Studies of the J/ψ, $\psi(2S)$ and $\psi(3770)$ at KEDR

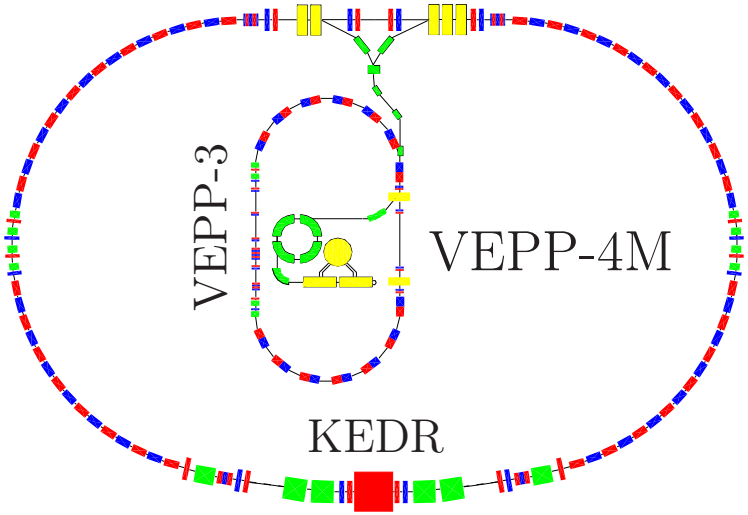
Simon Eidelman

Budker Institute of Nuclear Physics RAS
and Novosibirsk State University,
Novosibirsk, Russia

Outline

1. J/ψ and $\psi(2S)$ masses
2. $\Gamma_{ee}\mathcal{B}_h$, Γ_{ee}, Γ of $\psi(2S)$
3. Parameters of $\psi(3770)$
4. Search for narrow resonances
5. Conclusions

VEPP–4M collider

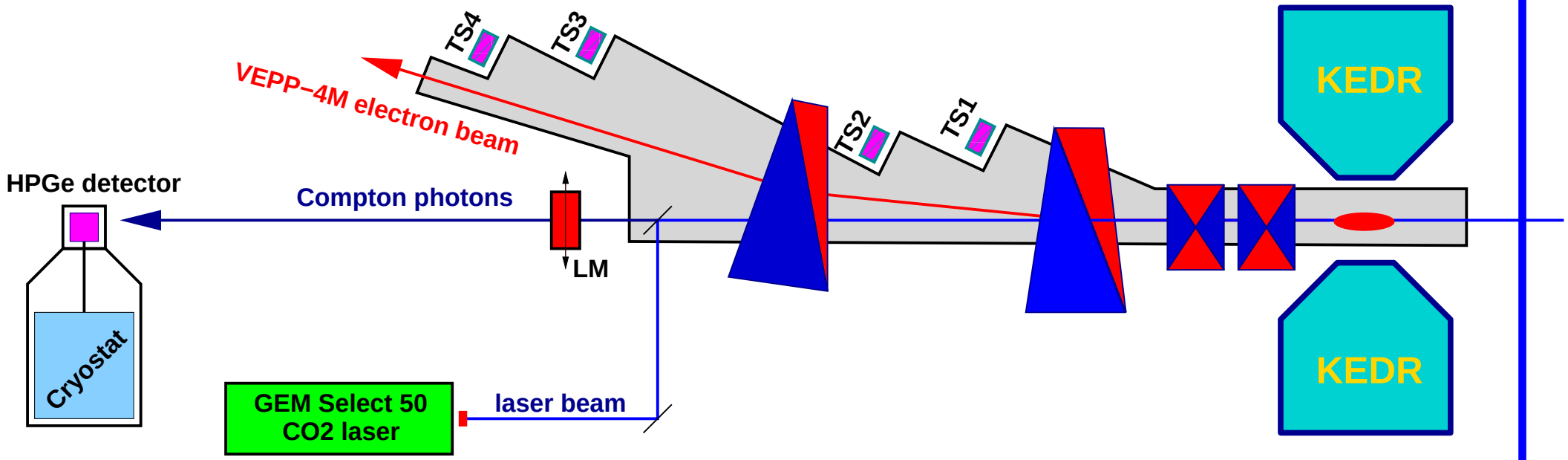


Circumference	366 m
Beam energy	$1 \div 6$ GeV
Number of bunches	2×2
Luminosity, $E = 1.5$ GeV	2×10^{30} cm^{-2}s^{-1}
Luminosity, $E = 5.0$ GeV	2×10^{31} cm^{-2}s^{-1}

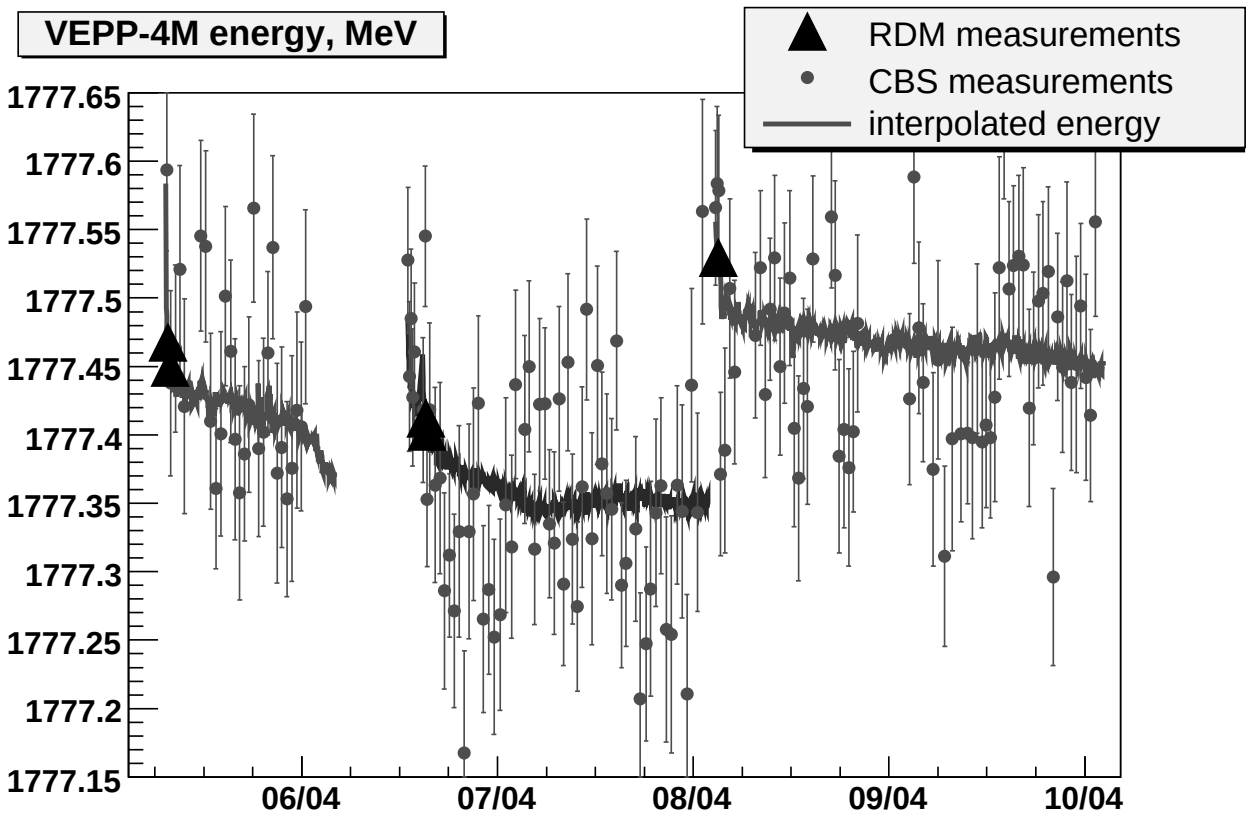
- Resonant depolarization technique:
  - Instantaneous measurement accuracy $\simeq 1 \times 10^{-6}$
  - Energy interpolation accuracy $(5 \div 15) \times 10^{-6}$ $(10 \div 30$ keV$)$
- Infrared light Compton backscattering:
  - Statistical accuracy $\simeq 5 \times 10^{-5}$ / 30 minutes
  - Systematic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

Compton Backscattering Monitor

Realized at BESSY-I in 1987

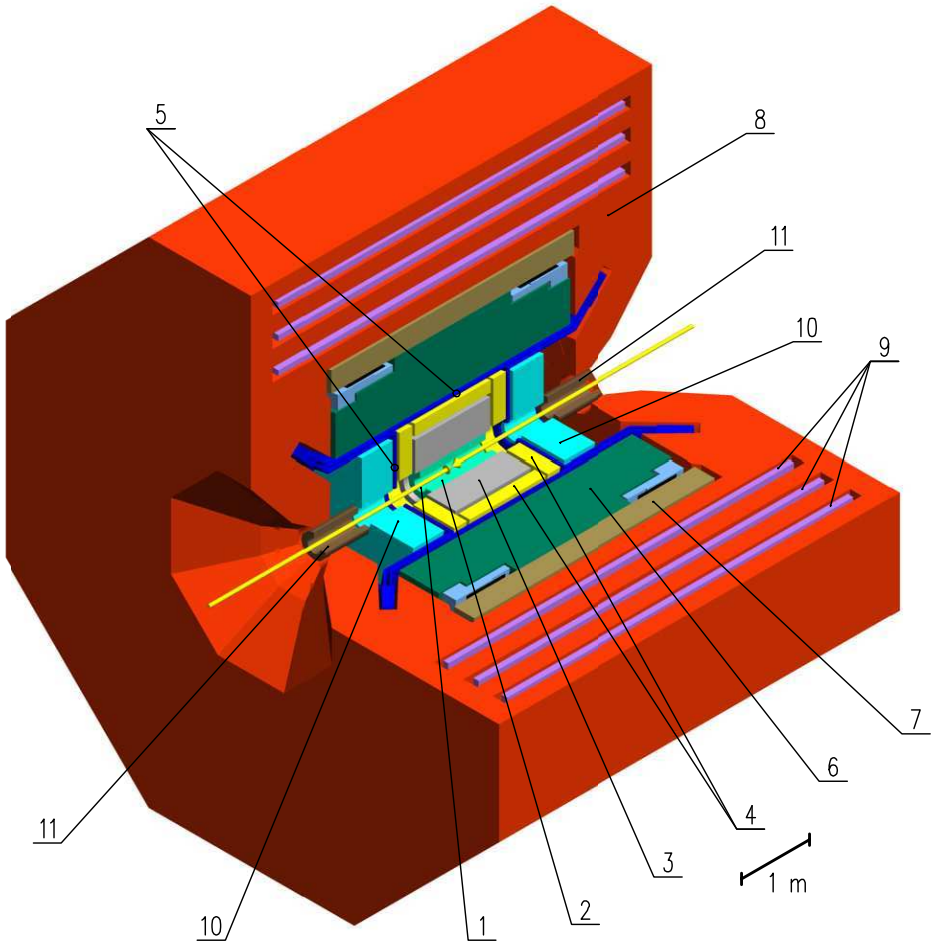


VEPP-4M Energy Behaviour



During the run, E measured by CBS and from interpolation

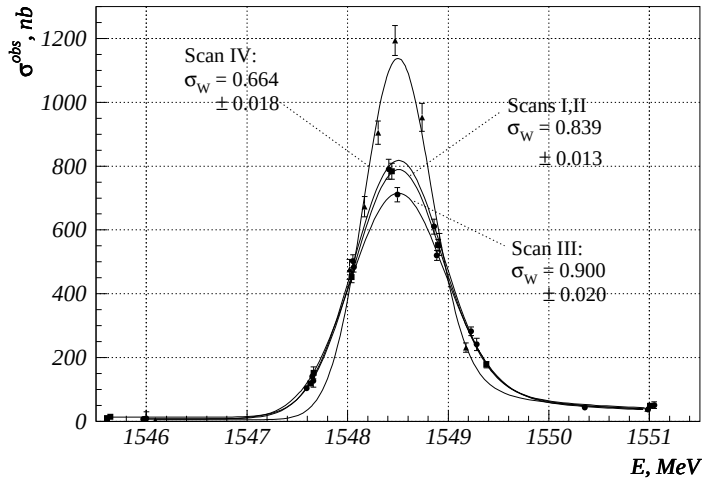
KEDR detector

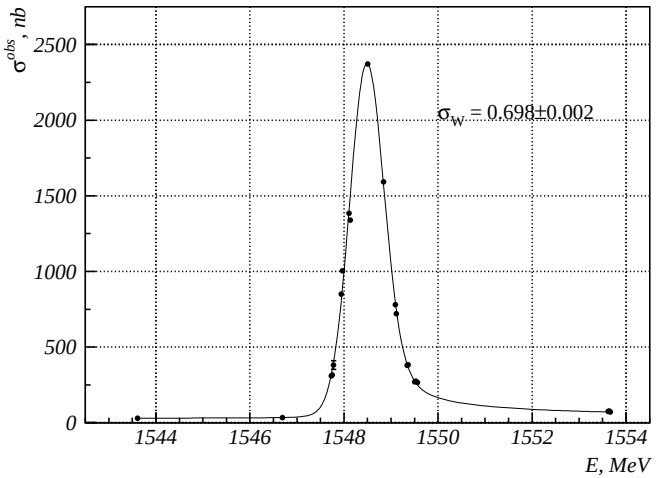


1. Vacuum chamber
2. Vertex detector
3. Drift chamber
4. Threshold aerogel counters
5. ToF counters
6. Liquid krypton calorimeter
7. Superconducting coil
8. Magnet yoke
9. Muon tubes
10. CsI calorimeter
11. Compensating s/c solenoid

J/ψ Mass Measurement

4 scans in 2002 and 1 scan in 2005





$$M_{J/\psi}^{2002} = (3096.924 \pm 0.010 \pm 0.008)\ \text{MeV}$$

$$M_{J/\psi}^{2005} = (3096.905 \pm 0.002 \pm 0.008)\ \text{MeV}$$

The combined result is $M_{J/\psi}^{KEDR} = 3096.911 \pm 0.004 \pm 0.009$ MeV
(differs by -6 keV from the value published in PL B573 (2003) 63)

Systematic uncertainties in the J/ψ mass (keV)

Uncertainty source	2002	2005	Common
Energy spread variation	3.4	1.0	1.0
Energy assignment	3.8	4.5	2.0
Beam misalignment in the I.P.	1.8	1.2	1.2
e^+-, e^--energy difference	<2.0	5.5	2.0
Symmetric dL/dE shape distortion	<1.3	<1.5	1.0
Asymmetric dL/dE shape distortion	2.7	2.2	2.2
Beam potential	1.0	1.5	1.0
Single energy calibration	0.7	1.5	0.7
Vertical orbit disturbances	0.6	0.9	0.6
Detection efficiency instability	2.3	2.3	1.2
Luminosity measurements	2.3	4.0	0.5
Interference in the hadronic channel	1.7	1.5	1.5
Sum in quadrature	≈ 6.0	≈ 7.9	≈ 4.7

$\psi(2S)$ Mass Measurement

3 scans in 2002, 2 scans in 2004 and 1 scan in 2006

Mass values to be averaged (in MeV):

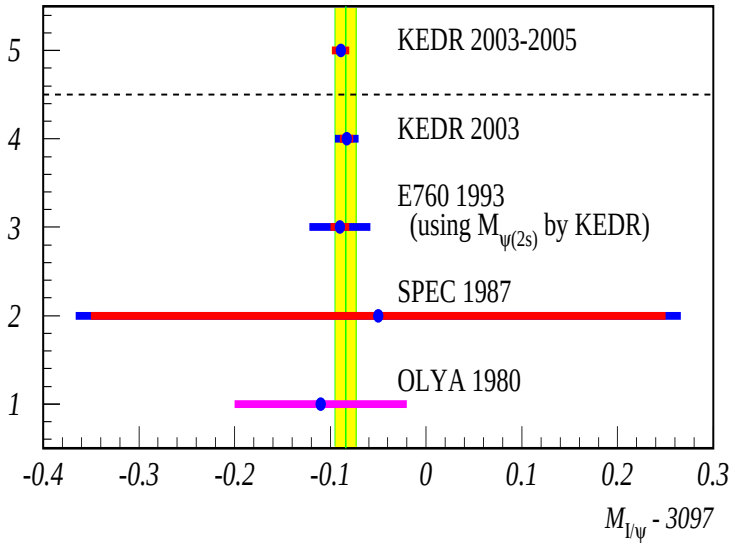
$$M^{2002}_{\psi(2S)} = 3686.094 \pm 0.025 \pm 0.013$$
$$M^{2004}_{\psi(2S)} = 3686.122 \pm 0.011 \pm 0.011$$
$$M^{2006}_{\psi(2S)} = 3686.110 \pm 0.010 \pm 0.012$$

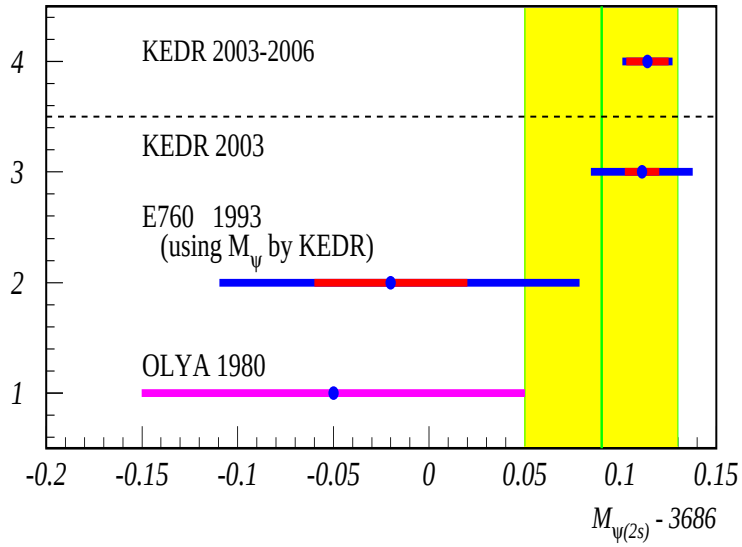
The combined result is $M^{KEDR}_{\psi(2S)} = 3686.114 \pm 0.007 \pm 0.011$ MeV
(differs by +3 keV from the value published in PL B573 (2003) 63)

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

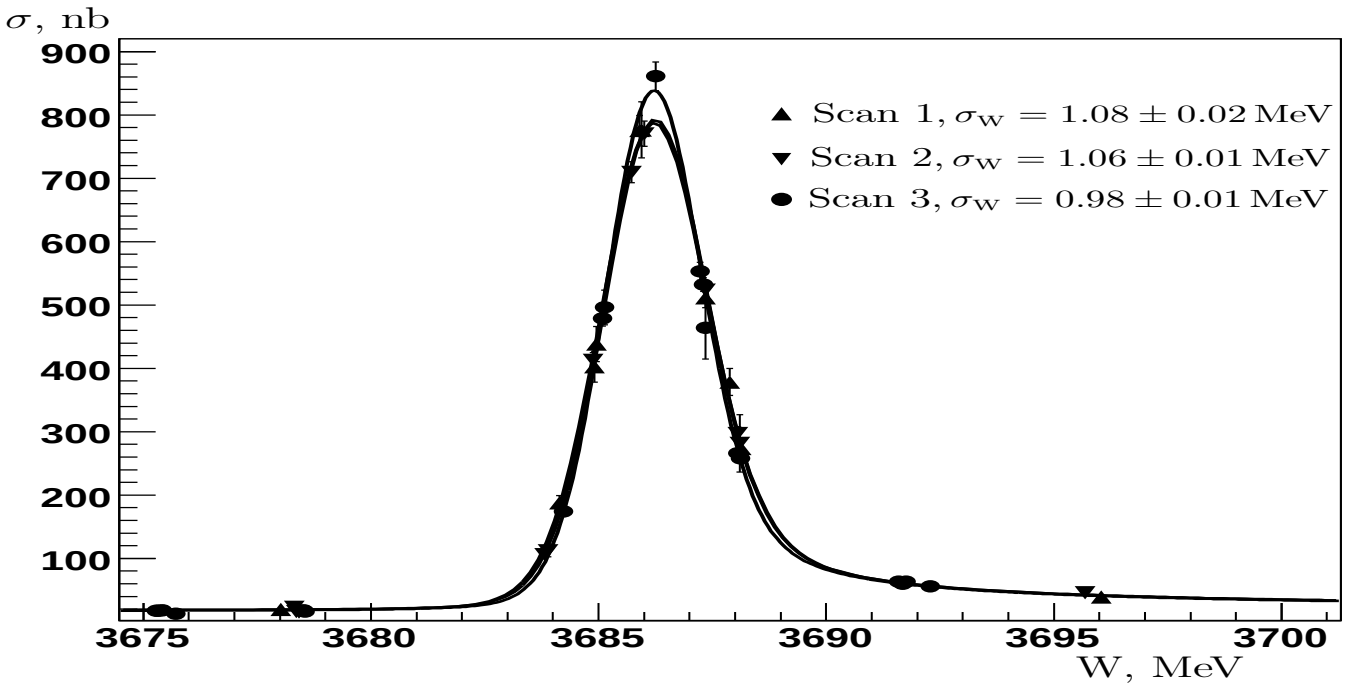
Error source	2002	2004	2006	Common
Energy spread variation	2.0	1.5	1.5	1.5
Energy assignment	4.3	4.0	6.0	4.0
Beam misalignment in the I.P.	5.1	4.0	4.0	4.0
e^+-, e^--energy difference	9.0	7.0	7.0	7.0
Symmetric dL/dE shape distortion	<2.0	<1.5	<1.5	<1.2
Asymmetric dL/dE shape distortion	3.5	4.2	4.2	3.5
Beam potential	1.0	1.5	1.5	1.0
Single energy calibration	0.8	0.6	0.6	0.6
Vertical orbit disturbances	0.5	0.6	0.6	0.6
Detection efficiency instability	2.0	2.0	1.0	1.0
Luminosity measurements	3.0	3.7	2.0	0.5
Interference in the hadronic channel	1.5	1.5	1.5	0.8
Sum in quadrature	≈ 12.8	≈ 11.2	≈ 11.6	≈ 10.1

J/ψ and $\psi(2S)$ Mass Measurement in PDG





Measurement of $\Gamma_{ee} \cdot \mathcal{B}(\psi(2S) \to hadrons)$ – I



V.V. Anashin et al., arXiv:1109.4215

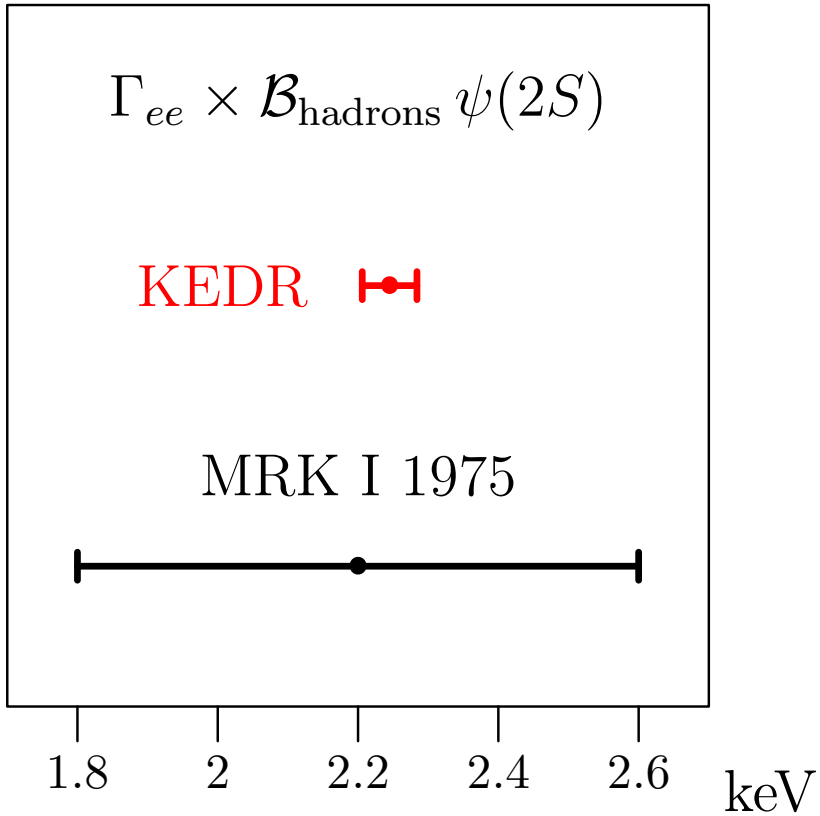
Measurement of $\Gamma_{ee} \cdot \mathcal{B}(\psi(2S) \to hadrons)$ – II

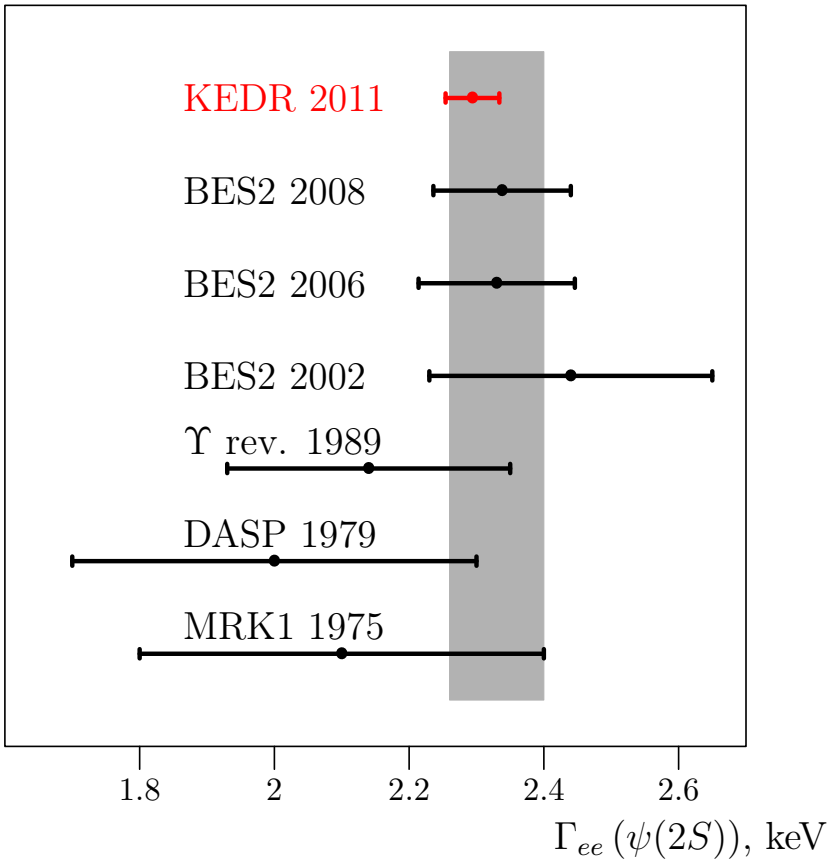
Source	Scan 1	Scan 2	Scan 3	Common 1-2	Common
Lumin.	1.6	1.7	1.2	1.6	0.5
MC gener.	1.0	1.0	1.1	1.0	1.0
Trigger	0.2	0.2	0.2	0.2	0.2
Selection	0.5	0.3	0.6	0.3	0.3
MC nucl.	0.2	0.2	0.3	0.2	0.2
Energy	0.15	0.18	0.60	0.15	0.15
Fit	0.3	0.3	0.3	0.3	0.3
Total	2.0	2.1	1.9	2.0	1.2

Measurement of $\Gamma_{ee} \cdot \mathcal{B}(\psi(2S) \to hadrons)$ – III

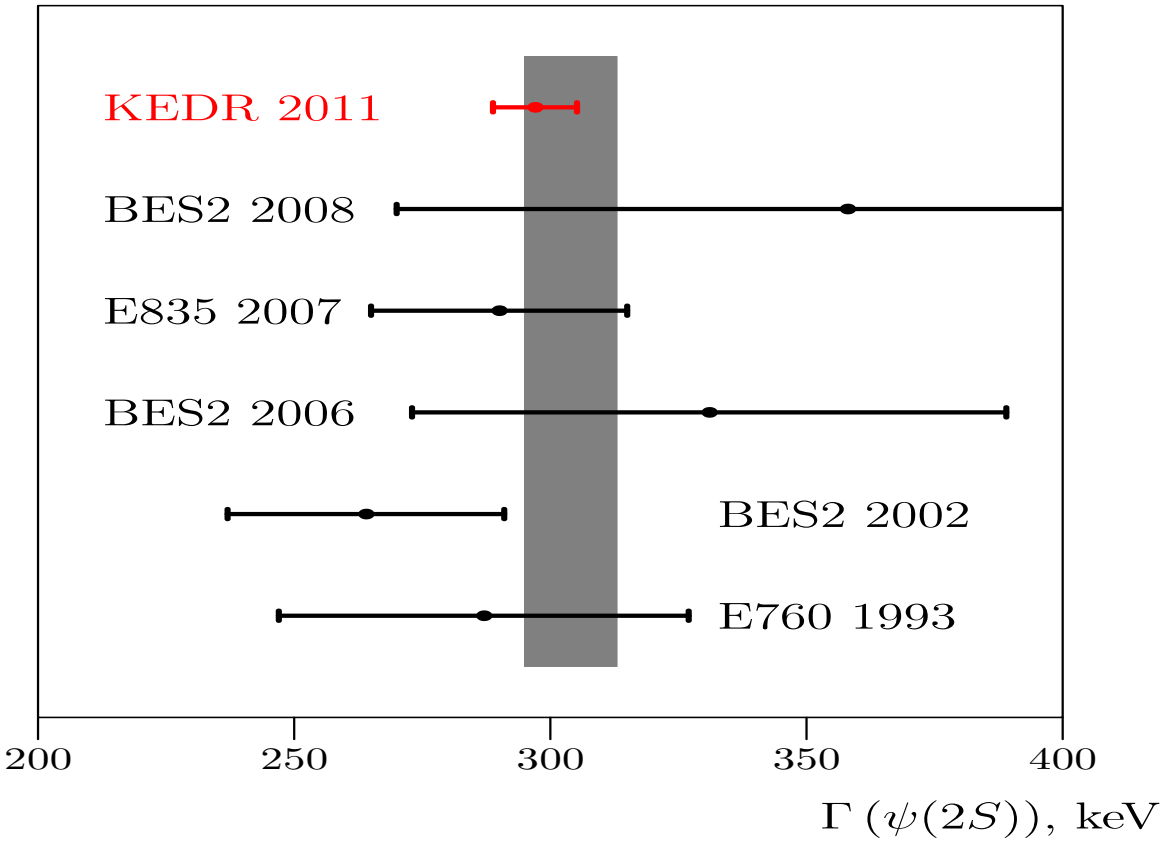
- $\Gamma_{e^+e^-} \cdot \mathcal{B}(\psi(2S) \to h) = (2.233 \pm 0.015 \pm 0.036)$ keV,
  much more precise than the only previous direct measurement
- Using the world-average value of $\mathcal{B}_h$
  $\Gamma_{e^+e^-} = (2.282 \pm 0.015 \pm 0.037)$ keV,
  more than 2 times better than the best previous one.
- Using the world-average values of $\Gamma_{e^+e^-}$ and $\mathcal{B}_h$
  $\Gamma = (296 \pm 2 \pm 8)$ keV,
  again more than 2 times better than the best previous one.

Measurement of $\Gamma_{ee} \cdot \mathcal{B}(\psi(2S) \to hadrons)$ – IV





Measurement of $\Gamma_{ee} \cdot \mathcal{B}(\psi(2S) \to hadrons)$ – V



Cross section of $e^+e^- \to \psi(3770) \to D\bar{D}$ – I

$$\sigma^{\rm obs}_{mh} = \epsilon_{\psi(2S)}\,\sigma^{RC}_{\psi(2S)} + \epsilon_{D^+D^-}\,\sigma^{RC}_{D^+D^-} + \epsilon_{D^0\bar{D}^0}\,\sigma^{RC}_{D^0\bar{D}^0} + \epsilon_{\tau\tau}\,\sigma^{RC}_{\tau\tau} + \sigma^{obs}_{1/s} + \sigma^{obs}_{D\bar{D}\pi} + \epsilon_{c\bar{c}\to LH}\,\sigma^{RC}_{c\bar{c}\to LH}. \quad (1)$$

$$\sigma^{RC}_{D\bar{D}}(W) = \int z_{D\bar{D}}\left(W'\sqrt{1-x}\right)\,\sigma_{D\bar{D}}\left(W'\sqrt{1-x}\right) \times \mathcal{F}(x, W'^2)\,G(W, W')\,dW'dx, \quad (2)$$

$$z_{D^+D^-} = \frac{\pi\alpha/\beta_{D^+}}{1-\exp\left(-\pi\alpha/\beta_{D^+}\right)} \times \theta(W - 2m_{D^+}). \quad (3)$$

Cross section of $e^+e^- \to \psi(3770) \to D\bar{D}$ – II

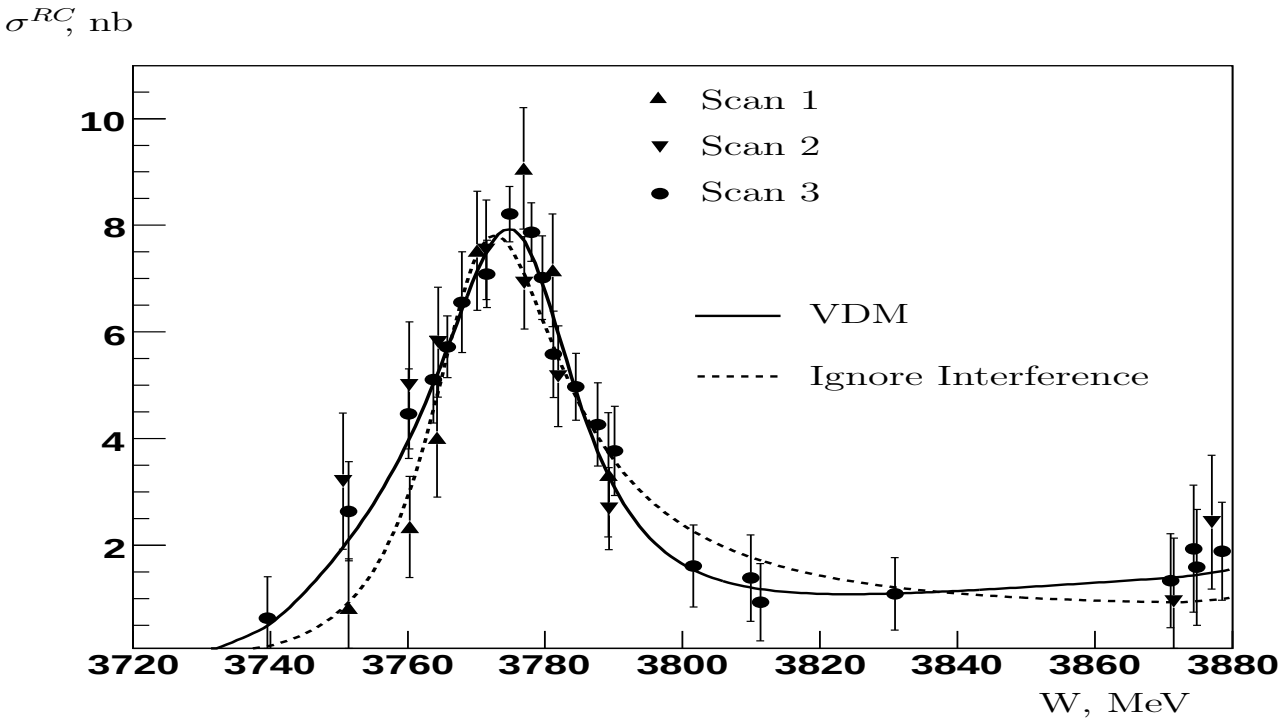
$$\sigma_{D\bar{D}}(W) = \frac{\pi\alpha^2}{3W^2}\,\beta_D^3\,|F_D(W)|^2\,, \quad \beta_D = \sqrt{1-4m_D^2/W^2} \tag{4}$$

Resonance amplitudes above the $D\bar{D}$ threshold should be separated in F_D:

$$F_D(W) = \sum_i F_D^{R_i}(W)\,e^{i\phi_i} + F_D^{NR}(W), \tag{5}$$

We assume the $\psi(2S)$ dominance:
$F_D^{NR}(W) = F_D^{\psi(2S)}(W) + c$
and check the model dependence with some empirical form factors

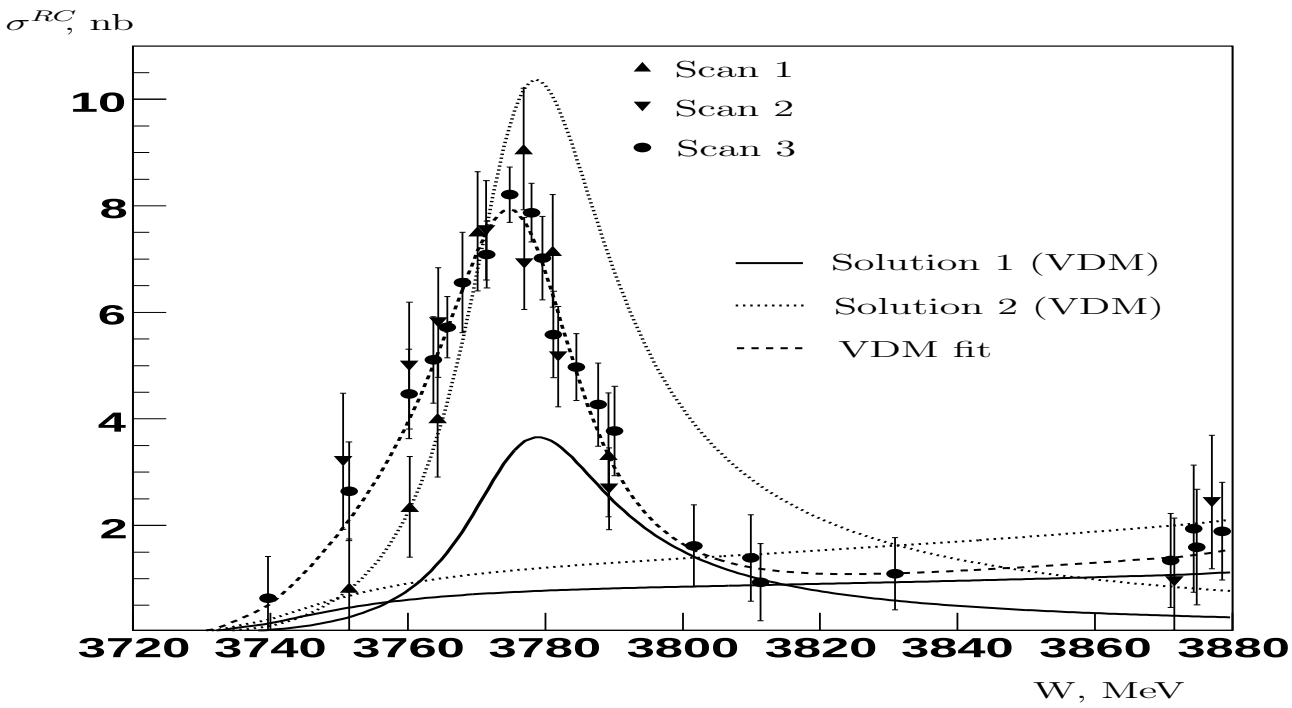
Determination of $\psi(3770)$ Parameters – I



Note that the energy spread affects the shape!

V.V. Anashin et al., arXiv:1109.4205

Determination of $\psi(3770)$ Parameters – II



Two different resonant and non-resonant parts add to the same curve because of two solutions corresponding to different interference phases!

2 solutions (fit for the $\psi(2S)$ dominance)

Solution	Mass, MeV	Γ, MeV	Γ_{ee}, eV
1	$3779.28^{+1.79}_{-1.69}$	$25.3^{+4.6}_{-4.1}$	147^{+97}_{-62}
2	$3778.97^{+1.82}_{-1.72}$	$25.0^{+4.4}_{-3.8}$	415^{+59}_{-58}
i.i.	3773.3 ± 0.5	$23.4^{+2.5}_{-2.2}$	250^{+25}_{-23}

Solution	φ, deg	$\Gamma^{\psi(2S)}_{D\bar{D}}$	$P(\chi^2)$, %
1	198.7 ± 42.4	$14.3^{+21.0}_{-14.0}$	35.4
2	257.4 ± 17.2	$20.1^{+11.3}_{-10.7}$	35.9

The ambiguity is principal!

Determination of $\psi(3770)$ Parameters – III

Source	Mass, MeV	Width, MeV	Γ_{ee}, %
$\mathcal{B}_{nD\bar{D}}$	0.3	0.1	8.0
R_0 variation	0.3	0.3	2.0
$\Gamma_{D^0\bar{D}^0}/\Gamma_{D^+\bar{D}^-}$	0.1	0.1	0.4
$D, \bar{D}$ mass	0.06	0.04	0.3
$\sigma_{D\bar{D}\pi}$	0.15	0.05	1.
Fit	0.05	0.1	0.5
Event selection	0.3	0.3	3.
Luminosity	0.1	0.1	2.
Energy assignment	0.03	–	–
Total	0.6	0.5	9.1

Final results for $\psi(3770)$

Under the assumption of the $\psi(2S)$ dominance
and averaging over 2 solutions

KEDR: $M = (3779.1^{+1.8}_{-1.7} \pm 0.6^{+0.2}_{-0.3})$ MeV, $\Gamma = (25.2^{+4.6}_{-4.1} \pm 0.5^{+0.5}_{-0.2})$ MeV

PDG: $M = (3772.92 \pm 0.35)$ MeV, $\Gamma = (27.3 \pm 1.0)$ MeV

For the leptonic width we can't choose between 2 solutions:

KEDR (1): $\Gamma_{ee} = 147^{+97}_{-62} \pm 13^{+11}_{-10}$ eV,

KEDR (2): $\Gamma_{ee} = 415^{+59}_{-58} \pm 38^{+160}_{-10}$ eV,

PDG: $\Gamma_{ee} = 265 \pm 18$ eV

Most of the potential models support the first solution,
but barely tolerate the second one!

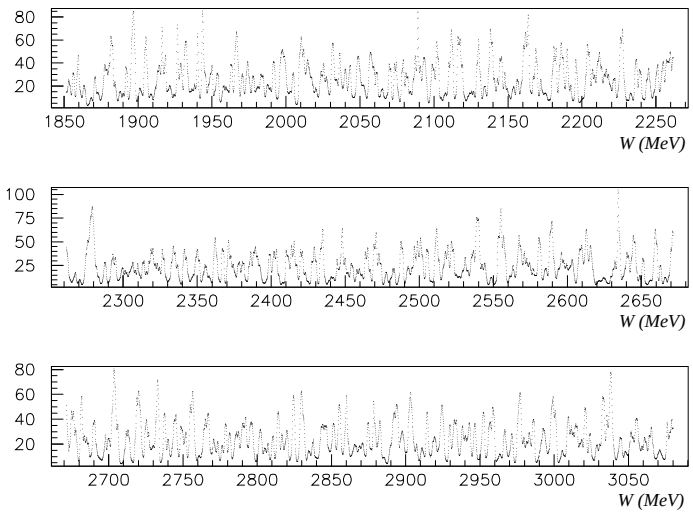
Determination of $\psi(3770)$ Parameters – IV

A few general conclusions:

- Mass is higher than in previous measurements, but agrees with BaBar that also took into account interference
- Width is in reasonable agreement with previous measurements
- With our data sample we do not observe any shape anomaly
- Absolutely mandatory to take into account interference:
- There are usually two solutions with the same mass, width and likelihood, but strongly differing (a factor of up to 3) leptonic width
- While the current world-average value is $\Gamma_{e^+e^-} = 265 \pm 18$ eV, with interference effects included it can vary in the (100-500) eV range $\Rightarrow$ direct averaging of results in different groups is impossible

Search for Narrow Resonances – I

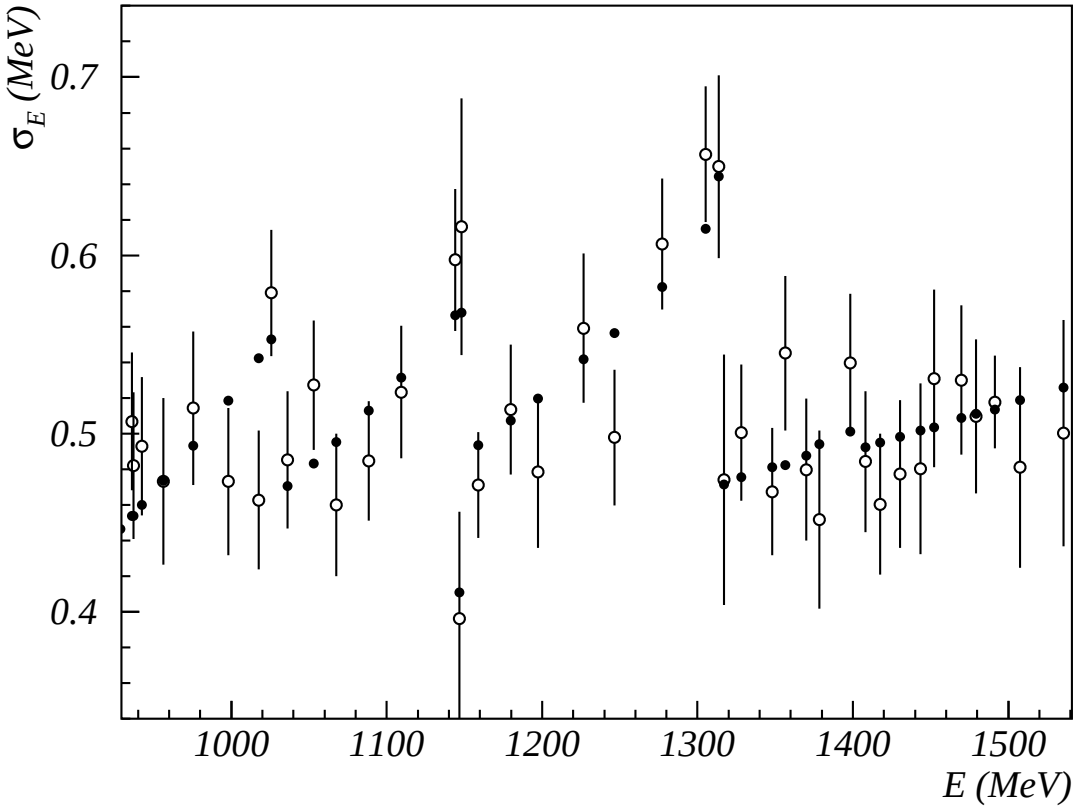
KEDR scanned the c.m.energy range from 1.85 to 3.1 GeV searching for narrow resonances



V.V. Anashin et al., Phys. Lett. B703, 543 (2011)

Search for Narrow Resonances – II

$\int \mathcal{L}dt \approx 300$ nb^{-1} was collected
in a scan with a step $\approx$ $2\sigma_W$ (1.4-1.9 MeV)



Search for Narrow Resonances – III

- The model: a resonance with M_R, Γ_{ee}^R on top of a flat BG
- The fits use the range $M_R \pm 13$ MeV
- M_R is varied in 0.1 MeV steps
- A systematic error of $\sim 50\%$ conservatively
- $\Gamma_{ee}^R \cdot \mathcal{B}(R \to hadrons) < 120$ eV,
  4-5 times more stringent than at ADONE in 1975-1978:
  $\gamma\gamma 2$, $B\bar{B}$ and BOSON groups scanned 1.42-3.1 GeV
- KEDR hopes to measure R in this W range to 5%

Conclusions

- Masses of J/ψ and $\psi(2S)$ measured. The accuracy reaches $(3-5)\cdot 10^{-6}$ setting an important mass calibration scale ($D^{\pm}$, D^0, D_s)
- New precise value of $\Gamma_{e^+e^-}\cdot\mathcal{B}(\psi(2S))$ significantly improves the values of both leptonic and total width for $\psi(2S)$
- Interference effects are important for M and Γ of $\psi(3770)$
- Multiple solutions make difficult $\Gamma_{e^+e^-}$ determination for $\psi(3770)$
- No narrow states found between 1.85 GeV and J/ψ
- New R measurements are planned between 2 and 11 GeV