Measuring the inclusive cross section of e^+e^- annihilation into hadrons at the KEDR experiment

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KEDR collaboration

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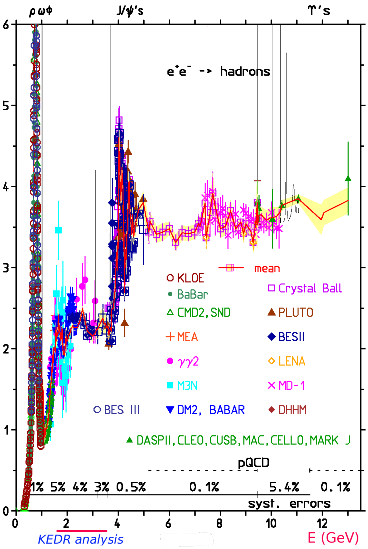
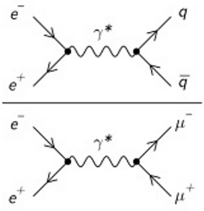
In memoriam of Simon Eidelman our colleague, friend and teacher.

$R(s)$ measurement. Motivation.



F. Jegerlehner arXiv:1511.0447

$$R = \frac{\sigma(e^-e^+ \to \text{hadrons})}{\sigma(e^-e^+ \to \mu^-\mu^+)} \approx$$



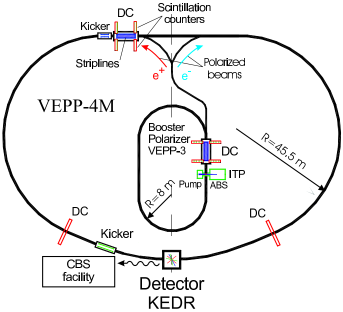
In first approximation:

$$R(s) \simeq 3 \sum e_q^2$$

$R(s)$ is used to determine:

- $\alpha_s(s)$
- $(g_\mu - 2)/2$
- $\alpha(M_Z^2)$

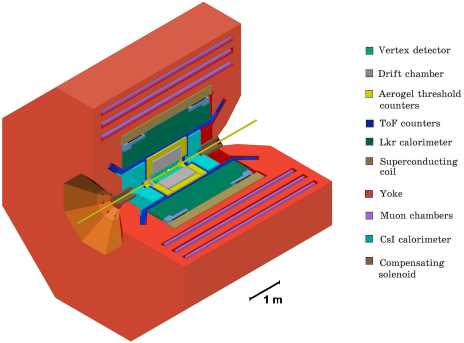
VEPP-4M and KEDR



Beam energy	$1 \div 5$ GeV
Number of bunches	2×2
Luminosity 1.8 GeV	1.5×10^{30} cm^{-2} s^{-1}

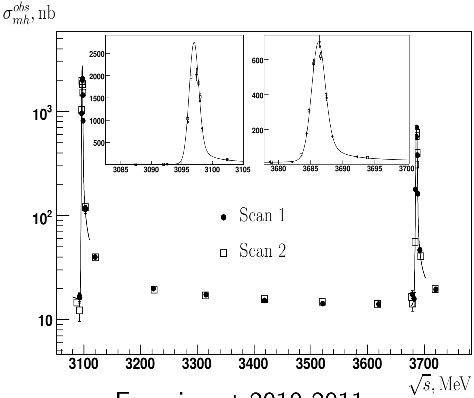
Energy measurement:

- Resonant depolarization method:
  Instant measurement accuracy ~ 1 keV
  Energy interpolation accuracy $10 \div 30$ keV
- Compton backscattering method ~ 100 keV

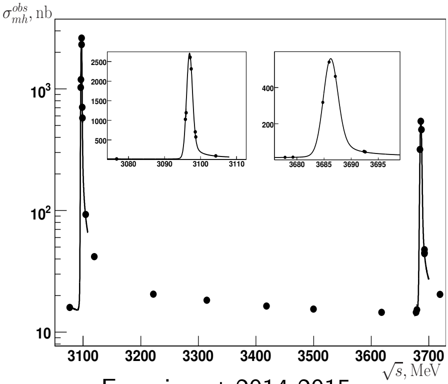


R measurement between J/ψ and $\psi(2S)$

The observed multihadron cross section as a function of the c.m. energy



Experiment 2010-2011



Experiment 2014-2015

- The c.m. energy range between 3.076 and 3.72 GeV studied
- An integrated luminosity of 2.7 pb^{-1} collected at 9 energies 3.077, 3.120,3.223, 3.315, 3.418, 3.500, 3.521, 3.618, 3.719 GeV
- $\sim (2-6)\times 10^3$ m.h. events per point, $\sim 38\times 10^3$ in total

Analysis

The way that we are measuring R:

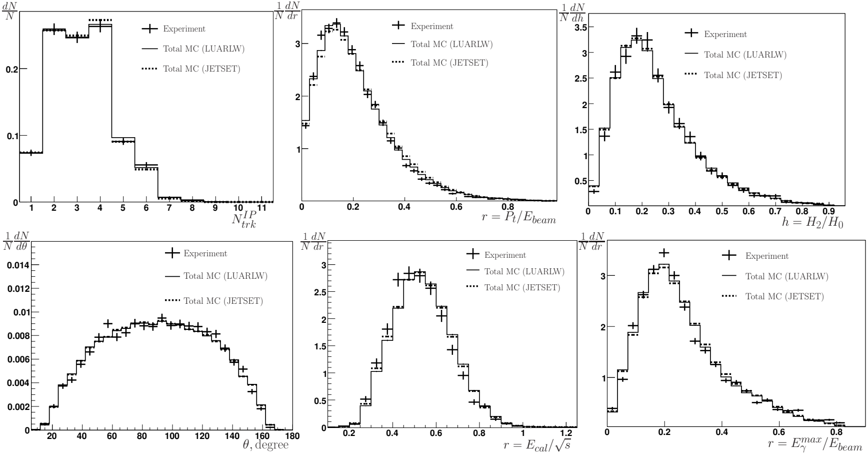
$$R = \frac{\sigma_{obs}(s) - \sum \varepsilon_{\psi}^{tail}(s)\sigma_{\psi}^{tail}(s) - \sum \varepsilon_{bg}^{i}(s)\sigma_{bg}^{i}(s)}{\varepsilon(s)(1+\delta(s))\sigma_{\mu\mu}^{0}}$$

with $\sigma_{obs}(s) = \frac{N_{mh} - N_{res.bg.}}{\int \mathcal{L}dt}$ where N_{mh} represent all events pass hadronic selection criteria, $N_{res.bg.}$ – residual machine background
$\sum \varepsilon_{\psi}^{tail}(s)\sigma_{\psi}^{tail}(s)$ is contribution from J/ψ and $\psi(2S)$ resonances
$\sum \varepsilon_{bg}^{i}(s)\sigma_{bg}^{i}(s)$ is contribution from physical processes: $e^+e^- \to l^+l^-$, $\gamma\gamma$-processes.
$\varepsilon(s)$ – multihadron efficiency.

$$1 + \delta(s) = \int dx \frac{1}{1-x} \frac{\mathcal{F}(s,x)}{\left|1 - \tilde{\Pi}(s(1-x))\right|^2} \frac{\tilde{R}(s(1-x))\varepsilon(s(1-x))}{R(s)\varepsilon(s)}$$

$\mathcal{F}(s,x)$ – radiative correction kernel (E.A.Kuraev, V.S.Fadin Sov.J.Nucl.Phys.41(466-472)1985) Here $\tilde{\Pi}$ and $\tilde{R}$ does not includes J/ψ and $\psi(2S)$ resonances. **To determine the contributions of the J/ψ and $\psi(2S)$ without external data, the additional data samples of about 0.4 pb^{-1}(2010-2011) and 0.34 pb^{-1}(2014-2015) were collected in the vicinity of peak regions.**

Simulation: JETSET and LUARLW



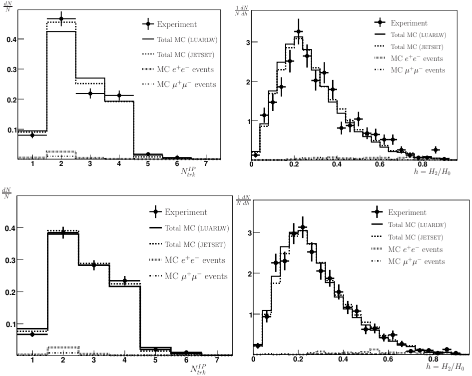
Properties of hadronic events produced in the uds continuum at 3.119 GeV (2014-2015).

Here N is the number of events, N_{trk}^{IP} is the number of tracks originated from IP, P_t is a transverse momentum of the track, H_2 and H_0 are Fox-Wolfram moments, θ is a polar angle of the track, E_{cal} is energy deposited in the calorimeter, E_γ^{max} is energy of the most energetic photon.

R for $\sqrt{s}$= 1.84 – 3.05 GeV

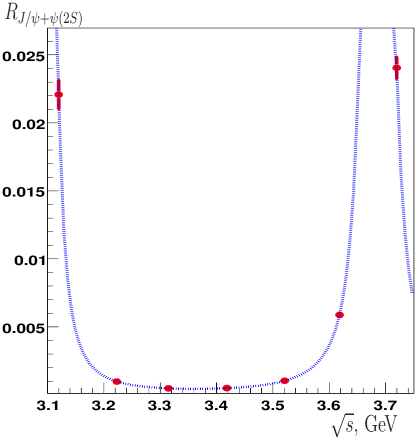
- An integrated luminosity 0.66 pb^{-1} collected at 13 equidistant points with a step $\sim$ 0.1 GeV: 1.841, 1.937 ... 3.048 GeV
- $\sim 10^3$ hadronic events per point, 14.8×10^3 events in total
- Simulation of the *uds* continuum based on the LUARLW generator, tuned JETSET alternatively used at 6 points for a cross-check.
- Measured value of $R = \frac{\sigma_{obs}(s) - \sum \varepsilon^i_{bg}(s)\sigma^i_{bg}(s)}{\varepsilon(s)(1+\delta(s))\sigma^{\mathbf{0}}_{\mu\mu}}$

Experimental distribution and two variants of MC simulation based on LUARLW and tuned JETSET are plotted ($\sqrt{s} = 1.94$ GeV and $\sqrt{s} = 2.14$ GeV).



Results R for $\sqrt{s} = 1.84 - 3.72$ GeV

$\sqrt{s}$, GeV	$R_{uds}(s)\{R(s)\}$	$\frac{\delta R}{R}\left(\frac{\delta R_{syst}}{R}\right)$,%
1.841	$2.226 \pm 0.139 \pm 0.158$	9.5(7.1)
1.937	$2.141 \pm 0.081 \pm 0.073$	5.1(3.4)
2.037	$2.238 \pm 0.068 \pm 0.072$	4.4(3.2)
2.134	$2.275 \pm 0.072 \pm 0.055$	4.0(2.4)
2.239	$2.208 \pm 0.069 \pm 0.053$	3.9(2.4)
2.340	$2.194 \pm 0.064 \pm 0.048$	3.7(2.2)
2.444	$2.175 \pm 0.067 \pm 0.048$	3.8(2.2)
2.543	$2.222 \pm 0.070 \pm 0.047$	3.8(2.1)
2.645	$2.220 \pm 0.069 \pm 0.049$	3.8(2.2)
2.745	$2.269 \pm 0.065 \pm 0.050$	3.6(2.2)
2.850	$2.223 \pm 0.065 \pm 0.047$	3.6(2.1)
2.949	$2.234 \pm 0.064 \pm 0.051$	3.7(2.3)
3.048	$2.278 \pm 0.075 \pm 0.048$	3.9(2.3)
3.077	$2.188 \pm 0.056 \pm 0.042$	3.2(2.1)
3.120	$2.212\{2.235\} \pm 0.042 \pm 0.049$	2.9(2.2)
3.223	$2.194\{2.195\} \pm 0.040 \pm 0.035$	2.4(1.6)
3.315	$2.219\{2.219\} \pm 0.035 \pm 0.035$	2.2(1.6)
3.418	$2.185\{2.185\} \pm 0.032 \pm 0.035$	2.2(1.6)
3.500	$2.224\{2.224\} \pm 0.054 \pm 0.040$	3.0(1.8)
3.521	$2.200\{2.201\} \pm 0.050 \pm 0.044$	3.0(2.0)
3.618	$2.212\{2.218\} \pm 0.038 \pm 0.035$	2.3(1.6)
3.720	$2.204\{2.228\} \pm 0.039 \pm 0.042$	2.6(1.9)



Using J/ψ and $\psi(2S)$ parameters, we obtain

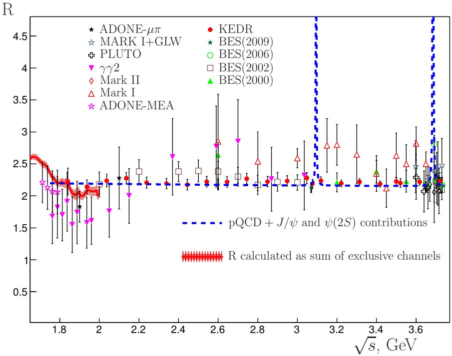
$$R_{uds}(s) + R_{J/\psi+\psi(2S)} \Longrightarrow R(s)$$

PLB **753** (2016) 533 [arXiv:1510.02667].

PLB **770C** (2017) 174 [arXiv:1610.02827].

PLB **788** (2019) 42 [arXiv:1805.06235].

Comparison with others experiments



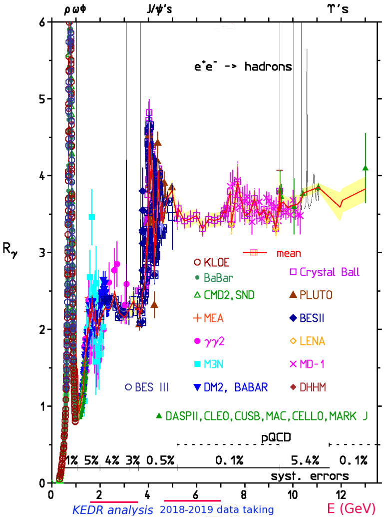
The quantity R versus the c.m. energy and the sum of the prediction of perturbative QCD and a contribution of narrow resonances.

In the c.m.energy range 3.08-3.72 GeV the weighted average $\overline{R}_{\text{uds}} = 2.204 \pm 0.014 \pm 0.026$ is approximately one sigma higher than that theoretically expected, $R^{\text{pQCD}}_{\text{uds}} = 2.16 \pm 0.01$ calculated according to the pQCD In the lower c.m.energy range 1.84-3.05 GeV the weighted average is $2.225 \pm 0.020 \pm 0.047$ (the pQCD prediction of 2.18 ± 0.02).

Plans

R measurement in the energy range 4.7-7 GeV.

- Data-taking was finished in 2019. An integrated luminosity $\sim 13.7\ \mathrm{pb}^{-1}$ collected at 17 points
- Total uncertainty is expected to be about 3%.



F. Jegerlehner arXiv:1511.0447

$\sigma^{e^+e^-\to\textbf{hadrons}}$ and $\sigma^{e^+e^-\to e^+e^-}$ nearby a narrow resonance

In the soft photon approximation analytical expression for the annihilation cross section nearby a narrow resonance.

Ya.I. Azimov *et al.* JETP Lett. 21 (1975) 172. With up-today modifications one has

$$\sigma^{e^+e^-\to\textbf{hadr}}(s) = \sigma^{e^+e^-\to\textbf{hadr}}_{\textbf{continuum}} + \frac{12\pi}{s}\,(1+\delta_{sf})\left[\frac{\Gamma_{ee}\tilde{\Gamma}_h}{\Gamma M}\,\mathrm{Im}\,f(s) - \frac{2\alpha\sqrt{R\,\Gamma_{ee}\tilde{\Gamma}_h}}{3\sqrt{s}}\,\lambda\,\mathrm{Re}\,\frac{f^*(s)}{1-\Pi_0}\right],$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{ee\to ee} = \left(\frac{d\sigma}{d\Omega}\right)^{ee\to ee}_{\text{QED}} + \frac{1}{s}\,(1+\delta_{sf})\left\{\frac{9}{4}\frac{\Gamma_{ee}^2}{\Gamma M}(1+\cos^2\theta)\,\mathrm{Im}\,f - \frac{3\alpha}{2}\frac{\Gamma_{ee}}{M}\left[(1+\cos^2\theta)\,\mathrm{Re}\,\frac{f^*}{1-\Pi_0(s)} - \frac{(1+\cos\theta)^2}{(1-\cos\theta)}\,\mathrm{Re}\,\frac{f^*}{1-\Pi_0(t)}\right]\right\},$$

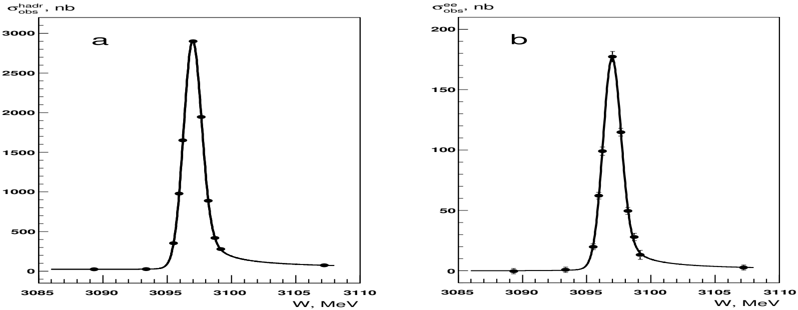
It was verified in the work X. Y. Zhou, Y. D. Wang and L. G. Xia, Chin. Phys. C **41** (2017) no.8, 083001

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

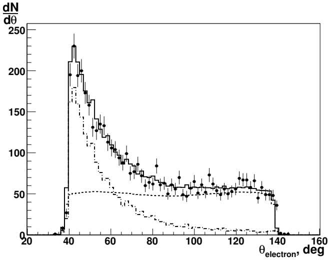
$$\beta = \frac{2\alpha}{\pi}\,(L-1), \qquad f(s) = \frac{\pi\beta}{\sin\pi\beta}\left(\frac{s}{M^2 - s - iM\Gamma}\right)^{1-\beta}$$

Γ_{ee}, Γ, M – 'dressed' parameters including corrections to the vacuum polarization, $\Gamma_{ee} = \Gamma_{ee}^{(0)}/|1-\Pi_0|^2$, λ–parameter controls the resonance–continuum interference,$\tilde{\Gamma}_h \neq \Gamma_h$
Numerical convolution with the collision energy distribution is used to fit resonance.

Measurement $\Gamma_{e^+e^-}(J/\psi)$ and $\Gamma_{e^+e^-}(J/\psi) \times \mathcal{B}(J/\psi \to \text{hadrons})$

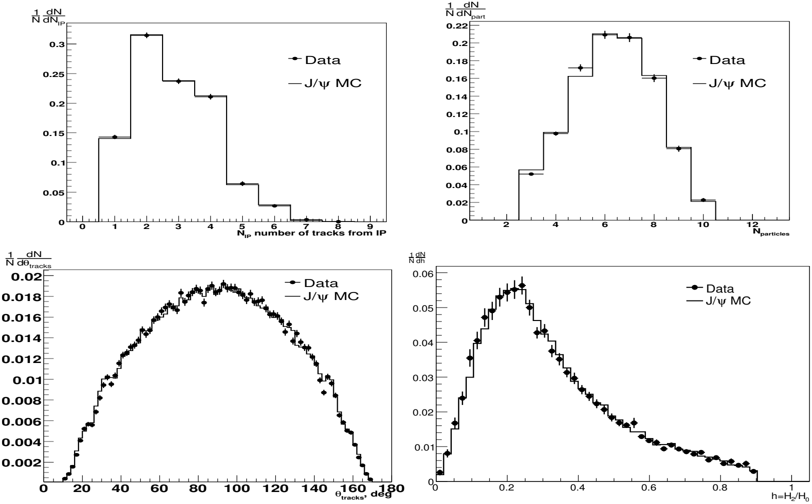


11-point scan J/ψ, $\int\mathcal{L}dt \simeq 0.23$ pb^{-1}. Joint fit of *hadronic* and e^+e^- cross section in few polar angle bin. For the absolute luminosity determination e^+e^- events used. Relative luminosity was obtained by single bremsstrahlung.



Distribution of electron polar angle in the energy range of J/ψ meson peak. The points show experimental data. The histograms correspond to MC simulation: dashed-doted – Bhabha scattering, dashed – J/ψ resonance and their interference, solid-line – sum of the contributions.

Properties of hadronic events produced in J/ψ decay



The points represent experimental data, the histograms correspond to J/ψ meson decays simulation. Number of tracks from interaction point N_{IP}, total number of particles N_{part}, θ_{tracks} distribution and the ratio of Fox-Wolfram moments H_2/H_0.

Results and systematic uncertainties

$(\Gamma_{ee}, \Gamma_{ee} \times \mathcal{B}_{\text{hadrons}})$, $(\Gamma_{ee} \times \mathcal{B}_{\text{ee}}, \Gamma_{ee} \times \mathcal{B}_{\text{hadrons}})$, $(\Gamma_{hadrons}, \Gamma_{ee})$ and (Γ, Γ_{ee}) values, absolute luminosity calibration factor, resonance mass, beam energy spread and continuum contribution σ_0 were considered as free fit parameters. The ratio $\mathcal{B}_{ee}(J/\psi)/\mathcal{B}_{\mu\mu}(J/\psi) = 1.0022 \pm 0.0065$ was fixed according to KEDR result (PLB **731** (2014).)

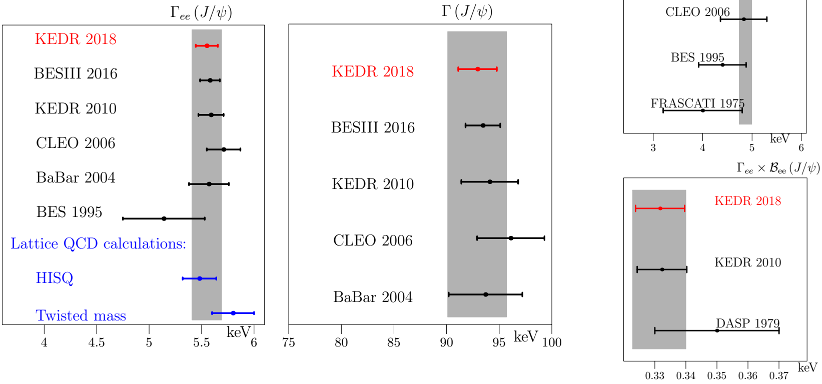
List of systematic uncertainties,%

Source	Γ_{ee}	$\Gamma_{ee} \times \mathcal{B}_{\text{hadrons}}$	$\Gamma_{ee} \times \mathcal{B}_{ee}$	Γ	$\Gamma_{hadrons}$
Luminosity measurement	1.0	1.0	1.0	1.0	1.0
Simulation of J/ψ decays	0.7	0.7	–	0.7	0.7
Detector response	0.8	0.8	0.4	0.8	0.8
Accelerator related effects	0.4	0.4	0.4	0.4	0.4
Theoretical uncertainties	0.4	0.4	0.2	0.4	0.4
Sum in quadrature	1.6	1.6	1.2	1.6	1.6

$$\Gamma_{ee}(J/\psi) = 5.550 \pm 0.056 \pm 0.089\,\text{keV}$$
$$\Gamma_{ee}(J/\psi) \times \mathcal{B}_{\text{hadrons}}(J/\psi) = 4.884 \pm 0.048 \pm 0.078\,\text{keV}$$
$$\Gamma_{ee}(J/\psi) \times \mathcal{B}_{\text{ee}}(J/\psi) = 0.3331 \pm 0.0066 \pm 0.0040\,\text{keV}$$
$$\Gamma(J/\psi) = 92.45 \pm 1.40 \pm 1.48\,\text{keV}$$
$$\Gamma_{hadrons}(J/\psi) = 81.37 \pm 1.36 \pm 1.30\,\text{keV}$$

JHEP **05** (2018) 119. Addendum: JHEP **07** (2020) 112.

Comparison with others experiments

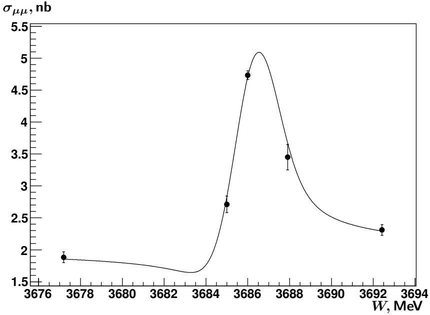


The electron and full widths obtained in our analysis agree well with world averages.

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

6.5 pb^{-1} collected in $\psi(2S)$ region, corresponding $\sim 4 \times 10^6$ $\psi(2S)$, five peak/continuum (p/c) couples and four scans for energy spread determination:

$\psi(2S)$ datasets	started at	$\mathcal{L}_{int}$ nb^{-1}	σ_W MeV
p/c 1	begin 2005	358	1.08
p/c 2	autumn 2005	222	0.99
scan 1	spring 2006	255	0.99
p/c 3	spring 2006	631	0.99
p/c 4	autumn 2006	701	0.99
p/c 5	autumn 2007	1081	1.01
scan 2	end 2007	967	1.01
scan 3	summer 2010	379	1.00
scan 4	end 2010	2005	0.98



The observed $e^+e^- \to \mu^+\mu^-$ cross section in scan 4.

$$\left(\frac{d\sigma}{d\Omega}\right)^{ee\to\mu\mu} \approx \frac{3}{4s}\left(1+\delta_{\text{fs}}\right)\left(1+\cos^2\theta\right) \times$$

$$\left\{\frac{3\Gamma_{ee}\Gamma_{\mu\mu}}{\Gamma M}\,\text{Im}\,f - \frac{2\alpha\sqrt{\Gamma_{ee}\Gamma_{\mu\mu}}}{M}\,\text{Re}\,\frac{f}{(1-\Pi_0)^*}\right\} + \left(\frac{d\sigma}{d\Omega}\right)^{\mu\mu}_{\text{QED}}$$

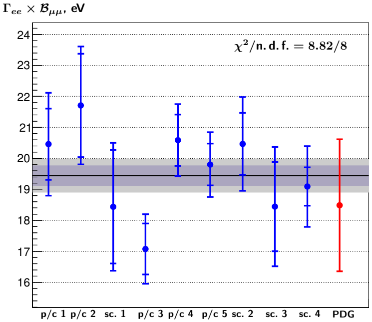
$\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma$ determination for $\psi(2S)$

The following event selection criteria for e^+e^- and $\mu^+\mu^-$ were used:

- Two-prong central event, opposite charges, acollinearity on θ and ϕ less than 28°, energy deposit on each track less than 700 MeV for $\mu^+\mu^-$ or greater than 800 MeV for e^+e^-.
- $40^\circ < \theta < 140^\circ$ for e^+e^-, $30^\circ < \theta < 150^\circ$ for $\mu^+\mu^-$.
- Not more than one extra cluster, with energy less than 160 MeV.
- For muons - confirmation from muon system for both tracks, anti-cosmic veto from ToF.

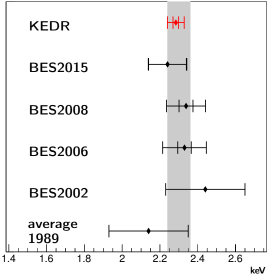
Systematic uncertainty source		p/c 1	p/c 2	sc. 1	p/c 3	p/c 4	p/c 5	sc. 2	sc. 3	sc. 4	σ
1	Energy spread	2.0	2.2	1.1	3.0	2.5	2.5	1.1	2.8	2.0	0
2	Fixed values of M, Γ	0.7	0.7	0.1	0.3	0.7	0.7	0.5	0.2	0.8	0.1
3	Energy measurement	3.1	0.6	< 0.1	1.7	0.3	0.5	0.2	0.9	2.7	< 0.1
4	Bhabha simulation	0.6	0.2	0.2	0.2	0.2	0.5	0.2	0.8	0.2	0.2
5	$\mu^+\mu^-$ scattering simulation	0.2	0.2	0.3	0.2	0.2	0.2	0.3	0.2	0.2	0.2
6	Collinearity cuts	0.2	1.3	2.0	1.8	0.9	1.3	1.4	3.7	1.5	0.2
7	e^+e^- polar angle range	3.5	1.2	2.3	0.9	2.1	1.3	3.4	2.2	1.6	0.9
8	Charge determination	0.1	0.7	0.8	0.3	0.2	1.1	0.8	0.5	0.9	0.1
9	Detector asymmetry	0.5	0.3	0.4	0.5	0.2	< 0.1	0.2	0.3	0.1	< 0.1
10	Extra energy deposit cut	1.3	1.1	1.8	0.7	1.3	1.0	2.3	1.5	2.1	0.7
11	Muon system cut	0.7	1.1	< 0.1	0.4	0.8	1.5	1.1	0.4	1.6	0
12	ABG thresholds	0.1	0.8	0.6	0.2	0.3	—	—	—	—	0.1
13	Calo trigger thresholds	0.5	0.2	2.1	0.7	< 0.1	0.4	< 0.1	2.2	2.0	< 0.1
14	RND trigger application	0.1	0.5	2.0	0.9	0.1	0.1	0.6	1.8	1.7	0.1
15	FSR accounting	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
16	e^+e^- events θ binning	0.6	0.1	0.4	0.1	0.3	0.2	0.3	0.4	0.2	0.1
17	ToF measurement efficiency	1.9	2.1	1.6	1.2	0.9	0.9	2.8	3.0	2.2	0.9
18	Trigger efficiency	0.9	< 0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.1	< 0.1
19	Theoretical accuracy	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sum in quadrature		5.9	4.2	5.1	4.5	3.9	4.0	5.5	6.9	6.0	1.5

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



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

$$\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma = 19.4 \pm 0.3 \pm 0.4 \text{ eV}$$



The $\Gamma_{ee} \times \Gamma_{ee}/\Gamma$ value was also obtained: $\Gamma_{ee} \times \Gamma_{ee}/\Gamma = 22.5 \pm 0.6 \pm 1.3$ eV. Using KEDR results for $\Gamma_{ee} \times \mathcal{B}_{\mathbf{hadrons}}$ (PLB **711** (2012)) and $\Gamma_{ee} \times \mathcal{B}_{\tau\tau}$ (Pis'ma v ZhETF **85** (2007)) channels we obtained the following value of the Γ_{ee} width:

$$\Gamma_{ee} = 2.284 \pm 0.015 \pm 0.042 \text{ keV}$$

PLB **781** (2018),174

Summary

- KEDR measured the R values at 22 center-of-mass energies between 1.84 and 3.72 GeV.
- In the energy range between 1.84 and 3.05 GeV the achieved accuracy is about or better than 3.9% at most of the energy points with a systematic uncertainty less than 2.4%.
- For the energies above J/ψ resonance the total error is about or better than 2.6% and a systematic uncertainty of about 1.9%.
- We plan to measure R at the energy range from 4.7 to 7 GeV. Analysis is in progress.
- KEDR measured precisely the electronic partial widths of J/ψ and $\psi(2S)$ mesons.

Thank you for your time and attention!

BACKUP SLIDES

An application of the $R(s)$

Correlated uncertainties of R_{uds} in %

Source	**Uncertainty in %**	
	Data 2010	**Data 2010 / 2011,2014**
Luminosity		
Cross section calc.	0.5	0.4
Calorimeter response	0.7	-
Calorimeter alignment	0.2	0.2
Rad. correction		
Π approx.	0.3	0.1
$\delta R_{\mathrm{uds}}(s)$	0.2	0.2
$\delta\epsilon(s)$	0.3	0.2
Continuum simulation	1.2	0.4 ÷ 0.8
Track reconstr.	0.5	0.4
e^+e^-X contribution	0.2	0.1
l^+l^- contribution	0.3	0.2
Trigger efficiency	0.3	0.2
Nuclear interaction	0.4	0.2
Sum in quadrature	1.8	0.8 ÷ 1.1

$$R_{\mathrm{uds}}(s) \simeq 2\times\left(1+\frac{\alpha_s}{\pi}+\frac{\alpha_s^2}{\pi^2}\times\left(\frac{365}{24}-9\zeta_3-\frac{11}{4}\right)\right)$$

where ζ is the Euler-Riemann zeta function,

$$\alpha_s(s) = \frac{1}{b_0 t}\left(1 - \frac{b_1 l}{b_0^2 t} + \frac{b_1(l^2 - l - 1) + b_0 b_2}{b_0^4 t^2} + \frac{b_1^3(-2l^3 + 5l^2 + 4l - 1) - 6 b_0 b_2 b_1 l + b_0^2 b^3}{2 b_0^6 t^3}\right)$$

with $t = \ln\frac{s}{\Lambda^2}$, $l = \ln t$ parametrized in terms of the QCD scale parameter Λ and coefficients b_0, b_1, b_3 (can be found in PDG). To determine Λ, we minimise the χ^2 function

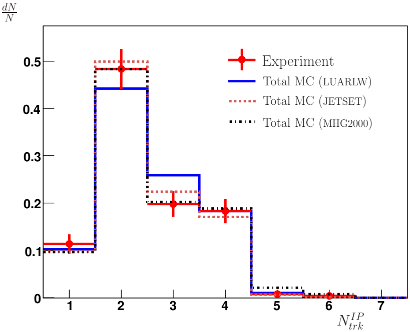
$$\chi^2 = \sum_i \sum_j \left(R^{\mathrm{meas}}_{\mathrm{uds}}(s_i) - R^{\mathrm{calc}}_{\mathrm{uds}}(s_i)\right) C^{-1}_{ij} \left(R^{\mathrm{meas}}_{uds}(s_j) - R^{\mathrm{calc}}_{\mathrm{uds}}(s_j)\right),$$

The obtained value of $\Lambda = 0.361^{+0.155}_{-0.174}$ GeV corresponds to $\alpha_s(m_\tau) = 0.332^{+0.100}_{-0.092}$. If the next order of pQCD is included in the expansion of R_{uds}, the fitting results are as follows: $\Lambda = 0.437^{+0.210}_{-0.215}$ GeV and $\alpha_s(m_\tau) = 0.378^{+0.173}_{-0.120}$.

$\alpha_s(m_\tau)$ determined from our $R(s)$ results is consistent with obtained in semileptonic τ decays ($\alpha_s(m_\tau) = 0.331 \pm 0.013$)

Detection efficiency uncertainty in the energy range $\sqrt{s} = 1.84 \div 3.05$ GeV

- Used two essentially different MC generators (LUARLW and tuned JETSET)
- We validated our estimate of the systematic uncertainty related to simulation of the *uds* continuum using an unfolding method (Chinise Physics C Vol. 37, No. 6 (2013) 063001).
- The estimate at the most problematic energy point 1.84 GeV was additionally verified using the exclusive generator MHG2000.



Detection efficiency uncertainties obtained by different methods

Energy, MeV	$\delta\epsilon/\epsilon$		
	LUARLW JETSET	Unfolding method	LUARLW MHG2000
1841.0	6.6%	3.6%	3.8%
$1937.0 \div 2135.7$	2.5%	1.9%	–
$2135.7 \div 3048.1$	1.2%	0.5%	–

Systematic uncertainties (3.08-3.72 GeV)

Source	Syst. uncertainty, %		
	Scan 1 and 2 (2010-2011)	Scan 2014-2015	Correlated
Luminosity	1.1	0.9	0.4
Rad. corr.	$0.4 \div 0.6$	$0.5 \div 0.8$	$0.2 \div 0.4$
uds simulation	$1.3 \div 2.0$	1.1	0.9
Track reconstruction	0.5	0.4	–
J/ψ	$0.1 \div 2.7$	$0.1 \div 1.8$	–
$\psi(2S)$ (at 3.72 GeV)	1.4	1.1	–
l^+l^-	$0.1 \div 0.2$	$0.3 \div 0.4$	$0.1 \div 0.2$
e^+e^-X	$0.1 \div 0.2$	0.1	0.1
Trigger	0.2	0.2	0.2
Nuclear interaction	0.2	0.2	0.2
Machine background	$0.5 \div 1.1$	$0.4 \div 0.8$	–
Cuts	0.6	0.6	–
Total	$2.1 \div 3.6$ (correlated $1.8 \div 2.5$)	$1.9 \div 2.7$	1.1

R for $\sqrt{s} = 1.84 - 3.05$ GeV

Measured value of $R = \frac{\sigma_{obs}(s) - \sum \varepsilon^{i}_{bg}(s)\sigma^{i}_{bg}(s)}{\varepsilon(s)(1+\delta(s))\sigma^{0}_{\mu\mu}}$

$\sqrt{s}$, MeV	$R(s)$
1841.0	$2.226 \pm 0.139 \pm 0.158$
1937.0	$2.141 \pm 0.081 \pm 0.073$
2037.3	$2.238 \pm 0.068 \pm 0.072$
2135.7	$2.275 \pm 0.072 \pm 0.055$
2239.2	$2.208 \pm 0.069 \pm 0.053$
2339.5	$2.194 \pm 0.064 \pm 0.048$
2444.1	$2.175 \pm 0.067 \pm 0.048$
2542.6	$2.222 \pm 0.070 \pm 0.047$
2644.8	$2.220 \pm 0.069 \pm 0.049$
2744.6	$2.269 \pm 0.065 \pm 0.050$
2849.7	$2.223 \pm 0.065 \pm 0.047$
2948.9	$2.234 \pm 0.064 \pm 0.051$
3048.1	$2.278 \pm 0.075 \pm 0.048$

The main systematic uncertainties in the R:

Source	Error,%
Luminosity	1.2
Rad. corr.	$0.5 \div 2.0$
uds simulation	$1.2 \div 6.6$
l^+l^-	$0.3 \div 0.6$
e^+e^-X	0.2
Trigger	0.3
Nuclear interaction	0.4
Machine background	$0.4 \div 0.9$
Cuts	0.7
Total	$2.1 \div 7.1$

V.V. Anashin et al., Phys.Lett. B 770C, 174 (2017)