High-precision mass measurements of charmonium states and $\tau$ lepton

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Resonant depolarization technique:
- Instant measurement accuracy $\approx 1 \times 10^{-6}$
- Energy interpolation accuracy $(5 \div 15) \times 10^{-6}$ (10 $\div$ 30 keV)

Infra-red light Compton backscattering (2005):
- Statistical accuracy $\approx 5 \times 10^{-5}$ / 30 minutes
- Systematic uncertainty $\approx 3 \times 10^{-5}$ (50 $\div$ 70 keV)
Resonant Depolarization Method

\[ \Omega_{\text{spin}} / \omega_{\text{rev}} = 1 + \gamma \cdot \mu' / \mu_0 \]

Touschek (intra-beam scattered) electron pairs are detected with 2×2 scintillation counters (s.c.)

\[ \Omega_{\text{spin}} \pm \Omega_{\text{dep}} = n \cdot \omega_{\text{rev}} \]

Scattering rates from unpolarized ↑↓ and polarized ↑↑ beams are compared

\[ \Delta = \frac{f_{\text{pol}} - f_{\text{unpol}}}{f_{\text{pol}}} \]
Energy monitoring using IR-light Compton backscattering


- CO₂ laser (CW 30W)
- 150ml HPGe detector
- gamma ray beam
- 4x4mm lead collimator
- Cryostat
- electron beam
- inside VEPP-4M vacuum chamber

\[ \omega'_{\text{max}} = \frac{E^2}{E + m^2/4\omega_{\text{laser}}} \]

- CO₂ – laser (\(\lambda = 10.591 \, \mu\text{m}, \omega_{\text{laser}} = 0.12 \, \text{eV}, \omega'_{\text{max}} \approx 6 \, \text{MeV}\)
Compton backscattering spectrum

- **Whole spectrum**
  - Entries: 4020671
  - $\chi^2$/ndf: 47.034 / 27
  - Prob: 0.010
  - $p_0$: 2712.005 ± 46.254
  - $p_1$: 1303.668 ± 0.075
  - $p_2$: 2.847 ± 0.047
  - $p_3$: -0.063 ± 0.024
  - $p_4$: 1177.243 ± 6.871
  - $p_5$: -0.248 ± 0.316

- **Edge spectrum**
  - Entries: 4020671
  - $\chi^2$/ndf: 203.765 / 194
  - Prob: 0.301
  - $p_0$: 11117.704 ± 83.19
  - $p_1$: 9.180 ± 0.781
  - $p_2$: -0.017 ± 0.030
  - $p_3$: 114.283 ± 3.171
  - $p_4$: -0.014 ± 0.005
  - $p_5$: 11.490 ± 0.725

- **Average stat. error:** 70.1 keV

- **Final CBS calibration with resonant depolarization**
  - Energy determination accuracy: $50 \div 100$ keV (stat), 60 keV (syst)
  - Energy spread determination accuracy $\simeq 7\%$ (syst)

- Unlike BESSY-II, only standard isotopes are used for the detector calibration
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. Compensation solenoid
12. VEPP–4M quadrupole
$J/\psi$ mass measurement

$J/\psi$ MASS

<table>
<thead>
<tr>
<th>VALUE (MeV)</th>
<th>EVTS</th>
</tr>
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<tr>
<td>3096.916±0.011</td>
<td>OUR AVERAGE</td>
</tr>
<tr>
<td>3096.917±0.010±0.007</td>
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<td>3096.89 ± 0.09</td>
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<tr>
<td>3096.91 ± 0.03 ± 0.01</td>
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<td>3096.95 ± 0.1 ± 0.3</td>
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<table>
<thead>
<tr>
<th>DOCUMENT ID</th>
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<td>KEDR</td>
<td>$e^+ e^- \rightarrow$ hadrons</td>
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<td>ARTAMONOV 00</td>
<td>OLYA</td>
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<tr>
<td>ARMSTRONG 93B</td>
<td>E760</td>
<td>$\bar{p} p \rightarrow e^+ e^-$</td>
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<td>BAGLIN 87</td>
<td>SPEC</td>
<td>$\bar{p} p \rightarrow e^+ e^- \chi$</td>
</tr>
</tbody>
</table>

New result (preliminary):

$$M_{J/\psi}^{2005} - M_{J/\psi}^{2002} = 7 \pm 10 \pm 17 \text{ keV}$$
ψ(2S) mass measurement

ψ(2S) MASS

<table>
<thead>
<tr>
<th>VALUE (MeV)</th>
<th>EVTS</th>
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<th>COMMENT</th>
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<tr>
<td>3686.09 ± 0.04 OUR FIT</td>
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<td>Error includes scale factor of 1.6.</td>
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<tr>
<td>3686.093 ± 0.034 OUR AVERAGE</td>
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<td>3686.111 ± 0.025 ± 0.009</td>
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<td>413</td>
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<td>3685.95 ± 0.10</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3685.98 ± 0.09 ± 0.04</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

New results (preliminary):

\[ M_{\psi(2S)}^{2004} - M_{\psi(2S)}^{2002} = 6 \pm 12 \pm 15 \text{ keV} \]

\[ M_{\psi(2S)}^{2006} - M_{\psi(2S)}^{2002} = 14 \pm 10 \pm 15 \text{ keV} \]
$\psi(3770)$ mass measurement

$$M_{\psi(3770)} = 3772.9 \pm 0.6 \pm 0.8 \text{ MeV}$$ (preliminary)

$$\int \mathcal{L} \, dt \simeq 2.4 \text{ pb}^{-1} \text{ in two scans}$$

Dominant systematic error: detector instabilities.
For compatibility, the resonance fitting form is same to that used in MARKI, MARK2, DELCO, BES(2005) experiments.
τ mass measurement

- Metrological issue
- Lepton universality test

τ mass measurements methods

- Pseudomass technique
- Measurement of the threshold behavior of the cross section
  DELCO(1978), BES(1996)

PDG-2006

\[ M_\tau = 1776.99^{+0.29}_{-0.26} \text{ MeV} \]

dominated by BES(1996)
General experimental scenario

Narrow region \( |E_{\text{beam}} - m_\tau| \sim \sigma_E \)
is most sensitive to the mass value
\[ \downarrow \]
High requirements on \( E_{\text{beam}}, \sigma_E \)
accuracy and stability

- Luminosity distribution:
  - \( \approx 10\% \) below the threshold (background)
  - \( \approx 60\% \pm 0.5 \) MeV around the threshold (mass)
  - \( \approx 30\% \) well above the threshold (detection efficiency)

- Threshold search: \( E_{\text{beam}} = m_\tau - 0.5, \ m_\tau, \ m_\tau + 0.5, \ m_\tau + 1 \) or \( m_\tau - 1 \) MeV
Energy spread determination

- Compton backscattering accuracy on $\sigma_E$ seems insufficient
- VEPP-4M settings related to $\sigma_E$
  - optimized for $m_\tau$ measurements
  - kept unchanged since 2004

2004-2006: 3 scan of $\psi(2S)$

$$\sigma_W = 1.08 \pm 0.02 \pm 0.02 \text{ MeV}$$

2005: scan of $J/\psi$, $\int Ldt = 230 \text{ nb}^{-1}$

$$\sigma_W = 0.70 \pm 0.01 \text{ MeV}$$

9% deviation from the expected dependence $\sigma_W(E) \propto E^2$
  - the same in $J/\psi$, $\psi(2S)$–mass experiment (2002)

**assuming linear growth of the deviation with $E - M_{\psi(2S)}/2$:**

$$\sigma_W(m_\tau) = 1.00 \pm 0.02 \pm 0.03 \text{ MeV}$$
**Tau event selection**

- Event selection: 2–prong events, $|\cos \phi| < 0.93$, 0÷3 photons

$$e^+ e^- \rightarrow (\tau \rightarrow e\nu_\tau \bar{\nu}_e), (\tau \rightarrow e\nu_\tau \bar{\nu}_e, \mu\nu_\tau \bar{\nu}_\mu, \pi\nu_\tau, K\nu_\tau, \rho\nu_\tau)^* + c.c$$

- $\mu/\pi/K$ identification is not used, no extra photons with $E_\gamma > 30$ MeV

$E < 2200$ MeV, $p_T > 200$, $p_T/(W-E) > 0.06$

- Detection efficiency $\varepsilon \approx 0.025$, 10% reduction for $W = 2M_\tau \rightarrow M_\psi(3770)$

- No distortion of the residual background $W$ dependence due to cuts
Published result on partial statistics

- 6.7 pb\(^{-1}\), 11 events at the threshold

4-parameter data fit:

\[ \varepsilon = 2.25 \pm 0.28, \quad \sigma_B = 0^{+0.58}_{-0.25} \text{ pb}, \quad \Gamma_{ee} \cdot B_{\psi(2S) \to \tau \tau} = 8.0 \pm 2.2 \text{ eV} \]

\[ M_{\tau}^{KEDR} = 1776.81^{+0.25}_{-0.23} \pm 0.15 \text{ MeV} \]

\[ M_{\tau}^{KEDR} - M_{\tau}^{PDG} = -0.18^{+0.25}_{-0.23} \pm 0.15 (\pm 0.29 \text{ PDG}) \text{ MeV} \]
Preliminary result on full statistics

- 14.3 pb\(^{-1}\), 26 events at the threshold
- 5-parameter data fit: the detection efficiency for two scans,
  \( \varepsilon = 2.07 \pm 0.25 \% \), \( \varepsilon' = 1.49 \pm 0.25 \% \), \( \sigma_B = 0^{+0.32} \text{ pb} \)

\[ M^{KEDR}_{\tau} = 1776.69^{+0.17}_{-0.19} \pm 0.15 \text{ MeV (preliminary)} \]
## Systematic uncertainties

**Conservative estimates**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Beam energy determination</td>
<td>35 keV</td>
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<tr>
<td>Detection efficiency variations</td>
<td>120 keV</td>
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<tr>
<td>Energy spread determination accuracy</td>
<td>20 keV</td>
</tr>
<tr>
<td>Background dependence on the beam energy</td>
<td>20 keV</td>
</tr>
<tr>
<td>Luminosity measurement instability</td>
<td>80 keV</td>
</tr>
<tr>
<td>Beam energy spread variation</td>
<td>10 keV</td>
</tr>
<tr>
<td>Cross section calculation (r.c., $\psi(2S)$ interference)</td>
<td>30 keV</td>
</tr>
<tr>
<td><strong>Sum in quadrature</strong></td>
<td><strong>150 keV</strong></td>
</tr>
</tbody>
</table>

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High-precision mass measurements of charmonium states and $\tau$ lepton
Summary of $\tau$-mass results

Total (black) and systematic (yellow) errors are shown.

The result DELCO 1978 $M_\tau = 1783^{+3}_{-4}$ MeV is not drawn.
New KEDR results (preliminary):

- $M_{\psi(2S)} = 3686.122 \pm 0.008 \pm 0.012$ MeV
  Data analysis in progress, systematic errors can be reduced.

- $M_{\psi(3770)} = 3772.9 \pm 0.6 \pm 0.8$ MeV
  Systematic errors analysis in progress.

- $M_\tau = 1776.69^{-0.19}_{+0.17} \pm 0.15$ MeV
  We plan to achieve the accuracy of $0.15 \div 0.18$ MeV on completion of the data analysis
Resonant Depolarization Method

- Radiative polarization of electron beams (Sokolov–Ternov, 1964)

\[
\frac{1}{\tau_{pol}} \approx \frac{5\sqrt{3}}{8} \cdot \frac{\lambda_e r_e c}{R^3} \gamma^5
\]

- Spin precession around the guiding field with the frequency of

\[
\Omega_S = \omega_0 \left( 1 + \gamma \frac{\mu'}{\mu_0} \right)
\]

\(\omega_0\) – beam revolution frequency

\(\mu_0, \mu'\) – normal and anomalous parts of the electron magnetic moment

- Beam polarization can be destroyed by an external EM-field of the frequency \(\Omega_{dep}\) satisfying the resonant condition

\[
\Omega_S \pm \Omega_{dep} = \omega_0 n
\]

- \(\Omega_S\) is measured in the moment of the polarization destruction during the depolarizer frequency scan
Typical energy calibration run:

Complete procedure takes $\sim 2$ hours at the $\tau$ threshold

Energy measurement accuracy $2 \div 20$ keV depending on $d\Omega_{dep}/dt$

VEPP-4M polarization life time $\sim 25$ mins at $E = 1777$ MeV

No polarization at VEPP-3 at $E = 1700 \div 1830$ MeV

Special machine operation scenario at the $\tau$ threshold
Example of VEPP-4M energy behavior

- April 2006:

- Energy drop of about 0.1 MeV in 1.5 hours after the magnetization cycle (no data taking at that time, resonant depolarization delay of 1 hour)
\[
(\Delta m/m) \cdot 10^6 \text{ (PDG avg.)}
\]

<table>
<thead>
<tr>
<th>particle</th>
<th>(\frac{\Delta m}{m} \cdot 10^6) (PDG avg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p)</td>
<td>0.1</td>
</tr>
<tr>
<td>(n)</td>
<td>0.1</td>
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<tr>
<td>(e)</td>
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<tr>
<td>(\mu)</td>
<td>0.1</td>
</tr>
<tr>
<td>(\pi^\pm)</td>
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<tr>
<td>(J/\psi)</td>
<td>3.5</td>
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<tr>
<td>(\pi^0)</td>
<td>4.5</td>
</tr>
<tr>
<td>(\psi(2S))</td>
<td>9.2</td>
</tr>
</tbody>
</table>
VEPP-4M operation scenario

- Data taking cycle at given energy point (≈ 24 hours):

  - Magnetization cycle $E_{\text{set}} = \text{current-500-2500-1855 MeV}$
  - Injection of polarized beam
  - Resonant depolarization
  - High-rate CBS energy measurement
  - Low-rate CBS energy measurement

  In 2004-2005 only high-rate CBS measurements were used, incompatible with data taking.

  - RDM-energy is interpolated between calibrations using machine field and temperature measurements with $\approx 30$ keV accuracy
### Systematic errors of the meson masses (keV)

<table>
<thead>
<tr>
<th>Error source</th>
<th>$J/\psi$</th>
<th>$\psi(2S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy spread variation</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Energy assignment: statistical uncertainty</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>prediction function choice</td>
<td>2.7</td>
<td>1.7</td>
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<tr>
<td>radial betatron oscillations</td>
<td>$&lt;1.5$</td>
<td>$&lt;1.8$</td>
</tr>
<tr>
<td>beam separation in additional I.P.</td>
<td>0.4*</td>
<td>0.4*</td>
</tr>
<tr>
<td>Beam misalignment in the interaction point</td>
<td>1.8</td>
<td>5.1</td>
</tr>
<tr>
<td>$e^+, e^-$-energy difference</td>
<td>$&lt;2.0$</td>
<td>$&lt;2.0$</td>
</tr>
<tr>
<td>Non-gaussian collision energy distribution</td>
<td>$&lt;1.5$</td>
<td>$&lt;2.0$</td>
</tr>
<tr>
<td>$\beta$-function chromaticity</td>
<td>2.0*</td>
<td>2.5*</td>
</tr>
<tr>
<td>Beam potential</td>
<td>1.0*</td>
<td>1.0*</td>
</tr>
<tr>
<td>Single energy calibration</td>
<td>0.6*</td>
<td>0.8*</td>
</tr>
<tr>
<td>Detection efficiency instability</td>
<td>2.3</td>
<td>2.0</td>
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<tr>
<td>Luminosity measurements</td>
<td>2.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Interference in the hadronic channel</td>
<td>1.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Residual machine background</td>
<td>$&lt;1.0$</td>
<td>$&lt;1.0$</td>
</tr>
</tbody>
</table>

**Sum in quadrature**

$\approx 7.3 \quad \approx 8.9$

* — correction uncertainty
Extraction of $\psi(3770)$ characteristics

$$
\sigma(W) = \frac{3\pi}{M^2} \int dW' \ dx \frac{\Gamma_{ee}\Gamma_h}{(W'(1-x)-M)^2+\Gamma(W')^2/4} \mathcal{F}(x, W')
$$

$$
\Gamma(W) = \Gamma \frac{(R_0*p_{Dn}(W))^3}{1+(R_0*p_{Dn}(W))^2} + \frac{(R_0*p_{Dc}(W))^3}{1+(R_0*p_{Dc}(W))^2}
$$

$$
\frac{(R_0*p_{Dn}(M))^3}{1+(R_0*p_{Dn}(M))^2} + \frac{(R_0*p_{Dc}(M))^3}{1+(R_0*p_{Dc}(M))^2}
$$

$\mathcal{F}(x, W)$ – radiative correction


Fit parameters:

- visible background cross section
- efficiency for given $\Gamma_{ee}(3770)$
- $\psi(3770)$ mass
- $\Gamma$ total width
- $\sigma_W$ at $\psi(2S)$
- $\psi(2S)$ mass
- efficiency for given $\Gamma_{ee}(2S)$
- cross section $D\bar{D}$ nonresonant
- $R_0$ – interaction radius
Non-resonant $D\bar{D}$ cross section

\[
\sigma_{\text{cont}} = (\sigma^0 + \sigma^\pm)
\]

\[
\sigma^0,\pm_{\text{cont}} = \sigma_{D\bar{D}} \cdot \beta^3_{0,\pm} \cdot \left(\frac{2 \cdot M_{D^0,\pm}}{W}\right)^2
\]