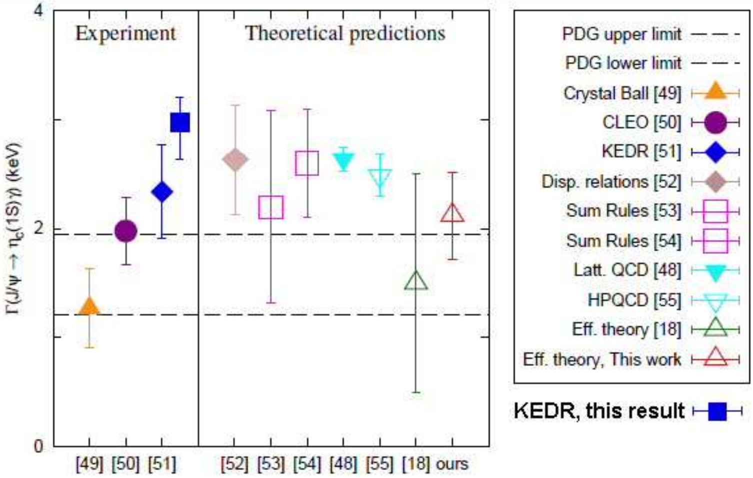
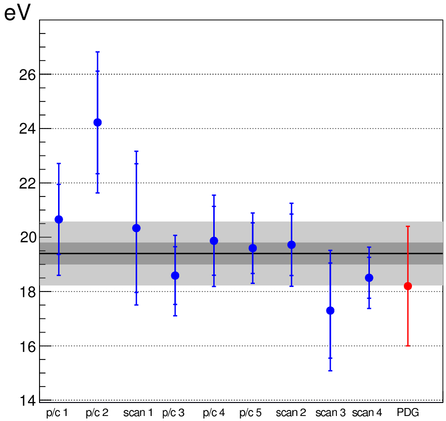


FIG. 9: *Comparison of different theoretical and experimental predictions for* $\Gamma_{J/\psi\to\eta_c\gamma}$.

$\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma$ determination for $\psi(2S)$

7 pb^{-1} collected in $\psi(2S)$ region, 3.5 M $\psi(2S)$, five peak/continuum couples and four scans for energy spread determination:

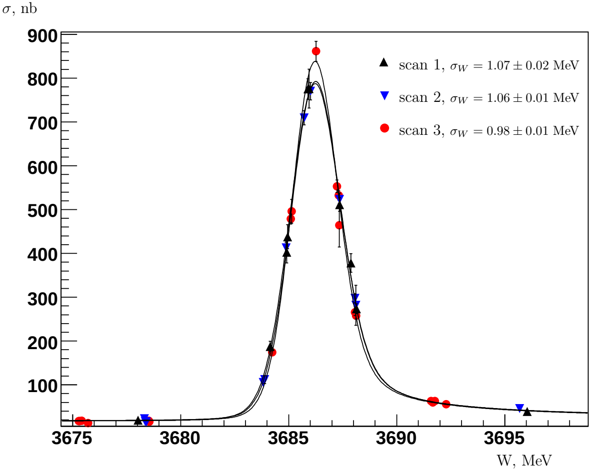
$$\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma = 19.4 \pm 0.4 \pm 1.1 \text{ eV}$$



Blue – individual KEDR measurements, gray – weighted KEDR result
Red – product of PDG's Γ_{ee} and $\mathcal{B}_{\mu^+\mu^-}$.

$\Gamma_{ee} \times \Gamma_h / \Gamma$ determination for $\psi(2S)$, PL B711(2012)280

Three $\psi(2S)$ scans with integrated luminosity of about 0.4 pb^{-1}:

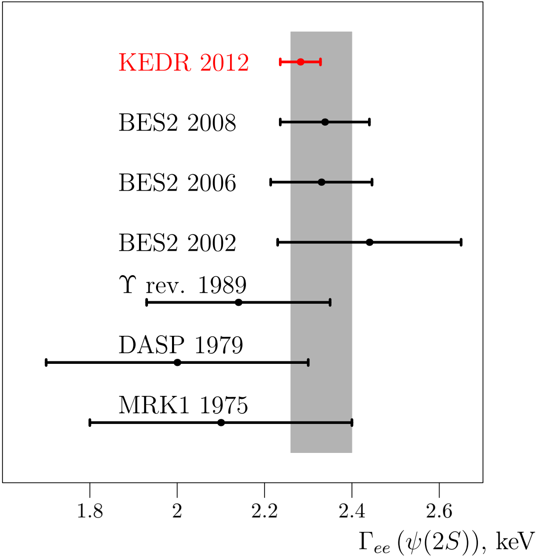


$$\Gamma_{ee} \times \Gamma_h / \Gamma = 2.233 \pm 0.015 \pm 0.037 \pm 0.020\,\text{keV}$$

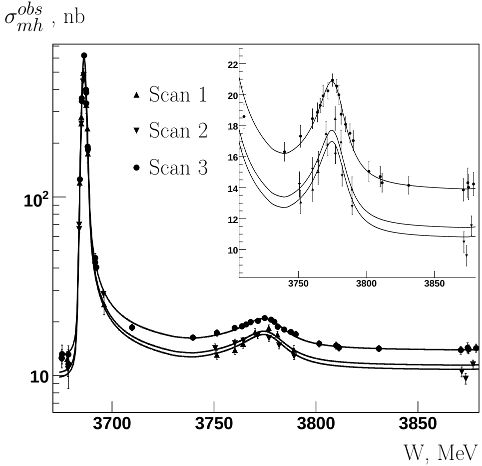
The third uncertainty quoted is an estimate of the model dependence of the result due to assumptions on the interference effects.

$\Gamma_{ee} \times \Gamma_h / \Gamma$ determination for $\psi(2S)$, PL B711(2012)280

After recalculations of $\Gamma_{ee} \times \Gamma_h / \Gamma$ to Γ_{ee} using world average value of Γ_h/Γ:



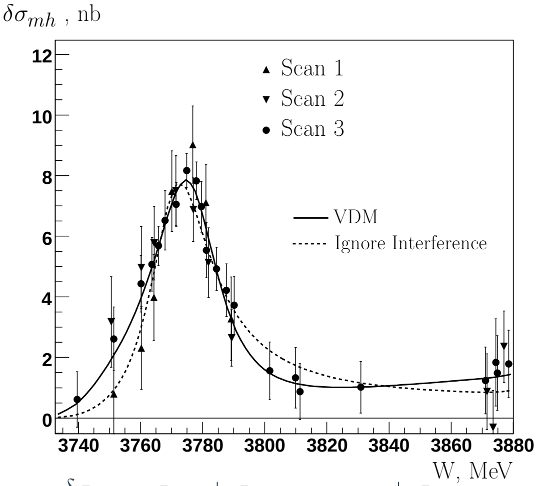
Three scans of the $\psi(2S)$–$\psi(3770)$ region with integrated luminosity of 2.6 pb^{-1}



$$\sigma_{mh}^{\text{obs}} = \epsilon_{\psi(2S)}\,\sigma_{\psi(2S)} + \epsilon_{J/\psi}\,\sigma_{J/\psi} + \epsilon_{\tau\tau}\,\sigma_{\tau\tau} + \sigma_{uds} + \epsilon_{D^+D^-}\,\sigma_{D^+D^-} + \epsilon_{D^0\overline{D}^0}\,\sigma_{D^0\overline{D}^0} + \epsilon_{nD\overline{D}}\,\mathcal{B}_{nD\overline{D}}\,\sigma_{\psi(3770)} + \sigma_{D\overline{D}\pi}$$

Determination of $\psi(3770)$ parameters, PL B711(2012)292

After background subtraction and detection efficiency correction



$$\delta\sigma_{mh} = \sigma_{D\overline{D}} + \sigma_{\psi(3770)\to nD\overline{D}} + \sigma_{D\overline{D}\pi}$$

$$\sigma_{D\overline{D}} = \frac{\pi\alpha^2}{3W^2}\,\beta_D^3\,|F_D|^2\,, \qquad \text{VDM: } F_D = F_D^{\psi(3770)}\,e^{i\phi} + F_D^{\psi(2S)} + F_0$$

The results are

$$M = 3779.2\,^{+1.8}_{-1.7}\,^{+0.5}_{-0.7}\,^{+0.3}_{-0.3}\ \text{MeV},$$
$$\Gamma = 24.9\,^{+4.6}_{-4.0}\,^{+0.5}_{-0.6}\,^{+0.2}_{-0.9}\ \text{MeV},$$

the third uncertainties quoted are for model dependence of the results.

For the electron partial width and the relative phase there are two solutions:

$$(1)\quad \Gamma_{ee} = 154\,^{+79}_{-58}\,^{+17}_{-9}\,^{+13}_{-25}\ \text{eV},\quad \phi = 171 \pm 17\ \text{degrees}$$
$$(2)\quad \Gamma_{ee} = 414\,^{+72}_{-80}\,^{+24}_{-26}\,^{+90}_{-10}\ \text{eV},\quad \phi = 240 \pm 9\ \text{degrees}$$

The unitarity condition gives some arguments that the interference phase ϕ should be close either to zero or 180 degrees. For this reason the first solution looks preferable.

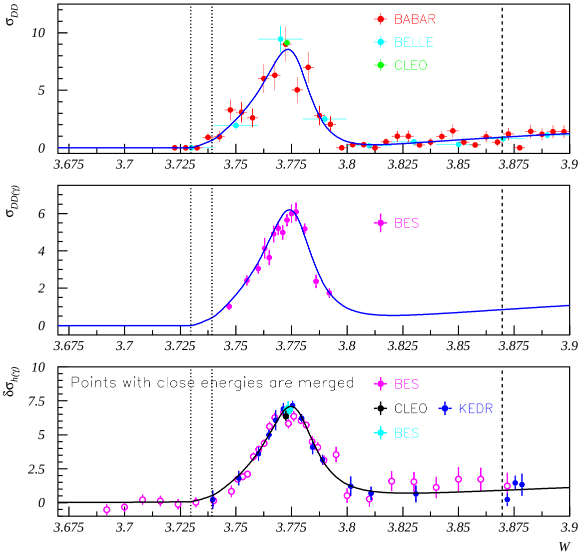
Analysis of BABAR, BELLE, BES, CLEO and KEDR data

204 data points with $3.678 < W < 3.9$ GeV:

- BES $e^+e^- \to hadrons$ [PRL 97 2006) 262001]
  68 points, $R(W)$, collected in December 2003
- BABAR $D\overline{D}$ [PRD 76 2007) 11105]
  36 points, $\int_{W-\Delta W/2}^{W+\Delta W/2} \sigma_{D\overline{D}}(W')\,dW'/\Delta W$, $\Delta W = 5$ MeV,
  number of events is known
- BES $D\overline{D}$ [PLB 668 (2008) 263]
  14 points, $\sigma_{e^+e^- \to D\overline{D}(\gamma)}(W)$
- BELLE $D\overline{D}$ [PRD 77 2008) 11103]
  9 points, $\int_{W-\Delta W/2}^{W+\Delta W/2} \sigma_{D\overline{D}}(W')\,dW'/\Delta W$, $\Delta W = 20$ MeV,
- CLEO $D\overline{D}$, $e^+e^- \to hadrons$ [PRL 104 (2010) 159901]
  1 point, $\sigma_{e^+e^- \to h(\gamma)}(W)$, $\sigma_{e^+e^- \to D\overline{D}(\gamma)}(W)$, $W = 3773$ MeV.
- KEDR $e^+e^- \to hadrons$ [PLB 711 (2012) 292]
  17+21+38 points in 3 scans, $\sigma^{\text{visible}}_{e^+e^- \to h(\gamma)}(W)$,
  number of events is known

The data set collected by BES in March 2003 and mentioned in [PRL 101(2008) 102004] is not available.

Analysis of BABAR, BELLE, BES, CLEO and KEDR data



The fit of data in the $e^+e^- \to D\overline{D}$, $e^+e^- \to D\overline{D}(\gamma)$ and $e^+e^- \to h(\gamma)$ channels. For the latter only the excess of the cross section associated with $D\overline{D}$–threshold is shown.

Analysis of BABAR, BELLE, BES, CLEO and KEDR data

A sum of likelihood functions for independent experiments is minimized with

$$\mathcal{L}^{exp} = \mathcal{L}_{data}(f_N, \Delta_W) + \mathcal{L}_{syst}(f_N, \Delta_W)$$

$\mathcal{L}_{data}$ – Poisson likelihood$\times$2 when the number of events is known, χ^2 when only the cross section and its error are known.

Additional free parameters f_N and Δ_W account for systematic uncertainties of the experiment in the cross section normalization and in the energy scale.

$$\mathcal{L}_{syst} = (f_N - 1)^2/\sigma_N^2 + \Delta_W^2/\delta_W^2$$

with σ_N and δ_W values taken from the appropriate publication.

Fit gives $\chi^2 = 232$ for 189 degrees of freedom, the probability of about 1.8%

Solution	M (MeV)	Γ (MeV)	$\mathcal{B}_{nD\overline{D}}$	Γ_{ee}(eV)	ϕ (deg)
1:	3779.3±1.0	26.7±1.4	0.19±0.05	202±18	185.6±5.2
2:	3779.5±1.0	26.8±1.4	0.11±0.03	346±19	228.6±3.0

The uncertainty estimates reflect a statistical error and essential systematic uncertainties.

Analysis of BABAR, BELLE, BES, CLEO and KEDR data

- Main conclusions of PL B711(2012)292 by KEDR are confirmed
- VDM satisfactory describes inclusive hadronic cross section and $D\overline{D}$ cross section from $D\overline{D}$-threshold up to 3.9 GeV
- Confirmation of the BES result on the $\psi(3770)$ non-$D\overline{D}$ decays obtained using 'inclusive non-$D\overline{D}$ selection':

$$\mathcal{B}_{nD\overline{D}} = 0.151 \pm 0.056 \pm 0.018 \qquad \text{[PLB 659 (2008) 74]}$$

- Statistical significance of $\mathcal{B}_{nD\overline{D}}$ value is not due to BES data solely

$$\Gamma_{nD\overline{D}} = 5.06^{+1.39}_{-1.46}\ \text{MeV} \qquad \text{(all data)}$$

$$\Gamma_{nD\overline{D}} = 4.44^{+1.38}_{-1.47}\ \text{MeV} \qquad \text{(all data but 3 deviating points)}$$

$$\Gamma_{nD\overline{D}} = 7.06^{+1.82}_{-1.97}\ \text{MeV} \qquad (D\overline{D}\ \text{and hadronic data by BES excluded})$$

Conclusion

- J/ψ results:

$$M = 3096.900 \pm 0.002 \pm 0.006 \text{ MeV}. \quad \lambda = 0.45 \pm 0.07 \pm 0.04$$

$$\Gamma_{ee} \times \Gamma_{ee}/\Gamma = 0.3323 \pm 0.0064 \pm 0.0048 \text{ keV}$$

$$\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma = 0.3318 \pm 0.0052 \pm 0.0063 \text{ keV}$$

$$\Gamma_{e^+e^-}(J/\psi)/\Gamma_{\mu^+\mu^-}(J/\psi) = 1.0022 \pm 0.0044 \pm 0.0048$$

$$\Gamma^0_{J/\psi \to \gamma\,\eta_c} = 2.98 \pm 0.18^{+0.15}_{-0.33} \text{ keV}$$

- $\psi(2S)$ results:

$$M = 3686.100 \pm 0.004 \pm 0.009 \text{ MeV}, \quad \lambda = 0.17 \pm 0.05 \pm 0.05$$

$$\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma = 19.4 \pm 0.4 \pm 1.1 \text{ eV}$$

$$\Gamma_{ee} \times \Gamma_{h}/\Gamma = 2.233 \pm 0.015 \pm 0.037 \pm 0.020 \text{ keV}$$

- main $\psi(3770)$ result:

$$M = 3779.2 \,^{+1.8}_{-1.7} \,^{+0.5}_{-0.7} \,^{+0.3}_{-0.3} \text{ MeV}$$

- In the next year KEDR plans to move beyond charmonium region for R and $\gamma\gamma \to \textit{hadrons}$ measurement

Systematic uncertainties in the J/ψ mass (keV)

Uncertainty source	2002	2005	2008	common
Energy spread variation	3.0	1.8	1.8	1.8
Energy assignment to DAQ runs	3.7	3.5	3.5	2.5
Energy calibration accuracy	1.6	1.9	1.9	1.6
Beam separation in parasitic I.P.s	0.9	1.7	1.7	0.9
Beam misalignment in the I.P.	1.8	1.5	1.5	1.5
e^+-, e^--energy difference	1.2	1.3	1.2	1.2
Symmetric dL/dE shape distortion	1.5	1.3	2.1	1.3
Asymmetric dL/dE shape distortion	2.1	1.9	1.9	1.9
Beam potential	2.0	2.0	2.0	2.0
Detection efficiency instability	2.3	1.7	1.8	0.0
Luminosity measurements	2.2	1.7	1.7	1.1
Residual machine background	1.0	0.7	0.7	0.0
Interference in the hadronic channel	2.7	2.7	2.7	2.6
Sum in quadrature	≈ 7.7	≈ 7.0	≈ 7.2	≈ 5.8

Systematic uncertainties in the $\psi(2S)$ mass (keV)

Uncertainty source	2002	2004	2006	2008	common
Energy spread variation	2.0	1.5	1.5	1.5	1. 5
Energy assignment to DAQ runs	3.9	3.9	3.8	2.4	1. 5
Energy calibration accuracy	1.9	2.3	2.3	2.3	1. 9
Beam separation in parasitic I.P.s	0.5	1.2	1.7	1.7	0. 5
Beam misalignment in the I.P.	5.1	3.3	3.3	3.3	2. 5
e^+-, e^--energy difference	1.6	2.1	2.1	1.6	1. 6
Symmetric dL/dE shape distortion	1.8	1.6	1.6	1.6	1. 6
Asymmetric dL/dE shape distortion	2.1	1.9	1.9	1.9	1 .9
Beam potential	2.0	2.2	2.2	2.2	2 .0
Detection efficiency instability	2.1	1.6	1.6	1.6	0 .0
Luminosity measurements	3.0	2.1	2.1	1.5	1 .2
Residual machine background	1.0	0.9	0.9	0.9	0 .0
Interference in the hadronic channel	4.1	4.1	4.11	4.1	4 .1
Sum in quadrature	≈ 9.7	≈ 8.7	≈ 8.6	≈ 8.4	≈ 7.0

Systematic uncertainties in $\Gamma_{ee} \times \Gamma_h / \Gamma$ of $\psi(2S)$

Source	Sc1	Sc2	Sc3	Com$_{12}$	Com$_{123}$
Absolute luminosity measurements	1.6	1.7	1.2	1.6	0.5
$\psi(2S)$ decay simulation	1.0	1.0	1.1	1.0	1.0
Detector response					
Trigger efficiency	0.2	0.2	0.2	0.2	0.2
Nuclear interaction	0.2	0.2	0.3	0.2	0.2
Cross talks in VD	0.1	0.17	0.1	0.1	0.1
Variation of cuts	0.5	0.3	0.6	0.3	0.3
Accelerator related effects					
Beam energy determination	0.15	0.18	0.6	0.15	0.15
Non-Gaussian energy distribution	0.2	0.2	0.2	0.2	0.2
Residual background	<0.1	<0.1	<0.1	<0.1	<0.1
Other uncertainties	0.3	0.3	0.3	0.3	0.3
Sum in quadrature	≈ 2.0	≈ 2.1	≈ 1.9	≈ 2.0	≈ 1.3

- N. N. Achasov and G. N. Shestakov [PRD 86 (2012) 114013] suggested a model of the D-meson form factor which guaranteed the elastic unitarity requirement.
- G.-Y. Chen and Q. Zhao [PLB 718(2013) 1369] studied the line shape of the $D\overline{D}$ cross section within effective field theory.

Model	χ^2/N_{DoF}	$P(\chi^2)\%$	χ^2/N_{DoF}	$P(\chi^2)\%$
VDM	71.8 / 54	5.3	34.07 / 29	23.7
A.-S.	80.0 / 54	1.2	33.52 / 28	21.7
C.-Z.	210.3 / 54		33.66 / 29	25.2
W	< 3.9 GeV		< 3.8 GeV	

The alternative models considered do not improve substantially the description of $D\overline{D}$ data. The model [PLB 718(2013) 1369] is applicable only in the narrow region around the $\psi(3770)$ peak.

Study of $J/\psi \to \gamma\,\eta_c$, PL B738(2014)391

Photon spectrum $d\Gamma/d\omega$:

$$\frac{d\Gamma}{d\omega} = \left(\frac{\omega}{\omega_0}\right)^3 \frac{f(\omega)}{f(\omega_0)}\,\frac{1}{2\pi}\,\frac{\Gamma_{\eta_c}\,\Gamma^0_{\gamma\,\eta_c}}{(\omega-\omega_0)^2+\Gamma^2_{\eta_c}/4}, \qquad \Gamma^0_{\gamma\,\eta_c} = \Gamma_{\eta_c}\,\frac{\pi}{2}\,\frac{d\Gamma}{d\omega}(\omega_0)$$

In the narrow resonance limit $\Gamma^0_{\gamma\,\eta_c} = \Gamma_{\gamma\,\eta_c}$

Systematic error	M_{η_c}, MeV	Γ_{η_c}, MeV	$\Gamma^0_{\gamma\,\eta_c}$, keV
Background subtraction	0.8	1.4	0.11
Calorimeter response function	2.2	0.8	0.06
Lineshape	0.7	2.8	0.05
η_c width	0.3	-	0.06
Interference effects	-2.1	+2.3	-0.18
Photon selection efficiency	-	-	0.16
J/ψ width	-	-	0.09
Total	$^{+1.6}_{-3.6}$	$^{+5.4}_{-2.6}$	$^{+0.15}_{-0.33}$