Measurement of the hadronic cross sections with the CMD-3 and SND detectors at the VEPP-2000 collider

Aleksandr Korol
Budker Institute of Nuclear Physics
Novosibirsk State University
(on behalf of the SND and the CMD-3 collaborations)

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VEPP-2000 $e^+e^-$ collider

- c.m. energy 0.3-2.0 GeV
- circumference – 24.4 m
- round beam optics
- luminosity at 2 GeV:
  - $1 \times 10^{32}$ cm$^{-2}$ sec$^{-1}$ (project)
  - $2 \times 10^{31}$ cm$^{-2}$ sec$^{-1}$ (achieved)

During 2010-2013 the luminosity was limited by shortage of positrons.
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.

[NIM A449 (2000) 125-139]

**Calorimeter**
- $13.5X_0$, $0.95 \times 4\pi$
- Energy resolution
  $$\frac{\sigma_E}{E} = \frac{0.042}{\sqrt{E[GeV]}}$$
- Angular resolution
  $$\sigma_\varphi = \frac{0.82^\circ}{\sqrt{E[GeV]}} \oplus 0.63^\circ$$

**Tracking system**
- 9 layers, $0.94 \times 4\pi$
- Angular resolution
  $$\sigma_\varphi = 0.55^\circ, \sigma_\theta = 1.2^\circ$$
- Vertex position resolution
  $$\sigma_R = 0.12cm, \sigma_Z = 0.45cm$$

**Aerogel counters**
- K/π separation $E < 1 \text{ GeV}$
CMD-3 detector

Calorimeter

\[ 13.5X_0 \]
\[ \frac{\sigma E}{E} \sim 3...10\% \]
\[ \sigma_0 \sim 5 \text{ mrad} \]

Tracking

\[ 1...1.3 \text{ T} \]
\[ \sigma_{R\varphi} \sim 100 \mu \]
\[ \sigma_z \sim 2...3 \text{ mm} \]

1 – vacuum chamber, 2 – drift chamber, 3 – electromagnetic calorimeter BGO, 4 – Z-chamber, 5 – CMD SC solenoid, 6 – electromagnetic calorimeter LXe, 7 – electromagnetic calorimeter CsI, 8 – yoke, 9 – VEPP-2000 solenoid
Beam energy measurements: CBS system

Backscattered photons spectrum edge: parameters B, S, E

\[ \frac{\Delta E}{E} \leq 5 \cdot 10^{-5} \]

E.V. Abakumova et al., PRL 110 2013 140402
# Data collected 2010-2013

<table>
<thead>
<tr>
<th>Years</th>
<th>Energy $\sqrt{s}$ (GeV)</th>
<th>$L$(pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-2012</td>
<td>1.05 − 2.0</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>&gt;1.88</td>
<td>8.8</td>
</tr>
<tr>
<td>2013</td>
<td>0.32 − 1.06</td>
<td>22</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>67</strong></td>
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</tbody>
</table>

Collected $L \sim 67$ pb$^{-1}$ per detector

- 8.3 pb$^{-1}$ $\omega$-region
- 9.4 pb$^{-1}$ below 1 GeV (except $\omega$)
- 8.4 pb$^{-1}$ $\phi$-region
- 41 pb$^{-1}$ above $\phi$
Collider upgrade

Collider upgrade

e^+/sec  \(2 \times 10^7\) to \(2 \times 10^8\)
e^-/sec  \(10^9\) to \(10^{11}\)

booster up to 1 GeV

started end 2016

BEP, 1000 MeV booster

VEPP-2000
Collected data graphs

CMD-3 Integrated Luminosity

1/pb

Day

2011
2012
2013
2017
Physical program

1. **Study of dynamics of hadron production**, i.e. separation between different intermediate states, for example, $\omega \eta$, $\varphi \eta$, $\rho a_0$ etc. in the reaction $e^+ e^- \to \pi^+ \pi^- \pi^0 \eta$. This is needed for understanding hadronization mechanisms.
2. **Hadron spectroscopy**: study of light-vector-meson excitations, in particular, search for their radiative decays.
3. **Search for rare and forbidden decays** of the $\rho$, $\omega$, and $\varphi$ mesons.
4. **Study of nucleon-antinucleon pair production**, extraction of the proton and neutron electromagnetic formfactors.
5. **Two-photon physics**, in particular, measurement of the photon-meson transition form factors for $\pi^0$, $\eta$, $\eta'$.
6. **Search for production of C-even resonances**: $e^+ e^- \to \eta$, $\eta'$, $f_1, f_2, a_2$ ...
7. **Using radiative return** technique as alternative method for measurement of hadronic cross sections.
8. **Measurement of exclusive hadronic cross sections below 2 GeV**. The goal is to obtain the total cross section for $e^+ e^- \to hadrons$, which used for calculation HVP contribution to the muon (g-2) and the running $\alpha_{QED}$.
9. **Test of high-order QED**: $2 \to 4, 5$.
10. etc.
e^+e^- \rightarrow \pi^+\pi^-

\[(g-2)_\mu\]

\[a_{\mu}^{\text{had, LO-VP}} = \frac{\alpha^2 m_\mu^2}{9\pi^2} \int_{m_\mu^2}^{\infty} ds \frac{K(s)}{s^2} R(s)\]

\[R(s) = \frac{\sigma(e^+e^- \rightarrow \gamma^* \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}\]

Contribution to the hadronic part of \((g-2)_\mu\) value from the VEPP-2000 energy region is about 92%:

Contribution and squared error fraction:

The goal is to reach systematic error under 0.36% (now radiative correction to 0.2-0.4%, e/\mu/\pi separation 0.1-0.5%, 0.3-0.6% pion decay and nuclear interaction).
R(s) at $\overline{N}N$ threshold

One of first results from CMD-3:
Sudden drop of $3\pi^+3\pi^-$ cross section at $\overline{N}N$ threshold.
Preliminary studies of dynamics of $3\pi^+3\pi^-$ show also hint of energy dependent dynamics in 1.7-1.9 GeV energy range.
In 2017, detectors collected ~ 13 pb\textsuperscript{−1} per detector in the narrow energy range around threshold. Very first look at the (CMD-3) 3π\textsuperscript{+}3π\textsuperscript{−} data: the sharp drop in cross section is confirmed and can be described either as a single transition with ~2.5 MeV width or as two narrow transitions at pp and nn thresholds (consistent with only beam energy spread, MeV)
Process $e^+e^- \rightarrow \pi^0\gamma$

- Third largest cross section (after $2\pi$ and $3\pi$) below 1 GeV
- Measurement of the $\pi^0\gamma^*\gamma$ transition form factor
- Measurement of the radiative decays $V \rightarrow \pi^0\gamma$, $V=\rho, \omega, \phi, \ldots$
- There is a tension between the KLOE measurement of the ratio $\Gamma(\omega \rightarrow \pi^0\gamma)/\Gamma(\omega \rightarrow \pi^+\pi^-\pi^0)$ and other measurements of $\omega$-meson parameters:

  KLOE have studied the $e^+e^- \rightarrow \omega\pi^0$ process near the $\phi$-meson resonance in two decay modes $\omega \rightarrow \pi^+\pi^-\pi^0$ and $\omega \rightarrow \pi^0\gamma$

The $\omega$-meson parameters obtained through KLOE studies have a large shifts from the previously measurements, especially for $\omega \rightarrow \pi^0\gamma$ decay.

F. Ambrosino, et. al.,
VEPP-2M and VEPP-2000 data
The process $e^+e^-\rightarrow\gamma\gamma$ is used for normalization.

Common selection criteria for $2\gamma$ and $3\gamma$ final states:

- trigger, no charged tracks, total energy deposition and momentum, muon system veto.

Final selection is **based on 4C kinematic fit:**

$$\chi^2_{3\gamma} < 30, \quad 36^\circ < \theta_\gamma < 144^\circ, \quad 80 < M_{\text{rec}} < 190 \text{ MeV},$$

here $M_{\text{rec}}$ is the mass recoiling against largest energy photon.

The number of signal events is determined from the fit of $\pi^0$ in $M_{\text{rec}}$ spectrum.

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Results on radiative decays

\[ B(\omega \to \pi^0 \gamma)B(\omega \to e^+e^-) = (6.336 \pm 0.056 \pm 0.089) \times 10^{-6} \]

Using PDG value for \( B(\omega \to \pi^+\pi^-\pi^0) \times B(\omega \to e^+e^-) \) we have obtained
\[ \Gamma(\omega \to \pi^0 \gamma)/\Gamma(\omega \to \pi^+\pi^-\pi^0) = 0.0992 \pm 0.0023, \]
which is higher than the KLOE value \( 0.0897 \pm 0.0016 \) by \( 3.4\sigma \).

\[ B(\rho \to \pi^0 \gamma) = (4.20 \pm 0.47 \pm 0.22) \times 10^{-4} \]

By \( 1.8\sigma \) lower than the current PDG value \( (6.0 \pm 0.8) \times 10^{-4} \), but agrees with the branching fraction for the charged mode \( B(\rho^\pm \to \pi^\pm \gamma) = (4.5 \pm 0.5) \times 10^{-4} \).

\[ B(\phi \to \pi^0 \gamma)B(\phi \to e^+e^-) = (3.92^{+0.71}_{-0.40} \pm 0.51) \times 10^{-7} \]

The model uncertainties of the previous measurements (\( \sim 8\% \)) were underestimated. For \( \phi_\phi \) fixed at the value \( (163 \pm 7)^\circ \) obtained in the VMD fit to \( e^+e^- \to \pi^+\pi^-\pi^0 \) data
\[ B(\phi \to \pi^0 \gamma)B(\phi \to e^+e^-) = (4.04 \pm 0.09 \pm 0.19) \times 10^{-7} \]
$K_L K_S$ and $K^+ K^-$ at $\varphi(1020)$

$e^+ e^- \rightarrow K^0_S K^0_L$

Used luminosity $\sim 6 \text{ pb}^{-1}$
Systematic error for $K_L K_S$ is 1.8%
Systematic error for $K^+ K^-$ is 2.5%
(preliminary)
The complex form of these cross sections is due to interference of many excited vector resonances in this energy region.

K⁺, K⁻ selection was done using aerogel counters.
\( e^+ e^- \rightarrow \omega \pi^0 \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \)

The result is based on the data subset 2011-2012

- Statistical error 2-16% depending from energy
- Systematic error 1-9%

preliminary
Exclusive vs inclusive measurements

Below 2 GeV the total hadronic cross section is calculated as a sum of exclusive cross sections.

Currently the exclusive and inclusive data below 2 GeV are in reasonable agreement.

In the energy region 1.5-2.0 GeV exclusive data are incomplete. There are no experimental data on the final states $\pi^+\pi^-\pi^0\eta$, $\pi^+\pi^-\eta\eta$, $\pi^+\pi^-\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0\pi^0\eta$, ...
The process $e^+e^- \rightarrow \pi^+\pi^-\pi^0\eta$ has been measured separately.

The known $\omega\eta$ and $\phi\eta$ contributions explain about 50-60% of the cross section below 1.8 GeV.

Above 1.8 GeV the dominant reaction mechanism is $a_0(980)\rho$.

The intermediate states are $\omega\eta$, $\phi\eta$, structureless $\pi^+\pi^-\pi^0\eta$ and $a_0(980)\rho$.

First measurements of this process.

The systematic error is 15%.

arXiv:1607.00371 [hep-ex]
arXiv: 1706.06267v1
Events of the $e^+e^- \rightarrow \pi^0\pi^0\eta\gamma \rightarrow 7\gamma$ process are selected. The dominant intermediate state is $\omega\pi^0\eta$. No noticeable $\eta'\gamma$ signal observed.

The $\eta\pi^0$ mass spectrum for selected $\omega\pi^0\eta$ events is well described by the model of the $\omega a_0 (980)$ intermediate state.
e^+e^- → ωπη: cross section

- First measurement of the e^+e^- → ωπη cross section.
- The cross-section energy dependence is described by a single-resonance model.
- The resonance mass and width are consistent with those for \( \rho(1700) \) and non-resonant is worse at 1.2σ.

The cross section is about **2.5 nb.**
5% of the total hadronic cross section in the energy region **1.8 – 2.0 GeV.**

It is assumed that the dominant reaction mechanism is $\phi(1680) \rightarrow \phi(1020)\eta$. This hypothesis is in agreement with the data.
Analysis is based on the integrated luminosity of 34 pb$^{-1}$

Two intermediate states are clearly seen: $\phi\pi^0$ and $K^*(892)K$ mechanism. The current systematic uncertainty is estimated as 10%
Conclusions

• During 2010 – 2013 the SND detector accumulated ~70 pb\(^{-1}\) of integrated luminosity at the VEPP-2000 electron-positron collider in the c.m. energy range 0.3 – 2 GeV.

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

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

• After VEPP-2000 upgrade the data taking runs are continued with a goal of ~1 fb\(^{-1}\) of integrated luminosity.
Thank you!
CBS interference illustration
Mass for \( \text{pi0 gamma} \)

**VEPP-2M and VEPP-2000 data**
The process \( e^+e^- \rightarrow \gamma\gamma \) is used for normalization.

**Common selection criteria for 2\( \gamma \) and 3\( \gamma \) final states:**
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Final selection is **based on 4C kinematic fit:**
\[
\chi^2_{3\gamma} < 30, \quad 36^\circ < \theta_\gamma < 144^\circ, \quad 80 < M_{\text{rec}} < 190 \text{ MeV},
\]
here \( M_{\text{rec}} \) is the mass recoiling against largest energy photon.

The number of signal events is determined from **the fit of \( \pi^0 \) in \( M_{\text{rec}} \) spectrum.**

![Graphs showing mass recoiling against largest energy photon](image)

around \( \omega \)  
around \( \phi \)  
below 1.4 GeV  
above 1.4 GeV
Magnetic moment

\[ \tilde{\mu} = g \frac{e \hbar}{2mc} \hat{S} \]

✓ The Dirac equation predicts \( g = 2 \) for point-like fermions.

✓ Higher order QFT contributions lead to nonzero

\[ a = (g-2)/2 \]

✓ \( a_\mu \) is sensitive to New Physics contributions

E821@BNL (1997-2001):
G.W. Bennett \textit{et al.},
\[ a_\mu = (11\,659\,209.1 \pm 6.3) \times 10^{-10} \) (0.54 ppm)\]

E989 @ FNAL (2017-...):
F. Gray \textit{et al.}, arXiv: 1510.003
\[ a_\mu = ... (0.14 \text{ ppm}) \]

E34 @ J-PARC (????-...):
T. Mibe \textit{et al.},
Chin. Phys. C \textbf{34} (2010) 745
\[ a_\mu = ... (0.1 \text{ ppm}) \]
The most precise measurement of the cross section

Systematic uncertainty at the $\omega$ peak is 1.4% (1.2% from luminosity and 0.6% due to selection criteria)