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Experimental Status Report on Vector Meson Spectroscopy

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The experimental status of light vector meson spectroscopy is discussed. The last results of e^+e^- experiments obtained at the VEPP-2M collider in Novosibirsk are described and the comparison with the old data in the mass region from 1 GeV to 2.5 GeV is performed.

1. INTRODUCTION

For the first time the e^+e^- spectroscopy study was performed in Novosibirsk in 60th at the VEPP-2 collider. The shape of the $\rho(770)$ resonance have been measured [1]. Since a lot of different experiments for spectroscopy have been done [2] and as a rule the most precise data on vector meson parameters were obtained in e^+e^- production. The current status of the vector meson spectroscopy is as follows:

- All main states of $q\overline{q}$ systems are established.
- Charmonium and bottomonium families are well known.
- Excitation states of $q\overline{q}$ system for u, d, s quarks are not well established.
- There is evidence for the existence of $K\overline{K}$ or 4-quarks states in the vector meson decays [3–6].
- There is evidence for the existence of $N\overline{N}$ or 6-quarks states [7].

The main problems of the light vector meson spectroscopy connect with the fact that in the mass region $2E = 1.4 \div 2.5$ GeV total integrated luminosity $\simeq 2\ pb^{-1}$ was collected at DCI and ADONE. This statistic is incompatible with that collected in the energy regions of the charmonium and bottomonium families.

At the contrary, in the low energy region from the hadron production threshold to 1.4 GeV, the systematic studies have been performed in Novosibirsk at the e^+e^- collider VEPP-2M. It was in operation from 1974 to 2000 and the total integrated luminosity $\simeq 80 pb^{-1}$ was collected. Important measurements were done by OLYA [8, 9] and ND [10] experiments, but the main part of integrated luminosity were taken by the CMD-2 [11] and SND [12] experiments. Now the experimental program is finished, and the final data analysis is in progress.

2. PRODUCTION OF LIGHT VECTOR MESONS IN ELECTRON-POSITRON COLLISIONS

Main advantages of the experiments on vector mesons production in e^+e^- annihilation are following: clean initial state with the well defined quantum numbers, high mass resolution, good conditions for an exclusive reactions study. The main problem of the e^+e^- data analysis connect with uncertainties in the interference between several resonances that often introduces model dependence into final results (for example [13]). There are also model dependences of the data analysis [14–18], which can be resolved only after significant increasing of experimental statistic.

2.1. $e^+e^- \to \pi^+\pi^-$ cross section

The precise measurement of the two pion production cross section have been performed for many years [2, 9, 19]. The systematic uncertainty of 0.6 % is achieved in the last CMD-2 experiment [20] in the energy range below 1 GeV. For higher energies the results are not so precise, but DM2 data [21] strongly emphasise the signal of $\rho(1700)$ (Figure 1). There is some wide enhancement in the the cross section around 1.25 GeV which may be taken as an evidence for the $\rho(1250)$ resonance, but at the same time other models are discussed [15, 22].

2.2. $e^+e^- \to \pi^+\pi^-\pi^0$ cross section

The main contributions to three pion production cross section at low energy come from the $\omega(782)$ and $\phi(1020)$ resonances. It is well known that the interference between these resonances are destructive [13]. For many years in the energy region above 1 GeV the experimental data was not so precise [10, 23]. The last SND measurement [24] shows that there is a visible peak in the cross section at 1.25 GeV (Figure 2). After applying the radiative corrections and the detection efficiencies the total cross section was obtained in which the clear resonance signal is seen. Taking into account the data below 1 GeV and the DM2 data [23] the set of fits were performed [24]. The best fit (Figure 3) requires contributions of ω, ϕ, $\omega(1200)$, and $\omega(1650)$ with the relative phases (+), (−), (−), (+).

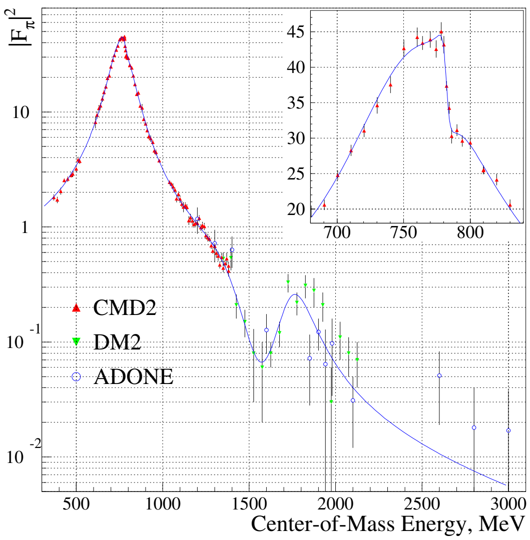

Figure 1: The $e^+e^- \to \pi^+\pi^-$ cross section.

2.3. $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section

The four charged pion production was studied by many groups [2]. The most detailed investigation have been reported by CMD-2 [25]. In this work the PWA analysis have been performed and it was shown that the $a_1(1260)\pi$ intermediate state dominates in the energy region below 1.4 GeV. The SND results [26] confirm the CMD-2 data (Figure 4).

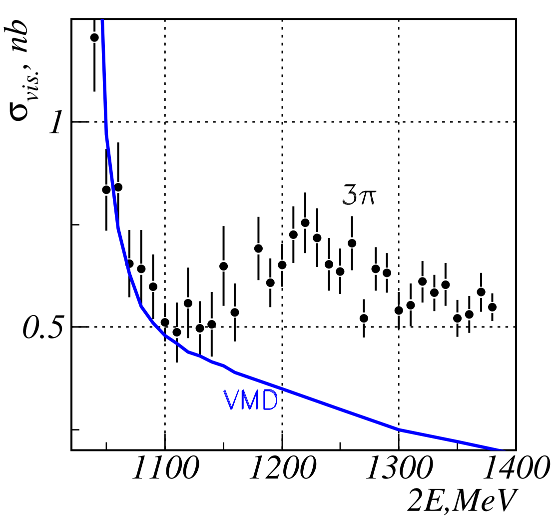

Figure 2: Visible cross section of the reaction $e^+e^- \to \pi^+\pi^-\pi^0$.

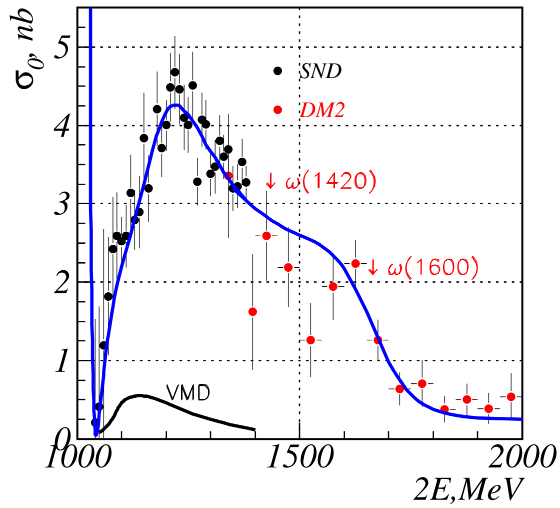

Figure 3: The $e^+e^- \to \pi^+\pi^-\pi^0$ cross section.

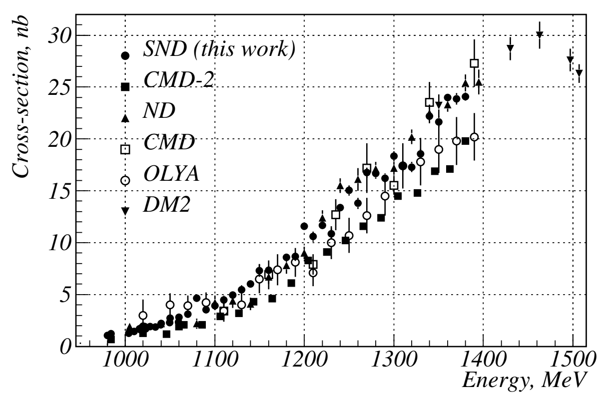

Figure 4: The $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section with the recent VEPP-2M data [26].

2.4. $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ cross section

Using the PWA analysis of the reaction $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ CMD-2 obtained [25] that $a_1(1260)\pi$ and $\omega\pi^0$ intermediate states dominate in the reactions mechanism (Figsure 5, 6). The recent SND data [26] are in agreement with the CMD-2 results within the systematic uncertainty of the experiments (Fig.7).

2.5. $e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0$ cross section

The five pions production cross section have been studied by CMD-2 [27] and DM2 [23]. It was shown that tree diagrams (Figures 8, 9) dominate in these reactions. In the $\omega\pi^+\pi^-$ cross section, the clear peak of the $\omega(1650)$ is seen and probably some contribution of the $\omega(1200)$ exists. In the $\eta\pi^+\pi^-$ reaction the clear peak of $\rho(1450)$ determines the cross section shape but some contribution of $\rho(1700)$ is not excluded.

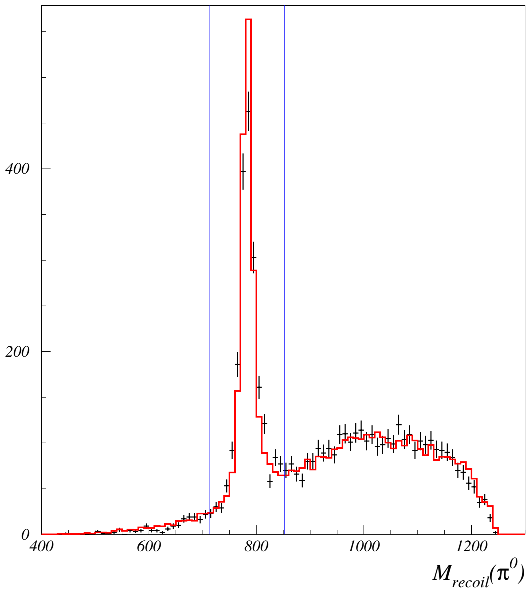

Figure 5: The invariant mass of $\pi^+\pi^-\pi^0$ in the reaction $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ [25].

2.6. $e^+e^- \to \omega\pi^0$ cross section

The main reaction channel $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$ is seen in the four pion final state but less systematic uncertainty in the cross section measurement was achieved by SND using the $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ reaction [28]. Combining SND data with the data of DM2 [29] and CLEOII [30] the fit of the cross section was performed (Figure 12). Note, that there is a systematic bias between the DM2 and CLEOII data, which can be connected with a normalisation problem or with the bias in the energy scale.

2.7. $e^+e^- \to \eta\gamma$ cross section

The first indication of a radiative decay of radial excitations of light vector mesons was found out by CMD-2 [31]. Two events of the reaction $e^+e^- \to \eta\gamma$ were identified. The estimated production cross section is in agreement with the data of CMD-2 [27] and DM2 [32] for the reaction $e^+e^- \to \eta\pi^+\pi^-$.

2.8. $e^+e^- \to K_SK_L, K^+K^-$ cross sections

The preliminary SND results on the cross section $e^+e^- \to K_SK_L$ [13, 33] together with the DM1 data [34] can be successfully fitted if the contributions of the ρ, ω, ϕ, and $\phi(1680)$ resonances are taken into account (Figure 13). The data on the reaction $e^+e^- \to K^+K^-$ [8, 35] are in agreement with a such model.

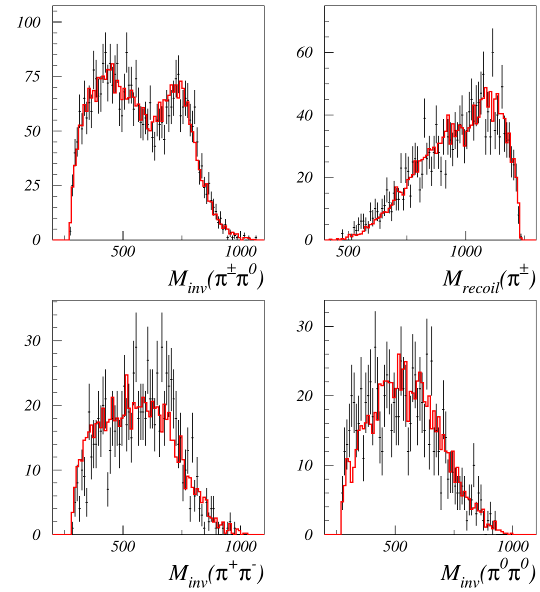

Figure 6: The two pions invariant mass in the reaction $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ [25].

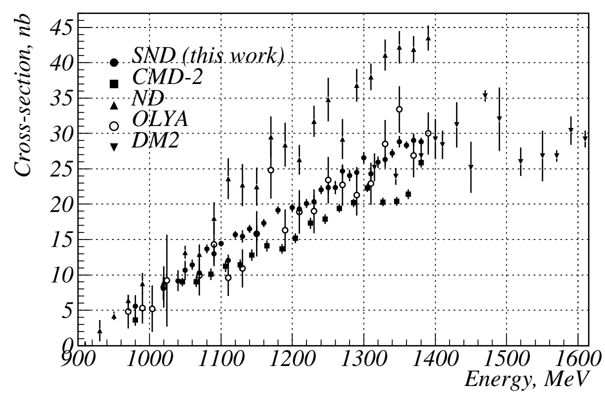

Figure 7: The $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ cross section with the recent VEPP-2M data [26].

2.9. $e^+e^- \to KK\pi$ cross sections

The PWA analysis of the $e^+e^- \to KK\pi$ reaction have been performed by DM2 [36]. It was shown that isoscalar process $\phi(1680) \to K^*K \to K_SK^\pm\pi^0$ dominates. The cross section $e^+e^- \to K^+K^-\pi^0$ is small. The 1.45 GeV vector state observed in the hadron production [37] is not confirmed in the e^+e^- production at VEPP-2M [33, 38].

3. THE LIGHT VECTOR MESON SPECTRUM

The classification (Table I) of the light vector mesons proposed by PDG [2] cannot be accepted without a serious discussion. Some resonances included in the table are not well established. On the contrary, the data on $\rho(1250)$ and $\omega(1200)$

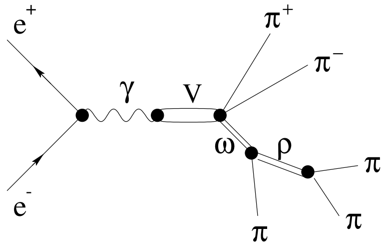

Figure 8: The $e^+e^- \to \omega\pi^+\pi^-$ main diagram.

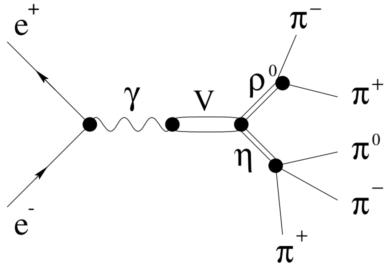

Figure 9: The $e^+e^- \to \eta\pi^+\pi^-$ main diagram.

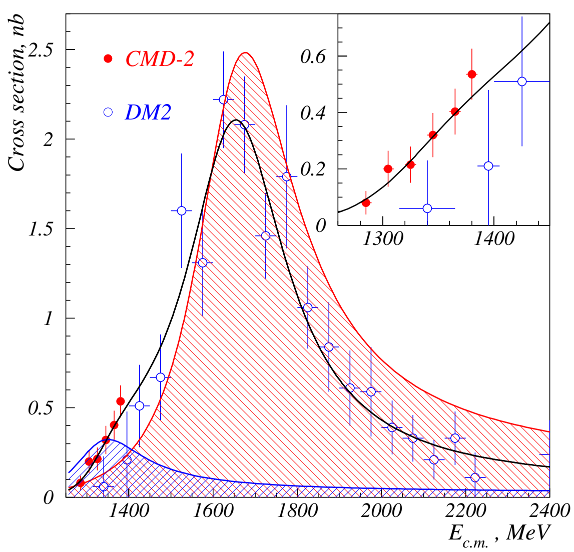

Figure 10: The $e^+e^- \to \omega\pi^+\pi^-$ cross section.

Table I The classification of vector mesons by PDG'00.

$N^{2S+1}L_J$	$\frac{(u\bar{u}-d\bar{d})}{\sqrt{2}}$	$\frac{(u\bar{u}+d\bar{d})}{\sqrt{2}}$	$s\bar{s}$
1^3S_1	$\rho(770)$	$\omega(782)$	$\phi(1020)$
2^3S_1	$\rho(1450)$	$\omega(1420)$	$\phi(1680)$
1^3D_1	$\rho(1700)$	$\omega(1650)$	-
3^3S_1	$\rho(2150)$		

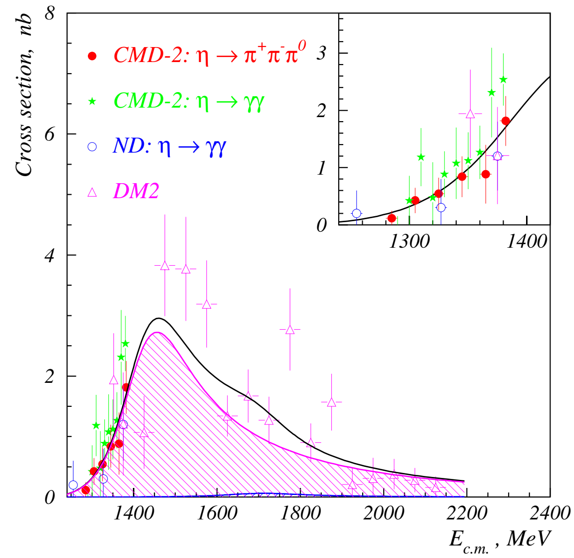

Figure 11: The $e^+e^- \to \eta\pi^+\pi^-$ cross section.

are ignored. The difficulty of the existing data analysis connect with the low statistical accuracy of the data above 1.4 GeV. Moreover the model uncertainty of resonances mass and width may exceed 200 MeV [18]. The quality of the experimental data is demonstrated in Table II and the following conclusions can be done after review of the current data:

- $\rho(1250)$ is ignored by PDG but as pointed out by D. Peaslee [39] there are several old and new experiments (OMEGA [40], LASS [41], OBELIX [42, 43]) in which some evidences for the $\rho(1250)$ were obtained.
- $\omega(1200)$ is identified by $\pi^+\pi^-\pi^0$ cross section [24].
- $\rho(1450)$ is identified by $\pi^+\pi^-\pi^+\pi^-$ and $\eta\pi^+\pi^-$ production in e^+e^- and in $p\bar{p}$ experiments.

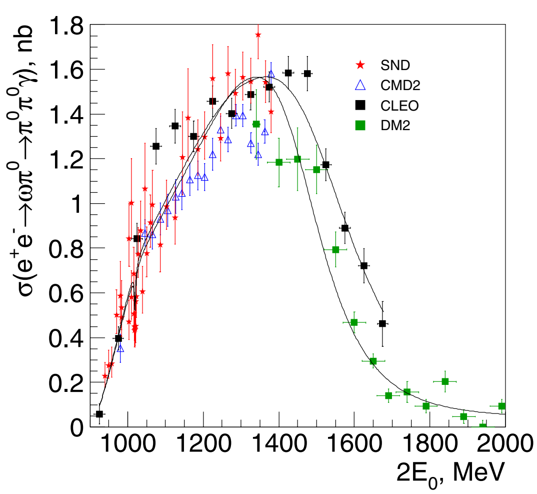

Figure 12: The $e^+e^- \to \omega\pi^0$ cross section.

Table II The level of experimental significance of the vector mesons in selected reactions: + - well established states, * - not well established states.

	$\rho(1250)$	$\omega(1200)$	$\rho(1450)$	$\omega(1420)$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\rho(2150)$
$e^+e^- \to \pi^+\pi^-$	*		*		+			*
$e^+e^- \to \pi^+\pi^-\pi^0$		+		*		*	*	
$e^+e^- \to 4\pi$			+		+			
$e^+e^- \to \omega\pi^0$			*		+			
$e^+e^- \to \omega\pi^+\pi^-$		*		*		+	*	
$e^+e^- \to \eta\pi^+\pi^-$			+		*			
$e^+e^- \to \eta\gamma$			*					
$e^+e^- \to K_SK_L$					*		+	
$e^+e^- \to K^+K^-$					*	*	*	+
$e^+e^- \to K^*K$					*		+	
$e^+e^- \to K^+K^-\pi^0$							*	
$\pi^-p \to \omega\pi^0 n$								+
$\pi^-p \to \phi\pi^0 n$					*			
$p\overline{p}, \overline{p}n \to$ hadrons	*		*		+			
$\gamma p \to$ hadrons	*				+			

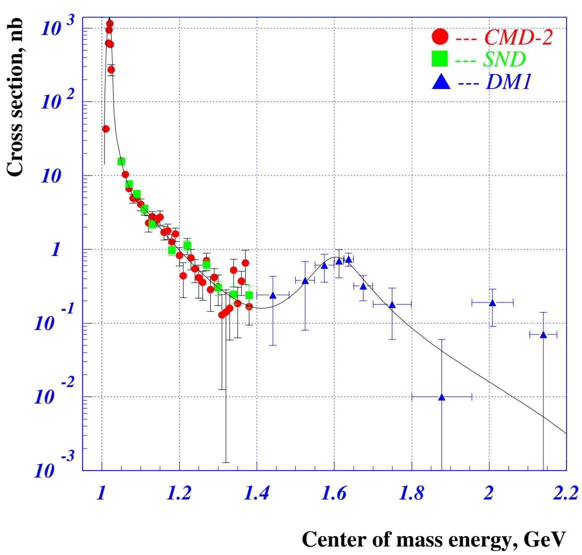

Figure 13: The $e^+e^- \to K_SK_L$ cross section.

- $\omega(1420)$ has no solid ground.
- $\rho(1700)$ is seen in the e^+e^- production in $\pi^+\pi^-$, $\omega\pi^0$, and $\pi^+\pi^-\pi^0\pi^0$ final states. It is identified in the gamma production [2] and in the $p\overline{p}$ production [44, 45].
- $\omega(1650)$ is identified by $\omega\pi^+\pi^-$ cross section [23].
- $\phi(1680)$ is identified by the K^*K cross section [36].
- $\rho(2150)$ is identified in the hadron production of $\omega\pi^0$ by GAMS [46].

4. PROSPECTS FOR PEP-N

There are a set of questions which must be answered to clear the situation with excited states of the light vector mesons:

- Do $\rho(1250)$ exist? What is the nature of this object? Is it 2^3S_1 $q\overline{q}$ state or is it lowest 4-quark vector state?
- Do $\omega(1200)$ is 2^3S_1 $q\overline{q}$ state or it is lowest 4-quark vector state?
- Do $\omega(1420)$ exist?
- $\rho(1700)$, $\omega(1650)$, and $\phi(1680)$ have practically the same mass. They have to have common decay channels, so its real inputs are hidden in cross section shapes because of the interference. Are there three resonances $\rho(1700)$, $\omega(1650)$, and $\phi(1680)$ or are there only two?
- Do other light quarks states exist?

The adequate e^+e^- collider for such a study is PEP-N. The experiment at PEP-N is able to provide a good efficiency and particle identification for hadron and radiative transitions between different states in the energy region $1-3$ GeV. The other methods using existing facilities are not able to solve all problems of the spectroscopy of the light vector mesons because of the following problems:

- Below 3 GeV the luminosity of existing e^+e^- colliders fall down. The designed maximum energy of the VEPP-2000 [47] is 2 GeV.
- Using the hadronic τ decays is not possible to establish the spectrum of vector mesons above 1.3 GeV because of kinematics.

- The Initial State Radiation method [48, 49] is a very effective method to demonstrate the cross section shape and to tag the most interesting phenomena, but the precision of this method is not known and some theoretical and experimental limits can be foreseen.
- The previous experience shows us that experiments for the hadron production, γ-production, and $p\overline{p}$ production cannot substitute precise e^+e^- experiments for the vector meson spectroscopy.

5. CONCLUSIONS

- The knowledge of the vector meson spectroscopy is incomplete.
- The heavy quarkonium spectra are known much better than the spectrum of the light vector mesons.
- It is required to measure a complete set of hadron production cross sections in the energy region $1-3\ GeV$ with the integrated luminosity about 200 pb^{-1}.
- This luminosity investment will provide an opportunity to study as traditional and exotic states, hadronic and radiative transitions.
- The two new e^+e^- projects VEPP-2000 [47] at Novosibirsk and PEP-N at SLAC intend to bring a light on the light vector meson spectroscopy. These two projects are complimentary in many aspects, so the realisation of both is very well required.

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