CMD-2 and SND results on $e^+e^- \rightarrow$ hadrons cross sections

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on behalf of the CMD2 & SND collaborations

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Workshop on $e^+e^-$ collisions from $\phi$ to $\psi$

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Cross-section e+e- → hadrons

Measurement of the cross-section e+e- → hadrons in VEPP-2M energy range is interesting for:

× measurement of parameters of light vector mesons ρ, ω, φ, ρ', ρ'', ω', ω''
× measurement of $R(s)$:

$$R(s) = \frac{\sigma^0(e^+e^- → γ^* → \text{hadrons})}{\sigma^0(e^+e^- → γ^* → μ^+μ^-)}$$

× comparison with spectral functions of the hadronic tau decays
At low s $R(s)$ has to be measured in each channel. The value and the error of the hadronic contribution to muon's $(g-2)$ are dominated by low energy $R(s)$. 
VEPP-2M collider:

- 0.36-1.4 GeV in c.m., \( L \approx 10^{30} \) 1/cm²s at 1 GeV
- Detectors CMD-2 and SND: \( \int L dt \approx 60 \) pb⁻¹ collected in 1993-2000
- Precise energy: \( \Delta E/E \sim 10^{-4} \) with depolarization method; \( 10^{-3} \) from field in magnets
- All major hadronic modes were measured:
  - \( e^+e^- \rightarrow 2\pi, 3\pi, 4\pi, KK, .. \)
  - \( e^+e^- \rightarrow \rho, \omega, \phi \)
1 – vacuum chamber, 2 – drift chamber, 3 – Z-chamber, 4 – superconducting solenoid, 5 – compensating magnets, 6 – BGO end cap calorimeter, 7 – CsI(Tl,Na) calorimeter, 8 – muon system, 9 – magnet yoke.

1 – vacuum chamber, 2 – drift chambers, 3 – scintillation counter, 4 – light guides, 5 – PMT, 6 – NaI(Tl) crystals, 7 – VPT, 8 – iron absorber, 9 – streamer tubes, 10 – iron plates, 11 – scintillation counters
Inclusive Hadronic Cross-Sections with CMD2&SND

Measured cross-sections have difference about 4 orders of magnitude.
Cross-section $e^+e^- \rightarrow \pi^+\pi^-$

Events signature:
- two collinear tracks are almost back-to-back
- vertex located near interaction point

Data sample includes events with:
- $e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$, cosmic muons

Mostly doesn't have any other background at $\sqrt{s} < 1$ GeV
Event separation (CMD-2)

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

- $e/\mu/\pi$ separation using energy deposition
- $N(\mu\mu)/N(ee)$ is fixed according to QED

**Likelihood minimization:**

$$\mathcal{L} = -\sum_{\text{events}} \ln \left( \sum_{\text{type}} N_{\text{type}} \cdot f_{\text{type}} \left| E^+, E^-, E^+, E^-, \cosmics\right. \right) + \sum_{\text{type}} N_{\text{type}}$$

- $\text{type}=e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \cosmics$
Event separation (SND)

Event separation is based on neural network:

- 7 input parameters: energy deposition in each layer for both clusters and polar angle
- 2 hidden layers 20 neurons each
- 1 output parameter - $R_{e/\pi}$
- Trained on simulated events
- Checked on experimental $3\pi$ and $e^+e^-$ events

Distribution by separation parameter

Misidentification ~ 0.5--1%
Pion formfactor

\[ \sigma_{\mu^+\mu^-}^{measured} - 1 = -2 \pm 1.3 \pm 0.7\% \]

\[ \sigma_{\mu^+\mu^-}^{QED} \]

CMD2

SND

Systematic error

CMD2: 0.7%  
SND: 3.2%

0.6% (95)/ 0.8% (98)  
1.2-4.2%
Comparison of CMD-2 and SND

$\sqrt{s} < 0.55 \text{ GeV}$

$\Delta(SND-CMD2) \approx 1.2\% \pm 3.6\%$

$0.6 < \sqrt{s} < 1 \text{ GeV}$

$\Delta(SND-CMD2) \approx -0.53\% \pm 0.34\%$

April 8, 2008
Cross-section $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$

- Systematic error $\approx 10\%$
- Systematic error $\approx 5-7\%$

Efficiency determination gives main contribution to the systematic error.
Cross-section $e^+e^- \rightarrow \pi^+\pi^-2\pi^0;\pi^+\pi^-\pi^0$

$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$

Systematic error

**SND** = 8%

CMD2 = 15% (discrepancy 15-25%)

Problem with efficiency determination was understood

CMD2-reanalysis preliminary = 8%

Systematic error: 5.6% (>1GeV),
1.3% on omega;
2.5% on phi

The curve is the result of the fit taking into account $\omega, \rho, \phi, \omega', \omega''$.  

April 8, 2008
e^+e^- → π^+π^-π^0 at ϕ (CMD2)

\[ \sigma_{3\pi} = (637 \pm 23 \pm 16) \text{ nb} \]

\[ \Gamma_\phi = (4.30 \pm 0.06 \pm 0.17) \text{ MeV} \]

\[ \Phi_{\omega\phi} = 167^\circ \pm 14^\circ \pm 10^\circ \]

\[ \int \! L \! d\tau = 12 \text{ pb}^{-1} \]

\[ N_\Phi = 16 \cdot 10^6 \]
Cross-section $e^+e^- \rightarrow 2K$

$e^+e^- \rightarrow K_S K_L$

$e^+e^- \rightarrow K^+K^-$

Systematic error: SND $\approx$ 3%  
CMD2 $\approx$ 8-9%

Systematic error is $\approx$ 2% at $\phi$ resonance

For data description the $\phi$, $\rho$, $\omega$, $\phi'$ resonances are required.

April 8, 2008  
CMD-2 & SND
Cross-section $e^+e^- \rightarrow K^+K^-$ (CMD2)

1.0 pb$^{-1}$ of integrated luminosity, collected in $E_{cm} = 1010 - 1034$ MeV

Idea of selection

Kaon from $\phi$ meson decay is a low momentum track with big $dE/dx$ value, coming from the beam.

We determine "good" kaon as:

$P_{tot} < 200$ MeV/c

$dE/dx > 2 \, dE/dx_{MIP}$

$R_{min} < 0.4$ cm

$1.0 < \theta_K < \pi - 1.0$.

$N_{R\phi} > 6$, $N_{RZ} > 3$

$\sigma_{R\phi} < 0.07$ cm, $\sigma_{RZ} < 3.0$ cm

We select events with one or two "good" kaons.

542 000 events with one or two "good" kaons were used in the analysis.
Cross-section $e^+e^- \rightarrow K^+K^-$

Systematic errors CMD2 (2008)

<table>
<thead>
<tr>
<th>Source</th>
<th>, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection criteria</td>
<td>1.4</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1</td>
</tr>
<tr>
<td>Acceptance</td>
<td>0.7</td>
</tr>
<tr>
<td>Radiative corrections</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2.2</td>
</tr>
</tbody>
</table>

CMD-2 (1995)  
SND (2001)  
CMD-2 (2008)

CMD-2 (2008)

$B_{ee}B_{KK} = (14.29 \pm 0.05 \pm 0.31) \cdot 10^{-5}$  
$m_\phi = 1019.441 \pm 0.008 \pm 0.080 \text{ MeV}/c^2$  
$\Gamma_\phi = 4.24 \pm 0.02 \pm 0.03 \text{ MeV}$

April 8, 2008

PDG (2006)

$B_{ee}B_{KK} = (14.60 \pm 0.33) \cdot 10^{-5}$  
$m_\phi = 1019.455 \pm 0.020 \text{ MeV}/c^2$  
$\Gamma_\phi = 4.26 \pm 0.04 \text{ MeV}$

CMD-2 & SND
The cross section measurements were based on the $K_S \rightarrow \pi^0\pi^0$ and $\pi^+\pi^-$ decays.

Systematic errors:
- SND - 3.3%
- CMD-2 - 1.7%

Yellow area shows the average value.
Inclusive Hadronic Cross-Sections with CMD2 & SND

Systematic error: \(\sim 0.6 - 0.7\%\)

Total error: \(\sim 6 - 1\%\)

Combine precision of \(R(s)\) from CMD2 & SND

\(1.5\% \quad 1.5 -- 3.5\%\)

\(2.0\% \quad 2.5 -- 3.5\%\)
Conclusions

✗ Despite decades of experiments, precise studies of $e^+e^-$ annihilation into hadrons at low energies are still interesting and provides a lot of important information.

✗ In the 1995-2000 the experiments with CMD-2 and SND detectors at VEPP-2M were fulfilled.

✗ CMD-2 and SND data analyses are nearly completed.

✗ Cross sections of all major modes of $e^+e^- \rightarrow$ hadrons are measured in the energy region $\sqrt{s} = 0.36 - 1.38$ GeV.

✗ Results of these experiments determine nowadays the accuracy of the light vector mesons parameters knowledge. Them are one of the main sources of information about particle physics at low energies.

✗ In a few years new high precision data from CMD-3 and SND working at VEPP-2000 are expected
Example of CMD-2 and SND events

$e^+e^- \rightarrow \pi^+\pi^-$ in CMD-2

$e^+e^- \rightarrow K^+K^-$ in SND
Data taking history

**CMD-2**

- **1994-1995**: 114k $\pi^+\pi^-$
- **1996**: 4k $\pi^+\pi^-$
- **1997**: 33k $\pi^+\pi^-$
- **1998**: $\sim$1M $\pi^+\pi^-$
- **2000**: $\sim$2M $\pi^+\pi^-$

**SND**

- **1996, 1998**: 96, 98, 95, 98
- **1997, 2000**: 96, 98, 98, 2000

Graphs showing $|F|^2$ as a function of $\sqrt{s}$, MeV for CMD-2 and SND.
## Systematic errors

<table>
<thead>
<tr>
<th>Source of error</th>
<th>CMD-2 $\sqrt{s}&lt;1 \text{ GeV}$</th>
<th>SND</th>
<th>CMD-2 $\sqrt{s}&gt;1.0 \text{ GeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event separation</td>
<td>0.2-0.4%</td>
<td>0.5%</td>
<td>0.2-1.5%</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>0.2%</td>
<td>0.8%</td>
<td>0.2-0.5%</td>
</tr>
<tr>
<td>Energy calibration</td>
<td>0.1-0.3%</td>
<td>0.3%</td>
<td>0.7-1.1%</td>
</tr>
<tr>
<td>Efficiency correction</td>
<td>0.2%-0.5%</td>
<td>0.6%</td>
<td>0.5-2.0%</td>
</tr>
<tr>
<td>Pion losses (decay, NI)</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Other</td>
<td>0.2%</td>
<td>0.5%</td>
<td>0.6-2.2%</td>
</tr>
<tr>
<td>Radiative corrections</td>
<td>0.3-0.4%</td>
<td>0.2%</td>
<td>0.5-2.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.6-0.8%</strong></td>
<td><strong>1.3%</strong></td>
<td><strong>1.2-4.2%</strong></td>
</tr>
</tbody>
</table>
How cross-section is measured

All modes except $2\pi$

\[
\sigma(e^+e^-\rightarrow H) = \frac{N_H - N_{bg}}{L \cdot (1 + \delta_H) \cdot \epsilon_H}
\]

- Luminosity $L$ is measured using Bhabha scattering at large angles
- Efficiency $\epsilon$ is calculated via Monte Carlo + corrections for imperfect detector
- Radiative correction $\delta$ accounts for ISR effects only

\[
|F_{\pi}|^2 = \frac{N_{\pi\pi}}{N_{ee}} \cdot \frac{\sigma^B_{ee} \cdot (1 + \delta_{ee}) \cdot \epsilon_{ee}}{\sigma_{\pi\pi}^{\text{pointlike}} \cdot (1 + \delta_{\pi\pi}) \cdot \epsilon_{\pi\pi}}
\]

- Ratio $N(\pi\pi)/N(\text{ee})$ is measured directly $\Rightarrow$ detector inefficiencies are cancelled out
- Virtually no background
- Analysis does not rely on simulation
- Radiative corrections account for ISR and FSR effects
- Formfactor is measured to better precision than $L$
What is really measured?

Definition of $\sigma(e^+e^\rightarrow\text{hadrons})$ depends on the application

- **Hadron spectroscopy**: vacuum polarization (VP) is the part of the cross-section ("dressed"), final state radiation (FSR) is not
- **"Bare" cross-section used in R**: vice versa - FSR is the part of the cross-section, VP is not
- **Measured number of events** include VP and part of FSR allowed by the event selection

**CMD-2** published 2 cross-sections $e^+e^\rightarrow2\pi$:

- $\sigma_{\pi\pi}$  
  - radiative correction take into account part of FSR, allowed by the event selection (thus remove FSR completely from the measured cross-section); VP is left untouched.  
  - Used to get rho-meson mass, width, ...

- $\sigma_{\pi\pi(\gamma)}^0$  
  - VP is removed, all FSR is added.  
  - Used for R calculation

\[
\sigma_{\pi\pi(\gamma)}^0 = \sigma_{\pi\pi} \cdot \left(1 + \frac{\alpha}{\pi} \Lambda_{\text{FSR}}(s)\right) \cdot |1 - P(s)|^2
\]
Comparison of CMD2(95) and CMD2(98)

\[ \Delta (95-98) \approx 0.7\% \pm 0.5\% \]

Plotted is

\[ \frac{\Delta F}{F} = \frac{|F_\pi|^2 \text{ (exp)}}{|F_\pi|^2 \text{ (CMD-2 fit)}} - 1 \]
Comparison with ALEPH ($\tau \rightarrow \pi \pi^0 \nu$)
\[ e^+ e^- \rightarrow \pi^+ \pi^- \pi^0 \text{ at } \phi \ (CMD2) \]

**Dalitz diagram**

\[
N_k^{th} : \int dX dY \left| \frac{r}{p_+} - \frac{r}{p_-} \right|^2 |A_n a e^{i\phi} + A_{\rho \pi}|^2
\]

**CMD-2**

\[
\begin{align*}
\alpha &= 0.101 \pm 0.044 \pm 0.017 \\
\phi &= -2.91 \pm 0.14 \pm 0.07
\end{align*}
\]

**KLOE**

\[
\begin{align*}
\alpha &= 0.104 \pm 0.010 \pm 0.020 \\
\phi &= -2.47 \pm 0.08 \pm 0.08
\end{align*}
\]

... but addition of \( \rho'(1450)\pi \) provides equally good description with

\[
\begin{align*}
\alpha' &= 0.215 \pm 0.092 \pm 0.036 \\
\phi' &= 0.177 \pm 0.132 \pm 0.051
\end{align*}
\]
\[ e^+e^- \rightarrow K_L K_S, \quad K_S \rightarrow \pi^+\pi^- \text{ (CMD-2)} \]

- **2E=1.0-1.04 GeV**
  \[ L=2 \text{ pb}^{-1}, \quad N=2.7 \times 10^5 \]
  \[ \sigma_0(\phi \rightarrow K_L K_S )=1413\pm6\pm24 \text{ nb} \]
  \[ m_\phi=1413\pm6\pm24 \text{ MeV/c}^2 \]
  \[ \Gamma_\phi=4.280\pm0.033\pm0.025 \text{ MeV} \]
  systematic error in \( \sigma(e^+e^- \rightarrow K_L K_S ) \) 1.7%

- **2E=1.05-1.38 GeV**, \( L=5.8 \text{ pb}^{-1}, \quad N=10^3 \)
  systematic error in \( \sigma(e^+e^- \rightarrow K_L K_S ) \) 5-10%

solid curve is VDM with \( \rho(770), \omega(783), \phi(1020) + X \)
dash curve is VDM with \( \rho(770), \omega(783), \phi(1020) \) only
The $e^+e^- \rightarrow \eta\gamma$ cross section

The cross section was measured using $\eta \rightarrow p^0p^0p^0$, $p^+p^-p^0\bar{p}$, and $gg$ decays. For data description the following states are required $\phi$, $\rho$, $\omega$, $\rho'$. The systematic errors in the vicinity of the $\phi$-meson peak are 3-7%.
Inclusive Hadronic Cross-Sections

\[ M_\omega = 782.68 \pm 0.09 \pm 0.04 \text{ MeV} \]
\[ \Gamma_\omega = 8.68 \pm 0.04 \pm 0.15 \text{ MeV} \]
\[ \Gamma_{\omega e^+ e^-} = 0.653 \pm 0.003 \pm 0.021 \text{ keV} \]

\[ M_\phi = 1019.30 \pm 0.02 \pm 0.10 \text{ MeV} \]
\[ \Gamma_\phi = 4.280 \pm 0.033 \pm 0.025 \text{ MeV} \]
\[ Br_{\phi e^+ e^-} = 2.88 \pm 0.09 \cdot 10^{-4} \text{ keV} \]