Study of the process $e^+e^- \to \pi^+\pi^-\pi^0\eta$ at the SND detector

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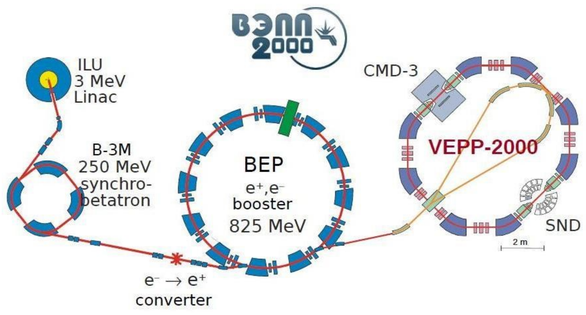
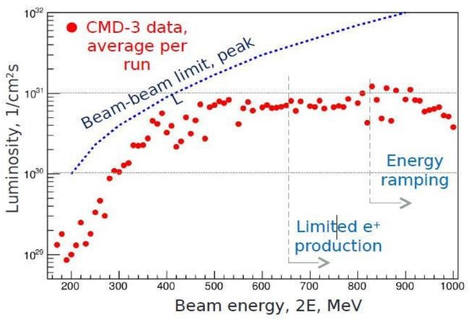
I. VEPP-2000 e^+e^- collider

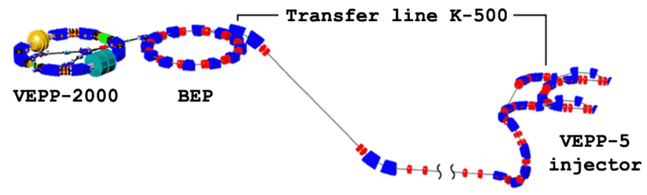


VEPP-2000 parameters:
- center-of-mass energy E=0.3-2.0 GeV
- circumference – 24.4 m
- round beam optics
- beam energy spread – 0.6 МэВ at E=1.8 GeV
- L = 1×10^{32} cm^{-2} sec^{-1} at E=1.8 ГэВ

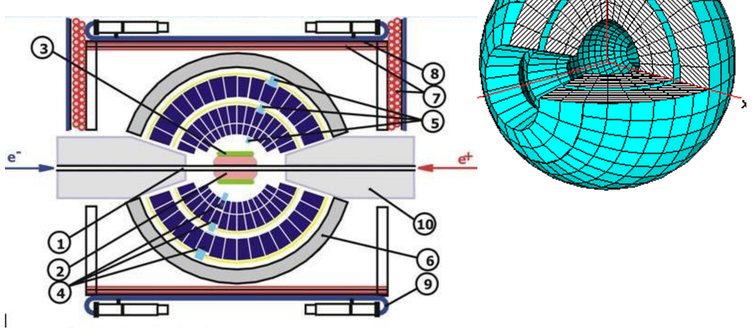


During 2010-2013 data taking period the luminosity was limited by the deficit of positrons

Currently the complex VEPP-2000 is being upgraded.
✓The maximum BEP energy will be increased up to 1 GeV.
✓The injection system will be changed. Electrons and positrons will be transported to BEP from the VEPP-5 injection complex through 250 m beamline.
✓Experiments at upgraded VEPP-2000 is expected to be started in 2016.



II. SND detector



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

Year	Energy(GeV)	L(pb^{-1})
2010	1.05-2.0	5
2011	1.05-2.0	25
2012	1.05-2.0	17
2013	0.32-1.06	22
Total	0.32-2.0	69

Experimental runs at VEPP-2000

Introduction

- Precise measurement of $e^+e^- \to hadrons$ cross section below 2 GeV is very important for determination of
  - the electromagnetic coupling constant $\alpha(M_Z)$
  - the anomalous momentum of muon
- Below 2 GeV the total cross section is calculated as a sum of exclusive cross sections
- The process $e^+e^- \to \pi^+\pi^-\pi^0\eta$ was not measured before
- This reaction proceeds via the four intermediate states:
  - $\omega\eta$ previously measured at
    - *BABAR* in the $e^+e^- \to 2(\pi^+\pi^-\pi^0)$ reaction
      B. Aubert et al. (BABAR Collaboration), Phys. Rev. D73, 052003 (2006)
    - *SND* in the process $e^+e^- \to \pi^+\pi^-\pi^0\eta$
      M. N.Achasov et al. (SND Collaboration), Phys. Rev. D94, 092002 (2016)
  - $\varphi\eta$ previously measured at BABAR in the $e^+e^- \to K^+K^-\gamma\gamma$ reaction
    B. Aubert et al. (BABAR Collaboration), Phys. Rev. D77, 092002 (2008)
  - $a_0(980)\rho$, with $a_0 \to \pi\eta$ and $\rho \to \pi\pi$ decays
  - structureless $\pi^+\pi^-\pi^0\eta$ state, which may be, for example, $\rho(1450)\pi$ with $\rho(1450) \to \rho(770)\eta$ decay
- The η meson is reconstructed via the $\eta \to \gamma\gamma$ decay

Abstract

The reaction $e^+e^- \to \pi^+\pi^-\pi^0\eta$ has been studied in the experiment with the SND detector at the VEPP-2000 e^+e^- -collider. The reaction proceeds via the four intermediate states: $\omega\eta, \varphi\eta, a^0\rho$ and structureless $\pi^+\pi^-\pi^0\eta$ state, which may be, for example, $\rho(1450)\pi$ with $\rho(1450) \to \rho(770)\eta$. The total $e^+e^- \to \pi^+\pi^-\pi^0\eta$ cross section and cross section for the four intermediate states have been measured and fitted in the vector meson dominance model.

Data and simulation

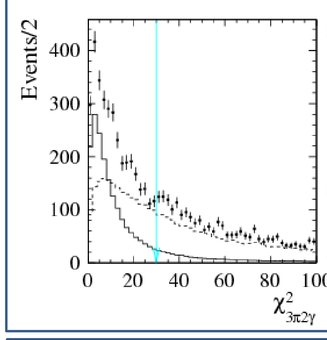
- We use data collected in 2011–2012 years
- In the c.m. energy region 1.34–2 GeV
- With integrated luminosity 27 pb^{-1}
- 36 experimental energy points are merged into 13 energy intervals with 50 MeV width
- The absolute c.m. energies for all scan points are determined with accuracy of 2–6 GeV
  - The beam energy was determined using measurements of the magnetic field in the collider bending magnets
  - To fix the absolute energy scale, a scan of the $\varphi(1020)$ resonance was performed and its mass was measured
  - In 2012 the beam energy was measured in several energy points near 2 GeV by the backscattering-laser-light system
  - The declared accuracy was obtained by the CMD-3 detector, which collected data at VEPP-2000 simultaneously with SND, using
    - laser-light system data for calibration of the momentum measurement
    - average momentum in Bhabha and $e^+e^- \to p\bar{p}$ events
- Simulation of the signal and background processes is done with Monte Carlo (MC) event generators
  - Radiative corrections to the initial particles are calculated according to
    E.A. Kuraev and V.S. Fadin, Yad. Fiz. 41, 733 (1985)
  - The angular distribution of additional photons radiated by the initial electron and positron is simulated according to
    G. Bonneau and F. Martin, Nucl. Phys. B 27, 381 (1971)
  - The cross-section energy dependences needed for radiative-correction calculation are taken from existing data for $\omega\eta, \varphi\eta$ channels and from measured cross sections for $a_0\rho$ and structureless $\pi^+\pi^-\pi^0\eta$ state through iterations
  - For simulation of the latter the hypothesis of $\omega'^{(\prime\prime)} \to \rho(1450)\pi \to \rho(770)\eta\pi\pi$ is used with coefficients nulling the η-meson recoil mass spectrum (see below) on its edges in cubic manner
- Interactions of the generated particles with the detector material are simulated using GEANT4 software
  S. Agostinelli et al., NIM in Phys. Res., Sect. A 506, 250 (2003)
- The simulation takes into account variation of experimental conditions during data taking, in particular dead detector channels and beam-induced background.
  - The latter leads to the appearance of spurious photons and charged particles in detected events. To take this effect into account, simulation uses special background events recorded during data taking with a random trigger, which are superimposed on simulated events

Luminosity

- Luminosity is measured using the process of Bhabha scattering $e^+e^- \to e^+e^-$ with the following selection:
  - There are at least two charged particles originated from the beam interaction region
  - The two most energetic of them must have
    - energies greater than $0.6E_{beam}$, where E_{beam} is the beam energy. The particle energies are determined on their energy depositions in the calorimeter
    - polar angles $\theta_{1,2}$, measured relative to the e^+e^--collision axis, satisfying conditions on mean angle $50^\circ < [\theta_1 + (180^\circ - \theta_2)]/2 < 130^\circ$ and $|\theta_1 + \theta_2 - 180^\circ| < 15^\circ$
    - their azimuthal angles $\phi_{1,2}$ be $||\phi_1 - \phi_2| - 180^\circ| < 10^\circ$
- The detection efficiency and cross section are determined using the event generator BHWIDE
  S. Jadach, W. Placzek, and B. F. L. Ward, Phys. Lett. B 390, 298 (1997)
- The theoretical uncertainty of the luminosity measurement is less than 0.5%
- The systematic uncertainty is estimated by variation of the selection criteria used and does not exceed 2%

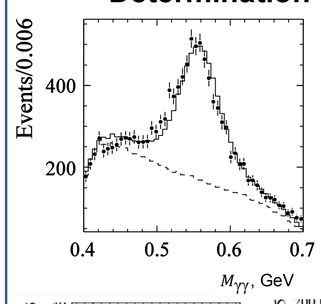
Event selection

- Preselection:
  - Two or three charged particles originated from the interaction region: $r_{1,2} < 0.3$ cm, $z_{1,2} < 15$ cm and $|\Delta z| < 5$ cm
  - At least four photons with energy greater than 20 MeV
  - The total energy deposition in the calorimeter > 300 MeV
- For selected events the vertex fit characterized by the parameter χ^2_r is performed using the parameters of two charged tracks
  - If there are three charged tracks in an event, the two tracks with the lowest χ^2_r value are selected
  - The found vertex is used to refine the measured angles of charged particles and photons
- Kinematic fit to the $e^+e^- \to \pi^+\pi^-\pi^0\gamma\gamma$ hypothesis characterized by the parameter $\chi^2_{3\pi2\gamma}$ is performed with the requirement of energy and momentum balance
  - The invariant mass of the first photon pair (π^0-meson candidate) must be in the range $70 < m_{12} < 200$ MeV
  - The invariant mass of the second photon pair (η-meson candidate) must be in the range $400 < m_{34} < 700$ MeV
  - Then m_{12} is constrained to π^0 mass
  - All possible combinations of photons are tested and the combination with the smallest $\chi^2_{3\pi2\gamma}$ is chosen
  - The photon parameters after the kinematic fit are used to recalculate the η-candidate invariant mass (M_η)
- The event is then refitted with the η-mass constraint
  - The refined η-candidate energy is then used to calculate the invariant mass of the system recoiling against the η meson (M^{rec}_η)
- Events of the process under study are selected by the conditions $\chi^2_{3\pi2\gamma} < 30$ and $0.65 < M^{rec}_\eta < 1.45$ GeV
- Suppression of the main background source from the process $e^+e^- \to \pi^+\pi^-2\pi^0(\gamma)$ is done using a kinematic fit to this hypothesis characterized by the parameter $\chi^2_{4\pi(\gamma)}$
  - In this fit, radiation of an additional photon along the beam axis is allowed
  - Events with $\chi^2_{4\pi(\gamma)} < 200$ are rejected.



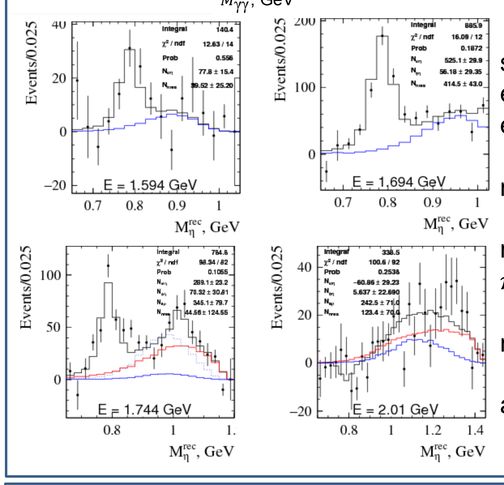
- The $\chi^2_{3\pi2\gamma}$ distribution for selected data events (points with error bars). The solid and dashed histograms represent the shapes of signal and background simulated distributions, respectively
- The narrow signal peak near zero is clearly seen in the distribution
- However, the region $\chi^2_{3\pi2\gamma} < 30$ contains a significant amount of background events.

Determination of the number of signal events



The spectrum of the two-photon invariant mass of the η-meson candidate for selected data events (points with error bars).

The solid histogram is the result of the fit to the data spectrum with a sum of signal and background distributions. The background contribution is shown by the dashed histogram



The M^{rec}_η distribution of the signal events for different c.m. energy intervals (points with error bars).

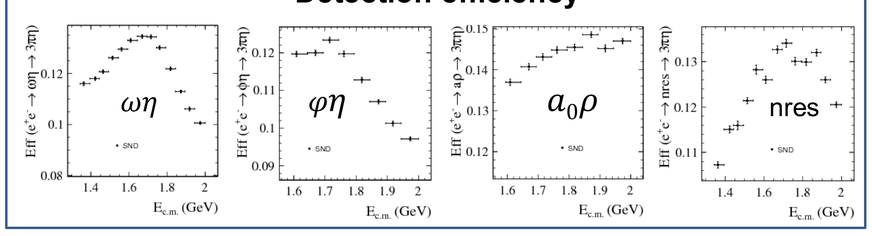
The black histogram represents the result of the fit.

The blue histogram represents the structureless $\pi^+\pi^-\pi^0\eta$ contribution.

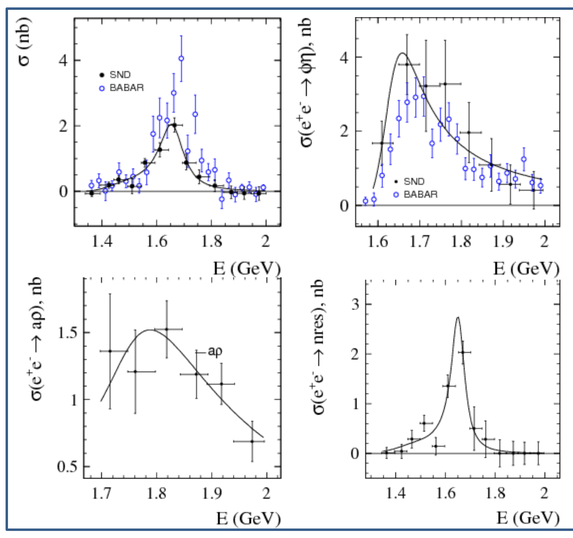
The red histogram represents the $a_0\rho$ contribution.

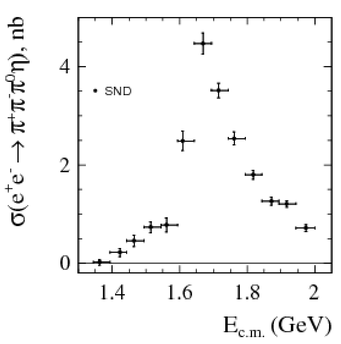
The peaks from $\omega\eta$ and $\varphi\eta$ are clearly seen.

Detection efficiency



Cross sections





$$\sigma(E) = \frac{12\pi}{E^3}\left|\sqrt{\frac{B_{\omega'}}{P_f(m_{\omega'})}}\frac{m^{3/2}_{\omega'}\Gamma_{\omega'}}{D_{\omega'}} - \sqrt{\frac{B_{\omega''}}{P_f(m_{\omega''})}}\frac{m^{3/2}_{\omega''}\Gamma_{\omega''}}{D_{\omega''}}\right|^2 P_f(E)$$

$$P_f(s) = q^3(s)/3,\ q(s) = \frac{1}{2\sqrt{s}}\sqrt{(s-(m_\omega - m_\eta)^2)(s-(m_\omega + m_\eta)^2)}.$$

$$P_f(s) = q^3(s)/3,\ q(s) = \frac{1}{2}\sqrt{1/s[s-(m_\phi - m_\eta)^2][s-(m_\phi + m_\eta)^2]}$$

$$f = a_0\rho : P_f(s) = \frac{1}{3}q_f \cdot \frac{2}{3} = \frac{2}{9}\int_{4m_\pi^2}^{(\sqrt{s}-m_{a_0})^2}\frac{dm^2}{\pi}\frac{m\Gamma_\rho(m)q(\sqrt{s},m,m_{a_0})}{(m^2-m_\rho^2)^2 + (m\Gamma_\rho(m))^2}, \Gamma_\rho(m) = \Gamma_\rho(s=m^2)$$

$$f = nres : P_f(s) = 1.$$