Study of the processes \( e^+e^- \rightarrow K^+K^-\pi^+\pi^- \), \( K^+K^-\eta \) with the CMD-3 detector at \( e^+e^- \) collider VEPP-2000

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Outline

- VEPP-2000
- CMD-3
- $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$
- $e^+e^- \rightarrow K^+K^-\eta$
- Conclusion
Maximum c.m. energy is 2 GeV, design luminosity is $L = 10^{32} \text{1}/\text{cm}^2\text{s}$ at $\sqrt{s} = 2$ GeV. Unique optics, “round beams”, allows to reach higher luminosity. Experiments with two detectors, CMD-3 and SND, started by the end of 2010.
Study of the processes $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$, $K^+K^-\eta$ (CMD-3, VEPP-2000)

CMD-3 detector

1 – beam pipe,
2 – drift chamber,
3 – end-cap electromagnetic BGO calorimeter,
4 – Z – chamber,
5 – CMD SC solenoid (1.3 T),
6 – electromagnetic LXe calorimeter,
7 – electromagnetic CsI calorimeter,
8 – yoke,
9 – VEPP-2000 solenoid, (not shown) muon range system and TOF system

~ 22 pb$^{-1}$ has been collected in the center-of-mass energy region from 1.5 to 2 GeV
Motivation

- Study intermediate states
- Measure parameters of intermediate mesons
- Calculation of hadronic contribution to anomalous magnetic moment of muon


New \((g-2)\) experiments at FNAL and J-PARC have plans to improve the precision by a factor of four to the level \(1.5 \times 10^{-10}\)

\(\text{LO hadronic contribution } (694.1 \pm 4.3) \times 10^{-10} \text{ HLMNT 11}\)

\(\text{KK2}\pi \text{ c.m. energy region below } 2 \text{ GeV } (3.31 \pm 0.58) \times 10^{-10} \), based on BaBar.

arXiv:1105.3149
Study of the processes $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$, $K^+K^-\eta$ (CMD-3, VEPP-2000)
When all four particles have tracks in DC, energy-momentum conservation is used to extract $e^+e^- \rightarrow K^+K^\pi^+\pi^-$ events.

Momentum of charged particle is reconstructed from the track curvature in DC.

Particle type is identified using information about ionization losses ($dE/dX$) in DC.
K/π separation based on dE/dx in DC

Particle separation is based on minimization of the maximum likelihood function.

Probability density function with momentum and dE/dx as parameters is constructed for kaons $f_K(p, dE/dx)$ and pions $f_\pi(p, dE/dx)$.

Likelihood function $L_{KK\pi\pi}$ is probability that a four-track event is $K^+K^-\pi^+\pi^-$ and defined as:

$$L_{KK\pi\pi}(p, \frac{dE}{dx}, \alpha) = \ln(\prod_i \frac{f_{\alpha_i}(p_i\frac{dE}{dX_i})}{f_\pi(p_i\frac{dE}{dX_i})+f_K(p_i\frac{dE}{dX_i})}), \quad i - \text{track index, } \alpha_i (\alpha) - \text{type of particle for } i\text{-track.}$$

$L_{KK\pi\pi}$ maximum corresponds to the most probable $\alpha_i (\alpha_i)$ combination.
Using $L_{KK\pi\pi}$ for background rejection

$L_{\pi\pi\pi\pi}, L_{KKK\pi}, L_{\pi\pi\pi K}, L_{KKKK}$ are constructed in the same way.
Four-track events

Energy vs momentum histograms are presented for four-track events.

Conditions:
\[ | \Sigma E - 2 \times E_{\text{beam}} | < 100 \text{ MeV} \]
\[ | \Sigma \vec{P} | < 100 \text{ MeV/c} \]
\[ L_{KK\pi\pi} > -2 \]

Cut on likelihood value allows to suppress background by a factor of 20. It was obtained from simulation of processes:
\[ e^+e^- \rightarrow K_s K \pi, \pi^+\pi^+\pi^-\pi^-\gamma, \pi^+\pi^+\pi^-\pi^0\pi^0, \pi^+\pi^+\pi^-\pi^-\gamma. \]
Events with one missing track in DC

Likelihood function $L_{KK\pi\pi}$ for three-track events is constructed in the same way, as it was done for $L_{KK\pi\pi}$ with four tracks.

Momentum of fourth particle is determined by momentum conservation law.

Total energy of four particles minus double beam energy is plotted in histogram.

Histogram is fitted by Gaussian function with quadratic background subtracted.
Dynamics

\[ \phi(1020) \]

\[ \rho^0(770) \]

\[ K^*(892) \]
Simulation

Effective matrix elements have been written for main two-particle intermediate states, which have been chosen according to BaBar results (J.P. Lees et al., Phys. Rev. D86 012008 (2012):

\[ \text{K}^\ast(892) \text{ K}_\text{bar}^\ast(892) \]
\[ \phi(1020)f_0(600) \]
\[ \rho(770) (K+K-)_{\text{Swave}} \]
\[ (K_1(1410) K)_{\text{Swave}} \rightarrow K^\ast(892) \pi K, (K_1(1270) K)_{\text{Swave}} \rightarrow K^\ast(892) \pi K \]
\[ (K_1(1270) K)_{\text{Swave}} \rightarrow \rho(770) K K \]

Maximum likelihood function is given by:

\[ L = \prod_i M_i^2 (\vec{\alpha}, P_{iK^+} P_{iK^+} - P_{i\pi^+} P_{i\pi^+}) , \]

where the multiplication is over the experimental events.

Normalization of the matrix element is performed using simulation events. Events are simulated by four-particle phase space, pass through the detector using GEANT4 package and reconstructed with the same software as experimental data.
Comparison of the experimental angular and momentum distributions with simulation.

**RED** – EXPERIMENT, **BLACK** – SIMULATION, **BLUE** - PHASE SPACE
Calculation of the cross section
\[ \text{e}^+\text{e}^- \rightarrow K^+K^-\pi^+\pi^- \]

\[ \sigma = \frac{N_3 + N_4}{L \cdot \varepsilon \cdot (1 - \delta) \cdot \xi} \]

\[ \xi = \frac{P_1^{4 \text{exp}} + 4 \cdot P_1^{3 \text{exp}} \cdot (1 - P_1^{\text{exp}})}{P_1^{4 \text{mc}} + 4 \cdot P_1^{3 \text{mc}} \cdot (1 - P_1^{\text{mc}})} \]

\[ \varepsilon = \frac{N_3^{\text{mc}} + N_4^{\text{mc}}}{N_{\text{all}}^{\text{mc}}} \]

\[ N_4 = P_1^{4} \cdot N_{\text{all}} \]

\[ N_3 = 4 \cdot P_1^{3} \cdot (1 - P_1) \cdot N_{\text{all}} \]

\[ P_1 = \frac{4 \cdot N_4}{4 \cdot N_4 + N_3} \]

**Efficiency:**
- **red points** – 3+4 tracks
- **black points** – 4 tracks

**Radiative correction**

N\(_4\) — number of four-track events,
N\(_3\) — number of three-track events,
L — integrated luminosity,
\(\varepsilon\) — detection efficiency,
\(\delta\) — radiative correction,
\(\xi\) — corrections, taking into account difference between simulation and experiment,
P\(_1\) — probability to detect one track in DC.
Cross section of the process
\[ e^+e^- \rightarrow K^+K^-\pi^+\pi^- \]
$e^+ e^- \rightarrow \phi \eta \rightarrow K^+ K^- \eta$
Process $e^+e^- \rightarrow K^+K^\pm\eta$

- Process $e^+e^- \rightarrow K^+K^-\eta$ was studied in BABAR experiment in $\eta \rightarrow 2\gamma$ channel ($\sim 480$ events), and in the channel $\eta \rightarrow \pi^+\pi^-\pi^0$ ($\sim 250$ events).
- It is established that the process basically goes through $\phi\eta$ intermediate channel, and the non-resonant cross section $\sigma(e^+e^- \rightarrow K^+\bar{K}^-\eta)$ is suppressed by a factor of 15, so we measure cross section $\sigma(e^+e^- \rightarrow \phi\eta \rightarrow K^+K^-\eta)$.
- Analysis is based on integrated luminosity about 21 pb$^{-1}$ in center of mass energy range $\sqrt{s} \in 1.57 \text{ - } 2.0$ GeV.
- Main decay modes: $Br(\eta \rightarrow 2\gamma) \approx 39.31\%$, $Br(\eta \rightarrow 3\pi^0) \approx 32.57\%$, $Br(\eta \rightarrow \pi^+\pi^-\pi^0) \approx 22.74\%$.
- In this analysis, we use only the tracks of charged kaons in DC, without using of information about the neutral particles. It allows to significantly increase the statistics and facilitate data analysis.
- To perform the analysis, matrix elements were written: $e^+e^- \rightarrow K^+K^-\eta$, $e^+e^- \rightarrow K^+K^-\pi^0$ (using intermediate channel $K^*K$, $\phi\pi^0$ and other), $e^+e^- \rightarrow \phi f'_0(600)$. 

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Selection criteria

- Two tracks in DC from interaction $e^+e^-$ point
- Total charge = 0
- Momentum of particle $\in [40,550 \text{ MeV}/c$
- Ionization losses must conform to ionization losses of kaons.
- $1000 \text{ MeV} < M_{\text{inv}}(K^+K^-) < 1050 \text{ MeV}$
- Constraints on the angle between kaons

So we have two “kaons”

The total energy of particles system defined as:

$$E_{\text{tot}} = \sqrt{P_{K^+}^2 + m_{K^+}^2} + \sqrt{P_{K^-}^2 + m_{K^-}^2} + \sqrt{(P_{K^-} + P_{K^+})^2 + m_\eta^2} - 2 \cdot E_{\text{beam}}.$$
**K^+K^- invariant mass and missing mass**

![Graphs showing K^+K^- invariant mass and missing mass distributions.](image)

- **Number of events** vs. **M_{inv}(K^+,K), MeV**
- **Number of events** vs. **Missing mass of (K^+,K), MeV**

- Peaks for different mass distributions are marked:
  - K^+K^-\pi^0
  - K^+K^-\eta (CMD-3, VEPP-2000)
  - K^+K_0(600)
  - \omega K^+K^-

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Energy of $K^+K^-\eta$ system

All energy points are combined.
Red points corresponds to experiment, blue histogram – simulation of $K^+K^-\eta$,
green histogram – simulation of background, black – simulation of background and signal.
Radiative correction and efficiency
Cross section of process $e^+e^- \rightarrow K^+K^-\eta$

$$\sigma(s) = \frac{N_{\text{exp}} \cdot \text{Corr}}{L(s)\epsilon_{\text{MC}}\epsilon_{\text{trig}} \left(1 + \delta_{\text{rad}}(s)\right) Br(\phi \rightarrow K^+K^-)}$$

BABAR
CMD-3 (preliminary)
statistics $\sim 2500$ events
Approximation of cross section

\[ \sigma_{\phi\eta}(s) = 12\pi P_{\phi\eta}(s) \left| \frac{A_{n.r.}}{s} + \sqrt{B_{\phi\eta} \Gamma_{\phi\eta} \Gamma_{ee}} \left( \frac{\Gamma_{\phi'}}{P_{\phi\eta}(M_{\phi'}^2 \phi')} e^{i\psi} \right) \right|^2 \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BABAR</th>
<th>CMD-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_{\phi\eta} \Gamma_{ee}, \text{eV} )</td>
<td>76.1±16.1</td>
<td>77.8±8</td>
</tr>
<tr>
<td>( M_{\phi'}, \text{GeV} )</td>
<td>1675.0±10.9</td>
<td>1667.0±5.5</td>
</tr>
<tr>
<td>( \Gamma_{\phi'}, \text{GeV} )</td>
<td>141.1±34.0</td>
<td>153.1±19.0</td>
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</table>
Conclusion

• 22 pb\(^{-1}\) was collected in 1.5-2 GeV c.m. energy region.

• Method of \(\pi/K\) separation using ionization losses in Drift Chamber was developed.

• Cross section of the process \(e^+e^- \rightarrow K^+K^-\pi^+\pi^-\) was measured in the energy region 1.5-2 GeV with statistical error about 4-10% (number of four track events is about 12000, three track events - about 15000) and systematic uncertainty is estimated as 7%.

• Cross section of the process \(e^+e^- \rightarrow K^+K^-\eta\) was measured in the energy region 1.57-2 GeV with statistical error about 7-10% (number of events is about 2500) and systematic uncertainty is estimated as 10%.

• New positron injection complex will increase luminosity up to \(10^{32} \text{ cm}^{-2}\text{s}^{-1}\) on 2E=2 GeV and it is commissioned now. After that experiments will be continued and statistics will be increased by a factor of 10.
Thank you for attention!