Recent results on $e^+e^- \rightarrow$ hadrons cross sections from SND and CMD-3 detectors at VEPP-2000 collider

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Main parameters:
- collision period – 82 ns
- beam current – 0.2 A
- bunch length – 3.3 cm
- perimeter – 24.4 m
- Energy spread – 0.7 MeV
- $\beta_x \approx \beta_z = 6.3$ cm

Designed luminosity:
- $L \sim 2 \times 10^{31}\text{cm}^{-2}\text{c}^{-1}$ (2E=1.0 GeV)
- $L \sim 10^{32}\text{cm}^{-2}\text{c}^{-1}$ (2E=2.0 GeV)

Achieved luminosity (2011-2013):
- $L \sim 5 \times 10^{30}\text{cm}^{-2}\text{c}^{-1}$ (2E=1.0 GeV)
- $L \sim 2 \times 10^{31}\text{cm}^{-2}\text{c}^{-1}$ (2E=2.0 GeV)
Detectors for VEPP-2000

SND

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

CMD-3

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
## Collected Luminosity

### Experiments 2010 - 2012

<table>
<thead>
<tr>
<th>Experiment/ year (1.05 – 2.0 GeV)</th>
<th>Integrated luminosity</th>
<th>√s &gt; 1.88 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>5 pb⁻¹</td>
<td>0.07 pb⁻¹</td>
</tr>
<tr>
<td>2011</td>
<td>25 pb⁻¹</td>
<td>3.8 pb⁻¹</td>
</tr>
<tr>
<td>2012</td>
<td>17 pb⁻¹</td>
<td>4.9 pb⁻¹</td>
</tr>
<tr>
<td>Total</td>
<td>47 pb⁻¹</td>
<td>8.8 pb⁻¹</td>
</tr>
</tbody>
</table>

### Experiment 2013

<table>
<thead>
<tr>
<th>Energy region (√s, GeV)</th>
<th>Integrated luminosity, pb⁻¹</th>
<th>ρ - ω region, pb⁻¹</th>
<th>η' - meson region, pb⁻¹</th>
<th>φ - meson region, pb⁻¹</th>
<th>non-resonant, pb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.32–1.06</td>
<td>25</td>
<td>8.8</td>
<td>2.7</td>
<td>6.9</td>
<td>6.6</td>
</tr>
</tbody>
</table>

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# List of processes

1. $e^+e^- \rightarrow \eta\gamma \rightarrow 7\gamma$
2. $e^+e^- \rightarrow \pi^+\pi^-$
3. $e^+e^- \rightarrow K^+K^-$
4. $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$
5. $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$
6. $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$
7. $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^+\pi^+\pi^0\pi^0$
8. $e^+e^- \rightarrow \pi^+\pi^-\pi^0$
9. $e^+e^- \rightarrow \pi^+\pi^-\eta$
10. $e^+e^- \rightarrow \pi^+\pi^-\pi^0\eta$
11. $e^+e^- \rightarrow p\ anti-p$
12. $e^+e^- \rightarrow n\ anti-n$

And some others already published or planned to be studied.
$e^+e^- \rightarrow \eta\gamma \rightarrow 7\gamma$ (32 pb$^{-1}$)  
(first measurement for $\sqrt{s} > 1.4$GeV)

It is the first observation of radiative decays of $\rho(1450)$ and $\phi(1680)$ mesons.

Sum of $\rho(770)$, $\omega(782)$, $\phi(1020)$ and $\rho(1450) \ eta \phi(1680)$ with interference

About 30 events $\eta\gamma$ above 1.15 GeV, are explained by $\rho(1450)$ and $\phi(1680)$ decays.

Peak cross sections are much larger than theoretical predictions from quark model: about 15 pb for $\rho(1450)$ and about 10 pb for $\phi(1680)$.
\[ e^+e^- \rightarrow \pi^+\pi^- \]

- Gives largest contribution to \((g-2)_\mu\) calculation (65% of \(\delta a_\mu\))
- Goal is to reach systematic uncertainty at the level of 0.35%

\[ |F_\pi|^2 \]

\[ \frac{(N_{\mu\mu}/N_{ee})_{\text{exp}}}{(N_{\mu\mu}/N_{ee})_{\text{QED}}} \]

- \(e/\mu/\pi\) separation using particles momentum
- can measure \(N(\mu\mu)/N(\text{ee})\) and compare to QED

\[ \chi^2 / \text{ndf} \]

Preliminary
Complicated form of cross section is connected with interference of all excited vector resonances of this energy region.

Kaon selection was done using aerogel counters.
\[ e^+e^- \rightarrow K^+K^-\pi^+\pi^- \]

**Preliminary**

BABAR
CMD-3

Analysis is close to publication

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\[ e^+ e^- \rightarrow \pi^+ \pi^- \pi^+ \pi^- \]

- Clean selection of 4 and 3 charged pions
- Statistical errors are at the level of 1-2\% per point
- Systematical errors are under investigation

Preliminary mass distributions:

- \(a_1(1260)\pi\) dominance
- Other states (\(\rho(770)f_0(600)\), \(\rho(770)f_0(980)\), etc.) are seen, but small.
$e^+ e^- \rightarrow 6\pi$

$e^+ e^- \rightarrow 3(\pi^+\pi^-)$

$e^+ e^- \rightarrow 2(\pi^+\pi^-\pi^0)$


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\(e^+e^- \rightarrow \pi^+\pi^-\gamma\gamma\)

\(e^+e^- \rightarrow \pi^+\pi^-\pi^0\)

\(e^+e^- \rightarrow \pi^+\pi^-\eta\)

- Preliminary

\(\omega(783), \omega'(1420), \omega''(1650)\)

\(\rho(770), \rho'(1450), \rho''(1700)\)

Systematic error: \(\sim 5\%\)

Only half of statistics

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$e^+e^- \rightarrow \pi^+\pi^-\pi^0\eta \ (\eta \rightarrow 2\gamma)$

First measurement

Intermediate states $\omega\eta$, $\phi\eta$, $\alpha\rho$ are clearly seen

Preliminary

Domain $\sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^0\eta)$, nb

SND

$\Omega''(1650)$

$\phi'(1680)$

Events/0.025

$\omega(783)$

$\phi(1020)$

Domain $M_{\eta}^{\text{rec}}$ (GeV)

E_{c.m.} (GeV)
Baryon cross sections

Total cross section: \[
\sigma(s) = \frac{4\pi\alpha^2 \beta C}{3s} \left( |G_M(s)|^2 + \frac{2M^2_N}{s} |G_E(s)|^2 \right),
\]

where C is the Coulomb factor, \(G_E\) and \(G_M\) are the electric and magnetic form factors.

For protons: \[C \approx \frac{\pi\alpha}{\beta} \left( 1 - e^{-\frac{\pi\alpha}{\beta}} \right)\]
for neutrons: C=1

Cross section is not zero at threshold

From the measured cross section, a combination of the squared form factors \((G_E,G_M)\) can be extracted.

Differential cross section: \[
\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4s} \left( |G_M(s)|^2 \left( 1 + \cos^2 \vartheta \right) + \frac{4M^2_N}{s} |G_E(s)|^2 \sin^2 \vartheta \right)
\]

The ratio of the form factors \(|G_E/G_M|\) can be determined from the analysis of the polar-angle distribution.
$e^+e^- \rightarrow p\bar{p}$

**Cross section**

- **Systematic error**: $\sim 6\%$

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**Preliminary**

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e^+ e^- \rightarrow p \bar{p} \\
(Angular distribution)

|G_E|^2 \leftrightarrow \sin^2 \theta \\
|G_M|^2 \leftrightarrow (1+\cos^2 \theta)

E_{\text{beam}} = 960-1000\text{MeV}, \\
|G_E/G_M| = 1.64 \pm 0.26

Preliminary
Systematics: ~0.25 nb (~30%)

Cross section

Preliminary

Effective form factor:

\[ |F|^2 = \frac{|G_M|^2 + |G_E|^2}{1 + 1/2 \tau}, \quad \tau = \frac{s}{4m_N^2} \]

Angular distribution is consistent with \( |G_E/G_M| = 1 \).

Preliminary

\[ \sigma_{\text{aver}} = 0.8 \pm 0.2 \text{ nb} \]

A comparison of proton and neutron FFs

Preliminary
Conclusions

1. VEPP-2000 e+e- collider since 2010 had accumulated \( \sim 70 \text{ pb}^{-1} \) data with each SND and CMD-3 detectors in the range \( E=0.3 \) – 2 GeV.

2. Data analysis on meson and nucleon production is in progress. The already collected data have same or better statistical precision on cross sections than previous experiments.

3. First publications on data analysis appeared\((6\pi, \omega\pi^0, \eta\gamma)\), many preliminary results are in preparation for publications.

4. After VEPP-2000 upgrade in 2015 the data taking runs will be resumed with the goal of \( \sim 1 \text{ fb}^{-1} \) of integrated luminosity.
Backup slides
VEPP-2000 Physical program

1. Precise measurement of the quantity

\[ R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \]

2. Cross section measurements of the processes of $e^+e^-$-annihilation into hadrons: $e^+e^- \to 2h, 3h, 4h \ldots$, $h = \pi, K, \eta, \ldots$

3. Study of “excited” vector mesons: $\rho', \rho'', \omega', \omega'' \phi',\ldots$

4. CVC tests: comparison of $e^+e^- \to \text{hadrons}$ cross sections and $\tau \to \nu_\tau + \text{hadrons}$ decay spectra

5. Study of nucleon - antinucleon pair production $e^+e^- \to n\bar{n}, p\bar{p}$ and nucleon electromagnetic form factors, search for N anti-N resonances

6. Hadron production in “radiative return” processes:

\[ e^+e^- \to \gamma^*\gamma, \gamma^* \to \text{hadrons} \]

7. Two photon physics: $e^+e^- \to e^+e^- + \text{hadrons}$

8. Test of high order QED $2 \to 4, 5$
Process $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0 (30\text{pb}^{-1})$

Selection criteria:
- at least 2 charged particles and 4 $\gamma$'s;
- 2 tracks are from IP;
- Kinematic fit:
  $\chi^2 < 40$
- $M_{\pi^0}$ in 70-200 MeV.

The bump is a sum of contributions of $\rho(770)$, $\rho'(1450)$, $\rho''(1700)$.

Main feature – many intermediate states: $\omega\pi^0$, $a_1\pi$, $\rho\pi\pi$, $\rho^+\rho^-$, $\rho f_0$.

Only statistical errors
Systematics $\leq 10\%$

Preliminary
Typical view of $e^+e^- \rightarrow \pi^+\pi^-\gamma\gamma$ event
\( \gamma \gamma \rightarrow \pi^0, \eta \)
Process $e^+e^- \rightarrow \eta\pi^+\pi^-$ (30pb$^{-1}$)

Selection criteria:
2 central charged particles,
2 photons,
$\theta_{\text{charged}}$ (22.5°-157.5°),
$\theta_{\text{photon}}$ (36°-144°),
kinematic fit
($\pi^+\pi^-\gamma\gamma$): $\chi^2 < 20$

Cross section

Preliminary

Systematic error: 4.7%
(1450–1700 MeV)

Fit: sum of
$\rho(770)$, $\rho'(1450)$, $\rho''(1500)$

CVC hypothesis:
$\text{Br}(\tau^- \rightarrow \eta\pi^-\pi^0\nu_{\tau}) = (0.188 \pm 0.058 - 0.057)\%$

PDG:
$\text{Br}(\tau^- \rightarrow \eta\pi^-\pi^0\nu_{\tau}) = (0.139 \pm 0.01)\%$
Process $e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\gamma$

Cuts:
- at least 5\(\gamma\)
- no charged particles
- total energy depos. $> E_{\text{beam}}$
- kinemat. reconstruction:
  $\chi^2_{5\gamma} < 30$; $\chi^2_{\pi^0\pi^0\gamma} - \chi^2_{5\gamma} < 10$; $|M_{\pi^0\gamma} - M_\omega| < 100$ MeV

Fitting:
sum of $\rho(770)$ and $\rho(1450)$
Process $e^+e^- \rightarrow p\bar{p}$ (10 pb$^{-1}$)

Events features (from threshold up to $E_{\text{beam}}=960\text{MeV}$):
- No signal from $p$
- “star” from $\bar{p}$ annihilation in vacuum tube

Events features ($E_{\text{beam}}>960\text{MeV}$):
- charged track and no energy deposition for $p$
- charged track and “star” from $\bar{p}$ annihilation in Cherenkov counters
$e^+e^- \rightarrow n\bar{n}$ $(10 \text{ pb}^{-1})$

**Event signature:**

- Small energy deposition in calorimeter from $n$
- "star" from $\bar{n}$ annihilation point in Cherenkov counters or calorimeter
Main features of the cross section:
1 – cross section has a threshold behavior,
2 – selected events are delayed on 5-10 nsec,
3 – cross section is stable under condition variations,
4 – uniform $\phi$ distribution.

Systematics: $\sim 0.25$ nb ($\sim 30\%$)
$\ e^+e^- \rightarrow n\bar{n}$

Effective form factor:

$$|F|^2 = \frac{|G_M|^2 + |G_E|^2}{1 + 1/2\tau}, \quad \tau = \frac{s}{4m_N^2}$$

Neutron effective time-like form factor (Preliminary)

A comparison of proton and neutron FFs (Preliminary)

Only statistical errors
Cosmic suppression using event time

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

Main parameters:

Calorimeter:

Energy resolution:

\[ \frac{\sigma_E}{E} = \frac{4.2\%}{\sqrt[4]{E(GeV)}} \]

Angular resolution:

\[ \sigma_\phi = \frac{0.82^\circ}{\sqrt{E(GeV)}} \oplus 0.63^\circ \]

Tracking system:

Angular resolution:

\[ \sigma_\phi = 0.55^\circ, \sigma_0 = 1.2^\circ \]

Spatial resolution:

\[ \sigma_R = 0.12cm, \sigma_Z = 0.45cm \]

Aerogel counters:

\[ \pi/K \text{ separation } E < 1 \text{ GeV} \]
CMD-3 for VEPP-2000

Advantages compared to previous CMD-2:
- new drift chamber with x2 better resolution, higher B field
  - better tracking,
  - better momentum resolution
- thicker barrel calorimeter (8X₀->15X₀)
  - better particle separation
- LXe calorimeter
  - measurement of conversion point for γ’s,
  - shower profile
- TOF system
  - time separation for p

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