Recent results from SND detector at VEPP-2000 collider.

M.N. Achasov

Budker Institute of Nuclear Physics, SB RAS, Novosibirsk

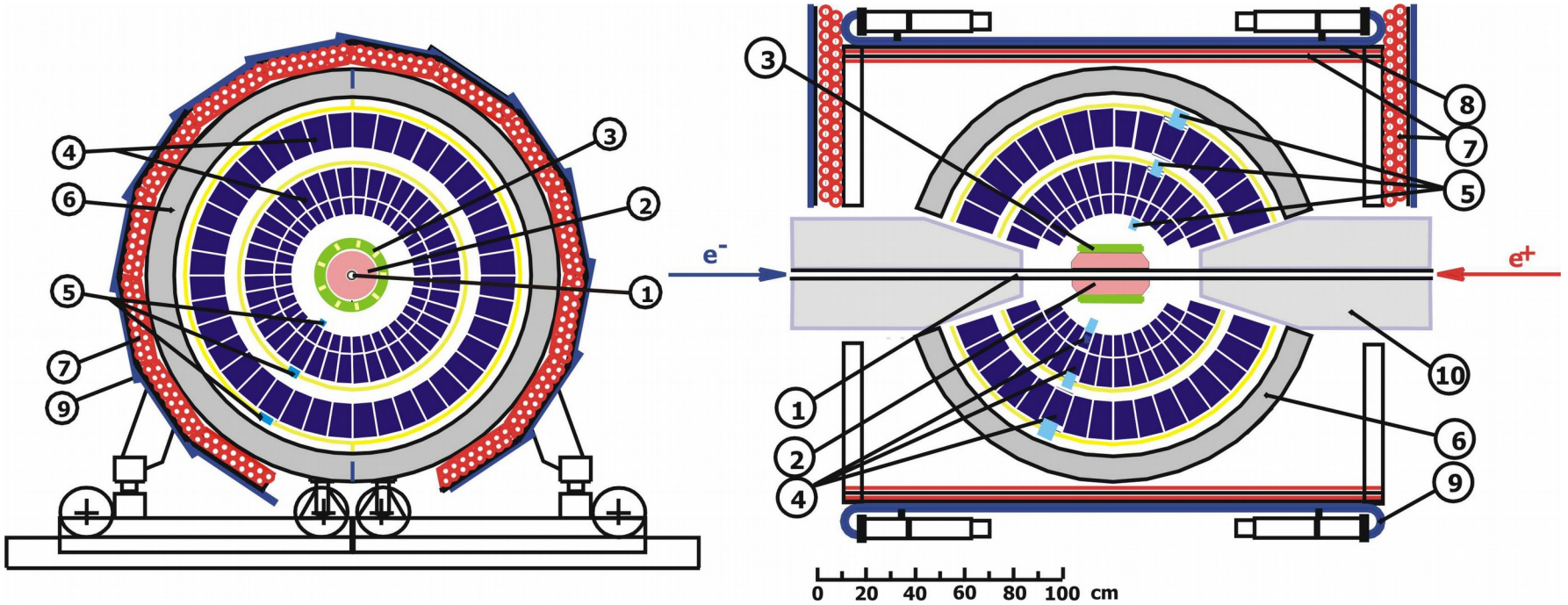
Physical goals.

SND experiment at VEPP-2000 collider studies e+e– annihilation to hadrons at low energy region ($\sqrt{s}$<2 GeV). These studies include:

- **Measurement of the cross sections $e^+e^- \to hadrons$. Measurement of the cross sections and elctromagnetic form-factors, study of many hadron processes dynamics.**
- **Study of the vector mesons ρ, ω, ϕ and their excited states ρ', ρ'', ω', ω'', ϕ', …**
- **Study of e+e– annihilation to C-even resonances:**

  $e^+e^- \to S, P, A, T$.

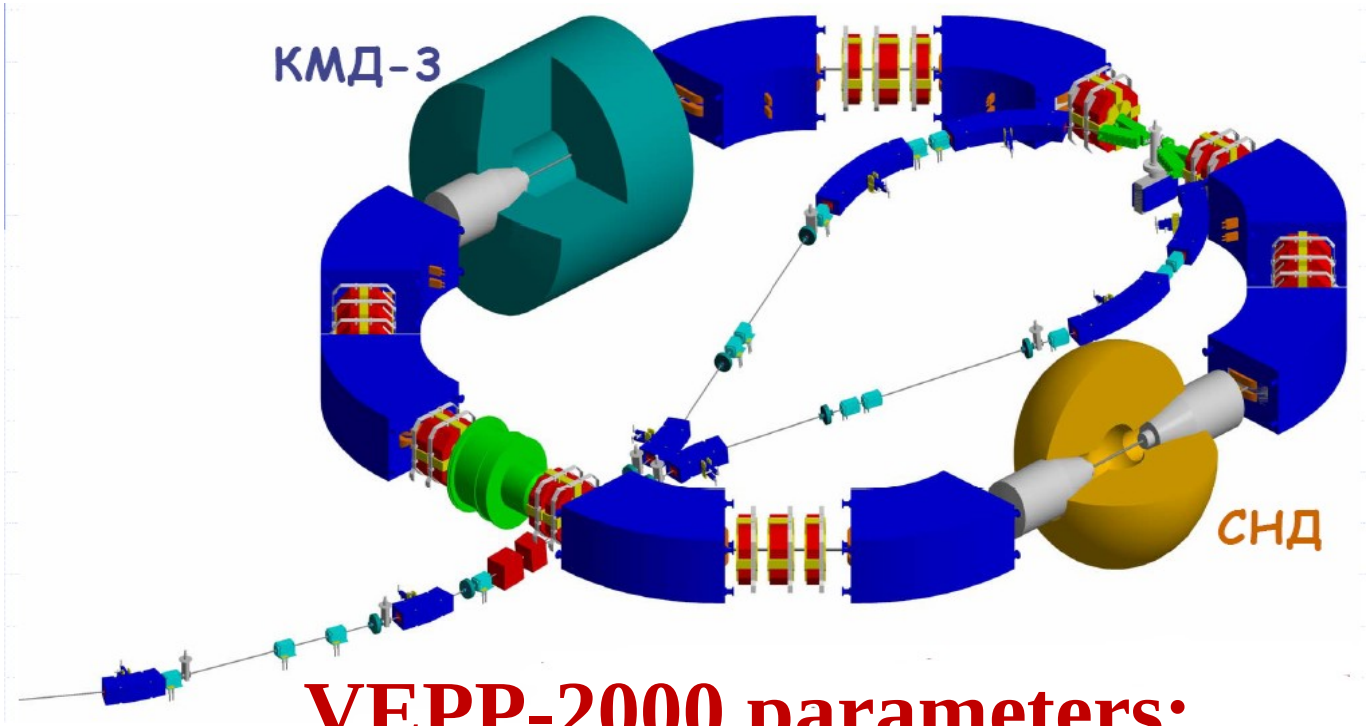
SND detector.



1 – beam pipe, 2 – tracking system, 3 – aerogel Cherenkov counter , 4 – NaI(Tl) crystals, 5 – phototriodes, 6 – iron muon absorber, 7–9 – muon detector, 10 – focusing solenoids.

SND collected data at VEPP-2M (1996-2000) and
at VEPP-2000 (2010-2013, 2017-...)

VEPP-2000 e^+e^- collider.



VEPP-2000 parameters:

c.m. energy 0.3-2.0 GeV

circumference – 24.4 m

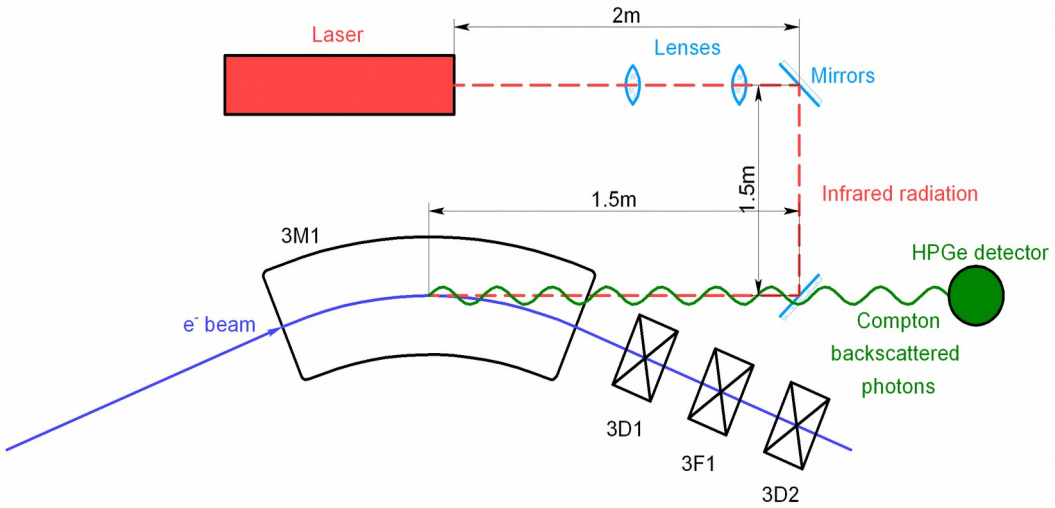
round beam optics

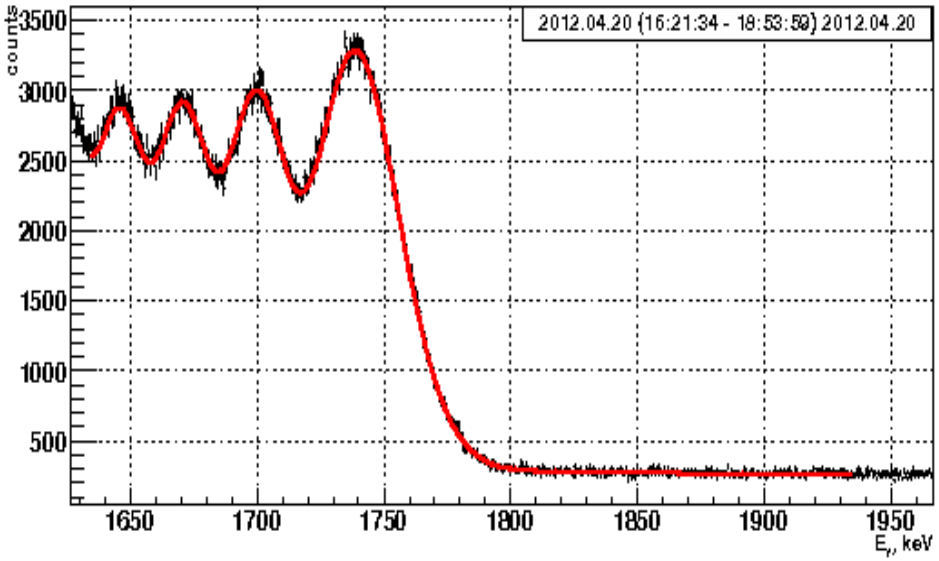
Luminosity at 2 GeV

1×10^{32} cm^{-2} sec^{-1} (project)

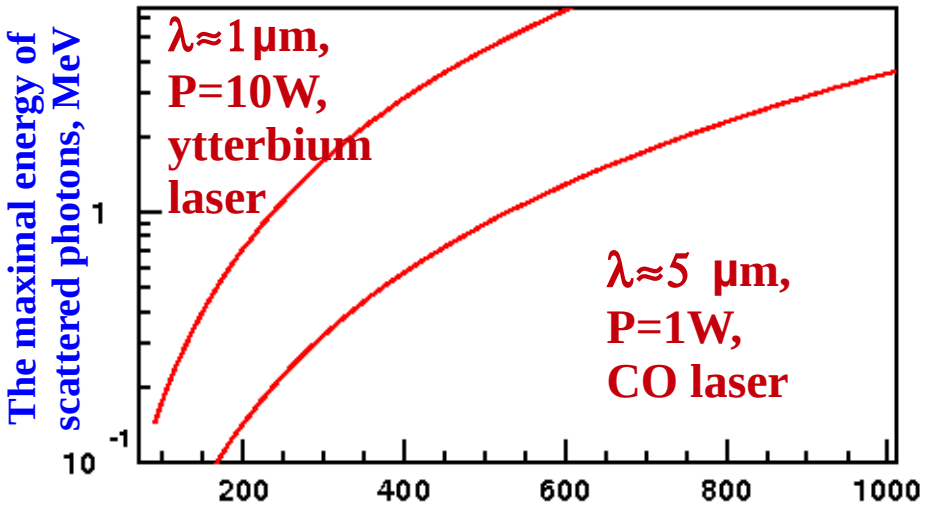
4×10^{31} cm^{-2} sec^{-1} (achieved)

Beam energy measurement system.





The beam energy is measured using the Compton scattering of the laser photons on the electron beam. The measurement accuracy is about 30 keV.



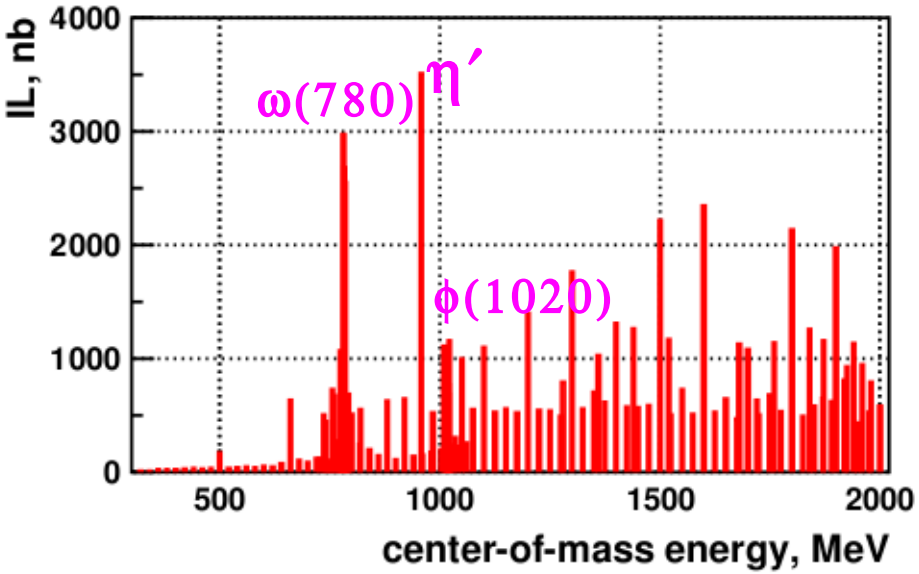
Two sources of photons are used:

ytterbium and **CO lasers**.

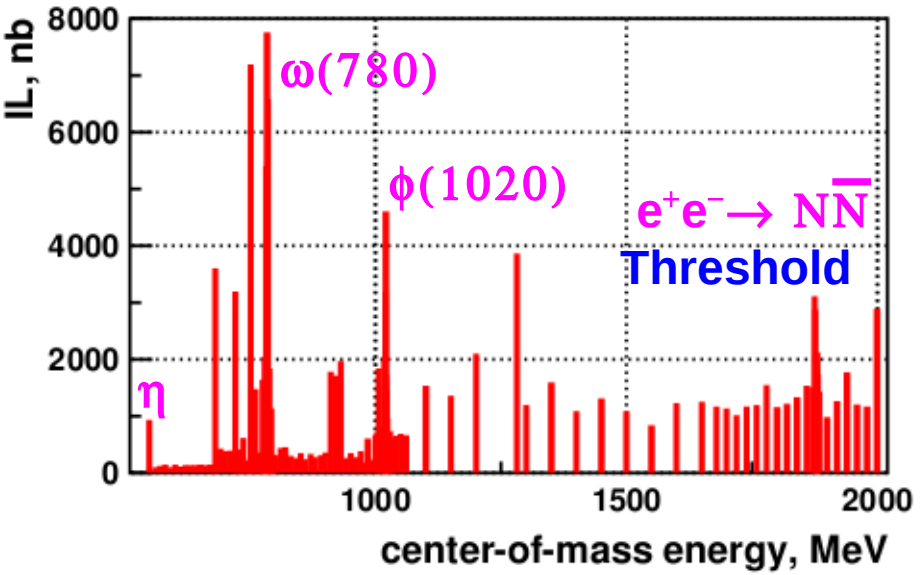
CO at the energy above **500 MeV**,

Nd:YAG at the energy below **500 MeV**.

SND data.



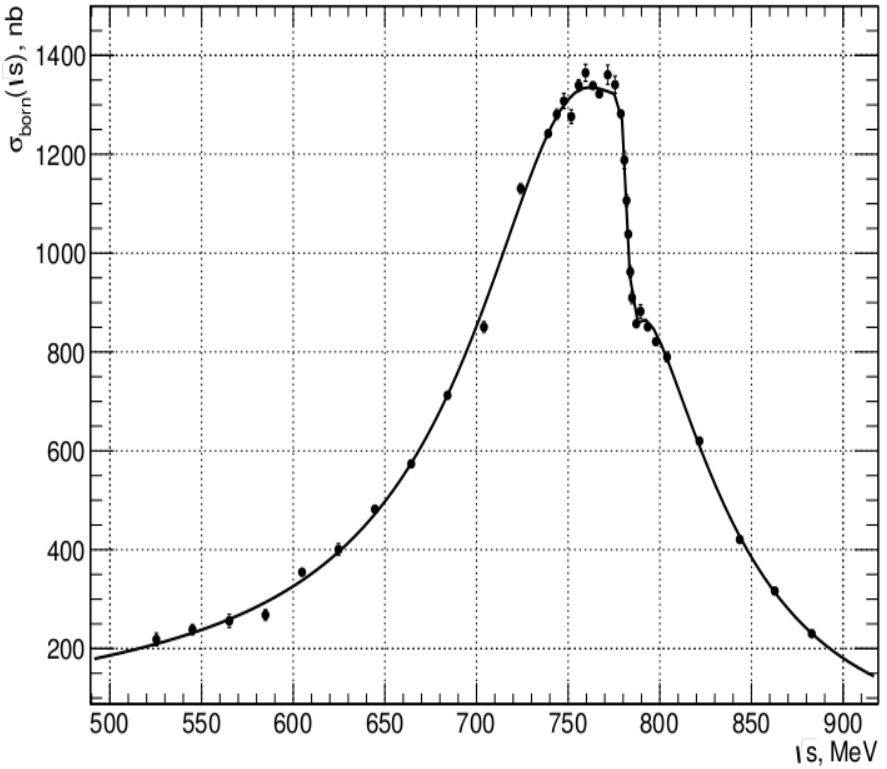
Distribution of integrated luminosity **IL≈70 pb-1** collected in **2010-2013** over c.m. energy.



Distribution of integrated luminosity **IL≈140 pb-1** collected in **2017-2018** over c.m. energy.

	Below ϕ		Arround ϕ		Above ϕ	
	2010-2013	2017-2018	2010-2013	2017-2018	2010-2013	2017-2018
IL, pb-1	15	62	7	24	47	54
√s, GeV	≲1		≈1-1,05		≳1,05	

$e^+e^- \to \pi^+\pi^-$ below 1 GeV (prelimenary).



The collinear events $e^+e^- \to e^+e^-$, $\pi^+\pi^-$, $\mu^+\mu^-$ were selected. The cosmic background was rejected by veto of the muon system.

Using energy depositions in the calorimeter's counters the selected events were divided into two classes: $e^+e^- \to e^+e^-$ and $e^+e^- \to \pi^+\pi^-$, $\mu^+\mu^-$. The events separation was based on the machine learning approach (boosted decision trees network).

$e^+e^- \to e^+e^-$ events were used to obtain ***IL***.

The number of $e^+e^- \to \mu^+\mu^-$ events were subtracted according to QED calculation.

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

$$\sigma_{\pi\pi} = \frac{N_{\pi\pi}}{IL} \frac{1}{\varepsilon_{\pi\pi}(1+\delta_r)}$$

$e^+e^- \to \pi^+\pi^-$ cross section. Systematic error 0,8-0,9 %. *IL= 5pb-1.*

The cross section was fitted by VDM taken into account ρ, ω and ρ′ resonances.

	SND, VEPP-2000
m_ρ, MeV	**775.9 ± 0.5 ± 0.8**
Γ_ρ, MeV	**145.7 ± 0.7 ± 1.6**
$B(\rho \to \pi^+\pi^-)B(\rho \to e^+e^-)$, 10^{-5}	**4.892 ± 0.015 ± 0.039**
$B(\omega \to \pi^+\pi^-)B(\omega \to e^+e^-)$, 10^{-5}	**1.358 ± 0.056 ± 0.011**
$\varphi_{\rho\omega}$, degrees	**112.6 ± 1.4**

$e^+e^- \to \pi^\circ\gamma$ in the energy range $\sqrt{s}$=1.075–2 GeV.

Earlier the $e^+e^- \to \pi^\circ\gamma$ cross section was measured below **1.4 GeV** by SND and CMD-2 at VEPP-2M.

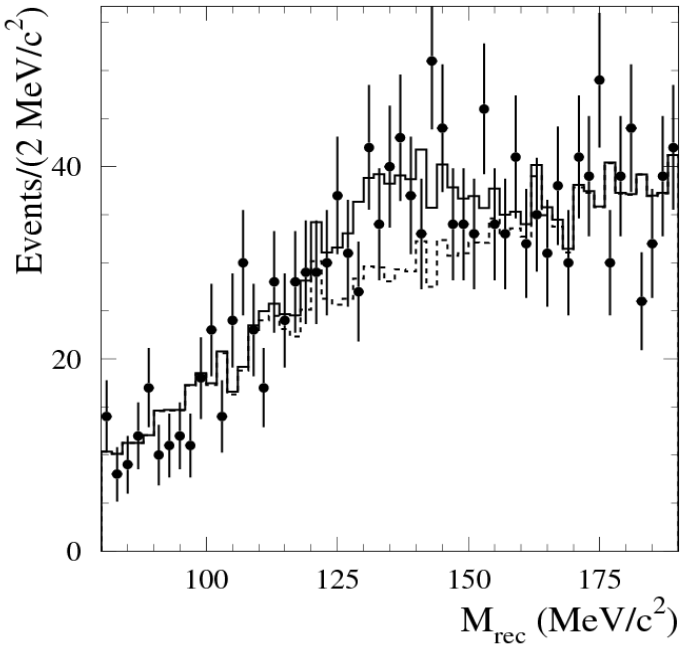
Here the ***IL=41 pb-1*** collected by SND at VEPP-2000.
In the range 1.4-2.0 GeV the process $e^+e^- \to \pi^\circ\gamma$ was studied for the first time.

Analysis features.

N_{tr}=**0** and N_γ=**3**, muon system veto.

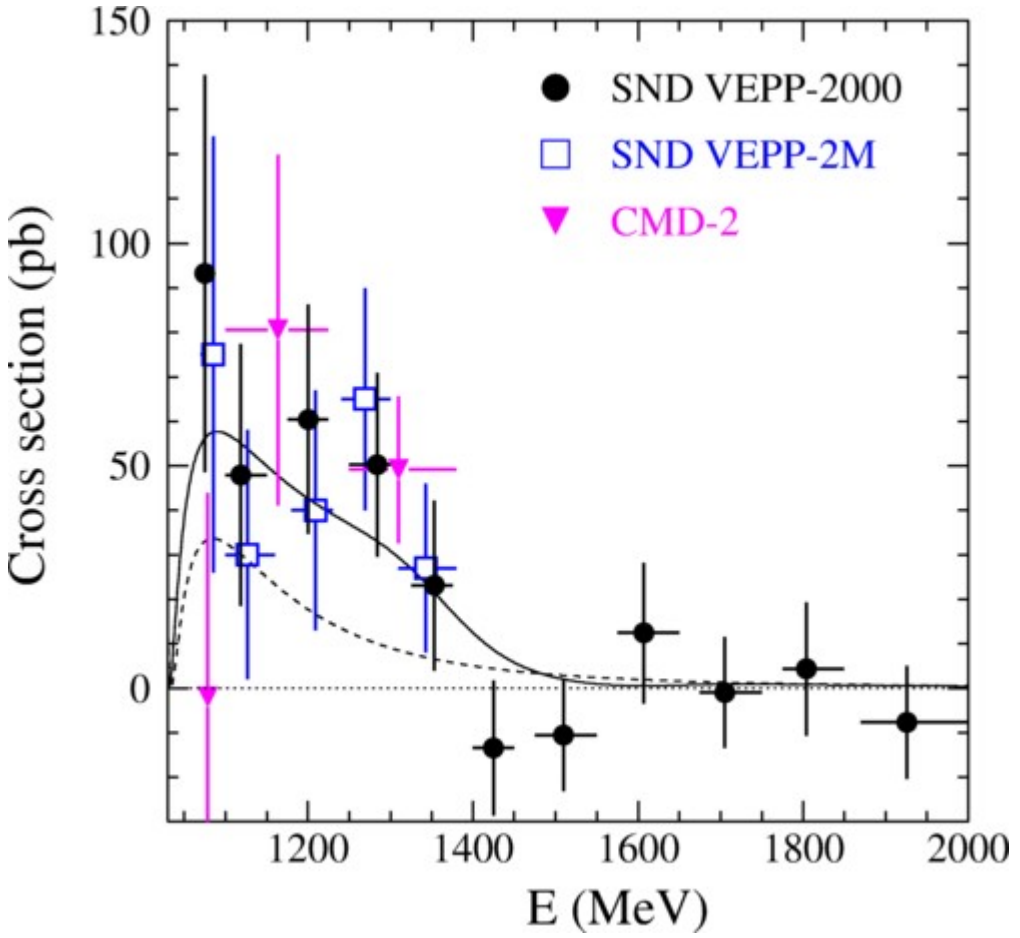
Final selection is based on 4C kinematic fit $\chi^2_{3\gamma} < 20$.

The number of $e^+e^- \to \pi^\circ\gamma$ events is determined from the fit of spectrum M_{rec} of the mass recoiling against largest energy photon .



$\sqrt{s}$ = 1075- 1375 MeV.

$e^+e^- \to \pi^\circ\gamma$ in the energy range $\sqrt{s}$=1.075–2 GeV.



The $e^+e^- \to \pi^\circ\gamma$ cross section above 1.4 GeV is consistent with zero within statistical errors of about 15 pb.

Below 1.4 GeV the cross section is about 50 pb and agrees with previous SND and CMD-2 measurements at VEPP-2M.

To explain the $e^+e^- \to \pi^\circ\gamma$ cross section beside $\rho(770)$, $\omega(782)$ and $\phi(1020)$ resonances (dashed line) the contributions of $\rho(1450)$ and $\omega(1420)$ resonances is required with significance of 4σ.

M.N. Achasov, et. al., Phys.Rev. D98 (2018) no.11, 112001.

$e^+e^- \to \omega\pi^\circ \to \pi^+\pi^-\pi^\circ\pi^\circ$ above ϕ-meson (preliminary).

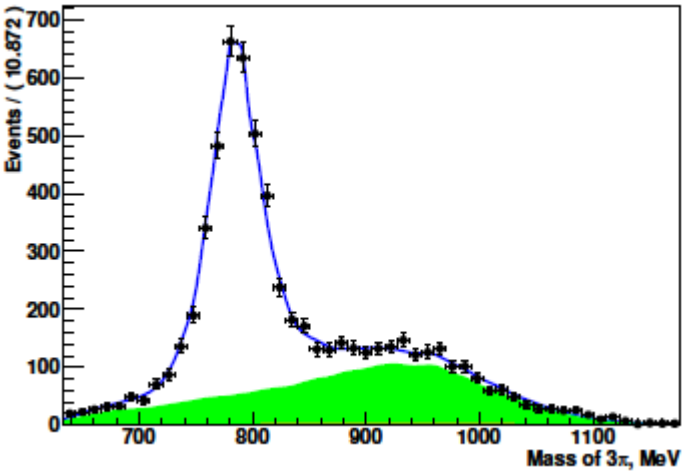
$e^+e^- \to \omega\pi^\circ$ is one of the dominated processes in the energy region 1050-2000 MeV. It was studied using ***IL=41pb-1***.

Analysis features.

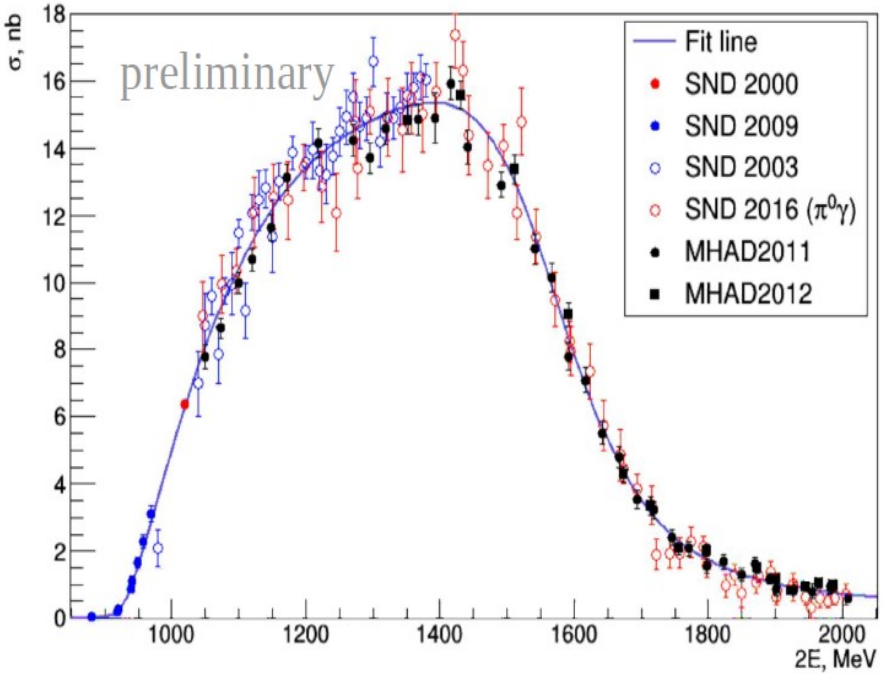
$N_{tr}=2$ and $N_\gamma \geq 4$. Final selection of $e^+e^- \to \pi^+\pi^-\pi^\circ\pi^\circ$ is based on kinematic fit, which takes into account energy-momentum conservation and constraints on the invariant masses of the photons pairs to be equal to the π° mass.

The number of $e^+e^- \to \omega\pi^\circ$ events is determined from the fit of the $\pi^+\pi^-\pi^\circ$ invariant mass spectrum.

Statistical error **2-16%**, systematical error **1-9%**.



Fit to $\pi^+\pi^-\pi^\circ$ invariant mass spectrum at $\sqrt{s}$ = 1360 MeV.



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

$e^+e^- \to \pi^+\pi^-\pi^\circ$ above ϕ-meson (preliminary).

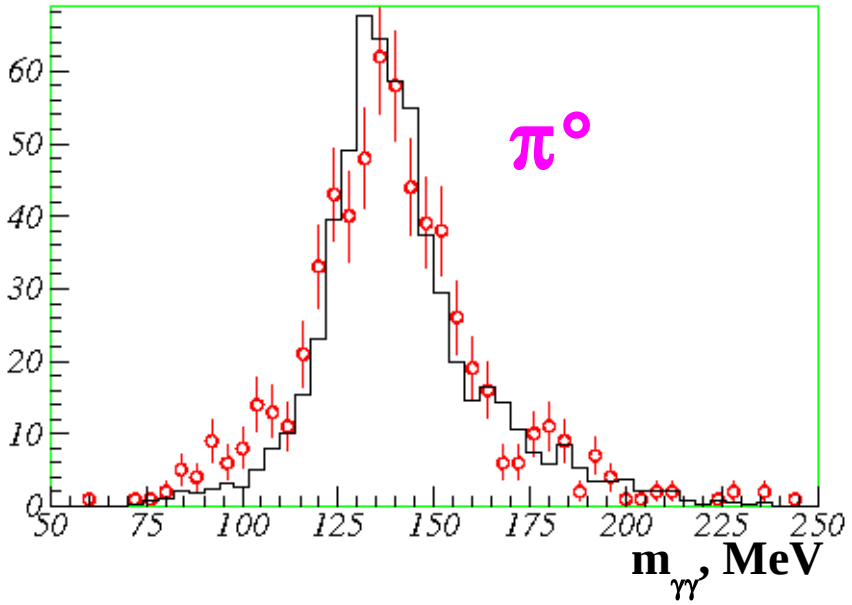
$e^+e^- \to \pi^+\pi^-\pi^\circ$ process in the energy region 1050-2000 MeV was studied using ***IL=41pb-1***.

Analysis features. $N_{tr}=2$ and $N_\gamma=2$. Final selection is based on 4C kinematic fit.

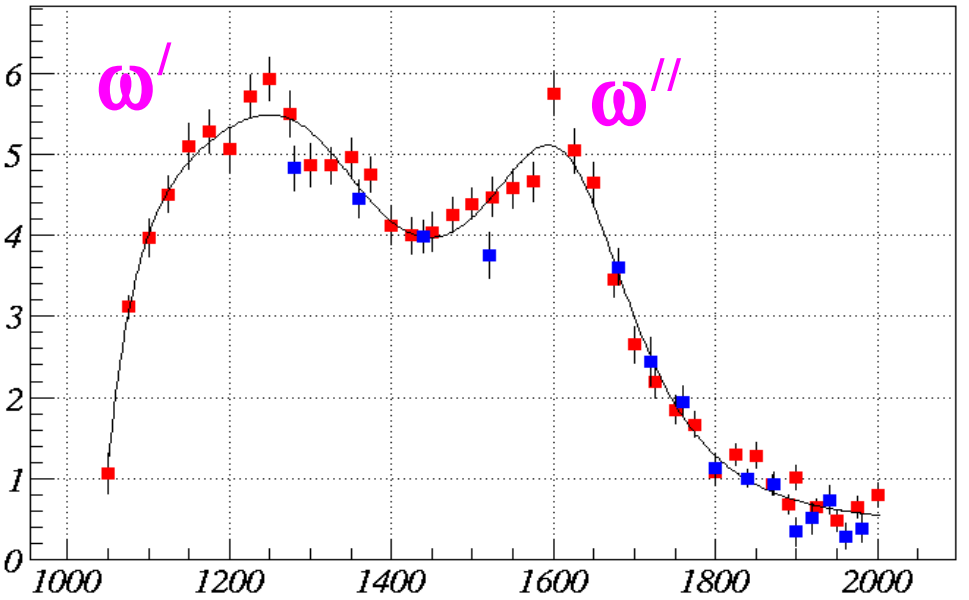
The number of $e^+e^- \to \pi^+\pi^-\pi^\circ$ events is determined from the fit of the $\gamma\gamma$ invariant mass spectrum.

Red points is 2011 year data was published *V.M. Aulchenko, et. al., Zh.Eksp.Teor.Fiz. 148 (2015) no.1, 34-41.*

Blue points is 2012 year data, preliminary result.



Fit to $\gamma\gamma$ invariant mass spectrum.



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

$e^+e^- \to \pi^+\pi^-\pi^\circ\eta$ below 2 GeV (preliminary).

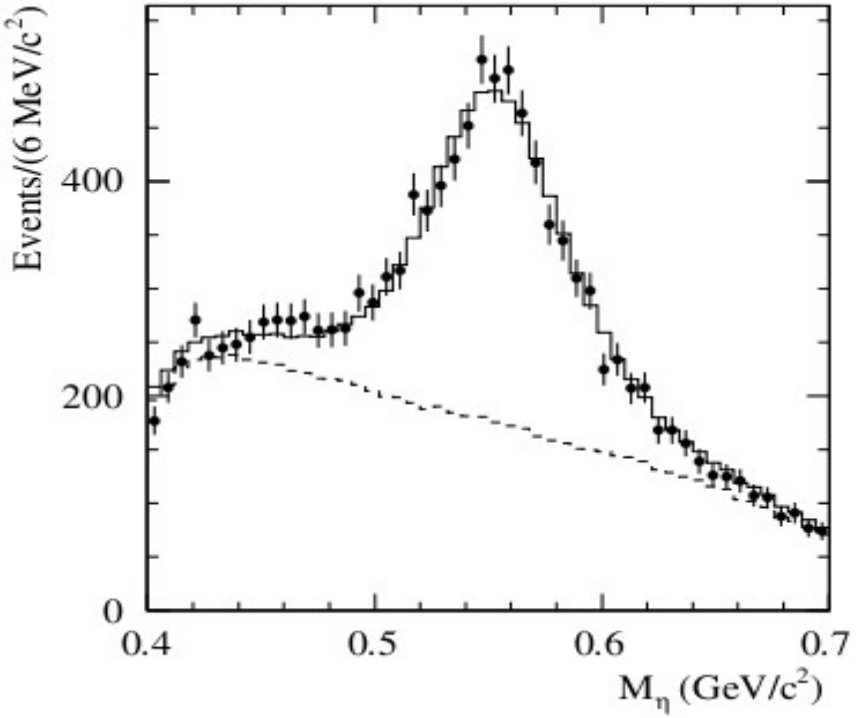
The dynamics of the $\pi^+\pi^-\pi^\circ\eta$ final state includes the following mechanisms:

(1) $e^+e^- \to \omega\eta$ $(\omega \to \pi^+\pi^-\pi^\circ)$,

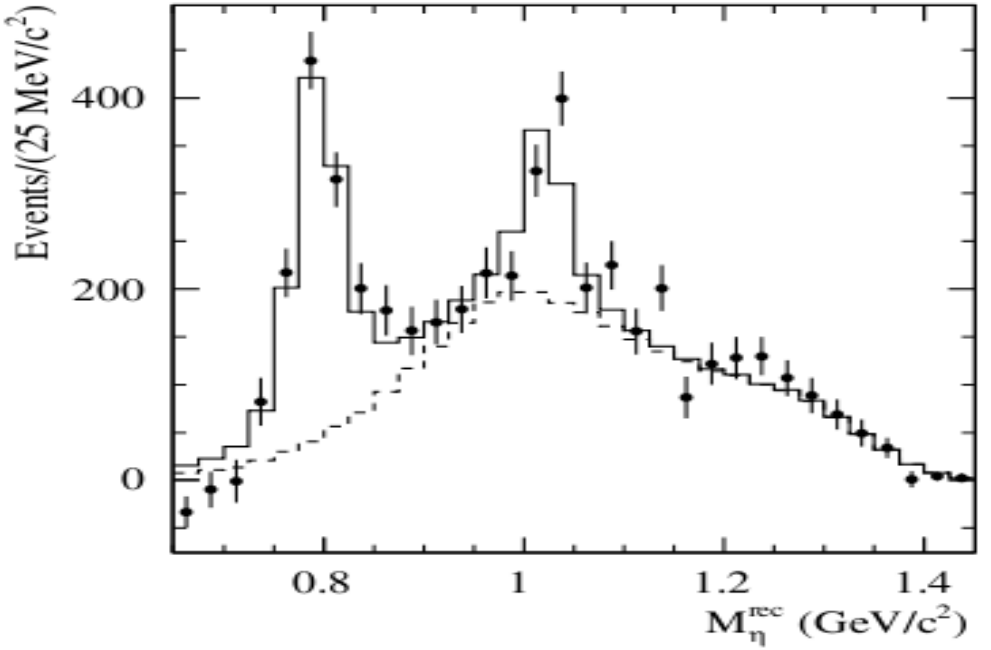
(2) $e^+e^- \to \phi\eta$ $(\phi \to \pi^+\pi^-\pi^\circ)$,

(3) $e^+e^- \to a_0(980)\rho$ $(a_0(980) \to \eta\pi,\ \rho \to 2\pi)$,

(4) $e^+e^- \to \pi^+\pi^-\pi^\circ\eta$ ($3\pi\eta$ structureless), which were previously studied by BaBar, SND and CMD-3. Analysis was based on events with $\eta \to \gamma\gamma$ decay. The number of $e^+e^- \to \pi^+\pi^-\pi^\circ\eta$ events is determined from the fit to the η meson candidates $\gamma\gamma$ invariant mass spectrum.



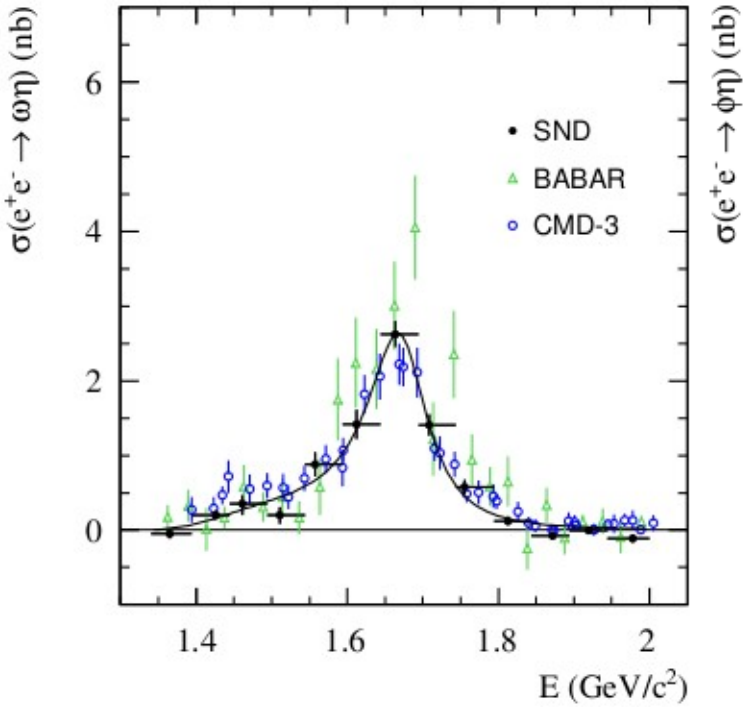
The fit to the η candidates $\gamma\gamma$ invariant mass. Background – dashed histogram.



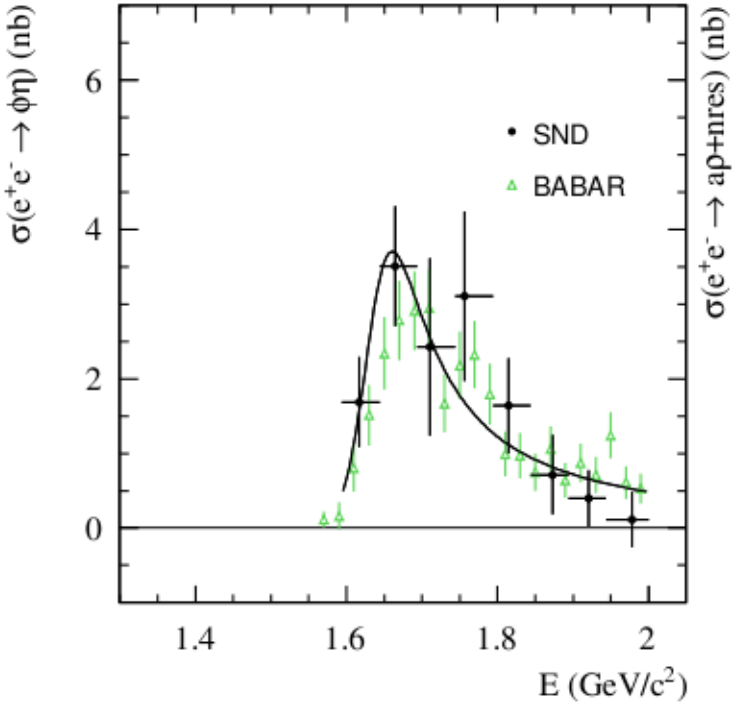
Mass recoiling against η. The solid histogram is the result of the fit with the sum of processes (1-4). The dashed histogram is the sum of the processes (3) and (4).

$e^+e^- \to \pi^+\pi^-\pi^\circ\eta$ measured cross sections (preliminary).

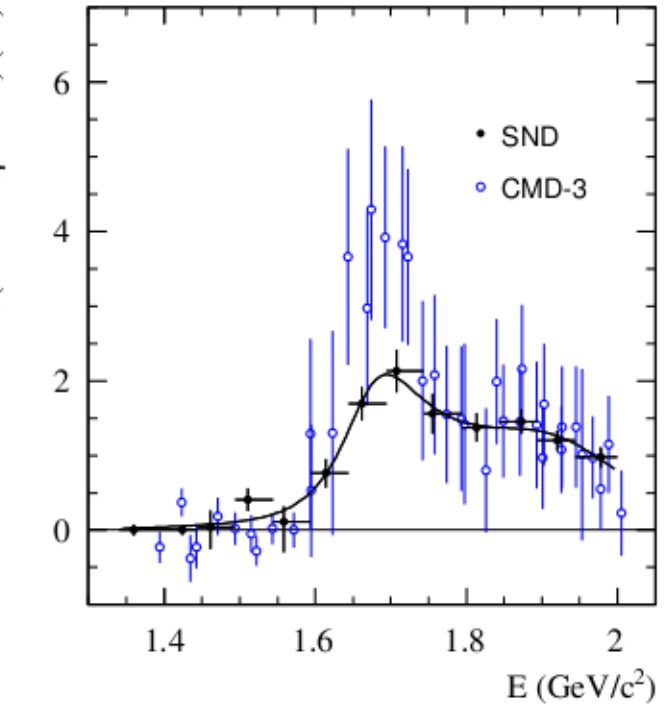
$e^+e^- \to \omega\eta$



$e^+e^- \to \phi\eta$



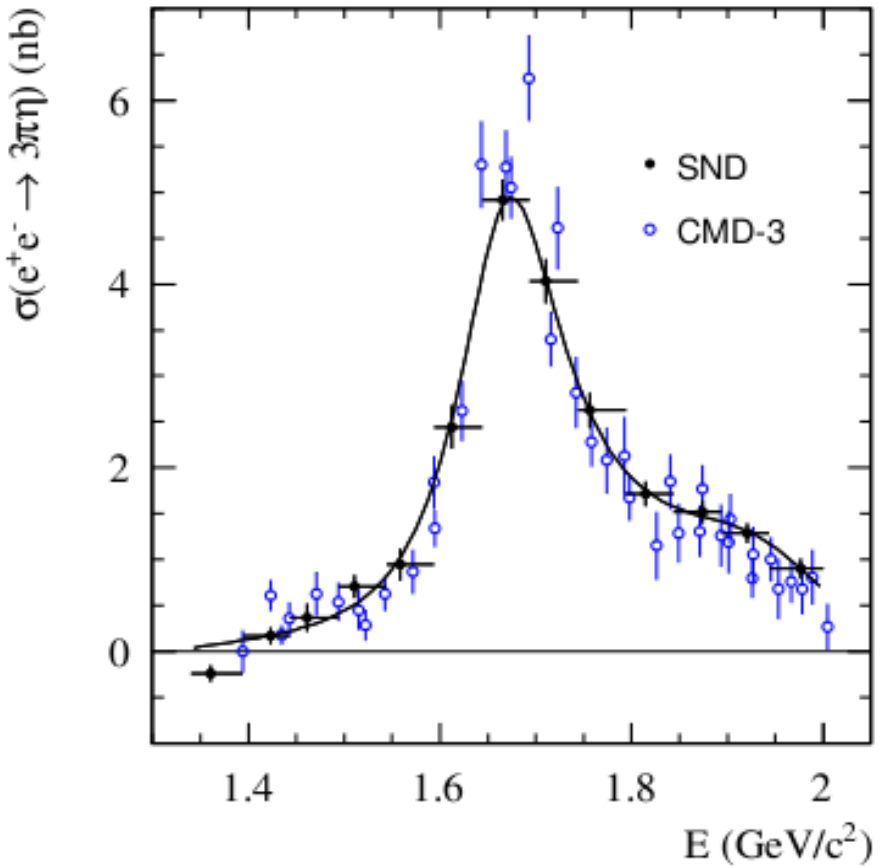
$e^+e^- \to a_0(980)\rho+3\pi\eta$



The cross-sections energy dependences are described by:

$e^+e^- \to \omega\eta$	ω' and **V(1660)** which presented ω'' and/or ϕ', $\varphi = 180^\circ$
$e^+e^- \to \phi\eta$	**V(1660)** which presented ω'' and/or ϕ'
$e^+e^- \to a_0(980)\rho+3\pi\eta$	**V(1660)** which presented ω'' and/or ϕ' and **V(1940)** which presented $\rho(1950)$ and/or $\phi(2170)$, $\varphi = 133^\circ \pm {}^{87}$

$e^+e^- \to \pi^+\pi^-\pi^\circ\eta$ below 2 GeV (preliminary).



The total cross section of the annihilation $e^+e^- \to \pi^+\pi^-\pi^\circ\eta$.

More details are available in poster by A.A. Botov

«Measurement of the $e^+e^- \to \pi^+\pi^-\pi^\circ\eta$ cross section below $\sqrt{s}$=2GeV.»

$e^+e^- \to n\bar{n}$ below 2 GeV (preliminary).

Differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4s}\left[|G_M(s)|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E(s)|^2\sin^2\theta\right], \quad \beta = \sqrt{1-4m_N^2/s}, \quad \tau = \frac{s}{4m_N^2}.$$

G_E and G_M are electromagnetic and magnetic form factors, $|G_E|=|G_M|$ at the reaction threshold, C is Colomb form factor.

The total cross section:

$$\sigma_0(s) = \frac{4\pi\alpha^2\beta C}{3s}\left[|G_M(s)|^2 + \frac{1}{\tau}|G_E(s)|^2\right].$$

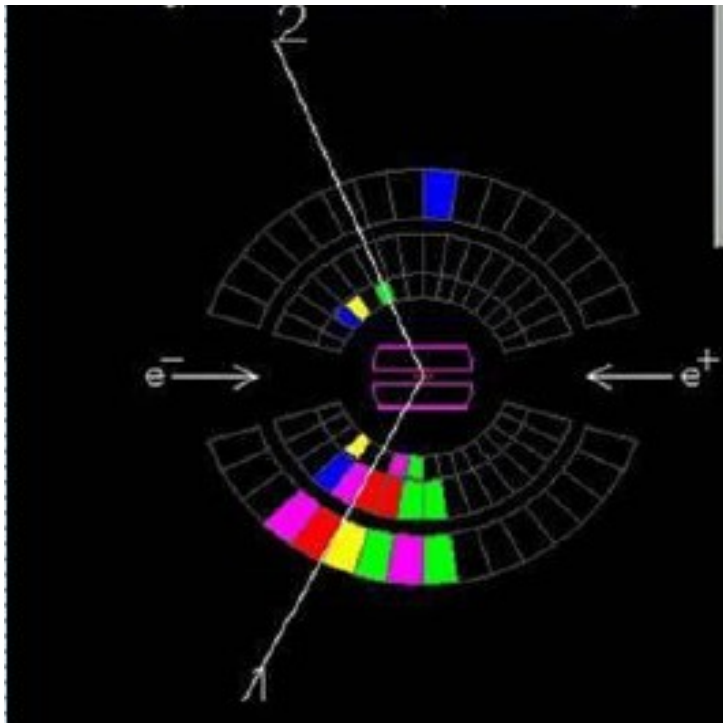
$$F(s)^2 = \frac{2\tau|G_M(s)|^2 + |G_E(s)|^2}{2\tau+1}.$$

The effective form factor can be calculated from the measured $e^+e^- \to n\bar{n}$ cross section.

The $|G_E|/|G_M|$ ratio can be obtained using $\cos\theta$ distribution.

Features of the $e^+e^- \to n\bar{n}$ events in SND.

- $\bar{n}$ annihilates in calorimeter with large energy deposition.
- Energy deposition of n is very low and it is not reconstructed.
- $\bar{n}$ is rather slow. This leads to large time-of-flight.



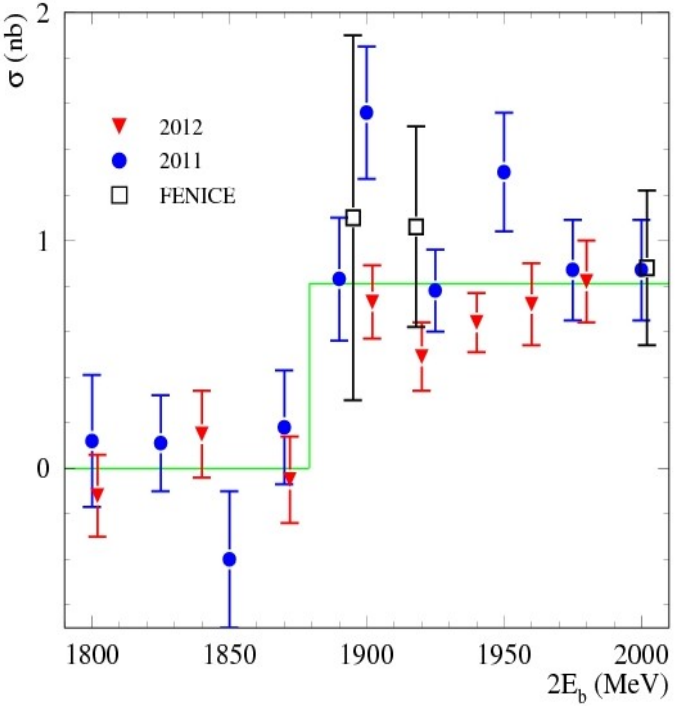
$e^+e^- \to n\bar{n}$ below 2 GeV (preliminary).

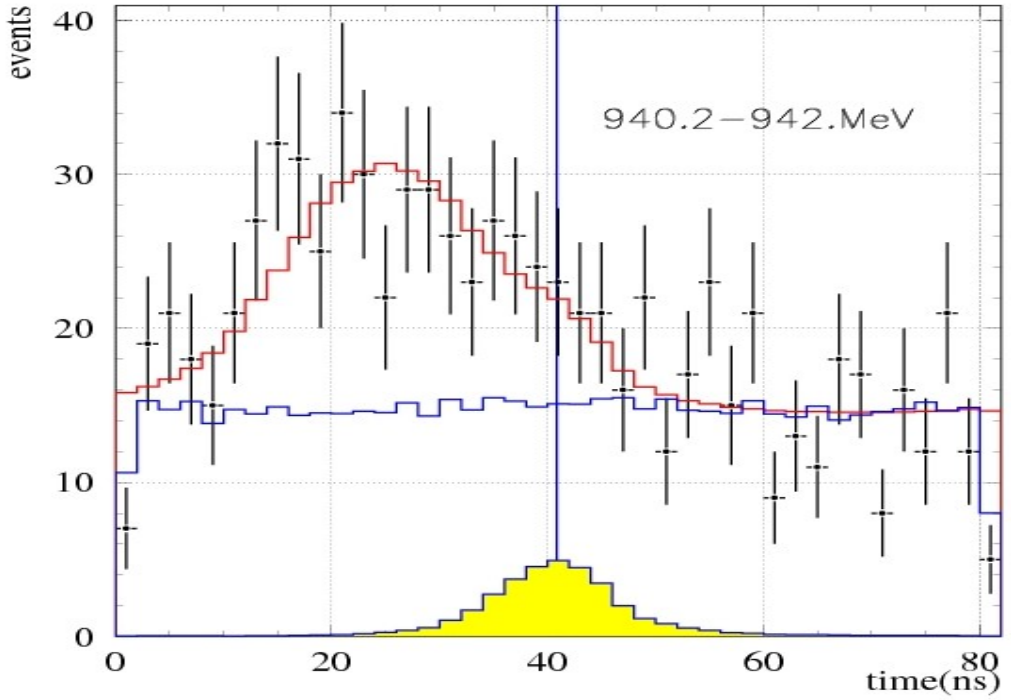
Earlier the $e^+e^- \to n\bar{n}$ process below **2 GeV** was studied by SND at VEPP-2000 (***IL=10 pb-1*** above threshold collected in 2011 and 2012) and FENICE experiments.

The ***IL=19 pb-1*** collected by SND at VEPP-2000 in 2017 above $e^+e^- \to n\bar{n}$ threshold was used.

Analysis features.

$N_{tr}=0$, $\chi^2_\gamma>0$ (no «good» photons), $36° < \theta_n < 144°$ (angular accuracy about **6°**), muon system veto, no cosmic tracks in calorimeter, **P>0.4Ebeam** (large unbalanced momentum in calorimeter), **1.05Beam<Etot<1.8 GeV**, E_3**<0.7Ebeam**.





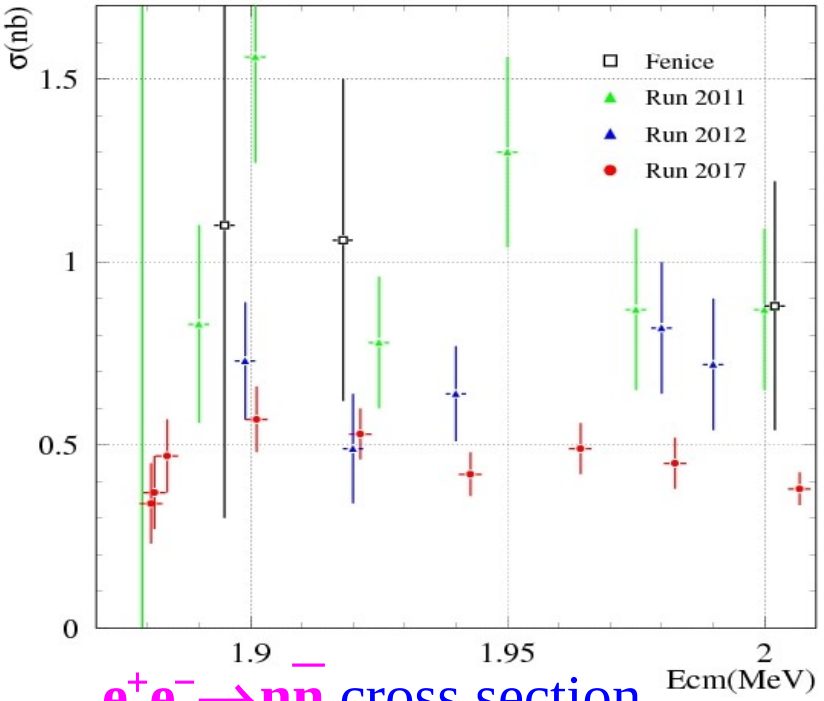
The number of $e^+e^- \to n\bar{n}$ events was obtained by the fit to distribution of event time measured by calorimeter in respect to the beam collision moment.

Blue histogram is distribution for the cosmic events,

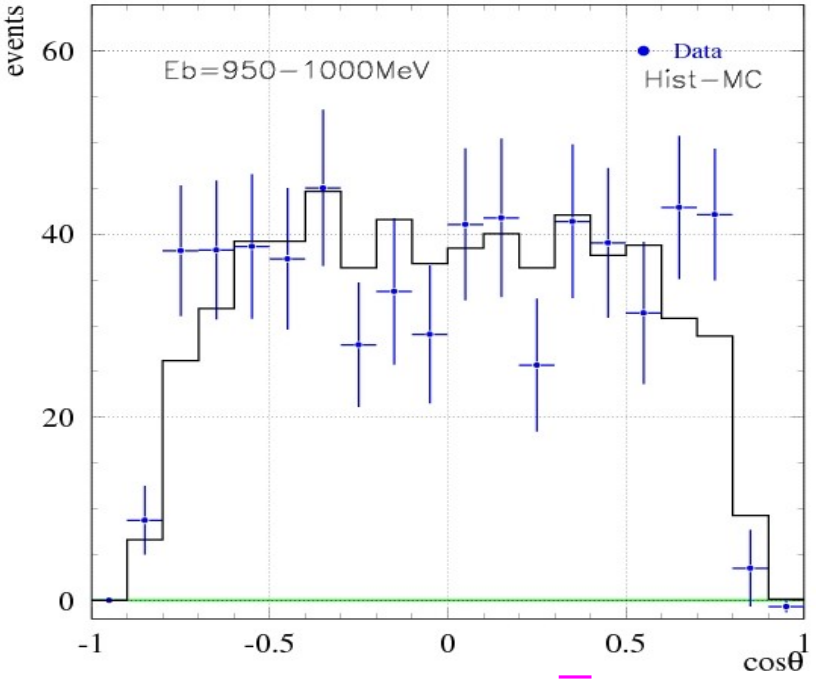
Yellow histogram is beam and e^+e^- annihilation background,

Red histogram is distribution for $e^+e^- \to n\bar{n}$ events.

$e^+e^- \to n\bar{n}$ below 2 GeV (preliminary).

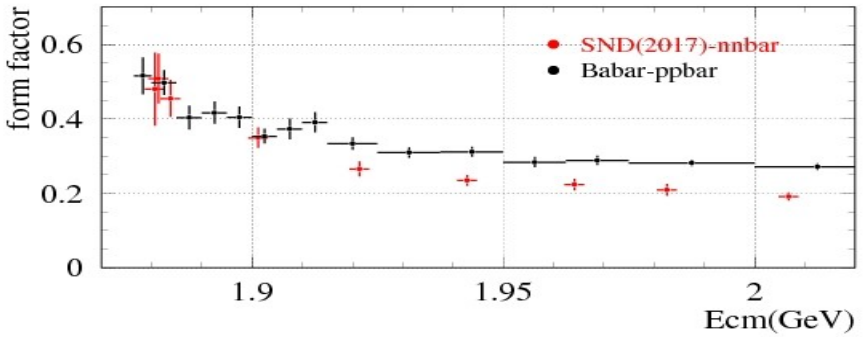


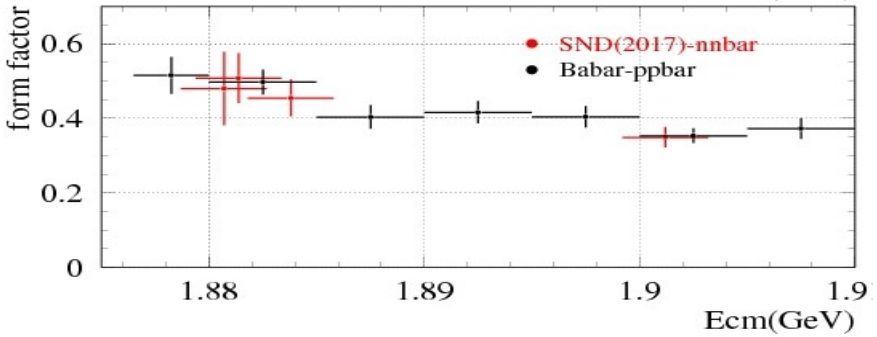
$e^+e^- \to n\bar{n}$ cross section.



cosθ for $e^+e^- \to n\bar{n}$ events.

$|G_E|/|G_M|<1.3$ 90% CL.





Neutron formfactor.

More details are available in poster

by S.I. Serednyakov

«Measurement of the $e^+e^- \to n\bar{n}$ cross section with the SND detector at the VEPP-2000 collider.»

$e^+e^- \to \pi^+\pi^- 4\pi^\circ$ belov 2 GeV (preliminary).

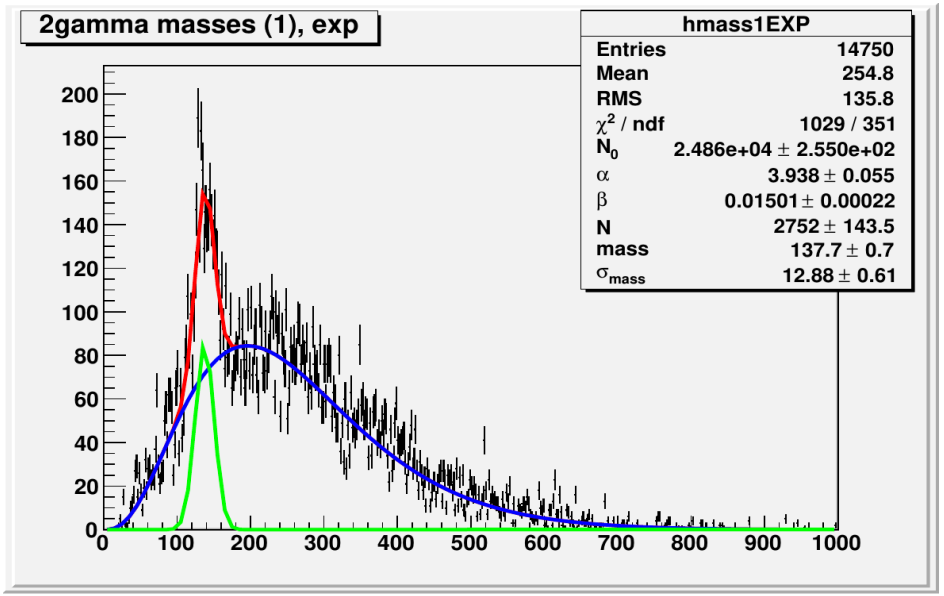
$e^+e^- \to 3\pi^+3\pi^-$ and $e^+e^- \to 2\pi^+2\pi^-2\pi^\circ$ were studied before by DM-2, BaBar and CMD-3.

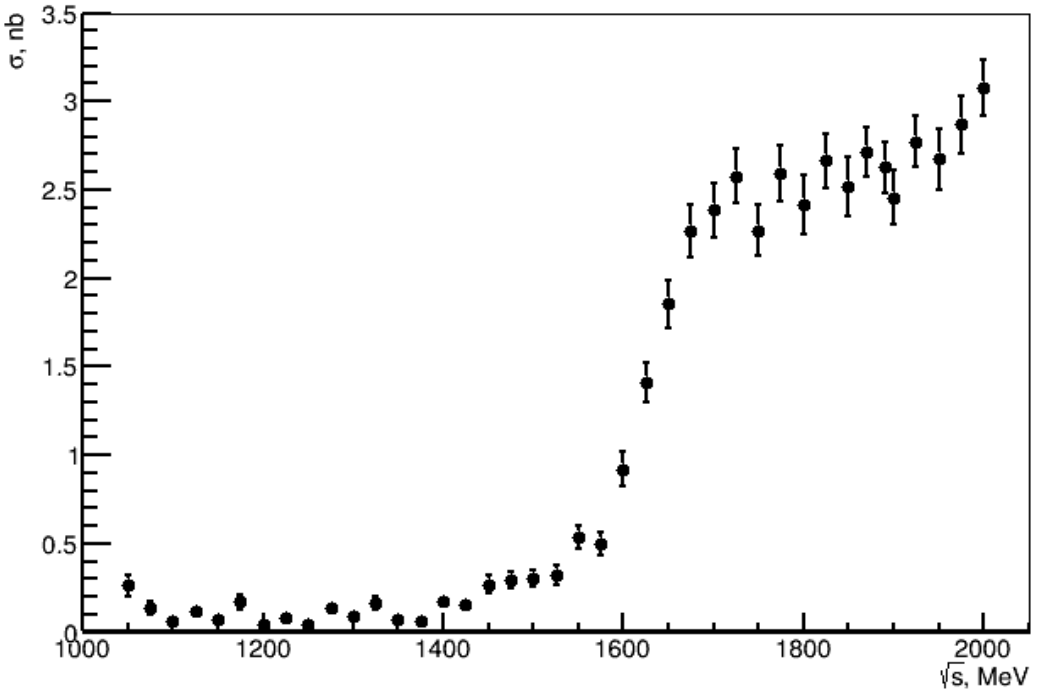
$e^+e^- \to \pi^+\pi^- 4\pi^\circ$ no data exist.

Analysis features.

$N_{tr}=2$ and $N_\gamma \geq 8$, $27^\circ < \theta_\gamma < 153^\circ$, $\sum E_\gamma > 400$ MeV.

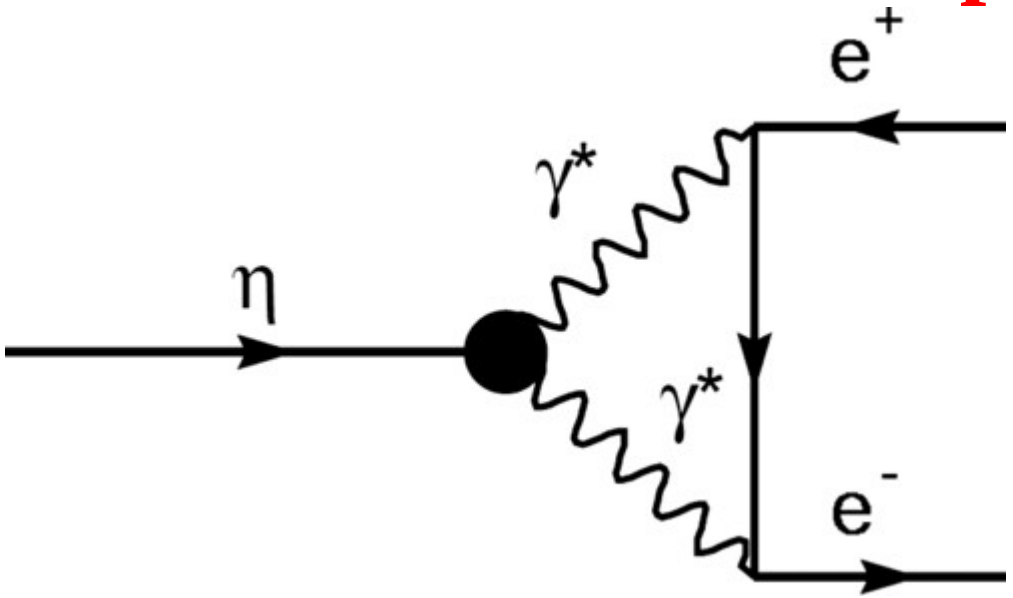
The number of $e^+e^- \to \pi^+\pi^- 4\pi^\circ$ events is determined from the fit of $m_{\gamma\gamma}$ spectrum:





$e^+e^- \to \pi^+\pi^- 4\pi^\circ$ cross section.

Search for the process $e^+e^- \to \eta$.



A search for the rare decay $\eta \to e^+e^-$ was performed using the inverse process $e^+e^- \to \eta$.
Unitary limit prediction:
$Br(\eta \to e^+e^-) = 1.78 \times 10^{-9}$.

The ***IL=654 pb-1*** collected by SND at VEPP-2000 in 2018 at the energy

$\sqrt{s} = m_\eta = 547.865 \pm 0.017$ **MeV** was used.

The beam enery was measured by Compton backscattering method.

The events $e^+e^- \to \eta \to 3\pi^\circ \to 6\gamma$ were selected. The detection efficiency was equal to 14%. No (ZERO) events was found.

The upper limit $Br(\eta \to e^+e^-) < 7 \times 10^{-7}$ ***90% CL*** was set.

Previous upper limit: $Br(\eta \to e^+e^-) < 2.3 \times 10^{-6}$ ***90% CL***.

M.N. Achasov, et. al., Phys. Rev. D98 (2018) no.5, 052007

Search for the process $e^+e^- \to f_1(1285)$.

Theoretical VDM based calculation predicts: $Br(f_1(1285) \to e^+e^-) = (3\text{-}8) \times 10^{-9}$.
A. S. Rudenko, Phys. Rev. D 96, 076004 (2017)

The $IL = 3.4\ pb^{-1}$ collected by SND at VEPP-2000 in 2017 at $\sqrt{s} = 1285$ MeV was used.

Analysis was based on selection of $e^+e^- \to \eta\pi^0\pi^0 \to 6\gamma$ events.

The main background is $e^+e^- \to \pi^0\pi^0\gamma \to 5\gamma$.

Other background processes: $e^+e^- \to \omega\pi^0\pi^0$, $\omega\eta\pi^0$, $\eta\gamma \to 7\gamma$.

Analysis features. $N_{tr} = 0$ and $N_\gamma = 6$, muon system veto, $\chi^2_\gamma < 0$ (all photons are «good»).

The events were reconstructed in tree hypothesis: $e^+e^- \to \pi^0\pi^0\gamma$, $e^+e^- \to 6\gamma$, $e^+e^- \to \eta\pi^0\pi^0$.

$\chi^2_{\pi\pi\gamma} > 25$, $\chi^2_{6\gamma} < 25$, there are no combinations $|m_{3\gamma} - m_\omega| < 35$ MeV and $|m_{2\gamma} - m_\pi| < 35$ MeV,

$\chi^2_{\eta\pi\pi} < 25$.

The detection efficiency was equal to 15%.

Two events was found. The calculated background (mainly $e^+e^- \to \pi^0\pi^0\gamma$) is 1.2 event.

The upper limit $Br(f_1(1285) \to e^+e^-) < 3.5 \times 10^{-9}$ *90% CL* was set.

Conclusion.

During **2010 – 2018** the **SND** detector accumulated **~210 pb^{-1}** of integrated luminosity at the **VEPP-2000** electron-positron collider in the c.m. energy range **0.3 – 2 GeV**.

The data taking runs are continued with a goal of **~1 fb^{-1}** of integrated luminosity.

Data analysis on hadron production is in progress. The obtained results have comparable or better accuracy than previous measurements.

For several processes the cross sections have been measured for the first time.