Recent results from VEPP-2000

KAZANIN VASSILI

On behalf of CMD-3 and SND collaborations
Budker Institute of Nuclear Physics
Novosibirsk State University

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VEPP-2000 collider (2010-2013)

Maximum c.m. energy is 2 GeV, project luminosity is $L = 10^{32} \text{ 1/cm}^2\text{s}$ at $\sqrt{s} = 2 \text{ GeV}$

Unique optics, “round beams”, allows to reach higher luminosity

Experiments with two detectors, CMD-3 and SND, started by the end of 2010
Starting from 2012, energy is monitored continuously using Compton backscattering.

E. V. Abakumova et al., Phys. Rev. Lett. 110 (2013) 14, 140402,
Advantages compared to CMD-2:

- new drift chamber with two times better resolution, higher B field
  better tracking
  better momentum resolution
- thicker barrel calorimeter \((8.3 \times X_0 \rightarrow 13.4 \times X_0)\)
  better particle separation
- LXe calorimeter
  measurement of conversion point for \(\gamma\)'s
  measurement of shower profile
- TOF system
  particle id (mainly p, n)
1 – beam pipe
2 – tracking system
3 – aerogel
4 – NaI(Tl) crystals
5 – phototriodes
6 – muon absorber
7–9 – muon detector
10 – focusing solenoid

Advantages compared to previous SND:
• new system - Cherenkov counter (n=1.05, 1.13)
  e/π separation E<450 MeV
  π/K separation E<1 GeV
• new drift chamber
  better tracking
  better determination of solid angle
Currently the luminosity is limited by a deficit of positrons (650+ MeV) and limited energy of the booster (from 825 MeV). After upgrade (ongoing) we expect luminosity increase by up to factor 10 at maximum energy.

**Collected L ~ 60 pb\(^{-1}\) per detector**

- 8.3 pb\(^{-1}\) \(\omega\)-region
- 9.4 pb\(^{-1}\) region below 1 GeV (except \(\omega\))
- 8.4 pb\(^{-1}\) \(\phi\)-region
- 34.5 pb\(^{-1}\) region higher than \(\phi\)
1. Precision measurement of $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ exclusive approach, up to 1% for major modes;
2. Study of hadronic final states:
   
   $e^+e^- \rightarrow 2h, 3h, 4h, ...$ where $h = \pi, K, \eta$;
3. Study of vector mesons and their excitations:
   
   $\rho', \rho'', \omega', \varphi', ...$;
4. Comparison of cross-sections $e^+e^- \rightarrow \text{hadrons} (I = 1)$ with spectral functions of $\tau$-decays;
5. Study of nucleon electromagnetic formfactors at threshold
   
   $e^+e^- \rightarrow p \bar{p}, n \bar{n}$;
6. Measurement of the cross-sections using ISR;
7. Study of higher order QED processes.

**Overall, we plan to collect $0.5 \div 1 \text{ fb}^{-1}$**
$e^+e^- \rightarrow \pi^+\pi^-$ very preliminary @ CMD-3

$|F_\pi|^2$

2013 data
CMD-3

Work in progress

$\left( \frac{N_{\mu\mu}}{N_{ee}} \right)_{exp}$

$\left( \frac{N_{\mu\mu}}{N_{ee}} \right)_{QED}$

$\chi^2$/ndf
21.39/16

Prob
0.1639

$p^0$
0.9957 ± 0.004684

by momentum

by energy deposition

separation
Main sources of systematics:

separation – 0.2%

multiple ways to get detector response from data itself

fiducial volume – 0.1%

2 independent systems, which can be used to determine fiducial volume

beam energy – 0.1%

constant monitoring with Compton backscattering

radiative corrections – 0.1%

proof from data

Many systematic studies rely on high statistics
$e^+e^- \rightarrow \pi^+\pi^-\gamma @ \text{SND}$

- **$\pi^+\pi^-\pi^0$ mode:** It’s interesting to disentangle the $\rho(')\pi$ and direct $3\pi$ modes, currently the $\rho\pi$ mechanism only is assumed; fit is made with $\omega(783)$, $\omega'(1420)$, $\omega''(1650)$ contributions. To be published;
- **$\pi^+\pi^-\eta$ mode:** fit is made with $\rho(770)$, $\rho'(1450)$, $\rho''(1700)$ contributions, Phys.Rev D91 052013 (2015);
- Systematic error is about 5% for both processes.

**CVC test:**
SND $\text{Br}(\tau \rightarrow \eta\pi\pi^0\nu_\tau) = (0.188 \pm 0.058 - 0.057)\%$;
PDG $\text{Br}(\tau \rightarrow \eta\pi\pi^0\nu_\tau) = (0.139 \pm 0.01)\%$
CMD-3 studied $e^+e^→\eta\pi^+\pi^-$ in two decay modes: $\eta→\gamma\gamma$ and $\eta→\pi^+\pi^-\pi^0$.

- The $\pi^+\pi^-$ mass spectrum agrees with $\rho$, but a search for a non-$\eta\rho$ contribution is in order;
- A CVC test by comparing the $\eta\pi^0$ mass spectrum in $\tau^-$ decays with the energy dependence of $\sigma(e^+e^→\eta\pi^+\pi^-)$ needed;
- A fit of the energy dependence of $\sigma(e^+e^→\eta\pi^+\pi^-)$ will determine the parameters of the $\rho(1450)$, $\rho(1700)$ and their interference.
A \rho^0 is always present, \alpha_1(1260)\pi (\alpha_2(1320)\pi) significant, at higher energies other mechanisms like \rho^0f_0, \rho^0f_2(1270) appear.
Systematic error is 6%, main source is model dependence. High statistics will help to reduce this error.

Preliminary studies of dynamics:
- Main production mode: (phase space or $f_0(1370)$);
- Hint of energy dependent dynamics in 1.7-1.9 GeV energy range;
- $3\pi^+3\pi^-$: The dip structure near $n\bar{n}$ threshold is confirmed;
Search for $e^+e^- \rightarrow \eta'(958) \ @ \ VEPP-2000$

C-even resonances can be produced via

Theory: assuming real $\gamma$, $B(\eta \rightarrow e^+e^-) = 3.7 \times 10^{-11}$. Virtuality and transition form factor can enhance it.

- CMD-3 uses 2.69 pb$^{-1}$ at $\sqrt{s} \sim M_\eta$ to look for $e^+e^- \rightarrow \eta'(958)$, $\eta' \rightarrow \eta \pi^+\pi^-$, $\eta \rightarrow 2\gamma$.
  $\Gamma(\eta \rightarrow e^+e^-) < 0.0024$ eV at 90%CL, Phys. Lett. B740 (2015) 273;
- SND uses 2.9 pb$^{-1}$ at $\sqrt{s} \sim M_\eta$ to look for $e^+e^- \rightarrow \eta'(958)$:
  $\eta' \rightarrow \eta \pi^+\pi^-$, $\eta \rightarrow 2\gamma$, $3\pi^0$,
  $\eta' \rightarrow \eta \pi^0\pi^0$, $\eta \rightarrow 2\gamma$, $3\pi^0$, $\pi^+\pi^-\pi^0$,
- $\Gamma(\eta' \rightarrow e^+e^-) < 0.0020$ eV at 90%CL, Phys. Rev. D 91, 092010;
- Combine SND data with CMD-3:
  $\Gamma(\eta' \rightarrow e^+e^-) < 0.0011$ eV at 90%CL,
  $B(\eta' \rightarrow e^+e^-) < 5.6 \times 10^9$ at 90%CL.
**Transition formfactor** $\gamma^* \rightarrow \omega \pi_0$, $F_{\omega \pi \gamma}$, **cross section of** $e^+e^- \rightarrow \omega \pi^0$

\[
\sigma_{\omega \pi^0} = \frac{4\pi\alpha^2}{E^3} \left| F_{\omega \pi \gamma}(E^2) \right|^2 P_f(E), \quad P_f(E) - \text{phase space factor}
\]

- **Solid line** - fit with $\rho(770)$, $\rho'(1450)$, $\rho''(1700)$, **dashed line** – only $\rho(770)$;
• Analysis uses statistics 32 pb\(^{-1}\);
• First measurement above 1.4 GeV;
• Fit contains sum of \(\rho(770), \omega(782), \phi(1020)\) and \(\rho(1450), \phi(1680)\) with interference;
• It is first observation of radiative decays of \(\rho(1450), \phi(1680)\) mesons;
• Phys. Rev. D 88 (2013) 054013
e^+e^- \rightarrow K^+K^-\pi^+\pi^- \ @ \ CMD-3

CMD-3 studies uses 22 \ \text{pb}^{-1} \ \text{between 1.5 and 2 GeV, more than 10000 events with 3 and 4 tracks observed; Ionisation losses in DC dE/dx provide good K/\pi separation; Analysis of } \pi^+\pi^-, K^+\pi^-, KK \ \text{invariant masses shows clear signals from } \rho^0, K^{*0}(892), \phi^0; \ \text{Many different mechanisms seen: } K_1(1270)\overline{K} \rightarrow K\overline{K}\rho, K^{*}(892)\overline{K}\pi, K_1(1400)\overline{K} \rightarrow K^*(892)\overline{K}\pi, \phi\pi^+\pi^-.
CMD-3, @ \( \phi(1020) \)
Cross-section of \( K^+K^- \) production is shown together with \( K_S K_L \)

Complicated \( \sigma(s) \) due to interference of excited vector resonances
Aerogel Cherenkov counters provide kaon PID
**e^+e^- → K^+K^-η @ CMD-3**

- A data sample of 22 pb\(^{-1}\) collected in 2011-2012 is used to study e^+e^- → K^+K^-η;
- 23 c.m. energy points between 1.57 and 2.0 GeV;
- Analysis method emphasizes the dominant φη signal, studies of non-resonant K^+K^-η needed;
- Rich background with numerous components seen;
- The data sample includes 1600 events of the signal and about 600 background events;
Recent results from VEPP-2000

$e^+e^- \rightarrow K^+K^-\pi^0$ @ CMD-3

Cross section, very preliminary

- The $K\pi$ vs. $K+K-$ plot clearly shows the $\phi\pi^0$ and $K^*(892)K$ mechanisms;
- Cross section is consistent with and more precise than BaBar.
PID by dE/dx, secondaries

Angular distribution allows to measure

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4s} \left( |G_M(s)|^2 (1 + \cos^2 \Theta) + \frac{4m^2}{s} |G_E(s)|^2 \sin^2 \Theta \right)$$

CMD3

$e^+e^- \rightarrow p\bar{p}$ @ VEPP-2000

$\sigma(e^+e^- \rightarrow p\bar{p})$

$|G_E/G_M|$
$e^+e^- \rightarrow n\bar{n} @ SN$D

**Main features of the cross section:**
- Cross section has a threshold behavior;
- Selected events are delayed by 5-10 nsec;
- Cross section is stable under condition variations;
- Uniform $\phi$ distribution;
- First and more precise measurement after FENICE;

**Signature:**
- Small energy in calorimeter from $n$;
- "Star" from $\bar{n}$ annihilation in cerenkov/calorimeter

**Systematics:** ~0.25 nb (~30%)

**Effective formfactor**

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

- VEPP-2000 was running smoothly with CMD-3 and SND in 2011-2013 and collected about 60 pb\(^{-1}\) per detector;
- New channels observed: 3\(\pi^+3\pi^-\), nn, \(\eta\gamma\), ...;
- Various studies of transition form factors are in progress: \(e^+e^- \rightarrow \pi^0\gamma\), \(\eta\gamma\), \(\pi^0e^+e^-\), \(\eta e^+e^-\), \(\eta'\), \(\eta\), ...;
- Extensive studies of multibody dynamics demands MC generators;
- In fall 2015 experiments with an upgraded booster and new injection complex will resume to provide \(L \sim 10^{32}\) cm\(^{-2}\)s\(^{-1}\);
- CMD-3 and SND at VEPP-2000 will provide high accuracy, compatible or better than ISR measurements for HPV, the tentative goals are 0.35% (0.5%) for \(\pi^+\pi^-\) and \(\sim 3\%\) for multibody modes;
- We expect to produce new precise measurements of hadron production \(R(s)\), to improve the precision of the hadronic contribution to muon \((g-2)\).