Measurement of J/psi leptonic widths with the KEDR detector

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   - On vacuum polarization treatment in $e^+e^- \rightarrow J/\psi \rightarrow \ell^+\ell^-$
   - Calculation of $\sigma^{e^+e^-\rightarrow J/\psi\rightarrow \ell^+\ell^-}(W)$

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The leptonic width and the total width of $J/\psi$–meson are its fundamental characteristics providing us with the important information on the interaction of $c$–quarks.

Study of the $e^+e^- \rightarrow J/\psi \rightarrow \ell^+\ell^-$ cross section as function of energy allows one to determine the leptonic width $\Gamma_{\ell\ell}$ and its product to the decay ratio $\Gamma_{ee} \times \Gamma_{\ell\ell}/\Gamma$ thus the total width $\Gamma$ can be also found

- high accuracy for $\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma$ (peak cross section)
- low accuracy for $\Gamma_{ee}$ (interference effect)

$B(J/\psi \rightarrow \ell^+\ell^-) = \Gamma_{\ell\ell}/\Gamma$ is known with accuracy of 0.7% from the cascade decay $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$

We report the results of high precision measurements

- $\Gamma_{ee} \times \Gamma_{ee}/\Gamma$ (PHIPS'I'08)
- $\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma$ (new result)

Measured values of $\Gamma_{ee}$ and $\sqrt{\Gamma_{ee}\Gamma_{\mu\mu}}$ are used to check the analysis consistency
Consensus in the experimental data analysis

- $\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma$ by BaBar(2004), CLEO(2006)
- $\Gamma_{ee} \times \Gamma_{ee}/\Gamma$ by KEDR(PHIPSI’08)

\[
\sigma_{ee \to J/\psi \to \ell^+\ell^-} \propto \frac{\Gamma_{ee} \Gamma_{\ell\ell}}{\Gamma}
\]

$\Gamma_{\ell\ell}$ – “experimental” partial width recommended to use by PDG

$\Gamma_{\ell\ell}^0$ – lowest order QED value

\[
\Gamma_{\ell\ell} \equiv B_{ll(n\gamma)} \times \Gamma = \frac{\Gamma_{\ell\ell}^{(0)}}{|1 - \Pi_0|^2}
\] (Y.-S. Tsai, 1983)

$B_{ll(n\gamma)}$ – branching ratio as it is measured in experiments

$\Pi_0$ – vacuum polarization excluding $J/\psi$ contribution

Sec. 8.2.4 of the review “Heavy Quarkonium Physics” (2005)
On vacuum polarization treatment in $e^+e^- \rightarrow J/\psi \rightarrow \ell^+\ell^-$

Single-photon annihilation cross section according to Kuraev, Fadin (1985):

$$\sigma(s) = \int dx \frac{\sigma_0((1-x)s)}{|1 - \Pi((1-x)s)|^2} f(s,x)$$

$\sigma_0(s)$ – Born level cross section, $\Pi(s)$ – vacuum polarization

Sec. 8.2.4 of “Heavy Quarkonium Physics”:

$$\frac{12\pi \Gamma_{ee}^0 \Gamma_{\ell\ell}^0}{(s - M^2)^2 + M^2\Gamma^2} \Rightarrow \sigma_0, \quad \Pi_0 \Rightarrow \Pi(s)$$

one of the two $\Gamma^{(0)}$ survives!

Actually (thanks to V.S. Fadin for clarification):

$$\Pi = \Pi_0 + \Pi_R(s), \quad \Pi_R(s) = \frac{3\Gamma_{ee}^0}{\alpha} \frac{s}{M_0} \frac{1}{s - M_0^2 + iM_0\Gamma_0}$$

$M_0, \Gamma_0$ – “bare” resonance parameters, $\Pi_0 = \Pi_{ee} + \Pi_{\mu\mu} + \Pi_{\tau\tau} + \Pi_{q\bar{q}}$

$$\sigma_0^{ee\rightarrow\ell\ell} = \frac{4\pi\alpha}{3s} = -\frac{4\pi\alpha}{s} \text{Im} \Pi_{\ell\ell} \quad (\ell\ell = ee, \mu\mu)$$
On vacuum polarization treatment in $e^+ e^- \rightarrow J/\psi \rightarrow \ell^+ \ell^-$

- KF’s formula with “bare” resonance parameters gives the cross section without separation to the continuum, resonant and interference parts.

- To obtain the resonance contribution the continuum one must be subtracted from the amplitude

$$\frac{1}{1 - \Pi_0 - \Pi_R(s)} \equiv \frac{1}{1 - \Pi_0} + \frac{1}{(1 - \Pi_0)^2} \frac{3\Gamma^0_{ee}}{\alpha} \frac{s}{M_0} \frac{1}{s - \tilde{M}^2 + i\tilde{M}\tilde{\Gamma}}$$

$$\tilde{M}^2 = M_0^2 + \frac{3\Gamma^0_{ee}}{\alpha} \frac{s}{M_0} \text{Re} \frac{1}{1 - \Pi_0},$$

$$\tilde{M}\tilde{\Gamma} = M_0\Gamma_0 - \frac{3\Gamma^0_{ee}}{\alpha} \frac{s}{M_0} \text{Im} \frac{1}{1 - \Pi_0}$$

- The narrow resonance in $e^+ e^-$, $\mu^+ \mu^-$ and $q\bar{q}$ channels can be described by the Breit-Wigner amplitude with “dressed” parameters $\tilde{M} \approx \tilde{M}(M_0^2)$ and $\Gamma \approx \tilde{\Gamma}(M_0^2)$ ($M - M_0 \approx 1$ MeV for $J/\psi$).

- The resonance contribution in these channels has the factor of $1/(1 - \Pi_0)^2$ in the amplitude for the two intermediate photons.
On vacuum polarization treatment in $e^+e^- \rightarrow J/\psi \rightarrow \ell^+\ell^-$

- The same “line shape” in the gluonic channels with
  \[
  \sigma_{0 \rightarrow ggg,gg\gamma}^e(s) = -\frac{4\pi\alpha}{s} \text{Im} \Pi_R(s),
  \]
  the amplitude has the factor of $1/(1-\Pi_0)$ in this case.

- Got three types of “Feynman diagrams” for $e^+e^-$ annihilation

- No needs to reanalyze the experimental results!
Calculation of $\sigma^{e^+e^-\rightarrow J/\psi\rightarrow \ell^+\ell^-}(W)$

- Analytical expressions for radiative correction integral in the soft photon approximation was first obtained in Ya.l. Azimov et al. JETP Lett. 21 (1975) 172

- With some up-to-day modifications for $\mu^+\mu^-$ channel

$$
\left( \frac{d\sigma}{d\Omega} \right)^{ee\rightarrow \mu\mu} = \left( \frac{d\sigma}{d\Omega} \right)^{ee\rightarrow \mu\mu}_{\text{QED}} + \frac{3}{4M^2} (1+\cos^2 \theta) \times
$$

$$
(1 + \delta_{sf}) \left\{ \frac{3\Gamma_{ee}\Gamma_{\mu\mu}}{\Gamma M} \text{Im } \mathcal{F} - \frac{2\alpha \sqrt{\Gamma_{ee}\Gamma_{\mu\mu}}}{M} \text{Re } \frac{\mathcal{F}}{1-\Pi_0} \right\}
$$

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

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

$\delta_{sf}$ – from the structure function approach by Kuraev and Fadin

$\mathcal{F}(\cdot)$ – from the integration over the radiated energy on the complex plain
Calculation of $\sigma^{e^+e^- \rightarrow J/\psi \rightarrow \ell^+\ell^-}(W)$

- For $e^+e^-$ channel

$$
\left(\frac{d\sigma}{d\Omega}\right)^{ee\rightarrow ee} = \left(\frac{d\sigma}{d\Omega}\right)_{QED}^{ee\rightarrow ee} + \frac{1}{M^2} \left\{ \frac{9}{4} \frac{\Gamma_{ee}}{\Gamma M} (1+\cos^2 \theta) (1 + \delta_{sf}) \text{Im } \mathcal{F} - \frac{3\alpha \Gamma_{ee}}{2} \frac{\Gamma_{ee}}{M} \left[ (1+\cos^2 \theta) - \frac{(1+\cos^2 \theta)^2}{(1-\cos \theta)} \right] \text{Re } \frac{\mathcal{F}}{1-\Pi_0} \right\}
$$

accuracy of the interference term $\sim \beta$ is sufficient for our analysis

- $\sigma_{QED}^{ee\rightarrow ee}$ and $\sigma_{QED}^{ee\rightarrow \mu\mu}$ have to be calculated with MC generators

- Final state radiation must be simulated for the resonance production

- Numerical convolution with the collision energy distribution

$$
\rho(W) = \frac{1}{\sqrt{2\pi} \sigma_W} \exp \left\{ -\frac{(W-W_{\text{beam}})^2}{2\sigma_W^2} \right\}
$$

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$e^+e^-$ collision from $\phi$ to $\psi'$  
16-Oct-2009
VEPP–4M collider

- Wide energy range $E_{beam} \approx 1 \div 6$ GeV
- Peak luminosity $1.5 \times 10^{30}$ at $J/\psi$
- Precise beam energy determination:
  - Resonant Depolarization Method, $\sigma_E \approx 1.5$ keV
  - interpolation for DAQ runs $\sigma_E = 8 \div 30$ keV
  - IR-light Compton BackScattering, $\sigma_E \lesssim 100$ keV
KEDR detector

1. Vacuum chamber
2. Vertex detector
3. Drift chamber
4. Threshold aerogel counters
5. ToF-counters
6. Liquid krypton calorimeter
7. Superconducting coil (0.65 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

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\(e^+e^-\) collision from \(\phi \) to \(\psi''\)

16-Oct-2009

11/20
Description of the experiment

- **11-point scan of $J/\psi$**

\[
\sigma_{\text{obs}} \hspace{1cm} J/\psi \rightarrow \text{hadrons}
\]

\[
\begin{array}{c|c|c|c|c|c|c|c}
W (MeV) & 3088 & 3092 & 3096 & 3100 & 3104 & 3108 \\
\hline
\sigma_W & 0.697 \pm 0.014 \text{MeV} & & & & & \\
\mathcal{L}_{\text{int}} & 230 \text{nb}^{-1} & & & & & \\
\end{array}
\]

- $J/\psi$ hadrons'

$W = 0$

$W (\text{MeV})$

April 2005

$\approx 15,000 \ J/\psi \rightarrow l^+l^- \ \text{decays}$

Luminosity measurements with single bremsstrahlung, point-to-point stability $\approx 1\%$
Event selection:
- Exactly two tracks of opposite charges with continuation in EMC
- Vertex in the interaction region
- EMC: $E_1, E_2 > 0.7$ GeV, $E_1 + E_2 > 2$ GeV, $(E_1 + E_2)/E_{tot} > 0.95$
- Acollinearity $|\Delta \phi|, |\Delta \theta| < 40^\circ$
- Fiducial volume cut $\theta > 40^\circ$

2D-fit: 11 energy points $\times$ $n$ angular bins ($n = 4 \div 16$)

$$N_{exp}(E_i, \theta_j) = R_{\mathcal{L}} \times \mathcal{L}(E_i) \times \left( \sigma_{\text{peak}}(E_i, \theta_j) \cdot \epsilon_{\text{peak}}(E_i, \theta_j) + \sigma_{\text{inter}}(E_i, \theta_j) \cdot \epsilon_{\text{inter}}(E_i, \theta_j) + \sigma_{\text{Bhabha}}(E_i, \theta_j) \cdot \epsilon_{\text{Bhabha}}(E_i, \theta_j) \right)$$

- $\mathcal{L}(E_i)$ – luminosity by single bremsstrahlung
- $\sigma_{\text{peak}} \cdot \epsilon_{\text{peak}}, \sigma_{\text{inter}} \cdot \epsilon_{\text{inter}}$ – trivial MC generators + FSR with PHOTOS
- $\sigma_{\text{Bhabha}} \cdot \epsilon_{\text{Bhabha}}$ – BHWIDE and MCGPJ event generators

Free parameters:
- $R_{\mathcal{L}}$ – absolute luminosity calibration $\times$ efficiency correction
- $\sigma_{\text{peak}} \cdot \epsilon_{\text{peak}} \propto \Gamma_{ee} \times \Gamma_{ee}/\Gamma$ – main result
- $\sigma_{\text{inter}} \cdot \epsilon_{\text{inter}} \propto \Gamma_{ee}$ – “nuance parameter”
$\Gamma_{ee} \times \Gamma_{ee}/\Gamma$ analysis

- **Fit picture (4 angular bins):**

  \begin{itemize}
  \item $\sigma_{\text{obs}} (\text{nb})$
  \item $W (\text{MeV})$
  \item $40^\circ \leq \theta < 65^\circ$
  \item $65^\circ \leq \theta < 90^\circ$
  \item $90^\circ \leq \theta < 125^\circ$
  \item $125^\circ \leq \theta \leq 140^\circ$
  \end{itemize}

- **Fit results (10 angular bins):**

  $\Gamma_{ee} \times \Gamma_{ee}/\Gamma = 0.3324 \pm 0.0064 \text{ (stat.) keV}$
  $\Gamma_{ee} = 5.7 \pm 0.7 \text{ (stat.) keV}$
  $R_L = 93.4 \pm 0.7 \text{ (stat.)} %$
\( \Gamma_{ee} \times \Gamma_{ee}/\Gamma \) analysis

- Detection efficiency correction (\( \approx 70\% \) of total event sample)
  - Select events with EMC calorimeter “only” \( \Rightarrow \epsilon_{\text{track}}^{\exp}/\epsilon_{\text{track}}^{\text{sim}}(\theta) \)
  - Select events with tracking system “only” \( \Rightarrow \epsilon_{\text{EMC}}^{\exp}/\epsilon_{\text{EMC}}^{\text{sim}}(\theta) \)

\[ \delta R_L = 1.7\%, \ \delta \Gamma_{ee} \times \Gamma_{ee}/\Gamma = 0.75 \pm 0.63 \text{ (stat.)} \pm 0.5 \text{ (syst.)} \%

- List of systematic uncertainties:

<table>
<thead>
<tr>
<th>Systematic uncertainty source</th>
<th>Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity monitor instability</td>
<td>0.8</td>
</tr>
<tr>
<td>Offline event selection</td>
<td>0.7</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.5</td>
</tr>
<tr>
<td>Energy spread accuracy</td>
<td>0.2</td>
</tr>
<tr>
<td>Beam energy measurement (10–30 keV)</td>
<td>0.3</td>
</tr>
<tr>
<td>Fiducial volume cut</td>
<td>0.2</td>
</tr>
<tr>
<td>Calculation of radiative correction</td>
<td>0.3</td>
</tr>
<tr>
<td>Cross section for Bhabha (MC generators)</td>
<td>0.4</td>
</tr>
<tr>
<td>Uncertainty in the final state radiation (PHOTOS)</td>
<td>0.4</td>
</tr>
<tr>
<td>Background from ( J/\psi ) decays</td>
<td>0.2</td>
</tr>
<tr>
<td>Fitting procedure</td>
<td>0.2</td>
</tr>
</tbody>
</table>

| Quadratic sum                                          | 1.4      |

- Final result:

\[ \Gamma_{ee} \times \Gamma_{ee}/\Gamma = 0.3323 \pm 0.0064 \text{ (stat.)} \pm 0.0048 \text{ (syst.)} \text{ keV} \]
**Event selection:**
- Exactly two tracks of opposite charges with continuation in EMC
- Vertex in the interaction region
- EMC: $60 < E_1, E_2 < 500 \text{ MeV}$, $E_1 + E_2 < 750 \text{ MeV}$, $(E_1 + E_2)/E_{\text{tot}} > 0.7$
- Acollinearity $|\Delta \phi| < 15^\circ$, $|\Delta \theta| < 10^\circ$
- Fiducial volume cut $\theta > 40^\circ$, minimal TOF system requirements

**1D-fit: 11 energy points**

$$N_{\text{exp}}(E_i) = \mathcal{R}_{\mathcal{L}}^{e^+e^-} \times \mathcal{L}(E_i) \times \left( \sigma_{\text{peak}}(E_i) \cdot \epsilon_{\text{peak}}(E_i) + \sigma_{\text{inter}}(E_i) \cdot \epsilon_{\text{inter}}(E_i) + \sigma_{\text{cont}}(E_i) \cdot \epsilon_{\text{cont}}(E_i) \right) + F_{\text{cosmic}} \times t_{\text{live}}$$

- $\mathcal{R}_{\mathcal{L}}^{e^+e^-} \times \mathcal{L}(E_i)$ – corrected luminosity by single bremsstrahlung
- $\sigma_{\text{peak}} \cdot \epsilon_{\text{peak}}$, $\sigma_{\text{inter}} \cdot \epsilon_{\text{inter}}$ – trivial MC generators + FSR with PHOTOS
- $\sigma_{\text{cont}} \cdot \epsilon_{\text{cont}}$ – Berends and MCGPJ event generators
- $t_{\text{live}}$ - data taking time

**Free parameters:**
- $\sigma_{\text{peak}} \cdot \epsilon_{\text{peak}} \propto \Gamma_{ee} \times \Gamma_{ee}/\Gamma$ – main result
- $\sigma_{\text{inter}} \cdot \epsilon_{\text{inter}} \propto \sqrt{\Gamma_{ee} \Gamma_{\mu\mu}}$ – “nuance parameter”
- $F_{\text{cosmic}}$ – cosmic event rate
$\Gamma_{ee} \times \Gamma_{\mu\mu} / \Gamma$ analysis

- Fit picture:

$$\sigma_{\text{obs}}, \text{nb}$$

$$\chi^2/\text{ndf} = 11/8$$

- Fit results:

$$\Gamma_{ee} \times \Gamma_{\mu\mu} / \Gamma = 0.3318 \pm 0.0052 \text{ (stat.) keV}$$

$$\sqrt{\Gamma_{ee} \Gamma_{\mu\mu}} = 5.6 \pm 0.7 \text{ (stat.) keV}$$
Correction to efficiency difference for $e^+e^-$ and $\mu^+\mu^-$ events ($\sim$65% of total event sample)

- Select events reconstructing single track with a kink, separate $e^+e^-$ and $\mu^+\mu^-$ events using EMC

$\left( \frac{\epsilon_{\mu\mu}^{\text{exp}}}{\epsilon_{\mu\mu}^{\text{sim}}} \right) / \left( \frac{\epsilon_{ee}^{\text{exp}}}{\epsilon_{ee}^{\text{sim}}} \right) = 1.005 \pm 0.005 \text{ (stat.)} \pm 0.008 \text{ (syst.)}.$

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</tr>
<tr>
<td>Cosmic ray background</td>
<td>0.1</td>
</tr>
<tr>
<td>Quadratic sum</td>
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</table>

Final result:

$\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma = 0.3318 \pm 0.0052 \text{ (stat.)} \pm 0.0063 \text{ (syst.)} \text{ keV}$
Summary of $\Gamma_{ee} \times \Gamma_{\ell\ell}/\Gamma$ results

Gray strip for $\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma$ world average
Following products were measured at the VEPP-4 collider with the KEDR detector:

\[ \Gamma_{ee} \times \Gamma_{ee} / \Gamma = 0.3323 \pm 0.0064 \text{ (stat.)} \pm 0.0048 \text{ (syst.) keV} \]

\[ \Gamma_{ee} \times \Gamma_{\mu\mu} / \Gamma = 0.3318 \pm 0.0052 \text{ (stat.)} \pm 0.0063 \text{ (syst.) keV} \]

Assuming $e/\mu$–universality the result is

\[ \Gamma_{ee} \times \Gamma_{\ell\ell} / \Gamma = 0.3320 \pm 0.0041 \text{ (stat.)} \pm 0.0050 \text{ (syst.) keV} \]

For the world average value $\Gamma_{\ell\ell} / \Gamma = 5.935 \pm 0.042$ this corresponds to

\[ \Gamma_{\ell\ell} = 5.59 \pm 0.12 \text{ keV} \]

\[ \Gamma = 94.2 \pm 2.3 \text{ keV} \]

The results are in good agreement with the world average values a bit better accuracy.