Measurements of $e^+e^- \rightarrow \text{hadrons}$ at VEPP-2M

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Cross-section $e^+e^- \rightarrow$ hadrons

VEPP-2M energy range:

$\pi^+\pi^-$ production threshold - 1.4 GeV c.m. energy

- parameters of light vector mesons: $\rho$, $\omega$, $\phi$, $\rho'$, $\rho''$, $\omega'$, $\omega''$
- measurement of $R(s)$

$$R(s) = \frac{\sigma^{(0)}(e^+e^- \rightarrow \gamma^* \rightarrow \text{hadrons})}{\sigma^{(0)}(e^+e^- \rightarrow \mu^+\mu^-)}$$

- comparison with spectral functions of the hadronic tau decays
• **VEPP-2M collider**: 0.36-1.4 GeV in c.m., $L \sim 10^{30}$ 1/cm$^2$/s at 1 GeV
• Latest detector generation - CMD2 and SND:
• 75 pb$^{-1}$ collected through operation years 1973-2000
CMD2 and SND detectors

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
Example of CMD2 and SND events

$e^+e^- \rightarrow \pi^+\pi^-$ in CMD2

$e^+e^- \rightarrow K^+K^-$ in SND
How cross-sections are measured

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

- Luminosity \( L \) is measured using Bhabha scattering at large angles
- Efficiency \( \varepsilon \) is calculated via Monte Carlo and corrections for detector imperfections are applied

\[ |F_\pi|^2 = \frac{N_{2\pi}}{N_{ee}} \cdot \frac{\sigma_{ee} \cdot (1 + \delta_{ee})}{\sigma_{2\pi} \text{ (point-like } \pi) \cdot (1 + \delta_{2\pi})} \]

- Ratio \( N(2\pi)/N(ee) \) is measured directly \( \Rightarrow \) detector inefficiencies are cancelled out
- Virtually no background
- Analysis does not rely on simulation
- Formfactor is measured to better precision than \( L \)

- Radiative corrections \( \delta \) accounts for ISR and FSR (except “bare” case required for \( R \))
Event separation (CMD2)

- e/μ/π separation using particles momentum
- can measure N(μμ)/N(ee) and compare to QED

\[ L = - \sum_{\text{events}} \ln \left( \sum_{a} N_{a} \cdot f_{a}(E_{+}, E_{-}) \right), \]

\[ a = e^{+}e^{-}, \mu^{+}\mu^{-}, \pi^{+}\pi^{-}, \text{cosmic} \]

\(<0.6 \text{ GeV}\)

\(>0.6 \text{ GeV}\)
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 - $R_{e/\pi}$

Distribution by separation parameter
Pion form factor (CMD2)

\[ |F_\pi|^2 \]

Systematic error:
- 0.7%
- 0.6% (95)/ 0.8% (98)
- 1.2–4.2%
Systematic error
0.7% 0.6% (95)/ 0.8% (98) 1.2–4.2%
Pion form factor (SND)

<table>
<thead>
<tr>
<th></th>
<th>F₁²</th>
</tr>
</thead>
<tbody>
<tr>
<td>√s, MeV</td>
<td>400</td>
</tr>
</tbody>
</table>

Systematic error
3.2% 1.3%
Comparison of CMD2(95) and CMD2(98)

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

Plotted is

$$\frac{\Delta F}{F} = \frac{|F_{\pi}|^2 \text{(exp)}}{|F_{\pi}|^2 (CMD - 2_{\text{fit}})} - 1$$
Comparison of CMD2 and SND

$\sqrt{s}<0.55$ GeV

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

Systematic errors: CMD2 0.7%  
SND 3.2 - 1.3%

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

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

Systematic errors: CMD-2 0.6%  
SND 1.3%
Comparison with KLOE

Systematic errors: CLOE 0.9 %
Comparison with tau data

ALEPH vs e^+e^-  BELLE vs ALEPH and CLEO
Comparison with tau data

ALEPH vs BELL and $e^+e^-$
Cross-section $e^+e^- \rightarrow \pi^+\pi^-\pi^0$

Systematic error $\approx 7\%$ (outside resonances), $\approx 2-3\%$ (resonances)
Cross-section $e^+e^- \rightarrow 4\pi$

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

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

Systematic error $\approx 5\%$

Systematic error $\approx 8\%$

Efficiency determination gives main contribution to the systematic error
Cross-section $e^+e^- \rightarrow 2K$

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

$e^+e^- \rightarrow K_SK_L$

Systematic error $\approx 5-8\%$

Systematic error $\approx 5-10\%$

Systematic error is $\approx 2-3\%$ at $\phi$ resonance
Overview of the results (CMD2)
VEPP-2000

- Circumference: 24.4 m
- Revolution time: 82 nsec
- Beam current: 0.2 A
- Beam length: 3.3 cm
- Energy spread: 0.7 MeV
- $\beta_x = \beta_z = 6.3$ cm
- $L = 10^{32}$ cm$^{-2}$s$^{-1}$ at $2E=2.0$ GeV
- $L = 10^{31}$ cm$^{-2}$s$^{-1}$ at $2E=1.0$ GeV

$\int L dt \geq 500$ pb$^{-1}$ per detector per year

Total integrated luminosity with all detectors on VEPP-2M $\sim 70$ pb$^{-1}$
Physics at VEPP-2000

1. Precise measurement of $R$ ($\sim 0.4 \%$ for $\pi^+\pi^-$)
2. Study of hadronic channels:
   \[ e^+e^- \rightarrow 2h, 3h, 4h \ldots, h = \pi, K, \eta \]
3. Study of ‘excited’ vector mesons: $\rho', \rho'', \omega', \phi', \ldots$
4. Search for hybrids and exotics
5. CVC tests: comparison of $e^+e^- \rightarrow$ hadrons ($T=1$) with $\tau$-decay spectra
6. Study of nucleon-antinucleon pair production –
   nucleon electromagnetic form factors, search for $NN\bar{\text{n}}$ resonances, ..
7. ISR processes
8. Two photon physics
9. Test of the higher order QED $2 \rightarrow 4, 5$
CMD-3 detector

1 - beam pipe, 2 - drift chamber, 3 - BGO, 4 - Z - chamber, 5 - s.c. solenoid, 6 - LXe, 7 - CSI, 8 - yoke, 9 - VEPP s.c. solenoid
## Systematic errors

<table>
<thead>
<tr>
<th>Source of error</th>
<th>CMD-2 √s&lt;1 GeV</th>
<th>SND</th>
<th>CMD-2 √s&gt;1.0 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>Total</td>
<td>0.6-0.8%</td>
<td>1.3%</td>
<td>1.2-4.2%</td>
</tr>
</tbody>
</table>
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 a few years new high precision data from CMD-3 and SND working at VEPP-2000 are expected.
Backup slides
$e^+e^- \rightarrow \pi^+\pi^-\pi^0$ at $\phi$ (CMD2)

$\Lambda = 12 \text{ pb}^{-1}$

$\sigma_{3\pi} = (637 \pm 23 \pm 16) \text{ nb}$
$\Gamma_\phi = (4.30 \pm 0.06 \pm 0.17) \text{ MeV}$
$\phi_{\omega\phi} = 167^\circ \pm 14^\circ \pm 10^\circ$

$\mathcal{B}_{ee}B_{3\pi} = (4.35 \pm 0.27 \pm 0.08) \times 10^{-5}$
$e^+e^- \rightarrow \pi^+\pi^-\pi^0$ at $\phi$ (CMD2)

$$N_k^{th} = \frac{1}{2} \int \frac{dXdY}{k} | \vec{p}_+ \times \vec{p}_- |^2 | A_n e^{i\phi} + A_{\rho \pi} |^2$$

**Dalitz diagram**

CMD-2
\[ \alpha = 0.101 \pm 0.044 \pm 0.017 \]
\[ \varphi = -2.91 \pm 0.14 \pm 0.07 \]

KLOE
\[ \alpha = 0.104 \pm 0.010 \pm 0.020 \]
\[ \varphi = -2.47 \pm 0.08 \pm 0.08 \]

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

\[ \alpha' = 0.215 \pm 0.092 \pm 0.036 \]
\[ \varphi' = 0.177 \pm 0.132 \pm 0.051 \]
Cross-section $e^+e^- \rightarrow \eta\gamma$ (SND)

$\Lambda = 27.8$ pb$^{-1}$

$\mathcal{B}(\rho \rightarrow \eta\gamma) = (2.53 \pm 0.29 \pm 0.07) \times 10^{-4}$

$\mathcal{B}(\omega \rightarrow \eta\gamma) = (4.70 \pm 0.47 \pm 0.13) \times 10^{-4}$

$\mathcal{B}(\phi \rightarrow \eta\gamma) = (1.354 \pm 0.016 \pm 0.035) \times 10^{-2}$

$\varphi_\omega = (12.0 \pm 7.9 \pm 0.3) ^\circ$

$\varphi_\phi = (170 \pm 13 \pm 4) ^\circ$
Why \( e^+ e^- \rightarrow N\bar{N} \)

\[
\frac{d\sigma}{d\omega} = \frac{\alpha^2 \beta C}{4s} \left[ \left| G_M(s) \right|^2 (1+\cos^2\theta) + \frac{4m_N^2}{s} \left| G_E(s) \right|^2 \sin^2\theta \right]
\]

\( C = y/(1-e^{-y}) \), \( y = \frac{2\pi \alpha m_p}{\beta s} \)

At VEPP-2000 energies:
\( \sigma \sim 0.7 \text{ nb} \) \( L = 10^{31}\text{cm}^{-2}\text{c}^{-1} \) \( \Rightarrow \) 700 events/day
(BaBar from threshold to 2 GeV 874 events)