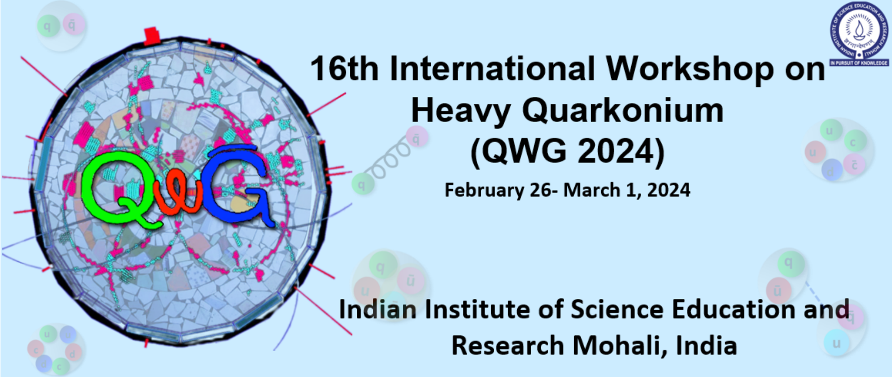
Masses of D–mesons and narrow Υ states

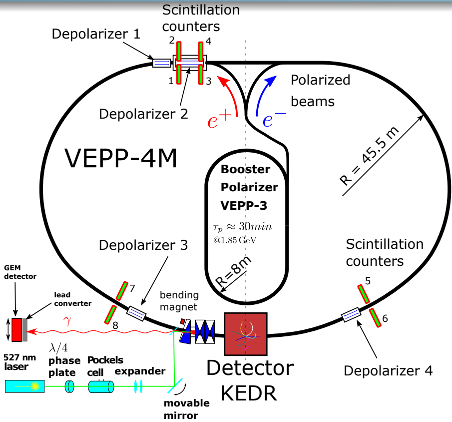
A.G. Shamov, MD-1@VEPP-4 – KEDR@VEPP-4M
Budker Institute of Nuclear Physics, Novosibirsk, Russia



Outline: masses of D-meson and narrow Υ states

1. Measurement of D-mesons mass at KEDR/VEPP-4M
   - VEPP-4M collider and KEDR detector
   - Current status of D masses
   - Data set and analysis method
   - D^0– and $D^{\pm}$–mass results
2. Revision of results on Υ(1S)–Υ(3S) masses
   - Reasons of revision
   - Analysis of published data Mackay *et al.* [CUSB@CESR]
   - Correction to radiative corrections
   - Refining of electron mass value
   - Resonance-continuum interference
   - $\Upsilon(1S)$ mass, MD-1@VEPP-4 vs CUSB@CESR
   - Summary on masses
3. Backup

VEPP–4M collider



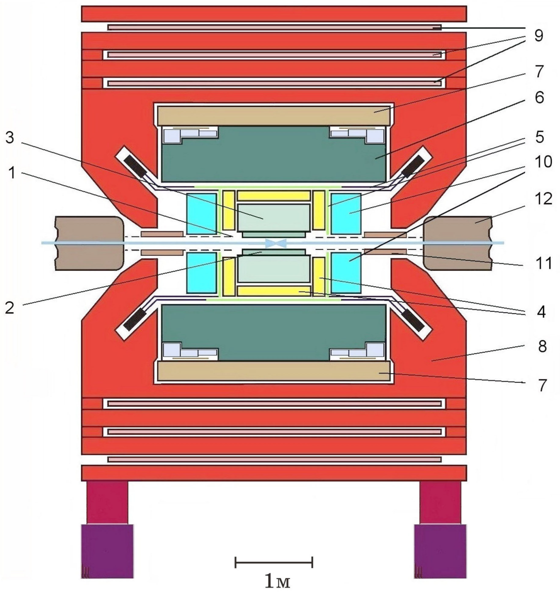
VEPP-4(M) started to operate in 1981

Circumference		366 m
Beam energy		$1 \div 5$ GeV
Number of bunches		2×2
Luminosity:	$E = 1.9$	$2 \cdot 10^{30} \frac{1}{cm^2 \cdot s}$
	$E = 3.5$	$1 \cdot 10^{31} \frac{1}{cm^2 \cdot s}$

Beam energy determination with resonant depolarization technique:

- Touschek polarimeter (intrabeam scattering in dedicated runs), $E < 2$ GeV
  Instant measurement accuracy $\simeq 1 \times 10^{-6}$
  Energy interpolation accuracy $(5 \div 15) \times 10^{-6}$ $(10 \div 60$ keV$)$
- Laser polarimeter (polarized light scattering asymmetry). At 4.73 GeV
  statistical accuracy $\simeq 3 \times 10^{-6}$ / 15 minutes
  correctable systematic uncertainty 3×10^{-6} (30 keV)

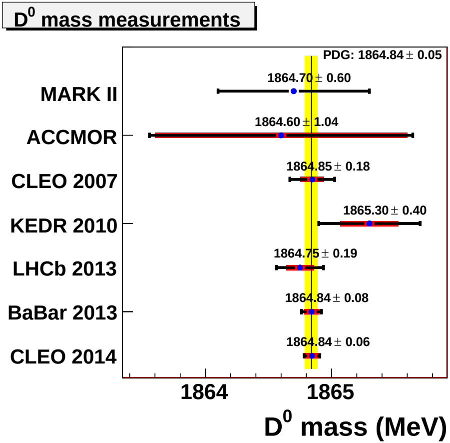
KEDR detector

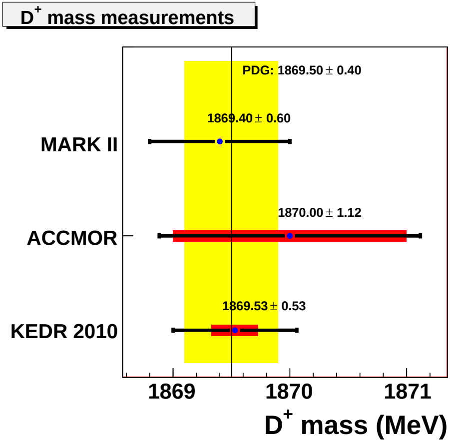


1. Vacuum chamber
2. Vertex detector
3. Drift chamber
4. Aerogel threshold counters
5. ToF–counters
6. Liquid krypton calorimeter
7. Superconducting coil (0.6 T)
8. Magnet yoke
9. Muon tubes
10. CsI-calorimeter
11. Compensation solenoid
12. VEPP–4M quadrupole

- Luminosity monitoring by single Bremsstrahlung in e^+ and e^- directions
- Scattering electron tagging system for two-photon studies

Current status D masses





Main goal of new KEDR experiment was to improve accuracy of D^+ mass.

Data set and analysis method

- $\psi(3770) \to D\overline{D}$ with reconstruction of one D meson as in MARK expriments at SPEAR and the previous KEDR experiment
- In addition to 0.9 pb^{-1} in 2004 (KEDR-2010),
  4 pb^{-1} in 2016–2017 at $\sim$1 MeV vicinity of $\psi(3770)$ peak
- Resonant depolarization method for beam energy determination
- Decays $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^-$ and c.c. were reconstructed
- Variables

$$M_{bc} = \sqrt{\left(\frac{W}{2}\right)^2 - \left(\sum_i \vec{p}_i\right)^2}, \quad \triangle E = \sum_i \sqrt{(m_i^2 + p_i^2)} - E_{beam}$$

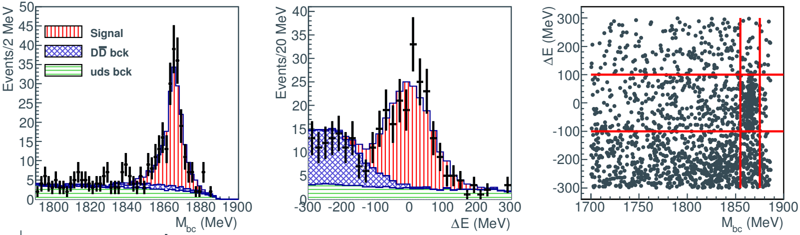
$$\sigma^2(M_{bc}) = \frac{\sigma_W^2}{4} + \left(\frac{p_D}{M_D}\right)^2 \sigma_{p_D}^2 = \frac{\sigma_W^2}{4} + 0.02\,\sigma_{p_D}^2, \qquad \triangle E \approx 0$$

- Difference of $W = 2E_{beam}$ and actual $D\overline{D}$ mass is accounted in M.C. simulation (ISR, machine energy spread)

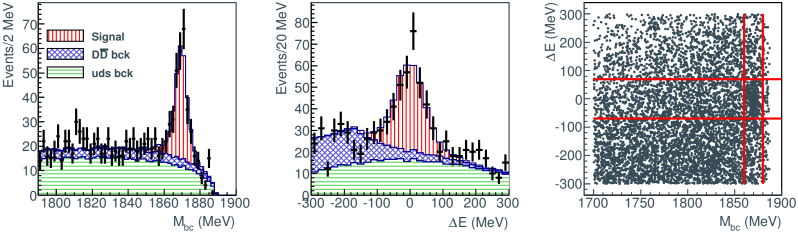
Analysis, data 2016-2017

- Unbinned maximum likelihood fit of M_{bc} and $\triangle E$ in selected events with signal and background (uds, $D\overline{D}$) PDFs obtained with M.C.

D^0, 169 signal events, M_{D^0}=1864.910±0.288 MeV:



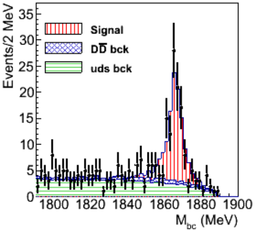
$D^{\pm}$, 349 signal events, M_{D^+}=1869.587±0.357 MeV:

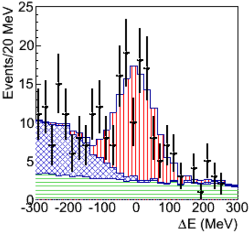


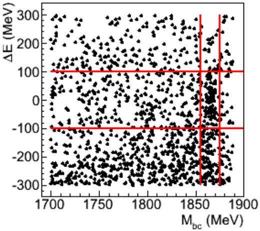
Analysis, data 2004

- 2004 data were reanalyzed to reduce systematic uncertainties

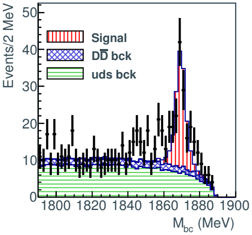
D^0, 84 signal events, M_{D^0}=1865.341±0.309 MeV:

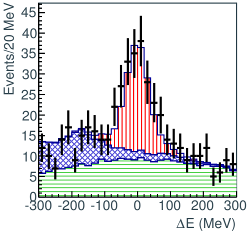


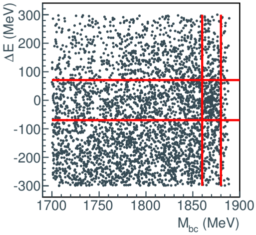




$D^{\pm}$, 178 signal events, M_{D^+}=1869.487±0.490 MeV:







Systematic uncertainties (MeV)

Uncertainty source	KEDR-2010	2004 data	2016 data
Absolute momentum calibration	0.040	0.005	0.005
Ionization loss in material	0.010	0.010	0.010
Momentum resolution	0.130	0.014	0.018
ISR corrections and energy spread	0.160	0.050	0.027
Signal PDF	0.070	0.017	0.023
uds background PDF	0.040	0.008	0.035
$D\overline{D}$ background PDF	0.030	0.010	0.036
Beam energy calibration	0.010	0.007	0.005
total D^0	0.230	0.061	0.061
Absolute momentum calibration	0.040	0.005	0.014
Ionization loss in material	0.030	0.028	0.020
Momentum resolution	0.100	0.061	0.062
ISR corrections and energy spread	0.110	0.014	0.025
Signal PDF	0.050	0.083	0.027
uds background PDF	0.090	0.014	0.005
$D\overline{D}$ background PDF	0.060	0.015	0.020
Beam energy calibration	0.010	0.005	0.005
total $D^{\pm}$	0.200	0.110	0.078

D^0– and $D^\pm$–mass results (preliminary!)

Data set 2004, published in 2010:

- $M_{D^0} = 1865.300 \pm 0.330 \pm 0.230$ $M_{D^+} = 1869.530 \pm 0.490 \pm 0.200$ MeV

Data set 2004:

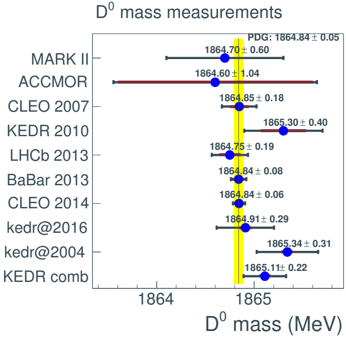
- $M_{D^0} = 1865.341 \pm 0.309 \pm 0.061$ $M_{D^+} = 1869.487 \pm 0.490 \pm 0.110$ MeV

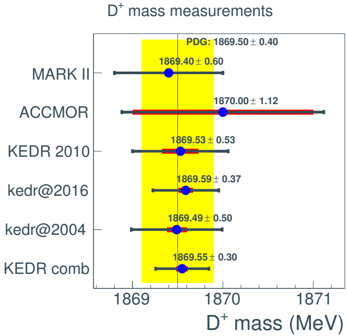
Data set 2016:

- $M_{D^0} = 1864.910 \pm 0.288 \pm 0.061$ $M_{D^+} = 1869.587 \pm 0.357 \pm 0.078$ MeV

Combined result (should supersede KEDR-2010):

- $M_{D^0} = 1865.110 \pm 0.210 \pm 0.058$ $M_{D^+} = 1869.550 \pm 0.288 \pm 0.066$ MeV





$\Upsilon(1S)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
9460.30±0.26 OUR AVERAGE	Error includes scale factor of 3.3.		
9460.51±0.09±0.05	[1] ARTAMONOV 00	MD1	$e^+e^- \rightarrow$ hadrons
9459.97±0.11±0.07	MACKAY 84	REDE	$e^+e^- \rightarrow$ hadrons

Discrepancy of 3.25σ!

$\Upsilon(2S)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
10023.26±0.31 OUR AVERAGE			
10023.5 ±0.5	[1] ARTAMONOV 00	MD1	$e^+e^- \rightarrow$ hadrons
10023.1 ±0.4	BARBER 84	REDE	$e^+e^- \rightarrow$ hadrons

$\Upsilon(3S)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
10355.2±0.5	[1] ARTAMONOV 00	MD1	$e^+e^- \rightarrow$ hadrons

[1] Reanalysis of BARU 92B and ARTAMONOV 84 using new electron mass (COHEN 87).

Introduction: reasons of reanalysis

Problems:

- Incorrect radiative correction accounting in
  W. W. MacKay *et al.*, PRD **29**(1984),2483 (CUSB@CESR),
  D. P. Barber *et al.*, PLB **135**(1984),498 (ARGUS+CB@DORIS)
- Use of obsolete electron mass value in these two works
- Ignoring of the interference effect in all three measurements
- Discrepancy of MD-1 and CUSB results on $\Upsilon(1S)$ mass due to difference in calculation of special functions

Goal:

- To urge PDG update values of masses as was done for quarkonia electronic widths after J. P. Alexander *et al.*, Nucl.Phys.B **320**(1989)45

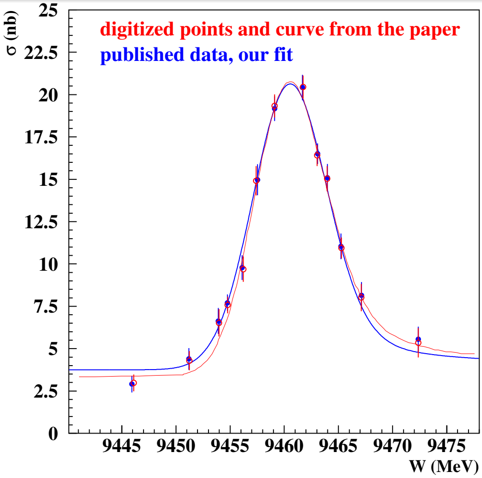
Why now?

- Preparation to new experiment of KEDR@VEPP-4M with expected accuracy of about 50 keV

A.G.Shamov and O.L.Rezanova, Phys.Lett.B 839 (2023) 137766

Experimental aspects of the works were not considered!

Analysis of in Mackay *et al.* [CUSB*@CESR]



Our fit of published CUSB data performed in 1986 with identical radiative corrections accounting gave the mass value 0.375 MeV higher than the published one. Attempts to clarify situation with authors had failed.

?Did a misprint in the data occur?

The data form the journal figure were restored as good as possible, points coincide, unlike the curves.

The mass difference is due to calculation of the resonance curve. We have tried a few independent implementations, the result was stable.

One misprint has been found and fixed in the table of assignment of 22 runs of the experiment to 13 points of the fit. The influence on the mass was negligible.

Correction to radiative corrections

The first published paper on r.c. to the production of narrow resonances:
Ya.I.Azimov, A.I.Vainshtein, L.N.Lipatov, V A.Khoze, JETP Lett. **21**(1975)172,
in a few months a good alternative appeared:
M.Greco, G.Pancheri-Srivastava, Y.Srivastava, Nucl.Phys. **B101**(1975)234

However, the most analysis of ψ and Υ before 1985 were performed according to
J.D.Jackson and D.L.Scharre, NIM **128**(I975)13

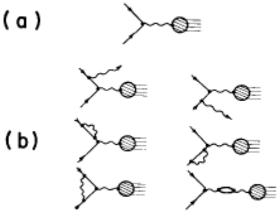


Fig. 1. e⁺e⁻ annihilation via one-photon exchange. (a) Lowest order diagram; (b) Higher order diagrams, the top two involving real (soft) photon emission and the next four each involving one additional virtual photon.

The 'radiative gaussian' G_R was derived with convolution of the gaussian energy spread G and the probability of energy radiation in the approximation of zero resonance width.

The radiation of additional soft photons we accounted in the case (a), but not in (b)

$$\sigma(W) \propto G_R(W-M)+\delta_v \cdot G(W-M) \text{ instead of } (1+\delta_v)\cdot G_R(W-M)$$

Mass shift depends on the energy spread, $\sim$ 100 keV for Υ

Refining of electron mass value

For beam energy determination in experiments the resonant depolarization method was employed. It gives the mean Lorentz factor of beam electrons thus the beam energy is proportional to electron's mass m_e. In 1983 the accuracy of m_e was about 2.8 ppm, that corresponds to 26 keV uncertainty is $\Upsilon(1S)$ mass.

«The 1986 adjustment of the fundamental physical constants», E.R.Cohen and B.N.Taylor, Rev.Mod.Phys. **59**(1987)1121: the value of m_e was shifted to -8.5 ppm with reduction of uncertainty to 0.3 ppm due to refining of e/h value

The results from VEPP-4 were recalculated in Phys.Lett. **B474**(2000)427 The shifts of masses were -80, -85 и -88 keV for $\Upsilon(1S)$, $\Upsilon(2S)$ и $\Upsilon(3S)$, respectively

The results from CESR and DORIS stayed unchanged

Ya.I. Azimov *et al.*, JETP Lett. **21**(1975)172

contribution of a resonance to a final state f in soft photon approximation (needs small modifications nowadays):

$$\sigma^{\Upsilon\to f}(W)=\frac{12\pi}{M^2}\left(1+\frac{3}{4}\beta\right)\left[\frac{\Gamma_{ee}\Gamma_f}{\Gamma M}\,\mathrm{Im}\,f(W)-\frac{2\alpha\sqrt{R\,\Gamma_{ee}\Gamma_f}}{3W}\,\lambda\,\mathrm{Re}\,\frac{f(W)}{1-\beta/6}\right]$$

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

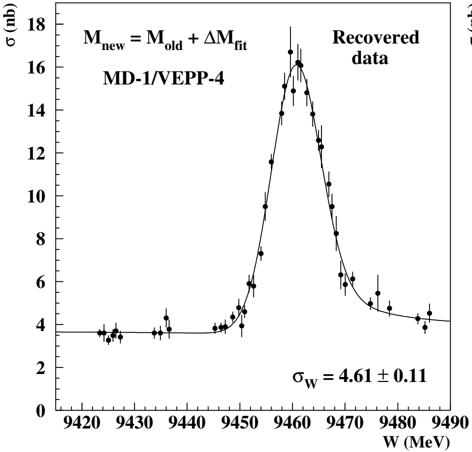
The parameter λ determines the strengths of interference effects, $\lambda=1$ for $f=\mu^+\mu^-$. For the sum of hadronic modes (b_m and $\mathcal{B}_m^{(s)}$ are relative mode probabilities in electromagnetic and strong decays, respectively, ϕ is the interference phase of electromagnetic and strong amplitudes)

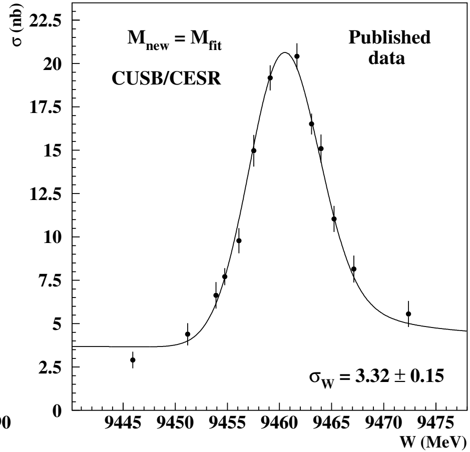
$$\lambda=\sqrt{\frac{R\mathcal{B}_{ee}}{\mathcal{B}_h}}+\sqrt{\frac{1}{\mathcal{B}_h}}\sum_m\sqrt{b_m\mathcal{B}_m^{(s)}}\,\langle\cos\phi_m\rangle\;. \qquad (1)$$

At the parton model level the strong $3g$ decays and the electromagnetic $q\bar{q}$ decays do not interfere thus the sum in the left part of (1) must be zero.

Υ mass shifts grows with the energy spread, $\sim$ 100 keV

$\Upsilon(1S)$ mass (MeV)





$$M_{old} = 9460.51 \pm 0.09 \pm 0.05$$
$$M_{new} = 9460.40 \pm 0.09 \pm 0.04$$
$$\Delta(int) = -0.112$$

MD-1 – CUSB: $3.25\sigma \rightarrow 1.83\sigma$

$$M_{old} = 9459.97 \pm 0.11 \pm 0.07$$
$$M_{new} = 9460.11 \pm 0.11 \pm 0.07$$
$$\Delta(int) = -0.071 \quad \Delta(m_e) = -0.081$$
$$\Delta(JS) = -0.081 \quad \Delta(fit) = +0.375$$

Summary on masses

- It was demonstrated that the analysis of CUSB/CESR data on mass of $\Upsilon(1S)$ was not fully correct, the mass was shifted by -0.375 MeV
- When necessary, published mass values were corrected to:
  - Improper radiative correction accounting
  - Use of obsolete electron mass value in these two works
  - Resonance-continuum interference

$\Upsilon(1S)$:	$9460.51 \pm 0.09 \pm 0.05$	$\rightarrow$	$9460.40 \pm 0.09 \pm 0.04$	MD-1
	$9559.97 \pm 0.11 \pm 0.07$		$9460.11 \pm 0.11 \pm 0.07$	CUSB
$\Upsilon(2S)$:	10023.5 ± 0.5	$\rightarrow$	10023.4 ± 0.5	MD-1
	10023.1 ± 0.4		10022.7 ± 0.4	ARGUS+CB
$\Upsilon(3S)$:	10355.2 ± 0.5	$\rightarrow$	10355.1 ± 0.5	MD-1

- The discrepancy in MD-1 and CUSB results on $\Upsilon(1S)$ mass reduced from $3.25\,\sigma$ to $1.83\,\sigma$

The average $\Upsilon(1S)$ mass value calculated according PDG rules is

$$9460.29 \pm 0.15 \text{ MeV}$$

$\Upsilon(1S)$ MASS 9460.40 ± 0.10 MeV

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9460.40 ±0.09 ±0.04	[1] SHAMOV	2023	RVUE	$e^+ e^- \to$ hadrons
• • We do not use the following data for averages, fits, limits, etc. • •				
9460.11 ±0.11 ±0.07	[2] SHAMOV	2023	RVUE	$e^+ e^- \to$ hadrons
9460.51 ±0.09 ±0.05	[3,4] ARTAMONOV	2000	MD1	$e^+ e^- \to$ hadrons
9460.60 ±0.09 ±0.05	[5,6] BARU	1992B	MD1	$e^+ e^- \to$ hadrons
9460.59 ±0.12	BARU	1986	MD1	$e^+ e^- \to$ hadrons
9460.6 ±0.4	[7,6] ARTAMONOV	1984	MD1	$e^+ e^- \to$ hadrons
9459.97 ±0.11 ±0.07	[8] MACKAY	1984	CUSB	$e^+ e^- \to$ hadrons

[1] Reanalysis of MD1 data using the electron mass from COHEN 1987 , the radiative corrections from KURAEV 1985 and interference effects.

[2] Obtained by reanalysing CUSB data (MACKAY 1984), but not authored by the CUSB collaboration.

[3] Reanalysis of BARU 1992B and ARTAMONOV 1984 using new electron mass (COHEN 1987).

[4] Superseded by SHAMOV 2023 .

[5] Supersedes BARU 1986 .

[6] Superseded by ARTAMONOV 2000 .

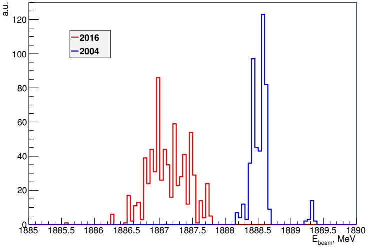
[7] Value includes data of ARTAMONOV 1982 .

[8] Reanalysed by SHAMOV 2023 .

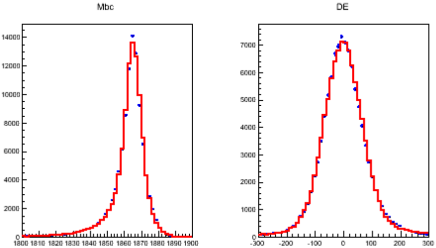
IMHO: Using of the revised CUSB result into averaging could increase reliability of the mass value (question of accelerator-related uncertainties)

Thanks for attention!

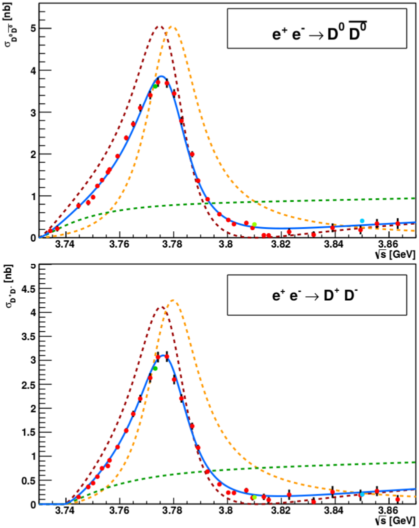
D^0– and $D^\pm$–mass backup



Beam energy distribution
for runs 2016-2017 and 2004



Check of signal PDFs for $D^0 \to K^-\pi^+$
(blue points on red MC–histogram)



BES-III data for ISR simulation and
accounting for machine energy spread

Forthcoming experiment KEDR@VEPP-4M (1)

Experience of KEDR@VEPP-4M:

"Final analysis of KEDR data on J/ψ and ψ(2S) masses" PLB **749**(2015)50

- 6 J/ψ and 7 $\psi(2S)$ high precision scans in 2002–2008
- systematic uncertainty in one scan 7$\div$10 keV (2.5 ppm)
- more than 15 sources of the uncertainty were considered

Difference between ψ and Υ conditions:

ψ: Injection from VEPP-3 to VEPP-4M at the energy of scan point
Υ: Acceleration at VEPP-4M from 1.9 to 4.73 GeV

Υ: Some systematic uncertainties $\propto E_{beam}^2$

Goals for $\Upsilon(1S)$:

- Systematic uncertainties < 30 keV (6.3 ppm)
- Statistical uncertainty on mass $M < 40$ keV
- Statistical uncertainty on electronic width $\Gamma_{ee} < 1\%$

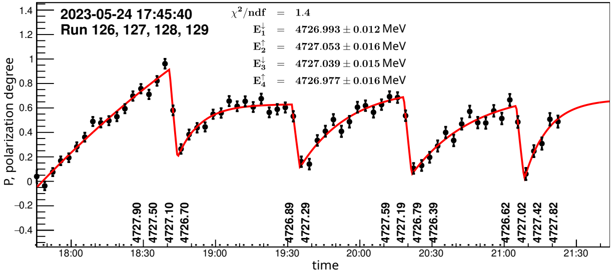
Luminosity $\simeq 10$ pb^{-1}, $\simeq 200$ runs, optimistic time estimate $\simeq 2$ months

$\Upsilon(2S)$,$\Upsilon(3S)$: much more difficult, $\Delta M \simeq 100$ keV ?

Forthcoming experiment KEDR@VEPP-4M (2)

Status of preparation:

- Polarization was obtained around $E_{beam} = 4.73$ GeV
- Short test scan of $\Upsilon(1S)$ with energy calibrations was done
- Works to improve energy stability of VEPP-4M
- Laser polarimeter is in good operation:



★ Hope to start experiment in 2024

Expected systematic uncertainties

Systematic uncertainties in J/ψ scans (keV):

Uncertainty source	2002	2005	2008	Common
Energy spread variation	3.0	1.8	1.8	1.8
Energy calibration accuracy	1.6	1.9	1.9	1.6
Energy assignment to DAQ runs	3.7	3.5	3.5	2.5
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 distortion of the energy distribution	1.5	1.3	2.1	1.3
Asymmetric distortion of the energy distribution*	2.1	1.9	1.9	1.9
Beam potential	1.9	1.9	1.9	1.9
Detection efficiency instability	2.3	1.7	1.8	<0.1
Residual machine background	1.0	0.7	0.7	<0.1
Luminosity measurements	2.2	1.7	1.7	1.1
Interference in the hadronic channel	2.7	2.7	2.7	2.7
Sum in quadrature	≈ 7.7	≈ 7.0	≈ 7.2	≈ 5.8

* — correction uncertainty

Resonant depolarization method

The electron beam in the accelerator spontaneously becomes polarized, the spin precesses around guiding field with the frequency

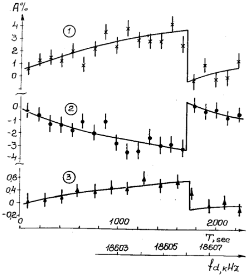
$$\Omega_{\text{spin}} = \omega_{\text{rev}}\,(1+\mu'/\mu\,\gamma) \quad \text{depending on the beam energy } E = \gamma\, m_e$$

External electromagnetic field of variable frequency f_d depolarizes the beam at the resonance condition

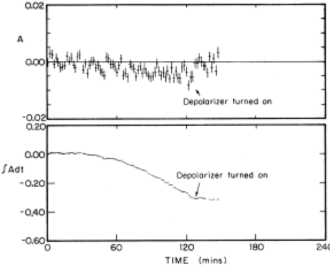
$$\Omega_{\text{spin}} = m \cdot \omega_{\text{rev}} + n \cdot f_d \quad (\Upsilon(1S) \text{ at VEPP-4: } m = 11, n = 1)$$

Measurement f_d and ω_{rev} at the moment of depolarization allows for the beam energy determination with accuracy $\sim 10^{-6}$

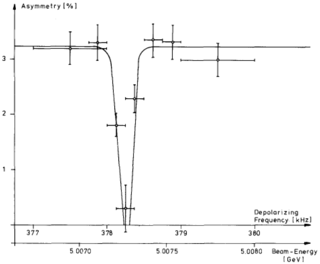
The moment of depolarization was detected using asymmetry in scattering of longitudinally polarized photons on the transversely polarized electron beam:



VEPP-4 (synchrotron radiation)



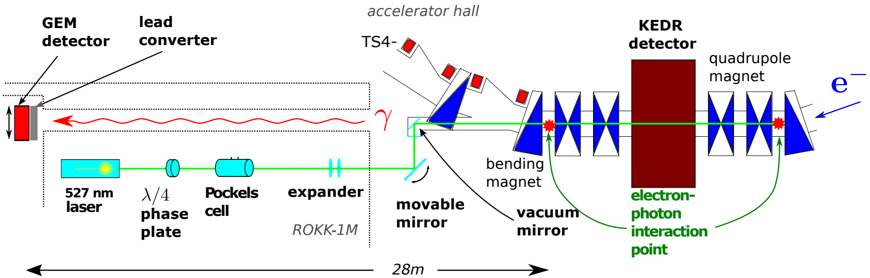
CESR (laser)



DORIS (laser)

VEPP-4M polarimeter

Layout of the laser polarimeter:



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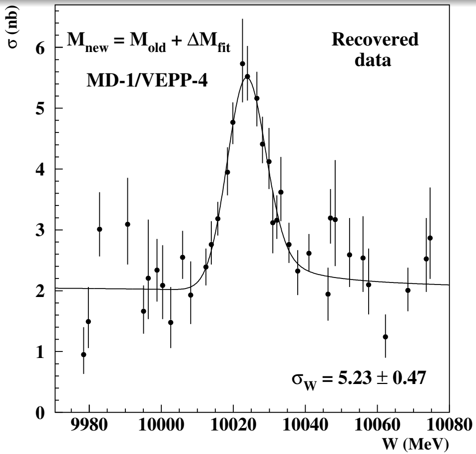
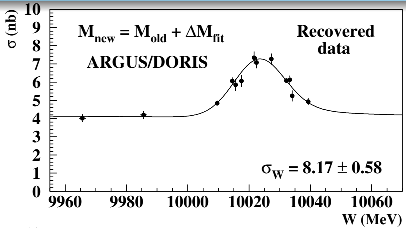
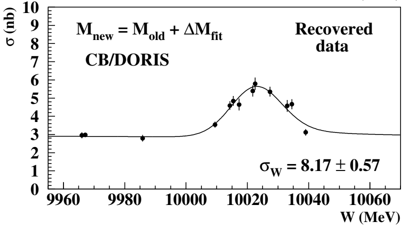
$\Upsilon(2S)$ mass (MeV)







$M_{old} = 10023.5 \pm 0.5$

$M_{new} = 10023.4 \pm 0.5$

$\Delta(int) = -0.105$

$M_{old} = 10023.1 \pm 0.4$

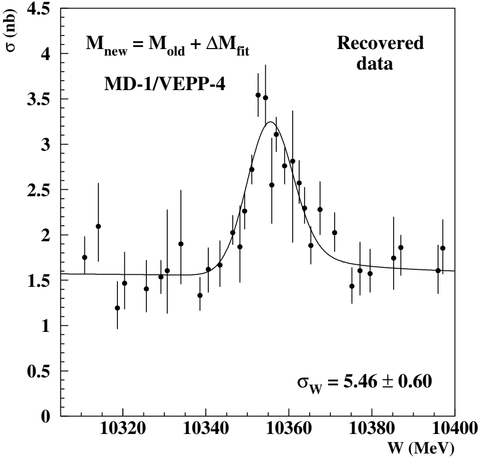
$M_{new} = 10022.7 \pm 0.4$

$\Delta(int) = -0.168 \quad \Delta(m_e) = -0.086$

$\Delta(JS) = -0.181$

MD-1 – (ARGUS+CB): $0.62\sigma \to 1.06\sigma$

$\Upsilon(3S)$ mass (MeV)



$$M_{old} = 10355.2 \pm 0.5$$
$$M_{new} = 10355.1 \pm 0.5$$
$$\Delta(int) = -0.130$$