Parameters of Charmonium States from KEDR

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KEDR/VEPP-4M

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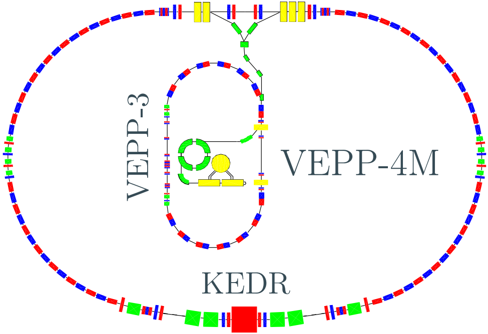
Outline

1. VEPP-4M/KEDR
2. J/ψ, $\psi(2S)$ mass measurement
3. J/ψ $e^+e^-/\mu^+\mu^-$ widths comparison
4. Study of $\psi(2S) \to \mu^+\mu^-$ decay with KEDR detector
5. Measurement of main parameters of the $\psi(3770)$
6. $\mathcal{B}(J/\psi \to \gamma\eta_c)$
7. Summary

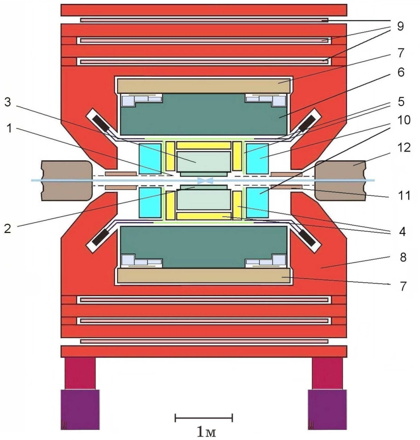
VEPP-4M collider



- Beam energy $1 \div 6\,\text{GeV}$
- Number of bunches 2×2
- For $E = 1.5\,\text{GeV}$
  - Beam current $1.5\,\text{mA}$
  - Luminosity $10^{30}\ \frac{1}{\text{cm}^2 \cdot \text{c}}$

Beam energy measurement:

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



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

Narrow resonance mass definition

Resonance cross section in soft photon approximation:

$$\sigma(W) = \frac{12\pi}{W^2}(1+\delta_{\mathrm{rc}})\left[\frac{\Gamma_{ee}\tilde{\Gamma}_h}{\Gamma M}\operatorname{Im}\mathcal{F}(W) - \frac{2\alpha\sqrt{R\Gamma_{ee}\tilde{\Gamma}_h}}{3W}\lambda\operatorname{Re}\frac{\mathcal{F}^*(W)}{1-\Pi_0}\right],$$

$$\text{where } \mathcal{F} = \frac{\pi\beta}{\sin\pi\beta}\left(\frac{\frac{M}{2}}{-W+M-\frac{i\Gamma}{2}}\right)^{1-\beta}, \quad \beta = \frac{4\alpha}{\pi}\left(\ln\frac{W}{m_e}-\frac{1}{2}\right).$$

$\sigma(W)$ must be convoluted with energy distribution:

$$G(W,W') = \frac{g(W-W')}{\sqrt{2\pi}\sigma_W}\exp\left(-\frac{(W-W')^2}{2\sigma_W^2}\right),$$

$$\text{where } g(\Delta) = \frac{1+a\,\Delta+b\,\Delta^2}{1+b\,\sigma_W^2}.$$

$$\lambda = \sqrt{\frac{R\Gamma_{\mu\mu}}{\Gamma_h}}$$

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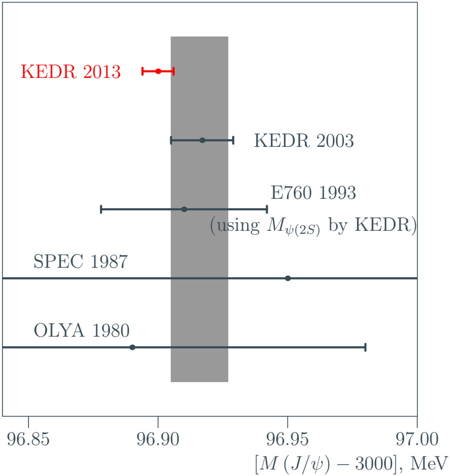
$$\text{where } g(\Delta) = \frac{1+a\,\Delta+b\,\Delta^2}{1+b\,\sigma_W^2}.$$

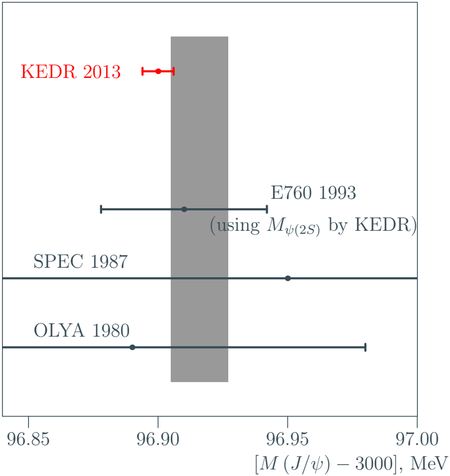
$$\lambda = \sqrt{\frac{R\Gamma_{\mu\mu}}{\Gamma_h}} + \frac{1}{\Gamma_h}\sum_m\sqrt{b_m\Gamma_m^{(s)}}\,\langle\cos\phi_m\rangle_\theta\,.$$



$$M_{J/\psi}^{2002\text{–}2013} = 3096.900 \pm 0.002 \pm 0.006\,\mathrm{MeV}\ \ (6\ \text{scans}),$$

$$\lambda = 0.45 \pm 0.07 \pm 0.04,\ \ \lambda_{\text{expected}} = \sqrt{R\Gamma_{\mu\mu}/\Gamma_h} = 0.38$$

J/ψ mass measurement



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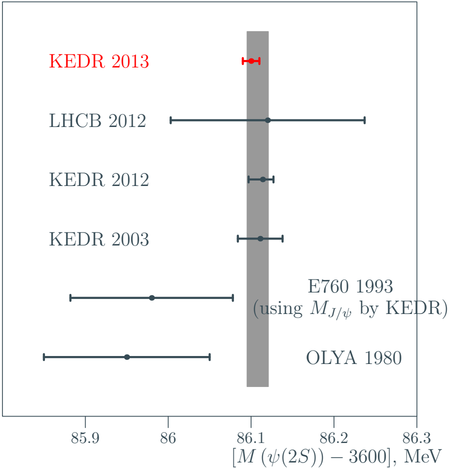
Systematic uncertainties in the J/ψ mass (keV)

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

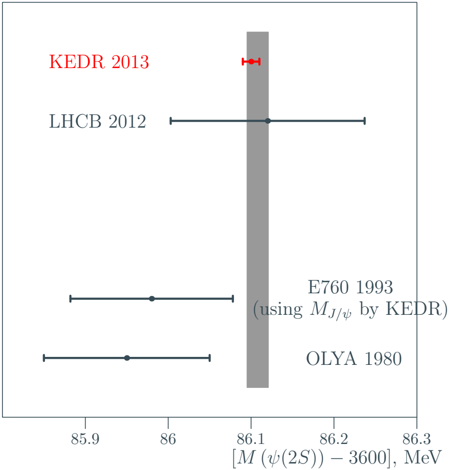
$\psi(2S)$ mass measurement



$$M_{\psi(2S)}^{2002\text{–}2013} = 3686.100 \pm 0.004 \pm 0.009 \ \text{ MeV } \ (6 \text{ scans}),$$

$$\lambda = 0.17 \pm 0.05 \pm 0.05, \ \ \lambda_{\text{expected}} = \sqrt{R\Gamma_{\mu\mu}/\Gamma_h} = 0.13$$

$\psi(2S)$ mass measurement



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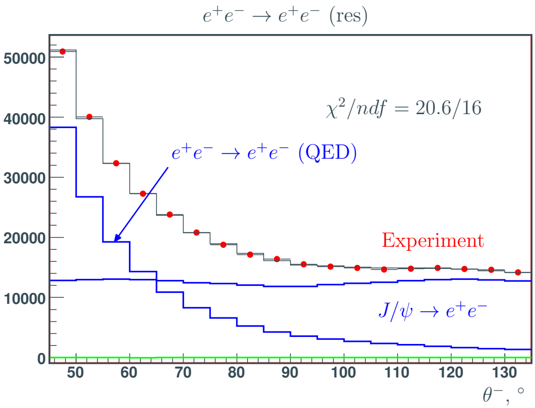
Systematic uncertainties in the $\psi(2S)$ mass (keV)

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 IPs	0.5	1.2	1.7	1.7	0.5
Beam misalignment in the IP	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 $\frac{dL}{dE}$ shape distortion	1.8	1.6	1.6	1.6	1.6
Asymmetric $\frac{dL}{dE}$ 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 hadr. chan.	4.1	4.1	4.1	4.1	4.1
Sum in quadrature	9.7	8.7	8.6	8.4	7.0

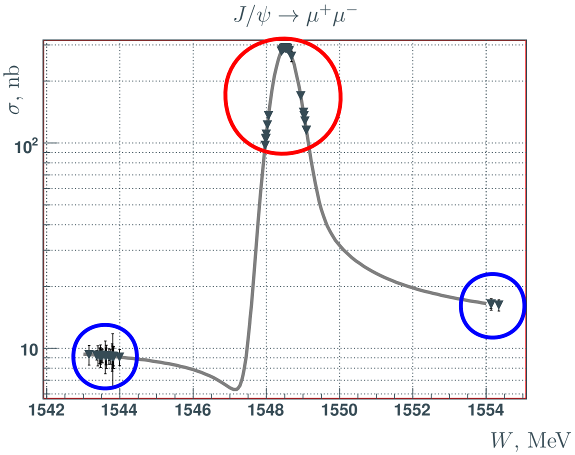
$J/\psi \to e^+e^-$ (resonance) counting



$$\frac{dN_{ee}^{\text{obs}}}{d\theta} = aN_0^{\text{sim}} \left(\text{Res}(\theta) + \frac{2\alpha}{3\mathcal{B}_{ee}} \langle F_{\text{res}}(E) \rangle \, \text{Int}(\theta) \right) + L_{\text{res}} \left(\frac{d\sigma}{d\theta} \right)_{\text{QED}}$$

$$N_{J/\psi\to ee} = \frac{aN_0^{\text{sim}}}{\varepsilon_{J/\psi\to ee}}, \quad \frac{\delta N_{J/\psi\to ee}}{N_{J/\psi\to ee}} = 0.33\%$$

$J/\psi \to \mu^+\mu^-$ counting



$$N_{J/\psi\to\mu\mu} = \frac{\left\{ N^{\rm exp}_{\rm res} - N^{\rm th}_{\rm int} - \frac{L_{\rm res}}{L_{\rm cont}} \times \left(N^{\rm exp}_{\rm cont} - N^{\rm th}_{\rm int} \right) \right\}}{\varepsilon_{J/\psi\to\mu\mu}}, \quad \frac{\delta N_{\mu\mu}}{N_{\mu\mu}} = 0.29\%$$

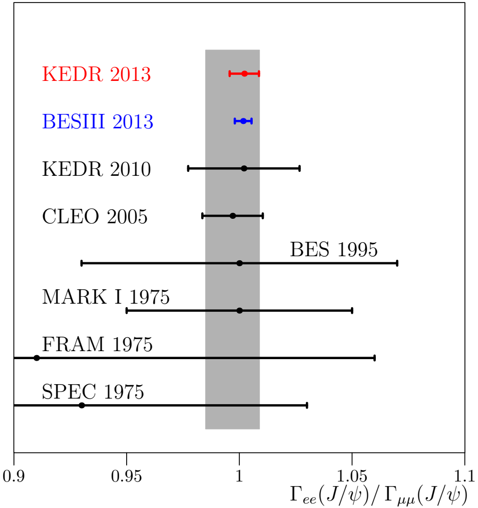
Systematic uncertainty $\Gamma_{ee}/\Gamma_{\mu\mu}(J/\psi)$ (1)

Source	Err, %
Interference	
Relative luminosity	0.01
Energy measurement	0.02
Radiation corrections	0.10
Background	
$J/\psi \to$ hadrons	0.10
Cosmic	0.07
Simulation	
Bhabha	0.11
PHOTOS	0.02

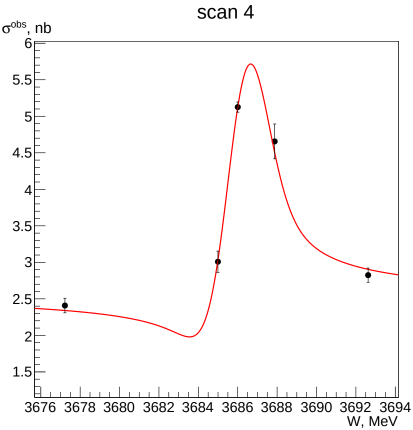
to be continued $\nearrow$

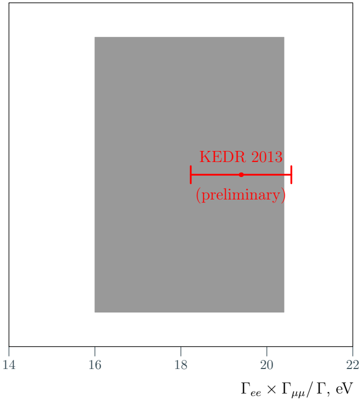
Source	Err, %
Trigger	
1st level	0.20
2nd level	0.11
Event selection	
tracking system	0.10
calorimeter	0.10
muon system	0.04
θ angle cuts	0.10
θ angle determination	0.14
Selection asymmetry	0.14
ToF inefficiency	0.26
Total	0.48

J/ψ $e^+e^-/\mu^+\mu^-$ widths comparison



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





$$\Gamma_{ee} \times \Gamma_{\mu\mu}/\,\Gamma = (19.4 \pm 0.4 \pm 1.1)\,\mathrm{eV}. \qquad \text{(preliminary)}$$

No direct measurement of $\Gamma_{ee} \times \Gamma_{\mu\mu}/\,\Gamma$ is listed in the PDG tables. For comparison the product of the two world average values Γ_{ee} and $\mathcal{B}_{\mu\mu}$ is shown.

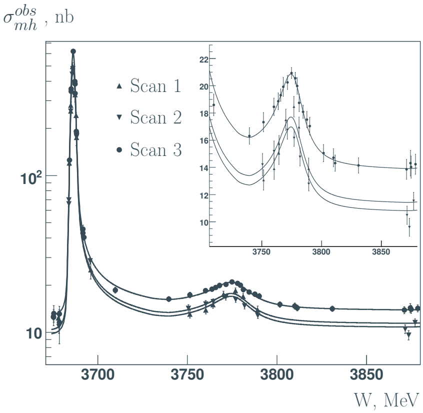
- Data analysis takes into account interference between the resonant and nonresonant $D\overline{D}$ production.

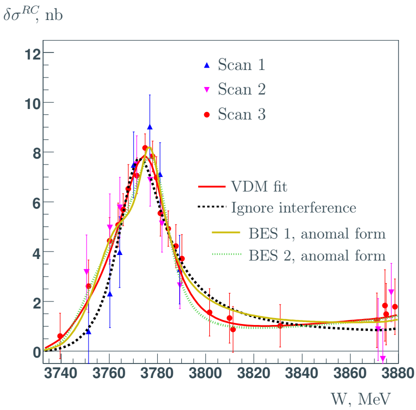
- The nonresonant form factor can be obtained with an application of the Vector Dominance Model (VDM) to charm production. In this work we employ VDM in a simplified form:

$$F_{D\overline{D}}^{nonresonant}(W) = F_{D\overline{D}}^{\psi(2S)}(W) + F_0$$

  where $F_{D\overline{D}}^{\psi(2S)}(W)$ is the main part of the form factor corresponding to the $\psi(2S)$ and F_0 is a real constant representing the contributions of the $\psi(4040)$ and higher ψ's.

- To evaluate the model dependence of the $\psi(3770)$ parameters we tried a few nonresonant form factor parameterizations, which do not assume VDM.

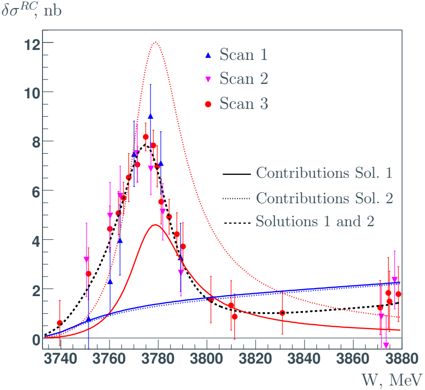




$$M = 3779.2 \;{}^{+1.8}_{-1.7}\;{}^{+0.5}_{-0.7}\;{}^{+0.3}_{-0.3}\;\text{MeV}$$

$$\Gamma = \quad 24.9 \;{}^{+4.6}_{-4.0}\;{}^{+0.5}_{-0.6}\;{}^{+0.2}_{-0.9}\;\text{MeV}$$

Ambiguity of $\psi(3770)$ resonance parameters



Excess of the multihadron cross section in the $\psi(3770)$ region. Solid and short-dashed curves correspond to two VDM solutions. Resonant and non-resonant parts are presented separately.

$$(1) \quad \Gamma_{ee} = 154\,^{+79}_{-58}\,^{+17}_{-9}\,^{+13}_{-25}\ \text{eV}, \qquad \phi = (171 \pm 17)^\circ,$$

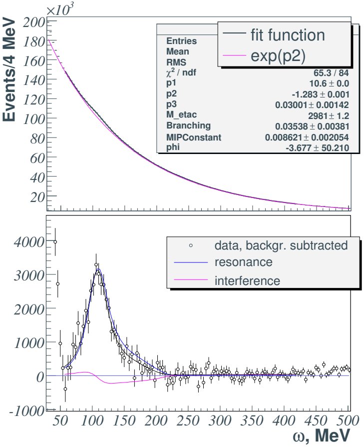
$$(2) \quad \Gamma_{ee} = 414\,^{+72}_{-80}\,^{+24}_{-26}\,^{+90}_{-10}\ \text{eV}, \qquad \phi = (240 \pm 9)^\circ.$$

Details in Phys. Lett. B 711 (2012), 292-300

Poster session: An attempt of a joint analysis of BABAR, BELLE, BES, CLEO and KEDR data for determination of $\psi(3770)$ parameters.

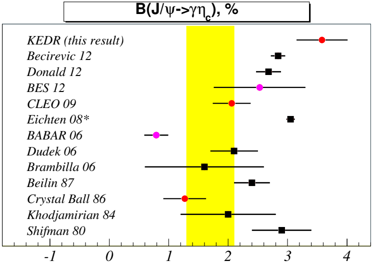
$J/\psi \to \gamma\eta_c$ measurement

- η_c mass, width and $\mathcal{B}(J/\psi \to \gamma\eta_c)$ have been measured in the inclusive photon spectrum of multihadron J/ψ decays
- M1 transition between 1S states of charmonium $\to$ rate can be easily calculated in potential models in the limit of a zero width of the resonance. In this decay $\Gamma(\eta_c)/\omega_0 \sim 30 MeV/114\,\text{MeV} \Rightarrow$ photon line shape deviates from Breit-Wigner
- ω^3 factor near the η_c resonance and interference with $J/\psi \to \gamma gg$ and FSR process were taken into account



arXiv:1309.xxxx

- Photon line shape in the radiative $J/\psi \to \gamma\eta_c$ decay was taken in the form $d\Gamma/d\omega \sim \omega^3 f(\omega) BW(\omega)$, where correction factor $f(\omega) = 1$ near the η_c resonance and falls quickly far from resonance
- Our result on $\mathcal{B}(J/\psi \to \gamma\eta_c)$ is higher than the old Crystal Ball and CLEO results and is consistent with the new Lattice QCD theoretical predictions.



direct experiment, theory, indirect experiment

$$\mathcal{B}(J/\psi \to \gamma\eta_c) = (3.58 \pm 0.38 \pm 0.20)\%$$

Summary

- $M^{\text{final}}_{J/\psi} = 3096.900 \pm 0.002 \pm 0.006\,\text{MeV},$
- $M^{\text{final}}_{\psi(2S)} = 3686.100 \pm 0.004 \pm 0.009\,\text{MeV},$
- $\Gamma_{e^+e^-}(J/\psi)/\Gamma_{\mu^+\mu^-}(J/\psi) = 1.0022 \pm 0.0044 \pm 0.0048\ (0.65\%)$
- $\Gamma_{ee} \times \Gamma_{\mu\mu}/\,\Gamma = (19.4 \pm 0.4 \pm 1.1)\,\text{eV}$ for $\psi(2S)$ (preliminary)
- $\psi(3770)$ parameters

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

$$\Gamma = 24.9^{+4.6}_{-4.0}\,{}^{+0.5}_{-0.6}\,{}^{+0.2}_{-0.9}\ \text{MeV}$$

$$\Gamma^{(1)}_{ee} = 154\,{}^{+79}_{-58}\,{}^{+17}_{-9}\,{}^{+13}_{-25}\ \text{eV}$$

$$\Gamma^{(2)}_{ee} = 414\,{}^{+72}_{-80}\,{}^{+24}_{-26}\,{}^{+90}_{-10}\ \text{eV}$$

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Summary

- $M^{\text{final}}_{J/\psi} = 3096.900 \pm 0.002 \pm 0.006\,\text{MeV}$,
  - $3096.916 \pm 0.011\,\text{MeV}$ (PDG fit)
- $M^{\text{final}}_{\psi(2S)} = 3686.100 \pm 0.004 \pm 0.009\,\text{MeV}$,
  - $3686.109^{+0.012}_{-0.014}\,\text{MeV}$ (PDG fit)
- $\Gamma_{e^+e^-}(J/\psi)/\Gamma_{\mu^+\mu^-}(J/\psi) = 1.0022 \pm 0.0044 \pm 0.0048$ (0.65%)
  - 0.998 ± 0.012 (PDG fit)
- $\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma = (19.4 \pm 0.4 \pm 1.1)\,\text{eV}$ for $\psi(2S)$ (preliminary)
  - $(18.2 \pm 2.2)\,\text{eV}$ (PDG fit $\times$ PDG fit)
- $\psi(3770)$ parameters

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  - $(1.7 \pm 0.4)\%$ (PDG average, scale factor 1.6)

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  - $3686.109^{+0.012}_{-0.014}\,\text{MeV}$ (PDG fit)
- $\Gamma_{e^+e^-}(J/\psi)/\Gamma_{\mu^+\mu^-}(J/\psi) = 1.0022 \pm 0.0044 \pm 0.0048$ (0.65%)
  - 0.998 ± 0.012 (PDG fit) $1.0017 \pm 0.0017 \pm 0.0033$ (BESIII 2013)
- $\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma = (19.4 \pm 0.4 \pm 1.1)\,\text{eV}$ for $\psi(2S)$ (preliminary)
  - $(18.2 \pm 2.2)\,\text{eV}$ (PDG fit $\times$ PDG fit)
- $\psi(3770)$ parameters $\approx$ all published data fit

$M = 3779.2^{+1.8}_{-1.7}{}^{+0.5}_{-0.7}{}^{+0.3}_{-0.3}\,\text{MeV}$	$M = 3779.2 \pm 1.0\,\text{MeV}$
$\Gamma = 24.9^{+4.6}_{-4.0}{}^{+0.5}_{-0.6}{}^{+0.2}_{-0.9}\,\text{MeV}$	$\Gamma = 26.4 \pm 1.0\,\text{MeV}$
$\Gamma^{(1)}_{ee} = 154\,^{+79}_{-58}{}^{+17}_{-9}{}^{+13}_{-25}\,\text{eV}$	$\Gamma^{(1)}_{ee} = 202 \pm 18\,\text{eV}$
$\Gamma^{(2)}_{ee} = 414\,^{+72}_{-80}{}^{+24}_{-26}{}^{+90}_{-10}\,\text{eV}$	$\Gamma^{(2)}_{ee} = 346 \pm 19\,\text{eV}$

- $\mathcal{B}(J/\psi \to \gamma\eta_c) = (3.58 \pm 0.38 \pm 0.20)\%$
  - $(1.7 \pm 0.4)\%$ (PDG average, scale factor 1.6)

Theory (misc)

The formulae used in this analysis are based on the analytical expression of radiative correction integral in the soft photon approximation (SPA) first obtained in Y. I. Azimov *et al.*, JETP Lett. **21** (1975) 172.

The accuracy improved using E. A. Kuraev and V. S. Fadin, Sov. J. Nucl. Phys. **41** (1985) 466. as described in V. V. Anashin *et al.*, Phys. Lett. B **711** (2012) 280

In the SPA the formulae are equivalent to that of R. N. Cahn Phys. Rev. D **36** (1987) 2666 corrections beyond SPA are not essential for this analysis.

Cross section

Cross section (J/ψ)

$$\left(\frac{d\sigma}{d\Omega}\right)^{ee\to ee} = \frac{1}{M^2}\left(1+\delta_{\mathrm{rc}}\right)\left\{\frac{9}{4}\frac{\Gamma^2_{e^+e^-}}{\Gamma M}\left(1+\cos^2\theta\right)\operatorname{Im}\mathcal{F}-\right.$$

$$\left.-\frac{3\alpha}{2}\frac{\Gamma_{e^+e^-}}{M}\left[\left(1+\cos^2\theta\right)-\frac{(1+\cos\theta)^2}{(1-\cos\theta)}\right]\operatorname{Re}\mathcal{F}\right\}+\left(\frac{d\sigma}{d\Omega}\right)^{ee\to ee}_{\mathrm{QED}}$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{ee\to\mu\mu} = \frac{1}{M^2}\left(1+\delta_{\mathrm{rc}}\right)\left\{\frac{9}{4}\frac{\Gamma_{e^+e^-}\Gamma_{\mu^+\mu^-}}{\Gamma M}\operatorname{Im}\mathcal{F}-\right.$$

$$\left.-\frac{3\alpha}{2}\frac{\sqrt{\Gamma_{e^+e^-}\Gamma_{\mu^+\mu^-}}}{M}\operatorname{Re}\mathcal{F}\right\}\left(1+\cos^2\theta\right)+\left(\frac{d\sigma}{d\Omega}\right)^{ee\to\mu\mu}_{\mathrm{QED}}$$

$$\text{where } \mathcal{F} = \left(\frac{\frac{M}{2}}{-W+M-\frac{i\Gamma}{2}}\right)^{1-\beta}, \quad \beta = \frac{4\alpha}{\pi}\left(\ln\frac{W}{m_e}-\frac{1}{2}\right) \simeq 0.077$$

Corrections to the vacuum polarization are omitted in the interference terms.

$$\delta_{\mathrm{rc}} = 1 + \frac{3}{4}\beta + \frac{\alpha}{\pi}\left(\frac{\pi^2}{3} - \frac{1}{2}\right) + \beta^2\left(\frac{37}{96} - \frac{\pi^2}{12} - \frac{L}{72}\right),$$

where $L = \ln(W^2/m_e^2)$.

[Kuraev and Fadin, Sov. J. Nucl. Phys. 41, 466–472, 1985]

Cross section

$J/\psi \to e^+e^-$ (resonance) counting (misc)

$$\langle F(E)\rangle = \frac{\sum L_i^{1\gamma} \mathrm{Re}\,\mathcal{F}(E_i)}{\sum L_j^{1\gamma} \mathrm{Im}\,\mathcal{F}(E_j)} \times \left(1 - \frac{\int \frac{(1+\cos\theta)^2}{(1-\cos\theta)}\, d(\cos\theta)}{\int 1+\cos^2\theta \; d(\cos\theta)}\right),$$

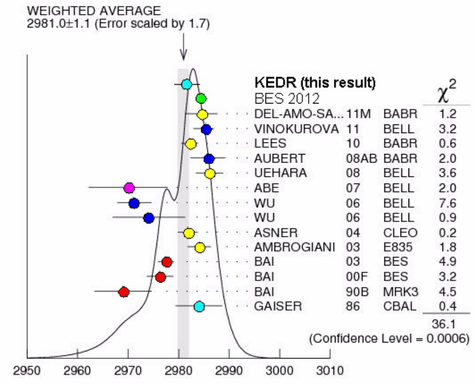
$$\langle b(E)\rangle = \frac{\sum L_i^{1\gamma} \mathrm{Im}\,\mathcal{F}(E_i)}{\sum L_j^{1\gamma}},$$

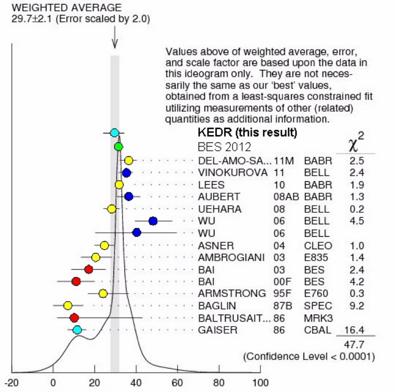
where $L_{1\gamma}$ — integrated luminosity by single bremsstrahlung.

▸ $J/\psi \to e^+e^-$ event counting

▸ $e^+e^- \to e^+e^-$ (continuum)

Results on η_c mass and width





$$M(\eta_c) = (2981.4 \pm 1.0 \pm 2.5)\,\text{MeV},$$
$$\Gamma(\eta_c) = (29.5 \pm 3.0 \pm 4.9)\,\text{MeV}.$$

Results on $\Gamma(J/\psi \to \gamma\eta_c)$

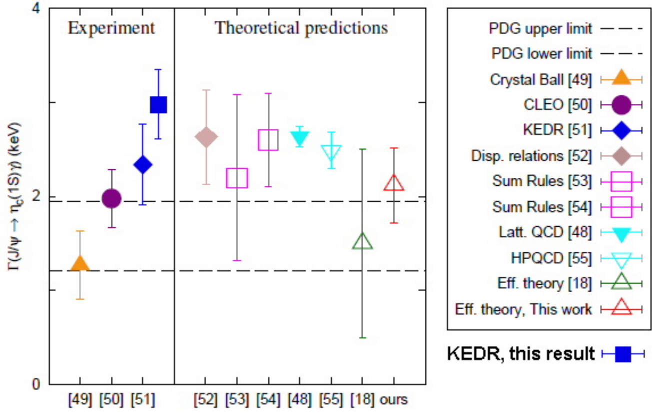


FIG. 9: *Comparison of different theoretical and experimental predictions for* $\Gamma_{J/\psi\to\eta_c\gamma}$.

$$\Gamma(J/\psi \to \gamma\eta_c) = (2.99 \pm 0.32 \pm 0.21)\,\text{keV}.$$

Results on $\Gamma(J/\psi \to \gamma\eta_c)$

Our new result on $\Gamma(J/\psi \to \gamma\eta_c)$ decay is higher than our 2010 year result, because we use another model for η_c resonance description, take into account interference effects and measure photon efficiency with better accuracy. Possible reasons for discrepancy of our result with Crystal Ball and CLEO results are: background subtraction in the Crystal Ball analysis may be incorrect (polynom degree in fit is too high), and the fact that CLEO does not take into account the effects of interference, although it is necessary for exclusive processes.