Study of the process $e^+e^- \longrightarrow \pi^+\pi^-\pi^0\eta$ with the CMD-3 detector on VEPP-2000

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Abstract

The analysis of the process $e^+e^- \longrightarrow \pi^+\pi^-\pi^0\eta$ uses data collected by the CMD-3 detector at the VEPP-2000 accelerator during the 2019-2023 years, corresponding to an integrated luminosity of 481.7 pb^{-1} in the center-of-mass energy range of 1440 - 2007 MeV. The preliminary cross section of the process $e^+e^- \longrightarrow \pi^+\pi^-\pi^0\eta$ and the contributions from intermediate resonant states $\omega(782)\eta$, $\phi(1020)\eta$ and $a_0(980)\rho(770)$ were measured. The current status of the analysis is presented.

VEPP-2000 and CMD-3

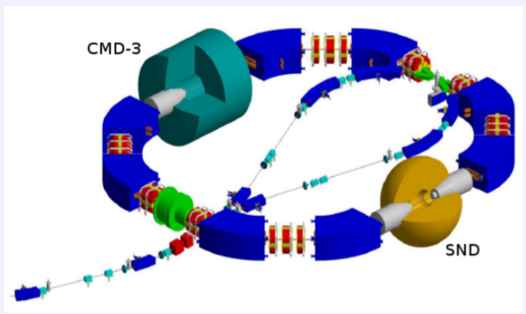

Figure 1. Scheme of the VEPP-2000.

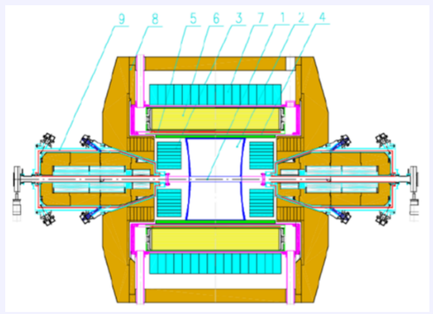

Figure 2. Scheme of the CMD-3 detector.

- round beam optics
- beam current – 0.2 A
- beam length – 3.3 cm
- beam energy spread – 0.7 MeV
- $L = 10^{32} cm^{-2} s^{-1}$ at 2E=2.0 GeV
- $L = 2 \cdot 10^{31} cm^{-2} s^{-1}$ at 2E=1.0 GeV

1. vacuum chamber,
2. drift chamber,
3. BGO-calorimeter,
4. Z-chamber,
5. superconducting solenoid,
6. LXe-calorimeter,
7. CsI-calorimeter,
8. yoke,
9. solenoid of VEPP-2000.

Selection criteria

- **Good tracks** $\pi^+\pi^-$
  - Opposite charges
  - Noncollinearity $||\phi_1 - \phi_2| - \pi| < 0.15$ and $||\Theta_1 + \Theta_2| - \pi| < 0.25$
  - Momentum p is greater than 40 MeV/c and less than the beam energy
  - Number of hits is greater than 5
  - Vertex in the beam interaction region: impact parameter $|\rho| < 0.5cm$ and z-coordinate of the track vertex $|z| < 12cm$
  - Quality of track reconstruction in the $r - \phi$ and z-planes $\chi^2 < 30$
  - Track ionization losses dE/dx in the drift chamber:

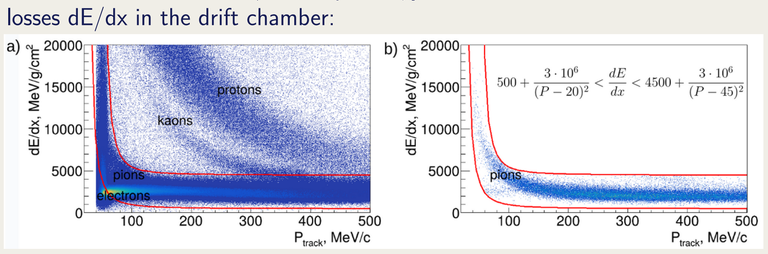

Figure 3. Ionization losses in a drift chamber as a function of track momentum in experiment and simulation.

- **Good photons** $\eta \to \gamma\gamma$, $\pi^0 \to \gamma\gamma$
  - 3 < number of photons < 10
  - photon energy > 30 MeV, partially suppresses background from processes with low-energy photons
  - beam energy greater than 120 MeV, exceeding the photon energy
  - photons from BGO at small angles with energies < 60 MeV are excluded
- **Total momentum and energy** $\Delta E = \Sigma E - 2E_{beam} < 150$; $\Sigma P < 150$

Kinematic reconstruction

For the selected events, a kinematic reconstruction procedure[*] is performed in the 5C hypothesis:

- The coordinates of the vertex in the transverse plane are fixed, and the z-coordinate is sought.
- The sum of the particle momenta is zero.
- The particle energy is equal to twice the beam energy.
- π^0 mass constrain. The four photons with the smallest χ^2 are selected.

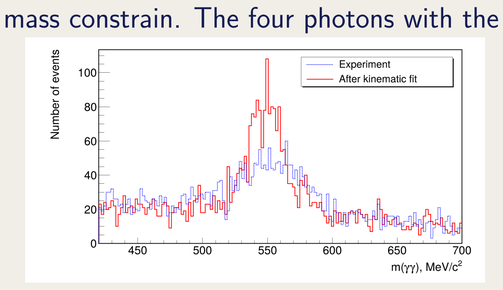

Figure 4. Signal from the η-meson at the point with $E_{c.m.} = 1600$ MeV before reconstruction (dashed line) and after (solid line)

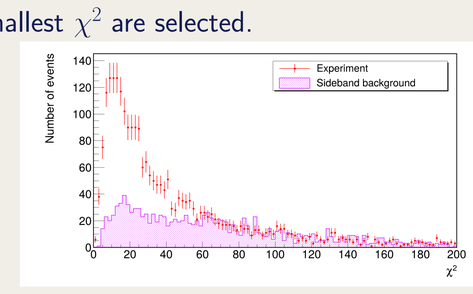

Figure 5. Distribution χ^2 for signal (mass of $\eta \in (500; 600) MeV$) and background (mass of $\eta \in (450; 500) \cup (600; 650) MeV$) regions

[*] Gribanov S.S., Popov A.S. Kinematic and vertex fitting package for the CMD-3 experiment // arXiv:2208.11569v7

Fit functions

The resonances were fitted by convolution of a Gaussian with a Breit-Wigner:

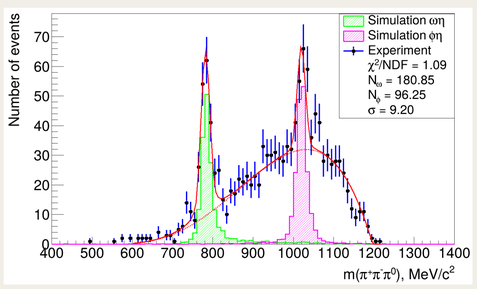

Figure 6. The $\pi^+\pi^-\pi^0$ invariant mass distribution. Histograms show expected MC-simulated signals from the $\omega(782)\eta$ and $\phi(1020)\eta$ intermediate states.

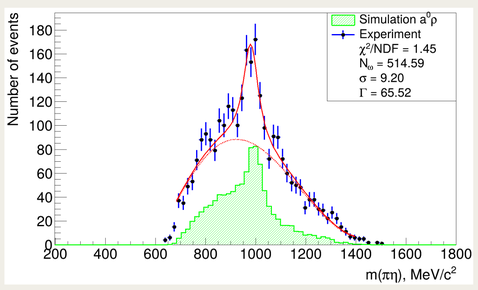

Figure 7. The $\pi\eta$ invariant mass distribution. Histogram shows expected MC-simulated signal from the $a_0(980)\rho(770)$ intermediate state.

Detection efficiency

To determine the detection efficiency, a simulation of $N_0 = 50,000$ events for three intermediate states $\omega(782)\eta$, $\phi(1020)\eta$ and $a_0(980)\rho(770)$ was used.

$$\epsilon = N/N_0,\ \Delta\epsilon = \sqrt{\epsilon(1-\epsilon)/N_0}$$

The efficiency for $e^+e^- \to \pi^+\pi^-\pi^0\eta$ was calculated as a weighted average of the efficiencies of these states, where the weights corresponded to the numbers of events observed in the experiment: $\overline{\varepsilon} = \Sigma N_i \varepsilon_i / \Sigma N_i$

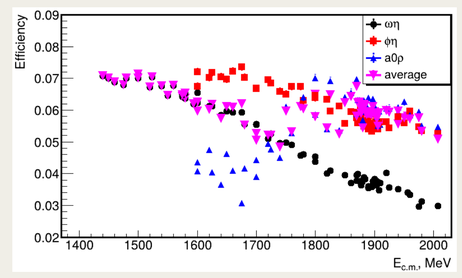

Figure 8. The detection efficiency depending on the energy in the c.m.

Radiative correction

The radiative correction is calculated iteratively using the formula:

$$\sigma_{vis} = \int_0^{\Delta E/E} \sigma_{born}(s(1-x))F(x,s)dx,$$

where $\sigma_{vis} = \sigma_{born}(1 + \delta_R)$

Initial approximation: $\sigma_{vis} = N_{data}/(L\varepsilon)$

The cross section is fitted in a two-resonance model.

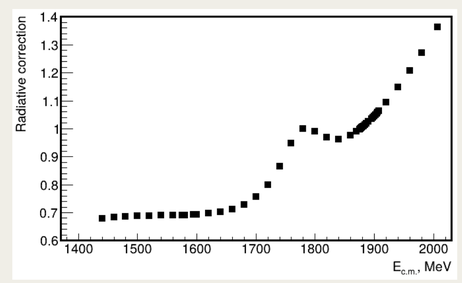

Figure 9. The radiation correction depending on the energy in the c.m.

Correction to the registration efficiency

To determine the discrepancy in the registration efficiency of neutral particles η and π^0 in experiment and simulation, a kinematic fit was made in the 2C hypothesis of lost π^0 and the correction was calculated as follows:

$$\frac{N_{events\ with\ \pi^0}}{N_{all\ events}}(MC) \cdot \frac{N_{events\ with\ \pi^0}}{N_{all\ events}}(Exp) = 1.05 \pm 0.02$$

The correction for charged pions was studied with the 3C hypothesis of lost $\pi^\pm$, calculated similarly and amounted to 0.99 ± 0.05

The values shown are averaged over all energy points.

Cross sections

The Born cross section:

$$\sigma_{born} = \frac{N_{data}}{L\epsilon(1+\delta_R)(1+\delta_\varepsilon)}$$

, where N_{data} - number of signal events, L - integral luminosity, ϵ - registration efficiency, $(1+\delta_R)$ - radiation correction, $(1+\delta_\varepsilon)$ - correction to the registration efficiency.

Systematic uncertainty: luminosity 1%, radiative correction 1%, correction for the detection efficiency of charged 9% and neutral 4% particles, selection criteria variation 1%. The quadratic sum — 10%.

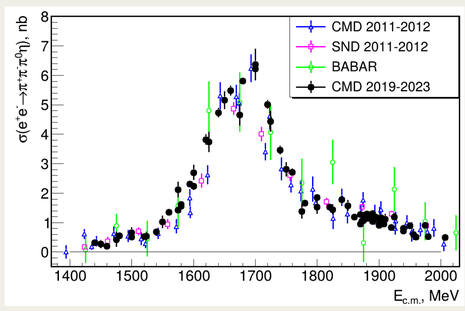

Figure 12. The cross section of the process $e^+e^- \to \pi^+\pi^-\pi^0\eta$

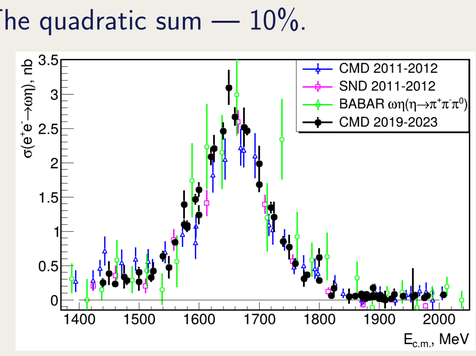

Figure 10. The cross section of the process $e^+e^- \to \omega(782)\eta$

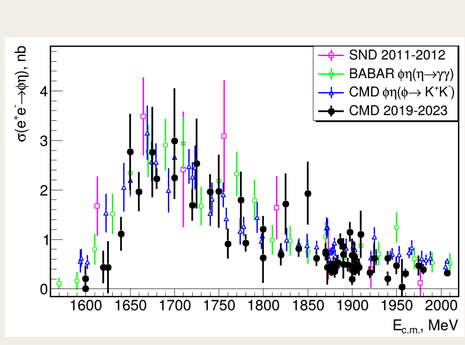

Figure 13. The cross section of the process $e^+e^- \to \phi(1020)\eta$

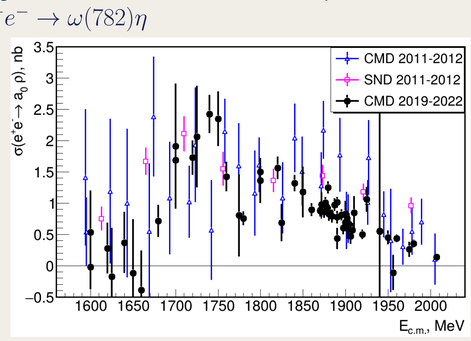

Figure 11. The cross section of the process $e^+e^- \to a_0(980)\rho(770)$

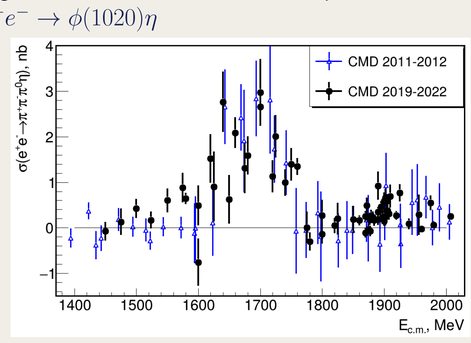

Figure 14. The cross section of the process $e^+e^- \to \pi^+\pi^-\pi^0\eta$ $(no\ \omega, \phi, a_0)$

Future plan

Study the dynamics of the process for the presence of contributions from unaccounted intermediate resonances, investigate the interference between resonances.